RICHARD MACY NOYES
1919–1997

A Biographical Memoir by
RICHARD J. FIELD AND JOHN A. SCHELLMAN

Richard M. Noyes

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BY RICHARD J. FIELD AND JOHN A. SCHELLMAN

RICHARD MACY NOYES WAS an exceptionally fine physical chemist who dedicated his abundant personal and intellectual abilities to making the world a better place for his having been a part of it. He directed his scientific work almost entirely toward understanding the details of how chemical reactions occur; making seminal contributions in isotopic-exchange processes, the theory of molecular diffusion in solution, and treatment of complex kinetics and reaction mechanisms; and most memorably, pioneering work on the mechanisms of oscillating chemical reactions and nonlinear dynamics in chemistry. He participated actively in public affairs, mainly through protection of the natural world he loved, promotion of international cooperation, and in administrative and leadership roles at the University of Oregon, where he spent many happy and productive years. His goodwill, integrity, and intelligence were highly valued and respected by all who met him.

Dick was born in Champaign, Illinois, on April 6, 1919, the first child of William Albert Noyes, Sr., and Katharine Haworth (Macy) Noyes. He was the third of four surviving children of his father, then nearly sixty-two years old and chairman of the Department of Chemistry at the University

of Illinois. It is rumored that the senior Noyes near his sixty-fifth birthday responded to the dean's discreet inquiry concerning his retirement plans with an invitation to the christening of Dick's younger brother Pierre, born in 1923 and destined to become a prominent theoretical physicist. The boys grew up in a close but intense and formal Congregationalist family that received many prestigious visitors and emphasized all things intellectual, as well as active summers at the family's rural retreat near Frankfort, Michigan.

William A. Noyes, Sr., was a dominant figure in American chemistry from 1890 to 1930, and in 1977 Dick became at least the fourth descendent of the Massachusetts Puritan leader Nicholas Noyes (1615-1701) to be elected to the National Academy of Sciences. The other three, all professors of chemistry, being his father (Rose Polytechnic Institute, National Bureau of Standards, University of Illinois, elected 1910), half-brother W. Albert Noyes, Jr. (Brown University and the universities of Rochester and Texas, elected 1943), and distant cousin Arthur Amos Noyes (MIT and Caltech, elected 1905). Dick and his father also were elected to the American Academy of Arts and Sciences. The family tradition of scientific excellence and service is further exemplified by the three older Noyeses being president of the American Chemical Society, something Dick himself never aspired to, being somewhat shy personally and preferring to quietly "think globally-act locally." Dick did serve the American Chemical Society on the Nomination and Elections Committee and the Publications Committee, as well as the Committee on Committees and as chairman of the Division of Physical Chemistry.

W. A. Noyes, Sr., founded and was first editor of both *Chemical Abstracts* and *Chemical Reviews*. He and W. Albert Noyes, Jr., were editors of the *Journal of the American Chemical Society* and *Chemical Reviews* (the latter at one point was

simultaneously editor of *JACS* and the *Journal of Physical Chemistry*). A. A. Noyes wrote a number of influential early chemistry textbooks, often based on his own research, and was known as a superb teacher and administrator. Dick served as associate editor of the *Journal of Physical Chemistry* in 1980-82 in order to bring nonlinear dynamics into the mainstream of physical chemistry, and he served on the editorial advisory boards of *Chemical Reviews*, *Journal of Physical Chemistry*, *Annual Review of Physical Chemistry*, *International Journal of Chemical Kinetics*, and *Physical Review A*. The development of departments of chemistry of international stature at the University of Illinois and at Caltech is credited largely to the efforts of W. A. Noyes, Sr., and A. A. Noyes, respectively. Dick himself served four staggered terms between 1960 and 1978 as head of the University of Oregon Department of Chemistry. Dick's maternal grandfather, Professor Jesse Macy of Grinnell College and a teacher of W. A. Noyes, Sr., was widely known in the field of political science, especially international peace and cooperation, an influence Dick felt throughout his life. Katharine Macy was teaching English at Grinnell College at the time of her marriage.

Steeped in these traditions and expectations, Dick entered Harvard College in 1935, shortly after his sixteenth birthday, where, as he occasionally quipped, "Having absolutely no imagination, I majored in chemistry." Chemistry classmates Frank Lambert and Dick Juday remember Dick for his polite demeanor, as well as personal and intellectual discipline, keen, precocious scientific insight, and the ability to express himself clearly. He and Pierre, who also entered Harvard at sixteen, both started their formal training in chemistry at the university level, because their father advised them not to take high school chemistry in Champaign but to wait for Harvard to do it. Dick was one of the top students of the class of 1939, graduating summa cum laude

and a member of the Senior Sixteen elected to ΦBK. He participated fully in undergraduate activities, including house wrestling and crew. The two wrestling victories of "Deacon" Noyes in the final event of the season gave Kirkland House the 1939 campus championship.

Dick chose to do his graduate work at California Institute of Technology, feeling that it had the strongest department in physical chemistry in the country at that time. He chose not to work with Linus Pauling, the dominant Caltech, and perhaps American figure in physical chemistry, because "I was interested in chemical reactions rather than structure." Independence was a mark of Dick's scientific and personal life. But he was correct! Despite the dramatic progress made since 1939, chemical reactions were and likely will remain the most mysterious part of physical chemistry. Dick instead did his Ph.D. with Roscoe Gilvey Dickinson, who had followed A. A. Noyes from MIT, had pioneered X-ray crystallography at Caltech, and had been Linus Pauling's Ph.D. mentor. Dickinson was then interested in chemical kinetics and mechanism and was in close contact with W. Albert Noyes, Jr., a pioneer in photochemical reactions.

Dick finished his Ph.D. in 1942 under the pressure of World War II, working mainly on the simultaneous *cis-trans* isomerization and iodine-exchange kinetics of diiodoethylene. He made some of the very first radioisotope exchange-kinetics measurements using very small samples of unknown isotopes of iodine obtained from a Berkeley cyclotron. Dick often commented that the only chemical reactions that are well understood are those that have not been investigated in detail. That is certainly true in this case, and even in his tenacious last paper on this process in 1967, he is not satisfied completely with explanations of why exchange is so much faster than isomerization.

The war kept Dick at Caltech until 1946 as a temporary

instructor and research associate mainly involved with the analytical and physical chemistry of nitrocellulose smokeless powders. He systematically expanded personal and social interests during his seven years in Pasadena, developing an interest in folk dancing and focusing his intense devotion to the outdoors—mountains in particular. He joined with friends to buy and keep running an ancient Ford for trips to the mountains. Despite less than superb physical gifts, but with intensity, discipline, and enthusiasm, he made a number of climbs in the Sierra Nevada. He became deeply involved with the Sierra Club, in which he played an active role for over 50 years. After Roscoe Dickinson's untimely death in 1945, Dick loyally saw to it that Dickinson's major ongoing work was completed and published. Both at Caltech and later he carried on with some of the research ideas Dickinson was most anxious to see accomplished, especially photochemical space-intermittency, a method for determining the diffusion coefficients of reactive intermediate species.

Dick met and in 1946 married Winninette Arnold, a chemist and daughter of a prominent geologist. The newlyweds left California for New York City to begin his independent academic career as instructor of chemistry at Columbia University. His early work there was built on I_2-exchange kinetics, which could be carried out with good quantitative precision even in the 1940s, and which proved to be exquisitely sensitive to mechanistic detail. The juxtaposition of radical and polar mechanisms, as well as the characterization of free-radical kinetics and mechanism in these and a number of other systems, thermal and photochemical, were carefully and insightfully investigated. Dick continued I_2-exchange work until 1970, creating a characteristically detailed and thorough understanding of how such reactions occur.

This path led him to consideration of the fundamentals

of molecular diffusion and diffusion-controlled reactions in solution. He and graduate student Fred Lampe noted in 1954 that the quantum yield of I_2 resulting from the photolysis of allyl iodide depends on solvent molecular weight, an indication that transport (diffusion) must be an important component of the mechanism. They concluded that the two geminate radicals ($I^\bullet$ and $CH_2{=}CHCH_2^\bullet$) produced in the primary photochemical event must be lodged initially in a "solvent cage" and that a competition must exist between their recombination and diffusion out of the cage in order to participate in secondary reactions leading to I_2. He then extended the cage concept profoundly by asking whether it exists if two radicals are close, even if not geminate. Using the exclamation mark, as Dick often did to display his passion for a remarkable observation: it does! The result is that in very rapid, diffusion-controlled reactions the equilibrium homogeneous spatial distribution of reactive species is destroyed in a manner equivalent to the disruption of the Boltzmann distribution of highly excited species if they are very reactive. The definition of a diffusive encounter becomes very important in this case, and Dick showed that a diffusion-controlled rate constant depends on time because the spatial distribution of very reactive species changes as the extent of reaction increases. The capstone of this work is his 1961 review of molecular diffusion in the first volume of *Progress in Reaction Kinetics.* It remains today a fundamental resource, receiving about 20 citations annually, 36 years after its appearance.

Dick returned in the mid 1950s to Roscoe Dickinson's photochemical space-intermittency suggestion, whose implementation caused him in 1957 to be among the first to solve numerically a reaction-diffusion equation on a digital computer, as well as to undertake prior to laser technology the very difficult experimental problem of projecting sharply

focused leopard and tiger patterns of light into a reactive solution. This eventually successful effort was continued at the University of Oregon, and it was to work on this problem that I (R.J.F.) started in 1968 my long collaboration and friendship with Dick.

Dick and Win were warmly regarded at Columbia. In the department they were especially close with George and Alice Kimball. They were notable for their friendly social manner, close interactions with and concern for students, a broad array of scientific visitors, and an interest in travel and international customs and affairs. Dick had an abiding commitment to world peace, acquired from his father, who was intensely active in this area, especially in the period after World War I. He was a charter subscriber to the *Bulletin of the Atomic Scientists* and a regular participant at the annual meetings of the National Academy of Sciences's Committee on International Security and Arms Control. After being tenured at Columbia he and Win spent a sabbatical year on a Guggenheim Fellowship at Leeds in England.

New York City did not succeed in urbanizing the young couple. They took up backpacking in the Appalachian Mountains long before such a thing was fashionable, and thus it required Win's homemade equipment. They made a systematic effort to reach the highest geographical point of each of the contiguous 48 states, an RMN-like endeavor if there ever was one. They missed the influence and activities of the Sierra Club, and since they could not live in California, they brought the Sierra Club to New York. Dick was instrumental in founding the Atlantic Chapter of the Sierra Club, now the New York Chapter. At the same time he contributed dedicated service to important conservation issues of the day, especially the proposed construction of dams on the Delaware and Colorado rivers. Thus he was a major figure in the conversion of the Sierra Club from a regional

to a national organization. (Later he was chairman of the Northwest Chapter, now split into state chapters, and established Eugene, Oregon, as the first local subdivision of the Sierra Club. In the late 1960s and 1970s he and Win played a major role in the effort to preserve the valley of French Pete Creek, near Eugene. This campaign was successful in 1978 when Congress added French Pete, as well as the adjacent drainages of Rebel and Walker creeks, to the Three Sisters Wilderness, helping to change forever the ethic of the USDA Forest Service and its sensitivity to public concerns.)

Despite these efforts, life in the canyons of New York City, rather than the canyons of the western mountains, was confining for them. They were personally devastated by the loss of two infant sons, Win's bout with tuberculosis, and her long-standing diabetes, as well as some resulting personal and marital problems. Happily for all, the University of Oregon in Eugene at the same time was undertaking the construction of a world-class Department of Chemistry and had identified a group of outstanding younger people to build that department, four of whom went to Oregon and were eventually elected to the National Academy of Sciences. Dick was one of these, and in 1958 he eagerly accepted the position of professor of chemistry and the challenge and joy of helping to build an outstanding department. He and I (J.A.S.) arrived almost on the same day at the University of Oregon and thus began almost 40 years of friendship and scientific association.

In Eugene, Dick continued his work on various aspects of molecular diffusion and isotopic-exchange kinetics, as well as mechanistic studies in related systems. He began new fundamental work on the thermodynamics of ion formation, and he made a major thrust into the reactions of diatomic molecules (e.g., the formation of HI from H_2 and

I_2) presumed at that time to be a concerted reaction proceeding through a four-centered transition state, rather than the currently accepted $I^\bullet$-based mechanism. Much of his time and energy in the 1960s was spent in administration of a rapidly growing department. He was acting head of the department in 1960-61 and head in 1963-64 and 1966-68, with 1964-65 split between Victoria University of Wellington, New Zealand (Fulbright fellowship) and with Manfred Eigen at the Max Planck Institute für Physikalische Chemie, Göttingen. These two locations indicate the breadth of Dick's scientific as well as geographical interests.

By 1969 the combination of administrative work, steady deterioration of Win's health, development of fast direct methods in chemical kinetics, a global and local shift of interest to modern spectroscopic investigation of biochemical systems, some bad luck, and perhaps even his independent streak, left his research running down. The reactions of diatomic molecules thought to be concerted turned out to be mainly orbital-symmetry forbidden and probably radical or even heterogeneous in nature, making them of less theoretical interest. Photochemical space-intermittency is excruciatingly difficult to apply broadly, and he had pushed the diffusion work about as far as he could without taking into account the discontinuous nature of solvents. Dick and Win were increasingly directing their energies toward Sierra Club activities.

In 1969 a scientific challenge appeared that Dick's 30 years of work in complex reaction mechanisms and reactive diffusion had fitted him to meet probably better than any other person in the world: the Belousov-Zhabotinsky (BZ) Reaction. Starting with elucidation in 1971 of the BZ mechanism, he pioneered and solidified over the next 25 years an entirely new area of physical chemistry: oscillating chemical reactions. Over one-half of his 208 scientific publica-

tions are in this area and appeared after his fiftieth birthday.

The second law of thermodynamics requires that all spontaneous processes be accompanied by a decrease in Gibbs free energy; thus a reacting chemical system must move monotonically toward equilibrium. This means that the amounts of some species, referred to as reactants, must always decrease, and that the amounts of other species, referred to as products, must always increase in a spontaneous chemical reaction. Until the 1960s this absolute requirement of monotonic approach to equilibrium was widely thought to forbid oscillations in the concentrations of chemical species during such a reaction. However, the second law requires only that the amounts of reactants and final products change monotonically; the amounts of intermediate species, present in much lower concentrations than those of reactants, may indeed oscillate if the governing dynamic law contains suitable feedback loops. By 1968 Ilya Prigogine and coworkers had used a hypothetical chemical model known as the Brusselator to investigate the dynamic requirements for temporal oscillation, as well as for spontaneous spatial pattern formation, to occur in chemical systems. Both phenomena were dubbed dissipative structures by Prigogine because they are supported by the dissipation of free energy. The final approach to equilibrium however must be monotonic, and Prigogine's work showed that chemical oscillations are a far-from-equilibrium phenomenon. Similar advances were being made in other areas of physics, biology, mathematics, and engineering, partially spurred by the advent of digital computing. These ideas form the basis of what is now known as nonlinear dynamics and complexity theory.

There was in 1969 no unequivocal example of a real chemical reaction exhibiting oscillations based on a mechanism

involving only homogenous component reactions to provide credibility to theory and to serve as a learning tool. The best known system, the IO_3^--catalyzed decomposition of H_2O_2, during which the concentrations of I_2 and I^- oscillate and O_2 is produced in pulses, is still not understood mechanistically, and the gas pulses allowed the oscillations to be attributed to supersaturation rather than to homogeneous chemical kinetics. Solving the BZ mechanism provided the unequivocal example that allowed an explosion of progress to be made. Beyond striking the spark, Dick contributed mightily to the blast that followed. Furthermore, he supplied a great deal of personal and intellectual leadership to the new area of research, working hard to assure communication and cooperation, and the opportunity for all, around the world and of all ages and stature, to contribute and to be respected for their contributions. The co-authorships of his papers are remarkable both for the range of his international collaborators and for the order of authors, which nearly always has Dick's younger or international coworkers first. Dick chaired the 1985 Gordon Conference on Oscillations and Dynamic Instabilities, and he was scientific and financial patron of this conference, as well as those in 1988, 1991, and 1994, working to assure participation of young people, especially from Eastern Europe and underdeveloped countries.

The BZ reaction had a shadowy history in Russia before arriving in Dick's hands. Boris Belousov was unable to publish his 1951 discovery of the oscillations because of the second law shibboleth. A. M. Zhabotinsky continued the work in the 1960s and managed to get word of its existence into the West. News of the BZ reaction reached Eugene in October 1969 with Bob Mazo, a University of Oregon chemical physicist just returned from a sabbatical year with Prigogine in Brussels. Upon hearing that essentially nothing was known

of its mechanism, Dick and I (R.J.F.), soon to be joined by visitor Bandi Kőrös on sabbatical from the Eőtvös Loránd University in Budapest, undertook to change that circumstance. The result in 1972 was the so-called Field-Kőrös-Noyes (FKN) mechanism.

The BZ reaction in its classic form is the metal-ion {e.g., Ce(IV)/Ce(III) or $Fe(phen)_3^{3+}/Fe(phen)_3^{2+}$} catalyzed oxidation of an organic substrate, e.g., $CH_2(COOH)_2$, by BrO_3^- in an acidic medium. Oscillation in the concentrations of intermediate species are driven by the exothermicity of the oxidation of $CH_2(COOH)_2$ by BrO_3^-.

$$3BrO_3^- + 5CH_2(COOH)_2 + 3H^+ \rightarrow 3BrCH(COOH)_2 + 2HCOOH + 4CO_2 + 5H_2O$$
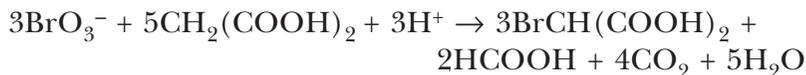
The ratio of the oxidized and reduced forms of the metal-ion catalyst, as well as the concentrations of Br^- and a num-
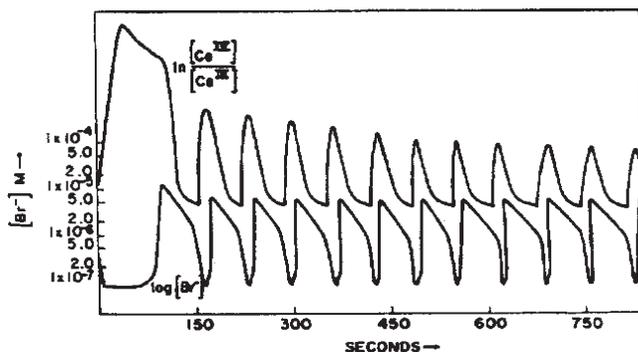

Figure 1.   Belousov-Zhabotinsky oscillations in Ce(IV)]/[Ce(III)] and [Br^-]. [$CH_2(COOH)_2$]$_0$ = 0.13 M (6.7 g), [$KBrO_3$]$_0$ = 0.063 M (5.3 g), and [$Ce(NH_4)_2(NO_3)_6$] = 0.005 M (1 g) in 500 mL of 0.8 M H_2SO_4. Reproduced from R. J. Field, E. Kőrös, and R. M. Noyes, *J. Am. Chem. Soc.* 94(1972):8649-64.

ber of other species, are easily observed to oscillate, some-
times through hundreds and even thousands of cycles as
the overall oxidation reaction rushes toward equilibrium. A
typical experiment is shown in Figure 1.

The FKN mechanism is shown below.

Process A (Polar)

A1   Reduction and exhaustion of Br^-

(R3) $Br^- + BrO_3^- + 2H^+ \rightleftarrows HBrO_2 + HOBr$
(R2) $Br^- + HBrO_2 + H^+ \rightarrow 2HOBr$
(R1) $3 \times (Br^- + HOBr + H^+ \rightleftarrows Br_2 + H_2O)$

(NET: A1) $5Br^- + BrO_3^- + 6H^+ \rightarrow 3Br_2 + 3 H_2O$
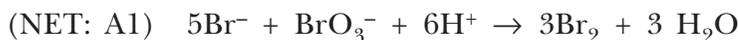
A2 Bromination of organic substrate

(A2) $3 \times (Br_2 + CH_2(COOH)_2 \rightarrow BrCH(COOH)_2$
$+ Br^- + H^+)$

(NET: A = A1 + A2) $2Br^- + BrO_3^- + 3CH_2(COOH)_2$
$+ 3H^+ \rightarrow 3BrCH(COOH)_2 + 3H_2O$
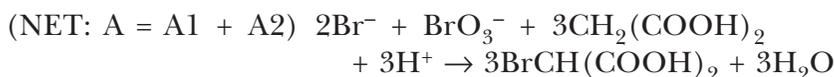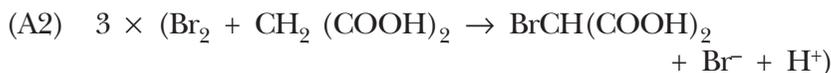
Process B (Radical)

B1 Radical generation and oxidation of Ce(III)

(R5) $2 \times (HBrO_2 + BrO_3^- + H^+ \rightleftarrows 2BrO_2^\bullet + H_2O)$
(R6) $4 \times (BrO_2^\bullet + Ce(III) + H^+ \rightleftarrows Ce(IV) + HBrO_2)$

(NET: B1) $2 \times (HBrO_2 + BrO_3^- + 2Ce(III) + 3H^+ \rightarrow$
$2HBrO_2 + 2Ce(IV) + H_2O)$
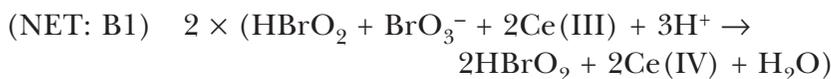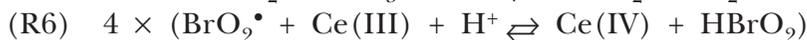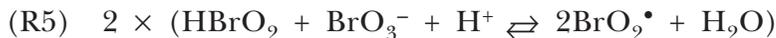
B2 HBrO$_2$ disproportionation

(R4) $2HBrO_2 \rightarrow HOBr + BrO_3^- + H^+$

(NET: B = B1 + B2) $4Ce(III) + BrO_3^- + 5\ H^+ \rightarrow$
$$4Ce(IV) + HOBr + 2H_2O$$
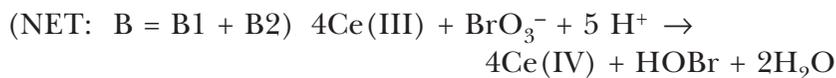
Process *C* (Feedback, regeneration of Br$^-$ and Ce(III))

(C) $Ce(IV) + \sim HOBr + \sim BrCH(COOH)_2 +$
$$\sim CH_2(COOH)_2 \rightarrow Ce(III) + f\,Br^- + \sim CO_2 + ...\ ?$$
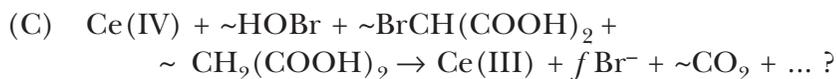
~ indicates variable stoichiometry. *f* is a coefficient indicating the effectiveness of the major negative feedback loop that destabilizes the steady state and leads to oscillation.

Process *A* is a series of polar, two-electron oxidations carried out via oxygen-atom transfers. It is dominant at high [Br$^-$], but its net effect is only the removal of Br$^-$. None of the singlet oxybromine species in Process *A* carry out with any facility the single-electron oxidation of Ce(III) to Ce(IV). Thus high [Br$^-$] inhibits the oxidation of Ce(III) to Ce(IV). However, when [Br$^-$] falls below a critical value, $[Br^-] \lesssim k_{R5}/k_{R2}[BrO_3^-]$, the reaction of HBrO$_2$ with BrO$_3^-$ to yield the radical species BrO$_2^{\bullet}$ (Reaction *R*5) becomes competitive with removal of HBrO$_2$ by Br$^-$ (Reaction *R*2), and the autocatalytic oxidation of Ce(III) to Ce(IV), as well as simultaneous growth in [HBrO$_2$], explodes via the single-electron oxidant BrO$_2^{\bullet}$ in *R*6. Process *C* provides a negative feedback loop via which Process *B* inhibits itself by the production of Br$^-$ from its products, Ce(IV) and HOBr. This brings Process *A* back into control, and the system reinitializes itself as Process *C* reduces Ce(IV) back to Ce(III) at high

[Br$^-$], preparing for the next cycle. The stoichiometric co-efficient f in Process C is the number of Br$^-$ produced per Ce(IV), which must be > 1, but less than some maximum value for the usual pseudo-steady state to be unstable, allowing oscillation to occur. Otherwise either Process A or B retains control indefinitely.

The FKN mechanism removed any doubt that homogeneous chemical oscillations can and do occur solely as the result of nonlinear dynamic structure. The source of the instability and oscillations in the BZ reaction is made clear as resulting from a negative feedback on an autocatalytic process. The FKN chemistry is reasonable and is supported by analysis of a large body of kinetic data, as well as deduction of a thermodynamically consistent set of rate constants for its principal component reactions. Numerical simulations based on the FKN mechanism reproduce nearly quantitatively the observed behavior of the BZ reaction. The chemical world now took chemical oscillations seriously, the shibboleth disappeared, and the search for other examples began in earnest. Many were found, particularly after the development of systematic search techniques by I. R. Epstein and colleagues.

This period of exhilarating scientific adventure and achievement sadly occurred under very difficult personal circumstances for Dick. He and Win had taken 1971-72 as a sabbatical year in Oxford, England, on the prayer that a period of rest would allow her some recovery from the ravages of diabetes. Indeed, the final form of the FKN mechanism emerged in an early-morning phone call between Dick in Oxford and me (R.J.F.) in Eugene. Dick was devastated by Win's death in Oxford in March 1972 after years of his attentive care. In January 1973 Dick married Patricia Harris, a well-known developmental biologist who shared his devotion to science and to environmental matters.

Meanwhile Dick's scientific work continued. His under-standing of diffusion carried over to this work, because, when the BZ reagent is unstirred, the interaction of reac-tion and diffusion of the autocatalytic species $HBrO_2$ may lead to the formation of traveling waves of reaction. Initia-tion of Process B in a small area produces a wave front of metal-ion catalyst oxidation that propagates through an area under the control of Process A, much as a fire moves across a dry field. A wave front is followed by a transient refrac-tory region under the control of Process C. Thus the inter-action of several BZ waves produces elaborate patterns that may serve as models of such diverse biological phenom-enon as Ca^{2+} waves in the cell and the complexity of heart muscle contraction. The reaction-diffusion equation result-ing from the FKN mechanism rationalizes the BZ wave fronts.

The BZ reaction is experimentally reliable, easy to work with, and shows most of the behaviors typical of systems governed by nonlinear dynamic laws (e.g., simple and com-plex oscillations, multistability, excitability, traveling waves, and even deterministic chaos). The connection between the BZ reaction and the mathematics of nonlinear dynamics was made firm by Dick and R.J.F. in 1974 by their introduc-tion of the Oregonator, a simple model derived from the FKN mechanism and similar to Prigogine's Brusselator. It is named after the State of Oregon, and its basic form and significance occurred to R.J.F. during an exceedingly dull sermon. The relationship of the Oregonator, shown below, to the FKN mechanism is made clear by the identifications: $A \equiv BrO_3^-$, $X \equiv HBrO_2$, $Y \equiv Br^-$, $Z \equiv Ce(IV)$, $P \equiv HOBr$, Reactions 1 and 2 $\equiv$ Process *A*, Reactions 3 and 4 $\equiv$ Process *B*, and Reaction 5 $\equiv$ Process *C*.

$$A \;+\; Y \;\rightarrow\; X \;+\; P \tag{1}$$

$$X \;+\; Y \;\rightarrow\; P \;+\; P \tag{2}$$

$$A \;+\; X \;\rightarrow\; 2X +\; Z \tag{3}$$

$$X \;+\; X \;\rightarrow\; A \;+\; P \tag{4}$$

$$Z \;\rightarrow\; fY \tag{5}$$

The Oregonator differential equations,

$$
\begin{aligned}
dx/dt &= k_1\,ay - k_2\,xy + k_3\,ax - 2k_4\,x^2 \\
dy/dt &= -k_1\,ay - k_2\,xy + f\,k_5\,z \\
dz/dt &= k_3\,ax - k_5\,z,
\end{aligned}
$$

reproduce these behaviors, and feedback between this model and BZ experiments was and remains a work horse in the dramatic development of understanding of complex, non-linear dynamical systems that has occurred in most areas of science since the 1970s.

The FKN mechanism and the Oregonator were pivotal to the development of an entirely new and broadly applicable area of science. Ilya Prigogine was awarded the 1977 Nobel Prize in chemistry for his theoretical work on dissipative structures. This likely would not have occurred without the BZ reaction and the FKN mechanism.

Dick underwent heart-valve replacement surgery in 1976, but it did not slow down his scientific work or interest in the world. He continued to work out details of the FKN mechanism and to generalize it to the class of catalyzed and uncatalyzed BrO_3^--driven oscillators. He investigated a large class of chemical oscillators in which gas supersaturation is important, as well as the cobalt-catalyzed air oxida-

tion of benzaldehyde, an important industrial process. He served a final long term as head of his department in 1975-78. He and Pat spent 1978-79 and 1982-83 (Alexander von Humboldt fellowship) at the Max Planck Institute für Biophysikalische Chemie, Göttingen, a center where they both could follow their scientific interests. He formally retired in 1984, but he and Pat continued to travel worldwide as Dick continued service as an international focus and leader of nonlinear dynamics. A series of strokes beginning in 1992 left him increasingly incapacitated, despite his heroic efforts to keep going. He passed away on November 25, 1997.

Dick Noyes was a classic progressive who practiced his conviction that human goodwill and intelligence will lead to a better world for all. His fundamental work on molecular diffusion, the cage effect, and especially the BZ reaction has found its place in textbooks of physical chemistry. Dick himself in his sixtieth year reflected on his life for the 1978-79 edition of *Who's Who in America*:

When I was young, I wanted to be an "explorer." I am fortunate to have a job in which I can make discoveries as exciting as those of the explorers who first sailed uncharted seas. Then I can try to convey the excitement to another generation. As an avocation, I try to influence government policies toward our least developed lands. It is a gratifying mix of satisfying curiosity and serving society.

He will be warmly remembered by the many people whose lives he touched.

WE WOULD LIKE TO thank the following for supplying us with information and insights into Dick's early life and activities: Pat Harris Noyes, Pierre Noyes, Sandy Tepfer, Seymour Adler, Barbara Allred, John Amneus, Edward Anders, David Booth, John Bujake, David Curtin, Ben Dailey, Ted Eyring, Dick Juday, Alice Kimball, Frank Lambert, Fred Lampe, Wolfgang Panofsky, Prudence Kimball Phillips, Charlotte Schellman, and Cheves Walling.

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