Julian Schwinger: Prodigy, Problem Solver, Pioneering Physicist

He made major contributions to atomic, nuclear and particle physics, statistical mechanics, QED and field theory, and discovered many of the principles and methods we now take for granted.

Paul C. Martin and Sheldon L. Glashow

Most theoretical physicists rely on interactions with others to stay abreast of theoretical and experimental advances. In classrooms and seminars, on blackboards and napkins, they exchange and clarify ideas with colleagues and students. Rare is the theoretical physicist who makes repeated and varied contributions apart from the throng; rarer still is one who not only contributes but also sets standards and priorities singlehandedly. Julian Seymour Schwinger, who died 16 July 1994 at the age of 76, was such an individual. Gentle but steadfastly independent, quiet but dramatically eloquent, self-taught and self-propelled, brilliant and prolific, Schwinger remained active and productive until his death. His ideas, discoveries and techniques pervade all areas of theoretical physics.

Most scientists are lucky to make a single significant scientific discovery. No wonder that the events surrounding the repeated triumphs of a great young scientist (the counterpart of a Mozart or a Galois) capture the imagination. In the middle of this century, to physicists and also to a public vaguely conscious of relativity and quantum mechanical uncertainty but keenly aware of the pros and cons of nuclear energy, Schwinger's reputation matched that of earlier giants.

A *New York Times* article describing Schwinger's talk at the June 1948 American Physical Society meeting in Pasadena, California, carried the subhead, "Physicists Awed as Harvard Man of 30 Tells Version of Electrodynamic Forces," under the headline, "Schwinger States His Cosmic Theory." The story went on to say that the "new theory of the interaction of energy and matter . . . presented by Dr. Julian Schwinger, whom American physicists regard as the heir-apparent to the mantle of Einstein . . . is looked upon by top-flight theoretical physicists as the most important development in the last twenty years."

As Schwinger furthered the development of relativistic quantum theory and invented methods for working with the theory, his reputation soared. In the early 1950s the *Journal of Jocular Physics*, a publication of the Bohr Institute for Theoretical Physics, in Copenhagen, included a template for articles by aspiring theorists. It began, "According to Julian Schwinger," and invoked "the Green's function expression for. . . ." References to unpublished Schwinger lecture notes and some classic Schwinger papers followed. Although it brought forth smiles, the recipe was poignantly accurate.

Paul Martin *is the John H. Van Vleck Professor of Pure and Applied Physics and dean of the Division of Applied Sciences at Harvard University, in Cambridge, Massachusetts.*
Sheldon Glashow *is the Higgins Professor of Physics at Harvard University.*

The prodigy

Schwinger was born in upper Manhattan on 12 February 1918. He went to P. S. 186, to Townsend Harris High School (then New York City's leading public high school) and to the College of the City of New York, as had his brother Harold six years earlier. Harold was the outstanding student, the valedictorian, their mother would explain; Julian took teachers and their priorities less seriously. From some, most notably his physics teacher, Irving Lowen, he benefited greatly. But he had better things to do. In high school he had already quietly adopted the policy he articulated more than three decades later: "If you can't join them, beat them." Armed with the 11th edition of the *Encyclopaedia Britannica* and the books and journals in nearby libraries, Schwinger set himself apart from the establishment of teachers, textbooks and assignments.

Schwinger was in the third grade in 1926 when Werner Heisenberg and Paul Dirac were developing quantum mechanics. Eight years later, before completing high school, he had assimilated these ideas and written an unpublished paper extending Dirac's ideas to describe many electrons. By then, word of the wunderkind had spread among graduate students at City College, where he enrolled in the fall of 1934, and at Columbia University, to which—thanks to that institution's support and the subsequent intervention of I. I. Rabi—he was able to transfer in 1936.

By then his abilities were evident to Hans Bethe who, in a remarkable letter to Rabi dated 10 July 1935, wrote: "I entirely forgot that he [Schwinger] was a sophomore 17 years of age. . . . His knowledge of quantum electrodynamics is certainly equal to my own, and I can hardly understand how he could acquire that knowledge in less than two years and almost all by himself." Bethe concludes that "Schwinger will develop into one of the world's foremost theoretical physicists if properly guided, i.e., if his curriculum is largely left to his own free choice."

Apart from the speed of his trajectory (Schwinger completed all of his undergraduate and graduate course work between 1934 and 1937), his activities resembled those of many outstanding young theorists. As a sophomore, with Otto Halpern, he predicted the polarization of electrons by double scattering, and with Lloyd Motz he computed the neutron lifetime. On his own as a junior Schwinger computed how neutrons were polarized by double magnetic scattering from atomic electrons. That the electron current must be treated relativistically by

JULIAN SCHWINGER as a young instructor at Purdue University on the occasion of a visit by Wolfgang Pauli. From left to right in the front row: Pauli, Schwinger, Edward Condon and Joseph Becker. In the back: Karl Lark-Horovitz, William Hansen and David Kerst. (This and all other photos were provided by Clarice Schwinger.)

means of the Dirac equation (that is, that classical approximations made by Felix Bloch were inadequate) was noted *sotto voce*. Next, he calculated the influence of a rotating magnetic field on a spin of any magnitude j. His analysis for $j = \frac{1}{2}$ remains the prototype for all discussions of transitions in two-level systems by "Rabi flipping."

With Edward Teller, during the spring of 1937, he studied coherent neutron scattering by hydrogen molecules. They showed how the spin-dependent zero-energy neutron–proton scattering amplitudes could be determined from the data. This topic was the theme of Schwinger's doctoral thesis.

By the fall of 1937, having earned his undergraduate degree, virtually completed his thesis and written eight significant papers, Schwinger decided to leave New York. He planned to spend one half of the year at the University of Wisconsin with Gregory Breit and Eugene Wigner and the other at the University of California, Berkeley with J. Robert Oppenheimer. However, nights in Madison were so much to his liking that he did not move on to sunny California. By working at night, he kept his distance from Breit and Wigner and thereby was able to set his own agenda and conserve his time for research. He would keep to this nocturnal schedule for most of his career.

During 1938–39 Schwinger was back at Columbia. As house theorist he worked with Hyman Henry Goldsmith, John Manley, Victor Cohen and Morton Hammermesh on nuclear energy-level widths and on the neutron–proton interaction and with Rabi and his associates on molecular beams. He obtained his PhD under Rabi's supervision in 1939. Physicists throughout the world soon learned of the efforts of this precocious 21-year-old to solve the mystery of nuclear forces.

Schwinger spent the next two years at Berkeley, working with Oppenheimer, students and visitors (Herbert Corben, Edward Gerjuoy, Herbert Nye and William Rarita). With Rarita, he determined definitively the role of the tensor force in the deuteron's magnetic and quadrupole moments. He also studied the effects of exchange and tensor forces between nucleons on many particles and processes, including the magnetic moments and quadrupole moments of small nuclei, nuclear pair emission, deuteron photodisintegration and particles of higher spin. The Rarita–Schwinger equation—one of the few of his innumerable contributions that bear his name—was all but forgotten for many years. But this generalization of the Dirac equation to a particle with spin $\frac{3}{2}$, and the study of its invariances when the particles are massless, have been recalled by theorists in describing the gravitino, a fundamental spin-$\frac{3}{2}$ particle in today's supergravity theory.

The war years

Prior to World War II, and despite a ticker tape parade for Albert Einstein, theoretical physics held little fascination for the American public or its major universities. However, with the country's impending involvement in the war, one might have expected the great universities to recruit fiercely an acknowledged young genius who lectured along with Wolfgang Pauli, Frederick Seitz and Victor Weisskopf at the world-famous Michigan summer school for theoretical physics in 1941. They did not. At least in some quarters, a tradition of anti-Semitism persisted. Schwinger was offered, and accepted, a lowly instructorship at Purdue University with just one concession to his preferred work schedule: His introductory physics section would start at noon.

Led by an able physicist, Karl Lark-Horovitz, Purdue attracted first-rate graduate students and postdoctoral fellows. Among them was Robert Sachs, who (as Sylvan Schweber reported in his 1994 book on QED) recalled that in February 1942, "We had to spend the whole time trying to cheer Julian up" at his 24th birthday party "because he had not yet made the great discovery expected of him."

Along with physicists at Cornell University and the University of Rochester, and with colleagues at Purdue, Schwinger spent 1942 and the spring of 1943 working on

WITH I. I. RABI AND VICTOR WEISSKOPF on the occasion of a party to celebrate Schwinger's 60th birthday, in Los Angeles in 1978.

the properties of microwave cavities. This work was supported by, and coordinated with, MIT Radiation Laboratory radar research projects.

In 1943, invited by Oppenheimer to join the Manhattan Project, Schwinger spent the summer at the University of Chicago's Metallurgical Laboratory, where John Wheeler, Eugene Wigner and other scientists were designing the first Hanford reactor. Once again Schwinger worked nights, and so Bernard Feld (formerly a Columbia colleague) decided to work the evening shift so that he could help link Schwinger on the night shift with the members of the day shift.

After "a brief sojourn to see if I wanted to help develop the Bomb—I didn't," recalled Schwinger. "I spent the war years helping to develop microwave radar." Reluctance to follow others' agendas once again helped determine his course. Thus, in the fall of 1943, after most luminaries with nuclear expertise had left the MIT Rad Lab for Los Alamos, Schwinger arrived in Cambridge with little notion that he would remain in the area for more than a quarter century.

Many of Schwinger's colleagues during his three-year stint at the Rad Lab became his lifelong friends. Among them were Harold Levine from Cornell, Nathan Marcuvitz, an electrical engineer from Brooklyn College, and David Saxon, an MIT graduate student. Schwinger's collaboration with Levine led to a series of papers that creatively used variational methods and Green's functions—two themes common to so much of Schwinger's work—to obtain important new results on radiation and diffraction.

His discussions with Marcuvitz underscored the virtues of integral equation formulations, which incorporate boundary conditions of partial differential equations and allow waveguide theory to be cast in the engineering language of transmission lines and networks. The isolation of complex internal properties of components and the characterization of these components in terms of a smaller set of parameters provided new insights into nuclear theory—insights that later gave rise to effective range theory and new formal approaches to scattering theory.

At the Rad Lab Schwinger gave a series of lectures on microwave propagation, for which David Saxon served as his Boswell. Many of the ideas and techniques in them recur in his later theoretical work on quantum mechanics, electrodynamics, nuclear physics and statistical mechanics. So insightful were these lectures that decades later some of them were published in a small volume entitled *Discontinuities in Waveguides*. Reminiscing about them, Schwinger observed that the name "Green" or simply "G" (for Green's function) appeared more than 200 times in the volume's introduction and 138 pages of text. Some powerful relations imposed on scattering amplitudes by time reversibility and energy conservation can also be traced back to Schwinger's work during that period.

As the war ended, Schwinger turned to the physics of high-energy accelerators and the impediments to producing them. It struck him that the energy loss of a highly relativistic electron accelerating in a circular orbit could be straightforwardly derived from the covariant expression for radiation damping, making the fourth-power law for the radiated energy transparent. Such "manifestly covariant" calculations would play an important role in Schwinger's work on quantum electrodynamics. In addition to his work on synchrotron radiation, Schwinger designed a novel accelerator, later called the minotron.

Also to be found on notepads in his desk drawers at that time were calculations of other features of synchrotron radiation and of neutron scattering in a Coulomb field, along with his own group-theory-free approach to the properties of angular momentum using a representation of angular momentum operators in terms of oscillator creation and annihilation operators. "On Angular Momentum," a set of his notes using this approach exhaustively, circulated widely for 15 years before it was finally published in 1965.

Schwinger's long and diverse bibliography, with more than 200 publications, contains no entries for the years between 1942, when he went to Purdue, and 1946. During that period, however, the intellectual and social mores and values of the American public and its premier universities underwent sweeping changes. In February 1946, the month he turned 28, Schwinger was offered and accepted a tenured position at Harvard. Professorship offers from Columbia and Berkeley soon followed, but he turned them down.

The classroom concertmaster

The students attending topflight universities were also a new breed. What had been insuperable barriers to students from Townsend Harris suddenly became superhighways for outstanding students from New York's postwar select public high schools—Stuyvesant, Bronx Science and Brooklyn Tech.

Schwinger's first year at Harvard, 1946–47, was a busy one. He offered courses on waveguides and theoretical nuclear physics, and accepted a number of graduate students whom he set to work on a wide range of problems. Among them were the integral equation formulation of scattering theory (the Lippmann–Schwinger equations) and, with Walter Kohn, investigations of variational principles for scattering. Others working with him included Roy Glauber, Bryce DeWitt and Ben Mottelson. He and longtime friend Herman Feshbach pursued their studies of the internucleon potential.

As the academic year ended, Schwinger and 22 other physicists headed off to the Shelter Island conference on the foundations of quantum physics, where the electrodynamic origin of the spectral lineshift measured by Willis Lamb and Robert Retherford was discussed. Legend has it that Weisskopf and Schwinger proposed that in the Dirac theory compensating effects of electrons and positrons could lead to a cancellation of divergences, whereupon Hans Bethe—on his way home from the conference—recognized that the bulk of the effect could be estimated nonrelativistically.

Four days after the conference concluded, Schwinger married Clarice Carroll, whom he had been courting for several years and with whom he would share the next 47 years.

Schwinger's lectures—from his early days at Harvard on—have been likened to concerts at which a virtuoso brilliantly performs a piece never heard before. Each lecture was an event. Speaking eloquently, without notes, and writing deftly with both hands, he revealed fundamental truths, weaving original examples and deep insights into beautiful patterns. Audiences would listen to his performances with rapture and reverence, seeking to discern the unheralded difficult cadenzas in each. As at a concert, interruptions to the natural flow were out of place. The topics varied, and even courses with the same title—be it electromagnetic theory of light, theoretical nuclear physics, quantum mechanics or the quantum theory of fields—rarely covered the same material the same way. What may not have been apparent to the audience was the careful preparation these lectures required. If Schwinger appeared at the lecture room a bit late, it was not because he left gathering materials for the course he was giving to the last minute. Not only in the early years but throughout his long career, he insisted on staying home the evening before a lecture to prepare exactly what he would say and how best to say it.

For faculty, Schwinger's lectures were surely informative and illuminating. For graduate students and undergraduates, the chance to be part of that privileged audience was inspiring and exhilarating. A lucky subset—his thesis students—could have occasional lengthy private audiences. This privilege was not exploited. "We would," Schwinger's former student Abe Klein noted, "first exhaust all other available resources—our own ingenuity, that of our fellow students, and the literature." To do otherwise seemed sacrilegious.

In his lectures, Schwinger introduced techniques, approaches and examples that strongly influenced significant

SCHWINGER WITH MANY OF HIS DOCTORAL STUDENTS on his 60th birthday.

RECEIVING THE NOBEL PRIZE in Sweden, December 1965.

an overflow crowd that afternoon. He discussed his calculations in fuller detail at the Pocono conference in the spring and in lectures at the University of Michigan summer school. Demonstrating his computational virtuosity, he published his reformulation of relativistic quantum mechanics in three long papers, *Quantum Electrodynamics I, II* and *III*. They include several of the results for which he, Richard Feynman and Sin-Itiro Tomonaga shared the 1965 Nobel Prize in Physics. Those who appreciate Schwinger's eloquence find it ironic that these three uncharacteristically opaque papers should have helped secure his place in Nobel history.

By 1950 Schwinger recognized the need for a more systematic approach to quantum field theory relying upon a covariant quantum version of Hamilton's principle. In 1951, in a pair of brief papers in the *Proceedings of the National Academy of Sciences*, the techniques and concepts on which we field theorists all rely made their appearance. Using "sources" as functional variables, Schwinger provided the functional differential equation version of what, in integral form, is now called functional integration. Of lasting importance, much of this material has been rediscovered by others.

portions of many of today's texts on nuclear physics, atomic physics, optics, electromagnetic theory, waveguides, statistical physics, quantum mechanics and quantum field theory. Many now-standard treatments can be traced to notes taken by the assembled throng.

Word of Schwinger's masterly performances was not limited to the Harvard community. His audiences quickly grew to include faculty and students from throughout the Boston area. Notes taken by John Blatt, an MIT instructor, were shipped to a team of Princeton graduate students who, in swift relays, copied them onto duplicator masters for reproduction. Underground notes in multiple handwritings, with some pages containing picturesque mistranscriptions (such as "military matrices" for "unitary matrices") spread quickly here and abroad. While Schwinger reworked and honed ideas and examples, earlier versions would appear, often without attribution, in articles and lecture notes throughout the world.

Quantum electrodynamics

Not until September 1947 did Schwinger begin to work on the electrodynamic effects responsible for deviations of experimental observations from values predicted by the Dirac equation. Hyperfine-structure measurements of hydrogen, deuterium and tritium by John Nafe, Edward Nelson and Rabi indicated a 0.12-percent error in the electron's magnetic moment, and measurements by Lamb and Retherford displayed a splitting of about 1050 megahertz between states of the hydrogen atom with degenerate Dirac energies. "By the end of November I had the results," Schwinger later recalled. He described them to a capacity audience at an American Physical Society meeting at Columbia University on a Saturday morning in January 1948, giving a command repeat performance to

For theoretical students at Harvard at the time, Schwinger's techniques provided a special language, a common bond and an Aladdin's lamp for parsing, analyzing and solving physical problems:

> The temporal development of quantized fields is described by propagation functions, or Green's functions. The construction of these functions for coupled fields is usually considered from the viewpoint of perturbation theory. Although the latter may be resorted to for detailed calculations, the formal theory of Green's functions should not be based on the assumption of expandability in powers of the coupling constant.

After relating the outgoing wave boundary condition to the vacuum state, the second paper defined functions (such as self-energies and effective interactions) that describe exactly (that is, non-perturbatively) the propagation and interaction of quantum fields. This approach opened the way for major conceptual and computational advances in quantum electrodynamics. A series of papers called the *Theory of Quantized Fields* ensued.

Relativistic invariance and gauge invariance constrain the formally divergent expressions appearing in quantum electrodynamics calculations. Colleagues of Pauli, ignoring the consequences of gauge invariance, had recast and manipulated these expressions to predict a finite photon mass. Schwinger's 1950 paper on vacuum polarization and gauge invariance addressed some of these issues with a novel and elegant proper-time formalism. The nonperturbative properties of a Dirac field coupled to a prescribed external electromagnetic field, first derived in this paper, are still widely used and admired. Schwinger saw that many ambiguities associated with interacting quantum fields lay in the treatment of formal expressions for composite operators such as currents. Indeed, the "triangle anomalies" that play a major role in modern (post 1969) field theory were first identified here and studied further by Schwinger and Ken Johnson during the 1950s. Further studies of quantized fields led in 1958 to Schwinger's important series of papers, *Spin, Statistics, and the TCP Theorem*.

The diagrammatic techniques of Feynman and Freeman Dyson were not foreign to Harvard theorists during the 1950s. With Schwinger's tools, they generated directly and succinctly the connected diagrams with dressed propagators describing various processes. Using them, they calculated lion's shares of the quantum electrodynamic corrections to hydrogen and positronium bound states, and of the higher-order corrections—for example, to the electron's magnetic moment—computed at that time.

Elementary particles and their symmetries

During the 1950s, puzzles posed by elementary-particle physics preoccupied Schwinger. What role could strange particles, whose properties were just being elucidated, play in the grand scheme of things? He was convinced that the answer had to do with their transformation properties under a generalization of isotopic-spin symmetry, which he took to be the four-dimensional rotation group. The group generators, under commutation, defined what would later become known as the "algebra of charges."

Schwinger gathered particle species together, both strange and nonstrange, into representations of his proposed group. In this manner, the otherwise mysterious Gell-Mann–Nishijima formula, which relates charge, hypercharge and isospin, had a natural explanation. It later turned out that Schwinger's intuition was correct, although his choice for the relevant transformation group was not.

The approximate symmetries of mesons and baryons were not shared by the leptons. For these particles, Schwinger proposed a direct analog to isospin. Just such a group was later to become an integral part of today's successful electroweak theory. The known leptons—in Schwinger's perversely original interpretation—were to form a weak isospin triplet: (μ^+, ν, e^-). An immediate consequence of this notion was the selection rule forbidding $\mu \to e + \gamma$ and the obligatory distinction between neutrinos associated with electrons and muons. "Is there a family of bosons that realizes the $T=1$ representation of [the lepton symmetry group]?" Schwinger asked. If so, the charged counterparts of the photon could mediate the weak interactions. Both the vectorial nature of the weak force and its apparent universality would arise as simple consequences of the underlying symmetry structure. He also suggested that vacuum expectations of scalar fields could provide a way of breaking symmetries and giving fermions their masses.

Schwinger's 1957 paper on particle symmetries appeared at a time of rapid progress and great confusion, between the discoveries of parity violation and the *V–A* nature of weak interactions. His ambitious paper concluded with the modest suggestion that "it can be of value if it provides a convenient frame of reference in seeking a more coherent account of natural phenomena." It did just that.

Field theory widely applied

As Schwinger noted in his last paper, a tribute to George Green, the utilization of Green's functions had been central to his work, to that of his students and to physics in general. Going far beyond Green, Schwinger extended the approach to describe many types of correlations of field variables in physical states. Thereby, he introduced a set of functions in terms of which most quantum mechanical and classical measurements (and even some nonmeasurable correlations) can be described—and often calculated.

A 1959 paper with Martin extended Schwinger's vacuum field-theoretic techniques to material systems in equilibrium at non-vanishing densities and temperatures, and a 1961 paper, camouflaged by the title *Brownian Motion of a Quantum Oscillator*, paved the way for studying non-equilibrium systems. Extended by K. T. Mahantappa, Pradip Bakshi, Victor Korenman and many others, Schwinger's approach is now widely used in studies of cosmology, quark–gluon plasmas and microelectronic devices. For years students mastered these techniques and

EXPLAINING RELATIVITY on British television.

many extensions and elaborations by studying the monograph, "Quantum Statistical Mechanics," authored by Gordon Baym (Schwinger's student) and Leo Kadanoff (Paul Martin's student).

As indicated above, for some time Schwinger had recognized that the composite operators for observables must be treated with care. Naive manipulations with canonical commutation relations suggest that the space and time components of a current commute with each other. In 1959 Schwinger published an argument, dazzling in its simplicity, that moved this problem to the fore and identified a class of anomalies, now called "Schwinger terms." He followed it, in papers directed toward the gravitational field, with a study of the conditions imposed on stress tensor commutation relations if a field theory is to be consistent. Today, we recognize the key roles such terms play in particle physics and statistical mechanics.

In the late 1960s Schwinger turned much of his attention to his source theory. The motivation was clear. In spite of field theory's early triumphs, prospects for predicting the results of experiments involving strongly interacting particles from a unified field theory seemed dim. So were the prospects for a renormalizable theory of the electroweak interactions. Whether or not a local field theory existed, effective Lagrangians could be used to make predictions at sufficiently low energies. Why not try to develop a theory that would progress in the same way as experiment—from lower to higher energies? Source theory offered mechanisms for reaching these modest goals.

As gauge field theories were shown to be renormalizable and in accord with more phenomena, incentives to spurn field theory lessened. But Schwinger remained steadfast. Differences in the philosophical underpinnings and predictive powers of source theory and field theory were, in his view, enormous. Might he have been waiting and hoping for new experiments to display structure absent from the standard model and "reopen the ball game"?

In 1971 the Schwingers left Harvard and their Belmont home for UCLA and the Bel Aire hills. In sunny southern California, with students, new collaborators and longtime friends, Schwinger continued working on source theory ("source" appears in the title of more than 15 publications) and contributing significantly to a host of interesting physical problems not in vogue. With Lester DeRaad Jr and Berthold-Georg Englert, he explored statistical models of the atom that extend the Fermi–Thomas approximation and, with Kimball Milton and DeRaad, various aspects of the Casimir effect. In his new surroundings he published more than 70 papers. Ever the independent optimist, he maintained the hope that somehow, in some way, through highly nonlinear effects, perhaps related to intriguing sonoluminescence experiments under way at UCLA (see PHYSICS TODAY, September 1994, page 22), cold fusion might prove feasible.

Teacher and mentor

The enormous impact of Schwinger's lectures and lecture notes defies documentation. Many ideas and approaches introduced in his lectures and never published will circulate forever without attribution; some may be attributed to others who adapted, adopted and published them. Occasionally, a gem appears to remind us of the riches he provided. In his recent article on George Green, Schwinger recalls being stimulated in 1964 "to rescue from the quiet death of lecture notes" a beautiful discussion of Coulomb Green's functions "worked out to present in a quantum mechanics course given in the late 1940s." The bound-state momentum-space wave functions are deftly and concisely constructed as four-dimensional spherical harmonics.

Notes for that course also include elegant and revealing unpublished treatments of Coulomb scattering and of the unusual ways in which the Stark effect lifts hydrogenic degeneracies. These and other jewels should become available when the UCLA archives assembles lecture notes, chapters and preliminary editions of books on quantum mechanics, field theory and electromagnetism that failed to meet his demanding standards.

Not only as a brilliant scientist and expositor, but also as a mentor of future generations of theoretical physicists, Schwinger made contributions that cannot be overestimated. He directed the research of some 70 doctoral students and perhaps 20 postdoctoral associates who, in turn, have amplified his personal influence immensely over the past 40 years.

Two features shared by Schwinger's professional offspring are striking: the diversity of their specialties and the consistently high regard and great debt they express for his mentorship. The group includes leaders in particle theory, nuclear physics, astrophysics, gravity, space physics, optics, atomic physics, condensed matter physics, electromagnetic phenomena and applied physics. It also includes many who, like Schwinger, have worked in a variety of fields, mirroring Schwinger's own broad interests and his passion for seeking patterns and paradigms that put new facts in proper perspective.

Most theoretical physics students at Harvard wanted to work with Schwinger, and he accepted almost every qualified student who asked. Their recollections are remarkably uniform. Schwinger posed problems when requested and sometimes offered students and colleagues notes on problems to pursue, but he also welcomed students who preferred to formulate their own thesis topics. Few ex-students considered him a close friend, but almost all speak fondly of his kindness and generosity. He was considerate and willing to do his best to provide scientific advice when he thought help was needed. His insights and suggestions were often decisive.

Schwinger also had a remarkable knowledge of matters nonscientific, and a gentle humor. While not relaxed enough to relish media stardom, he enjoyed presenting relativity to a wide audience in a popular book and on BBC television. He was always willing to lend his name and support to worthy causes. Fond recollections of the warmth and interest displayed by both Julian and Clarice Schwinger abound.

Throughout his life Schwinger conveyed not only knowledge but also lofty aspirations: to approach every problem in a broad context, but to assume as little as possible; to seek new and verifiable results, and to present them as elegantly as possible; to avoid energy- and time-consuming political maneuvering; to understand, extend, unify and generalize—to reveal the hidden beauty of nature. Walter Kohn spoke for all Schwinger's students in saying, "We carried away the self-admonition to try and measure up to his high standards; to dig for the essential; to pay attention to the experimental facts; to try to say something precise and operationally meaningful, even if—as is usual—one cannot calculate everything *a priori*; not to be satisfied until ideas have been embedded in a coherent, logical and aesthetically satisfying structure."

We have benefited greatly from comments and suggestions by Stephen Adler, Gordon Baym, Lowell Brown, Stanley Deser, Roy Glauber, Kenneth Johnson, Margaret Kivelson and Norman Ramsey, and from the information gathered by Silvan Schweber for his book, QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga *(Princeton U.P., Princeton, New Jersey, 1994).* ■