NATIONAL ACADEMY OF SCIENCES

# W. CONYERS HERRING
# 1914–2009

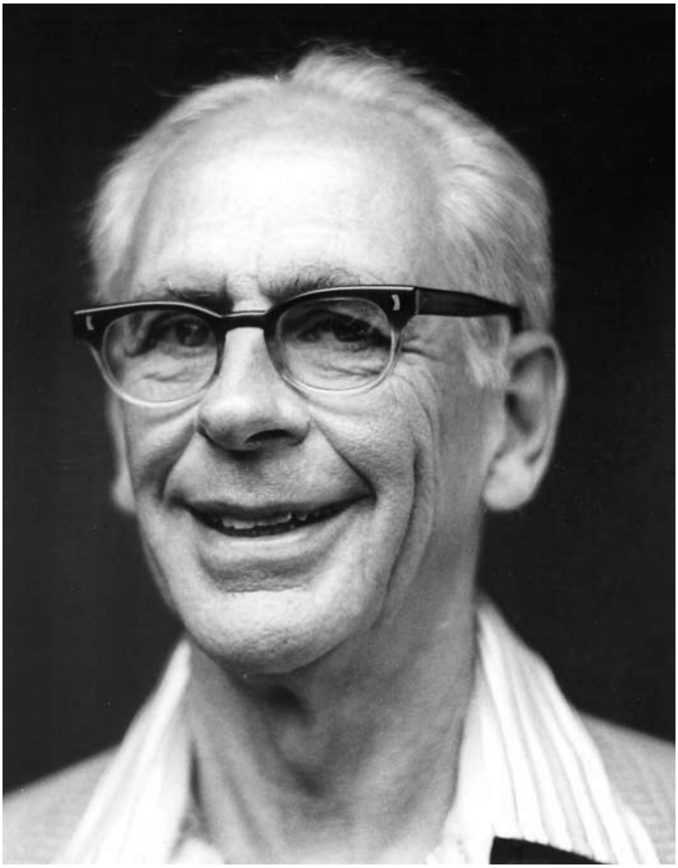
*A Biographical Memoir by*

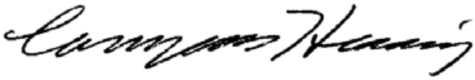
BY PHILIP W. ANDERSON, THEODORE H. GEBALLE,

AND WALTER A. HARRISON

*Any opinions expressed in this memoir are those of the authors and do not necessarily reflect the views of the National Academy of Sciences.*

*Biographical Memoir*





# W. CONYERS HERRING

*November 15, 1914–July 23, 2009*

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William Conyers Herring passed away at his home in Palo Alto, California, on July 23, 2009, at the age of 94. He had suffered a heart attack in the early 1980s but remained active until the mid-1990s. His scholarly interests embraced all aspects of solid-state physics during the last six decades of the 20th century. His contributions brought major new understanding to band theory, semiconductor physics, and magnetic, transport, and thermal phenomena. His theories of solid-state diffusion, plasticity, sintering, and surface properties are of fundamental importance in materials science. His scholarly review articles remain of lasting value. Conyers was readily approachable and widely consulted by colleagues throughout the world.

Conyers was born on November 15, 1914, in Scotia, New York, the only child of William and Mary Herring. His father was a physician and his mother a nurse. Conyers delighted in telling how his father as a young man was dropped by ship in the south of Japan and how he traveled across the island on a penny-farthing bicycle, to be picked up on the other side. This was 1881, only 27 years after Commodore Matthew C. Perry opened Japan to the West. Once his father left the coast, the people he met had mostly never seen a white man, or a bicycle.

The family moved to places in North Carolina and Mississippi before settling down in Parsons, Kansas, when Conyers was five and he grew up there through his school years. He had already learned to read quite well, apparently on his own. When he started school, he was put in the fifth grade, able to read better than most but had to catch up on arithmetic. Being four years younger than his classmates, he was subjected to teasing, and as he told his wife, Louise, it was hurtful and he vowed never to treat others that way. In junior high he became interested in electricity and in astronomy and with friends constructed crystal sets. Unfortunately, they were unsuccessful in picking up radio signals—the nearest broadcasting station was 150 miles away. His father's death when Conyers was 13 left the family impoverished, but one year later he was awarded a full scholarship by the University of Kansas. In his oral history interview for the American Institute of Physics with Lillian Hoddeson in 1974 he recounts that in the summer following his junior year his interest in astronomy led to his reading Eddington's *Mathematical Theory of Relativity*. In the fall he gave a lecture course on the subject (*http:www.aip.org/history/story/ohilist/4666_1.html*). After completing his bachelor's degree in astronomy in 1933, he spent a year studying at the California Institute of Technology, where he took a course in quantum mechanics from J. Robert Oppenheimer. He was hesitant because the others sitting in were professors, but E. C. Watson, the faculty adviser for graduate students, suggested he sign up; he would be the only registered student and Oppenheimer would have to, and did, lecture to him.

Conyers was frustrated with the number of required courses and transferred to Princeton, which had also offered him a fellowship and allowed much free time for him to pursue his own interests. He became interested in solid-state physics after meeting Fred Seitz and John Bardeen and reading the Sommerfeld-Bethe article in the *Handbuch der Physik*[1]. He joined Eugene Wigner's small, informal group organized by Ed Condon that included Bardeen who was just completing his thesis; Seitz, who had just completed his; and John Blewett. They met regularly and together created the modern band theory of solids. Wigner remarked years later that whenever he did not know something and wanted to find out, the first thing he did was to go and ask Conyers.

Conyers wrote his thesis over the summer that he spent with his mother on Staten Island, working alone and without a library. It was accepted by Wigner and published in *Physical Review* in two papers[2,3] before he formally received his degree. They were prescient studies of the degeneracy due to time reversal symmetry and of accidental degeneracy where there is no symmetry at all. In the latter case he proved an important theorem that no infinitesimal change in the crystal potential can lift the degeneracy.

Conyers received his Ph.D. in 1937 and spent the next two years at MIT supported by a National Research Council Fellowship. During that time, he invented the orthogonalized plane wave (OPW) method,[4] the first workable scheme for calculating the electronic energy bands in solids, and the basis of modern pseudopotential theory. With A. G. Hill[5] he used the OPW method to calculate the band structure of beryllium and the method was subsequently employed by Frank Herman at RCA to make the first realistic band structure calculations of germanium and silicon. There he was also asked by Marvin Chodorow, a graduate student of John Slater, what to use for a potential for a copper calculation, because a Hartree-Fock approach would be too complicated. Conyers's suggestion using a simple potential that gave the right answer for the copper atom was the seed that grew to free-electron exchange by John Slater, and then density-functional theory, formulated later by Lu J. Sham and Walter Kohn, the basis of most modern electronic-structure calculations.

At that same time, as told to Richard M. Martin by Conyers, Richard Feynman was an undergraduate student advised by Slater. As a student Feynman wrote a paper giving what Slater called the Hellmann-Feynman theorem, though Hellmann's role was marginal, being only the author of a text that gave a formal derivation of a general expression. Feynman's paper that gave the now well-known physical interpretation acknowledged Conyers for his "excellent criticisms," and gave no other references. The Hellmann-Feynman theory is now central to many treatments of the forces on atoms.

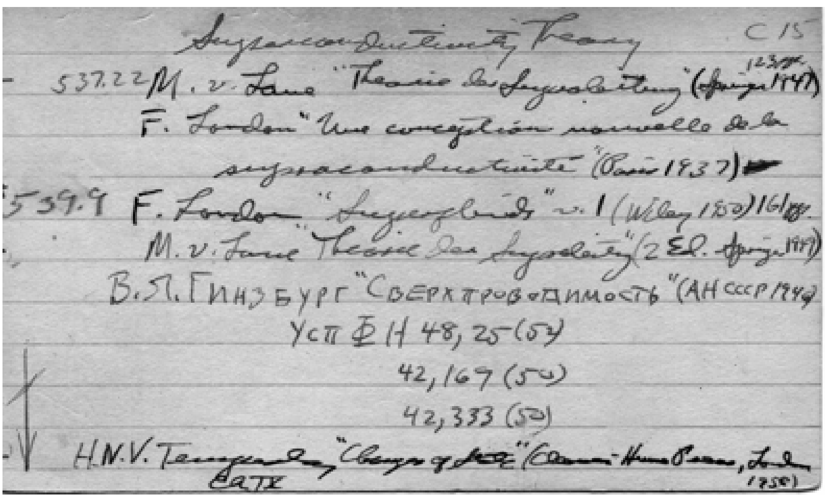
Conyers taught physics at the University of Missouri before joining the Columbia University Division of War Research in 1941, which occupied the entire 64th floor of the Empire State Building. That division was engaged in undersea warfare. He found time to make an important study on the transmission of explosive sound in the sea.[6] He was also made a part-time member of the operations research group located in Washington, which was set up to counter the severe losses that German submarines were inflicting along the east coast shipping lanes. The Germans had found ways of detecting and rendering relatively useless the 30 cm radar being used to detect the submarines. Not so with the newly developed and very effective 10 cm radar made operational after being developed at the MIT Radiation Laboratory, because the German Navy was not able to identify the radar for a long time. Fortunately for the Allies, the German army had captured an operating 10 cm radar but had not informed their navy because of tight internal security.

At the end of the war Conyers became a professor of applied mathematics at the University of Texas but only for a short time. In 1946 he was attracted to the Bell Laboratories in Murray Hill, New Jersey, by William Shockley, who had been impressed with Conyers's work during the war. That same year he met Louise Preusch in Bear Mountain, New York, where the 23rd Street YMCA of New York City held retreats. She had just graduated from Barnard College in mathematics and physics. They soon married and settled in Summit, New Jersey, where they raised their four children: Lois, Alan, Brian, and Gordon. They were devoted parents and active participants in school activities.

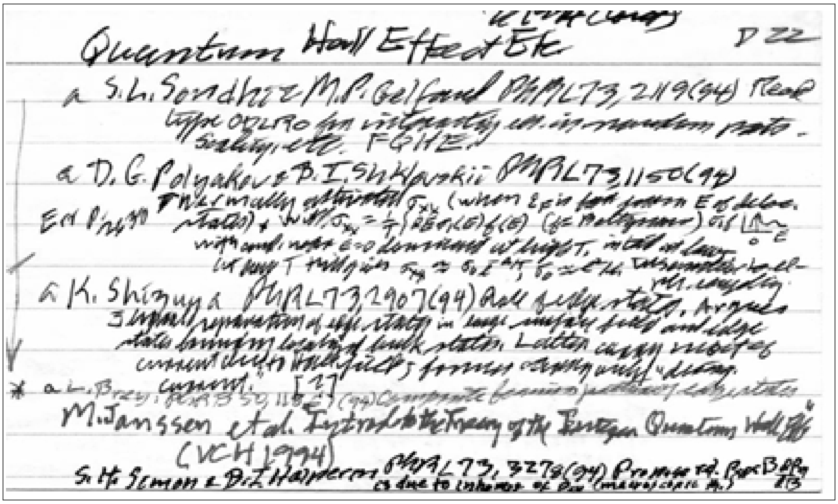
In 1956 Conyers was instrumental in creating the theoretical physics department at Bell from the strong group already there. It was organized democratically with a rotating chair. After two years, he relinquished the chair to Phil Anderson, who in turn passed it on after another two years; but Conyers's strong influence remained crucial. Perhaps its quality can best be illustrated by the fact that the first postdocs hired were J. J. Hopfield, J. C. Phillips, and T. M. Rice. It became recognized internationally as the premier solid-state theory department and attracted outstanding candidates, postdocs, and visitors from the United States, Europe, and Asia.

Conyers and Louise were gracious hosts and made many friends throughout the world. Conyers also kept himself informed of new advances by spending many hours in the library, reading the latest journals as they arrived at the extensive Bell library. He preserved the information with handwritten scrawls on 3 × 5 cards that he stored in a big black suitcase he jokingly called his "brain box." The habit of jotting down references and filing them carefully for later retrieval had begun innocently back in his student days. It continued during his long professional career, eventually amassing more than 15,000 cards on which were scribbled more than 100,000 scientific citations and corresponding notes. The brain box was conceptually similar to a modern computer-searchable database, except that the entries were carefully selected. Each corresponded to a journal article or book that Herring had read, thought about, and judged to be important. He was able to use it with immense effect over time at Bell and elsewhere, as someone who knew things not just vaguely but in sharp detail. Notwithstanding the rise of modern electronic research, the brain box remains a remarkable creation today not just because of its comprehensiveness and good taste, which will never become dated, but also because of its historical significance. It is a remarkable compilation of the golden age of physics and the birth of the electronic age.

The following two figures show representative cards. In keeping with Herring's wishes, a project to digitize the brain box and post it on the Internet has been undertaken by Prof. R. B. Laughlin.




"C15-superconductivity theory," with references to papers of von Laue, London, Ginzburg, and Temperley.



A card generated 40 years later referencing ongoing quantum Hall work by Sondhi, Shklovskii, Halperin and others.

In order to keep up with the important work being done in the Soviet Union during the cold war, and not wanting to depend upon much delayed translations, Conyers simply learned Russian. More than one successful experimental development at Bell Labs owed its existence to Conyers's survey of the Russian literature (for instance, electron-hole droplets, mentioned by Maurice Rice below). He was a member of the first delegation from the United States to visit the Soviet Union during the Cold War. As a gesture of respect he gave some lectures in Russian. Conyers thought carefully before speaking and his lectures, even in English, were slow-paced. A Russian visitor to Bell Labs, on the *quid pro quo* return visit to Bell, discreetly commented that they would have preferred for him to have given them all in English.

Conyers kept Bell Labs colleagues and visitors alerted to important advances in science by running what became a celebrated weekly journal club. Qualified colleagues were solicited to give short presentations on promising publications that he had noted. The 2,600$^{th}$ (more or less) special session of the journal club was held at Stanford on November 18, 1994, in honor of his 80th birthday. The following abbreviated quotes taken from talks and letters show the extraordinary appreciation of his colleagues:

Walter Kohn wrote: "Conyers, those many summers at Bell Labs when I and Quin [Luttinger] used to come to our Solid State Mecca, and learn the difference between real science and the typical *Phys. Rev.* papers, [when] barely 40, you were already the wise old man, to whom we all went for advice and information, those were among the best and most stimulating times of my life. Great science, great hospitality, unbearable heat and humidity, yes, those were the days."

David Turnbull: "With John Bardeen he [Conyers] made the key pioneering contribution to the theory of correlation effects in solid state diffusion. His theory for equilibrium configurations of surfaces is still a landmark in materials science."

Jacques Friedel: "For me you have been a great example, first on the fact that metal physics and electronic structures on the one hand, and metallurgy and crystal defects on the other, could be attacked usefully by the same man, and were complementary. But perhaps more important, I took from my early contact with you the idea that physics had to be strict in its reasoning but could be great fun."

William O. Baker: "We seek to symbolize the meaning of the Journal Club achieved by the time of your eighth decade. That meaning is not less than a strategic element in the growth of solid state physics. You reflected from the very beginning the principal that the advance in science is cumulative, and represents the assimilation of theory and experiment that has been, and is, going on. This classic principle of all research has often been neglected in the hurry and diversity of 20th century science, but your example has notably advanced its observance in solid state work."

Phil Anderson: "I can best describe the massive impact you have had on solid state physics by visualizing a tree structure of the scientific literature of solid state physics. I colored red all the branches which originate in papers which were either yours or had (or should have had) an acknowledgement of your invaluable help. My conclusion is that the whole tree would have ended up being bright red."

Fred Seitz: "The integrated effect of his very profound work has been enormous. He has never let any issue that needs explication pass by unnoted and was a prime mover in raising the standards of research."

David Pines: "You were responsible for making a key link between the theoretical work Dave Bohm and I were doing on quantum plasma oscillations in metals and the experiments on electron energy losses in solids."

Maurice Rice: "There are so many Journal Clubs I remember with affection. The one that stands out was Prokrovski's first luminescence spectra and Keldysh's speculation of a condensed metallic electron-hole liquid. It determined my research and exciting times for many years.

Frances Hellman: "Even as a young [Stanford] student, even if I (and most of the audience) initially had no idea why he was asking the seminar speaker a particular question, it always turned out to be a profound one going right to the heart of the problem. Later in writing my thesis, I thought I had a clever idea, describing a thermally driven compositional inhomogeneity. Conyers upon reading the chapter promptly reached into his famous black suitcase, pulled out a card and said, 'This is known as the Soret effect; it was discovered 100 years ago and here are the references.'"

Albert Overhauser asserted that Conyers was "the Patron Saint of Referees."

Conyers's most productive years were at Bell Labs. In 1949 he and M. H. Nichols published a highly valued review of thermionic emission, including thermodynamic and quantum-mechanical treatments, and an original theoretical analysis of the temperature variation of the work function.[7] It was the forerunner of other scholarly reviews he wrote, which led to his being honored in 1980 by the National Academy of Sciences with the James Murray Luck Award for excellence in scientific reviewing.

In 1950 Conyers contributed the theory for the shift of the nuclear magnetic resonance frequencies in metals caused by electronic paramagnetism [the Knight shift] that had been discovered experimentally by Charles Townes and Walter Knight.[8]

In 1951 Conyers and Charles Kittel published a seminal paper on spin waves in metals,[9] which—along with Bohm and Pines's discussions of plasmons, and primitive beginnings by the Russian school—was the origin of the idea of collective excitations of the electron gas in metals. These works are the first to treat what Landau later termed the "Fermi liquid" as a collectively interacting fluid and six years prior to Landau's zero sound. Conyers followed this up with two scholarly papers estimating the stiffness of Bloch walls in ferromagnetic systems, from which he could obtain the spin-wave spectrum.[10,11] These seminal papers, far ahead of their time, have been neglected by historians of many-body theory.

Many years later he took up the very different problem of exchange between "well-separated atoms"[12] He invented a very ingenious and rigorous formulation of this complicated problem, which nicely illustrates both the pitfalls that can be encountered and the generalizations that can be achieved. He gave the picturesque name "the stay-at-home principle" to one of them. Others associate the name of Mott with it. In his book on magnetism, which started out as a mere chapter of the Suhl-Rado series of books, he synthesized his various different understandings of magnetic interactions. John H. Van Vleck in reviewing that book[13] said, "The preprint at Harvard was so bulky it was usually called the telephone book, because of its origin at Murray Hill and its accuracy, attention to detail and usefulness, but it has one detail that the telephone book lacks—the quality of being critical in the best sense of the word."

In 1954 Herring explained the anomalously large and temperature-dependent thermoelectric (Seebeck) voltages found experimentally in tetrahedral semiconductors as being due to the electrons being preferentially scattered by the phonons streaming from hot to cold.[14] Such phonon drag effects with much smaller signals had been predicted earlier to exist in metals by L. Gurevich. Herring found a simple solution using the relationship between Peltier and Seebeck to transform to isothermal conditions and showed that the corresponding Peltier current would drag the low-energy phonons along. An unusual prediction that the thermal conductivity would be size dependent at temperatures well above the usual boundary scattering regime was verified.[15] The work was extended to an extensive study of thermomagnetic behavior.[16] Conyers showed that the magnetic field, by altering the phonon drag effect as well as the electron distribution, introduces an anisotropy in the Nernst effect that provides a wealth of information on electron-phonon scattering processes in formerly inaccessible frequency regions.

In his study "Effect of Random Inhomogenities on Electrical and Galvanometric Measurements"[17] Conyers showed that the nonsaturation of the Hall voltage in high-mobility indium antimonide was due to nonuniform transverse voltages that caused in circulating currents. He recalled this 30 years later with one of his typical limericks:

Septuagenarian Ted
Is known *not* to have holes in his head.
Since one time when his peers
Soldered leads to his ears
A minus Hall voltage was read.

The experimental discovery of many-valley minima in the conduction bands in germanium and silicon led Conyers to extend transport theory to include the effect of their anisotropic effective masses and bring theory and experiment together.[18] With Eric Vogt he published a companion paper[19] that went further, using anisotropic deformation potentials. He analyzed the transfer of electrons between valleys under the influence of shear strain and found that this changed populations to make the conductivity anisotropic, predicting a large effect.[20] These predictions were verified and led to useful detectors and strain gages.

During the same time period, Conyers retained his interest in surface and bulk mechanical properties that led to an important chapter on "The Use of Classical Macroscopic Concepts in Surface-Energy Problems"[21] and papers on sintering[22] and with John Bardeen the chapter "Diffusion in Alloys and the Kirkendall Effect."[23] He explored the strength of metal whiskers.[24] Conyers predicted that such whiskers would not be able to deform by dislocation motion and would be amazingly strong. The prediction was verified by experiments with John Galt.

Conyers analyzed the effect of gravity on electric fields near the surface of a conductor[25] in order to understand controversial results reported by William Fairbank and his student F. C. Witteborn at Stanford University. These two had undertaken the very difficult experiment of weighing an electron by following its trajectory in the gravitational field. They used an enveloping copper tube to shield the much larger forces due to stray charges. Leonard Schiff and M. V. Barnhill, motivated by this work, had used an ingenious argument to show that there would be no net force on the electron in this tube; the mass of the electron would be canceled by the equal and opposite mass of the image charge in the tube. This appeared indeed to be confirmed by the experiment. A subsequent theoretical treatment by A. J. Dessler and coworkers at Rice University concluded, in contrast, that a very large force would be felt by the electron in this situation. Conyers considered the matter and concluded that the Rice group was correct. In an informal meeting Conyers showed that part of the image charge came from atomic rather than electronic shifts, making the mass of the image huge. He argued that the Schiff-Barnhill calculation had missed this effect due to an incorrect interchanging of a limit and an integral. At this point the experimentalist Fairbank exploded: "Why are you theorists arguing about limits and integrals when the answer is known from experiment?" In the end Schiff agreed that Conyers was right, so the theoretical question was settled, but the experimental question remains unresolved. Later on, but before the discovery of high temperature cuprate superconductors, Fairbank suggested that the image charge might be shielded by a superconducting copper oxide surface layer.

Conyers moved to Stanford University as professor of applied physics in 1978 because of Bell Labs' compulsory retirement age of 65. Conyers took on the responsibility of chairing a National Academy of Sciences committee charged with evaluating the validity of risk assessments that had been made for the operation of nuclear power plants. This proved to be an exhausting, time-consuming task that occupied a major part of his time during the transition from Bell to Stanford.[26] Possibly from the stress of preparing the report he suffered a major heart attack. Conyers seemed to feel that the heart attack was not fair: he had never smoked, was never overweight, had done nothing unhealthy. However, a doctor pointed out that if he had not been so healthy the attack would have killed him; the only thing not in his favor was being male. At Stanford, Conyers remained a great resource for students in preparing theses, and by livening seminars with penetrating questions.

His active research continued until the mid-1990s, and was concerned with the migration of hydrogen in silicon and other semiconductors, in collaboration with Noble M. Johnson and other colleagues at the Xerox Palo Alto Research Center, where he was a consultant. They came to the remarkable conclusion that hydrogen atoms in the $1^+$, 0, and $1^-$ charge states were all important in the properties of hydrogen in silicon.

Near the end of his scientific career Conyers was engaged in preparing one final review to be titled "The Evolution of Solid State Physics." He gave but was unable to complete a series of public lectures at Stanford based upon notes he had prepared for the lectures that are contained in four large boxes. Unfortunately, Conyers succumbed to the infirmities of old age before he could finish what would have been an authoritative and unique history. Perhaps someday some science historian will be able to use the notes and complete the task. It is sad that Conyers could not do this himself, but it is wonderful that he never gave up trying, even after seven marvelous decades.

The wide range of Conyer's contributions has been recognized by his peers. He was elected to the American Academy of Arts and Sciences in 1962 and to the National Academy of Sciences in 1968. He received the Oliver Buckley Prize of the American Physical Society in 1959 for "his interpretation of the transport properties of semiconductors," the Von Hippel Award of the Materials Research Society in 1980, with the citation that he "demonstrated that whiskers of high crystalline perfection would exhibit extraordinary mechanical properties. He is also held in esteem for his theoretical contributions to the understanding of surfaces and surface tension."

The citation of the Wolf Prize that he shared in 1984 with Philipe Nozières reads in part: "Professor Conyers Herring has laid the foundations of band structure calculations of metals and semiconductors, culminating in the discovery of the Orthogonalized Plane Wave Method (O.P.W.). He was years ahead of his time in this contribution. A great deal of modern solid state physics as produced today stems from this original and early paper. His influence on the development of solid state physics extends to a deep understanding of many facets such as surface physics, of thermionic emission, of transport phenomena in semiconductors and of collective excitations in solids such as spin waves."

In the John Murray Luck award given in 1980 by the Academy for excellence in scientific reviewing, his review with Nichols on thermionic emission and his book "Exchange Interactions Among Itinerant Electrons"[27] were cited as being particularly influential.

Conyers had many outside interests. He had a deep non-judgmental faith in Jesus Christ. He was one of 10 lecturers of a science and religion series at Stanford in 1985. He believed that theology underlies science because "science is ultimately based on leaps of intuition and aesthetic perceptions." He was an avid and competitive tennis player and not surprisingly was a scholar of the game as well. He produced numerous limericks that were appropriate, humorous, and frequently spontaneous.

Conyers's contributions to physics will live on. Those who knew him will cherish memories of this remarkable man.

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