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A Biographical Memoir by

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BY CHARLES H. BENNETT AND ALAN B. FOWLER

ROLF W. LANDAUER IS REMEMBERED for wide-ranging contributions to mesoscopic condensed matter and statistical physics, especially the theory of conductivity of disordered media (as described by Landauer's formula) and for discovering the fundamental law (Landauer's principle) governing the thermodynamics of information processing by physical systems. He is also remembered as an outstanding scientific and technical manager of IBM's Watson Research Laboratory, guiding it from relative obscurity to become by 1970 one of the world's two most important and innovative engineering and scientific laboratories.

Rolf Landauer was born in Stuttgart, Germany, to Karl and Anna Landauer on February 4, 1927. Until Hitler had consolidated power Rolf lived in a prosperous, assimilated Jewish family. His father, a successful architect and builder, had been severely wounded while serving the kaiser in the First World War, in which he earned an Iron Cross, and was an ardent German nationalist. He eventually died of war wounds in 1934, after Hitler's accession to power, still believing that Nazi rule was just a temporary aberration. In a last letter to Rolf's mother his father asked that she raise the boys as good Germans. In a sense she did: the mark of German discipline and devotion to duty remained with Rolf throughout his life. Fortunately his mother better understood the nature of the Third Reich and brought the family to New York early in 1938.

Rolf attended the public schools and graduated from Stuyvesant, one of New York's premier high schools. He attended Harvard College in 1943. Because of the accelerated academic schedule and further acceleration on his own, skipping every other math course with only an examination and taking extra courses, he was able to graduate in 1945 before entering the Navy shortly after his 18th birthday. He was trained as an electronic technician's mate. In later years he gave credit to this training for insight into practical problems that were a mystery to many others trained as theoreticians.

After the war he returned to Harvard for graduate study. Harvard, like other universities, was filled with returnees, eager to make up for lost years. Among his fellow graduate students close to Rolf were Philip Anderson, Lewis Branscomb, Helmut Juretschke, Walter Kohn, Tom Lehrer, Charles Slichter, and John Swanson, all of whom distinguished themselves, some in other ways than in science. Rolf began a thesis with Léon Brillouin but finished with Wendell Furry after Brillouin left Harvard. He studied rather formal problems—reflections in one-dimensional wave mechanics and phase integral approximations in wave mechanics. Interest in the former may have been an introduction to some of his later work.

In 1950 Rolf married Muriel Jussim, who became his lifelong companion and friend and the mother of their three children: Karl, Karen Walsh, and Thomas. His devotion to his family, including the brother and father-in-law he nursed and looked after in their final illnesses, was warmly reciprocated. Not that they weren't aware of his obsessiveness and impatience. What was clear was his devotion to them and to his vocation and hobby, physics.

After finishing his thesis in 1950, Rolf was not strongly courted, as most universities and industrial laboratories were still reluctant to hire Jews. He went to the Lewis Aeronautics Laboratory of the National Advisory Committee for Aeronautics (now the National Aeronautics and Space Administration) in Cleveland. His work there was primarily concerned with conduction and diffusion in metals for an exploratory project on nuclear-powered aircraft. In 1952 he joined his old friend John Swanson at the recently established IBM Research Laboratory in Poughkeepsie, New York.

IBM had existed for roughly 50 years and had prospered without a formal research organization. However, that was in a period when its products were mechanical or electromechanical. During the war IBM had been involved in the building of one of the earliest electronic computers at Harvard. It was clear that a modern electronics-oriented lab was needed. The chairman, Thomas Watson, responded at the end of the war by establishing the Watson Laboratory associated with Columbia University under Wallace Eckert, the first Ph.D. hired by the company. The Watson laboratory quickly established itself in the general research community partly because of its connection with Columbia. An initially separate research lab at Poughkeepsie, started in 1950, tended to address problems closer to company business and was many years in approaching the status of Watson or of older well-established industrial labs. The original lab was located in a former pickle factory on the grounds of the main plant in Poughkeepsie. It was not until 1956 that a proper lab was built at a different site nearby.

In his first years at IBM, from 1953 until 1959, Rolf published 11 papers. Many were on interpretations of experiments in ferroelectrics, which IBM was exploring as possible memory elements. Many, some with John Swanson, had to do with electron transport in nonuniform materials. The most important was "Spatial Variations of Currents and Fields Due to Localized Scatterers in Metallic Conduction," published in 1957 in the *IBM Journal of Research and Development*, not a widely read journal. At the same time he was advancing in management. When the Poughkeepsie lab moved to Yorktown Heights in 1960, he was the head of the Physical Sciences Department and had restricted time for research.

Rolf's role in management continued to grow. The lab had expanded rapidly and focus had been lost. By 1963 the company was beginning to question its value. During the 1950s and 1960s, many corporations had started and then closed research laboratories. Under the Research Division director, Gardner Tucker, Rolf had responsibility for reorganizing and redirecting not just the Physical Sciences Department at Yorktown but also research at San Jose and Zurich. As a technical leader he made several key contributions. For instance, he strongly supported the work of Peter Sorokin, who invented the four-level laser and the tunable dye laser in the early and mid-1960s. He pushed the effort to make GaAs injection lasers, which brought to IBM its first major contribution in semiconductors. Probably his most important technological contribution was to recognize early on the potential for large-scale integration of semiconductor circuits and the role of MOSFETs (metal-oxide-semiconductor field-effect transistors) in realizing that potential. He killed other less promising programs mercilessly to populate MOSFET technology, engineering, and science areas. The result was that by 1968 the Research Division had developed the world's first viable n-channel technology. Other technologies fostered were design automation and electron beam lithography.

By 1968 he was associate director of the Research Division, and in 1969 was made an IBM fellow. In 1970 he decided to go back to individual research. After that he confined his management activities to leading technical task forces, advising management, and being an ombudsman in personnel matters. He and Tucker, more than anyone else, had made IBM Research viable, relevant to the company, and a force in physics.

Rolf's research touched many fields and scientists, as evidenced by the contributions to a special issue of *Superlattices and Microstructures* in honor of Rolf Landauer on the occasion of his 70th birthday (83[1998]:365-980). Among the broad topics were the physics of computing, statistical mechanics, ferroelectricity and antiferroelectricity, classic wave propagation and diffusion, general mesoscopic physics, thermal and thermoelectric effects, local fields, atomic conductors, devices, tunneling time, noise, Andreev reflection, and superconductivity. Rolf's contributions to all fields usually demonstrated an original point of view, often seemingly orthogonal to conventional thought. He tended to eschew popular topics and trends unless he had made early seminal contributions. While not all of his ideas have received general acceptance, many have and have changed the way physicists look at nature.

His two main areas of interest were conduction and the physics of computing. Interest in the former started with Rolf's Harvard thesis and was spurred by work done in the 1950s with Helmut Juretschke and John Swanson on conduction in inhomogeneous conductors. The approach Rolf took was different from the usual approach as exemplified by the Boltzmann and the Kubo formulations. Conventionally, conductance was calculated by applying a field to a conductor, accelerating the carriers and then calculating the scattering and the resistance. Rolf's approach was to pass a current through the sample and then ask what was the dipole potential built up by the scattered carriers. This approach was applied in his extensive studies of electromigration with J. W. F. Woo.

Attempts to understand conductance in one-dimensional lattices may have led to some of Rolf's more fruitful work in this area, starting with the long-ignored paper in 1957 and revisited in 1970. Among other things he found a scaling rule for resistance in a one-dimensional disordered wire This formula has been essential to the understanding of conductance in many nanoelectronic structures, as well as giving a simple picture of conductance by edge states in the quantum Hall effect.

Another topic that occupied Rolf in the 1980s and 1990s was the question of traversal time in tunneling. With collaborators Markus Büttiker and Thierry Martin, he wrote about 10 papers on this subject. It is an area in which experiments are very difficult. With Büttiker he also contributed to statistical physics in his studies of solitons. His studies of noise were also of major importance.

Rolf, more than anyone else, established the fundamental physics of information processing, especially the thermodynamic limits to computing, as a field of disciplined inquiry. His interest in the field stemmed partly from its technological importance—waste heat removal has always been a major engineering problem in computer design. It also reflected a deeply held belief that information is physical, by which he meant that computer designers and even theorists of computing ought never to lose sight of the fact that every bit must be embodied and every logic operation accomplished by some real, physical apparatus. An admirer of P. W. Bridgman, Rolf took this belief further than most, sometimes arguing that mathematical concepts like the 10^{1000}th digit of pi, which had no chance of being physically implemented, are consequently of dubious reality and not proper subjects of scientific inquiry.

Before Rolf Landauer, efforts to understand the thermodynamics of information processing had not been very rigorous and had led to a widespread but vague belief that, to paraphrase von Neumann, every elementary act of information processing, involving a decision between two alternatives, requires a dissipation of at least kT ln 2 of energy, where k denotes Boltzmann's constant and T the absolute temperature. In a landmark 1961 paper "Irreversibility and Heat Generation in the Computing Process" Rolf put forward a thermodynamically analyzable model of computation involving modulated potential wells and used it to show that while some information processing operations do indeed have an irreducible energy cost of order kT, others can in principle be accomplished with arbitrarily little dissipation. The thermodynamically irreversible operations are precisely those that are logically irreversible (i.e., operations like erasure that lack a single-valued inverse). "Landauer's principle," as it is now known, became the basis of a thermodynamics of information processing and led, in work with IBM colleague C. H. Bennett and others, to techniques for reversible programming, where logically irreversible operations are avoided, as well as to the currently accepted resolution of the Maxwell's Demon paradox; according to the latter the Demon's inability to violate the Second Law arises from the cost of erasing information rather than, as formerly thought, the cost of acquiring it. Pessimistic informal beliefs about the cost of information processing had their parallel in the field of communication, where many people, overgeneralizing from Shannon's example of a linear channel with additive noise, believed that it must cost at least kT ln 2 to transmit a bit of information by any means whatever. Rolf enjoyed refuting this by a simple counterexample: a reel of magnetic tape can contain a large number of bits, yet costs arbitrarily little energy to transport from place to place.

Beginning in the mid-1980s and indeed partly stimulated by the theory of reversible computing, a more radical challenge arose to conventional notions: the theory of quantum computing. Though it is now regarded as a prime example of the physical nature of information, Rolf was at first hostile to quantum computing. Though he did not dispute its validity as a mathematical concept, he felt that its proponents were wantonly creating false hopes by ignoring the unattainable levels of hardware perfection that would be needed in practice. His many objections to quantum computation only served to spur its proponents to find answers to them, and eventually, after the discovery of threshold theorems for quantum error correction, Rolf became a reluctant supporter of what he had once opposed.

Rolf Landauer was a keen critic of science and especially of science as applied to technology. He set high standards for his own work and expected (or rather hoped for) the same levels of honesty and taste in others. He was ever critical of attempts to sell some newly observed physical phenomenon as a source of world-changing technology, especially as applied to computers, a skepticism epitomized in his papers "Nanostructure Physics: Fashion or Depth?" (1989) and "Advanced Technology and Truth in Advertising" (1990). He understood what was needed to build a computer very well and along with Robert Keyes tried to pass such knowledge to the promoters of every cockamamie scheme that emerged. As a result he took a dim view of optical computing, logic based on threshold devices, such as Esaki diodes and Josephson junctions, which had stringent requirements on reproducibility. His similarly based initial opposition to quantum computing has already been noted. In science two of his bêtes noires were catastrophe theory and the idea that there is some simple criterion for identifying preferred states of systems far from equilibrium, without reference to the system's detailed dynamics.

Rolf received many honors and would undoubtedly have received more had he lived longer. He was a member of both the National Academy of Sciences and the National Academy of Engineering, as befitted his contributions to both disciplines. He was a fellow of the American Academy of Arts and Sciences, the IEEE, the American Physical Society, and the European Academy of Sciences and Arts. He received the Stuart Ballantine Medal of the Franklin Institute, the Oliver Buckley Prize of the American Physical Society, and the Edison Medal of the IEEE, all for essentially different work.

Rolf Landauer was a man of sometimes brutal honesty. He could be both admired and feared by his colleagues, friends, and family. Few acquaintances close or distant did not at one time receive some barbed comment. On the other hand, he was quick to help those who needed it and whom he felt merited his aid. His interests were relatively narrow but focused and deep, primarily on his physics and his family. He demonstrated little interest in literature or the arts, none in spectator sports (though he enjoyed rowing and skiing), and little in politics. One colleague said that he had a deep loyalty to institutions and people. As a refugee from Europe he was slow to criticize the United States. He was intensely loyal to IBM. In the personal sphere he nursed his aged father-in-law for several years before he died and helped his brother immeasurably in his last years, not long before Rolf's own death on April 27, 1999, of a brain tumor. He is survived by his wife, their three children, and two grandchildren. He left a large void in many people's lives as well as in the world of science and, in particular, in the IBM research community.

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