ROLF LANDAUER

1927–1999

BY ROBERT W. KEYES

ROLF LANDAUER, the source of much innovative thought about computing and computing devices, died on 27 April, 1999, after a short illness. He is survived by his wife, Muriel Landauer, three children, Karen Walsh, Carl, and Thomas, and three grandchildren. At the time of his death he was an International Business Machines (IBM) fellow emeritus at the IBM Thomas J. Watson Research Center.

Rolf was born in Stuttgart on February 4, 1997. His family left Germany in 1938 and emigrated to New York, where Rolf attended Stuyvesant High School, graduating in 1943. Rolf entered Harvard University, where he was awarded a B.S. degree in 1945. He then served for a brief period in the U.S. Navy as an electronic technician's mate and returned to Harvard, where he was awarded a Ph.D. in theoretical physics in 1950. From Harvard he went to work at the Lewis Laboratory of the National Advisory Committee for Aeronautics, predecessor of the National Aeronautics and Space Administration. Two years later, he joined IBM, which was then building teams of scientists to support the company's transition into the era of solid-state electronics.

Although Rolf was an accomplished theoretical physicist, he was most interested in what physics had to say about technology. Thus, his early work at IBM focused on ferroelectric materials, which were regarded as candidates for electronic memories at that time, and on semiconductors. The latter interest and a fa

miliarity with problems in metal physics gained at Lewis soon led him to question current thinking about electrical conductivity in materials other than perfect crystals. An involvement with questions of electromigration in metals also connected with those of conductivity. By 1957 he had formulated and reported at a conference the revolutionary approach to a theory of electrical conductivity that much later earned him the Buckley Prize of the American Physical Society. This important work became widely recognized only after its publication in an expanded form with more detail and in a more accessible place in 1970 and its conceptual basis gained fame as the "Landauer formula."

During the late 1950s and early 1960s, when there was still uncertainty about the future of transistor logic, other approaches to computing were also studied in IBM. One depended parametric amplification of oscillators with a negative resistance element. Another used the negative resistance of the recently invented Esaki diode to form a circuit with two metastable states. Boolean logic depended on switching the circuit between these states. Perhaps prompted by this multiplicity of possible courses, Rolf sought a fundamental device-independent physical understanding of logical operations. He conceived of information as the position of a particle in a potential well in generalized coordinates that can be manipulated to perform logical operations. His report on this effort in 1961 proposed that a minimum dissipation of the order of the thermal energy, kT, is associated with each logical step and that the energy is dissipated when information is discarded to reset a device for another use, a thermodynamically irreversible operation.

Rolf extended the study of the physics of information to its representation with dissipative states. He used the metastable tunnel diode circuit as an example and asked how stable the states really are and how stability could be measured. Analogies he developed with the problem of a particle in a potential well led to a quantitative dynamic model of stability. A lifelong series of contributions to the theory of stable states far from equilibrium and the role of fluctuations in escape from metastable states followed from this investigation.

Rolf's easily recognized intellect and strong opinions soon

led him to be tapped for management responsibility in the rapidly growing IBM Research Division. In 1962 he took the post of director of a Solid State Sciences Department. His first success in this position was the concentration of considerable talent on the development of a semiconductor injection laser. The injection laser was realized in a fairly short time, essentially simultaneously with its invention at the General Electric Laboratory and soon also at Bell Telephone Laboratories.

IBM introduced the 7030 “Stretch” machine in 1960 as the industry's first large transistorized computer, and it was becoming clear in the early 1960s that the future of the computer lay with the transistor. Another of Rolf's managerial achievements was recognition of the implications of the invention of the integrated circuit and silicon field-effect transistor technology for the IBM business. He drew together a group of talented scientists focused on bringing this technology into IBM. The group had many successes, notably the invention of the one-device memory cell and the discovery of quantization in thin-surface inversion layers and its effect on transistor threshold voltages. The advances in silicon technology made by the group were widely copied throughout the industry. Rolf was elected to the National Academy of Engineering in 1978 in recognition of his leadership in the development of MOS (metal-oxide semiconductor) technologies.

Rolf's managerial responsibilities and the scope of his influence on directions of research widened with his appointment as assistant director of research in 1965. IBM Research became recognized as one of the nation's premier industrial research establishments during the time that Rolf shared in its management. However, he had little time for his first love, physics and its relevance to information processing, and in 1969 he gave up management and was appointed an IBM fellow. He immediately resumed contributions to his long-term scientific interests, including wave propagation in nonlinear structures, electrical conductivity in inhomogeneous media, ferroelectricity, the physics of computing devices, and escape from metastable states. Although most of Rolf's work was inspired by questions related to information processing technology, his determination to under

stand them at a fundamental level often had far-reaching implications for basic science. His impact on science was recognized by his election to the National Academy of Sciences in 1988.

As an IBM fellow Rolf continued to have an important influence in the Research Division. I was privileged to have an office adjacent to Rolf's for many years and therefore had frequent contact with him. I could not avoid noticing that many other colleagues also visited him to take advantage of his wide knowledge of physics and technology and his managerial experience. He was a good person to talk to because he was a skeptic. He was willing to listen, but hard to convince. Further, Rolf had great integrity. When he listened he made an effort to understand what was being said and to respond candidly, with hard questions. Even after a discussion, he often continued to think about the subject and came back with additional thoughts.

Much attention was attracted by Rolf's thoughts on the dissipation of energy in logical operations. That energy must be dissipated to heat in a logical operation had been accepted as fact since the time of John von Neumann. Rolf returned to his earlier argument that the dissipation occurred when information was discarded in resetting the computing apparatus. He investigated the limits on dissipation when potential wells are used to perform logical AND and OR operations in some detail, including other sources of dissipation. Thinking on this subject was profoundly altered, however, when Charles Bennett demonstrated that logical operations can in principle be performed in a reversible way and that therefore information need not be discarded during the computing process. Rolf accepted this argument as injecting a powerful new notion into the subject of energy dissipation. He arranged that IBM Research hire Bennett. Bennett and Landauer in *Scientific American* eventually explained their combined thinking about the subject for a wide audience. Reversible computing has not been turned to practical use, but the thought has stimulated research into means for recovering part of the energy associated with electrical logic.

Rolf also enlisted a few postdoctoral collaborators in his research as an IBM Fellow. James Woo participated in work on escape from metastable states. Martin Buttiker worked with Rolf

on a variety of problems, including one that had puzzled physicists for a long time: the traversal time for a particle tunneling through a barrier. Rolf also worked with Thierry Martin on additional aspects of the delay in tunneling events.

His observations about energy dissipation and the way that it is manifested in physical models convinced Rolf that it is wrong to think of information abstractly, independent of its physical representation. He had expressed this thesis in 1967 in a contribution to the Institute of Electrical and Electronics Engineers (IEEE) magazine *Spectrum* entitled *"Wanted: A Physically Possible Theory of Physics"* and much later in a work *"Information is Physical,"* a phrase that became enduringly associated with his name. He insisted that the use of energy and other physical resources in computing limits man's knowledge of the world and called for a science that did not demand infinite accuracy of its fundamental concepts, such as the value of p.

To the suggestion that quantum computation is possible and offers great advantages in some areas, Rolf naturally responded by developing his own views. He saw many difficulties with quantum computation and did not hesitate to call attention to them. Advocates of quantum computation recognized the validity of his criticism and worked to invent ways around them; although a skeptic, he had an essentially positive influence on the field.

Rolf received many honors in addition to his election to the two national academies and the 1995 Oliver E. Buckley Condensed Matter Physics Prize. He was awarded the 1992 Stuart Ballantine Medal of the Franklin Institute, the 1993 Centennial Medal of Harvard University, and the 1998 Edison Medal of the IEEE. He received an honorary degree from the Technion in Israel and was elected to membership in the European Academy of Arts and Sciences.

A memorial symposium at the IBM Research Laboratory in September 1993 attended by many colleagues and friends honored Rolf's long career. He will be missed.