Obituary

Rolf Landauer (1927–99)

Head and heart of the physics of information

It is well known that scientific progress requires intellect. Less advertised is science's need for conscience. Intellect creates new ideas; conscience examines them for consistency and correctness. In other words, a scientific field requires not only 'head' but 'heart' as well. Rolf Landauer was both head and heart to the field of physics of information. He died of cancer on 27 April this year at the age of 72.

Landauer based his research on a simple rule: information is physical. That is, information is registered by physical systems such as strands of DNA, neurons and transistors; in turn, the ways in which systems such as cells, brains and computers can process information is governed by the laws of physics. Landauer's work showed that the apparently simple and unproblematic statement of the physical nature of information had profound consequences.

Born in Stuttgart, Landauer was raised in New York from the age of eleven. He received both undergraduate and graduate degrees from Harvard, where he worked under Léon Brillouin and Wendell Furry. In 1952 he joined IBM, where he was employed for the rest of his life. In the late 1950s, after constructing an influential theory of electrical conductance based on the scattering of electrons, Landauer turned his attention to the physics of computation.

In 1961, Landauer discovered that logical operations that get rid of information, such as erasure, necessarily require the dissipation of energy. Erasure transforms information from an accessible to an inaccessible form, known as entropy, whereas logical operations that can be reversed do not lead to a rise in entropy. Landauer also identified the minimum amount of entropy increase required for each bit erased as $k\ln 2$, where k is Boltzmann's constant. Landauer's principle transformed the physics of information by identifying the basic trade-off between information and physical quantities.

In the 1980s, Landauer's colleague at IBM, Charles Bennett, applied his principle to provide a self-consistent solution to the century-old problem of Maxwell's demon. In his research into the molecular nature of heat in the mid-nineteenth century, James Clerk Maxwell had noted that a hypothetical being that

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could acquire information about the velocities of individual molecules of a gas could shepherd fast molecules in one direction and slow molecules in another, thereby decreasing the gas's entropy. But the second law of thermodynamics says that entropy does not decrease. Because of its pernicious effect, William Thompson and Lord Kelvin dubbed this being 'Maxwell's demon'. In order to preserve the second law of thermodynamics, scientists earlier this century postulated that getting and processing information must necessarily involve an increase in entropy. Landauer's principle shows that, whereas Maxwell's demon can, in principle, use information about the gas to do work without increasing entropy, when it erases that information it must pay a price of $k\ln 2$ in entropy per bit, exactly cancelling the advantage it obtained in the first place.

In the 1970s, working from Landauer's result, Bennett (and independently Ed Fredkin and Tom Toffoli of MIT) showed that all computation could, in principle, be carried out in a logically reversible fashion: as a result, computation does not require dissipation. The fact that modern computers dissipate large amounts of heat arises from practical engineering concerns rather than from physical necessity. The possibility of reversible computation was central to Paul Benioff's discovery at Argonne National laboratory in 1980 that quantum systems could perform computations in a coherent fashion, a result that led to quantum computation.

Although he may be considered the godfather of quantum computation, Landauer was fundamentally critical of the field. During the 1960s, he was a senior manager in IBM's research division, and played a role in many of the laboratory's successes, including the development of the injection laser and of large-scale integrated memory circuits. During his career, he witnessed the failure of many promising technologies, such as early attempts to construct computers using Josephson junctions and tunnel diodes. Having seen them come and go, Landauer was sceptical of new computer technologies, noting that most proposals gravely underestimated the difficulty in constructing a viable device. Over the past 30 years, he wrote a series of articles pointing out deficiencies in various alternative computing proposals, including quantum computation. When a researcher failed to pay adequate attention to his published admonitions, he would warn them in person. For example, he suggested that all papers on quantum computing should carry a footnote: "This proposal, like all proposals for quantum computation, relies on speculative technology, does not in its current form take into account all possible sources of noise, unreliability and manufacturing error, and probably will not work."

Landauer's footnote is, of course, correct. In any field of technology, let alone one that attempts to store information on subatomic particles, most ideas will probably not work. It is by identifying these wrong ideas that scientists and engineers winnow out those few ideas that are potentially right. Yet, despite the importance of mistakes in science, most published papers report work that is potentially right, rather than provably wrong. In such an environment, it is important for a field to have a mechanism for remembering past mistakes and for preventing them from recurring. In the field of physics of information, Landauer supplied such a mechanism by functioning as the field's conscience.

Landauer's bracing criticism had a highly positive and healthy effect on quantum computing. His critiques were always accompanied by advice, support and suggestions for making the suspect proposal work. Researchers explicitly addressed his concerns and developed methods for coping with noise, unreliability and manufacturing error, to the extent that, by the end of his life, although he still believed that large-scale quantum computers would not be built, he admitted that they were considerably more plausible than they had been a few years before. It is not yet clear what the future physical basis for computation will be, but, whatever its successes, they will be in no small part due to Rolf Landauer.

Seth Lloyd

Seth Lloyd is in the Department of Mechanical Engineering 3-160, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.
e-mail: slloyd@mit.edu