CLAUDE ELWOOD SHANNON, the creator of information theory and the primary architect of modern communication technology, died at the age of eighty-four after a long bout with Alzheimer's disease. In many ways, he enabled the Information Age. Much of his influence comes from his two-part monumental 1948 paper, "A Mathematical Theory of Communication,"[1] a topic that soon after was often referred to as information theory.

This theory created intense excitement in the scientific and intellectual communities. It was viewed by some as a scientific theory for human and machine intelligence, by others as a scientific theory for telecommunication, and by yet others as a fascinating but not very useful set of mathematical theorems. It is now widely accepted as establishing the science of telecommunication as well as providing important insights into a number of related areas.

Claude Shannon was a native of Gaylord, Michigan, and was educated in the public school system, graduating from the University of Michigan in 1936 with bachelor's degrees in both electrical engineering and mathematics. His dual interest in these fields continued throughout his life.

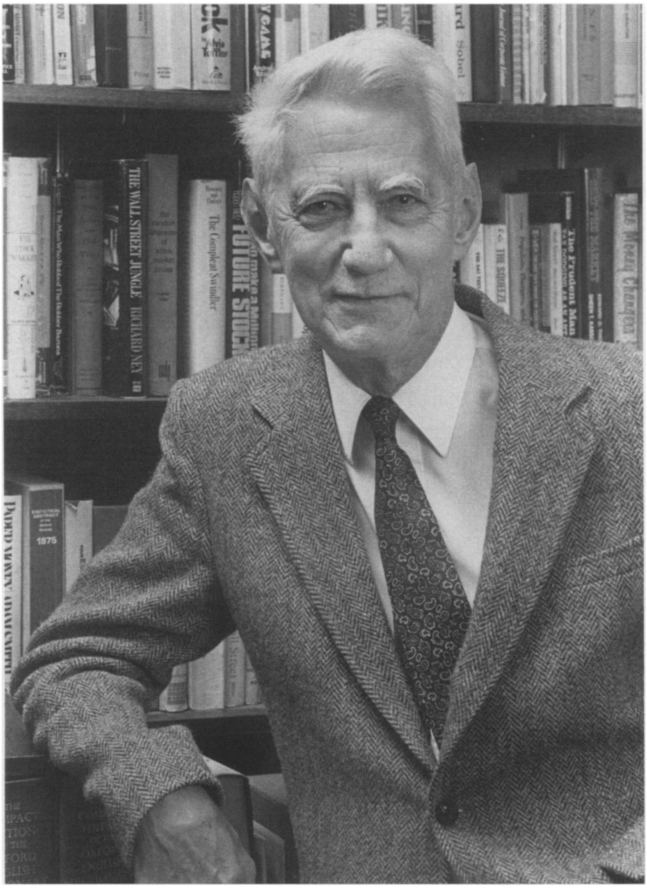
After graduation, Shannon applied for, and received, a research assistantship to work on the differential analyzer (an early analog computer) developed by Vannevar Bush at the Massachusetts Institute of Technology. Shannon was fascinated both by the analog gears in the computer and by the complex switching circuit controlling it. He soon discovered that switching circuits could be described by Boolean algebra and, after fleshing out this discovery, used it for his master's thesis. Shannon's thesis was quickly recognized as forming the scientific basis for the rapidly growing field of switching. As technology has become increasingly digital, this field, and Shannon's contribution, continue to grow in importance.

For his Ph.D. thesis, Shannon attempted to create a mathematical foundation for genetics. The thesis was completed in 1940, but Shannon rapidly lost interest, and the thesis was published only recently in his collected papers (IEEE Press, 1993). The results in the thesis were important, but were mostly discovered independently in the intervening forty-three years.

Shannon was never particularly interested in getting credit or recognition for his work, and his mind was constantly buzzing with creative new ideas; consequently, many of his results went unpublished. While doing his Ph.D. work, he was starting to get interested in the

[1] *Bell System Technical Journal* 27 (1948): 379–423; 623–56.

CLAUDE ELWOOD SHANNON



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fundamental problems of telecommunication, and was also continuing his work on switching. After graduation, he went to the Institute for Advanced Study in Princeton and concentrated on telecommunication.

By the summer of 1941, war was imminent and Shannon started to work on both antiaircraft fire control and cryptography at Bell Laboratories. He found that cryptography was closely related to his developing work on communication, and in 1945 wrote a classified paper, "A Mathematical Theory of Cryptography." This paper established the scientific principles of cryptography as used today. Although this predated his theory of communication papers by three years, the essential communication ideas on which his theory of cryptography was based had already been developed.

By 1948, all the pieces of his mathematical theory of communication had come together in Shannon's head. He had been working on this project, on and off, for eight years. There were no drafts or partial manuscripts; remarkably, he was able to keep the entire creation in his head. In a sense, this was necessary, because the theory was about the entire process of telecommunication.

Shannon showed that arbitrary sources (voice, video, and data) can be characterized in terms of entropy, i.e., the binary rates needed for their representation. Similarly, communication channels can be characterized in terms of their bit-carrying capacities. Finally, the conversion of sources into bit streams, i.e., data compression, can be separated from the communication process with no essential loss. This recognition that sources can be reduced to bits, and that channels need only transmit bits, has been crucial to the development of the Internet.

Shannon's development of communication science is very different from the usual process of scientific discovery, in which many people contribute piece by piece to an evolving conceptual framework. Here the entire framework was created in one monumental work. There have been many efforts over the years to interpret Shannon's work in terms of the evolving technology, but in retrospect it is clear that the technology has evolved to meet Shannon's original blueprint.

Claude Shannon remained in the mathematical research group at Bell Labs until 1956, and created a constant stream of new and stimulating results. There was a remarkable group of brilliant people to interact with, and he tended to absorb quickly what they were working on and to suggest totally new approaches. He would strip away all the complexity from the problem and then suggest some extremely simple and fundamental new insight.

One of Shannon's important results in this period was his demonstration that a universal Turing machine could be constructed with only two internal states. This is a beautifully written paper, which perhaps contains the best introduction available to Turing machine theory. Another important paper, done jointly with Edward Moore, showed how to use redundancy to achieve arbitrarily high reliability in computing with unreliable components.

Claude tended to work alone for the most part. He would work on whatever problem fascinated him most at the time, regardless of its practical importance. He often said that he was not interested in applications, and often worked on playful and fanciful topics such as theories of juggling, the stability of unicycles, programs enabling computers to play chess, and mechanical mice that find their way through mazes. His early chess-playing machines provided the basis for modern machines that can now beat human chess masters. These more playful projects have had an important impact on the field of artificial intelligence, and have led indirectly to many applications.

The great mathematician Kolmogorov summed up Claude Shannon's brilliance as a researcher very well. He wrote, "In our age, when human knowledge is becoming more and more specialized, Claude Shannon is an exceptional example of a scientist who combines deep abstract mathematical thought with a broad and at the same time very concrete understanding of vital problems of technology. He can be considered equally well as one of the greatest mathematicians and as one of the greatest engineers of the last few decades."

While recognizing his genius, however, many mathematicians of the day were frustrated by his style of sometimes omitting precise conditions on his theorems, and merely sketching the proofs. Shannon's engineering side usually took the dominant role in his theorem/proof style. He wanted to make the reasons for the theorems very clear, and realized that including details for concocted special cases would simply obscure the issue. Modern proofs of Shannon's major theorems generally follow his original outlines very closely.

In 1958, Shannon and his family moved to the Boston area and he accepted a joint appointment at MIT in electrical engineering and mathematics. There was a large and active group of graduate students and young faculty interested in information theory at MIT at the time. Shannon gave frequent seminars, and once gave an entire seminar course with new results created for each lecture. He did not really like to give conventional courses and talk about the same topic again and again. His mind was always too full of new topics that he was trying to understand. For the graduate students and faculty, this was a wonderful opportunity, since we all got many insights into his thinking processes.

Claude supervised a small number of graduate theses, but played an even more important role by being available to talk about research topics. He was somewhat shy by nature, but very helpful to students after the first contact was made. Many students learned from him that the most valuable ideas are the simplest, and that the purpose of theoretical research is to throw light onto an area rather than to produce long, obscure arguments. He would often start a lecture by discussing several trivially simple (but very carefully chosen) examples, after which the general result would become obvious.

Claude Shannon received innumerable honors and awards throughout his life. He was the first recipient of Japan's Kyoto Prize (1985), the first recipient of Israel's Harvey Prize (1972), and a recipient of the U.S. National Medal of Science (1966). He received honorary degrees from the Universities of Michigan, Pittsburgh, Edinburgh, Oxford, and East Anglia, and from Princeton, Northwestern, Carnegie Mellon, and Yale Universities.

Elected 1983

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