Obituary

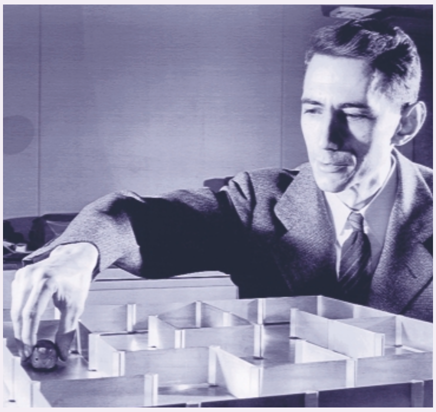
Claude Shannon (1916–2001)

Look at a compact disc under a microscope and you will see music represented as a sequence of pits, or in mathematical terms, as a sequence of 0s and 1s, commonly referred to as bits. The foundation of our Information Age is this transformation of speech, audio, images and video into digital content, and the man who started the digital revolution was Claude Shannon, who died on 24 February, at the age of 84, after a long struggle with Alzheimer's disease.

Shannon arrived at the revolutionary idea of digital representation by sampling a source of information at an appropriate rate, and converting the samples to a bit stream. He characterized the source by a single number, which he called entropy (a term adapted from statistical mechanics), to quantify the information content of the source. For a stream of text, Shannon viewed entropy as a statistical parameter that measured how much information is produced on average by each letter. He also created coding theory, by introducing redundancy into the digital representation to protect against corruption. If today you take a compact disc in one hand and a pair of scissors in the other, then score the disc along a radius from the centre to the edge, you will find that the disc still plays as new.

Before Shannon, it was commonly believed that the only way of achieving arbitrarily small probability of error in a communication channel, such as a telephone line, was to reduce the transmission rate to zero. All this changed in 1948 with the publication of *A Mathematical Theory of Communication*, in which Shannon characterized a channel by a single parameter, the channel capacity, and showed that it was possible to transmit encoded information at any rate below capacity with an arbitrarily small probability of error. His method of proof was to show the existence of a single good code for data transmission by averaging over all possible codes. The 1948 paper established fundamental limits on the efficiency of communication through noisy channels, but did not produce an explicit example of a good code that would achieve the highest capacity. It has taken 50 years for coding theorists to discover families of codes that come close to these fundamental limits for telephone lines.

The importance of Shannon's work was recognized immediately. According to a 1953 issue of *Fortune*, "It may be no exaggeration to say that man's progress in



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Inventor, mathematician and leader of the digital revolution

peace, and security in war, depend more on fruitful applications of information theory than on physical demonstrations, either in bombs or in power plants, that Einstein's famous equation works." In fact, his work has become more important over time with the advent of deep space communication, wireless phones, high-speed data networks, the Internet, and products like compact-disc players, hard drives and modems that make essential use of coding and data compression to improve reliability and speed.

Shannon grew up in Gaylord, Michigan, and began his education at the University of Michigan, where he majored in both mathematics and electrical engineering. As a graduate student at Massachusetts Institute of Technology (MIT), his familiarity with both the mathematics of boolean algebra and the practice of circuit design produced what science historian H. H. Goldstine called "one of the most important master's theses ever written… a landmark in that it changed circuit design from an art to a science". This thesis, *A Symbolic Analysis of Relay and Switching Circuits*, written in 1936, provided mathematical techniques for building a network of switches and relays to realize a specific logical function, such as a combination lock — an electrical circuit that works if, and only if, the right combination of buttons is pressed. This work won the Alfred Noble Prize of the combined engineering societies of the USA and is fundamental to the design of digital computers and integrated circuits.

Shannon's interest in circuit design was not purely theoretical, for he also liked to build, and his sense of play is evident in many of his creations. In the 1950s, when computers were given names like ENIAC (electronic numerical integrator and calculator), Shannon built a computer called THROBAC I (thrifty Roman-numeral backward-looking computer), which was able to add, subtract, multiply and even divide numbers up to 85 working only with Roman numerals. His study in Winchester, Massachusetts, was filled with such devices, including a maze-solving mechanical mouse and a miraculous juggling machine. Traversing the ceiling was a rotating chain, like those found at dry cleaners, from which were suspended the gowns from a score of honorary doctorates. They made a splendid sight flying around the room.

Shannon's 1941 doctoral dissertation, on the mathematical theory of genetics, is not as well known as his master's thesis, and in fact was not published until 1993, by which time most of the results had been obtained independently by others. After graduating from MIT, Shannon spent a year at the Institute for Advanced Study, and this is the period where he began to develop the theoretical framework that led to his 1948 paper on communication in the presence of noise.

He joined Bell Labs in 1941, and remained there for 15 years, after which he returned to MIT. During the Second World War, his work on encryption led to the system used by Roosevelt and Churchill for transatlantic conferences, and inspired his pioneering work on the mathematical theory of cryptography.

It was at Bell Labs that Shannon produced the series of papers that transformed the world, and that transformation continues today. In 1948, Shannon connected information theory with physics by developing a new perspective on entropy. That connection is evolving today, as others explore the implications of quantum computing, by enlarging information theory to treat the transmission and processing of quantum states.

Shannon must rank near the top of the list of major figures of twentieth century science, although his name is relatively unknown to the general public. His influence on everyday life, which is already tremendous, can only increase with the passage of time.

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