BIOGRAPHICAL MEMOIRS

Claude Elwood Shannon 30 April 1916 –– 24 February 2001

Ioan James

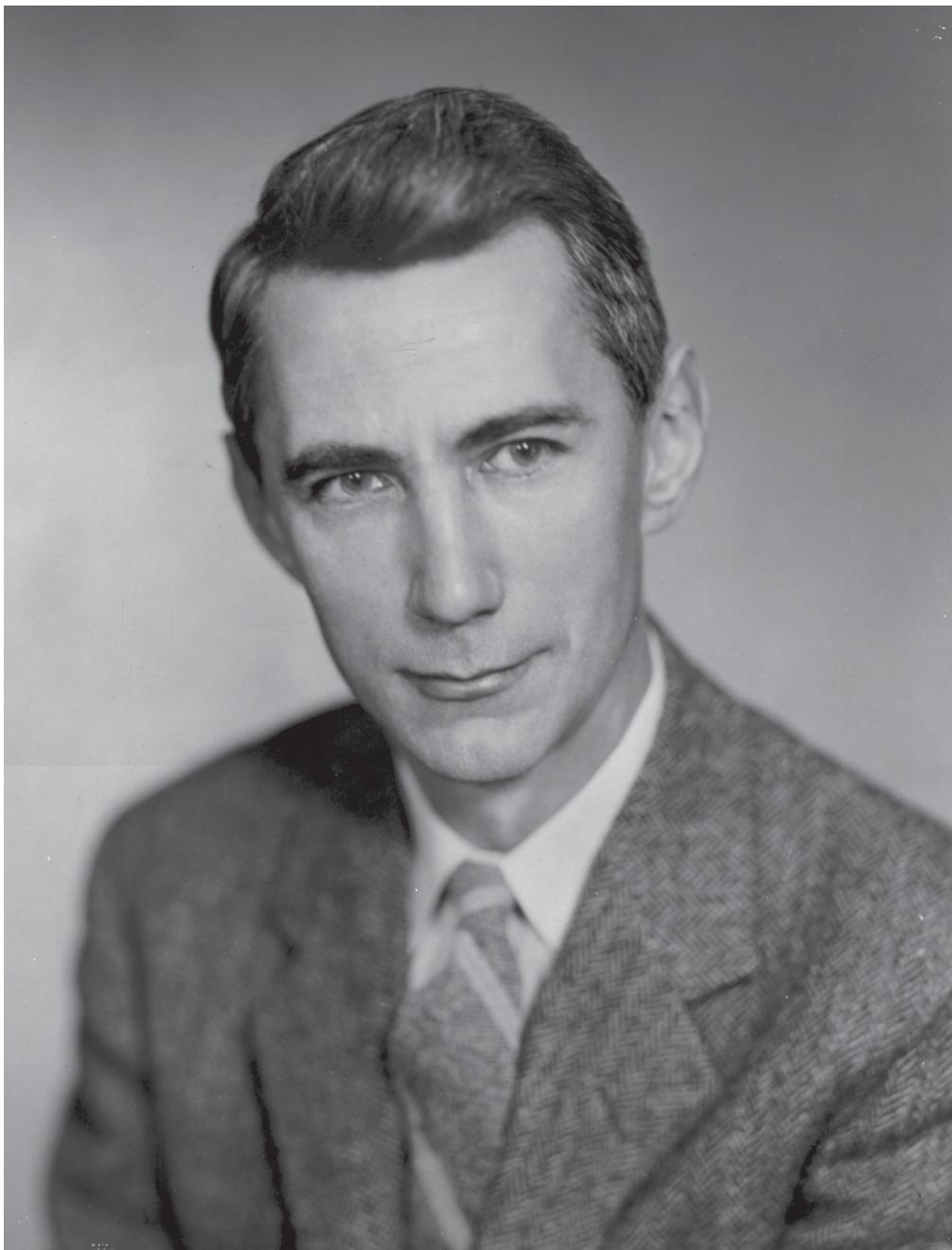|	
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Elected ForMemRS 1991

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According to an anonymous obituary in *The Times* newspaper on 12 March 2001, Claude Shannon was

> [a] playful genius who invented the bit, separated the medium from the message, and laid the foundations for all digital communications. … [He] single-handedly laid down the general rules of modern information theory, creating the mathematical foundations for a technical revolution. Without his clarity of thought and sustained ability to work his way through intractable problems, such advances as e-mail and the World Wide Web would not have been possible.
>
> Something of a loner throughout his working life, he was individually responsible for two of the great breakthroughs in understanding which heralded the convergence of computing and communications. To colleagues in the corridors at the Massachusetts Institute of Technology who used to warn each other about the unsteady advance of Shannon on his unicycle, it may have seemed improbable that he could remain serious for long enough to do any important work. Yet the unicycle was characteristic of his quirky thought processes, and became the topsy-turvy symbol of unorthodox progress towards unexpected theoretical insights.
>
> The ability to make astonishing leaps beyond the intellects of his colleagues (all the more remarkable at MIT, the forcing house of technological theory) had to be acknowledged as genius, and Claude Shannon was recognised as a giant throughout the industry.

EARLY YEARS

The Shannon parental home was in Gaylord, a town of some 3000 inhabitants in the northern part of the state of Michigan. Like his elder sister, Catherine (1910–2009), Claude Shannon was born in hospital at the nearby town of Petoskey. His paternal grandfather was a farmer and inventor, and his father (1862–1934), of the same name, was clever mathematically and worked as judge of probate in Gaylord. The descendant of New Jersey settlers, he married Mabel Wolf (1880–1945), the daughter of German immigrants who was a language teacher

and for a number of years principal of the high school in Gaylord. Claude Shannon junior was educated at the same school. In boyhood he already showed mechanical aptitude: he tinkered with radio sets given to him by his father and with mathematical puzzles provided by his sister. His hero was Thomas Edison, with whom he had a common ancestor.

EDUCATION AND RESEARCH

After leaving school in 1932, Shannon entered the University of Michigan, following his sister, who had just obtained a master's degree there in mathematics and who went on to teach mathematics at college. In 1936 he was awarded a first degree in electrical engineering and another in mathematics, the two subjects he was to pursue throughout his life. He joined the Department of Electrical Engineering at the Massachusetts Institute of Technology (MIT) as a research assistant, where he worked with Vannevar Bush on one of the early analogue computers, the differential analyser, which used a precisely honed system of shafts, gears, wheels and disks to solve equations in calculus. After two years he transferred to the Department of Mathematics, where he wrote a brilliant master's thesis entitled *An analysis of relay and switching circuits*.

Modern computers use Boolean algebra, the formalization of logical expressions devised by the nineteenth-century English mathematician George Boole FRS. Shannon saw how Boole's logical symbols could be regarded as a series of on–off switches so that binary arithmetic could be performed by electrical circuits. As a result he was able to develop mathematical techniques for building a network of switches and relays to realize a specific logical function, changing circuit design from an art to a science. This brought him the prestigious Alfred Noble prize of the combined engineering societies of the USA in 1939 (it was later found that Victor Shestakov, at Moscow State University, had proposed a similar theory much earlier, but this was not published until 1941).

In 1940, after a summer at the Cold Springs oceanographic research station on Long Island, Shannon completed his PhD dissertation, entitled *An algebra for theoretical genetics*. This overlapped with some of the early work by J. B. S. Haldane FRS on population genetics, of which he seemed to be unaware, and although an excellent thesis it was not published until 1993, by which time most of his results had been obtained independently by others.

After spending summer vacations working at the Bell Telephone Laboratories in Manhattan, Shannon was recruited as one their research mathematicians, a position he held for 15 fruitful years. The famous laboratories, which later moved to Murray Hill, NJ, were the research department of the giant Bell Telephone system, part of the AT&T empire. Many outstanding engineers were his colleagues, among them John Pierce, known for satellite communication, Harry Nyquist, with numerous contributions to signal theory, and Hendrik Bode of feedback fame. There were also physicists of the calibre of John Bardeen (ForMemRS 1973), Walter Brattain and William Shockley, who invented transistors and were to be awarded the Nobel Prize in Physics for 1956.

In 1940 Shannon was awarded a National Research Fellowship to work at the Institute for Advanced Study in Princeton, under the German émigré mathematician Hermann Weyl ForMemRS. Probably he was more influenced by the Hungarian mathematical polymath John von Neumann, whose many interests included computing, automata and game theory. During World War II, Shannon's official responsibility was developing fire-control systems

for anti-aircraft guns and cryptographic systems. In 1943 he met for the first time his British opposite number Alan Turing (FRS 1951), who was briefly visiting the Bell Laboratories. Turing's seminal 1936 paper, introducing what is now known as the universal Turing machine, contained ideas that were complementary to his own. However, under wartime conditions of secrecy what might otherwise have developed into a fruitful collaboration could not progress very far. Shannon also developed a mathematical theory of cryptography that led to the system used by Winston Churchill and Franklin D. Roosevelt for transoceanic conferences. This was described in his landmark 1949 paper on communication theory of secrecy systems, which transformed cryptography from an art to a science.

In 1948 Shannon published his most important paper, entitled 'A mathematical theory of communication'. This seminal work transformed the understanding of the process of electronic communication by providing it with a mathematics, a general set of theorems rather misleadingly called information theory. The information content of a message, as he defined it, has nothing to do with its inherent meaning, but simply with the number of binary digits that it takes to transmit it. Thus, information, hitherto thought of as a relatively vague and abstract idea, was analogous to physical energy and could be treated like a measurable physical quantity. His definition was both self-consistent and unique in relation to intuitive axioms. To quantify the deficit in the information content in a message he characterized it by a number, the entropy, adopting a term from thermodynamics. Building on this theoretical foundation, Shannon was able to show that any given communications channel has a maximum capacity for transmitting information. The maximum, which can be approached but never attained, has become known as the Shannon limit. So wide were its repercussions that the theory was described as one of humanity's proudest and rarest creations, a general scientific theory that could profoundly and rapidly alter humanity's view of the world. Few other works of the twentieth century have had a greater impact; he altered most profoundly all aspects of communication theory and practice.

On 29 March 1949 Shannon married Mary Elizabeth Moore, from Staten Island, who after graduating in mathematics at Rutgers University was working as a technical assistant in the microwave research department of the Bell Laboratories. They raised three very active children, Robert James (1952–98), who became a computer scientist, Andrew Moore (1954–), who became a pianist and composer, and Margarita Catherine (1959–), who became a college teacher.

LATER CAREER

In 1958 Shannon was appointed Donner Professor of Science at MIT (figure 1). In this capacity he supervised three doctoral students. He remained on the faculty for the next 20 years, although he maintained his connection with the Bell Laboratories until 1972. He worked mainly at home, a large house overlooking Mystic Lake in Winchester, MA, where students were always welcome and were frequent visitors. In the basement was a fully equipped machine shop where he spent much of his time making electrical and mechanical machines, for example a cable railway that ran to the lakeshore. The house contained many of the machines he made and others he purchased from other enthusiasts. It also contained numerous musical instruments, including five pianos; he played the clarinet himself and especially enjoyed Dixieland jazz. Although he formally retired from MIT in 1978, he

Figure 1. Claude Shannon in later life. (Reprinted with permission of Alcatel-Lucent USA Inc.)

continued happily working as before until he succumbed to Alzheimer's disease. He died on 24 February 2001, at the age of 84 years; he was survived by his wife, two of their three children and his sister.

Although highly regarded professionally at home and abroad, to the general public he was famous for the ingenious machines and gadgets he invented and built. Some of these were of real scientific value; for example, his mechanical 'mouse' Theseus, which learnt the path through a maze, was an early contribution to the field of artificial intelligence. There was also a 'mind-reading' machine that could anticipate, more than half the time, whether a challenger would choose heads or tails. Other ingenious gadgets he invented just for the fun of it. For example there was THROBAC, a calculator that operated in Roman numerals. Chess-playing machines fascinated him; as early as 1950 he wrote a paper on programming a computer to play chess. His masterpiece was a W. C. Fields figure that juggled three balls. A collection of

these machines can be seen in the MIT museum. Juggling was another passion of his. On one famous occasion he rode a unicycle through the corridors of MIT while juggling several balls in the air, a stunt normally performed by circus clowns.

Although Shannon is regarded as the founding father of the information age, he was not himself much interested in the applications of his theoretical work. In an interview he gave in 1984 he explained that he was attracted more to problems than to applications. He just liked to solve a problem, an interesting problem, and did not care whether someone else had been working on it. His rather offhand approach to problems was not always popular with his rather earnest colleagues, who felt he lacked the rigour of the true researcher. Like Babbage he was known as an irascible genius, because he was not always patient with those who did not readily follow his line of thought. Yet normally he was a shy man, gentle and quiet, with a whimsical sense of humour. Shannon was little interested in the applications of his scientific contributions, which were often capable of successful commercial exploitation. He became wealthy not from this but from carefully chosen investments in technological companies.

As well as his publications in scientific and technical journals, he wrote articles for the 14th edition of *Encyclopedia Britannica* on information theory and on cybernetics. Norbert Wiener, regarded as the father of cybernetics, was his colleague at MIT; Shannon had great respect for him. Shannon also edited and contributed to several books, but he never wrote one himself. The complete list of about 127 items, not all published, can be found in his *Collected papers* (Sloane & Wyner 1993). The selected bibliography given at the end of this memoir leaves out foreign translations, memoranda, patent applications, reports, reviews and popular articles. His publications essentially came to an end in 1967 when he was just over 50 years old, although there are a few unpublished typescripts from later years and he was by no means inactive.

In 1983 Shannon looked back on the development of information technologies in his lifetime, writing:

> The growth of both communication and computing devices has been explosive in the last century. It was about a hundred years ago that the telephone and phonograph were invented, and these were followed by radio, motion pictures and television. We now have vacuum tubes, transistors, integrated circuits, satellite communication and microwave cable. We have even talked to astronauts on the moon. Our life style has been totally changed by advances in communication. On the computing side we started the twentieth century with slide rules and adding machines. These were followed in quantum jumps by Bush analog computers, Stibitz and Aiken relay computers, Eckert and Mauchly vacuum tube machines …, transistor computers and, finally, the incredibly compact integrated circuit and chip computers. At each step the computers became faster, cheaper and more powerful. These hardware revolutions were matched by equally impressive developments in programming.

Shannon gave the Vanuxem Lectures at Princeton in 1958, the Gibbs Lecture to the American Mathematical Society in 1965, a Semicentennial lecture at Rice University, and other prestigious lectures. After retiring from MIT he spent Trinity term in 1978 as a visiting fellow at All Souls College, Oxford, during which he gave one of the Chichele Lectures, and the university conferred on him an honorary degree, one of more than a dozen he received from various universities at home and abroad. He received numerous other professional and scientific honours, including the National Medal of Science in 1966 and the Kyoto Prize in 1965, and other awards by which the engineering profession makes up for the absence of Nobel prizes. He was elected to membership of the American Academy of Arts and Sciences,

the National Academy of Sciences, the National Academy of Engineering and the American Philosophical Society, and a Foreign Member of the Royal Society in 1991. Five copies of a portrait bust, by the sculptor Eugene Daub, have been placed at various locations in the USA: in Gaylord, MI, where he grew up; at the University of Michigan, where he was an undergraduate; at MIT, where he was a graduate student and professor; at the San Diego campus of the University of California, where he was a fellow; and at the Bell Laboratories, where he spent his most fruitful years and where, after the forced break-up of the Bell Corporation, the part of its laboratories where Shannon worked was named after him. Both the busts and a painting, also at the Shannon Laboratories, were based on a photograph taken in his lifetime. Another copy of the bust has been placed at the remaining part of the Bell Laboratories at Murray Hill, which are now owned by Alcatel-Lucent.

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