Bit by Bit:

How Claude Shannon's Information Theory Built the Digital Age

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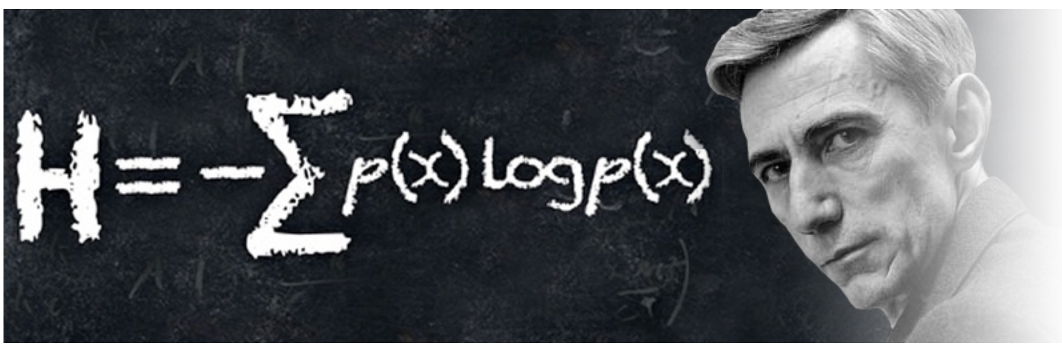

How often is a new scientific field created in a single year *by a single person*? This occurred in 1948, when Claude Shannon's little-known article "A Mathematical Theory of Communication" in *The Bell System Technical Journal* spawned the entire field of information theory. Today, information theory is a term and idea rarely seen or discussed, not because it is no longer relevant, but because it grew to include far too many fields, including electronic communication, data compression, and data storage, to remain a well-defined specialty on its own. Information theory proved how to define, quantify and transmit *information*, laying the theoretical groundwork for an entire modern society that now communicates and stores knowledge digitally.

If anyone were to invent an entire field on his own, Claude Shannon seemed to have the pedigree to do so. After graduating from the University of Michigan at the age of 20, Shannon received his PhD from MIT under advisor Vannevar Bush, where he wrote "one the most important master's theses ever written", a paper that detailed how electrical circuits could be used to implement logic, the basic idea behind today's computers. (Guizzo, p. 12) He followed his PhD with further research at the Institute for Advanced Study, where he worked in the same office as John von Neumann, Albert Einstein and Kurt Gödel. (Nahin, p. 31) By the time Shannon arrived at Bell Labs in the 1940s, he had already accumulated enough exposure to brilliant minds and ideas to formulate a theory of his own, information theory, which attacked the problem of most efficiently transmitting information from point A to B through a specified channel, like a wire.

The resulting 1948 paper, "A Mathematical Theory of Communication", pummeled the scientific community with its clear arguments and highly intuitive supporting mathematics. "It was simply a tour de force, simultaneously founding the entirely new research field of information theory, posing and solving some extremely difficult problems, and pointing its readers toward other problems that remained unanswered." (Nahin, p. 34) On page 1, Shannon first defined the *bit* (binary digit) as a unit for measuring information, which could either take the value 0 or 1. Intuitively, this meant any number, word or message could be represented by a series of 0's or 1's, or answers to yes or no questions. A transmitted message that required the receiver to ask more yes or no questions to interpret the meaning thus contained *more* information. By proving that all forms of media could be encoded and quantified in bits, Shannon introduced the possibility of a “digital age”, where anything from telegraph and telephone messages to pictures and radio waves could all be transmitted and stored as 0’s and 1’s. The possibility of “digitization” also encouraged researchers, including Shannon, to consider how redundant messages could be *compressed* into smaller strings of 0’s and 1’s to save time and storage. (Guizzo, p. 9)

On page 2 of his paper, Shannon included the following diagram:

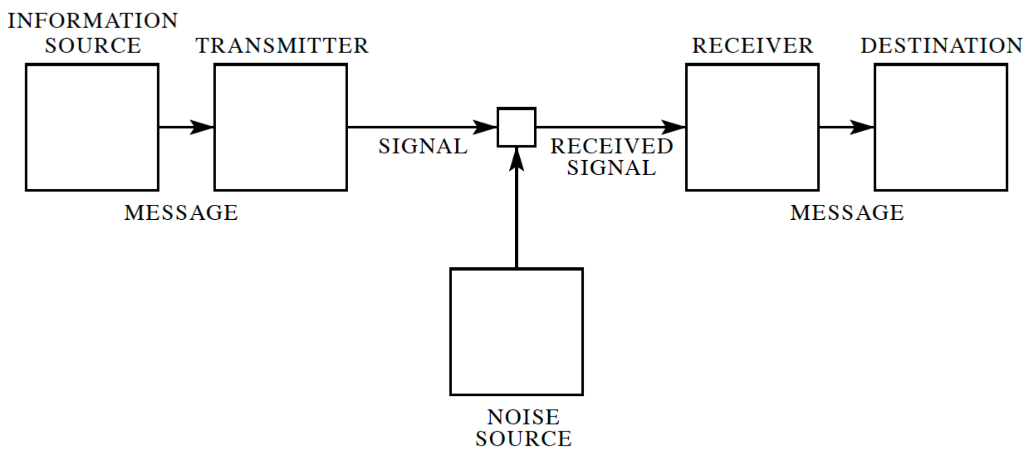

Fig. 1 — Schematic diagram of a general communication system.

As simple as this blueprint looks, it actually stated quite a lot in 1948. It clearly outlined for the first time a basic structure of a communication system and reinforced the entire goal of communication as “reproducing at one point either exactly or approximately a message selected at another point.” (Shannon, p. 1) Since Shannon showed all forms of communication, including text, pictures and sound, could now be encoded into bits, this diagram applied to telephones, televisions, and radios alike. The simplicity of the diagram implied that if further research could only improve how bits are transmitted, received, and protected from noise, the fundamental problems of communication over distances could be solved. Fortunately, Shannon provided a head-start to solving these various problems in the very next section of his paper.

Shannon next attacked the issue of channel capacity, which is how fast a communication channel can transmit information, now defined in bits per second. For the first time, he detailed what would later become the *Shannon limit*, or the maximum channel capacity over a channel given its bandwidth and noise levels. (Hardesty) Even proving that this theoretical limit existed was a big deal; it gave engineers designing communication systems a finite goal to work toward as they developed more sophisticated telephones and televisions and tried to overcome the problem of transmission errors. But Shannon went even further and also recommended a method to get as close to the limit as possible. Transmitting a clear signal, he proved, wasn't a function of blasting a signal at a higher energy or sending the same signal multiple times, the equivalent of yelling across the room at a crowded party. It had to do with how efficiently the message was encoded in bits. By choosing an optimal coding scheme to represent a message in 0's and 1's, he suggested the potential for communication across a channel with no noise and therefore no errors, as long as it remained below the Shannon limit. Shannon's colleagues were stunned. "To make the chance of error as small as you wish? Nobody had ever thought of that. How he got that insight, how he even came to believe such a thing, I don't know. But almost all modern communication engineering is based on that work." [1] In less than 30 pages of writing and proofs, "A Mathematical Theory of Communication" had quantified information and suggested optimal methods for compressing and encoding it for theoretically error-free communication and storage. The field of information theory, dedicated to improving upon Shannon's progress, was born.

The decade following Shannon's 1948 paper was the golden age of information theory, with researchers in electrical engineering, biology, and even psychology applying Shannon's ideas. Shannon appreciated the attention but was worried some researchers were applying information theory out of context, which prompted him to write a journal article called "The Bandwagon" in 1956, asking researchers to be more judicious in applying the theory. (Nahin, p. 34) For the most part, however, researchers in electrical and communication engineering built on Shannon's ideas beautifully. Robert Fano, Shannon's colleague, determined a more efficient way for compressing bits than Shannon's original method, which was then surpassed by David Huffman's method three years later. Huffman coding then became the basis for how future compression coding algorithms were built. Today, "satellite television channels, pocket music players, and efficient cameras and telephones and countless other modern appurtenances depend on coding algorithms to compress numbers – sequences of bits – and those algorithms trace their lineage to Shannon's original 1948 paper." (Gleick, p. 357)

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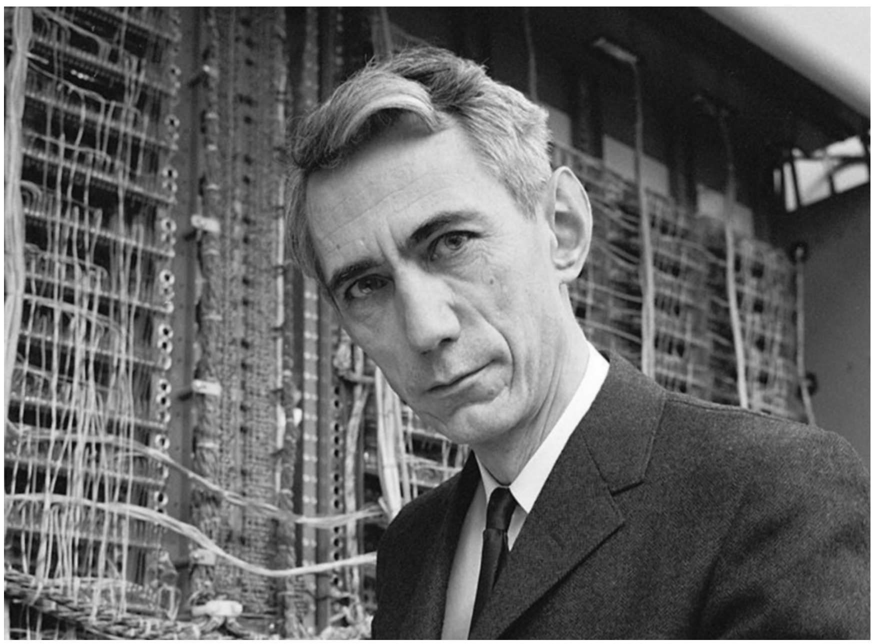
[1] Robert Fano quoted in Aftab, O., et al. Information theory: information theory and the digital age. p. 2.

By the 1960's, most of Shannon's ideas had been thoroughly digested by the scientific community: information could be quantified, compressed, and transmitted without error if bits were encoded properly. Some even declared information theory to be dead. But by the late 1960's and early 1970's, advances in computer hardware, like the microchip, established even further applications for information theory. In 1968, NASA launched the Pioneer 9, the first spacecraft equipped with a digital system for encoding and transmitting information. Shannon's theory for encoding information allowed the spacecraft to send over 4 billion bits of scientific data back to NASA during its 11 billion miles of space travel. (Guizzo, pp. 52-53) One year later, millions of excited Americans watched their televisions to see Neil Armstrong announce his iconic "one small step" on the Moon. (Teitel) Over the next few years, both computers and microchips started mass-production, leveraging ideas from information theory. Engineers started squeezing more and more transistors onto these chips, following the well-known Moore's Law, providing computers with the horsepower to store and transmit information at the theoretical limits originally specified by Shannon.

Today, the pioneering ideas of information theory power much of our digital technology. Hard-drives and modems contain error-correction schemes. Mobile phones communicate with each other thanks to sophisticated channel coding. Billions of encoded bits from videos, sounds, and images are efficiently compressed and transmitted, at lightning speeds, through the Internet to and from individuals across the world. Even the Internet itself, which supports a crucial digital economy in the 21st century, would not be possible if information could not be compressed and transmitted at dizzying speeds. As USC professor Solomon Golomb summarizes, "with Shannon's remarkable theorems telling communications engineers what ultimate goals to strive for, and integrated circuits providing ever-improving hardware to realize these goals, the incredible digital communications revolution has occurred." (Golomb, p. 10)

Before Claude Shannon's paper "A Mathematical Theory of Communication" in 1948, information was a poorly defined concept. Communicating through telephone, television, and radar were thought to be entirely different disciplines demanding entirely different theoretical frameworks. And electronic communication itself operated on shaky foundations, with engineers fudging frequency and power levels somewhat aimlessly to find clearer signals. When Shannon proved how various media could all be encoded into bits and even suggested methods for encoding these bits to eliminate transmission errors, communication engineers were no longer in the dark. Shannon's resulting information theory laid a unified foundation describing how information, in any medium, could be accurately communicated from any point A to point B. When computer hardware like the microchip made appropriate headway in the 1970's and 1980's, the full extent of Shannon's ideas was realized, leading to today's ubiquitous use of digital technology.



Claude Shannon (1916 – 2001)
Alfred Eisenstaedt / The Life Picture Collection / Getty

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