A Gentle Giant

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A Mind at Play: How Claude Shannon Invented the Information Age
by Jimmy Soni & Rob Goodman
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Comparisons with Albert Einstein were a recurring theme in Claude Shannon's life from the 1950s on. "Shannon is to communications as Einstein is to physics," was a common refrain.[1] Among his colleagues at Bell Laboratories and MIT, some even considered Shannon the greater genius.[2] The acclaim was not unwarranted. Shannon is widely credited with developing the modern idea of information and for bringing Boolean logic to the forefront in the design of electronic circuits. His work provided the basis for much of the technology that has emerged in the past seventy years. For all these reasons, it comes as something of a surprise to discover that Jimmy Soni and Rob Goodman's *A Mind at Play* is the first book-length biography of Shannon. The pair are in no doubt as to the significance of their subject. Before Shannon, they write,

> there was precious little sense of information as an idea, a measurable quantity, an object fitted out for hard science. … Just as geometers subjected a circle in the sand and the disc of the sun to the same laws, and as physicists subjected the sway of a pendulum and the orbits of the planets to the same laws, Claude Shannon made our world possible by getting at the essence of information.[3]

A Mind at Play has been rightfully acclaimed as an exhaustive yet highly accessible account of Shannon's life, work, contributions, and the nature of his brilliance. Although not envisaged solely as a text on information theory, the authors still devote considerable space to retracing the development of Shannon's key ideas. In doing so, they have produced a major work. It is truly a biography befitting of the man.

Claude Elwood Shannon was born on April 30, 1916, in the resort town of Petoskey, Michigan. He grew up in nearby Gaylord, where his father was a furniture salesman and his mother was the high school principal. "Shannon was a born tinkerer," Soni and Goodman recount. "[A] telegraph line rigged from a barbed-wire fence, a makeshift barn elevator, and a private backyard trolley tell the story of his small-town Michigan childhood."[4] It was, by all reports, a perfectly ordinary childhood. If Shannon had shown "any signs of early precocity," his biographers observe, "they were not memorable enough to have been written down or noted in the local press."[5]

After graduating high school in 1932, Shannon enrolled at the University of Michigan in Ann Arbor to study electrical engineering and mathematics. Four years later, he moved to Cambridge, Massachusetts, to continue his studies at MIT. He completed a master's degree in electrical engineering in 1937 and was awarded a PhD in mathematics in 1940. Shannon then accepted a full-time position in Manhattan at Bell Telephone Laboratories, the research and development branch of AT&T. "The goal of Bell Labs," Soni and Goodman write, "wasn't simply clearer and faster phone calls. … Bell researchers were encouraged to think decades down the road, to imagine how technology could radically alter the character of everyday life."[6] It was an ideal working environment for Shannon. "I had freedom to do anything I wanted from almost the day I started," he later recalled.[7]

Shannon's most important ideas built on earlier research that had taken place at Bell Labs. In retracing the origins of his innovations, *A Mind at Play* focuses on the groundwork laid by two of Shannon's direct predecessors. Harry Nyquist was an inventor, physicist, and electronic engineer who spent the majority of his career working at Bell Labs. "Nyquist showed," the authors explain, "how the bandwidth of any communications channel provided a cap on the amount of 'intelligence' that could pass through it at a given speed."[8] He also demonstrated that a continuous signal could be represented "as a series of samples, or discrete time-slices,"[9] without degrading the message. In the view of the authors, Nyquist's most important contribution appeared in a 1924 technical paper.[10] He was the first to make an attempt at "explaining the relationship between the physical properties of a channel and the speed with which it could transmit intelligence."[11] Nyquist calculated the speed as $W = k \log m$, where k is the number of signals the system can send per second and m is the number of possible discrete signals the system can transmit.[12] As Soni and Goodman point out, this led to a surprising result: "the larger the number of 'letters' a telegraph system could use, the faster it could send a message."[13]

Ralph Hartley joined Bell Labs at roughly the same time as Nyquist during the years following the First World War. He also retired around the same time as Nyquist in the early 1950s. Early in his career, Hartley had led the Bell Systems team responsible for the receivers used in the first transatlantic voice transmission, which took place in 1915 between Paris and Arlington, Virginia.[14] In *A Mind at Play*, Hartley's work is presented as extending that of Nyquist and playing a crucial role in the development of information theory. At a conference held at Lake Como in 1927, attended by Niels Bohr, Werner Heisenberg, and Enrico Fermi among others, Hartley presented a paper entitled "Transmission of Information."[15] Nyquist's "intelligence" was relabeled as "information" by Hartley. He wrote:

> [I]n estimating the capacity of the physical system to transmit information we should ignore the question of interpretation, make each selection perfectly arbitrary, and base our result on the possibility of the receiver's distinguishing the result of selecting any one symbol from that of selecting any other.[16]

"The real measure of information," Soni and Goodman add, "is not in the symbols we send—it's in the symbols we could have sent, *but did not* [emphasis original]. … Information measures freedom of choice."[17] The relationship between the ideas of Nyquist and Hartley then becomes clear: "what Nyquist demonstrated for telegraphy, Hartley proved true for any form of communication; Nyquist's ideas turned out to be a subset of Hartley's." The amount of information transmitted, according to Hartley, could be expressed as $H = k \log s^n$, where three variables dictate the quantity: k is the number of symbols transmitted per second, s is the set of possible symbols, and n is the length of the message.[18] As the first researcher to address this question, Hartley played a crucial role in the development of Shannon's subsequent work. According to Soni and Goodman, no one, aside from perhaps George Boole, was more influential on Shannon's thinking.[19] Despite acknowledging the debt he owed Hartley, the pair were never close, nor did they ever collaborate. Shannon later described Harley as being

> very bright in some ways, but in some ways he got hung up on things. He was kind of hung up on a theory that Einstein was wrong. … [B]ut the scientific community had finally come around to realizing that Einstein was right. All the scientific community except Hartley I guess.[20]

When examining the work of his predecessors, Shannon noted that most of the earlier ideas about information, such as those developed by Nyquist and Hartley, assumed that all symbols were chosen with equal probability. In his own work, Shannon assumed the opposite, adopting an inherently probabilistic model. He also adopted a new unit of measurement to represent, as the authors put it, "the amount of information that results from a choice between two equally likely options."[21] John Tukey, a colleague at Bell, suggested a name for Shannon's new unit: the *bit*. Shannon's key insight was that information is stochastic in nature, and "neither fully unpredictable nor fully determined. It unspools in roughly guessable ways."[22]

A fascinating section of *A Mind at Play* examines how Shannon's theoretical work on information theory was informed by his knowledge of cryptography and the "unexamined statistical nature of messages, and his intuition that a mastery of this nature might extend our powers of communication."[23] During the Second World War, Shannon had made important contributions to the development of cryptography. Soni and Goodman point to his 1945 paper, "A Mathematical Theory of Cryptography," which was only declassified after the war, as being particularly influential and foreshadowing some of his later ideas about information theory.[24] Shannon, for his part, was always circumspect when it came to his wartime service, maintaining a similar disposition to his counterparts in US intelligence, who he recalled "were not a very talkative bunch."[25]

Shannon's research on the predictability of messages and language led, in turn, to another area of his most important work, and one that was especially informed by cryptography—understanding and manipulating redundancy. Messages with high levels of predictability also have high levels of redundancy. Minimizing redundancy has the obvious benefit of streamlining transmissions, meaning that they can be sent faster and more efficiently. Shannon realized that there was also a situation in which redundancy could be added to useful effect: facilitating error correction. Rather than trying to boost signal strength or repeating a message in an effort to overcome noise and interference, Shannon demonstrated that messages could be represented using additional bits in such a way that if a bit, or two, was flipped during transmission, the output would still more closely resemble the original message than anything else. These ideas gave rise to complementary theorems that established theoretical limits for compression and the maximum speed at which data can be transmitted over a given channel without error. "Nyquist and Hartley had both explored the trade-offs among capacity, complexity, and speed," Soni and Goodman write, "but it was Shannon who expressed those trade-offs in their most precise, controllable form." They continue:

> The groundbreaking fact about channel capacity, though, was not simply that it could be traded for or traded away.

> It was that there is a hard cap—a "speed limit" in bits per second—on accurate communication in any medium.[26]

Shannon's most important theoretical work concerning information theory was published as "A Mathematical Theory of Communication" in the *Bell System Technical Journal* in 1948.[27] As word of Shannon's innovations spread, Warren Weaver, director of the division of natural sciences at the Rockefeller Foundation, arranged to publish it in book form. Published in 1949, *The Mathematical Theory of Communication* contained Shannon's original essay along with Weaver's explanation of the theory in lay terms. The book helped to further publicize Shannon's ideas, which were already recognized as constituting a remarkable breakthrough.

From the account provided by Soni and Goodman in *A Mind at Play*, it is clear that Shannon's genius was apparent to many of his colleagues. One of his most prominent admirers was the influential engineer and science administrator Vannevar Bush. When Shannon arrived at MIT in 1936, Bush was vice president of the university and dean of the School of Engineering. He hired Shannon to work on the development of his differential analyzer, an early analog computer. "I pushed hard for that job and got it," Shannon later claimed, describing it as, "one of the luckiest things of my life."[28]

Soni and Goodman describe how Bush nurtured and shaped Shannon's career. Bush saw in Shannon "a man who should be handled with great care."[29] In a way that would seemingly influence Shannon for the rest of his life, Bush shared his conviction that to specialize in just one topic was to stifle a brilliant mind.[30] Even though Shannon was a mathematician, Bush arranged for him to do his doctoral dissertation on a topic in genetics. In part, the assignment was a test of whether Shannon's brilliance would be apparent even when he had no prior knowledge of a field. Bush need not have worried. Shannon independently came up with several theories that were already familiar to trained geneticists. He also developed an entirely new formula that could predict the frequency with which any three alleles would appear within a population after any given number of generations.

Shannon never returned to genetics, but this brief foray served to demonstrate his abilities. The year Shannon completed his PhD, Henry Phillips, the head of MIT's Mathematics Department, wrote that Shannon was "one of the ablest graduates we have ever had and can do first class research in any field in which he becomes interested."[31] The mathematician Norbert Wiener was similarly impressed, declaring that Shannon was "a man of extraordinary brilliancy and intelligence."[32] Even at this early stage in his career, his biographers observe, it was clear that

> Shannon had acquired an imposing roster of supporters and patrons; these were math's kingmakers, and even without the usual conspicuous striving of the ambitious and talented, he had earned their backing. He had left a mark on men who were discerning judges of raw intellectual horsepower, and they found in him one of their own.[33]

According to Soni and Goodman, Shannon's "gifts were of the Einsteinian variety: a strong intuitive feel for the dimensions of a problem, with less of a concern for the step-by-step details."[34] Shannon's colleague David Slepian noted that, "[Shannon] didn't know math very deeply. But he could invent whatever he needed."[35] Some of the missing formal mathematical knowledge was supplied by Shannon's second wife, Mary Elizabeth Moore, a numerical analyst in the mathematics department at Bell Labs. She became one of Shannon's closest advisers on mathematical matters and helped him to formalize some of his intuitions.[36] Robert Gallager, another colleague, also noted Shannon's instinctive genius:

> He had a weird insight. He could see through things. He would say "Something like this should be true" … and he was usually right … You can't develop an entire field out of whole cloth if you don't have superb intuition.[37]

Once he had developed the basis for information theory, Shannon spent much of his time on a variety of other interests, ranging from juggling and juggling machines to chess and chess playing machines. He produced a digital mouse, Theseus, that could find its way out of a maze. As Shannon rode unicycles around the corridors of Bell Labs, Henry Pollak, director of the mathematics division, declared that Shannon "had earned the right to be non-productive."[38] Shannon's quirky and eclectic array of interests are discussed at length in *A Mind at Play*.

> With no particular academic ambitions, Shannon felt little pressure to publish academic papers. … What resulted were some of Shannon's most creative and whimsical endeavors. … The handmade unicycles, in every permutation: a unicycle with no seat; a unicycle with no pedals; a unicycle built for two. There was the eccentric unicycle: a unicycle with an off-center hub that caused the rider to move up and down while pedaling forward and added an extra degree of difficulty to Shannon's juggling.[39]

Shannon's ideas about the scientific community and the broader leadership roles scientists can play are examined in one of *A Mind at Play's* latter chapters.[40] During a 1950 talk, Shannon noted that "[a] very small percentage of the population produces the greatest proportion of the important ideas."[41] Roughly graphing the distribution of intelligence, he placed Einstein and Isaac Newton within that elite minority—and was quick to remark that he would not put himself or anyone he currently knew there. He also addressed what he saw as the forces that combine to elevate scientists into this gifted portion of the population. Training, experience, intelligence, talent, and motivation were, he believed, the essential criteria.

In attempting to identify precisely what it was that separated merely gifted scientists from the real innovators, Shannon equivocated somewhat, pointing to an underlying sense of "constructive dissatisfaction … a slight irritation when things don't look quite right."[42] It was a "refreshingly unsentimental picture of genius," Soni and Goodman remark: "a genius is simply someone who is usefully irritated."[43] If the origins of genius remained hazy, Shannon had no doubts about the payoffs. "I get a big bang out of proving a theorem," he remarked. "And I get a big kick out of seeing a clever way of doing some engineering problem."[44] As a solver of problems, whether in electrical engineering, mathematics, cryptography, information theory, or any other field that piqued his curiosity, Claude Shannon had few equals.

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1. Jimmy Soni and Rob Goodman, *A Mind at Play: How Claude Shannon Invented the Information Age* (New York: Simon & Schuster, 2018), 187.
2. Soni and Goodman, *A Mind at Play*, 187.
3. Soni and Goodman, *A Mind at Play*, xii.
4. Soni and Goodman, *A Mind at Play*, xii.
5. Soni and Goodman, *A Mind at Play*, 9.
6. Soni and Goodman, *A Mind at Play*, 66.
7. Soni and Goodman, *A Mind at Play*, 68.
8. Soni and Goodman, *A Mind at Play*, 127–28.
9. Soni and Goodman, *A Mind at Play*, 128.
10. Harry Nyquist, "Certain Factors Affecting Telegraph Speed," *Bell System Technical Journal* 3 (1924): 324–46.
11. Soni and Goodman, *A Mind at Play*, 128.
12. Soni and Goodman, *A Mind at Play*, 128.
13. Soni and Goodman, *A Mind at Play*, 129.
14. Soni and Goodman, *A Mind at Play*, 130–31.
15. Ralph Hartley, "Transmission of Information," *Bell System Technical Journal* 7, no. 3 (1928): 535–63.
16. Hartley, "Transmission of Information," 538.
17. Soni and Goodman, *A Mind at Play*, 133.
18. Soni and Goodman, *A Mind at Play*, 133.
19. Soni and Goodman, *A Mind at Play*, 130.
20. Soni and Goodman, *A Mind at Play*, 136–37.
21. Soni and Goodman, *A Mind at Play*, 141.
22. Soni and Goodman, *A Mind at Play*, 145.
23. Soni and Goodman, *A Mind at Play*, 151.
24. Claude Shannon, "A Mathematical Theory of Cryptography," September 1, 1945, Index PO.4, Memorandum for file (case 20878, MM 45-110-92).
25. Soni and Goodman, *A Mind at Play*, 102.
26. Soni and Goodman, *A Mind at Play*, 157.
27. Claude Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal* 27 (1948): 379–423, 623–56.
28. Soni and Goodman, *A Mind at Play*, 20.
29. Soni and Goodman, *A Mind at Play*, 58.
30. Soni and Goodman, *A Mind at Play*, 49.
31. Soni and Goodman, *A Mind at Play*, 74.
32. Soni and Goodman, *A Mind at Play*, 74.
33. Soni and Goodman, *A Mind at Play*, 75.
34. Soni and Goodman, *A Mind at Play*, 184.
35. Soni and Goodman, *A Mind at Play*, 184.
36. Betty remained with him through his Alzheimer's period to his death.
37. Soni and Goodman, *A Mind at Play*, 184.
38. Soni and Goodman, *A Mind at Play*, 199.
39. Soni and Goodman, *A Mind at Play*, 228.
40. Soni and Goodman, "Constructive Dissatisfaction," in *A Mind at Play*, 217–22.
41. Claude Shannon, "Creative Thinking," in *Claude Elwood Shannon: Miscellaneous Writings*, eds. Neil Sloane and Aaron Wyner (Murray Hill, NJ: Mathematical Sciences Research Center, AT&T Bell Laboratories, 1993), 529.
42. Shannon, "Creative Thinking," 531.
43. Soni and Goodman, *A Mind at Play*, 218.
44. Shannon, "Creative Thinking," 531–32.

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