EE 376A/Stat 376A
Information Theory
Prof. T. Cover

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ABOUT CLAUDE SHANNON

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Abstract. A glance at the accomplishments, life, and legacy of Claude Shannon.

Claude Elwood Shannon is best known as the founder of information theory. However, Shannon also started or made significant contributions to many other disciplines. In fact, upon considering the totality of his work, it may not be an overstatement to say that Shannon was the key visionary behind the Information Age we find ourselves in today.

Despite all his contributions, Shannon remains unknown to the general public. He was a very low-profile person that shied away from fame, and had no interest in recognition or promoting his own research. Perhaps he was more concerned with having fun.

1. Selected Research

- **Circuit Design, Boolean Logic, and Switching Theory** (1937):
  At the age of 21, Shannon writes his Master's thesis "A Symbolic Analysis of Relay and Switching Circuits" [Sha38] demonstrating that electrical circuits could be used to do Boolean logic, setting the foundation underlying all electronic digital computers and digital circuit design.
- **Genetics** (1940):
  Shannon writes his PhD thesis at MIT, "An Algebra for Theoretical Genetics", developing mathematical relationships for Mendelian genetics. It remained unpublished until the 1990s, although many considered it to be 30-40 years ahead of its time [RW02].

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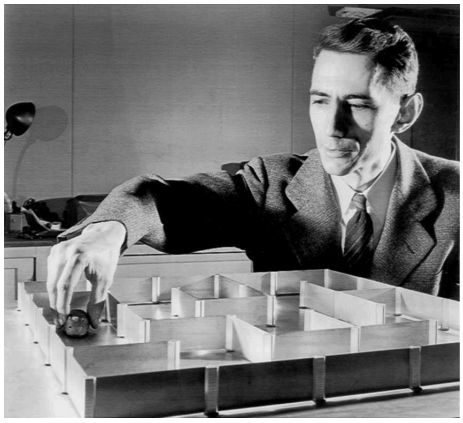
- **Communications and Information Theory** (1948):
  Shannon invents information theory with his touchstone work, "A Mathematical Theory of Communication" [Sha48], establishing the fundamental limits of data compression and reliable communication, and setting the benchmarks that communications engineers have been seeking to meet ever since.

- **Sampling Theory** (1949):
  Continuing to illuminate the path from analog to digital, Shannon proves the Nyquist-Shannon Sampling Theorem ("Communication in the Presence of Noise" [Sha49a]), showing that an analog waveform can be perfectly reconstructed from a (discrete) vector of samples taken at twice the highest frequency in the waveform.

- **Cryptography** (1949):
  Shannon works on cryptography and anti-aircraft ballistics systems during World War II at Bell Labs. In 1949, he publishes "Communication Theory of Secrecy Systems" [Sha49b], an important contribution to modern cryptography, in which he proves that all virtually unbreakable ciphers have properties similar to those of the one-time pad.

- **Artificial Intelligence** (1950):
  Shannon builds an electromechanical mouse named Theseus that can find its way out of a maze, conducting one of the first experiments in AI.



He also publishes "Programming a Computer for Playing Chess" [Sha50], in which he describes how to program a computer to play chess by using minimax game trees. Consequently, Shannon is considered the "Father of Computer Chess".

- **Linguistics** (1951):
  Shannon publishes "Prediction and Entropy of Printed English" [Sha51], describing how to estimate the uncertainty and redundancy of a language, backed by experiments.

- **Complexity Theory** (1957):
  In his paper "A universal Turing machine with two internal states" [Sha57], Shannon shows that there is a simple way to mimic an arbitrary Turing machine with a Turing machine possessing only two states. This constitutes the construction of a two-state universal Turing machine.

- **Gambling** (1960s):
  Shannon builds the first wearable computer, about the size of a cigarette pack, to predict outcomes in roulette. It had four buttons used to type in the speed of the roulette wheel and transmit sounds by radio to another gambler's hearing aid. [Tho98]

- **Mathematics of Juggling**:
  Shannon developed three theorems that established the mathematical theory of juggling [SSW93], describing properties that jugglable patterns must obey. The most famous of these is his first Theorem: $(F + D)H = (V + D)N$, where F is the flight time of a ball, D is the (down) time a ball spends in the hand, V is the time a hand is vacant, N is the number of juggled balls, and H is the number of hands [Pol02].

- **Gadgetry**:
  Shannon was the consummate tinkerer, building all sorts of zany contraptions for fun and amusement. They included: rocket-powered frisbees, motorized pogo sticks, mechanical Rubik's cube solvers [Wik], bounce-juggling mannequins, Batmanesque bookcases containing hidden doorways, +30 hand-built unicycles, chess-playing machines with mechatronic arms that beeped witty remarks, a computer that used only Roman numerals[1], a 'mind-reading' machine [Sha], a train track of honorary doctorates rotating on his ceiling [CS01], a motor home made from renovating a Volkswagon van, and a chair lift that swept his kids from the house to a lake six hundred feet away.

  In one poignant illustration of his sense of humor, Shannon built what he called the "The Ultimate Machine". It was a box with only one button on it. Upon pressing the button, the box would open, and a mechanical hand would crawl out and press the button again to close the box.

2. Shannon's Life

- Born in Petoskey, Michigan on April 30, 1916.
- Father: American businessman and descendant of early New Jersey settlers. [SSW93]
- Mother: Daughter of Germans. Language teacher and high school principal. [SSW93]
- Interest in engineering was sparked by his father giving him erector sets to play with.[2]
- Demonstrated knack for mechanics as a child, building planes, boats, radios, telegraphs.
- Childhood hero: Thomas Edison.

[1]He called it the THROBAC I (Thrifty Roman Numeral Backward Looking Computer) [CS01].
[2]Interview with Charles M. Vest. From [CLM+07]

- Entered the University of Michigan for four-year undergraduate studies in 1932. Double majored in mathematics and electrical engineering.
- Did graduate studies at MIT. Earned MSEE in 1938, and PhD in Math in 1940.
- Struggled with PhD language requirements in French and German. Hired tutors.
- Spent 15 years at Bell Labs, surrounded by legends such as Nyquist, Shockley, Bode, Hartley, Stibitz, Kruskal, Karnaugh, Kahng, Ritchie, Thompson, Oliver[3] ...
- Married Betty Moore in 1949, a numerical analyst at Bell Labs, and graduate of mathematics from Rutgers. Had three kids.
- Served on MIT faculty from 1956 to 1978.
- First recipient of the Kyoto Prize in the sciences.
- First recipient of the Claude E. Shannon Award in 1972.
- Advisors to Shannon:
  - RA advisor: Vannevar Bush, engineer and outspoken science policymaker
  - PhD advisor: Frank L. Hitchcock, algebraist
  - PhD mentor: Barbara Burks, behaviorial geneticist
  - Institute of Advanced Study advisor: Herman Weyl, mathematician
- Shannon's list of heroes: Edison, Newton, Darwin, Einstein, Von Neumann. [SSW93]
- An atheist, he saw no fundamental difference between men and machines [Bat].
- Favorite Music: Dixieland. Also played clarinet. [SSW93]
- Favorite Poets: T.S. Eliot, Rubaiyat, Ogden Nash [SSW93]
- Hobbies: Building gadgets, running, playing chess[4], juggling, unicycling
- Has been observed trying to beat his son's record in Pac-Man. [SSW93]
- Died in Medford, Massachusetts on February 24, 2001, after a long battle with Alzhiemer's.

3. Quotations

Many of the quotations which follow come from the following two sources:

- Interviews conducted by E. Chiu, J. Lin, B. Mcferron, N. Petigara, and S. Seshasai in their fascinating read "The Mathematical Theory of Claude Shannon" [CLM+07].
- The UCSD video "Claude Shannon: Father of the Information Age" [RW02], which is also linked to at ee376a.stanford.edu.

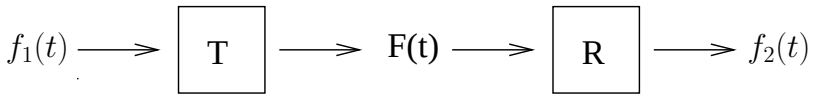
> *Many students learned from [Shannon] that the most valuable ideas are the simplest, and that the purpose of theoretical research is to throw light onto an area rather than to produce long, obscure arguments. He would often start a lecture by discussing several trivially simple (but very carefully chosen) examples, after which the general result would become obvious.*
>
> – Robert Gallager [Gal03]

[3]With Barney Oliver and John Pierce, Shannon filed the patent for Pulse Code Modulation (PCM) [OPS48]
[4]In 1965, Shannon almost drew Mikhail Botvinnik, the prevailing world chess champion. [Bat]

The fundamental problem of communication is that of reproducing at one point, either exactly or approximately, a message selected at another point.
– C.E. Shannon [Sha48]

Information is the resolution of uncertainty.
– C.E. Shannon

Off and on I have been working on an analysis of the some of the fundamental properties of general systems for the transmission of intelligence, including telephony, radio, television, telegraphy, etc. Practically all systems of communication may be thrown into the following general form:



– C.E. Shannon, in a letter to his mentor, Vannevar Bush[5] [CLM+07]

I am very seldom interested in applications. I am more interested in the elegance of a problem. Is it a good problem, an interesting problem?
– C.E. Shannon[6] [CLM+07].

Usefulness is not my main goal. I like to solve new problems all the time. I keep asking myself, how would you do this? Is it possible to make a machine to do that?
– C.E. Shannon [Den87]

Bob, I think you impute a little more practical purpose to my thinking that actually exists. My mind wanders around, and I conceive of different things day and night. Like a science-fiction writer, I'm thinking 'What if it were like this', or 'Is there and interesting problem of this type' and I'm not caring whether someone is working on it or not. It's usually just that I like to solve a problem, and I work on these all the time.
– C.E. Shannon[7] [CLM+07]

Claude never did care about money. He never even put his paycheck into a bank account that paid interest, until he married and his wife Betty suggested it to him.
– Arthur Lewbel [Lew]

I just wondered how things were put together.
– C.E. Shannon

Shannon's puzzle-solving research style was in full swing when I was an MIT graduate student (1956-60). Intellectualism was in the air. Everyone wanted to understand mathematics and physics as well as communication. Starting companies, making millions, developing real applications was secondary. There

[5]Correspondences to Vannevar Bush. December 1938 through July 1940. Vannevar Bush Collection, Manuscript Division, Library of Congress.
[6]Price, Robert. Interview with IEEE Communication Journal, 1984.
[7]Price, Robert. Interview with IEEE Communication Journal, 1984.

was interest in bringing the theory closer to reality, but it was theory-based. Our role models were relaxed, curious, and had time to reflect.

– Robert Gallager [Gal05]

Claude E. Shannon can't sit still. We're at his home, a stuccoed Victorian edifice overlooking a lake north of Boston, and I'm trying to get him to recall how he came up with the theory of information. But Shannon, who is a boyish 73, with an elfish grin and a shock of snowy hair, is tired of expounding on his past. Wouldn't I rather see his toys?

Without waiting for an answer, and over the mild protests of his wife, Betty, he leaps from his chair and disappears into the other room. When I catch up with him, he proudly shows me his seven chess-playing machines, gasoline-powered pogostick, hundred-bladed jackknife, two-seated unicycle and countless other marvels. Some of his personal creations – such as a juggling W. C. Fields mannequin and a computer called THROBAC that calculates in Roman numerals – are a bit dusty and in disrepair, but Shannon seems as delighted with everything as a 10-year-old on Christmas morning.

Is this the man who, as a young engineer at Bell Laboratories in 1948, wrote the Magna Carta of the information age: The Mathematical Theory of Communication? Whose work Robert W. Lucky, executive director of research at AT&T Bell Laboratories, calls the greatest 'in the annals of technological thought?' Whose 'pioneering insight' IBM Fellow Rolf W. Landauer equates with Einstein's? Yes. This is also the man who invented a rocket-powered Frisbee and who juggled while riding a unicycle through the halls of Bell Labs. 'I've always pursued my interests without much regard to financial value or value to the world,' Shannon says. 'I've spent lots of time on totally useless things.'

– John Horgan's Scientific American interview with Claude Shannon [Hor90]

He was just a loner and liked to work alone. He wouldn't go out of his way to collaborate with other people ... His work habits were not exemplary – he slept when he felt like sleeping.

– Betty Shannon, wife of C.E. Shannon[8] [CLM+07]

He was not someone who would listen to other people about what to work on.

– Robert Fano[9] [CLM+07]

To create new ideas, you really need to limit the amount of information that comes in. There are times when you act as a vacuum cleaner and suck everything in, other times you shut everything out and just think.

– Trenchard More, on how Shannon found himself in an environment not conducive to research thinking after becoming a professor[10] [CLM+07]

You may have heard that I received the Alfred Noble prize ... for my paper on switching circuits. In fact I have a sneaking suspicion that you have not only heard about it but had something to do with my getting it ... if so, thanks a lot. I was so surprised and pleased to receive the letter announcing the award that I nearly fainted!

[8]Interview with Betty Shannon.

[9]Interview with Robert Fano.

[10]Interview with Trenchard More.

– C.E. Shannon's letter to Vannevar Bush, who had secretly submitted Shannon's Master's thesis to the Alfred Noble committee [11] [CLM+07]

This, I feel strongly, should be polished a bit and then published. I will be very glad indeed, if you wish me to do so, to transmit it for publication for you with my endorsement, and to recommend some place where it might properly appear ... I do not believe you ought to wait to examine further problems before a publication.

– Advisor Vannevar Bush, recommending that Shannon publish his Ph.D. thesis on genetics [Sha40]; Shannon never bothered[12][CLM+07]

He was a very modest guy. He got a lot of awards but they never went to his head and he never talked about them.

– Betty Shannon[13] [CLM+07]

I first met Shannon in 1972 in Ashkelon, Israel, a few years after he had retired from research. He had been asked to give the first Shannon Lecture and was delighted by the prospect, mostly because of the recursive aspect. The lecture was on feedback, which he illustrated with Campbell soup cans on which were pictures of Campbell soup cans, sounds built up of sounds of sounds, and lecturers receiving their own awards.

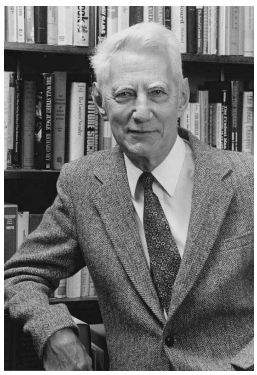
– Thomas Cover [GBC+02]

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.

– C.E. Shannon, 1983

All the advanced signal processing that enables us to send high-speed data was done as an outgrowth of Claude Shannon's work on information theory.

– Bob Lucky [RW02]



[11] Correspondence from Shannon to Bush. December 13, 1939.
[12] Correspondence from Bush to Shannon. January 27, 1939.
[13] Interview with Betty Shannon.

I think the lay public does not fully appreciate how much of an impact information theory has made on many things we take for granted, from storage like CD players, or communication of data, like your modem that dials up. Just about anything that has to do with communication, storage and compression follows in some way directly from the contribution that Shannon made.

– Ramesh Rao [RW02]

When I started talking in the late fifties about digital communications, this was considered a contradiction in terms by the traditional communications theorists. They were so wedded to the notion that communication involves continuous wave forms and continuous modulation. So the whole idea that communication was moving in the direction of going digital was a new idea that was very heavily influenced by Shannon ...

– Solomon W. Golomb [RW02]

... one of the most important master's theses ever written ... a landmark in that it changed circuit design from an art to a science.

– H. H. Goldstine, on Shannon's Master's thesis [Gol72]

He created the field of digital logic. That sounds simple to say now, but then, what did digital have to do with logic? Logic is reasoning, it's a subject in philosophy. He showed that AND OR and NOT, the connectives from Boolean algebra, could be used to build electronic circuits which led in no small part to the invention of the computer and the fast calculations that people like to do.

– Robert McEliece [RW02]

It may be no exaggeration to say that man's progress in 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.

– "The Information Theory," Fortune (Magazine), pp. 136 to 158, Dec. 1953.

It is no exaggeration to refer to Claude Shannon as the father of the information age, and his intellectual achievement as one of the greatest of the twentieth century.

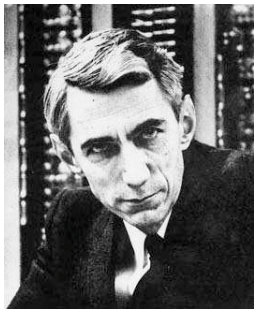
– Solomon W. Golomb [GBC+02]

This ability to create new fields and develop their form and depth surely places Shannon in the top handful of creative minds of the century.

– Thomas Cover [GBC+02]

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.

– A.N. Kolmogorov [Gal03]



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