THE FRANKLIN INSTITUTE

COMMITTEE ON SCIENCE AND THE ARTS

No. 3290. *Subject* THE STUART BALLANTINE MEDAL

Applicant

Address

Date of Application

Recipient ~~Inventor~~ Dr. Claude E. Shannon

Address

COMMITTEE: 1954 - 1955

Mr. Lewis P. Tabor, *Chairman*	*MEETINGS:*
Dr. Charles B. Bazzoni	December 27, 1954
Mr. William G. Ellis	March 23, 1955
Mr. Edward L. Forstall	May 9, 1955
Dr. Albert F. Murray	

Report presented to General Committee: May 11, 1955

Final Action: June 8, 1955

Approved by Board of Managers June 15, 1955

Award The Stuart Ballantine Medal

Report, Medal, and Certificate presented ~~forwarded~~ *to* Medalist ~~Inventor~~

To Claude Elwood Shannon

Medal Day, October 19, 1955.

THE FRANKLIN INSTITUTE OF THE STATE OF PENNSYLVANIA

FOR THE PROMOTION OF THE MECHANIC ARTS

Hall of the Institute,

Philadelphia, June 15, 1955.

Report No. 3290.

Investigating the Work of

Claude Elwood Shannon,

of Chatham, New Jersey.

THE FRANKLIN INSTITUTE OF THE STATE OF PENNSYLVANIA

For the Promotion of the Mechanic Arts

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Hall of the Institute,
Philadelphia, June 15, 1955.

Committee on Science and the Arts Case No. 3290.

The Franklin Institute of the State of Pennsylvania, acting through its Committee on Science and the Arts, has considered carefully the work of those who have contributed greatly to the field of research in communication and reconnaissance, and has selected as recipient of the award of the Stuart Ballantine Medal for 1955 -

CLAUDE ELWOOD SHANNON,
of Chatham, New Jersey,

In consideration of his recognition of communication as essentially a statistical process, his identification of the elements of communication systems with the appropriate statistical functions, and his welding of the powerful methods of mathematical statistics into a comprehensive theory of communication which permits precise and rapid evaluation of proposed new communication systems, and points the way for significant new developments.

This report may be introduced by several quotations from Dr. Warren Weaver's paper, "Recent Contributions to the Mathematical Theory of Communication":

"The word *communication* will be used here in a very broad sense to include all of the procedures by which one mind may affect another. This, of course, involves not only written and oral speech, but also music, the pictorial arts, the theatre, the ballet, and in fact all human behavior." ...

"Relative to the broad subject of communication, there seem to be problems at three levels. Thus it seems reasonable to ask serially:

"Level A. How accurately can the symbols of communication be transmitted? (The technical problem.)

"Level B. How precisely do the transmitted symbols convey the desired meaning? (The semantic problem.)

"Level C. How effectively does the received meaning affect conduct in the desired way? (The effectiveness problem.)

"The *technical problems* are concerned with the accuracy of transference from sender to receiver of sets of symbols (written speech), or of a continuously varying signal (telephonic or radio transmission of voice or music), or of a continuously varying two-dimensional pattern (television), etc. Mathematically, the first involves transmission of a finite set of discrete symbols, the second the transmission of one continuous function of time, and the third the transmission of many continuous functions of time or of one continuous function of time and of two space coordinates.

"The *semantic problems* are concerned with the identity, or satisfactorily close approximation, in the interpretation of meaning by the receiver, as compared with the intended meaning of the sender. This is a very deep and involved situation, even when one deals only with the relatively simpler problems of communicating through speech." ...

"The effectiveness problems are concerned with the success with which the meaning conveyed to the receiver leads to the desired conduct on his part. It may seem at first glance undesirably narrow to imply that the purpose of all communication is to influence the conduct of the receiver. But with any reasonably broad definition of conduct, it is clear that communication either affects conduct or is without any discernible and probable effect at all." ...

"So stated, one would be inclined to think that Level A is a relatively superficial one, involving only the engineering details of good design of a communication system; while B and C seem to contain most if not all of the philosophical content of the general problem of communication.

"The mathematical theory of the engineering aspects of communication, as developed chiefly by Claude Shannon at the Bell Telephone Laboratories, admittedly applies in the first instance only to problem A, namely, the technical problem of accuracy of transference of various types of signals from sender to receiver. But the theory has, I think, a deep significance which proves that the preceding paragraph is seriously inaccurate. Part of the significance of the new theory comes from the fact that levels B and C, above, can make use only of those signal accuracies which turn out to be possible when analyzed at Level A. Thus any limitations discovered in the theory at Level A necessarily apply to levels B and C. But a larger part of the significance comes from the fact that the analysis at Level A discloses that this level overlaps the other levels more than one could possibly naively suspect. Thus the theory of Level A is, at least to a significant degree, also a theory of levels B and C."

Plate I represents, symbolically, a communication system. "The information source selects a desired message out of a set of possible messages ..." ... "The transmitter changes this message into a signal which is actually sent over the communication channel from the transmitter to the receiver." ... "The receiver is a sort of inverse transmitter, changing the transmitted signal back into a message, and handing this message on to the destination." ...

"In the process of being transmitted, it is unfortunately characteristic that certain things are added to the signal which were not intended by the information source. These unwanted additions may be distortions of sound (in telephony, for example) or static (in radio), or distortions in shape or shading of picture (television), or errors in transmission (telegraphy or facsimile), etc. All of these changes in the transmitted signal are called noise.

"The kind of questions which one seeks to ask concerning such a communication system are:

a. How does one measure amount of information?

b. How does one measure the capacity of a communication channel?

c. The action of the transmitter in changing the message into the signal often involves a coding process. What are the characteristics of an efficient coding process? And when the coding is as efficient as possible, at what rate can the channel convey information?

d. What are the general characteristics of noise? How does noise affect the accuracy of the massage finally received at the destination? How can one minimize the undesirable effects of noise, and to what extent can they be eliminated?

e. If the signal being transmitted is continuous (as in oral speech or music) rather than being formed of discrete symbols (as in written speech, telegraphy, etc.), how does this affect the problem?"

Inspired by the earlier work in mathematical theory of communication by Nyquist and Hartley, and by the power of the statistical methods applied by Norbert Wiener in "The Extrapolation, Interpolation, and Smoothing of Stationary Time Series," Dr. Shannon has developed the mathematical techniques necessary to provide quantitative answers to the above questions for present day communication systems, including those employing some of the newer methods of modulation such as pulse-code modulation (PCM) and pulse position modulation (PPM) which exchange bandwidth for signal-to-noise ratio.

These techniques are summarized and generalized by Dr. Shannon in the paper "The Mathematical Theory of Communication," originally published in the Bell System Technical Journal in July and October 1948, and published in book form in 1949, together with the paper by Dr. Weaver from which the quotations above are taken.

While an extended analysis of this paper* is beyond the scope of this report, an attempt will be made to indicate the basis for the logical structure, and to define some of the terms frequently used in discussions of these methods.

In "The Mathematical Theory of Communication," Dr. Shannon considers first discrete noiseless systems. He defines the capacity of a discrete channel as the limit (as T approaches infinity) of the ratio $\frac{\log N(T)}{T}$ where N(T) is the number of allowed signals of duration T, and demonstrates how this applies to familiar cases. He then shows that since a physical system, or a mathematical model of a physical system which produces a sequence of symbols governed by a set

*Dr. Shannon's paper.

of probabilities is known as a stochastic process, a discrete source of information is a stochastic process, and may therefore be treated by the mathematical methods developed for such processes. It can then be shown that stochastic processes of the type governed by a set of probabilities similar to those covering word structure and sequencing are known as discrete Markoff processes, which have been studied extensively in the literature. Dr. Shannon then points out: "Among the possible discrete Markoff processes there is a group with special properties of significance in communication theory. This special class consists of the 'ergodic' processes, and we shall call the corresponding sources ergodic sources. Although a rigorous definition of an ergodic process is somewhat involved, the general idea is simple. In an ergodic process every sequence produced by the process is the same in statistical properties. Thus the letter frequencies, digram frequencies, etc., obtained from particular sequences, will, as the lengths of the sequences increase, approach definite limits independent of the particular sequence." ... "Roughly, the ergodic property means statistical homogeniety."

To define a quantity which will measure the rate at which information is produced in a Markoff process, it is possible to write down the specifications of this quantity. These specifications lead to a quantity $H = - K \sum_{i=1}^{n} p_i \log p_i$ where the p_i's are the probabilities of the occurrence of the possible events. This is precisely the form in which entropy is defined by Tolman and others in statistical mechanics. Quantities of this form play a major part in the development of information theory, as measures of information, choice, and uncertainty.

To quote Dr. Shannon again: "The ratio of the entropy of a source to the maximum value it could have while still restricted to the same symbols will be called its relative entropy. This, as will appear later, is the maximum compression possible when we encode into the same alphabet. One minus the relative entropy is the redundancy. The redundancy of ordinary English, not considering statistical structures over greater distances than about eight letters, is roughly 50%. This means that when we write English half of what we write is determined by the structure of the language, and half is chosen freely."

Further development of this logic leads to development of a mathematical description of the encoding and decoding operations, and to expressions relating statistical characteristics of source and channel.

When noise is introduced into a discrete system, it is, to quote again "not in general possible to reconstruct the original message or the transmitted signal with certainty by any operation on the received signal E." The problem then becomes one of finding ways of transmitting the information which are optimal in combating noise. The average ambiguity of the received signal is called the equivocation, and is equal to the conditional entropy. Channel capacity is then determined by maximizing the difference between the source entropy and the equivocation: $C = \text{Max}\ (H(x) - H_y(x))$. It can be demonstrated that for a given channel capacity and given entropy of a discrete source, there exists a coding system such that the output of the source can be transmitted over the channel with an arbitrarily small equivocation. An example of efficient coding is worked out.

In proceeding to the case of continuous information, it is necessary to consider signals as ensembles of functions, which may be continuous distributions, but may be bandwidth or amplitude limited. It is possible to calculate the entropy of such ensembles, and to apply statistical methods to problems of source rates, channel capacities and channel fidelities.

Channel capacity is again equal to the maximized difference between source entropy and equivocation, and in this case, can be shown to be equal to

$$C = \lim_{T \to \infty} \max_{P(x)} \frac{1}{T} \iint P(x,y) \log \frac{P(x,y)}{P(x)P(y)} \, dx \, dy.$$

As an example of the application of these methods to a practical problem, in a joint paper with B. M. Oliver and J. R. Pierce, entitled "The Philosophy of PCM" and published in November 1948, Dr. Shannon used these techniques in a comparison of PCM with broad band FM. The following results are easily derived:

1. PCM gives better signal-to-noise ratio than FM.

2. Binary PCM gives high quality signals where it is just possible to recognize the presence of each pulse through noise and interference.

3. PCM gives no improvement in signal-to-noise ratio in times of large signal or low noise.

4. PCM lends itself to time division multiplexing.

Another application of Dr. Shannon's methods is found in his paper, "Communication in the Presence of Noise," published in January 1949. This paper is described by the following abstract: "A method for representing any communication system geometrically. Messages and the corresponding signals are points in two function spaces, and the modulation process is a mapping of one space into another. Using this representation, a number of results in communication theory are deduced concerning expansion and compression of bandwidth, and the threshold effect. Formulas are found for the maximum rate of transmission of binary digits over a system when the signal is perturbed by various kinds of noise. Some of the properties of ideal systems which transmit at the maximum rate are discussed. The equivalent number of binary digits per second for certain information sources is calculated."

In a classified report, "A Mathematical Theory of Cryptography," dated September 1, 1945, Dr. Shannon applies many of these principles to an analysis of military secrecy systems. Plate II is a schematic of such a system. The relation between system structure and the amount of labor required for solution is demonstrated, and an indication is given as to how a system should be constructed in order to require a very large amount of labor to solve it without a key.

This paper has since been declassified, and was published in the Bell System Technical Journal in October 1944 under the title, "Communication Theory of Secrecy Systems."

In addition to his work in the field of communications, Dr. Shannon has worked extensively in the fields of switching circuit synthesis, and the analysis and synthesis of automata, including examples of game-playing and learning machines.

Twenty-two significant papers, of which Dr. Shannon has been author or co-author, have come to our attention, as well as numerous book reviews and informal discussions. These are listed in Appendix B.

In summary Dr. Shannon has recognized that complete communication processes can be studied by statistical methods, and has chosen appropriate statistical functions for the elements of the systems. In many cases there is considerable background in the literature regarding the properties of the models he has selected. He has organized this material into a comprehensive theory, with appropriate extensions, to permit the over-all study of complete communication systems of great complexity. This makes it possible to indicate methods by which performance for any particular application may be optimized, and permits rapid and precise comparison of the over-all characteristics of complex systems.

A biographical note on Dr. Shannon is attached as Appendix A.

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In consideration of his recognition of communication as essentially a statistical process, his identification of the elements of communication systems with the appropriate statistical functions, and his welding of the powerful methods of mathematical statistics into a comprehensive theory of communication which permits precise and rapid evaluation of proposed new communication systems, and points the way for significant new developments, THE FRANKLIN INSTITUTE awards its STUART BALLANTINE MEDAL to CLAUDE ELWOOD SHANNON, of Chatham, New Jersey.

President.

Secretary.

Chairman of the Committee on Science and the Arts.

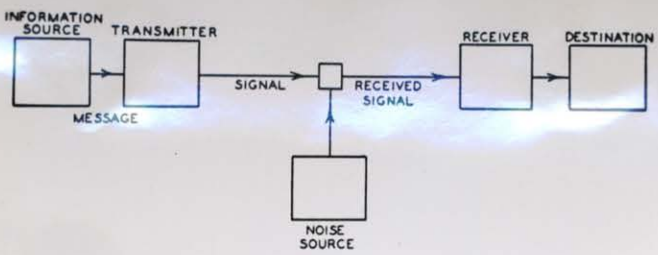

Fig. 1—General communications system.

S. & A. Case No. 3290,
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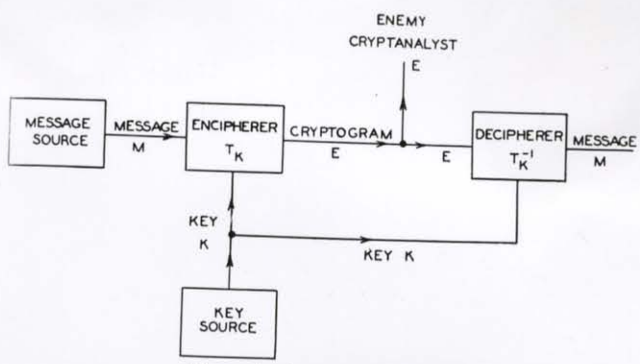
Plate I.

PLATE I.



Schematic of a general secrecy system.

S. & A. Case No. 3290,
The Stuart Ballantine Medal.
Plate II.

PLATE II.

C. E. SHANNON

S. & A. Case No. 3290,
The Stuart Ballantine Medal.
Plate III.

PLATE III.

APPENDICES

Appendix A

CLAUDE E. SHANNON

CLAUDE E. SHANNON, mathematician and inventor, has been a member of the technical staff at Bell Telephone Laboratories since 1941. He has made a number of outstanding contributions to the communication field, especially in the mathematical theory of communication, application of Boolean algebra, cryptography, and computing circuits.

Born in Petoskey, Michigan, on April 30, 1916, Dr. Shannon was graduated from the University of Michigan in 1936 (B.S. in E.E.). He continued his studies at Massachusetts Institute of Technology, where he received S.M. and Ph.D. degrees in 1940. While at M.I.T. he was awarded a Bowles Fellowship in 1939. The American Institute of Electrical Engineers granted him the Alfred Noble Prize in 1940 and that year he won a National Research Fellowship. He used the latter at Princeton University. He served with the N.D.R.C. as a consultant in fire-control work from December 1940 until August 1941 when he joined Bell Laboratories.

The Morris Liebmann Memorial Prize of the Institute of Radio Engineers was awarded to Dr. Shannon in 1949 for his "original and important contributions to the theory of the transmission of information in the presence of noise." The following year, he was made a Fellow of that Institute.

With W. Weaver, Dr. Shannon is the co-author of *The Mathematical Theory of Communication*. In addition a number of his articles have been published in the Bell System Technical Journal, Proceedings of the Institute of Radio Engineers, Journal of Mathematics and Physics, Philosophical Magazine, and others.

Dr. Shannon is a member of the American Mathematical Society, Sigma Xi, and Phi Kappa Phi.

Dr. Shannon and his wife, the former Mary Elizabeth Moore, make their home in Chatham, New Jersey.

17. Discussion of Dr. C. E. Shannon's papers (and reply), Great Britain, Ministry of Supply. Symposium on Information Theory. Royal Society, Burlington House, London, Sept. 26-29, 1950

18. "Lattice Theory of Information," Great Britain, Ministry of Supply. Symposium on Information Theory. Royal Society, Burlington House, London, Sept. 26-29, 1950

19. "Memory Requirements in a Telephone Exchange," Bell System Technical Journal, v. 29, July 1950

20. "Programming a Computer for Playing Chess," Phil. Mag., v. 41, Mar. 1950

21. "Recent Developments in Communication Theory," Electronics, v. 32, Apr. 1950

22. Review of book "Description of a Relay Calculator" by the Staff of the Harvard Computation Laboratory, IRE Proc., v. 38, Apr. 1950

23. "A Symmetrical Notation for Numbers," Am. Math. Monthly, v.57, Feb. 1950

24. "Prediction and Entropy of Printed English," Bell System Technical Journal, v. 30, Jan. 1951

25. "The Mathematical Theory of Communication," University of Illinois Press, 1949 (Book) (By C. E. Shannon and W. Weaver)

26. "Computers and Automata," IRE Proc., v. 41, Oct. 1953

Appendix B

Publications of Claude E. Shannon

1. "A Symbolic Analysis of Relay and Switching Circuits," A.I.E.E. Trans., v. 57, 1938

2. "Mathematical Theory of the Differential Analyzer," Journal of Mathematics and Physics, v. 20, 1941

3. "Number of Two-Terminal Series-Parallel Networks," Journal of Mathematics and Physics, v. 21, Aug. 1942 (By John Riordan and C. E. Shannon)

4. "Transmission of Information" (Presented at IRE meeting, New York, Nov. 1947, pamphlet.)

5. "Mathematical Theory of Communication," Bell System Technical Journal, v. 27, July, October 1948

6. "Philosophy of PCM," IRE Proc., v. 36, Nov. 1948 (By B. M. Oliver, J. R. Pierce, and C. E. Shannon.)

7. "Communication in the Presence of Noise," IRE Proc., v. 37, Jan. 1949

8. "Communication Theory of Secrecy Systems," Bell System Technical Journal, v. 28, Oct. 1949

9. "Programming a Computer for Playing Chess," IRE Proc., v. 37, Feb. 1949

10. Review of book "Cybernetics" by N. Wiener, IRE Proc., v. 37, Nov. 1949

11. "Synthesis of Two-Terminal Switching Circuits," Bell System Technical Journal, v. 28, Jan. 1949

12. Book review, "Transformations on Lattice and Structures of Logic," by Stephen A. Kiss, IRE Proc., v. 37, Oct. 1949

13. "Simplified Derivation of Linear Least Square Smoothing and Prediction Theory," IRE Proc., v. 38, Apr. 1950 (By H. W. Bode and C. E. Shannon)

14. "Chess-Playing Machine," Scientific American, v. 182, Feb. 1950

15. "Communication Theory - Exposition of Fundamentals," Great Britain, Ministry of Supply. Symposium on Information Theory. Royal Society, Burlington House, London, Sept. 26-29, 1950

16. "General Treatment of the Problem of Coding," Great Britain, Ministry of Supply. Symposium on Information Theory. Royal Society, Burlington House, London, Sept. 26-29, 1950

17. Discussion of Dr. C. E. Shannon's papers (and reply), Great Britain, Ministry of Supply. Symposium on Information Theory. Royal Society, Burlington House, London, Sept. 26-29, 1950

18. "Lattice Theory of Information," Great Britain, Ministry of Supply. Symposium on Information Theory. Royal Society, Burlington House, London, Sept. 26-29, 1950

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