1. Intro to Digital Communication Systems

Office Hours:
Check Google Calendar on the course website.
Dr. Prapun’s Office:
6th floor of Sirindhralai building, BKD
1 Elements of a Digital Communication System

1.1. Shannon's insight [13]:

The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.

1.2. Figure 1 illustrates the functional diagram and the basic elements of a digital communication system.

Figure 1: Basic elements of a digital communication system

1.3. The source output may be either

- an analog signal, such as an audio or video signal,
- or a digital signal, such as the output of a computer, that is discrete in time and has a finite number of output characters.

1.4. Source Coding: The messages produced by the source are converted into a sequence of bits.

- This process is called source coding or source encoding.
- For this course, we want to also represent the source output (message) by as few bits as possible.
  - In other words, we seek an efficient representation of the source output that results in little or no redundancy.
  - Therefore, source coding may be referred to as data compression.

1.5. Channel Coding:

- Introduce, in a controlled manner, some redundancy in the binary information sequence that can be used at the receiver to overcome the effects of noise and interference encountered in the transmission of the signal through the channel.
  - The added redundancy serves to increase the reliability of the received data and improves the fidelity of the received signal.
- See Examples 1.6 and 1.7.

Example 1.6. Trivial channel coding: Repeat each binary digit \( n \) times, where \( n \) is some positive integer.

Example 1.7. More sophisticated channel coding: Taking \( k \) information bits at a time and mapping each \( k \)-bit sequence into a unique \( n \)-bit sequence, called a codeword.

- The amount of redundancy introduced by encoding the data in this manner is measured by the ratio \( n/k \). The reciprocal of this ratio, namely \( k/n \), is called the rate of the code or, simply, the code rate.
“The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.”

"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point."


A Mathematical Theory of Communication
By C. E. SHANNON

INTRODUCTION

THE recent development of various methods of modulation such as PCM and PPM which exchange bandwidth for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist¹ and Hartley² on this subject. In the present paper we will extend the theory to include a number of new factors, in particular the effect of noise in the channel, and the savings possible due to the statistical structure of the original message and due to the nature of the final destination of the information.

The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have meaning; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one selected from a set of possible messages. The system must be designed to operate for each possible selection, not just the one which will actually be chosen since this is unknown at the time of design.

If the number of messages in the set is finite then this number or any monotonic function of this number can be regarded as a measure of the information produced when one message is chosen from the set, all choices being equally likely. As was pointed out by Hartley the most natural choice is the logarithmic function. Although this definition must be generalized considerably when we consider the influence of the statistics of the message and when we have a continuous range of messages, we will in all cases use an essentially logarithmic measure.

The logarithmic measure is more convenient for various reasons:
1. It is practically more useful. Parameters of engineering importance


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Printed in U. S. A.
WHO IS CLAUDE SHANNON?

John Hutton as Claude Shannon

Mark A. Levinson
Writer | Producer | Director

THE BIT PLAYER
A FILM BY MARK A. LEVINSON

THE IEEE INFORMATION THEORY SOCIETY PRESENTS A MARK A. LEVINSON FILM
THE BIT PLAYER
JOHN HUTTON JUDITH IVEY KALISWA BREWSTER
EXECUTIVE PRODUCERS: MICHELLE EFFROS CHRISTINA FRAGOULI ALON GOLITSKY RUDOLGER URBANKE
CREATIVE PRODUCER: SERGIO VERGO PRODUCTION DESIGN JEREMY WOODWARD YUKO SOBIRIN
COSTUME DESIGN: KATJA ANDRESEY JAN TROMBLAY GRAPHIC DESIGN INGRID ROBERTS ORIGINAL MUSIC ROBERT MILLER
DIRECTOR OF PHOTOGRAPHY CLAUDIA RAGINKE
WRITTEN, PRODUCED AND DIRECTED BY MARK A. LEVINSON

https://thebitplayer.com
Shannon: Father of the Info. Age

- Documentary
- Co-produced by the Jacobs School, UCSD-TV, and the California Institute for Telecommunications and Information Technology
- Won a Gold award in the Biography category in the 2002 Aurora Awards.

[http://www.uctv.tv/shows/Claude-Shannon-Father-of-the-Information-Age-6090]
[http://www.youtube.com/watch?v=z2Whj_nL-x8]
Hello, I'm Claude Shannon a mathematician here at the Bell Telephone laboratories.

He didn't create the compact disc, the fax machine, digital wireless telephones or mp3 files, but in 1948 Claude Shannon paved the way for all of them with the basic theory underlying digital communications and storage he called it information theory.
C. E. Shannon (1916-2001)

Claude Shannon had one of the most playful minds in science.

He used it to create **Theseus** the maze-solving mouse...

...one of the earliest examples of artificial intelligence.

https://www.youtube.com/watch?v=47ag2sXRDeU
C. E. Shannon (1916-2001)

One of the most influential minds of the 20th century

yet when he died on February 24, 2001, Shannon was virtually unknown to the public at large
[Shannon’s] discoveries were very much like Einsteins in the sense that Einstein was thinking about something that no one else was and suddenly came out with not just the question but the answer.

Shannon discovered these formulas about information transmission how fast, how many bits per second, you should be able to transmit over various media and other people weren't asking the question and he came out with this answer and it was just so beautiful that it inspired the people who ended up designing your cell phone and the communication links that make up the internet.
C. E. Shannon (1916-2001)

- 1938 MIT master's thesis: A Symbolic Analysis of Relay and Switching Circuits
- Insight: The binary nature of Boolean logic was analogous to the ones and zeros used by digital circuits.
- The thesis became the foundation of practical digital circuit design.
- The first known use of the term bit to refer to a “binary digit.”
- Possibly the most important, and also the most famous, master’s thesis of the century.
- It was simple, elegant, and important.
C. E. Shannon: Master Thesis

A SYMBOLIC ANALYSIS
OF
RELAY AND SWITCHING CIRCUITS

by
Claude Elwood Shannon
B.S., University of Michigan
1935

Submitted in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
from the
Massachusetts Institute of Technology
1940

Signature of Author___________________________
Department of Electrical Engineering, August 10, 1937

Signature of Professor
in Charge of Research_________________________

Signature of Chairman of Department
Committee on Graduate Students________________

[Recall, from ECS332,...]
Shannon wrote that pivotal thesis in 1938 at the age of 22, applying the two-value binary algebra and symbolic logic originally conceived by 19th century English mathematician George Boole to the on-and-off positions of switching circuits, envisioning them as the basis of what he called a logic machine.
C. E. Shannon: Master Thesis

[Shannon] created the field of digital logic. Now if you think about that, that sounds like a very simple thing to say now but what does logic have to do with digital … it's a subject in philosophy.

[Shannon] showed that AND, OR an NOT, simple connectives from theoretical boolean algebra could be used to build electronic circuits which led in no small part to the invention of the computer.

People said it's the most influential master's thesis in history which is certainly true but it understates the point; if he'd done nothing else he'd still be famous for inventing digital logic.
C. E. Shannon: Master Thesis

"One Of The Most Significant Master's Theses Of The 20th Century" (Britannica)

SHANNON, Claude. A Symbolic Analysis of Relay and Switching Circuits. New York, 1938. First edition of Shannon's master's thesis demonstrating how Boolean algebra could simplify the arrangement of relays underlying automatic telephone exchanges—and suggesting, for the first time, the concept of using 0 and 1 as true/false values to allow arithmetic by relay circuits—a crucial work with applications for all digital circuits including those in computer technology, and winner of the Alfred Noble American Institute of American Engineers Award.

$16,000.
Boole/Shannon Celebration

- Events in 2015 and 2016 centered around the work of
  - George Boole, who was born 200 years ago, and
  - Claude E. Shannon, born 100 years ago.

- Events were scheduled both at
  - the University College Cork (UCC), Ireland and
  - the Massachusetts Institute of Technology (MIT)

- http://www.rle.mit.edu/booleshannon/
An Interesting Book

- The Logician and the Engineer: How George **Boole** and Claude **Shannon** Created the Information Age
- by Paul J. Nahin
- ISBN: 9780691151007

[Recall, from ECS332,…]
C. E. Shannon (Con’t)

• 1948: A *Mathematical Theory of Communication*
  • September 1949: Book published. Include a new section by Warren Weaver that applied Shannon's theory to human communication.
  • Create the architecture and concepts governing digital communication.

• Invent *Information Theory*: Simultaneously founded the subject, introduced all of the major concepts, and stated and proved all the fundamental theorems.
A Mathematical Theory of Communication

The Bell System Technical Journal

July, 1948

Vol. XXVII

No. 3

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By C. E. SHANNON

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The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have meaning; that is, they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one selected from a set of possible messages. The system must be designed to operate for each possible selection, not just the one which will actually be chosen since this is unknown at the time of design.
A Mathematical Theory of Communication

- Link posted in the “references” section of the website.

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The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.

Shannon, Claude.
A Mathematical Theory of Communication. (1948)
C. E. Shannon

[Recall, from ECS332, ...]

...with some remarks by Toby Berger.
In research circles, the 1948 paper published in the Bell System technical journal made Shannon a star overnight. It revolutionized the way engineers and scientists thought about communications, galvanizing researchers and spawning a new school of thought called information theory.

By 1949, ..., he was an academic celebrity.
More than 40 years later, Scientific American and other publications would label Shannon's paper the magna carta of the information age.
It's one of the few times in history where somebody founded a field, stated all the major results, and proved most of them all pretty much at once.
Due to its expansion of scope into so many related fields, it is simply referred to by the letters I-E-E-E (pronounced Eye-triple-E).

As of 2018, it is the world's largest association of technical professionals.

The IEEE Transactions on Information Theory is a journal that publishes theoretical and experimental papers concerned with the transmission, processing, and utilization of information.
IEEE International Symposium on Information Theory (ISIT)

- The flagship meeting of the IEEE Information Theory Society.
- The main event of the symposium is the Shannon Lecture, which is given by the recipient of the prestigious Claude E. Shannon Award of the year
  - The year’s awardee was revealed during the previous ISIT.
Claude E. Shannon Award

Claude E. Shannon (1972)
David S. Slepian (1974)
Robert M. Fano (1976)
Peter Elias (1977)
Mark S. Pinsker (1978)
Jacob Wolfowitz (1979)
W. Wesley Peterson (1981)
Irving S. Reed (1982)
Robert G. Gallager (1983)
Solomon W. Golomb (1985)
William L. Root (1986)
James L. Massey (1988)
Thomas M. Cover (1990)
Andrew J. Viterbi (1991)
Elwyn R. Berlekamp (1993)
Aaron D. Wyner (1994)
G. David Forney, Jr. (1995)
Imre Csiszár (1996)
Jacob Ziv (1997)
Tadao Kasami (1999)
Thomas Kailath (2000)
Jack Keil Wolf (2001)
Toby Berger (2002)
Lloyd R. Welch (2003)
Richard Blahut (2005)
Rudolf Ahlswede (2006)
Sergio Verdu (2007)
Robert M. Gray (2008)
Jorma Rissanen (2009)
Te Sun Han (2010)
Shlomo Shamai (Shitz) (2011)
Abbas El Gamal (2012)
Katalin Marton (2013)
János Körner (2014)
Arthur Robert Calderbank (2015)
Alexander S. Holevo (2016)
David Tse (2017)
Gottfried Ungerboeck (2018)
Erdal Arikan (2019)
Charles Bennett (2020)
IEEE Richard W. Hamming Medal

1988 - Richard W. Hamming
1989 - Irving S. Reed
1990 - Dennis M. Ritchie and Kenneth L. Thompson
1991 - Elwyn R. Berlekamp
1992 - Lotfi A. Zadeh
1993 - Jorma J. Rissanen
1994 - Gottfried Ungerboeck
1995 - Jacob Ziv
1996 - Mark S. Pinsker
1997 - Thomas M. Cover
1998 - David D. Clark
1999 - David A. Huffman
2000 - Solomon W. Golomb
2001 - A. G. Fraser
2002 - Peter Elias
2003 - Claude Berrou and Alain Glavieux
2004 - Jack K. Wolf
2005 - Neil J.A. Sloane
2006 - Vladimir I. Levenshtein
2007 - Abraham Lempel
2008 - Sergio Verdú
2009 - Peter Franaszek
2010 - Whitfield Diffie, Martin Hellman, and Ralph Merkle
2011 - Toby Berger
2012 - Michael Luby, Amin Shokrollahi
2013 - Arthur Robert Calderbank
2014 - Thomas Richardson and Rüdiger L. Urbanke
2015 - Imre Csiszar
2016 - Abbas El Gamal
2017 - Shlomo Shamai
2018 - Erdal Arikan
2019 - David Tse
2020 - Cynthia Dwork

“For contributions to Information Theory, including source coding and its applications.”
A Mathematical Theory of Communication

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The recent development of various methods of modulation such as PCM and PM, which exchange bandwidth for signal-to-noise ratio, has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Vannevar Bush and Norbert Wiener on this subject. In the present paper we will extend the theory to include a number of new factors, in particular the effect of noise in the channel, and the savings possible due to the statistical structure of the original message and due to the nature of the final destination of the information.

The fundamental problem of communication is that of reproducing at one point another signal which is the function of another signal at another point. Frequently the signals are electrical in nature; and the problem is referred to as the transmission of electrical information. The most general form of the problem occurs when the signals are not entirely electrical, but are occurrences in a continuous parameter space, and when the terminals are not entirely electrical, but are devices for interpreting messages. An example of this is the case of human communication, where the message is a sequence of words, and the terminal is a pair of human ears.

A message consists of a sequence of symbols chosen from a finite alphabet of available symbols. A channel is a physical part of the system which determines the manner in which the messages are conveyed from the source to the destination. A noise process is a source of disturbances which is an inherent part of the channel and is not due to interference from outside. Noise may be defined as any process which corrupts the transmission of a message. Noise may be either a physical process or a statistical process.

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Elements of communication sys.

1 Introduction to communication systems

1.1. Shannon's insight [10]:

The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.

Definition 1.2. Figure 1 shows a commonly used model for a (single-link or point-to-point) communication system.

(a) Information\(^1\) source: produce a message

- Messages may be categorized as analog (continuous) or digital (discrete).

(b) Transmitter: operate on the message to create a signal which can be sent through a channel

(c) Channel: the medium over which the signal, carrying the information that composes the message, is sent

- Channel impairments/degradation/contaminations.

\(^1\)The concept of information is central to communication. But information is a loaded word, implying semantic and philosophical notions that defy precise definition. We avoid these difficulties by dealing instead with the message, defined as the physical manifestation of information as produced by the source. \([3, p \ 2]\)

- Include noise\(^2\), interference\(^3\), and distortion\(^4\)

- Although this degradation may occur at any point of the system, the standard convention is to lump them entirely on the channel \([15, p \ 5]\) \([3, p \ 4]\).

(d) Receiver: transform the signal back into the message

(c) Destination: a person or a machine, for whom or which the message is intended

Figure 1: Schematic diagram of a general communication system \([10, Fig. 1]\) [3, Fig. 1.1-2 p 4]

Definition 1.3. Note that the system shown in Figure 1 represents one-way, or simplex, transmission.

- Two-way communication requires a transmitter and receiver at each end.

(a) Full-duplex system: allow simultaneous transmission in both directions.

(b) Half-duplex system: allow transmission in either direction but not at the same time.

\(^2\)Random and unpredictable electrical signals produced by natural processes both internal and external to the system. \([3, p \ 4]\)

\(^3\)Contamination by extraneous undesired signals from human sources or other transmitters, power lines and machinery, switching circuits, and so on. Interference occurs most often in radio systems whose receiving antennas usually intercept several signals at the same time. \([3, p \ 4]\)

\(^4\)Waveform perturbation caused by imperfect response of the system to the desired signal itself. Unlike noise and interference, distortion disappears when the signal is turned off. If the channel has a linear but distorting response, then distortion may be corrected, or at least reduced, with the help of special filters called equalizers. \([3, p \ 4]\)
Elements of communication sys. (ECS 332)

[Recall, from ECS332,…]

[Shannon, 1948]

Fig. 1 — Schematic diagram of a general communication system.
1 Elements of a Digital Communication System

1.1. Shannon’s insight [14]:

The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.

1.2. Figure 1 illustrates the functional diagram and the basic elements of a digital communication system.

![](image1.png)

Figure 1: Basic elements of a digital communication system

1.3. The source output may be either

- an analog signal, such as an audio or video signal,
- or a digital signal, such as the output of a computer, that is discrete in time and has a finite number of output characters.

1.4. Source Coding: The messages produced by the source are converted into a sequence of bits.

- This process is called source coding or source encoding.
- For this course, we want to also represent the source output (message) by as few bits as possible.
  - In other words, we seek an efficient representation of the source output that results in little or no redundancy.
  - Therefore, source coding may be referred to as data compression.

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- Introduce, in a controlled manner, some redundancy in the binary information sequence that can be used at the receiver to overcome the effects of noise and interference encountered in the transmission of the signal through the channel.
  - The added redundancy serves to increase the reliability of the received data and improves the fidelity of the received signal.

- See Examples 1.6 and 1.7.

Example 1.6. Trivial channel coding: Repeat each binary digit \(n\) times, where \(n\) is some positive integer.

Example 1.7. More sophisticated channel coding: Taking \(k\) information bits at a time and mapping each \(k\)-bit sequence into a unique \(n\)-bit sequence, called a codeword.

- The amount of redundancy introduced by encoding the data in this manner is measured by the ratio \(n/k\). The reciprocal of this ratio, namely \(k/n\), is called the rate of the code or, simply, the code rate.
Elements of **digital commu. sys.**

- **Information Source**
- **Source Encoder**
- **Channel Encoder**
- **Digital Modulator**
- **Transmitter**
- **Transmitted Signal**
- **Channel**
- **Received Signal**
- **Noise & Interference**
- **Recovered Message**
- **Destination**
- **Source Decoder**
- **Channel Decoder**
- **Digital Demodulator**
- **Receiver**
Motivation for Digital Communications
Motivation for Digital Communications

Shannon saw the binary digit as the fundamental element in communication. Information could be boiled down to sequences of ones and zeros encoded, sent, then decoded at the other end. Messages could then be transmitted over long distances with virtually no loss in quality.
Motivation for Digital Communications

What Bell came up with was a technology called a regenerative repeater.

Instead of working with analog signals like my voice, if we had bits, if we didn't let the bits get too small, we could regenerate the bit perfectly.

So, instead of an amplifier, they put this device called the regenerative repeater, and then they started it out with a bit and a mile later they still had that same bit.
The Switch to Digital TV

**US**: Since June 12, 2009, full-power television stations nationwide have been broadcasting exclusively in a digital format.

**Japan**: Starting July 24, 2011, the analog broadcast has ceased and only digital broadcast is available.

**Thailand**: Use DVB-T2. Launched in 2014.

The Switch to Digital Radio in Norway

- **Norway** (the mountainous nation of 5 million) is the first country to shut down its national FM radio network in favor of digital radio.
- **Start on January 11, 2017**
  - At which point, 99.5% of the population has access to DAB reception with almost three million receivers sold.
  - 70% of Norwegian households regularly tune in digitally
- **Take place over a 12-month period, conducting changes region by region.**
- **December 13, 2017:** All national networks are DAB-only.
  - Local broadcasters have five years to phase out their FM stations.
- **New format:** Digital Audio Broadcasting (DAB)

Reference URLs:
- [www.worlddab.org/country-information/norway](http://www.worlddab.org/country-information/norway)
- [smithsonianmag.com/mart-nrws/norway-killed-radio-star-180961761/](http://smithsonianmag.com/mart-nrws/norway-killed-radio-star-180961761/)
Digital Audio Broadcasting

- Initiated as a European research project in the 1980s.
- The Norwegian Broadcasting Corporation (NRK) launched the first DAB channel in the world on 1 June 1995 (NRK Klassisk)
- The BBC and Swedish Radio (SR) launched their first DAB digital radio broadcasts in September 1995.
- Audio quality varies depending on the bitrate used.
The Switch to DAB in Norway

- Co-exist with FM since 1995.
- Provide a clearer and more reliable network that can better cut through the country's sparsely populated rocky terrain.
  - FM has always been problematic in Norway since the nation’s mountains and fjords makes getting clear FM signals difficult.
- Offer more channels at a fraction of the cost.
  - Allow 8 times as many radio stations
    - Norway currently has five national FM radio stations.
    - With DAB, it will be able to have around 40.
  - The FM radio infrastructure was coming to the end of its life,
    - Need to either replace it or fully commit to DAB anyway
- Can run at lower power levels
  - the infrastructure electricity bills are lower
Information Theory

The science of information theory tackles the following questions [Berger]

1. What is information, i.e., how do we measure it quantitatively?
2. What factors limit the reliability with which information generated at one point can be reproduced at another, and what are the resulting limits?
3. How should communication systems be designed in order to achieve or at least to approach these limits?
Shannon Capacity: a fundamental limit of communication
Shannon Capacity: a fundamental limit of communication

One of the things that Shannon did, which I think he's very widely known for, is this notion of a fundamental limit.

As long as you're working with a certain amount of bandwidth and as long as you're dealing with signals that are only so strong in the face of noise that you confront, no matter what you do, you cannot transmit more than a certain rate.

Today, that barrier is widely known as the Shannon limit or Shannon capacity.
Shannon Capacity: a fundamental limit of communication

It's like the speed of light;... you can travel no faster than the speed of light. But he didn't say how to build rocket ships to do that and so we've been trying since that time ... to find practical ways to get all the way up to channel capacity.
Rate-Distortion Theory

- The theory of **lossy** source coding