A BRIEF INTRODUCTION TO

TELEPHONE COMMUNICATION

Acknowledgements

- Prof. Abidi Lecture
- The Idea Factory: Bell Labs and the Great Age of American Innovation (The Penguin Press)
- Signals: The Science of Communication (Scientific American Library)
- Prof. E.A. Lee, UC Berkeley web page on audio

Understanding Communications

- One must understand:
  - Fourier Series representation of signals
  - Bandwidth
  - Noise
  - S/N ratio
  - Sampling Theorem
  - Information Theory
    - Compression
    - Error Correction

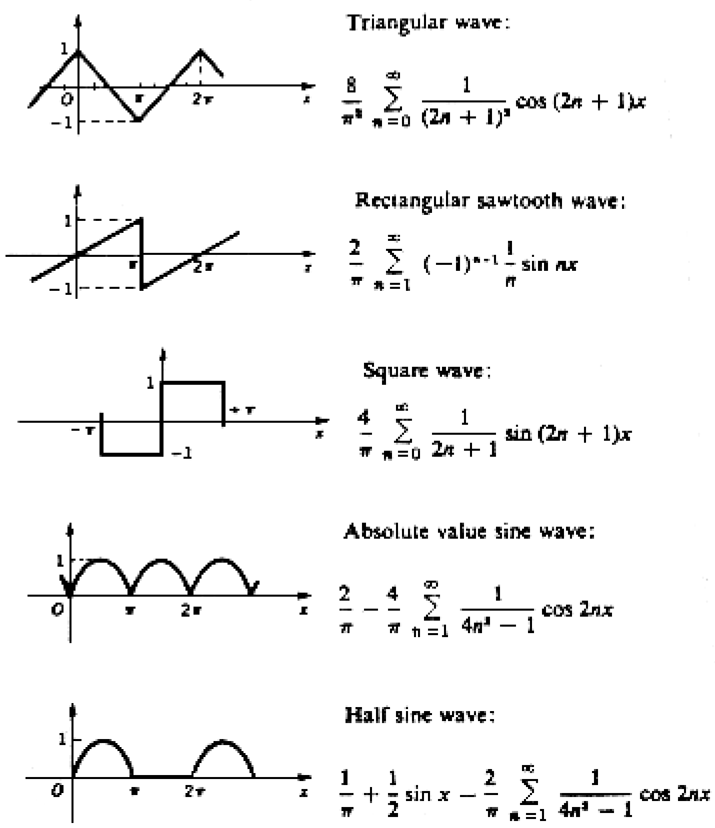
Fourier Series
and
Simple Harmonic Motion

Jean Baptiste (Joseph) Fourier (1768 – 1830)

Fourier Analysis

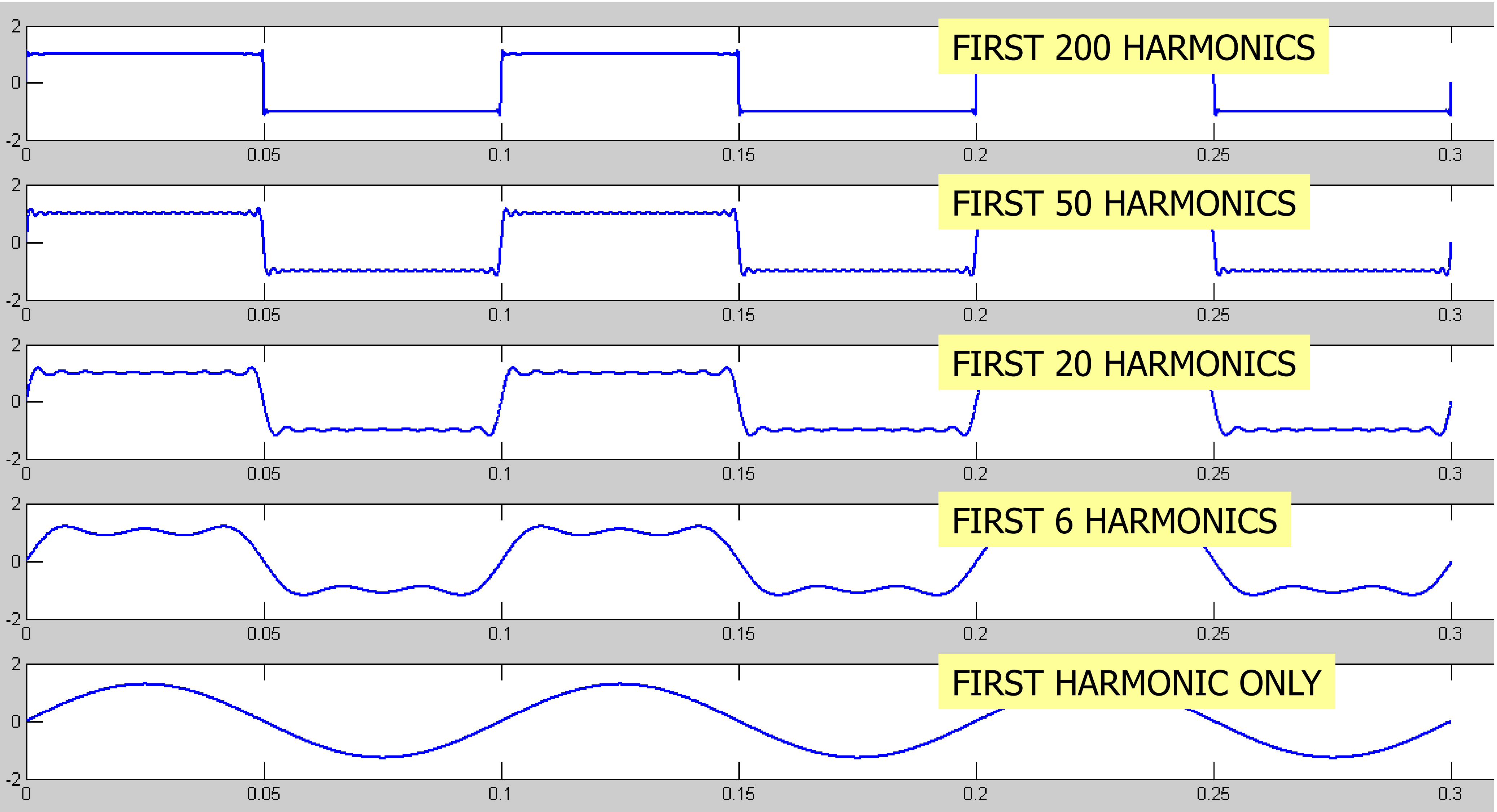
- Used in many technical areas
- Principle:

Any repetitive waveform can be represented by the sum of sinusoidal waveforms.

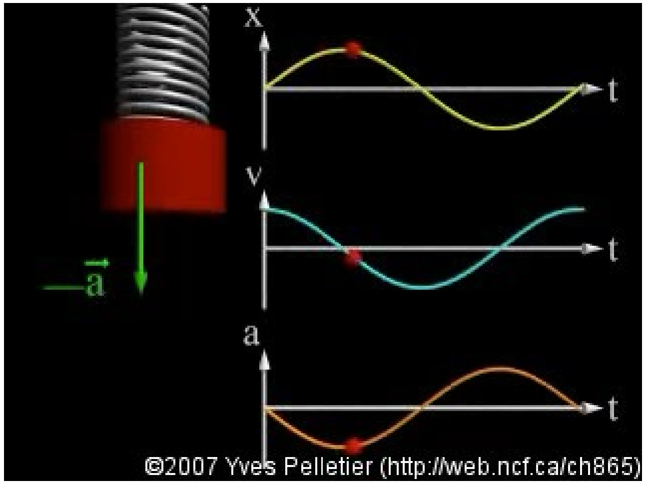


Gibbs Phenomenon

- Square wave with decreasing # harmonics



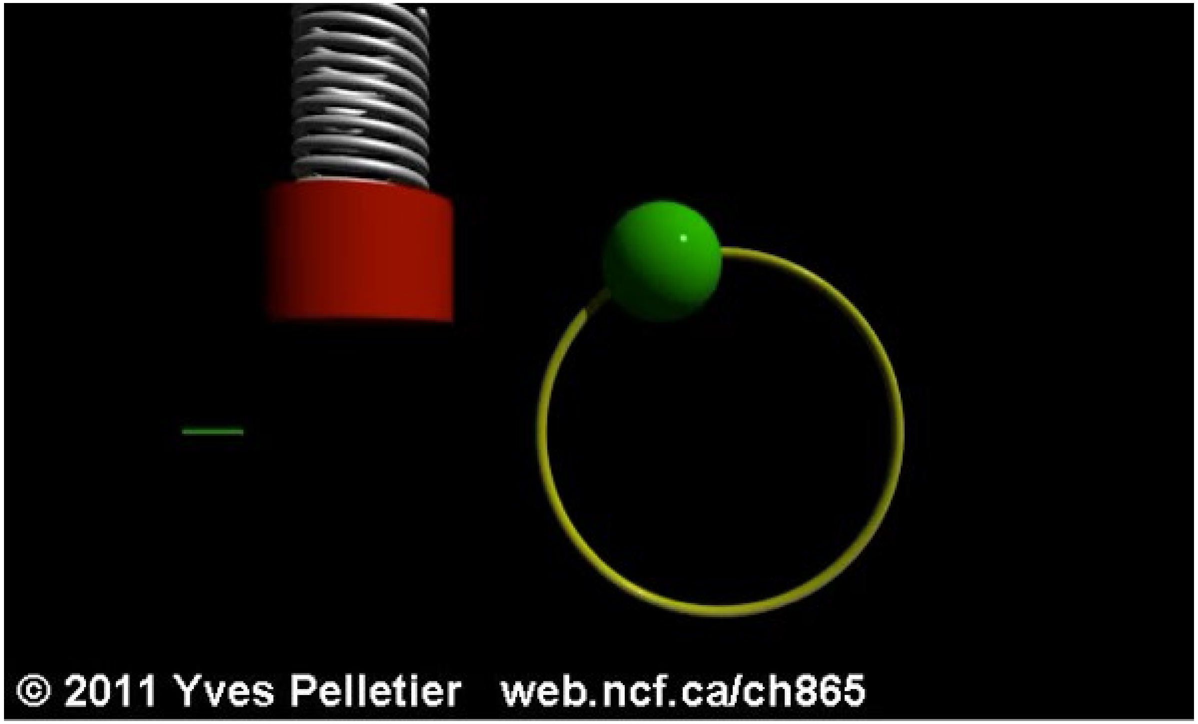
Simple Harmonic Motion



http://www.youtube.com/watch?v=eeYRkW8V7Vg

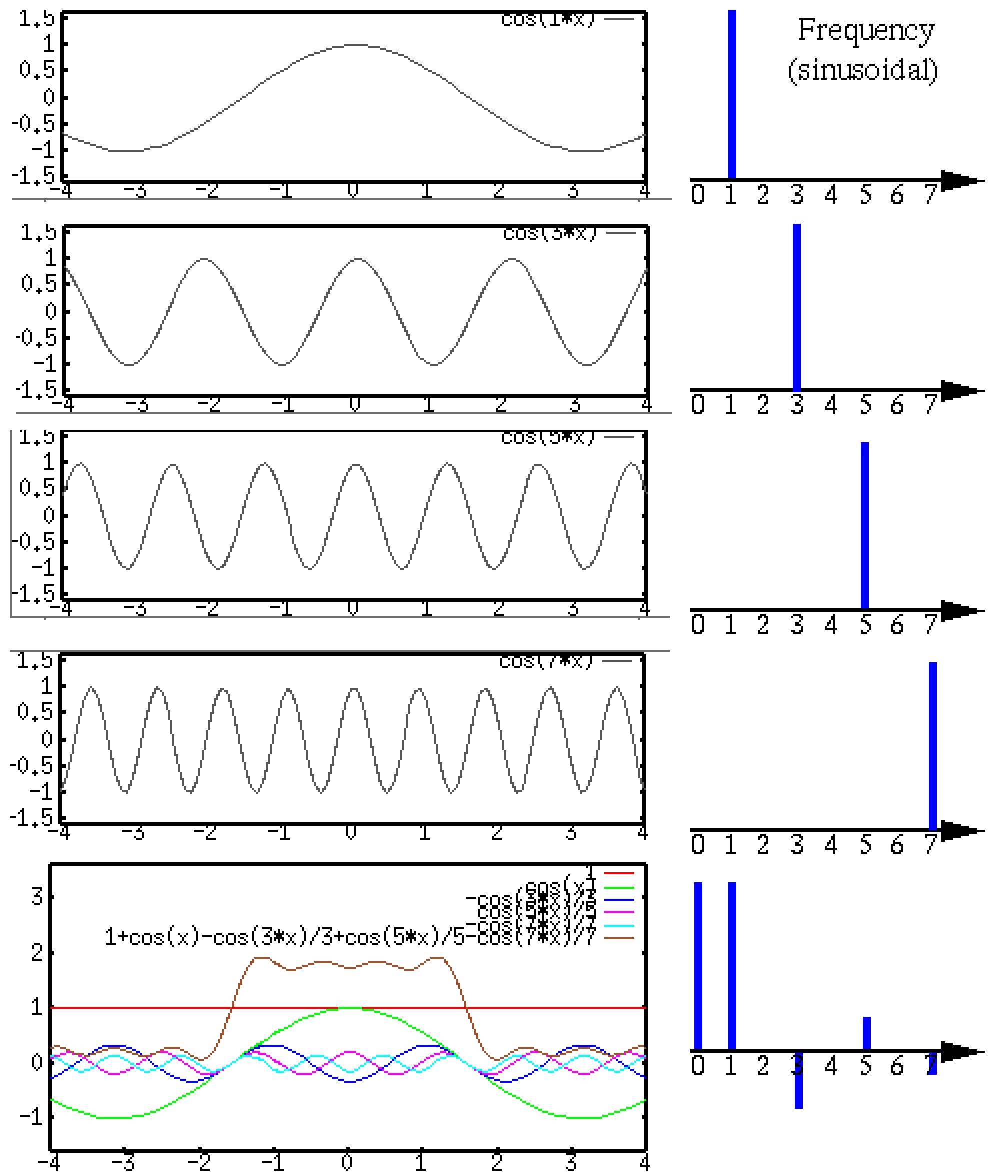
Simple Harmonic Motion

As a Constant Rotation



http://www.youtube.com/watch?v=9r0HexjGRE4

Time and Frequency Domains



Bandwidth

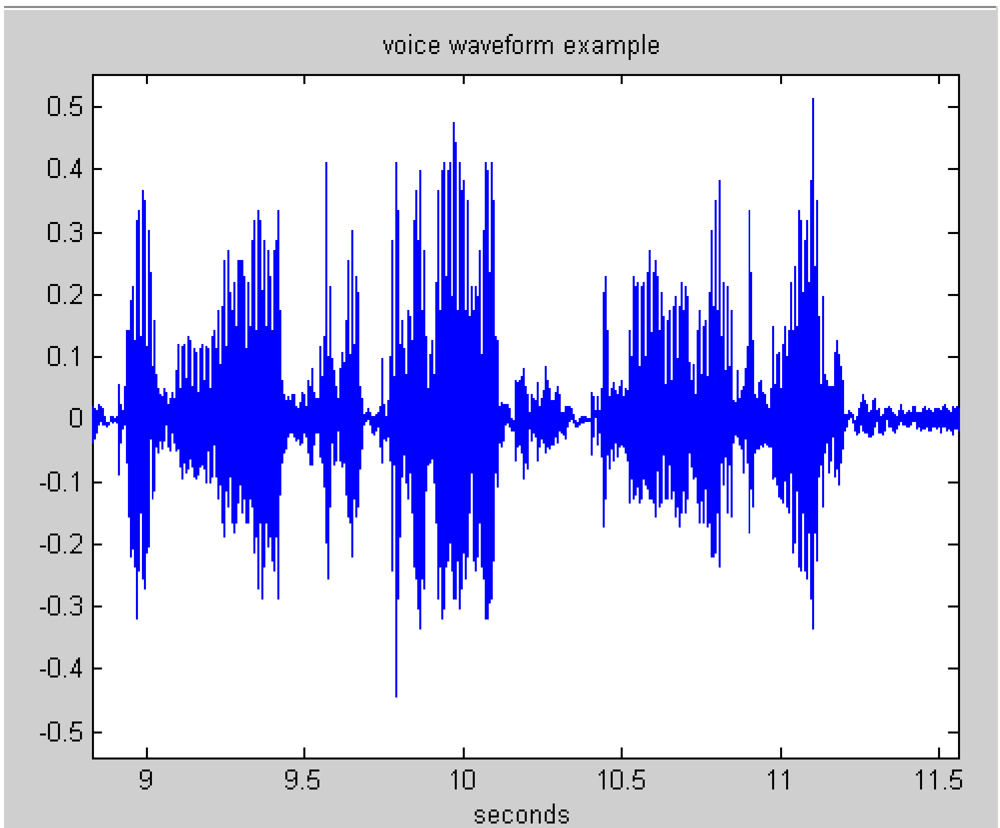
- Definition:
  - the range of frequencies contained in a signal
  - The range of frequencies that can be handled by a channel
- Why do we care about bandwidth?
  - A signal consisting of a single frequency carries little information (1 bit?)
  - To carry much information, a signal must have many frequencies

Bandwidth Examples

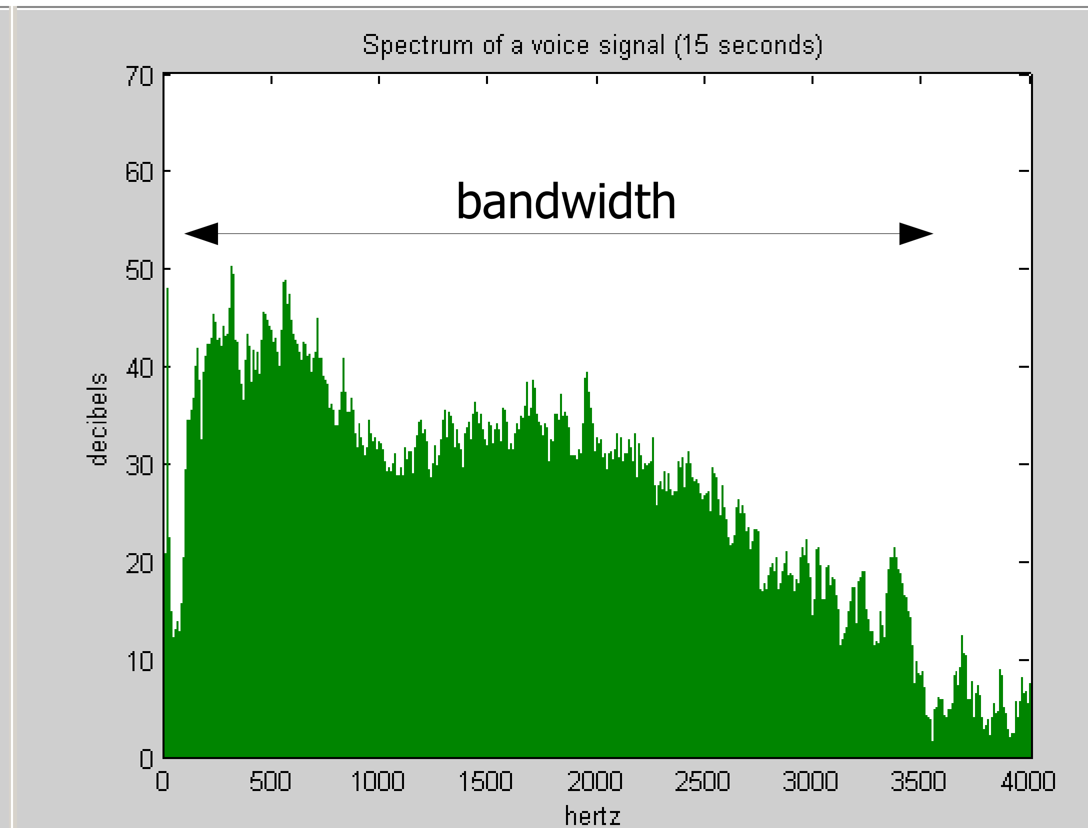
COMMUNICATION MODE	BANDWIDTH (Hz)
Telex	200
Telephone	4,000
Music CD	20,000
Standard Television	4,000,000
4K Television	44,000,000

Voice Characteristics

VOICE TIME SEQUENCE



VOICE SPECTRUM



Noise

- Corruption of the transmitted signal
- Has internal and external sources
- Sum all sources to define noise floor

External:

- Thunderstorms
- High-voltage transmission lines
- Auto ignitions
- Electric motors
- Fluorescent lamps
- Johnson Noise

What is this?

Internal:

- Clock jitter
- Oscillator phase noise
- Flicker noise
- Johnson Noise

Johnson Noise

- John Johnson, Bell Labs, 1928
- Thermodynamic noise from electron movement
- Proportional to absolute temperature
- Proportional to bandwidth
- Everywhere in the universe
- Essentially inescapable

Signal-to-Noise (S/N) Ratio
(AKA SNR)

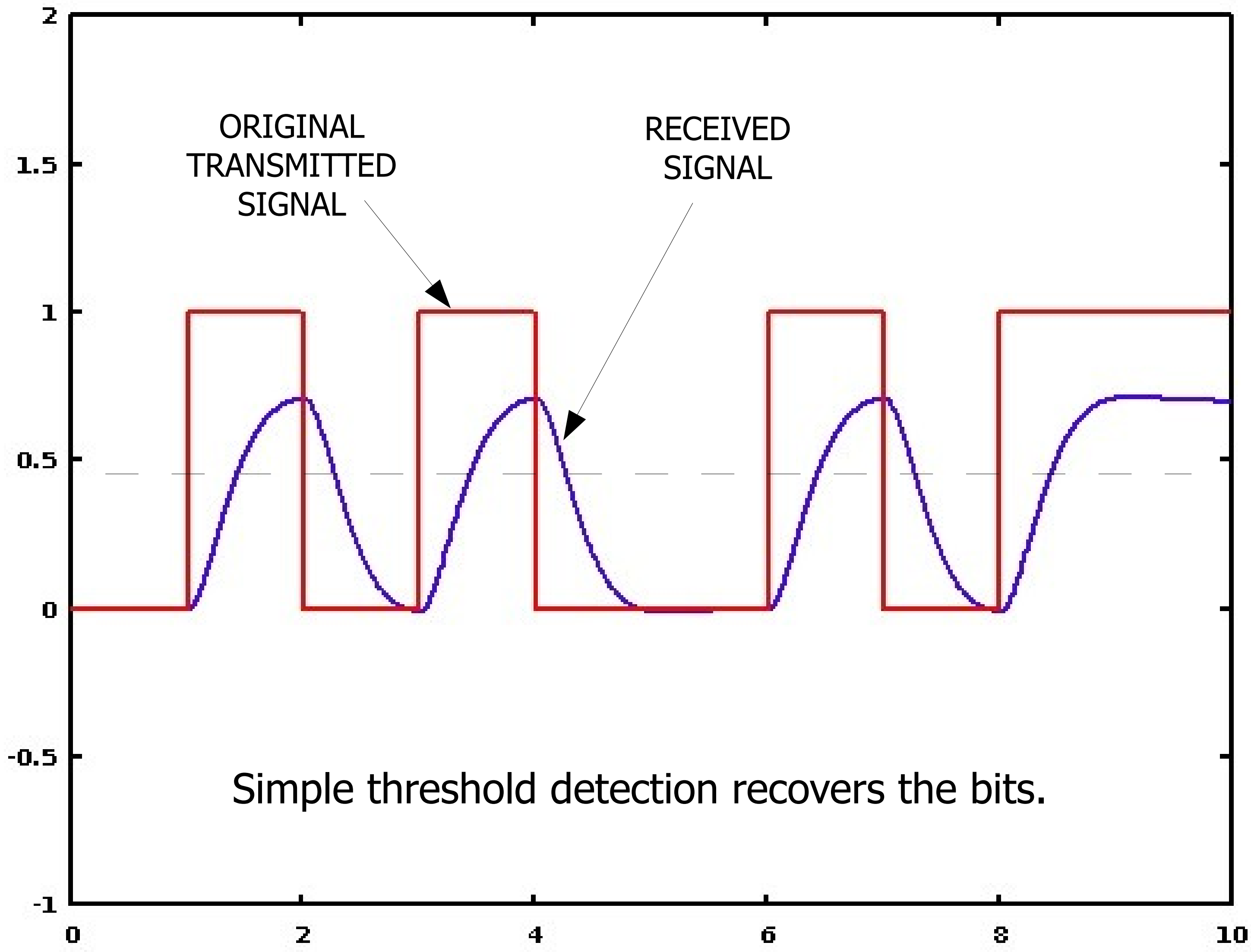
$$
\begin{aligned}
S/N &= 10\log\left(\frac{\text{Power of Transmitted Signal}}{\text{Powers of All Noise Sources}}\right) \\
&= 20\log\left(\frac{\text{Amplitude of Transmitted Signal}}{\text{Amplitudes of All Noise Sources}}\right)
\end{aligned}
$$

TECHNOLOGY	REQUIRED S/N RATIO
Telegraphy	15 dB
Telephony	20-40 dB
High Fidelity	60 dB
Compact Disc	90 dB

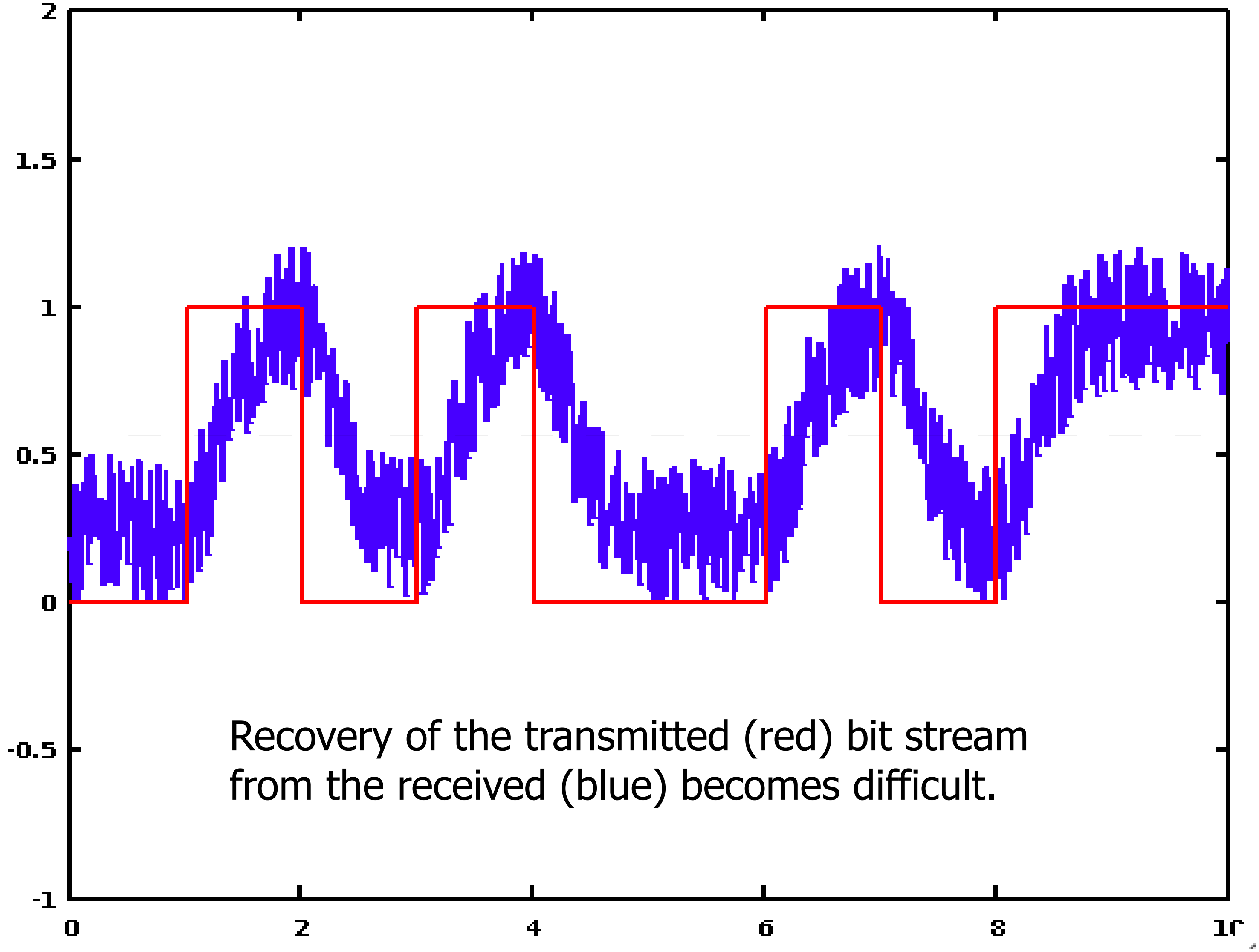
Signal Degradation

- Attenuation
- Distortion
- Delay
- Noise
- Analog signals are:
  - Very sensitive to these problems
  - Very difficult to restore to original transmitted signal
- Digital signals are much better at both

Digital Signal



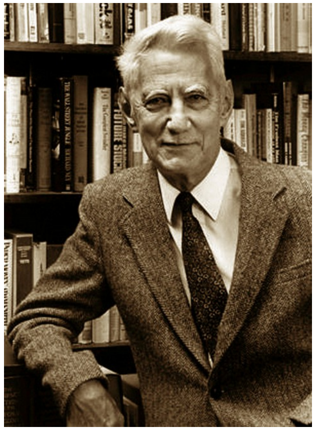
Why S/N Is Important



The Sampling Theorem

"Success has many fathers...."

Harry Nyquist



Claude Shannon

Edmund Whittaker

Vladimir Kotelnikov

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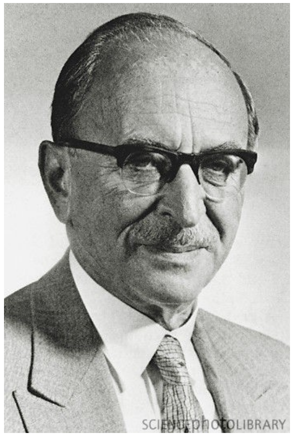
Karl Küpfmüller



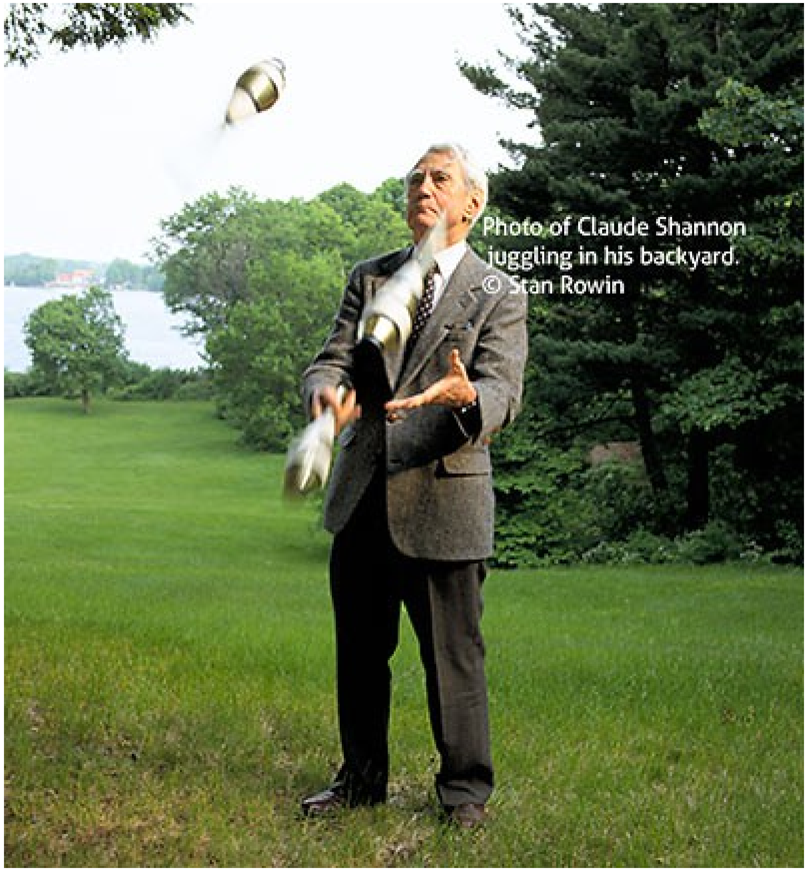
Dennis Gabor

Harry Nyquist

- Bell Labs
- The “Nyquist Frequency”: half the sample rate
- The “Nyquist Criterion”: a test for system stability

Claude Elwood Shannon

- Bell Labs
- Co-discoverer of The Sampling Theorem
- Developer of Information Theory
- “The Einstein of Information Theory”
- Juggler
- Unicycler
- Micromouser



$$\frac{b}{h} = \frac{(d+f)}{(d+e)}$$

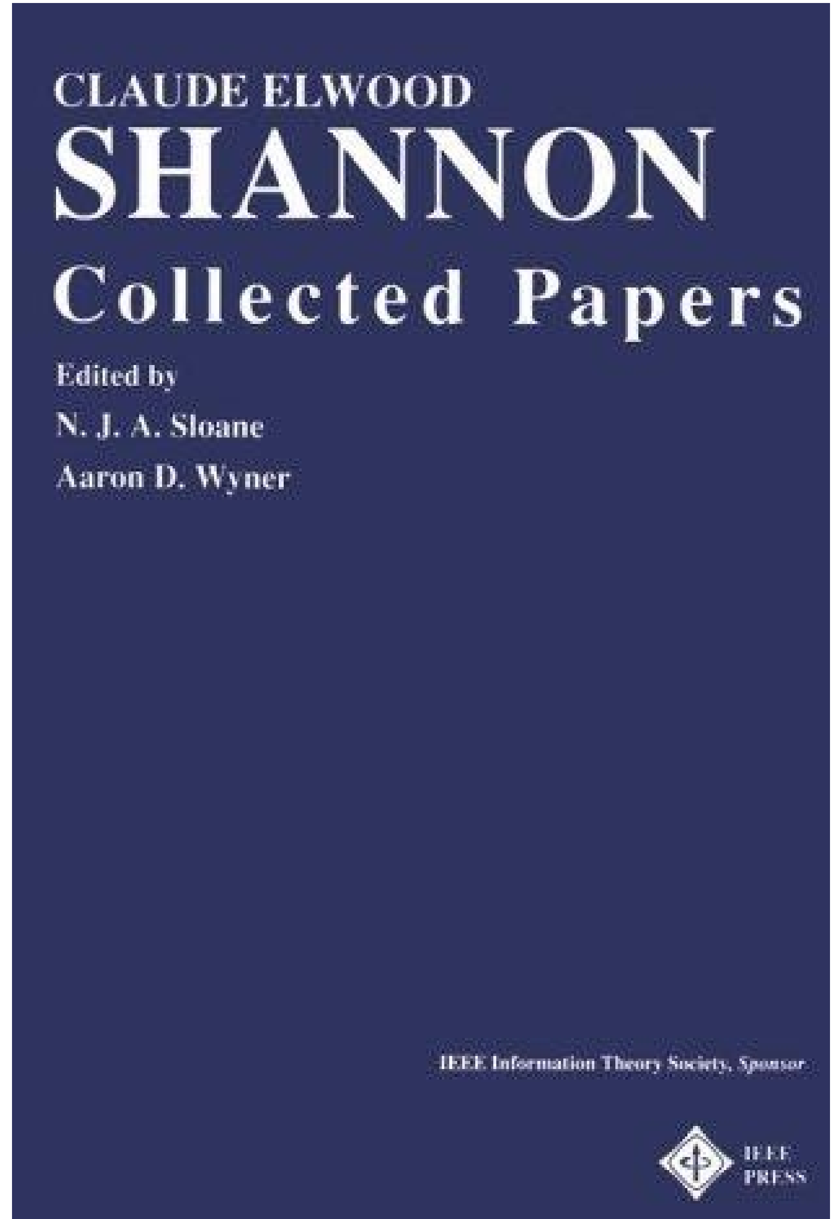
b : # clubs

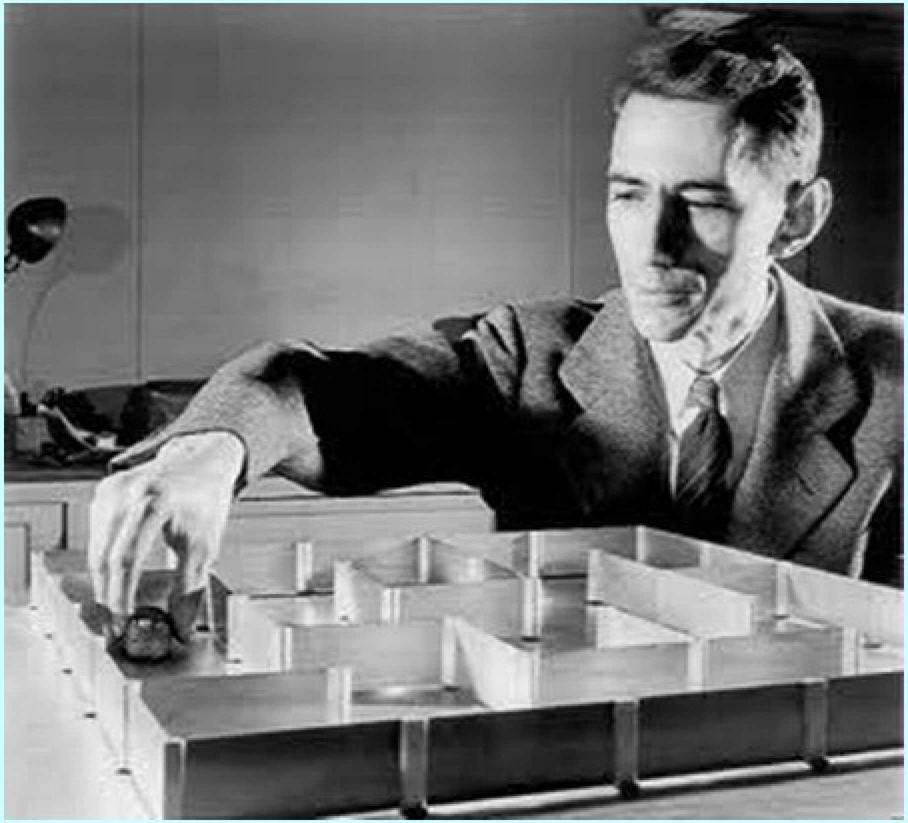
h : # hands

d : dwell time in hand

f : flight time

e : empty hand time



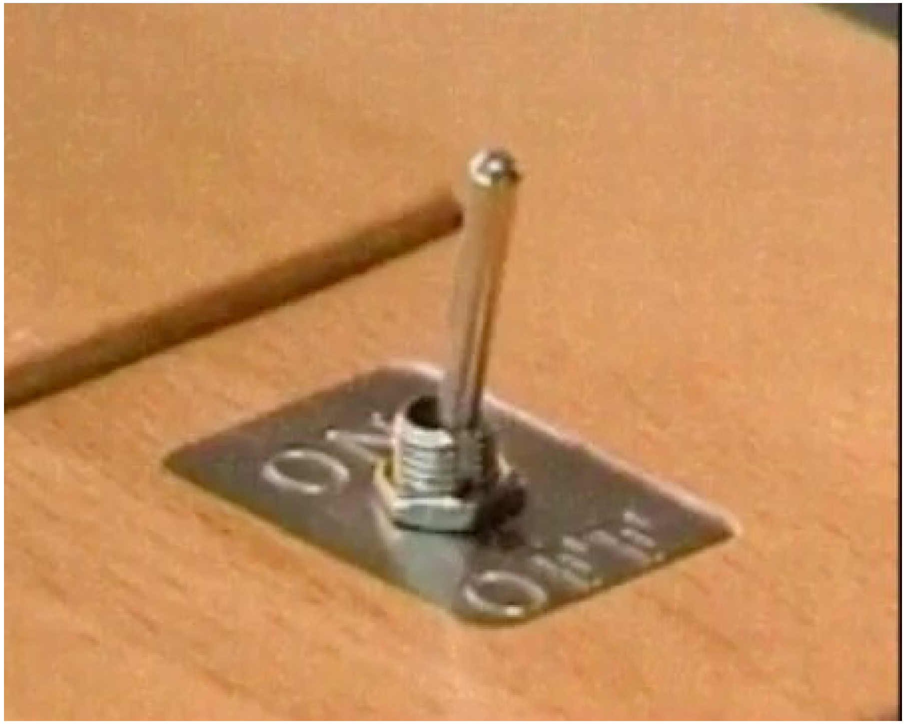


Claude Shannon's clever electromechanical mouse, which he called Theseus, was one of the earliest attempts to "teach" a machine to "learn" and one of the first experiments in artificial intelligence.

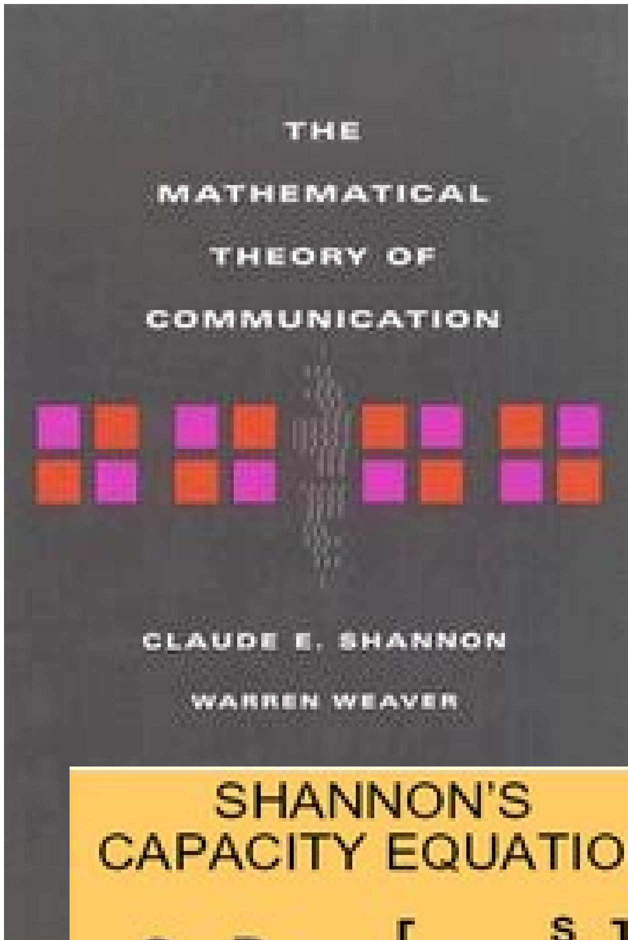
The Ultimate Machine

Invented by

Claude Elwood Shannon



http://www.youtube.com/watch?v=cZ34RDn34Ws



SHANNON'S CAPACITY EQUATION

$$C = B_{\omega} \log_2 \left[1 + \frac{S}{N} \right]$$

B_{ω} = bandwidth in Hertz
C = channel capacity in bits/second
S = signal power
N = noise power

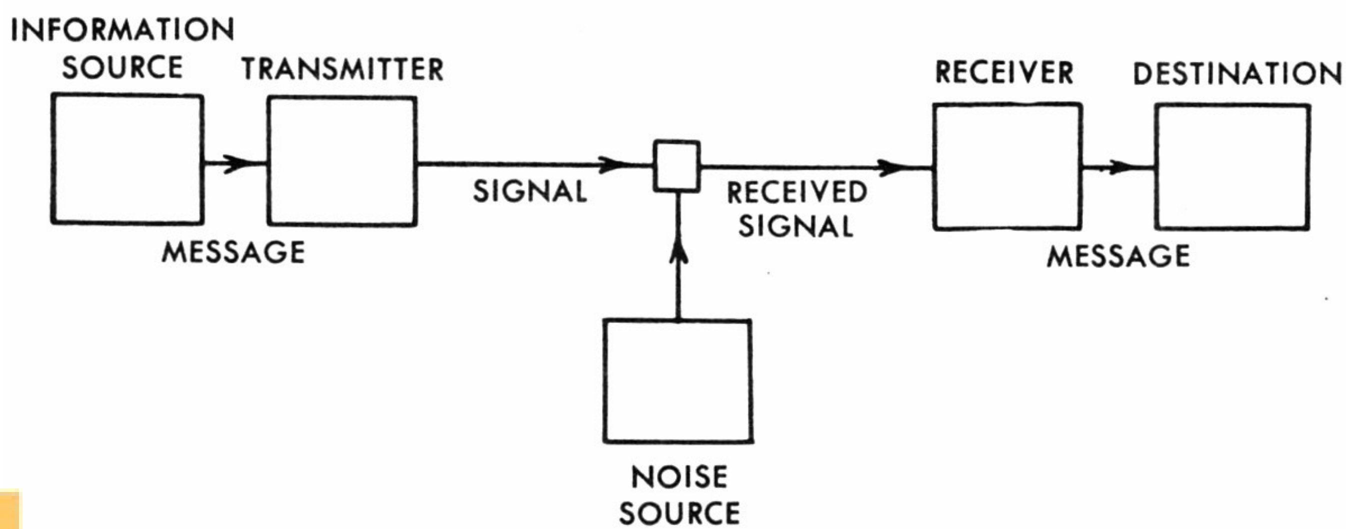


Fig. 1. — Schematic diagram of a general communication system.

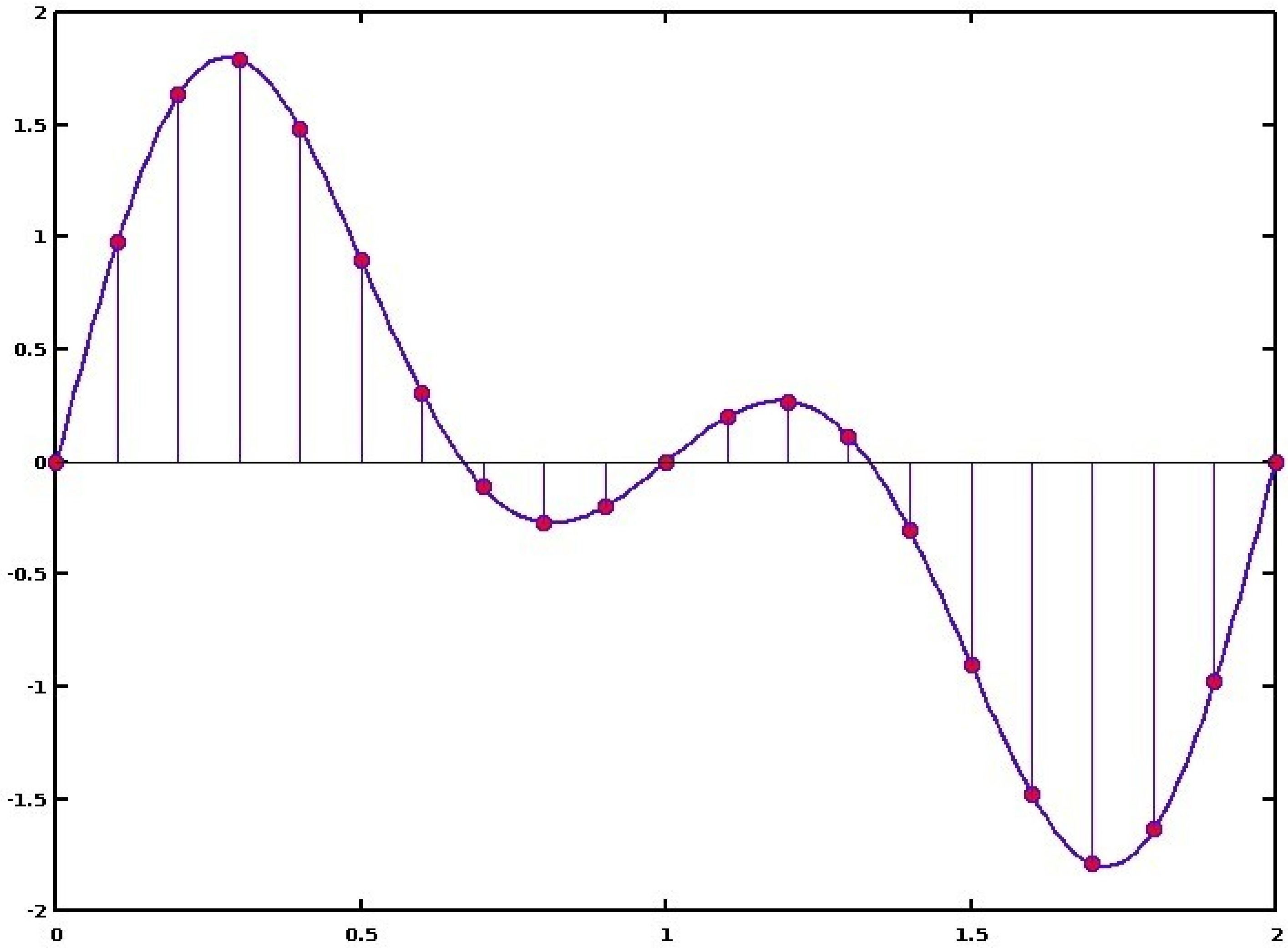
The Sampling Theorem

It is possible to recover completely a continuous waveform from its samples only if the sampling rate (in samples/second) is more than twice the highest frequency (in Hertz) contained in the waveform.

$$\boxed{\begin{array}{c}\text{SAMPLE RATE}\\ \text{(samples/second)}\end{array}} > 2\ \boxed{\begin{array}{c}\text{WAVEFORM}\\ \text{MAX FREQUENCY}\\ \text{(hertz)}\end{array}} \Rightarrow \boxed{\begin{array}{l}\text{Complete}\\ \text{Recovery}\\ \text{Possible}\end{array}}$$

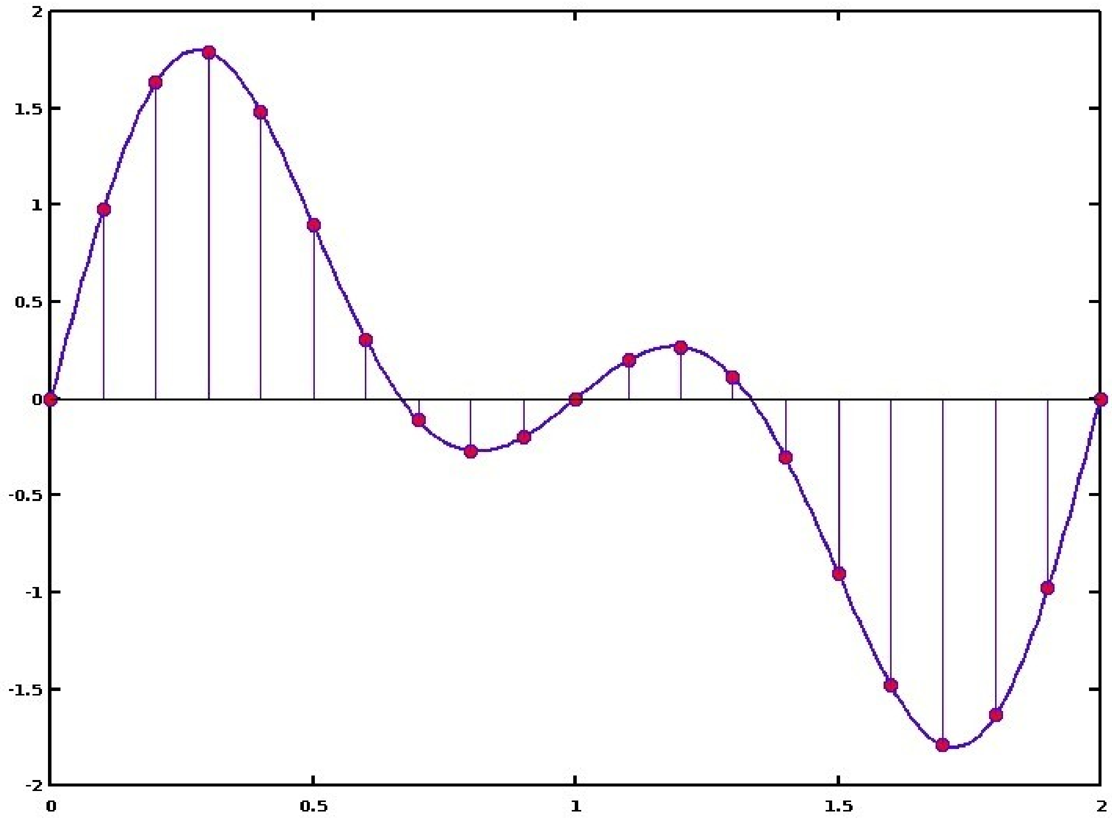
Given the proper reconstruction!

Sampling



Why Sample?

- We want to go digital, but:
- Can't store continuous data digitally
- Save space – don't need all that data between samples



Information Theory

The fundamental question in communications:

How to transmit a message with a given amount of fidelity?

The Next Question

What is a good measure of information?

Answer: UNPREDICTABILITY. If the message is known before it is transmitted, no information is conveyed.

Unpredictability

- Unpredictability is called Shannon Entropy ($\mathcal{H}$).
- Shannon Entropy is a measure of information.
- For N equiprobable events, $\mathcal{H} = \log_2 N$ bits/event

Ex.: fair coin toss $\mathcal{H} = \log_2 2 = 1$ bit/toss

Ex.: fair die throw $\mathcal{H} = \log_2 6 = 2.58$ bits/throw

- If <u>not</u> equiprobable, $\mathcal{H} < \log_2 N$ bits

Shannon Entropy of English Text

- 26 letters plus space
- If letters and space are equiprobable,

$$\mathcal{H} = \log_2 27 = 4.8 \text{ bits/character}$$

- Since some English letters occur more often, and some words occur more often, the current estimate of $\mathcal{H}$ for English text is

$$\mathcal{H} \approx 2 \text{ bits/char.}$$

- Predictability and compression allows fewer bits

Now Let's Send Some Text Data

We will encode the text at ≈ 2 bits/character.
Remember Shannon's channel and capacity equation.

34 *The Mathematical Theory of Communication*

SHANNON'S CAPACITY EQUATION

$$C = B_{\omega} \log_2 \left[1 + \frac{S}{N} \right]$$

B_{ω} = bandwidth in Hertz
C = channel capacity in bits/second
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N = noise power

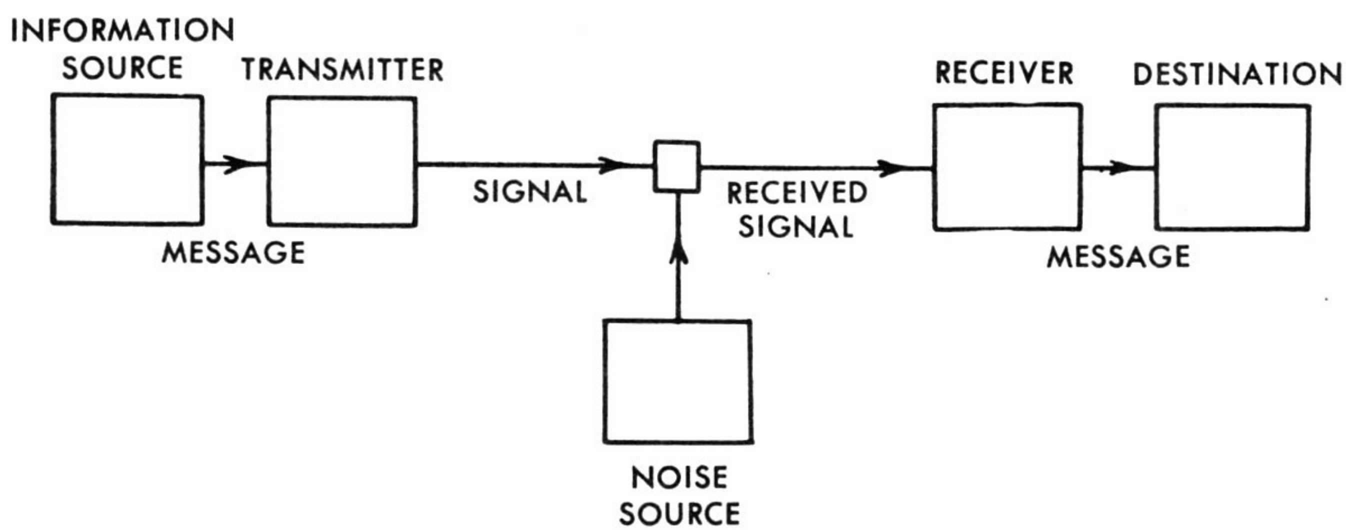
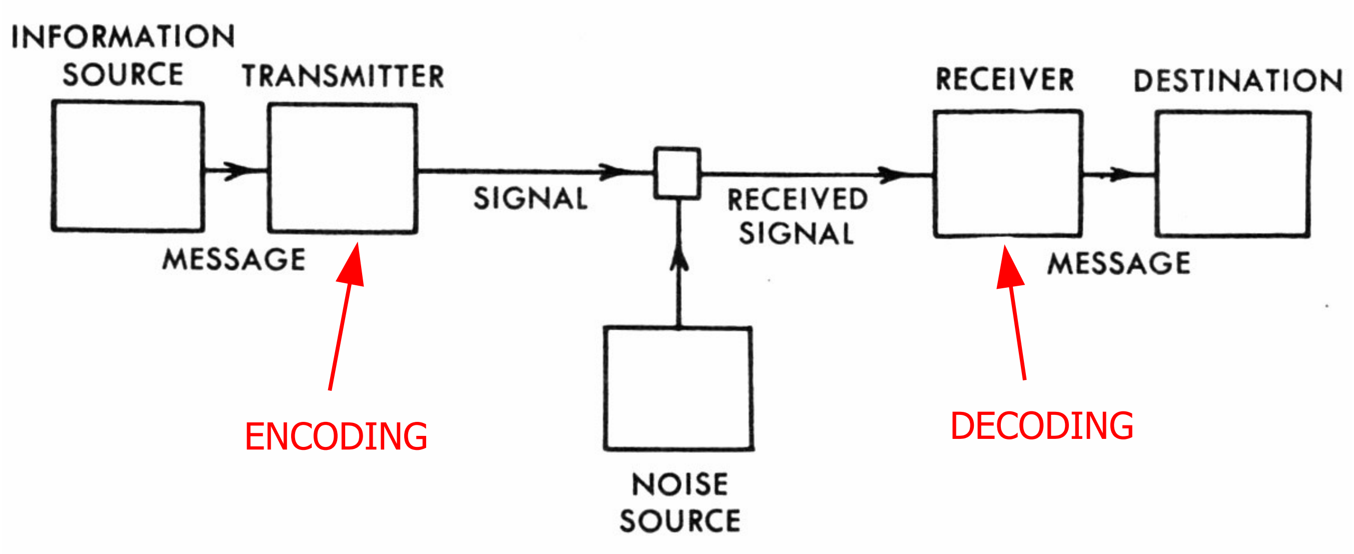


Fig. 1. — Schematic diagram of a general communication system.

Shannon Says ...



... in this channel, the error rate can be reduced to an arbitrarily small number,

PROVIDED:

proper encoding is done at the source. This is error detection and correction.

Error Detection and Correction

Very simple example:

- 16-bit string
- Represents 2 characters
- Find and correct ONE error.

1	1	0	1	0	0	1	0	1	1	1	0	1	0	0	1

Arrange into 4x4 block:

1	1	0	1
0	0	1	0
1	1	1	0
1	0	0	1

Add Redundancy and Send

Even parity bits (horizontal and vertical):

	1	**0**	**0**	**0**
1	1	1	0	1
1	0	0	1	0
1	1	1	1	0
0	1	0	0	1

Each DATA+PARITY row
and DATA+PARITY column
has an even number of 1's.

Send out through the channel:

1 **0** **0** **0** **1** 1 1 0 1 **1** 0 0 1 0 **1** 1 1 1 0 **0** 1 0 0 1

Receive and Check for Error

	1	**0**	**0**	**0**
1	1	1	0	1
1	0	1	1	0
1	1	1	1	0
0	1	0	0	1

This row has three 1's

This column has three 1's

Error in Parity Bits

	1	**1**	**0**	**0**
1	1	1	0	1
1	0	0	1	0
1	1	1	1	0
0	1	0	0	1

All DATA+PARITY rows have even # bits.

This column has three 1's

Generalizing

- The example finds one error.
- To find more than one error, more sophistication is used.
- Encoding consists of:
  - Removing redundancy at the source
  - Adding error correction bits

Now, Go To Speech

- Removing redundancy:
  - Earliest was the Dudley (Bell Labs) Vocoder; it would send:
    - Sound voiced or not (yes/no)
    - Pitch of voice
    - Spectrum

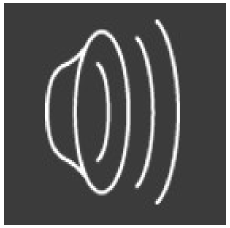
Detects features of speech waveform

Now, Go To Speech

- Removing redundancy:
  - Earliest was the Dudley (Bell Labs) Vocoder (1939); it would send:
    - Sound voiced or not (yes/no)
    - Pitch of voice
    - Spectrum

Detects features of speech waveform

Example of Vocoder Speech:



http://ptolemy.eecs.berkeley.edu/~eal/audio/vocoder.intro.wav

Digression: Vocoder at War

Vocoder was major part of SigSaly
Speech scrambler used in WW2 (1943)
First use of Frequency-Hopping Spread Spectrum
First use of Pulse Code Modulation

Photo: NSA

Top Secret Installation: The complete SIGSALY voice scrambler was a huge machine that relied on many analog-to-digital converters.

https://spectrum.ieee.org/geek-life/hands-on/rebuilding-a-piece-of-the-first-digital-voice-scrambler

2nd Digression: Frequency Hopping

Who invented it?
Hedy Lamarr, Movie Star
"The Most Beautiful Woman in the World"

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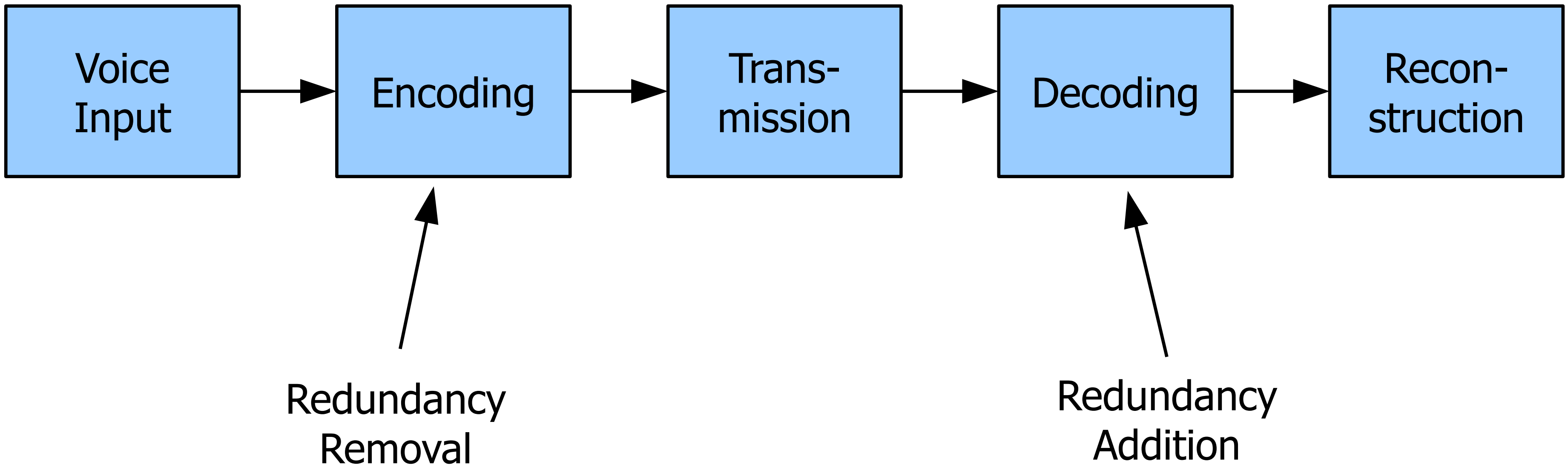
TECH

Hedy Lamarr: Not just a pretty face

How one of the best known actresses of mid-20th century revolutionized weapons systems and helped create cell phones

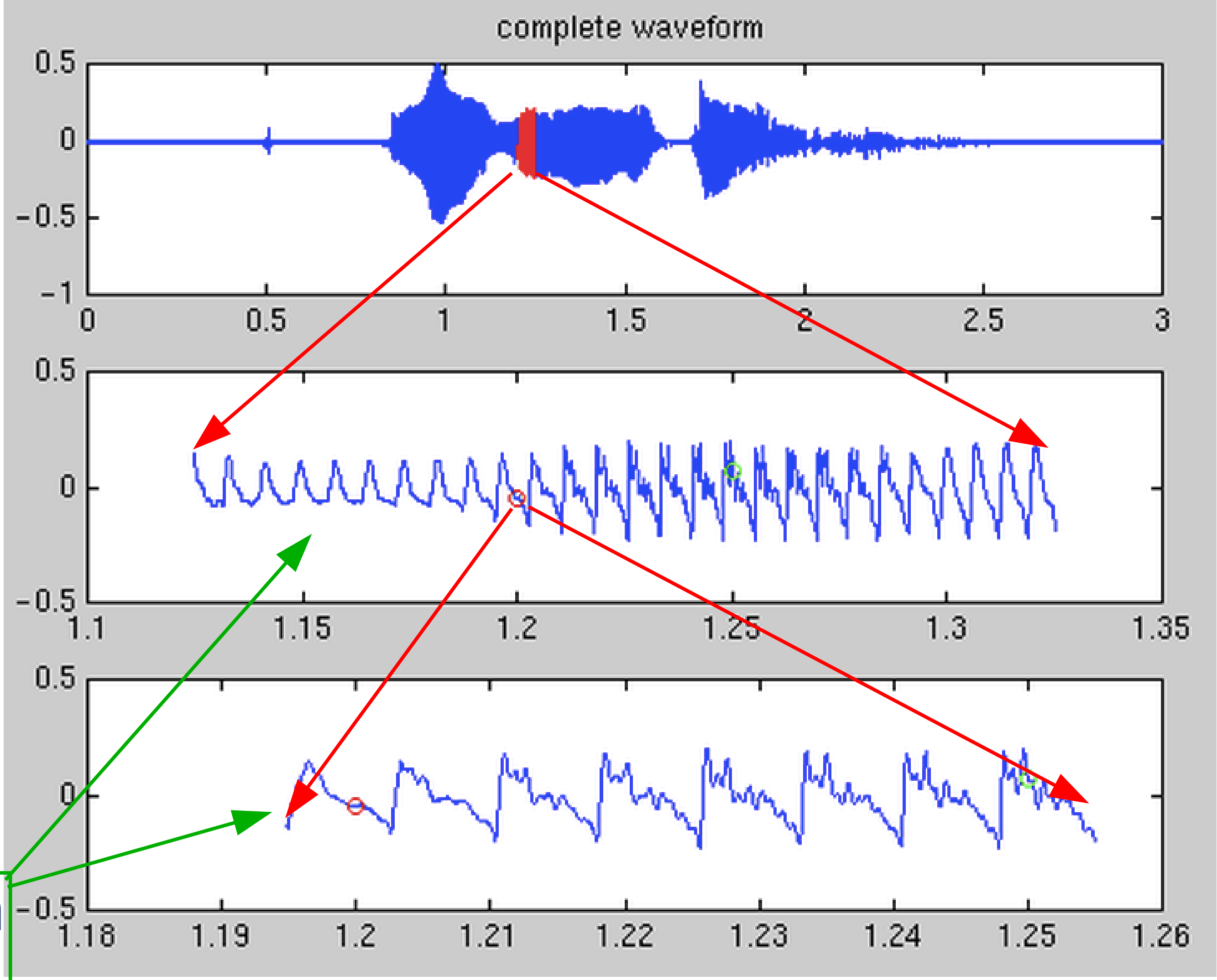
Co-invented with George Antheil, piano player.
First system used piano roll to schedule frequency changes.

Vocoder Concept



Now, Go To Speech

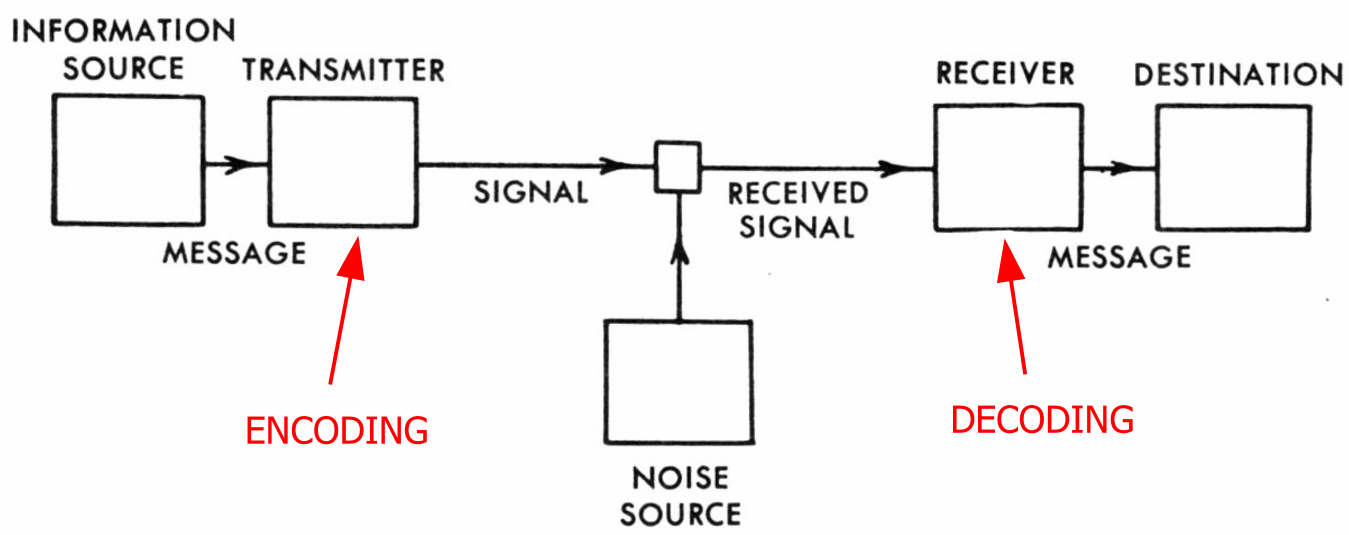
- Removing redundancy:
  - Currently in use: Linear Predictive Coding (LPC)
    - More efficient
    - Predicts next sample based on prior samples; possible because speech waveform has some predictability.



http://www.ineer.org/events/icee1999/proceedings/papers/425/425.htm

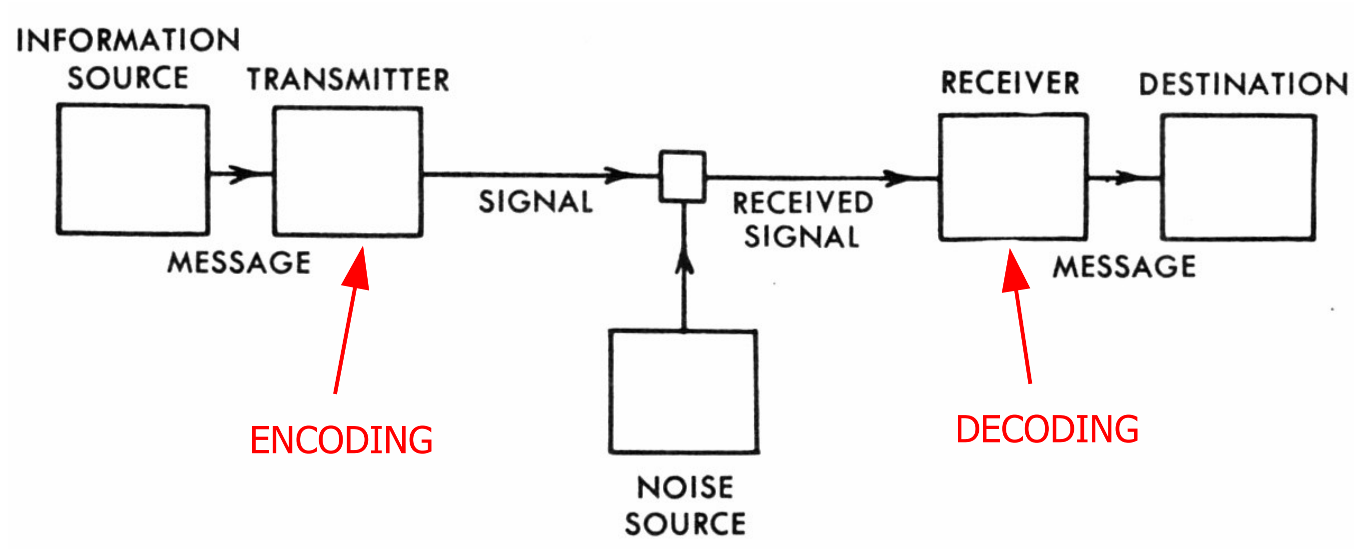
Linear Predictive Coding

- At the transmitter,
  - An algorithm predicts the next sample to come from the source.
  - When the actual sample arrives from the source, the error in the prediction is calculated by the transmitter and sent to the receiver.



Linear Predictive Coding

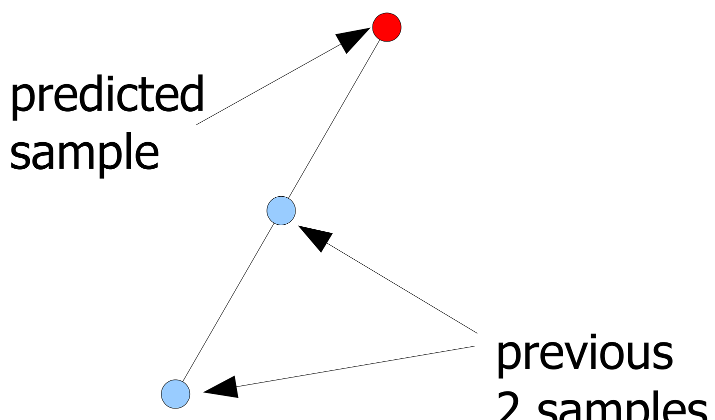
- At the receiver,
  - The same algorithm is used in reverse to regenerate the original value.
- Only the error is sent: much lower bandwidth is needed.



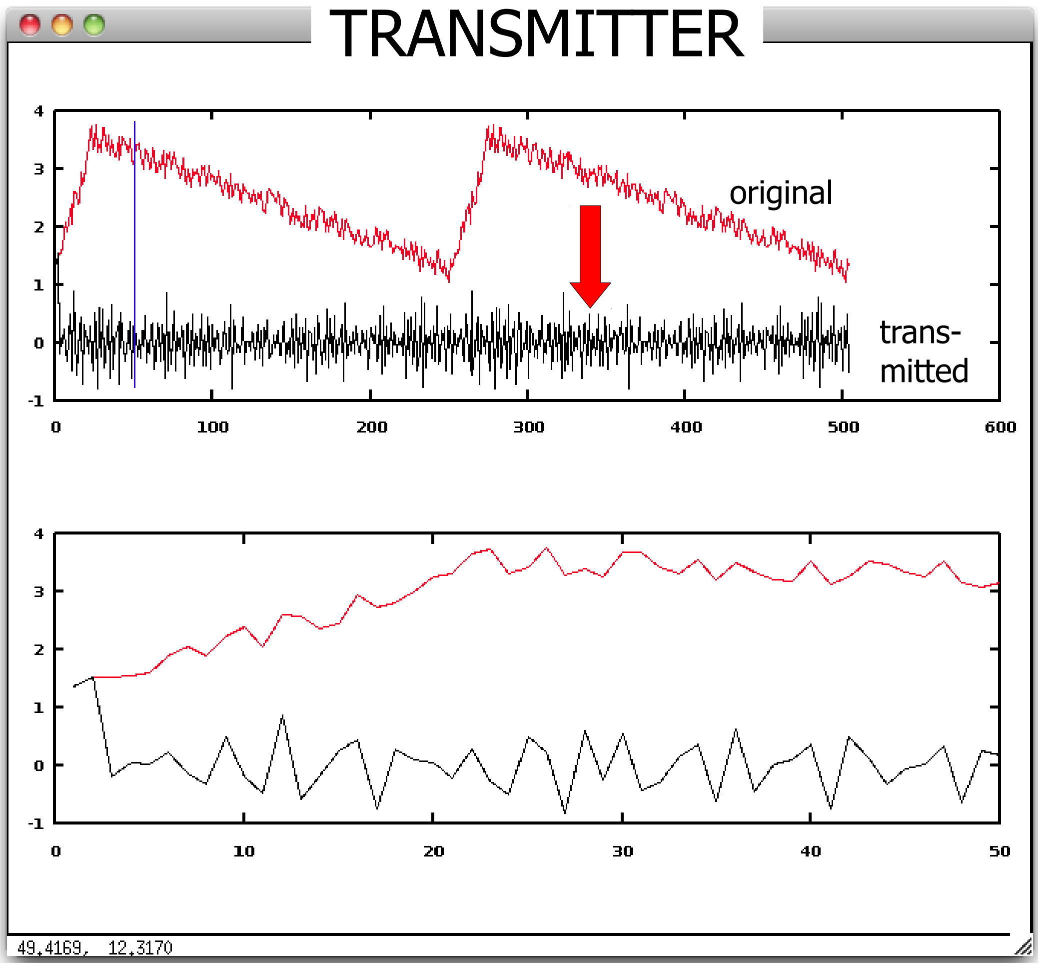
LPC Example

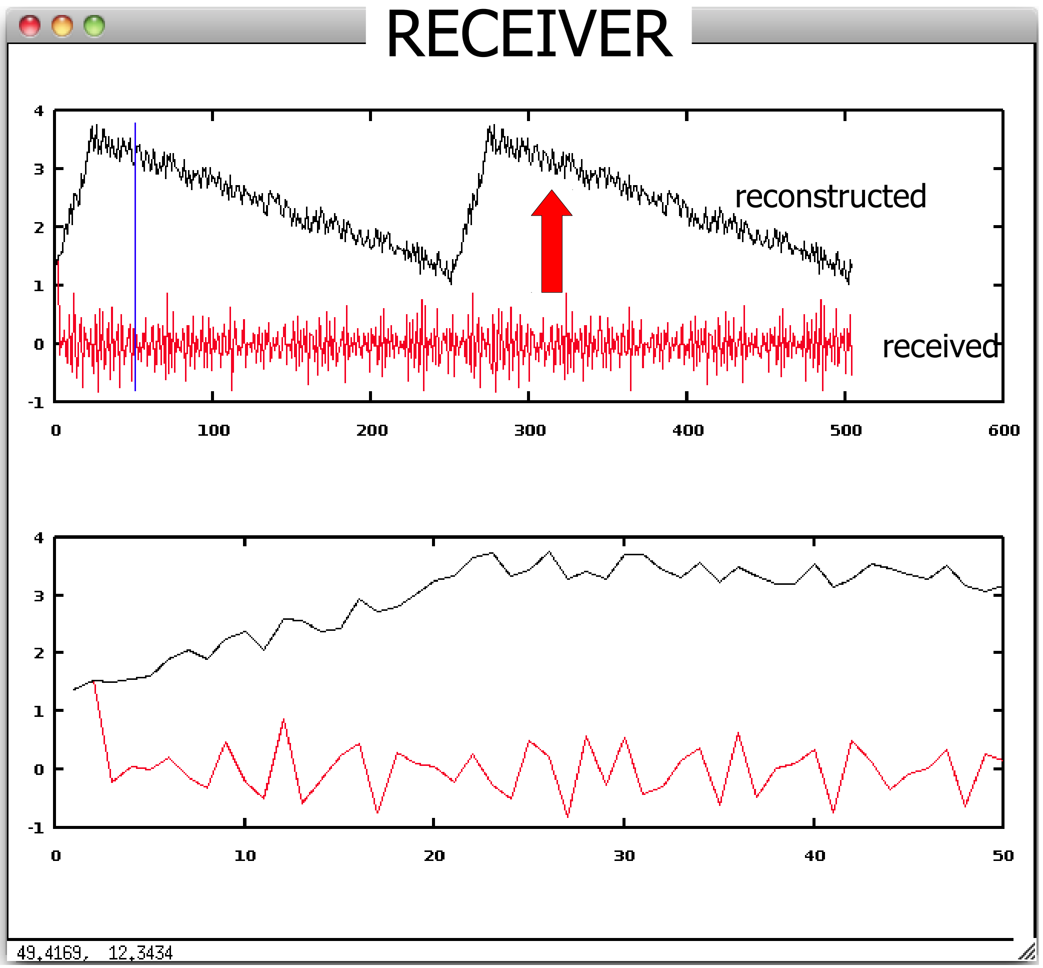
Extremely simple; no LPC algorithm is so basic.

Predictor: linear extension of previous two samples.



Naïve LPC Simulation





END

http://www.csc.kth.se/utbildning/kth/kurser/DD2431/mi08/03-trees-2x2.pdf

Example: rolling a dice

$p_1 = \frac{1}{6}; \quad p_2 = \frac{1}{6}; \ldots \quad p_6 = \frac{1}{6}$

$$\begin{aligned}\text{Entropy} &= \sum_i -p_i \log_2 p_i = \\ &= 6 \times -\frac{1}{6} \log_2 \frac{1}{6} = \\ &= -\log_2 \frac{1}{6} = \log_2 6 \approx 2.58\end{aligned}$$

The result of a dice-roll has 2.58 bit of information

Entropy

Entropy — measure of unpredictability

$$\text{Entropy} = \sum_i -p_i \log_2 p_i$$

p_i probability for event i

Entropy

Example: tossing a coin
$p_{\text{head}} = 0.5; \quad p_{\text{tail}} = 0.5$

$$\text{Entropy} = \sum_i -p_i \log_2 p_i =$$
$$= -0.5 \log_2 0.5 + -0.5 \log_2 0.5 \quad = -0.5 \underbrace{\log_2 0.5}_{-1} + -0.5 \underbrace{\log_2 0.5}_{-1} =$$
$$= 1$$

The result of a coin-toss has 1 bit of information

Entropy

Example: rolling a dice
$p_1 = \frac{1}{6}; \quad p_2 = \frac{1}{6}; \ldots \quad p_6 = \frac{1}{6}$

$$\text{Entropy} = \sum_i -p_i \log_2 p_i =$$
$$= 6 \times -\frac{1}{6} \log_2 \frac{1}{6} =$$
$$= -\log_2 \frac{1}{6} = \log_2 6 \approx 2.58$$

The result of a dice-roll has 2.58 bit of information

Entropi

Example: rolling a fake dice
$p_1 = 0.1; \ldots \quad p_5 = 0.1; \quad p_6 = 0.5$

$$\text{Entropy} = \sum_i -p_i \log_2 p_i =$$
$$= -5 \cdot 0.1 \log_2 0.1 - 0.5 \log_2 0.5 =$$
$$\approx 2.16$$

A real dice is more unpredictable (2.58 bit) than a fake (2.16 bit)

Entropy

Back to the decision trees

http://kuscholarworks.ku.edu/dspace/bitstream/1808/411/1/j42-hamid.pdf

```
clear
%sig = [1.0 2.0 2.8 4.1 4.7 4.5 3.9 3.0 2.7 2.2 1.3];
sig1=[1:0.1:3];
sig1=sig1+0.5*rand(1,length(sig1));
sig2=[max(sig1)-0.01:-0.01:1];
sig2=sig2+0.5*rand(1,length(sig2));
sig=[sig1 sig2 sig1 sig2];

% transmitter
for k=1:length(sig)
    if k<3,
        predS(k)=0;
        out(k)=sig(k);
    else
        predS(k)=1.0*(sig(k-1)-sig(k-2))+sig(k-1);
        out(k)=sig(k)-predS(k);
    end
end
figure(1),hold off
subplot(211)
hold off
plot(sig,'-r')
hold on
plot(out,'-k')
plot([50 50],[-0.8 3.8])

subplot(212)
hold off
plot(sig,'-r')
hold on
plot(out,'-k')
xlim([0 50])

% receiver
in = out;
for k=1:length(sig)
    if k<3,
        recon(k)=in(k);
    else
        predR(k)=1.0*(recon(k-1)-recon(k-2))+recon(k-1);
        recon(k)=in(k)+predR(k);
    end
end
figure(2),hold off
subplot(211)
hold off
plot(in,'-r')
hold on
plot(recon,'-k')
plot([50 50],[-0.8 3.8])

subplot(212)
hold off
plot(in,'-r')
hold on
plot(recon,'-k')
xlim([0 50])
```