Introduction to Computer Networks

Overview of the Physical Layer

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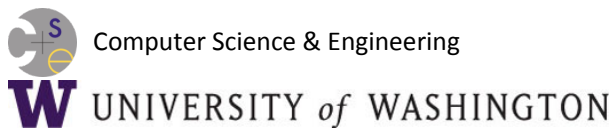
Where we are in the Course

- Beginning to work our way up starting with the Physical layer

Application
Transport
Network
Link
Physical

Scope of the Physical Layer

- Concerns how signals are used to transfer message bits over a link
    - Wires etc. carry <u>analog signals</u>
    - We want to send <u>digital bits</u>

10110...   ...10110

Signal →

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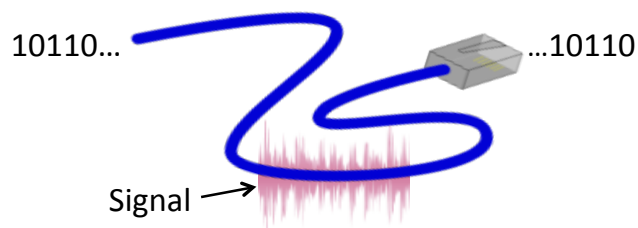
Topics

1. Properties of media
    - Wires, fiber optics, wireless
2. Simple signal propagation
    - Bandwidth, attenuation, noise
3. Modulation schemes
    - Representing bits, noise
4. Fundamental limits
    - Nyquist, Shannon

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Simple Link Model

- We'll end with abstraction of a physical channel
  - Rate (or bandwidth, capacity, speed) in bits/second
  - Delay in seconds, related to length

Message

Delay D, Rate R
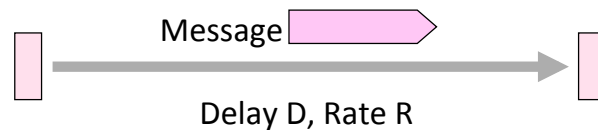
- Other important properties:
  - Whether the channel is broadcast, and its error rate

Message Latency

- <u>Latency</u> is the delay to send a message over a link
  - <u>Transmission delay</u>: time to put M-bit message "on the wire"

  - <u>Propagation delay</u>: time for bits to propagate across the wire

  - Combining the two terms we have:

Message Latency (2)

- <u>Latency</u> is the delay to send a message over a link
  - <u>Transmission delay</u>: time to put M-bit message "on the wire"

    T-delay = M (bits) / Rate (bits/sec) = M/R seconds

  - <u>Propagation delay</u>: time for bits to propagate across the wire

    P-delay = Length / speed of signals = $L/\tfrac{2}{3}c$ = D seconds

  - Combining the two terms we have: Latency = M/R + D

Metric Units

- The main prefixes we use:

Prefix	Exp.	prefix	exp.
K(ilo)	10^3	m(illi)	10^{-3}
M(ega)	10^6	μ(micro)	10^{-6}
G(iga)	10^9	n(ano)	10^{-9}

- Use powers of 10 for rates, 2 for storage
  - 1 Mbps = 1,000,000 bps, 1 KB = 1024 bytes
- "B" is for bytes, "b" is for bits

Latency Examples

- "Dialup" with a telephone modem:
    - D = 5ms, R = 56 kbps, M = 1250 bytes

- Broadband cross-country link:
    - D = 50ms, R = 10 Mbps, M = 1250 bytes

Latency Examples (2)

- "Dialup" with a telephone modem:
    D = 5ms, R = 56 kbps, M = 1250 bytes
    L = 5ms + (1250 x 8)/(56 x 10^3) sec = 184ms!

- Broadband cross-country link:
    D = 50ms, R = 10 Mbps, M = 1250 bytes
    L = 50ms + (1250 x 8) / (10 x 10^6) sec = 51ms

- A long link or a slow rate means high latency
    - Often, one delay component dominates

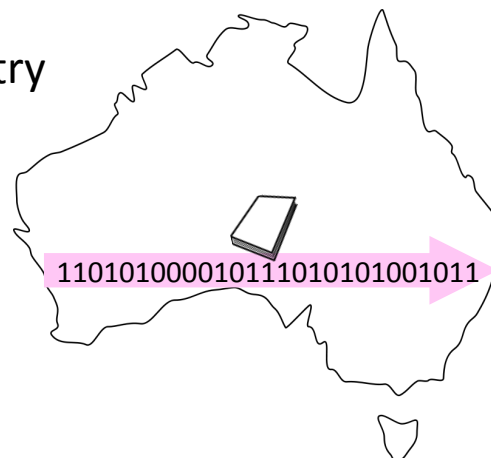# Bandwidth-Delay Product

- Messages take space on the wire!
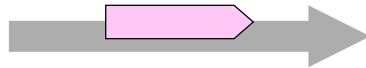
- The amount of data in flight is the
  <u>bandwidth-delay (BD) product</u>
    - Measure in bits, or in messages
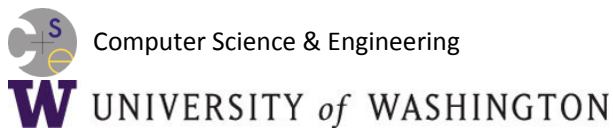   - Small for LANs, big for "long fat" pipes

Bandwidth-Delay Example

- Fiber at home, cross-country

  R=40 Mbps, D=50ms

  BD $= 40 \times 50 \times 10^3$ bits

  $ = 250$ KB

- That's quite a lot of data
  "in the network"!

110101000010111010101001011

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Media (Wires, etc.) (§2.2, 2.3)

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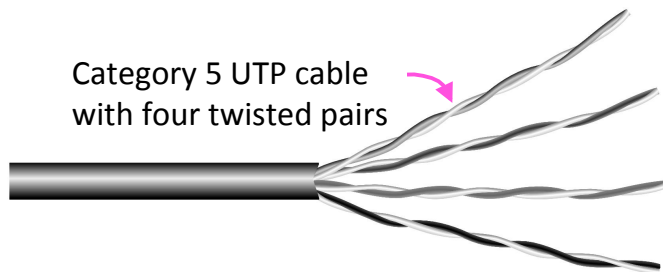**W** UNIVERSITY *of* WASHINGTON

Types of Media

- <u>Media</u> propagate <u>signals</u> that carry <u>bits</u> of information
- We'll look at some common types:
  - Wires »
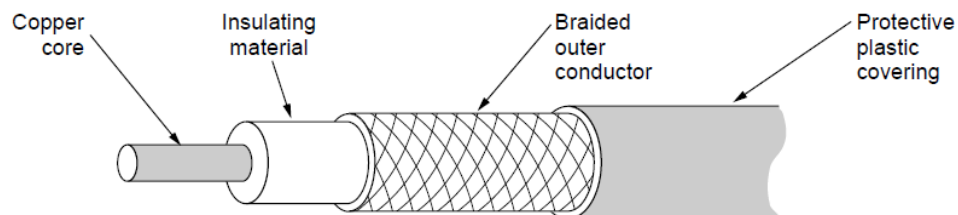 - Fiber (fiber optic cables) »
  - Wireless »

Wires – Twisted Pair

- Very common; used in LANs and telephone lines
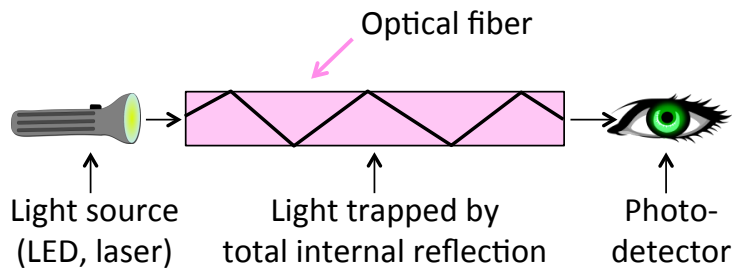 - Twists reduce radiated signal

Category 5 UTP cable with four twisted pairs

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Wires – Coaxial Cable

- Also common. Better shielding for better performance

Copper core   Insulating material   Braided outer conductor   Protective plastic covering

- Other kinds of wires too: e.g., electrical power

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Fiber

- Long, thin, pure strands of glass
  - Enormous bandwidth over long distances

Optical fiber

Light source
(LED, laser)

Light trapped by
total internal reflection

Photo-
detector

Fiber (2)

- Two varieties: multi-mode (shorter links, cheaper) and single-mode (up to ~100 km)

Core
(glass)

Cladding
(glass)

Jacket
(plastic)

One fiber

Sheath

Jacket

Core

Cladding

Fiber bundle in a cable

Wireless

- Sender radiates signal over a region
  - In many directions, unlike a wire, to potentially many receivers
  - Nearby signals (same freq.) <u>interfere</u> at a receiver; need to coordinate use
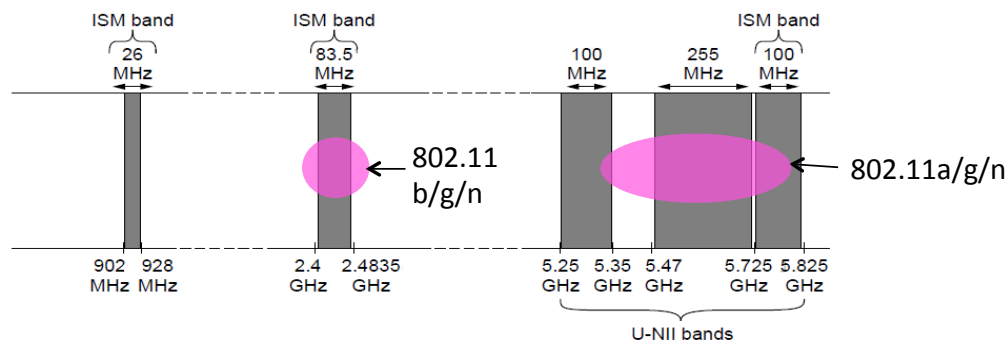

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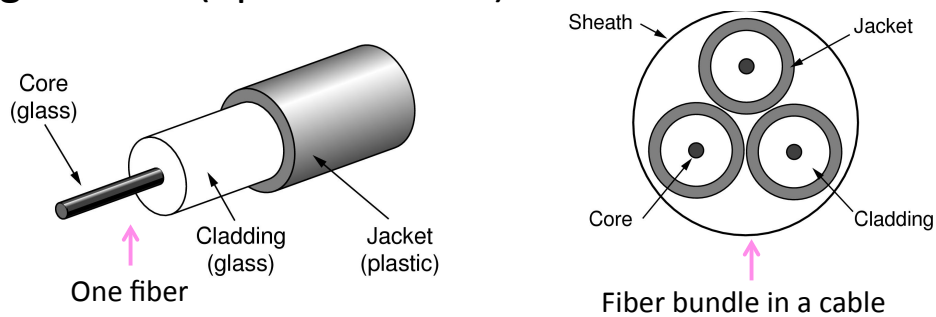
Wireless (2)

- Microwave, e.g., 3G, and unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking
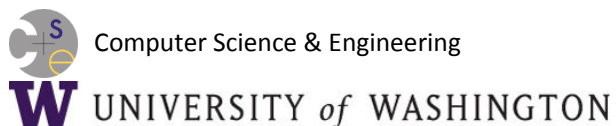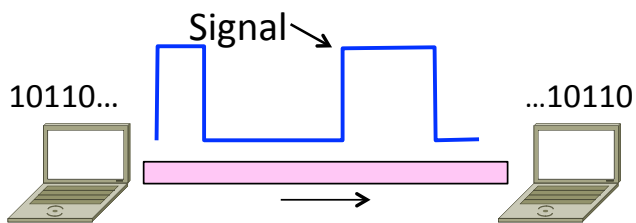

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Signals (§2.2)

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Topic

- Analog signals encode digital bits.
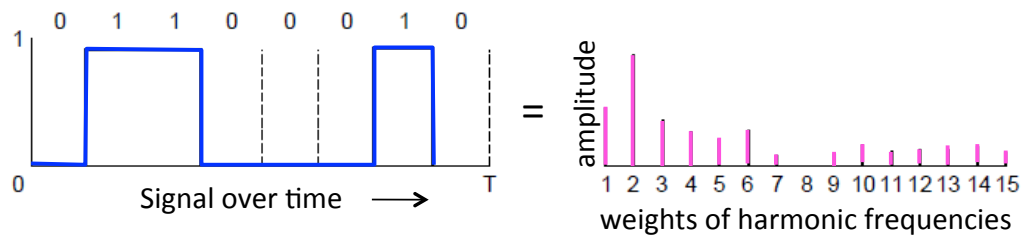 We want to know what happens as
  signals propagate over media

Signal

10110... ...10110

Frequency Representation

- A signal over time can be represented by its frequency
  components (called Fourier analysis)

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$
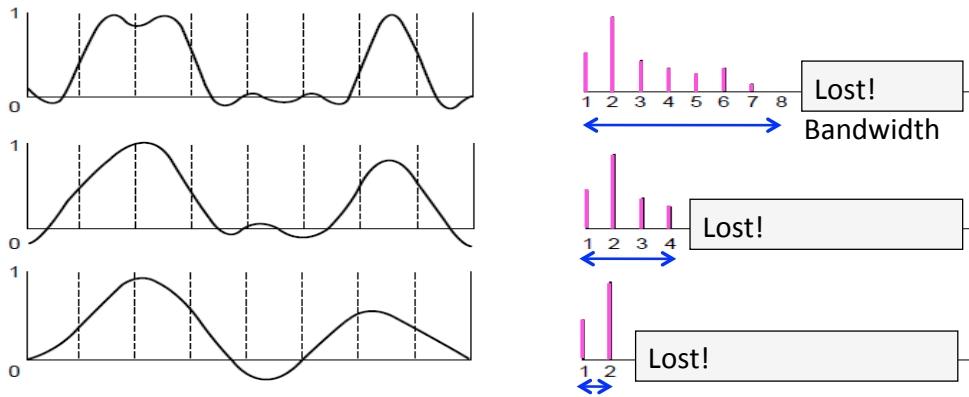
0 1 1 0 0 0 1 0

1

0   Signal over time   T

=

amplitude

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
weights of harmonic frequencies

Effect of Less Bandwidth

- Less bandwidth degrades signal (less rapid transitions)

Signals over a Wire

- What happens to a signal as it passes over a wire?
  - The signal is delayed (propagates at ⅔c)
  - The signal is attenuated (goes for m to km)
  - Noise is added to the signal (later, causes errors)
  - Frequencies above a cutoff are highly attenuated

EE: Bandwidth = width of frequency band, measured in Hz
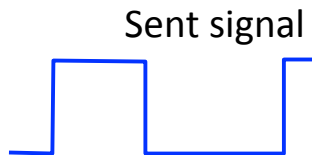CS: Bandwidth = information carrying capacity, in bits/sec

Signals over a Wire (2)
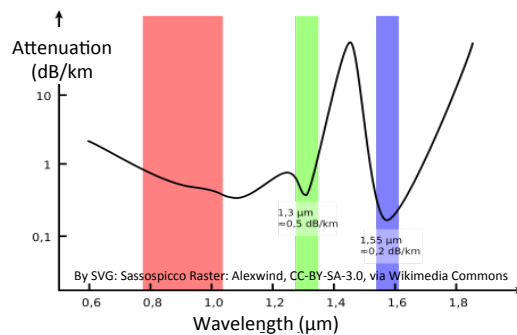
- Example:

Sent signal

1: Attenuation:

2: Bandwidth:

3: Noise:

Signals over Fiber

- Light propagates with very low loss in three very wide frequency bands
 - Use a carrier to send information

Attenuation (dB/km)

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1

0,1

1,3 μm
≈0,5 dB/km

1,55 μm
≈0,2 dB/km

By SVG: Sassospicco Raster: Alexwind, CC-BY-SA-3.0, via Wikimedia Commons

0,6   0,8   1,0   1,2   1,4   1,6   1,8

Wavelength (μm)

Signals over Wireless (§2.2)

- Signals transmitted on a carrier frequency
- Travel at speed of light, spread out and attenuate faster than $1/dist^2$
- Multiple signals on the same frequency interfere at a receiver
- Other effects are highly frequency dependent, e.g., multipath at microwave frequencies

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Wireless Multipath

- Signals bounce off objects and take multiple paths
  - Some frequencies attenuated at receiver, varies with location
  - Messes up signal; handled with sophisticated methods (§2.5.3)

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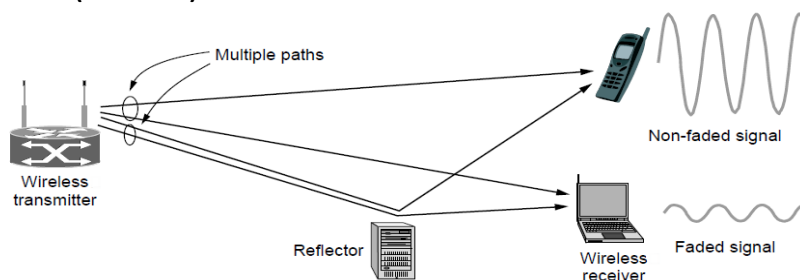
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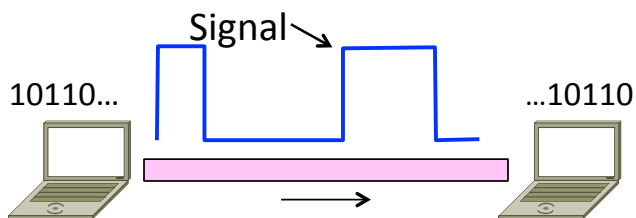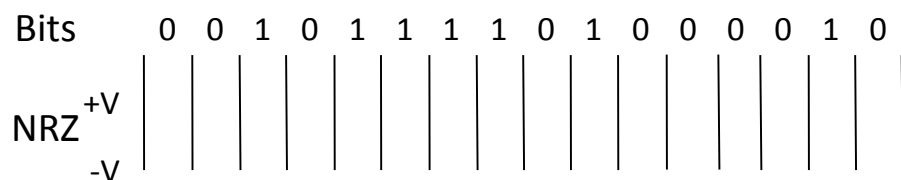
Modulation (§2.5)

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Topic

- We've talked about signals representing bits. How, exactly?
  - This is the topic of <u>modulation</u>

Signal

10110...   ...10110

A Simple Modulation

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)

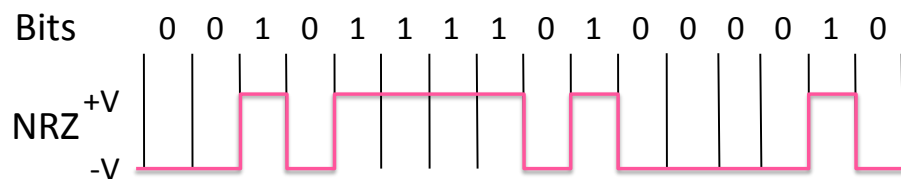Bits   0   0   1   0   1   1   1   1   0   1   0   0   0   0   1   0

NRZ +V
     -V

A Simple Modulation (2)

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)

Bits   0   0   1   0   1   1   1   1   0   1   0   0   0   0   1   0

NRZ +V
     -V

Many Other Schemes

- Can use more signal levels, e.g., 4 levels is 2 bits per <u>symbol</u>

- Practical schemes are driven by engineering considerations
  - E.g., clock recovery »

Clock Recovery

- Um, how many zeros was that?
  - Receiver needs frequent signal transitions to decode bits

    1 0 0 0 0 0 0 0 0 … 0

- Several possible designs
  - E.g., Manchester coding and scrambling (§2.5.1)

Clock Recovery – 4B/5B

- Map every 4 data bits into 5 code bits with a transition that are sent
  - 0000 → 11110, 0001 → 01001, 1110 → 11100, … 1111 → 11101
  - Has at most 3 zeros in a row

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Clock Recovery – 4B/5B (2)

- 4B/5B code for reference:
  - 0000→11110, 0001→01001, 1110→11100, … 1111→11101

- Message bits: 1 1 1 1 0 0 0 0 0 0 0 1

Coded Bits:

Signal:

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Passband Modulation

- What we have seen so far is
  <u>baseband</u> modulation for wires
  - Signal is sent directly on a wire
- These signals do not propagate well
  on fiber / wireless
  - Need to send at higher frequencies
- <u>Passband</u> modulation carries a
  signal by modulating a carrier

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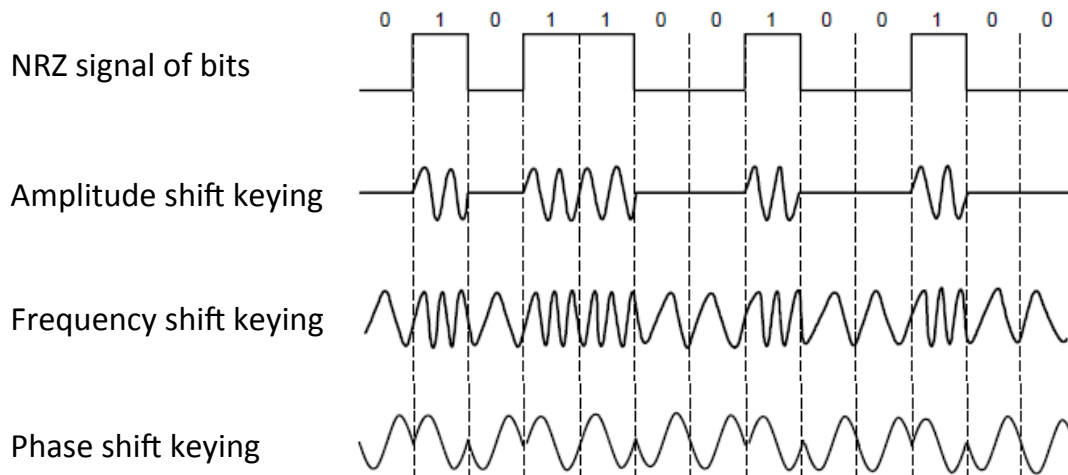
Passband Modulation (2)

- Carrier is simply a signal oscillating
  at a desired frequency:
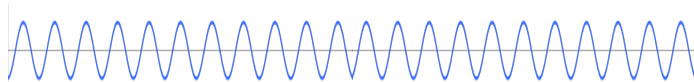
- We can modulate it by changing:
  - Amplitude, frequency, or phase

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Passband Modulation (3)

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying

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Fundamental Limits (§2.2)

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Topic

- How rapidly can we send information over a link?
  - <u>Nyquist</u> limit (~1924) »
  - <u>Shannon</u> capacity (1948) »

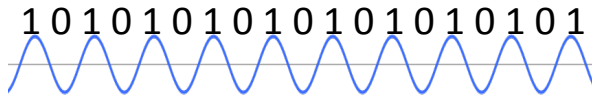- Practical systems are devised to approach these limits

Key Channel Properties

- The bandwidth (B), signal strength (S), and noise strength (N)
  - B limits the rate of transitions
  - S and N limit how many signal levels we can distinguish

Bandwidth B → Signal S, Noise N
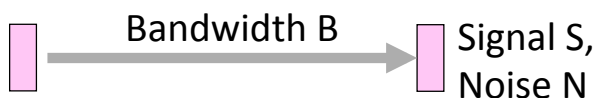
Nyquist Limit

- The maximum symbol rate is 2B

$$1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0\ 1$$
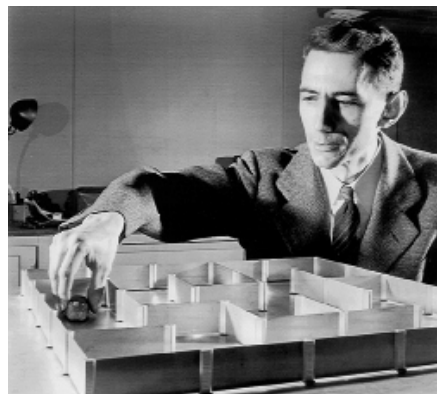
- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

$$R = 2B \log_2 V \text{ bits/sec}$$

Claude Shannon (1916-2001)

- Father of information theory
  - "A Mathematical Theory of Communication", 1948
- Fundamental contributions to digital computers, security, and communications

Electromechanical mouse that "solves" mazes! →

Credit: Courtesy MIT Museum

Shannon Limit

- How many levels we can distinguish depends on S/N
  - Or SNR, the <u>Signal-to-Noise Ratio</u>
  - Note noise is random, hence some errors
- SNR given on a log-scale in deciBels:
  - $SNR_{dB} = 10\log_{10}(S/N)$

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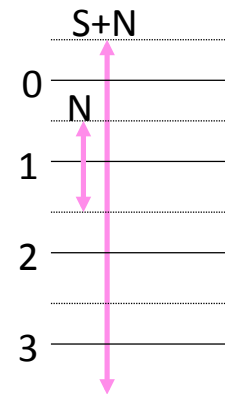
Shannon Limit (2)

- Shannon limit is for capacity (C), the maximum information carrying rate of the channel:

$$C = B \log_2(1 + S/N) \text{ bits/sec}$$
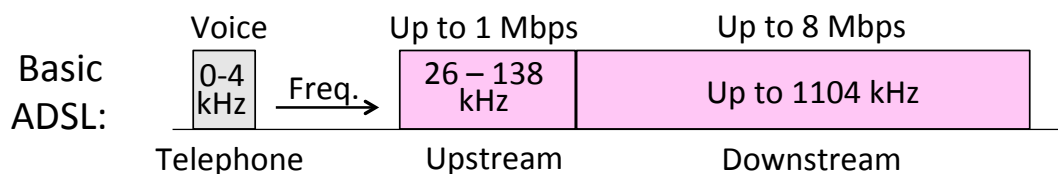
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Putting it all together – DSL

- DSL (Digital Subscriber Line, see §2.6.3) is widely used for broadband; many variants offer 10s of Mbps
  - Reuses twisted pair telephone line to the home; it has up to ~2 MHz of bandwidth but uses only the lowest ~4 kHz

DSL (2)

- DSL uses passband modulation
  - Separate bands for upstream and downstream (larger)
  - Modulation called QAM varies both amplitude and phase
  - High SNR, up to 15 bits/symbol, low SNR only 1 bit/symbol

Basic ADSL:	Voice		Up to 1 Mbps	Up to 8 Mbps
	0-4 kHz	Freq. →	26 – 138 kHz	Up to 1104 kHz
	Telephone		Upstream	Downstream

Wired/Wireless Perspective

- Wires, and Fiber
  - Engineer link to have requisite SNR and B
  - →Can fix data rate

- Wireless
  - Given B, but SNR varies greatly, e.g., up to 60 dB!
  - →Can't design for worst case, must adapt data rate

Wired/Wireless Perspective (2)

- Wires, and Fiber   Engineer SNR for data rate
  - Engineer link to have requisite SNR and B
  - →Can fix data rate

- Wireless   Adapt data rate to SNR
  - Given B, but SNR varies greatly, e.g., up to 60 dB!
  - →Can't design for worst case, must adapt data rate