Operating Systems and Networks

Networks Part 2: Physical Layer

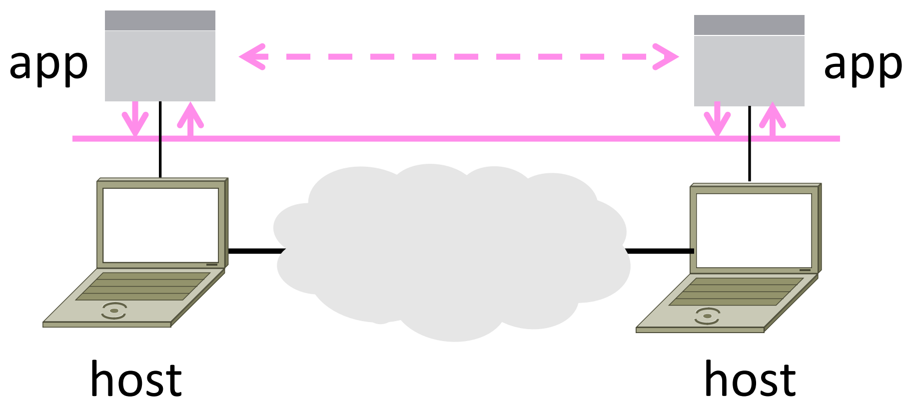
Adrian Perrig
Network Security Group
ETH Zürich

Overview

- Important concepts from last lecture
  - Statistical multiplexing, statistical multiplexing gain
  - OSI 7 layer model, interfaces, protocols
  - Encapsulation
- This lecture
  - Socket programming overview
  - Physical layer
- Online lecture videos: http://computernetworks5e.org

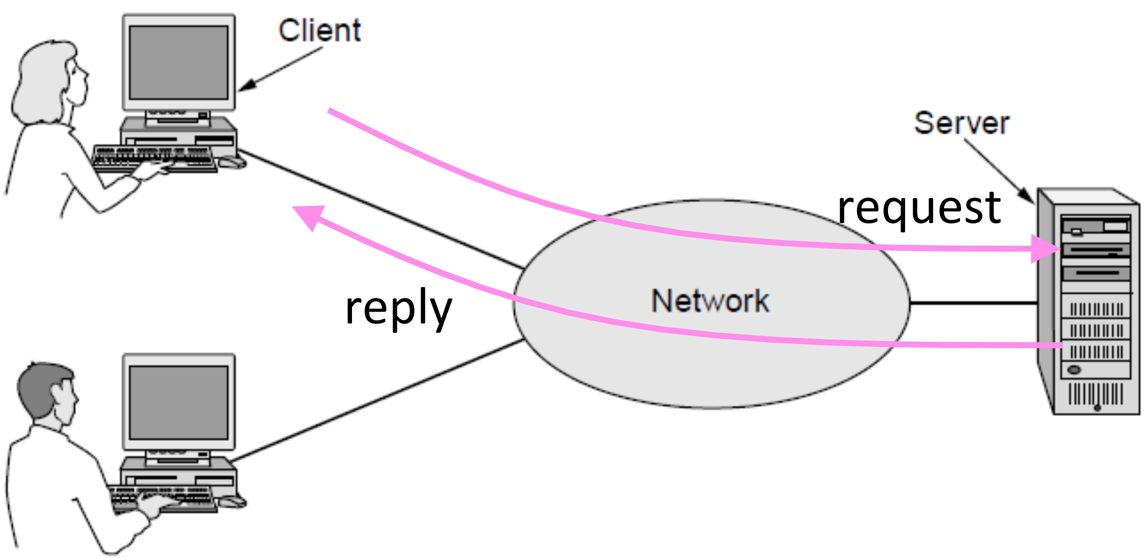
Network-Application Interface

- Defines how apps use the network
  - Lets apps talk to each other via hosts; hides the details of the network



Motivating Application

- Simple client-server connection setup



Motivating Application (2)

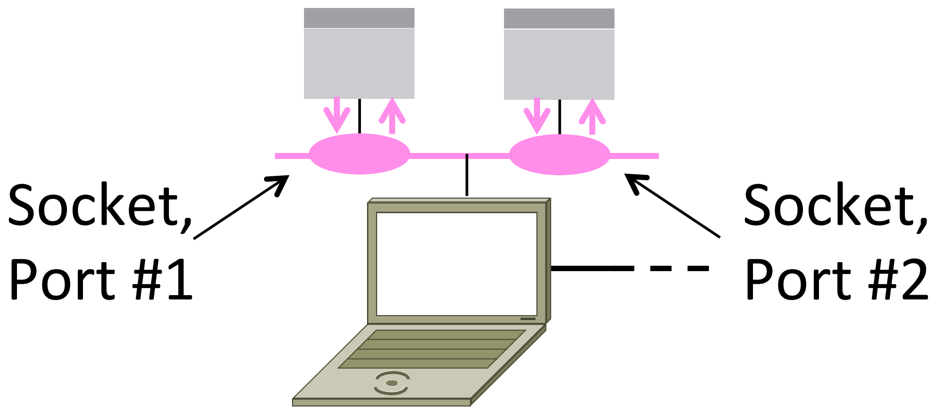
- Simple client-server connection setup
  - Client app sends a request to server app
  - Server app returns a (longer) reply
- This is the basis for many apps!
  - File transfer: send name, get file (§6.1.4)
  - Web browsing: send URL, get page
  - Echo: send message, get it back
- Let's see how to write this app …

Socket API

- Simple abstraction to use the network
  - The network service API used to write all Internet applications
  - Part of all major OSes and languages; originally Berkeley (Unix) ~1983
- Supports two kinds of network services
  - Streams: reliably send a stream of bytes
  - Datagrams: unreliably send separate messages. (Ignore for now.)

Socket API (2)

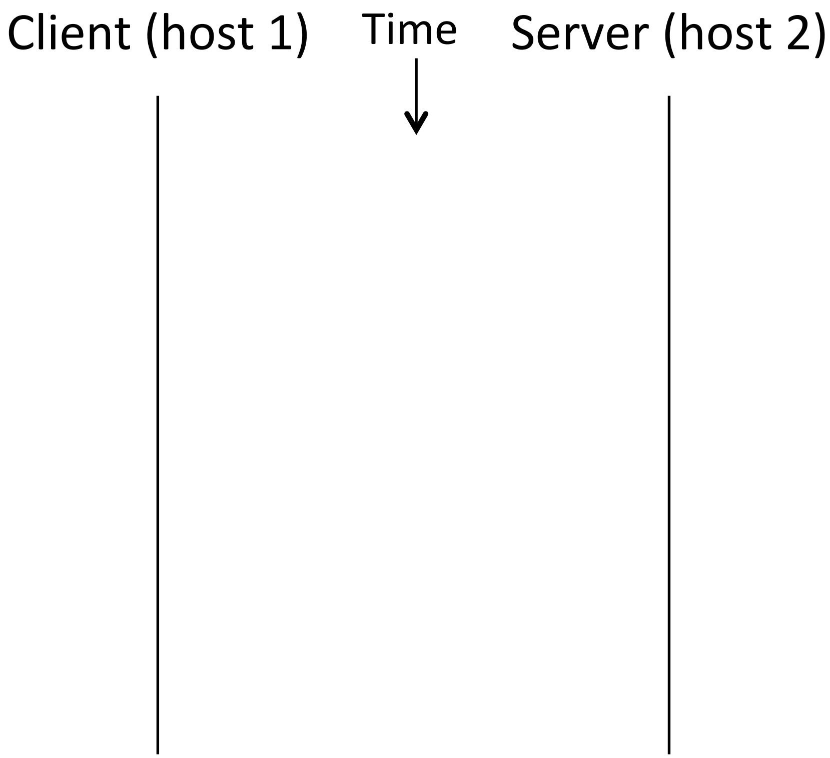
- Sockets let apps attach to the local network at different ports



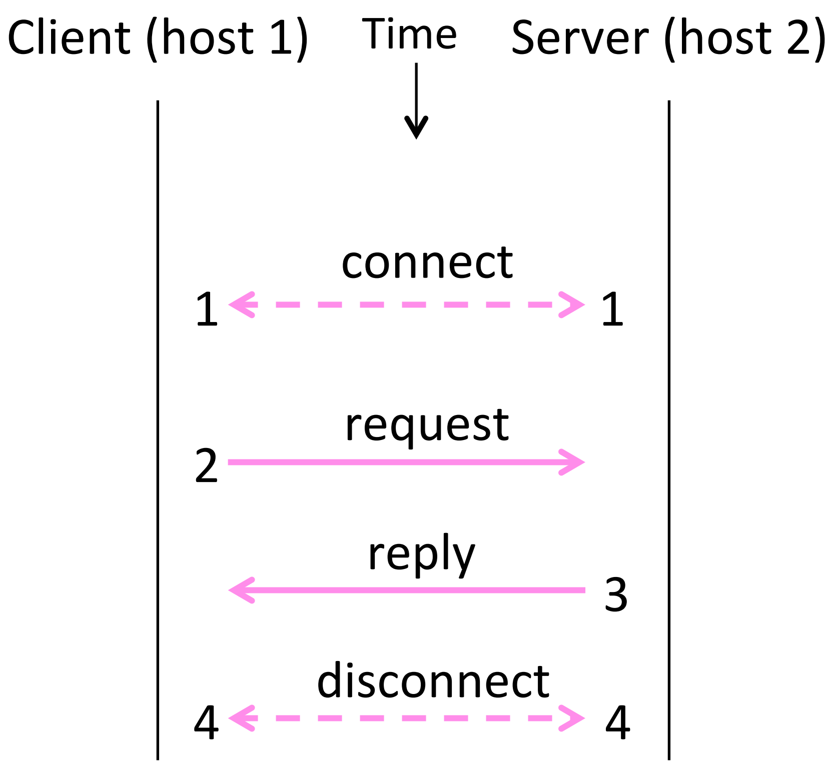
Socket API (3)

Primitive	Meaning
SOCKET	Create a new communication endpoint
BIND	Associate a local address with a socket
LISTEN	Announce willingness to accept connections; give queue size
ACCEPT	Passively establish an incoming connection
CONNECT	Actively attempt to establish a connection
SEND	Send some data over the connection
RECEIVE	Receive some data from the connection
CLOSE	Release the connection

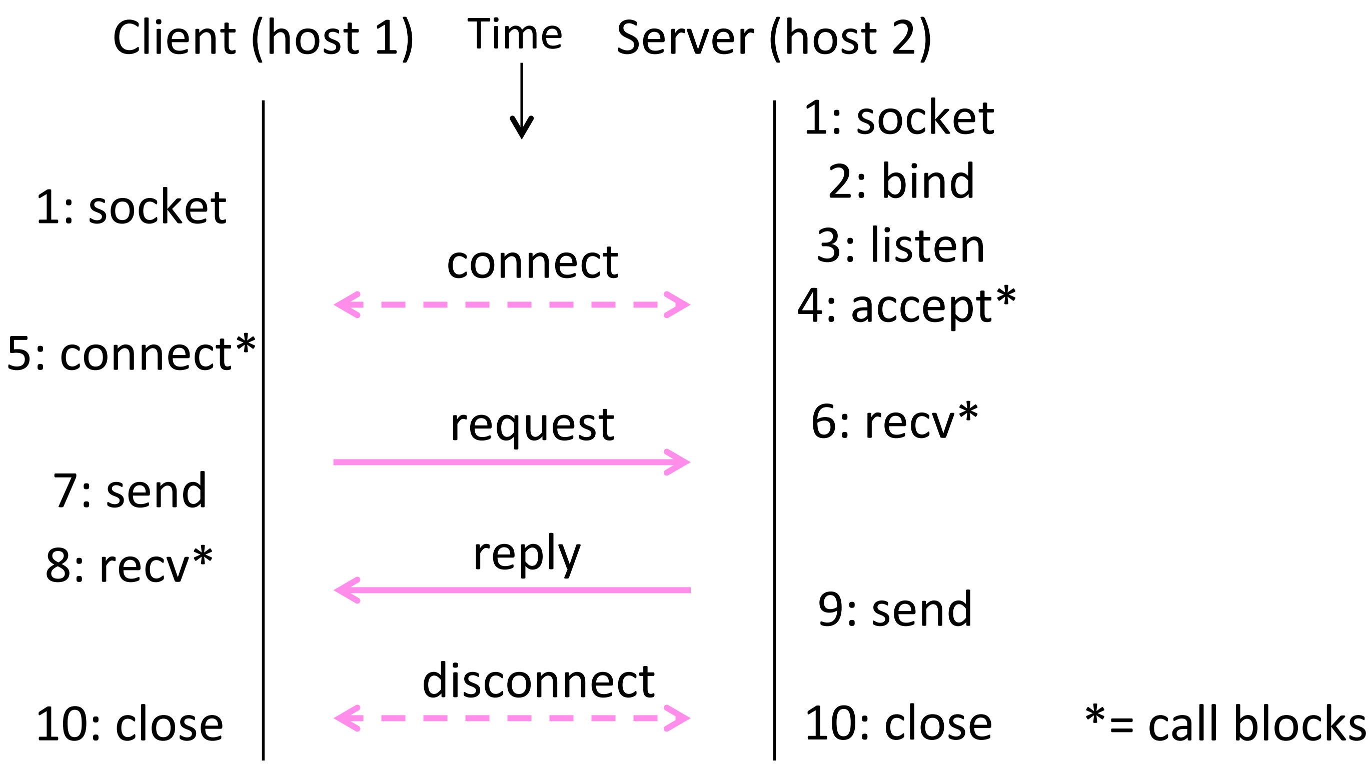
Using Sockets



Using Sockets (2)



Using Sockets (3)



Client Program (outline)

```
socket()          // make socket
getaddrinfo()     // server and port name
                  // www.example.com:80
connect()         // connect to server [block]
…
send()            // send request
recv()            // await reply [block]
…                 // do something with data!
close()           // done, disconnect
```

Server Program (outline)

```
socket()          // make socket
getaddrinfo()     // for port on this host
bind()            // associate port with socket
listen()          // prepare to accept connections
accept()          // wait for a connection [block]
…
recv()            // wait for request
…
send()            // send the reply
close()           // eventually disconnect
```

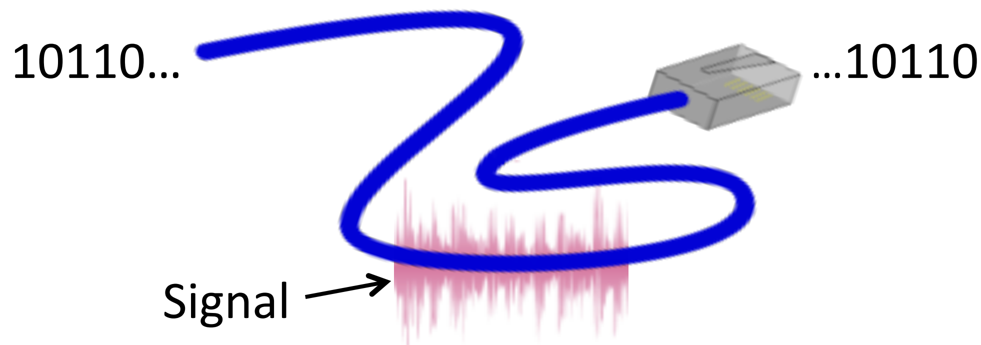
Where we are in the Course

- 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 analog signals
  - We want to send digital bits

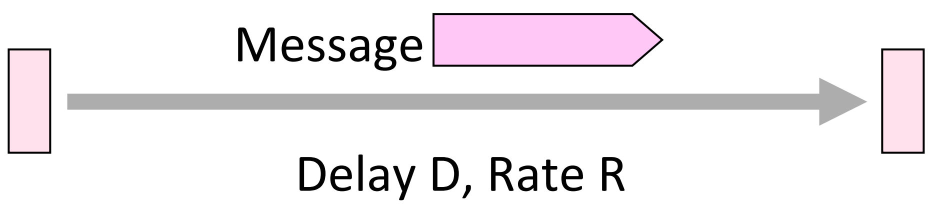


Topics

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

Simple Link Model

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



- Other important properties:
  - Whether the channel is broadcast, and its error rate

Message Latency

- Latency L: delay to send a message over a link
  - Transmission delay: time to put M-bit message "on the wire"

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

  - Propagation delay: time for bits to propagate across the wire

    P-delay = Length / speed of signals = Length / ⅔c = D seconds

  - Combining the two terms we have: L = 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 or data size
  – 1 Mbps = 1,000,000 bps, 1 KB = 2^{10} bytes
- "B" is for bytes, "b" is for bits

Latency Examples

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

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

Latency Examples (2)

- "Dialup" with a telephone modem:

  D = 5 ms, R = 56 kbps, M = 1250 bytes

  L = 5 ms + (1250x8)/(56×10^3) sec = 184 ms!

- Broadband cross-country link:

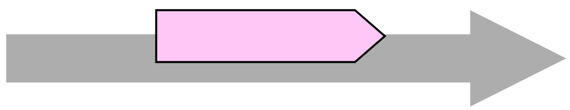
  D = 50 ms, R = 10 Mbps, M = 1250 bytes

  L = 50 ms + (1250x8) / (10×10^6) sec = 51 ms

- 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>

$$BD = R \times D$$

  - Measure in bits, or in messages
  - Small for LANs, big for "long fat" pipes

Bandwidth-Delay Example

- Fiber at home, cross-country

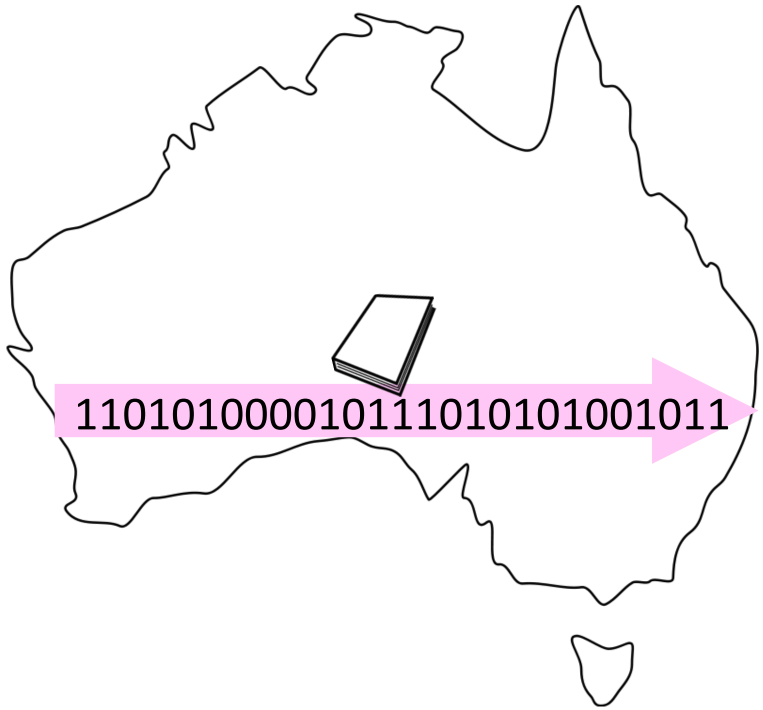
  R=40 Mbps, D=50 ms

  BD $= 40 \times 10^6 \times 50 \times 10^{-3}$ bits

  $= 2000$ Kbit

  $= 250$ KB

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



How “Long” is a Bit?

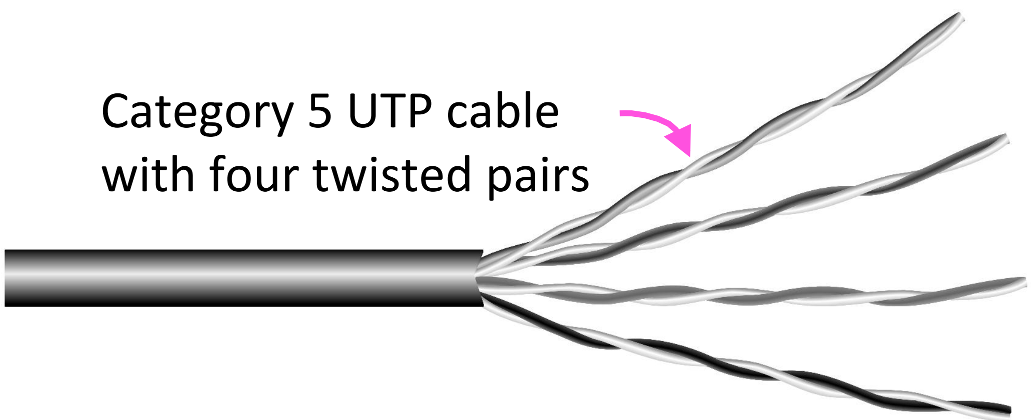
- Interesting trivia: how “long” is the representation of a bit on a wire?
- Considering a fiber optic cable
  - Signal propagation speed: 200’000’000 m/s
  - Sending rate: 1Gbps → duration of sending one bit: 1ns
  - Bit “length”: 1ns * 200’000’000 m/s = 0.2 m
  - “Length” of a 1Kb packet: 0.2m * 8 * 2^{10} = 1.6km

Types of Media (§2.2, 2.3)

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

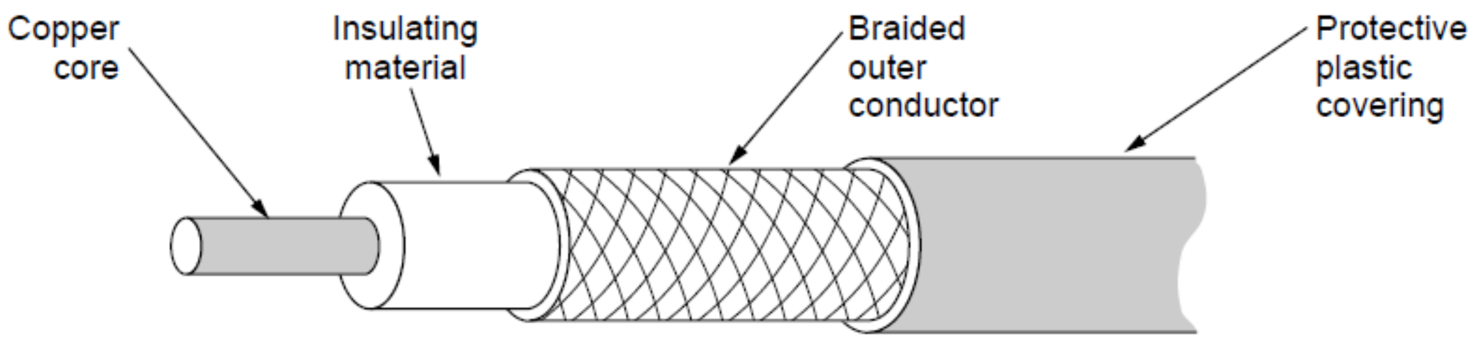
Wires – Twisted Pair

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



Wires – Coaxial Cable

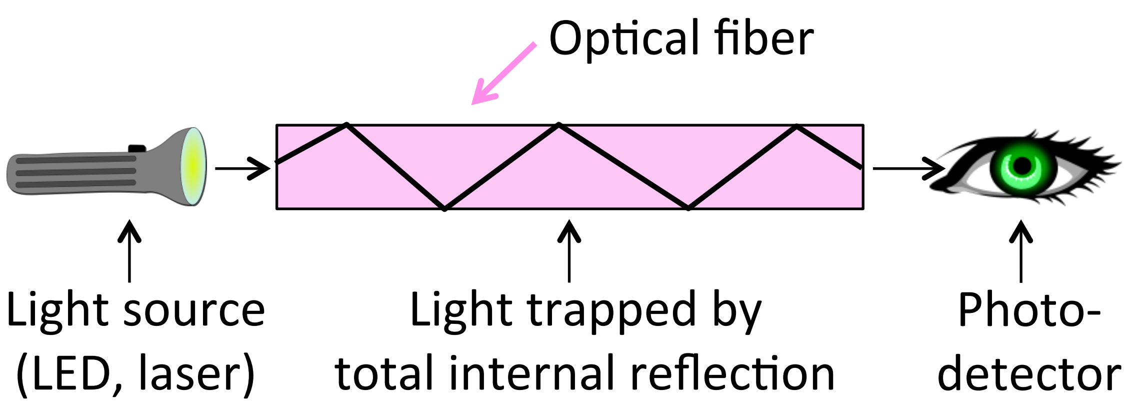
- Also common. Better shielding for better performance



- Other kinds of wires too: e.g., electrical power (§2.2.4)

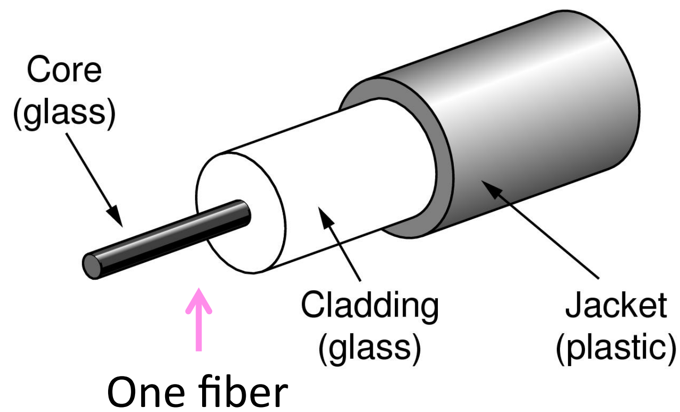
Fiber

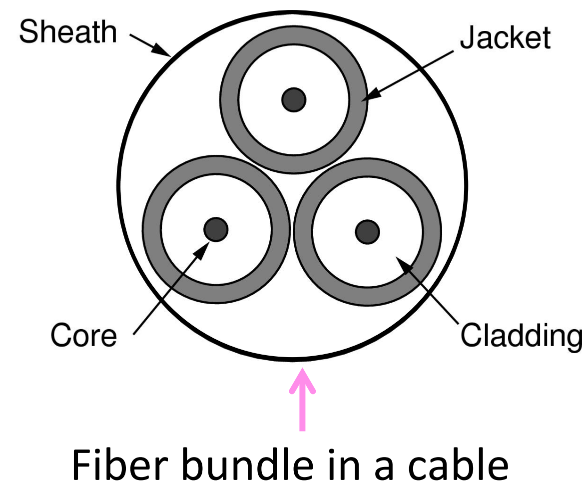
- Long, thin, pure strands of glass
  - Enormous bandwidth (high speed) over long distances



Fiber (2)

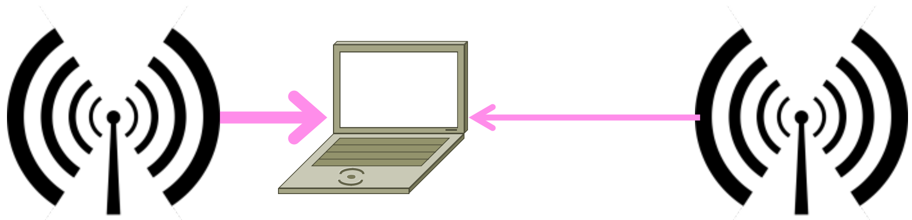
- Two varieties: multi-mode (shorter links, cheaper) and single-mode (up to ~100 km)

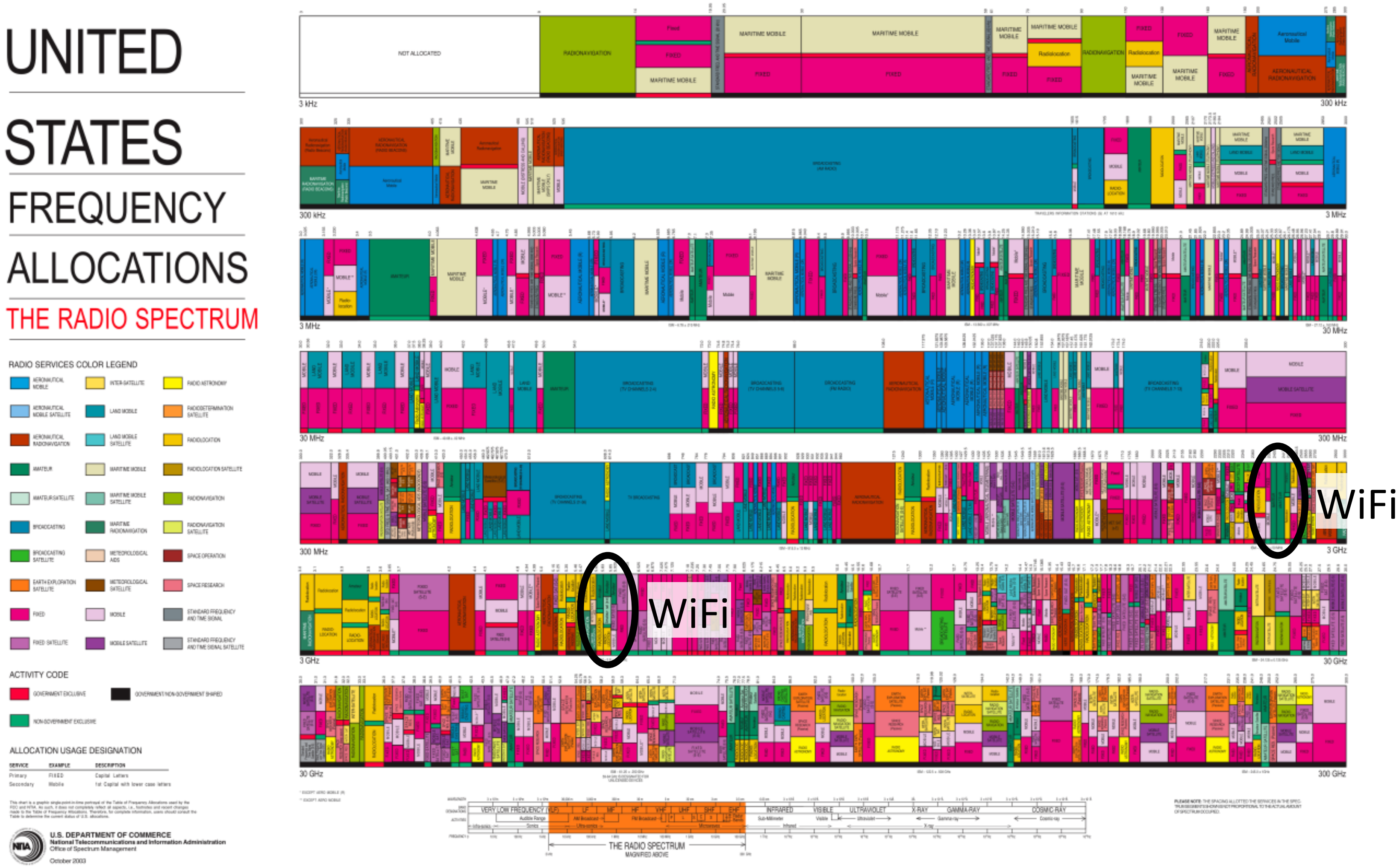




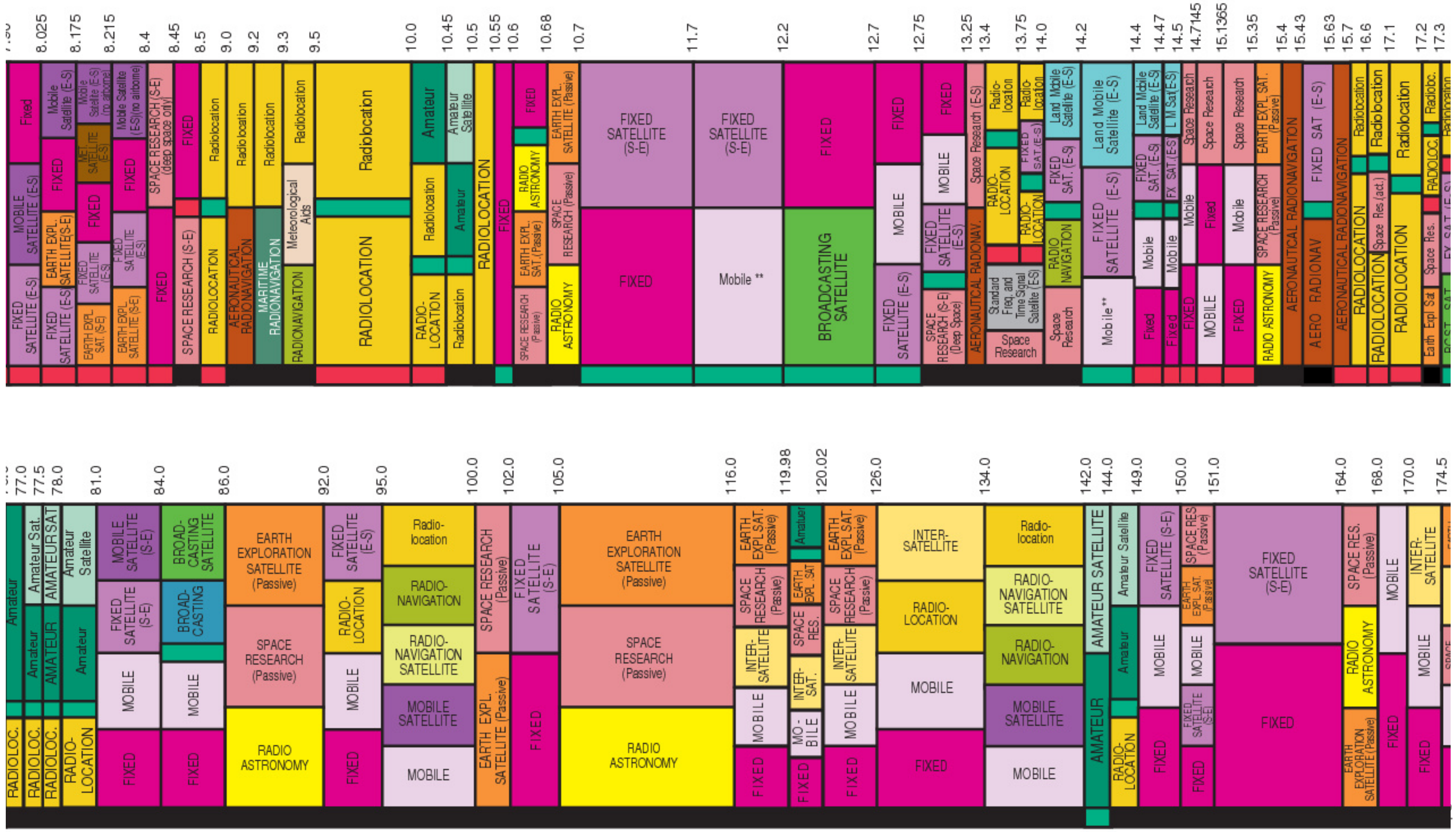
Wireless

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





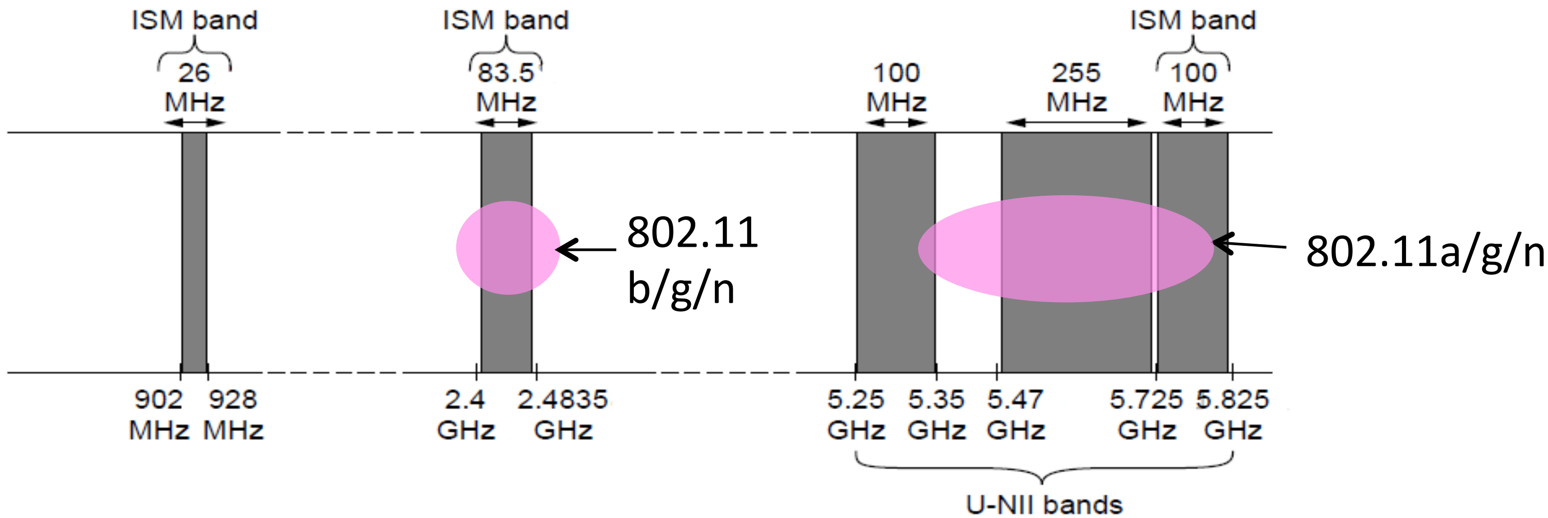
UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
WiFi
WiFi
THE RADIO SPECTRUM



8.025
8.175
8.215
8.4
8.45
8.5
9.0
9.2
9.3
9.5
10.0
10.45
10.5
10.55
10.6
10.68
10.7
11.7
12.2
12.7
12.75
13.25
13.4
13.75
14.0
14.2
14.4
14.47
14.5
14.7145
15.1365
15.35
15.4
15.43
15.63
15.7
16.6
17.1
17.2
17.3
FIXED SATELLITE (S-E)
FIXED
Mobile **
BROADCASTING SATELLITE
RADIOLOCATION
Radiolocation
Amateur
Amateur Satellite
AERONAUTICAL RADIONAVIGATION
MARITIME RADIONAVIGATION
Meteorological Aids
RADIONAVIGATION
SPACE RESEARCH (S-E) (deep space only)
SPACE RESEARCH (S-E)
Land Mobile Satellite (E-S)
Mobile
MOBILE
RADIO ASTRONOMY
77.0
77.5
78.0
81.0
84.0
86.0
92.0
95.0
100.0
102.0
105.0
116.0
119.98
120.02
126.0
134.0
142.0
144.0
149.0
150.0
151.0
164.0
168.0
170.0
174.5
EARTH EXPLORATION SATELLITE (Passive)
SPACE RESEARCH (Passive)
RADIO ASTRONOMY
INTER-SATELLITE
MOBILE SATELLITE
RADIO-NAVIGATION
RADIO-NAVIGATION SATELLITE
AMATEUR SATELLITE
AMATEUR
BROAD-CASTING SATELLITE
BROAD-CASTING

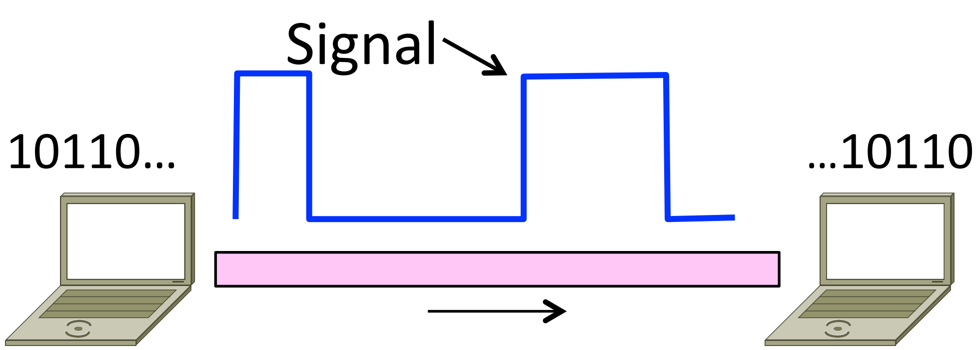
Wireless (2)

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



Signals (§2.2, 2.3)

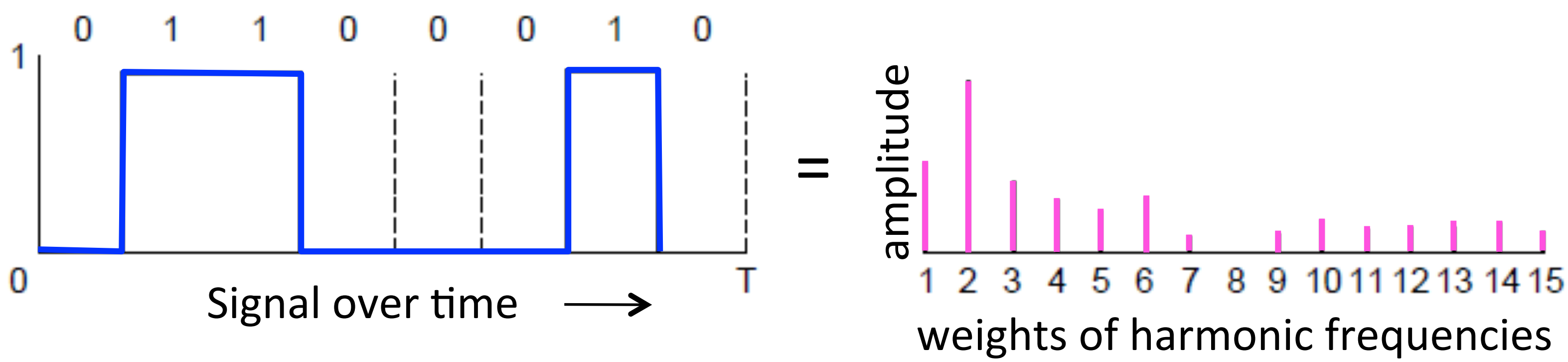
- Analog signals encode digital bits. We want to know what happens as signals propagate over media



Frequency Representation

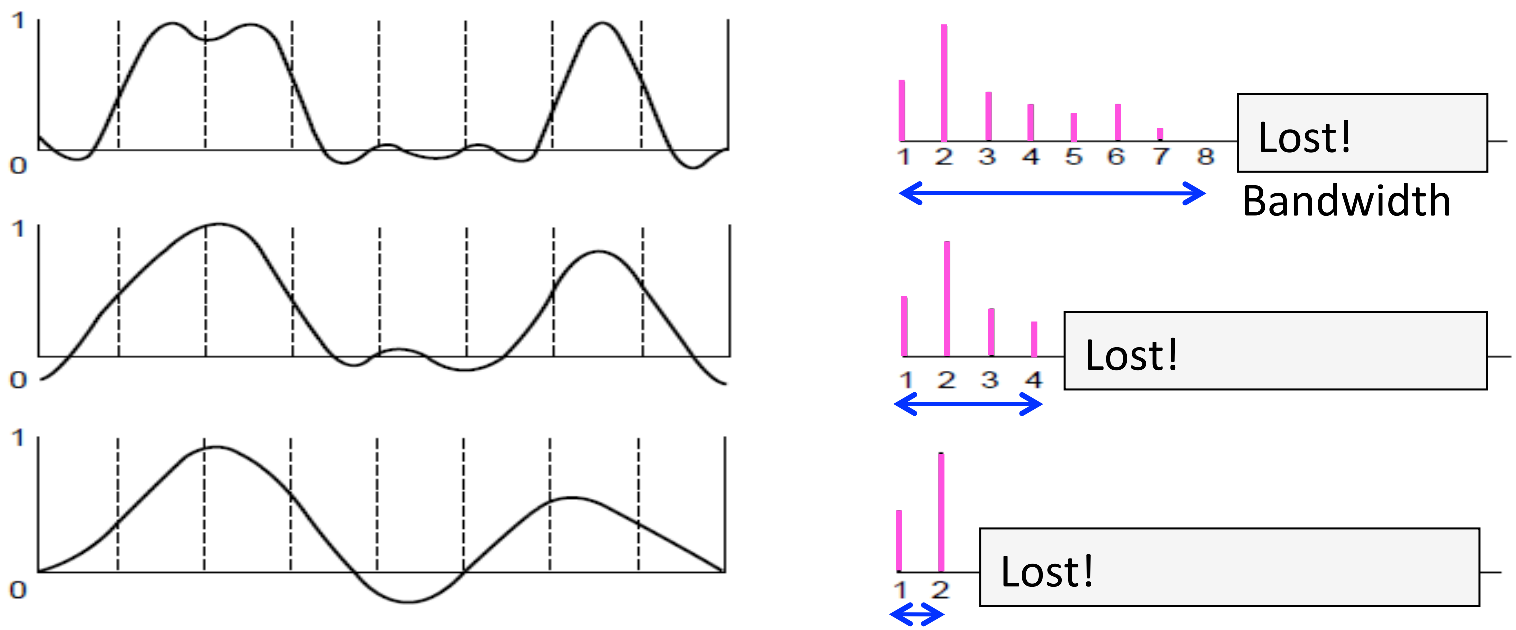
- A signal over time can be represented by its frequency components (called Fourier analysis)

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



Effect of Less Bandwidth

- Fewer frequencies (=less bandwidth) degrades signal



Signals over a Wire

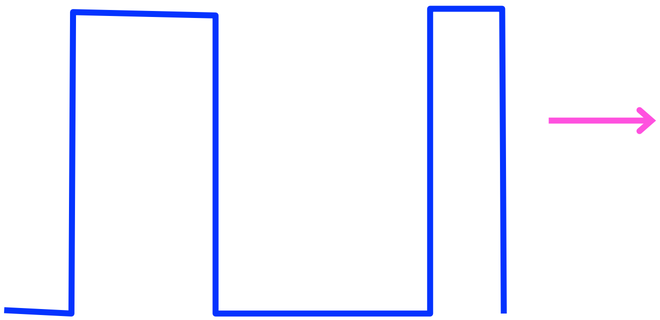
- What happens to a signal as it passes over a wire?
  1. The signal is delayed (propagates at ⅔c)
  2. The signal is attenuated (goes for m to km)
  3. Frequencies above a cutoff are highly attenuated
  4. Noise is added to the signal (later, causes errors)

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



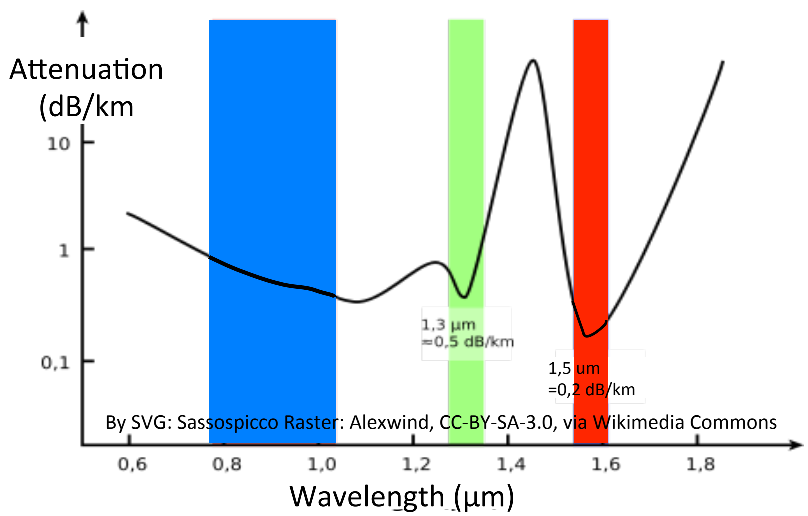
2: Attenuation:

3: Bandwidth:

4: Noise:

Signals over Fiber

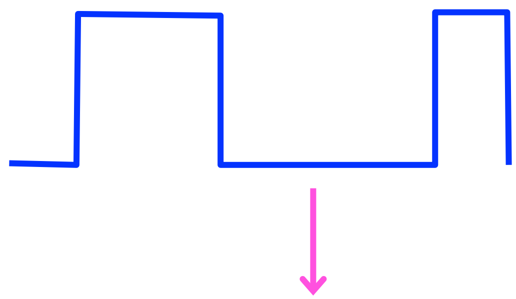
- Light propagates with very low loss in three very wide frequency bands
  - Use a carrier to send information



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

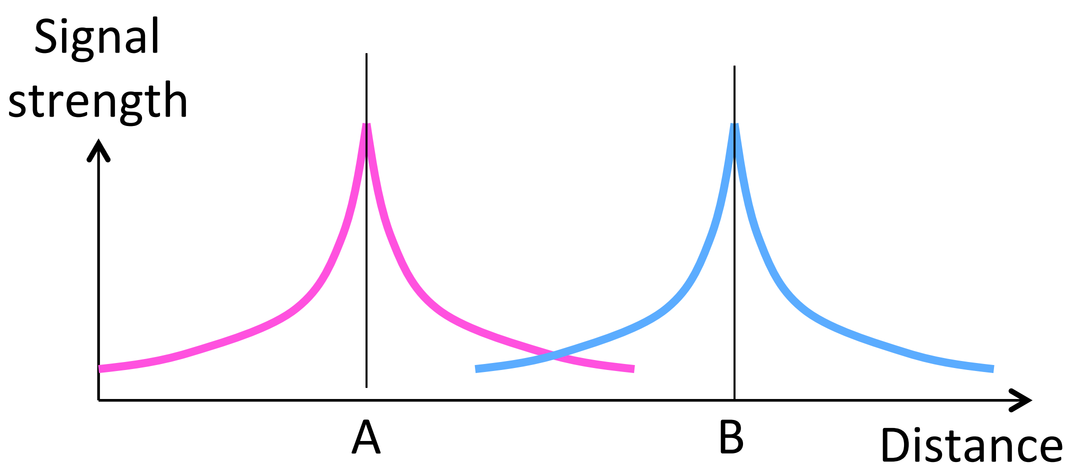
Signals over Wireless

- Signals transmitted on a carrier frequency, like fiber (more later)



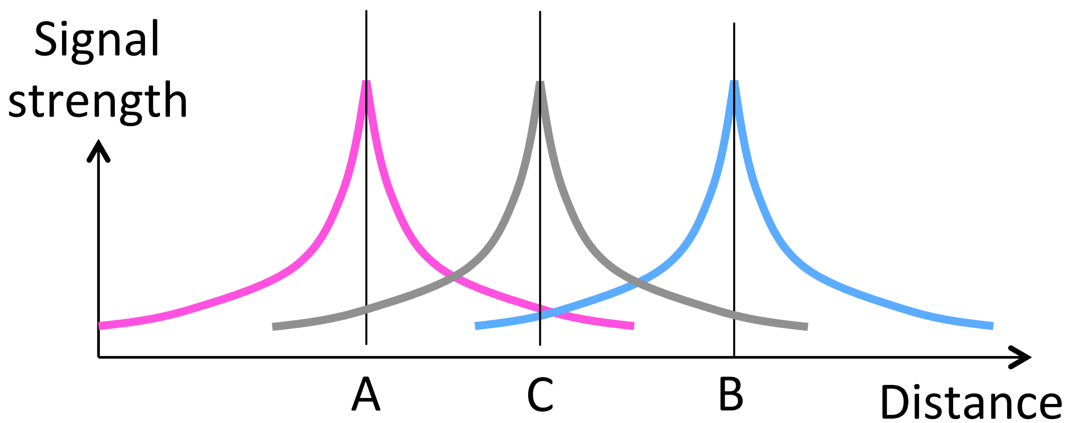
Signals over Wireless (2)

- Travel at speed of light, spread out and attenuate faster than $1/dist^2$



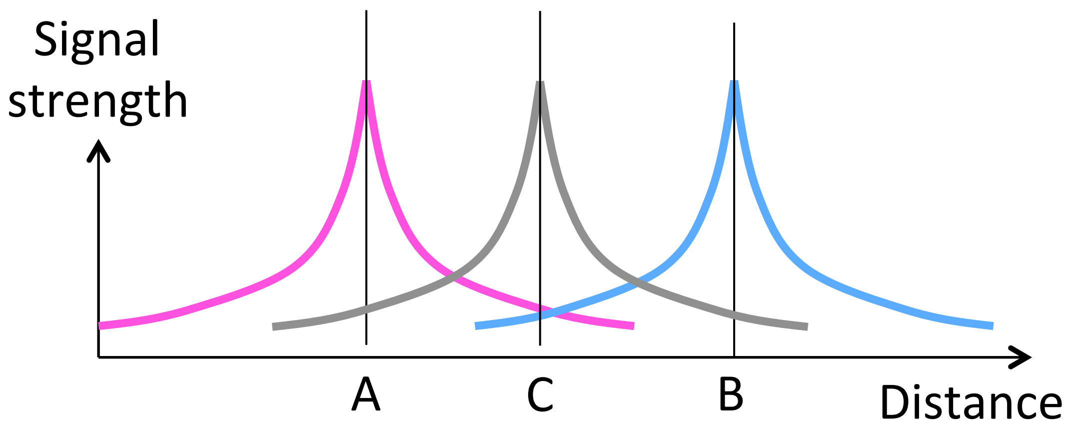
Signals over Wireless (3)

- Multiple signals on the same frequency interfere at a receiver



Signals over Wireless (4)

- Interference leads to notion of spatial reuse (of same freq.)

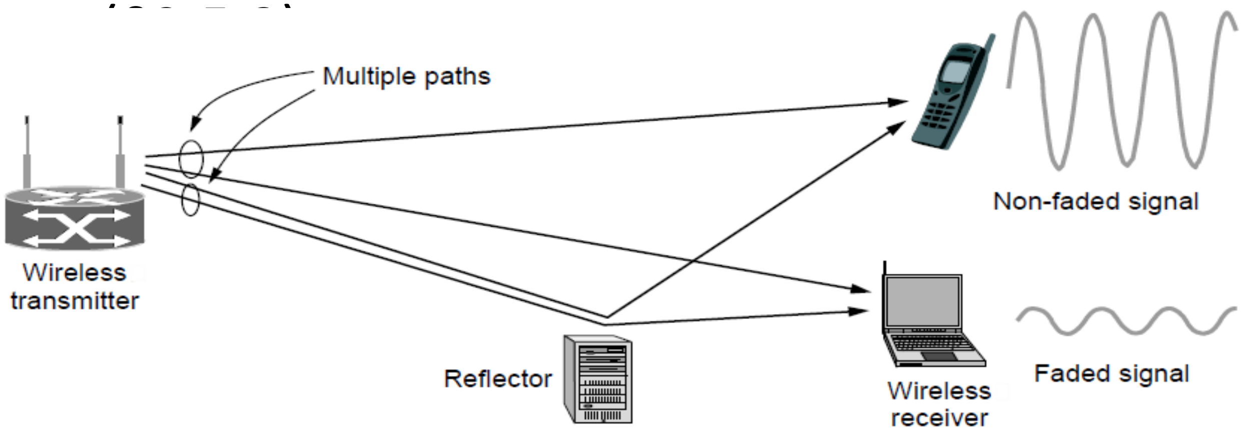


Signals over Wireless (5)

- Various other effects too!
  - Wireless propagation is complex, depends on environment
- Some key effects are highly frequency dependent
  - E.g., multipath at microwave frequencies

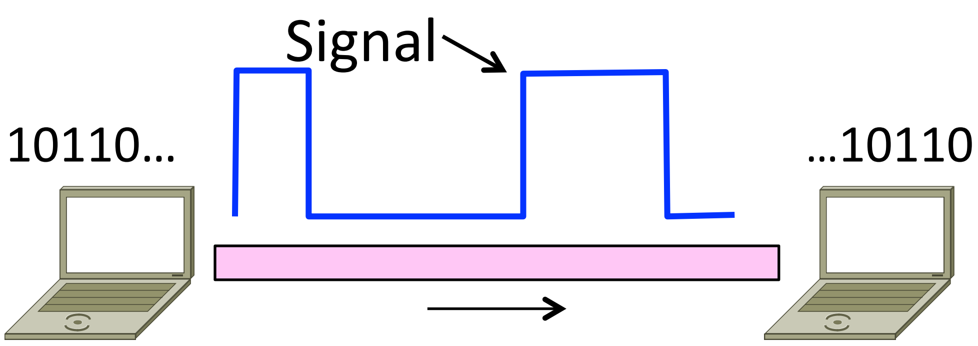
Wireless Multipath

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



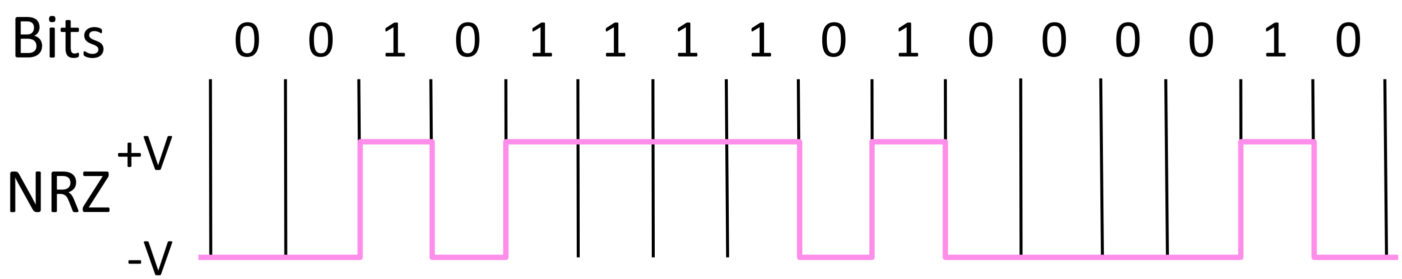
Modulation (§2.5)

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



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)



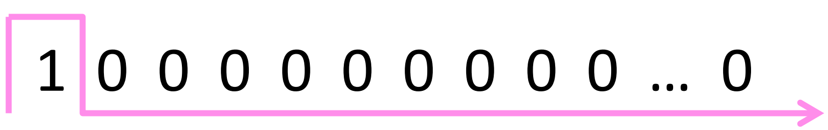
Many Other Schemes

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

- 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



- 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 without long runs of zeros
  - 0000 → 11110, 0001 → 01001,
    1110 → 11100, … 1111 → 11101
  - Has at most 3 zeros in a row
  - Also invert signal level on a 1 to break up long runs of 1s (called NRZI, §2.5.1)

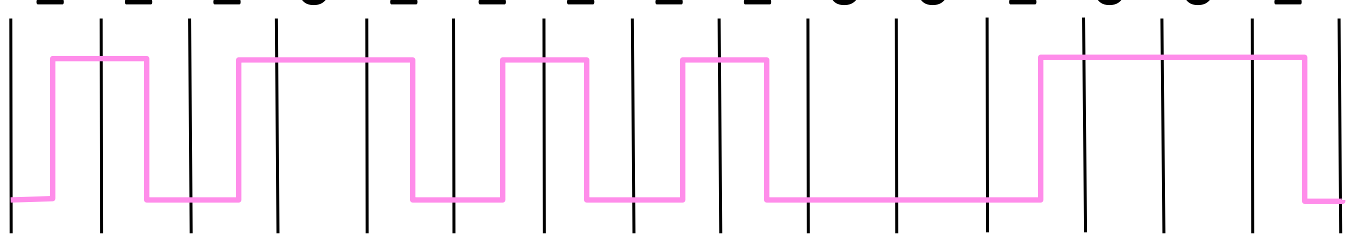
Clock Recovery – 4B/5B (2)

- 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: 1 1 1 0 1 1 1 1 1 0 0 1 0 0 1

Signal:

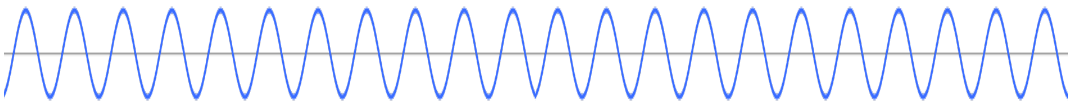


Passband Modulation

- What we have seen so far is baseband 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
- Passband modulation carries a signal by modulating a carrier

Passband Modulation (2)

- Carrier is simply a signal oscillating at a desired frequency:



- We can modulate it by changing:
  - Amplitude, frequency, or phase

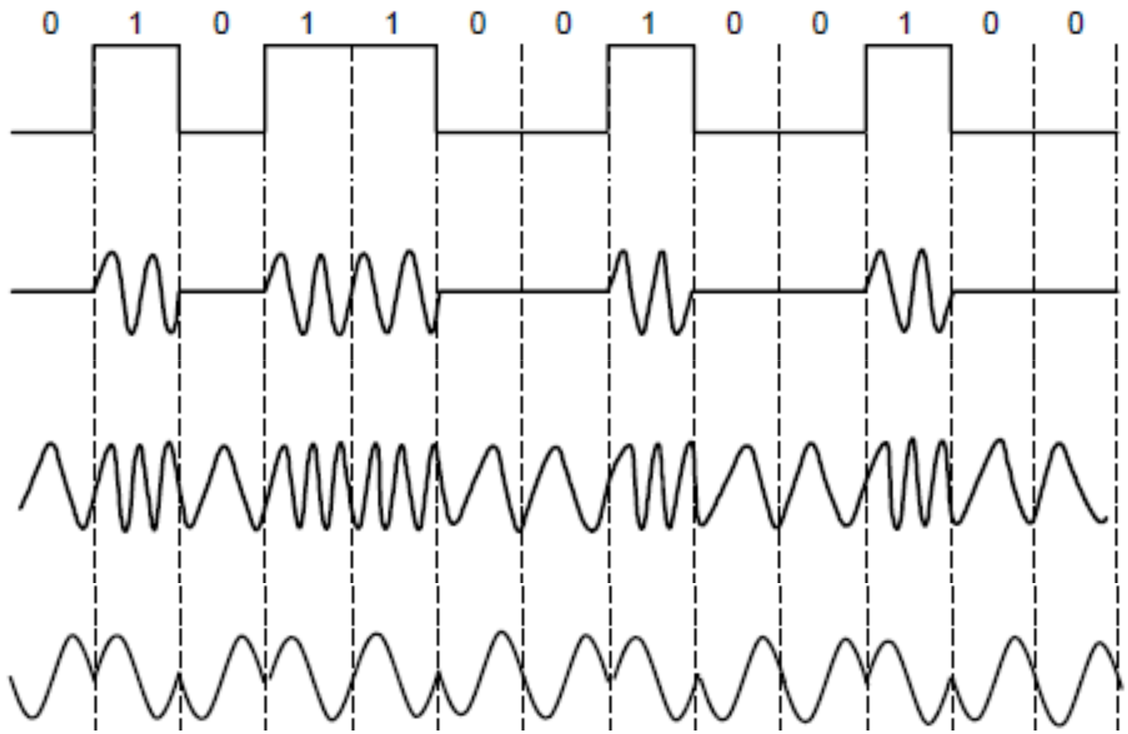
Passband Modulation (3)

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying



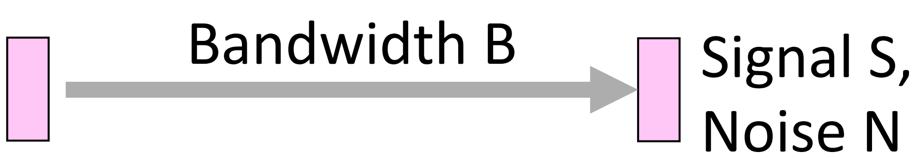
Fundamental Limits (§2.1)

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

- Practical systems are devised to approach these limits

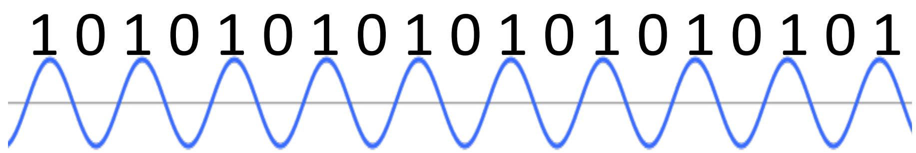
Key Channel Properties

- 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



Nyquist Limit

- The maximum <u>symbol</u> rate is 2B



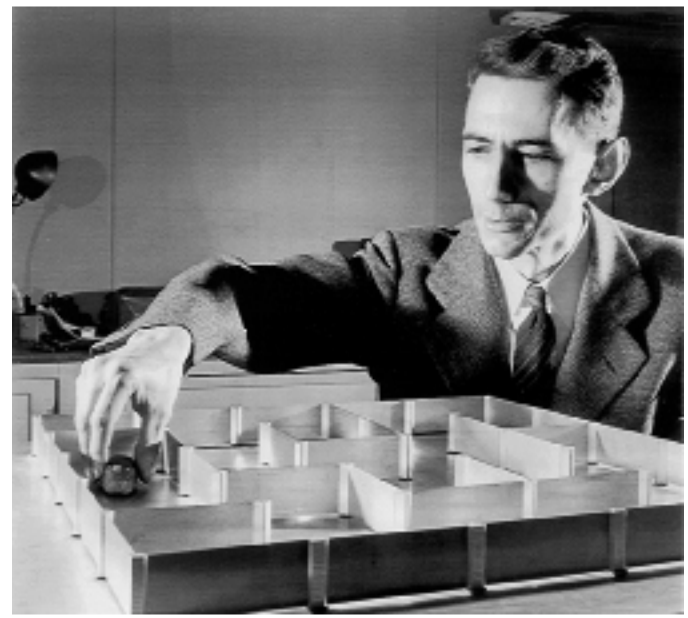
- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

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

Claude Shannon (1916-2001)

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

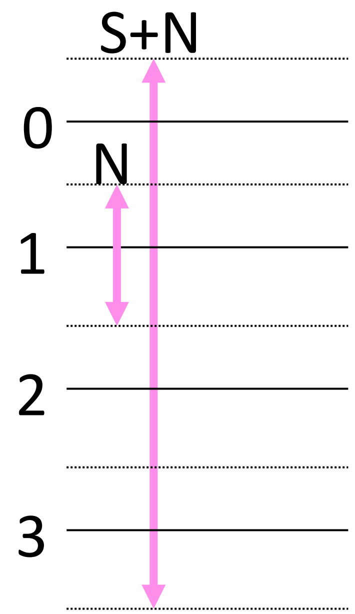
Electromechanical mouse that "solves" mazes!



Credit: Courtesy MIT Museum

Shannon Capacity

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



Shannon Capacity (2)

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

$$C = B \log_2(1 + S/N) \text{ bits/sec}$$

Wired/Wireless Perspective

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

Engineer SNR for 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

Adapt data rate to SNR

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 (called OFDM §2.5.1)
  - Separate bands for upstream and downstream (larger)
  - Modulation varies both amplitude and phase (called QAM)
  - High SNR, up to 15 bits/symbol, low SNR only 1 bit/symbol