

# Operating Systems and Networks

## Networks Part 2: Physical Layer

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# Extra Credit Points

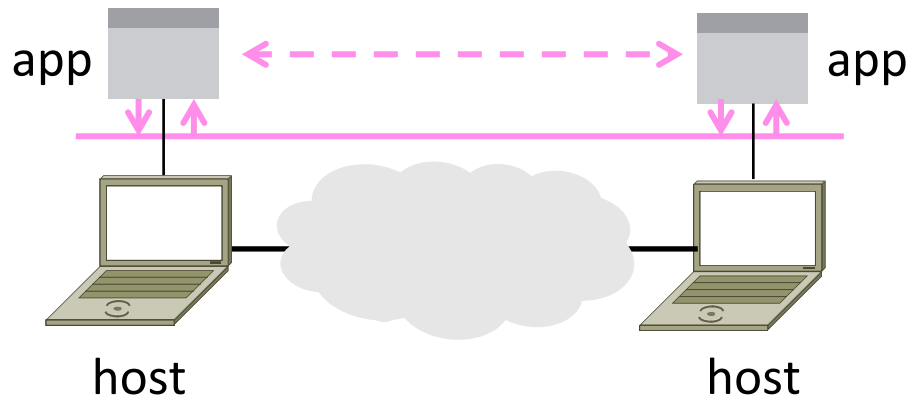
- Since we did not announce the Extra Credit Points in the course description, we are not allowed to have them increase your grade
- But we still want to provide incentives to study and to solve the projects
- So we will raffle off prizes at the end of the semester, and the more credit points you collect, the higher the chance of winning
  - Essentially, each credit point is like a lottery ticket that participates in each drawing
- Detailed description is on the course web site ...

# Overview

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

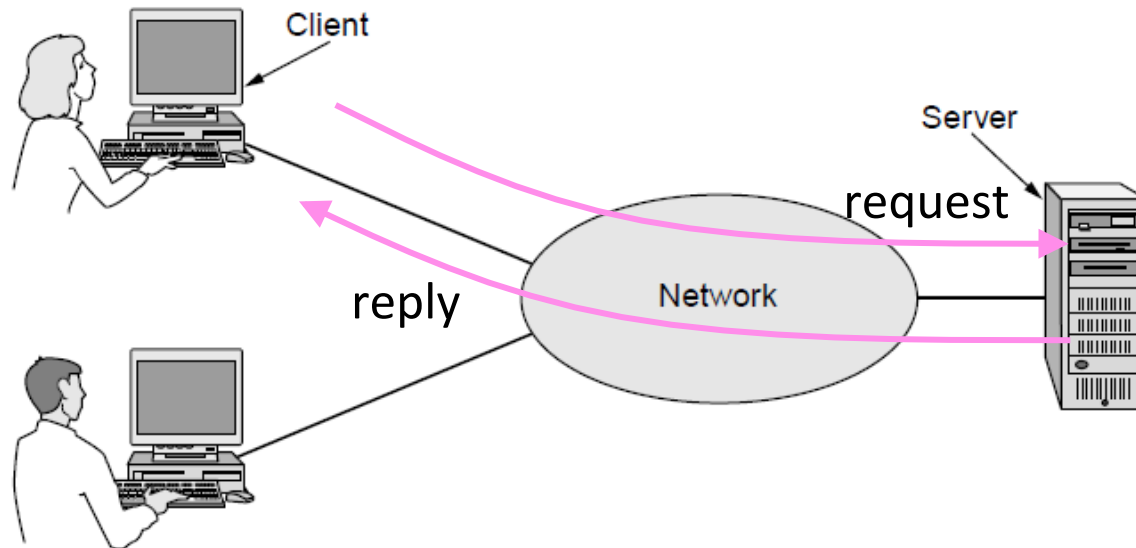
# Network-Application Interface

- 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)

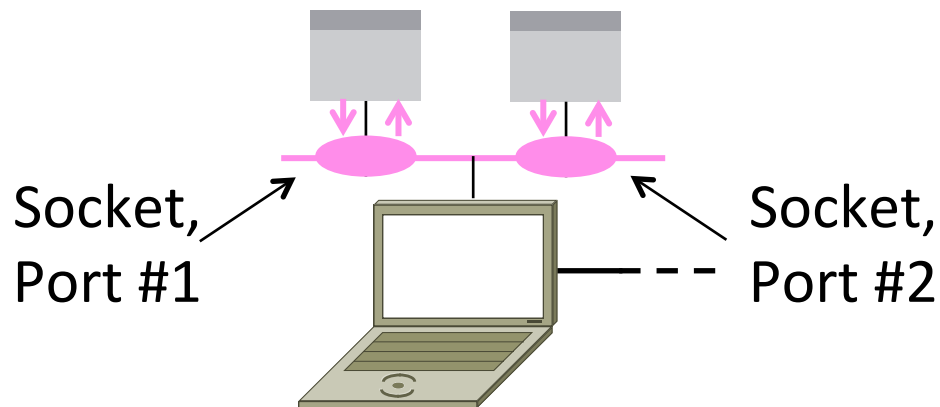
- Simple client-server connection setup
  - Client app sends a request to server app
  - Server app returns a (longer) reply
- This is the basis for many apps!
  - File transfer: send name, get file (§6.1.4)
  - Web browsing: send URL, get page
  - Echo: send message, get it back
- Let's see how to write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

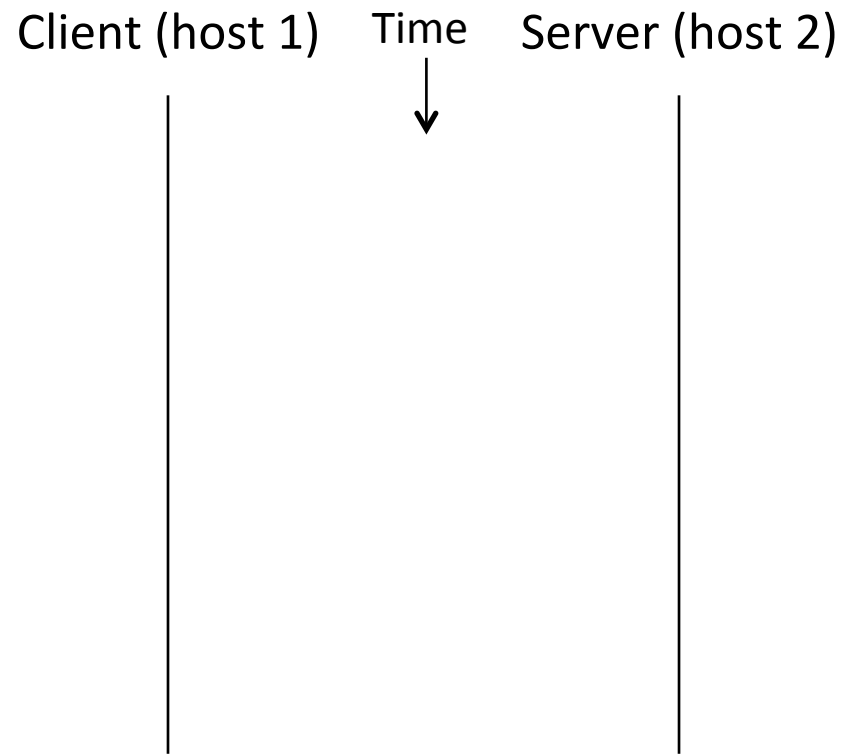




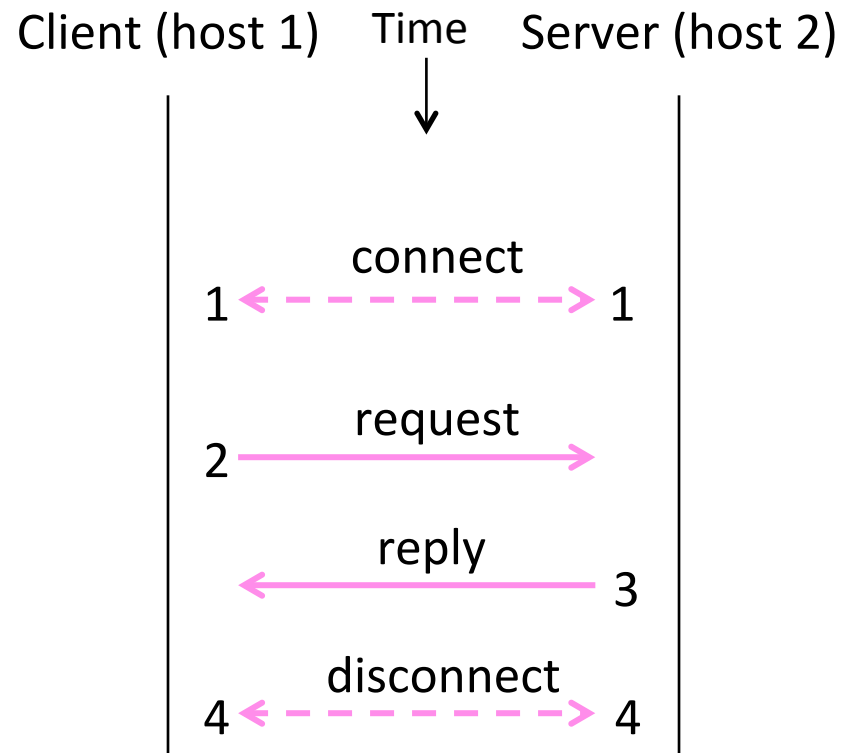
# Socket API (3)

<b>Primitive</b>	<b>Meaning</b>
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 wait for 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

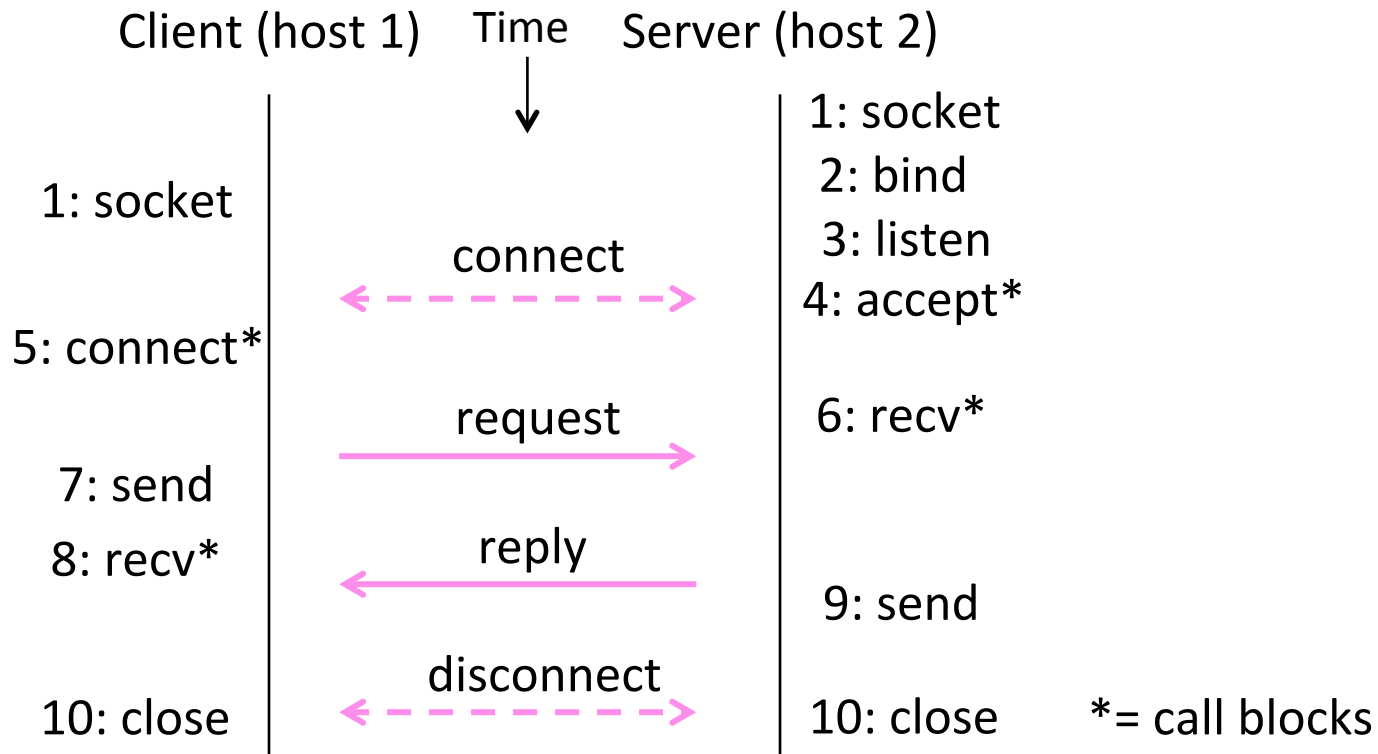
# Using Sockets



# 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
```

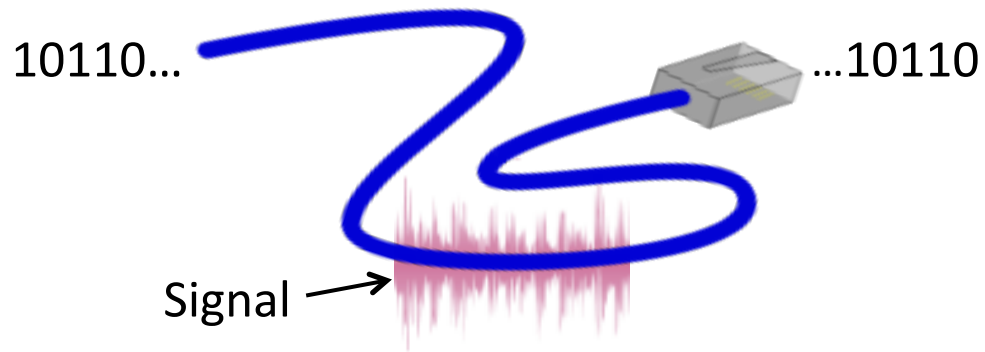
# Where we are in the Course

- 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



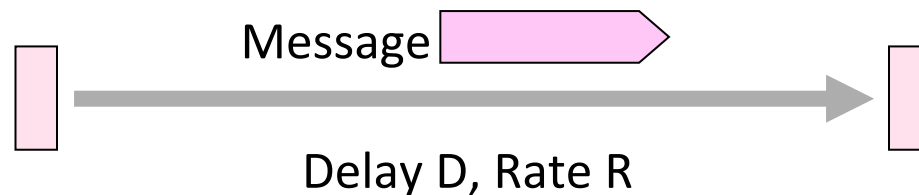


# Topics

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”  
$$T\text{-delay} = M \text{ (bits)} / \text{Rate (bits/sec)} = M/R \text{ seconds}$$
  - Propagation delay: time for bits to propagate across the wire  
$$P\text{-delay} = \text{Length} / \text{speed of signals} = \text{Length} / \frac{2}{3}c = D \text{ seconds}$$
  - Combining the two terms we have:  $L = M/R + D$

# Metric Units

- The main prefixes we use:

<b>Prefix</b>	<b>Exp.</b>	<b>prefix</b>	<b>exp.</b>
K(ilo)	$10^3$	m(illi)	$10^{-3}$
M(ega)	$10^6$	$\mu$ (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

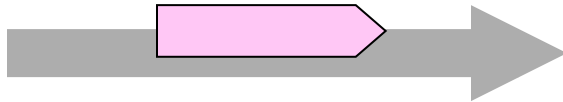
- “Dialup” with a telephone modem:
  - $D = 5 \text{ ms}$ ,  $R = 56 \text{ kbps}$ ,  $M = 1250 \text{ bytes}$
- Broadband cross-country link:
  - $D = 50 \text{ ms}$ ,  $R = 10 \text{ Mbps}$ ,  $M = 1250 \text{ bytes}$

## Latency Examples (2)

- “Dialup” with a telephone modem:  
D = 5 ms, R = 56 kbps, M = 1250 bytes  
L = 5 ms +  $(1250 \times 8) / (56 \times 10^3)$  sec = 184 ms!
- Broadband cross-country link:  
D = 50 ms, R = 10 Mbps, M = 1250 bytes  
L = 50 ms +  $(1250 \times 8) / (10 \times 10^6)$  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 bandwidth-delay (BD) product

$$BD = R \times D$$

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

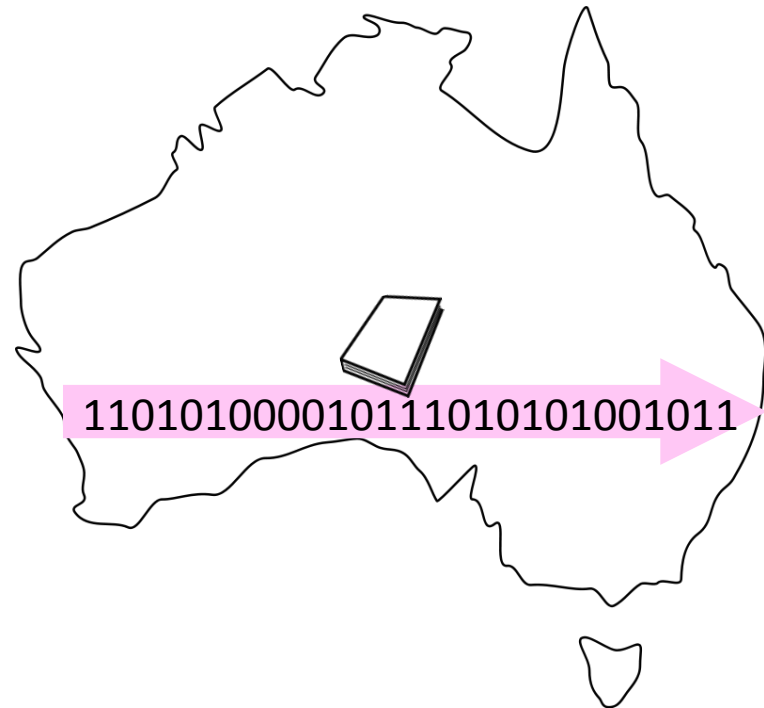
# Bandwidth-Delay Example

- Fiber at home, cross-country

$R=40$  Mbps,  $D=50$  ms

$$\begin{aligned}BD &= 40 \times 10^6 \times 50 \times 10^{-3} \text{ bits} \\ &= 2000 \text{ Kbit} \\ &= 250 \text{ KB}\end{aligned}$$

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





# How “Long” is a Bit?

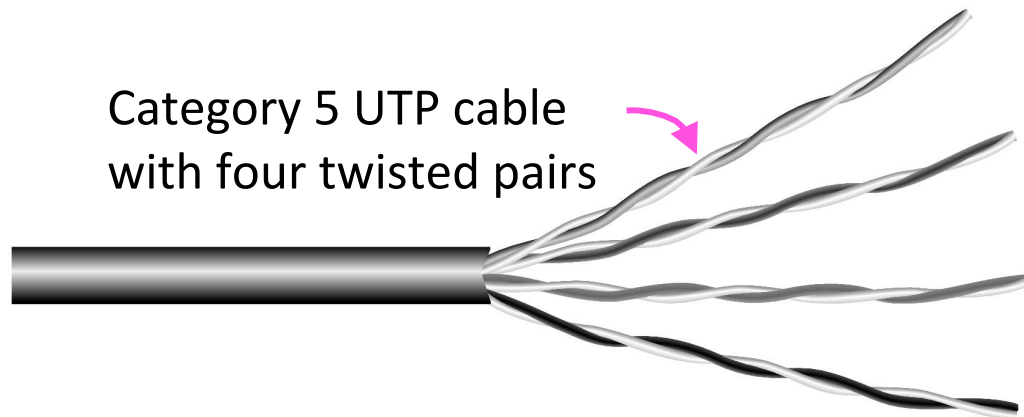
- Interesting trivia: how “long” is the representation of a bit on a wire?
- Considering a fiber optic cable
  - Signal propagation speed: 200'000'000 m/s
  - Sending rate: 1Gbps → duration of sending one bit: 1ns
  - Bit “length”:  $1\text{ns} * 200'000'000 \text{ m/s} = 0.2 \text{ m}$
  - “Length”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

# 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

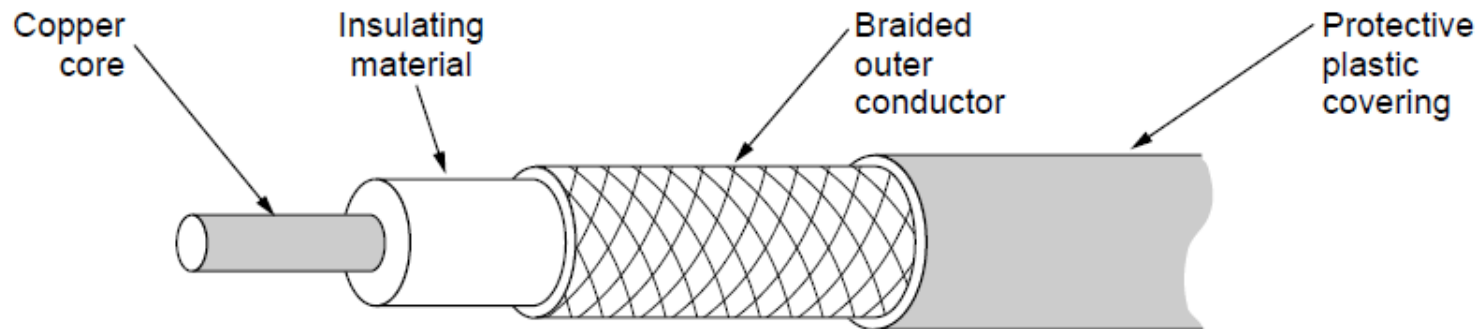
# Wires – Twisted Pair

- Very common; used in LANs and telephone lines
  - Twists can reduce radiated signal or reduce effect of external interference signal



# Wires – Coaxial Cable

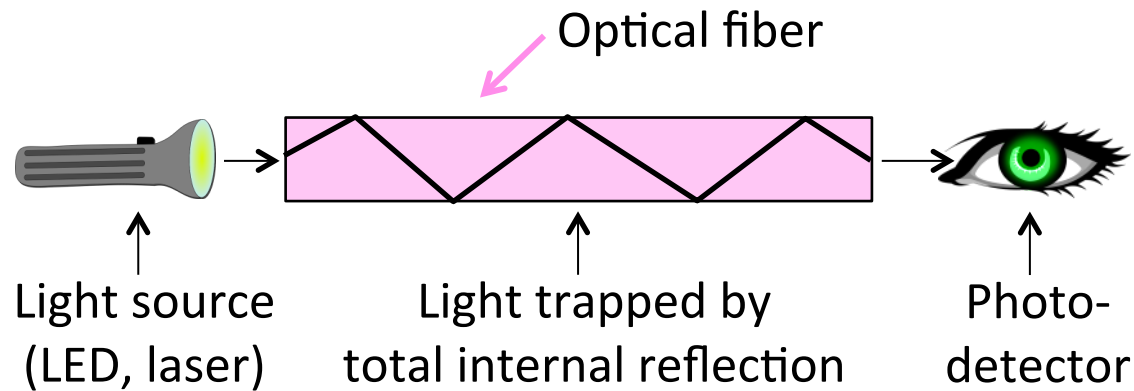
- Also common. Better shielding for better performance



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

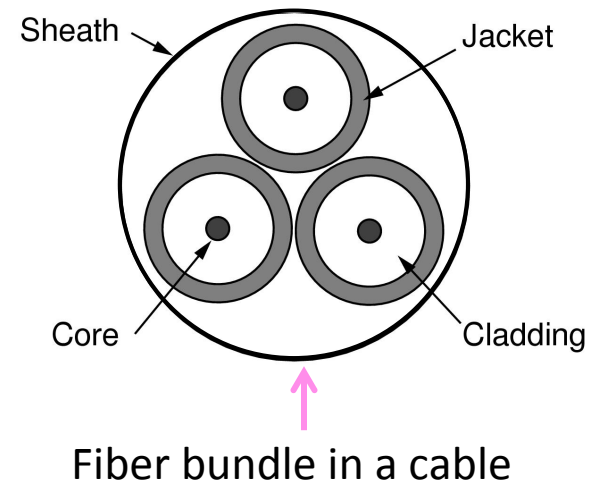
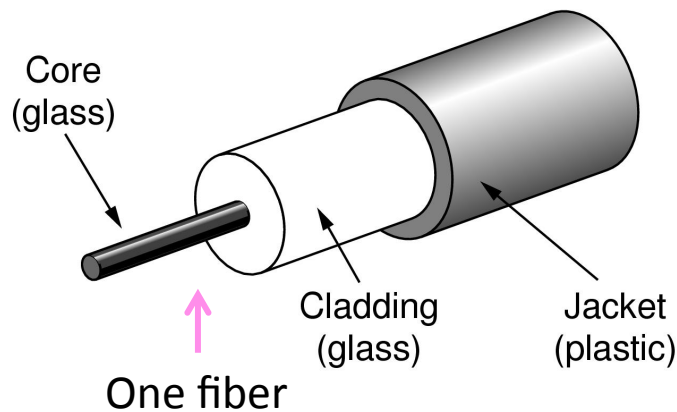
# Fiber

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



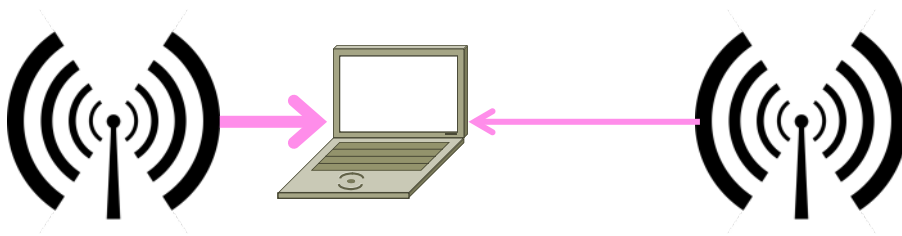
## Fiber (2)

- 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

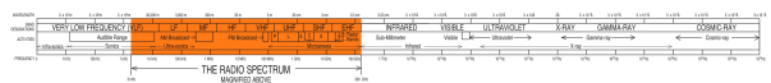
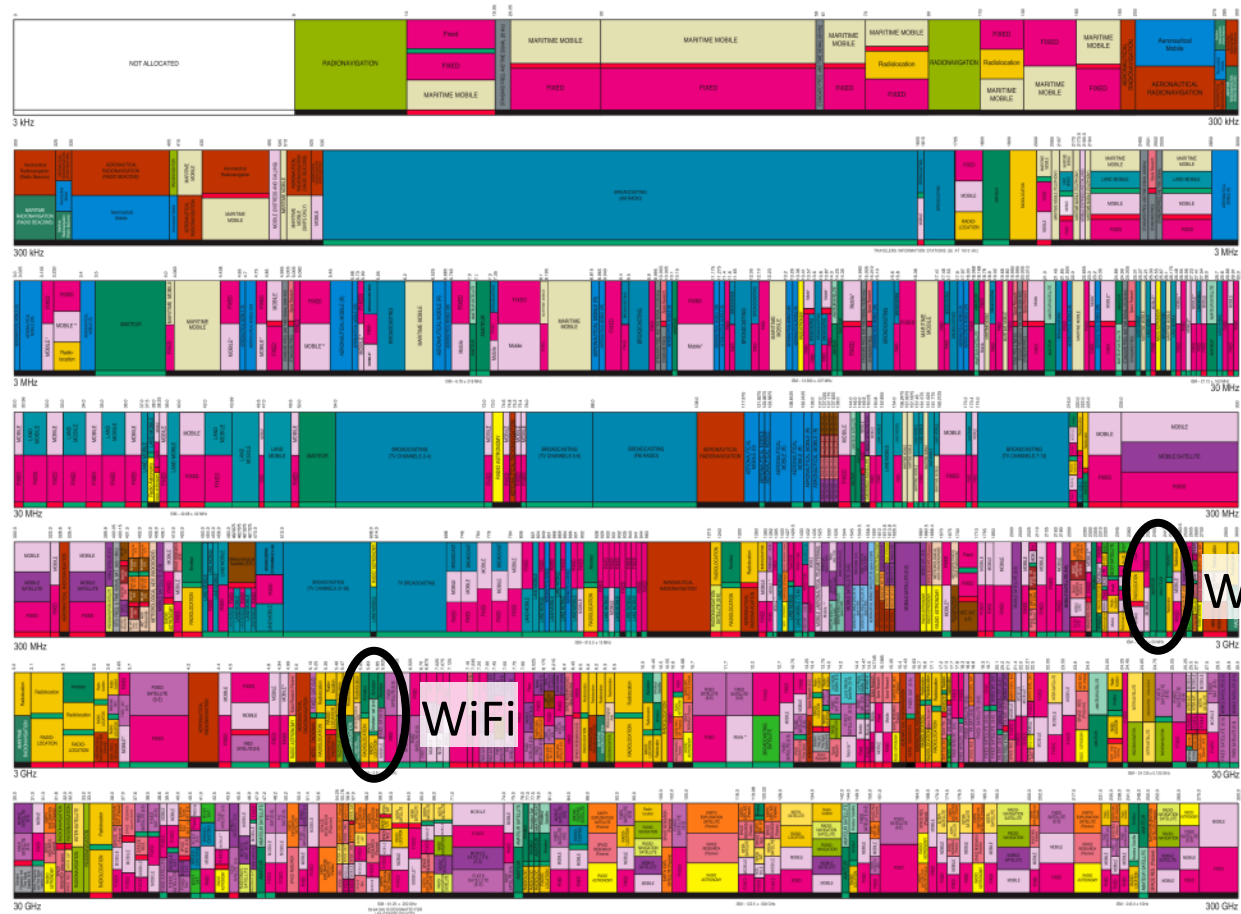
- RADIO SERVICES COLOR LEGEND**
- AERIALMOBILE MOBILE
  - AERIALMOBILE MOBILE SATELLITE
  - AERIALMOBILE RADIOAMATEUR
  - AIRTEL
  - AIRTEL MOBILE
  - AIRTEL MOBILE SATELLITE
  - AIRTEL MOBILE SATELLITE
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- ACTIVITY CODE**
- GOVERNMENT EXCLUSIVE
  - GOVERNMENT/NON-GOVERNMENT SHARED
  - NON-GOVERNMENT EXCLUSIVE
- ALLOCATION USAGE DESIGNATION**
- | SERVICE   | EXAMPLE | DESCRIPTION                          |
|-----------|---------|--------------------------------------|
| Primary   | F1E2D   | Capital Markets                      |
| Secondary | B1C3A   | 1st Capital with lower class letters |

The chart is partly adapted from chart of the State of Oregon. Citation used for the FCC and NIST. No part of this chart may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or by any information storage and retrieval system, without the prior written permission of the U.S. Department of Commerce. October 2003



U.S. DEPARTMENT OF COMMERCE  
National Telecommunications and Information Administration  
Office of Spectrum Management



WiFi

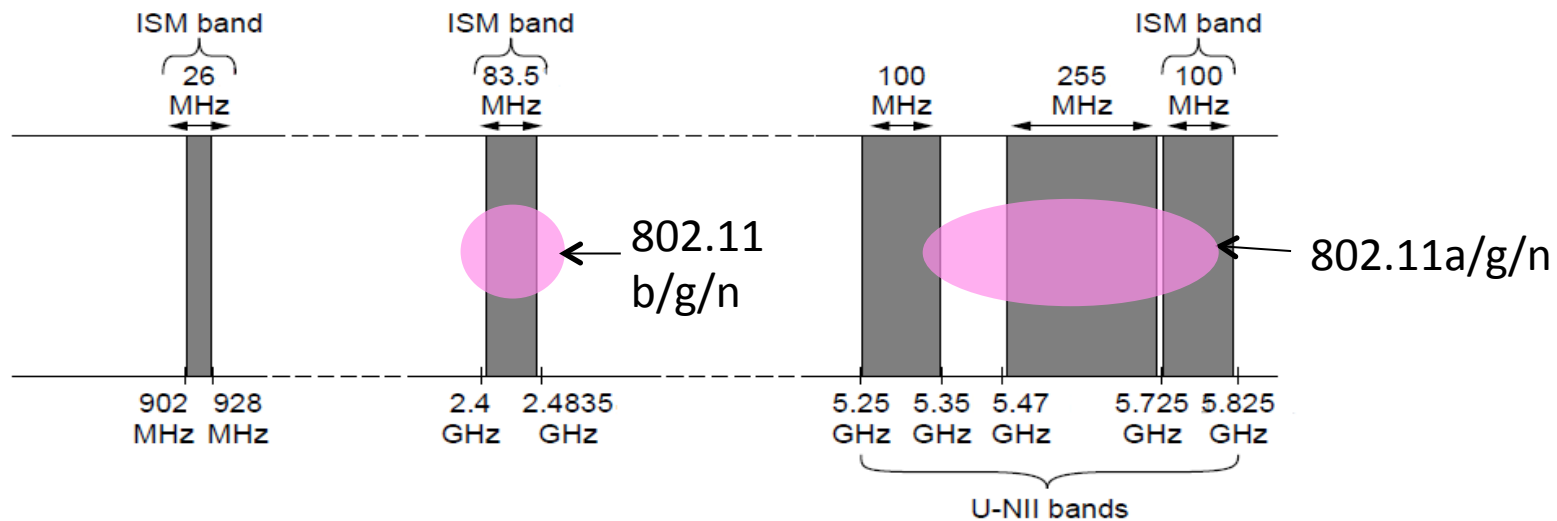


77.0	RADIOLOC.	Amateur	Amateur Sat.
77.5	RADIOLOC.	Amateur	AMATEURSAT
78.0	RADIO-LOCATION	Amateur	Amateur Satellite
81.0	FIXED	MOBILE	FIXED SATELLITE (S-E)
84.0	FIXED	MOBILE	BROAD-CASTING SATELLITE
86.0	RADIO ASTRONOMY	SPACE RESEARCH (Passive)	EARTH EXPLORATION SATELLITE (Passive)
92.0	FIXED	MOBILE	FIXED SATELLITE (E-S)
95.0	MOBILE	MOBILE SATELLITE	RADIO-NAVIGATION SATELLITE
100.0	EARTH EXPL SATELLITE (Passive)	SPACE RESEARCH (Passive)	FIXED SATELLITE (S-E)
102.0	FIXED	FIXED	SATELLITE (S-E)
105.0	RADIO ASTRONOMY	SPACE RESEARCH (Passive)	EARTH EXPLORATION SATELLITE (Passive)
116.0	FIXED	MOBILE	INTER-SATELLITE
119.98	FIXED	MOBILE	INTER-SATELLITE
120.02	FIXED	MOBILE	INTER-SATELLITE
126.0	FIXED	MOBILE	INTER-SATELLITE
134.0	MOBILE	MOBILE SATELLITE	RADIO-NAVIGATION SATELLITE
142.0	AMATEUR	AMATEUR SATELLITE	AMATEUR SATELLITE
144.0	RADIO-LOCATION	Amateur	Amateur Satellite
149.0	FIXED	MOBILE	FIXED SATELLITE (S-E)
150.0	FIXED	FIXED SATELLITE (S-E)	EARTH EXPL SAT (Passive)
151.0	FIXED	FIXED	FIXED SATELLITE (S-E)
164.0	EARTH EXPLORATION SATELLITE (Passive)	RADIO ASTRONOMY	SPACE RES. (Passive)
168.0	FIXED	MOBILE	MOBILE
170.0	FIXED	MOBILE	INTER-SATELLITE
174.5	FIXED	FIXED	FIXED SATELLITE (S-E)

8.025	FIXED SATELLITE (E-S)	MOBILE SATELLITE (E-S)	Fixed
8.175	FIXED SATELLITE (E-S)	FIXED	Mobile Satellite (E-S)
8.215	EARTH EXPL SATELLITE (S-E)	FIXED	Mobile Satellite (no orbital)
8.4	EARTH EXPL SATELLITE (S-E)	FIXED	Mobile Satellite (ES)(no orbital)
8.45	FIXED	SPACE RESEARCH (S-E) (deep space orb)	FIXED
8.5	SPACE RESEARCH (S-E)	FIXED	FIXED
9.0	RADIOLOCATION	Radio location	Radio location
9.2	AERONAUTICAL RADIO NAVIGATION	Radio location	Radio location
9.3	MARITIME RADIO NAVIGATION	Radio location	Radio location
9.5	RADIO NAVIGATION	Meteorological Aids	Radio location
10.0	RADIOLOCATION	Radio location	Radio location
10.45	RADIO-LOCATION	Radio location	Amateur Satellite
10.5	Radio location	Amateur	Amateur Satellite
10.55	RADIOLOCATION	FIXED	FIXED
10.6	SPACE RESEARCH (Passive)	RADIO ASTRONOMY	FIXED
10.68	RADIO ASTRONOMY	EARTH EXPL SATELLITE (Passive)	EARTH EXPL SATELLITE (Passive)
10.7	FIXED	FIXED	FIXED
11.7	Mobile **	FIXED SATELLITE (S-E)	FIXED SATELLITE (S-E)
12.2	BROADCASTING SATELLITE	FIXED	FIXED
12.7	FIXED SATELLITE (E-S)	MOBILE	FIXED
12.75	SPACE RESEARCH (S-E) (Deep Space)	FIXED SATELLITE (E-S)	FIXED
13.25	AERONAUTICAL RADIO NAV.	Space Research (E-S)	Radio location
13.4	Standard freq. and Time-Sig. Space Satellite (ES)	RADIO-LOCATION	Radio location
13.75	Space Research	RADIO-LOCATION	Radio location
14.0	Space Research	RADIO NAVIGATION	Land Mobile Satellite (E-S)
14.2	Mobile **	FIXED SATELLITE (E-S)	Land Mobile Satellite (E-S)
14.4	Fixed	Mobile	FIXED SATELLITE (E-S)
14.47	Fixed	Mobile	FIXED SATELLITE (E-S)
14.5	MOBILE	Mobile	Space Research
14.7145	MOBILE	Mobile	Space Research
15.1365	FIXED	Mobile	Space Research
15.35	RADIO ASTRONOMY	SPACE RESEARCH (Passive)	EARTH EXPL SAT (Passive)
15.4	AERONAUTICAL RADIO NAVIGATION	FIXED SATELLITE (E-S)	FIXED SATELLITE (E-S)
15.63	AERONAUTICAL RADIO NAVIGATION	RADIOLOCATION	Radio location
15.7	RADIOLOCATION	Space Res. (act.)	Radio location
16.6	RADIOLOCATION	Radio location	Radio location
17.1	RADIOLOCATION	Radio location	Radio location
17.2	Earth Expl Sat	Space Res.	RADIOLOC.
17.3	FIXED	FIXED	Radio location

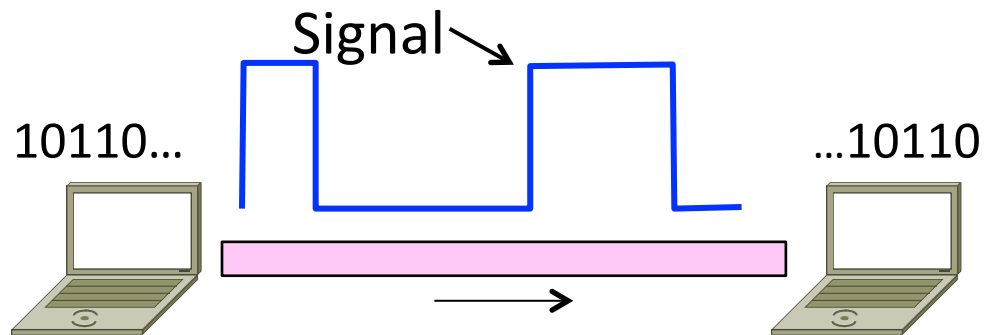
# Wireless (2)

- 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)

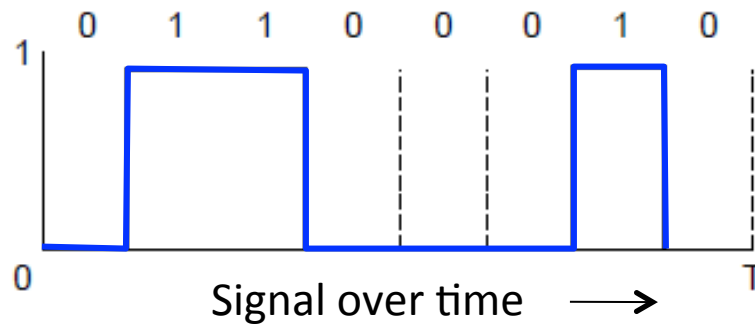
- Analog signals encode digital bits. We want to know what happens as signals propagate over media



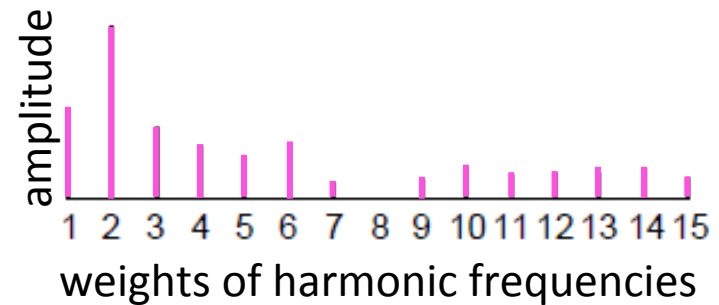
# Frequency Representation

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

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

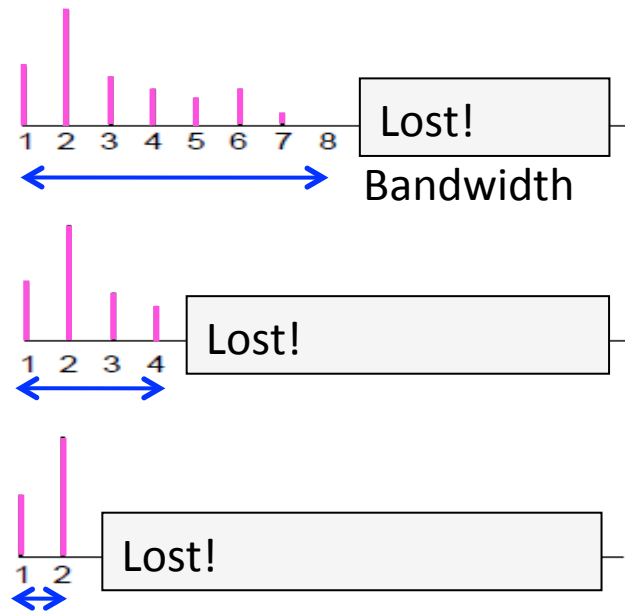
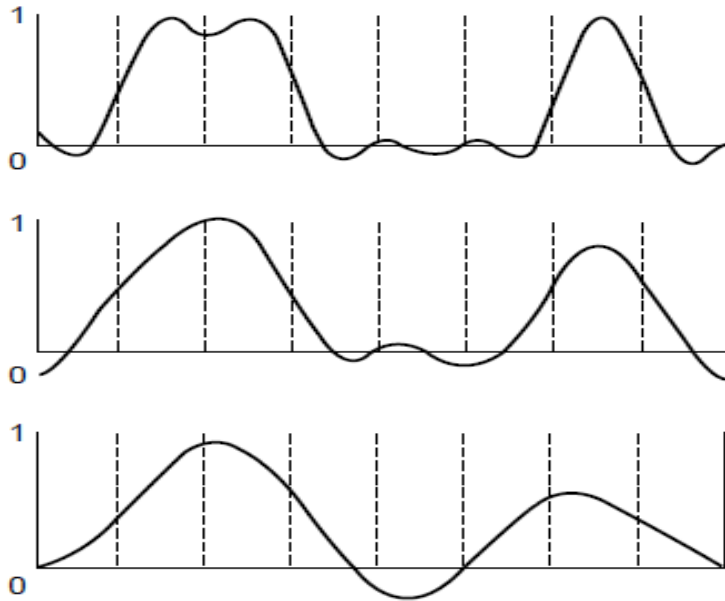


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# Effect of Less Bandwidth

- Fewer frequencies (=less bandwidth) degrades signal



# Signals over a Wire

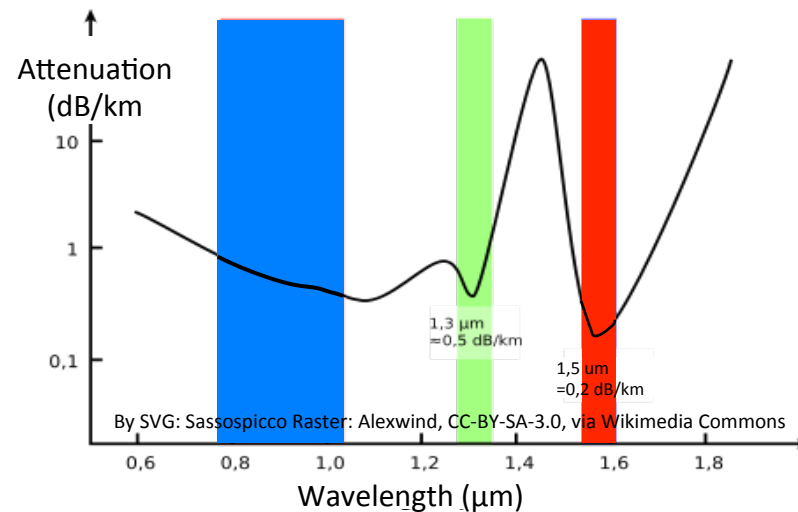
- What happens to a signal as it passes over a wire?
  1. The signal is delayed (propagates at  $\frac{2}{3}c$ )
  2. The signal is attenuated
  3. Frequencies above a cutoff are highly attenuated
  4. Noise is added to the signal (later, causes errors)

EE: Bandwidth = width of frequency band, measured in Hz

CS: Bandwidth = information carrying capacity, in bits/sec

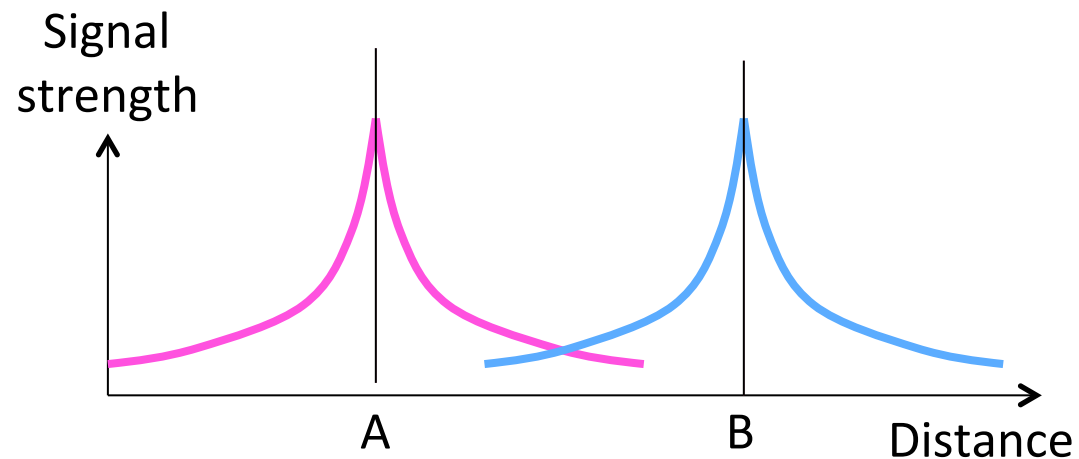
# Signals over Fiber

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



# Signals over Wireless

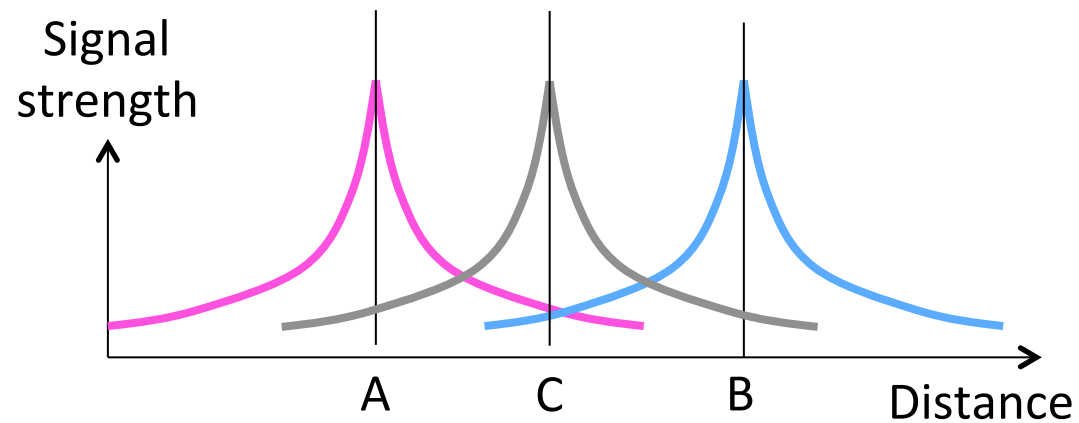
- Travel at speed of light, spread out and attenuate faster than  $1/\text{dist}^2$





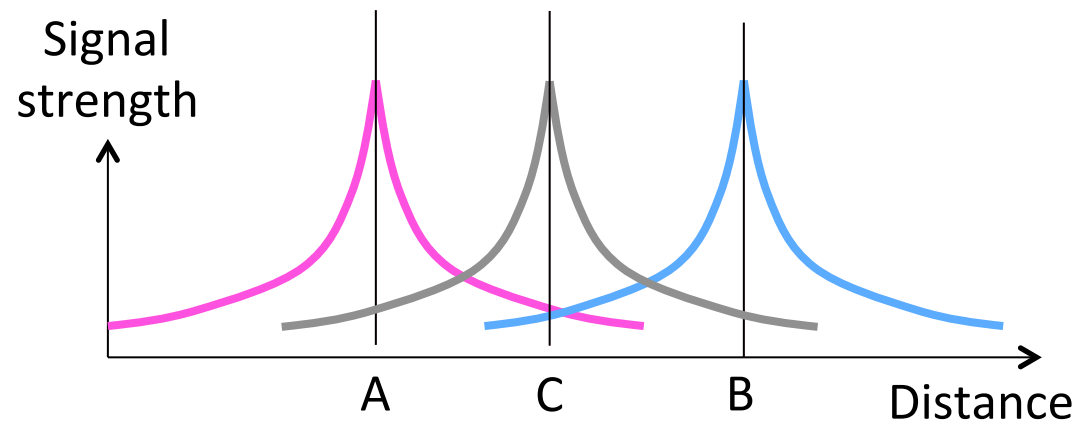
# Signals over Wireless (2)

- Multiple signals on the same frequency interfere at a receiver



# Signals over Wireless (3)

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

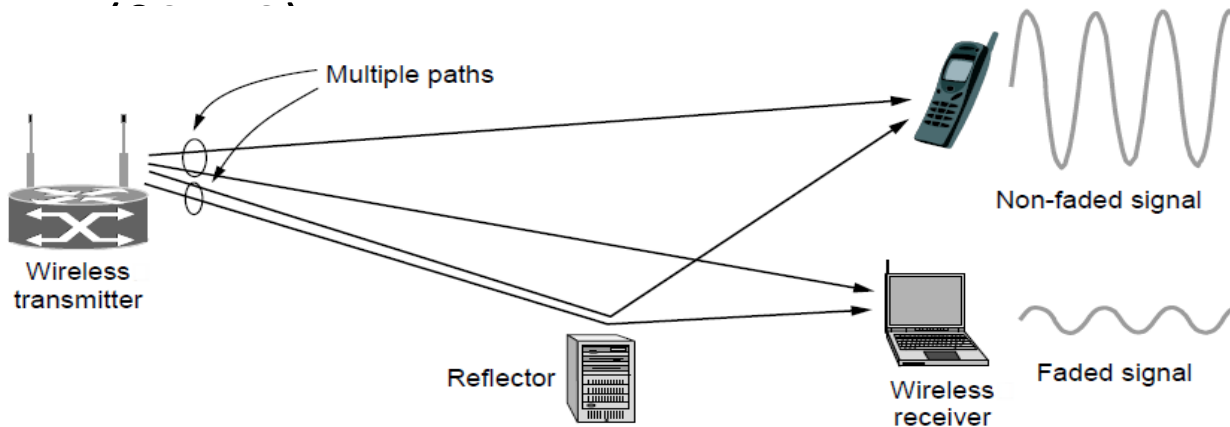


# Signals over Wireless (4)

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

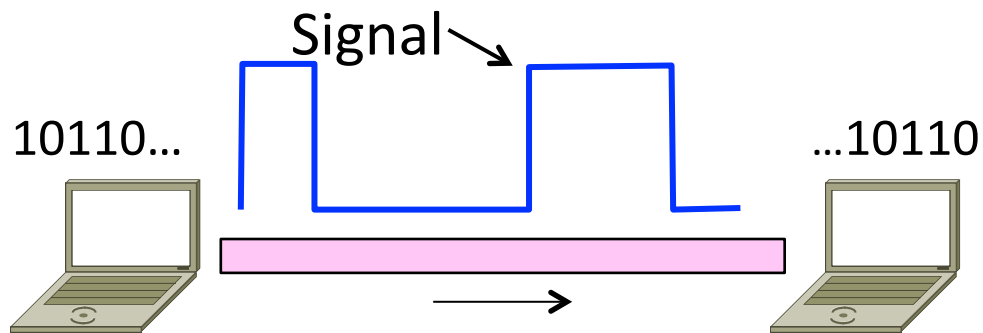
# Wireless Multipath

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



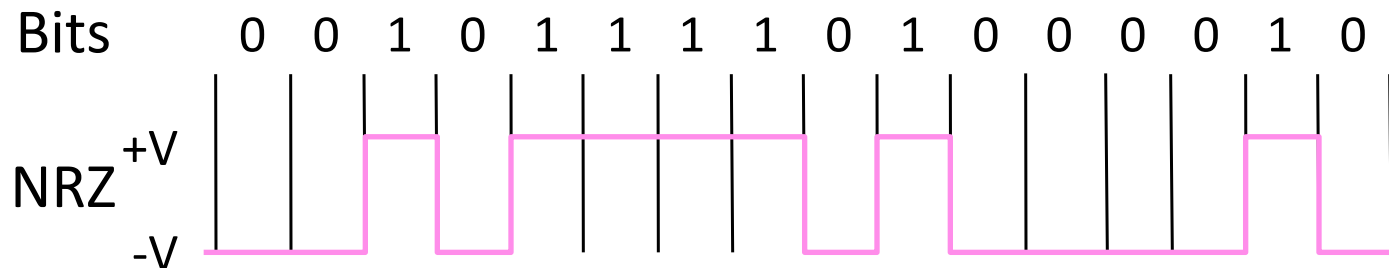
# Modulation (§2.5)

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



# 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

1 0 0 0 0 0 0 0 0 0 ... 0

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

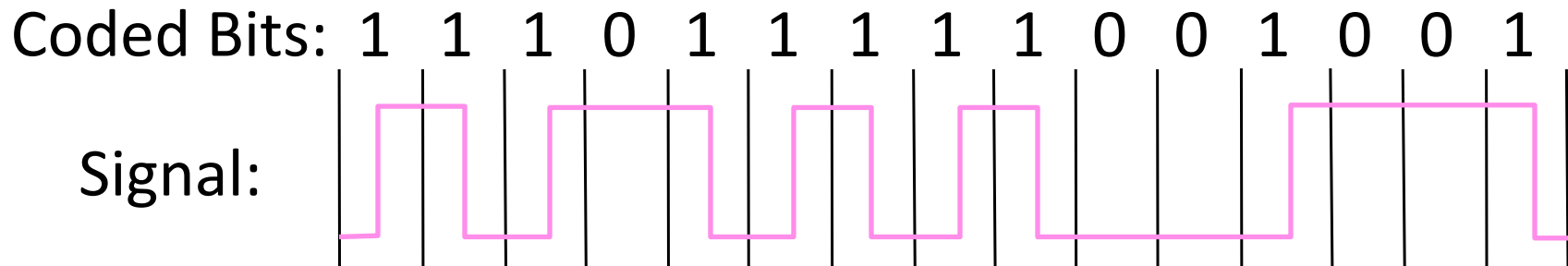


# Clock Recovery – 4B/5B

- Map every 4 data bits into 5 code bits 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

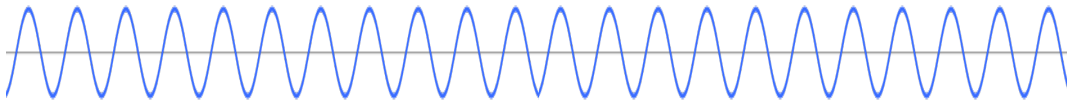


# Passband Modulation

- 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

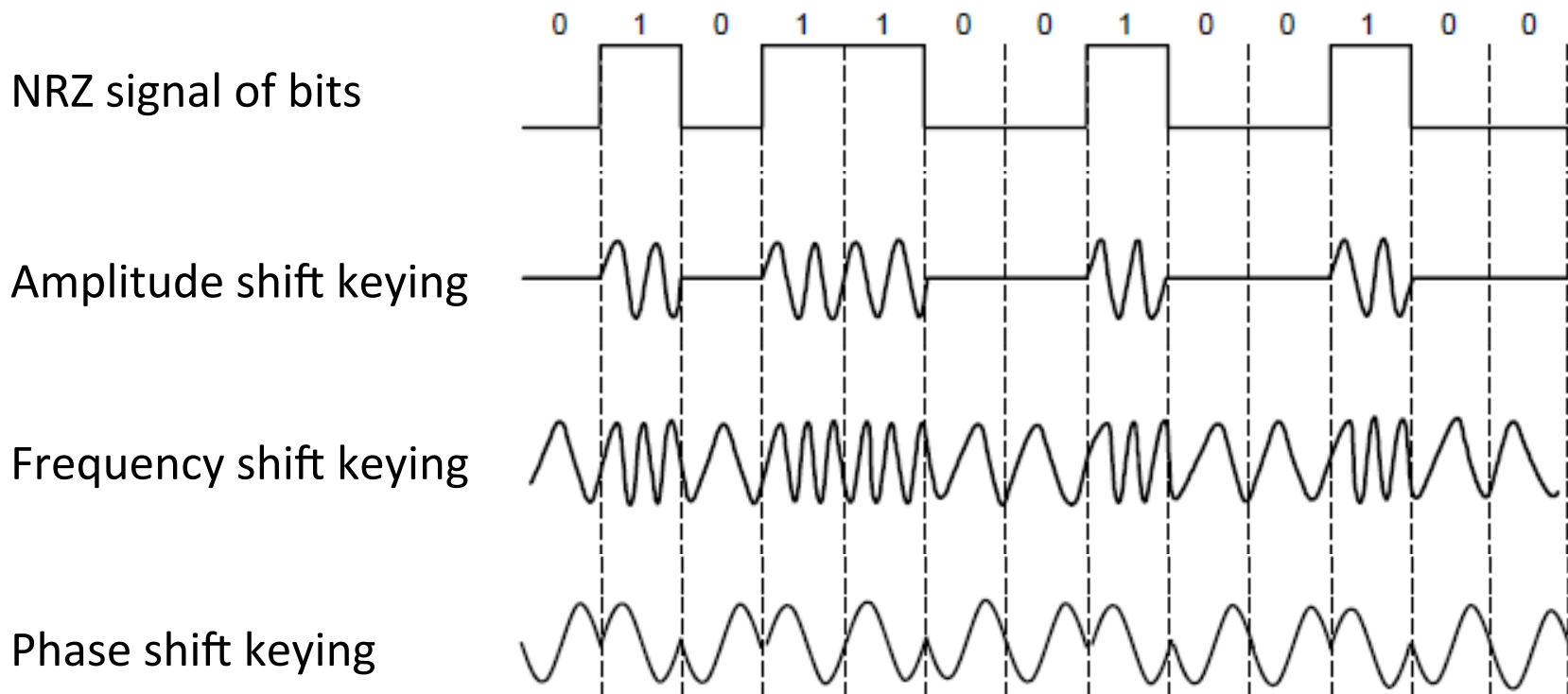
# Passband Modulation (2)

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



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

# Passband Modulation (3)



# 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

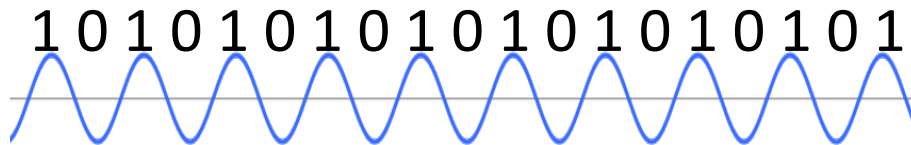
# Key Channel Properties

- 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 symbol 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

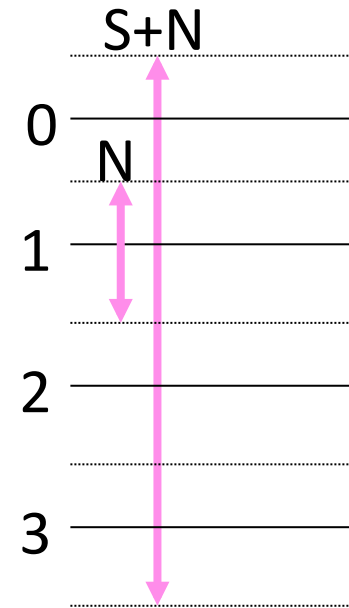
Electromechanical mouse  
that “solves” mazes! →



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:
  - $\text{SNR}_{\text{dB}} = 10\log_{10}(S/N)$



# Shannon Capacity (2)

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

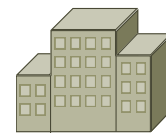
$$C = B \log_2(1 + S/N) \text{ bits/sec}$$

# Wired/Wireless Perspective

- Wires and Fiber Engineer 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

# 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

