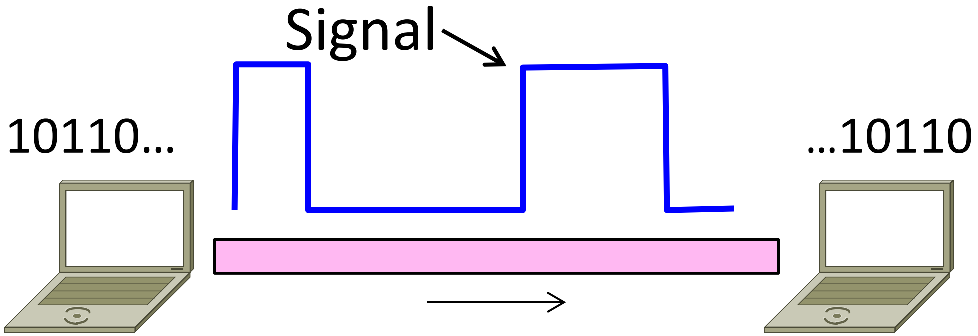
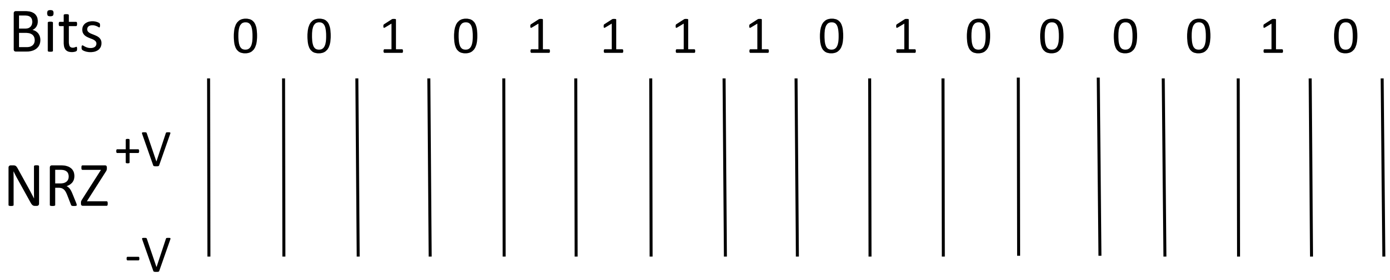
Topic

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



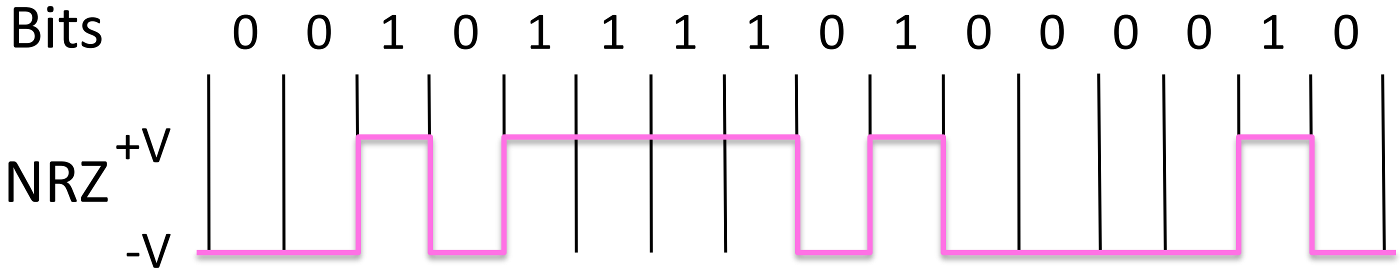
A Simple Modulation

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



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)



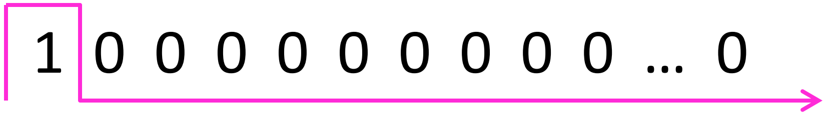
Many Other Schemes

- 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:

Signal:

Clock Recovery – 4B/5B (3)

- 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

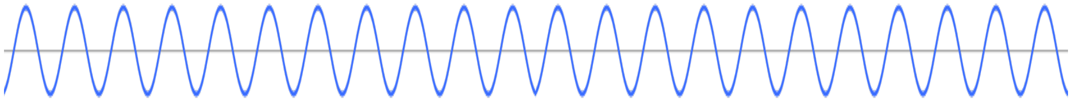
Coded Bits: 1 1 1 0 1 1 1 1 1 0 0 1 0 0 1

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

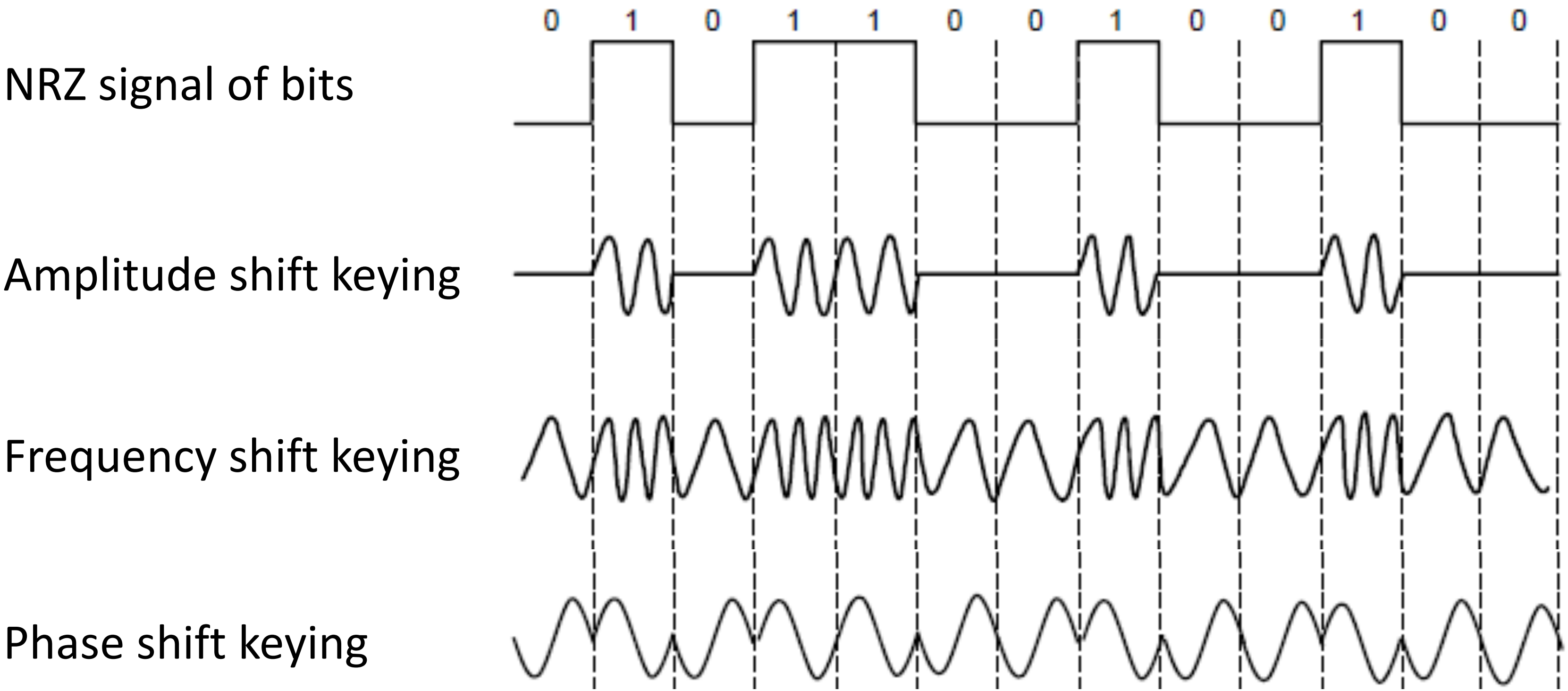
Passband Modulation (2)

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



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

Passband Modulation (3)



Topic

- How rapidly can we send information over a link?
  - Shannon capacity (1948) »

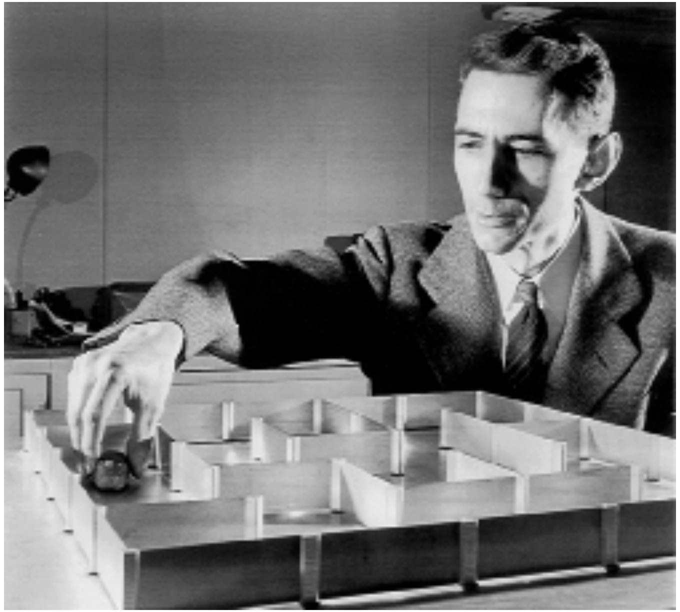
- Practical systems are devised to approach these limits

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

Claude Shannon (1916-2001)

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

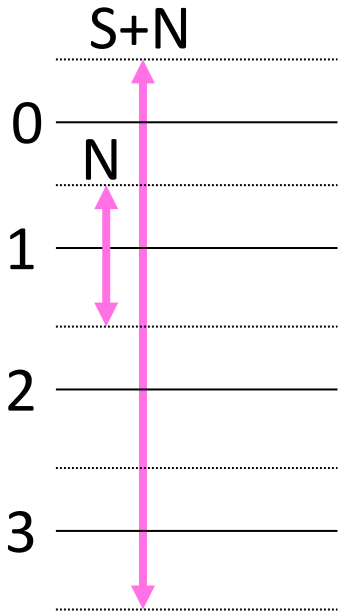


Credit: Courtesy MIT Museum

Electromechanical mouse that "solves" mazes!

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:

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

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!

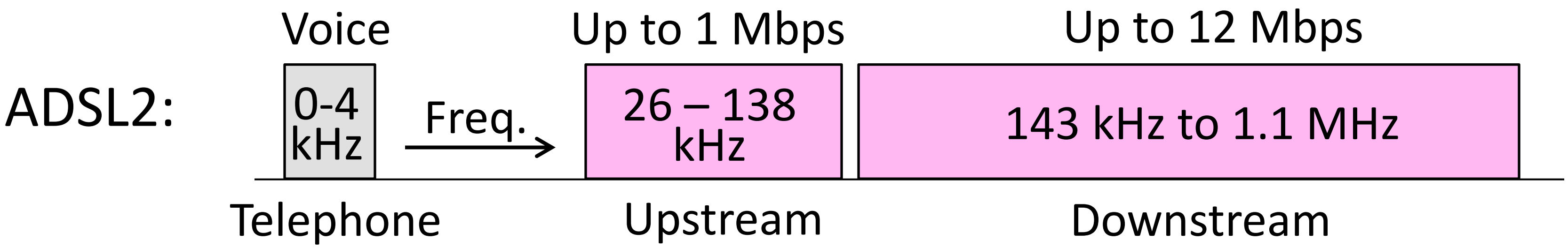
  →Can't design for worst case, must adapt data rate

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

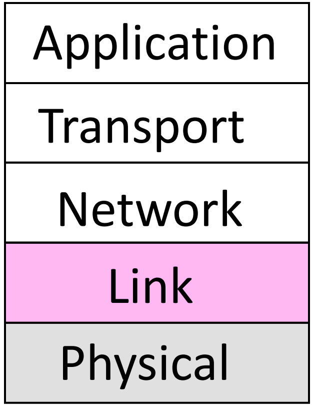
DSL (2)

- 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



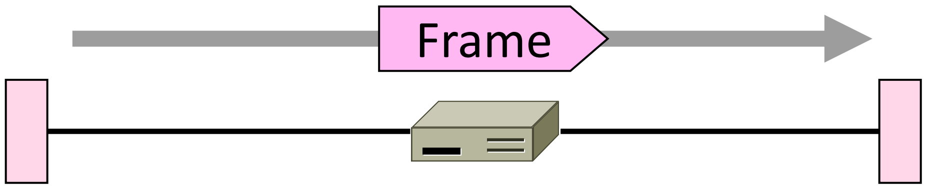
Where we are in the Course

- Moving on to the Link Layer!

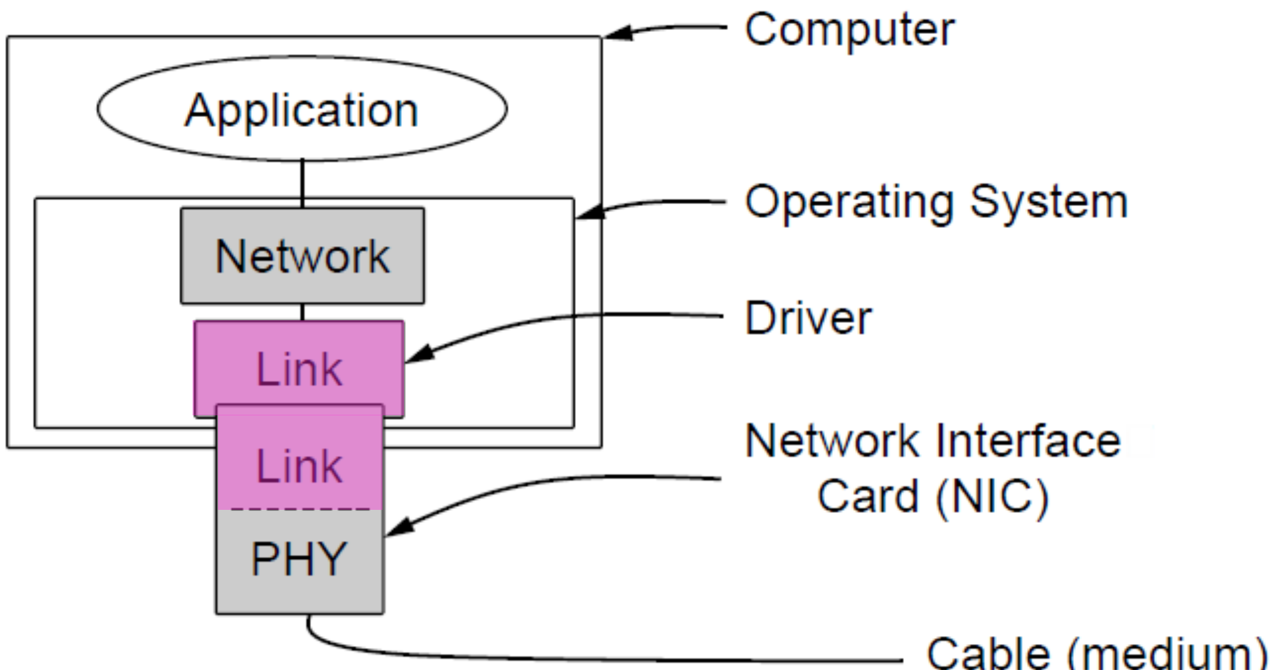


Scope of the Link Layer

- Concerns how to transfer messages over one or more connected links
  - Messages are frames, of limited size
  - Builds on the physical layer



Typical Implementation of Layers (2)



Topics

1. Framing
   – Delimiting start/end of frames
2. Error detection and correction
   – Handling errors
3. Retransmissions
   – Handling loss
4. Multiple Access
   – 802.11, classic Ethernet
5. Switching
   – Modern Ethernet

Later (items 3–5)