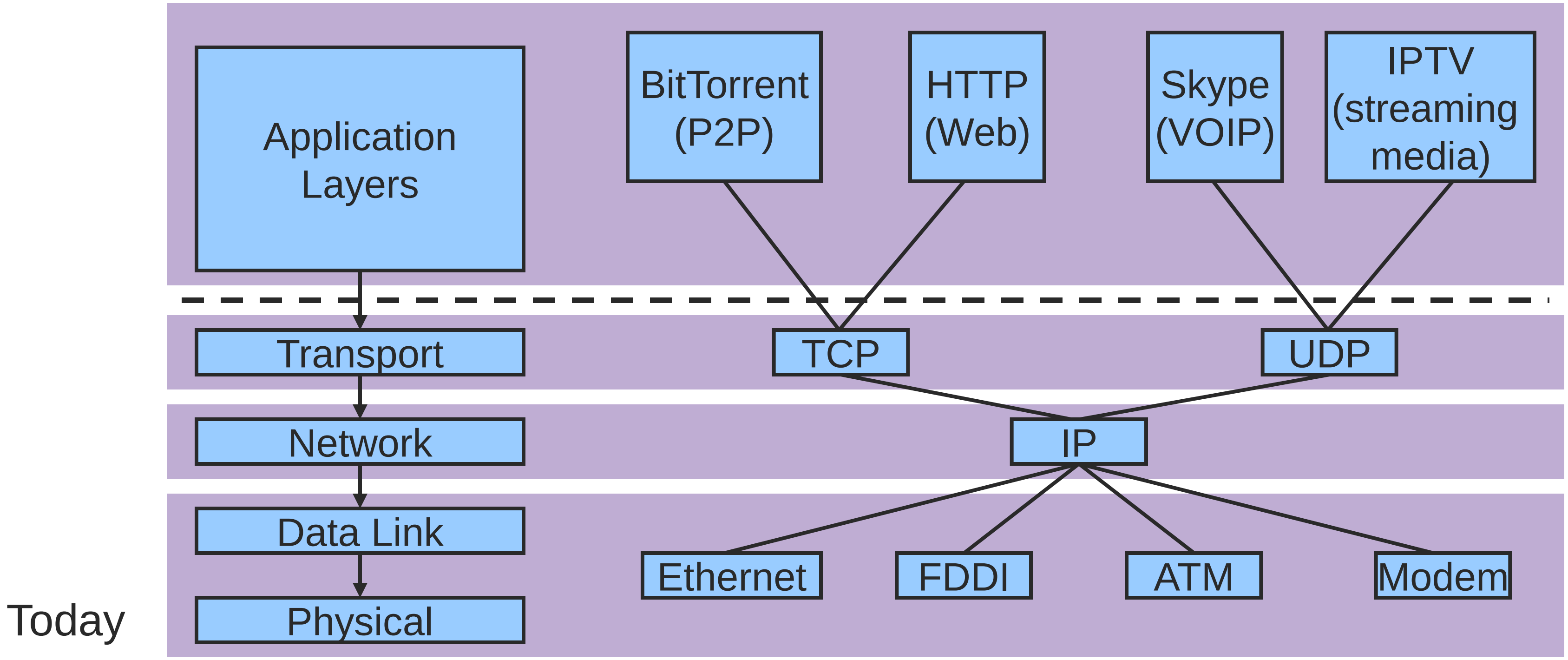
Direct Link Networks

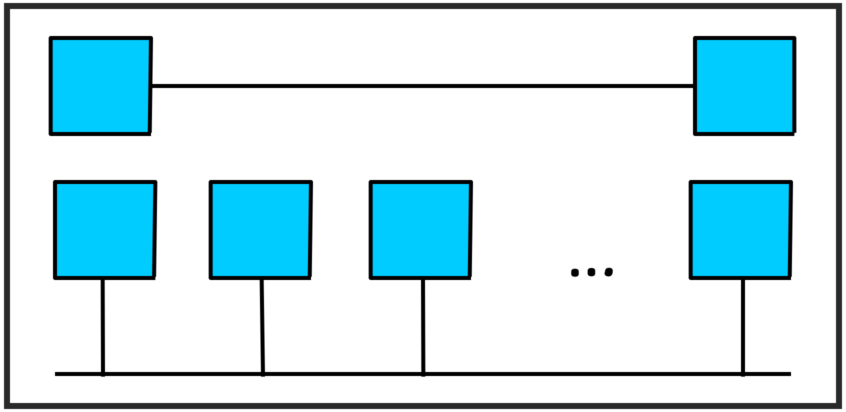
Reading: Peterson and Davie, Chapter 2

Where are we?

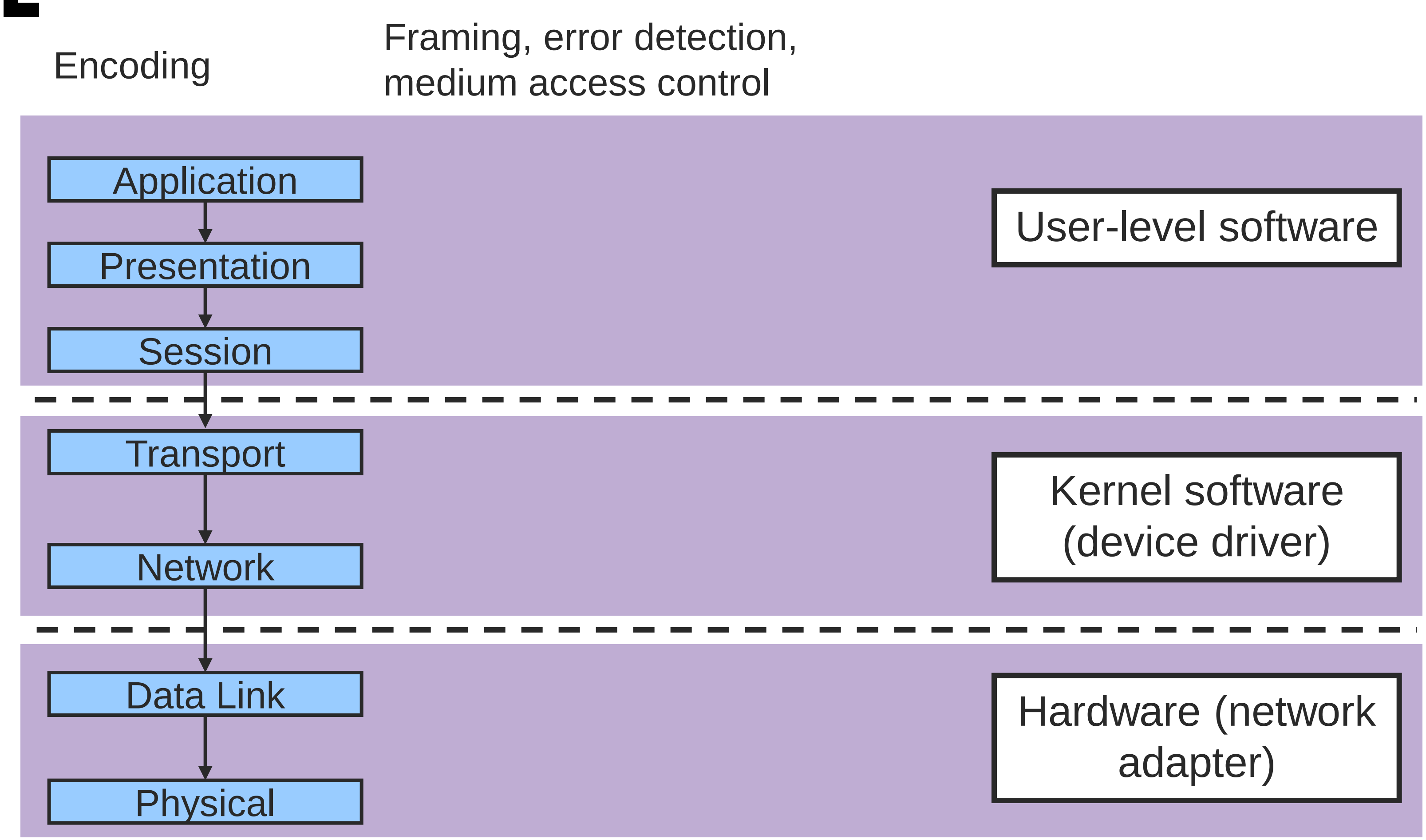

Application Layers
BitTorrent (P2P)
HTTP (Web)
Skype (VOIP)
IPTV (streaming media)
Transport
TCP
UDP
Network
IP
Data Link
Ethernet
FDDI
ATM
Modem
Today
Physical

Direct Link Networks

- All hosts are directly connected by a physical medium
- Key points
  - Encoding and Modulation
  - Framing
  - Error Detection
  - Medium Access Control



Internet Protocols



Direct Link Networks - Outline

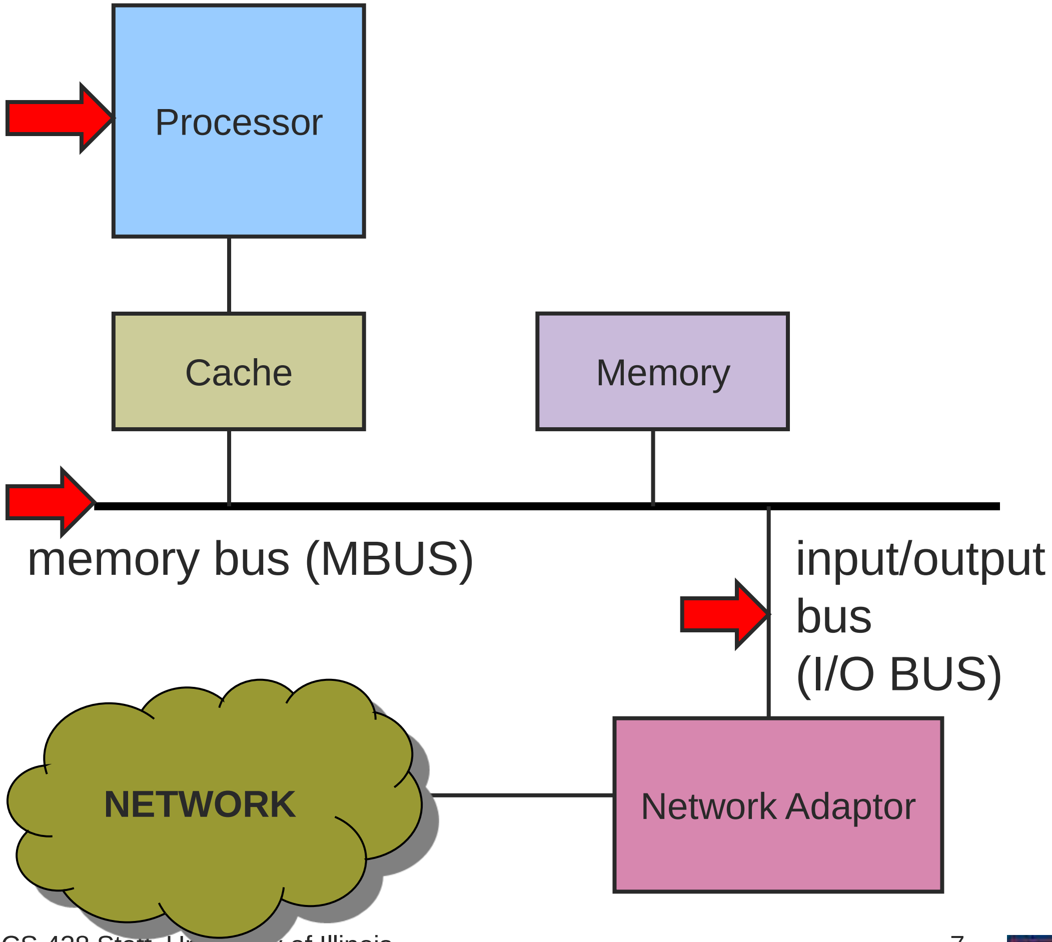
- Hardware building blocks
- Encoding
- Framing
- Error detection
- Multiple access media (MAC examples)
- Network adapters

Hardware Building Blocks

- Nodes
  - Hosts: general purpose computers
  - Switches: typically special purpose hardware
  - Routers: varied

Nodes: Workstation Architecture

- Finite memory
  - Scarce resource
- Runs at memory speeds, NOT processor speeds



Hardware Building Blocks

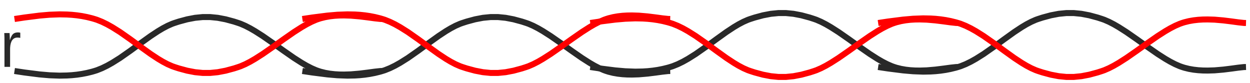
- Links
  - Physical medium carrying
  - Media
    - Copper wire with electronic signaling
    - Glass fiber with optical signaling
    - Wireless with electromagnetic (radio, infrared, microwave) signaling

Links - Copper

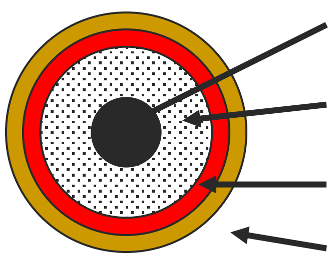
more twists, less crosstalk, better signal over longer distances

- Copper-based Media
  - Category 5 Twisted Pair 10-100Mbps 100m
  - ThinNet Coaxial Cable 10-100Mbps 200m
  - ThickNet Coaxial Cable 10-100Mbps 500m

twisted pair



coaxial cable (coax)

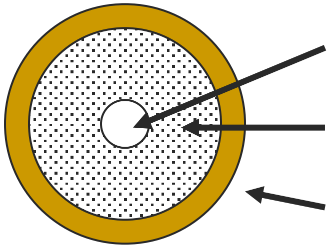


More expensive than twisted pair
High bandwidth and excellent noise immunity

Links - Optical

- Optical Media
  - Multimode Fiber 100Mbps 2km
  - Single Mode Fiber 100-2400Mbps 40km

optical fiber



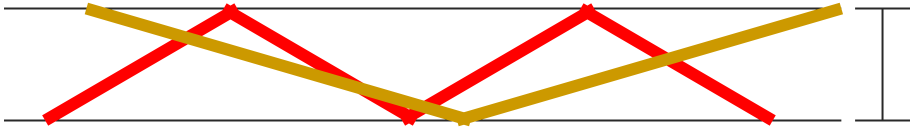
Links - Optical

- Single mode fiber
  - Expensive to drive (Lasers)
  - Lower attenuation (longer distances) ≤ 0.5 dB/km
  - Lower dispersion (higher data rates)
- Multimode fiber
  - Cheap to drive (LED’s)
  - Higher attenuation
  - Easier to terminate

core of single mode fiber

~1 wavelength thick = ~1 micron

core of multimode fiber (same frequency; colors for clarity)



O(100 microns) thick

Links - Optical

- Advantages of optical communication
  - Higher bandwidths
  - Superior attenuation properties
  - Immune from electromagnetic interference
  - No crosstalk between fibers
  - Thin, lightweight, and cheap (the fiber, not the optical-electrical interfaces)

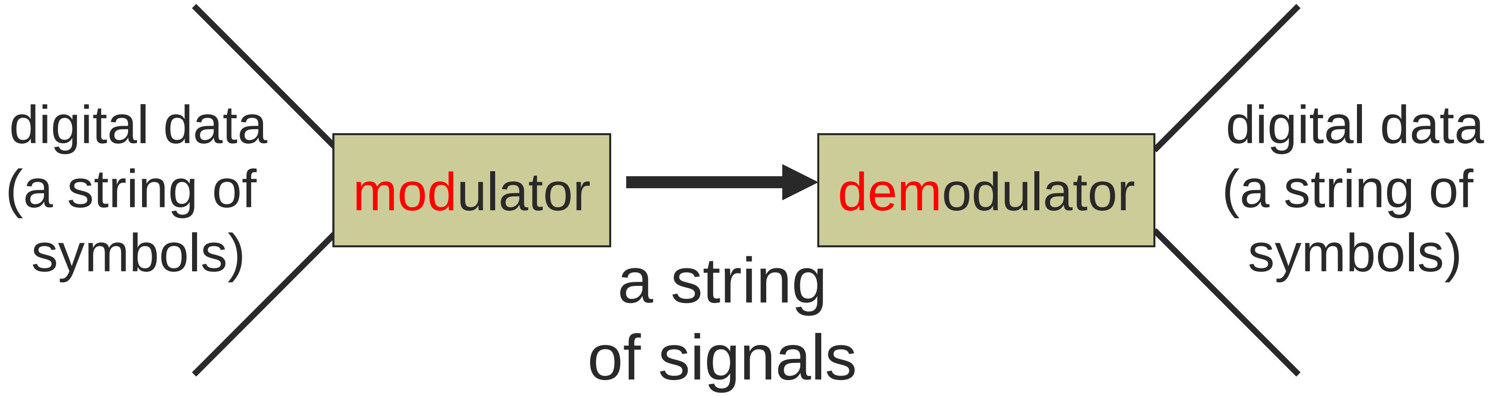
Leased Lines

POTS	64Kbps
ISDN	128Kbps
ADSL	1.5-8Mbps/16-640Kbps
Cable Modem	0.5-2Mbps
DS1/T1	1.544Mbps
DS3/T3	44.736Mbps
STS-1	51.840Mbps
STS-3 (ATM rate)	155.250Mbps (ATM)
STS-12 (ATM rate)	622.080Mbps (ATM)
OC-48	2.5 Gbps
OC-192	10 Gbps

Wireless

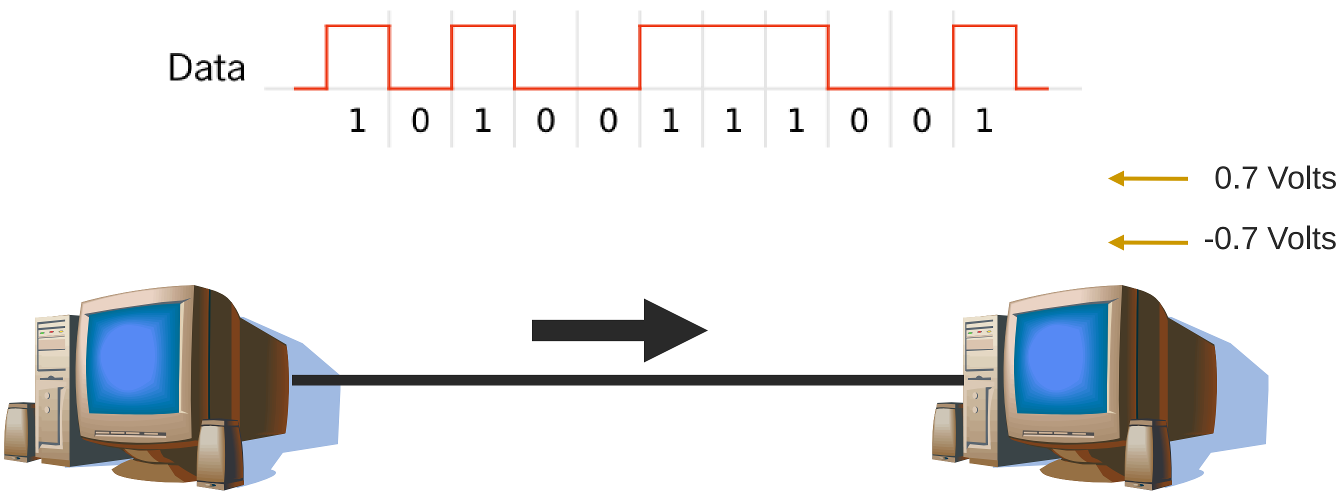
- Cellular
  - AMPS 13Kbps 3km
  - PCS, GSM 300Kbps 3km
- Wireless Local Area Networks (WLAN)
  - Infrared 4Mbps 10m
  - 900Mhz 2Mbps 150m
  - 2.4GHz 2Mbps 150m
  - 2.4Ghz 11Mbps 80m
  - 2.4Ghz 54Mbps 75m
  - 5Ghz 54Mbps 30m
  - Bluetooth 700Kbps 10m
- Satellites
  - Geosynchronous satellite 600-1000 Mbps continent
  - Low Earth orbit (LEO) ~400 Mbps world

Encoding



- Problems with signal transmission
  - Attenuation: Signal power absorbed by medium
  - Dispersion: A discrete signal spreads in space
  - Noise: Random background "signals"

How can two hosts communicate?



- Encode information on modulated “Carrier signal”
  - Phase, frequency, and/or amplitude modulation
  - Ethernet: self-clocking Manchester coding
  - Technologies: copper, optical, wireless

Encoding

- Goal
  - Understand how to connect nodes in such a way that bits can be transmitted from one node to another
- Idea
  - The physical medium is used to propagate signals
    - Modulate electromagnetic waves
    - Vary voltage, frequency, wavelength
  - Data is encoded in the signal

Analog vs. Digital Transmission

- Analog and digital correspond roughly to continuous and discrete
- Data: entities that convey meaning
  - Analog: continuously varying patterns of intensity (e.g., voice and video)
  - Digital: discrete values (e.g., integers, ASCII text)
- Signals: electric or electromagnetic encoding of data
  - Analog: continuously varying electromagnetic wave
    - May be propagated over a variety of media
  - Digital: sequence of voltage pulses
    - May be transmitted over a wire medium

Analog vs. Digital Transmission

- Advantages of digital transmission over analog
  - Cheaper
  - Suffers more attenuation
    - But reasonably low-error rates over arbitrary distances
    - Calculate/measure effects of transmission problems
    - Periodically interpret and regenerate signal
  - Simpler for multiplexing distinct data types (audio, video, e-mail, etc.)
  - Easier to encrypt
- Two examples based on modulator-demodulators (modems)
  - Electronic Industries Association (EIA) standard: RS-232
  - International Telecommunications Union (ITU) V.32 9600 bps modem standard

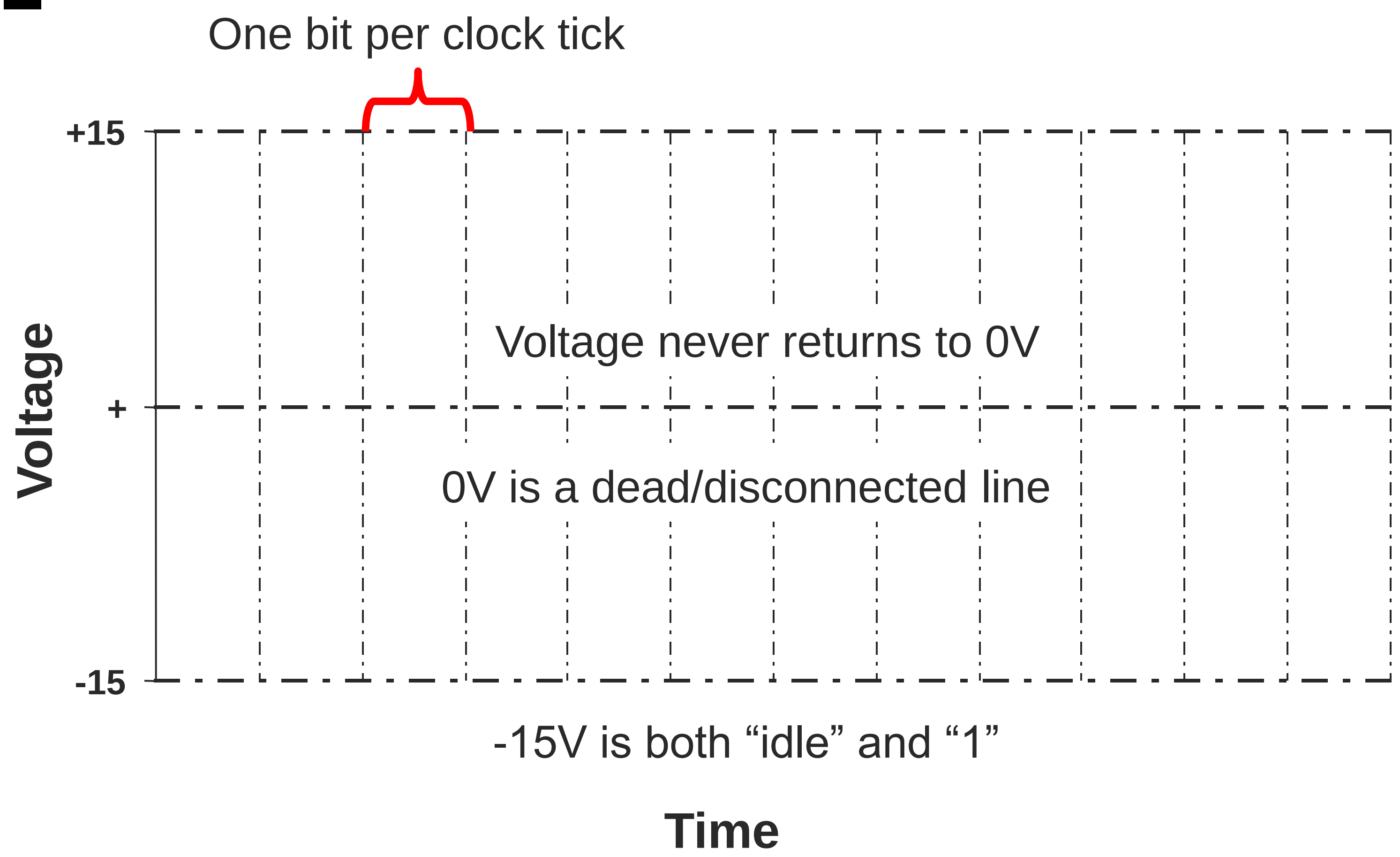
Bauds and Bits

- Baud rate
  - Number of physical symbols transmitted per second
- Bit rate
  - Actual number of data bits transmitted per second
- Relationship
  - Depends on the number of bits encoded in each symbol

RS-232

- Communication between computer and modem
- Uses two voltage levels (+15V, -15V), a binary voltage encoding
- Data rate limited to 19.2 kbps (RS-232-C); raised in later standards
- Characteristics
  - Serial
    - One signaling wire, one bit at a time
  - Asynchronous
    - Line can be idle, clock generated from data
  - Character-based
    - Send data in 7- or 8-bit characters

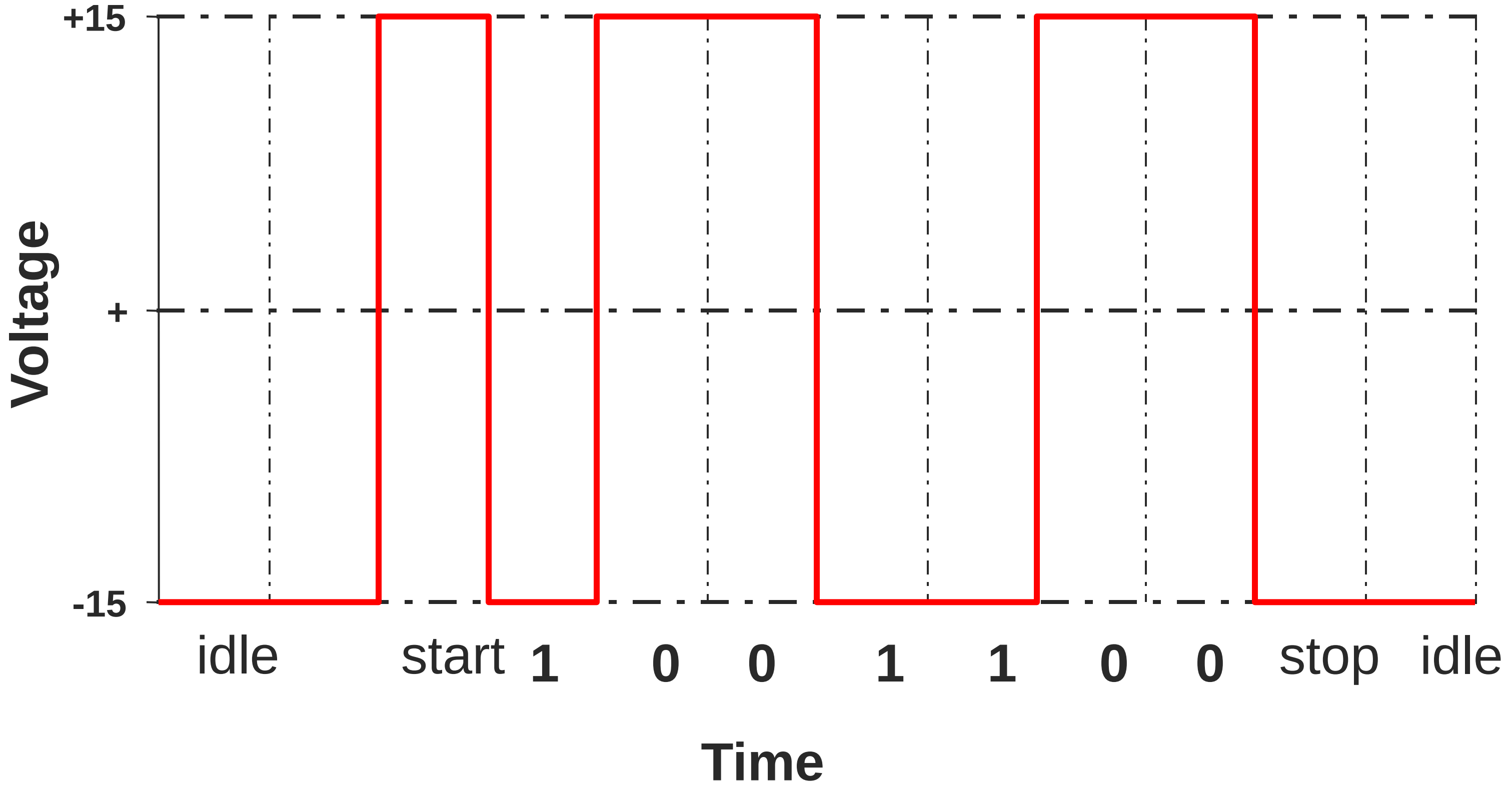
RS-232 Timing Diagram



RS-232

- Initiate send by
  - Push to 15V for one clock (start bit)
- Minimum delay between character transmissions
  - Idle for one clock at -15V (stop bit)
- One character
  - 2+ voltage transitions
- Total Bits
  - 9 bits for 7 bits of data (78% efficient)
- Start and stop bits also provide framing

RS-232 Timing Diagram

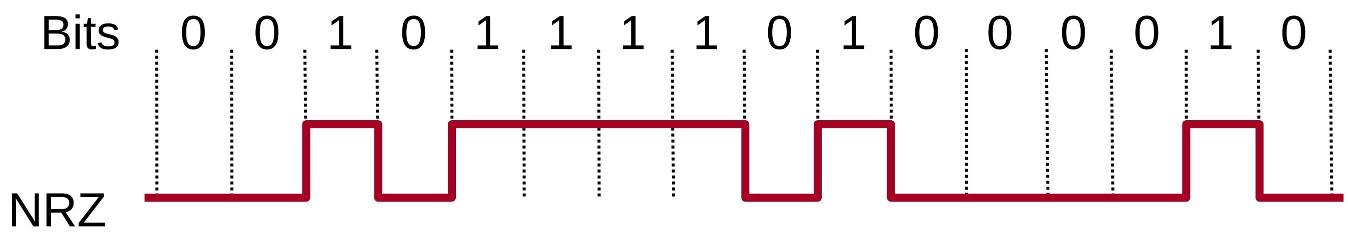


Voltage Encoding

- Binary voltage encoding
  - Done with RS-232 example
  - Generalize before continuing with V.32 (not a binary voltage encoding)
- Common binary voltage encodings
  - Non-return to zero (NRZ)
  - NRZ inverted (NRZI)
  - Manchester (used by IEEE 802.3—10 Mbps Ethernet)
  - 4B/5B

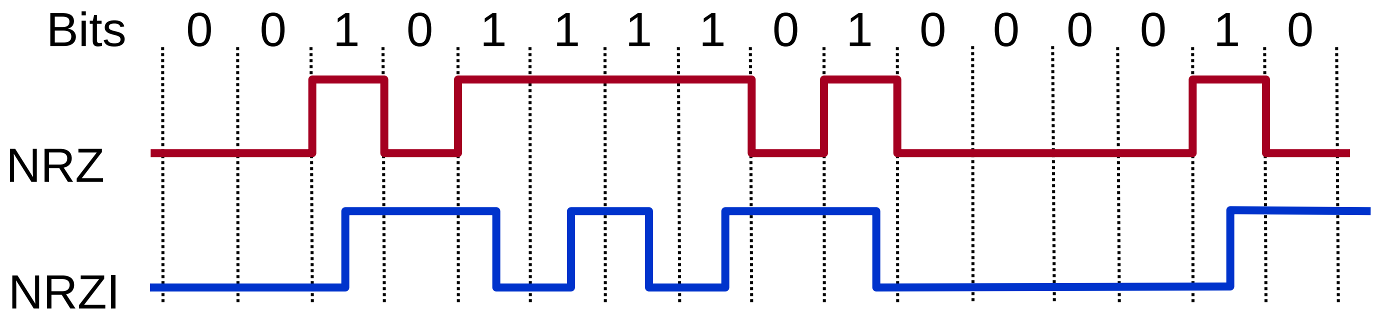
Non-Return to Zero (NRZ)

- Signal to Data
  - High ⇨ 1
  - Low ⇨ 0
- Comments
  - Transitions maintain clock synchronization
  - Long strings of 0s confused with no signal
  - Long strings of 1s causes baseline wander
  - Both inhibit clock recovery



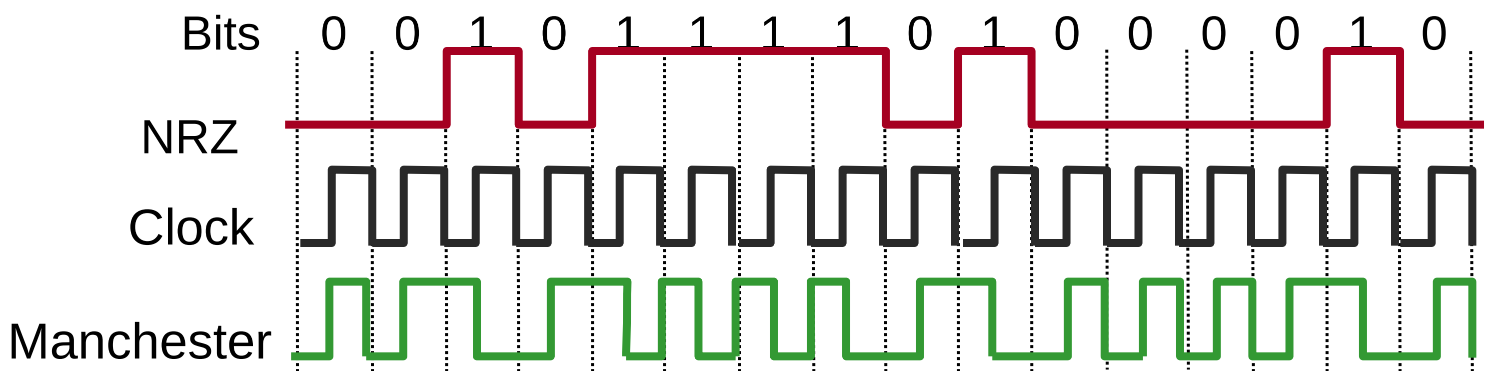
Non-Return to Zero Inverted (NRZI)

- Signal to Data
  - Transition ⇨ 1
  - Maintain ⇨ 0
- Comments
  - Solves series of 1s, but not 0s



Manchester Encoding

- Signal to Data
  - XOR NRZ data with clock
  - High to low transition ⇨ 1
  - Low to high transition ⇨ 0
- Comments
  - (used by IEEE 802.3—10 Mbps Ethernet)
  - Solves clock recovery problem
  - Only 50% efficient (½ bit per transition)



4B/5B

- Signal to Data
  - Encode every 4 consecutive bits as a 5 bit symbol
- Symbols
  - At most 1 leading 0
  - At most 2 trailing 0s
  - Never more than 3 consecutive 0s
  - Transmit with NRZI
- Comments
  - 16 of 32 possible codes used for data
  - At least two transitions for each code
  - 80% efficient

4B/5B – Data Symbols

At most 1 leading 0	At most 2 trailing 0s
0000 ⇒ 11110	1000 ⇒ 10010
0001 ⇒ 01001	1001 ⇒ 10011
0010 ⇒ 10100	1010 ⇒ 10110
0011 ⇒ 10101	1011 ⇒ 10111
0100 ⇒ 01010	1100 ⇒ 11010
0101 ⇒ 01011	1101 ⇒ 11011
0110 ⇒ 01110	1110 ⇒ 11100
0111 ⇒ 01111	1111 ⇒ 11101

4B/5B – Control Symbols

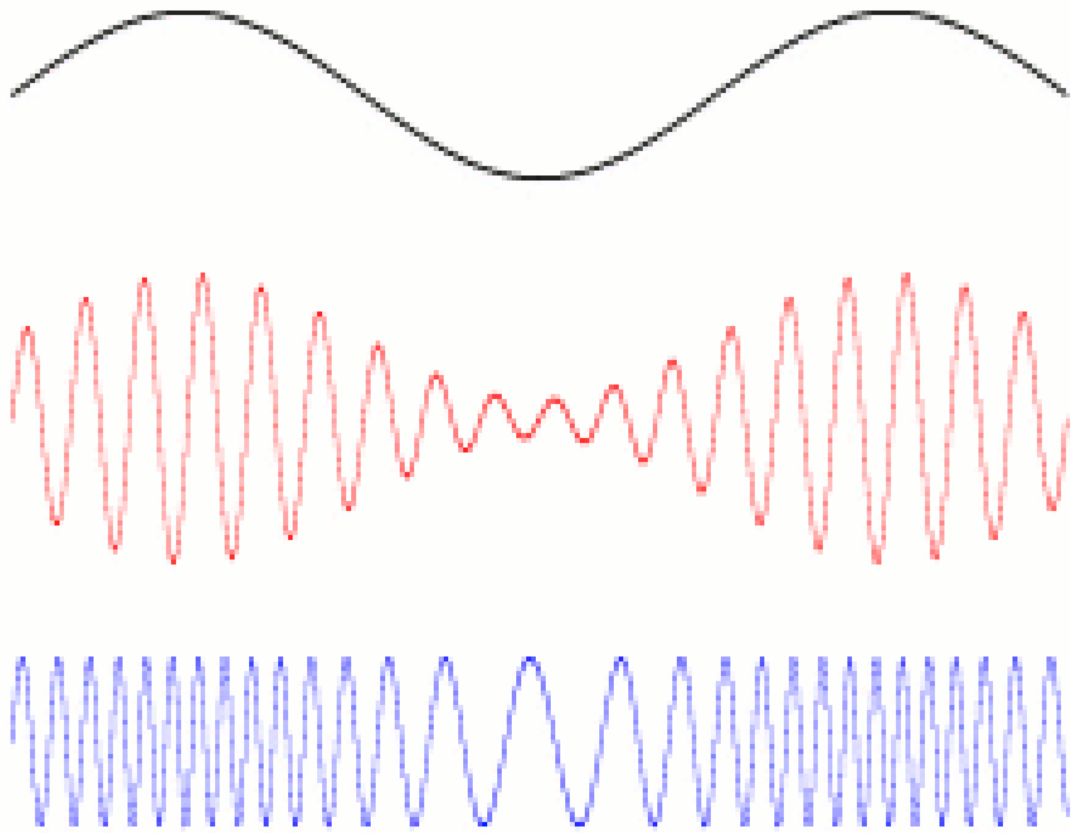
- `11111` ⇒ idle
- `11000` ⇒ start of stream 1
- `10001` ⇒ start of stream 2
- `01101` ⇒ end of stream 1
- `00111` ⇒ end of stream 2
- `00100` ⇒ transmit error
- Other ⇒ invalid

Binary Voltage Encodings

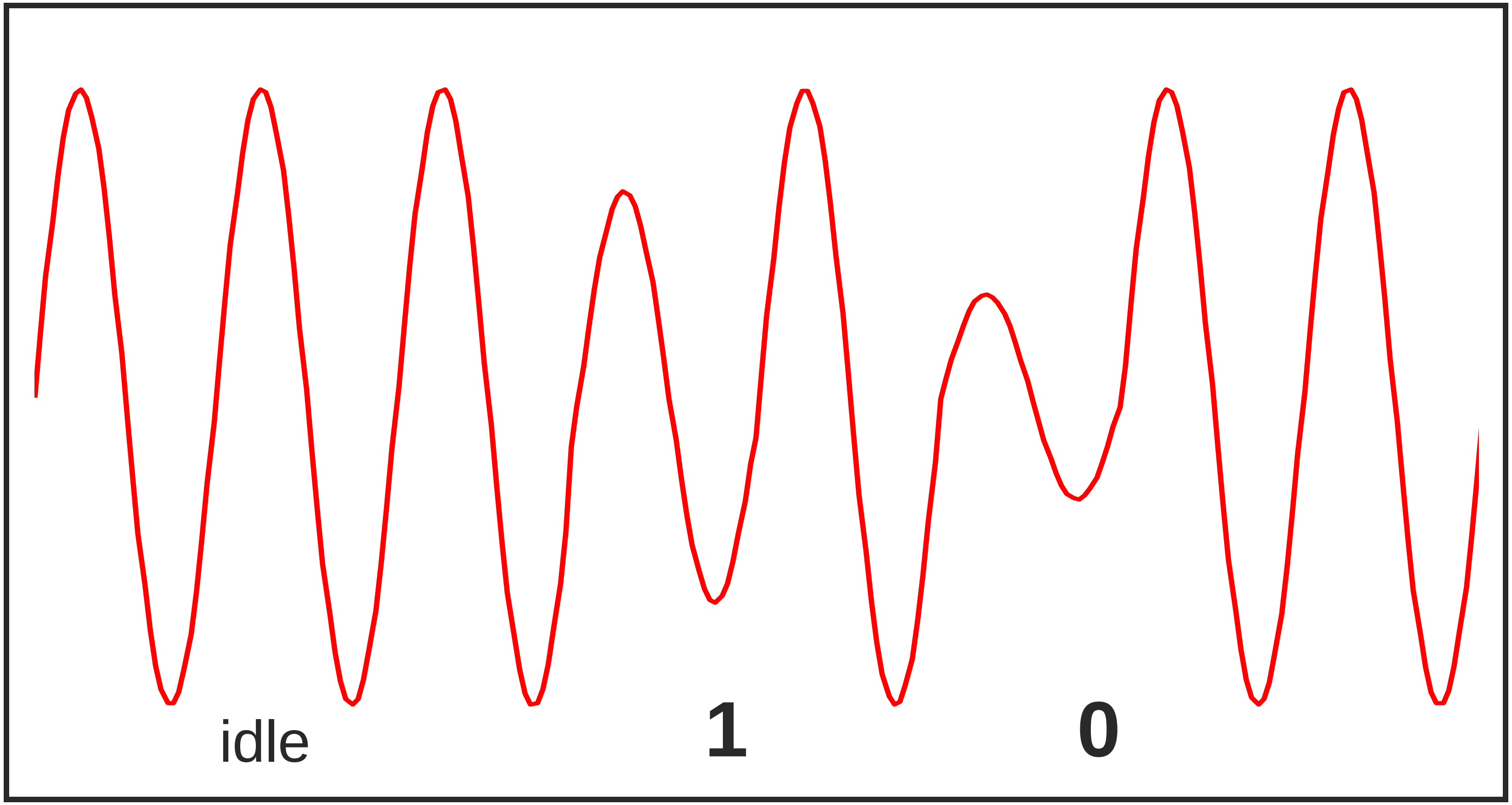
- Problem with binary voltage (square wave) encodings
  - Wide frequency range required, implying
    - Significant dispersion
    - Uneven attenuation
  - Prefer to use narrow frequency band (carrier frequency)
- Types of modulation
  - Amplitude (AM)
  - Frequency (FM)
  - Phase/phase shift
  - Combinations of these

Example: AM/FM for continuous signal

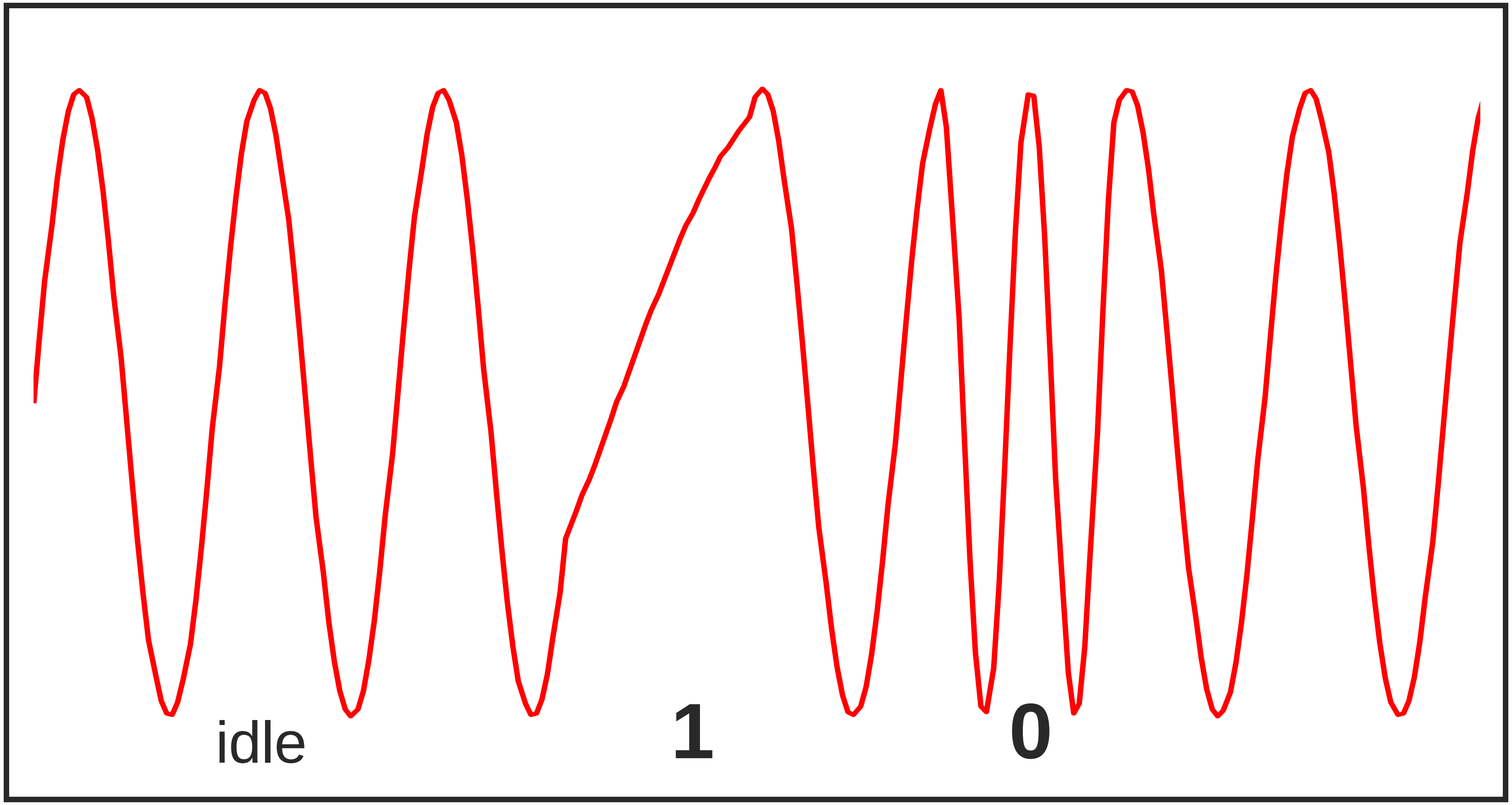
- Original signal
- Amplitude modulation
- Frequency modulation



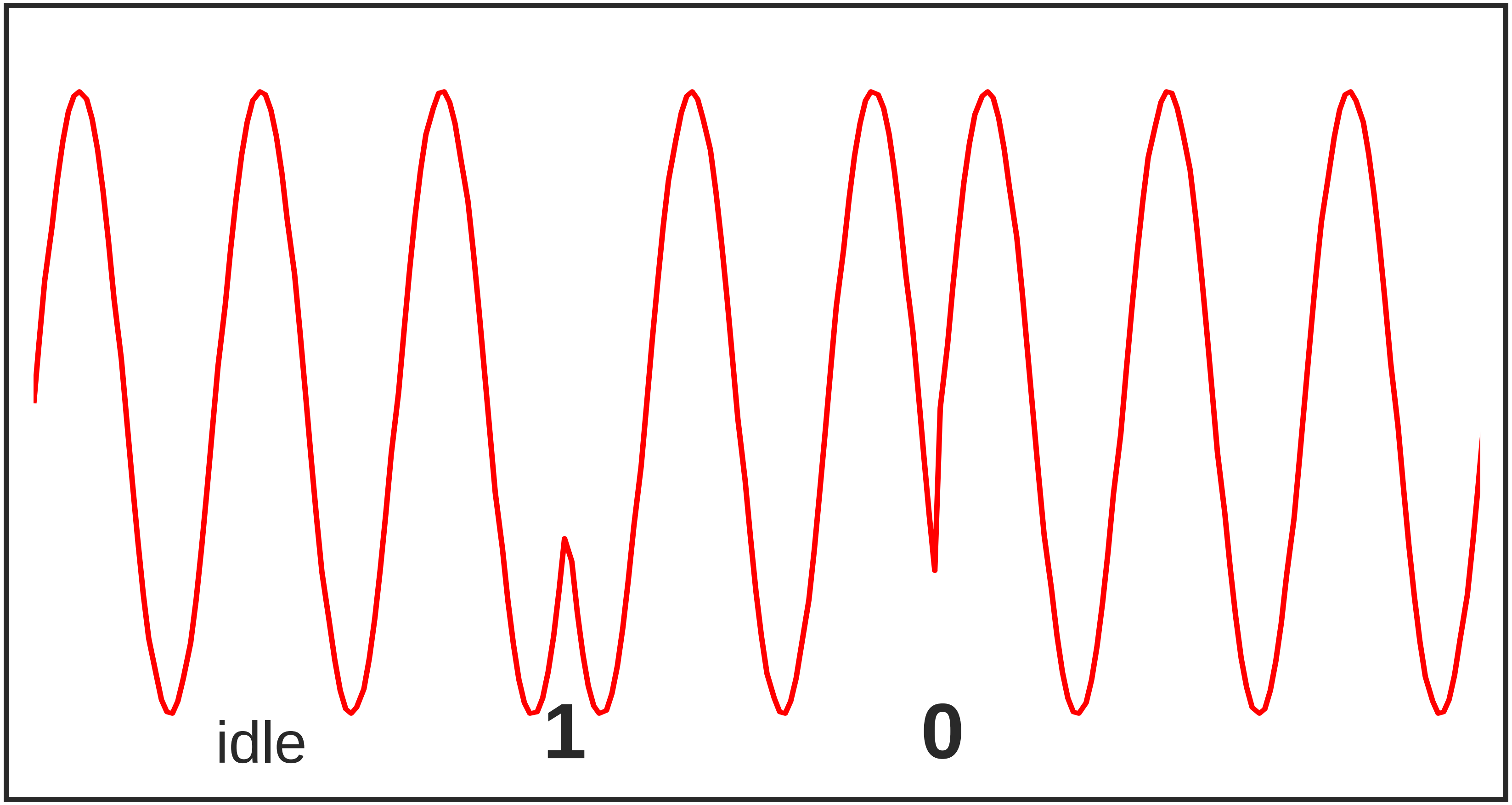
Amplitude Modulation



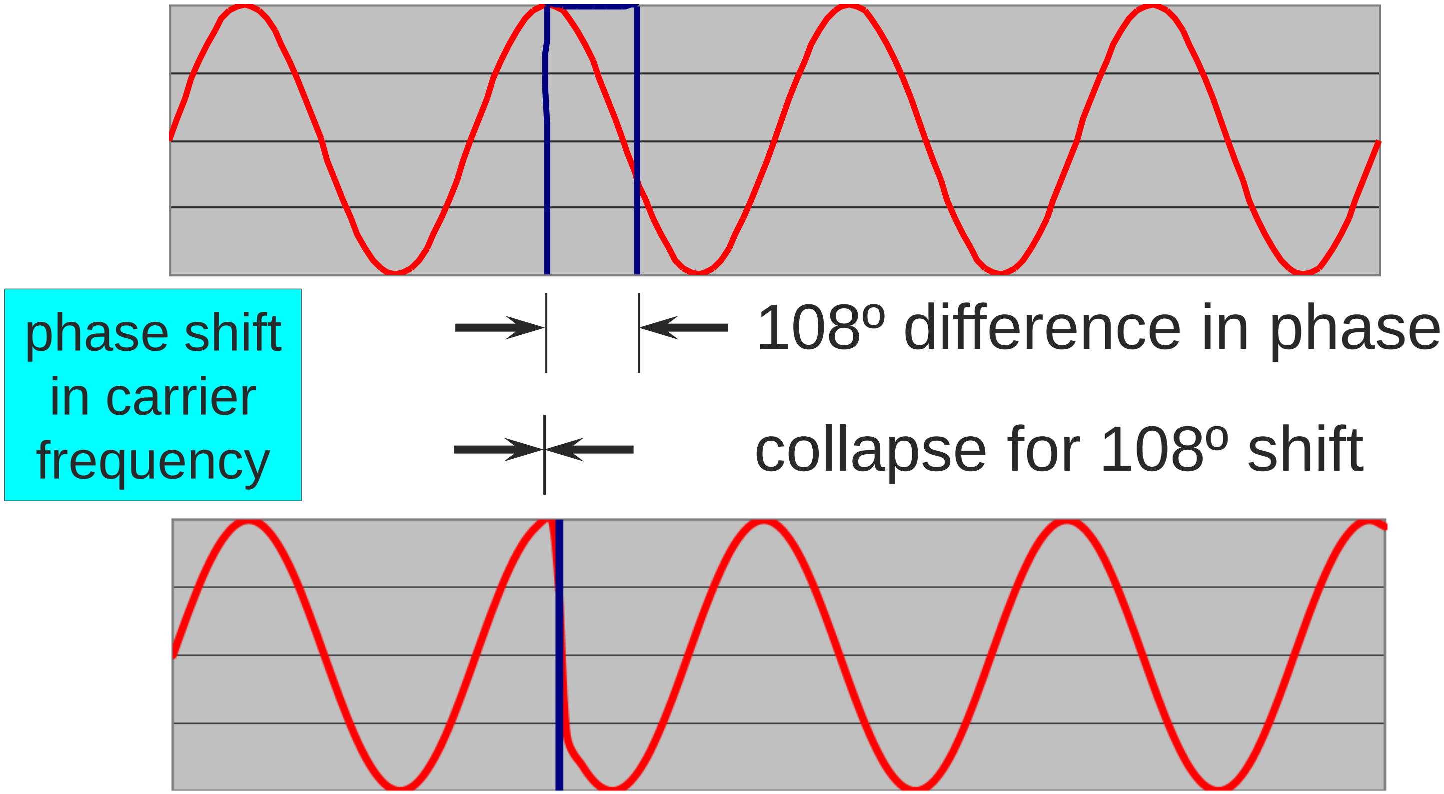
Frequency Modulation



Phase Modulation



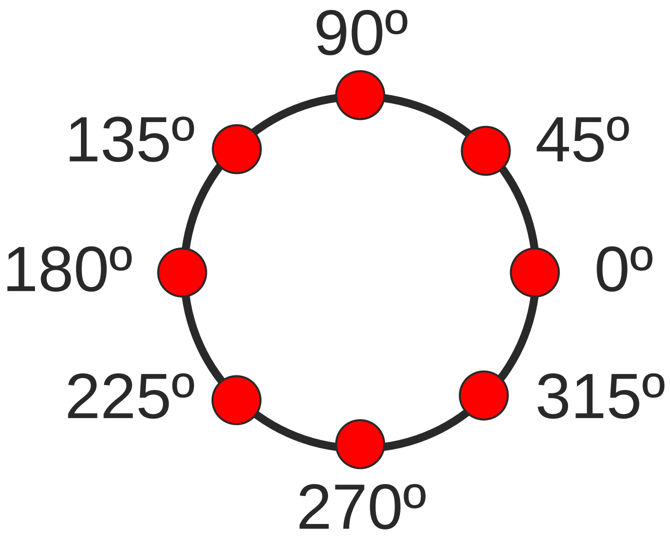
Phase Modulation



Phase Modulation Algorithm

- Send carrier frequency for one period
  - Perform phase shift
  - Shift value encodes symbol
    - Value in range [0, 360º)
    - Multiple values for multiple symbols
    - Represent as circle

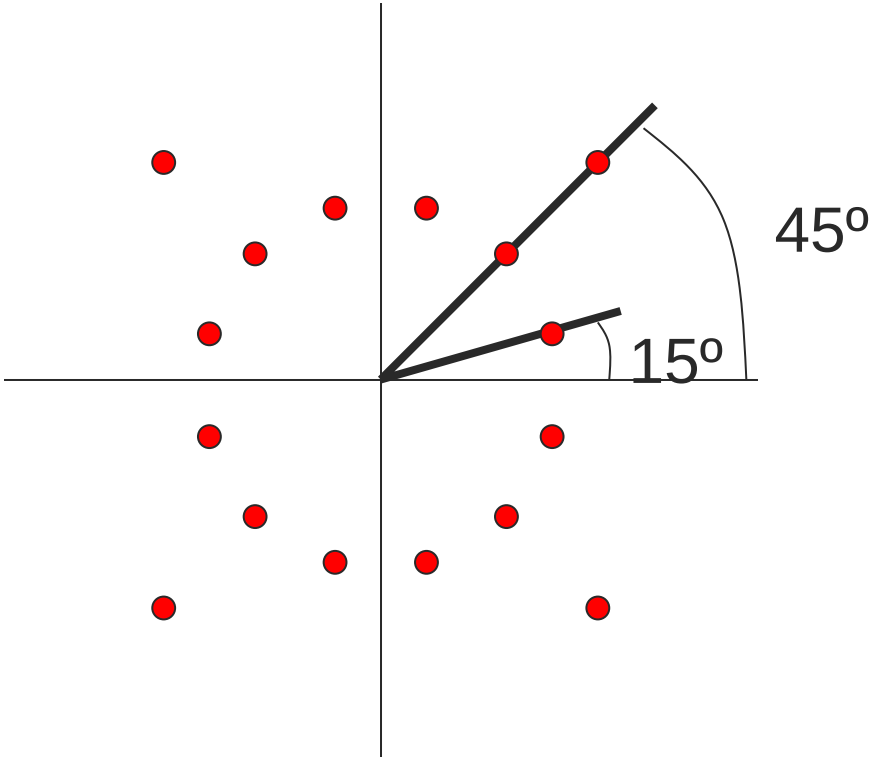
8-symbol example



V.32 9600 bps

- Communication between modems
- Analog phone line
- Uses a combination of amplitude and phase modulation
  - Known as Quadrature Amplitude Modulation (QAM)
- Sends one of 16 signals each clock cycle

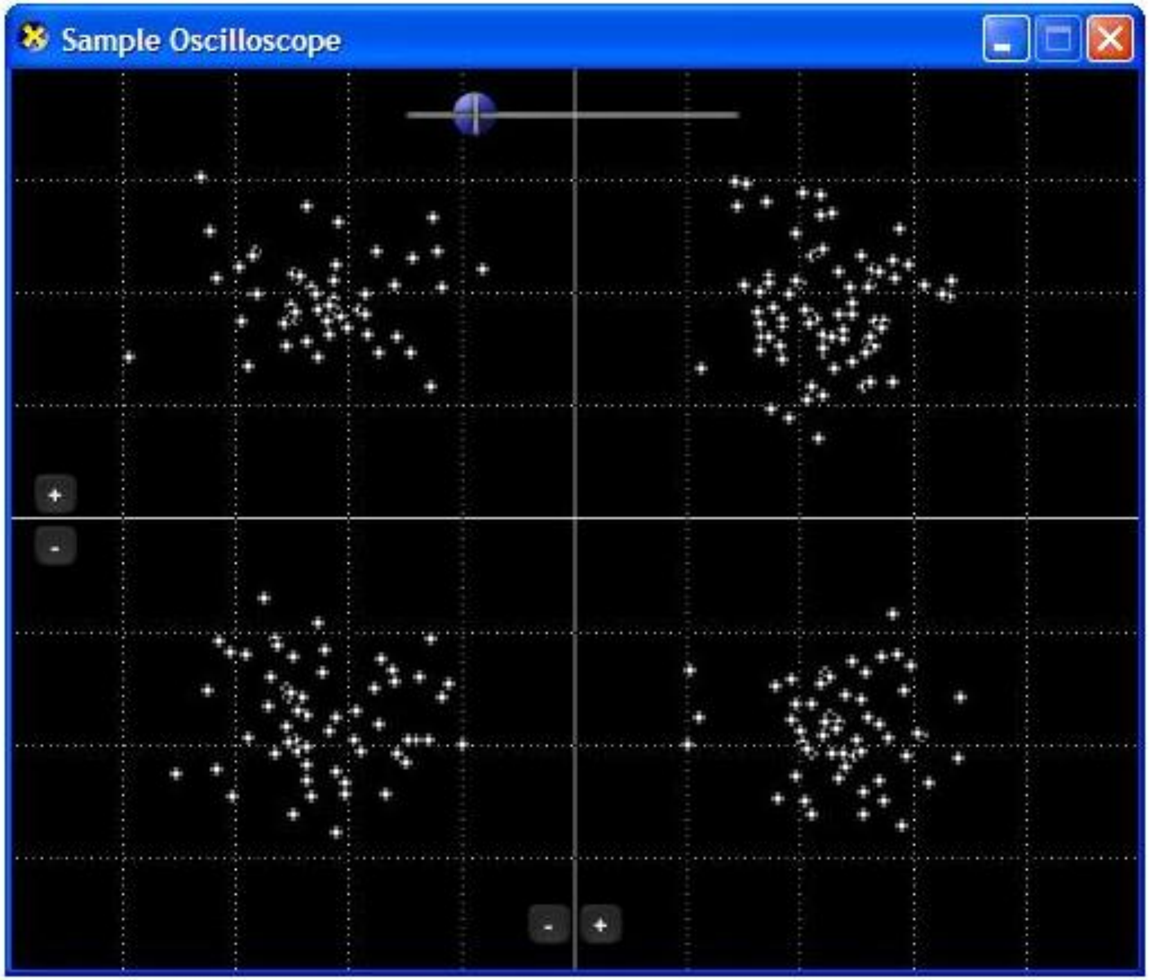
Constellation Pattern for V.32 QAM



16-symbol example

- Same algorithm as phase modulation
- Can also change signal amplitude
- 2-dimensional representation
  - Angle is phase shift
  - Radial distance is new amplitude

Example constellation



Comments on V.32

- V.32 transmits at 2400 baud
  - *i.e.*, 2,400 symbols per second
- How many bits per symbols?
  - Each symbol contains $\log_2 16 = 4$ bits
- What is the data rate?
  - 4 x 2400 = 9600 bps
- Points in constellation diagram
  - Chosen to maximize error detection
  - Process called trellis coding

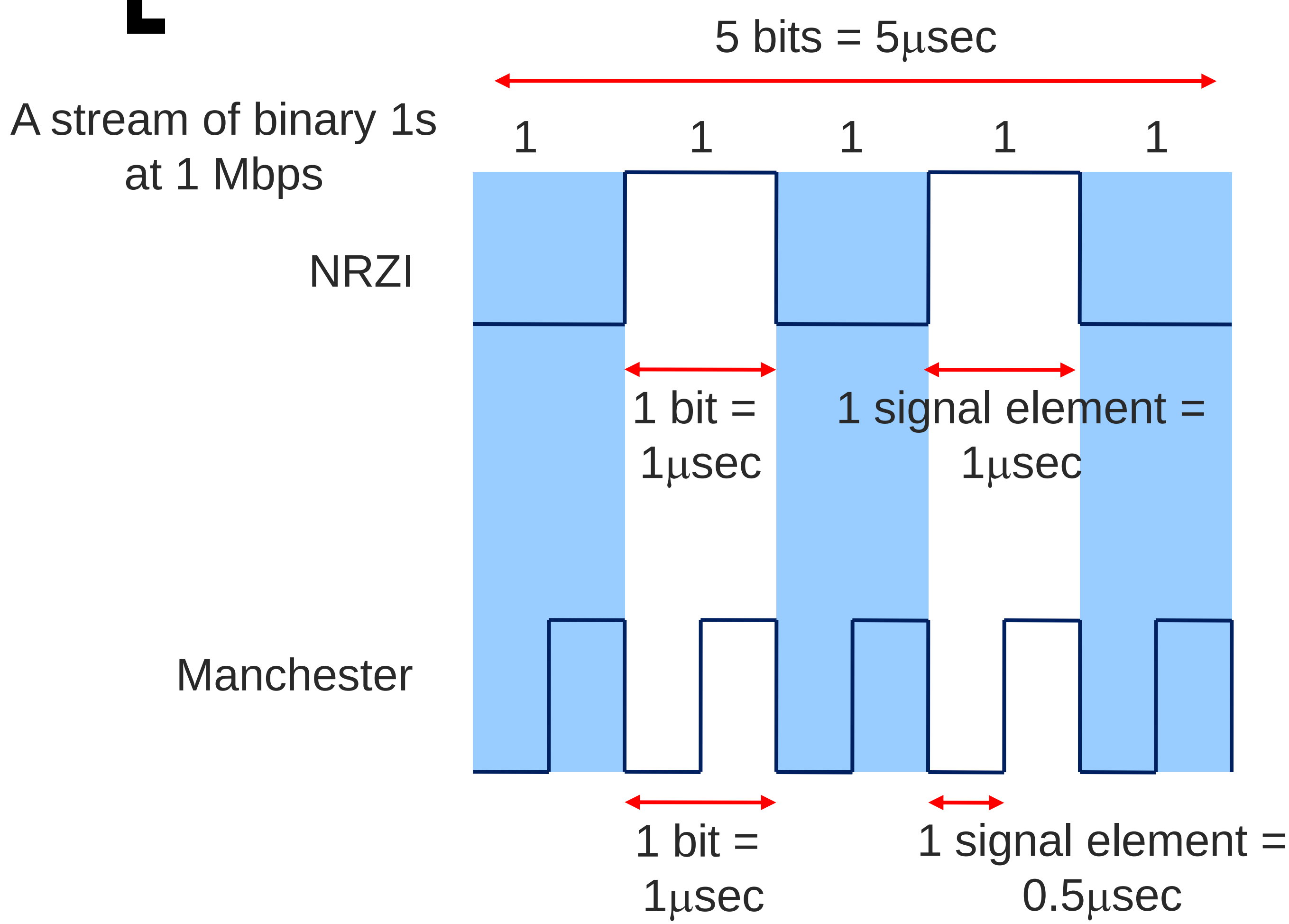
Generalizing the Examples

- What limits baud rate?
- What data rate can a channel sustain?
- How is data rate related to bandwidth?
- How does noise affect these bounds?
- What else can limit maximum data rate?

What Limits Baud Rate?

- Baud rate
  - Typically limited by electrical signaling properties
- Changing voltages takes time
  - No matter how small the voltage or how short the wire
- Electronics
  - Slow compared to optics
- Note
  - Baud rate can be as high as twice the frequency (bandwidth) of communication
  - One cycle can contain two symbols

Modulation (Baud) Rate



What is a bit?

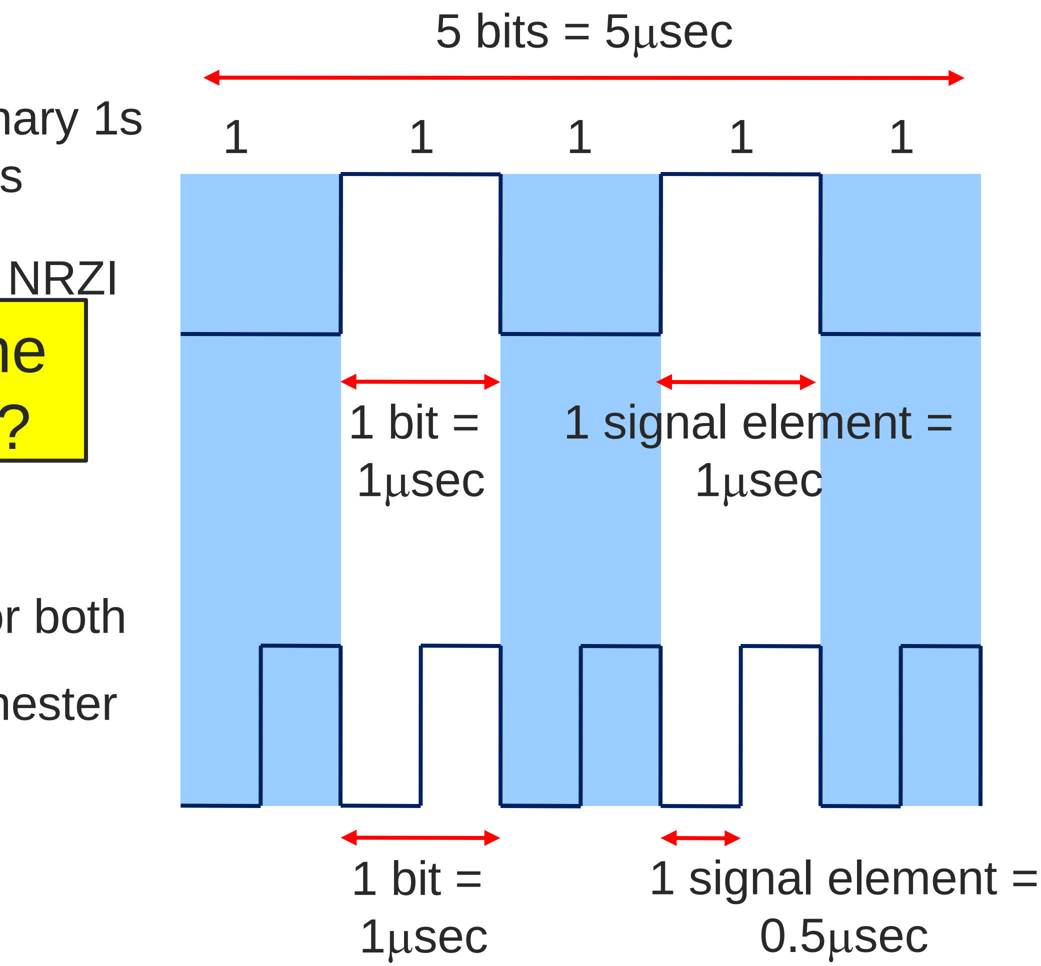
What is a signal element?

Modulation (Baud) Rate

A stream of binary 1s at 1 Mbps

What is the data rate?

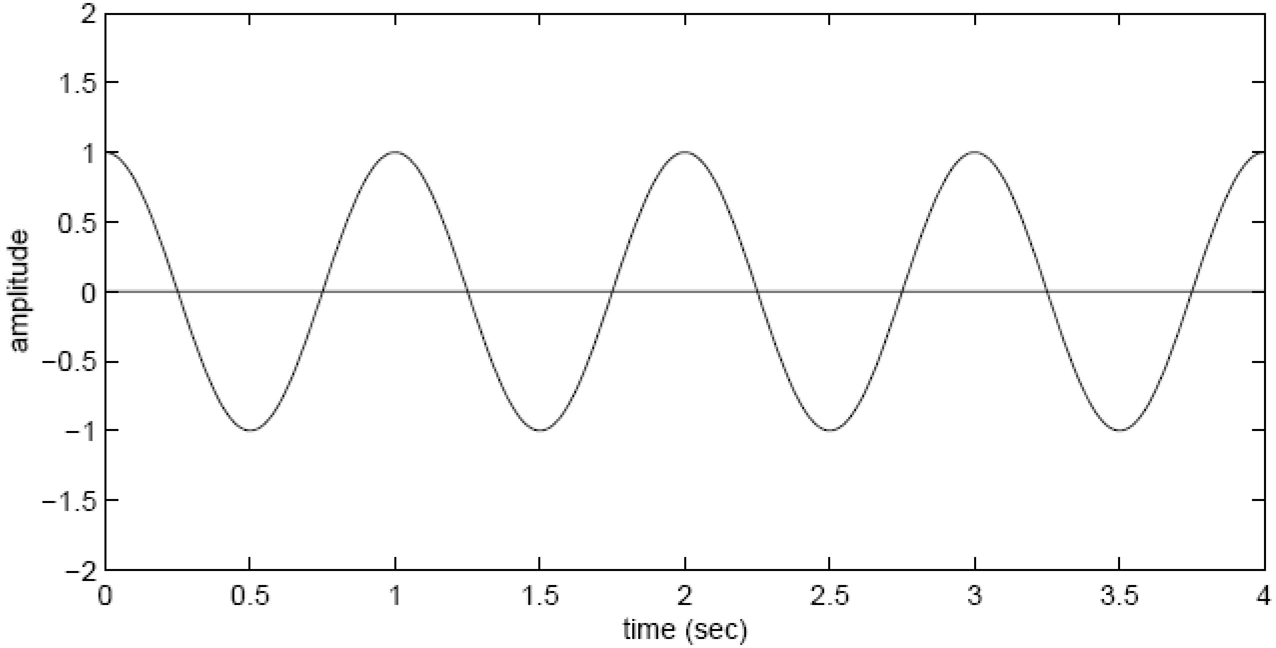
Data Rate (R)
= bits/sec
= 1 Mbps for both



What is the modulation rate?

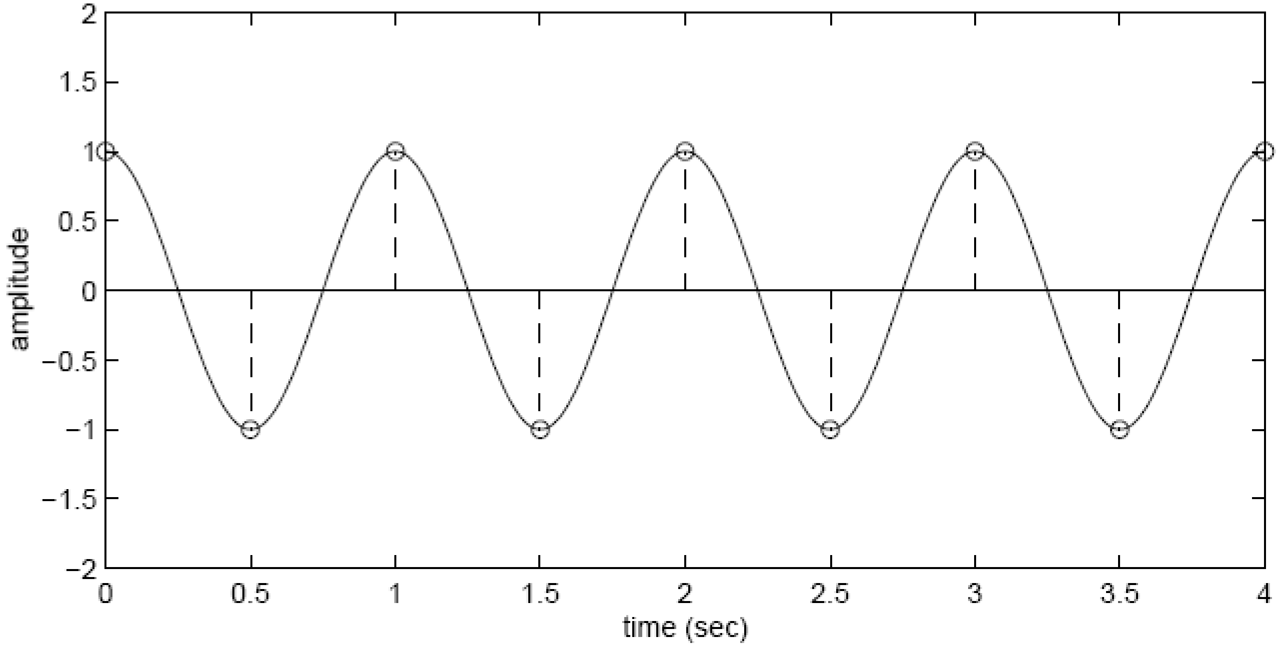
Modulation Rate
= Baud Rate
= Rate at which signal elements are generated
= R (NRZI)
= 2R (Manchester)

Sampling



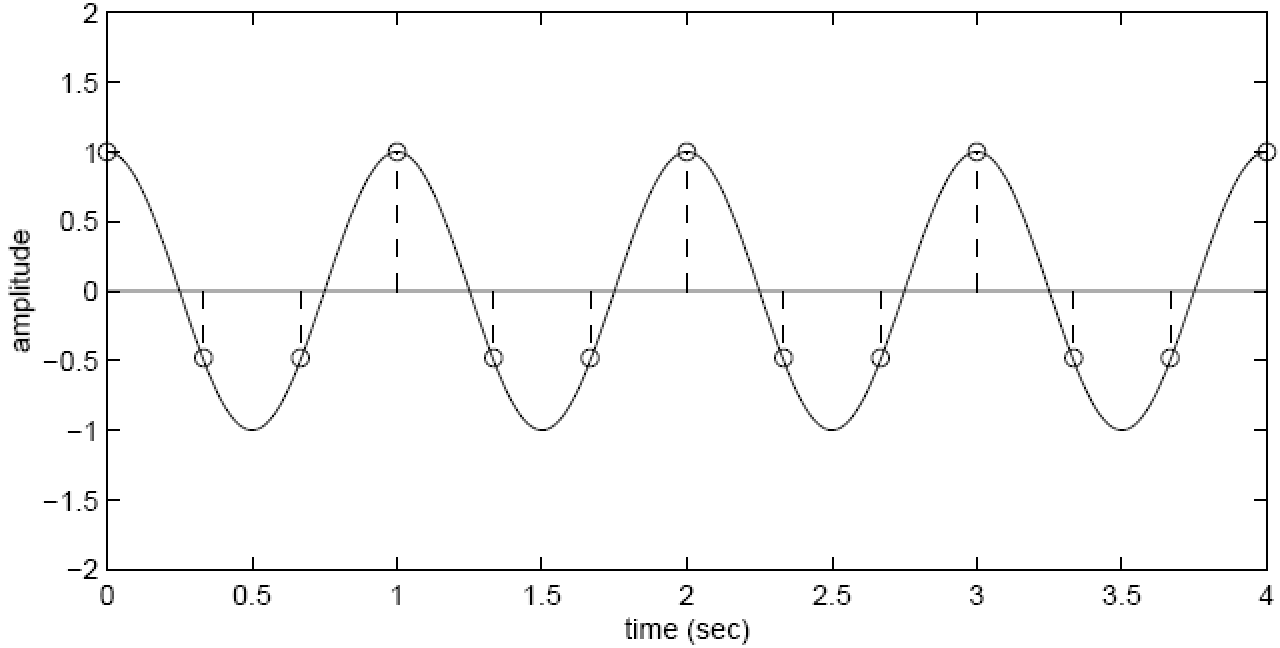
- Suppose you have the following 1Hz signal being received
- How fast to sample, to capture the signal?

Sampling



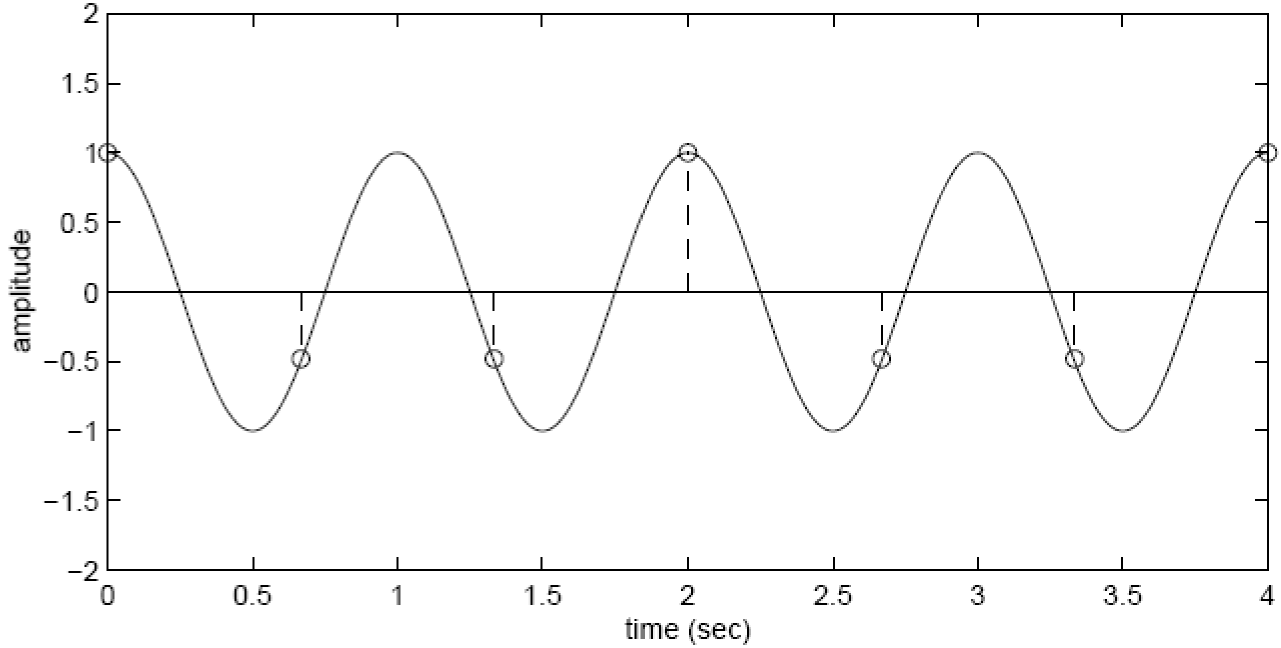
- Sampling a 1 Hz signal at 2 Hz is enough
  - Captures every peak and trough

Sampling



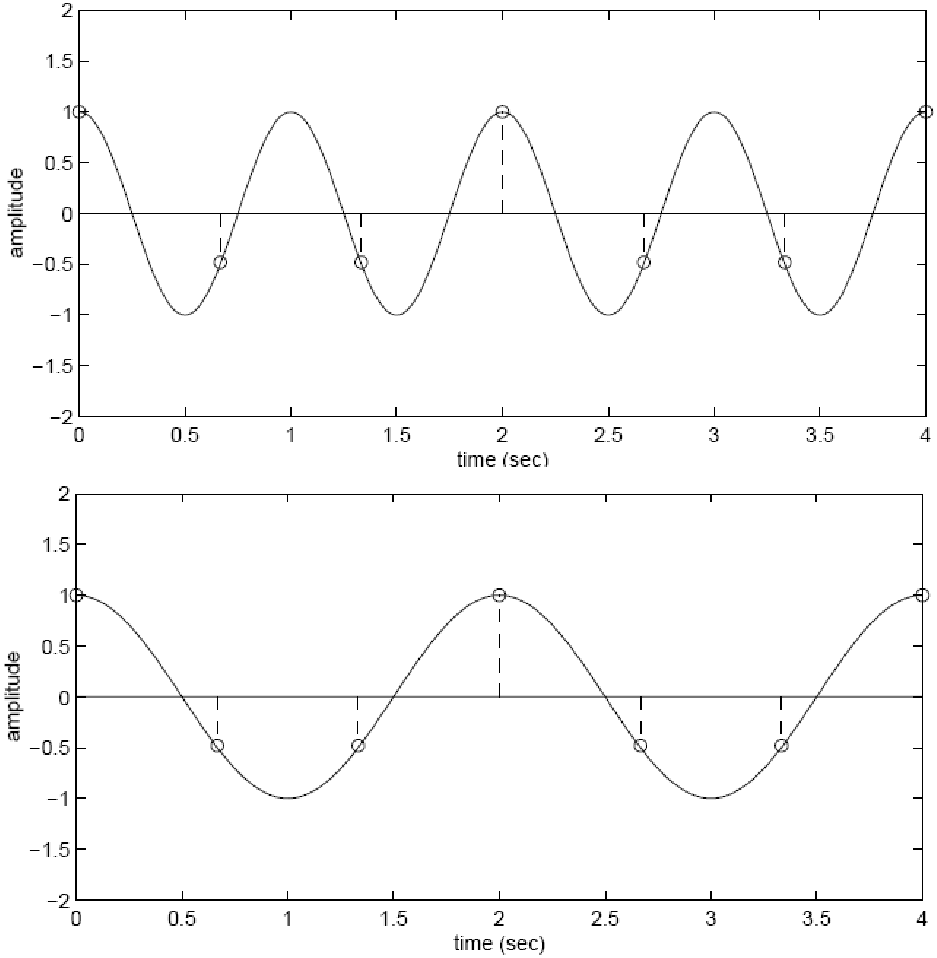
- Sampling a 1 Hz signal at 3 Hz is also enough
  - In fact, more than enough samples to capture variation in signal

Sampling



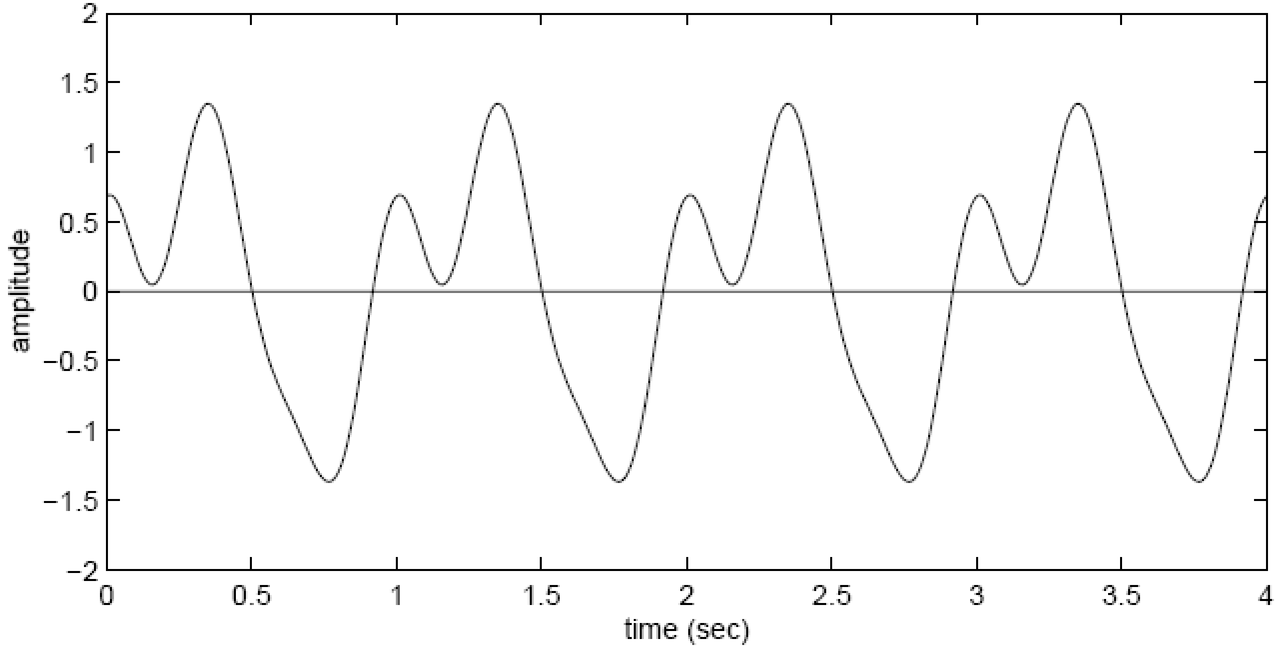
- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Why?

Sampling



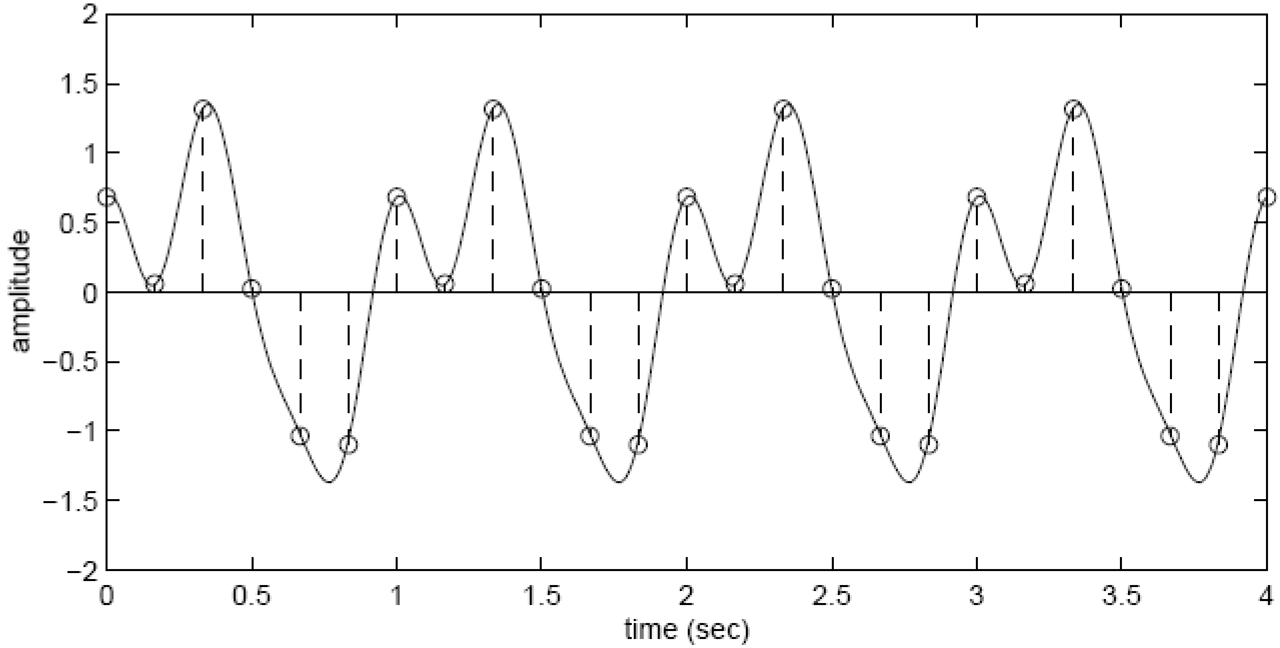
- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Can't distinguish between multiple possible signals
  - Problem known as **aliasing**

What about more complex signals?



- Fourier's theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample?

What about more complex signals?



- Fourier's theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample? **--> answer: 6 Hz**

What Data Rate can a Channel Sustain? How is Data Rate Related to Bandwidth?

- Transmitting N distinct signals over a noiseless channel with bandwidth B, we can achieve at most a data rate of

$$2B \log_2 N$$

- Nyquist's Sampling Theorem (H. Nyquist, 1920's)
  - B = highest frequency of signal
  - Sampling rate of 2B captures all information

Noiseless Capacity

- Nyquist's theorem: $2B \log_2 N$
- Example 1: sampling rate of a phone line
  - B = 4000 Hz
  - 2B = 8000 samples/sec.
    - sample every 125 microseconds

Noiseless Capacity

- Nyquist's theorem: $2B \log_2 N$
- Example 2: noiseless capacity
  - B = 1200 Hz
  - N = each pulse encodes 16 levels
  - C = $2B \log_2 (N) = D \times \log_2 (N)$
    $= 2400 \times 4 = 9600$ bps

What else (Besides Noise) can Limit Maximum Data Rate?

- Transitions between symbols
  - Introduce high-frequency components into the transmitted signal
  - Such components cannot be recovered (by Nyquist's Theorem), and some information is lost
- Examples
  - Phase modulation
    - Single frequency (with different phases) for each symbol
    - Transitions can require very high frequencies

How does Noise affect these Bounds?

- In-band (not high-frequency) noise
  - Blurs the symbols, reducing the number of symbols that can be reliably distinguished.
- Claude Shannon (1948)
  - Extended Nyquist's work to channels with additive white Gaussian noise (a good model for thermal noise)

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

where

B is the channel bandwidth

S/N is the ratio between signal power and in-band noise power

Noisy Capacity

$$\mathrm{SNR(dB)} = 10 \log_{10}\left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}\right)$$

- Telephone channel
  - 3400 Hz at 40 dB SNR
  - $C = B \log_2 (1+S/N)$ bits/s
  - SNR = 40 dB

    $40 = 10 \log_{10} (S/N)$

    $S/N = 10{,}000$
  - $C = 3400 \log_2 (10001) = 44.8$ kbps

Summary of Encoding

- Problems: attenuation, dispersion, noise
- Digital transmission allows periodic regeneration
- Variety of binary voltage encodings
  - High frequency components limit to short range
  - More voltage levels provide higher data rate
- Carrier frequency and modulation
  - Amplitude, frequency, phase, and combinations
  - Quadrature amplitude modulation: amplitude and phase, many signals
- Nyquist (noiseless) and Shannon (noisy) limits on data rates