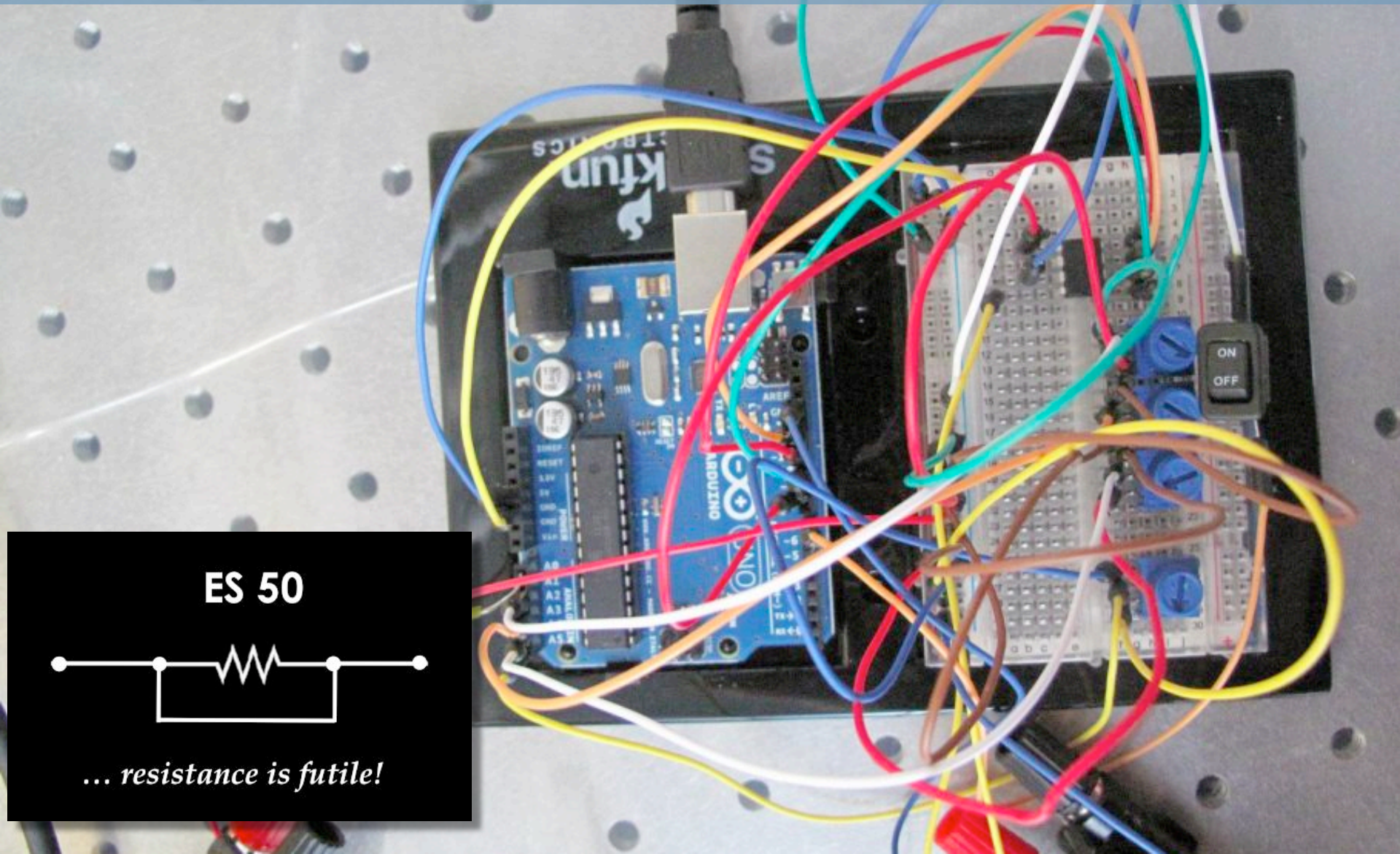
ES 50: Introduction to Electrical Eng.

Explore EE, satisfy a Gen Ed requirement & have fun



ES 50

… resistance is futile!

Lecture 20: Communication: sending information over long distances

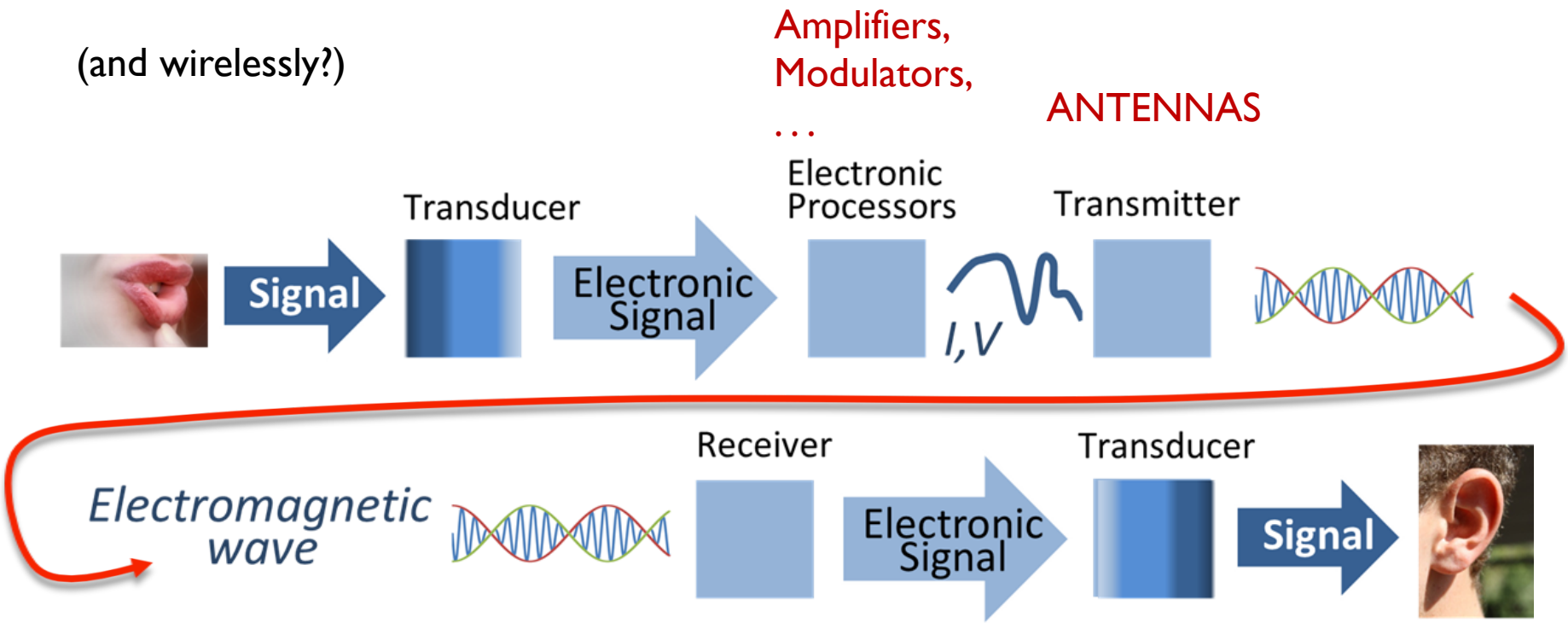
ES 50: Introduction to Electrical Engineering

How do we send information over long distances, quickly, reliably, efficiently…

(and wirelessly?)

Amplifiers,
Modulators,
…

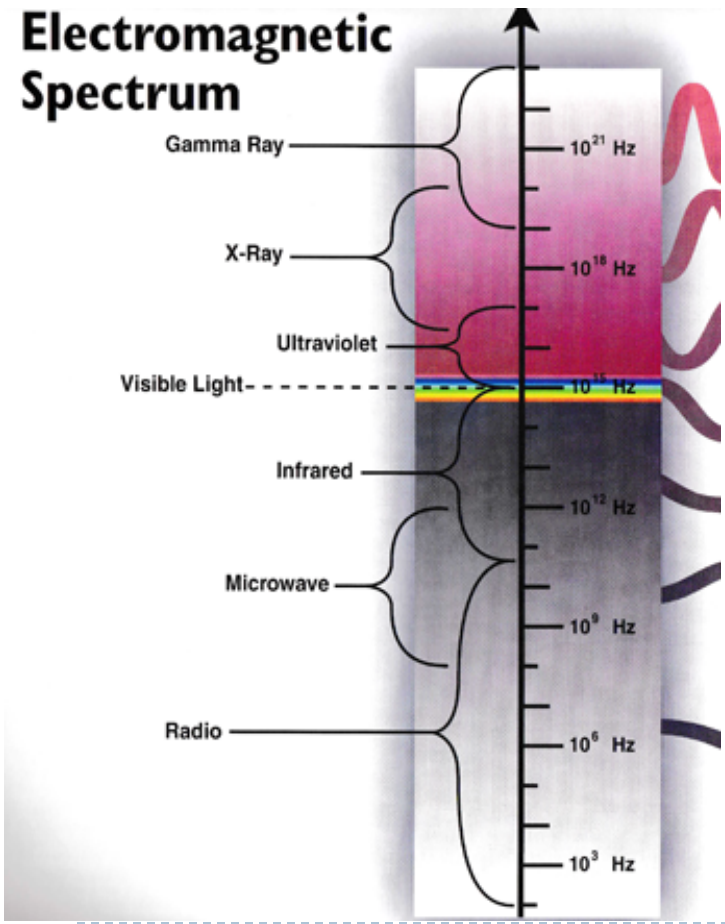
ANTENNAS

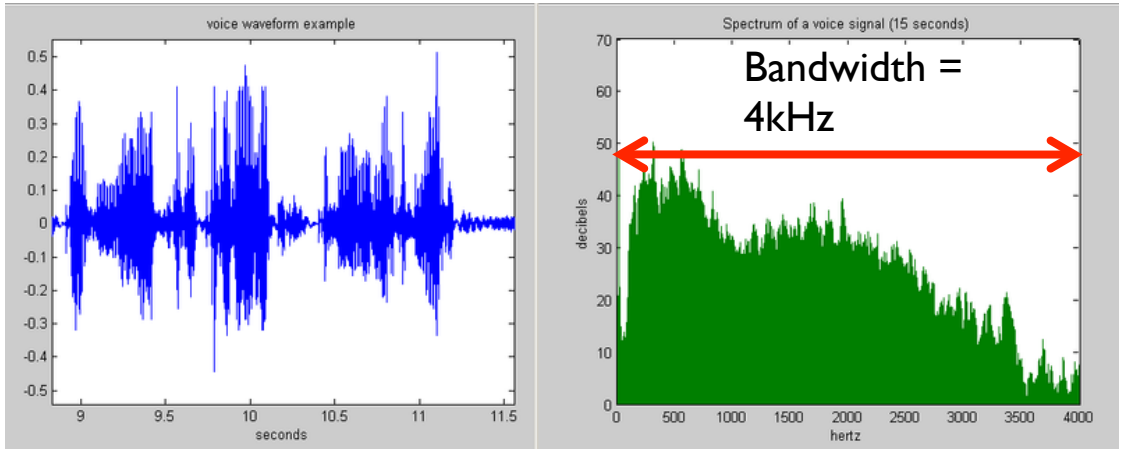


ANTENNAS

Tuner (select out particular signals)
Amplifiers
Demodulators

Transmitting speech wirelessly





Waveform of 'speech'

- Telephone-quality speech contains frequencies from 200 to 3000 Hz
- For efficient transmission and reception, antenna length should be ~ dimensions of the wavelength of the signal

To transmit a voice signal wirelessly, how long should the antenna be?

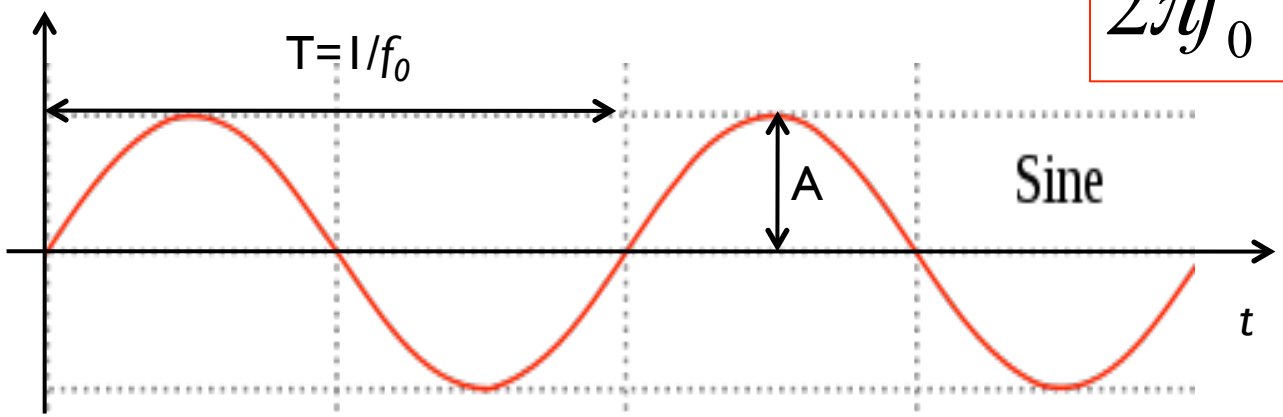
We'll first look at transmission of Analog Signals: Time and Frequency Domain

$$f(t) = A \cdot \sin(2 \cdot \pi \cdot f_0 \cdot t)$$

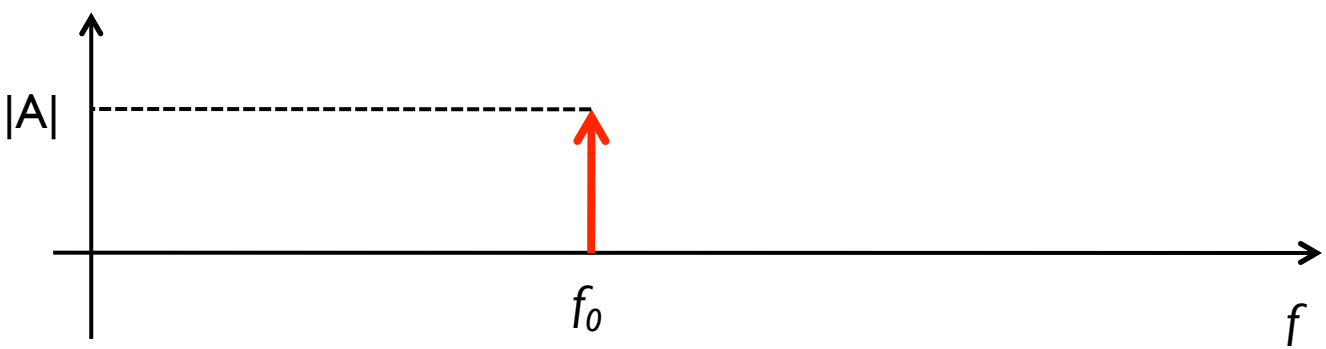
A – amplitude, f_0 – frequency, $T = 1/f_0$ = period

$$2\pi f_0 = \omega_0$$

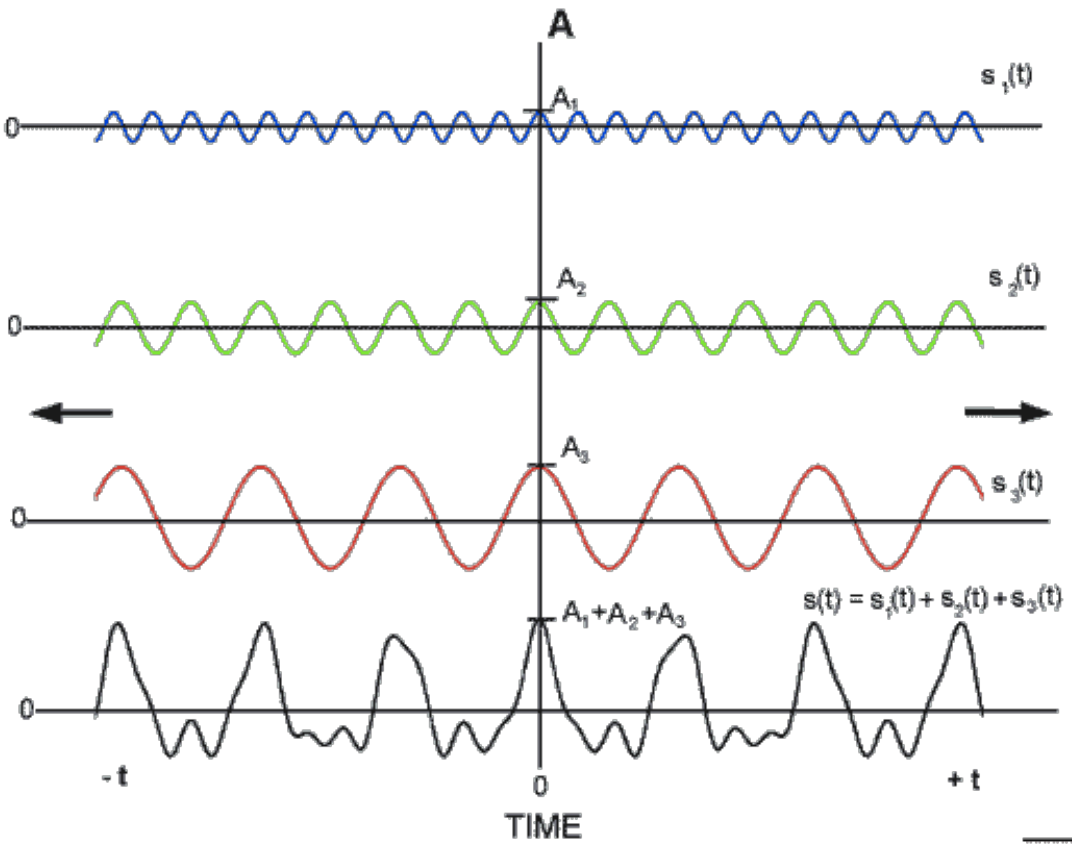
Time Domain



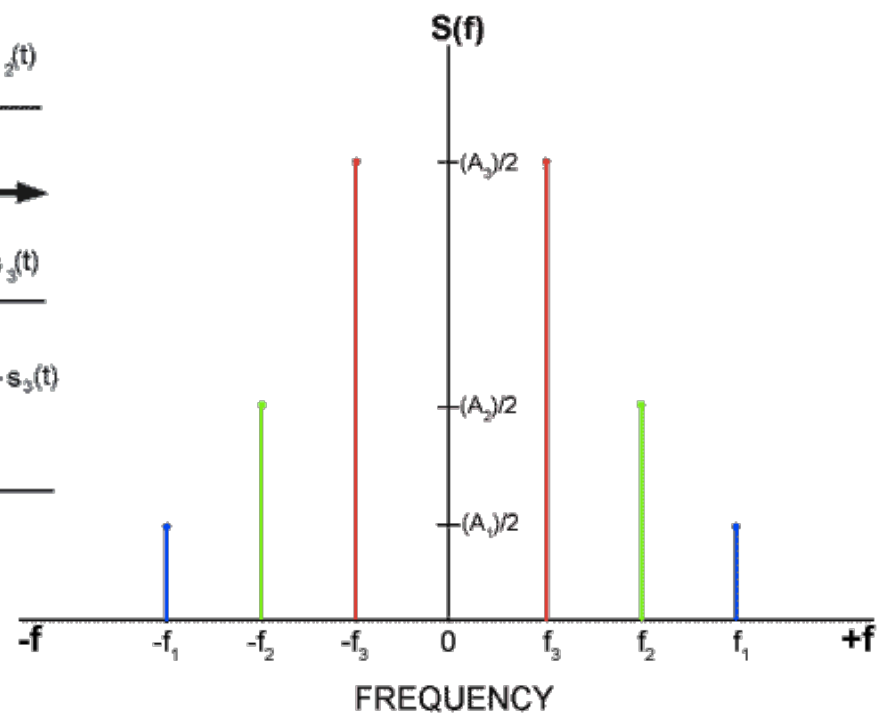
Frequency Domain



Analog Signals: Time and Frequency Domain



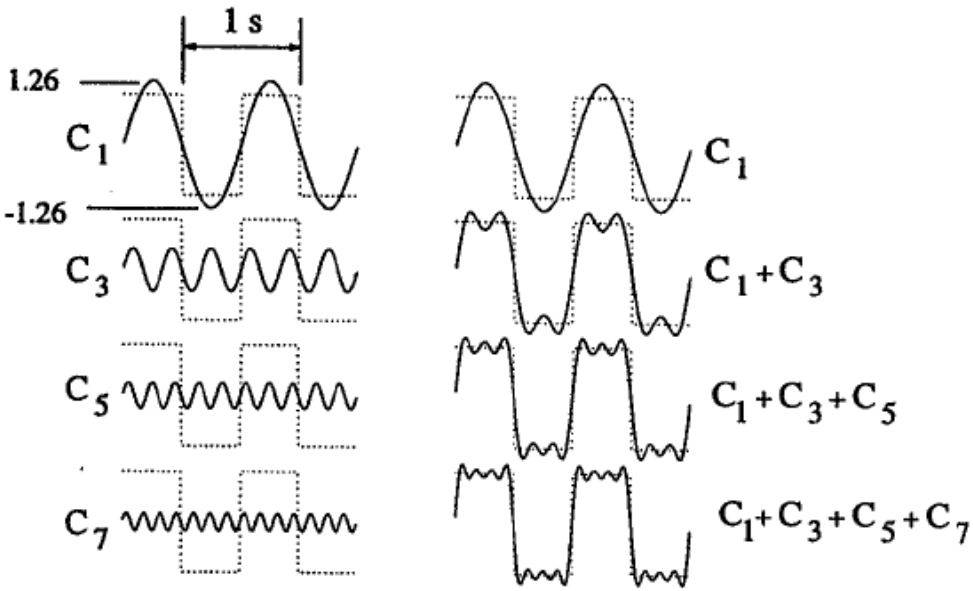
A way of looking at the world in terms of frequencies

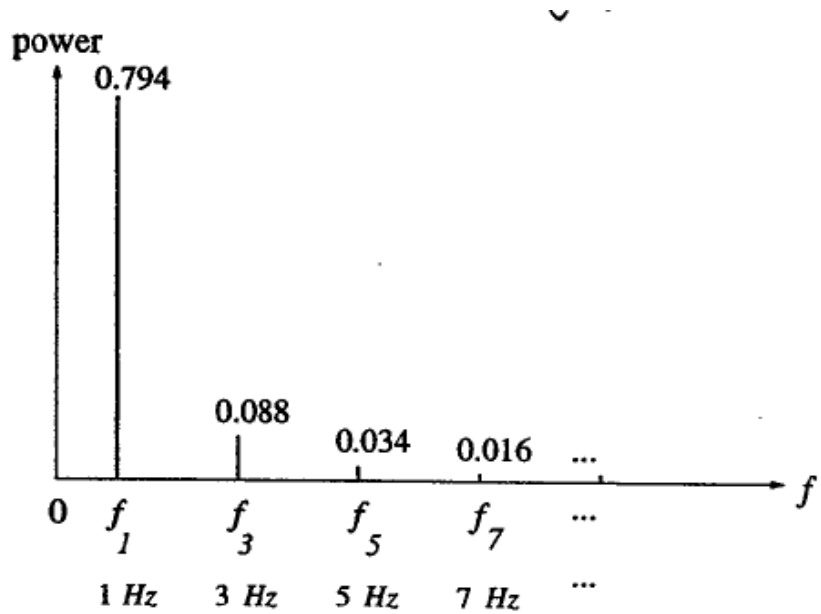


http://dagsaw.sdsu.edu/3.4.html

Analog Signals: Time and Frequency Domain

Frequency components of a square wave





- **Every time domain signal can be represented as a sum of sine and cosine waves**
- Mathematical formalism used to achieve this is called **Fourier transform**
- Fourier transform and frequency domain representation are VERY powerful and important! (and the details are beyond the scope of this course ☺)

How large an antenna would you need…?

frequency

velocity of light

$$\lambda f = c$$

wavelength

$$\lambda = \frac{c}{f} = \frac{3x10^8 m/s}{200 Hz} = 1500\ km$$

$$\lambda = \frac{c}{f} = \frac{3x10^8 m/s}{3000 Hz} = 100\ km$$

Transmitting voice frequencies alone

What electromagnetic wave frequency is well-matched to an antenna with a length of 10 centimeters?

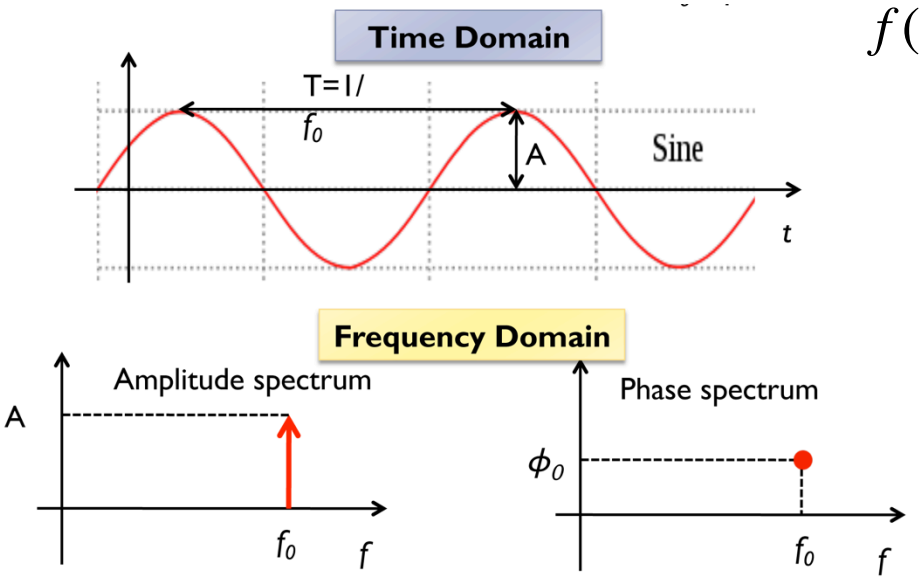
$$f = \frac{c}{\lambda} = \frac{3x10^8 m/s}{10\ cm} = 3x10^9\ Hz = 3GHz$$

So, the take-away message is….

Achieving the best match of signal (source) to signal (propagation)

Speech (as is) is not well matched to wireless transmission, so…

- We take the source signal and use it to *modulate* a <u>carrier signal</u>
- The carrier signal is selected to match the physical characteristics of the medium within which information propagates (e.g., a shorter wavelength to match smaller antennae)



$$f(t) = A \cdot \sin(2 \cdot \pi \cdot f_0 \cdot t)$$

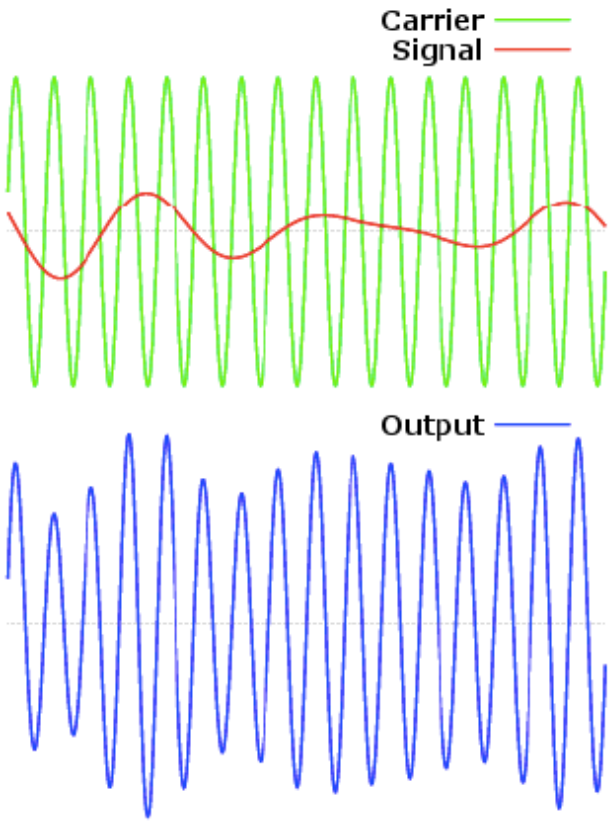
A – amplitude, f_0 – frequency,
$T=1/f_0$ = period

We'll look at all 3 modulations:
but AM is easiest for us to visualize

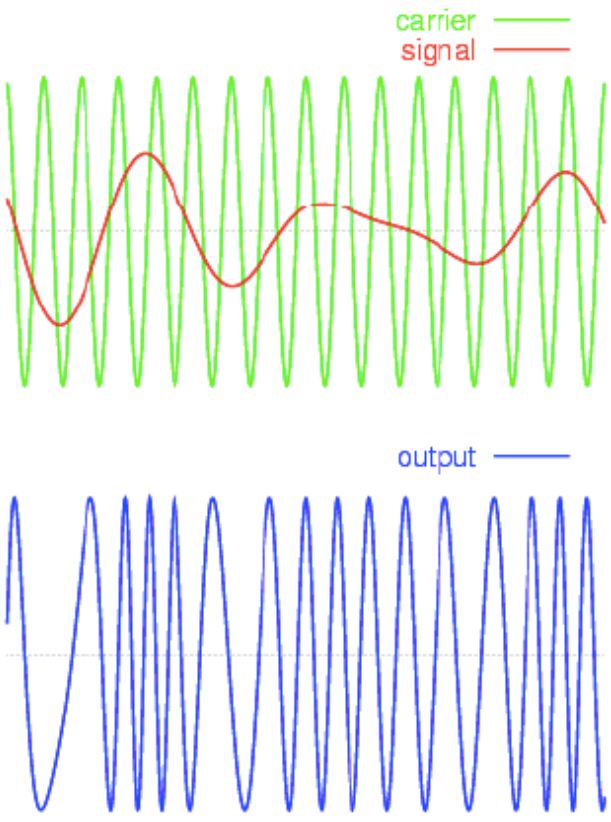
What attributes of this signal can we MODULATE?

- Amplitude ➔ AMPLITUDE MODULATION (AM)
- Frequency ➔ FREQUENCY MODULATION (FM)
- Phase ➔ PHASE MODULATION (PM)

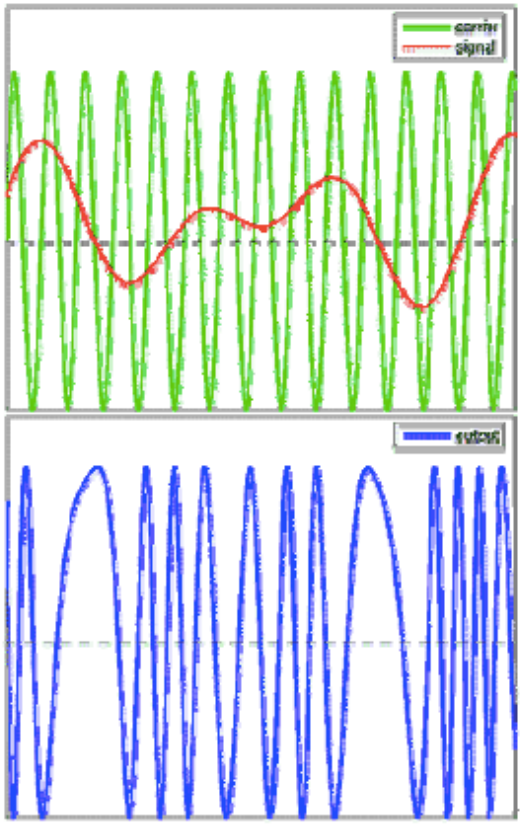
AM, FM, PM



AM



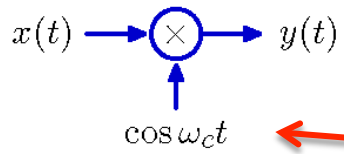
FM



PM

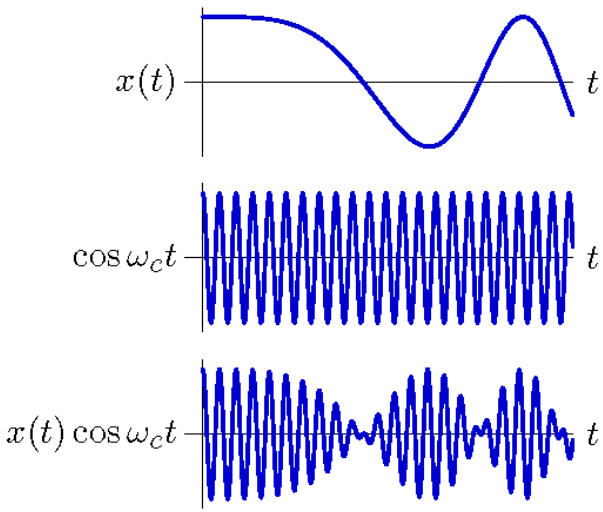
Amplitude Modulation (AM)

input signal
(information)



Output signal [modulated carrier signal]

Carrier signal



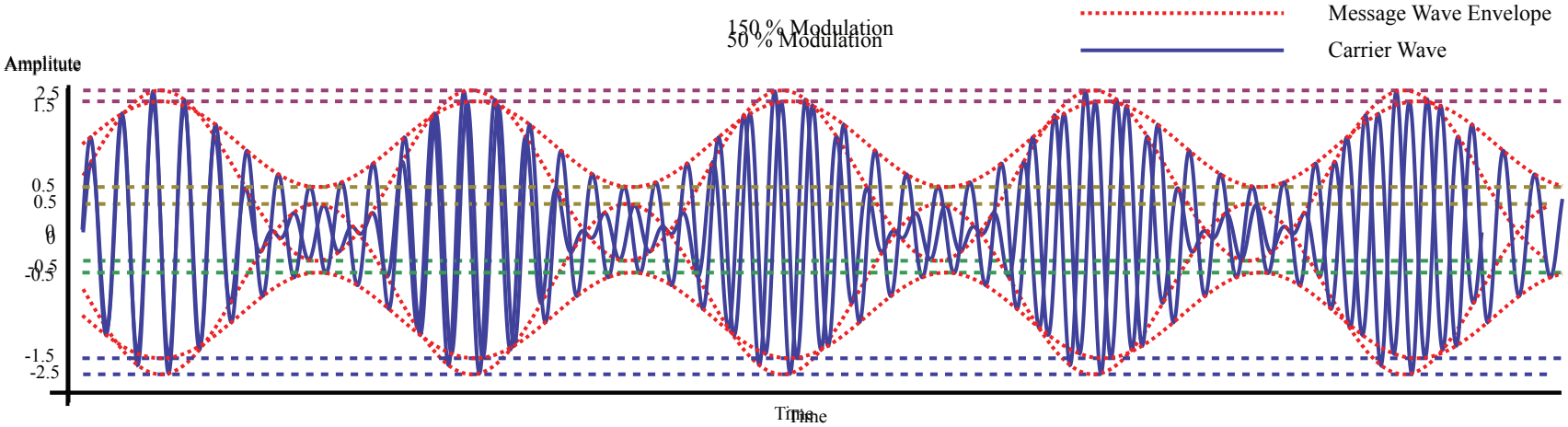
Input signal is used to <u>modulate the amplitude</u> of the carrier signal

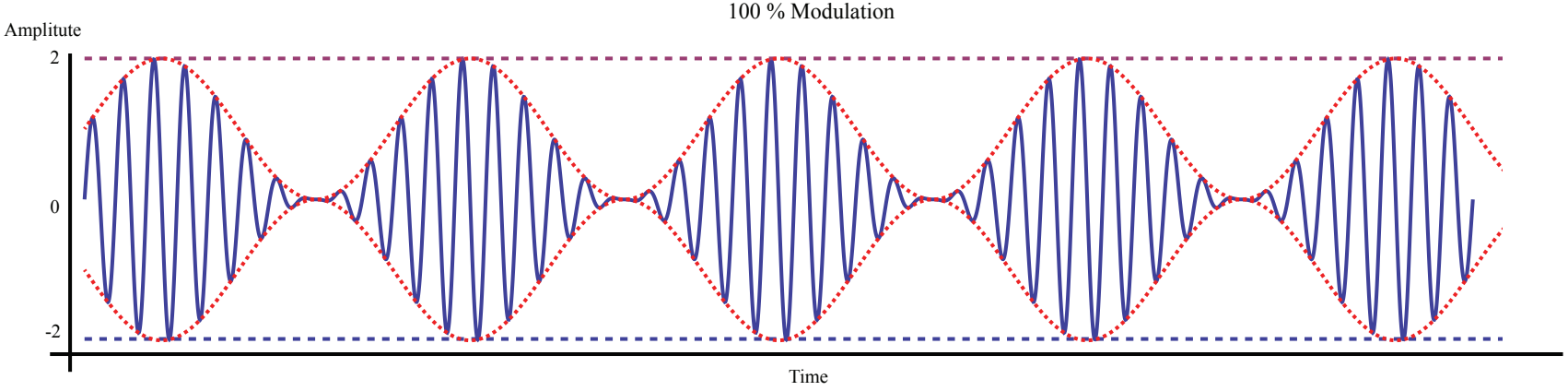
Suppose x(t) has a maximum voltage, V_m

The carrier signal has a maximum voltage, V_c

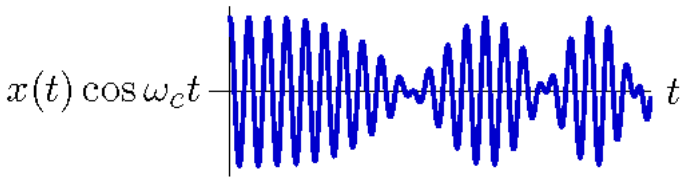
$$m = \text{modulation index} = \frac{V_m}{V_c}$$

Amplitude Modulation (AM)





Synchronous demodulation of AM signal

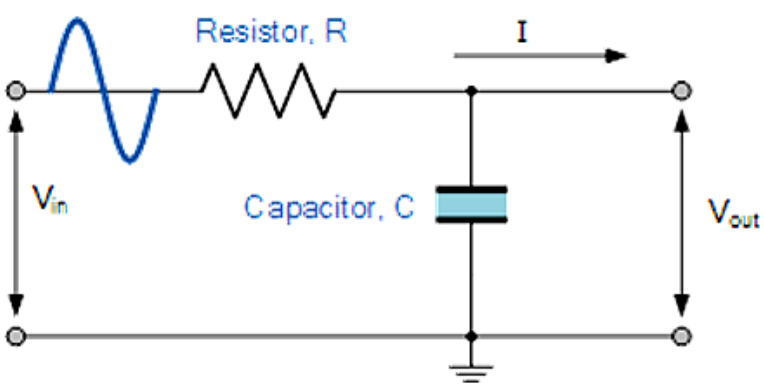


What is modulated must be <u>demodulated</u> (if we want to read the original message):
i.e., how do we *recover* the original signal x(t), having received y(t)?

Let's multiply the transmitted signal by a signal that has the <u>same carrier frequency:</u>

$$y(t) = x(t)\cos(\omega_c t)$$

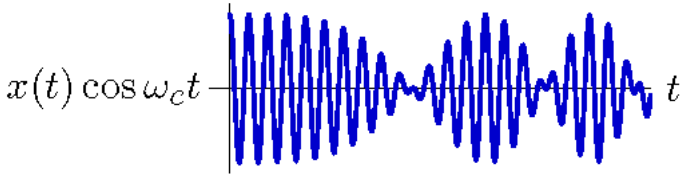
$$z(t) = y(t)\cos(\omega_c t) = x(t)\cos^2(\omega_c t) = x(t)[\frac{1}{2} + \frac{1}{2}\cos(2\omega_c t)]$$



Use a <u>low pass filter</u> to filter out the high frequency ($2\omega_c$) component, leaving you with x(t)/2 !

Also called a PRODUCT DETECTOR; the product of y(t) and $\cos(\omega_c t)$

Synchronous demodulation of AM signal

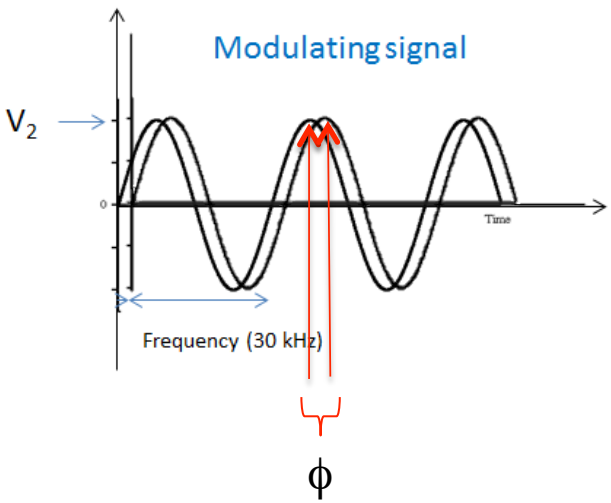


Over long distances, how can we be sure that there is no <u>shift in phase</u> between our local receiver signal and the original carrier signal?

$$y(t) = x(t)\cos(\omega_c t)$$

$$z(t) = y(t)\cos(\omega_c t) = x(t)\cos(\omega_c t)\cos(\omega_c t + \varphi)$$

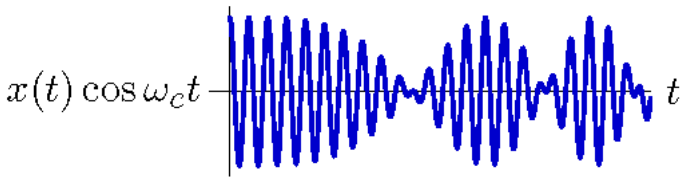
$$= x(t)[\frac{1}{2}\cos(\varphi) + \frac{1}{2}\cos(2\omega_c t + \varphi)]$$



If $\phi = \varphi/2$, then after filtering, the output is 0!
If ϕ changes with time, the signal 'fades'

Can try to 'lock' the phase (phase-lock loop), OR send an appreciable component of the carrier *with* the message

AM signal *with* carrier



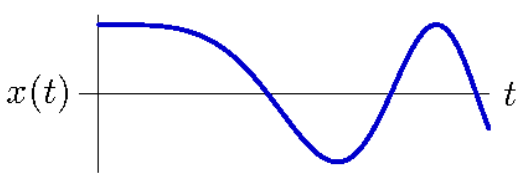
To ensure you have a good calibration for the original signal

$$y(t) = x(t)\cos(\omega_c t)$$

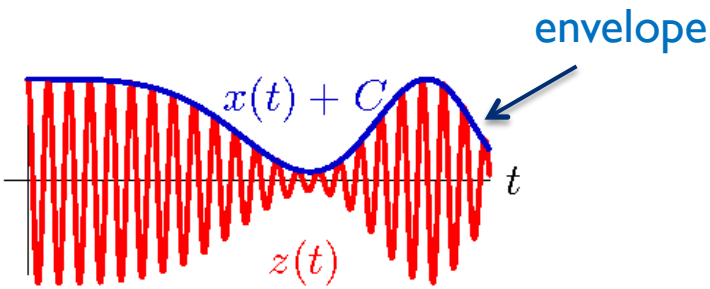
$$z(t) = x(t)\cos(\omega_c t) + C\cos(\omega_c t) = [x(t) + C]\cos(\omega_c t)$$

Adding the carrier signal is equivalent to shifting the DC value of x(t)

Shifting the DC value sufficiently, we can then *demodulate* by extracting the 'envelope' of the signal, and removing the high frequency components

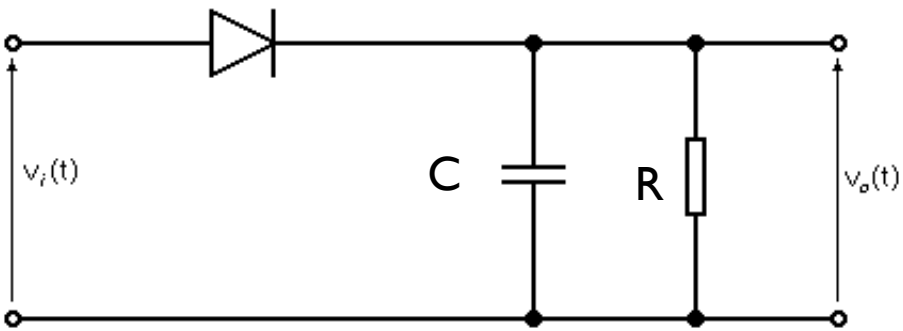


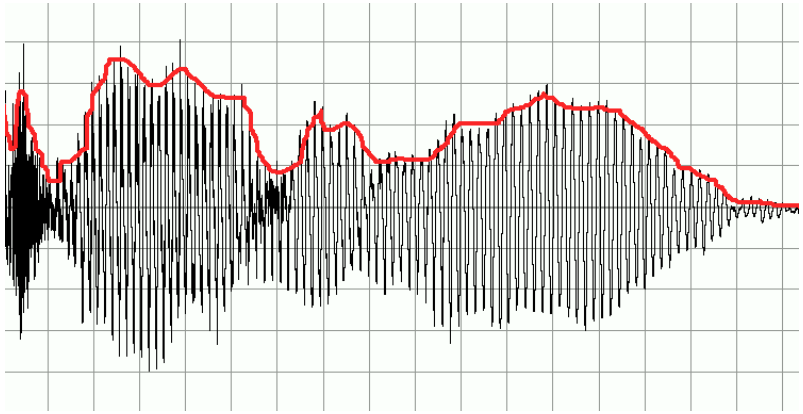
Original signal



Envelop Detection

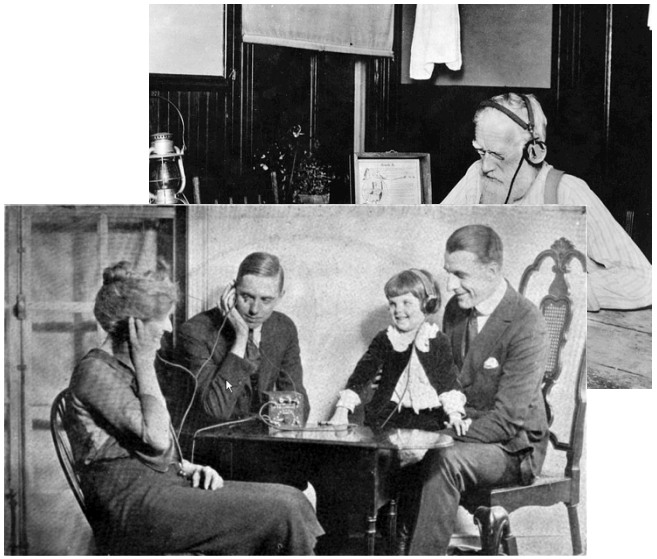
- Takes a high-frequency signal as input and provides an output which is the "envelope" of the original signal.
- One of earliest modulation and demodulation technique used in radio.
- Simple, inexpensive circuit (a story associated with David Sarnoff, broadcast radio and the sinking of the Titanic)
- Diode passes current for only positive voltage, capacitor charges up to peak value of signal: as signal falls, diode is reverse biased and capacitor discharges through resistor





Fun Facts about Amplitude Modulation

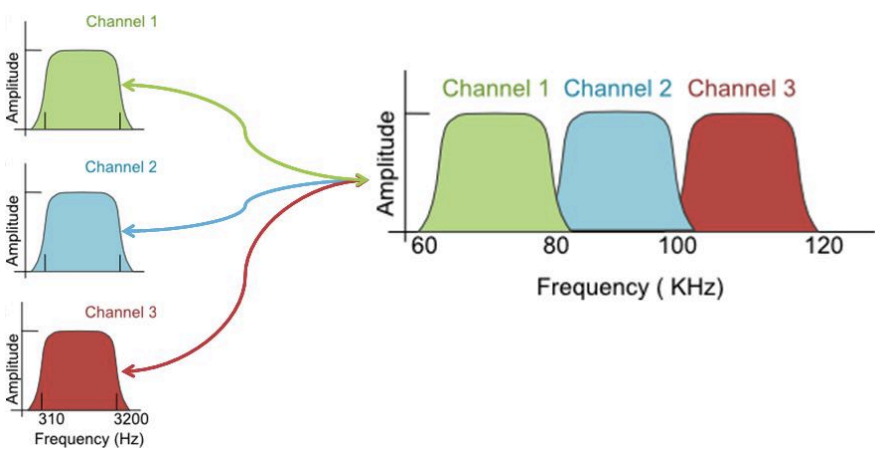
- First AM transmission on Dec 23, 1900
  - Morse code, not speech, amplifier technology was poor
- Amplification via Vacuum Tube was discovered in 1912
  - Enabled low-cost oscillators & amplifiers which could drive speakers
- 1919-1922 explosive growth in radio consumption
  - 1922 WEAF in NY, first radio commercial
- 20's, 30's, & 40's were the Golden Age of Radio
  - Radio dramas, sit coms, quiz shows, news, Roosevelt's Fireside Chats
  - Best quality audio before the LP
- The transistor radio fundamentally changed listening habits in the 1960s
  - The transistor was invented in 1946 – stay tuned next week for devices ☺!!! Same bat time, same bat channel
- Began to suffer fierce competition from TV & FM radio
  - Since the 80's & 90's, AM stations have largely been relegated to news, sports, religious, & talk radio
  - FM has become the preferred medium for music

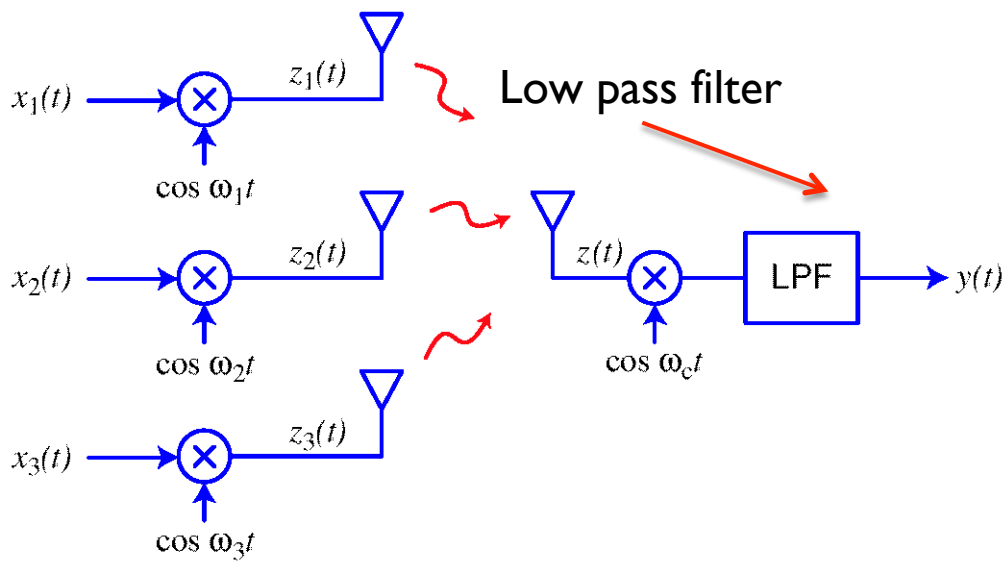


Amplitude Modulation (AM)

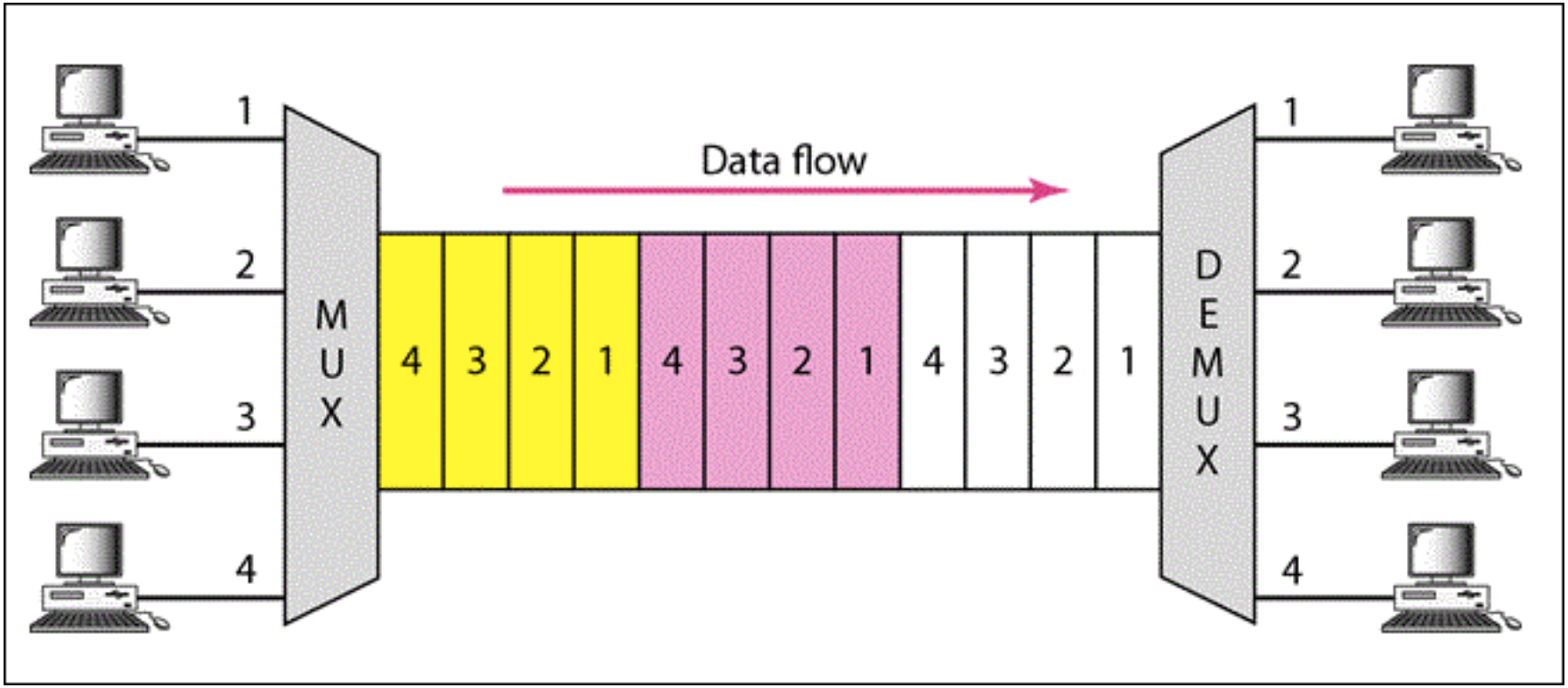
- One of the earliest modulation schemes to be implemented
- Perhaps the easiest modulation scheme to envision.
- Susceptible to background noise.
- Inefficient in power usage; at least two-thirds of the power is concentrated in the carrier signal, which carries no useful information (beyond the fact that a signal is present).

But even AM modulation, at different carrier frequencies, allows FREQUENCY-DIVISION MULTPLEXING





An alternative: Time-Division Multiplexing



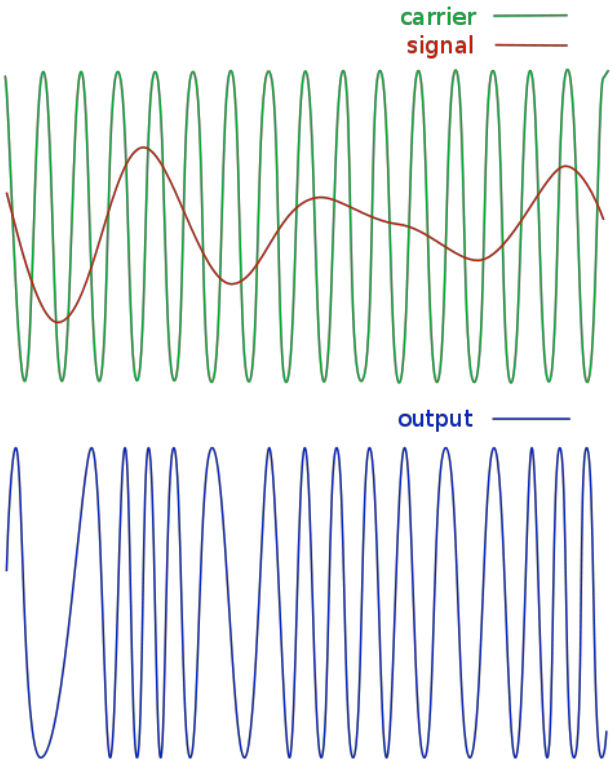
http://www.lastdaystudy.com/

Frequency modulation

- Conveys information over a carrier wave by varying its instantaneous frequency.
- FM is more complex than AM for both modulation and demodulation
- More robust to noise than AM, better power characteristics

$$y(t) = \cos\left(\omega_c t + \underbrace{k\int_{-\infty}^{t} x(\tau)\,d\tau}_{\omega_\mu(t)}\right)$$

$$\omega_i = \omega_c + \frac{d}{dt}\phi(t) = \omega_c + kx(t)$$

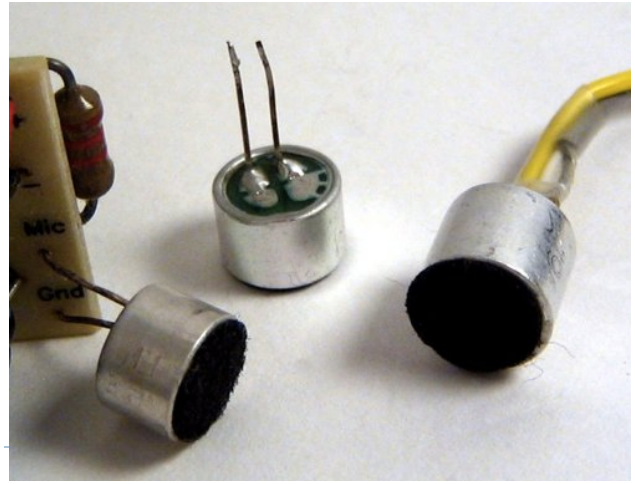


Characteristics of FM:

- Amplitude remains constant
- Better SNR as compared to AM, lower power
- More complex modulation and demodulation
- Magnetic tape storage (VHS), FM radio, early digital synthesizers, analog TV sound, radar, etc.

Fun facts about Frequency Modulation

- First patented in 1933
  - Early FM stations in the 40's-60's were "alternative" genres or AM simulcasts
- First stereo FM station in 1961, WGFM
- 60's & 70's led the Album Oriented Rock revolution which led to the prevalence of FM over AM
  - Today AM in the medium for alternative radio stations while FM is the mainstream medium
- Commonly used in microphone "bugs"
  - TV channel 6 (< 87.9 MHz) and/or aviation frequencies (>108 MHz)



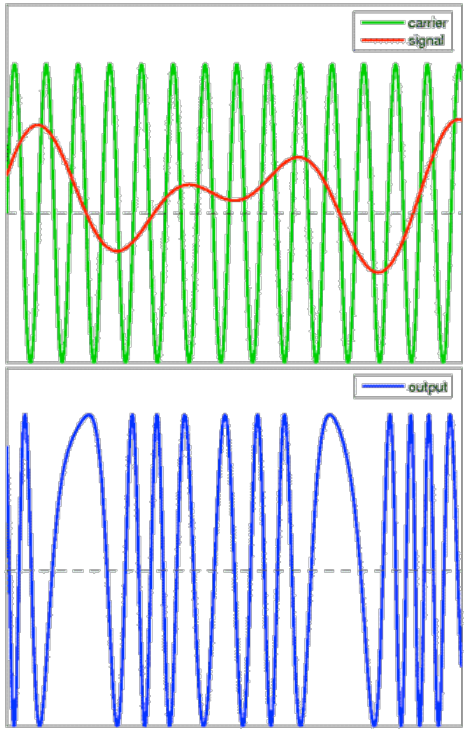
Phase Modulation

- Represents information as variations in the instantaneous phase of a carrier wave.
- Unlike FM, PM is not very widely used for radio transmissions as it require more complex receiving hardware. PM is used, however, in digital music synthesizers.

$$y(t) = \cos(\omega_c t + kx(t))$$

Carrier frequency

Information (modulation) signal is part of the phase

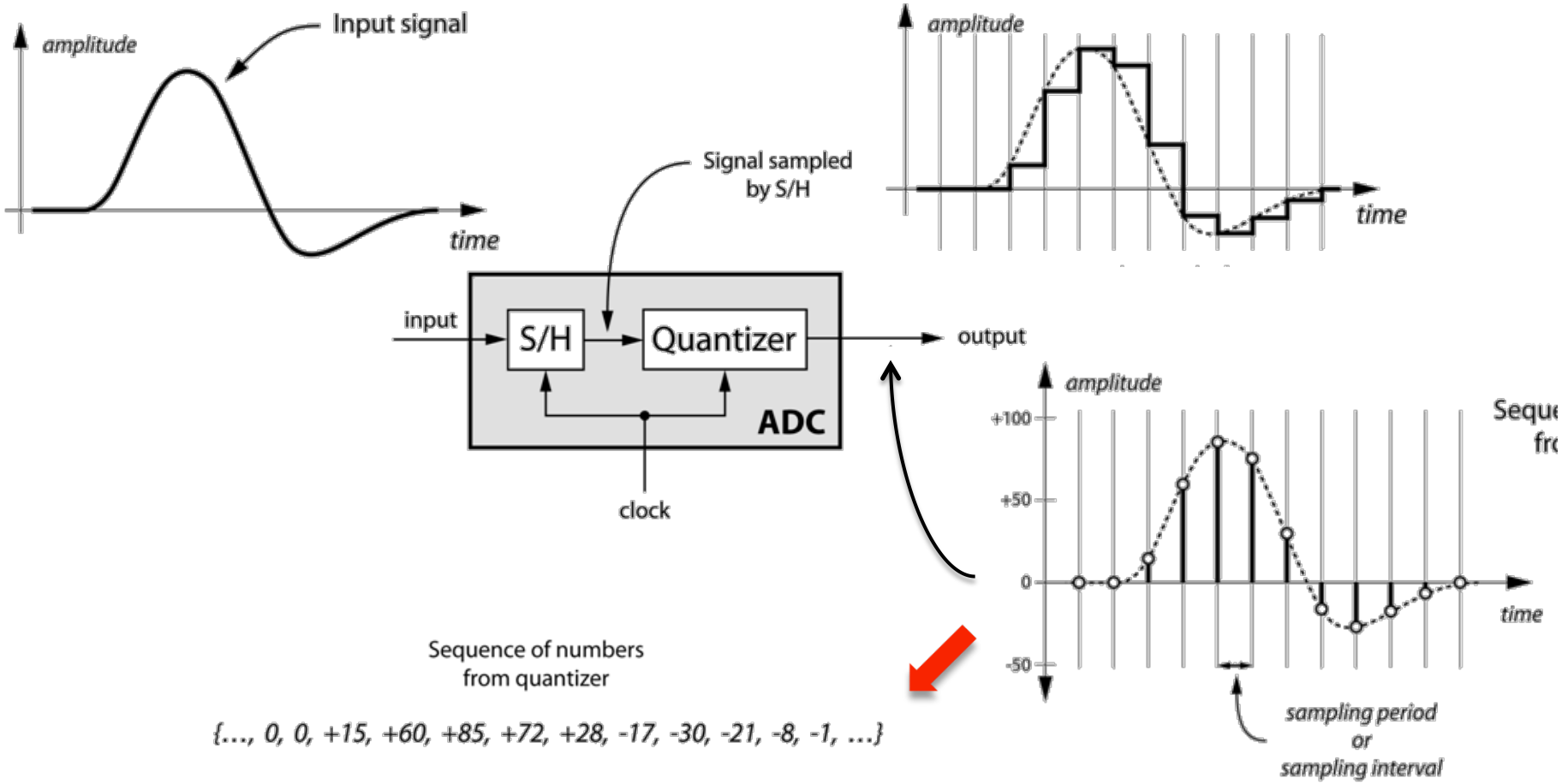


Characteristics of PM:

- Common in radio transmission, specifically digital information like WiFi, GSM, satellite television

Digital Signals

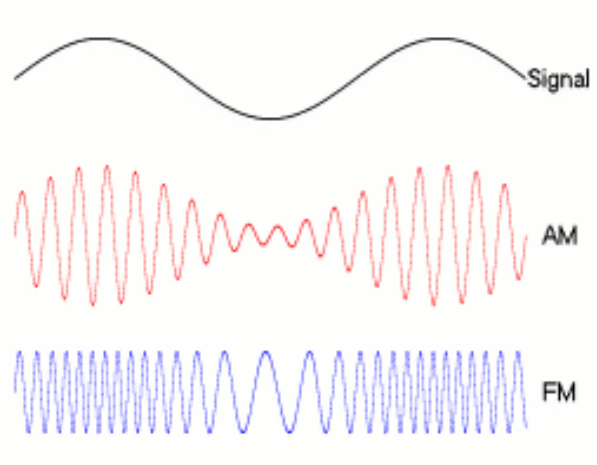
- Many digital signals come from analog signals!



So now what do we do with these digital signals?

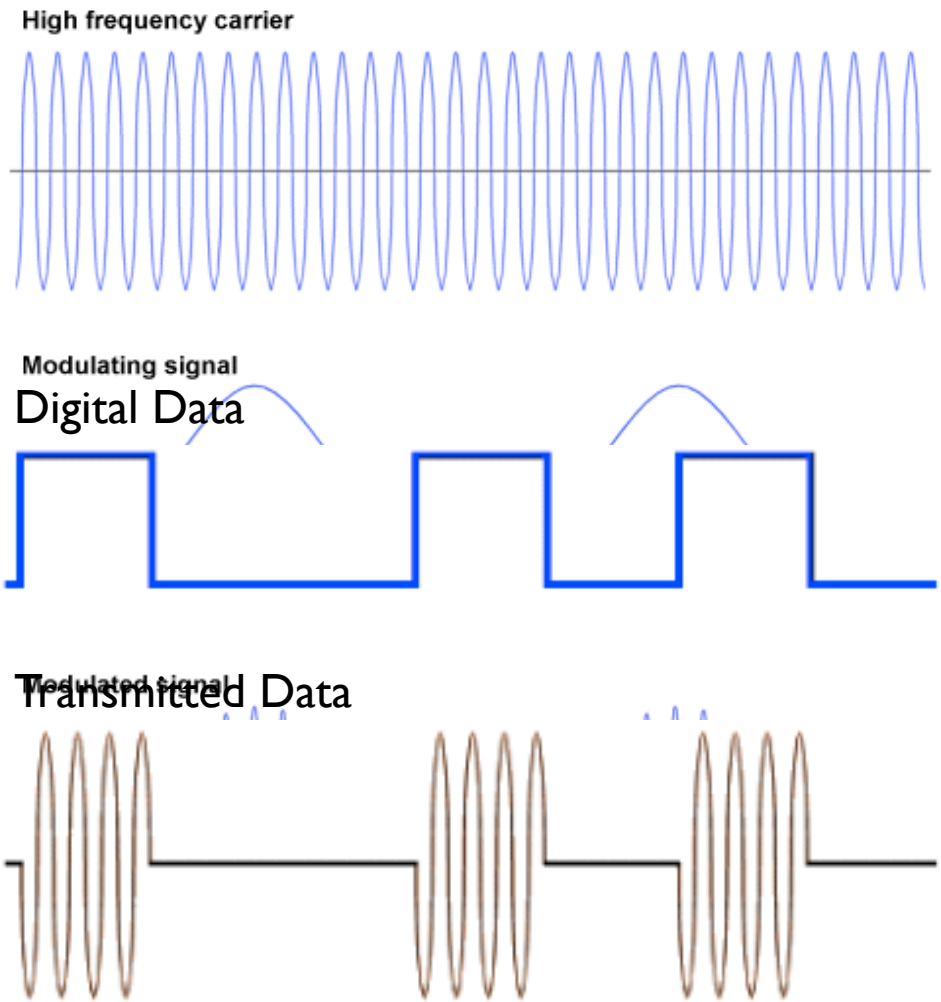
Modulation of Digital Signals

- We live in an analog world yet we want to send & receive digital information
- We must represent digital information using an analog medium
  - Analog channels (or media): voltage in a wire, E & B field for E-M waves (both radio & light!)
  - This is called Keying!!!
- Four common ways to key
  - Amplitude-shift keying (ASK)
    - A form of Amplitude Modulation
  - Frequency-shift keying (FSK)
    - A form of Frequency Modulation
  - Phase-shift keying (PSK)
    - A form of Phase Modulation
  - Quadrature Amplitude Modulation (QAM)
    - A fun mixture to come



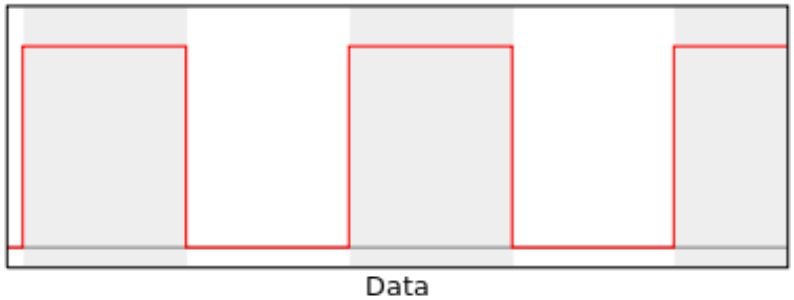
Amplitude Shift Keying

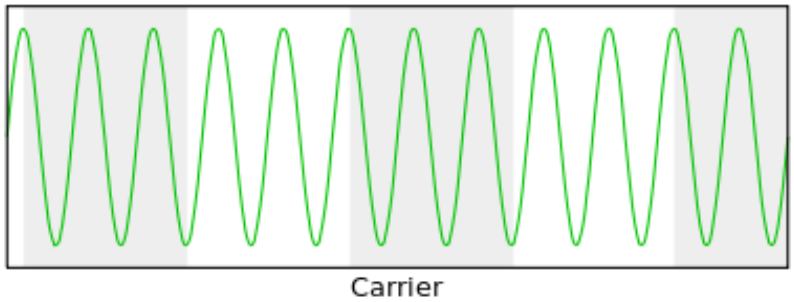
- Similar to AM
  - So let's quickly revisit AM
  - Transmitted signal = low frequency data x high frequency carrier
- Now with digital data
  - Simple two level case
  - Morse Code
  - Can use additional amplitudes to encode more bits of data
- Transmitters
  - LEDs use 1: on, 0: off
  - Lasers use 1: high amplitude, 0: low amplitude
- Still susceptible to noise like AM

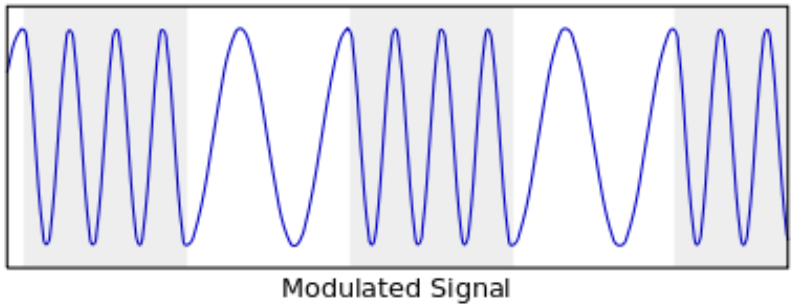


Frequency Shift Keying

- Now let's modulate the frequency, like FMs
  - Audio FSK uses a carrier wave which is audible
  - Two tones: 1: modified tone, 0: base tone
  - Used in computer modem, fax machine
- Audio FSK can also be transmitted via radio
  - Emergency broadcast system, NOAA weather radio
  - Also works in most AC coupled systems, those that pass music & speech
- More efficient Morse Code
  - Two tone as opposed to long & short tones, reduces transmission time
- Also used in wired Caller ID, GSM (T-Mobile & ATT)







Phase Shift Keying

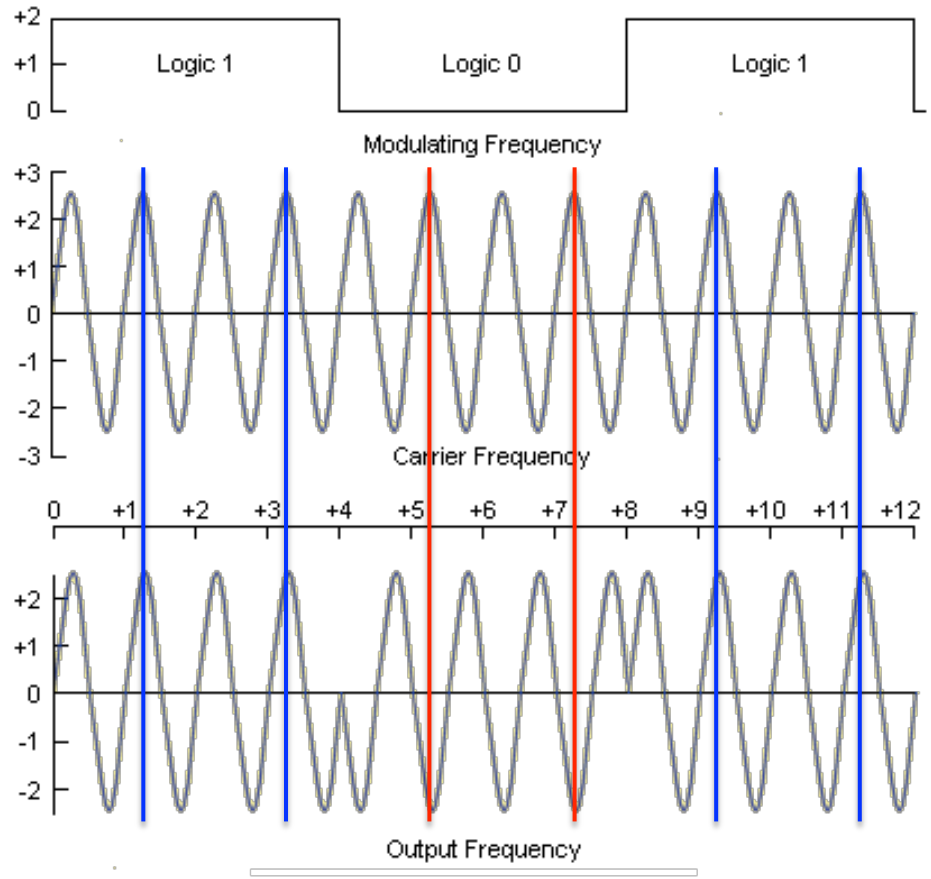
- Wait wait…we are encoding the digital data in the phase of the signal

$$y(t) = \cos\left(\underbrace{\omega_c t + \phi_c}_{\text{Carrier}} + \underbrace{\phi_m(t)}_{\text{Signal}}\right)$$

- Let's look a simple 2 level signal
  - Logic 1: 0° shift, logic 0: 180° shift
  - Let's take a look at this in terms of complex numbers…
- Any wave (sine or cosine) can represented by a complex exponential number

$$e^{ix} = \cos(x) + i\sin(x)$$

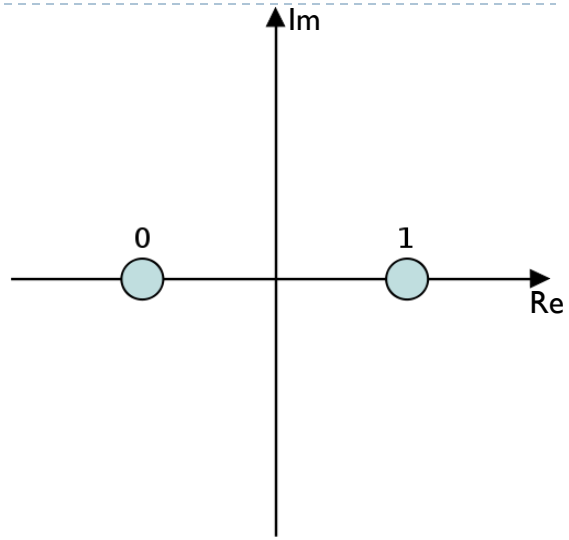
- This means all (most) waves have both real & imaginary components

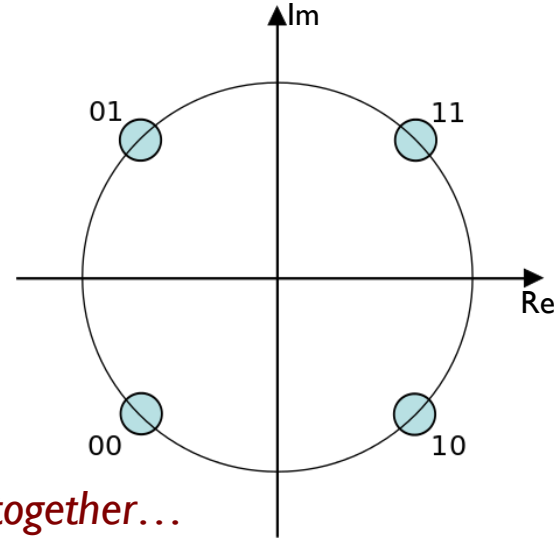


So let's consider how we can represent this phase data in another way

Phase Shifts in the Complex Plane

- So how can logic 1 & 0 represented in the complex plane
  - 1: ϕ_m= 0° shift = cos(0°)
  - 0: ϕ_m= 180° shift = cos(180°)
- What happens if we encode 2 bits?
  - 11: cos(0°) + i sin(0°) = 0 + i 0
    - No phase shift
  - 00: cos(180°) + i sin(180°) = -1 - i 1
    - Inversion in both real & imaginary parts
  - 10: cos(0°) + i sin(180°) = 0 - i 1
    - No change to real part, inversion in imaginary part
  - 01: cos(180°) + i sin(0°) = -1 + i 0
    - Inversion in real part, no change to imaginary part

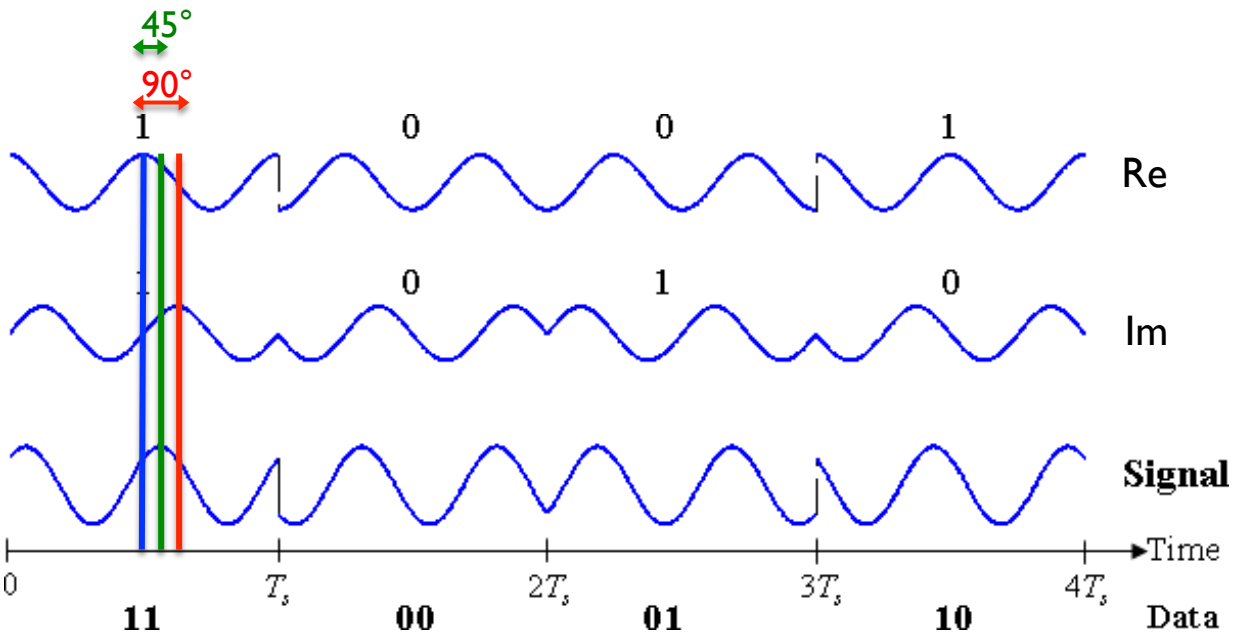


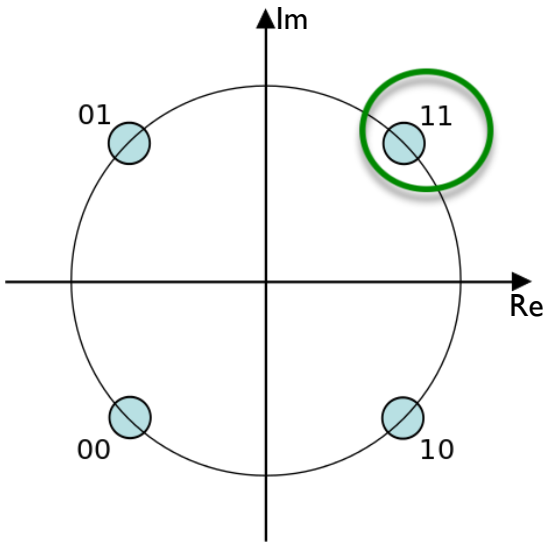


We can also see this change by adding the cosine & sine waves together…

Phase Shifts in the Waves

- Let's see what these changes really look like in the time domain…





$$\mathrm{Re}\left(e^{ix}\right) = \cos(x)$$

$$\mathrm{Im}\left(e^{ix}\right) = \sin(x)$$

$$e^{ix} = \cos(x) + i\sin(x)$$

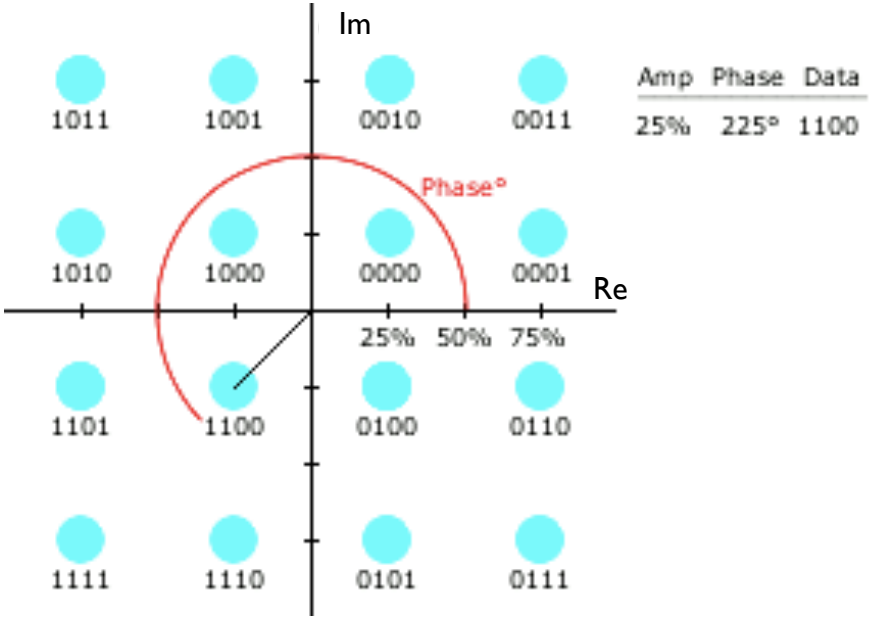
Four data phases is called quadrature phase shift keying, what about more bits?

Let's look at 4 bits, 16 values

- So we could have 16 equal phase points around the circle
  - That would be hard to resolve in phase angle
  - Only 22.5° difference if no errors are present
- Instead let's modulate the amplitudes of the cosine & sine functions individually

$$z(t) = x(t)\cos(\omega t) + i\, y(t)\sin(\omega t)$$

  - By changing relative amount of Re & Im parts, in effect we are changing the ***phase*** as well as the ***input power***!!!



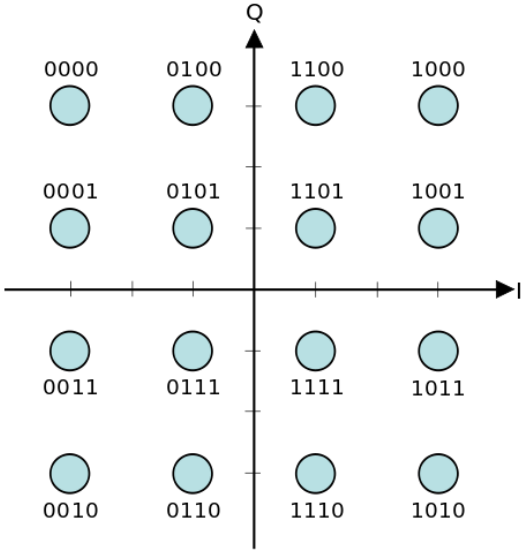
This is called Quadrature Amplitude Modulation (QAM)

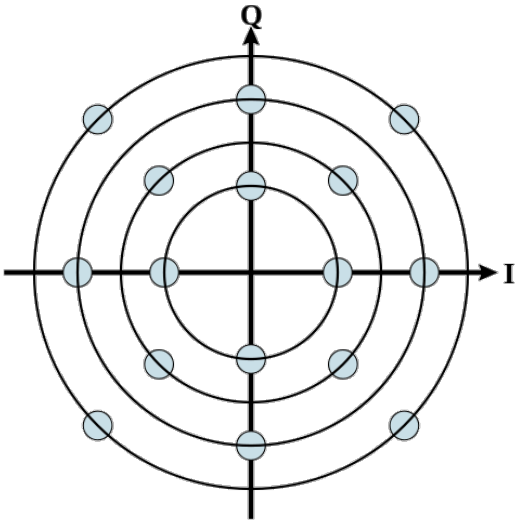
Quadrature Amplitude Modulation (QAM)

- In QAM we modulate the amplitudes of "basis" functions

$$z(t) = x(t)\cos(\omega t) + i\, y(t)\sin(\omega t)$$

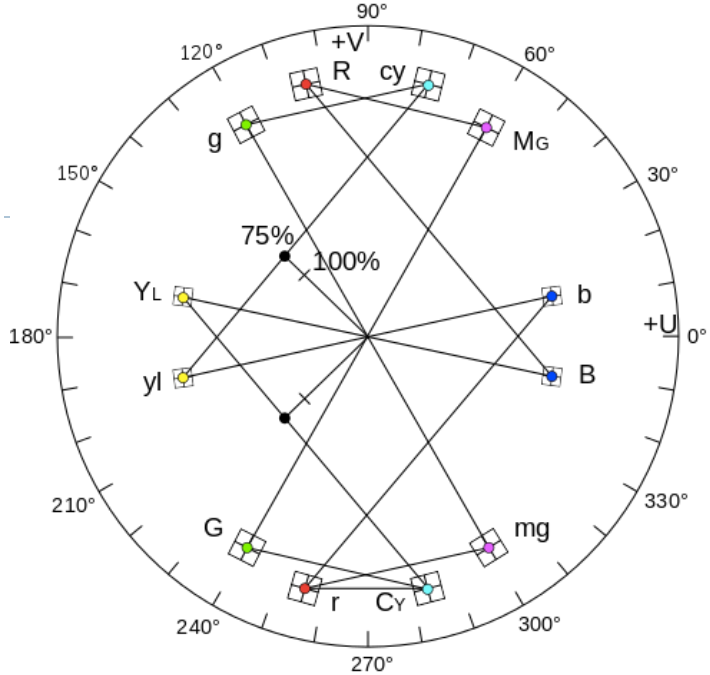
  - The has the effect of changing the phase in the composite transmitted signal
- We don't have to use a rectangular array of signal points
  - In fact, a circular array is more power efficient
  - Unfortunately, its much harder to demodulate

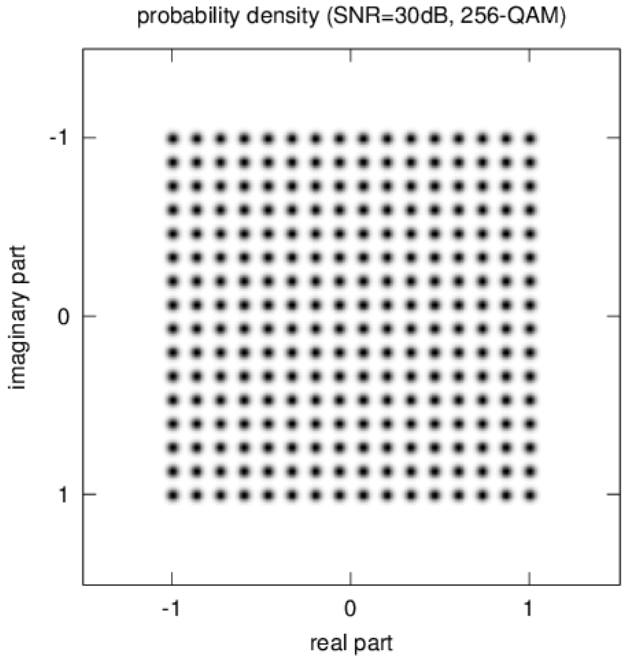




Applications of QAM

- Analog QAM
  - PAL & NTSC TV both use QAM
- Digital QAM
  - 64-QAM (8 bit) & 256-QAM (16 bit) are both commonly used in digital cable & cable modems
  - Very high density applications like 500 Mbps powerline ethernet use 4096-QAM

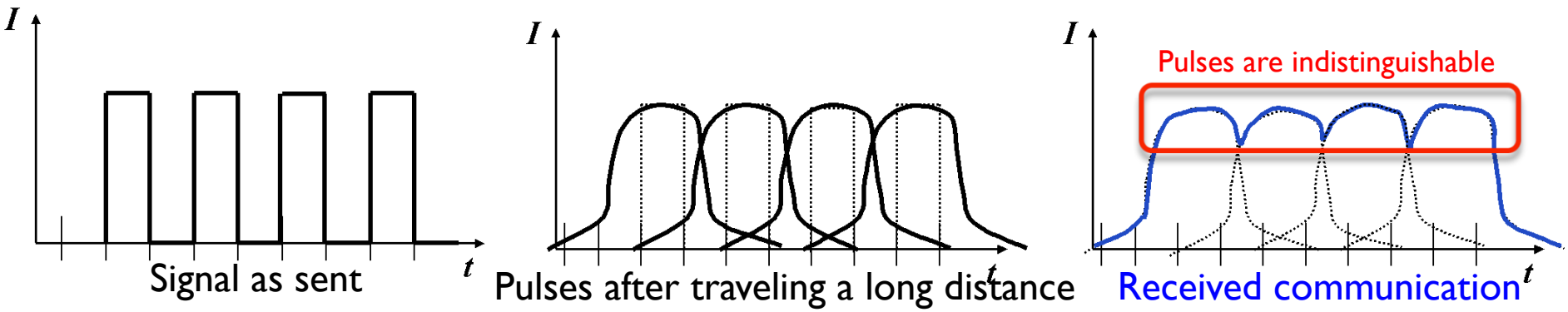




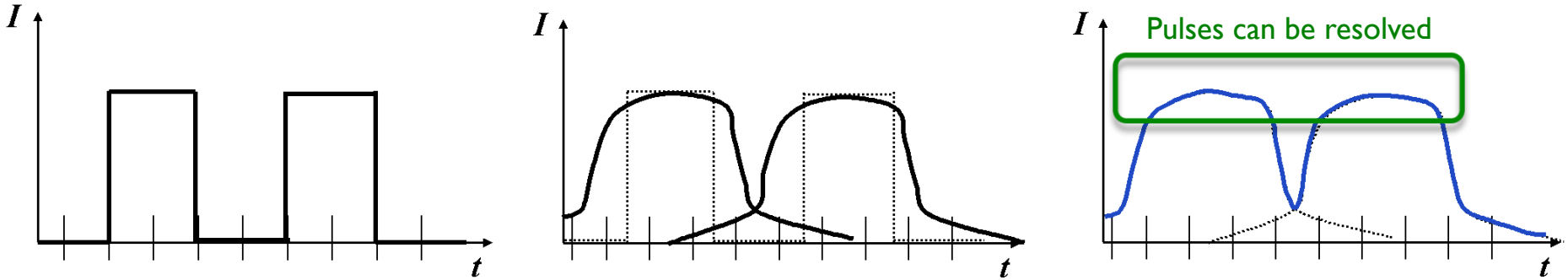
Noise…in the real world

- When we send a signal across a channel (copper wire, optical fiber, free space, etc.) noise will be added to the system
  - Some random environmental noise (later)
  - Also systematic dispersion, the decay of power being transmitted

High Bitrate Signal



Low Bitrate Signal



Noise…in the real world

- Gaussian (Thermal) Noise
  - Due to the thermal agitation of electrons in a conductor
  - Present in all electronic devices transmission lines
  - Distributed uniformly across the frequency spectrum, often referred to as white noise
  - It cannot be eliminated & limits overall system performance
- Intermodulation Noise
  - Occur if signals at different frequencies share the same transmission line
  - It results in signals that are the sum or difference of the original signals

- Crosstalk
  - When you hear someone else's conversation while using the telephone
  - Due to electrical coupling between two or more transmission paths (such as adjacent twisted-pair cables)
- Impulse Noise
  - Consists of random pulses (or spikes) of noise, usually of short duration & relatively high amplitude
  - Causes include external E-M disturbances: lightning, vehicle ignition systems, heavy-duty electrical equipment, etc.
  - Only a minor annoyance for analog systems such as a telephone
  - The primary cause of errors in digital communication

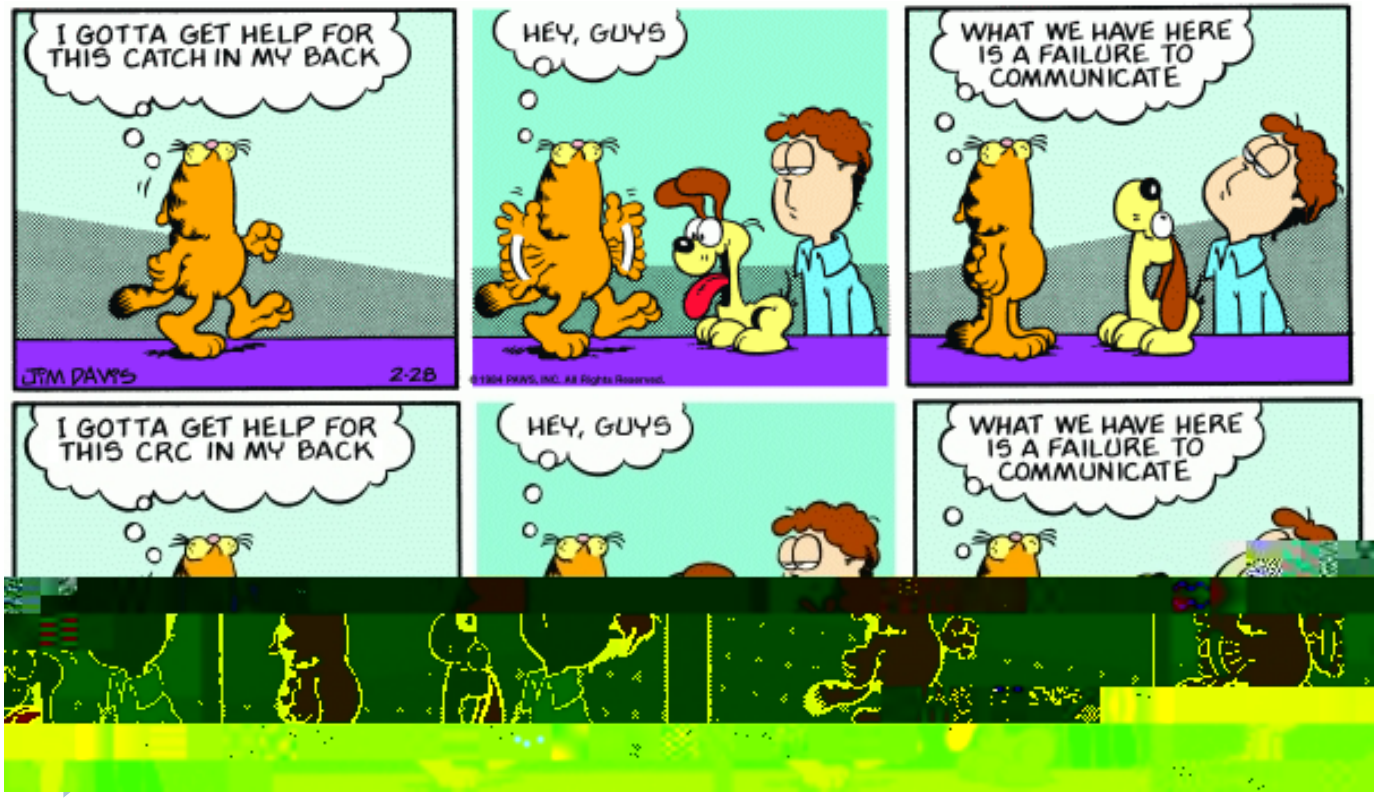
How can we detect these errors?

Error Detection

- Most common way is to add a additional bits to a message that can be calculated from the message itself
- Repetition Code
  - Let's say want to send 1011, let's send it a predetermined # of times
  - "…1011 1011 1011…", if we receive something different from 1011, we have an error
- Parity Bit
  - Let's add a bit to our communication to check the data
  - We'll look at this in a minute
- Cyclic redundancy check (CRC)
  - Commonly used but not secure, can generate original message from the CRC, well known flaw in WEP for wifi

Error Detection

- Cryptographic hash functions
  - Take a string of any length and produce a fixed length output
  - Should be easy to calculate not reversible
    - Can't recreate the original message from the hash
  - Good for checking the contents of a communication but requires some calculation
    - MD5, SHA1, & SHA2 are common examples



Original

This is the result of 5 single bit errors in the JPEG code

http://www.mezzacotta.net/garfield/?comic=459

Parity Bits

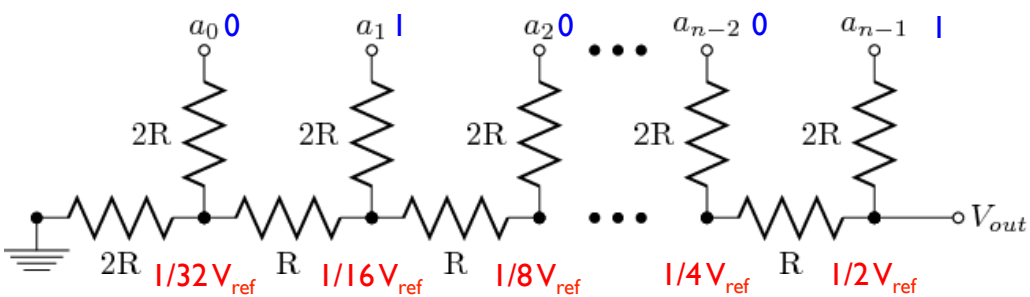
- Refers to the evenness or oddness of an integer
  - Calculated using XOR functions, even number of 1's = 0, odd number of 1's = 1
- Example
  - A wants to send 1001
  - A computes parity bit 1+0+0+1 = 2 mod 2 = 0
  - A sends 10010
  - B receives 10010
  - B computes parity bit 1+0+0+1+0 = 2 mod 2 = 0
  - B acknowledges correct transmission
- If there is an error
  - A wants to send 1001
  - A computes parity bit 1+0+0+1 = 2 mod 2 = 0
  - A sends 10010
  - Transmission Error
  - B receives 11010
  - B computes parity bit 1+1+0+1+0 = 3 mod 2 = 1
  - 1 ≠ 0 so
  - B says reports error
- Can only track an odd number of errors
- Used in many systems
  - As early as 1951
  - Hardware systems, microprocessor & serial buses, RAID
  - ASCII is 7 data bits & 1 parity bit

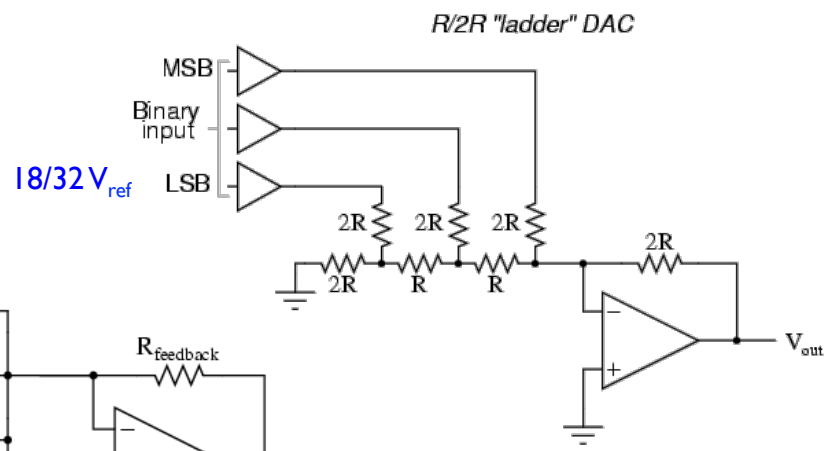
Seymour Cray, premier designer of supercomputers, held parity designs in contempt. He felt it showed poor design—if you designed your transmission paths to be reliable, you would not have to waste resources on parity, "Parity is for farmers". After he later included parity bits on the CDC 7600, Cray reputedly said that "I learned that a lot of farmers buy computers"

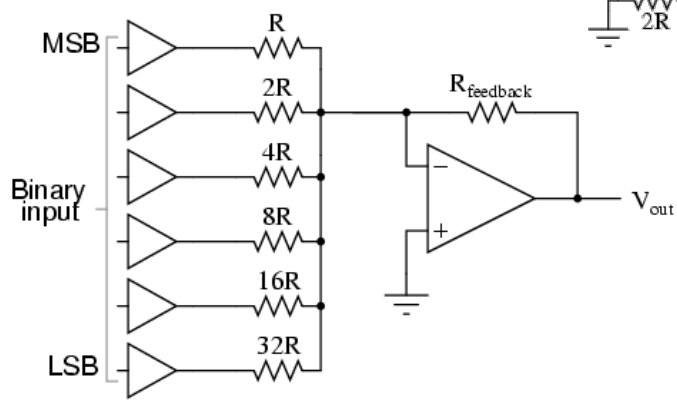
Digital to Analog Conversion

- So now that we have received these digital signals, we need to make the analog again
  - A common easy method is the R-2R ladder (you have seen this before)
- Example, with V_{ref} = 5 V & 5 bits
  - $V_{out} = V_{ref} \times \text{Input} / 2^N$
  - For 10010
    - V_{out} = 5 x 18 / 32 = 2.81 V

Just like an ADC, you can have unequal R values which provides a non-linear output

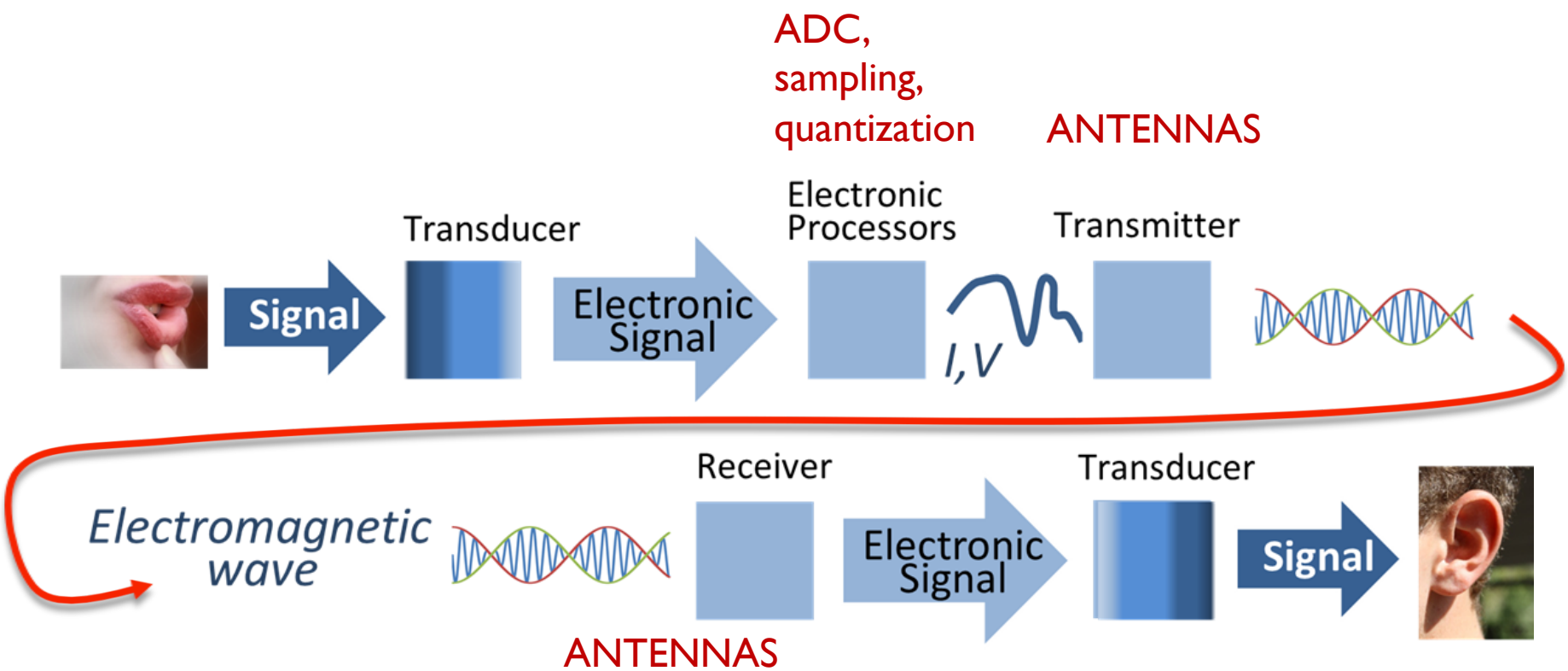






OpAmp based DACs

How do we send information over long distances, quickly, reliably, efficiently…



Tuner (select out particular signals)
DAC
Amplifiers
Demodulators

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL AIDS
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

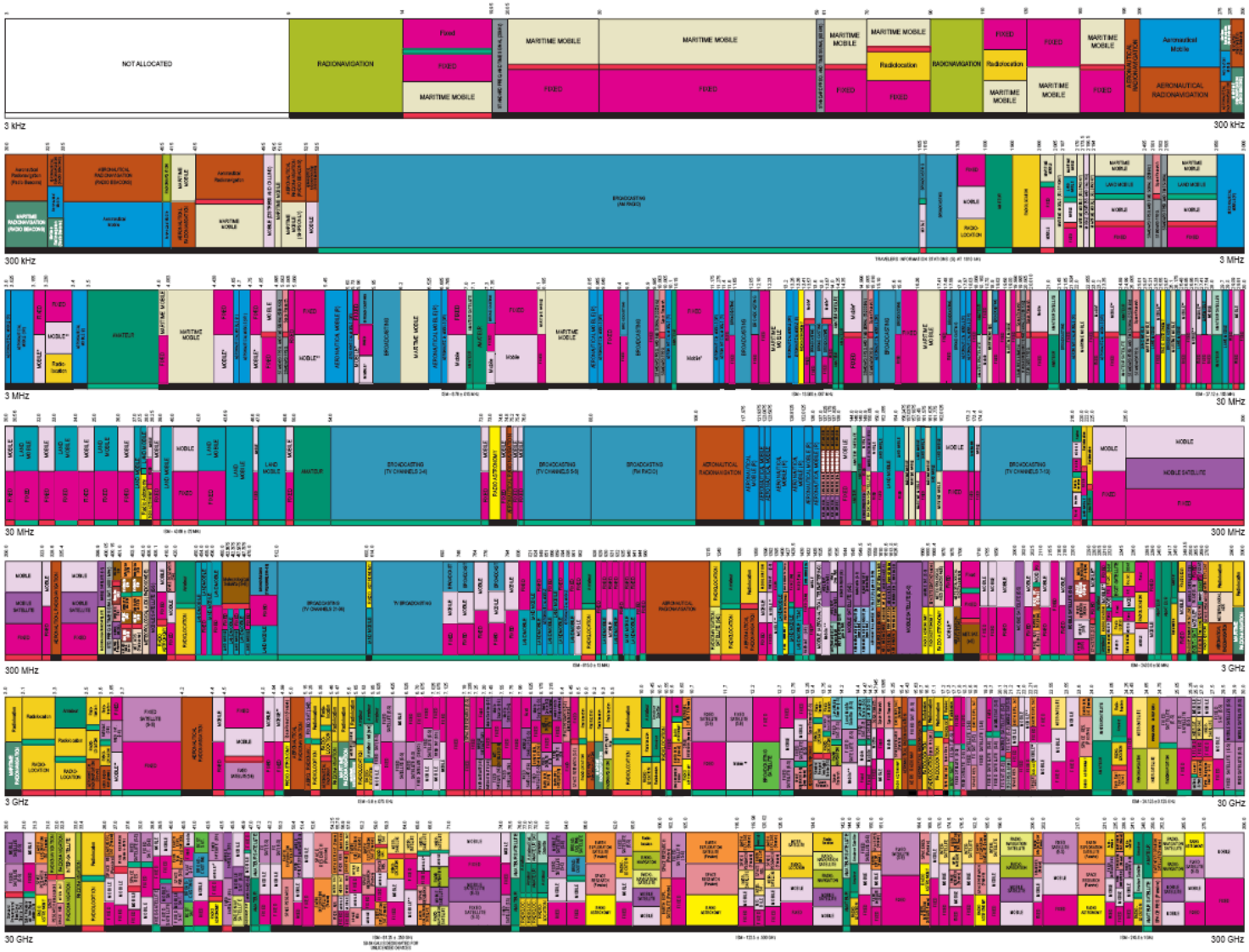
ACTIVITY CODE

- GOVERNMENT EXCLUSIVE
- GOVERNMENT/NON-GOVERNMENT SHARED
- NON-GOVERNMENT EXCLUSIVE

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it does not completely reflect all aspects, i.e., footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

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

October 2003