# Lecture 03-1: Physical Layer
# RF Intro

CS 356R

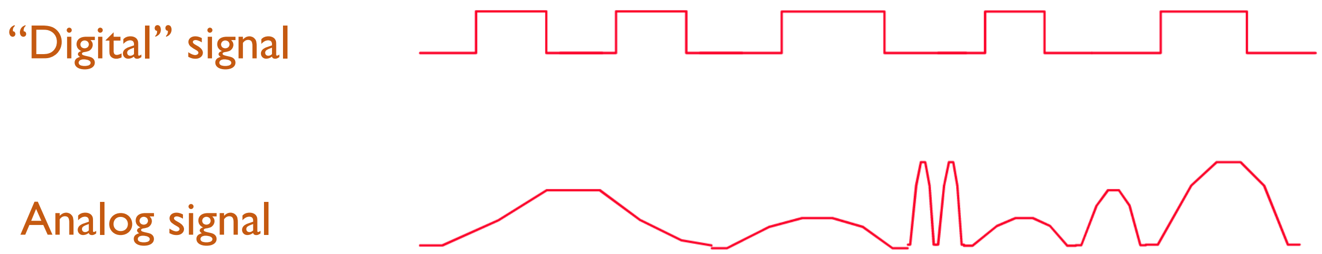
Intro to Wireless Networks

Mikyung Han


Please, interrupt and ask questions AT ANY TIME !

# Paradigm shift from software to hardware

- In hard disk, in RAM, or SSD.. How is the data represented?
    - In bits!
    - 1101010101000…
- In physical layer, network card cannot tx/rx bits
    - Bits needed to be coded into electric signal



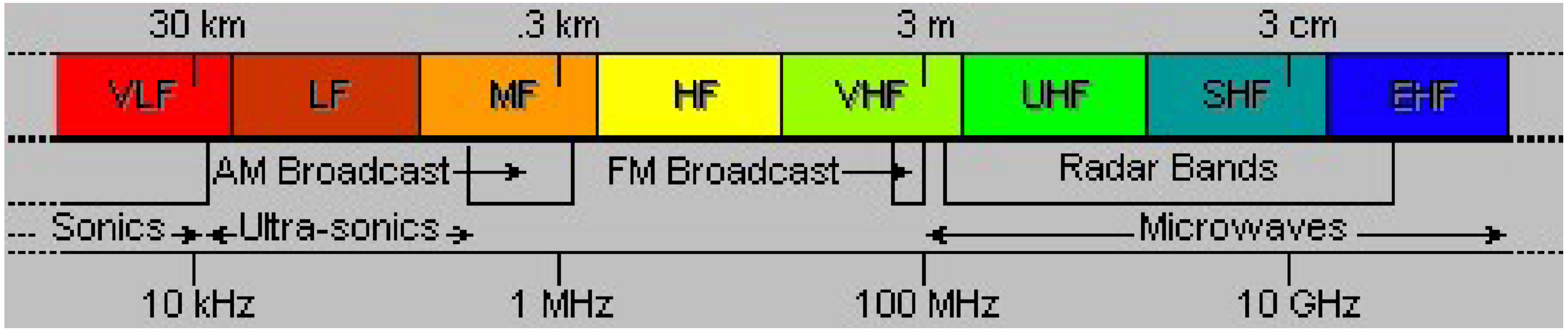

So, let's talk about electric signal

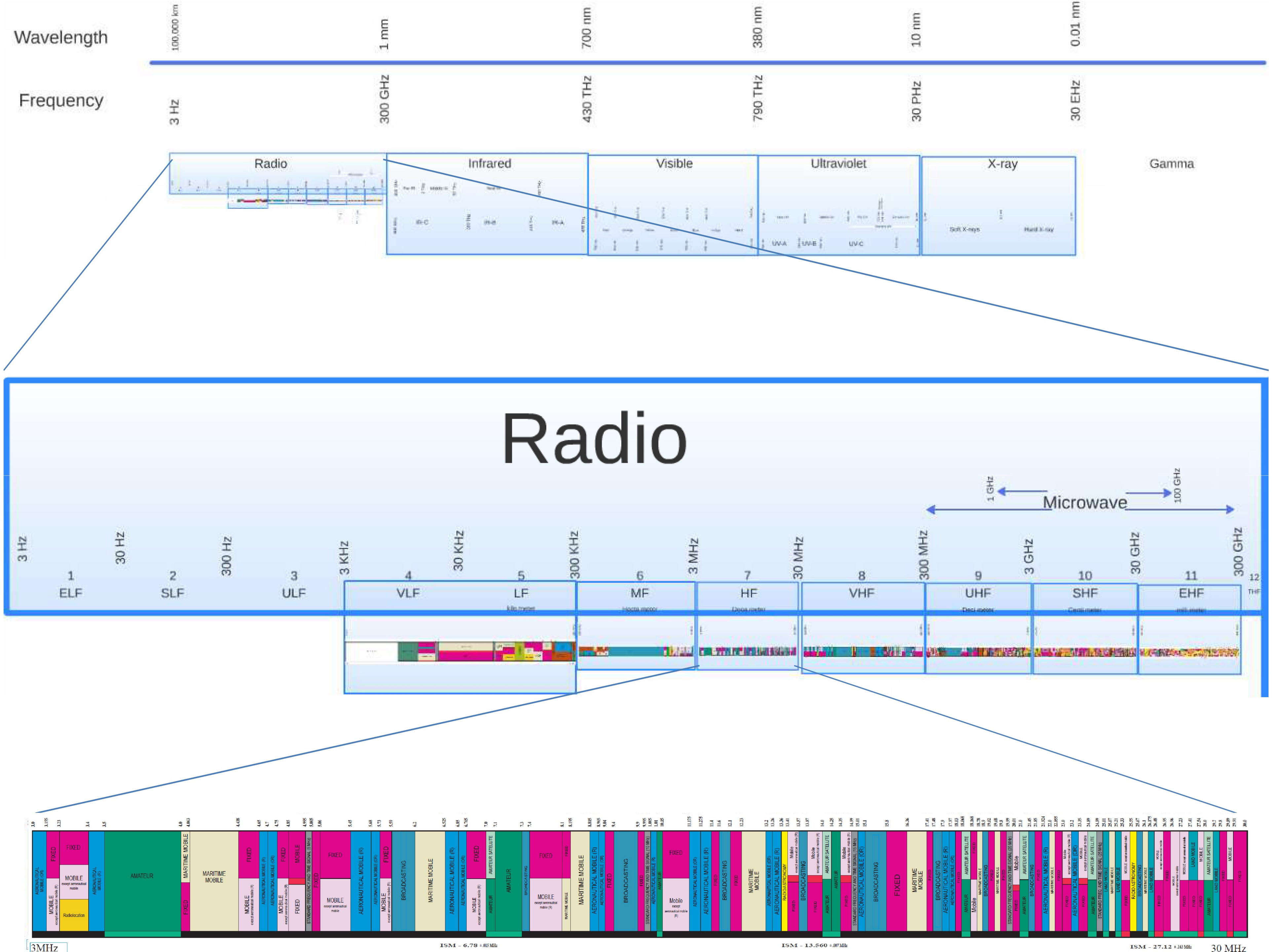
# Outline

1. Radio Frequency

# Intro to Radio Frequency (RF)

- Electromagnetic wave that propagates through "ether"
- Ranges 3KHz … 300 GHz (Or 100 km … 0.1 cm wavelength)
- Travels at speed of light
  - *299,792,458 meter/sec*
- Can take both time and frequency view





Wavelength
100,000 km
1 mm
700 nm
380 nm
10 nm
0.01 nm
Frequency
3 Hz
300 GHz
430 THz
790 THz
30 PHz
30 EHz
Radio
Infrared
Visible
Ultraviolet
X-ray
Gamma
Radio
Microwave
1 GHz
100 GHz
3 Hz
30 Hz
300 Hz
3 KHz
30 KHz
300 KHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
1 ELF
2 SLF
3 ULF
4 VLF
5 LF
6 MF
7 HF
8 VHF
9 UHF
10 SHF
11 EHF
12 THF
3MHz
ISM - 6.78
ISM - 13.560
ISM - 27.12
30 MHz

# UNITED STATES FREQUENCY ALLOCATIONS

## THE RADIO SPECTRUM

### RADIO SERVICES COLOR LEGEND

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

### ACTIVITY CODE

FEDERAL EXCLUSIVE
FEDERAL/NON-FEDERAL SHARED
NON-FEDERAL 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 may 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

JANUARY 2016

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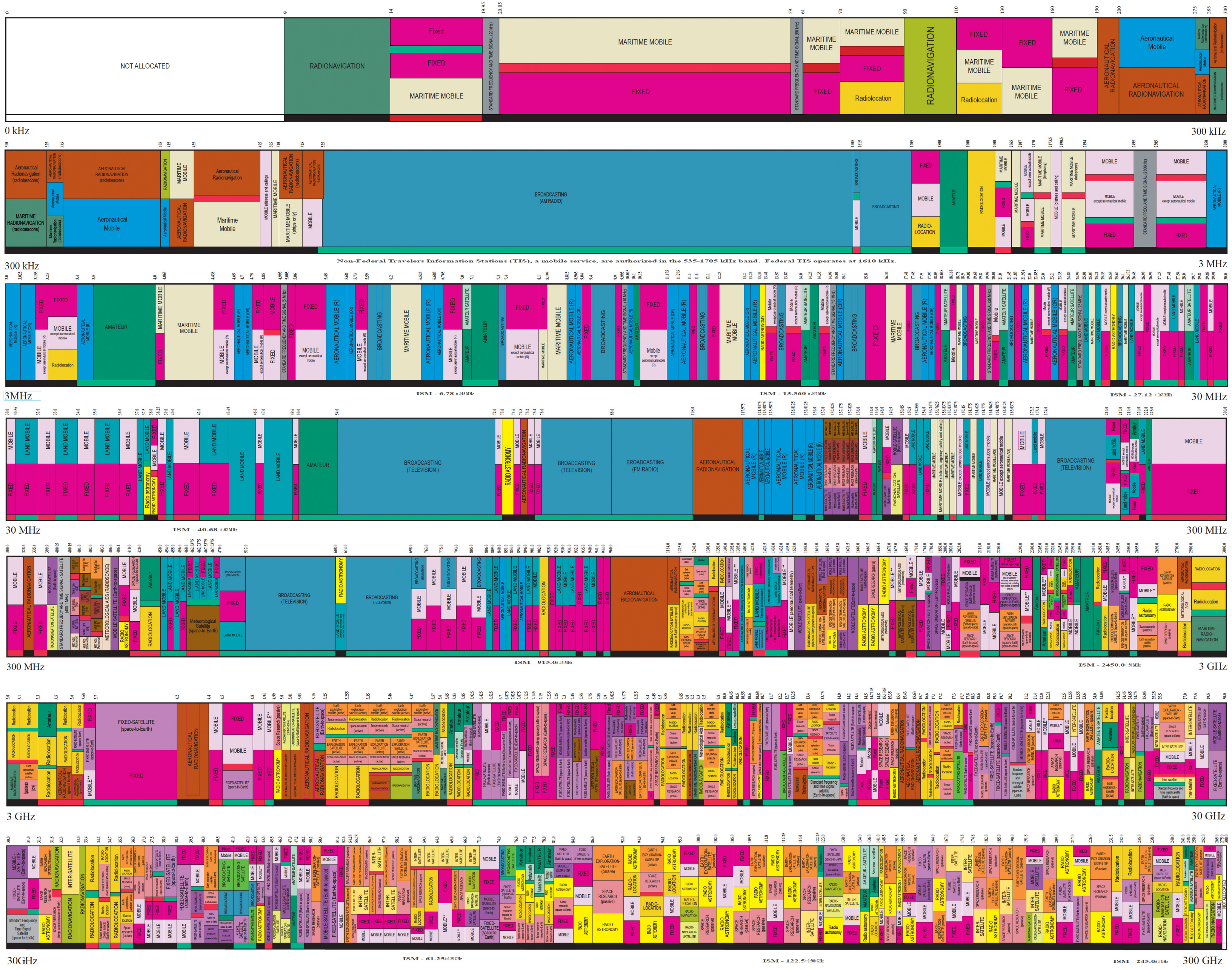
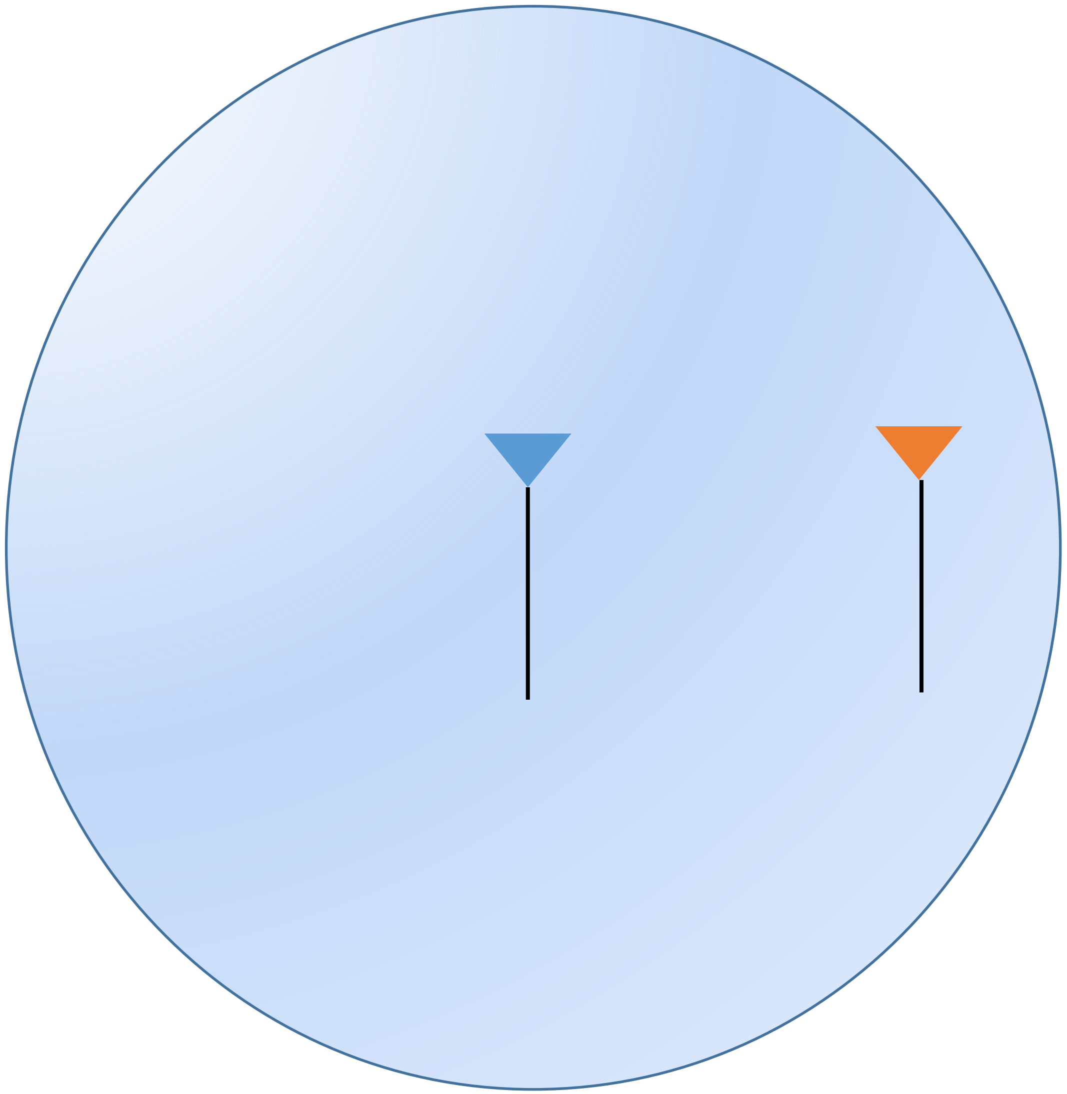



* EXCEPT AERONAUTICAL MOBILE (R)
** EXCEPT AERONAUTICAL MOBILE

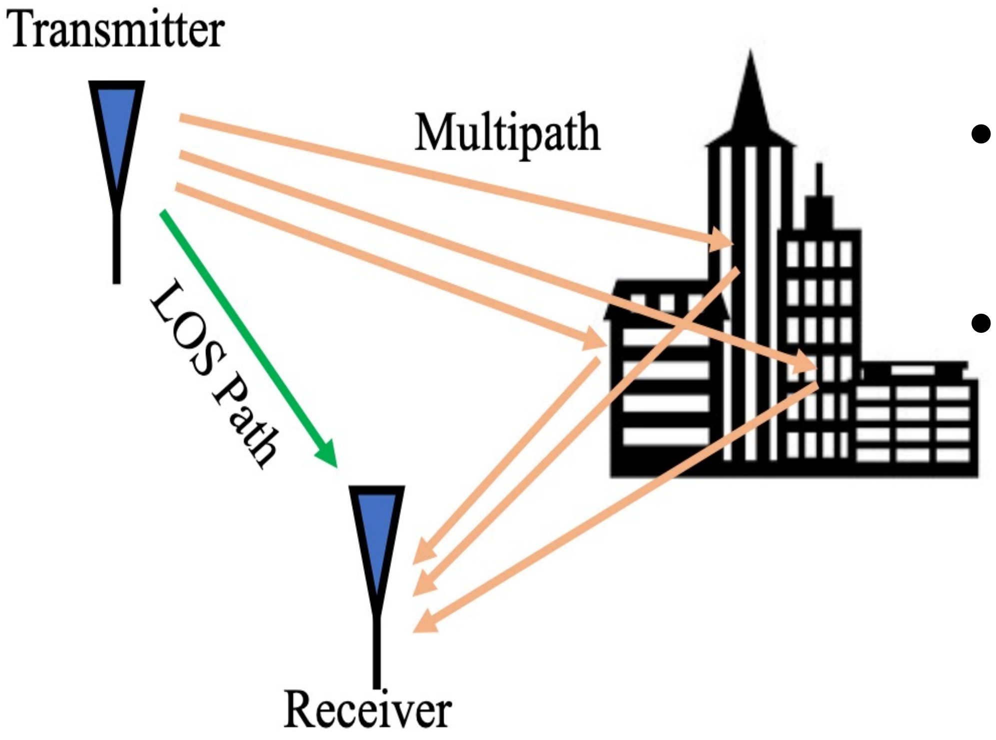
PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF SPECTRUM OCCUPIED.

# Cartoon View #1: A Wave of Energy



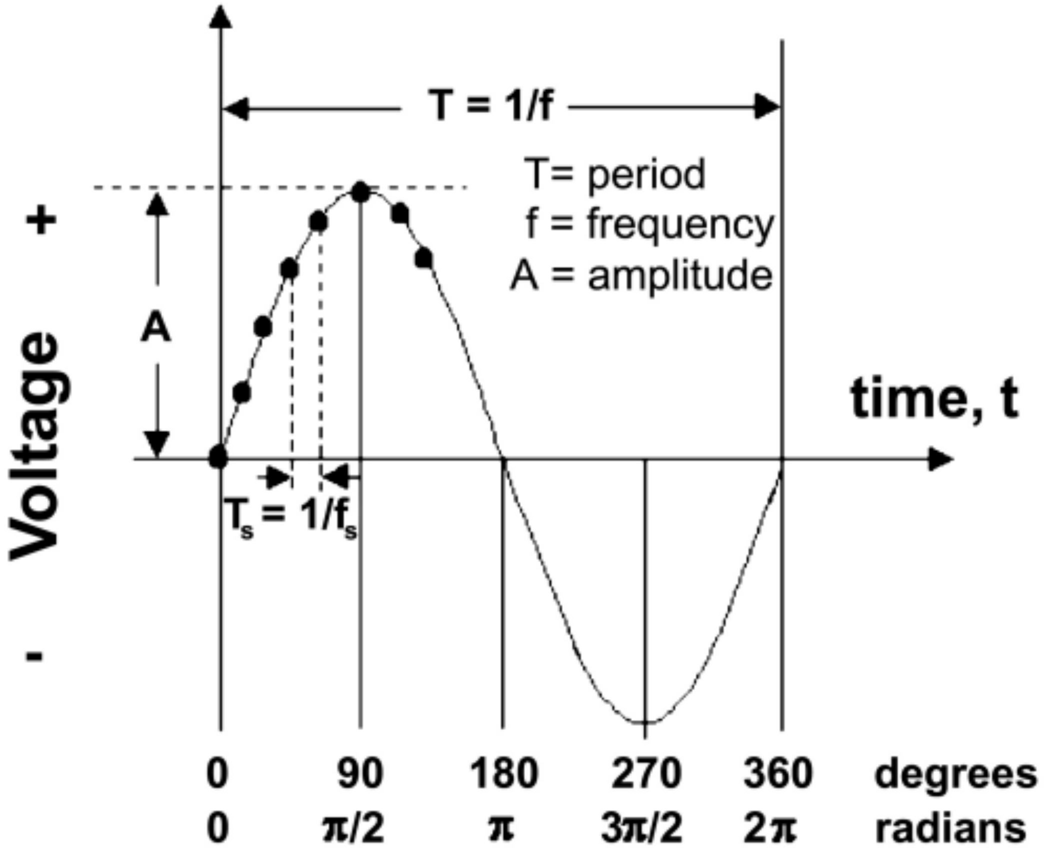
- **Think of energy that radiates from one antenna and picked up by another**
  - What happens to the energy as we move far away from the center?
- **Attenuation:**
  - Density of clouds reduces over time, distance
  - When signal strength is reduced error rate goes up
- **Spatial reuse is possible:**
  - Spread these energy balls over space and let them reuse the same frequency

# Cartoon View #2: Rays of Energy



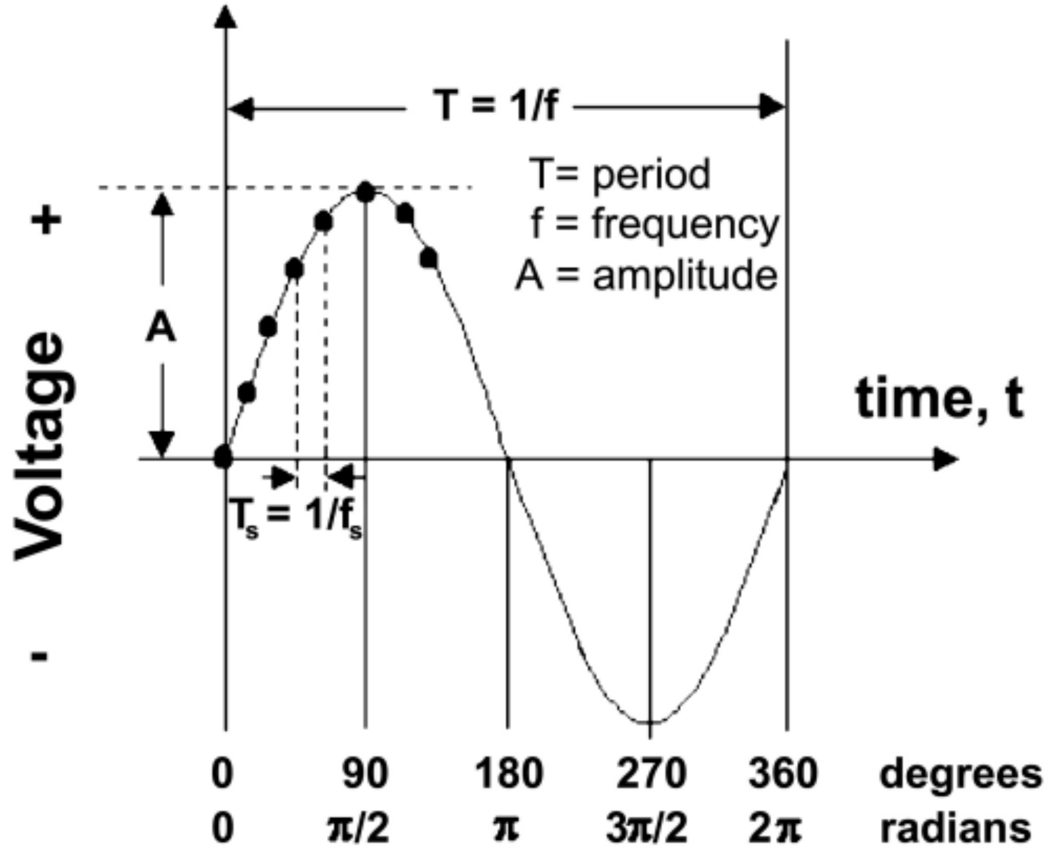

- What is happening here?
  - Rays can be reflected
- Multipath
  - channel including multiple rays that take different paths
- Implications for wireless
  - Can we provide connectivity without line of sight?
  - Receiver receives multiple copies of same signal
  - Combined with mobility it can lead to fast fading

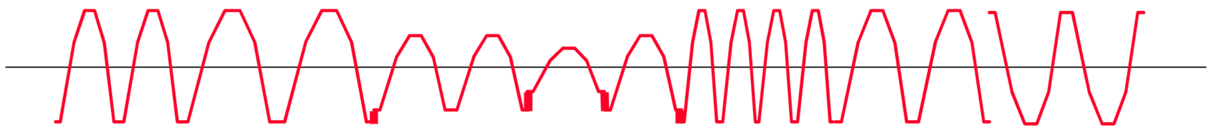
# Cartoon View #3: Sine Wave




- A signal is a combination of sine wave where each sine wave has
  - Frequency
  - Amplitude
  - Phase

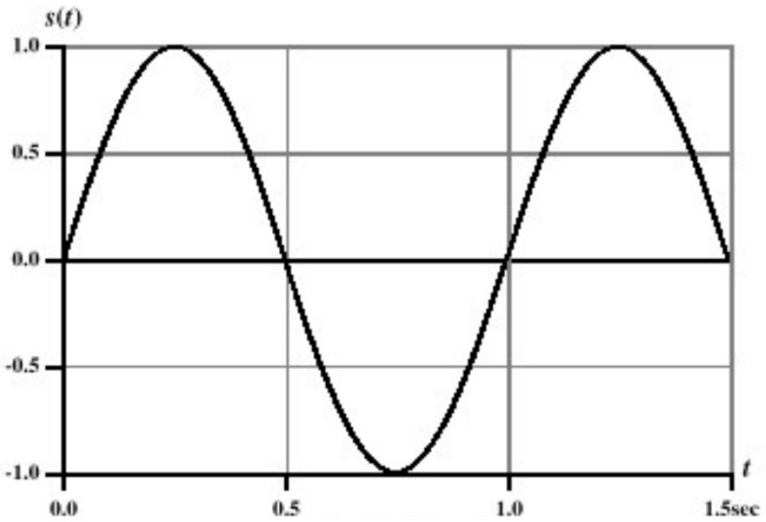
# Cartoon View #3: Sine Wave



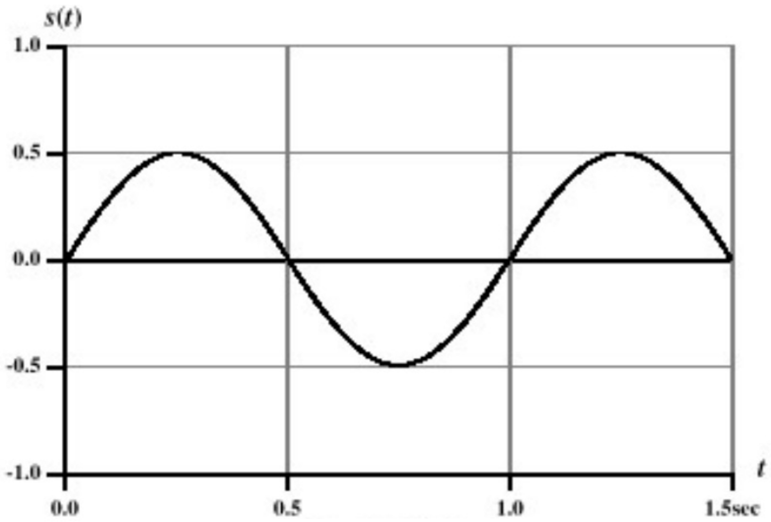



- A signal is a combination of sine wave where each sine wave has
  - Frequency
  - Amplitude
  - Phase
- Implications for wireless
  - Modulation: sender can change the properties of EM signal over time to convey information
  - Demodulation: receiver can observe these changes and extract the information

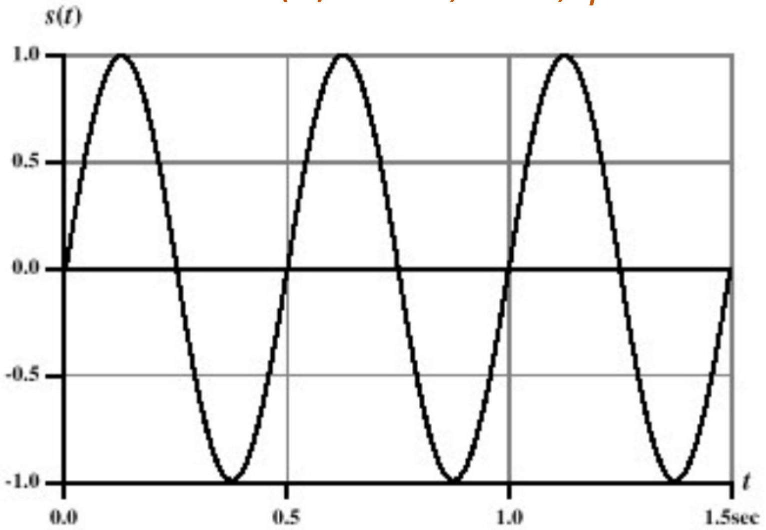
# $S(t) = \text{sine}(2 \pi f t + \varphi)$



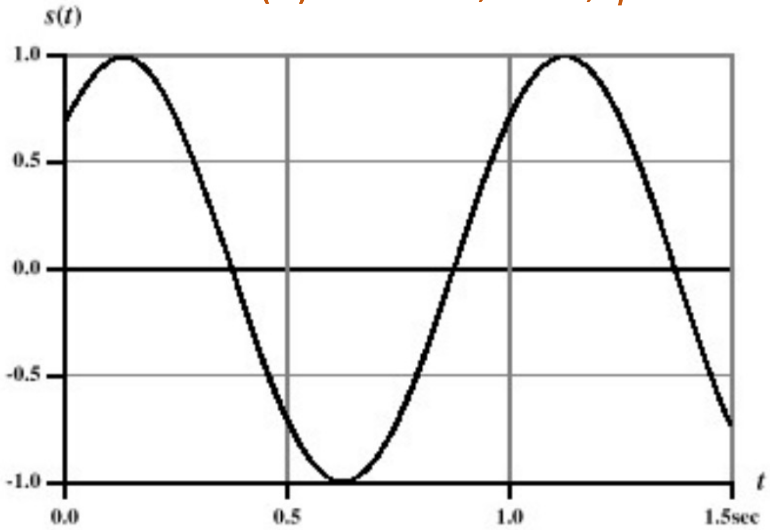

(1) $A = 1, f = 1, \varphi = 0$




(2) $A = 0.5, f = 1, \varphi = 0$



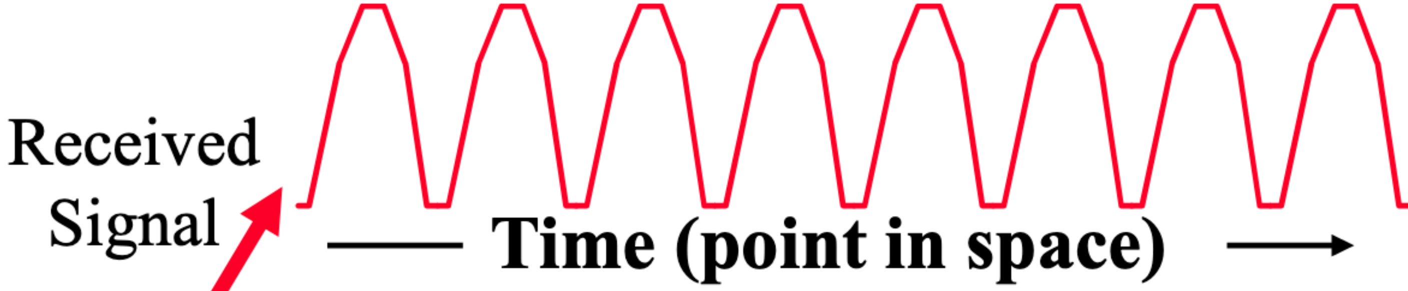

(3) $A = 1, f = 2, \varphi = 0$

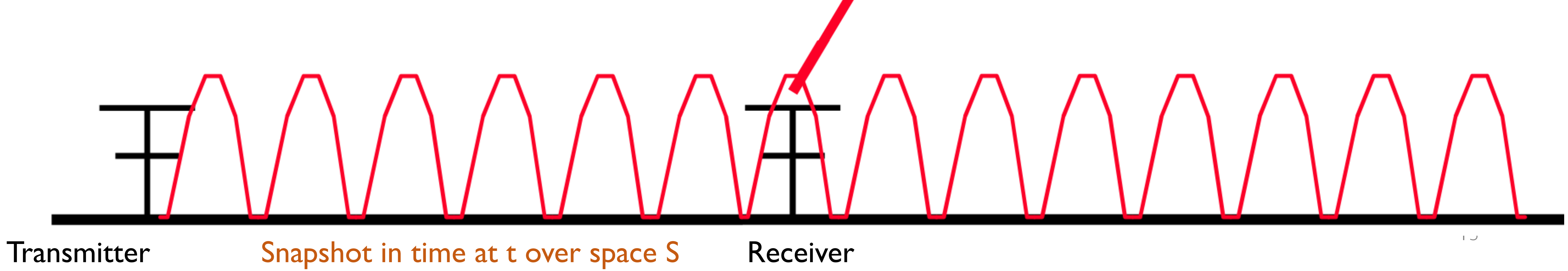



(4) $A = 1, f = 1, \varphi = \pi/4$

# Cartoon View #3-2: Time and Point View of Signal

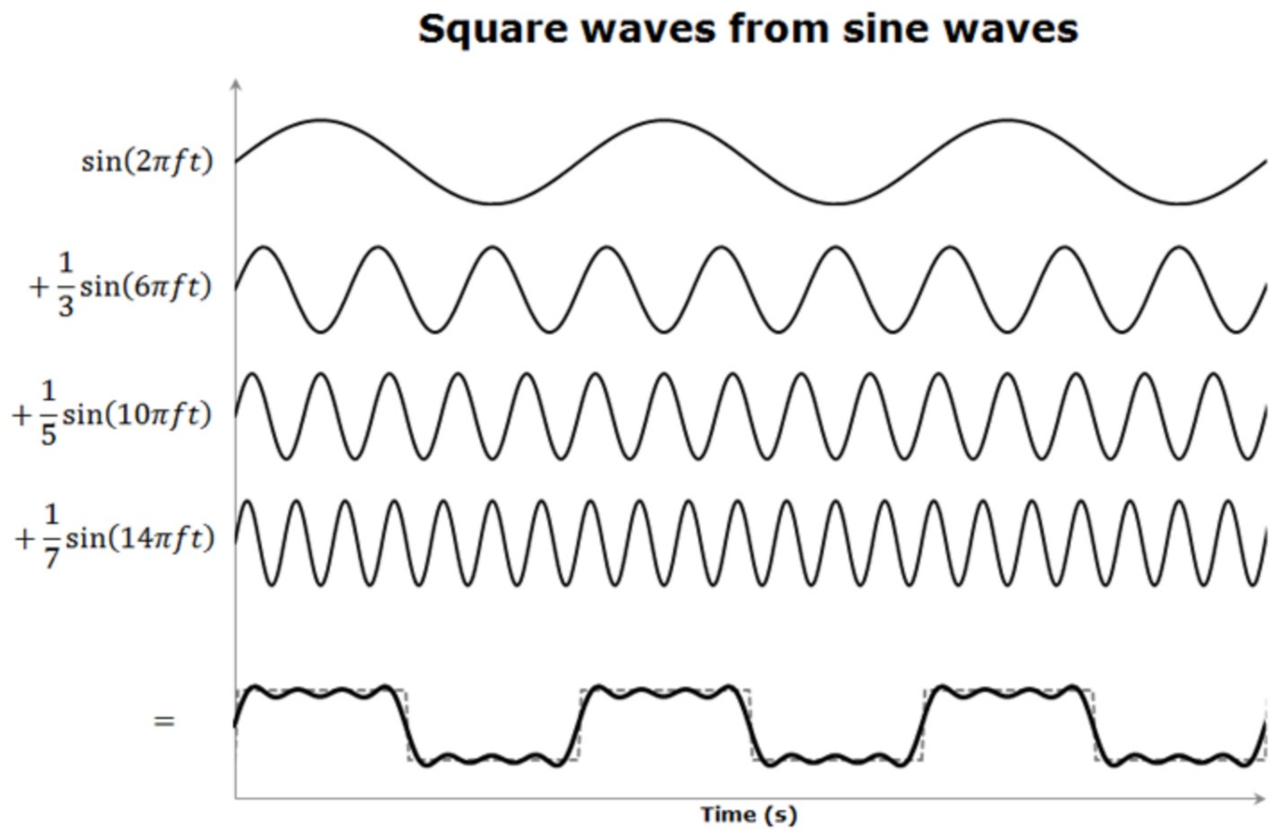
- Imagine you took a snapshot of space at time t
  - Signal will look like a sine function in space
  - Signal at different points are (rough) copies of each other
  - Transmitter can change Amplitude, Frequency, Phase (Modulation)
- Imagine standing in one spot and a wave is hitting you over time
  - Receiver receives the signal over time
  - Receiver can observe transmitter's change (De-Mod)



# Cartoon View #3-3: Signal = Sum of Sinusoids

- Any EM signal can be expressed as a combination of sin and cos waves
  - Even digital signal



# Key Idea of Wireless Communication

- Sender sends an EM signal and changes its properties over time
  - Changes reflect a digital signal (binary or multi-value signal)
  - Change amplitude, phase, frequency (or combination)
- Receiver learns the digital signal by observing how the signal changed
  - Note received signal is no longer simple sine wave or periodic

*"The wireless telegraph is not difficult to understand.*
*The ordinary telegraph is like a very long cat.*
*You pull the tail in New York, and it meows in Los Angeles.*
*The wireless is exactly the same, only without the cat."*

# Cats, Really?

- Key insight: sender "changes signal" (pull tail) and receiver "observes changes" (meows)
- Wireless network designers need to be more precise about the performance of wireless "links"
  - Can the receiver always decode the signal?
  - How many Kbit, Mbit, Gbit per second?
  - Does the physical environment, distance, mobility, weather, etc. matter?

We need a more formal way of reasoning about wireless communication

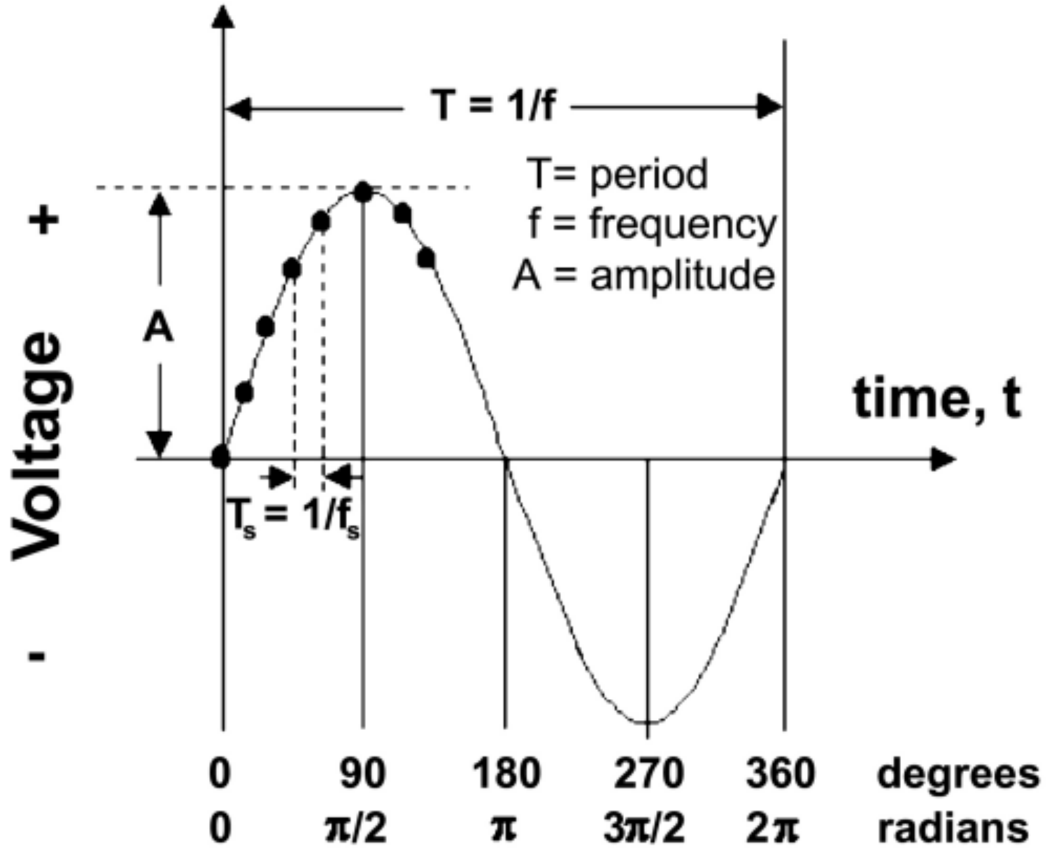
# Outline

1. Radio Frequency Intro
2. Time Domain View

# Time Domain View: Periodic vs Aperiodic Signals

- Periodic signal shows a pattern that repeats over time
  - s(s + T) = s(t) where T is the period of the signal
- Aperiodic signal doesn't show such repeating pattern
- Which is easier to analyze?
  - If a signal is periodic, it allows us to take a frequency view of the same signal
  - Often, we "make" an aperiodic signal periodic by taking a time slice T and repeating it

# Key parameters of periodic signal




- Peak amplitude (A): max strength of signal over time
  - Typically measured in volts
- Frequency (f): rate at which the signal repeats
  - In Hertz (Hz) : cycles per sec
- Period (T): amount of time it takes for one repetition of the signal
  - In seconds
  - What is 1/T?
- Phase ($\varphi$): measure of the relative position in time within a single period of a signal
  - In radians ($2\pi$ rad = 360°)
- Wavelength ($\lambda$): distance occupied by a single cycle
  - Measure two points with the same phase
  - Need propagation speed to calculate

# Time Domain View: Periodic vs Aperiodic Signals

- Periodic signal shows a pattern that repeats over time
  - $s(s + T) = s(t)$ where $T$ is the period of the signal
- Aperiodic signal doesn't show such repeating pattern
- Which is easier to analyze?
  - If a signal is periodic, it allows us to take a frequency view of the same signal
  - Often, we "make" an aperiodic signal periodic by taking a time slice $T$ and repeating it

# Key Property of Periodic EM Signals

- Any EM signal = a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases
- The period of the total signal == the period of the fundamental frequency
  - All other frequencies are an integer multiple of the fundamental frequency
- There is a strong relationship between the "shape" of the signal in the time and frequency domain

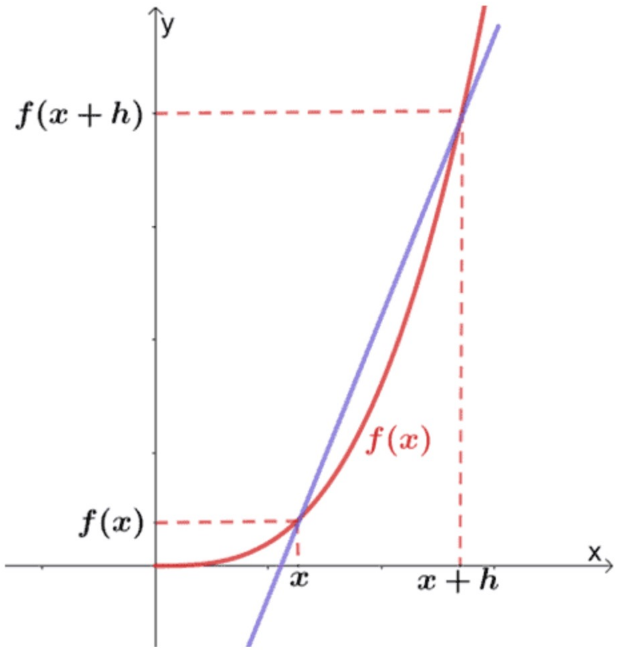
But before that we need to cover some bases

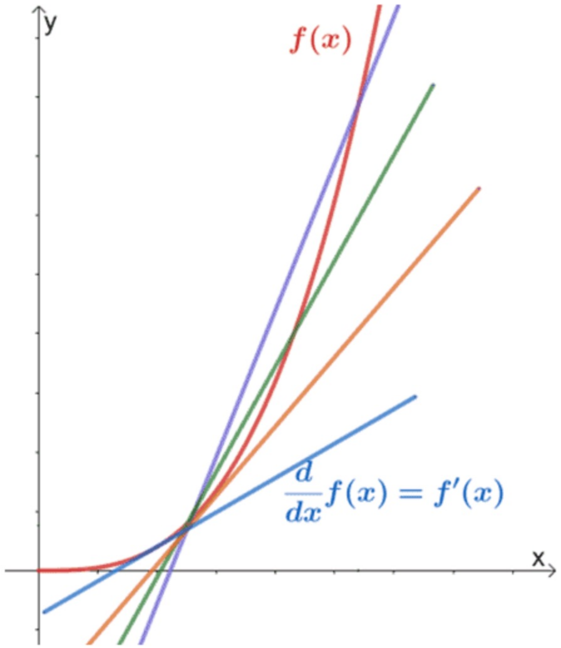
# Outline

1. Radio Frequency Intro
2. Time Domain View
3. Primer

# What is a derivative?

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h} = \lim_{dx \to 0} \frac{f(x+dx) - f(x)}{dx}$$

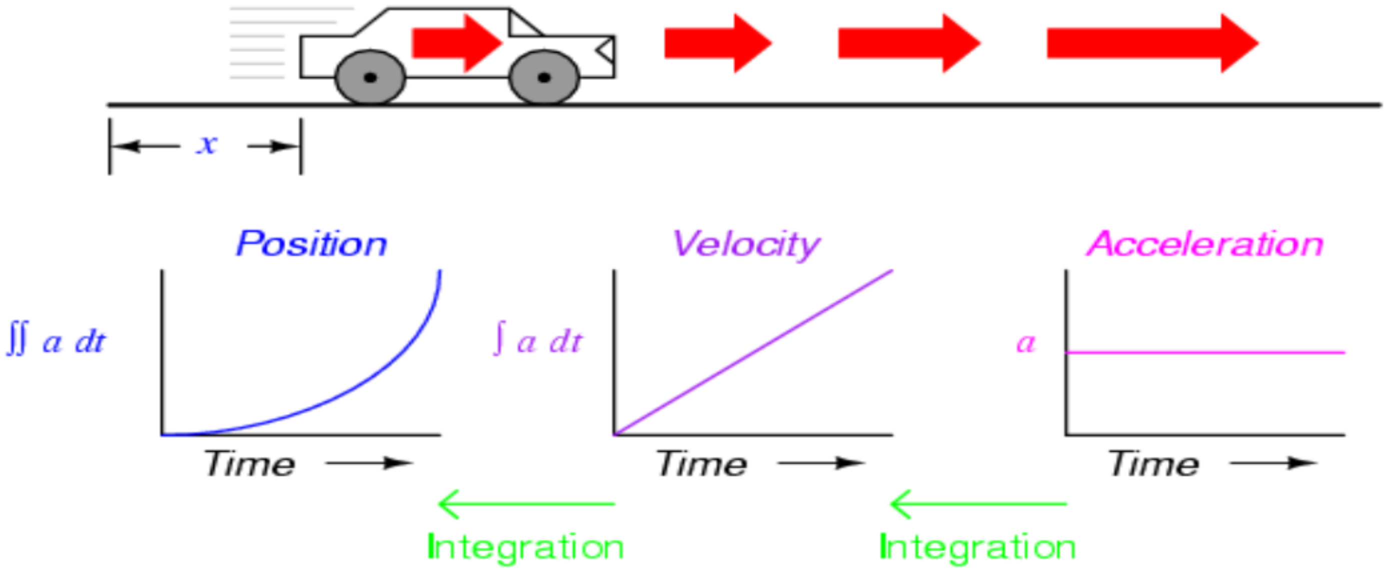


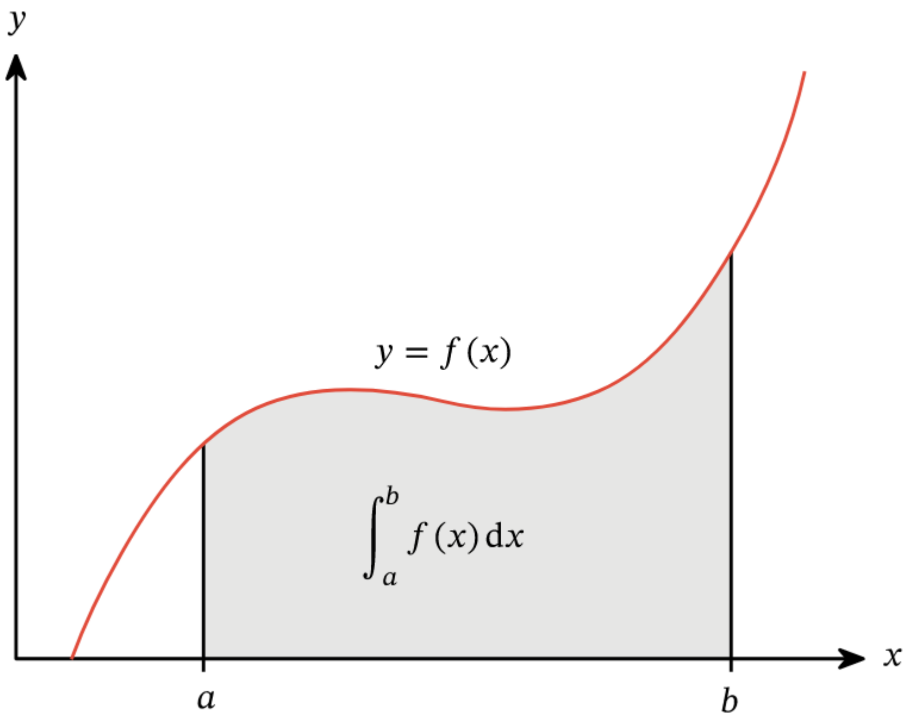

**Derivative represents a slope of the tangent line at the given point**

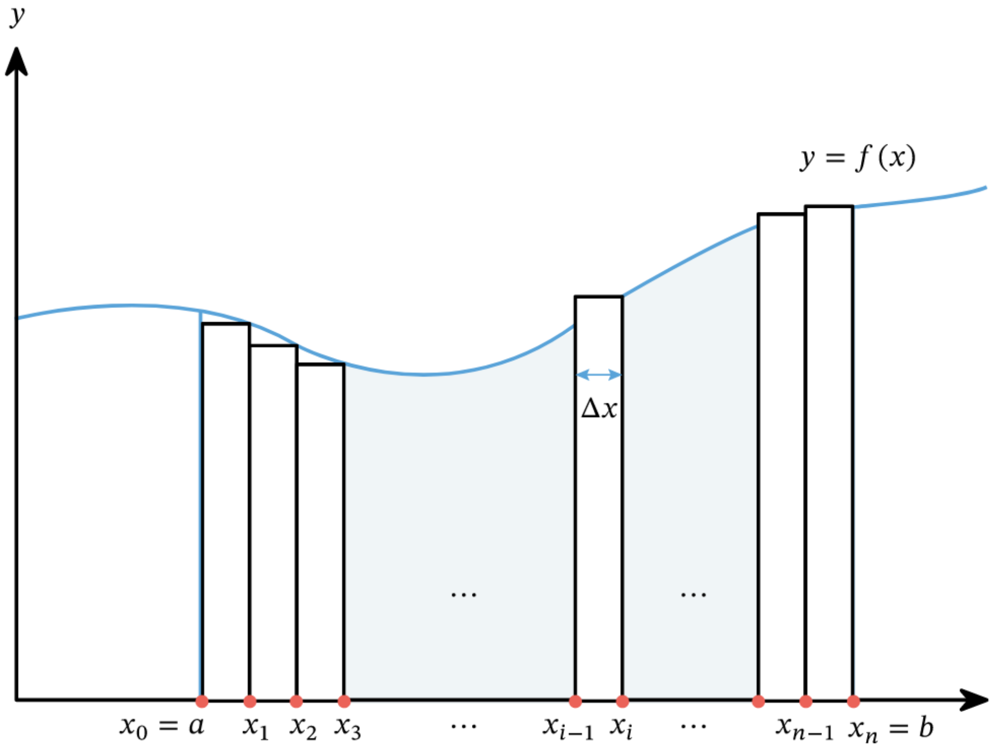
# In physics context

| F(x) | F'(x) | F''(x) |
|---|---|---|
| Position (meters) | Velocity (meters/second) | Acceleration (meters/second^2) |



# What is an integral?



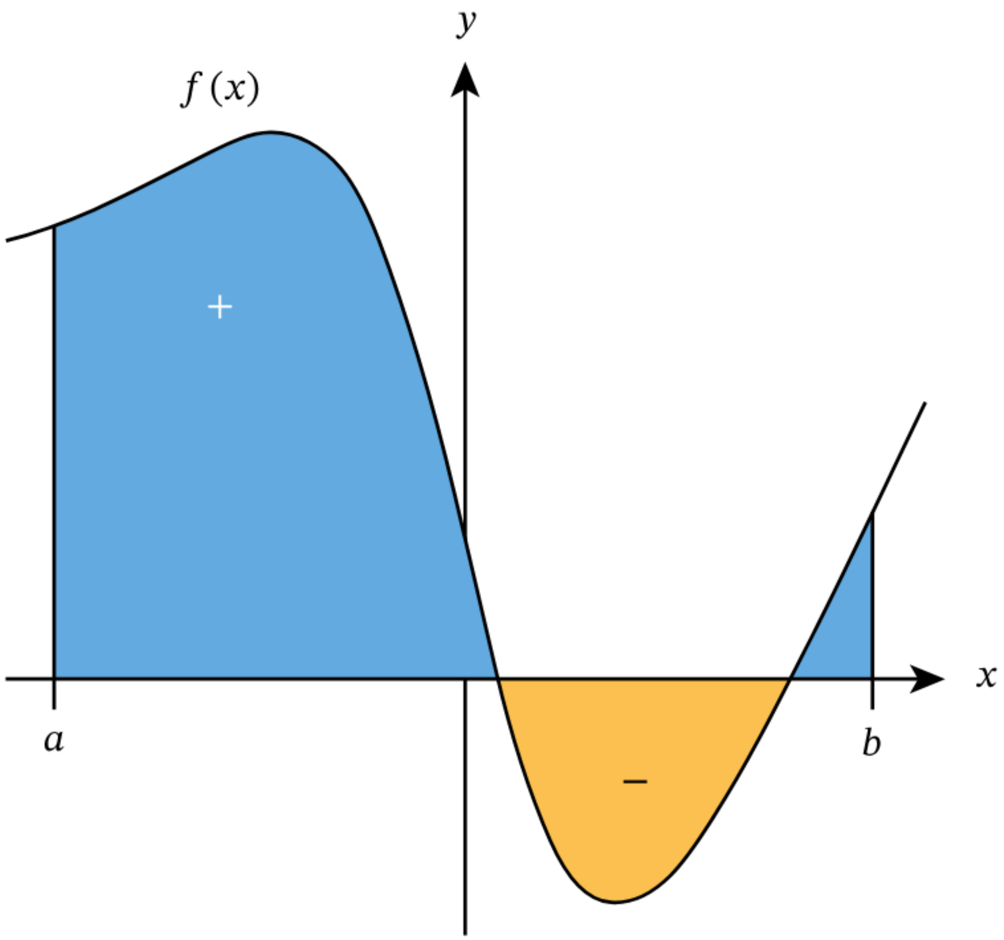




$$\int_a^b f(x)\,\mathrm{d}x = \lim_{n\to\infty} \sum_{i=1}^{n} f(x_i)\,\Delta x.$$

$$\text{area} \approx f(x_1)\,\Delta x + \cdots + f(x_n)\,\Delta x$$

**Integral represents the shaded with x range [a, b]**

# Due to direction negative area is possible



# Integral and derivative notation

$$F'(x) = f(x).$$

$$\int_a^b f(t)\,\mathrm{d}t = [F(t)]_a^b$$

$$= F(b) - F(a).$$

# Got e? Euler's number

- Has a real value 2.71828
- Has many special properties
- $e^x$ is defined to be
  - Taylor series
  - It is a fnfinite sum

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \frac{x^5}{5!} + \ldots$$

- Derivative of $e^x$ is $e^x$ itself!
  - $\frac{d}{dx}F(x) = F(x)$ when $F(x) = e^x$

# Let's do derivatives!

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + etc.$$

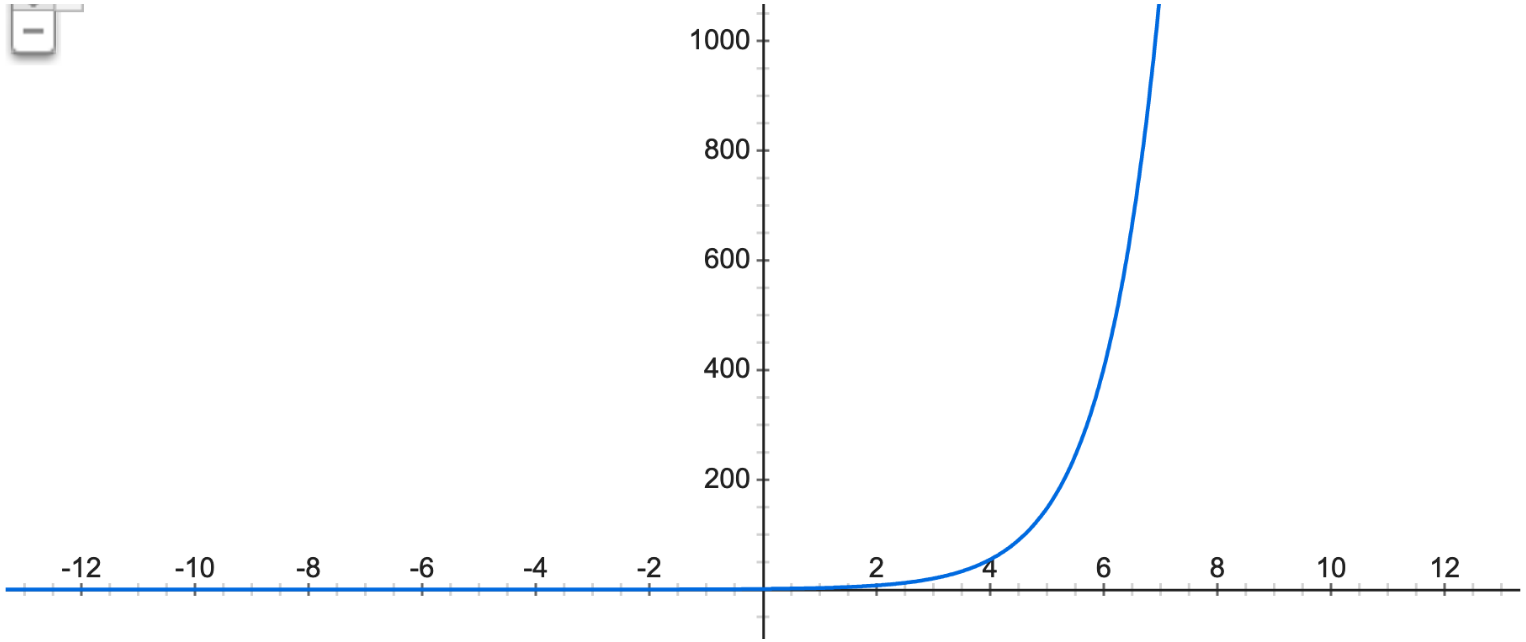
$$(e^x)' = 1' + (x)' + \left(\frac{x^2}{2!}\right)' + \left(\frac{x^3}{3!}\right)' + (etc.)'$$

$$(e^x)' = 0 + 1 + 2\frac{x}{1.2} + 3\frac{x^2}{1.2.3} + 4\frac{x^3}{1.2.3.4} + (etc.)'$$

$$(e^x)' = 0 + 1 + \cancel{2}\frac{x}{1.\cancel{2}} + \cancel{3}\frac{x^2}{1.2.\cancel{3}} + \cancel{4}\frac{x^3}{1.2.3.\cancel{4}} + (etc.)'$$

$$(e^x)' = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + etc.$$

# Graph of $f(x) = e^x$




Slope of f at x is $e^x$

# Got i? Imaginary unit

- i $= \sqrt{-1}$
- Complex number = a + ib  (where a and b are real)
- Complex conjugage of a + ib is a – ib
    - Same real part
    - Imaginary part equal in magnitude but opposite direction

# Ready for $e^{i\theta}$?

- Ready or not here I come!
  - Video illustration of $e^{i\pi}$


Any questions regarding the course?

# Backup Slides

# Acknowledgement

Slides adopted from Dr. Peter Steenkiste, CMU