CSE 562: Mobile Systems & Applications

Quals Course – Systems Area

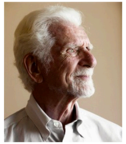
Shyam Gollakota

First Mobile Phone 1973

SIGMOBILE Outstanding Contribution Award

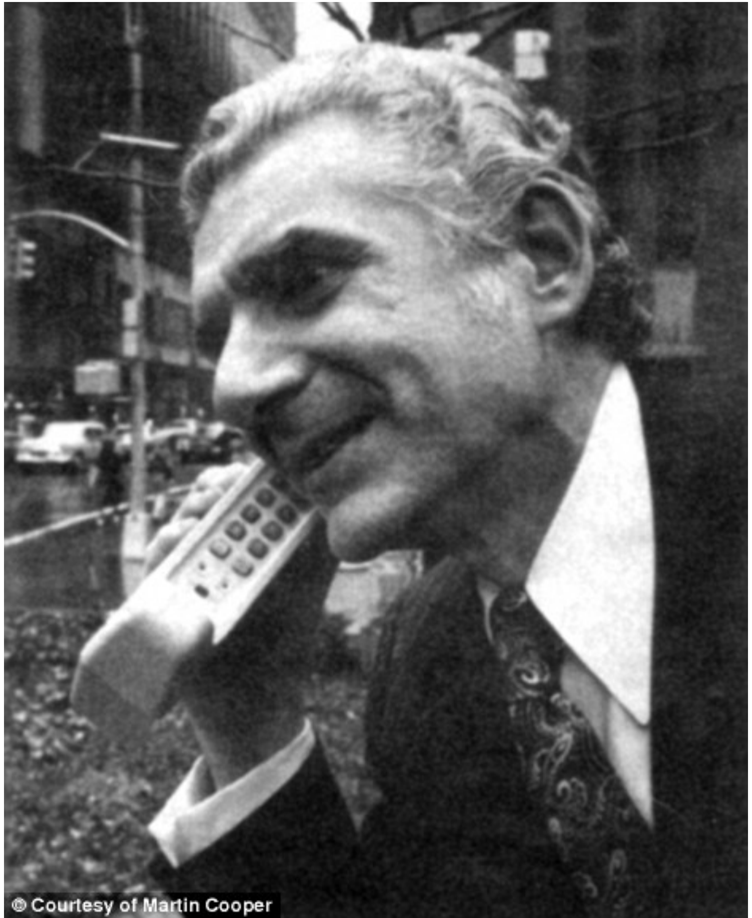
The SIGMOBILE Outstanding Contribution Award is given for significant and lasting contributions to the research on mobile computing and communications and wireless networking.

2020 Recipient



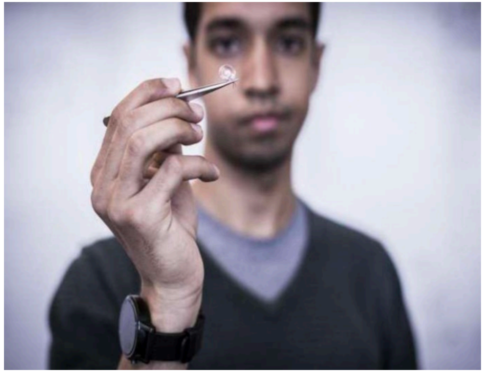
Marty Cooper

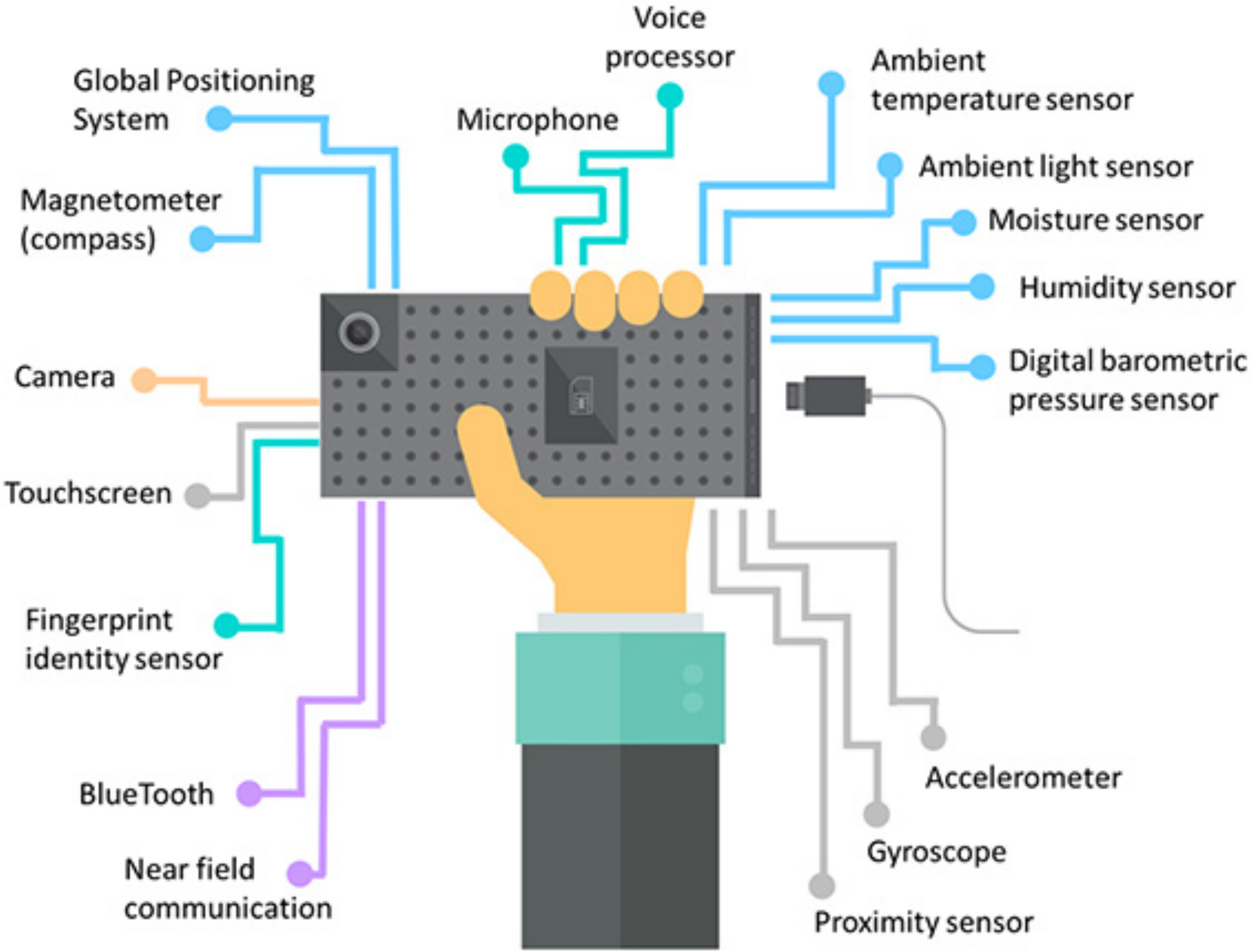
For seminal contributions to the conception, practice and adoption of portable telephony.




100%
Green Light
Lorde
Screen
Mirroring


TRAINING WITH KRISTA
68°
WED
12
11:15AM
1:09PM, +3HRS
NYC
UVI
3.6




Voice processor
Global Positioning System
Microphone
Ambient temperature sensor
Ambient light sensor
Magnetometer (compass)
Moisture sensor
Humidity sensor
Digital barometric pressure sensor
Camera
Touchscreen
Fingerprint identity sensor
BlueTooth
Near field communication
Accelerometer
Gyroscope
Proximity sensor

Goal of this course

- Have an understanding of state of the art mobile systems research
- Explore applications that are capable with mobile devices

Course material

1. Signal processing fundamentals
2. Acoustic device and device-free tracking
3. Physiological sensing using phones and speakers
4. IMW tracking and GPS localization
5. Wi-Fi localization and sensing
6. Designing and building IoT device hardware

Course material

7. Backscatter systems

8. Mobile privacy and security

9. Robotics mobile systems

Grading

3 hands-on assignments (20+20+20% in all)

- One every two weeks
- Requires programming phones, microcontroller, etc.

Class presentation of one paper (10%)

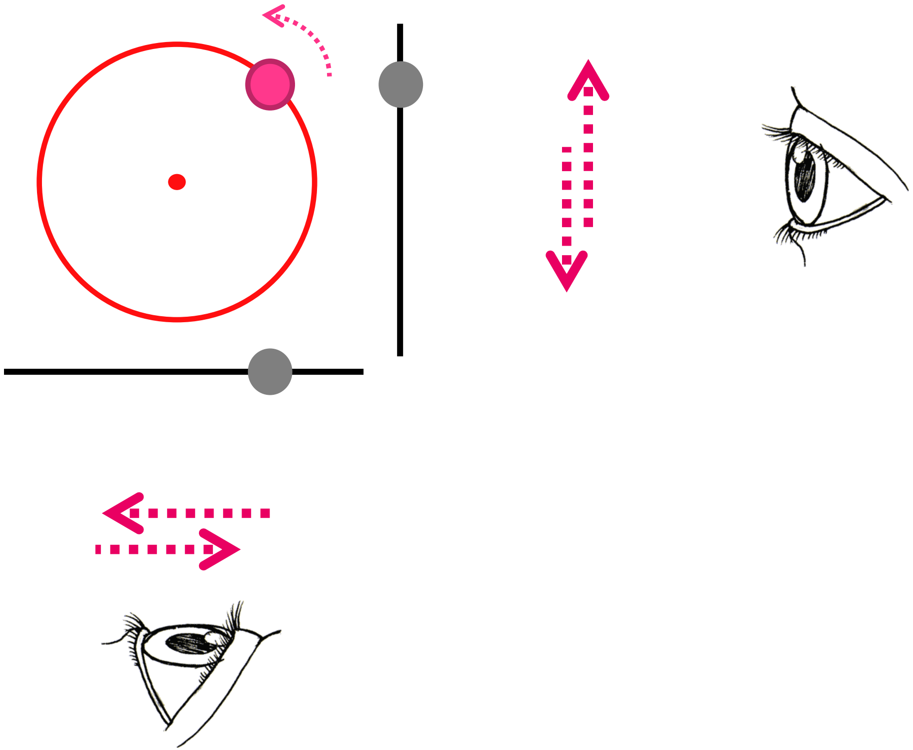
Final research project (30%)

- Proposal due on May 1
- 2-3 person project

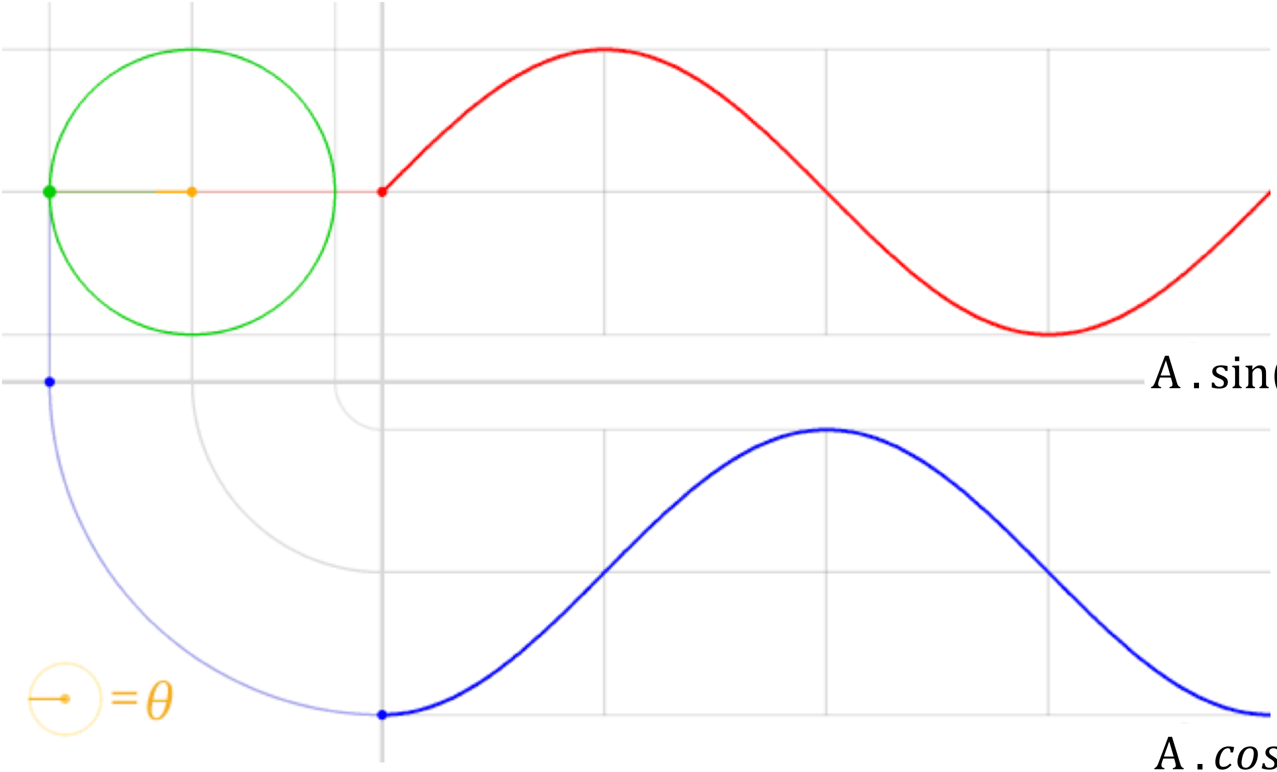
Signal processing basics

(Slides by Nirupam Roy)

Model for a signal (frequency, amplitude, and phase)



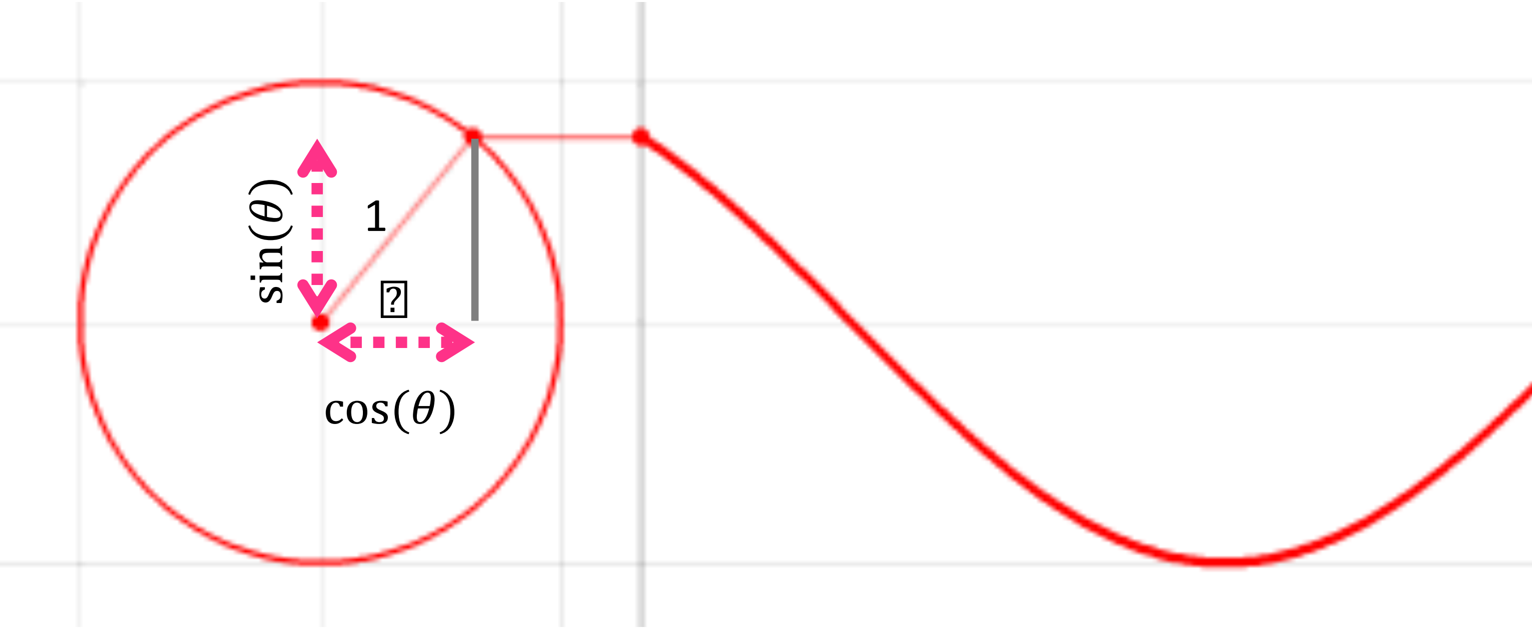
Model for a signal (frequency, amplitude, and phase)



$A . \sin(\theta)$

$A . cos(\theta)$

Model for a signal (frequency, amplitude, and phase)

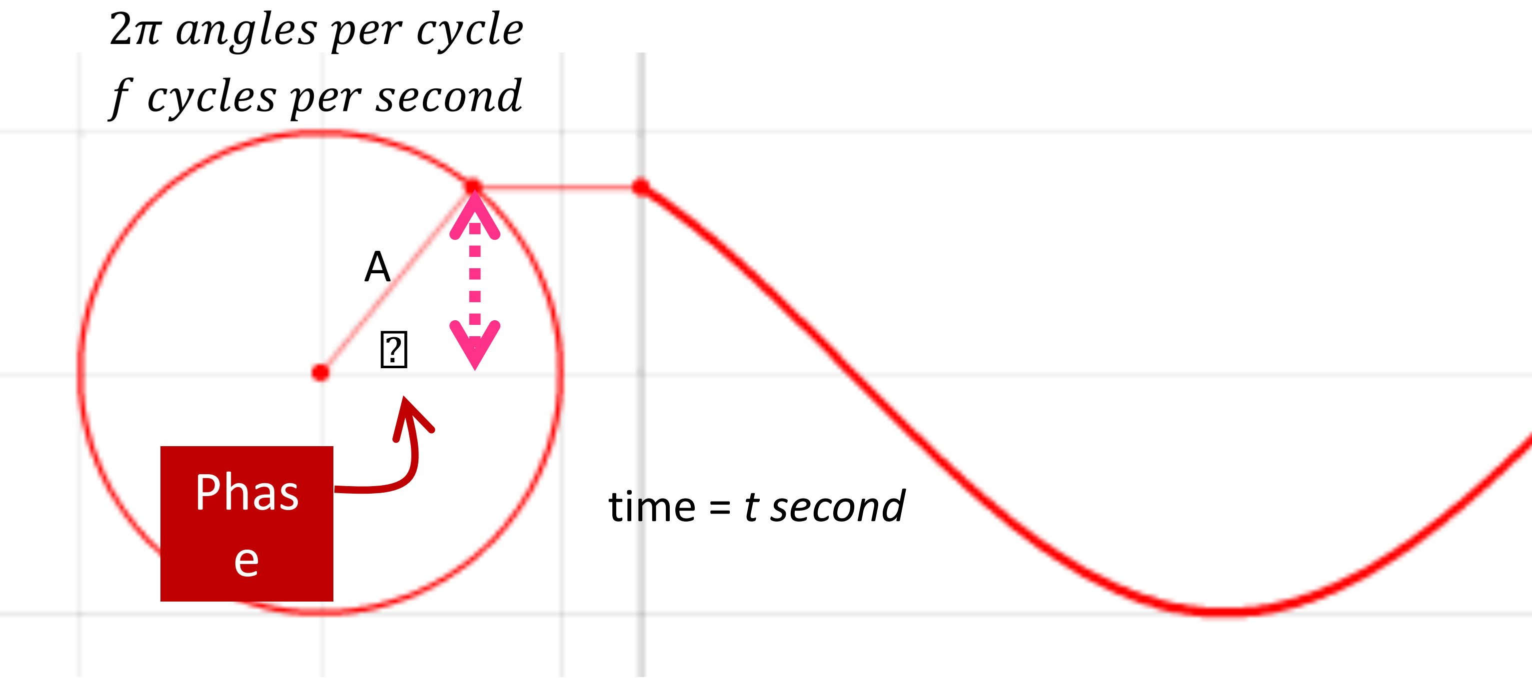


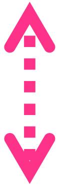
f cycles per second

2π angles per cycle

$$\theta = 2\pi f t$$

Frequency, Amplitude, and Phase

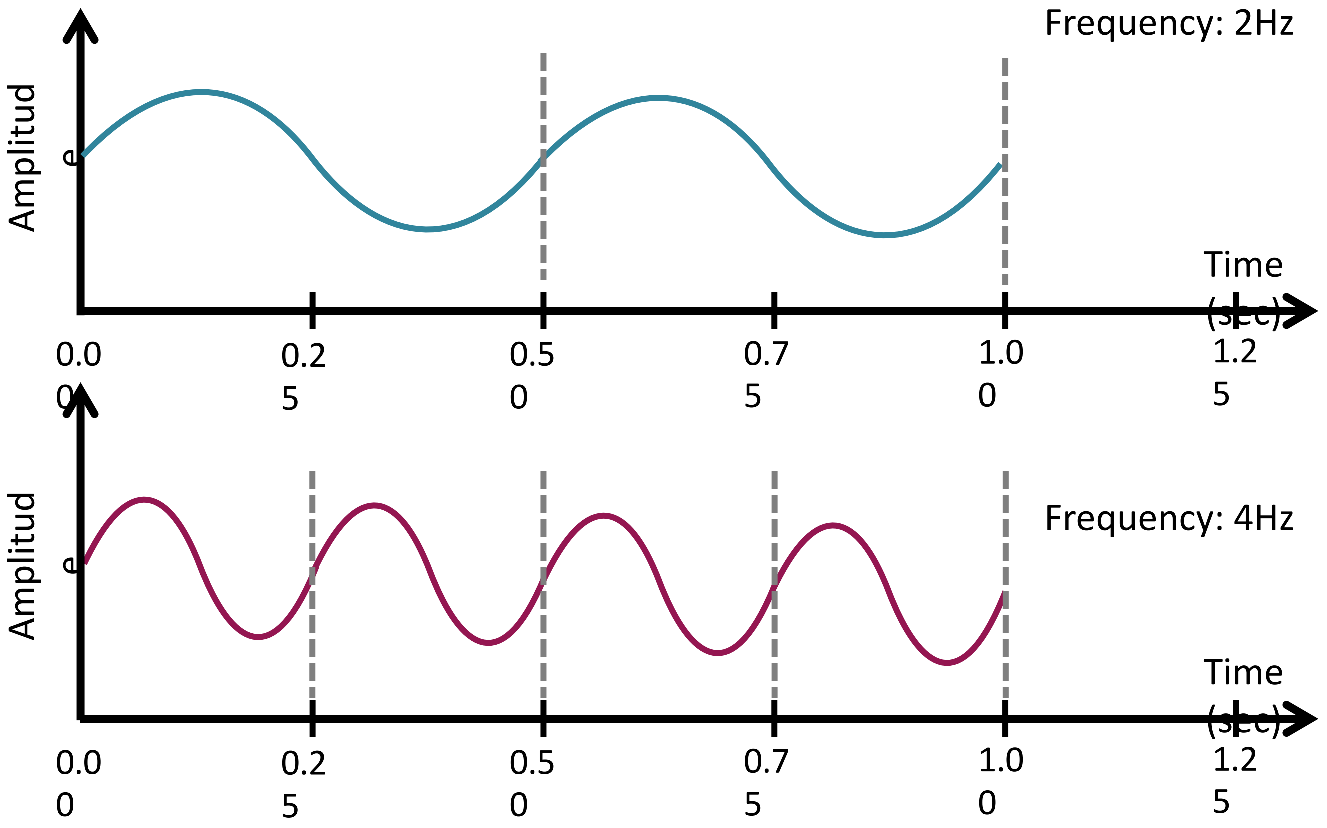




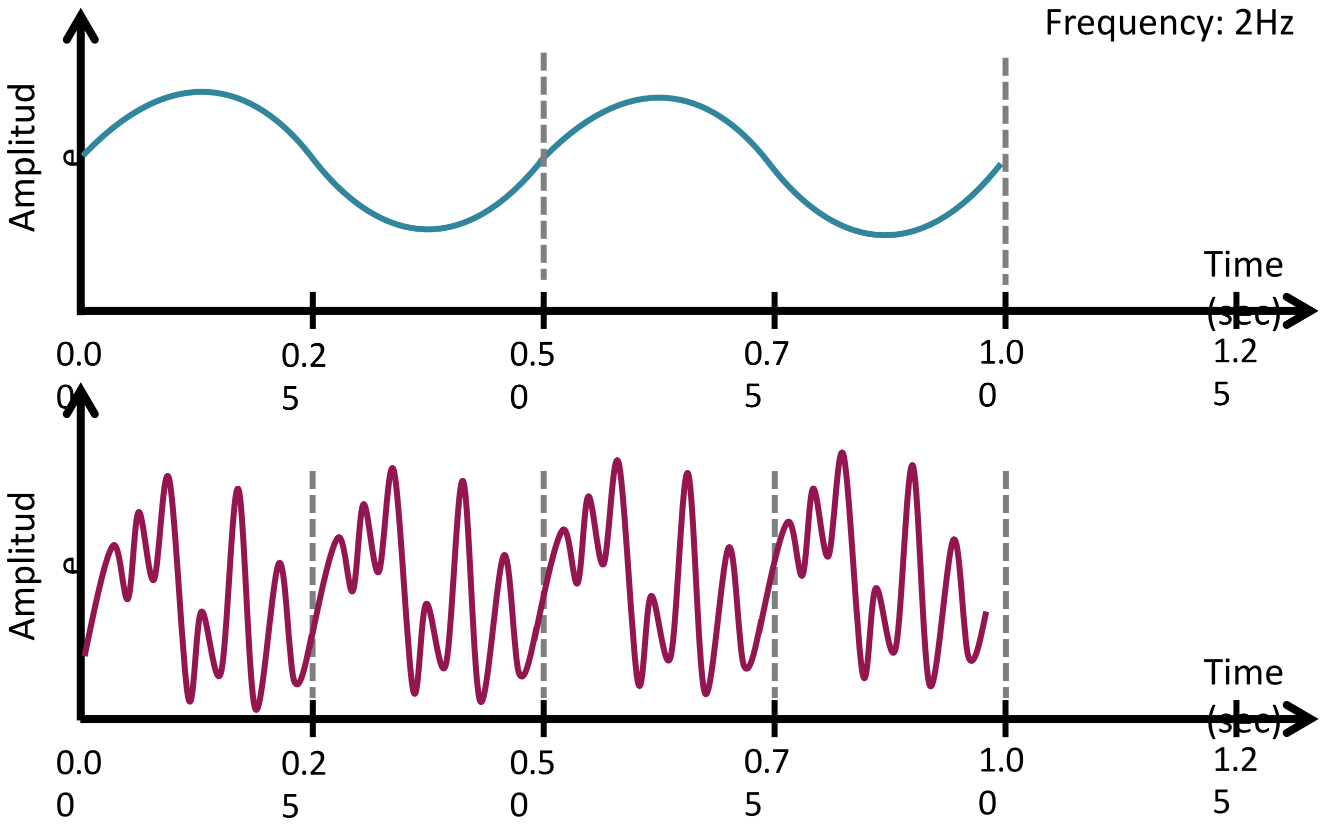
$$= \ A\,.\sin(\theta) \ = \ A\,.\sin(2\pi f t)$$

$A\,.\sin(2\pi f t + \phi)$ -- with initial/additional phase φ

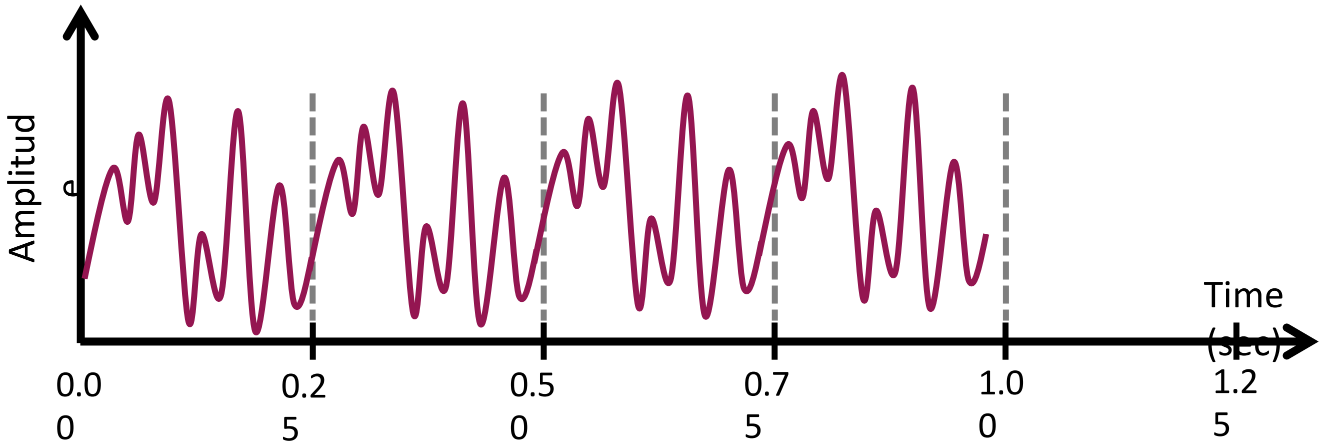
Frequency, Amplitude, and Phase

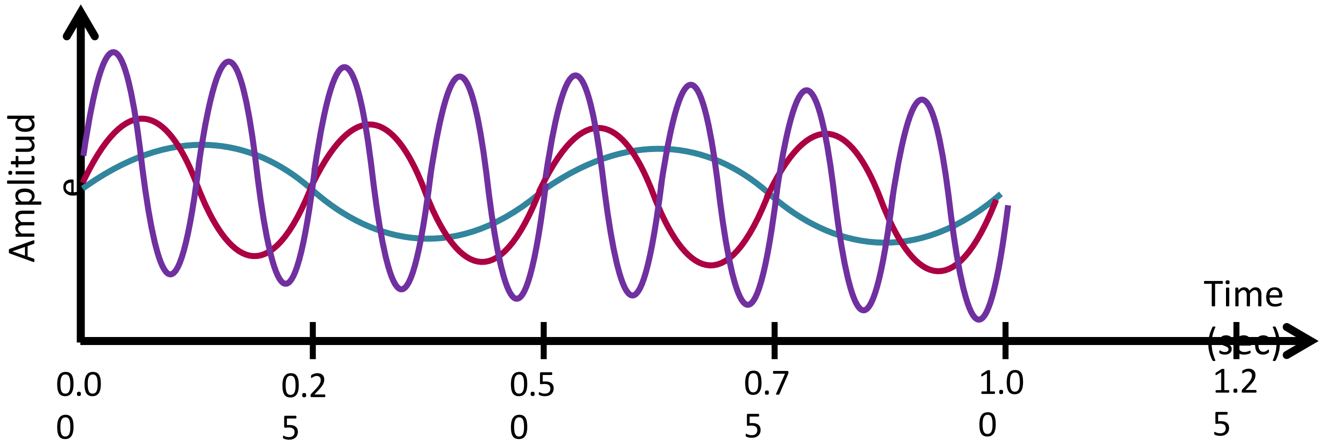


Frequencies of an arbitrary signal

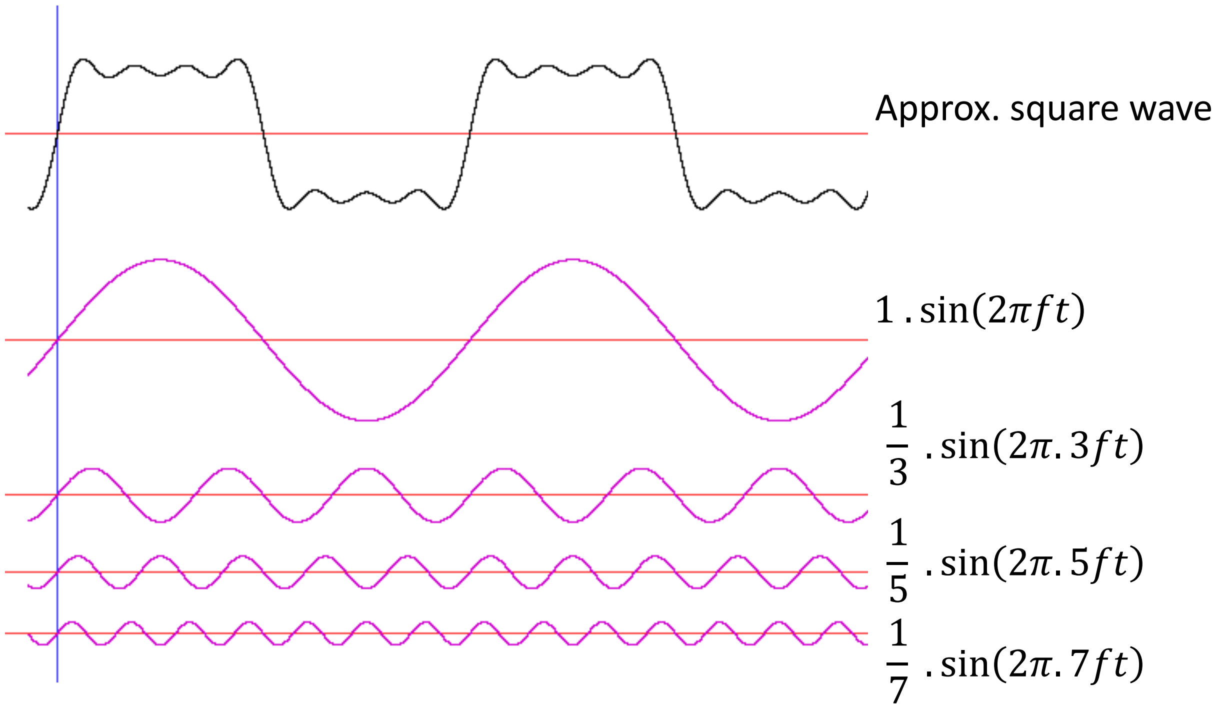


The concept of the Fourier series

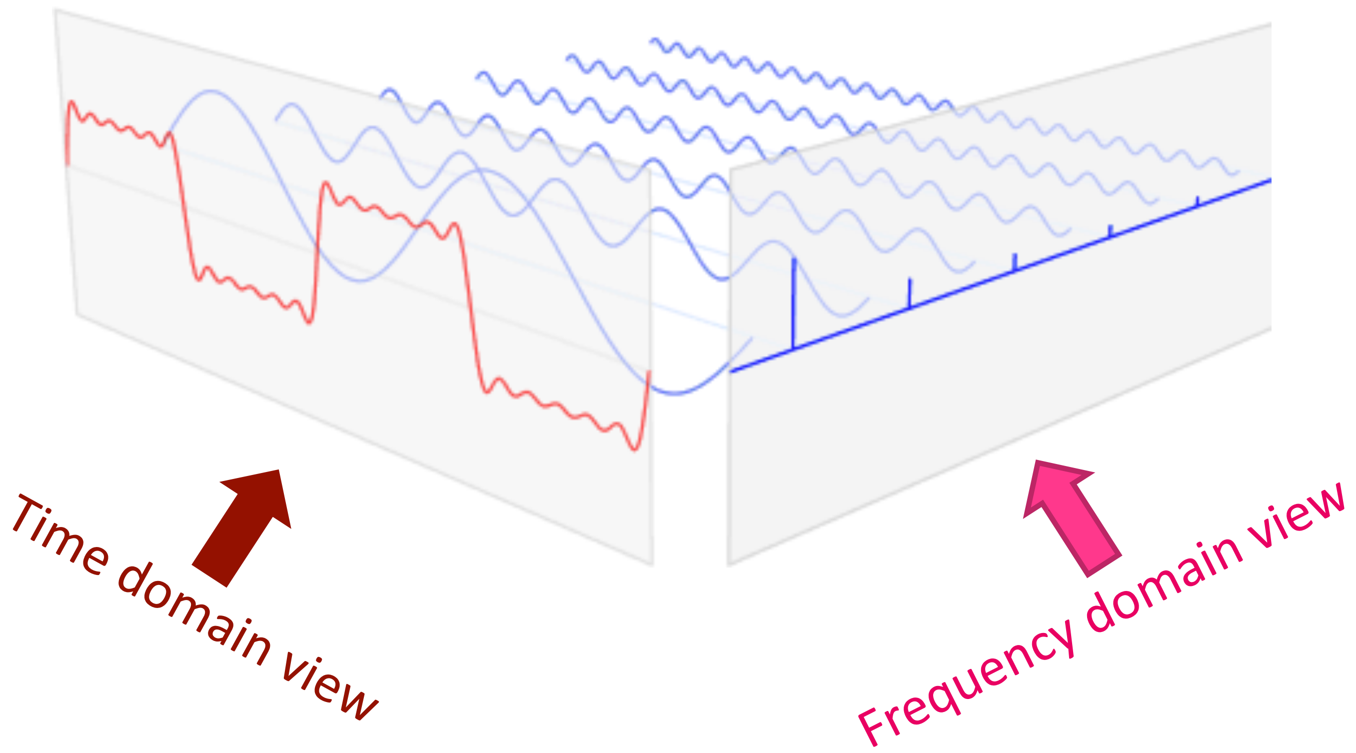




Time Domain and Frequency Domain



Time Domain and Frequency Domain



Analogy: Food coloring chart

Basis for food colors

Analogy: Food coloring chart

Basis for food colors

	RED	YELLOW	GREEN	BLUE
ORANGE	1	2		

Analogy: Food coloring chart

Basis for food colors

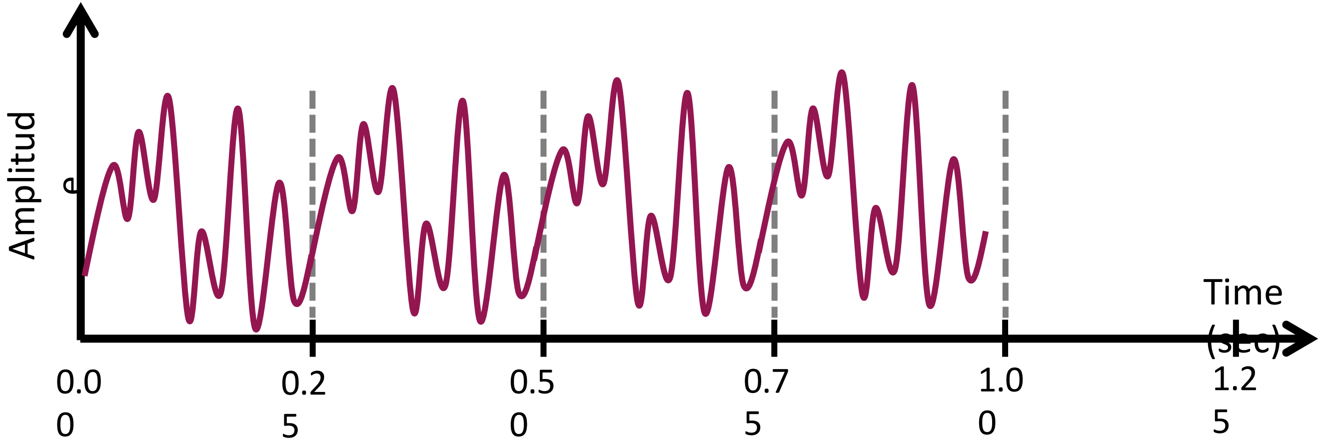
	RED	YELLOW	GREEN	BLUE
ORANGE	1	2		
PURPLE	3			1

Analogy: Food coloring chart

Basis for food colors

	RED	YELLOW	GREEN	BLUE
ORANGE	1	2		
PURPLE	3			1
DARK GREEN	1	1		4
LIME GREEN		3	1	
AQUA			2	4
FLESH	2	5		
BROWN	6	6		4

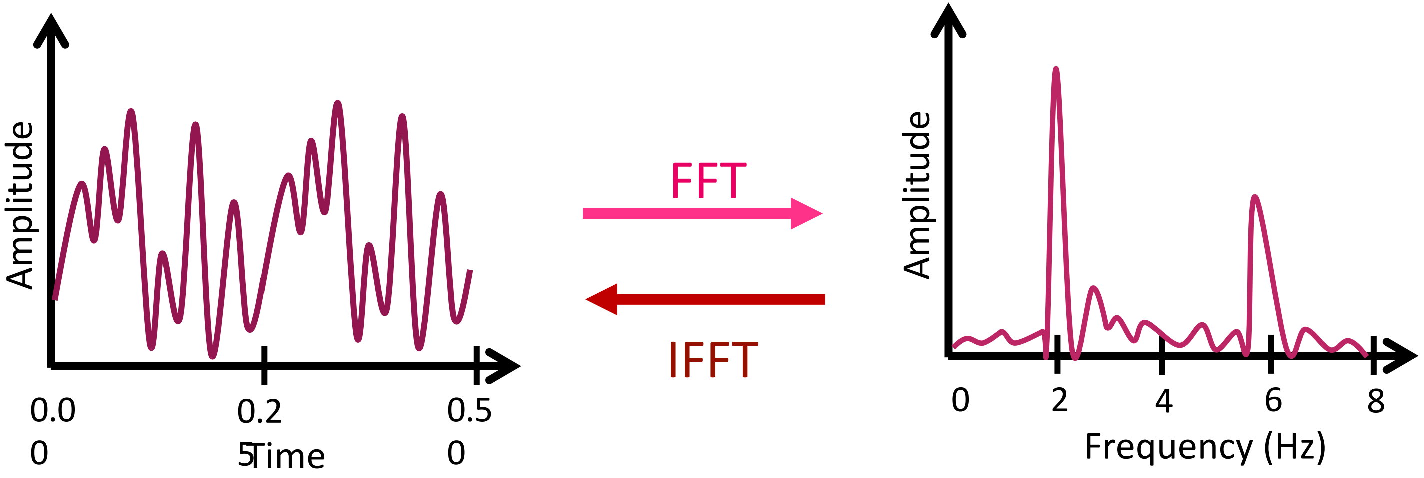
Time Domain and Frequency Domain



$$= A_1 . \sin(2\pi f_1 t) + B_1 . cos(2\pi f_1 t)$$
$$+ A_2 . \sin(2\pi f_2 t) + B_2 . cos(2\pi f_2 t)$$
$$+ A_3 . \sin(2\pi f_3 t) + B_3 . cos(2\pi f_3 t)$$
$$+ \ldots$$

Time Domain and Frequency Domain

Fourier Transform



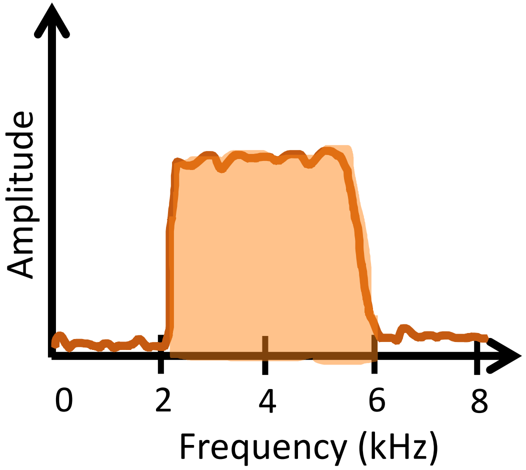
Time domain

Frequency domain

FFT = Fast Fourier Transform

IFFT = Inverse Fast Fourier Transform

Frequency band

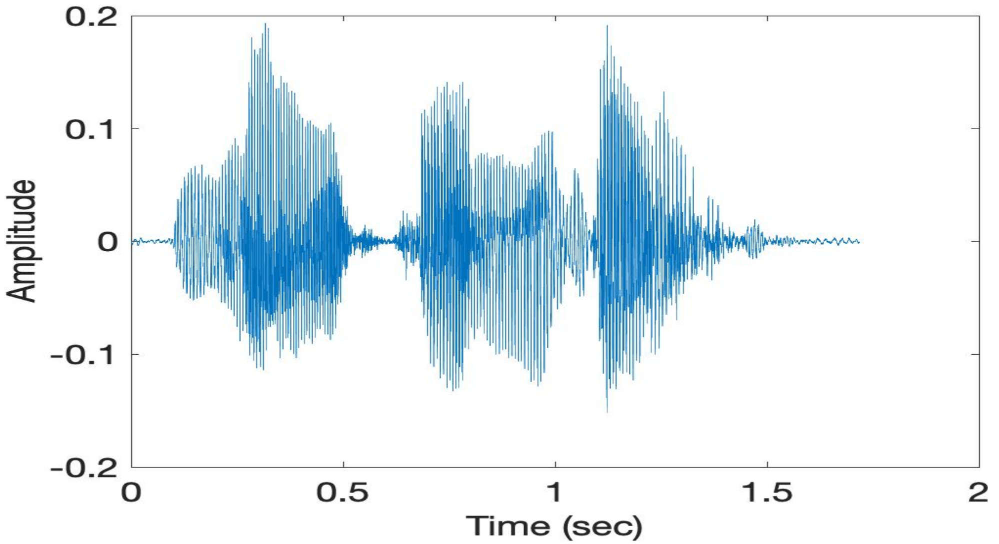


A 4 kHz frequency band starting at 2 kHz

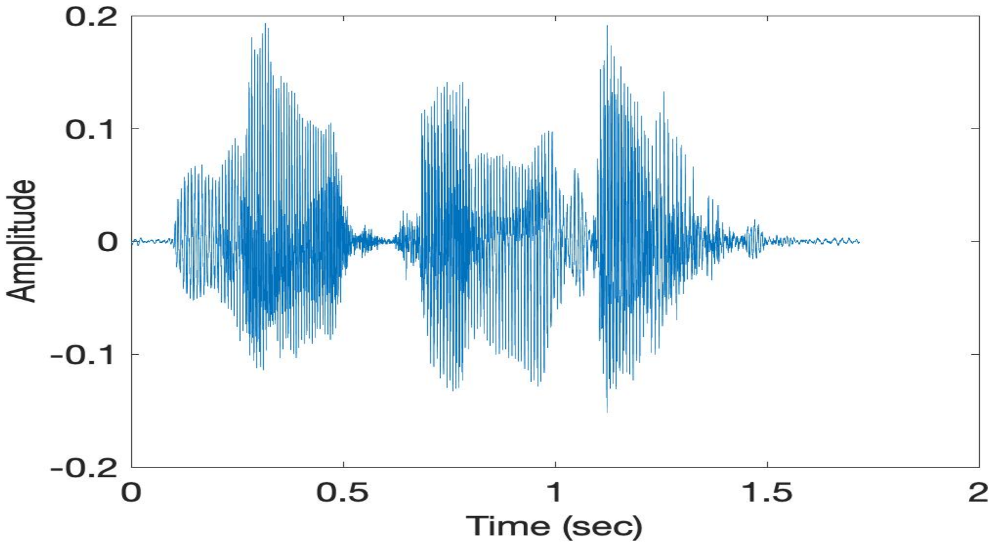
What is bandwidth?

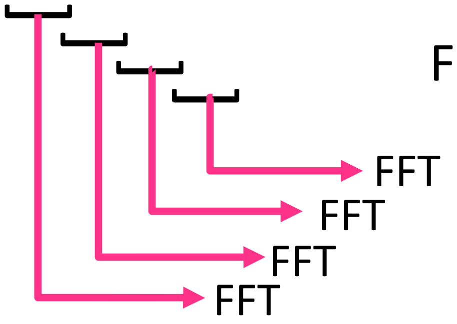
What is center frequency?

Spectrogram



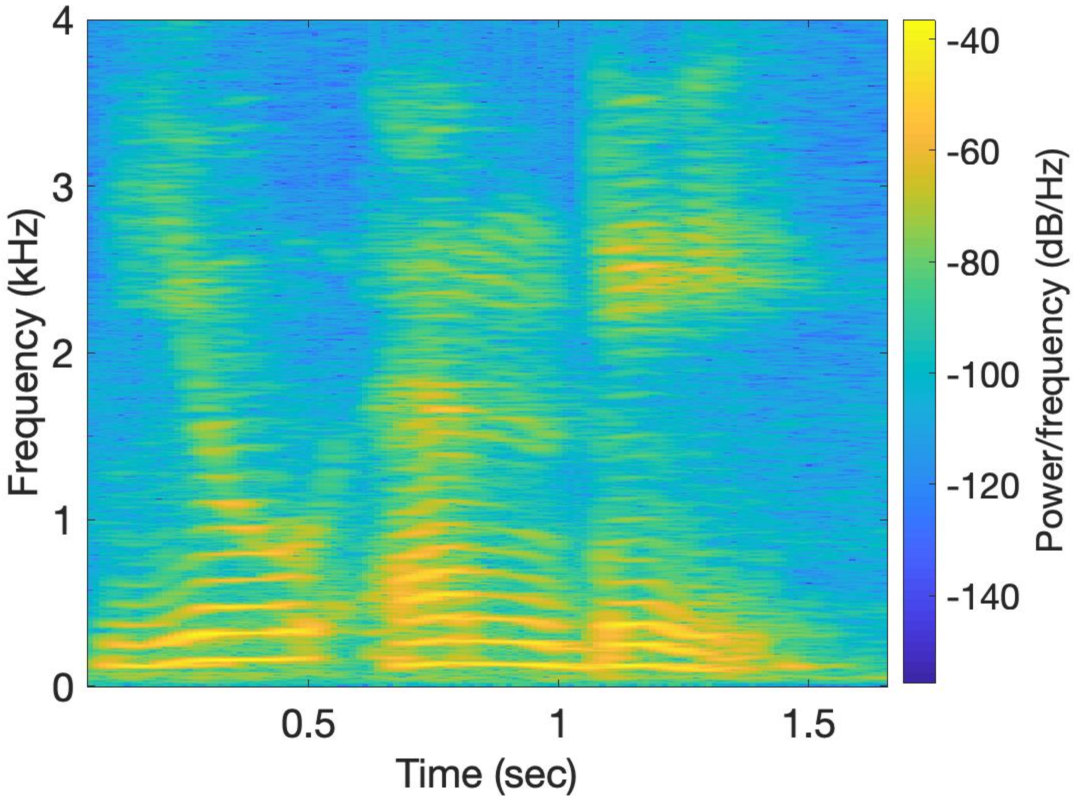
Spectrogram





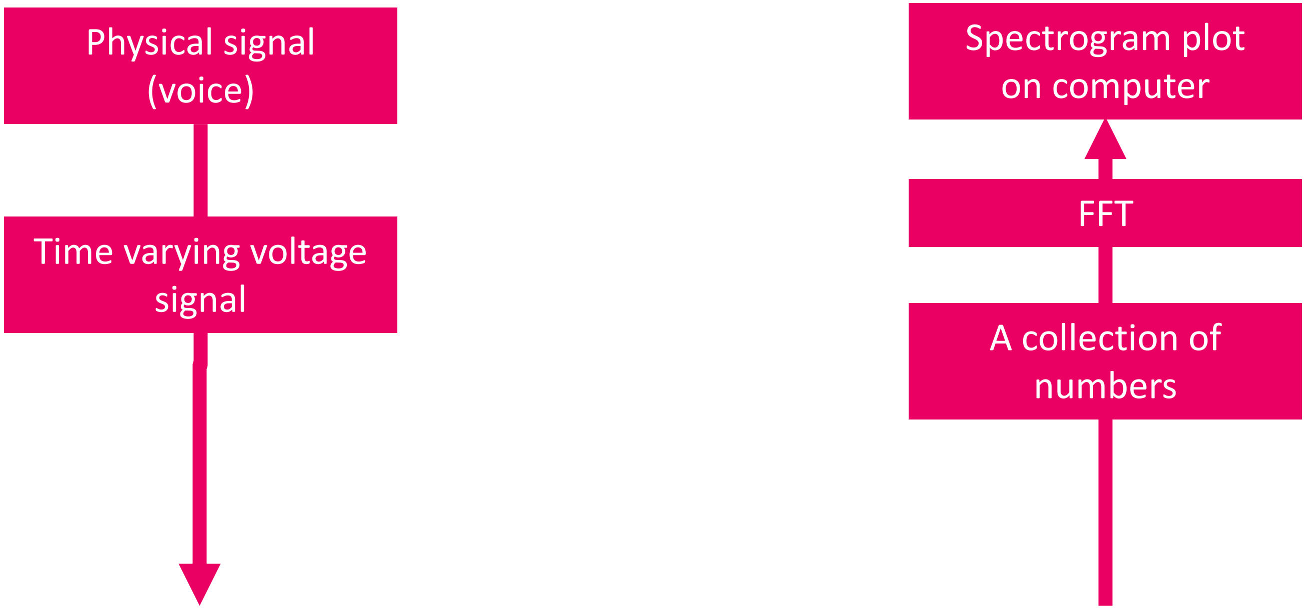
FFT of overlapping windows of samples (Spectrogram)

Spectrogram

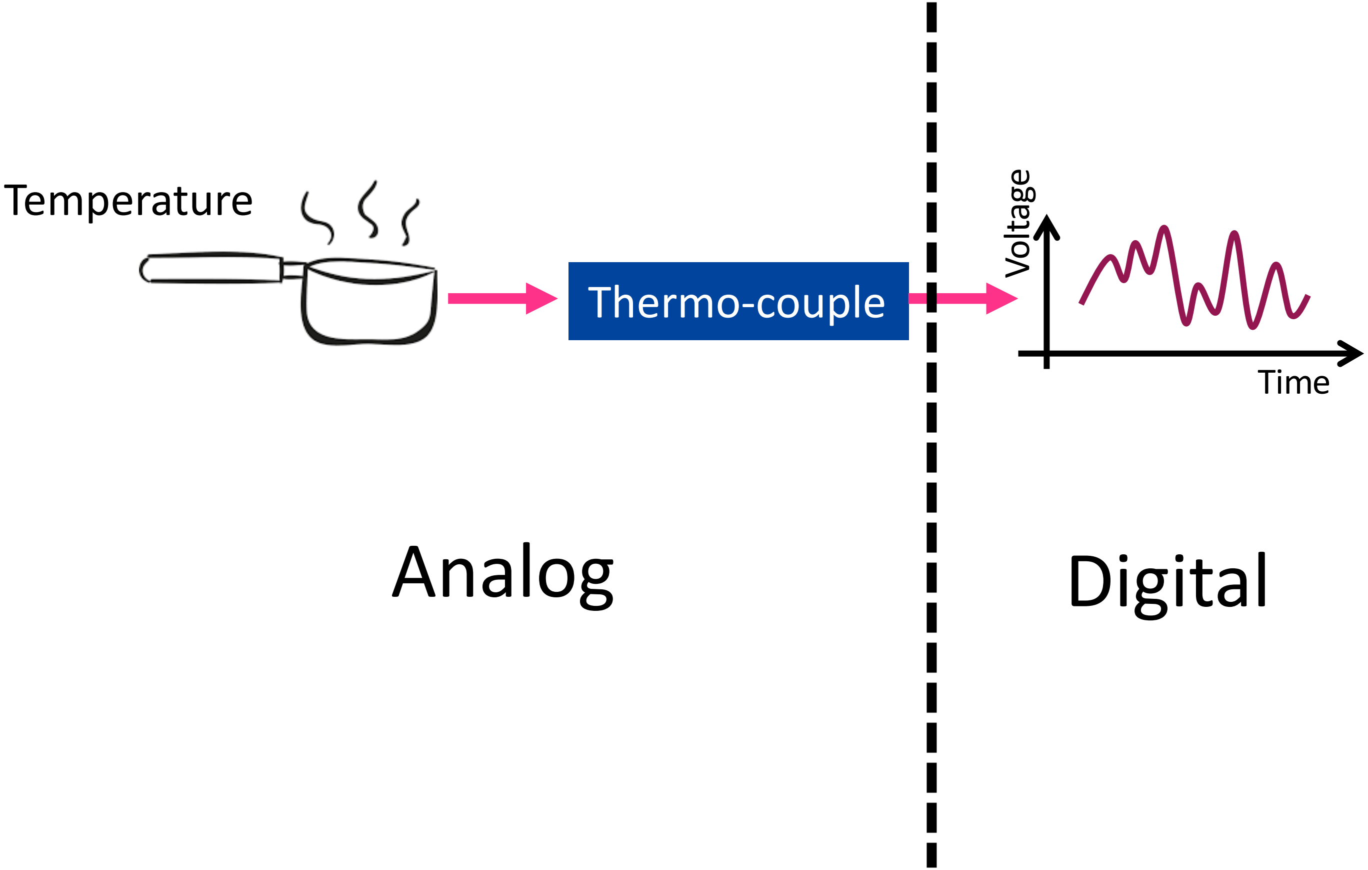


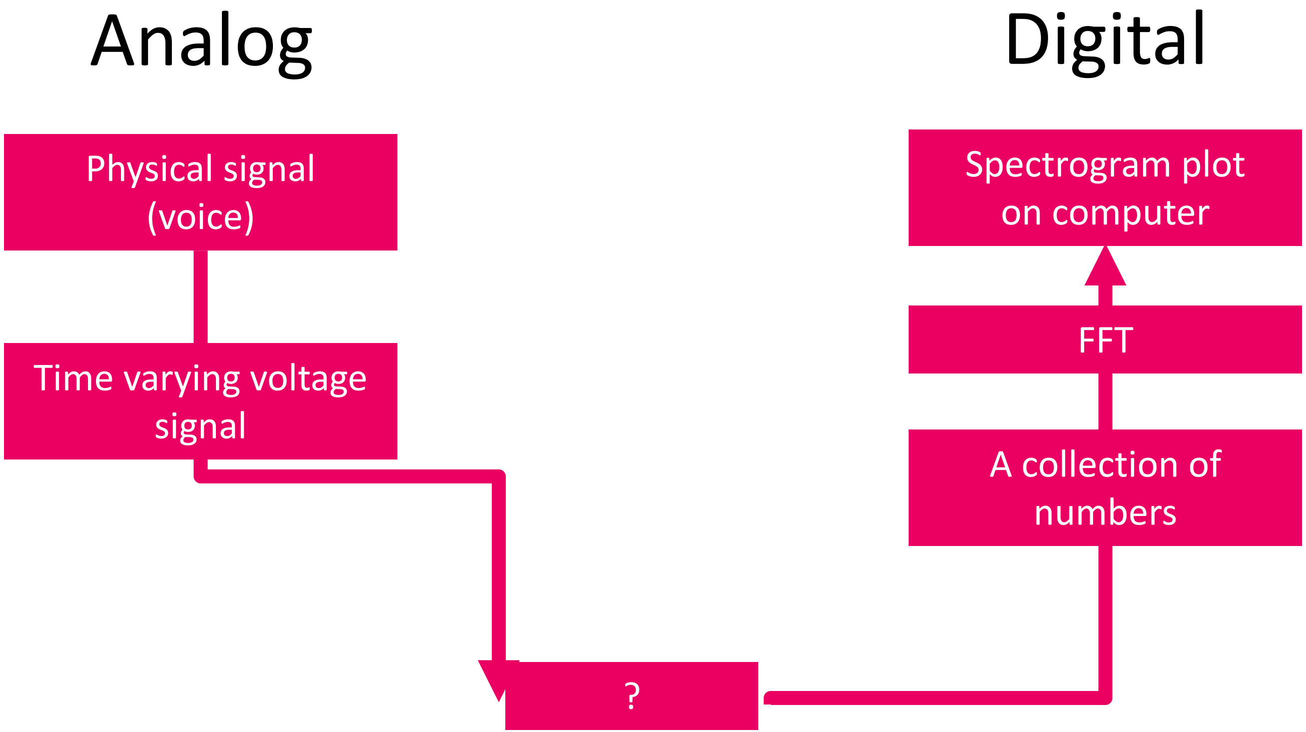
Analog

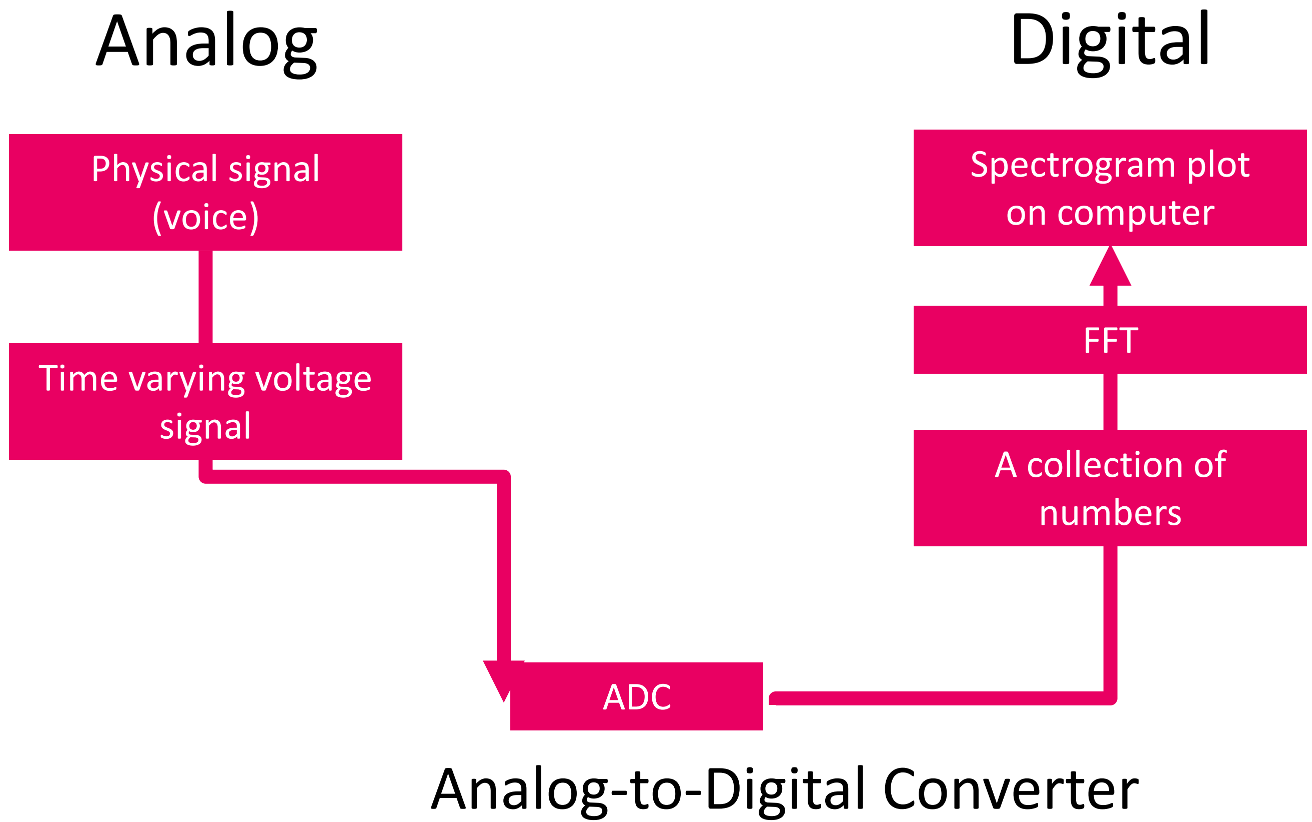
Digital



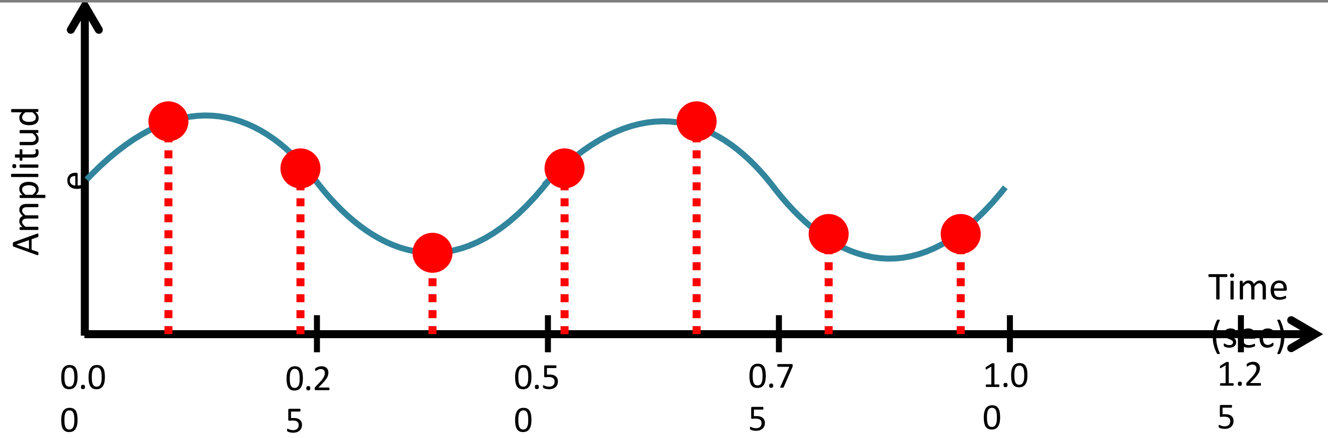
Analog vs Digital World



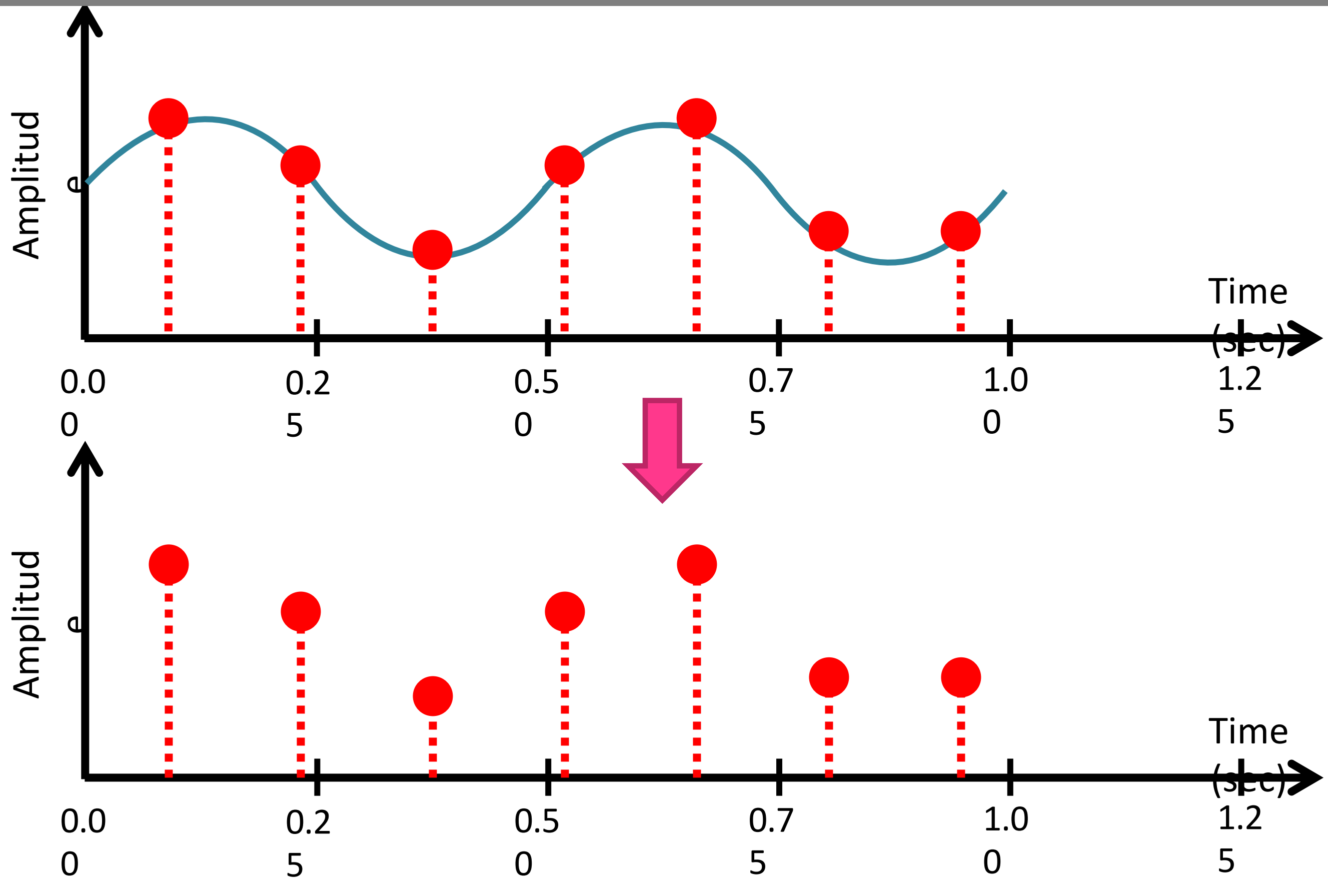

Analog
Digital
Physical signal (voice)
Time varying voltage signal
?
A collection of numbers
FFT
Spectrogram plot on computer


Analog
Digital
Physical signal (voice)
Time varying voltage signal
ADC
A collection of numbers
FFT
Spectrogram plot on computer
Analog-to-Digital Converter

Sampling theorem

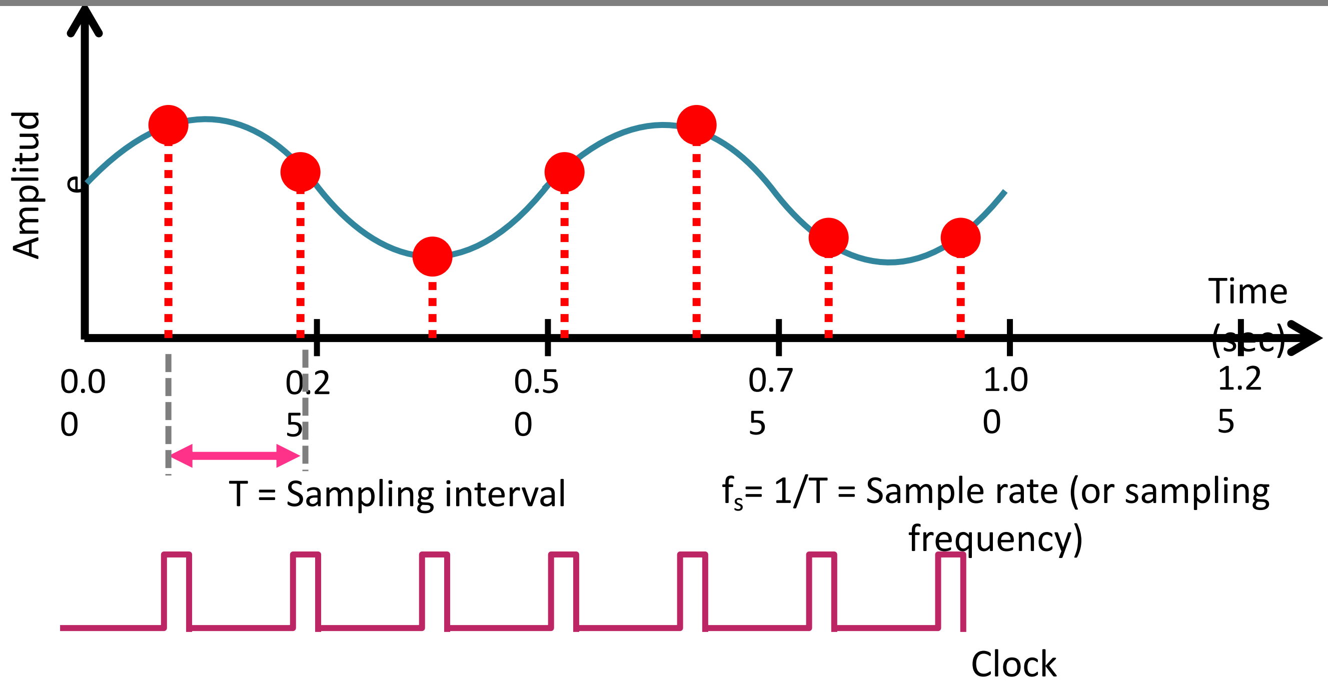


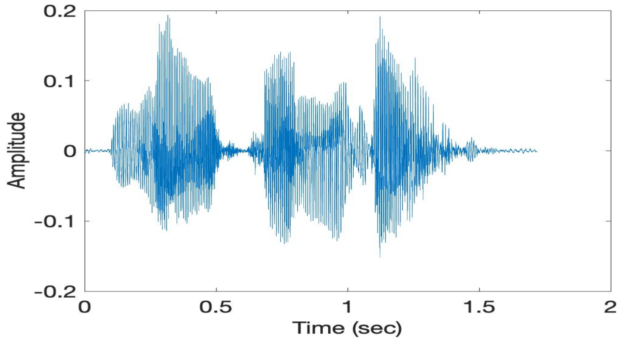
Sampling theorem



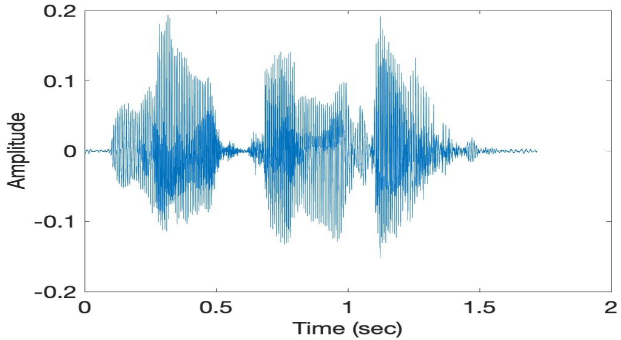
[0.34 0.22 0.09 0.21 0.30 0.08 0.09]

Sampling theorem

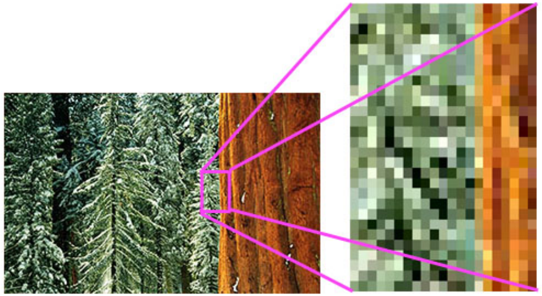




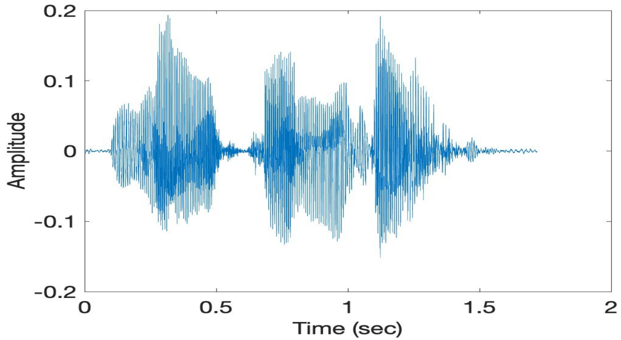
1-dimensional sampling



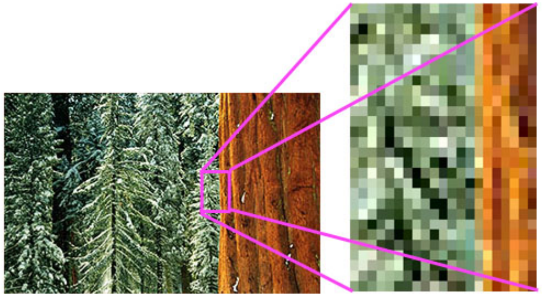
1-dimensional sampling



2-dimensional sampling



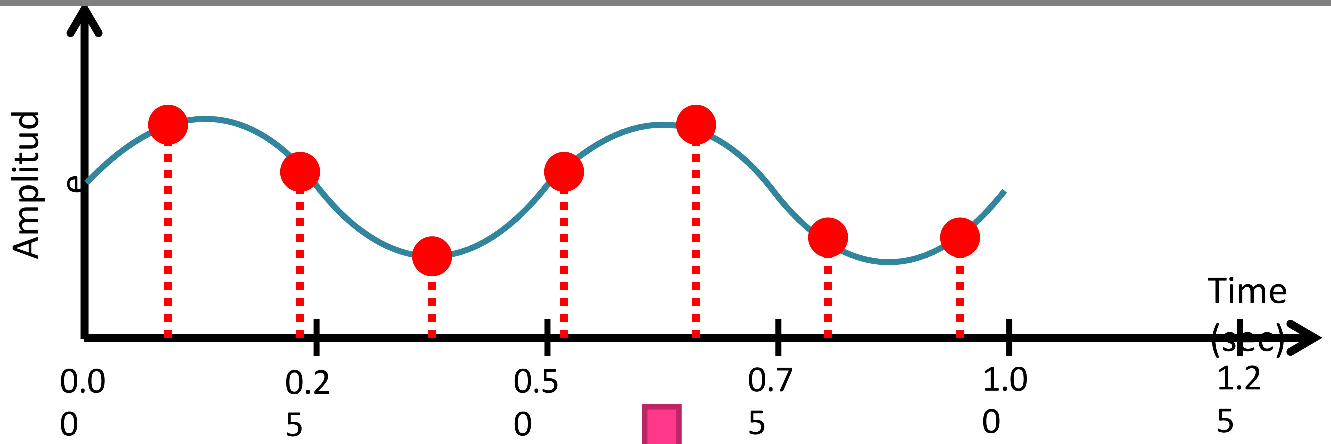
1-dimensional sampling

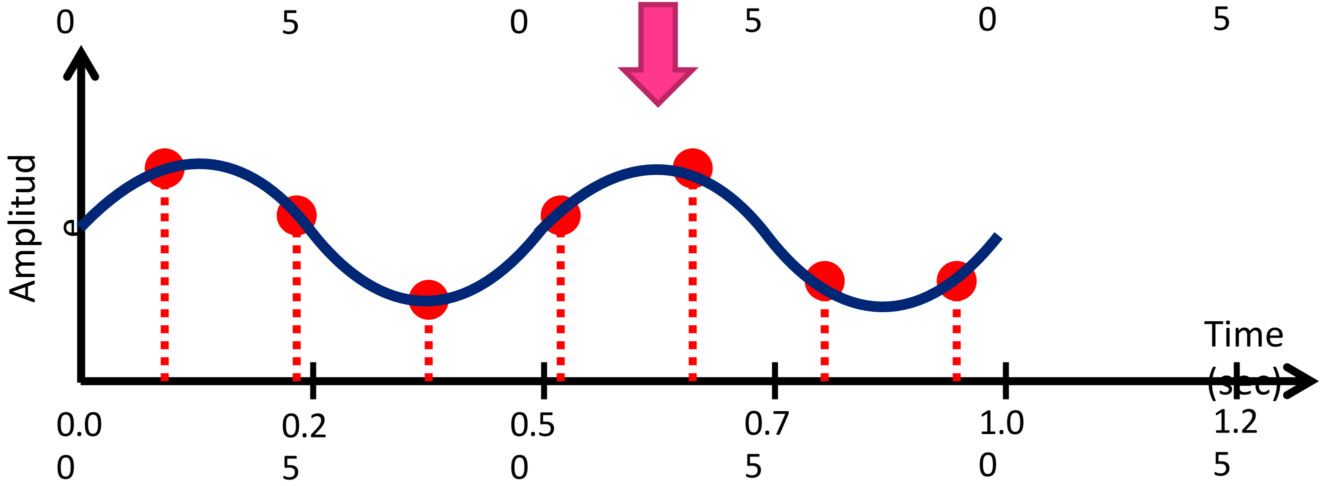


2-dimensional sampling

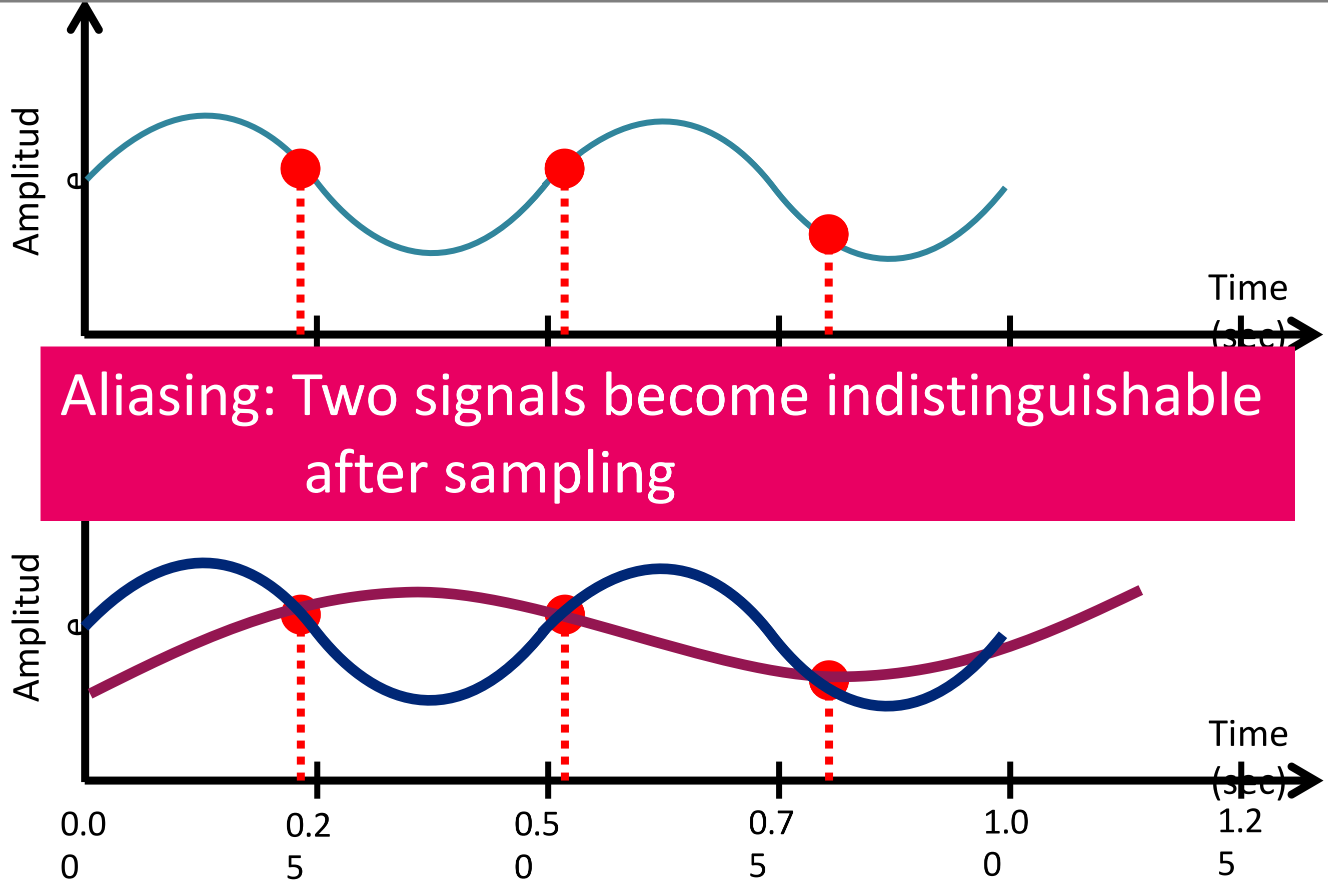
3-dimensional sampling

Sampling theorem



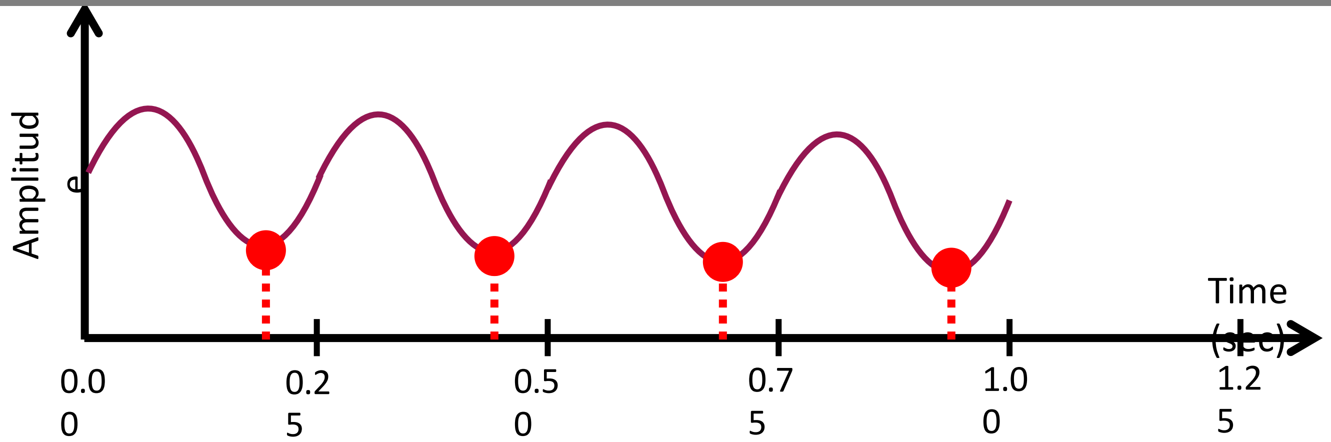


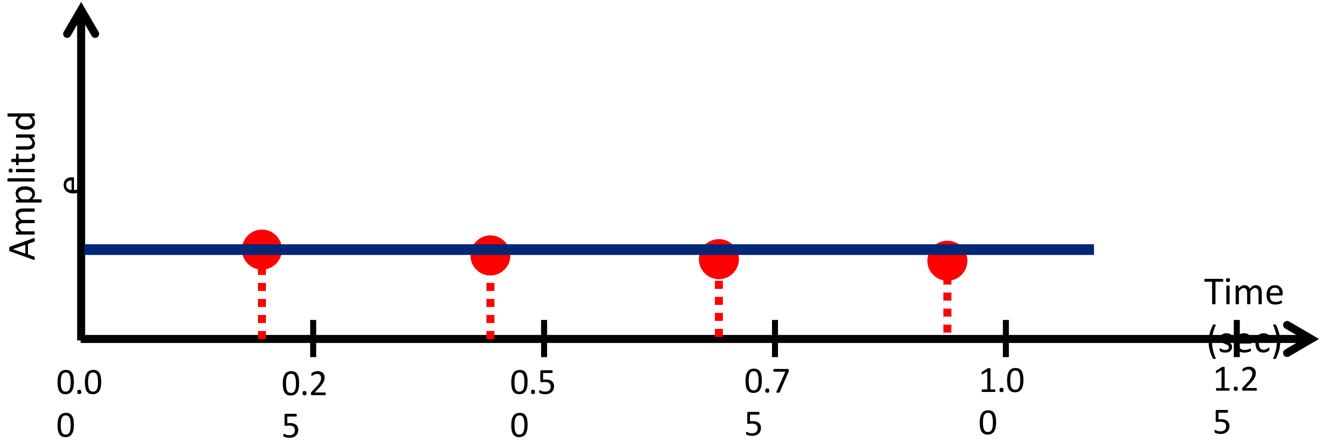
Sampling theorem



Aliasing: Two signals become indistinguishable after sampling

Aliasing


Amplitude
Time (sec)
0.00
0.25
0.50
0.75
1.00
1.25


Amplitude
Time (sec)
0.00
0.25
0.50
0.75
1.00
1.25

Aliasing

Aliasing in real life

https://www.youtube.com/watch?v=QOwzkND_ooU

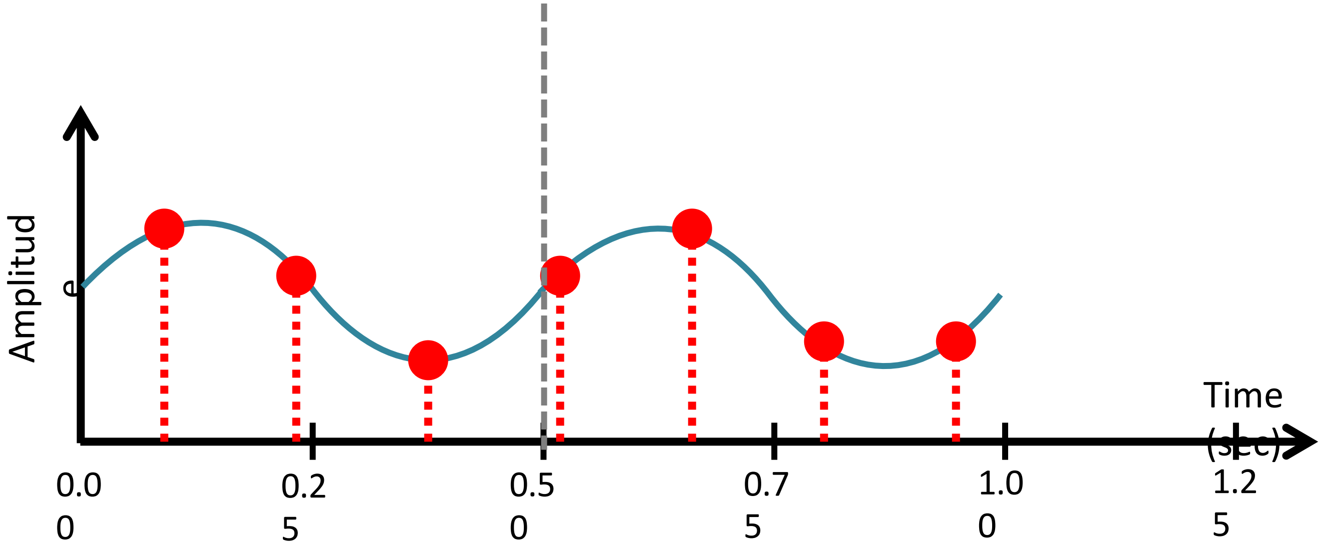
How to find a good sample rate?

How to find a good sample rate?

Nyquist sampling theorem:
In order to uniquely represent a signal F(t) by a set of samples, the sampling rate must be more than twice the highest frequency component present in F(t).

If sample rate is f_s and maximum frequency we want record is f_{max} , then

$$f_s > 2f_{max}$$

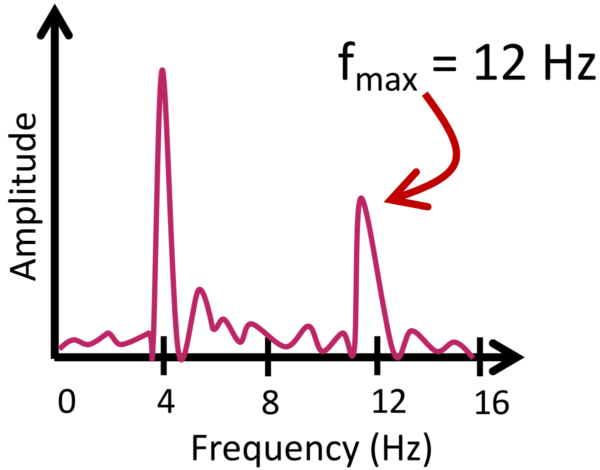


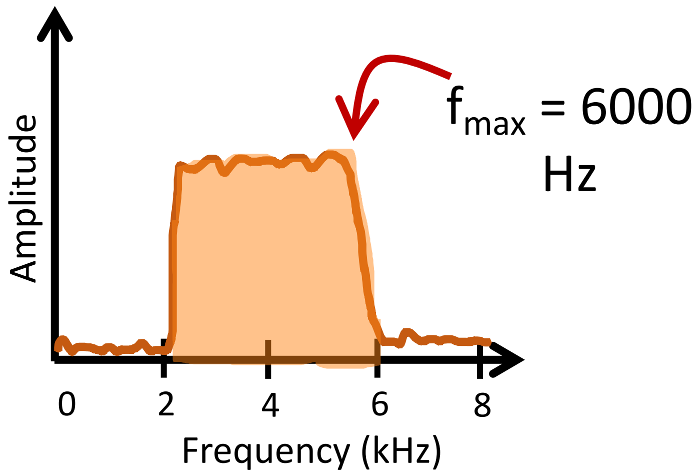
Nyquist frequency = Maximum alias-free frequency for a given sample rate.

Nyquist rate = Lower bound of sample rate for a signal

$$x(t) = \sum_{n=-\infty}^{\infty} x(nT) \cdot \mathrm{sinc}\left(\frac{t - nT}{T}\right),$$

Nyquist

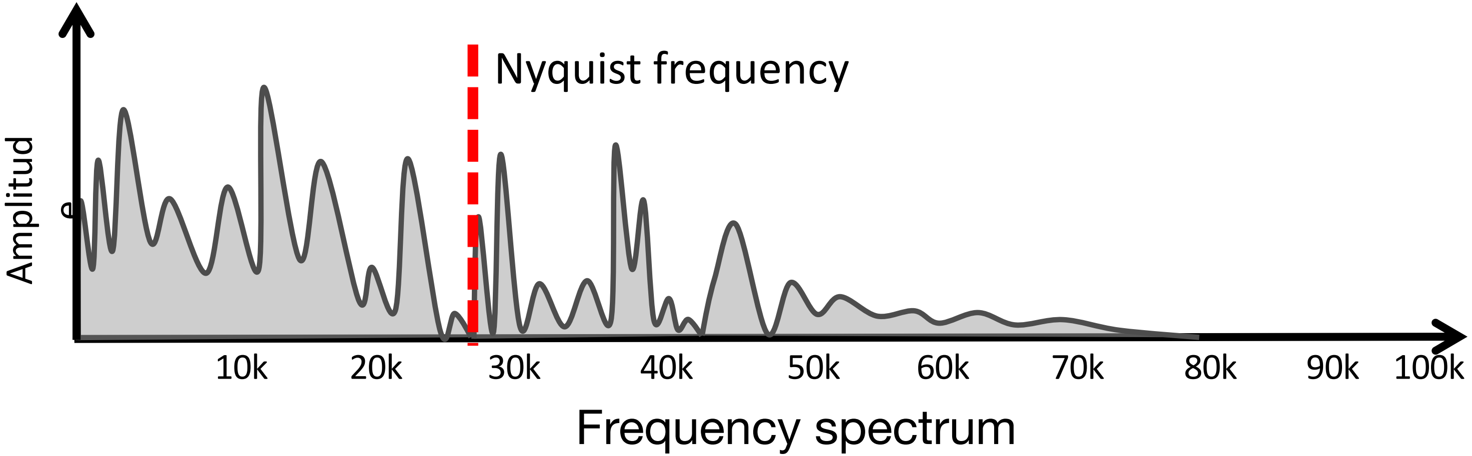




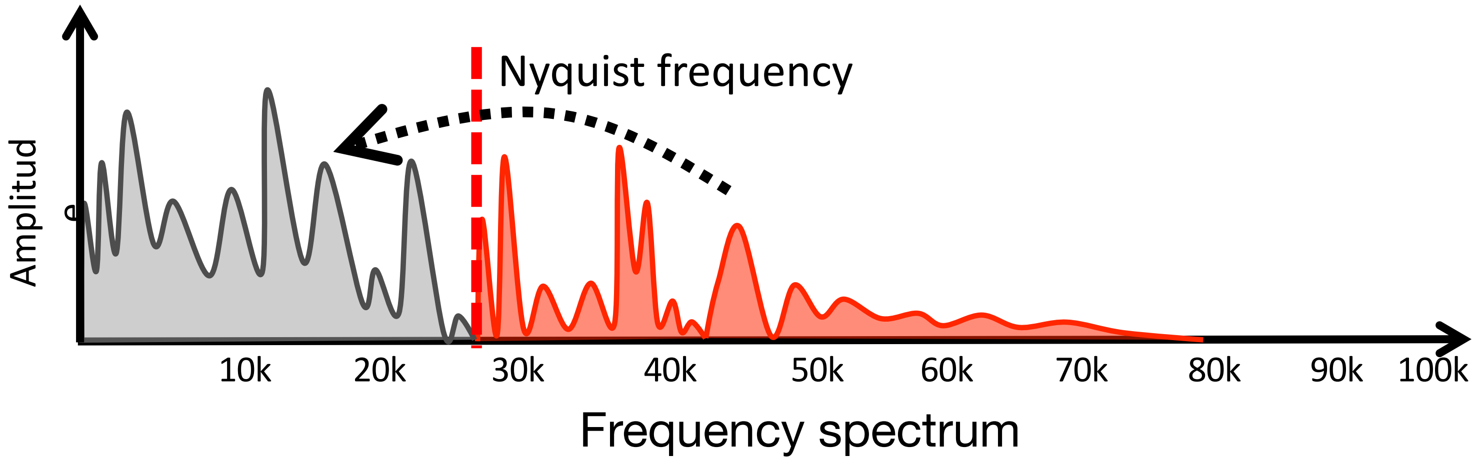
A 4 kHz frequency band starting at 2 kHz

Commonly, the maximum frequency in human voice is 4 kHz, what sample rate will you use in your audio recorder?

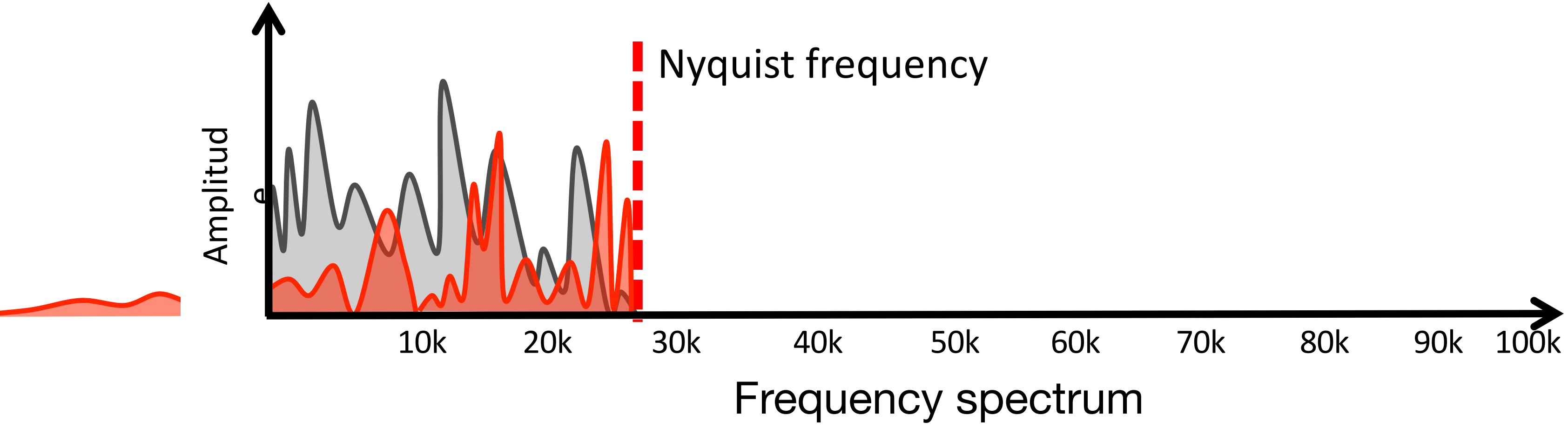
Aliasing: A real life scenario



Aliasing: A real life scenario

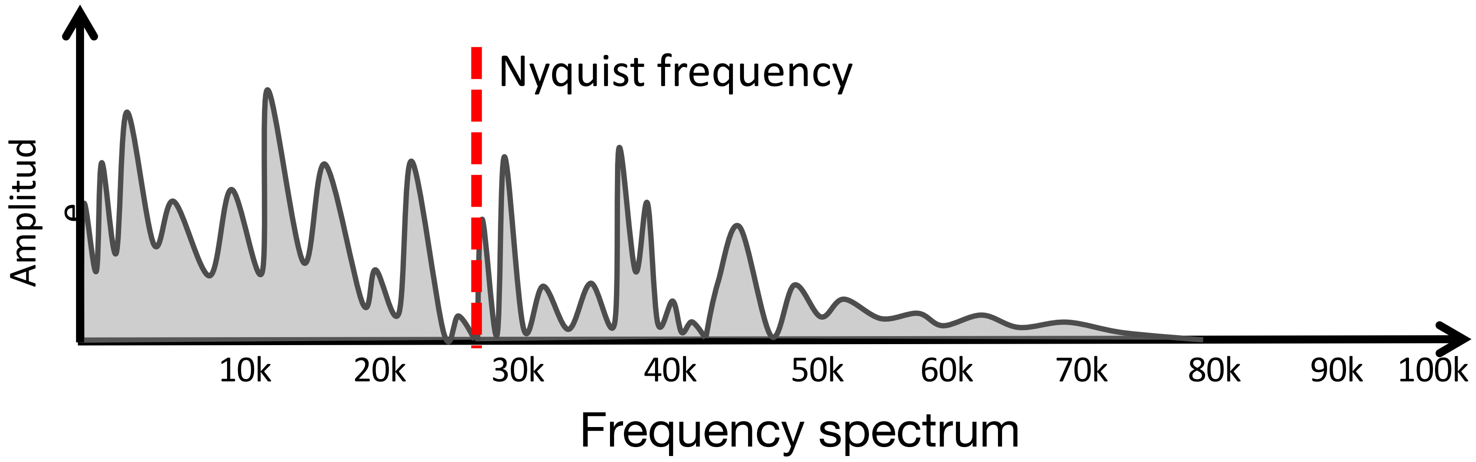


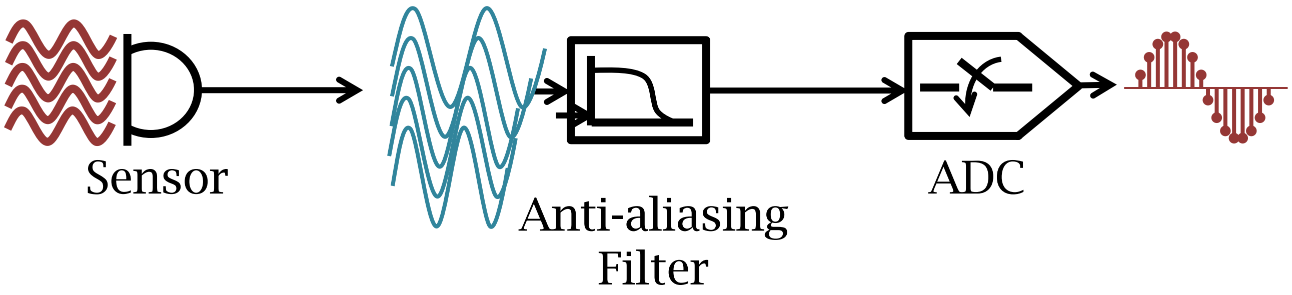
Aliasing: A real life scenario



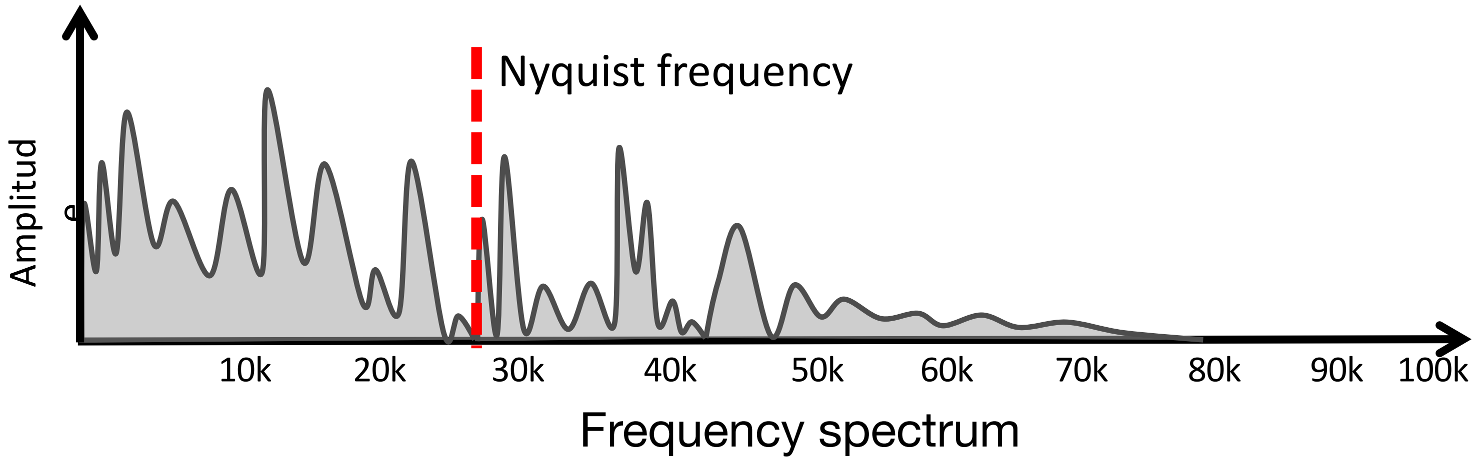
**We need a “Low-pass filter”
to remove unwanted high frequency signals**

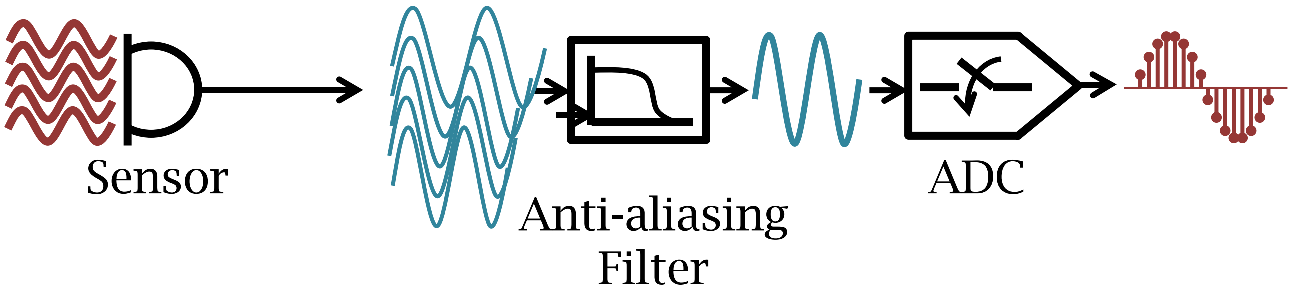
Anti-aliasing filter



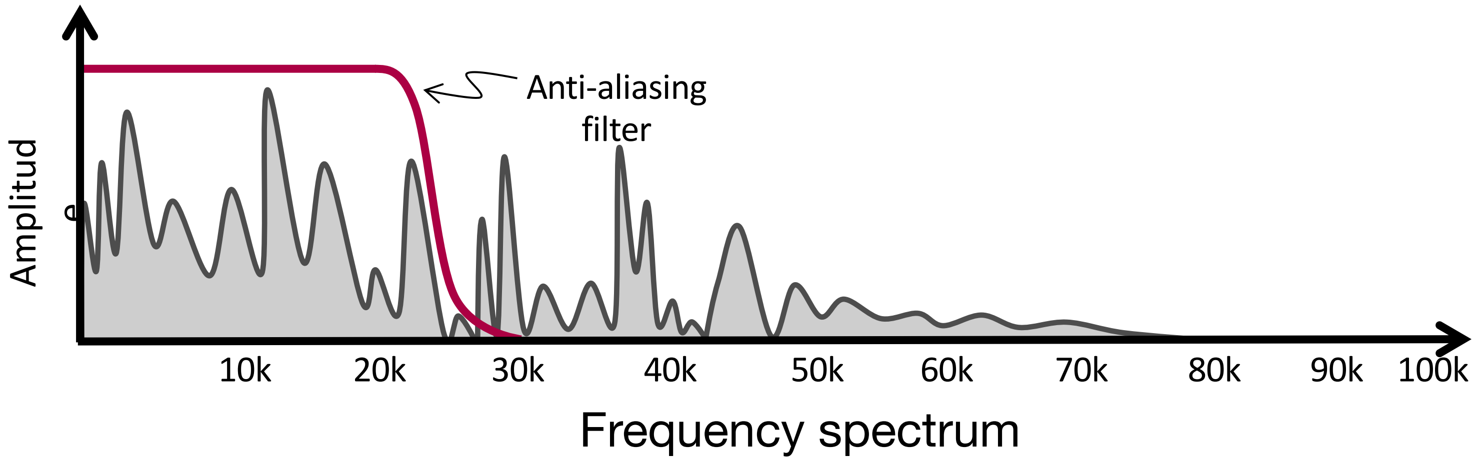


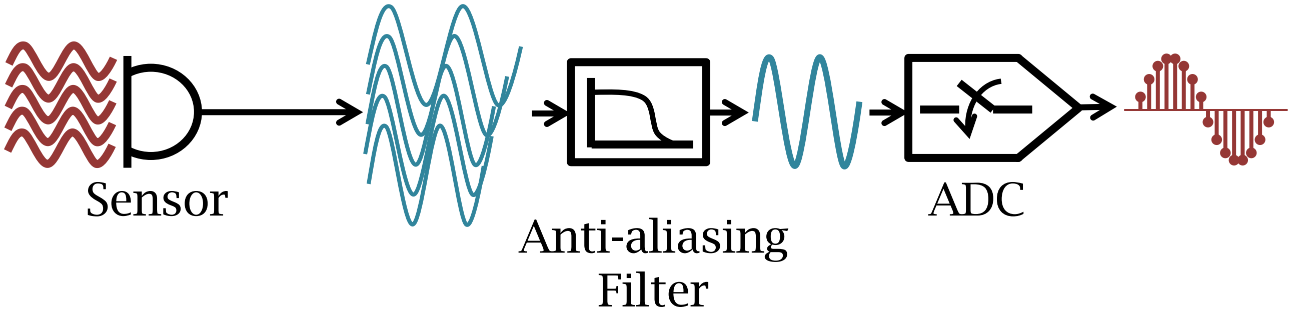
Anti-aliasing filter



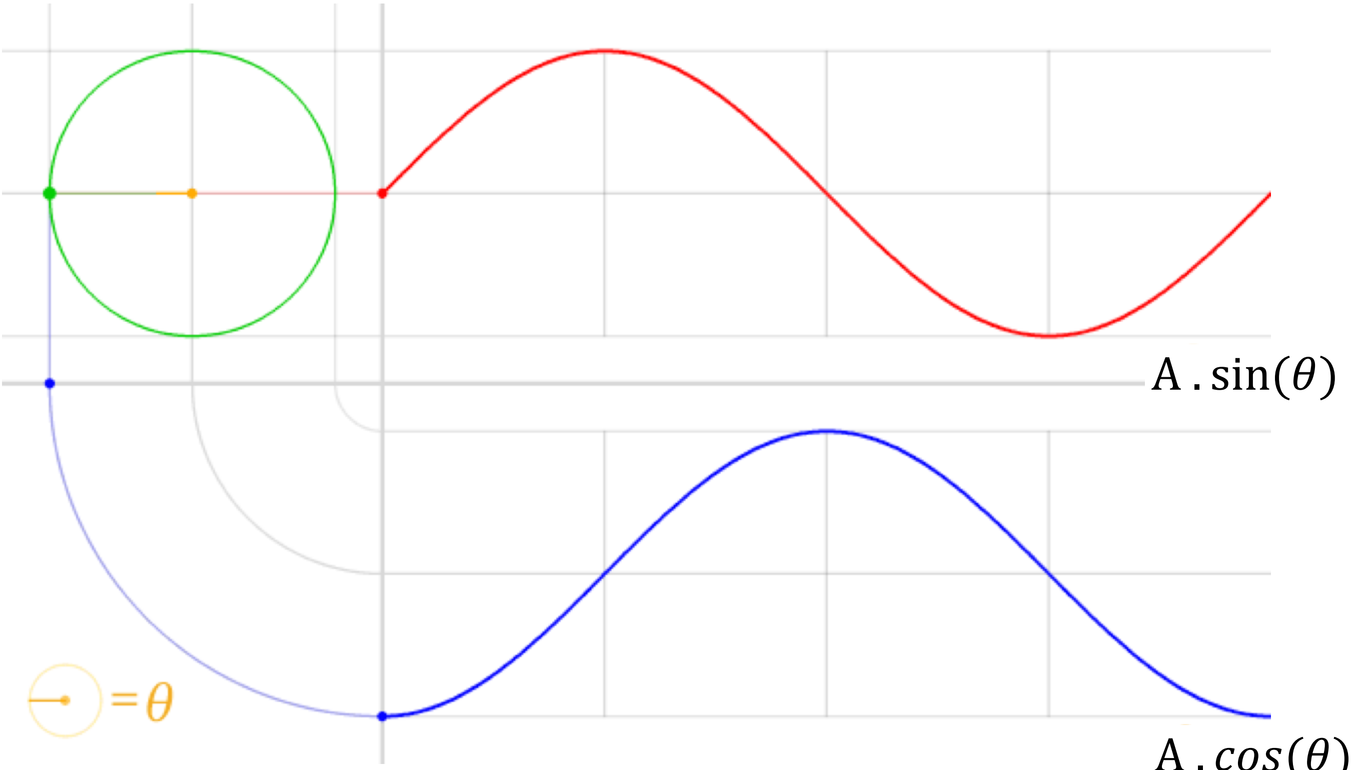


Anti-aliasing filter

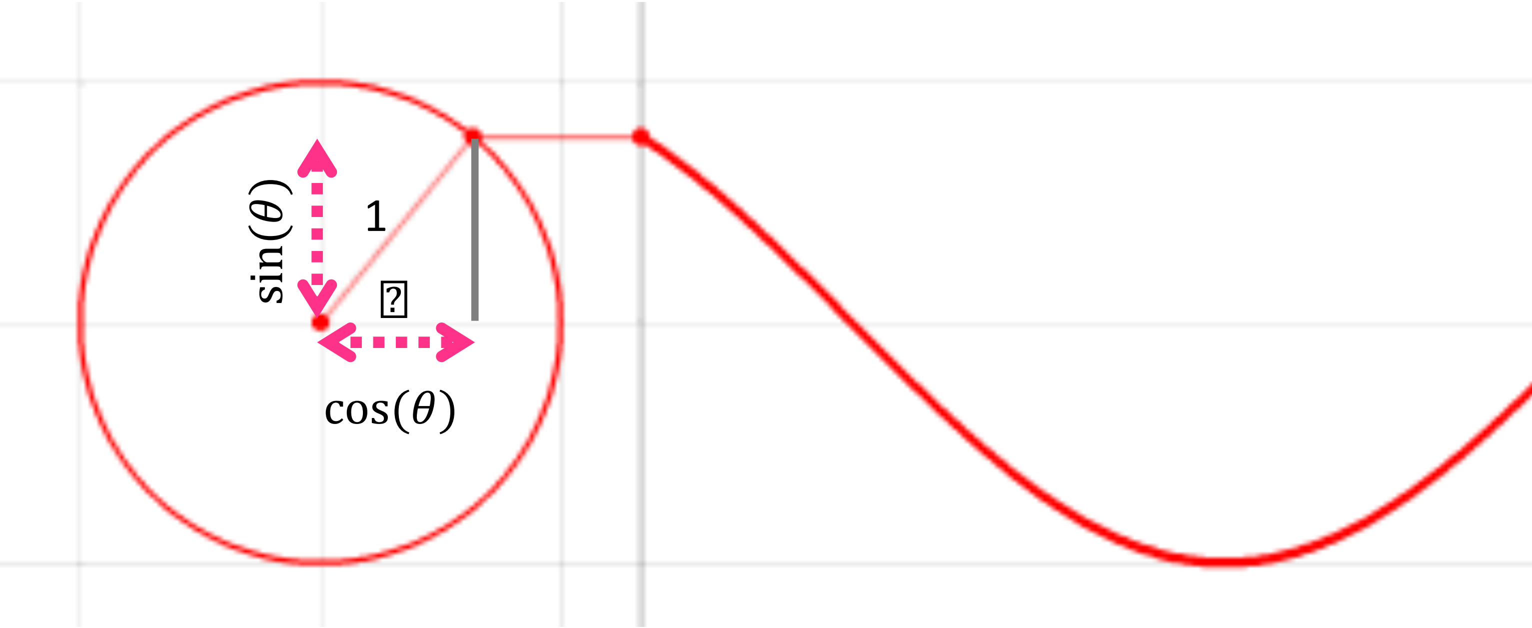




Model for a signal (frequency, amplitude, and phase)

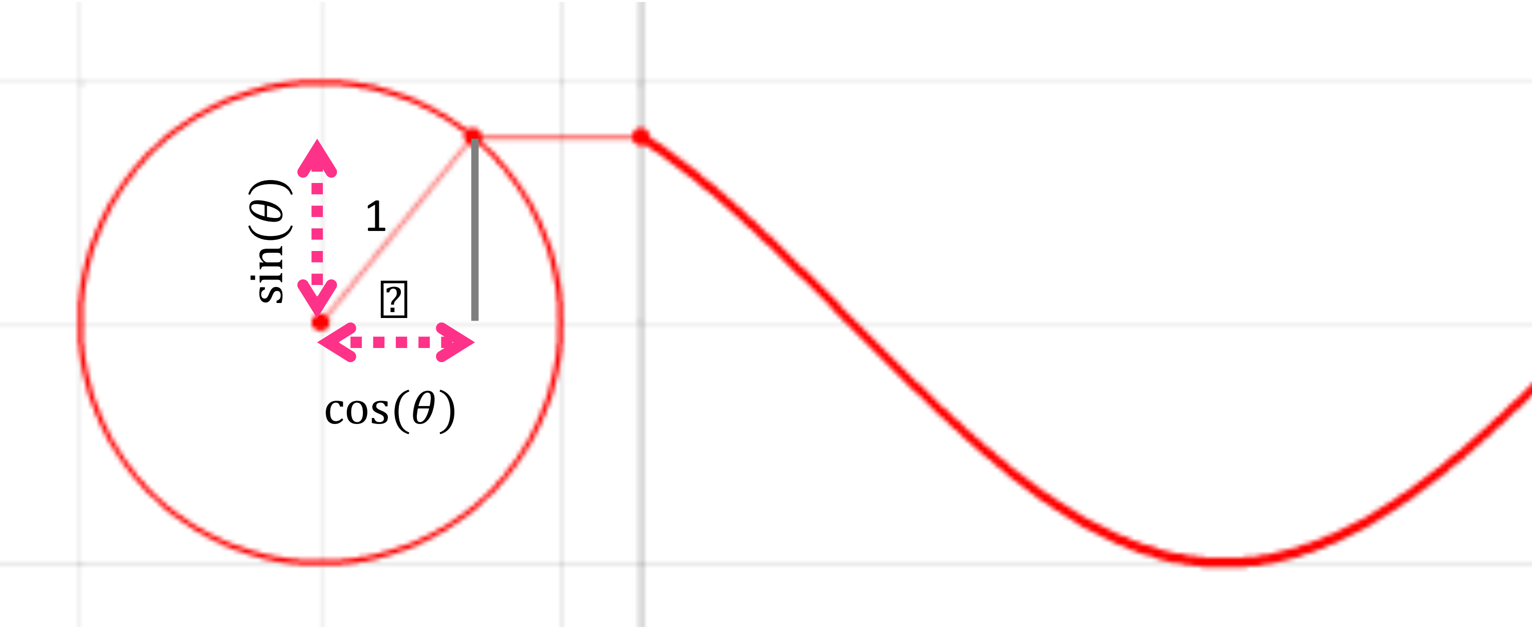


Model for a signal (frequency, amplitude, and phase)



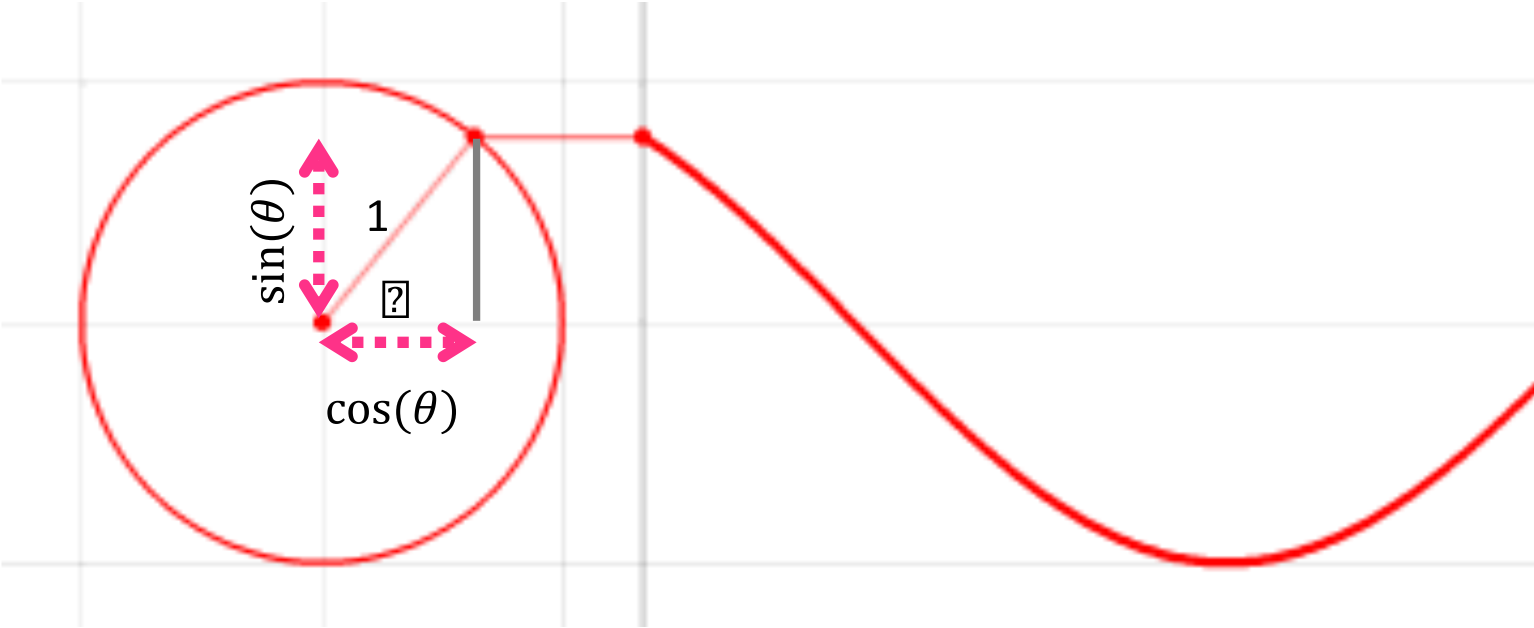
How can we incorporate both Sine and Cosine in the equation?

Model for a signal (frequency, amplitude, and phase)



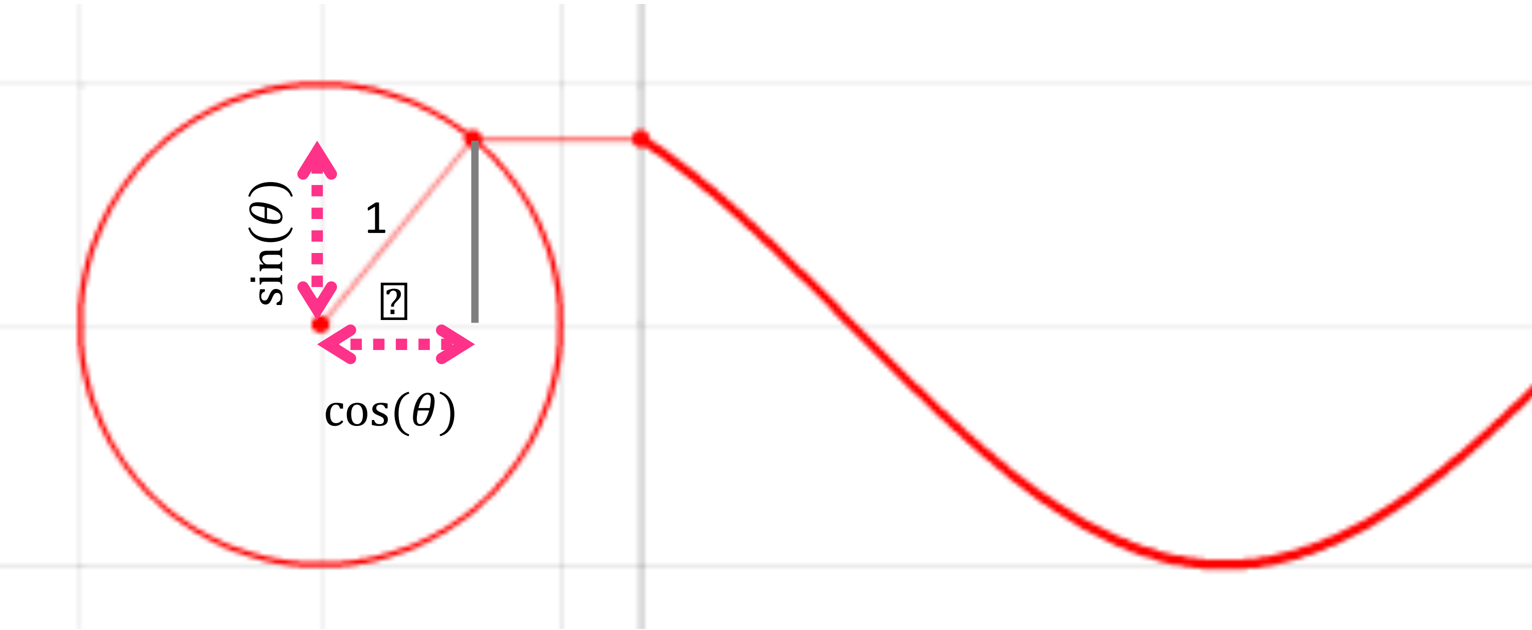
1. $cos(\theta) + \sin(\theta)$

Model for a signal (frequency, amplitude, and phase)



1. $cos(\theta) + \sin(\theta)$
2. $< cos(\theta), \sin(\theta) >$

Model for a signal (frequency, amplitude, and phase)



1. $cos(\theta) + \sin(\theta)$

2. $< cos(\theta) , \sin(\theta) >$

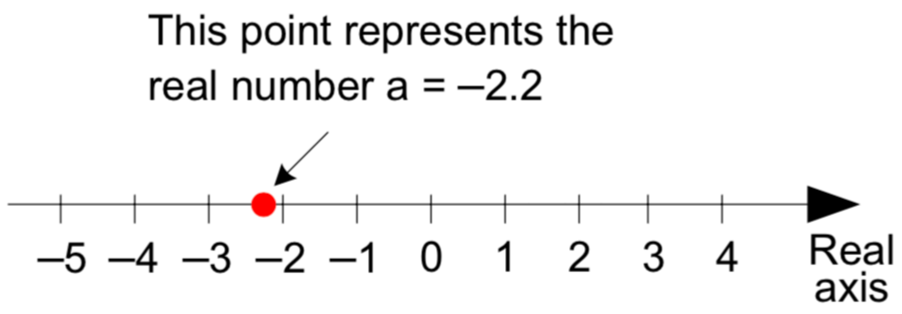
3. $cos(\theta) + j\ \sin(\theta)$

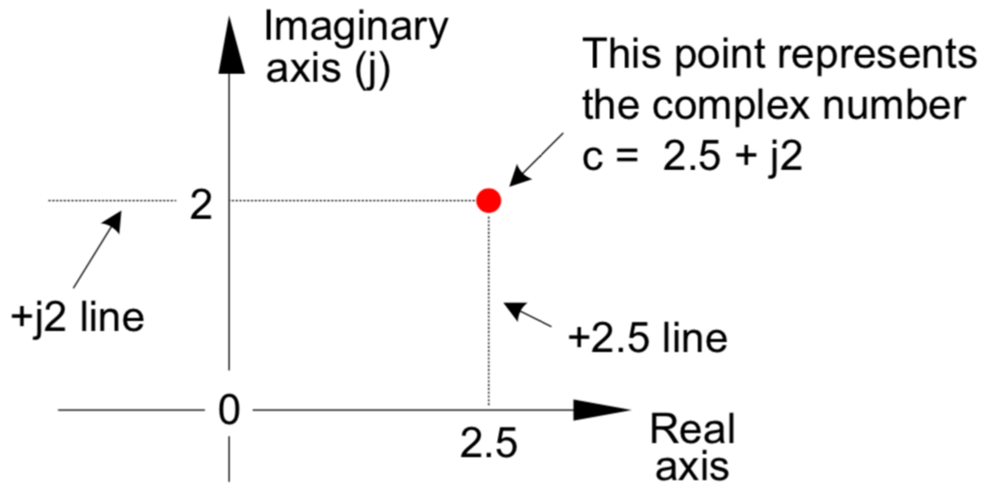
Complex numbers

Imaginary

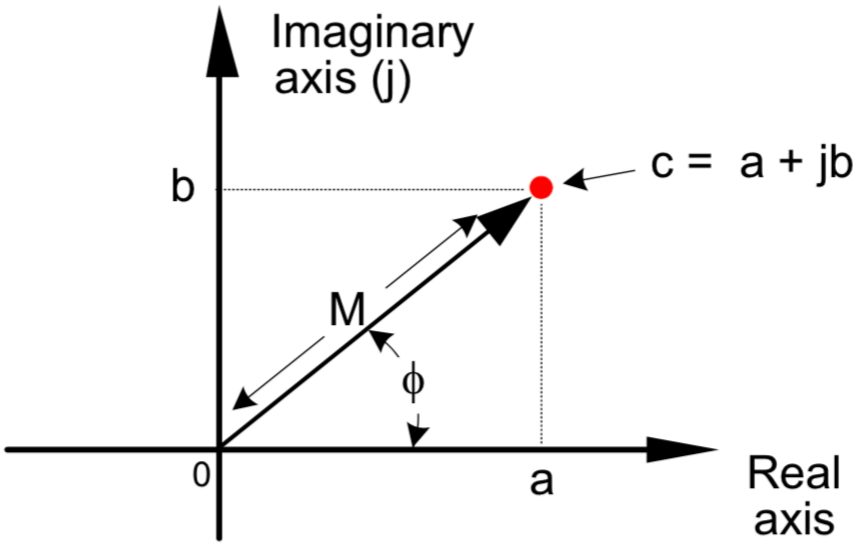
$$j = \sqrt{-1}$$

Complex numbers

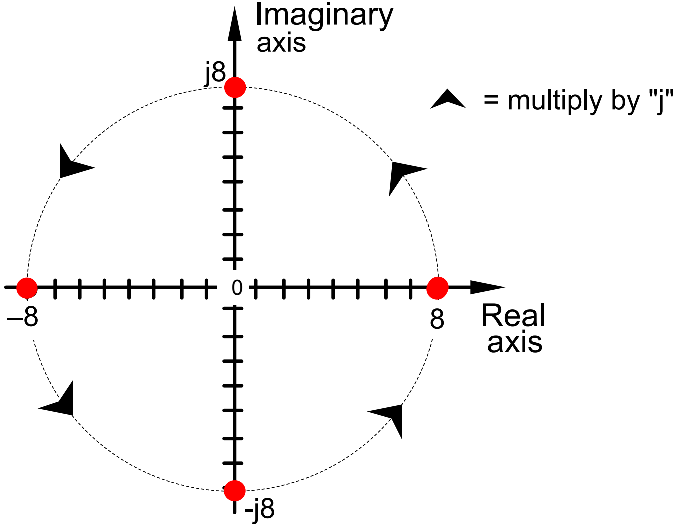




Complex numbers



Complex numbers



Complex numbers and Natural exponential

$$e^z = 1 + z + \frac{z^2}{2!} + \frac{z^3}{3!} + \frac{z^4}{4!} + \frac{z^5}{5!} + \frac{z^6}{6!} +$$

Complex numbers and Natural exponential

$$e^{z} = 1 + z + \frac{z^{2}}{2!} + \frac{z^{3}}{3!} + \frac{z^{4}}{4!} + \frac{z^{5}}{5!} + \frac{z^{6}}{6!} + $$

$$e^{j\phi} = 1 + j\phi + \frac{(j\phi)^{2}}{2!} + \frac{(j\phi)^{3}}{3!} + \frac{(j\phi)^{4}}{4!} + \frac{(j\phi)^{5}}{5!} + $$

Complex numbers and Natural exponential

$$e^z = 1 + z + \frac{z^2}{2!} + \frac{z^3}{3!} + \frac{z^4}{4!} + \frac{z^5}{5!} + \frac{z^6}{6!} +$$

$$e^{j\phi} = 1 + j\phi + \frac{(j\phi)^2}{2!} + \frac{(j\phi)^3}{3!} + \frac{(j\phi)^4}{4!} + \frac{(j\phi)^5}{5!}$$

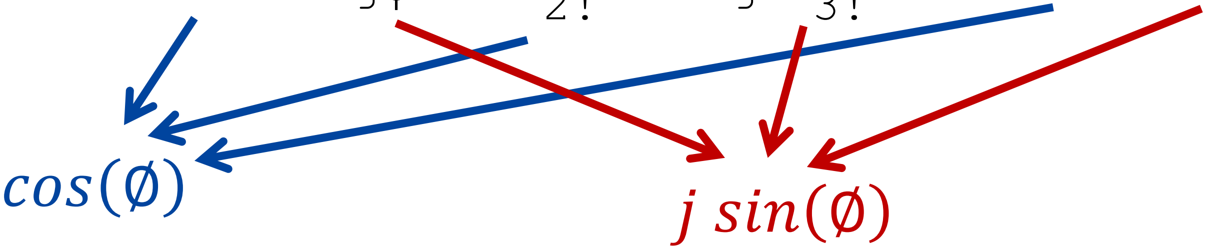
$$= 1 + j\phi - \frac{\phi^2}{2!} - j\frac{\phi^3}{3!} + \frac{\phi^4}{4!} + j\frac{\phi^5}{5!} - \frac{\phi^6}{6!}$$

Complex numbers and Natural exponential

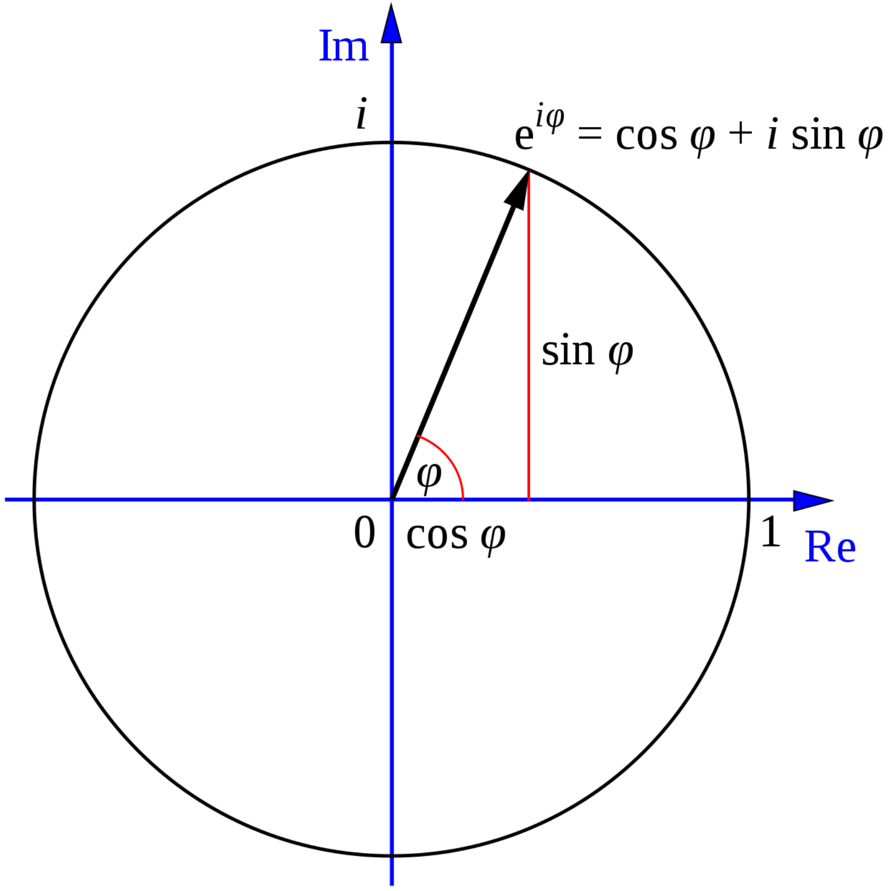
$$e^{z} = 1 + z + \frac{z^{2}}{2!} + \frac{z^{3}}{3!} + \cdots$$

$$e^{j\phi} = 1 + j\phi + \frac{(j\phi)^{2}}{2!} + \frac{(j\phi)^{3}}{3!} + \cdots$$

$$= 1 + j\phi - \frac{\phi^{2}}{2!} - j\frac{\phi^{3}}{3!} \cdots - \frac{\phi^{6}}{6!}$$



Complex numbers and Natural exponential



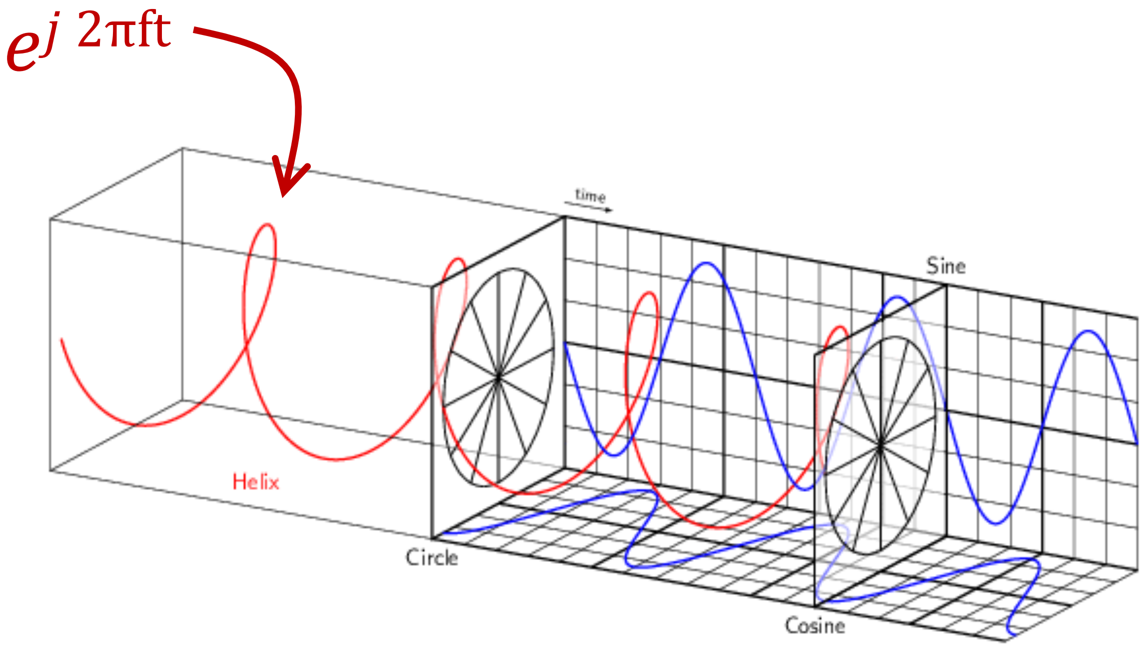
Model for a signal (frequency, amplitude, and phase)

$$cos(\theta) + j\ \sin(\theta) = e^{j\theta}$$

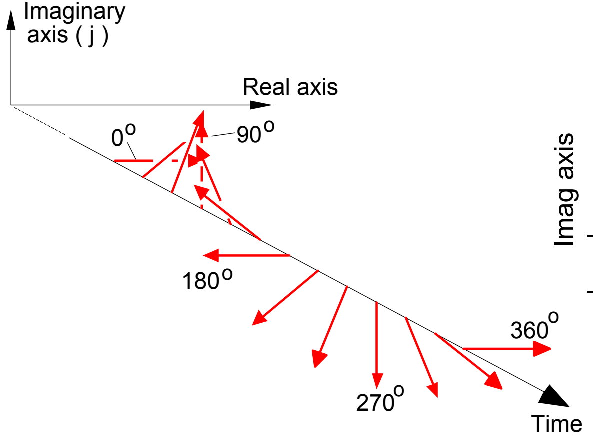
Model for a signal (frequency, amplitude, and phase)

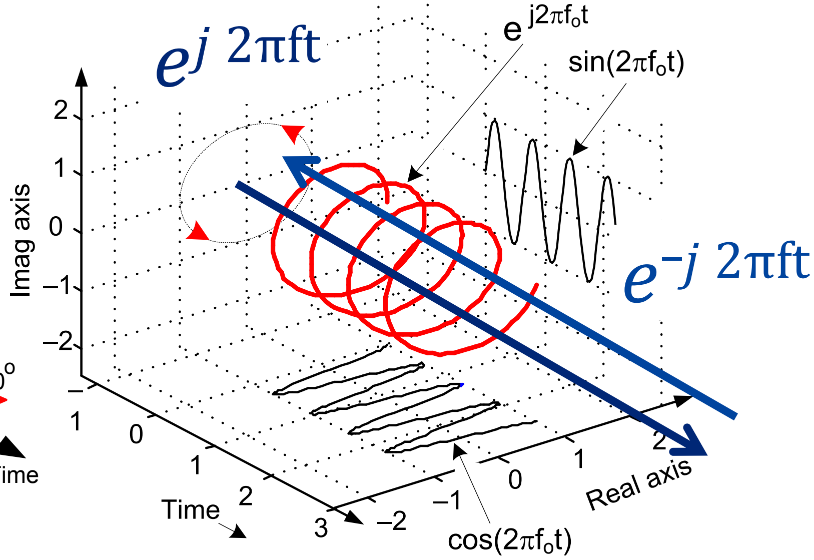
$$\cos(\theta) + j\ \sin(\theta) = e^{j\theta} = \quad e^{j\,2\pi ft}$$

Model for a signal (frequency, amplitude, and phase)



Model for a signal (frequency, amplitude, and phase)





Model for a signal (frequency, amplitude, and phase)

$$e^{j\theta} = cos(\theta) + j\ \sin(\theta)$$

$$e^{-j\theta} = cos(\theta) - j\ \sin(\theta)$$

How about real sinusoids?

$$cos(\theta) = ?$$

$$sin(\theta) = ?$$

Presenting real signal with the complex model

$$e^{j\theta} = cos(\theta) + j\ \sin(\theta)$$

$$e^{-j\theta} = cos(\theta) - j\ \sin(\theta)$$

$$cos(\theta) = \frac{e^{j\theta} + e^{-j\theta}}{2}$$

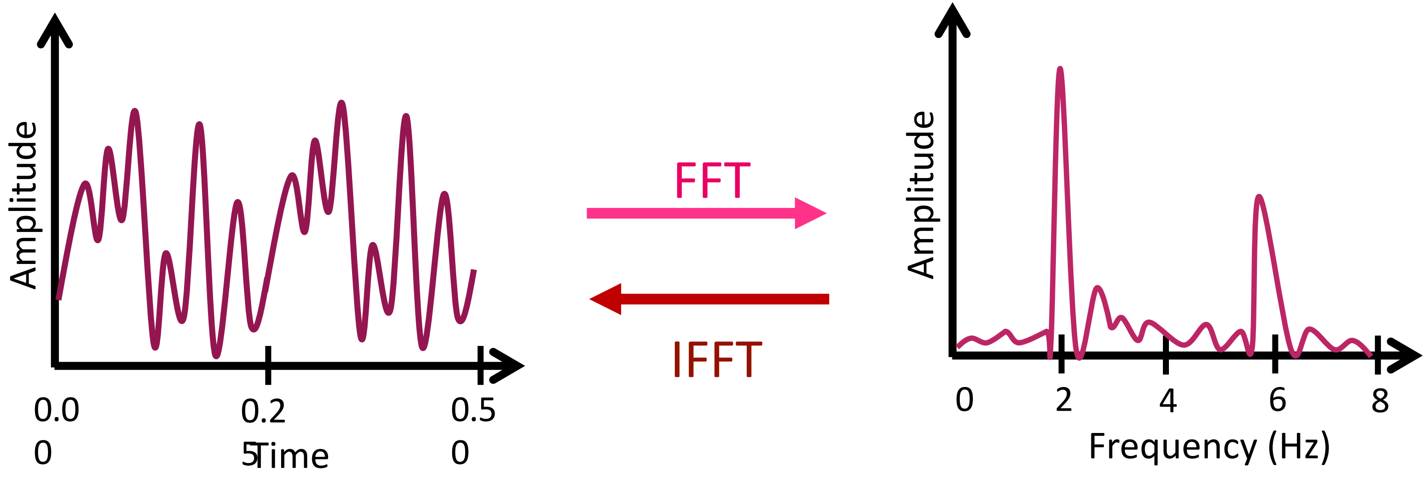
$$sin(\theta) = \frac{e^{j\theta} - e^{-j\theta}}{2j}$$

Presenting real signal with the complex model

- $e^{j\,2\pi ft} = cos(2\pi ft) + j\,\sin(2\pi ft)$
- $e^{-j\,2\pi ft} = cos(2\pi ft) - j\,\sin(2\pi ft)$
- $cos(2\pi ft) = \dfrac{e^{j\,2\pi ft} + e^{-j\,2\pi ft}}{2}$
- $sin(2\pi ft) = \dfrac{e^{j\,2\pi ft} - e^{-j\,2\pi ft}}{2j}$

Time Domain and Frequency Domain

Fourier Transform



Time domain

Frequency domain

FFT = Fast Fourier Transform

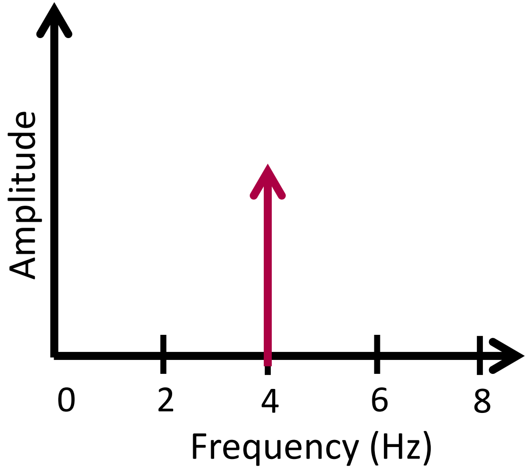
IFFT = Inverse Fast Fourier Transform

Time Domain and Frequency Domain

Fourier Transform

$$e^{j\,2\pi 4t}$$

FFT →



Time domain

Frequency domain

FFT = Fast Fourier Transform

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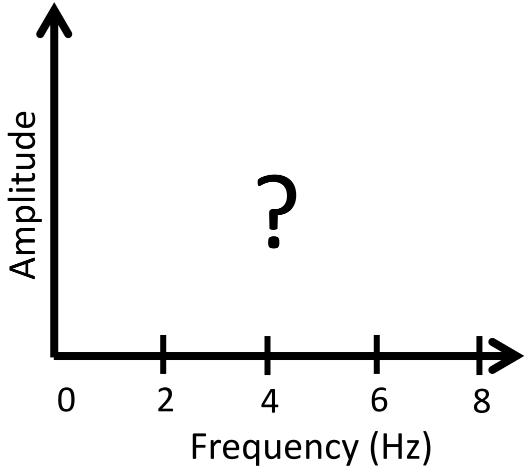
Time Domain and Frequency Domain

Fourier Transform

$cos(2\pi ft)$ —FFT→



Time domain

Frequency domain

FFT = Fast Fourier Transform

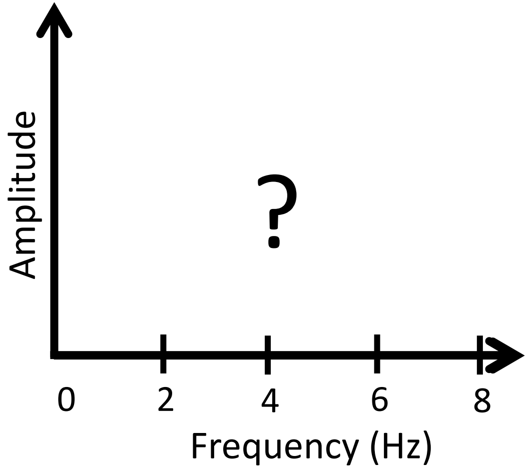
IFFT = Inverse Fast Fourier Transform

Time Domain and Frequency Domain

Fourier Transform

$$\cos(2\pi ft) = \frac{e^{j\,2\pi ft} + e^{-j\,2\pi ft}}{2}$$

FFT →



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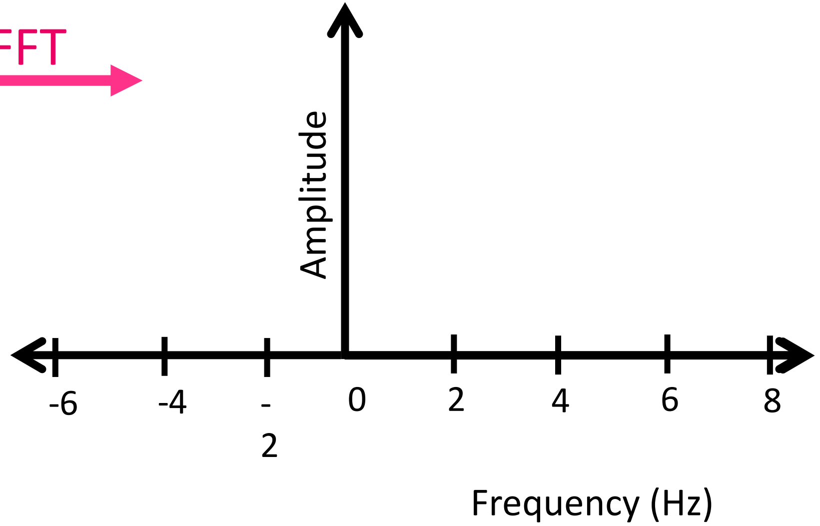
Time Domain and Frequency Domain

Fourier Transform

FFT →

$$\cos(2\pi ft) = \frac{e^{j\,2\pi ft} + e^{-j\,2\pi ft}}{2}$$



Time domain

Frequency domain

FFT = Fast Fourier Transform

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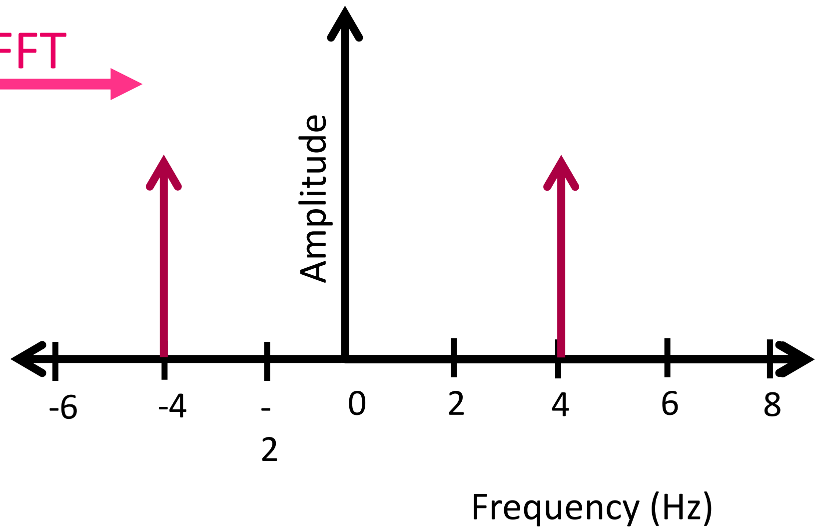
Time Domain and Frequency Domain

Fourier Transform

FFT →

$$\cos(2\pi 4t)$$

$$= \frac{e^{j\,2\pi ft} + e^{-j\,2\pi ft}}{2}$$



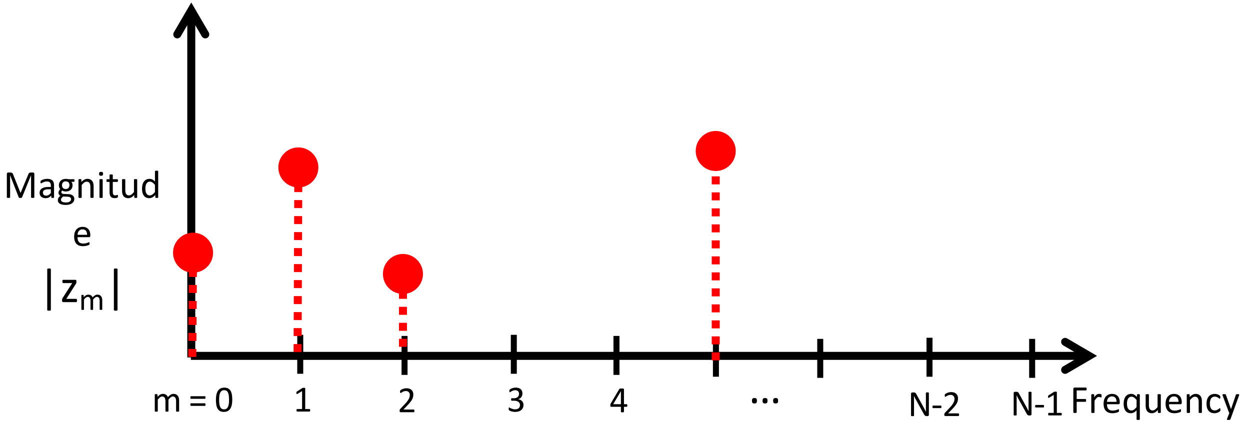
Time domain

Frequency domain

FFT = Fast Fourier Transform

IFFT = Inverse Fast Fourier Transform

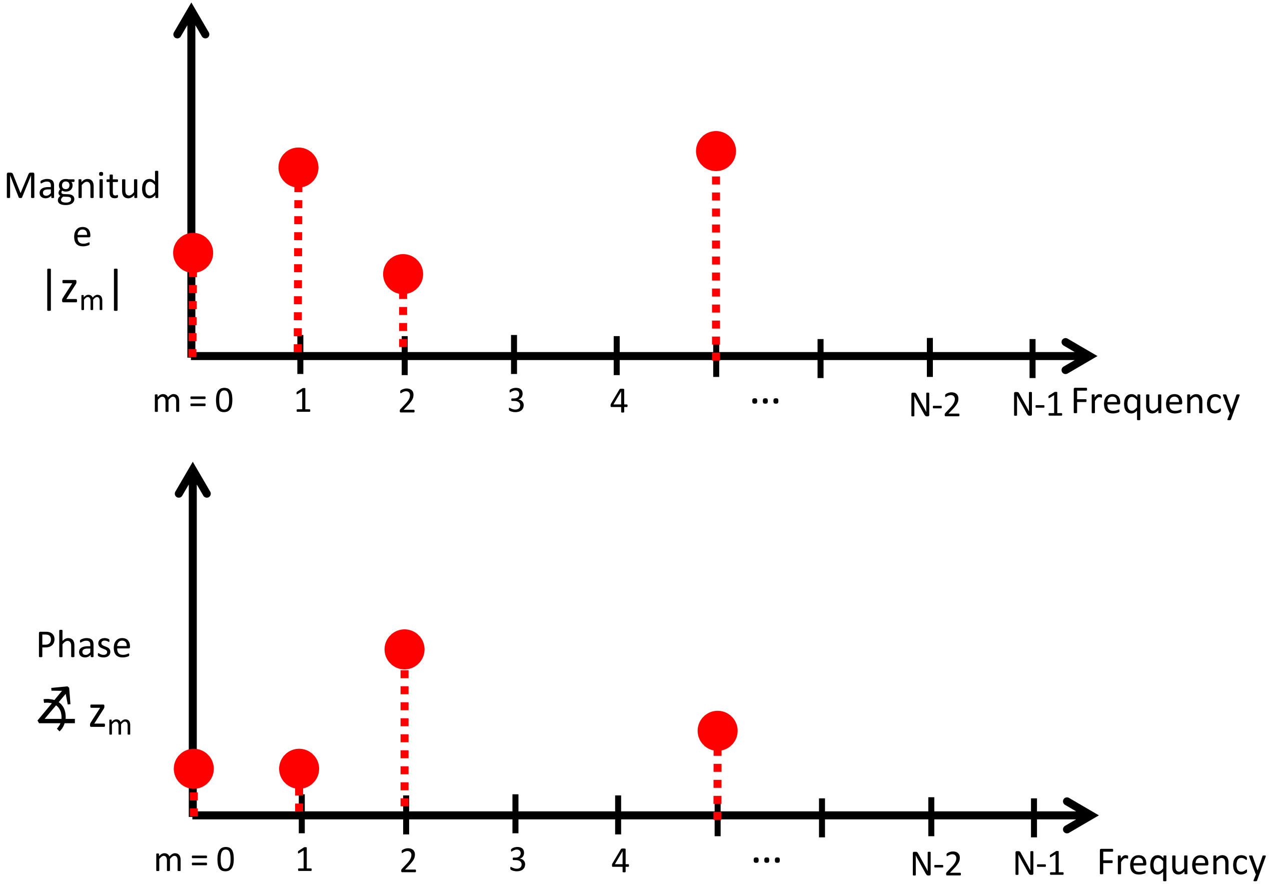
Plotting the DFT spectrum



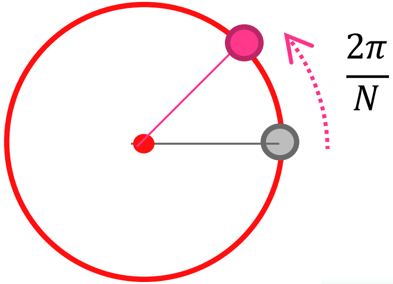
DFT (Discrete Fourier Transform)

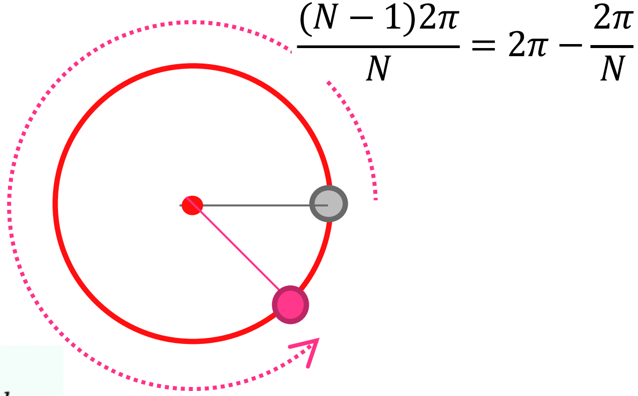
$$
\begin{aligned}
X_k &= \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn} \\
&= \sum_{n=0}^{N-1} x_n \cdot \left[\cos\left(\frac{2\pi}{N}kn\right) - i \cdot \sin\left(\frac{2\pi}{N}kn\right)\right]
\end{aligned}
$$

Plotting the DFT spectrum

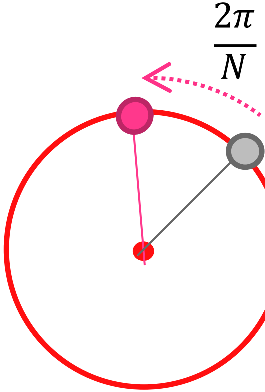


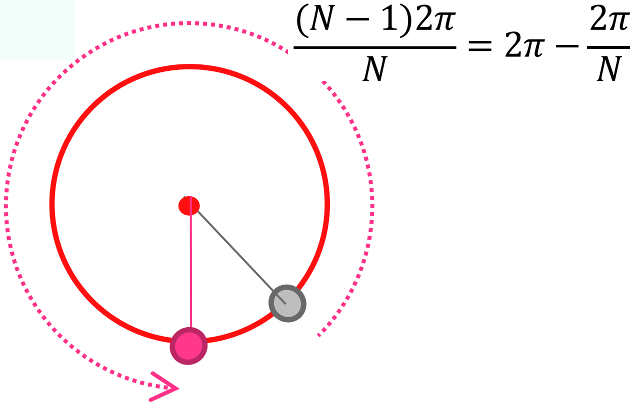
The Curious Case of "Negative frequency"





$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn}$$



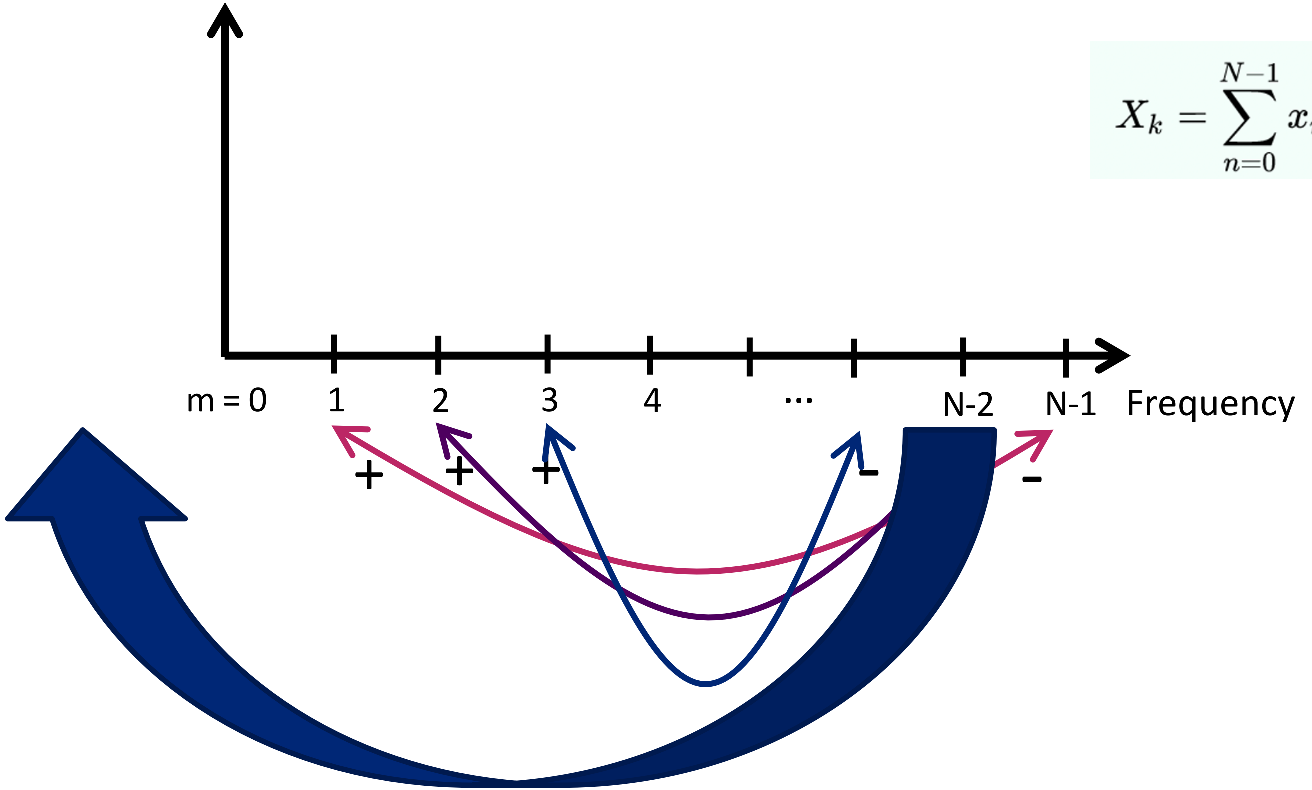


Positive rotation with $\frac{2\pi}{N}$ radian angle per step

Negative rotation with $\frac{2\pi}{N}$ radian angle per step

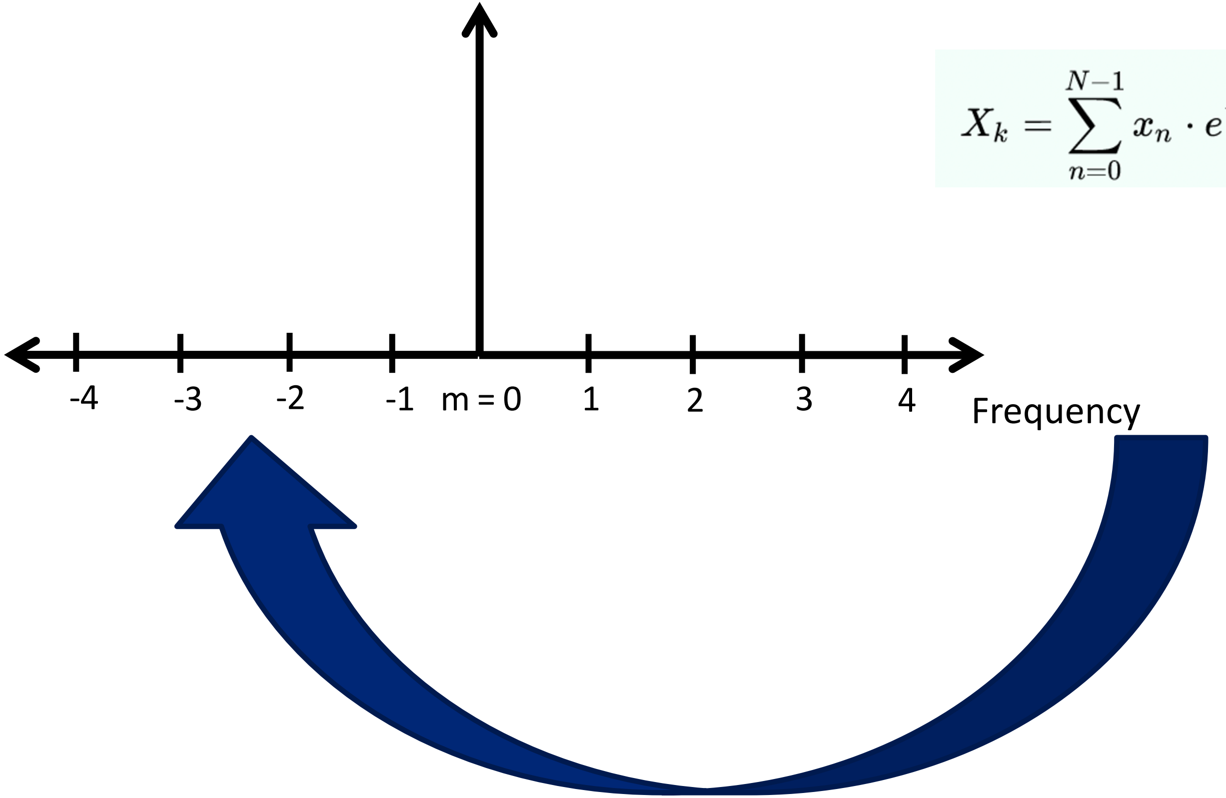
The Curious Case of "Negative frequency"

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn}$$

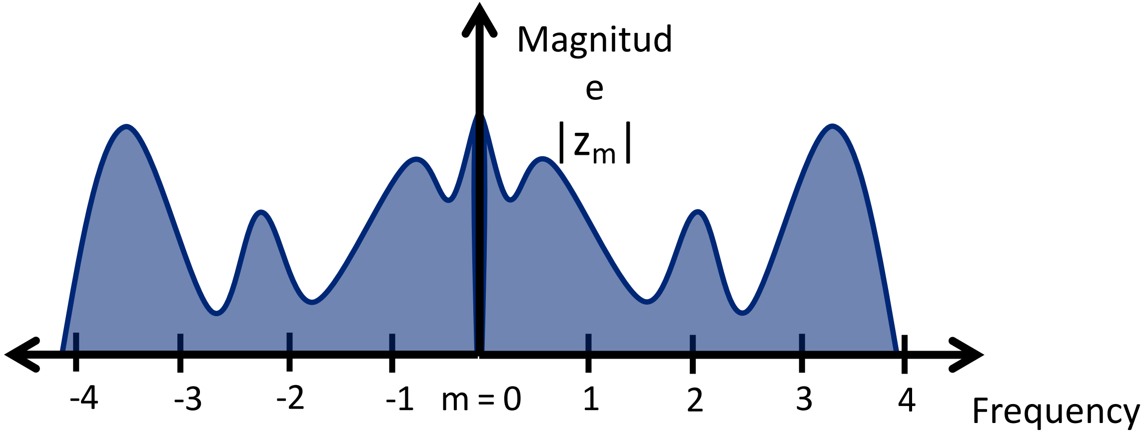


The Curious Case of "Negative frequency"

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn}$$



The Curious Case of “Negative frequency”

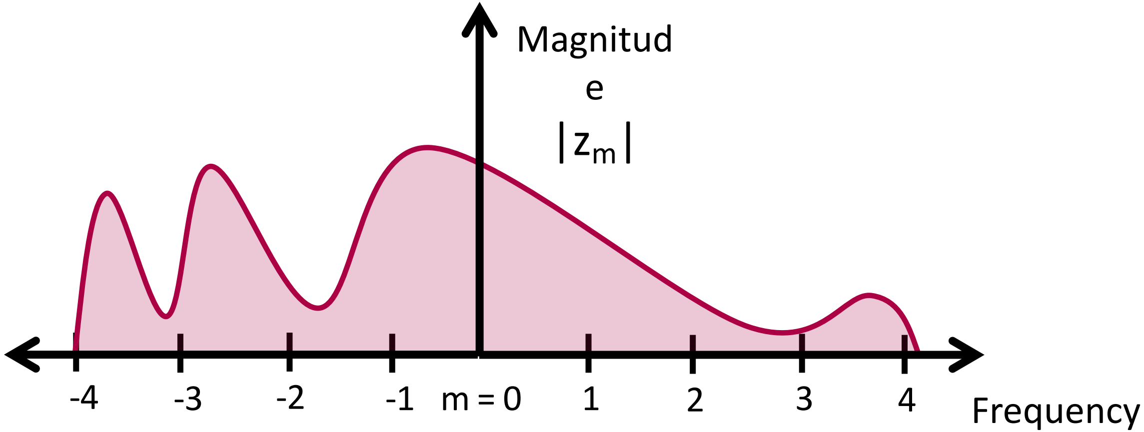


Real signal’s magnitude
spectrum is symmetric.

Why?

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn}$$

The Curious Case of "Negative frequency"



Complex signal's magnitude spectrum may or may not be symmetric.

Why?

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-\frac{i2\pi}{N}kn}$$

Estimating the real-world frequencies

Sampling frequency = f_s (i.e., f_s samples per second)

Slowest frequency ($\frac{2\pi}{N}$ radians per step) = N samples per rotation

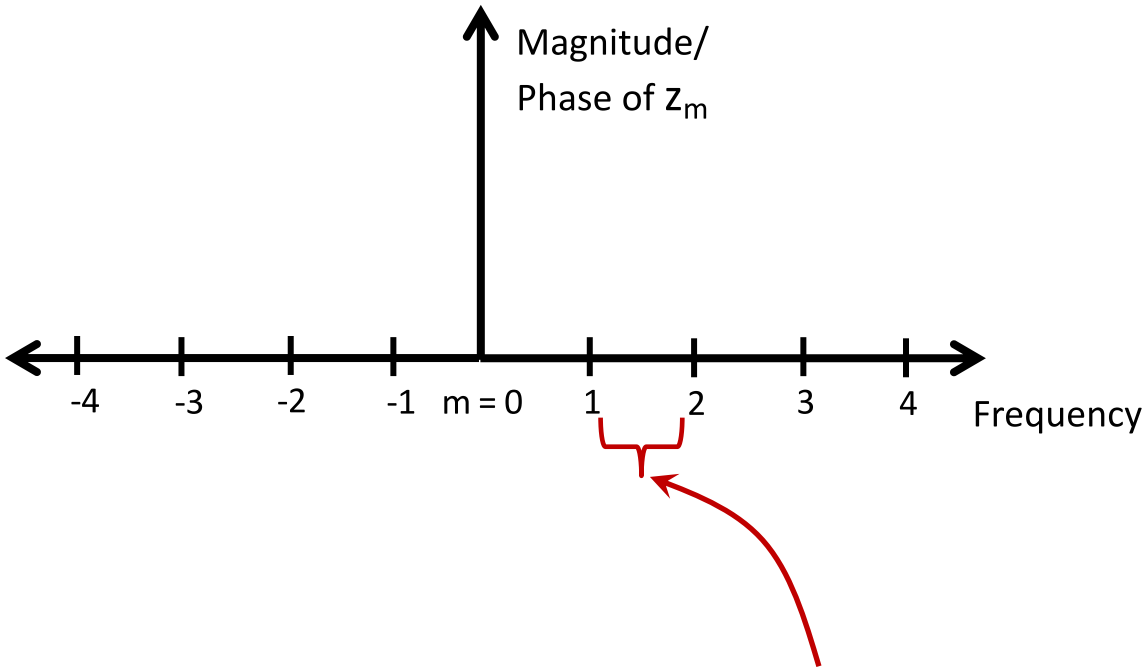
= (N/ f_s) seconds per rotation

Therefore, the slowest frequency = (f_s /N) Hz

Higher frequencies are integer multiple of (f_s /N) Hz

$$0, \frac{f_s}{N}, \frac{2f_s}{N}, \frac{3f_s}{N}, \frac{4f_s}{N}, \ldots,$$

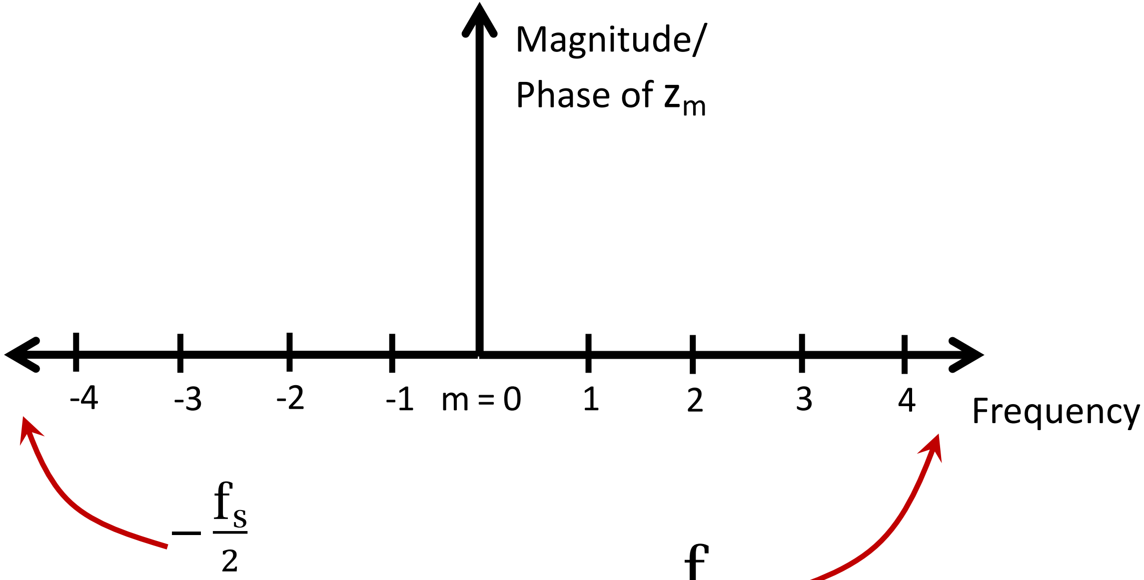
The resolution and the highest frequency



Resolution
= minimum observable frequency difference = $\frac{f_s}{N}$

What if the actual frequency falls in between two frequency bins?

The resolution and the highest frequency



$$\text{Highest frequency} = \frac{f_s}{2}$$

The resolution and the highest frequency

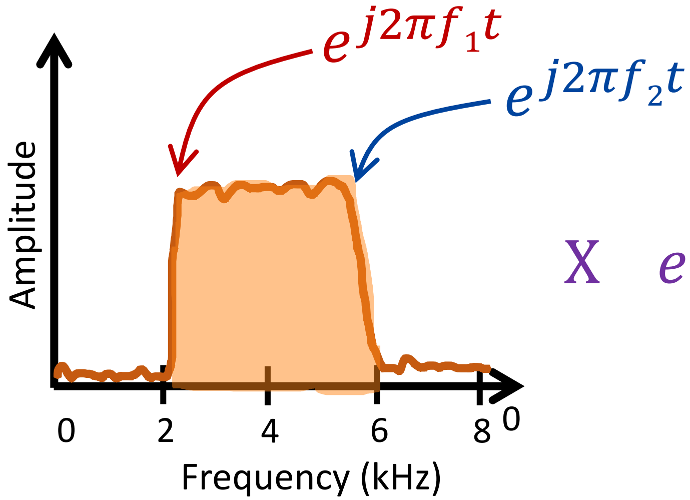
How can we increase the resolution?

$$\frac{f_s}{N} = \frac{\text{sample rate}}{\text{\# of FFT points}}$$

How can we increase the range of the spectrum?

$$[-\frac{f_s}{2}, \frac{f_s}{2}]$$

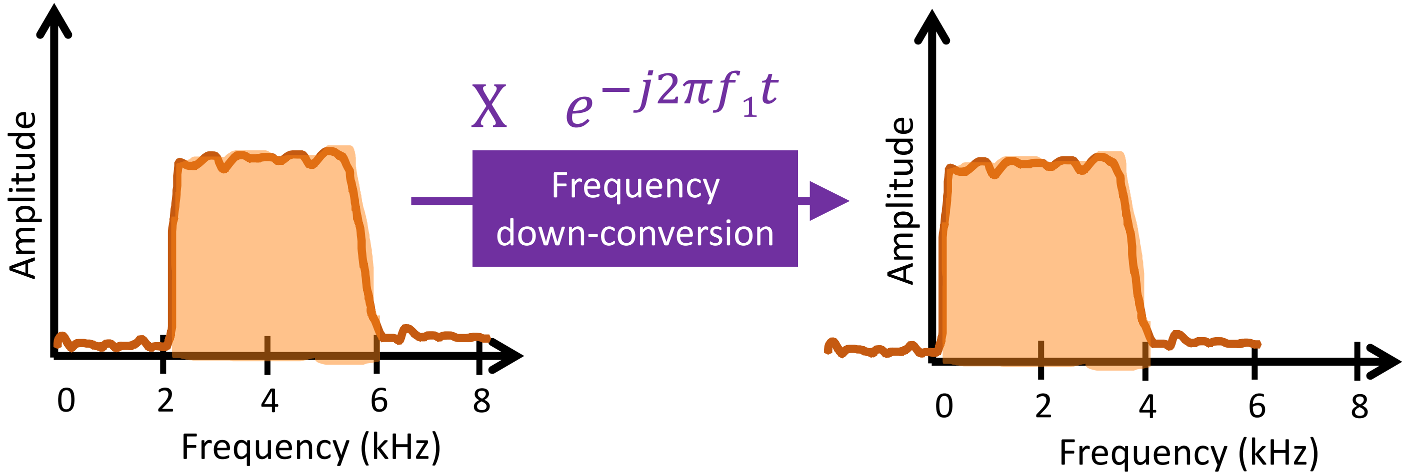
Downsampling



X $e^{-j2\pi f_1 t}$

What should be the sample rate?

Downsampling



What should be the sample rate?

Generally, bandwidth of the signal determines the sample rate.