Sensor Components

-- working principles and basics

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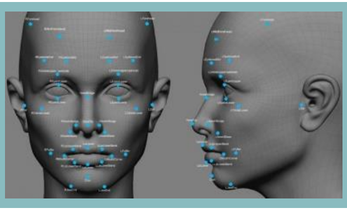
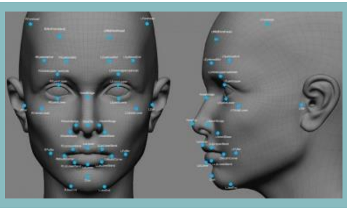
Abstraction

Computing: Models and Algorithms



Abstraction

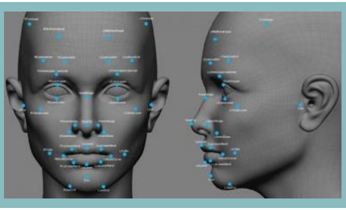
Computing: Models and Algorithms



Data

Abstraction

Computing: Models and Algorithms

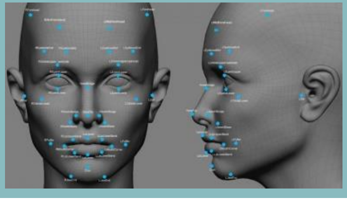


Data

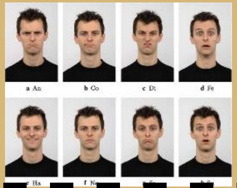
Sensing techniques

Abstraction: Traditional View

Computing: Models and Algorithms



Data



Data

Sensing techniques

Abstraction: Traditional View

Networking	Natural language processing	Computer vision
Data packets	Voice recording	Image/video

Abstraction: Traditional View

Networking

Natural language processing

Computer vision

Data packets

Voice recording

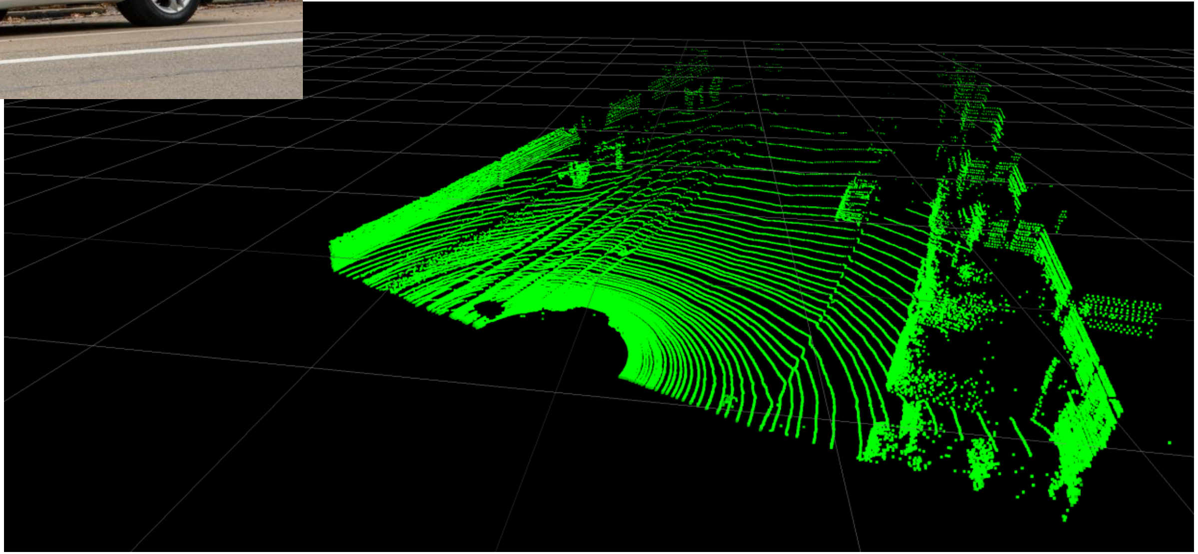
Image/video

WiFi signal

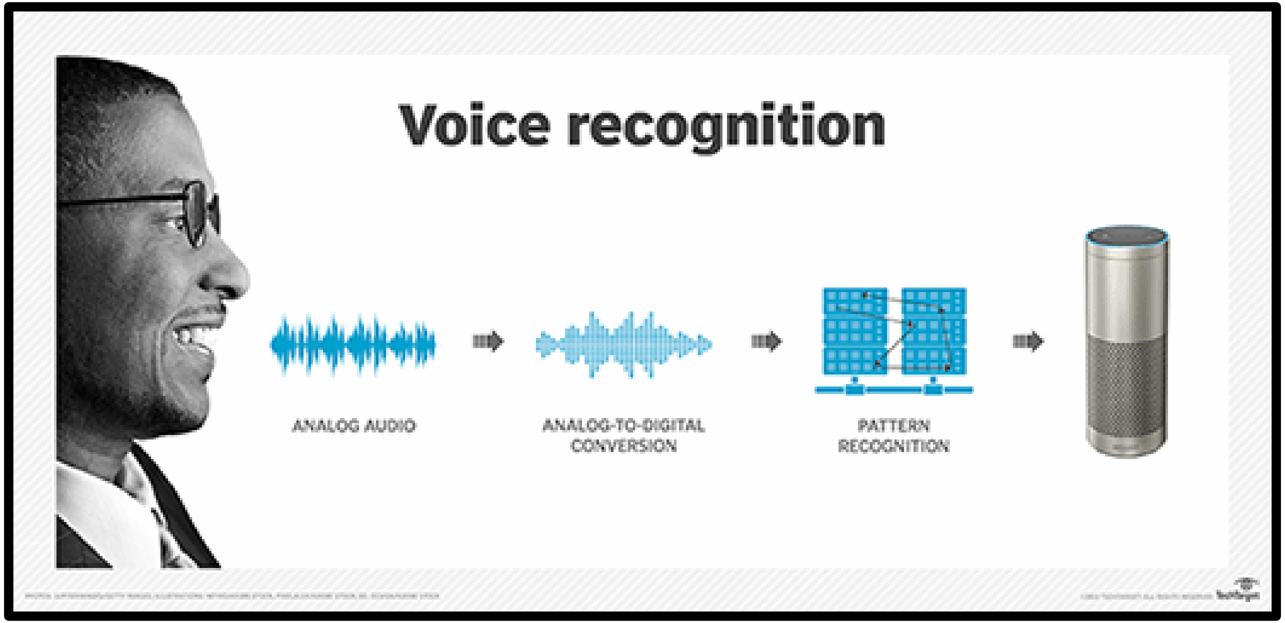
Acoustic signal

Light

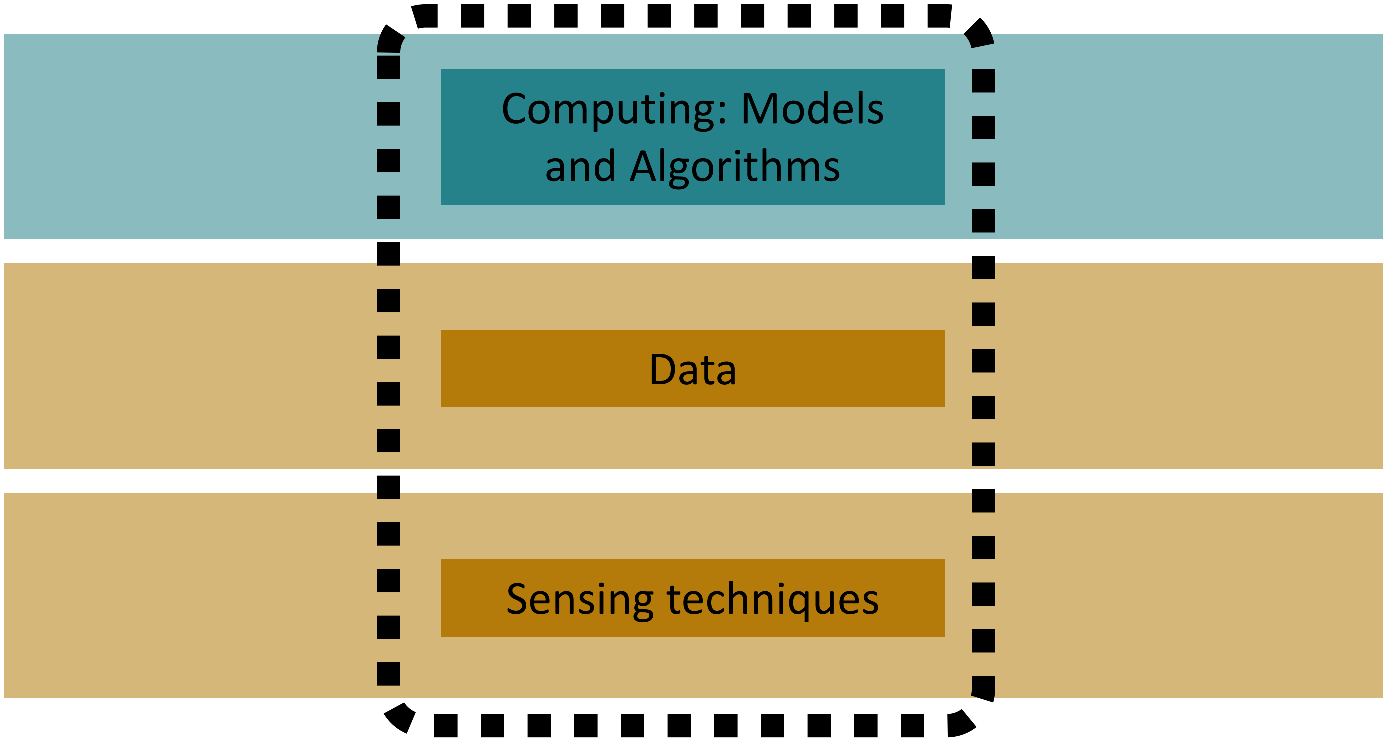
Integration of Sensing and Computing



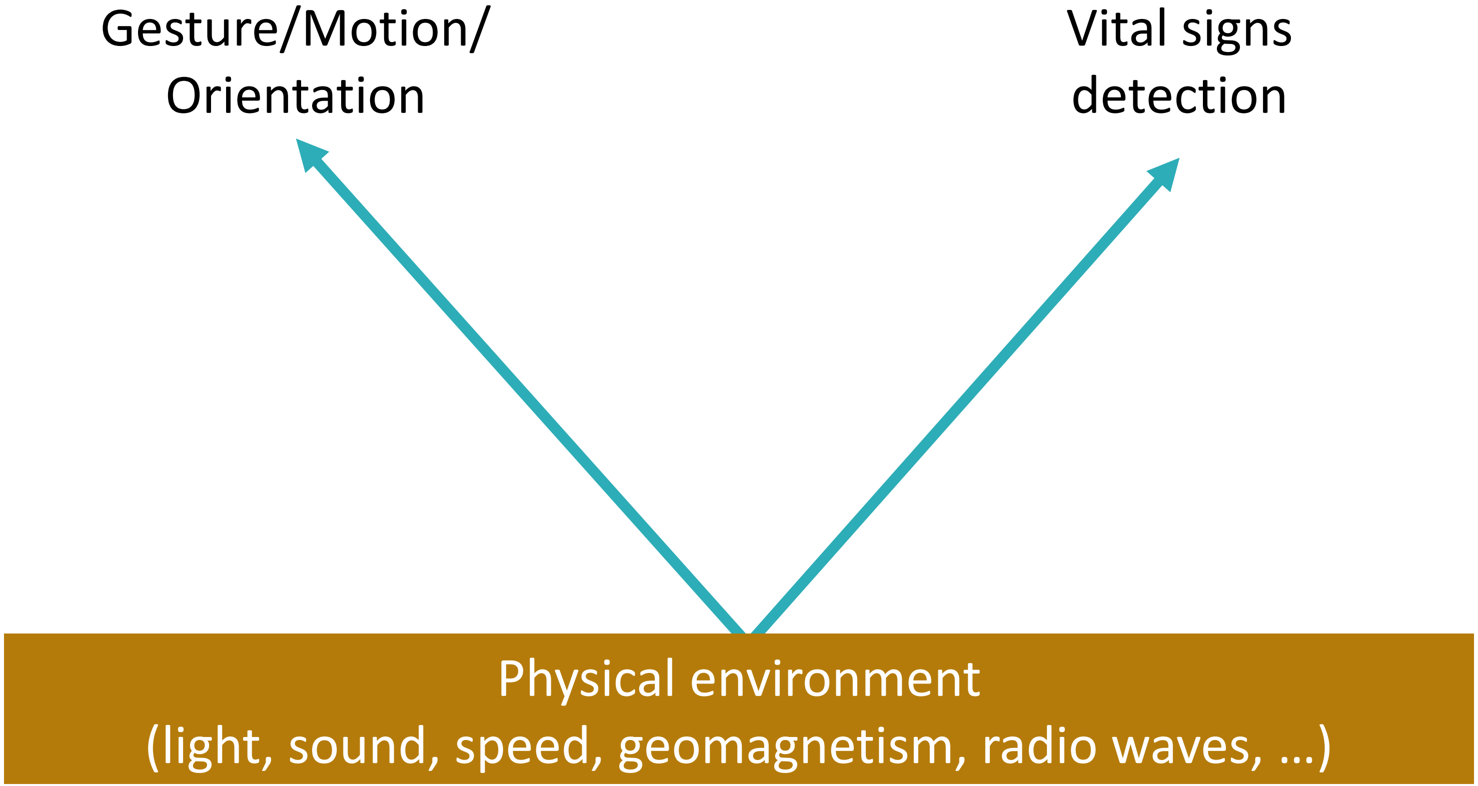
Integration of Sensing and Computing

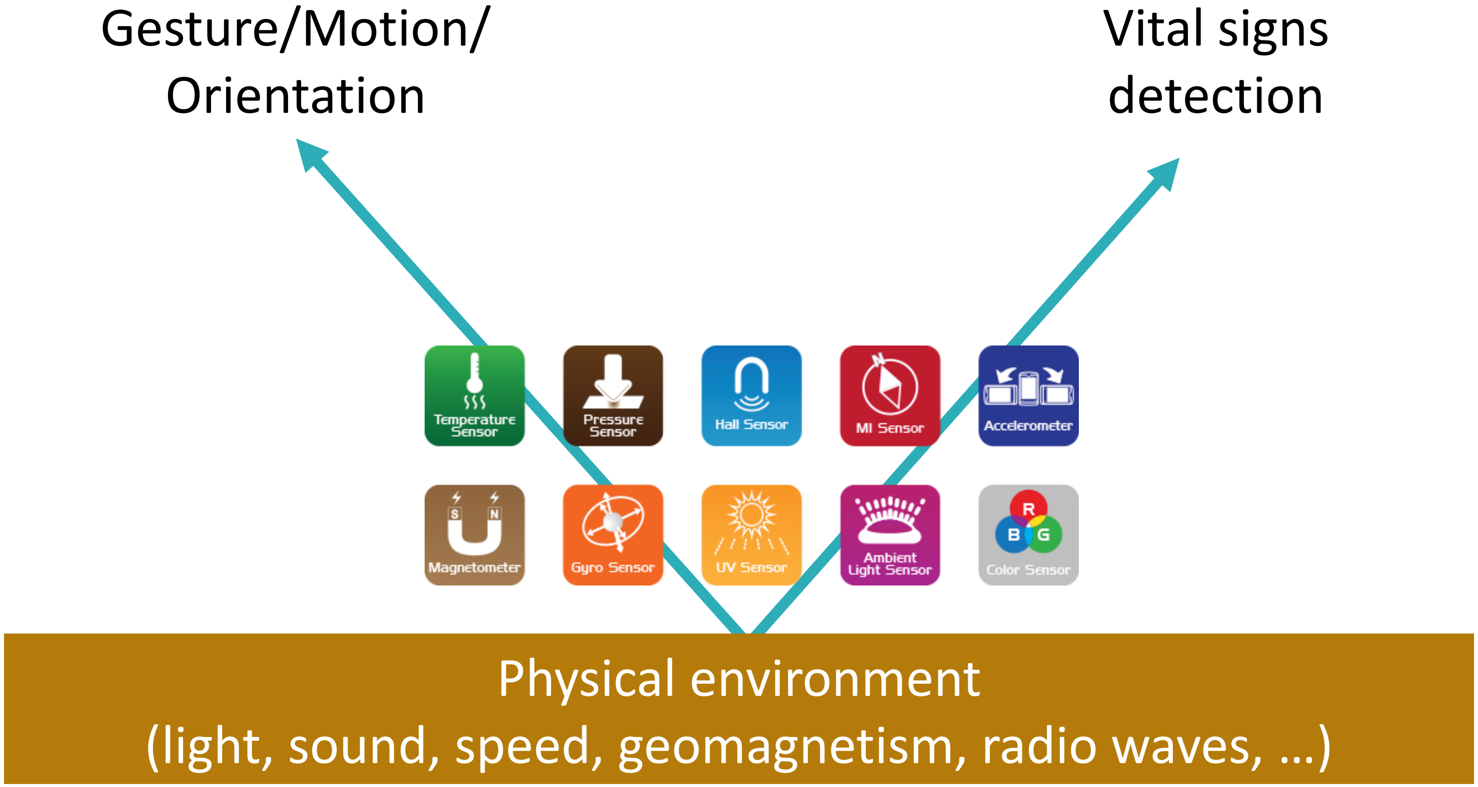


Abstraction



Concept of Sensing


Gesture/Motion/
Orientation
Vital signs
detection
Physical environment
(light, sound, speed, geomagnetism, radio waves, …)


Gesture/Motion/
Orientation
Vital signs
detection
Temperature Sensor
Pressure Sensor
Hall Sensor
MI Sensor
Accelerometer
Magnetometer
Gyro Sensor
UV Sensor
Ambient Light Sensor
Color Sensor
R
B
G
S
N
Physical environment
(light, sound, speed, geomagnetism, radio waves, …)

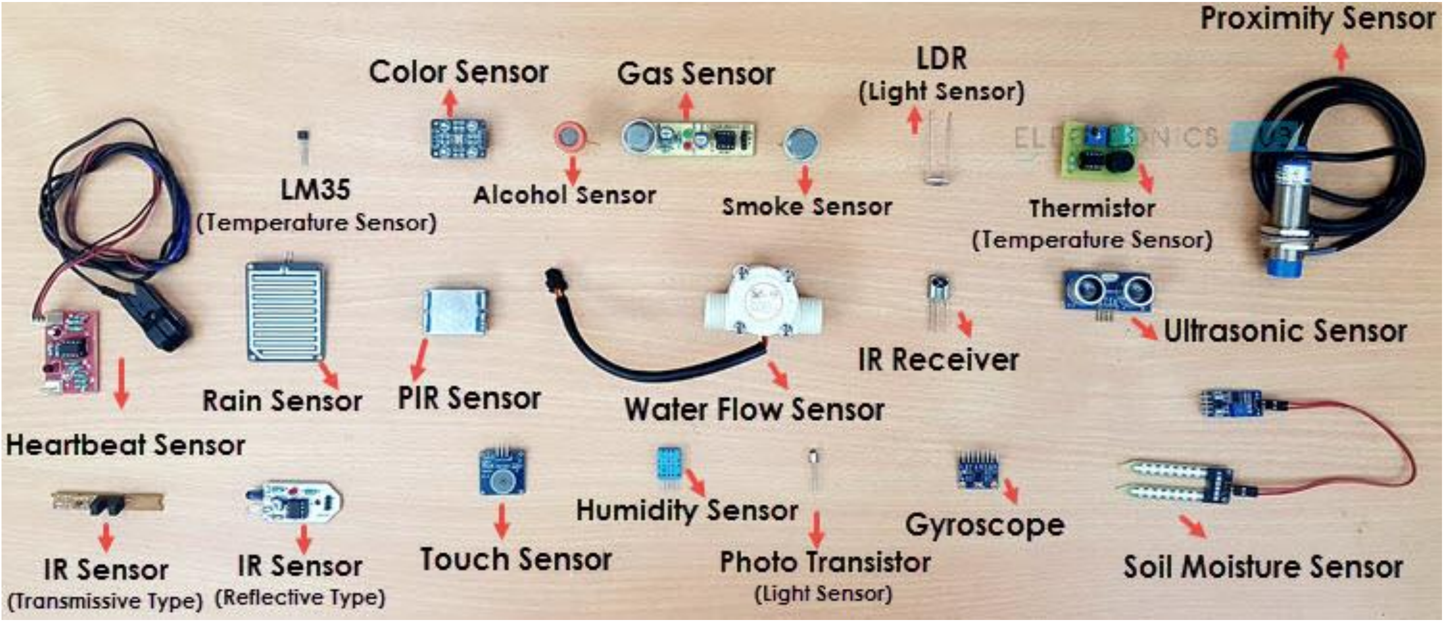
1. Sensors

   - Definitions
   - Generic working principle

2. Signals

   - Digital abstraction
   - Remove the noise

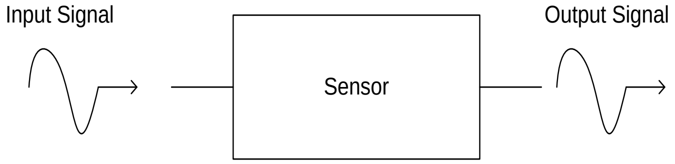
What is a Sensor?



Is there a common principle?

What is Sensor?

- American National Standards Institute (ANSI) Definition
  - A device which provides a usable output in response to a specified measurand



- A sensor acquires a physical parameter and converts it into a signal suitable for processing (e.g. optical, electrical, mechanical)

- A transducer
  - Microphone, Loud Speaker, Biological Senses (e.g. touch, sight, …, etc.)

Detectable Phenomenon

Stimulus	Quantity
Acoustic	Wave (amplitude, phase, polarization), Spectrum, Wave Velocity
Biological & Chemical	Fluid Concentrations (Gas or Liquid)
Electric	Charge, Voltage, Current, Electric Field (amplitude, phase, polarization), Conductivity, Permittivity
Magnetic	Magnetic Field (amplitude, phase, polarization), Flux, Permeability
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque

Physical Principles

- Amperes’s Law
  - A current carrying conductor in a magnetic field experiences a force (e.g. galvanometer)
- Curie-Weiss Law
  - There is a transition temperature at which ferromagnetic materials exhibit paramagnetic behavior
- Faraday’s Law of Induction
  - A coil resist a change in magnetic field by generating an opposing voltage/current (e.g. transformer)
- Photoconductive Effect
  - When light strikes certain semiconductor materials, the resistance of the material decreases (e.g. photoresistor)

Need for Sensors

- Sensors are omnipresent. They embedded in our bodies, automobiles, airplanes, cellular telephones, radios, chemical plants, industrial plants and countless other applications.

- Without the use of sensors, there would be no automation!!
    - Imagine having to manually fill Nongfu Spring bottles

Choosing a Sensor

Environmental Factors	Economic Factors	Sensor Characteristics
Temperature range	Cost	Sensitivity
Humidity effects	Availability	Range
Corrosion	Lifetime	Stability
Size		Repeatability
Overrange protection		Linearity
Susceptibility to EM interferences		Error
Ruggedness		Response time
Power consumption		Frequency response
Self-test capability		

Temperature Sensor

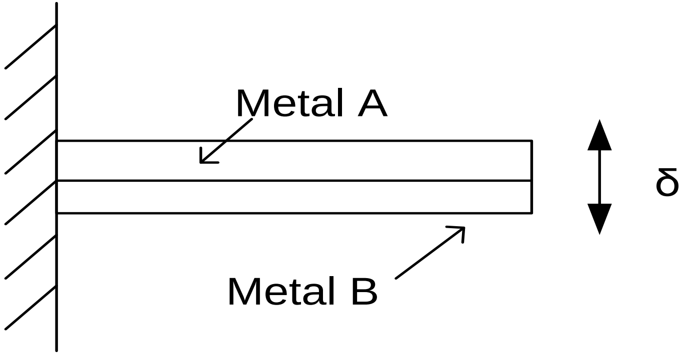
- Temperature sensors appear in building, chemical process plants, engines, appliances, computers, and many other devices that require temperature monitoring

- Many physical phenomena depend on temperature, so we can often measure temperature indirectly by measuring pressure, volume, electrical resistance, and strain

Temperature Sensor

- Bimetallic Strip

$$L = L_0[1 + \beta(T - T_0)]$$



- Application
  - Thermostat (makes or breaks electrical connection with deflection)

Temperature Sensor

- Resistance temperature device

$$R = R_0[1+\alpha(\mathrm{T} - \mathrm{T}_0)]$$

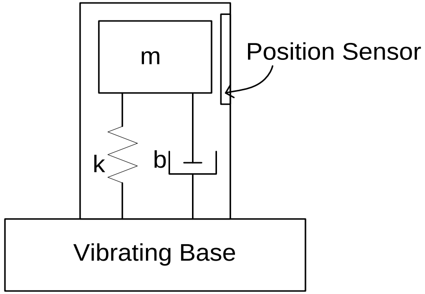
$$R = R_0 e^{\gamma\left[\frac{1}{T}-\frac{1}{T_0}\right]}$$

Accelerometer

- Accelerometers are used to measure along one axis and is insensitive to orthogonal directions

- Applications
  - Vibrations, blasts, impacts, shock waves
  - Air bags, washing machines, heart monitors, car alarms

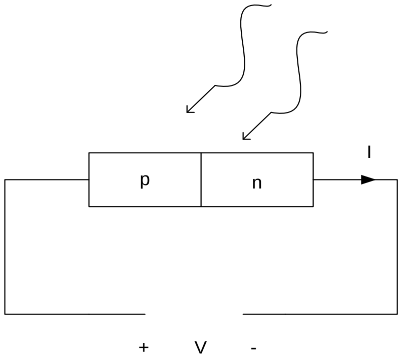
- Mathematical Description is beyond the scope of this course



Light Sensor

- Light sensors are used in cameras, infrared detectors, and ambient lighting applications

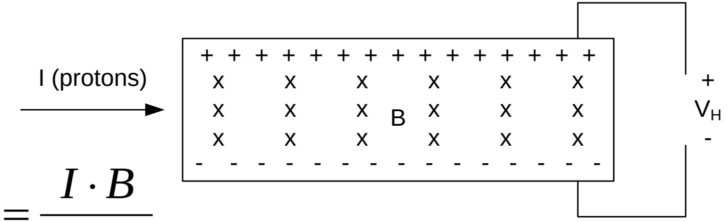
- Sensor is composed of photoconductor such as a photoresistor, photodiode, or phototransistor



Magnetic Field Sensor

- Magnetic Field sensors are used for power steering, security, and current measurements on transmission lines

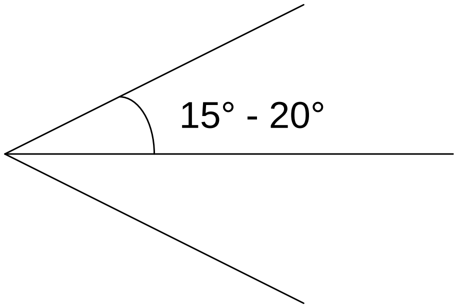
- Hall voltage is proportional to magnetic field



$$V_H = \frac{I \cdot B}{n \cdot q \cdot t}$$

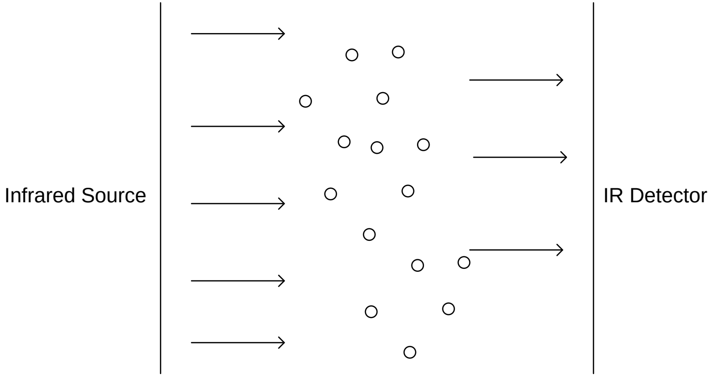
Ultrasonic Sensor

- Ultrasonic sensors are used for position measurements
- Sound waves emitted are in the range of 2-13 MHz
- **So**und **N**avigation **A**nd **R**anging (SONAR)
- **Ra**dio **D**ection **A**nd **R**anging (RADAR) – ELECTROMAGNETIC WAVES !!

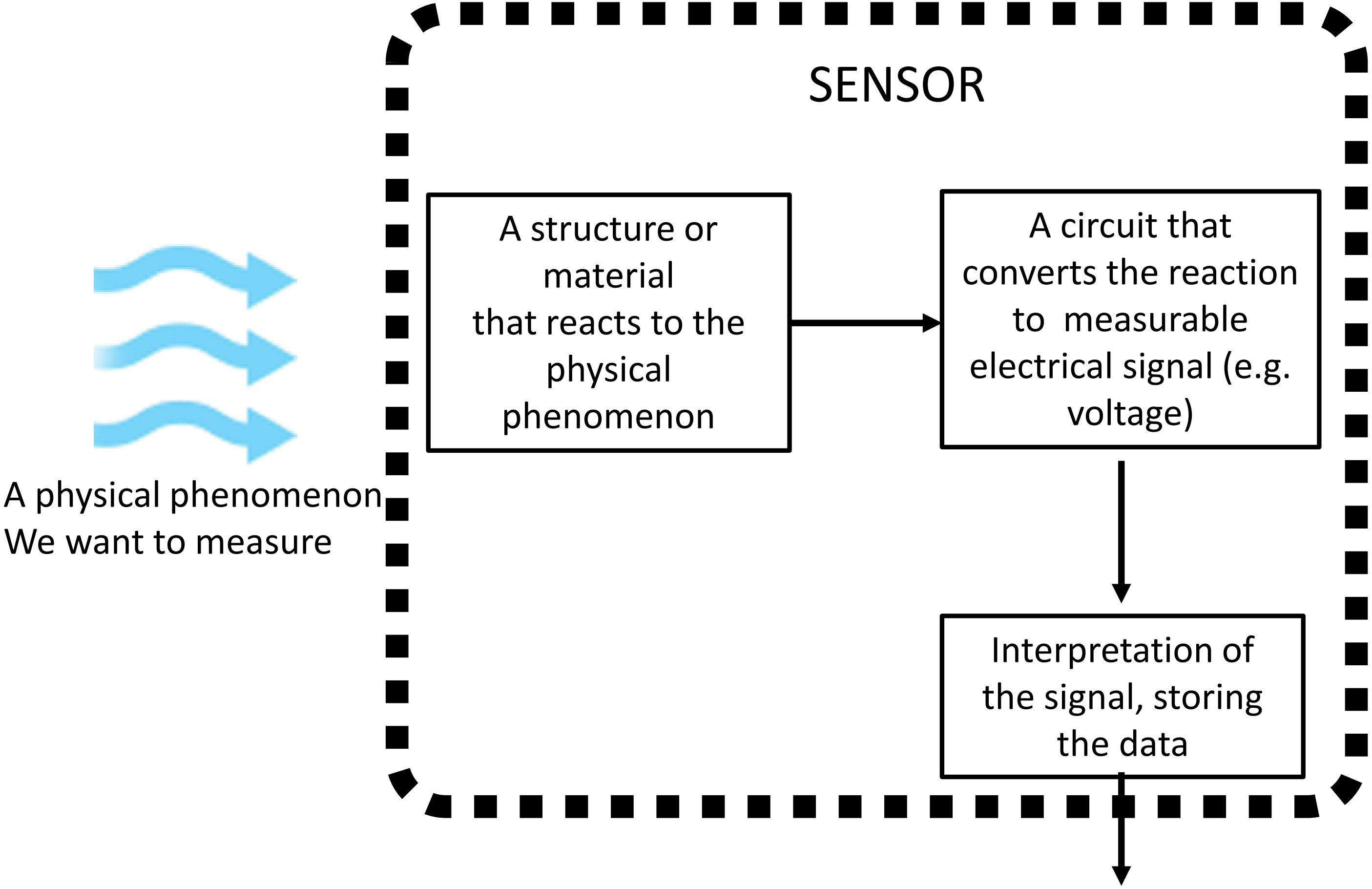


CO_2 Gas Sensor

- CO_2 sensor measures gaseous CO_2 levels in an environment
- Measures CO_2 levels in the range of 0-5000 ppm
- Monitors how much infrared radiation is absorbed by CO_2 molecules

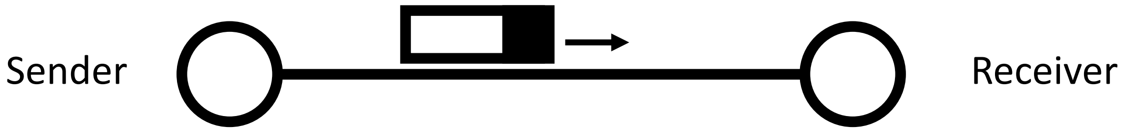


Fundamental principle of sensors



From Signals to Packets

Packet Transmission



Packets

01000101010111001010101010111011100000011110101011101010101011010110101110 01

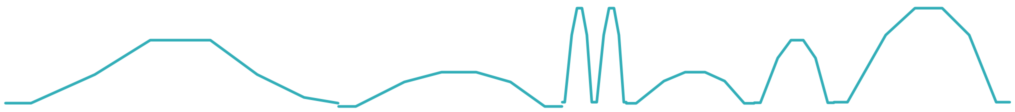
Header/Body Header/Body Header/Body

Bit Stream

0 0 1 0 1 1 1 0 0 0 1

"Digital" Signal

Analog Signal

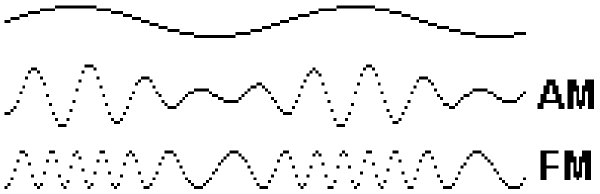


Modulation

- Changing a signal to convey information
- From Music:
  - Volume
  - Pitch
  - Timing

Modulation

- Changing a signal to convey information
- Ways to modulate a sinusoidal wave
  - Volume: Amplitude Modulation (AM)
  - Pitch: Frequency Modulation (FM)
  - Timing: Phase Modulation (PM)

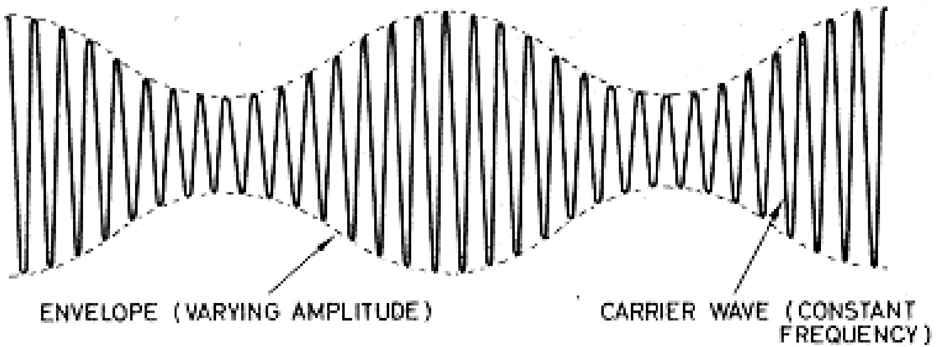


- In our case, modulate signal to encode a 0 or a 1.
  (multi-valued signals sometimes)

Amplitude Modulation

- AM: change the strength of the signal.
- Example: High voltage for a 1, low voltage for a 0

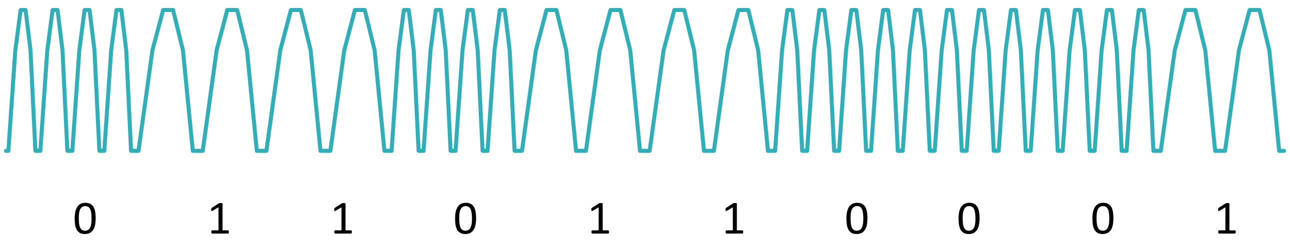
0 0 1 1 0 0 1 1 0 0 0 1 1 1 0 0 0 1 1 0 0 0 1 1 1 0

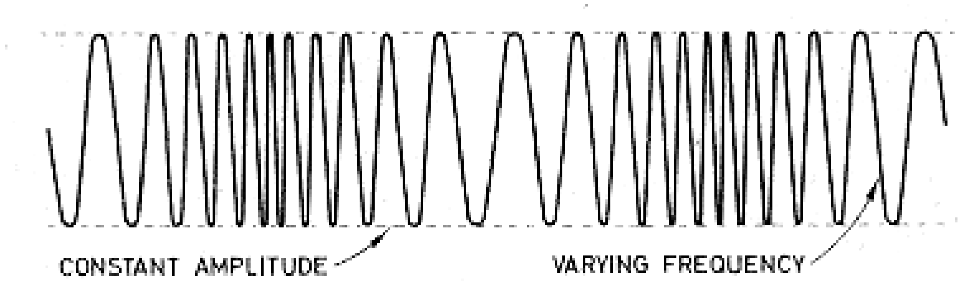


1 0 1 0 1

Frequency Modulation

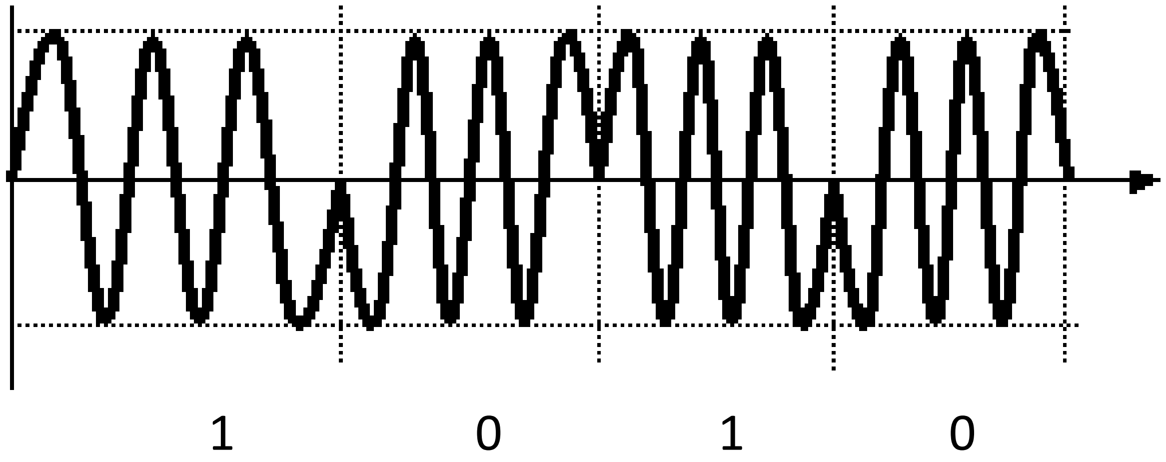
- FM: change the frequency



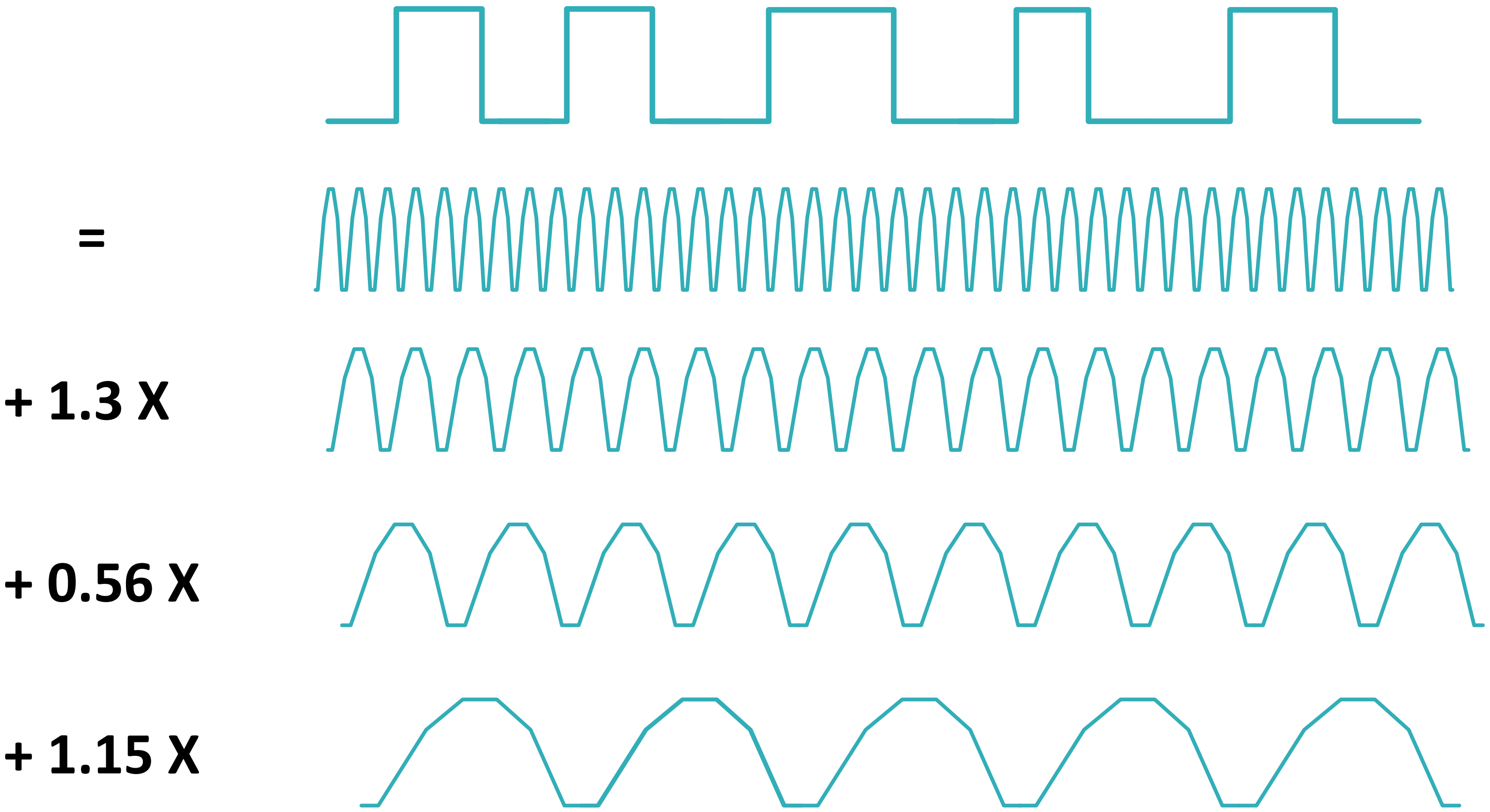


Phase Modulation

- PM: Change the phase of the signal

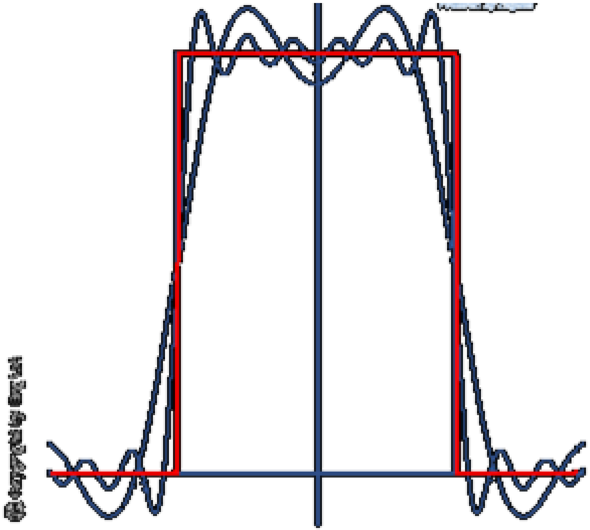


Signal = Sum of Waves

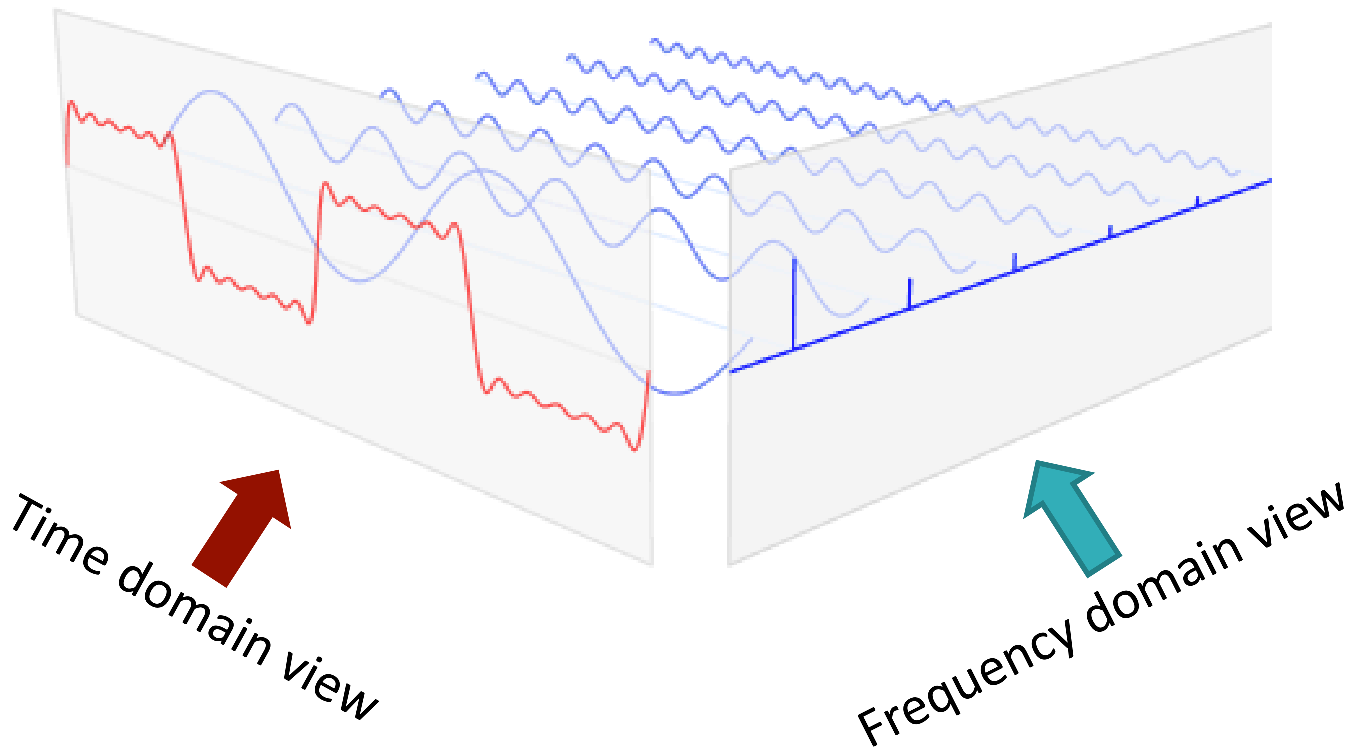


The Frequency Domain

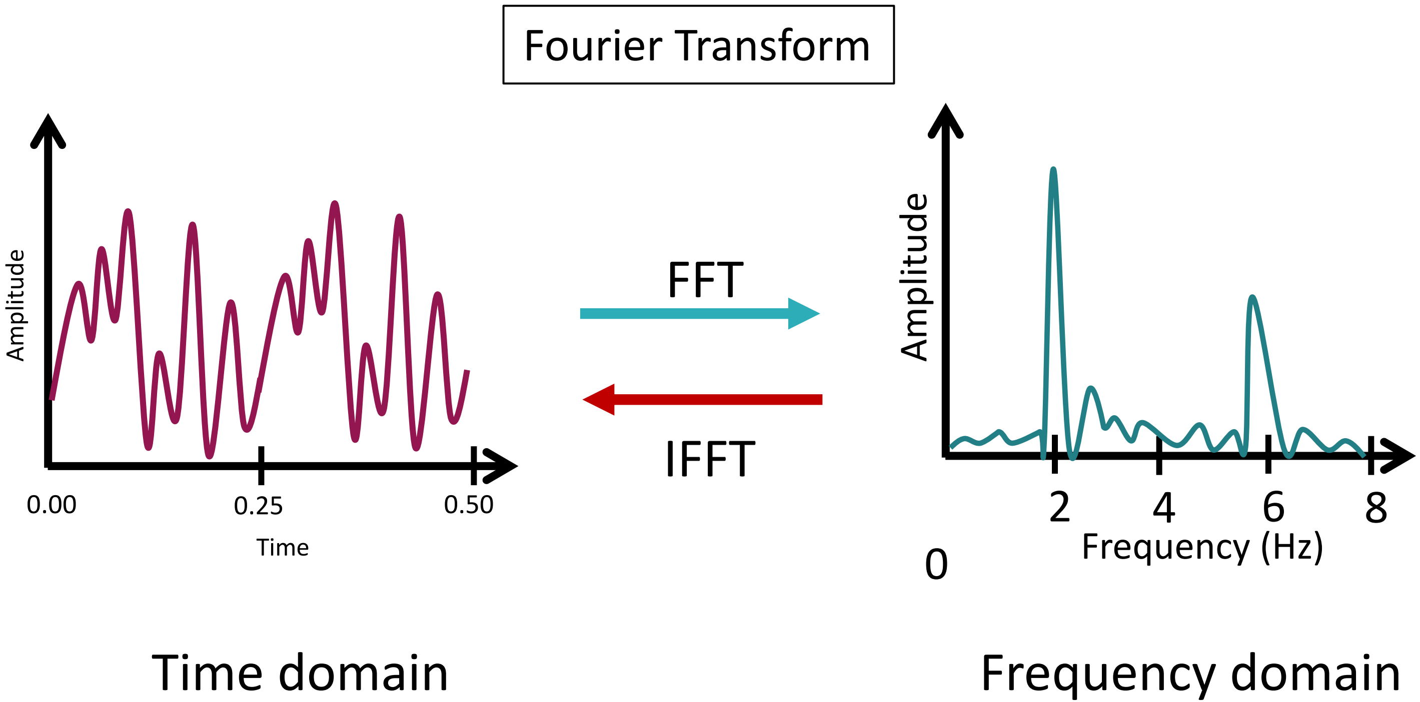
- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
  - Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
  - What frequencies are present and what is their strength (energy)
- E.g., radio and TV signals.



Time Domain and Frequency Domain



Time Domain and Frequency Domain



FFT = Fast Fourier Transform

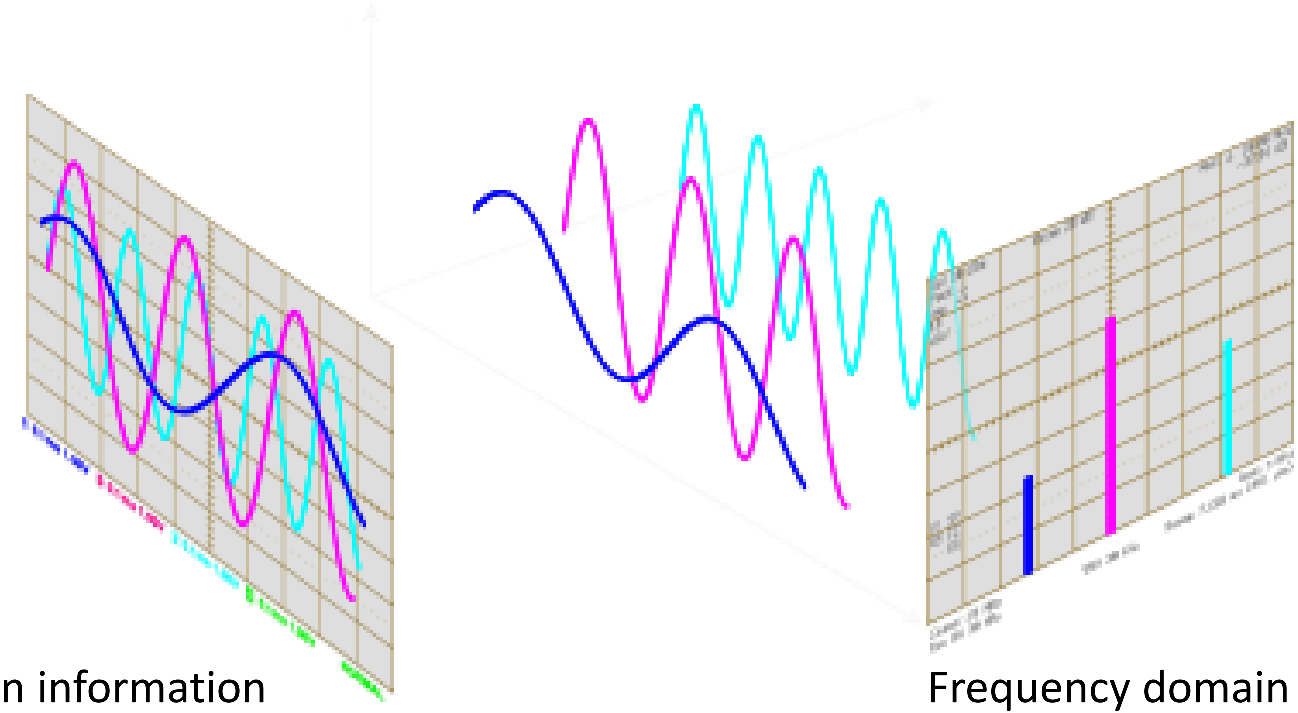
IFFT = Inverse Fast Fourier Transform

Removing Noise from Sensor Data

Outline

- Noise in sensor data
- Signal vs Noise
- Causes for noise
  - Accelerometer, ECG, Image, Audio, GPS
- Time-domain noise removal
- Frequency domain noise removal

Information and Noise in Signals

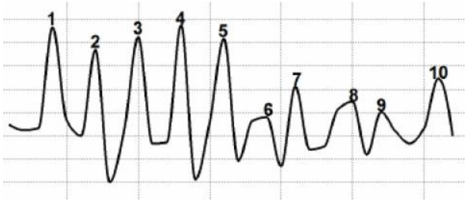


Time domain information

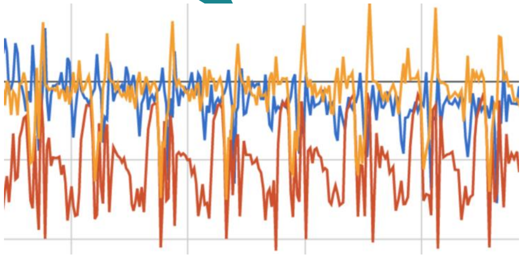
Frequency domain information

Noise in Sensor Data

Step Detection Algorithm



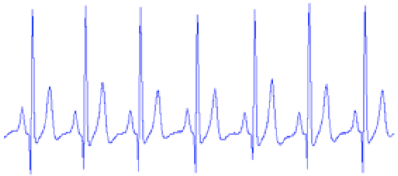
(you expect this)



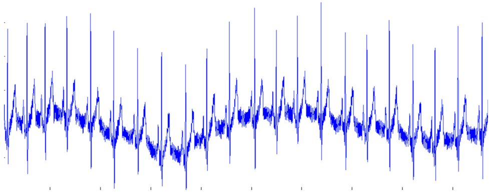
(you get this)

Noise in Sensor Data

Heart Arrhythmia detection

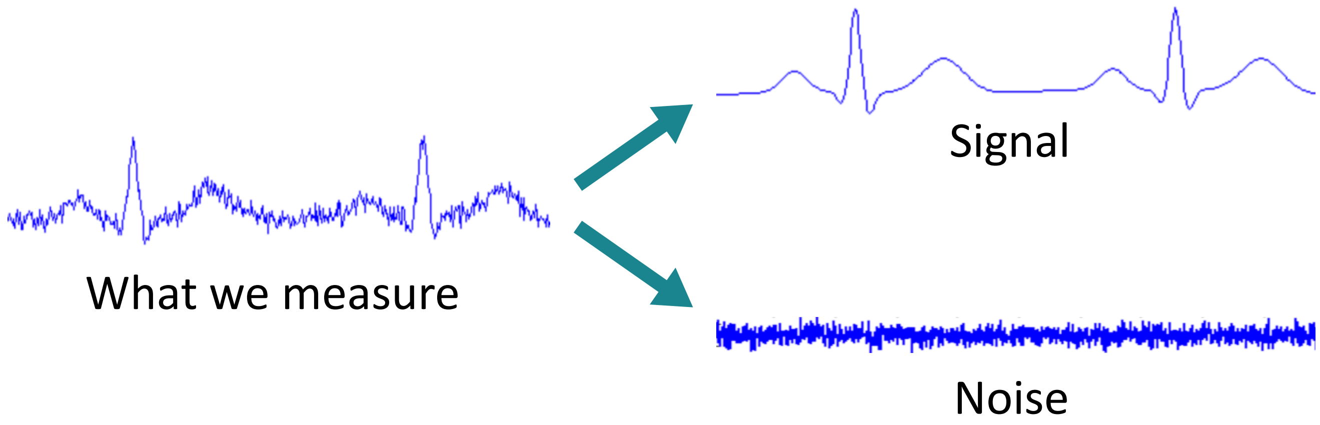


(you expect this)



(you get this)

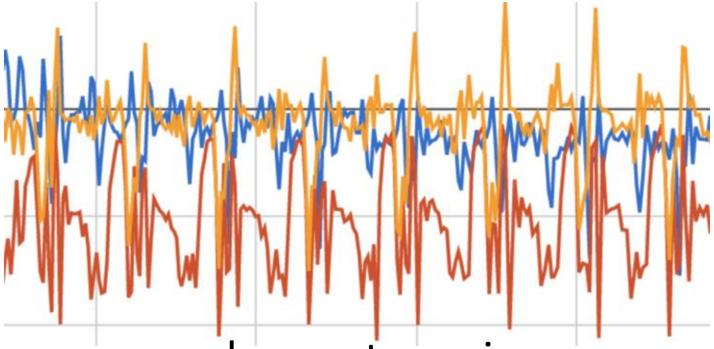
Signal and Noise



We need to remove noise while retaining the signal

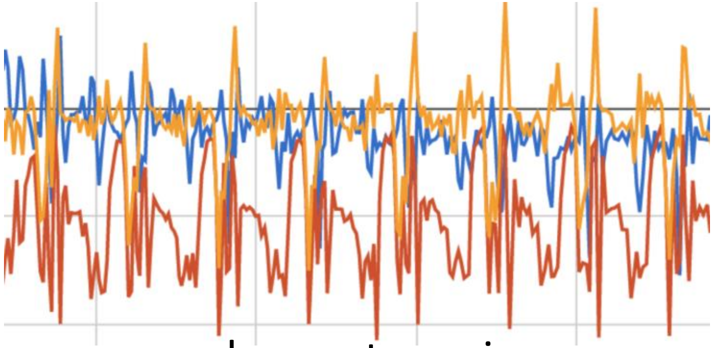
What are the sources of noise?

What are the sources of noise?



accelerometer noise

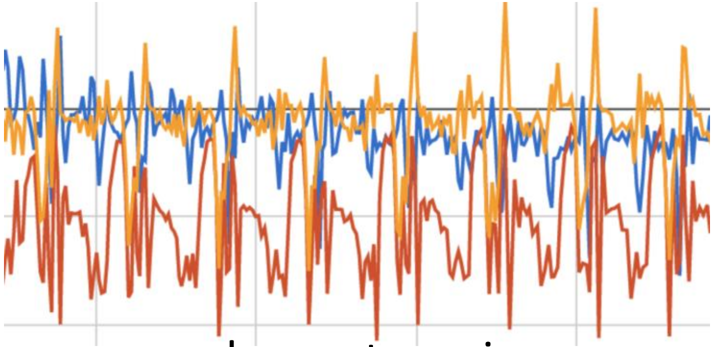
What are the sources of noise?



accelerometer noise

- Electronic noise
  - Electronics: Johnson noise, Shot noise, flicker noise...
  - Generally dealt with in hardware
- Mechanical noise
  - Thermo-mechanical noise
  - Environmental vibration noise (largest source)

What are the sources of noise?



accelerometer noise

- Electronic noise
  - Electronics: Johnson noise, Shot noise, flicker noise...
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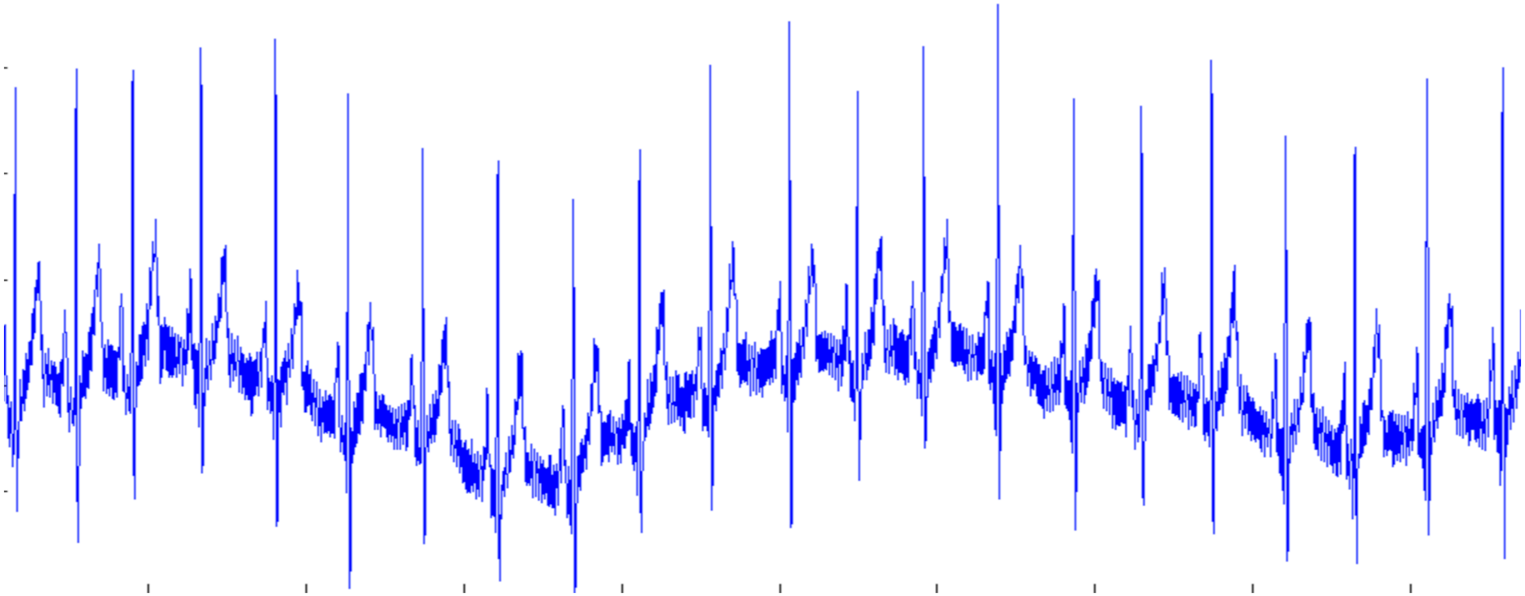
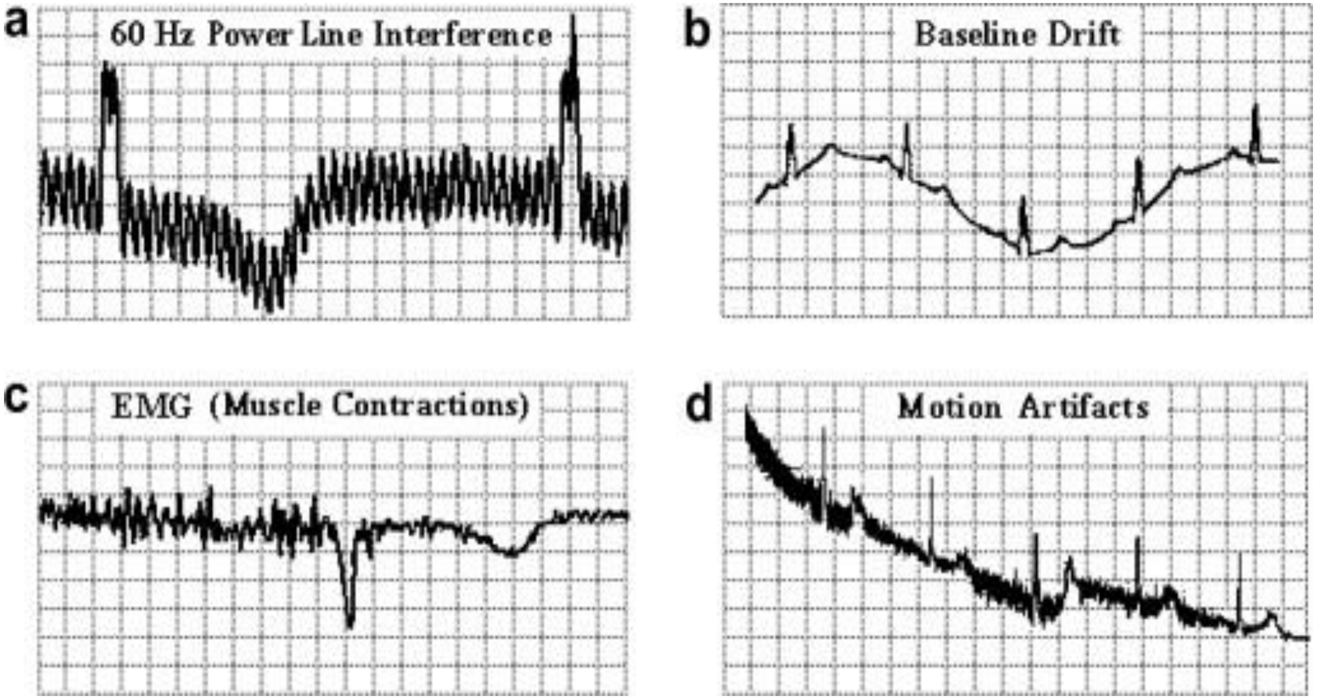
- Mechanical noise
  - Thermo-mechanical noise
  - Environmental vibration noise (largest source)
- External vibration noise
  - Case 1: Phone detection
  - Case 2: Screen orientation detection

What are the sources of noise?



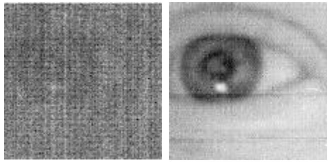
ECG signal

What are the sources of noise?



ECG noise

What are the sources of noise?

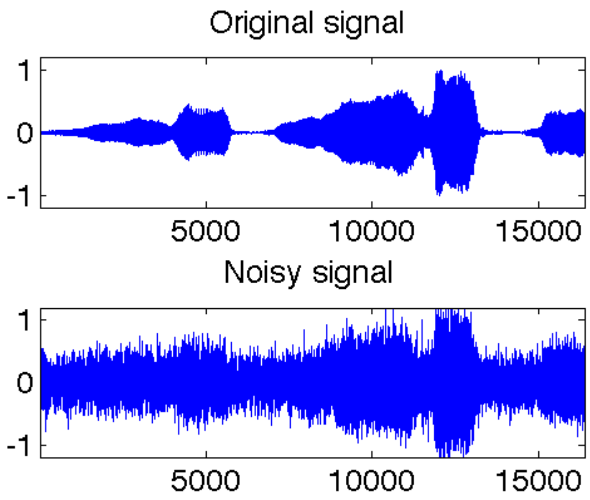


Images

- Intrinsic factors: Gaussian noise, Salt-and-Pepper noise, Shot noise, Quantization noise…
- External factors: Hand movement, Unwanted light, …

What are the sources of noise?

Audio signals



- Intrinsic: Pink noise, popcorn noise, shot noise, avalanche noise, thermal noise, …

- External: Simultaneous conversations, construction site, nearby traffic, …

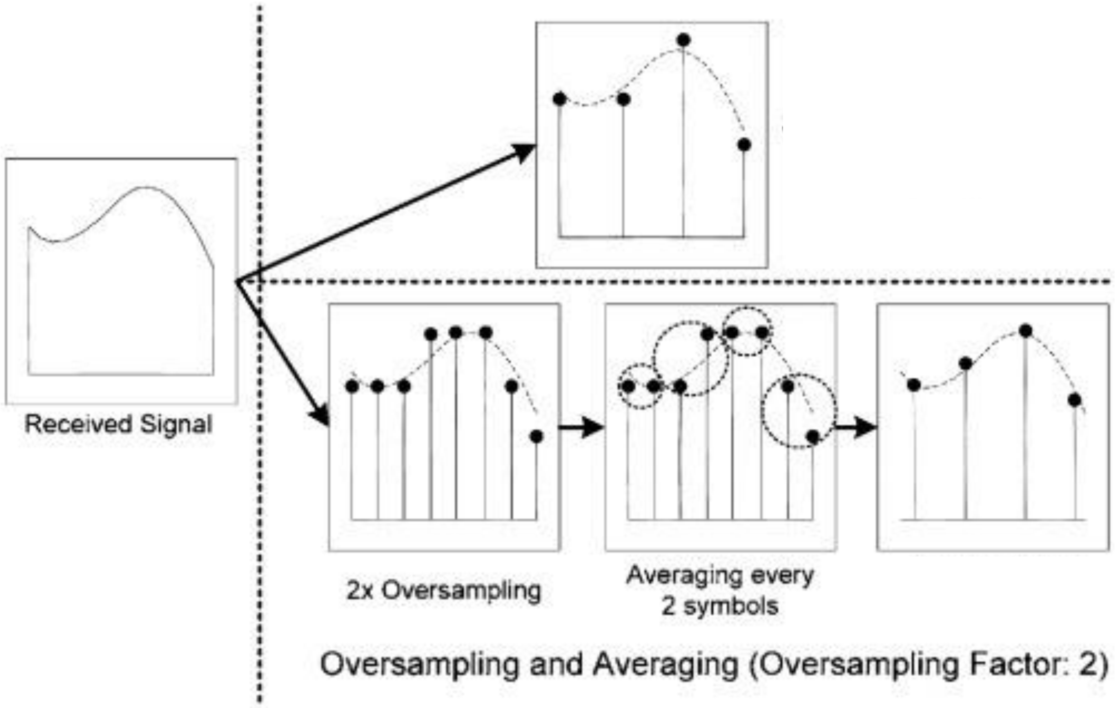
What are the sources of noise?

GPS signals

- Tropospheric delays
- Multipath effects due to buildings
- Weather conditions (intermittent signal)

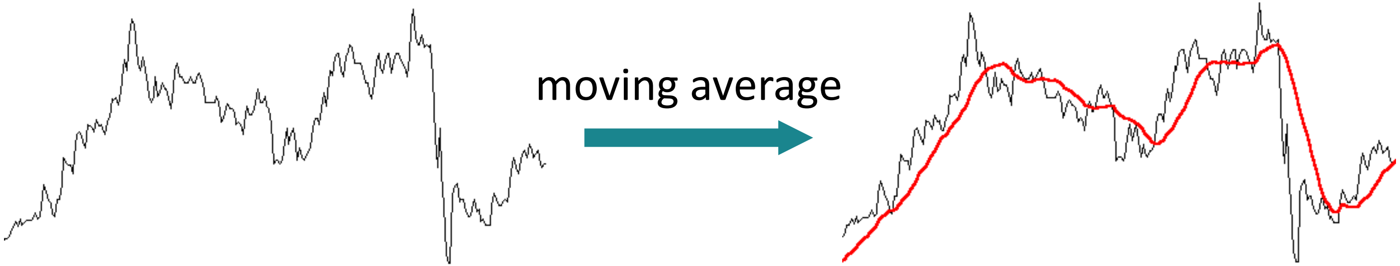
Removing noise by time-domain smoothing

Oversampling and Averaging



noise reduces by a factor of 1/√N

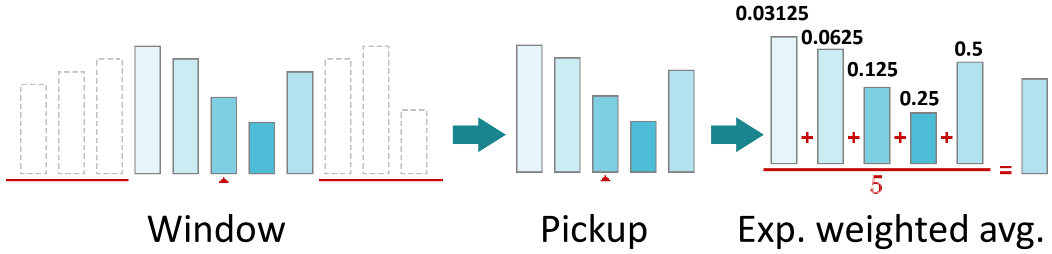
Moving average - example



Input x = $x_1, x_2, x_3, \ldots x_n$

$$s_1 = (x_1 + x_2 + x_3)/3$$
$$s_2 = (x_2 + x_3 + x_4)/3$$
$$s_3 = (x_3 + x_4 + x_5)/3$$
$$\ldots$$
$$s_{n-2} = (x_{n-2} + x_{n-1} + x_n)/3$$

Exponentially weighted moving average



- Steps in a exponential moving average filter
  - Place a window over samples
  - Pickup samples
  - Output exponentially weighted average of elements

Exponentially weighted moving average

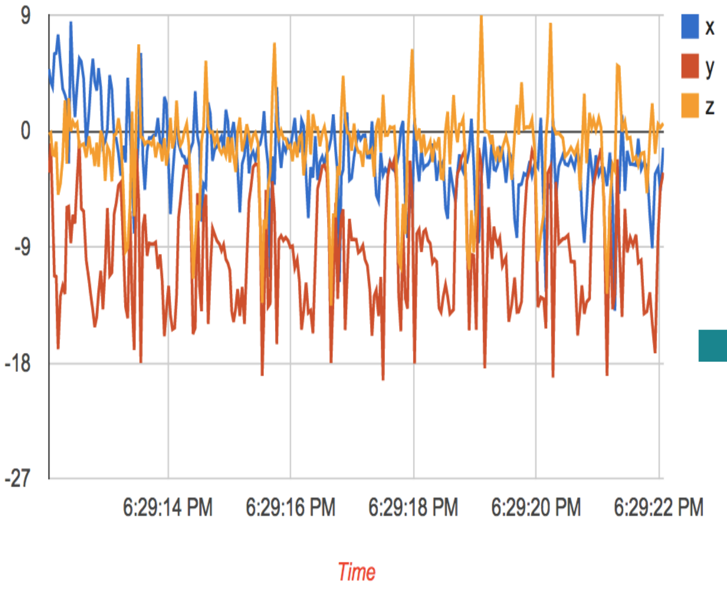
$$s_1 = x_0$$
$$s_t = \alpha x_{t-1} + (1-\alpha)s_{t-1} = s_{t-1} + \alpha(x_{t-1} - s_{t-1}), t > 1$$

Exponentially weighted moving average

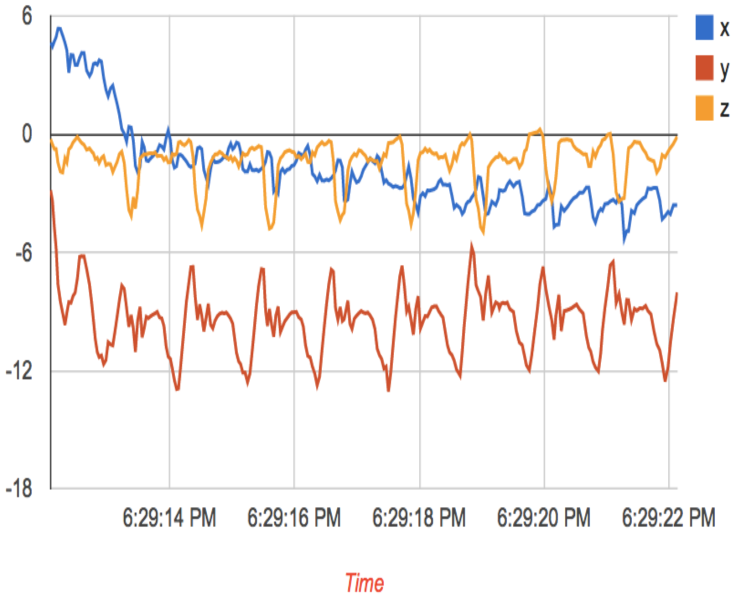
$$s_t = \alpha \cdot x_{t-1} + (1-\alpha) \cdot s_{t-1}$$

$$\begin{aligned} s_t &= \alpha x_{t-1} + (1-\alpha) s_{t-1} \\ &= \alpha x_{t-1} + \alpha(1-\alpha) x_{t-2} + (1-\alpha)^2 s_{t-2} \\ &= \alpha \left[x_{t-1} + (1-\alpha) x_{t-2} + (1-\alpha)^2 x_{t-3} + (1-\alpha)^3 x_{t-4} + \cdots \right] + (1-\alpha)^{t-1} x_0. \end{aligned}$$

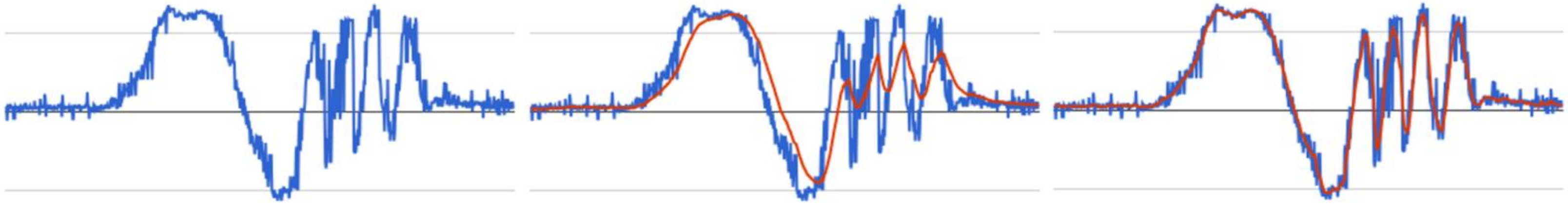
Exponentially weighted moving average



EWMA

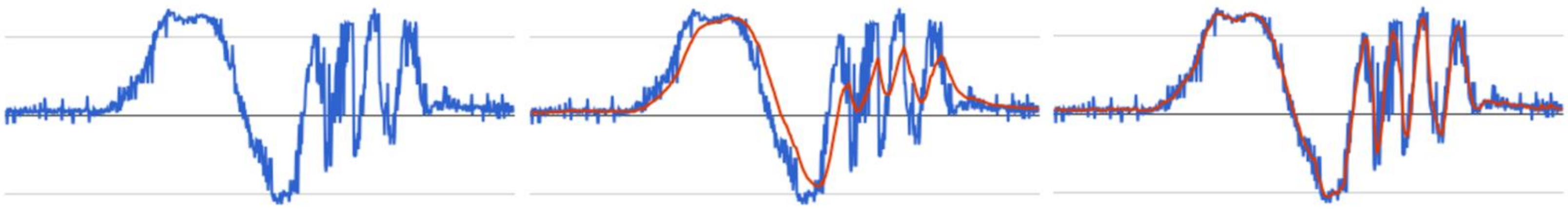


Median filter vs Exponential smoothing



(a) Raw accelerometer readings (b) Exponential smoothing (c) Median filtering

Median filter vs Exponential smoothing



(a) Raw accelerometer readings (b) Exponential smoothing (c) Median filtering

Input x = $x_1, x_2, x_3, \ldots x_n$

s_1 = median(x_1 , x_2 , x_3)

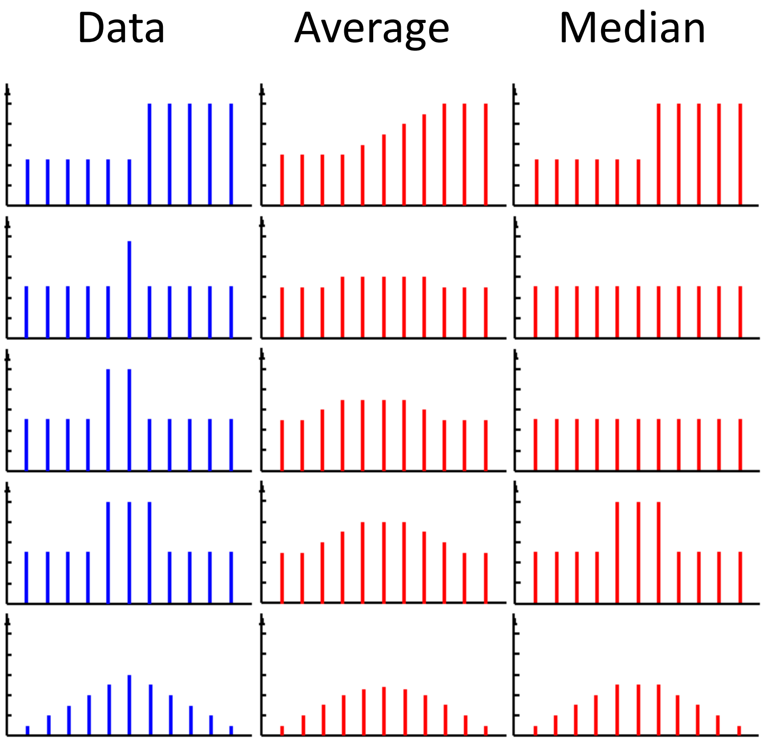
s_2 = median(x_2 , x_3 , x_4)

s_3 = median(x_3 , x_4 , x_5)

…

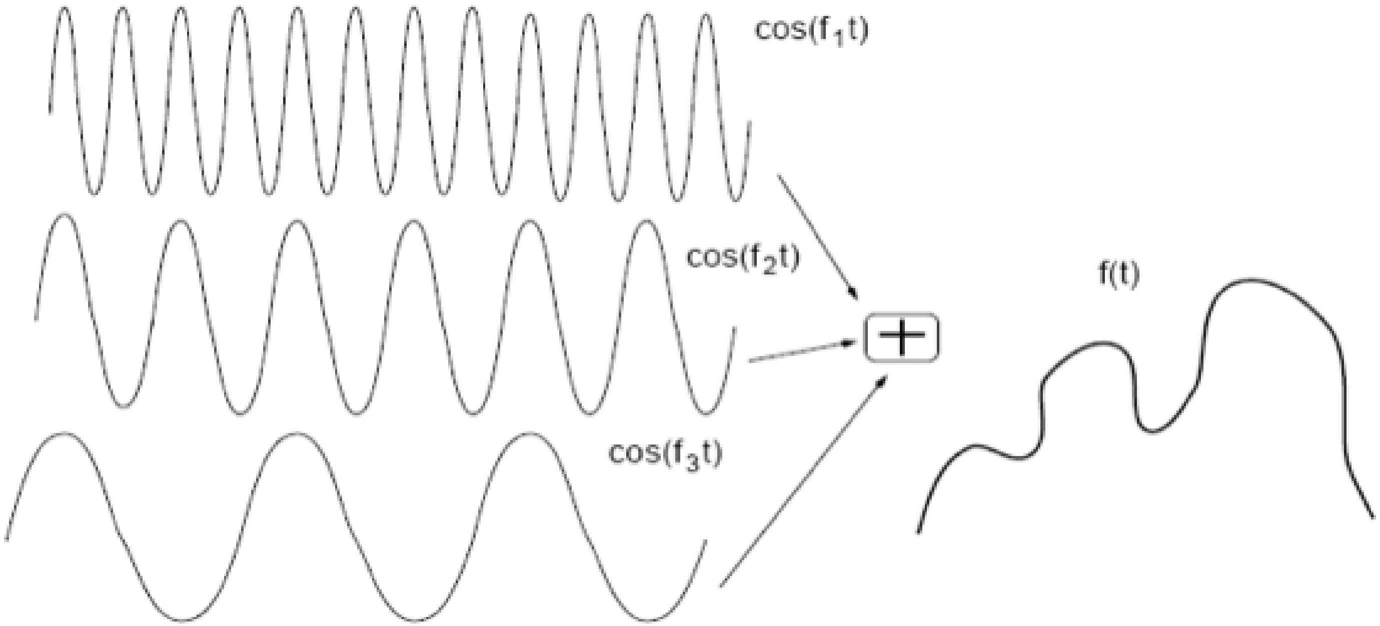
s_{n-2} = median(x_{n-2} , x_{n-1} , x_n)

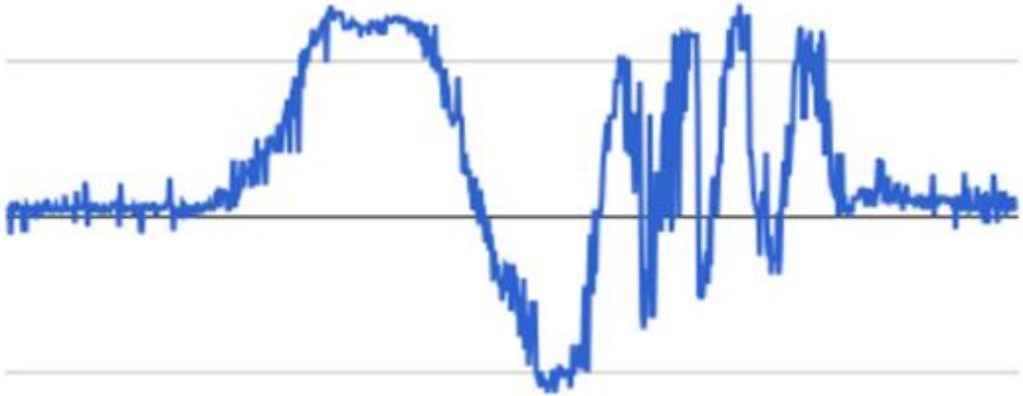
Median filter vs Exponential smoothing



Removing noise by frequency-domain filtering

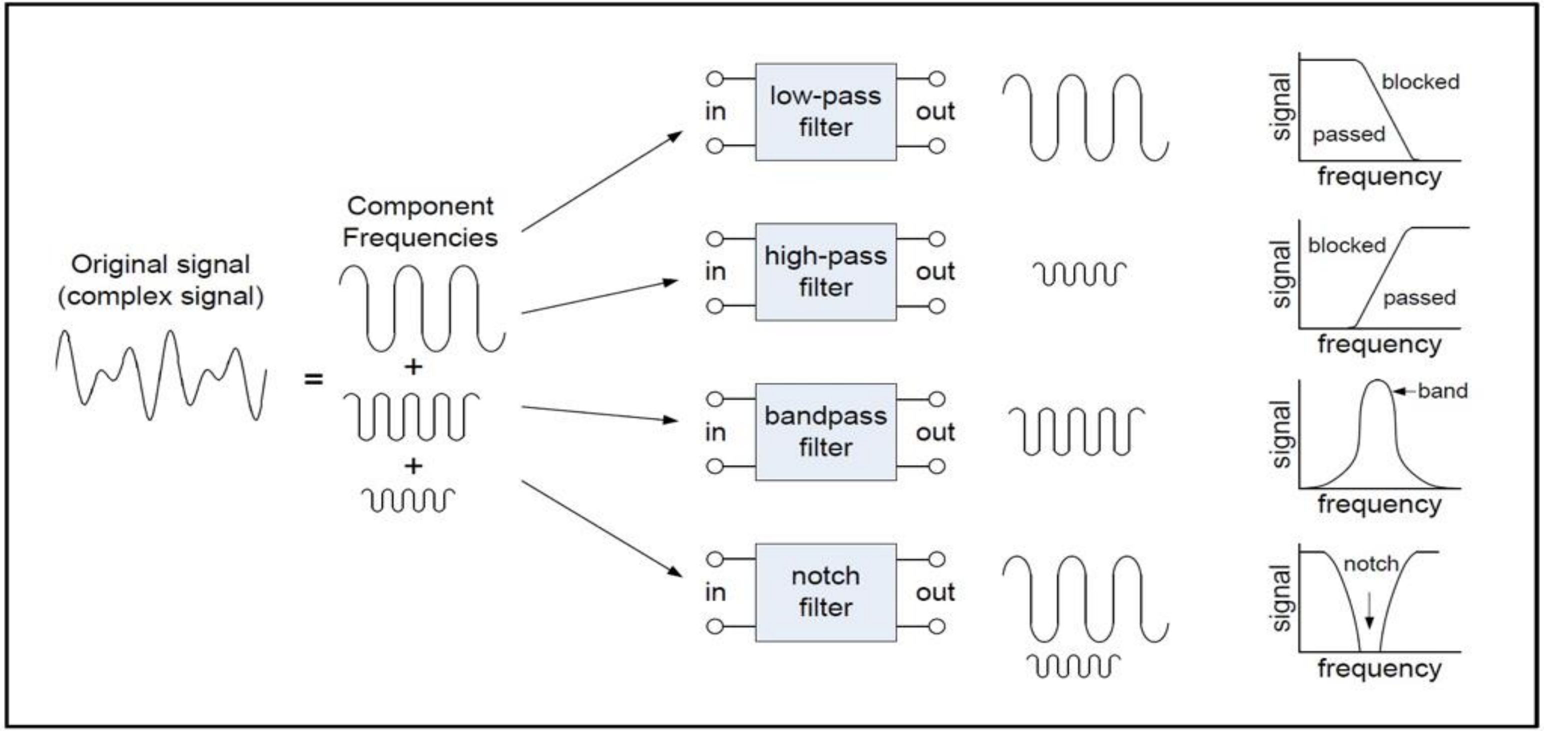
Frequency domain



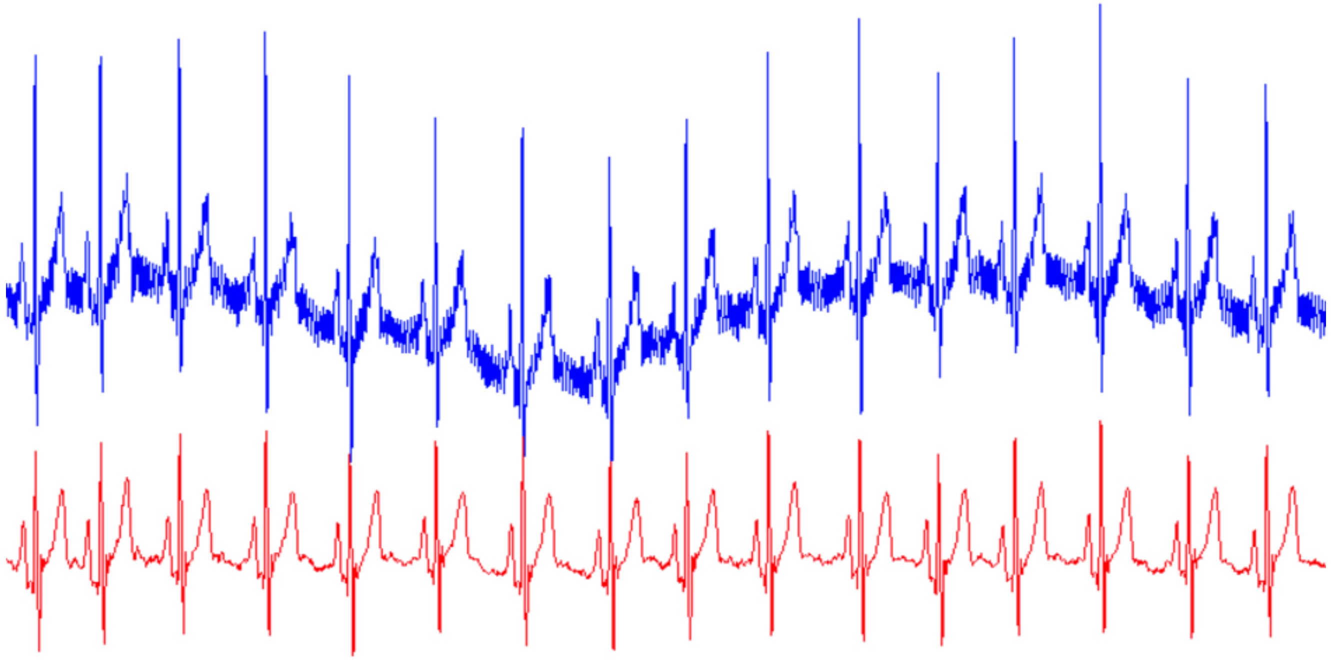


(a) Raw accelerometer readings

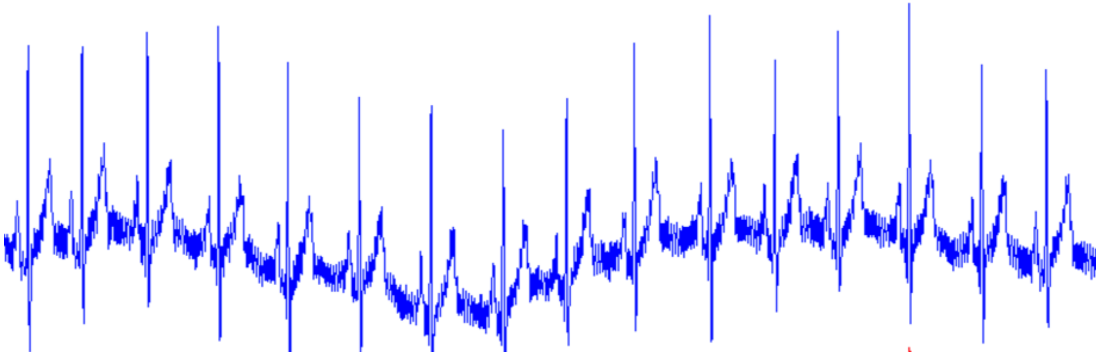
Frequency domain Filters



Example: ECG noise removal

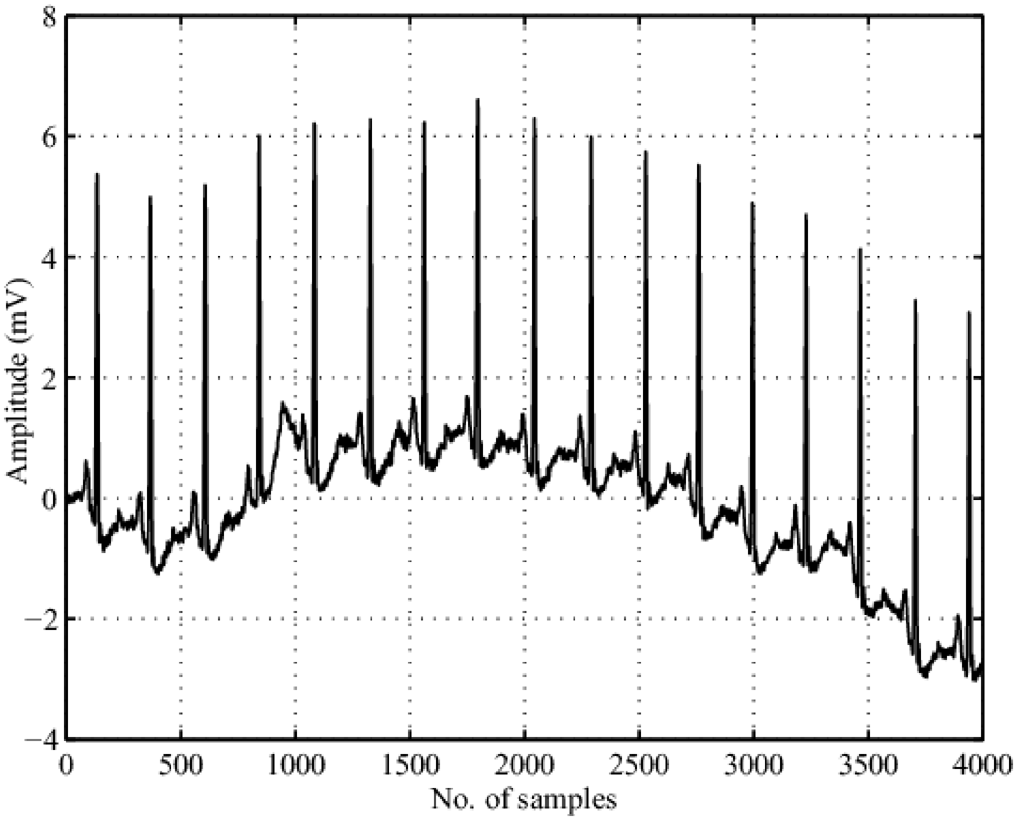


Example: ECG noise removal

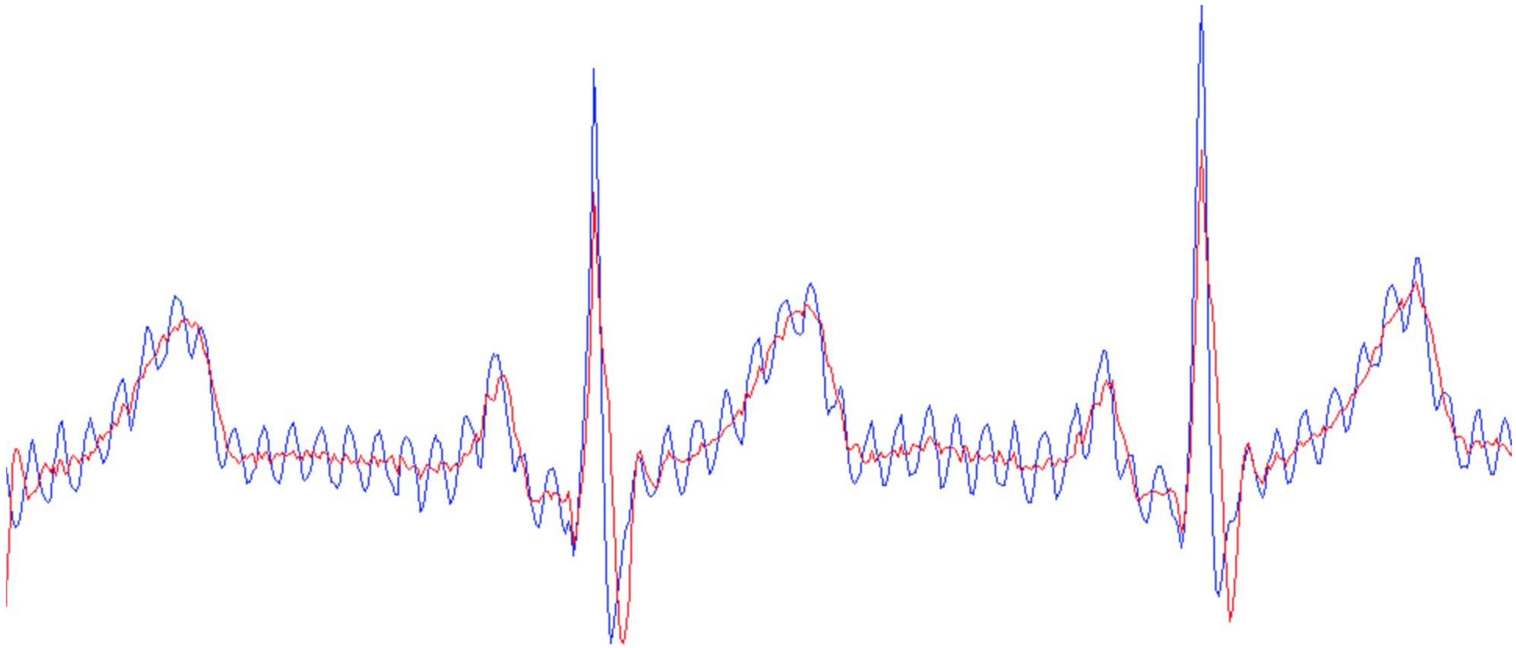


- Signal of interest: 0.5 Hz - 150 Hz
- Sources of noise:
  - Powerline Interference: 50Hz
  - Baseline Wander: <0.5Hz (slow oscillations)
  - Other: High frequency (> 150 Hz)

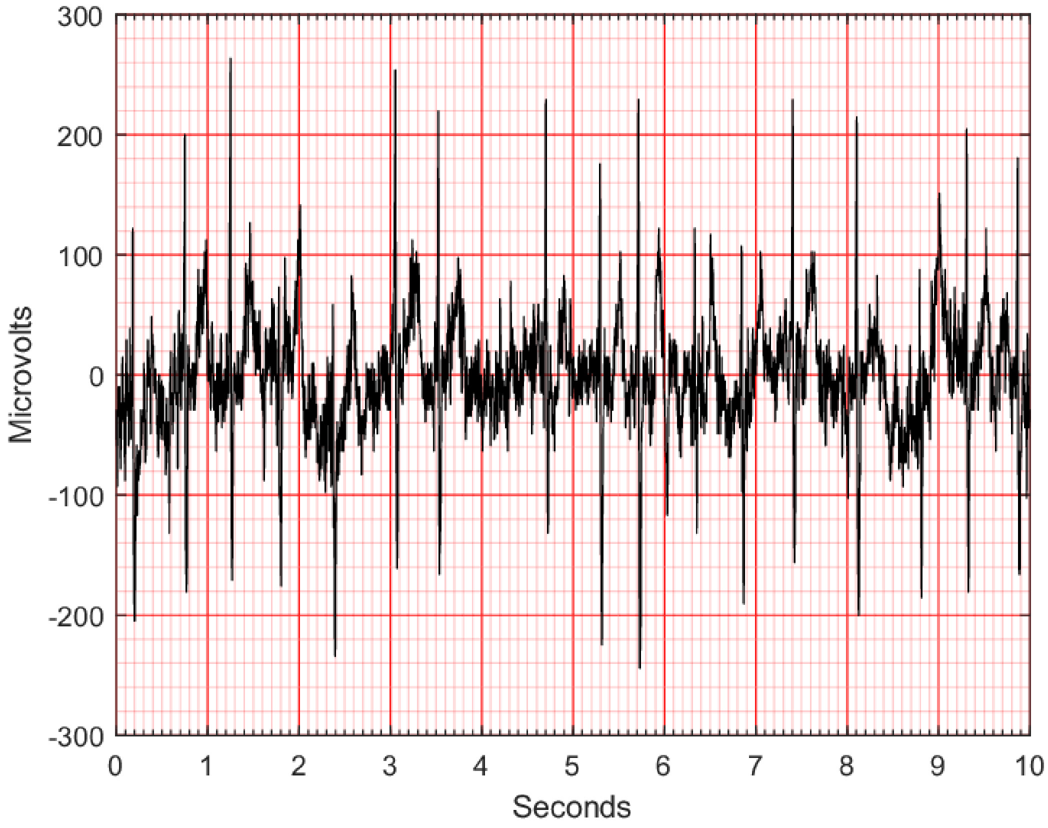
Baseline wander



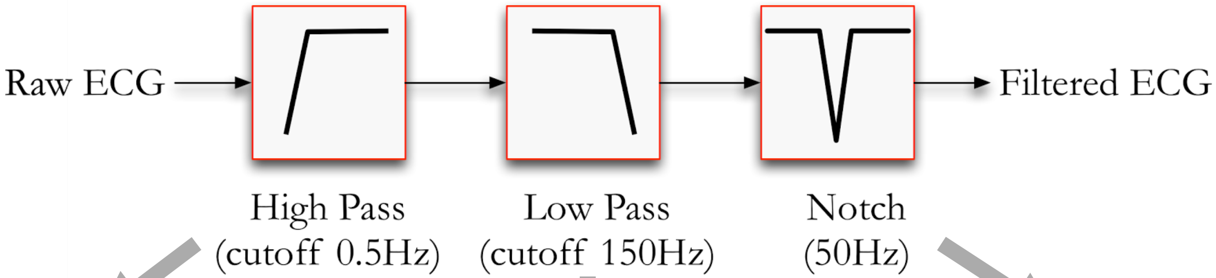
Powerline noise



High frequency noise



Example: ECG noise removal

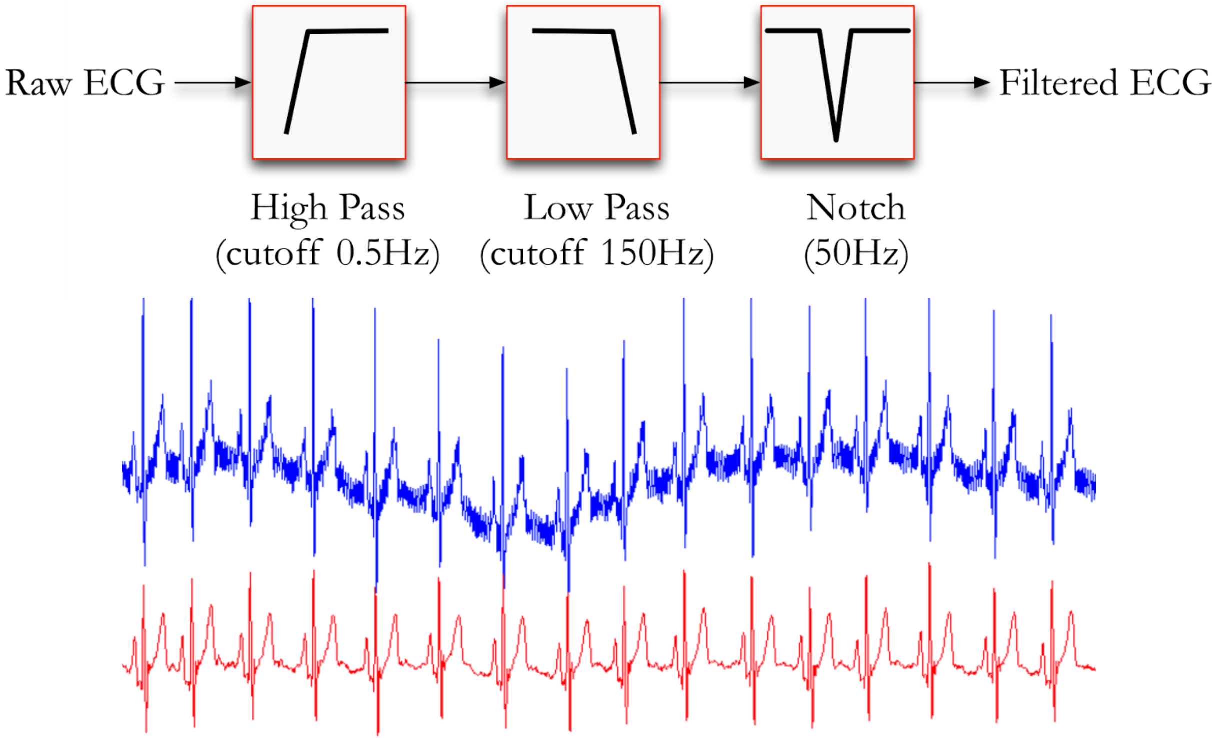


Baseline Wander
(< 0.5 Hz)

High Freq. Noise
(> 150 Hz)

Powerline Interference
(50 Hz)

Example: ECG noise removal



Conclusion

- Noise removal is the foundation for any signal analytics

- Noise removal can come with some unwanted artifacts