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# An introduction to Electronic Sensing Devices

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RELATORI

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SEDE

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DATA

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# Practical information

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# Sensing Devices Lab

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**What is a signal?**

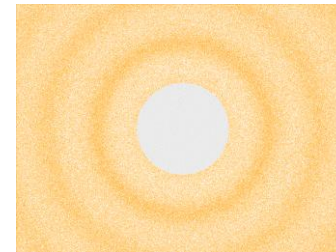
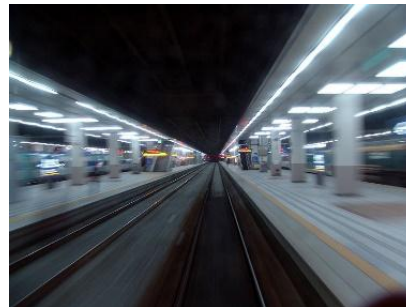
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# What is a *signal*?

- A *signal* is a function that **conveys information about a phenomenon**
- Several context-specific definitions
  - In biology, it can be part of any communication process (either mechanical or biochemical) that governs basic activities of cells
  - In electronics and telecommunications, it may refer to any time varying voltage or current wave that carries information

- Examples:

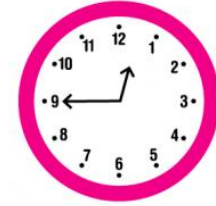
- Motion
- Sound
- Images and videos



# Analog VS Digital signals

- **Analog signal**

- A signal which changes continuously over time, allowing for a theoretically infinite number of values to be represented
  - E.g. the instantaneous voltage of an analog audio signal varies continuously with the sound pressure



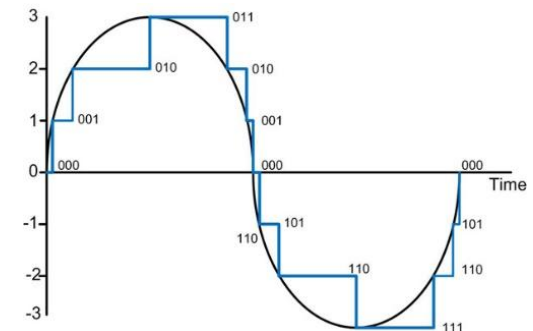
- **Digital signal**

- A signal which is discrete in time and has a finite set of possible values

A black digital clock display showing the time 12:45 in white digits.

- Digital signal often arise via sampling analog signals

- E.g. a circuit might read a continually fluctuating voltage on a line every 10 milliseconds, and represents such reading by a fixed number of bits

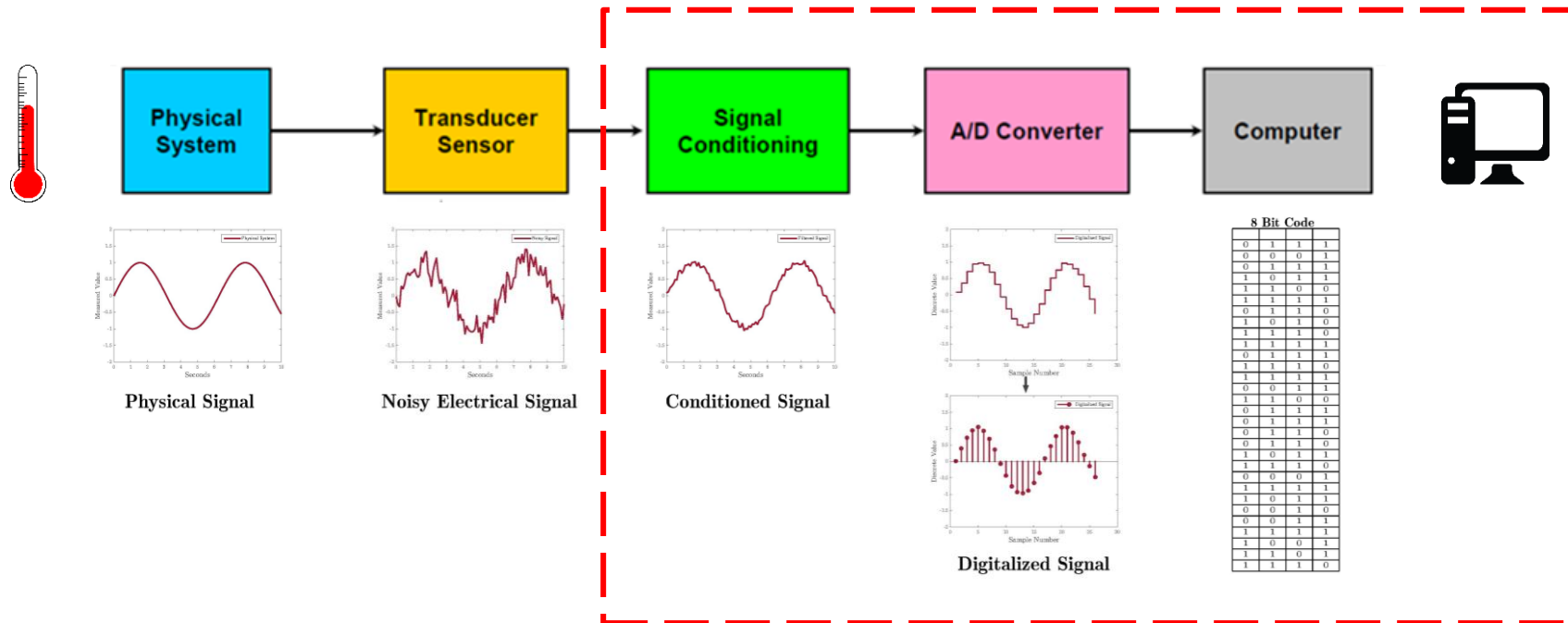


# Acquisition System

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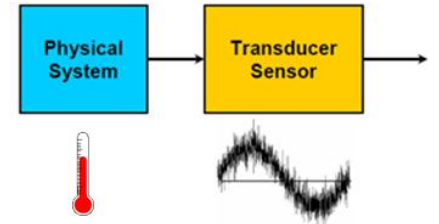
# Signal acquisition system

- The acquisition of signals is a process which includes:
  - The sampling of the signals containing the physical conditions of the real world
  - The conversion of such samples into digital numerical values, which can be manipulated by a computer



# Stage 1: Transducer

- A transducer converts a signal from one form of energy into another form
- Types of transducers:
  - **Mechanical transducers:** physical quantities are converted into mechanical quantities
    - E.g. a pressure gauge transforms the pressure of a fluid into the displacement of the needle
  - **Electrical transducers:** physical quantities are converted into electrical quantities
    - E.g. a thermocouple changes temperature differences into a small voltage



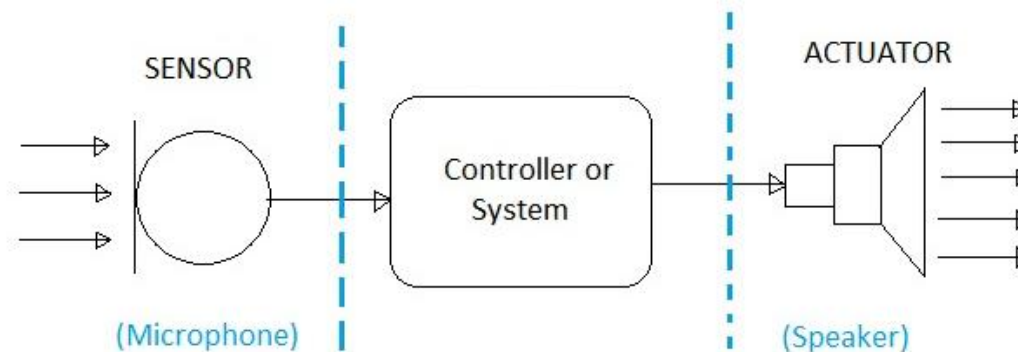
# Stage 1: Transducer

- **Sensor**

- It detects events or changes (more in general, *information*) in the surrounding environment, and outputs a signal (typically, electrical) in response to the measured parameter

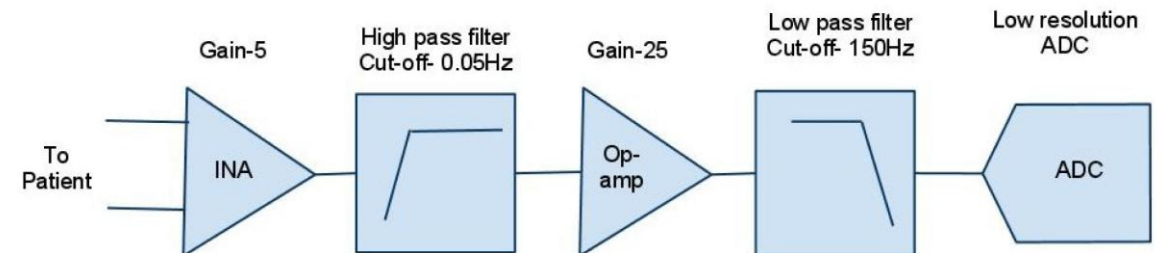
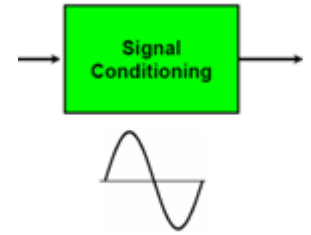
- **Actuator**

- It converts the signal's energy (e.g. electric current, hydraulic fluid pressure) into mechanical motion



# Stage 2: Signal conditioning

- Most of the electrical signals generated by sensors are not suitable for successive stages, e.g. due to:
  - Signal amplitude too small
  - Signal amplitude too large
  - Presence of invalid data other than the actual signal
  - ...
- Signal conditioning is the manipulation of an analog signal in a way that it meets the requirements of the next stage of processing. It includes:
  - Amplification
  - Attenuation
  - Filtering
  - ...

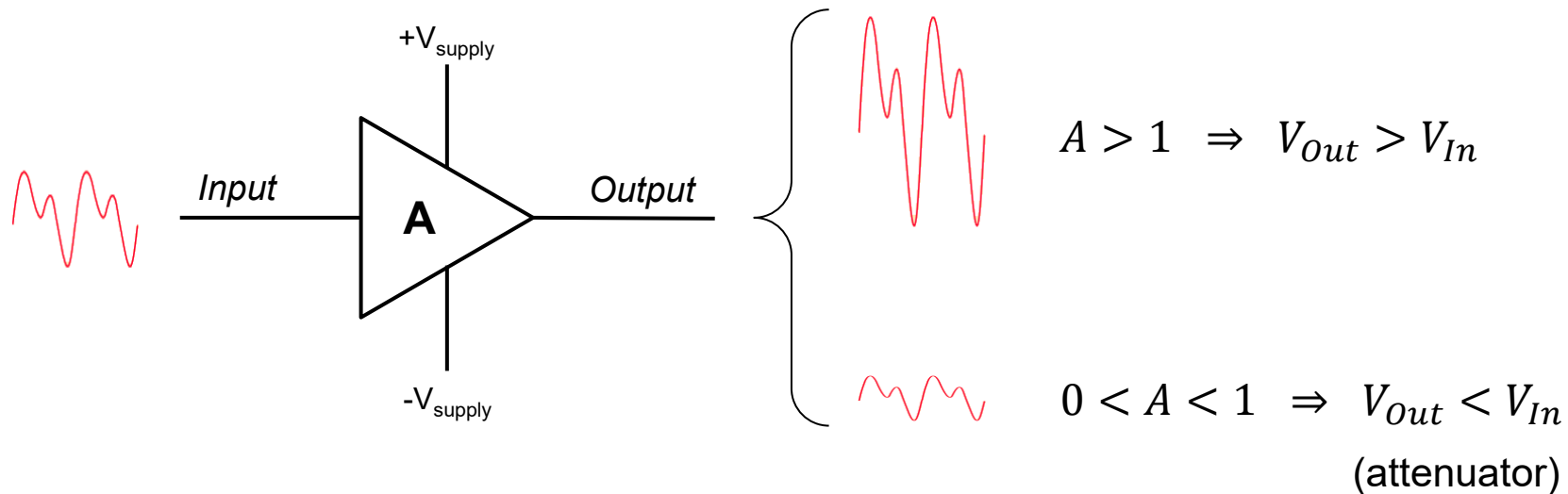


# Stage 2: Signal conditioning

- **Amplifier**

- It changes the amplitude of a voltage signal to a level suitable for the next stage

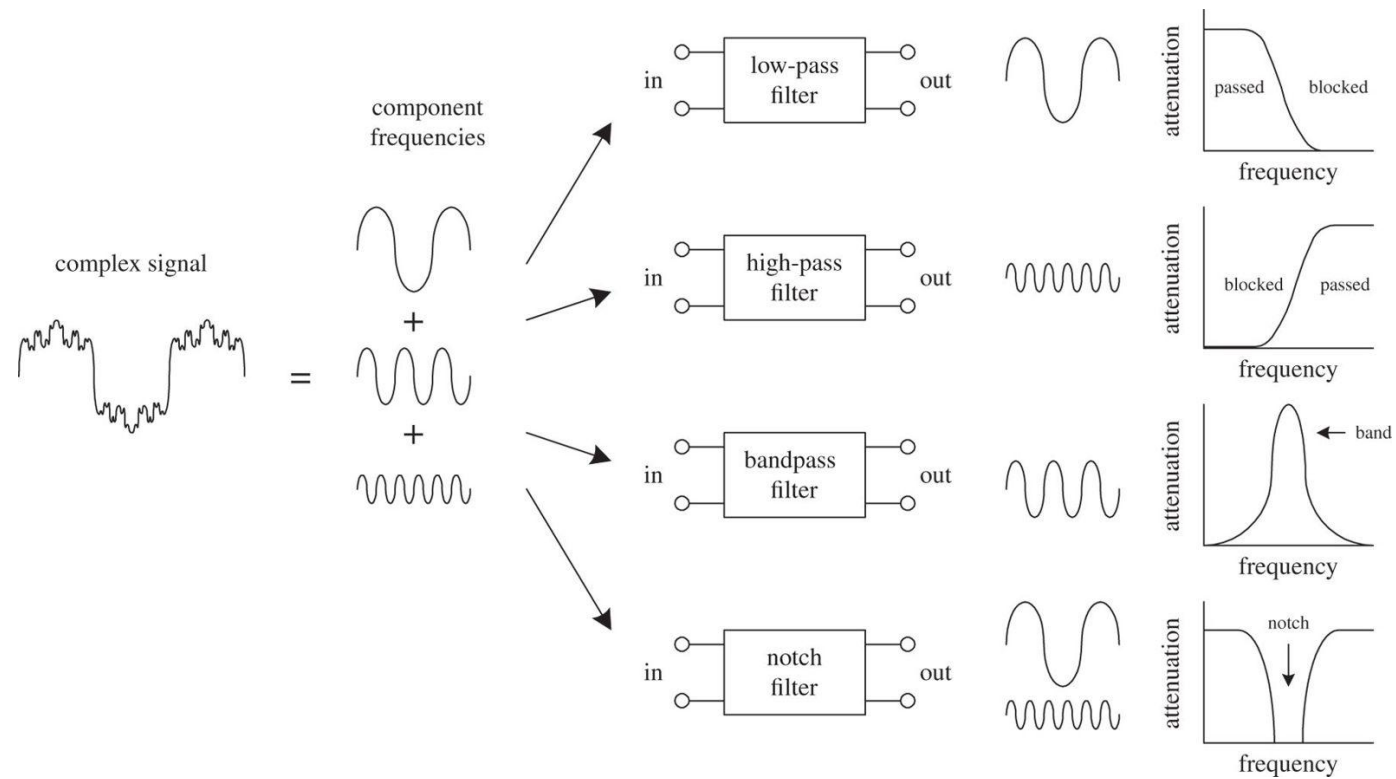
$$V_{Out} = A \cdot V_{In}$$



# Stage 2: Signal conditioning

- **Filter**

- It attenuates or removes unwanted frequency components from the input signal

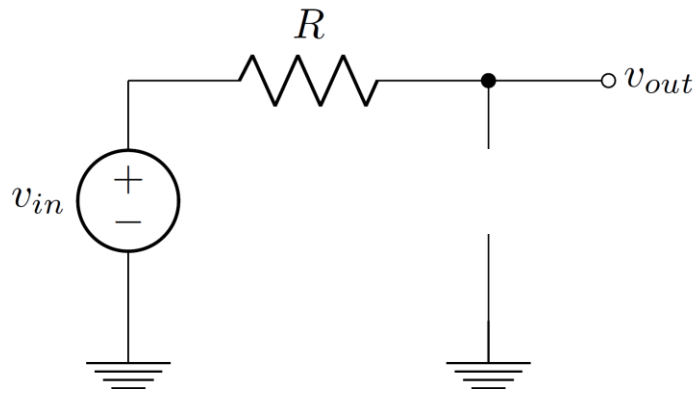


# Analog filters

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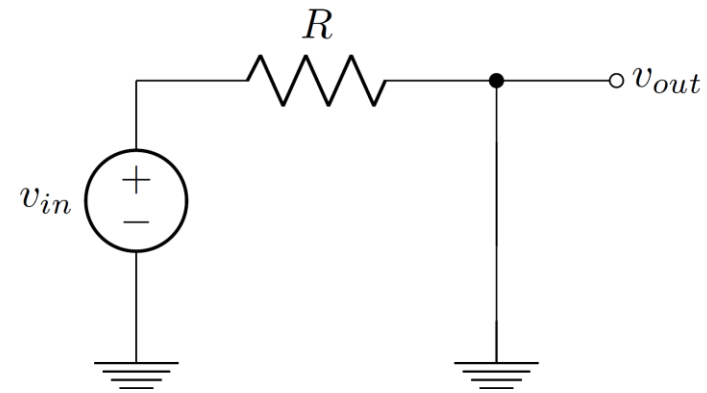
# RC circuit's behavior

- DC input voltage



- $I = 0$  (no closed path)
- $\frac{v_{in} - v_{out}}{R} = 0 \Rightarrow v_{out} = v_{in}$

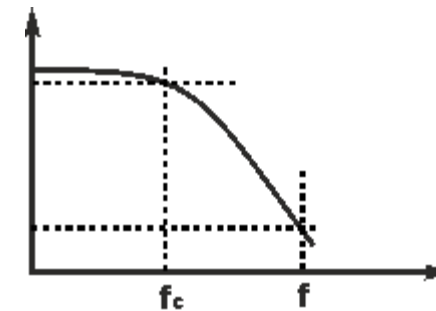
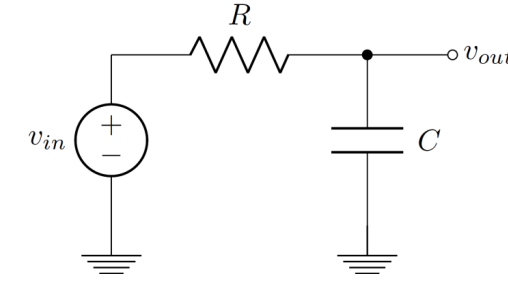
- AC input voltage



- $I = \frac{v_{in} - v_{out}}{R}$
- $v_{out} = 0$  (shorted to ground)

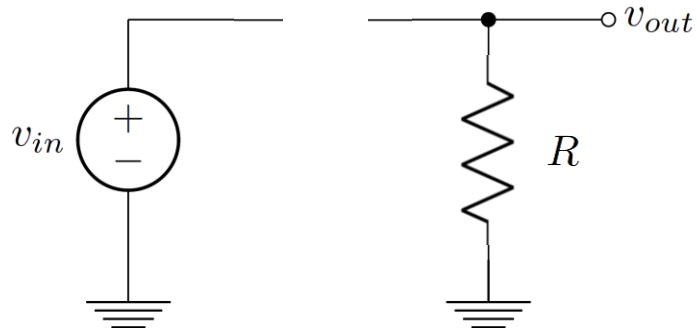
# Low-Pass Filter

- RC behavior
  - Nearly-constant signals:  $v_{out} = v_{in}$
  - Alternating signals:  $v_{out} = 0$
- An RC circuit is an analog **low-pass filter**
  - Signals (or components of a signal) characterized by **low frequencies pass unaltered** through the filter
  - Signals (or components of a signal) characterized by **high frequencies are attenuated** (or blocked) by the filter
- **Cutoff frequency  $f_c$**  defines which frequencies are considered “low” and which are “high”



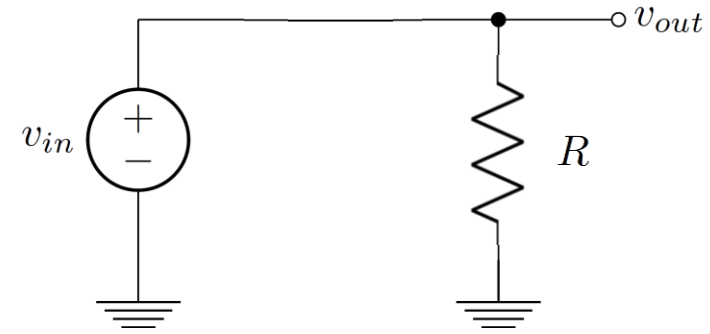
# CR circuit's behavior

- DC input voltage



- $I = 0$  (no closed path)
- $\frac{v_{out} - 0}{R} = 0 \Rightarrow v_{out} = 0$

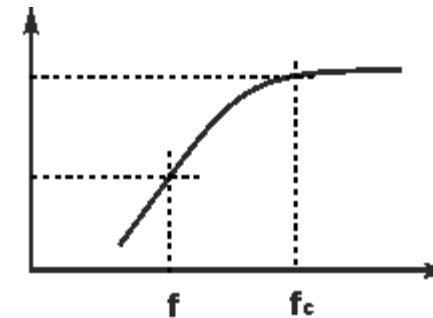
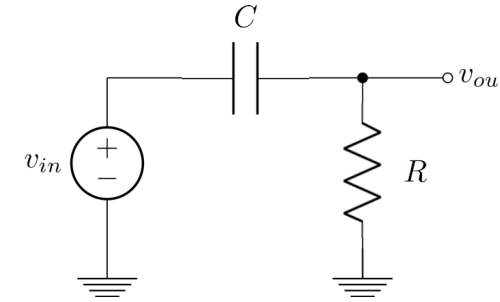
- AC input voltage



- $I = \frac{v_{out} - 0}{R}$
- $v_{out} = v_{in}$  (shorted to input)

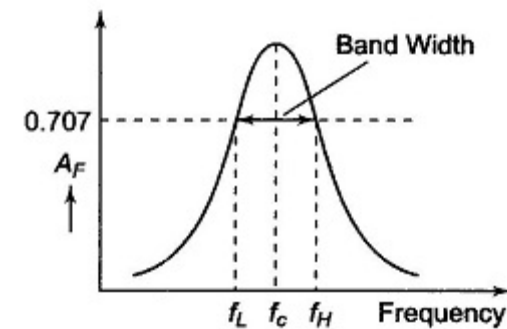
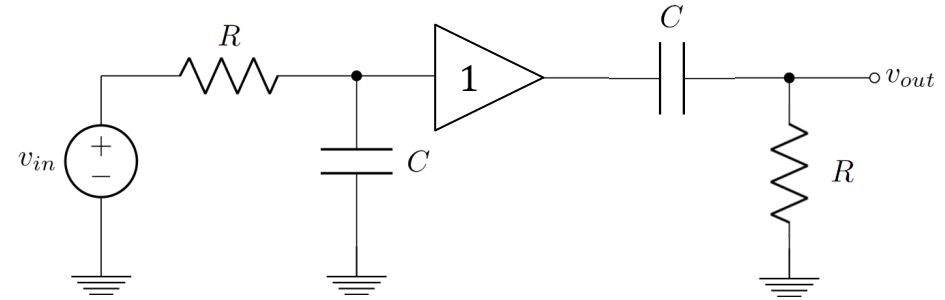
# High-Pass Filter

- CR behavior
  - Nearly-constant signals:  $v_{out} = 0$
  - Alternating signals:  $v_{out} = v_{in}$
- A CR circuit is an analog **high-pass filter**
  - Signals (or components of a signal) characterized by **low frequencies are attenuated** (or blocked) by the filter
  - Signals (or components of a signal) characterized by **high frequencies pass unaltered** through the filter
- **Cutoff frequency  $f_c$**  defines which frequencies are considered “low” and which are “high”



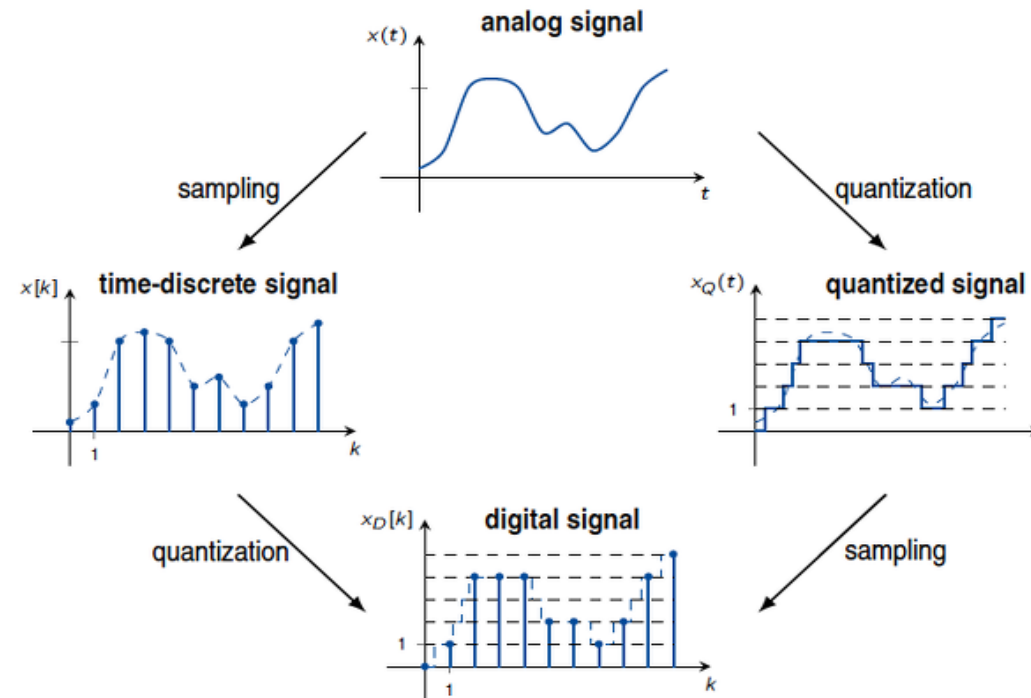
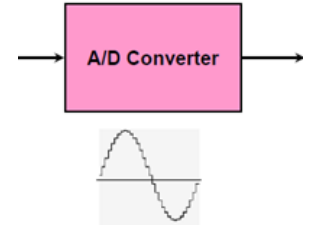
# Band-Pass Filter

- RC-CR behavior
  - Nearly-constant signals:  $v_{out} = 0$
  - Alternating signals:  $v_{out} = 0$
- A RC-CR circuit is an analog **band-pass filter**
  - Signals (or components of a signal) characterized by **low frequencies are attenuated** (or blocked) by the filter
  - Signals (or components of a signal) characterized by **high frequencies pass are attenuated** (or blocked) by the filter
  - Signals (or components of a signal) in the range of the **frequency band width pass unaltered** through the filter



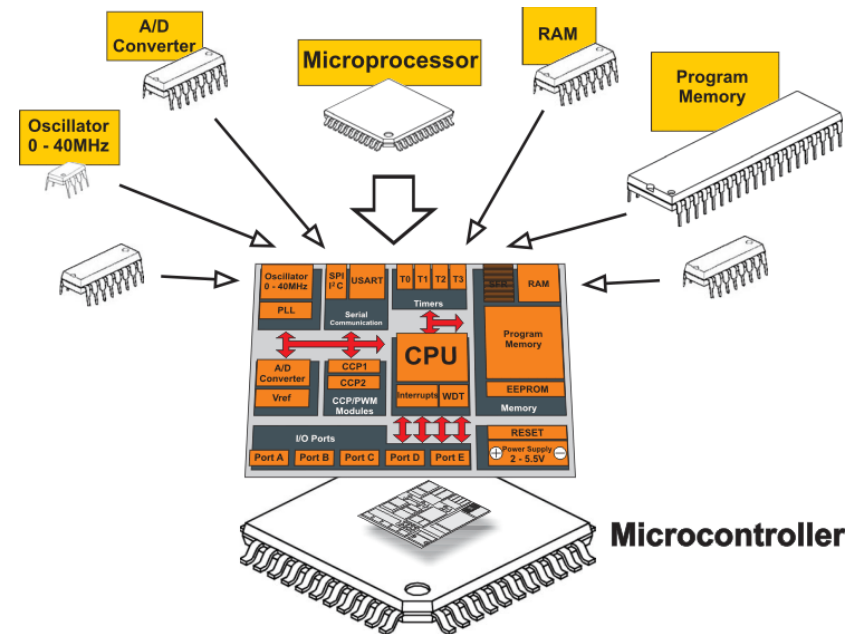
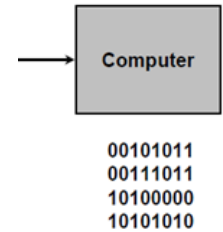
# Stage 3: Analog-to-Digital Converter

- An A/D converter is a system that converts an analog signal into a digital signal. It involves two stages:
  - Sampling: makes the signal discrete in time
  - Quantization: makes the signal discrete in amplitude



# Last stage: Computer

- It manipulates digital signals in order to extract useful information
- It handles the storage, the transmission and the display of collected and processed data

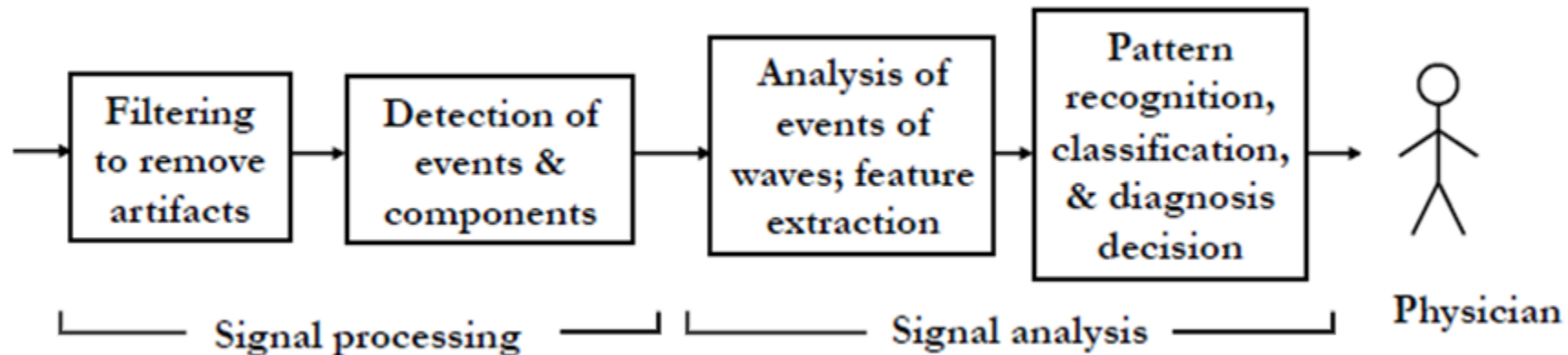


# Elaboration and analysis

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# Signal elaboration system

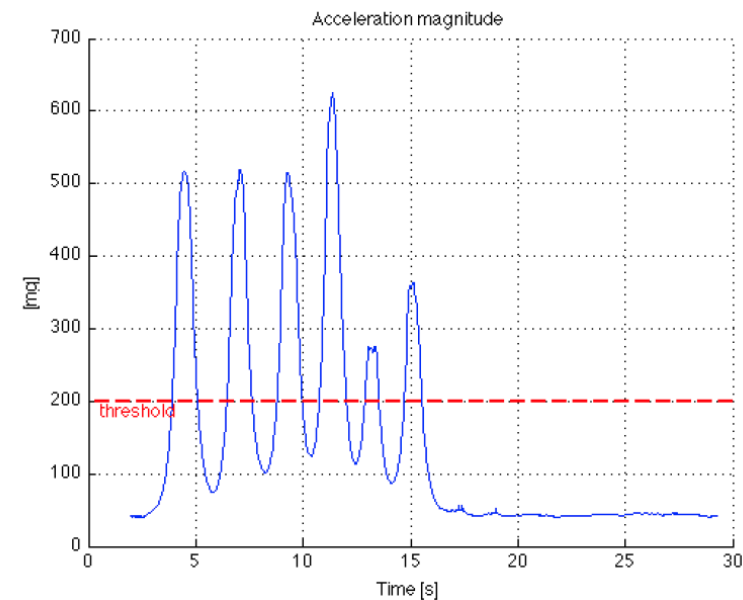
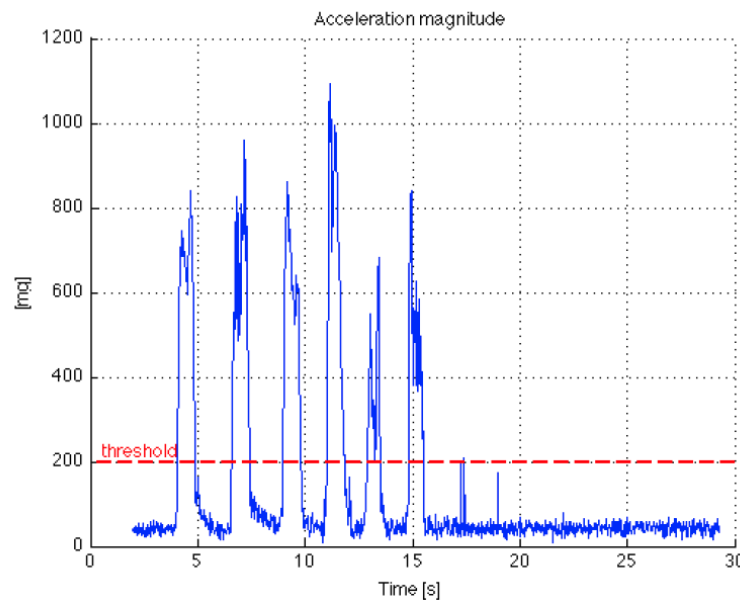
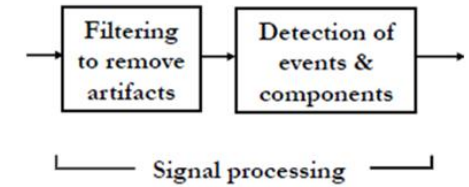
- The elaboration of the signals includes the theory, applications, algorithms and implementation of how to process information contained in signals
- It makes use of different tools:
  - Mathematical and statistical representation
  - Modeling, analysis, extraction and learning methods



# Signal elaboration system

- **Signal processing**

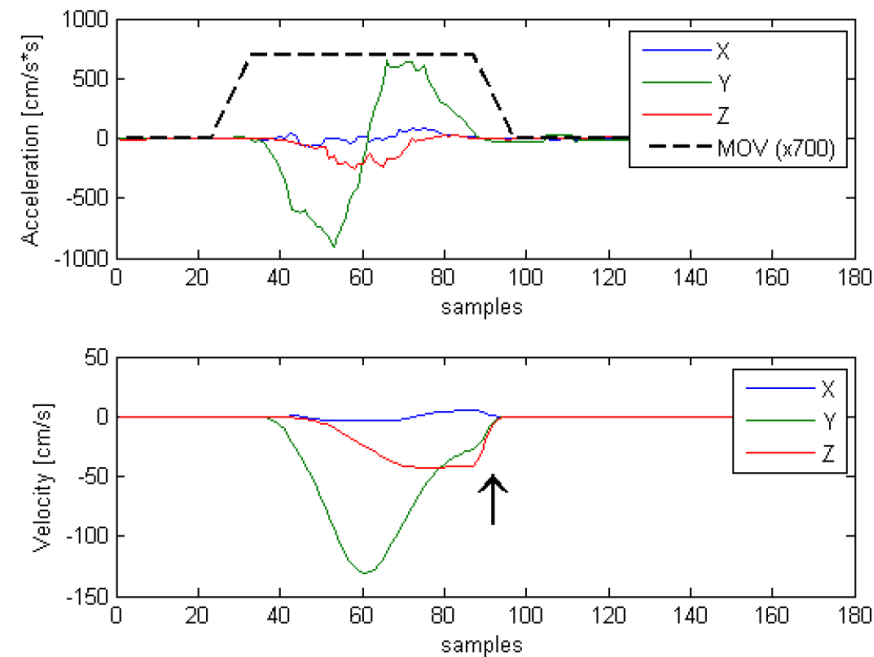
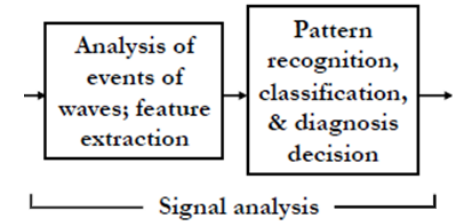
- Raw data filtering to isolate the signal of interest
- Identification of events and components within the signal



# Signal elaboration system

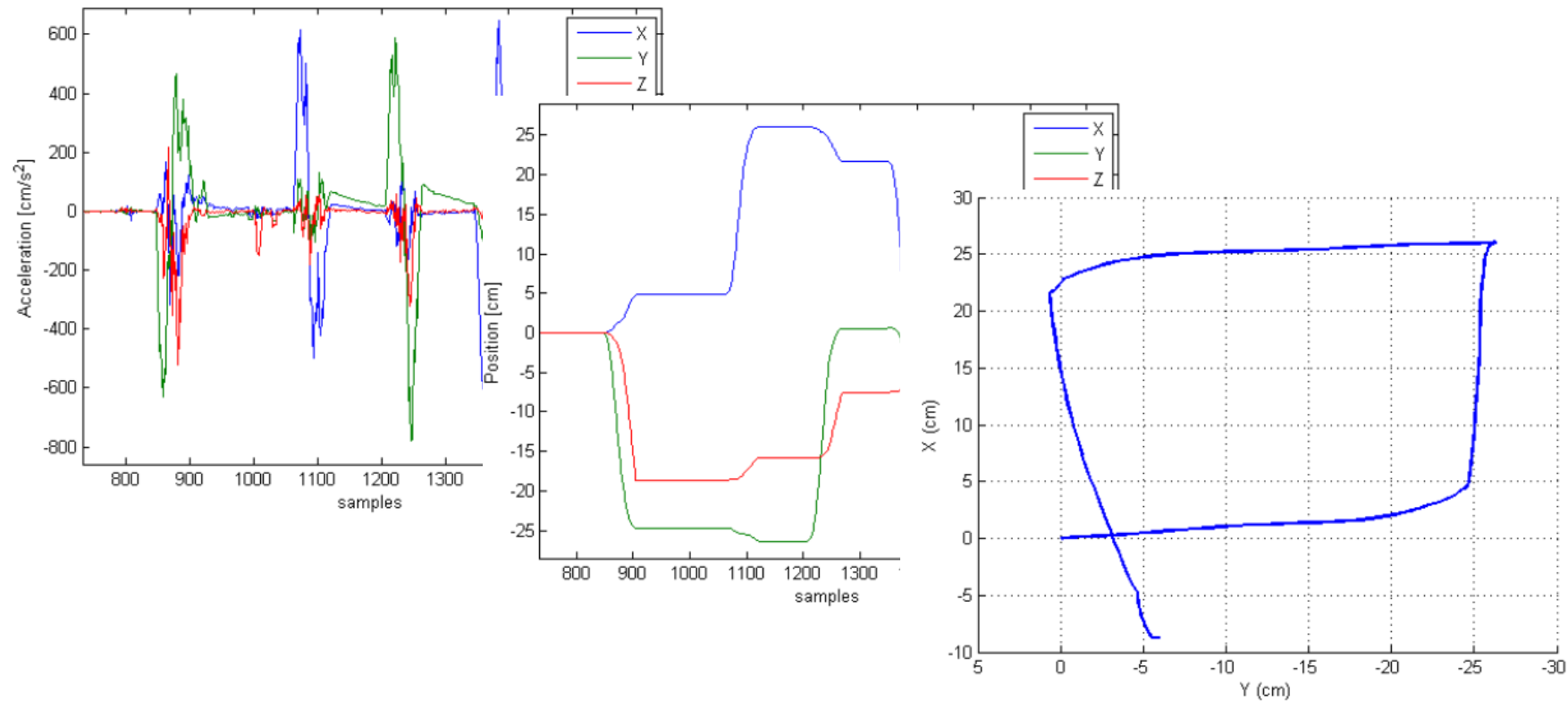
- **Signal analysis**

- Analysis of identified events
- Parameters and features extraction
- Classification and decision



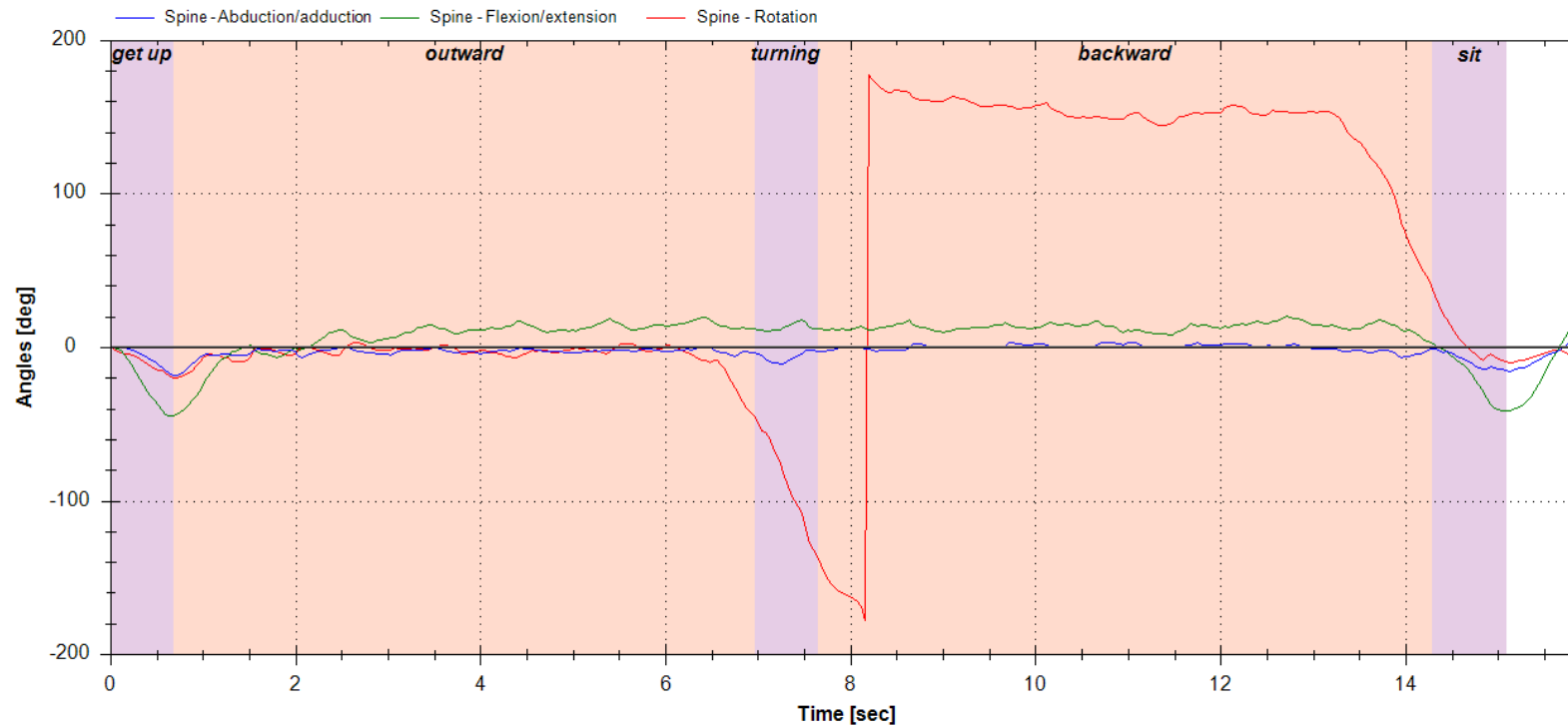
# Example 1

- Obtaining relative position starting from accelerometric data
- *Methods*: filtering, thresholding, integration



## Example 2

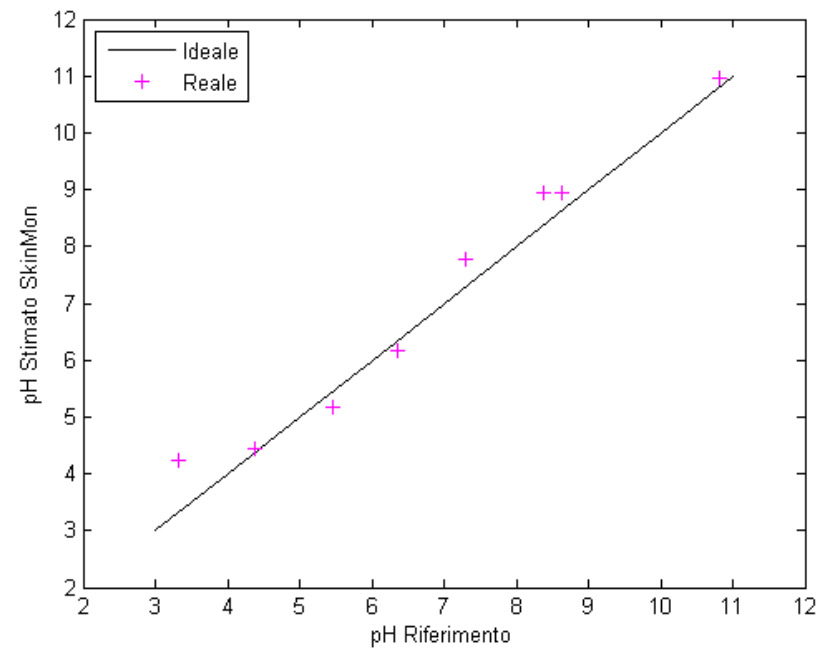
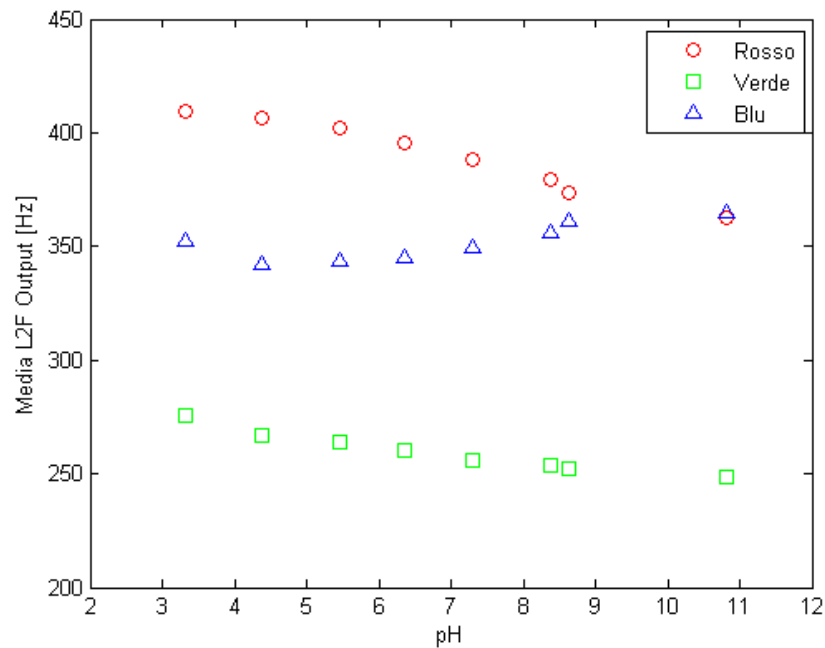
- Identification of the phases of a rehabilitation exercise, starting from the rotation of the subject's chest
- *Methods*: peak detection, thresholding



# Example 3

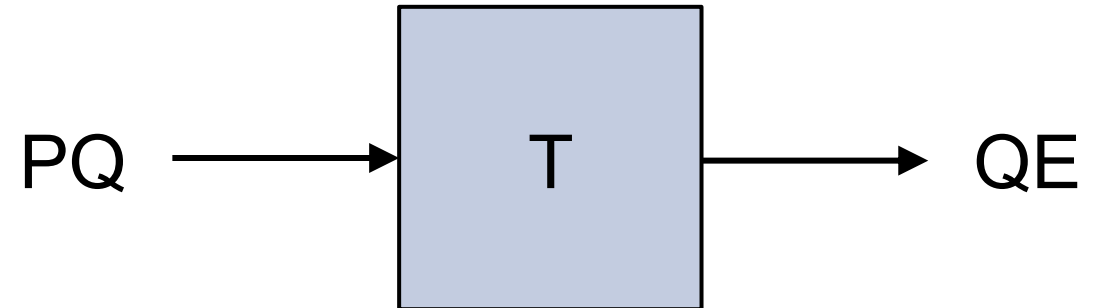
- Sweat pH estimation from light frequencies
- *Methods*: linear regression

$$\text{pH} = c_R \cdot f_R + c_G \cdot f_G + c_B \cdot f_B + c_0$$



# Sensor

- A device which converts a **physical quantity** (PQ) of any nature (temperature, velocity, acceleration, etc.) into:
  - An **electrical quantity** (EQ)
    - Voltage (V)
    - Current (I)
    - Charge (Q)
  - A variation of an **electrical parameter**
    - Resistance (R)
    - Capacitance (C)



# Classification (1/3)

- Based on the **input quantities**

Physical quantity	Transducer	Electrical quantity
Temperature	Thermocouple and thermopile Resistance thermometer (RTD) Thermistor (PTC, NTC) Semiconductor transducer	Voltage Resistance variation Resistance variation Current or voltage
Force and pressure	Strain gauge Piezoelectric transducer	Resistance variation Charge, voltage
Position and displacement	Potentiometer Capacitive transducer Differential transformer Absolute encoder Incremental encoder	Resistance variation Capacitance variation Voltage Digital code Pulse number
Speed	Incremental encoder Tachometer dynamo	Pulse frequency Voltage
Light intensity	Photodiode, phototransistor Photoresistor Photovoltaic cell	Current or voltage Resistance variation Voltage

# Classification (2/3)

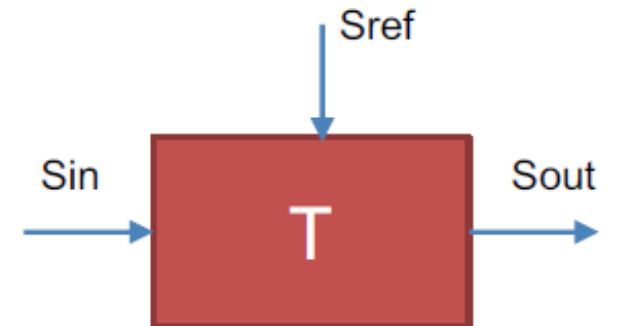
## Active

- They can independently generate a voltage (V), current (I) or charge (Q) signal depending on the input physical quantity



## Passive

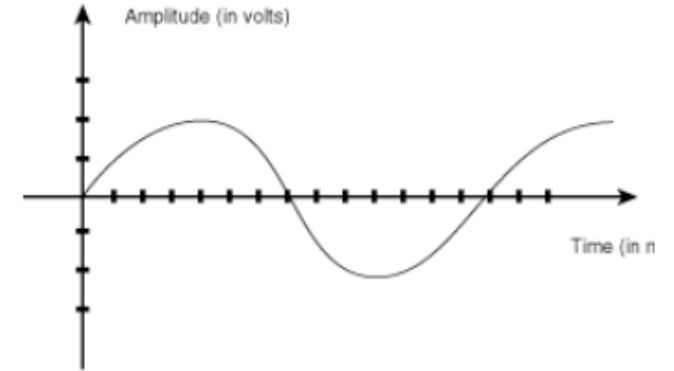
- They require an external power supply
- The variation of the input physical quantity causes the variation of an electrical parameter (R, C)



# Classification (3/3)

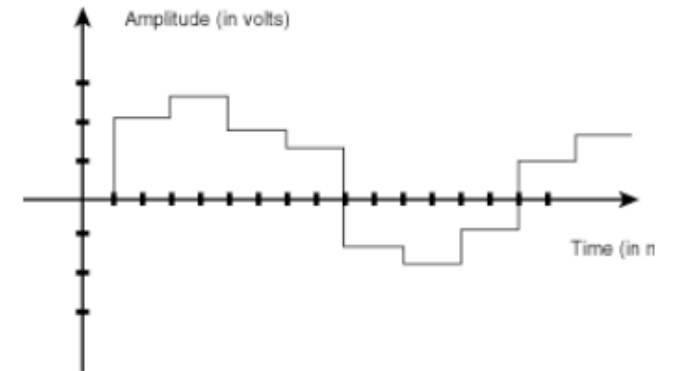
## Analog

- The transducer output signal is analog, i.e. **continuous over time and amplitude**



## Digital

- The transducer output signal is digital, i.e. **discrete over time (sampled) and amplitude (quantized)**



# Main features

## External features

- Small size
- Ease of positioning
- Resistance and durability (even in hostile environment)
- Reusability
- Shielding against external interference

## Internal features

- Precision
- Linearity (ease of calibration)
- Response speed
- Response stability in time
- Sensitivity independent of environmental factors
- Absence of hysteresis
- Ability to withstand an overload

# Features classification

## Static features

- They represent the behavior of the sensor in static conditions, obtained by slowly varying the sensor input variable and recording the corresponding output

## Dynamic features

- They represent the output behavior of the transducer when the input variable varies very quickly; this relates to the bandwidth limits of the control system.

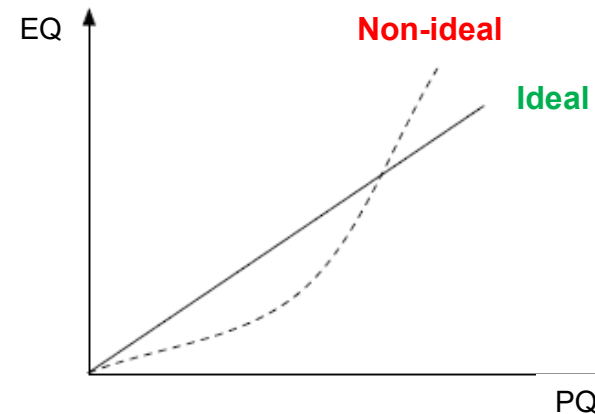
## Other features

- Usually they influence the behavior of a transducer (e.g. reliability, stability, etc.)

# Transfer Function (TF)

- Relationship between the sensor's output electrical quantity to the input physical quantity applied

$$EQ = f(PQ)$$



## Ideal case

- Directly proportional relationship between electrical and physical quantities

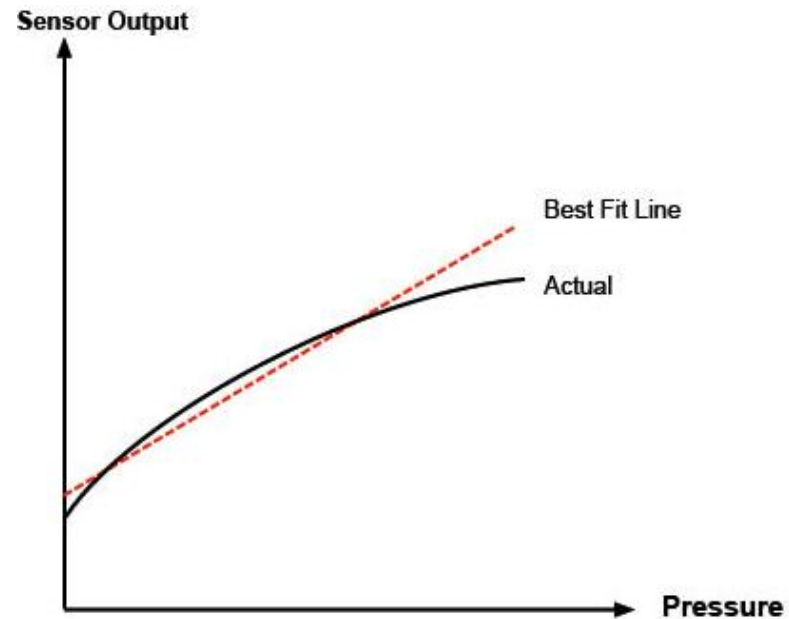
$$EQ = k \cdot PQ$$

## Non-ideal case

- TF can be provided in 3 different ways
  - Mathematical function
  - Table of values
  - Experimental curve

# Linearity

- Indicates how far the calibration curve (or the transfer function) deviates from a linear trend
- Specified by providing the maximum deviation of calibration curve points from a reference line



# Sensitivity

- The change of the output electrical quantity divided by the change of the input physical quantity

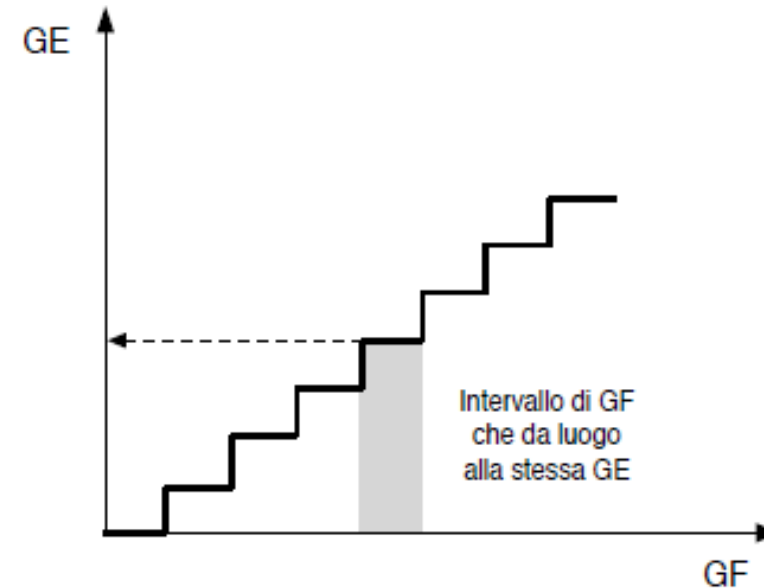
$$S = \frac{\Delta EQ}{\Delta PQ}$$

- **Linear** TF: the sensitivity is constant  $S = k$
- **Non-linear** TF: the sensitivity is not constant, but it depends on the point of the TF at which the sensor is working
  - Some intervals will be characterized by a greater/smaller sensitivity
- The measurement unit depends on the output's and input's ones
  - E.g. a pressure sensor which outputs a voltage has a sensitivity expressed in [V/bar]

**NB: the sensitivity represents the **gain** of the sensor!**

# Resolution

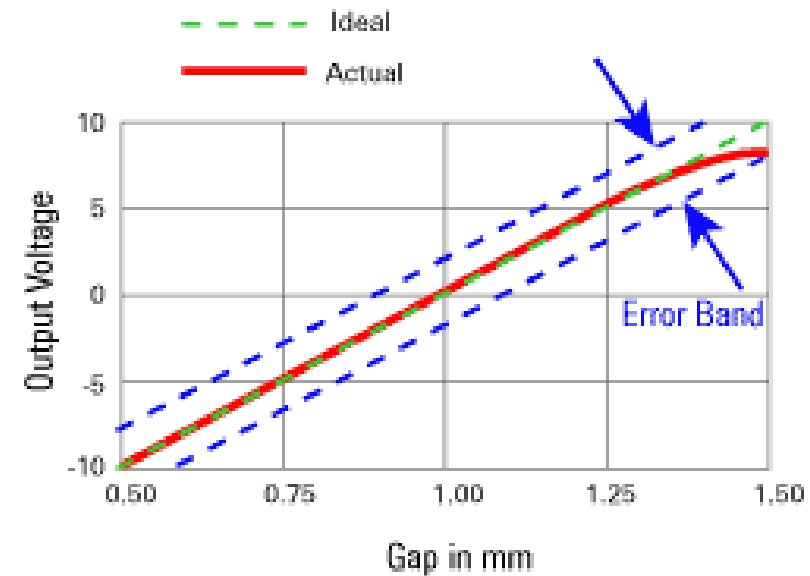
- The smallest variation of the measured physical quantity which causes a change of the output quantity
- The measurement unit is the same of the input's one
- If multiple values of the input physical quantity are associated to a same output value, then the resolution is said to be **finite**



# Calibration uncertainty (error)

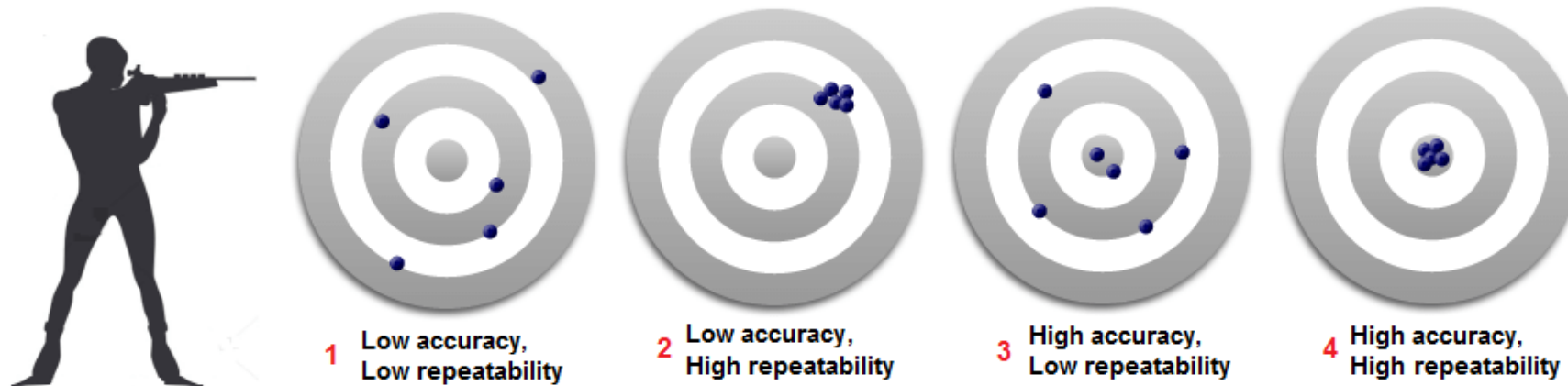
- Difference between the true value of a physical quantity and the measured one
- Typically provided in the form of *absolute* or *relative* error
- **Error band:** includes all the possible causes of error

- The static characteristic, which should be a line, is replaced by a range of values (band)
- Within this band, the correct value is found, but it is no longer uniquely determined



# Repeatability, accuracy, stability

- **Repeatability:** aptitude of the sensor to output values slightly different from one another when the same input is applied several times consecutively
- **Accuracy:** the measuring error, that is, the difference between the output and the input (when they have the same measurement unit)



# Sensors Type

## Motion sensors

- Inertial sensors (e.g. accelerometers, gyroscopes)
- Magnetic sensors
- Piezo-resistive sensors

## Environmental sensors

- Temperature
- Humidity
- Ambient pressure

## Physiological sensors

- Biopotentials
- Bio-impedance
- Blood pressure sensors
- Muscle stimulators
- Drug release systems
- Pacemaker

## Air quality sensors

- Dust sensor (dust, pollen, germs)
- Oxocarbon sensors (CO, CO<sub>2</sub>)
- Volatile Organic Compounds (VOC) sensors

# MEMS actuators: comb drives

- Also known as **drive capacitors**
- A couple made up of the left side of one finger and the right side of the next one form a capacitor, where the air acts as the insulant layer
- The upper and lower sides of the fingers form capacitors too

$$F_{el} = \frac{1}{2} \epsilon_0 A \cdot \frac{V^2}{d^2}$$

- Transverse actuators (a)
  - The mobile mass moves along the x axis
- Longitudinal actuators (b)
  - The mobile mass moves along the y axis

