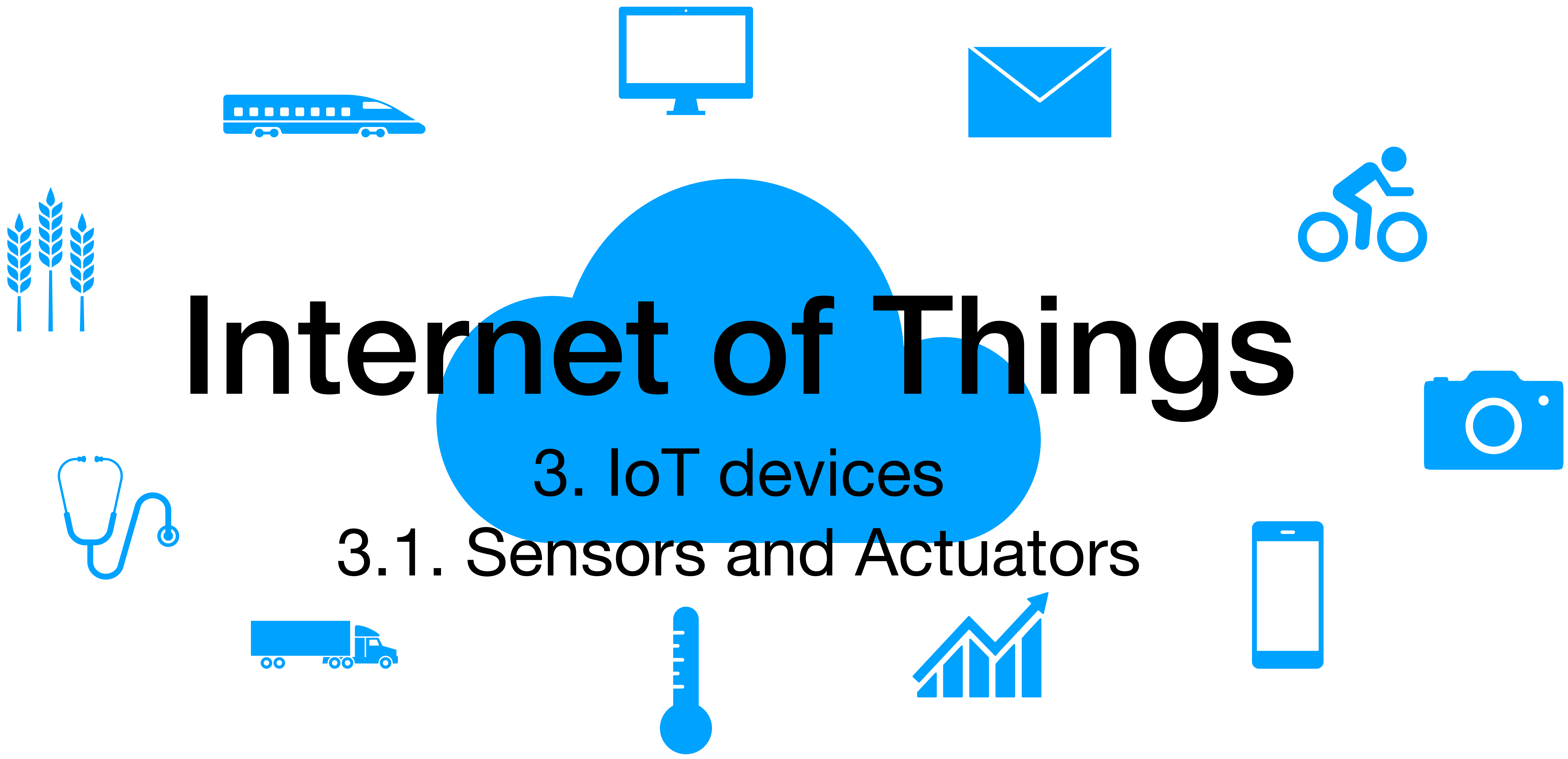


Internet of Things

3. IoT devices

3.1. Sensors and Actuators

M.Sc. Computer Science 2024-2025

Viviana Arrigoni

3.1.1. Basic Concepts

- The **force F** is physical quantity that can cause an object to change its velocity, causing a variation in its state of rest or in its state of motion.

  - It is measured in **Newtons** (**N**), where $\mathrm{N} = \dfrac{\mathrm{kg} \cdot \mathrm{m}}{\mathrm{s}^2}$ (recall the second Newton's law).

- The **energy e** is the ability to do work, i.e., the ability to exert a force causing displacement of an object.

  - It is measured in **Joule** (**J**), **kW h**, **calories**, etc.
    - A joule corresponds to the amount of work done when a force of one newton displaces a body through a distance of one metre in the direction of the force.
    - A kW h is the energy delivered by one kilowatt of power for one hour

- The **power P** is the amount of energy transferred to or converted per unit of time.

  - It is measured in **Watt** (**W**), that is equal to one joule per second.

- The **electric potential** is the amount of energy needed to move one unit of electrical charge from one point to another in an electrical field, or, analogously, it is the difference in potential energy per unit charge between two locations in an electric field.
  - It is measured in **Volts** (**V**) (analogy: pressure with which we pump water in a pump).
- The **electric current *I*** is a flow of charged particles (electrons) moving through an electrical conductor or space.
  - The intensity go the electric current is measured in **Ampere** (**A**), that is the rate of electron flow (current), i.e., how many charge carriers (electrons) move past a specific point in one second.
  - Batteries store energy through an electrochemical process, expressed in Ah.

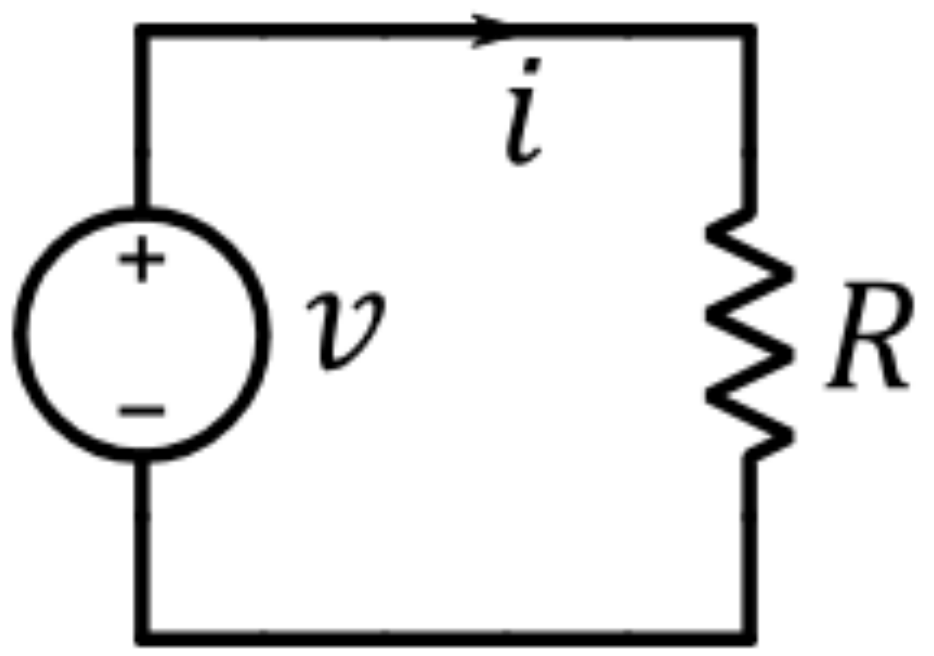
- Relation: J = V x A x s

- The **electrical resistance** of an object is a measure of its opposition to the flow of electrical current.

  - Measured in **Ohms** (**Ω**)

  - The resistance R of an object is defined as the ratio of voltage V across it to current I through it:

$$R = \frac{V}{I}$$



3.1.2 Sensors

Sensors

- Sensors detect (sense) changes in the ambient condition or in the state of another device or a system, and forward this information.

- Ideally, sensors should be sensitive only to the measured property and should not influence the environment they live in.

- Sensors come with different purposes, cost and **resolution**.

  - The resolution of a sensor is the smallest change it can detect in the quantity it is measuring. High resolution sensor provide more fine grained and precise measurements.

- Sensors are **transducers**, i.e., devices that converts variations in one physical quantity (e.g., pressure, brightness) into variations in another physical quantity (e.g., voltage, position).
  - Essentially, they convert physical signals into electrical signals.

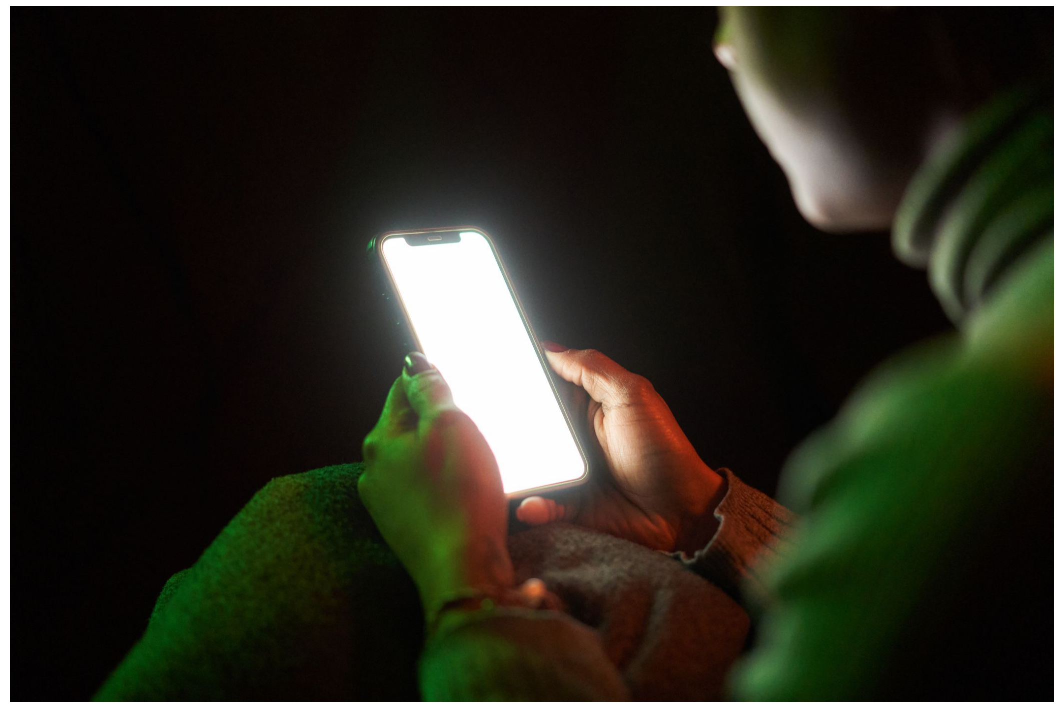
Colour Sensors

- Colour sensors can measure range of visible light.
- It is similar to a one pixel camera that pointed on something says what colour that is.

Medical test strip reading

Agriculture

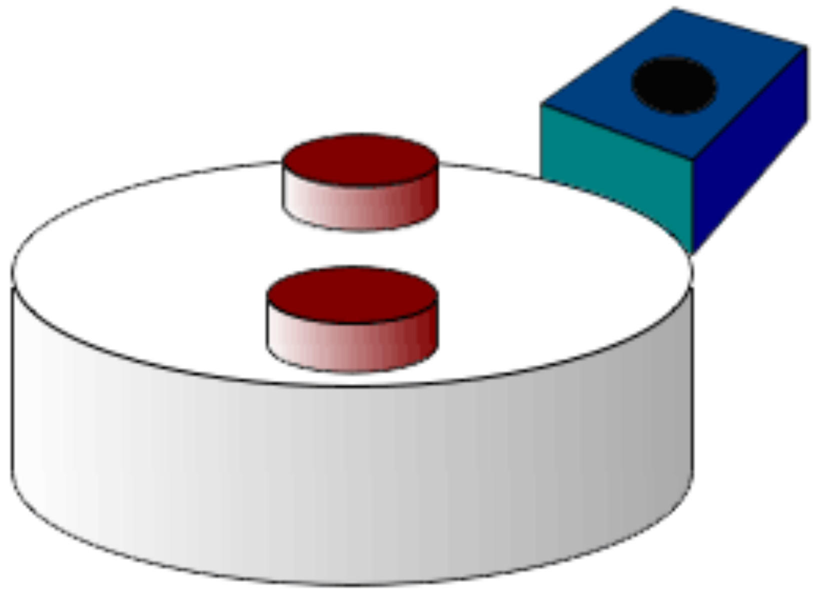
Ambient light sensing



Hall Effect Sensors

- Hall effect Sensors can sense the differences in electromagnetic fields and perceive the proximity to objects.

- The circuit inside the sensor is able to measure the changing voltage when the device is placed in a magnetic field.



Robots

Speed detector

Current sensor

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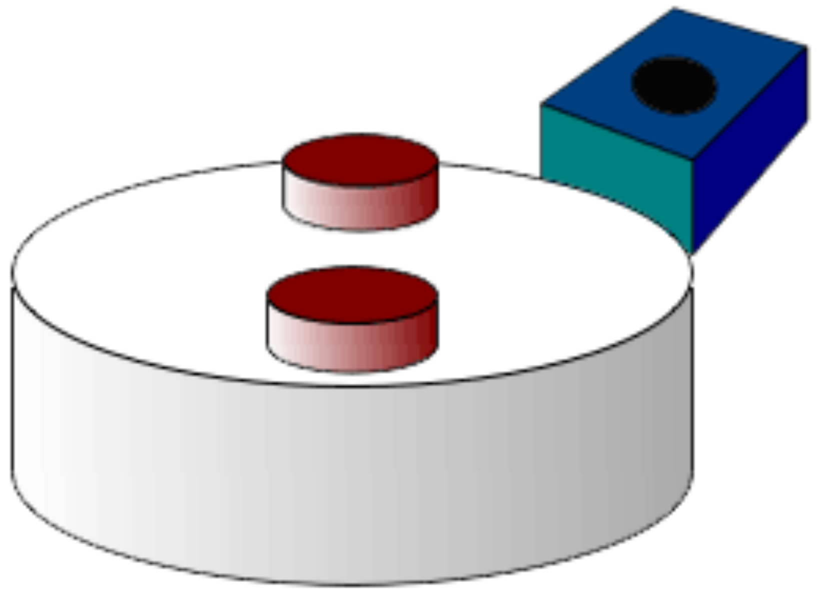


Robots

Speed detector

Current sensor

Microphones

- Microphones convert sound into electrical signals
- Applications:
  - Audio recording
  - Speech recognition
  - Detect wake phrases
  - Echolocation

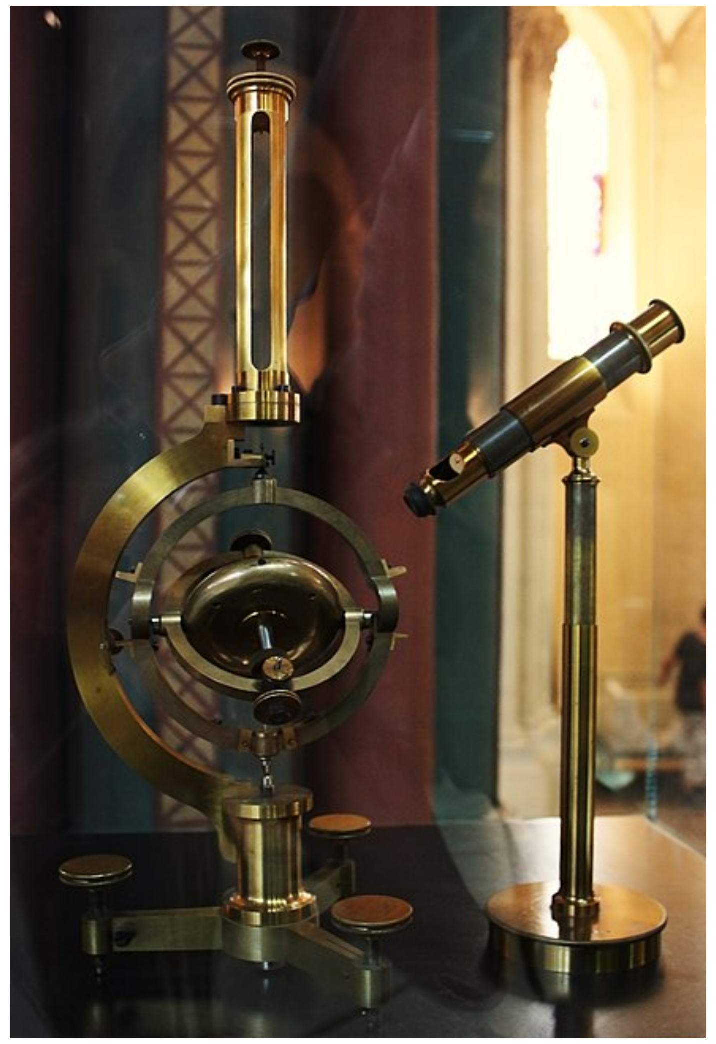
Accelerometers

- Accelerometers measure the physical acceleration experienced by an object.
- It has a damped proof mass on a spring. When the accelerometer experiences an acceleration, the spring is compressed (Newton's third law). The amount of compression of the spring is a measure of the force (acceleration) applied to the object.
- Applications:
  - Human mobility and health monitoring
  - Fall/drop detection

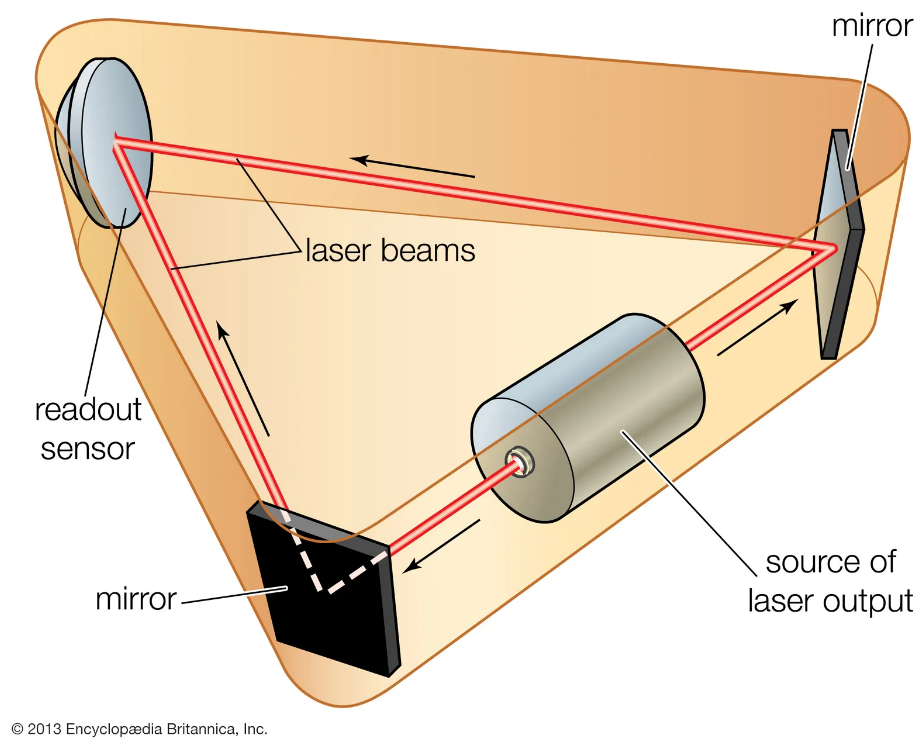
Gyroscopes

- Gyroscopes are devices that contain a rapidly spinning wheel or circulating beam of light and are used to detect the orientation of an object.
- Often paired with accelerometers for motion sensing and in game controllers
- Used for accurate navigation in submarines, aircrafts, missiles, spaceships.

Foucault, 1852



Optical gyroscope



Gas Sensors

- Gas sensors detect specific gases and measure the presence and concentration of gases in the air surrounding the sensor.

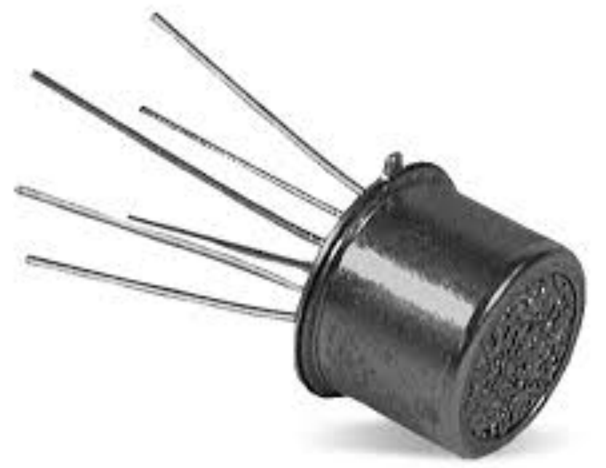
- Gases interact with an electrochemical electrode, producing an electrochemical reaction that converts the chemical change on the electrode into an electrical signal.

- Can detect carbon monoxide, methane, alcohol.

Passive Infrared Sensors

- Infrared Sensors convert infrared signals into electrical signals, allowing to detect presence of objects emitting infrared signals in the dark (for example, humans).
- Used for :
  - motion detection and entry alarm.
  - Remote control communication.
  - Maze navigation in robotic devices.

Humidity Sensors



- Humidity sensors sense the level of humidity and moist around them.
- Contain two electrical conductors and a non-conductive material with a film between them. Moisture assembles on the film and created voltage different between the two conductive plates.
- Used for moist sensing (e.g., agricultural purposes), microclimate monitoring.

Flow Sensors and Anemometers

- Flow sensors measure flow rates of gas and fluids flowing in a pipe.
    - Used in industrial systems, farming, water/gas meters, green building resource usage.
- Anemometers measure flow rate of a gas in plain air, e.g. wind speed.
    - Used for climate monitoring and measurements, architecture.

Touch Sensors

- Touch sensors can detect and record physical touch.

- Being mainly composed of water, the human body is a good conductor. Touch sensors sense the voltage difference caused by our touch.

- They do not only work for humans, but for anything that is conductive.

- Used in touchscreens, fingerprint-based authentication.

Photoresistors

- Photoresistors measure the intensity of light.
- Useful in smart homes to dim down the lights when it is becoming dark

Load cells

- Load cells are devices able to measure force/weight applied to them.

- They have a metal body bonded to a foil strain gauge.
  When stress is applied to a stationary object, the resulting deformation or displacement of its material causes strain that is captured by the strain gauge.

- Used for scales, presence arrival/detection (automatic door opening systems), impact measurements.

Temperature sensors

- Temperature sensors measure the temperature surrounding them.

- Used for smart homes (turn on/off heater if temperature is too low/high), health, circuit temperature, agriculture.

Cameras

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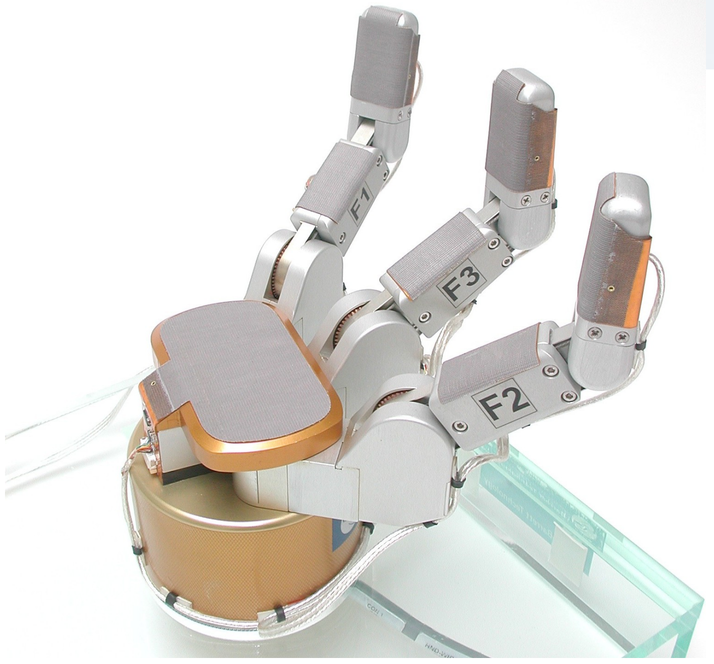
Emerging sensors

- Electronic noses measure chemical concentrations in scents/ smells. Used in human health (early disease detection), security (explosive, drugs).

- Tactile Sensors can determine texture, stiffness, coefficient of friction, thermal conductivity. Used in robotics and object recognition.



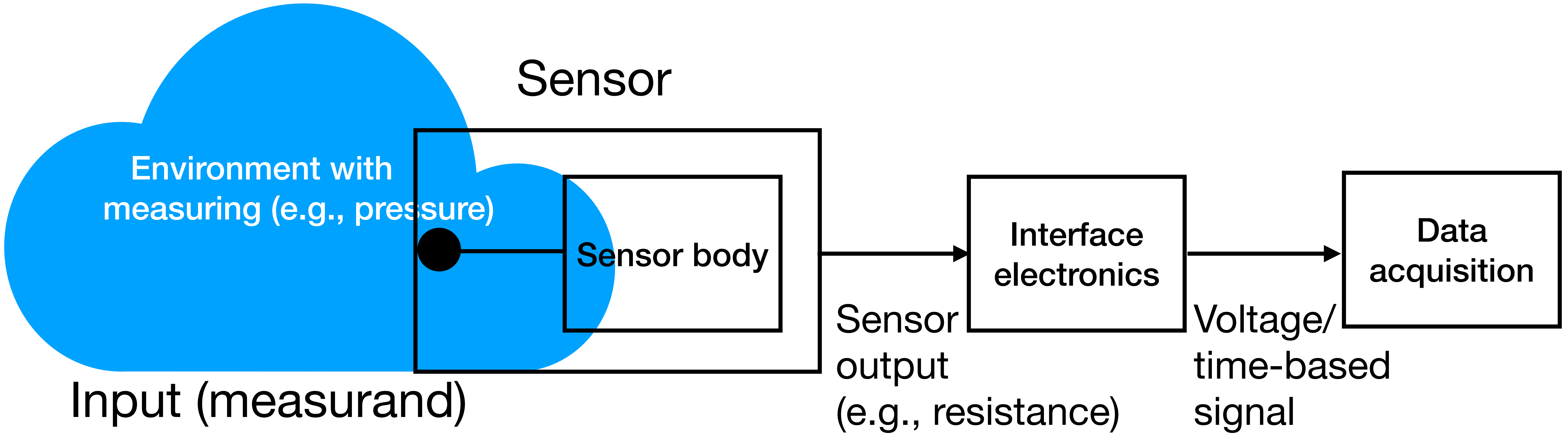
- Blood gas/sugar sensors measure composition of blood, including amount of arterial gases (egoxygen, carbon dioxide), pH, sugar, etc.

- Brainwave sensors measure electrical activity of brain. Can pinpoint activity to 3D location inside the brain.

CeTI
Centre for Tactile Internet
with Human-in-the-Loop

Generic sensing application

- In IoT systems, sensors are used for measuring certain quantities in an environments. The measurement will correspond to a certain action.



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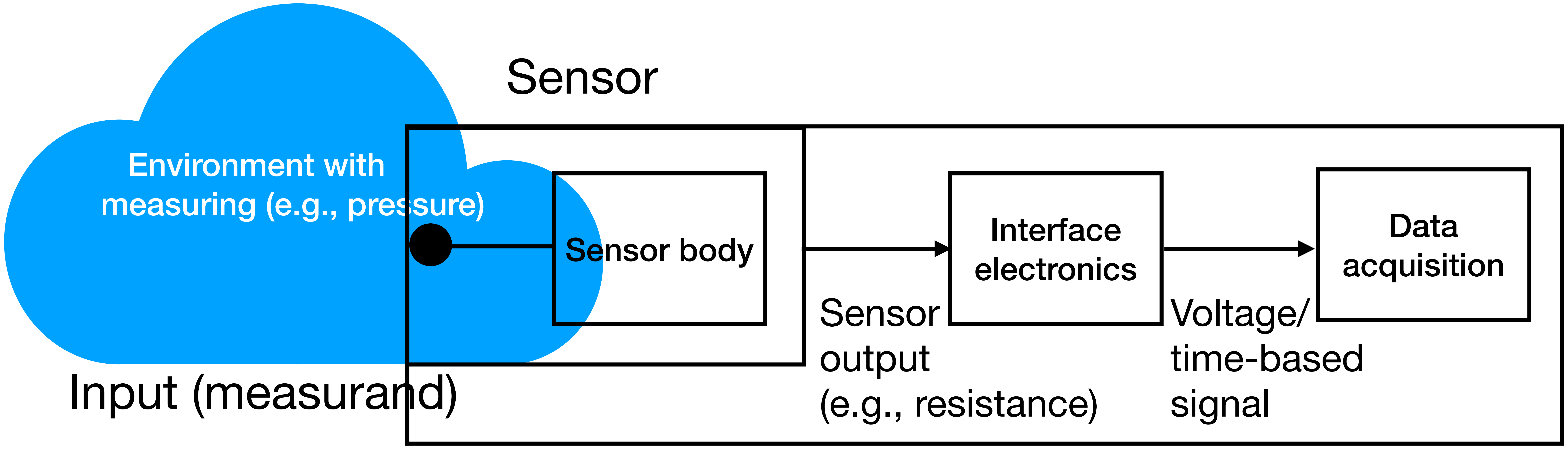
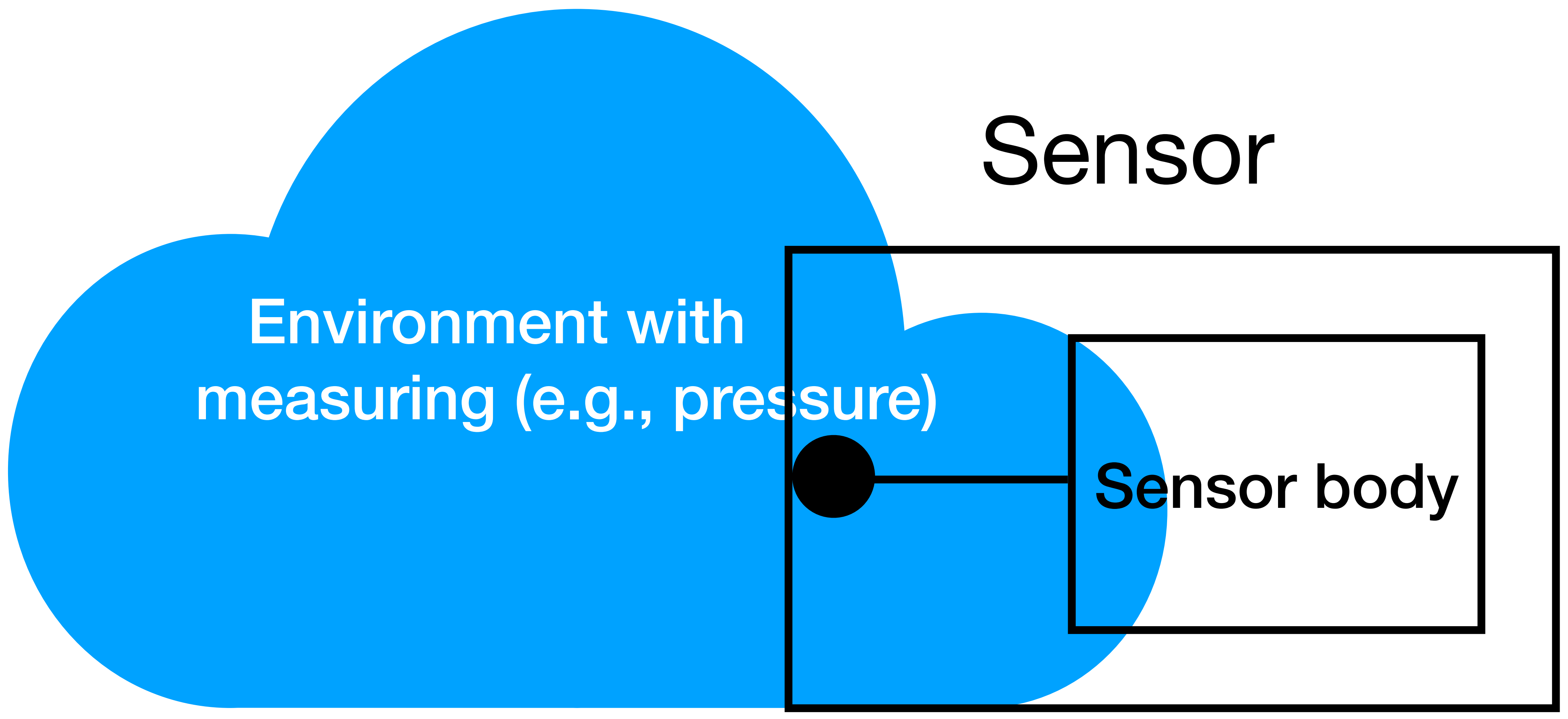
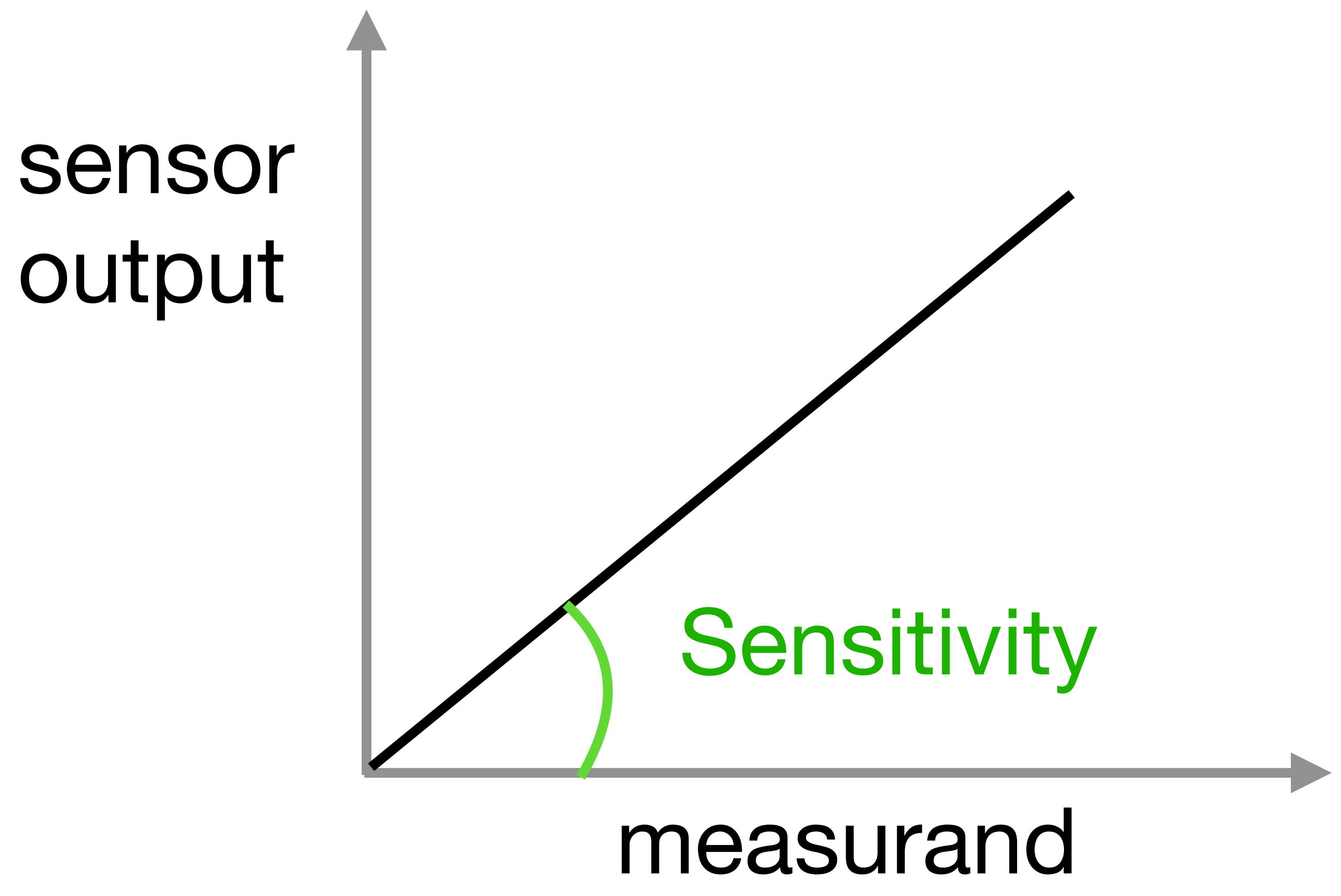


Ideal Sensor

- In an ideal sensor, we expect to have a simple relationship between our input and our output, e.g., a linear relation that is easy to interpret.





- High accuracy (no noise or drift, stable in time)
- Sensitivity only to input of interest (if interested in measuring pressure, we do not want the measurements to be influenced by other conditions e.g. temperature, humidity etc)

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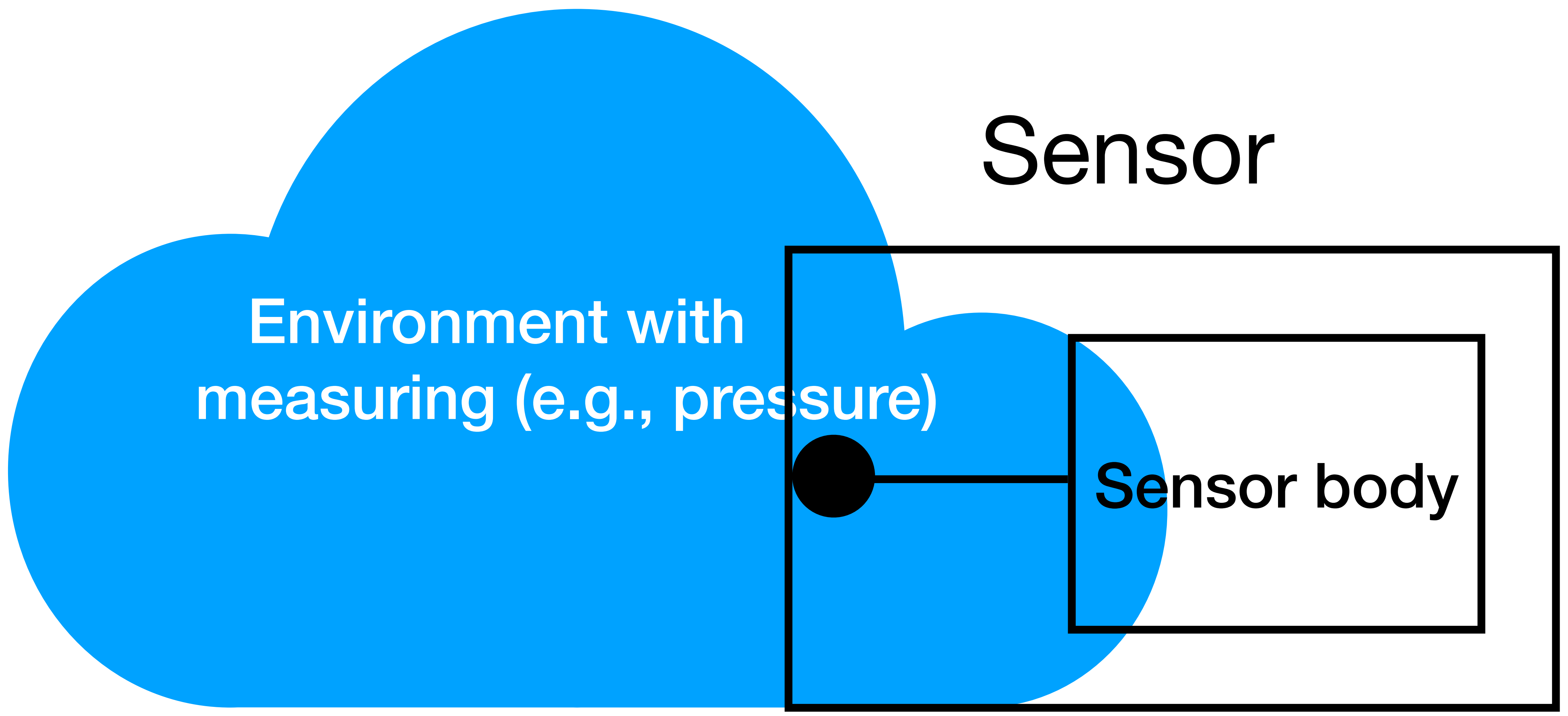

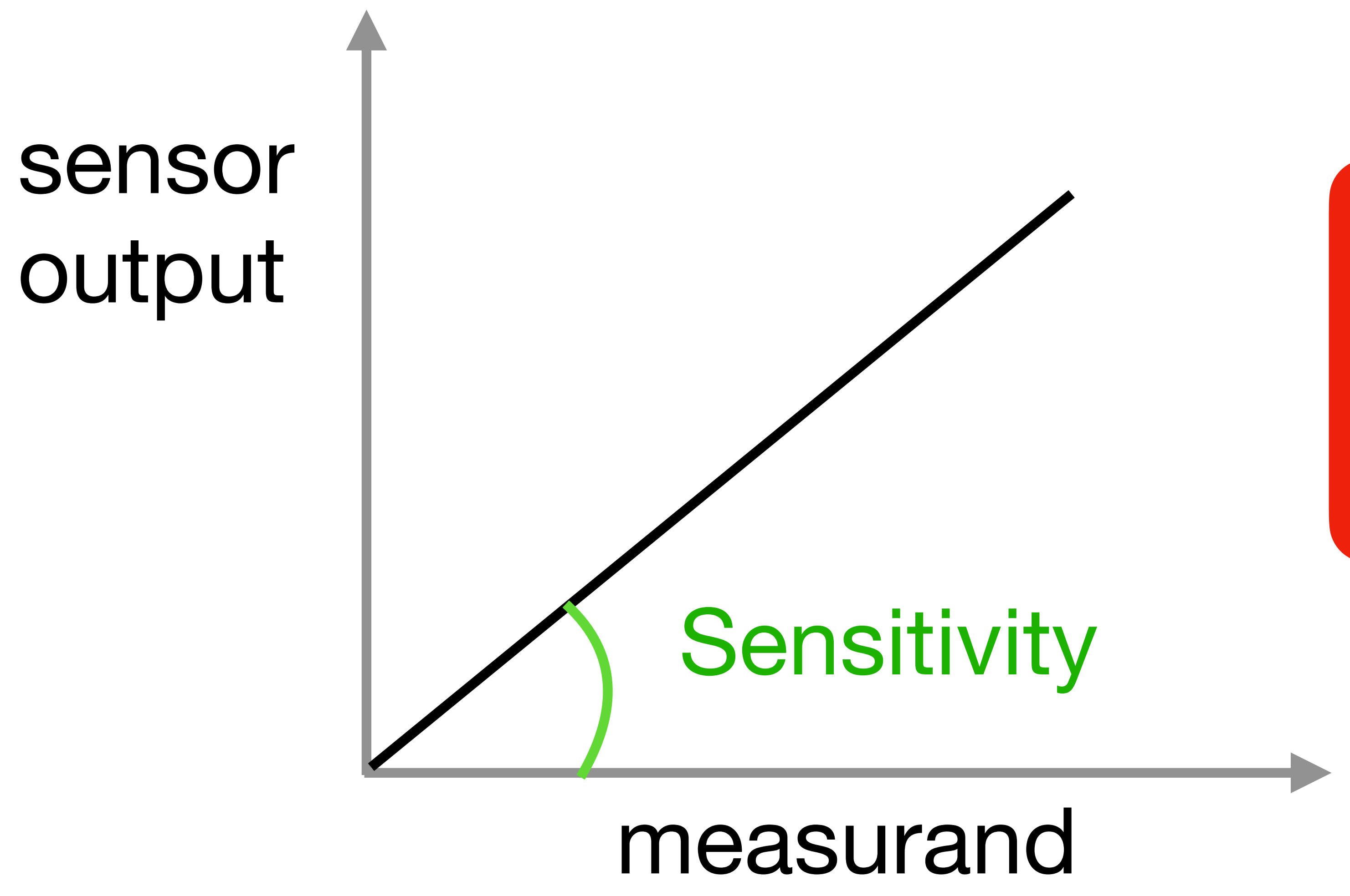

No ideal sensor exists tho

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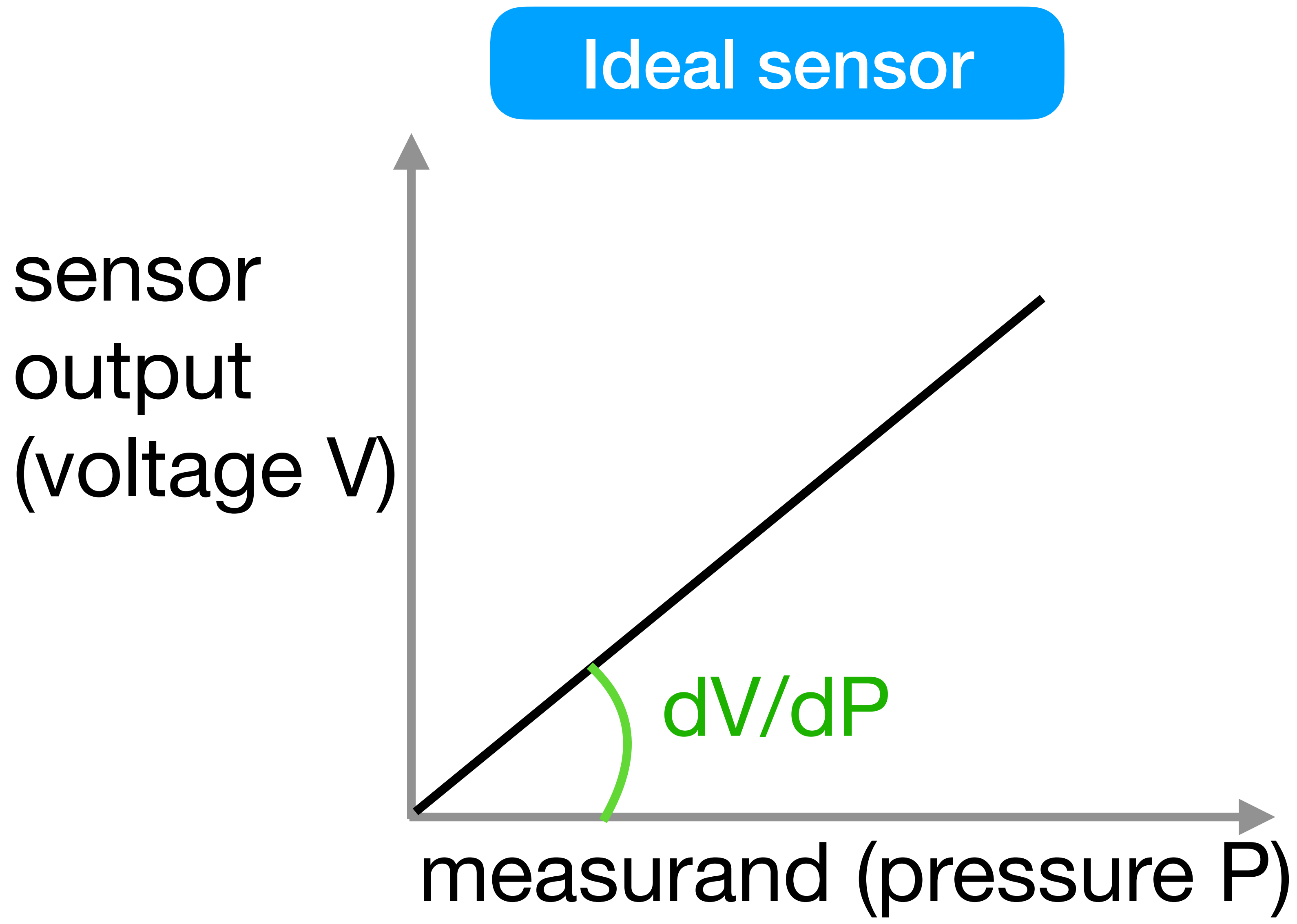
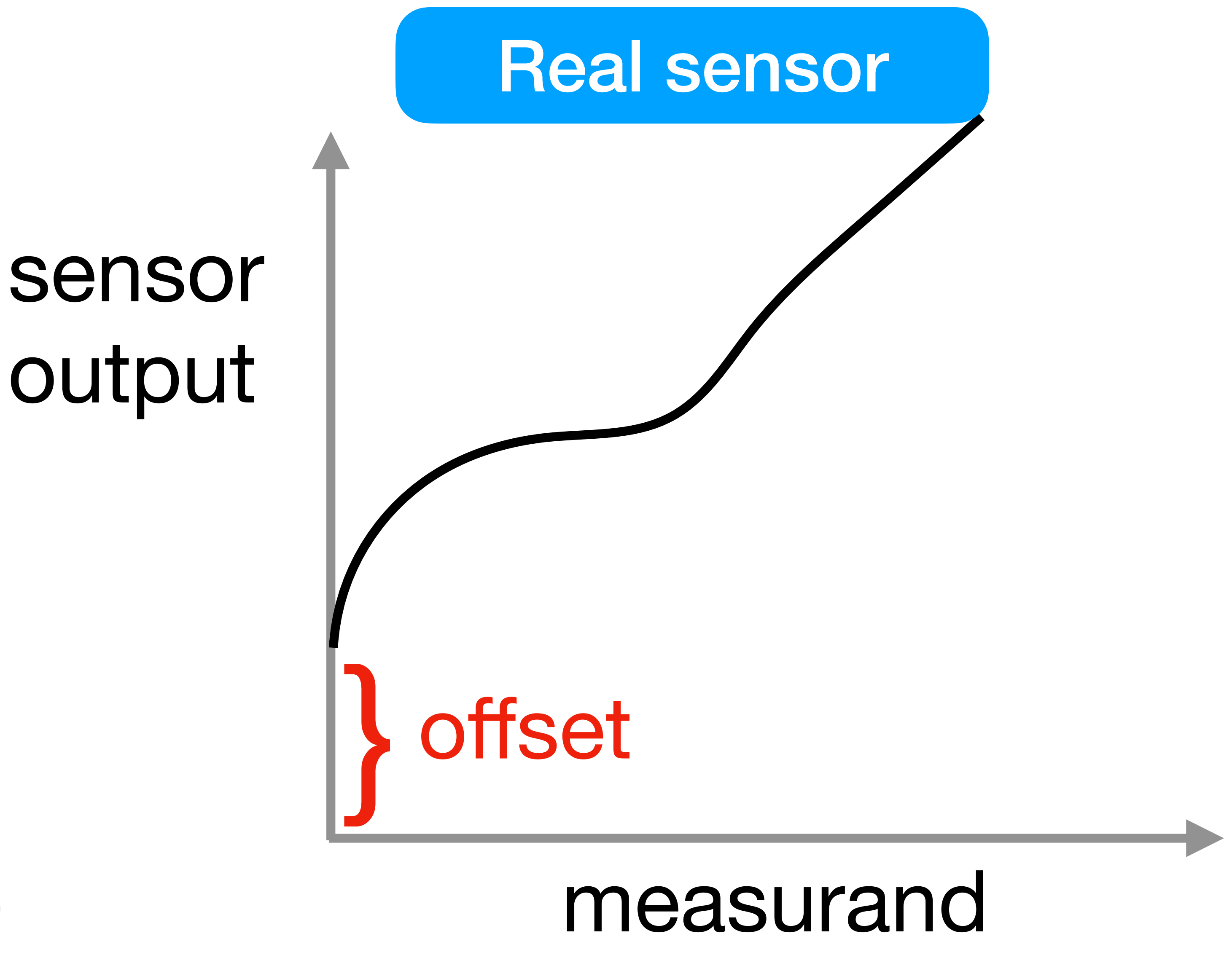
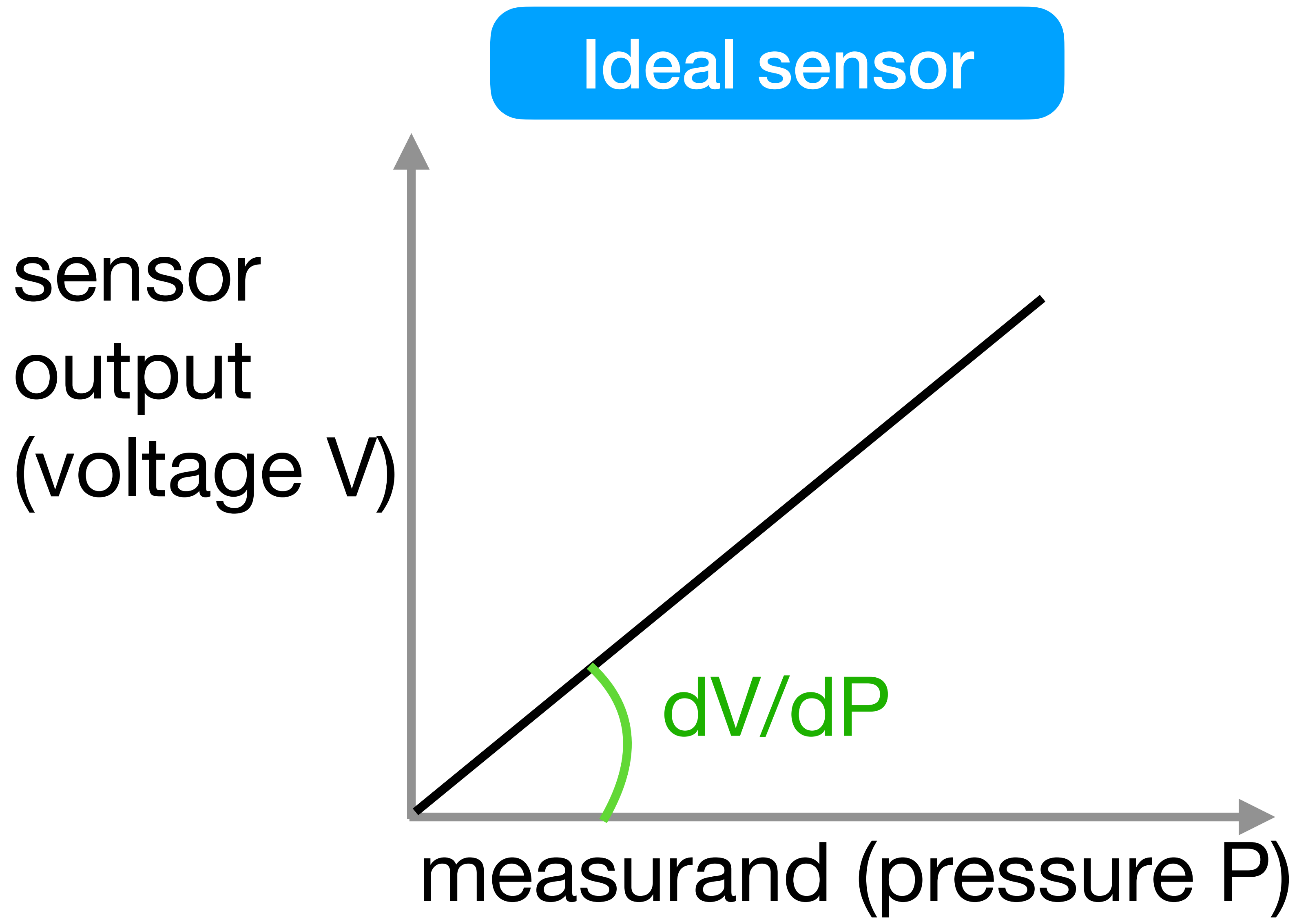
Sensitivity

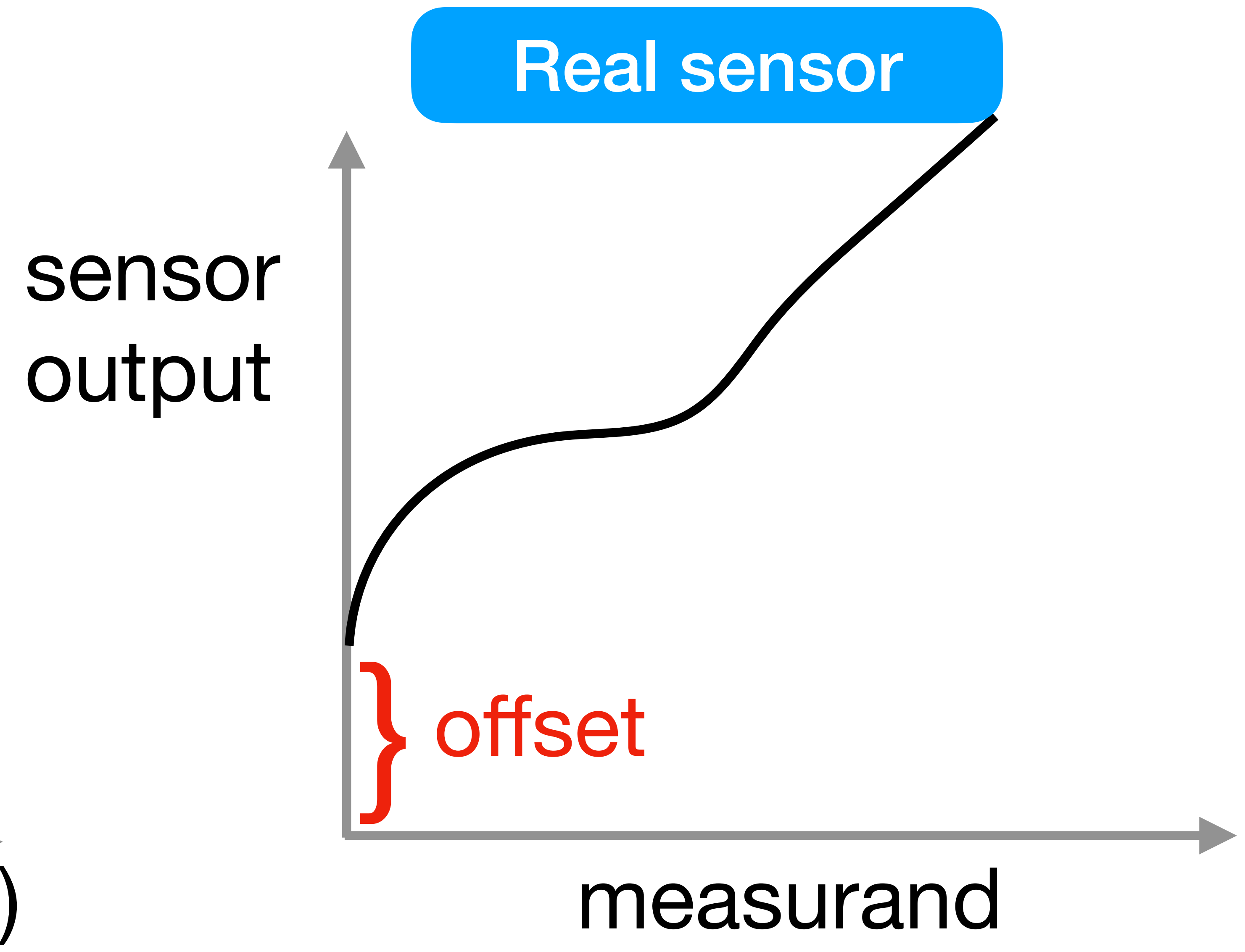




- Vendors provide **specs** that describe how the device behaves.

Sensitivity





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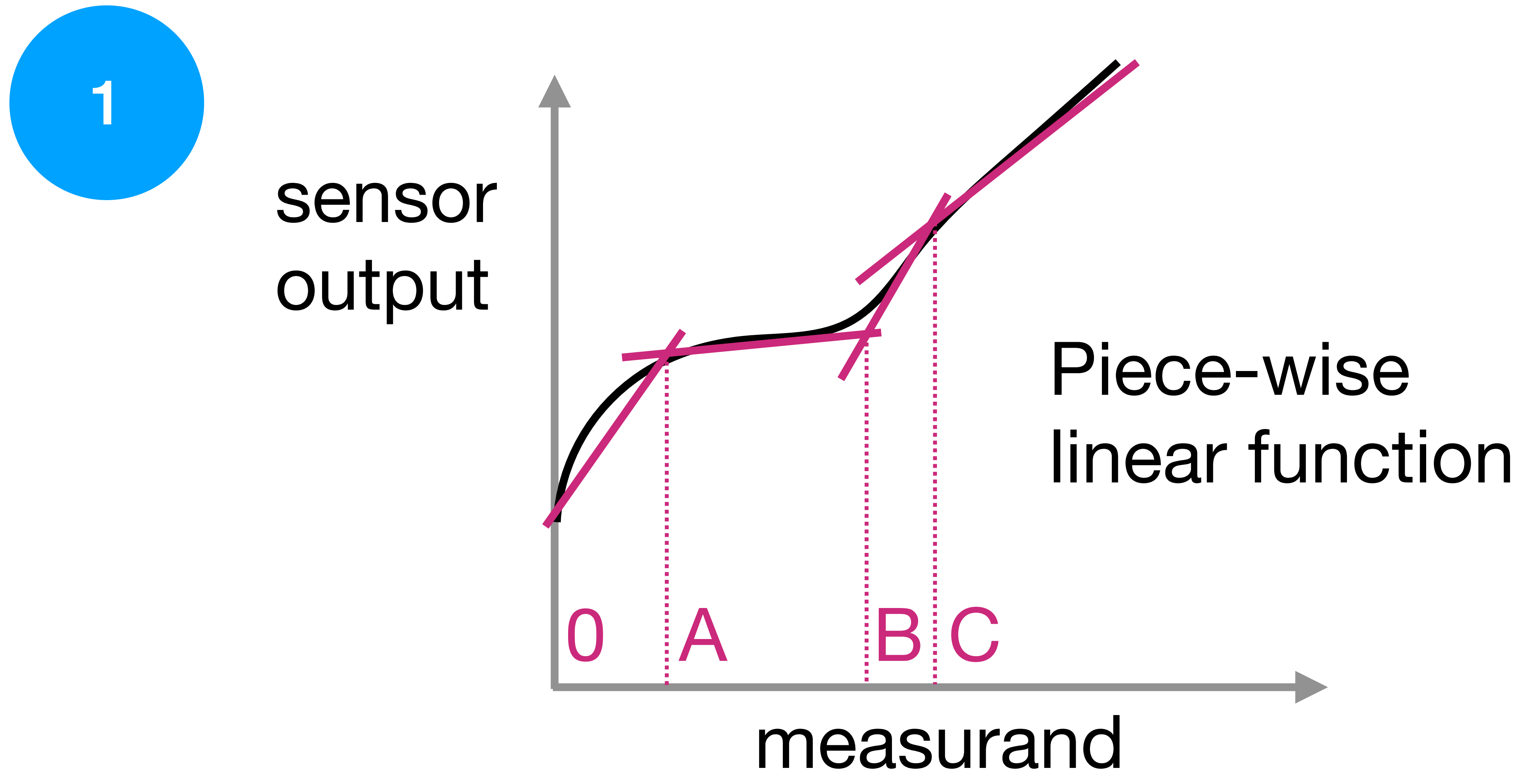

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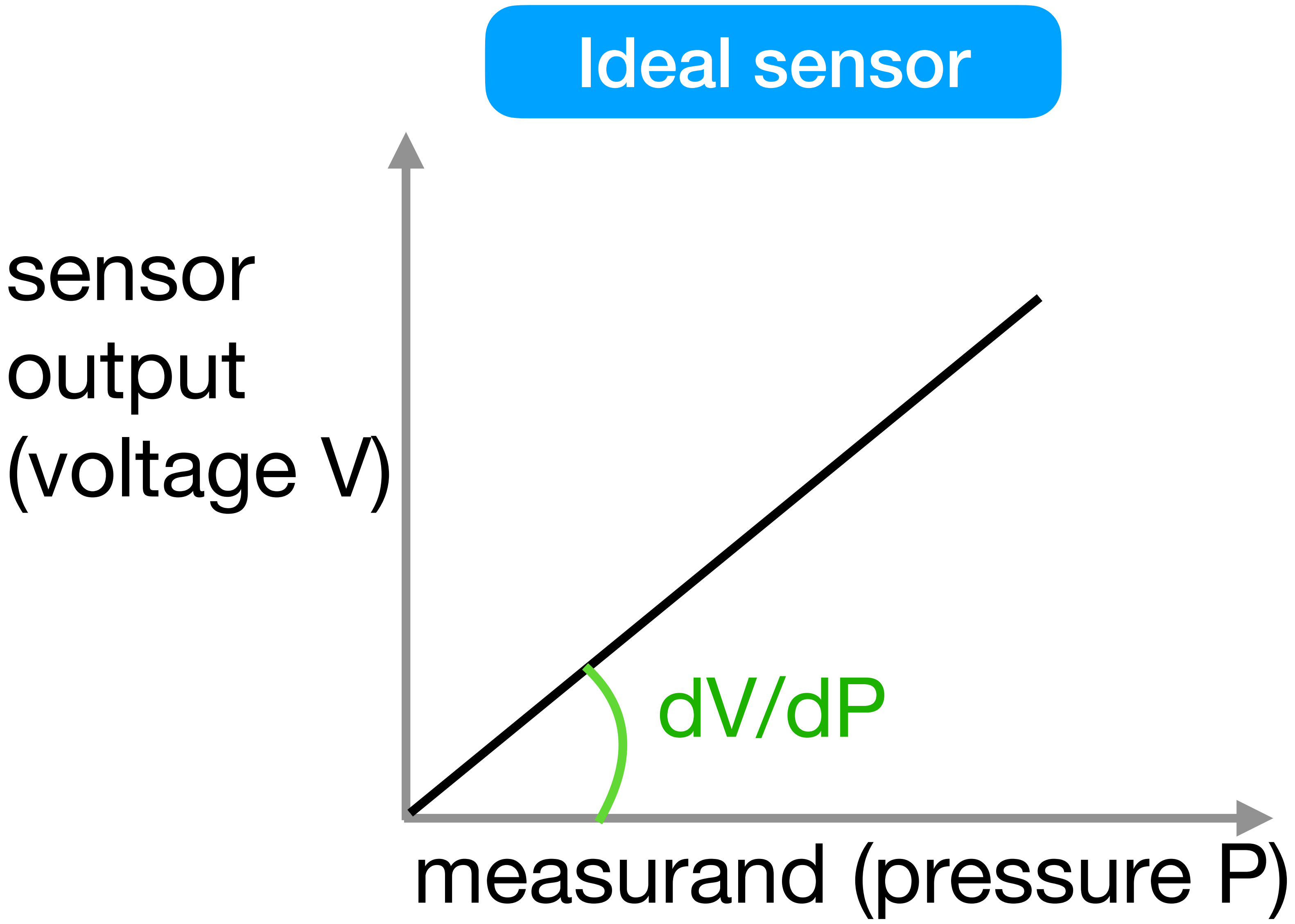

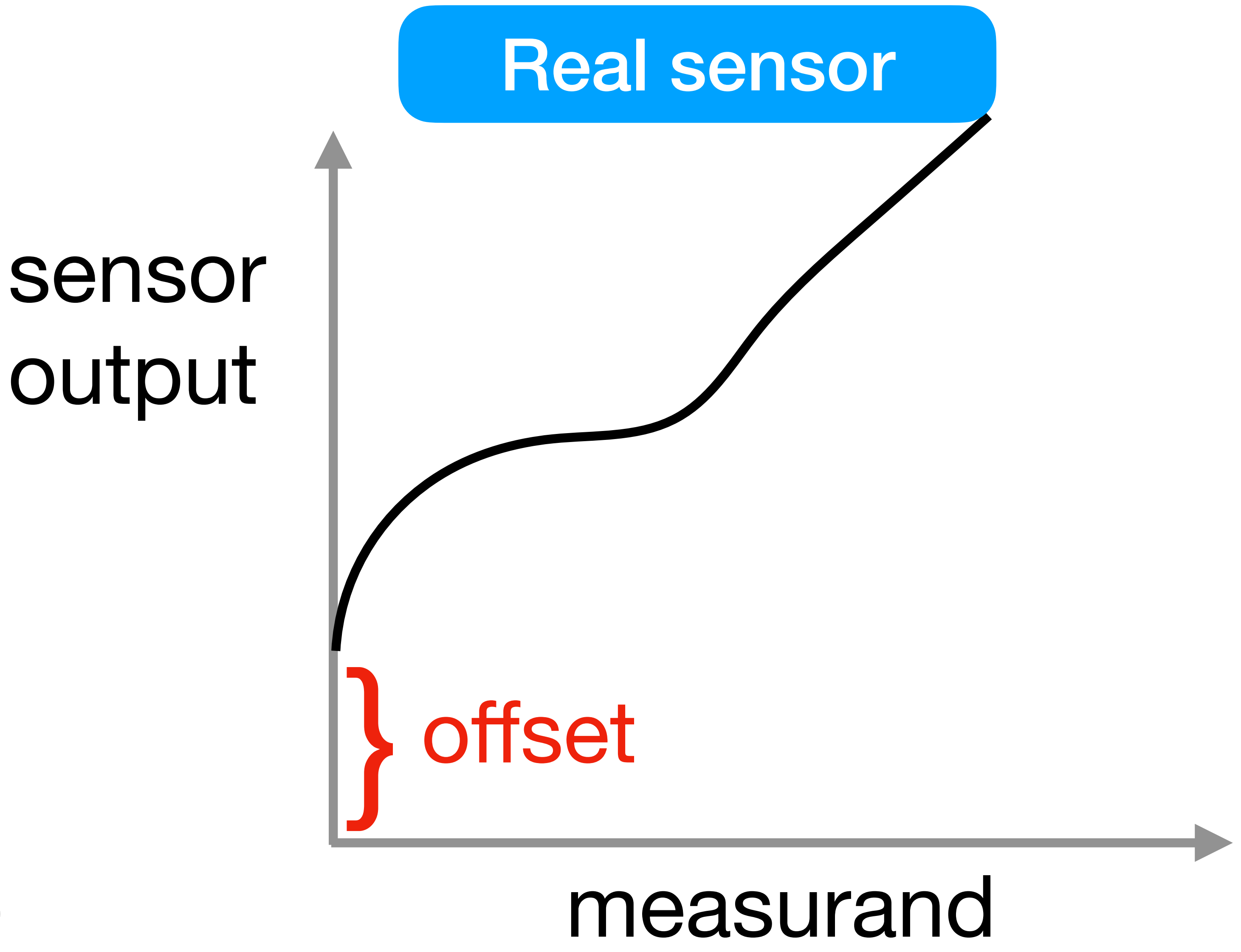

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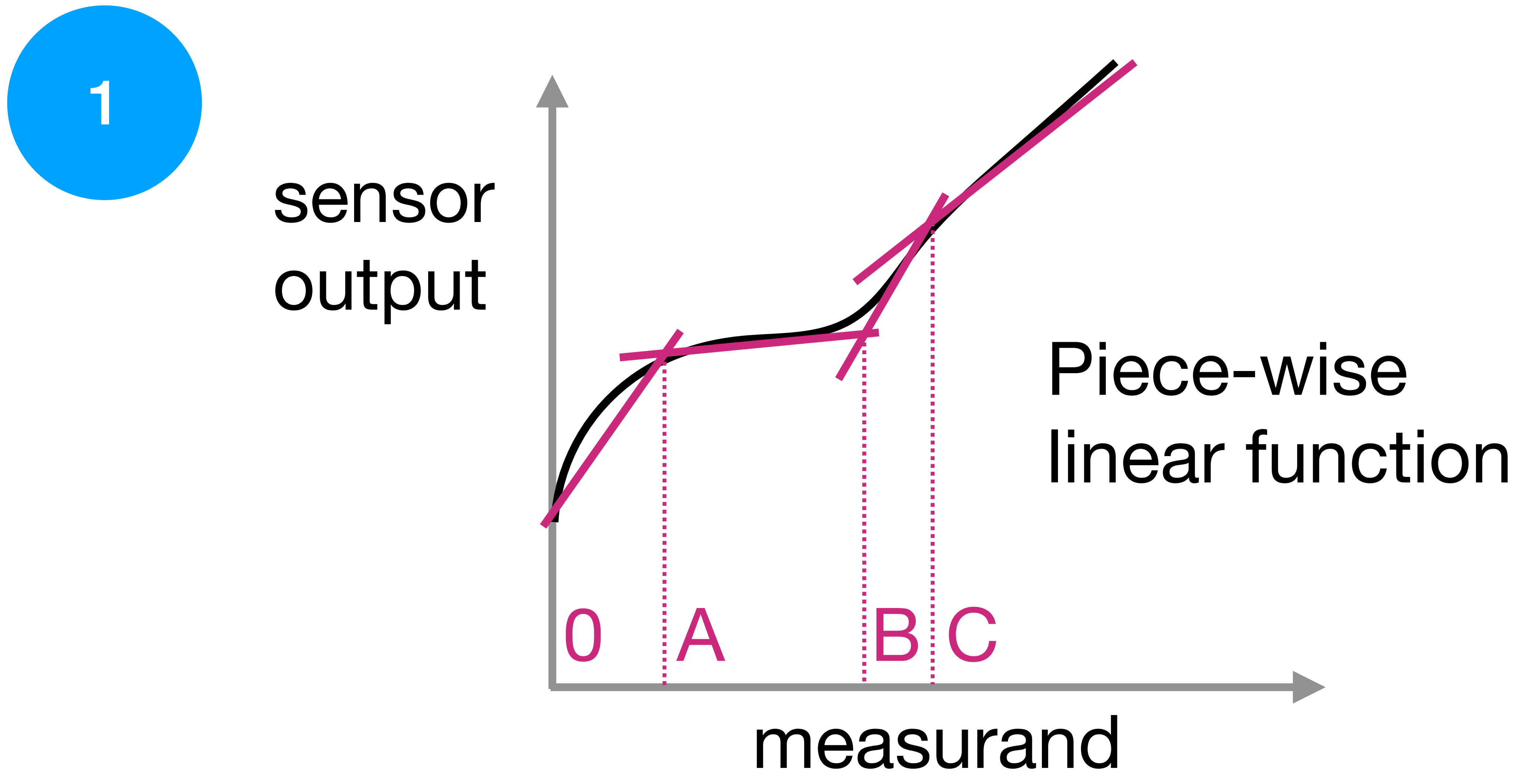
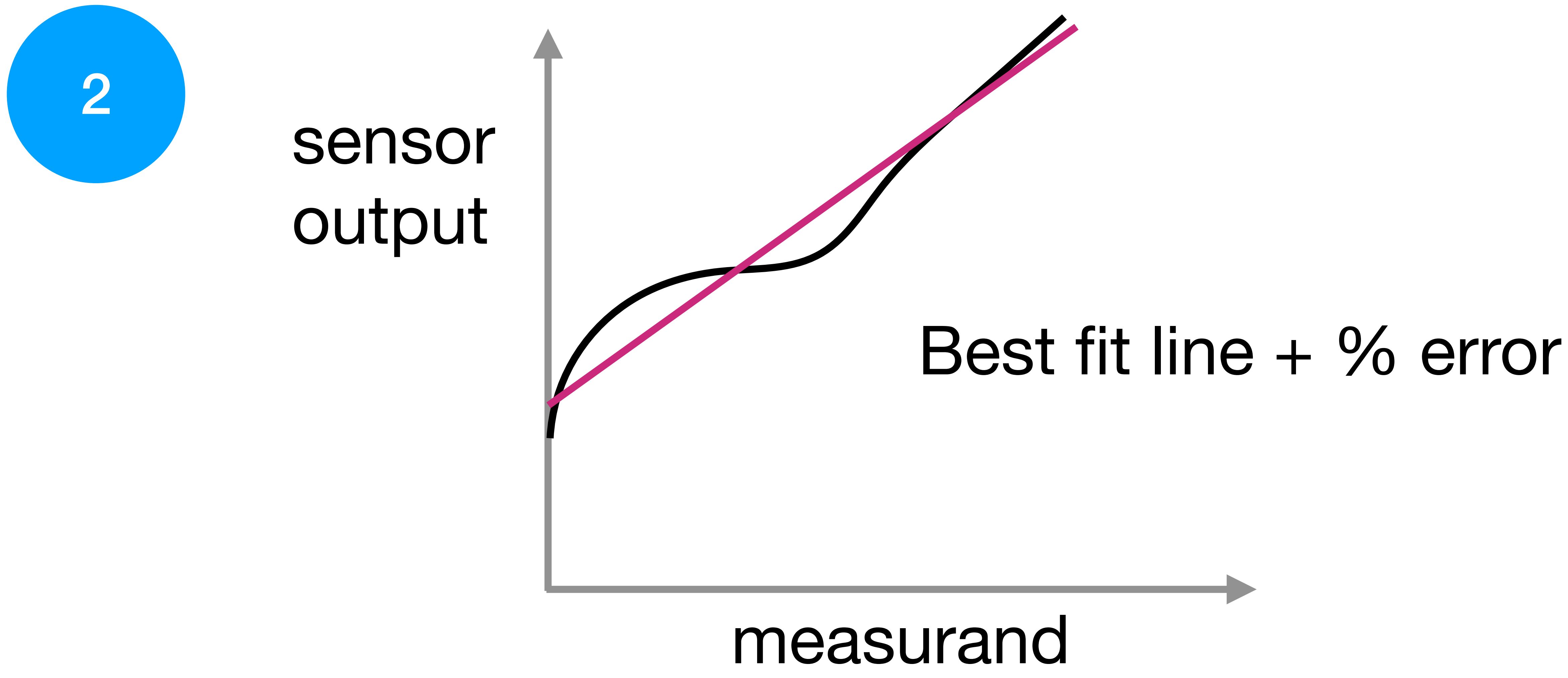
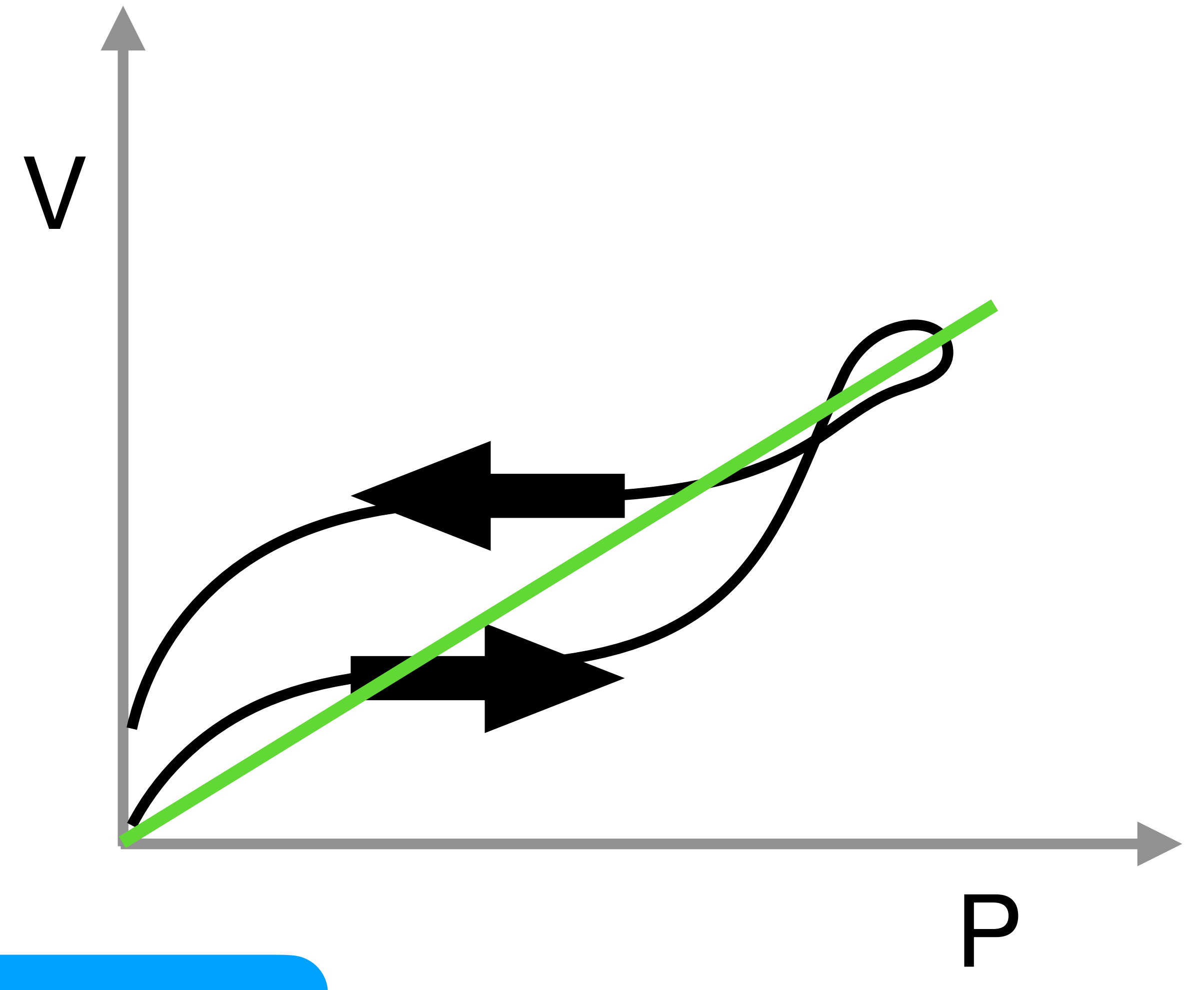




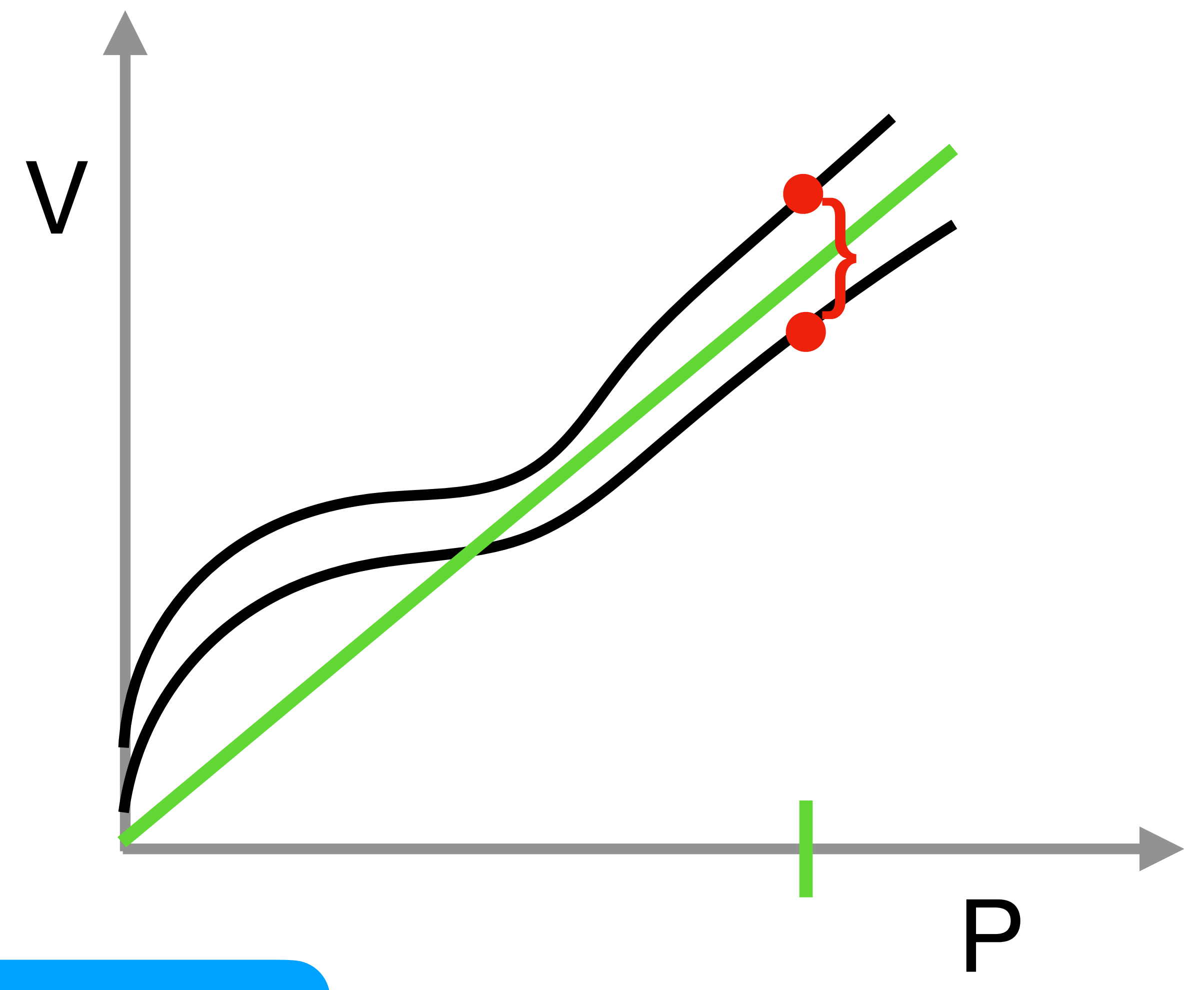
Non-linearity



Hysteresis

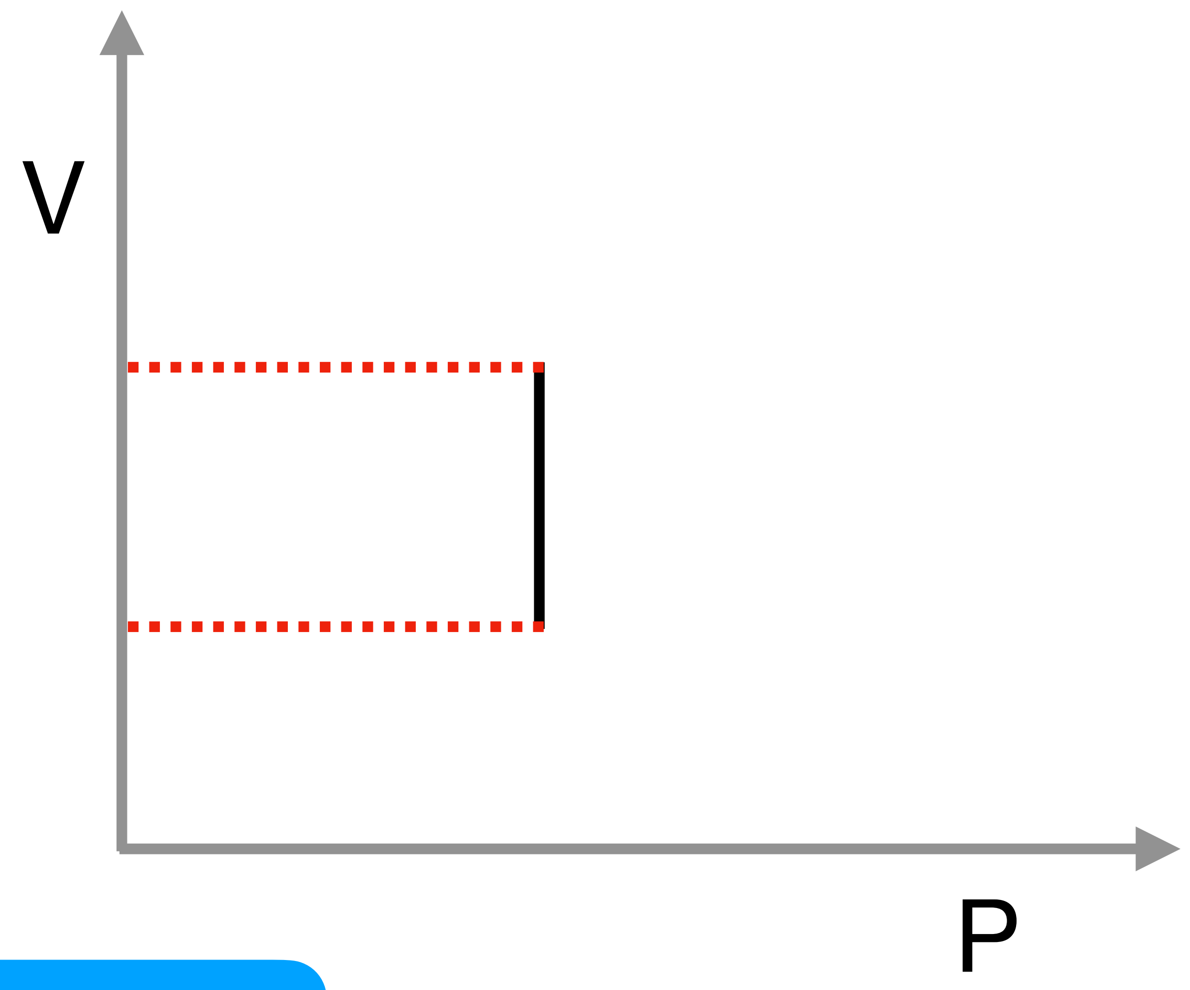
(History-dependent behaviour)

Measurements are different when pressure increases and decreases for whatever physical effect



Repeatability

The same repeated measure gives out different results

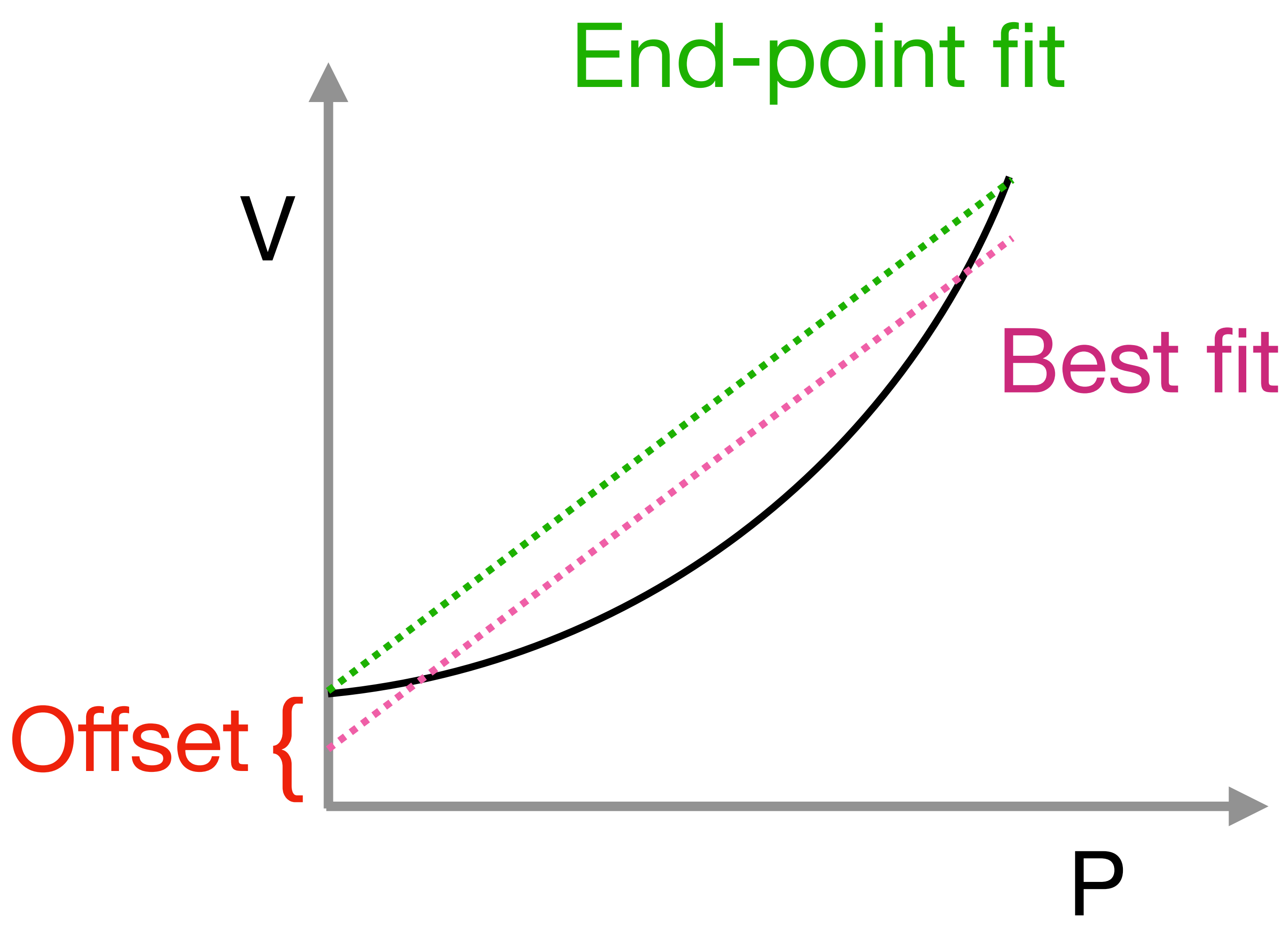


Drift

No variation of pressure, but holding the same pressure over time, and the sensor produces different outputs in voltage

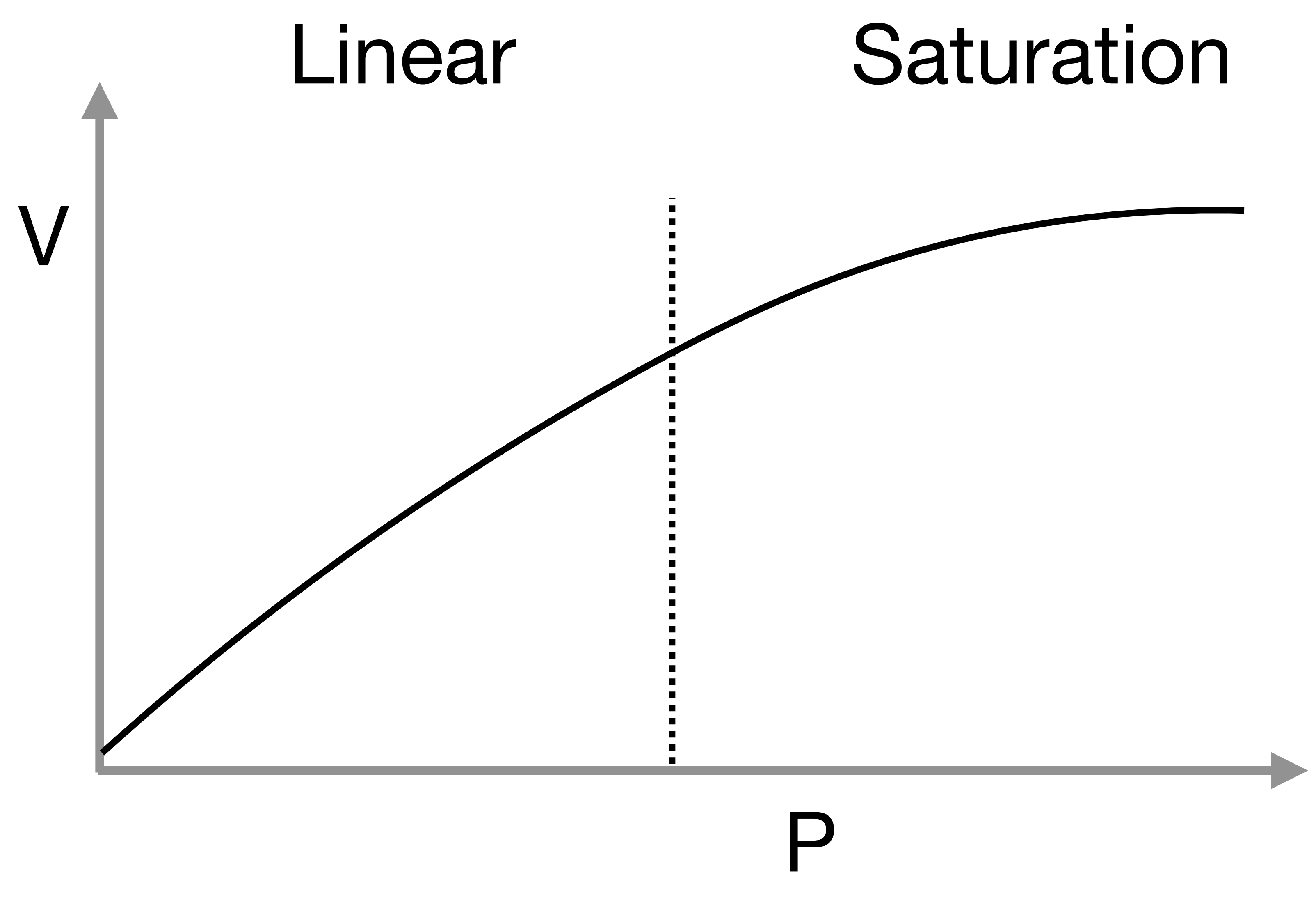
These effects are usually due to noise in the environment (e.g., temperature or electromagnetic changes)

Specifying non-linearity



- All the errors seen in the previous slide cause non linearity.
- In the specs of the sensor, the manufacturer can specify the parabolic model, or, more likely…
- …Specify the best fit line or the line passing through the end points of the curve
- Offset is usually specified too

Span/Range



- Manufacturers usually tell the span or the operating range of their devices, i.e., for what values of the measurand (e.g., pressure), you get a certain sensitivity.
- Out of that range, you should not expect the declared sensitivity.

Mechanical sensors - oscillatory motion (1)

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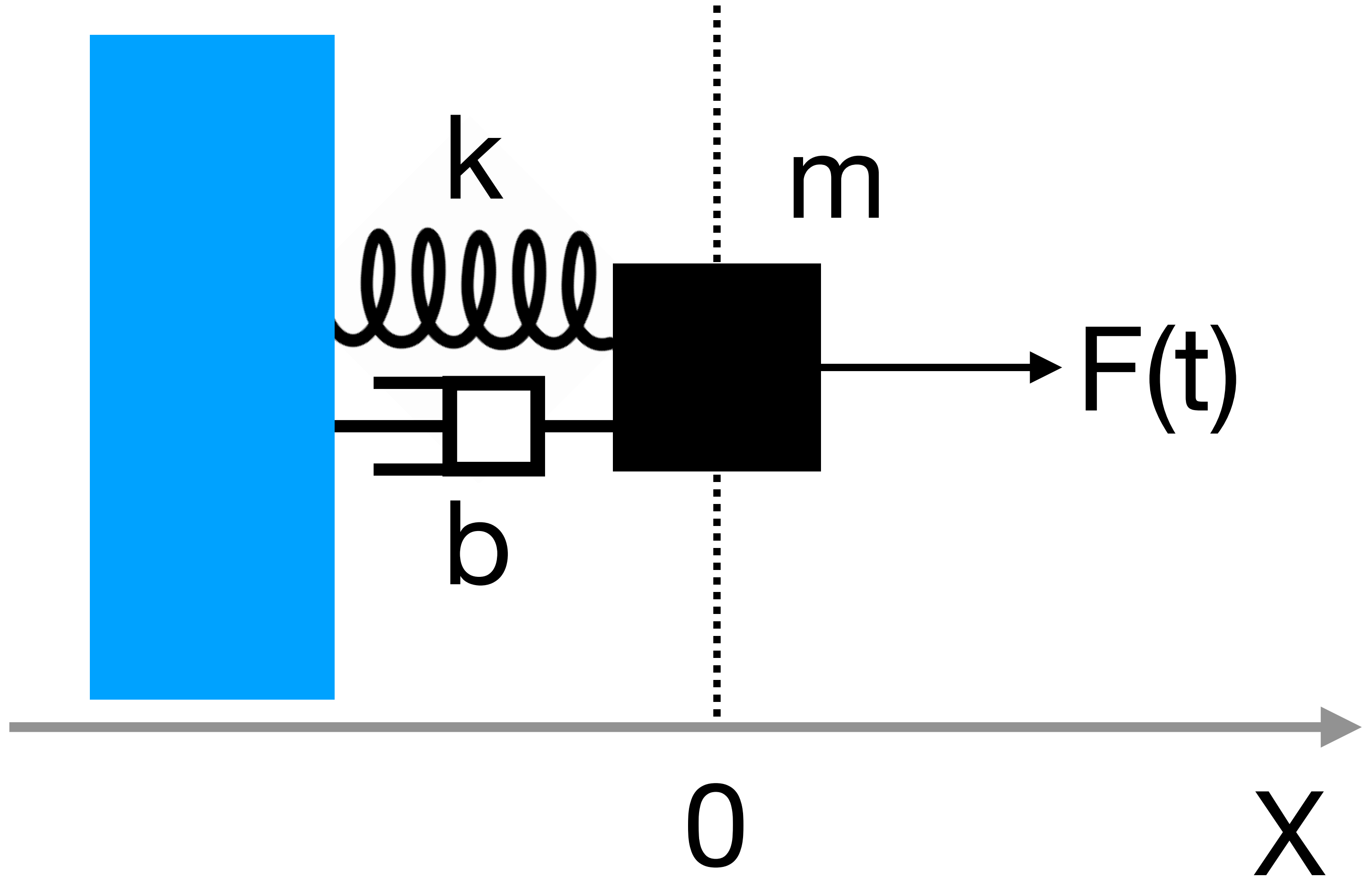

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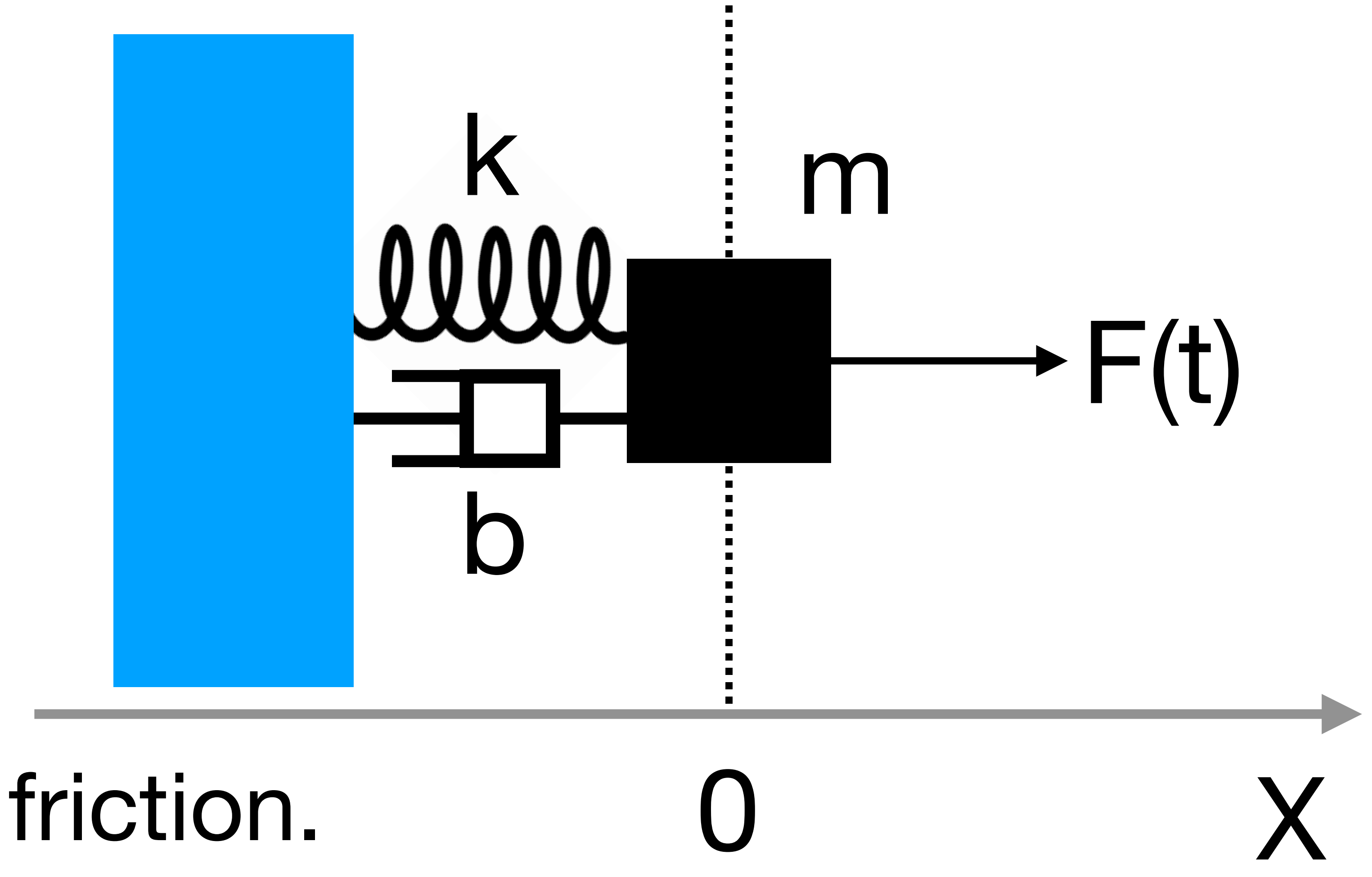
- Damper, $F_D=-bv$
  damping is the loss of energy of an oscillating system. A damper is a mechanical device that resist motion via friction.
- Spring, $F_S=-kx$
  k is the stiffness: higher = greater resistance to compression or stretching



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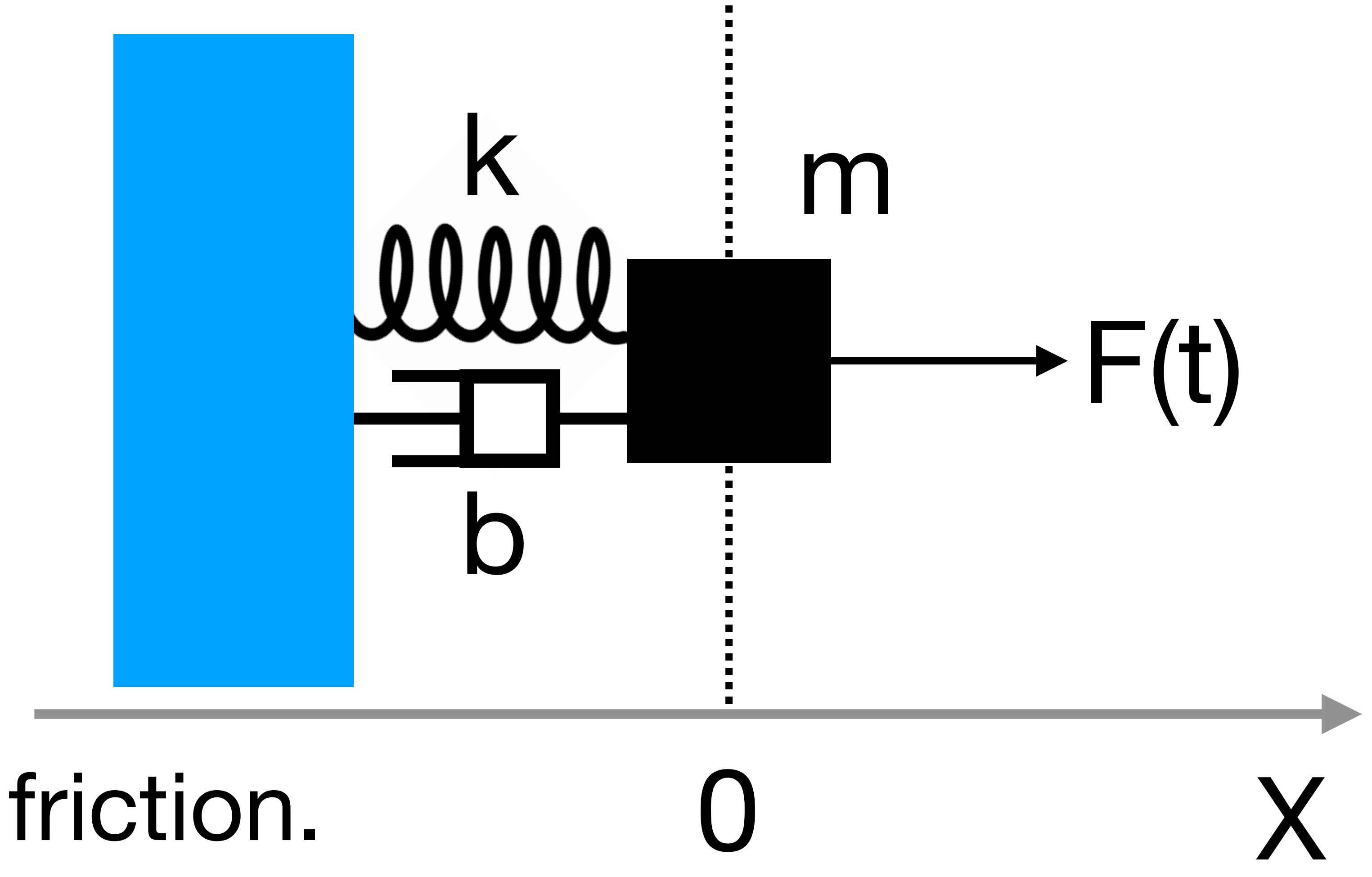

Inductors

Electric components that store energy in a magnetic field when current passes through them

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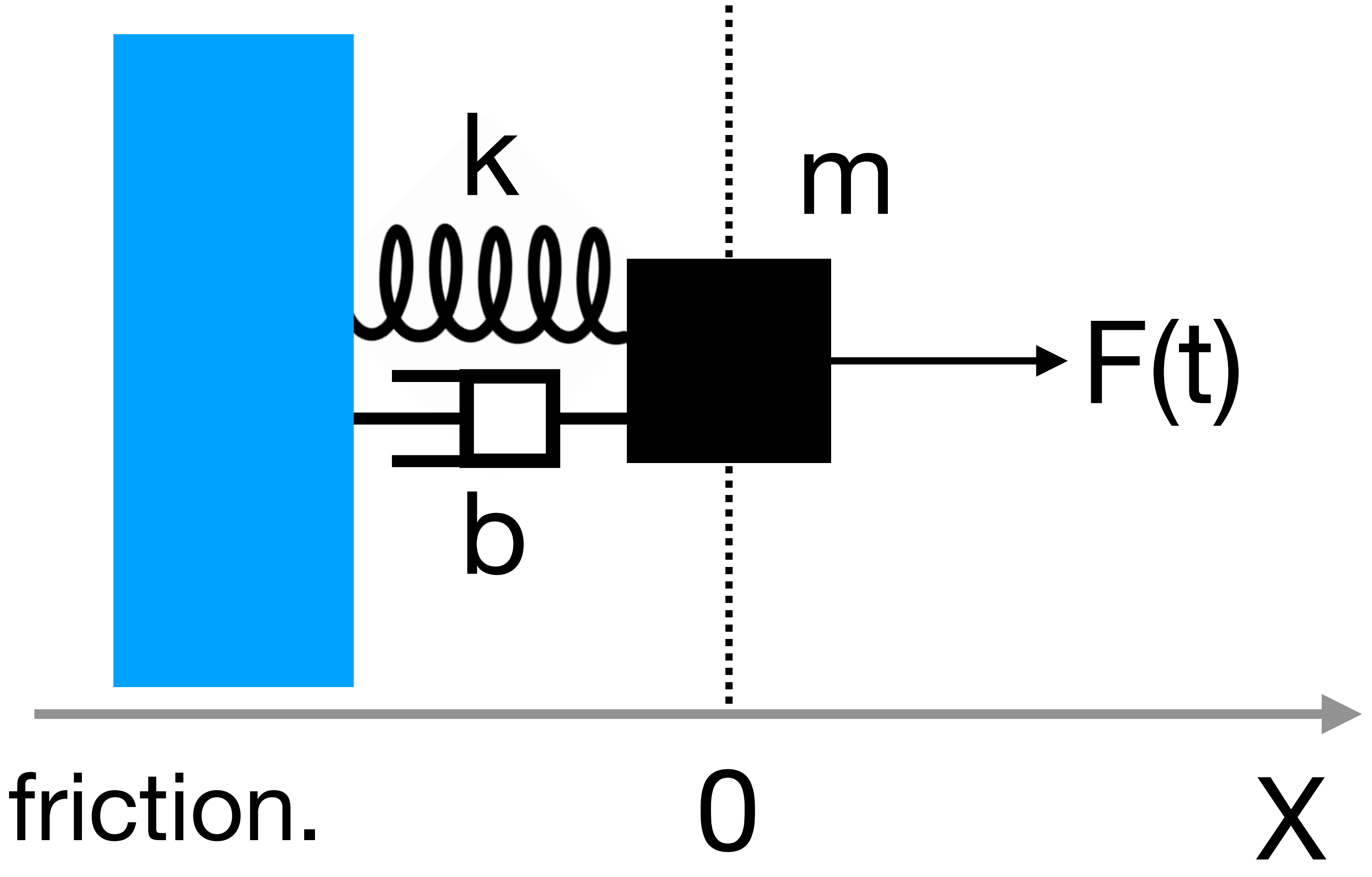

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Resistors

Electric components that implement resistance in a circuit (used to reduce current flow)

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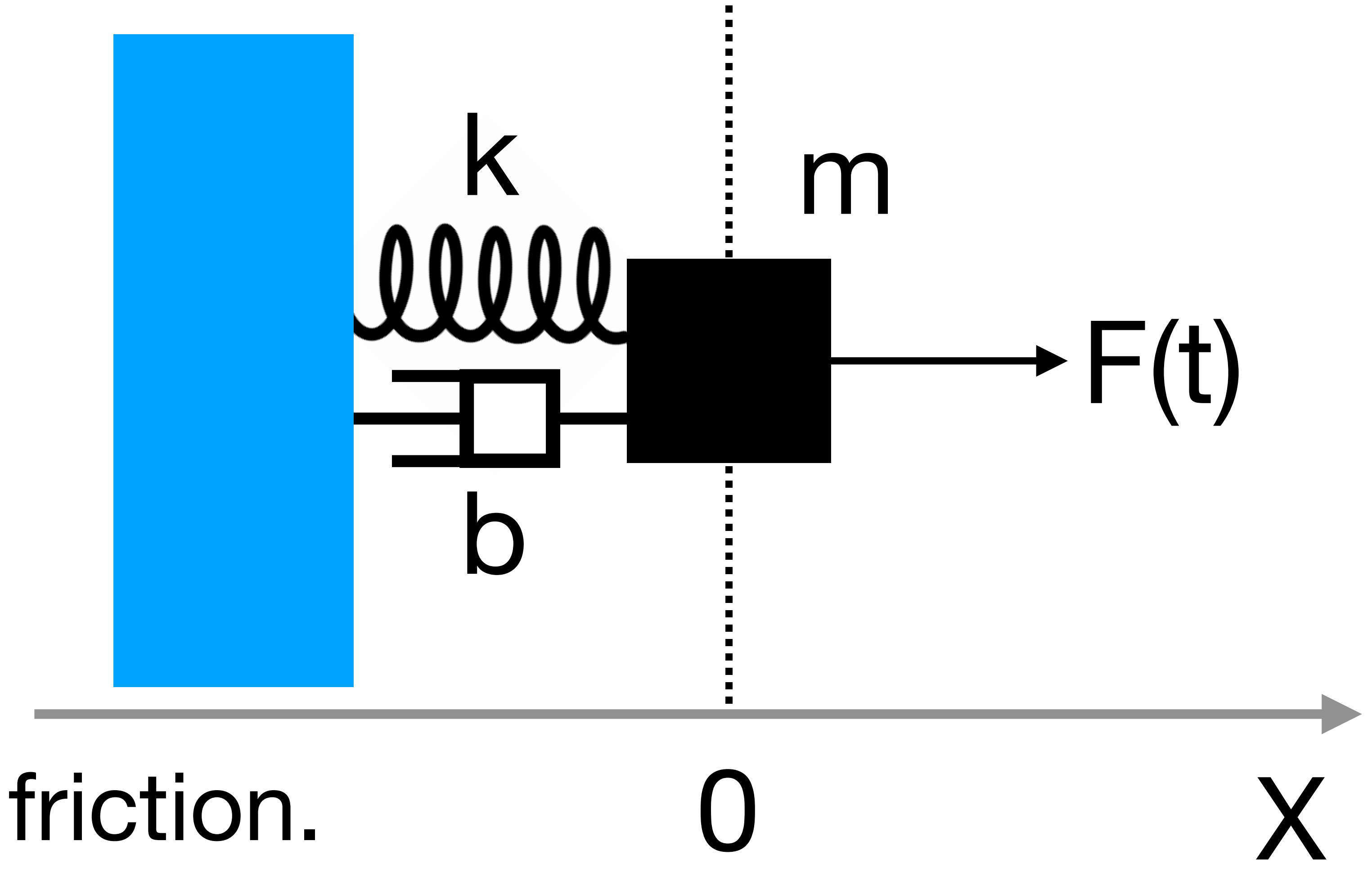

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Electric components that store energy in a magnetic field when current passes through them

Resistors

Electric components that implement resistance in a circuit (used to reduce current flow)

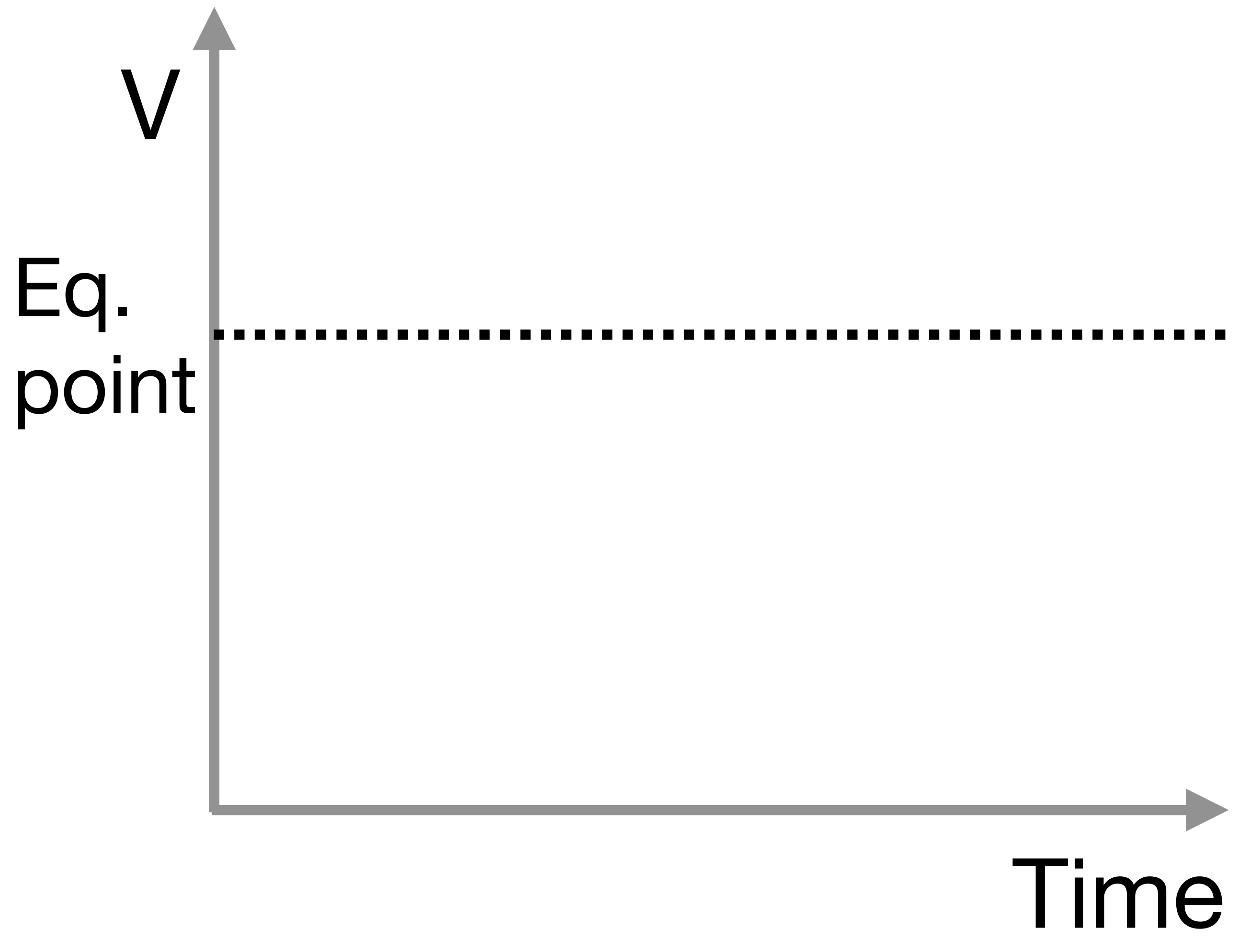
Capacitors

Electric components that store electrical energy by accumulating electrical charges on two closely spaced surfaces

What is going on?

- **We are modelling how a sensor reacts to changes in the environment.**
    - The force F represents the variation in the environment (e.g., temperature, pressure etc).
    - The Damping coefficient is the sensor’s internal resistance to change in the environment.
    - The stiffness is the sensitivity of the sensor’s to such variations.

Mechanical sensors - oscillatory motion (2)

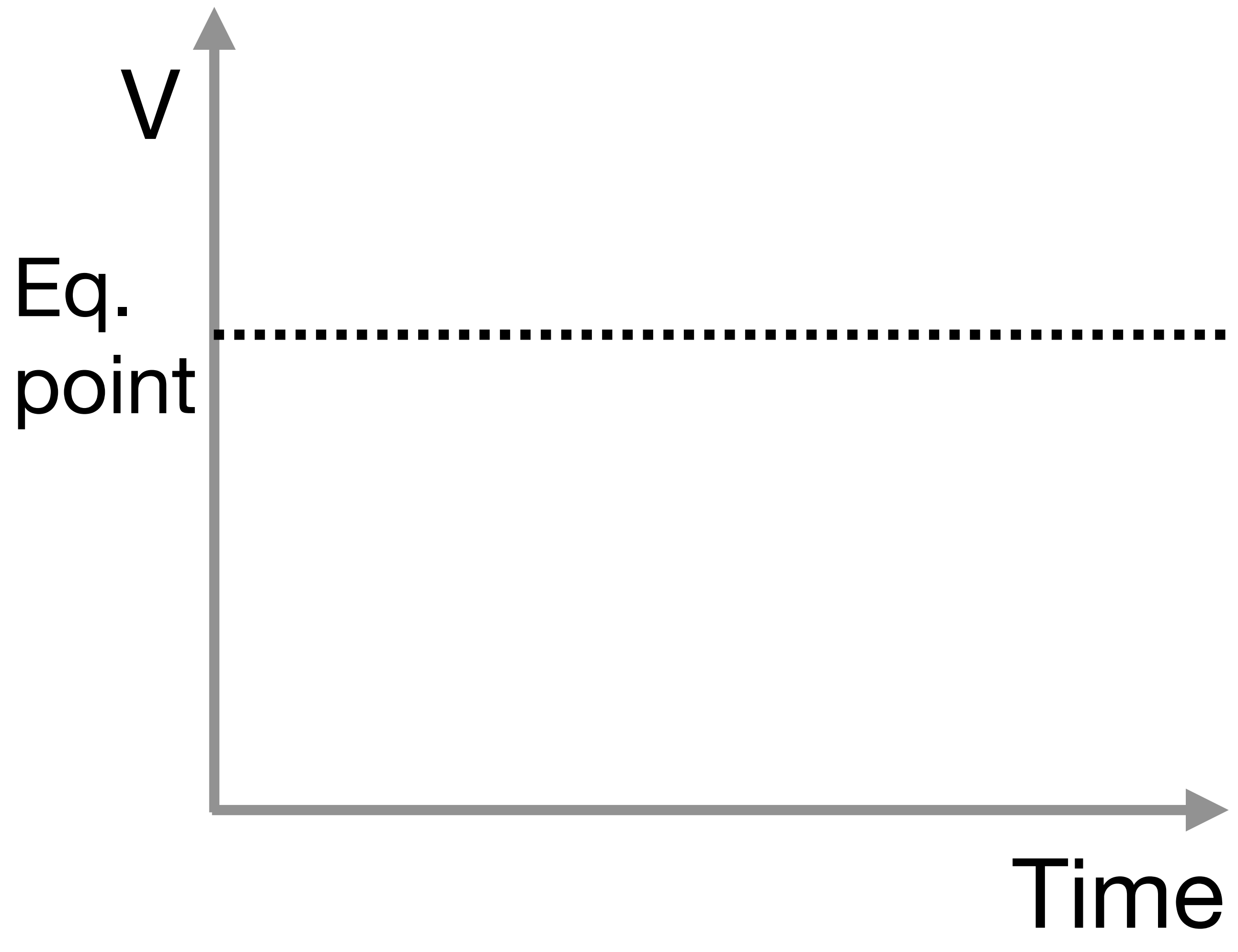


Mechanical sensors - oscillatory motion (2)

- The equation of the motion of a mass in a mass-spring damped model is given by:

$$f(t) = m\frac{dx^2}{d^2t} - b\frac{dx}{dt} - kx,$$

which is a second order ODE, which might have:



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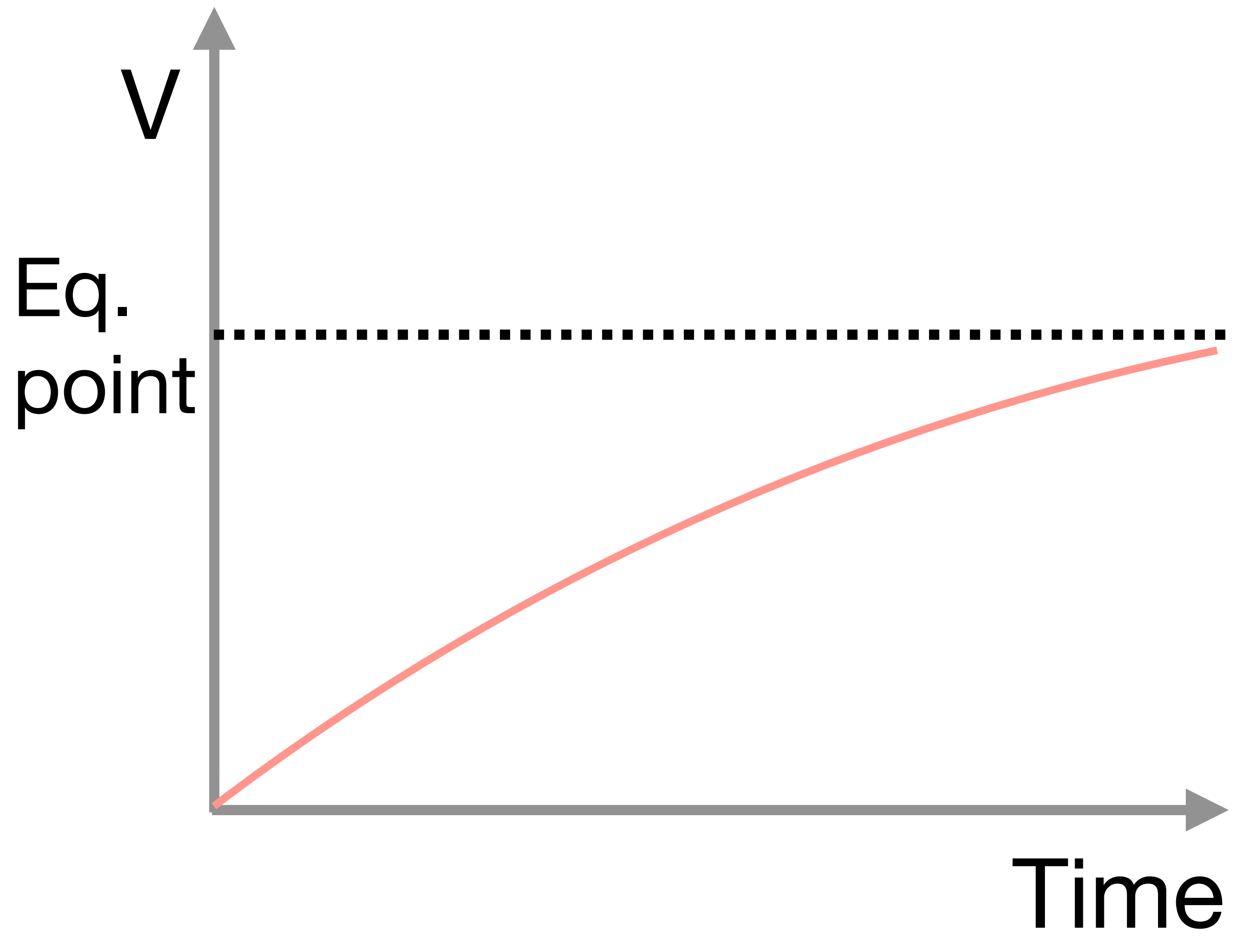
- Two distinct real solutions (overdamping, the damping is so strong that the mass cannot oscillate around the equilibrium point and the measure takes long time to reach the equilibrium).



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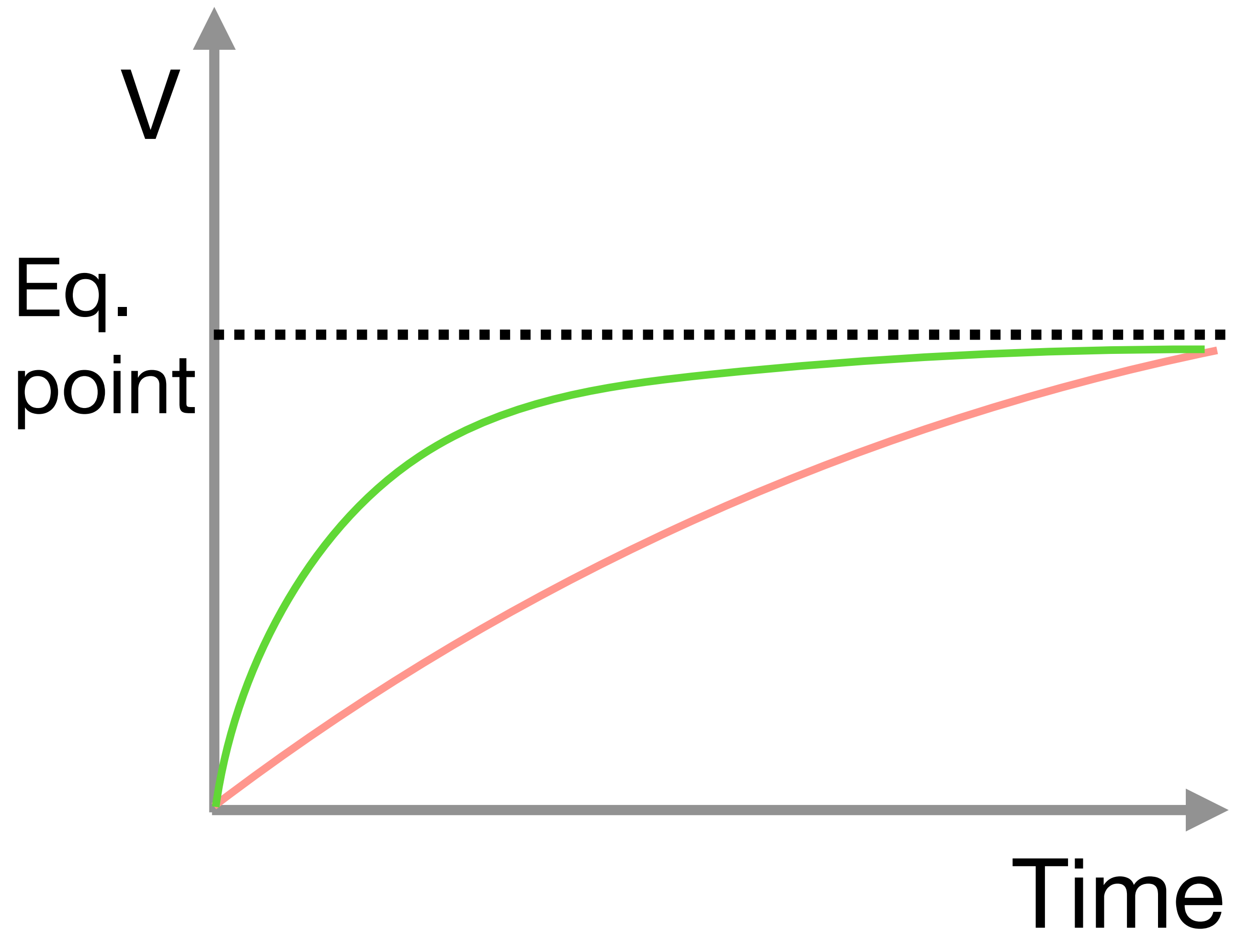

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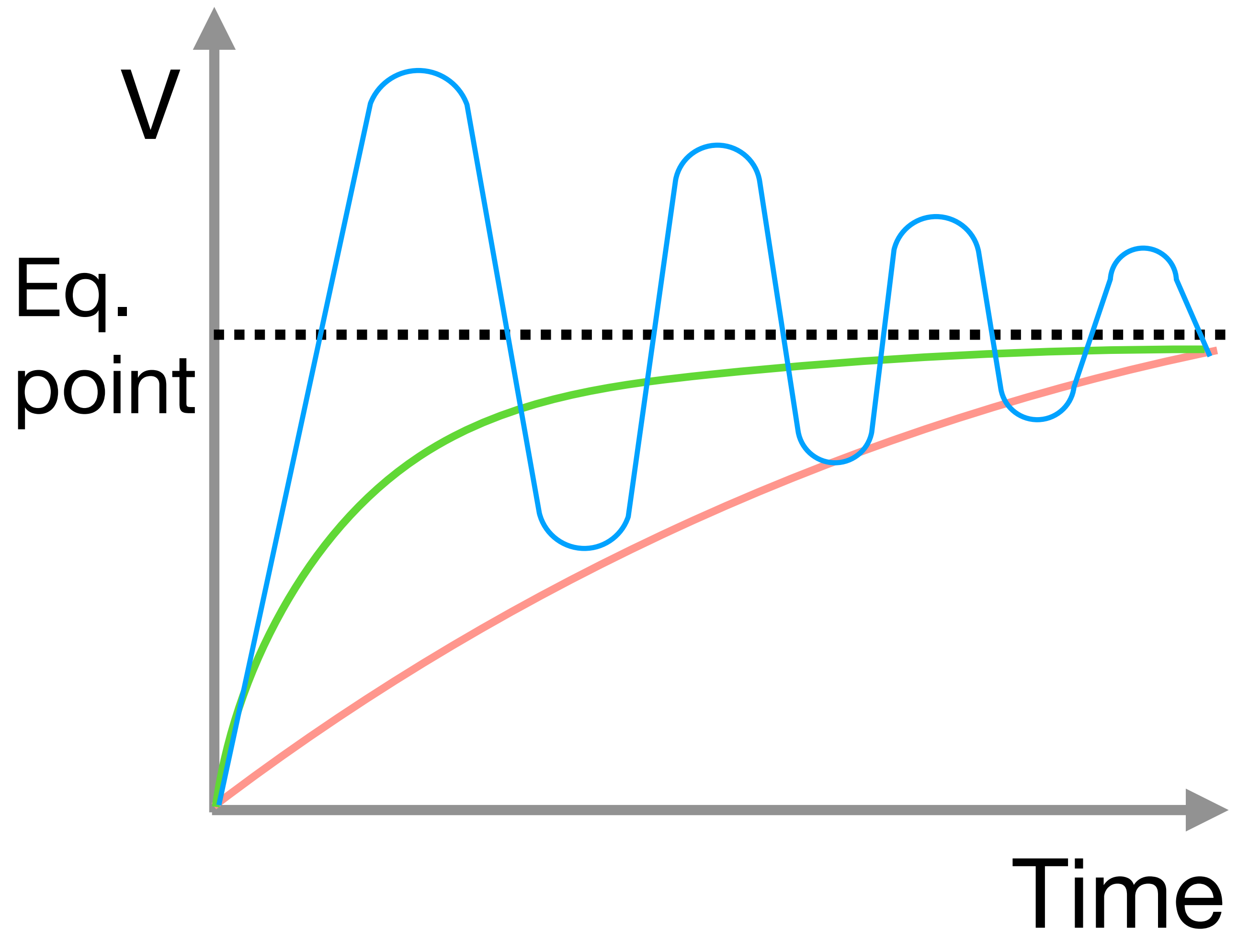
- One real solution (critical dumping, there is an initial oscillation and then the system goes back to the equilibrium point).
- Two distinct complex solutions (underdamping, the mass oscillates a few times before reaching the equilibrium point).

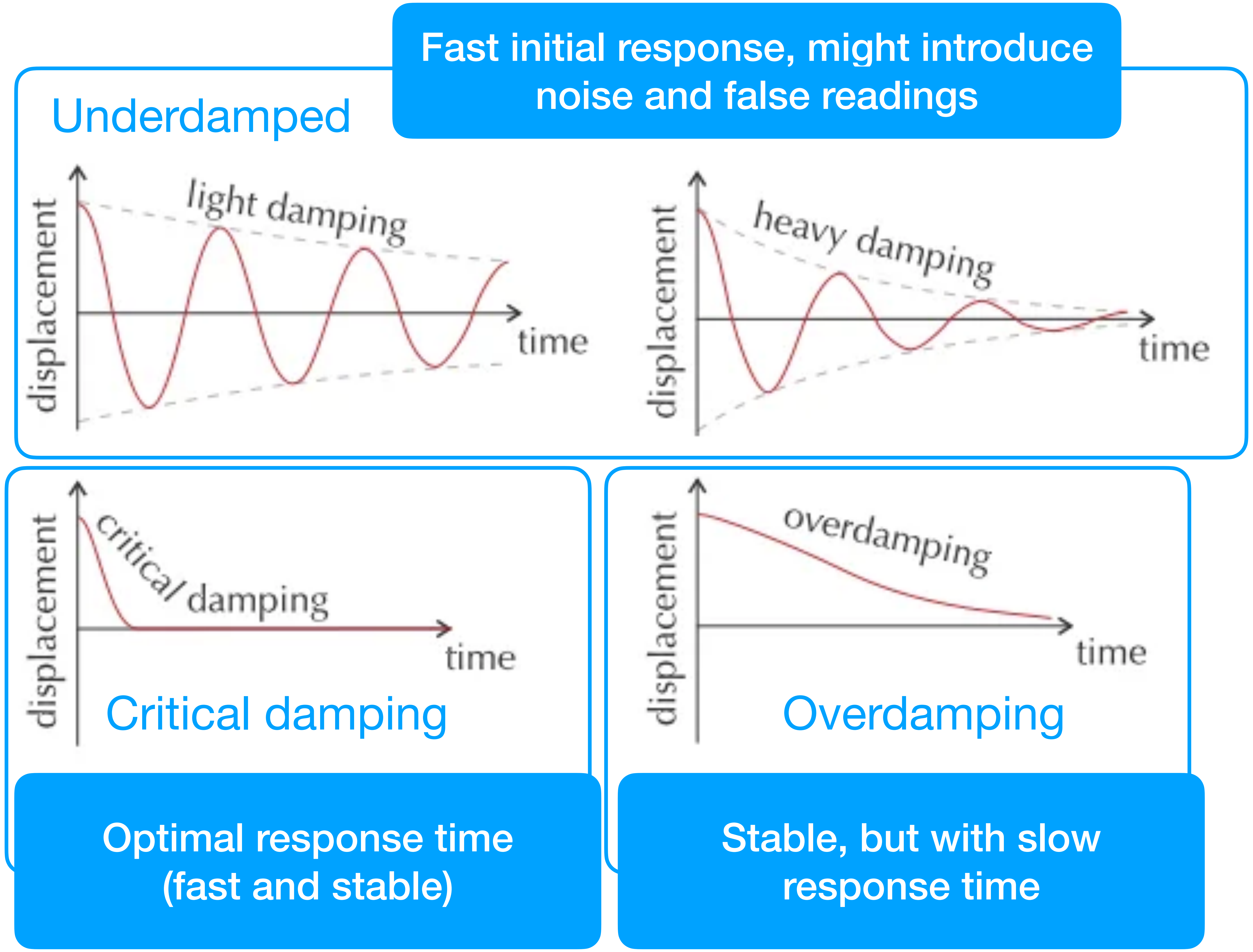


Mechanical sensors - oscillatory motion (3)

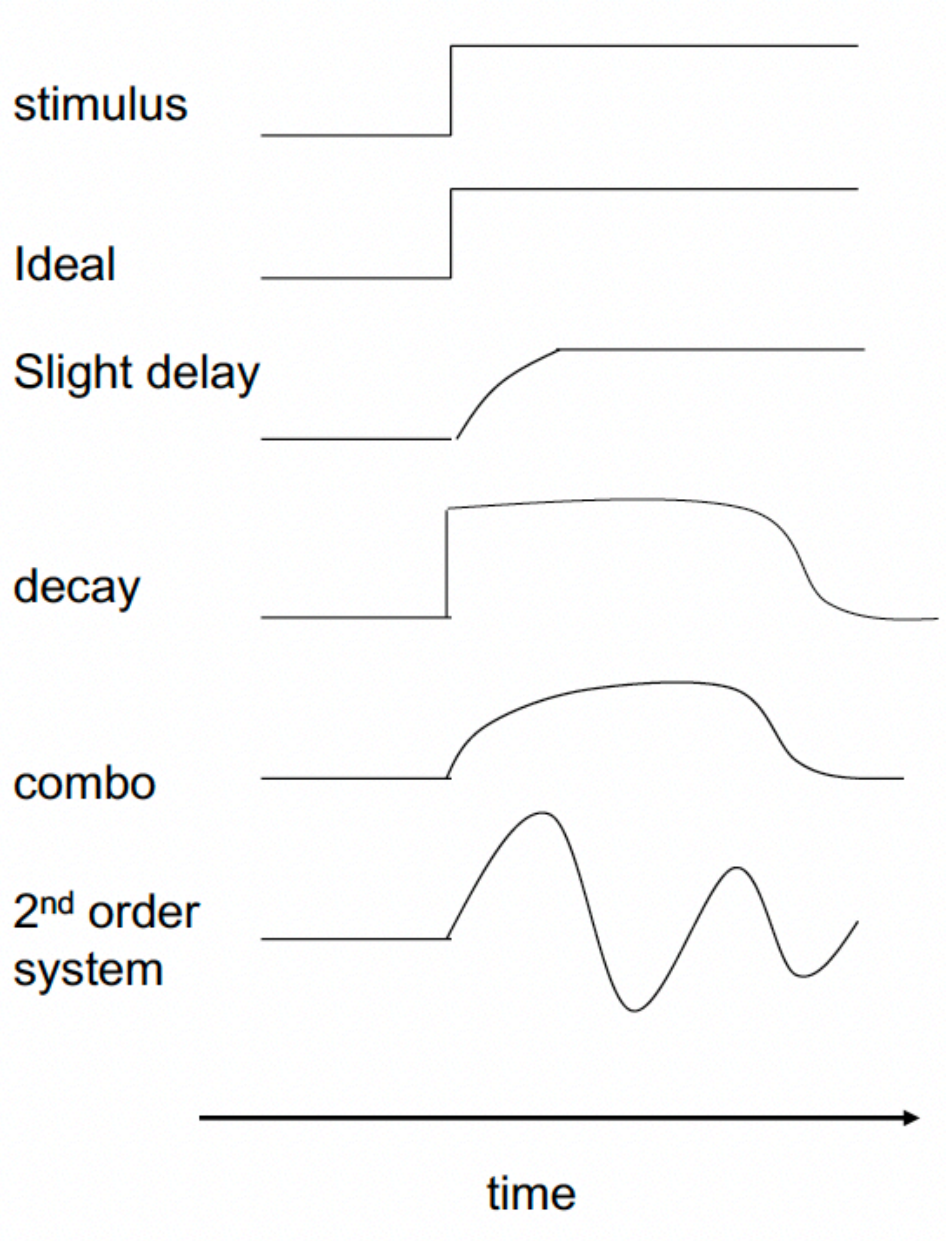
- Overdamping:
  A temperature sensor with too much thermal insulation might take too long to register rapid temperature changes.

- Underdamping:
  A vibration sensor in an industrial machine might produce overshoots in its readings before stabilising.

- Critical Damping:
  A well-tuned motion sensor, hard to achieve in practical systems.

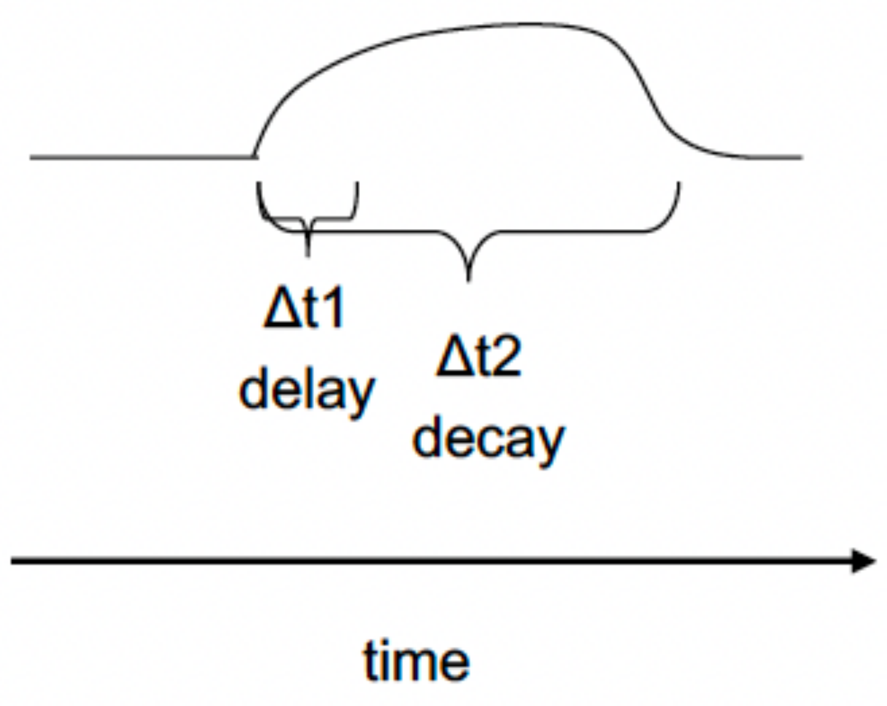


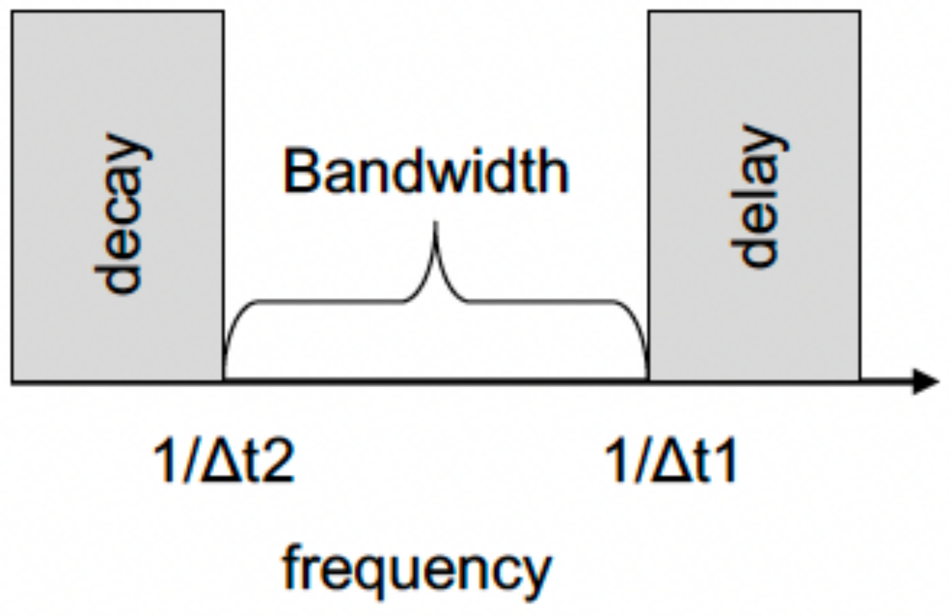
Bandwidth of a sensor



- The bandwidth of a sensor, also referred to "frequency response", is a measure of the ability of the sensor to perceive and respond to changes in the measurand.

- The bandwidth is the range between the highest and the lowest frequency limits that the sensor can sense.





3.1.3 Actuators

Actuators

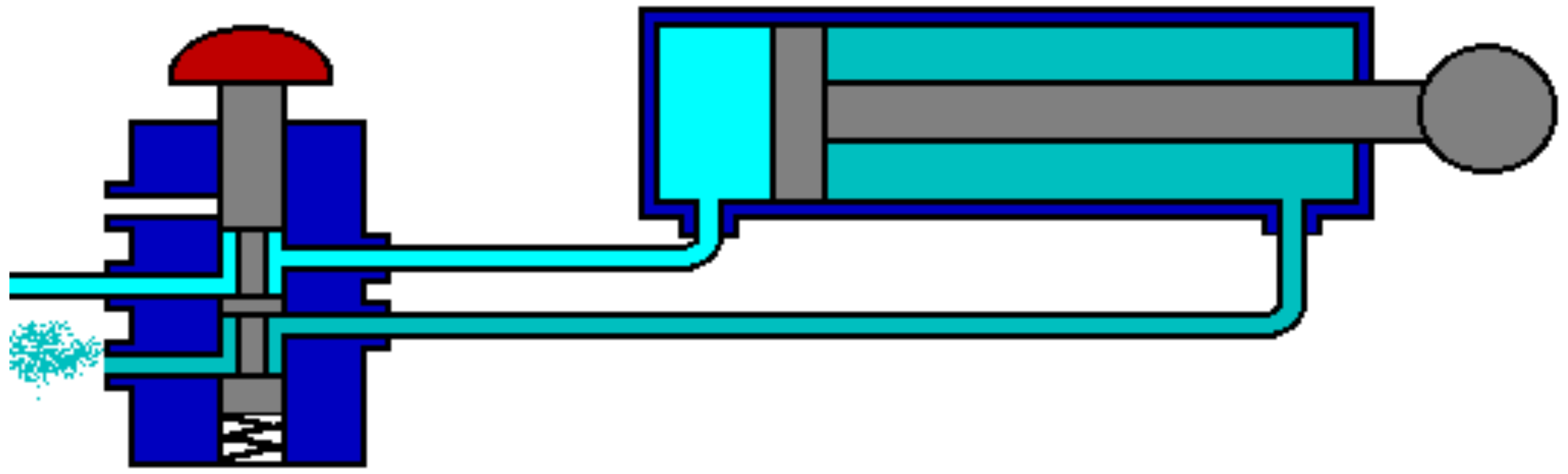
- Actuators are components of a device able to move the mechanism implemented in the device.
- An actuator is the mechanism by which a **control system** acts upon an environment, responding to the conditions measured by a sensor.
- Upon receiving a control signal, the actuator responds with the corresponding movement.
- For example, if a humidity sensor senses that the environment is too dry, the actuator can turn on the watering system. If the temperature of a room is too high, the actuator can switch the AC on.

Actuators' motion

- Actuators' motion can be:
  - Linear: the actuator generates movement along a straight line.
  - Rotary: the actuator generates a circular motion
- Combinations of linear and rotatory motions can be used for more sophisticated movements.

Actuators' energy source (1)

- **Hydraulic actuators** are composed of a cylinder where a liquid might flow, activating a piston that moves along a straight line.
- Since the hydraulic liquid is hardly compressible, the force exerted by the piston is strong.
- Require several auxiliary components, are vulnerable to leakage and pricy.



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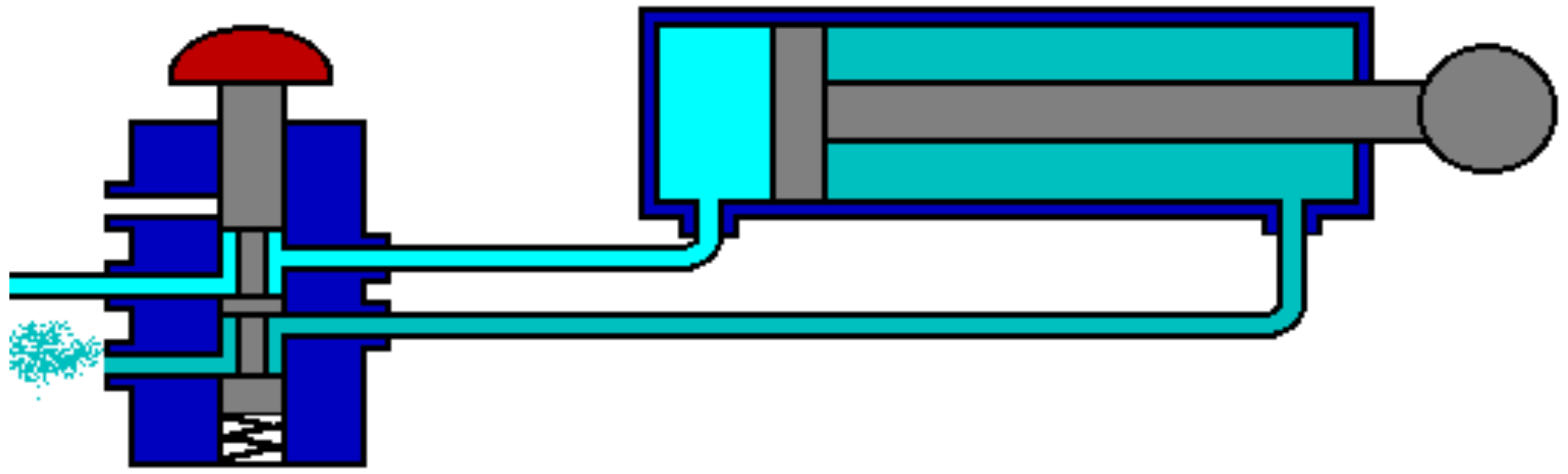
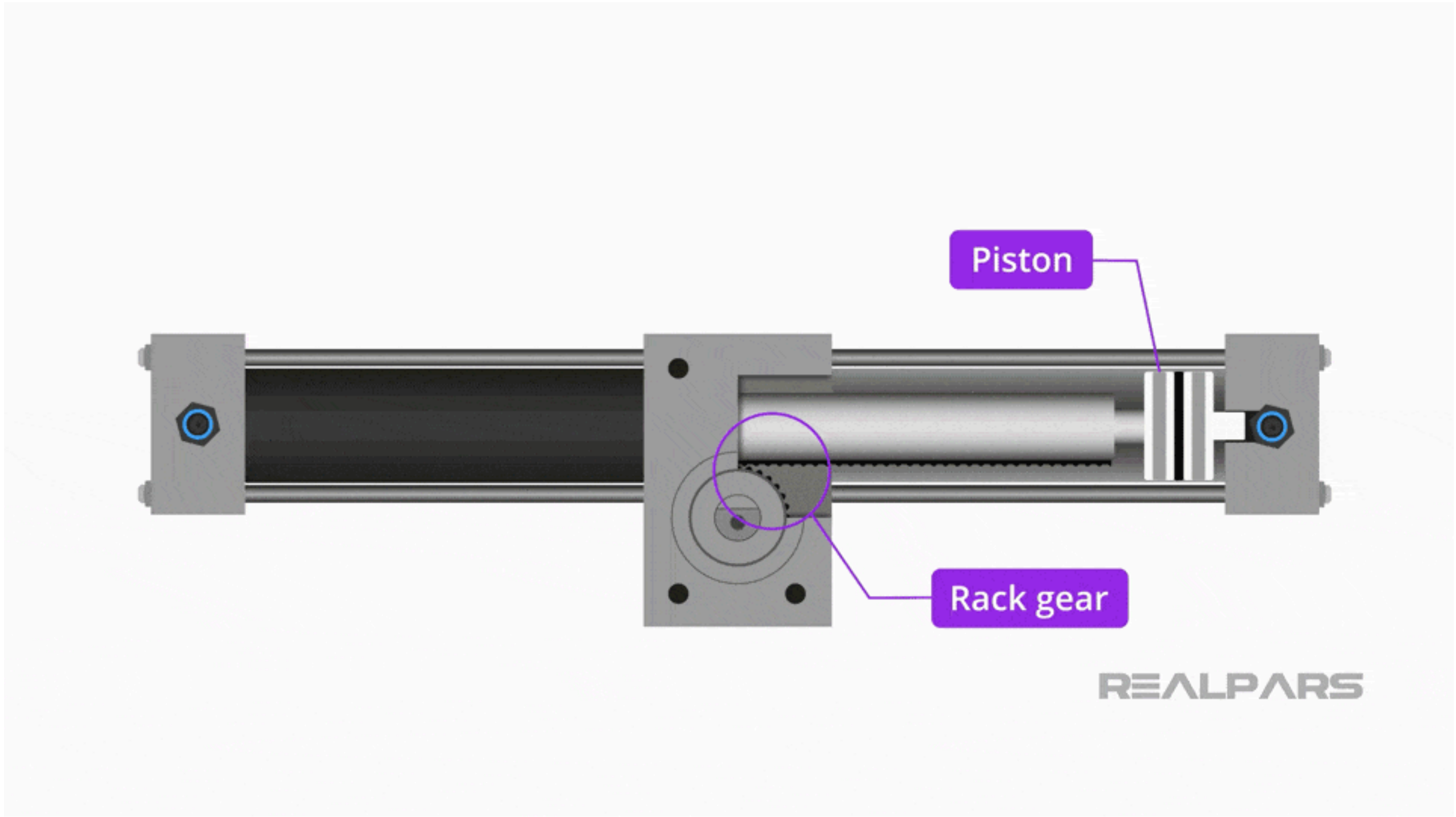


Actuators’ energy source (2)

- **Pneumatic actuators** transform compressed air energy into mechanical movement. Air enters the chamber and moves a piston similarly to what happens for hydraulic actuators.

- Used in high temperature situations where using gas is safer than chemicals. It is cheaper and the motion starts and stops quickly.

- Vulnerable to pressure losses.



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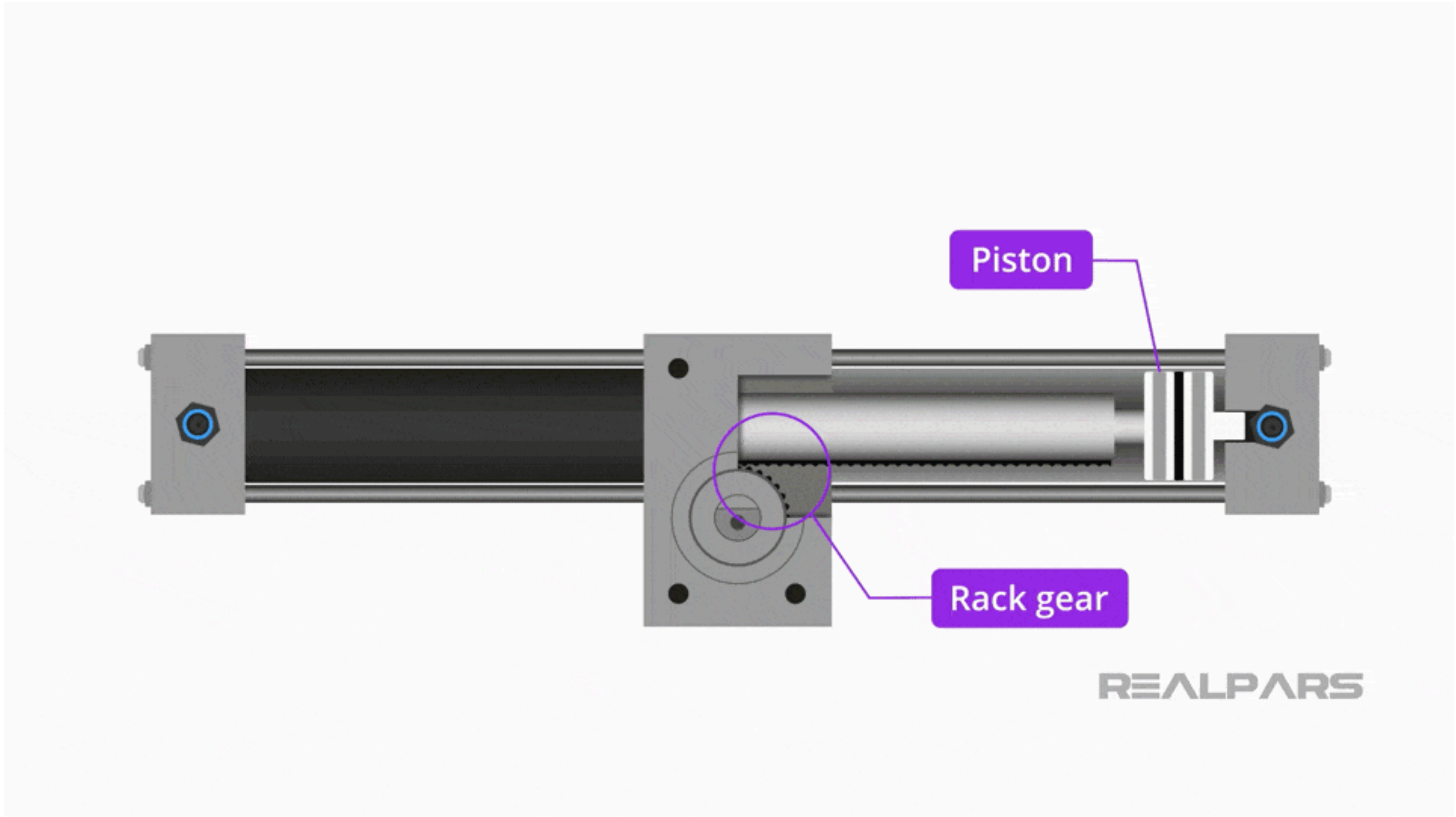

Actuators’ energy source (3)

- **Electric Actuators** are powered by motors converting electrical energy into mechanical energy.

- **Thermal Actuators** produce motion as a reaction to temperature variation of thermally sensitive materials.

- **Magnetic Actuators**, by the Joule Effect, use the energy produced by the power in a circuit and transform that into motion.

Bibliography

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