Embedded System Architecture - CSEN 701

Module 3: *Embedded Hardware*
Lecture 05: *Sensors Fundamentals*

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Outline

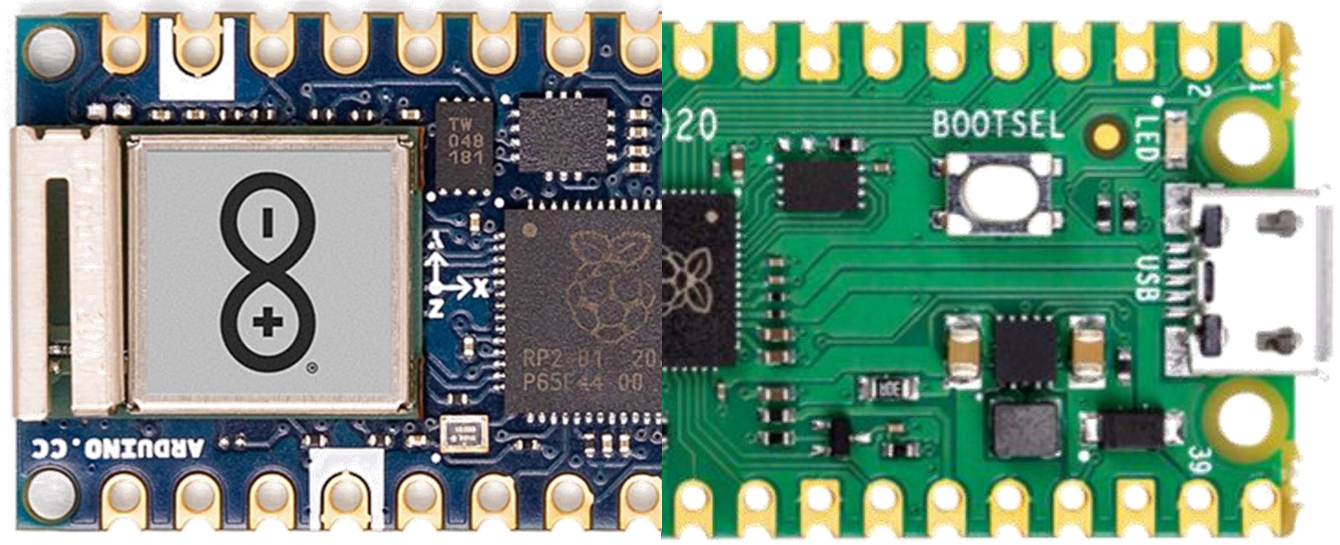
- Where are we?
- Signals
- Sensors
- Interface Techniques

Where are we?

An Embedded System

Physical
System Input
"Sensor"

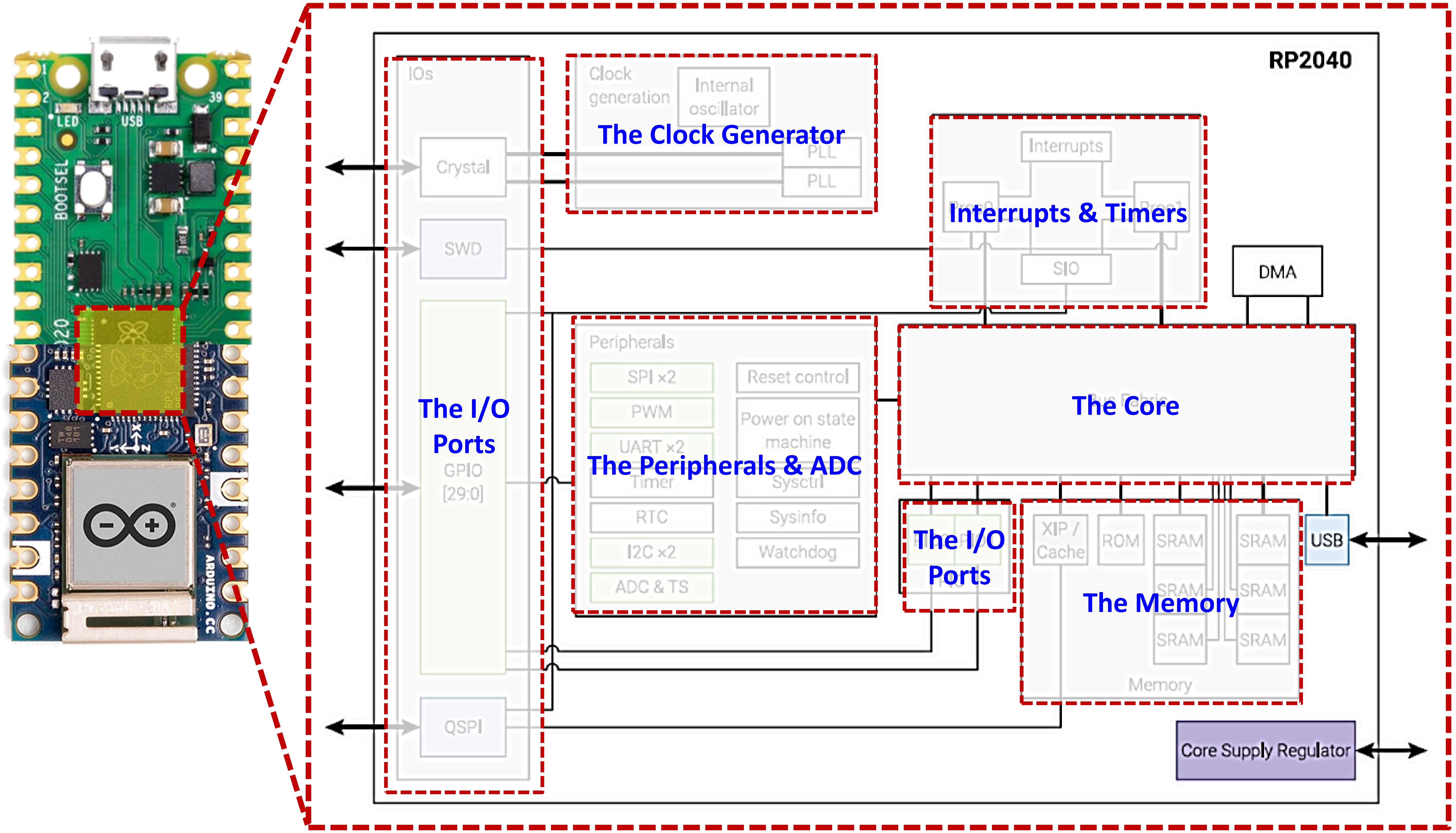
Microcontroller



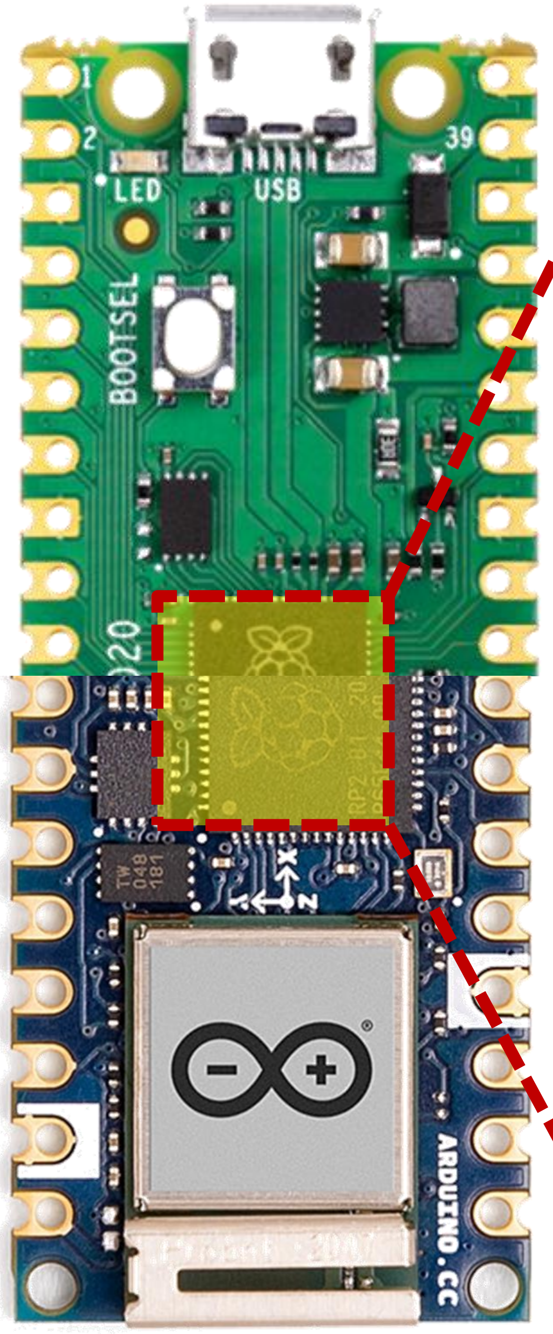
Physical
System Output
"Actuator"

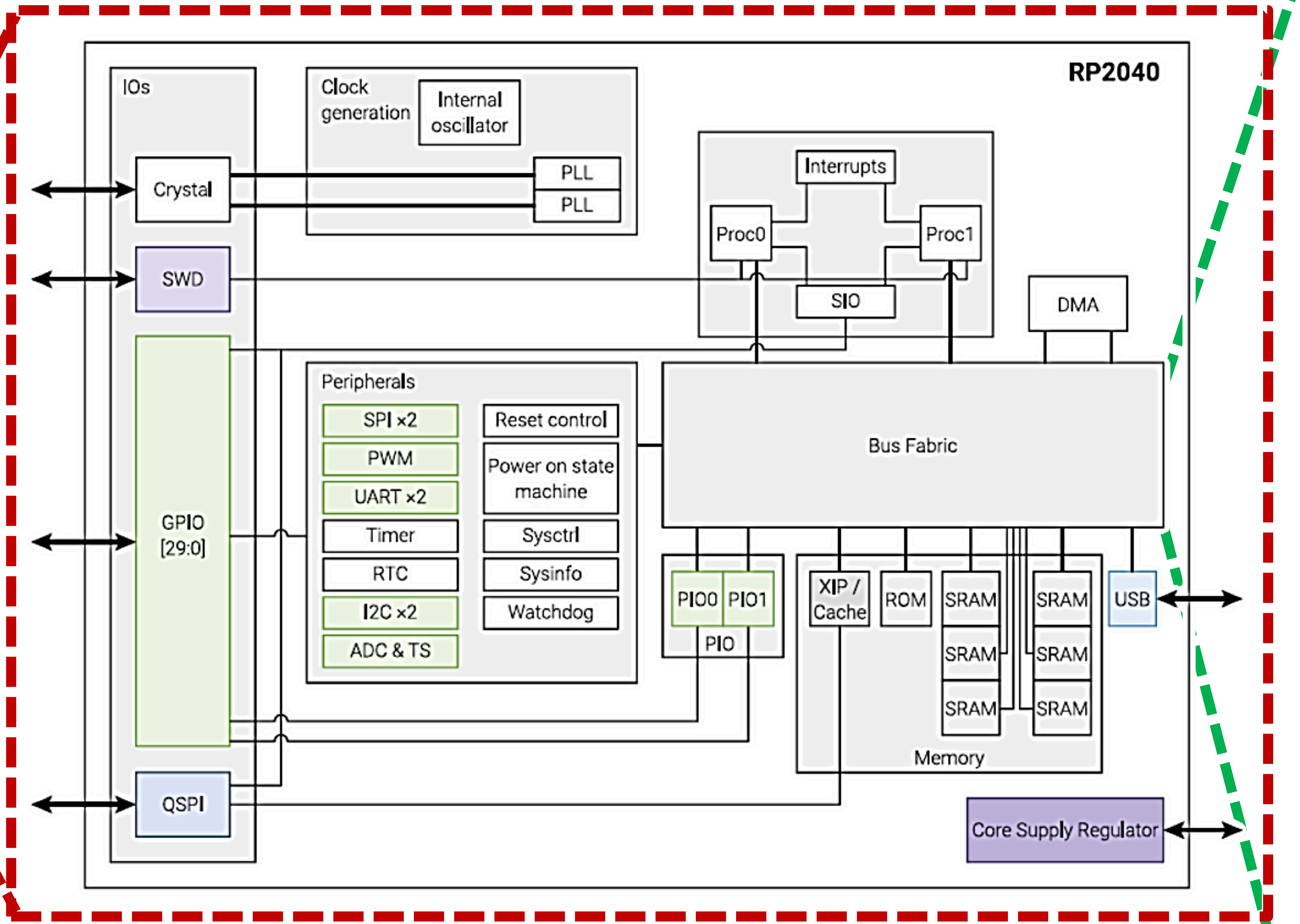
Where are we?

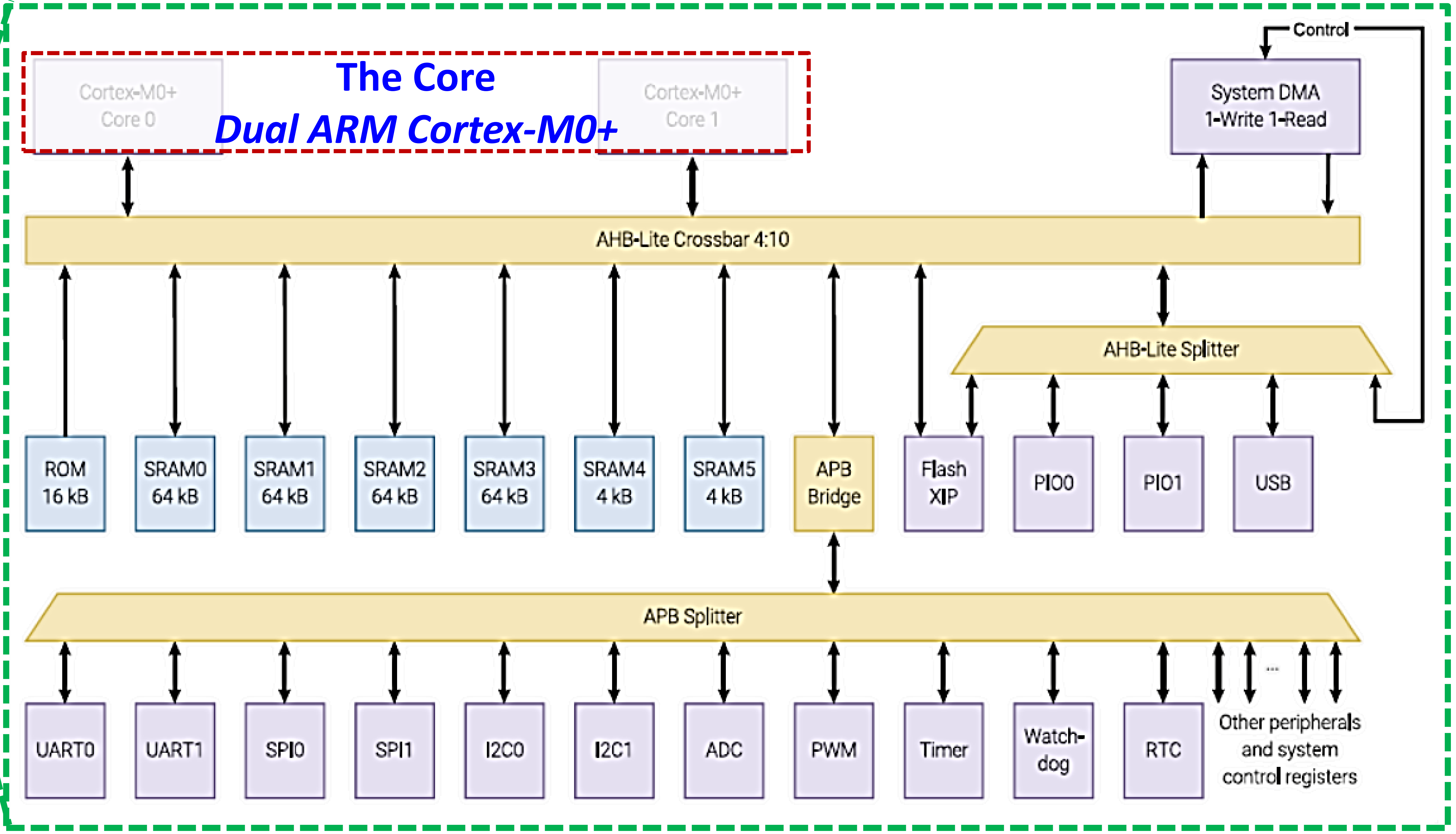
The RP2040 Microcontroller Architecture



The RP2040 Microcontroller Architecture





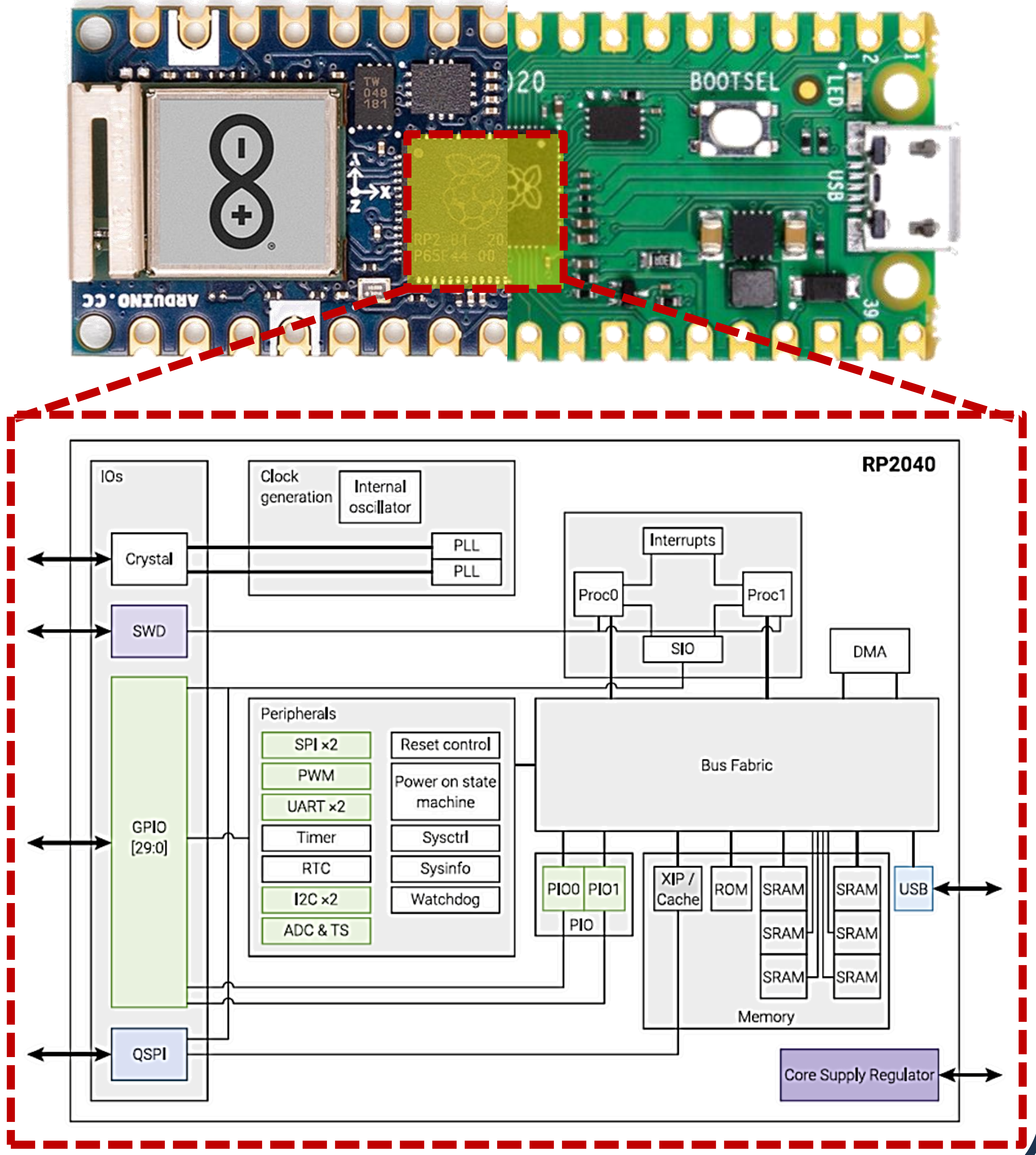


Where are we?

An Embedded System

Physical System Input
"Sensor"

Microcontroller



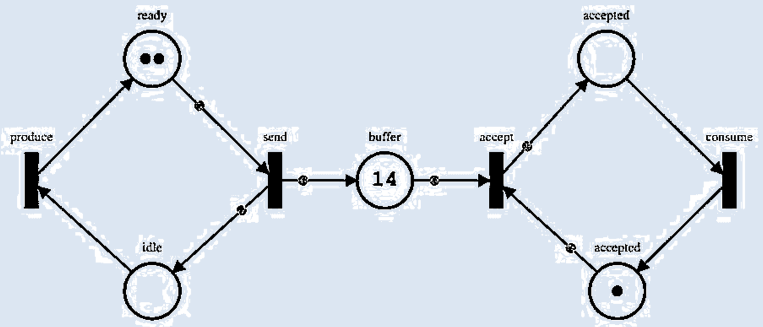
Physical System Output
"Actuator"

- What is the nature of the I/O Signals?
- How to make sure that the microcontroller understands these signals (Interfacing techniques) ?
- What are the sensors and actuators?
- How to read the sensor?
- How to control the actuators?

The big Picture

ES Modeling & Design
(*2 Modules*)

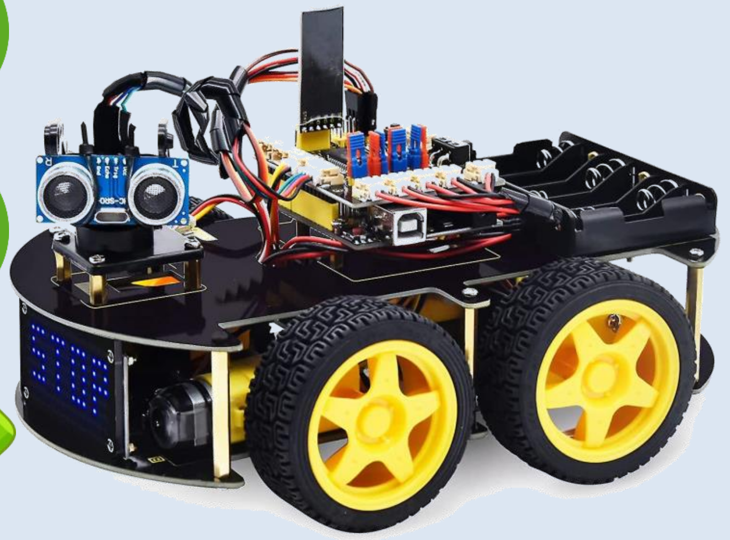
- System Modeling
- Design Considerations
- Power management and optimization
- Reliability and fault tolerance



The Real-time Embedded System

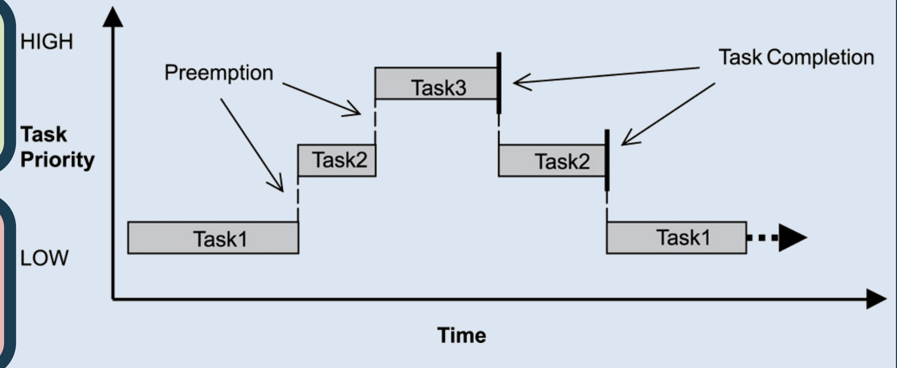
ES Hardware Components
(*4 Modules*)

- Microcontroller Fundamentals
- Embedded programming languages
- Embedded Hardware — *Let's go*
- Communication and Networking



ES Software Components
(*1 Module*)

- Real-Time Systems
- Multi-tasking
- Scheduling
- Resource Management

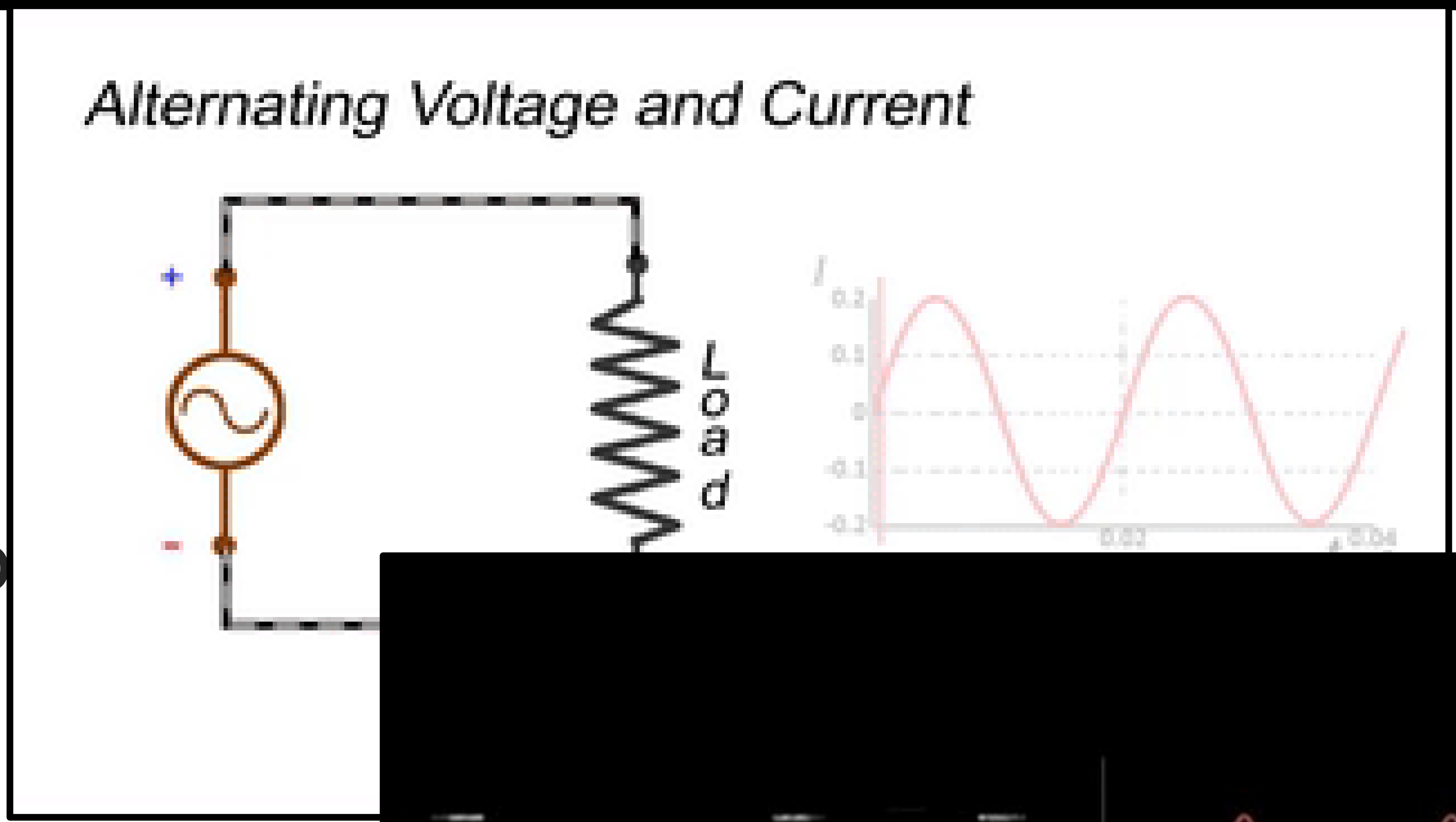


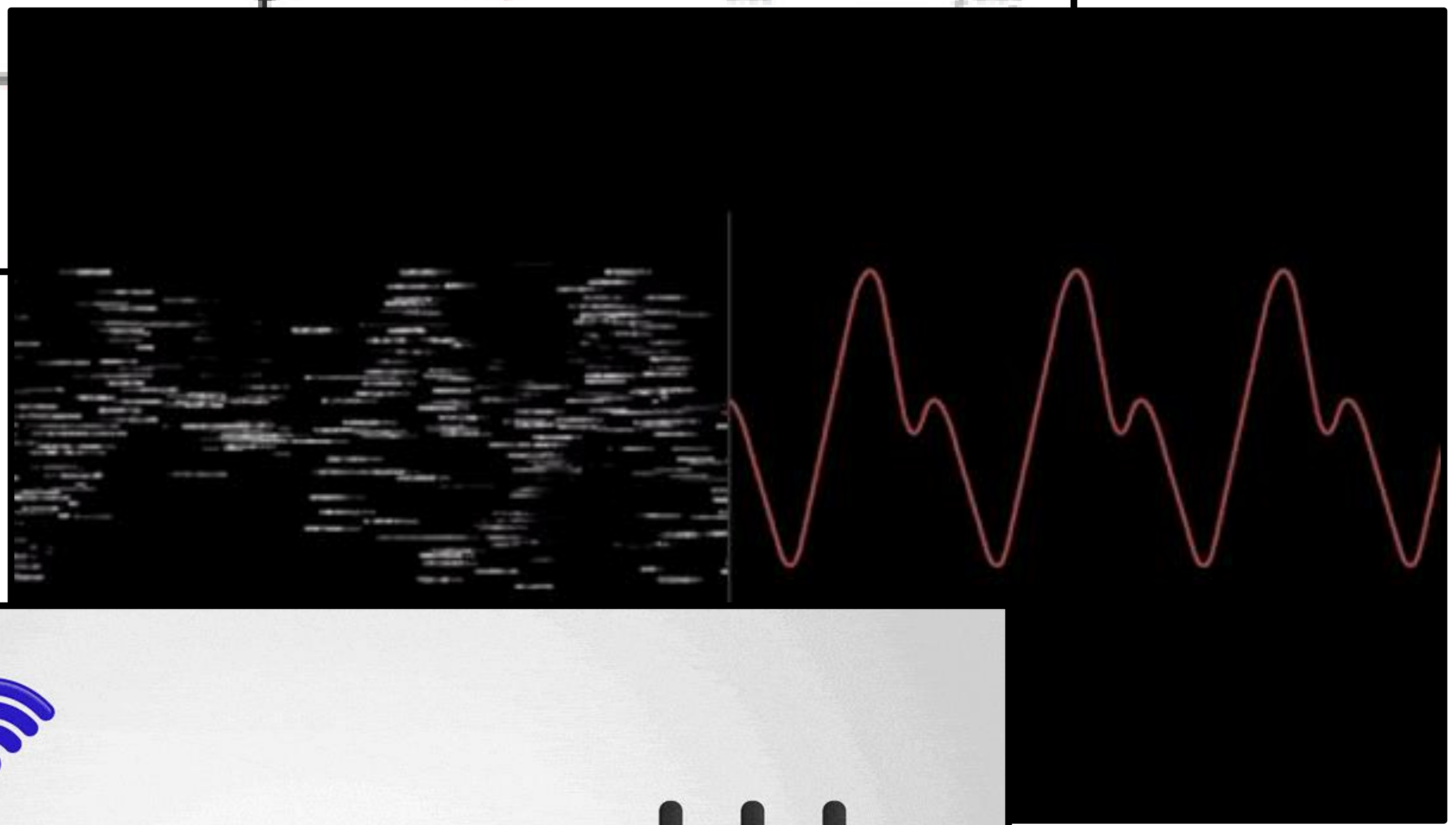
Embedded System Tools & Software Development
(*2 Modules*)

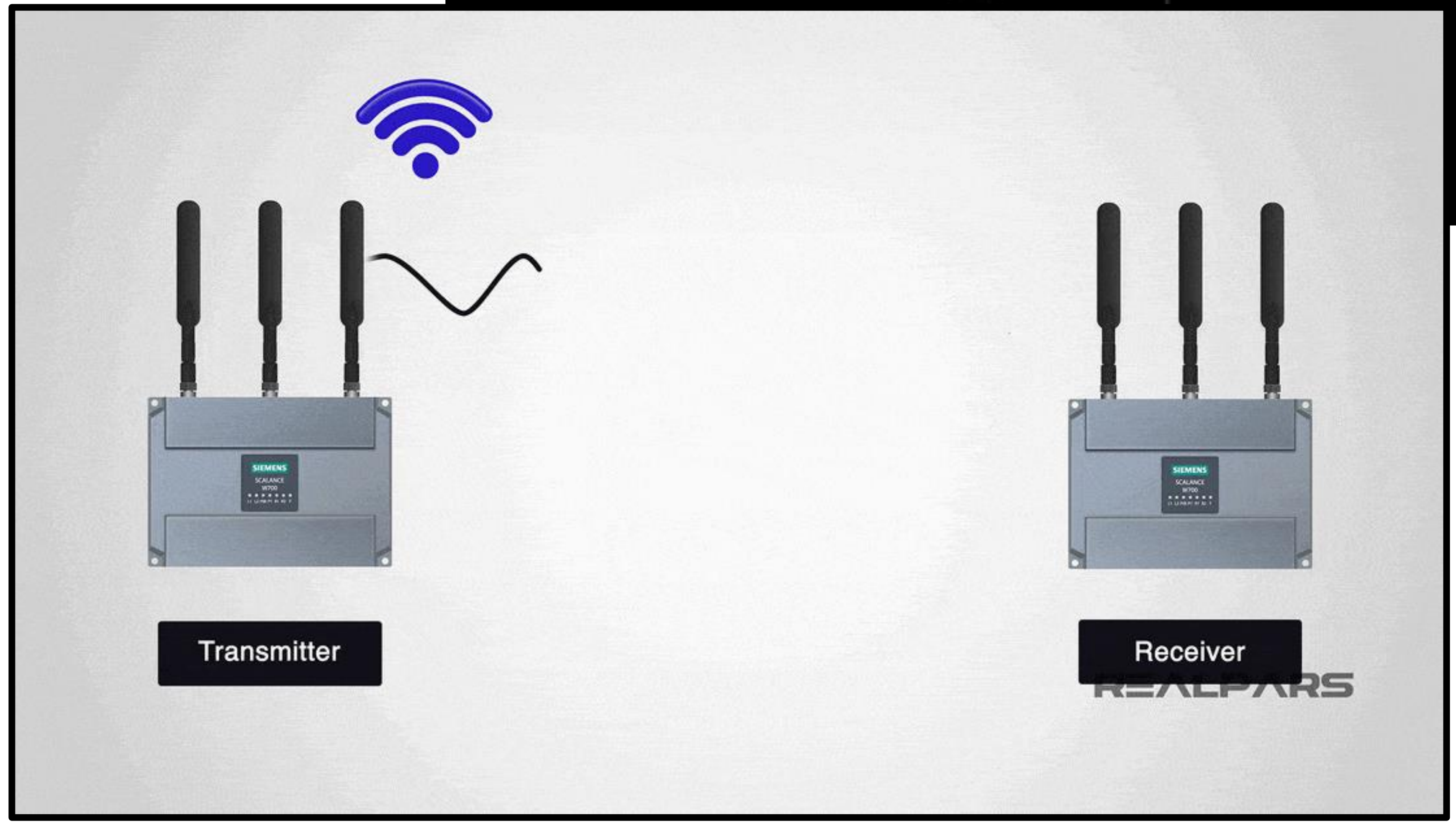
- Debugging techniques
- Interrupts and exception handling
- Memory management

What is a signal?

- The definition of a signal varies depends on the field:
  - ➢**In electronics and telecommunications**, signal refers to any time-varying voltage, current, or electromagnetic wave that carries information.
  - ➢**In signal processing**, signals are analog and digital representations of analog physical quantities.
  - ➢**In information theory**, a signal is a codified message, that is, the sequence of states in a communication channel that encodes a message.
  - ➢**In a communication system**, a transmitter encodes a message to create a signal, which is carried to a receiver by the communication channel.







Signals

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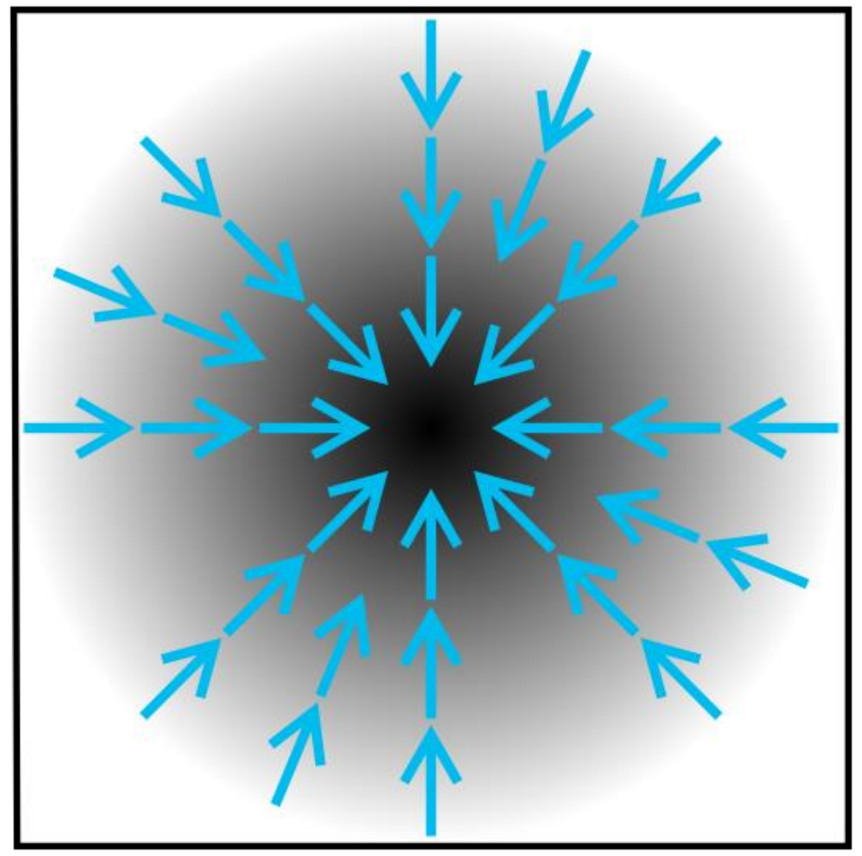
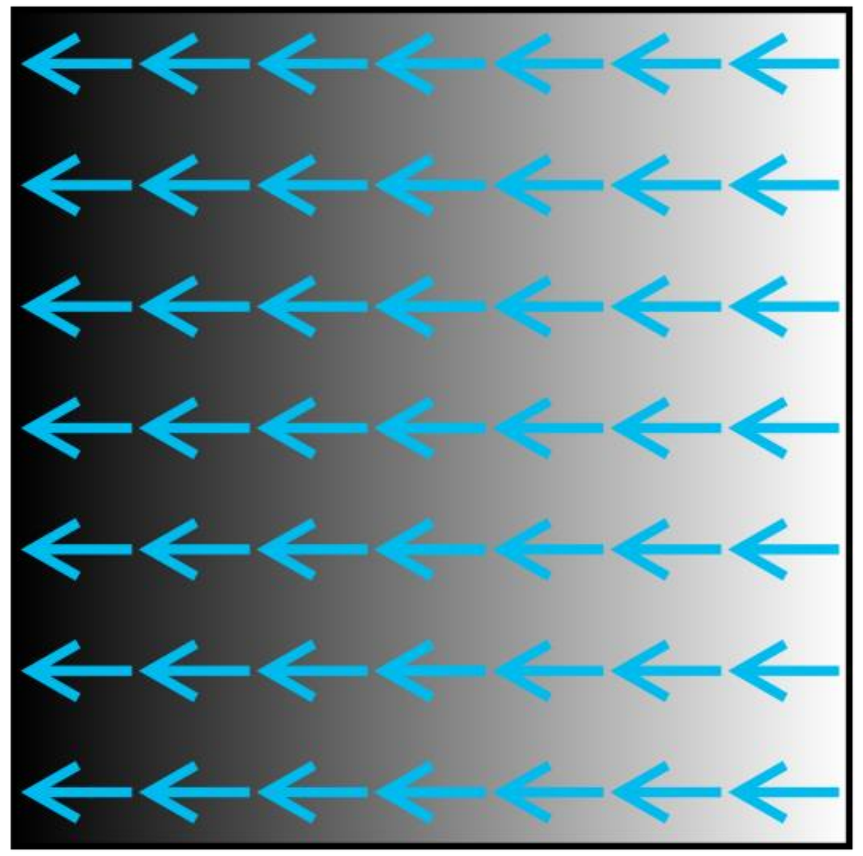
What is a signal?

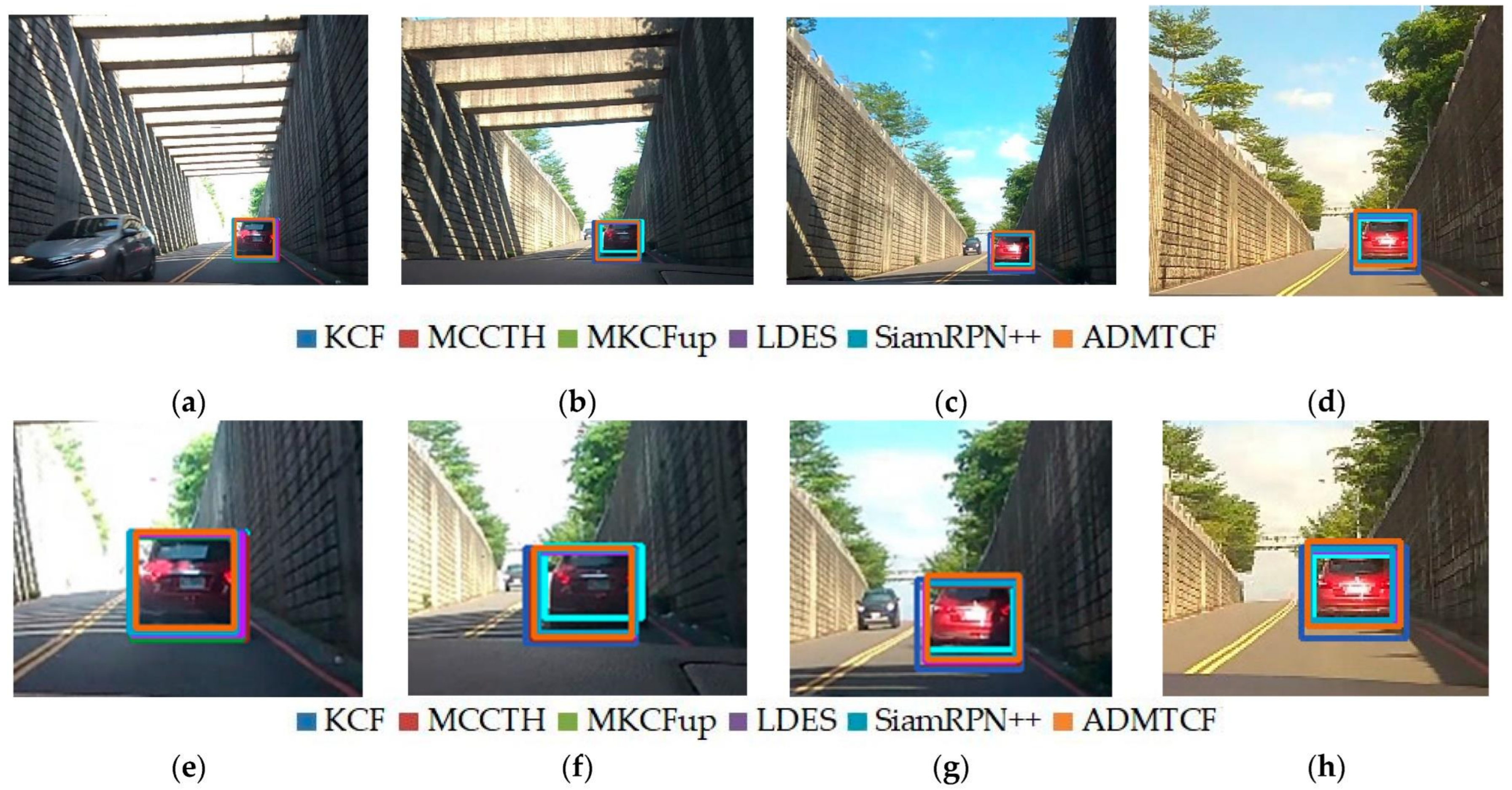
*“A signal is a function that conveys **information about a phenomenon**.”*

*“Any quantity that can vary over **space** or **time** can be used as a signal to share messages between observers.”*

Spatial Signal	***Temporal Signal***
Ex.: In Image Processing, Spatial information applies when you are analyzing one image. It includes but not limited to the coordinates, intensity, gradient, resolution, to name only a few.	Ex.: In Image Processing, Temporal information is when you have a series of images taken at different time. Correlations between the images are often used to monitor the dynamic changes of the object.





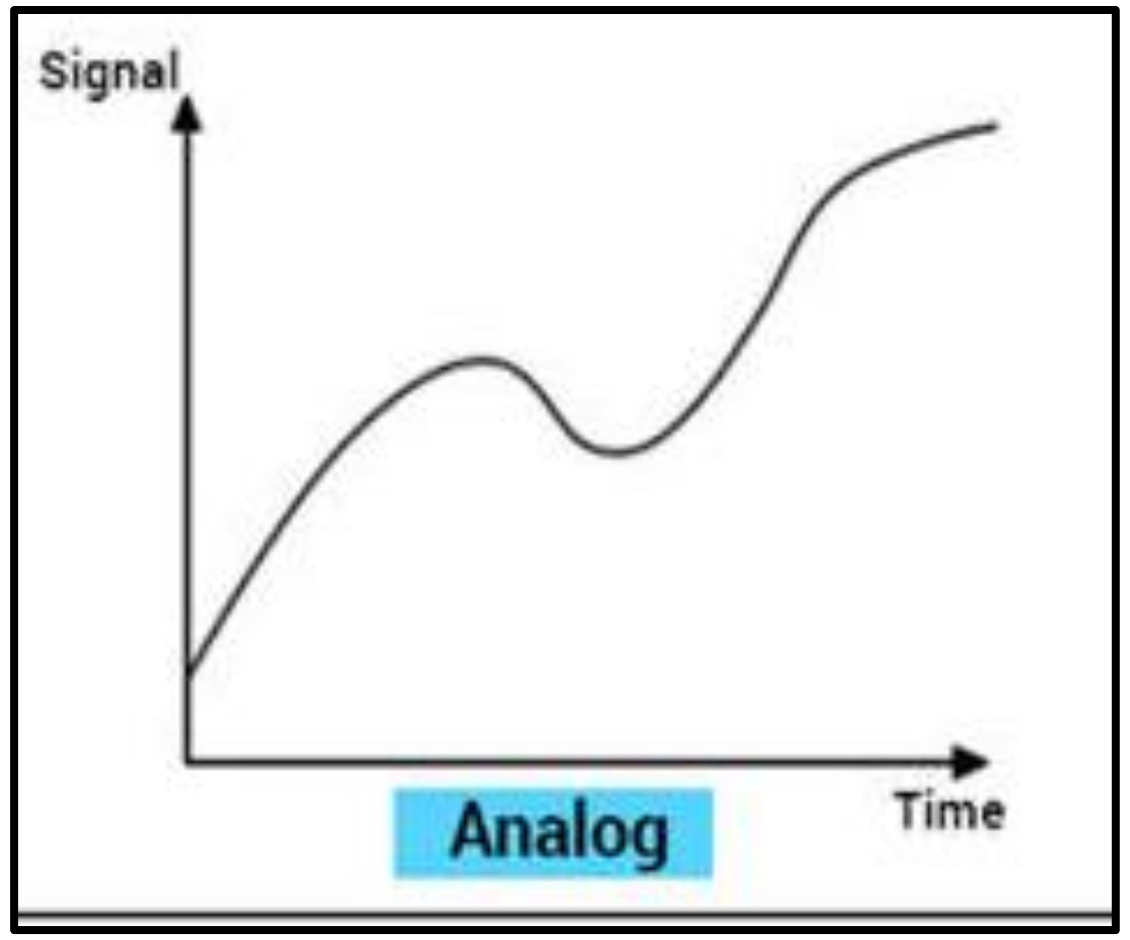


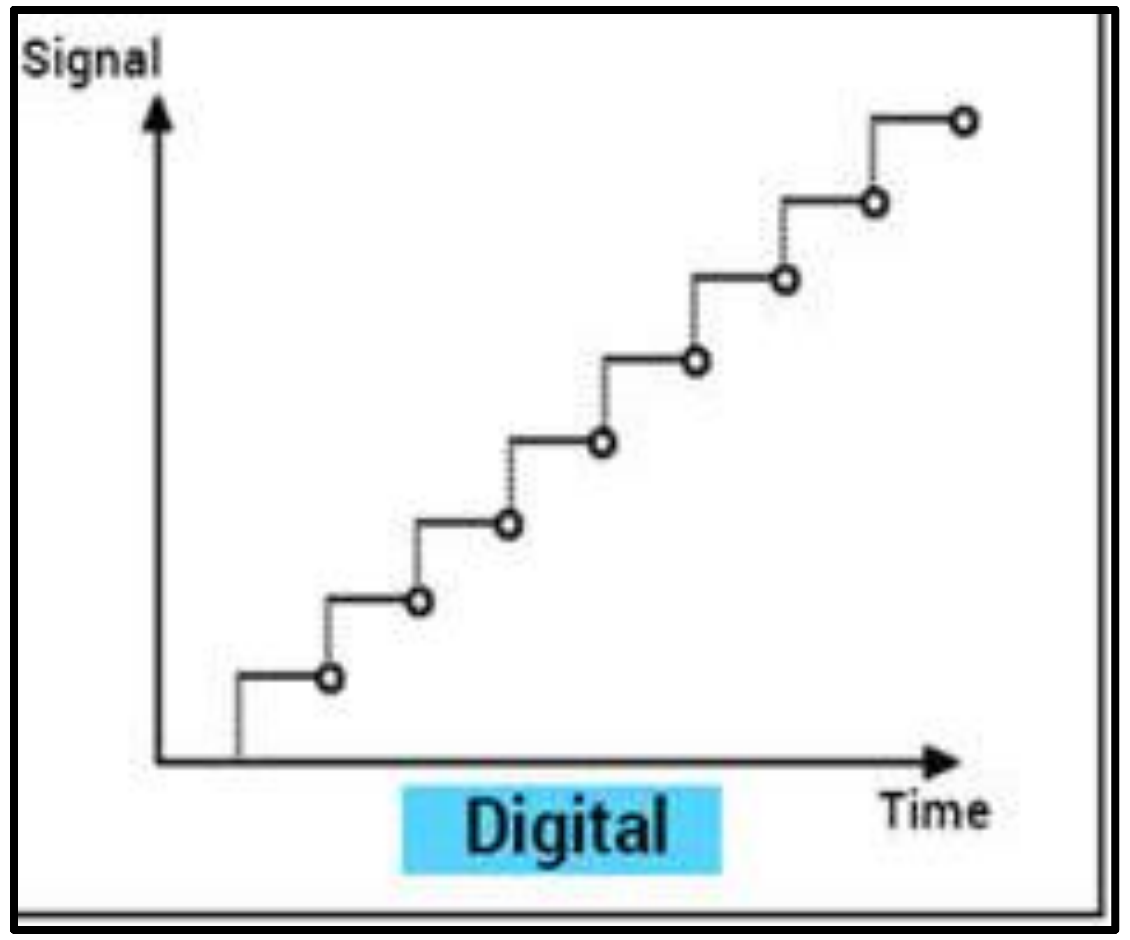
Analog Signal

- An analog signal is any **continuous signal** for which the time-varying feature of the signal is a representation of some other time varying quantity

Digital Signal

- A digital signal is a signal that is constructed from a **discrete set of waveforms** of a physical quantity so as to represent a sequence of discrete values.
- A ***logic signal*** is a digital signal with ***only two possible values***, and describes an arbitrary bit stream.





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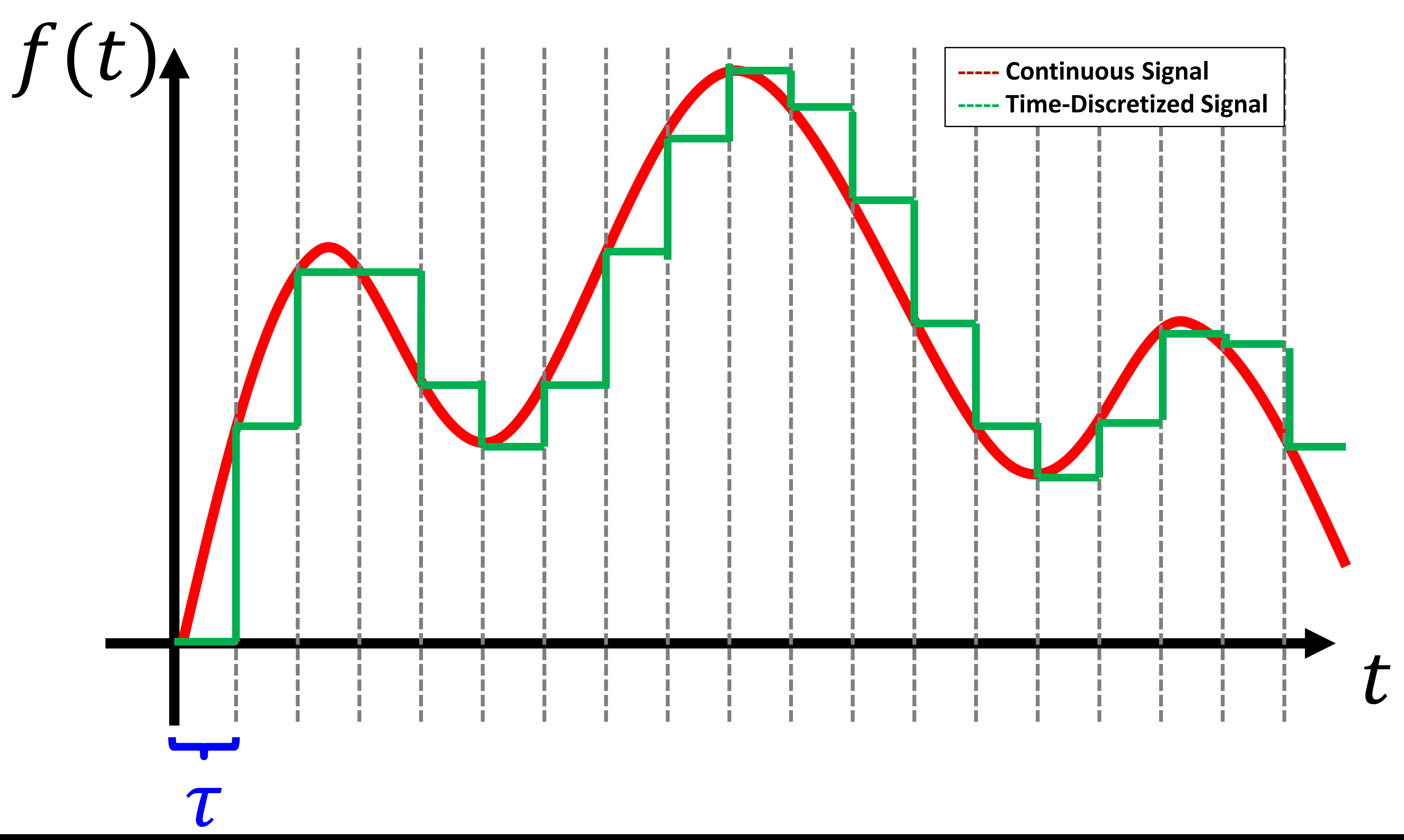
Time Sampling

- The process of sampling your signal, hence changing it from continuous time to discrete time based on a selected time sample τ.

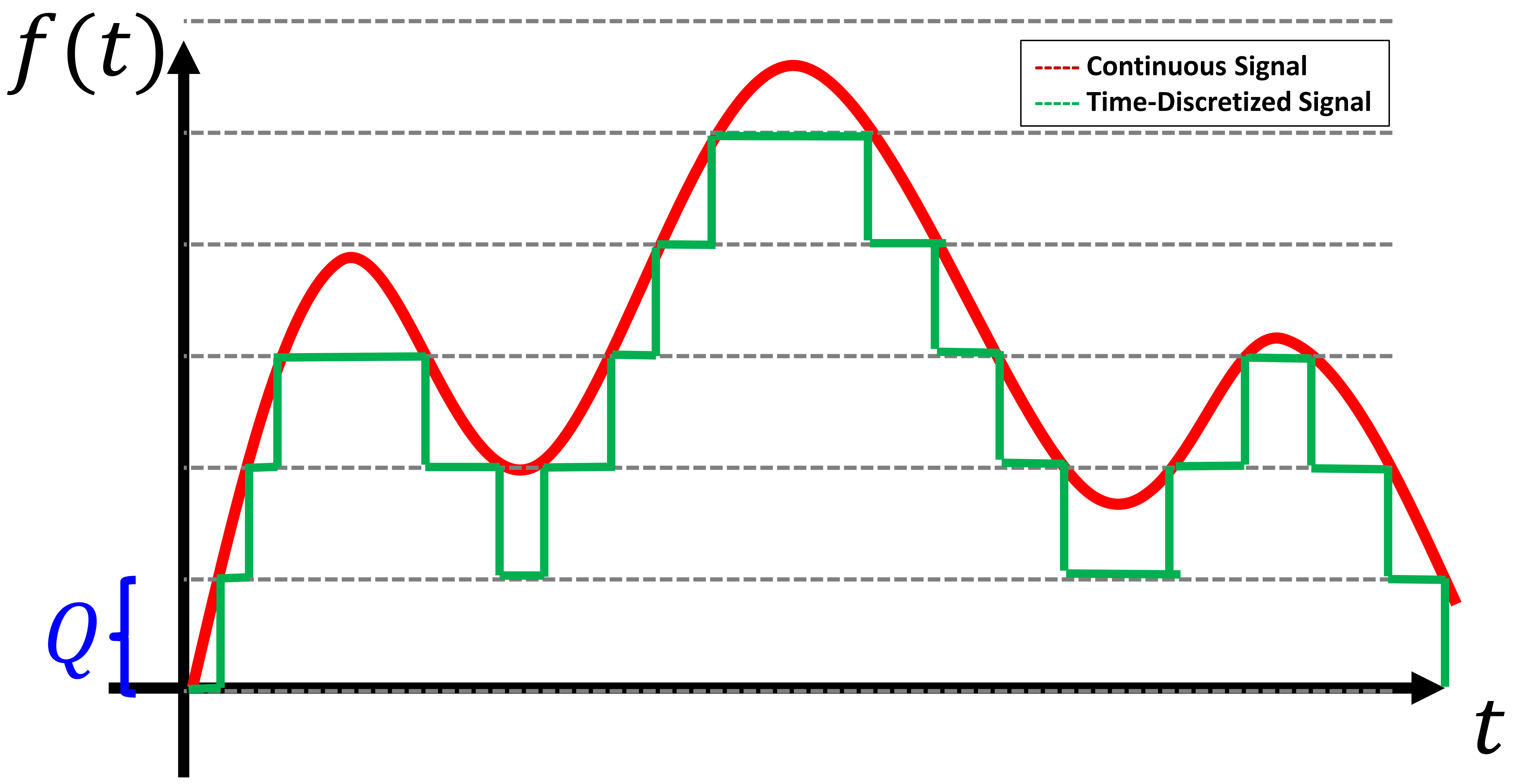
Digitizing the Domain



Amplitude Quantization

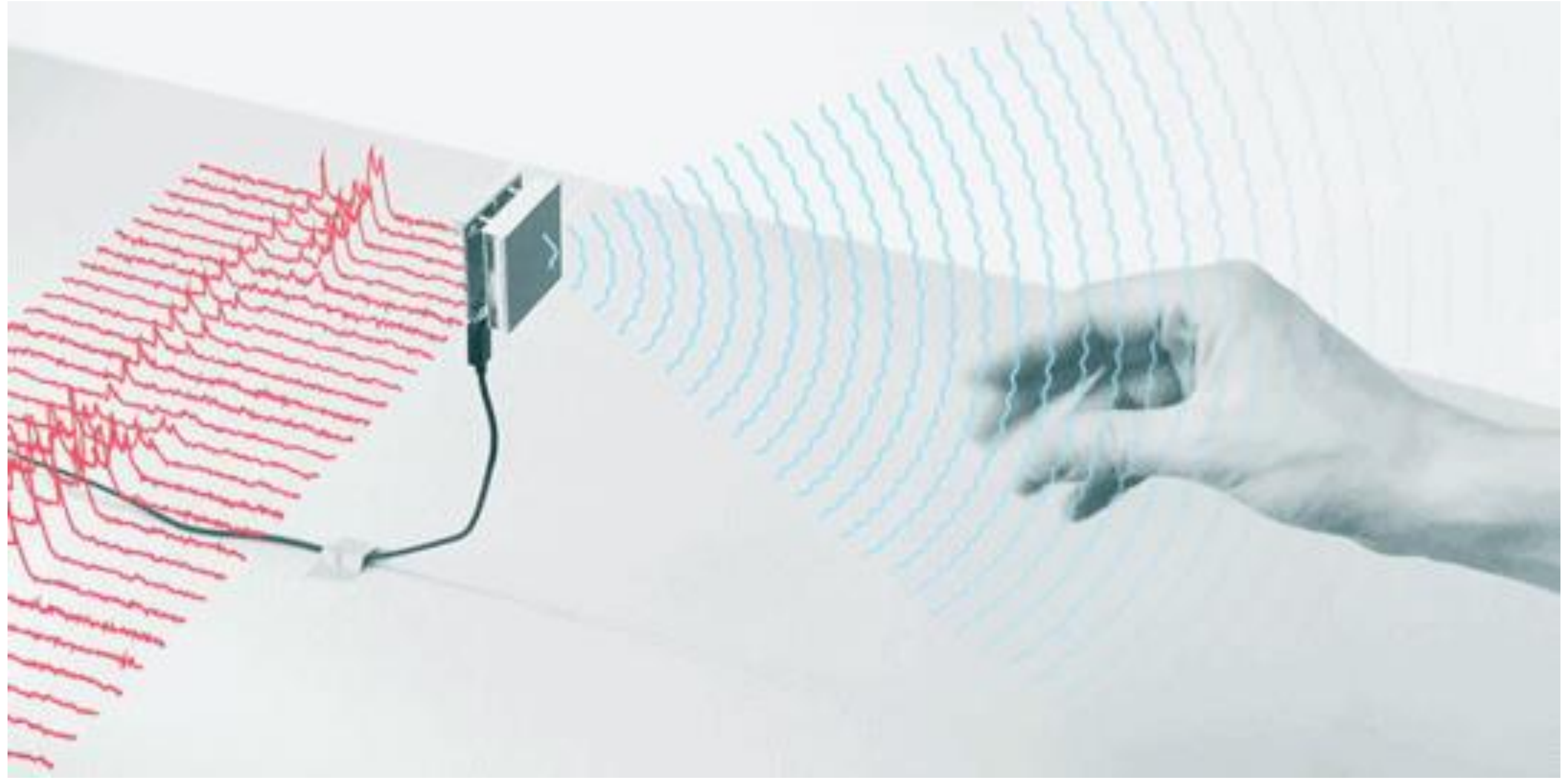
- Quantization is the process of mapping input values from a large continuous set to output values in a smaller countable set based on a selected quantizer Q.

Digitizing the Range



What is a sensor?

- A sensor is a device or component that is used to detect or measure physical properties or changes in the environment and convert them into electrical signals or other readable outputs.
- Sensors are widely used in various fields, including electronics, engineering, automation, and science, to **gather data and enable control systems to respond to changes in their surroundings**.



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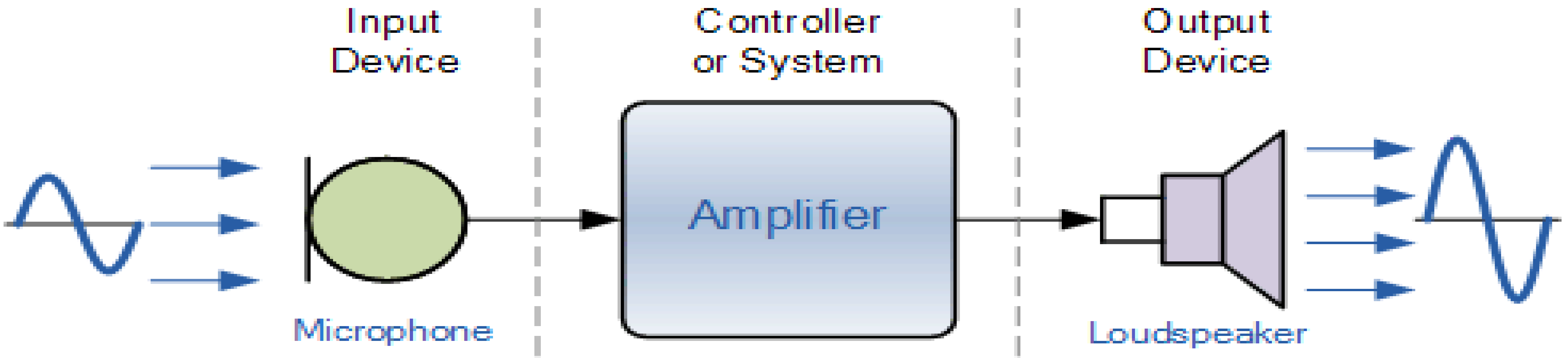
The Process

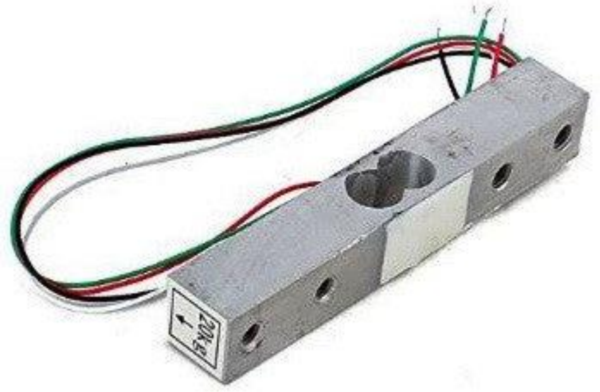
Detection → Transduction → Output



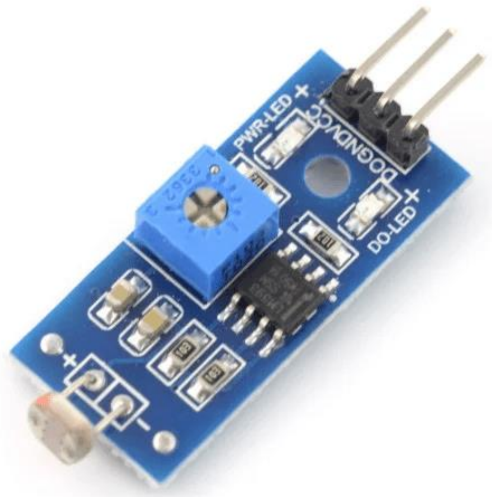
The Process: *Detection*

- Sensors are designed to detect **specific physical phenomena** or properties.
- This can include temperature, pressure, light, sound, humidity, motion, proximity, gas concentration, and many others.

Temperature Sensor

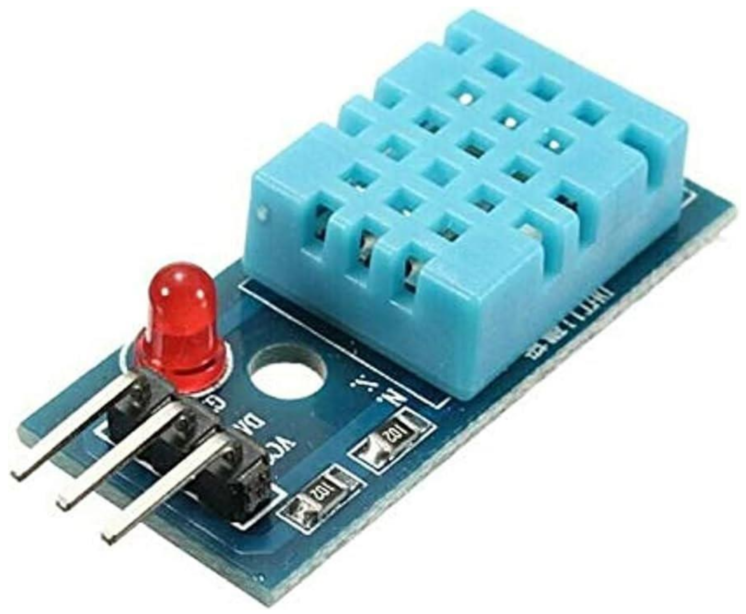


Weight Sensor



Light Sensor

Sound Sensor



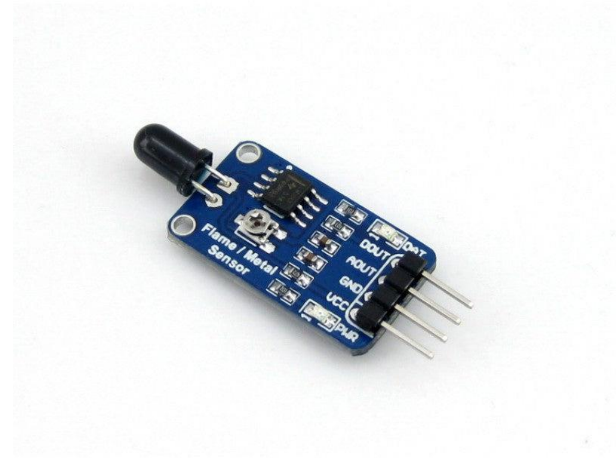
Humidity Sensor

Motion Sensor

Proximity Sensor

Speed Sensor

Distance Sensor



Flame Sensor

The Process: *Transduction*

- When a sensor detects a physical phenomenon, it **converts it into a measurable signal**.
- This measurable signal can be
  - ➢Electrical,
  - ➢Optical,
  - ➢Mechanical, or
  - ➢Another form depending on the type of sensor.

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The Process: *Output*

- Sensors produce an **output signal that represents the detected data or property**.
- This output signal can take various forms, such as:
  - ➢Voltage,
  - ➢Current,
  - ➢Frequency,
  - ➢Resistance, or
  - ➢Digital data.

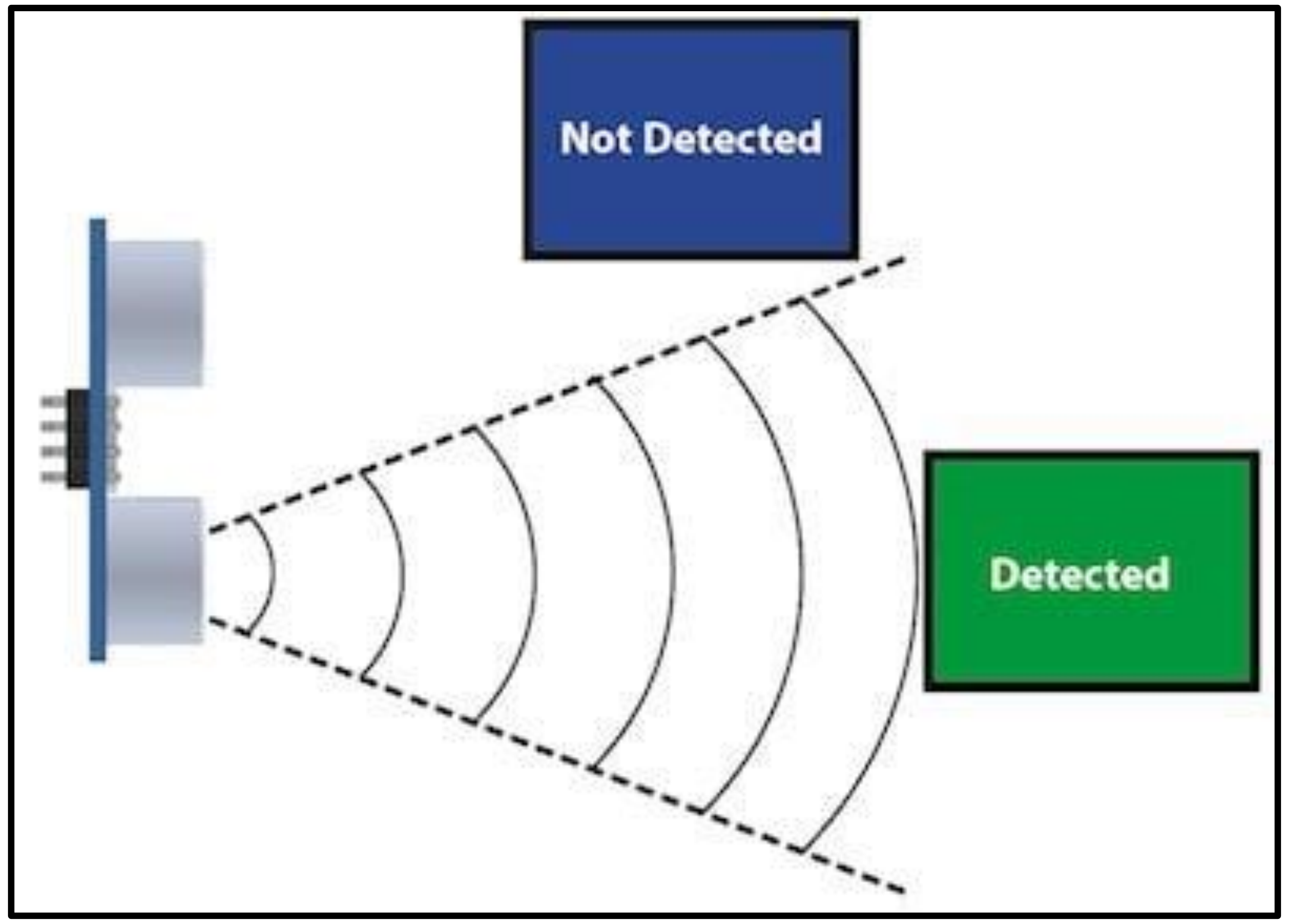
Sensor Characteristics

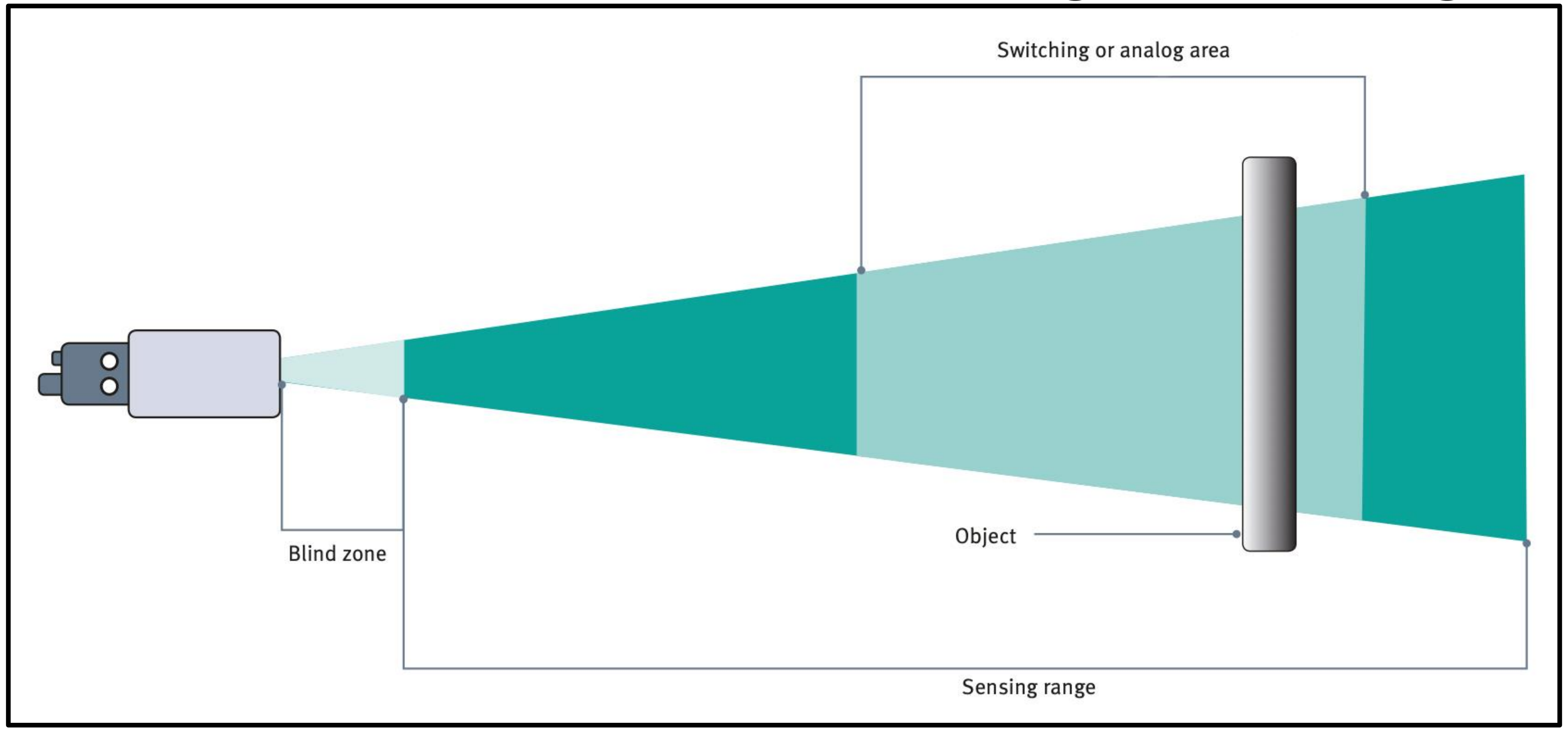
- The common measurement characteristics of a sensor include various parameters and properties that define **how a sensor performs its intended function**.
- These characteristics are essential for understanding **the sensor's capabilities and limitations**.
- The sensor characteristics can either be obtained either from the **datasheet** or **empirically** via trials.

Sensor Characteristics: *Range*

- Sensors have a **specific operating range** within which they can accurately detect and measure properties.
- Going beyond this range may result in **inaccurate readings** or sensor damage.
- ***Example:***

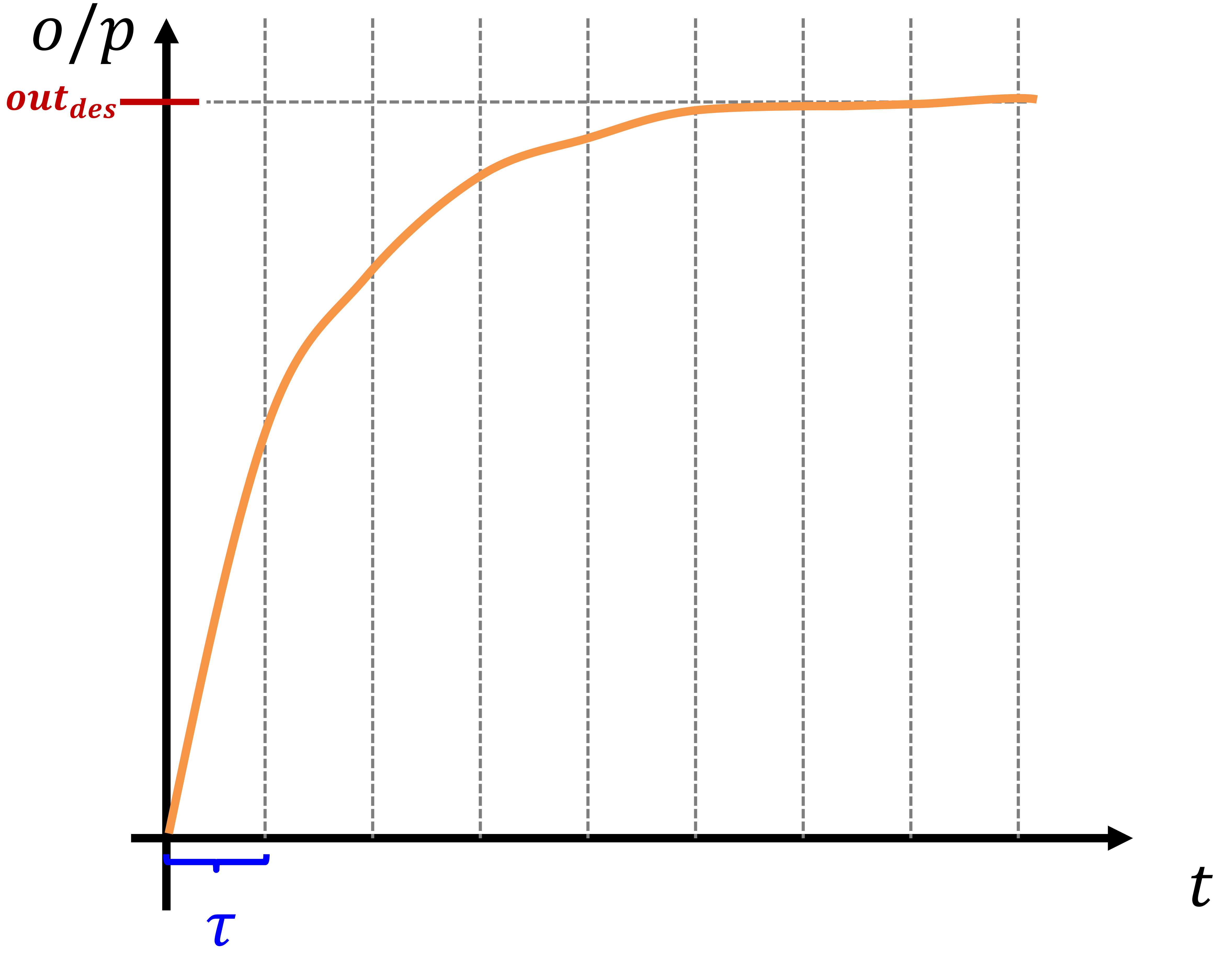
An ultrasonic sensor is used for distance detection has both radial and longitudinal range.





Sensor Characteristics: *Responsiveness*

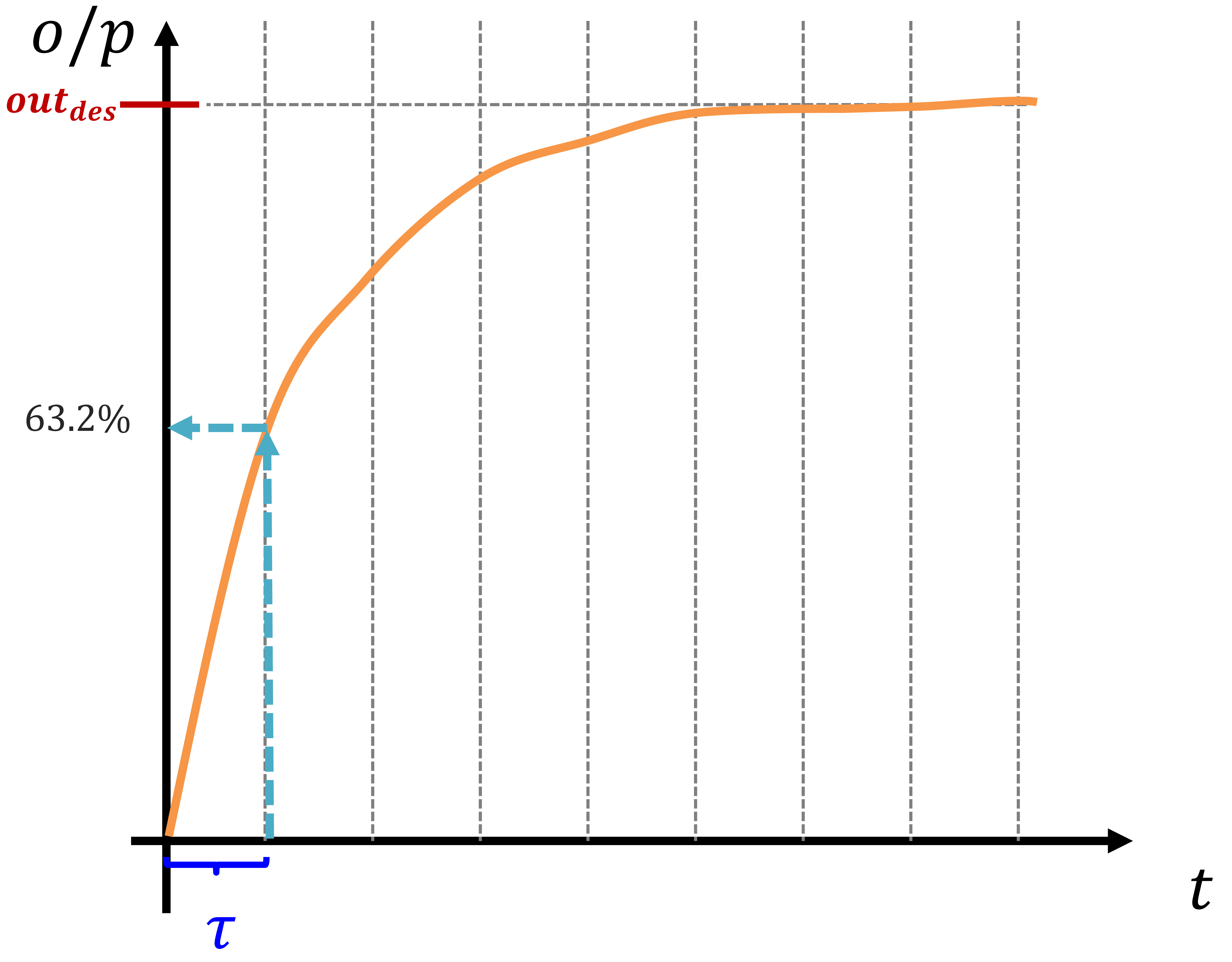
- Responsiveness indicates **how quickly a sensor can detect** and respond to changes in the property being measured.
- It is often defined as the time it takes for **the sensor's output to reach a certain percentage of its final value** after a step change in input.



Sensor Characteristics: *Responsiveness*

- Responsiveness of any sensor is usually given as a **Time Constant τ**.
- It is defined as the time required for the sensor reading/output to reach to 63.2% of its total step change in measurand.
- ***Example:***

  For a temperature sensor taken out of an ice bath at 0 °C into a room at 10 °C, it will take exactly one time constant (usually given in seconds) to reach 6.32 °C, which is exactly 63.2% of the 10 °C step change in temperature.



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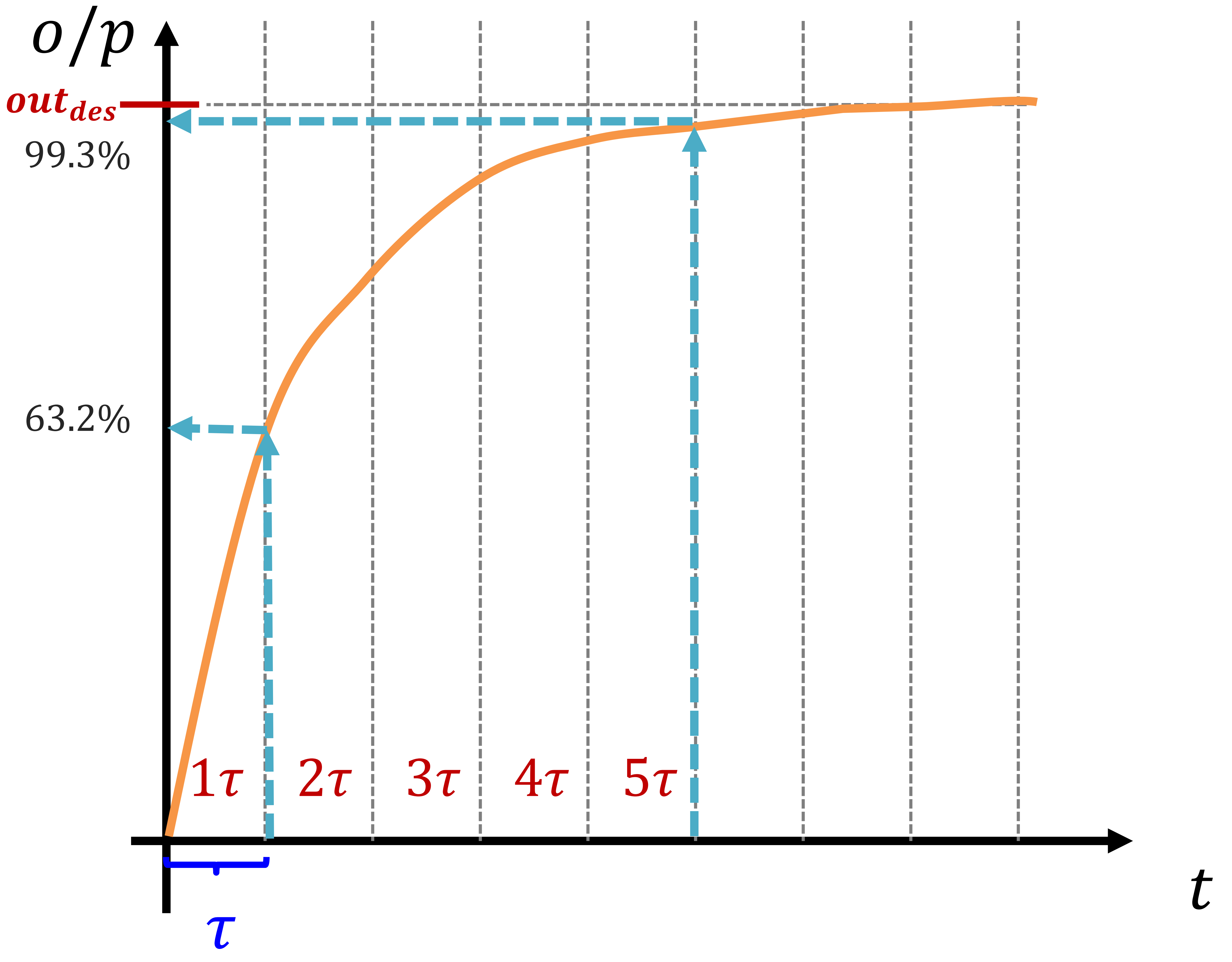
Sensor Characteristics: *Responsiveness*

- The Time Constant of a sensor is very different than its **Response Time**.
- In fact, the response time is exactly five times the time constant.

$$Response\ Time = 5 \times \tau$$

- Response Time is the time for the sensor reading to reach 99.3% of the total step change in measurand.
- ***Example:***

  For a temperature sensor taken out of an ice bath at 0 °C into a room at 10 °C, it will take exactly five time constants (five times longer) to reach 9.93 °C, which is exactly 99.3% of the 10 °C step change in temperature.



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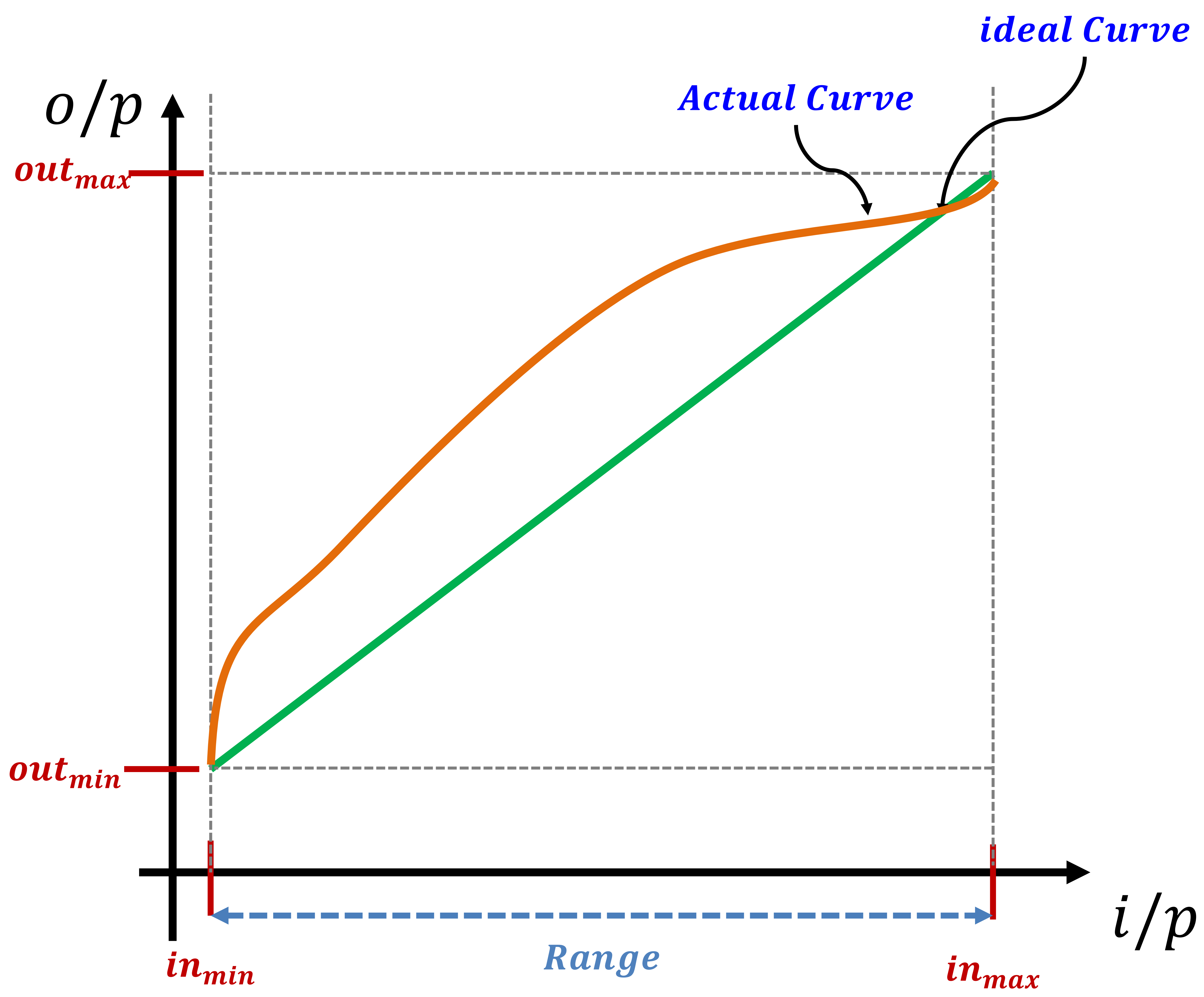
Sensor Characteristics: *Characteristic Curve*

- A sensor characteristic curve is also known as a sensor **response** curve or **calibration** curve.
- It is a graphical representation that illustrates the **relationship between the input** (or measured) quantity and the **output** signal or response of a sensor.
- This curve provides valuable information about **how a sensor responds to changes in the property it is designed to measure**.

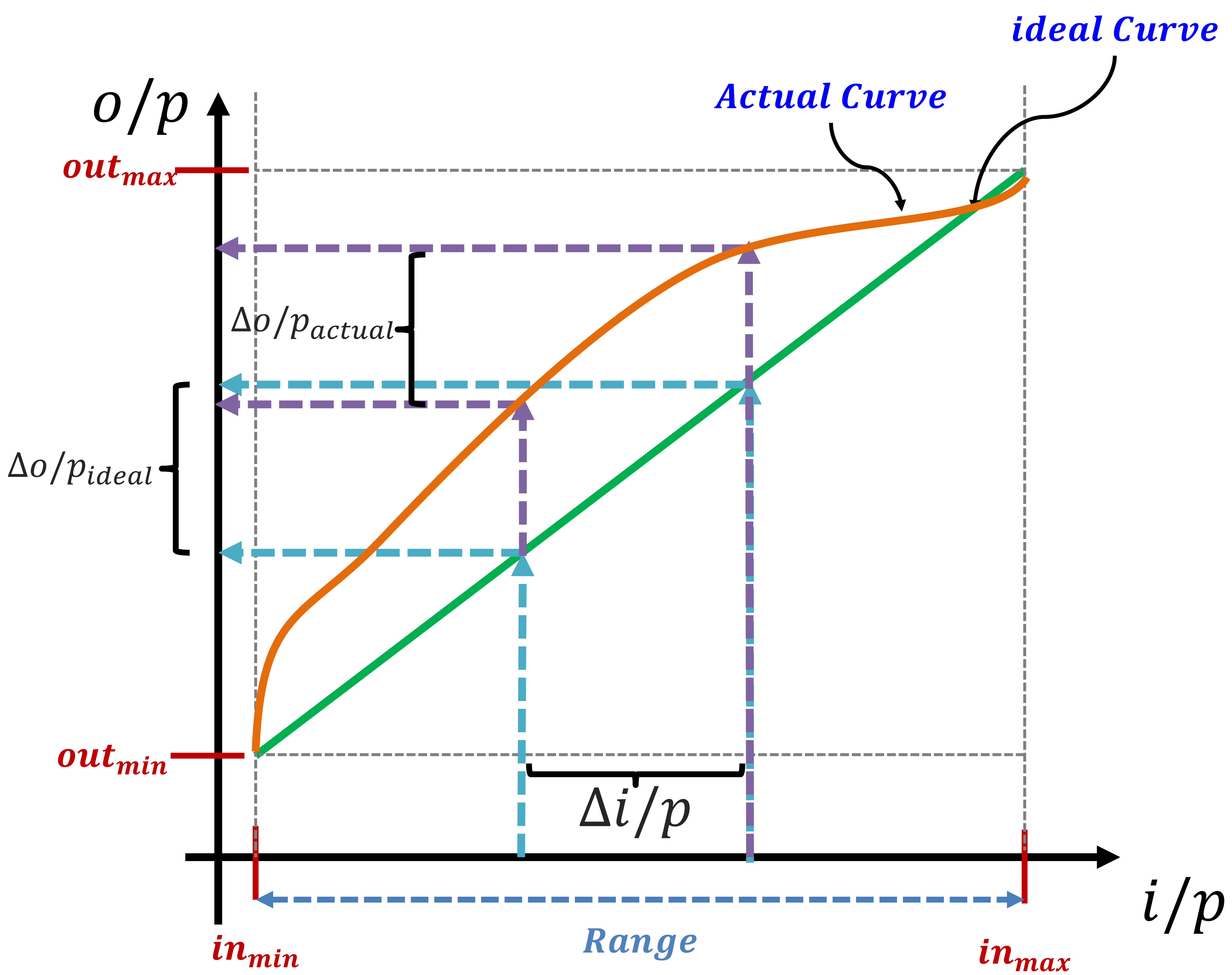


Sensor Characteristics: *Sensitivity*

- Sensitivity measures how much the **sensor's output changes in response to a unit change** in the property being measured.
- The ideal sensitivity can be measured as the slope of the curve.

$$Sensitivity_{ideal} = \frac{\Delta o/p_{ideal}}{\Delta i/p}$$

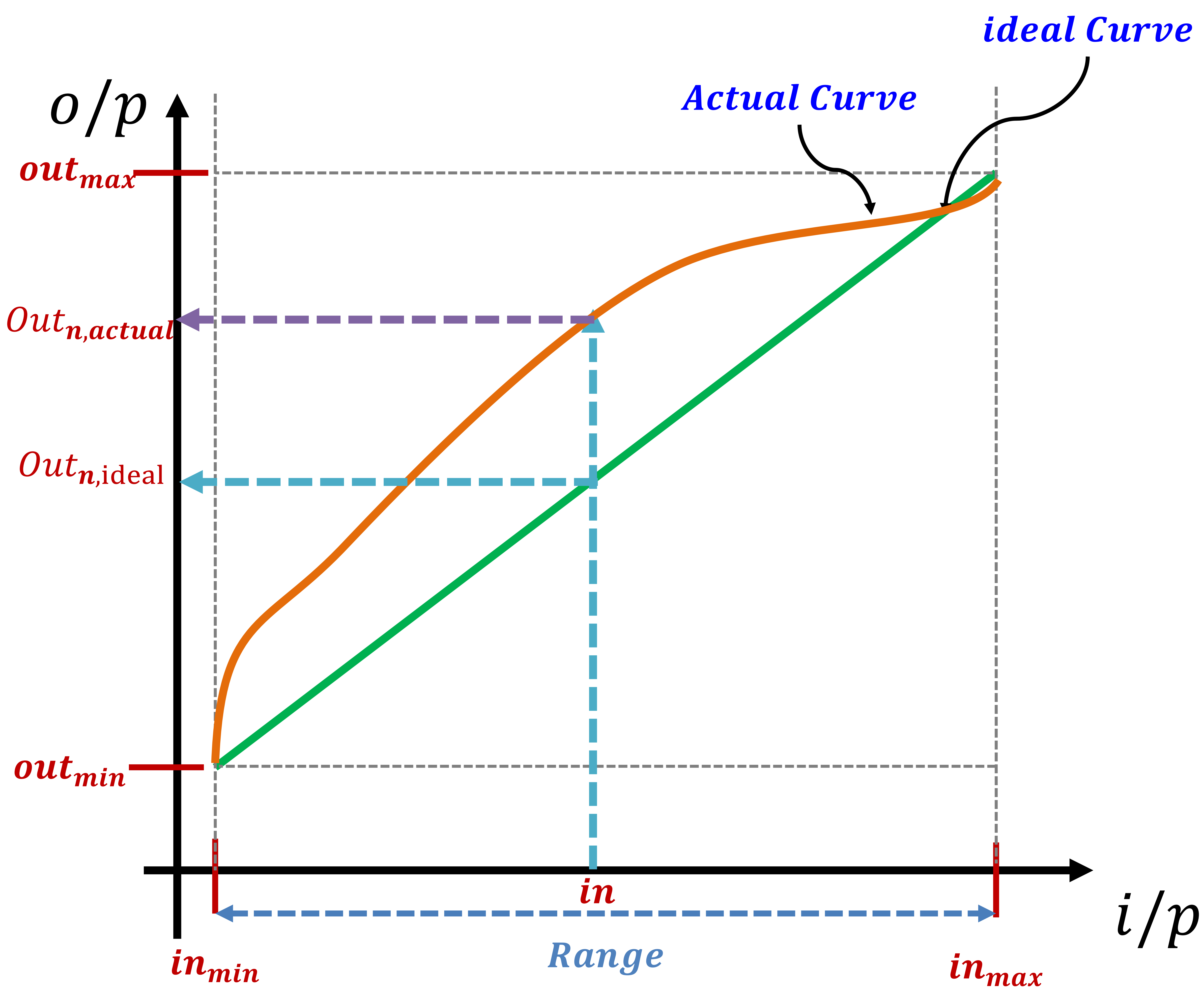
- The actual sensitivity can be measured as the slope of the curve at each point.
- A **highly sensitive** sensor will produce a **significant output change** for a **small input change**.



Sensor Characteristics: *Measurement Error*

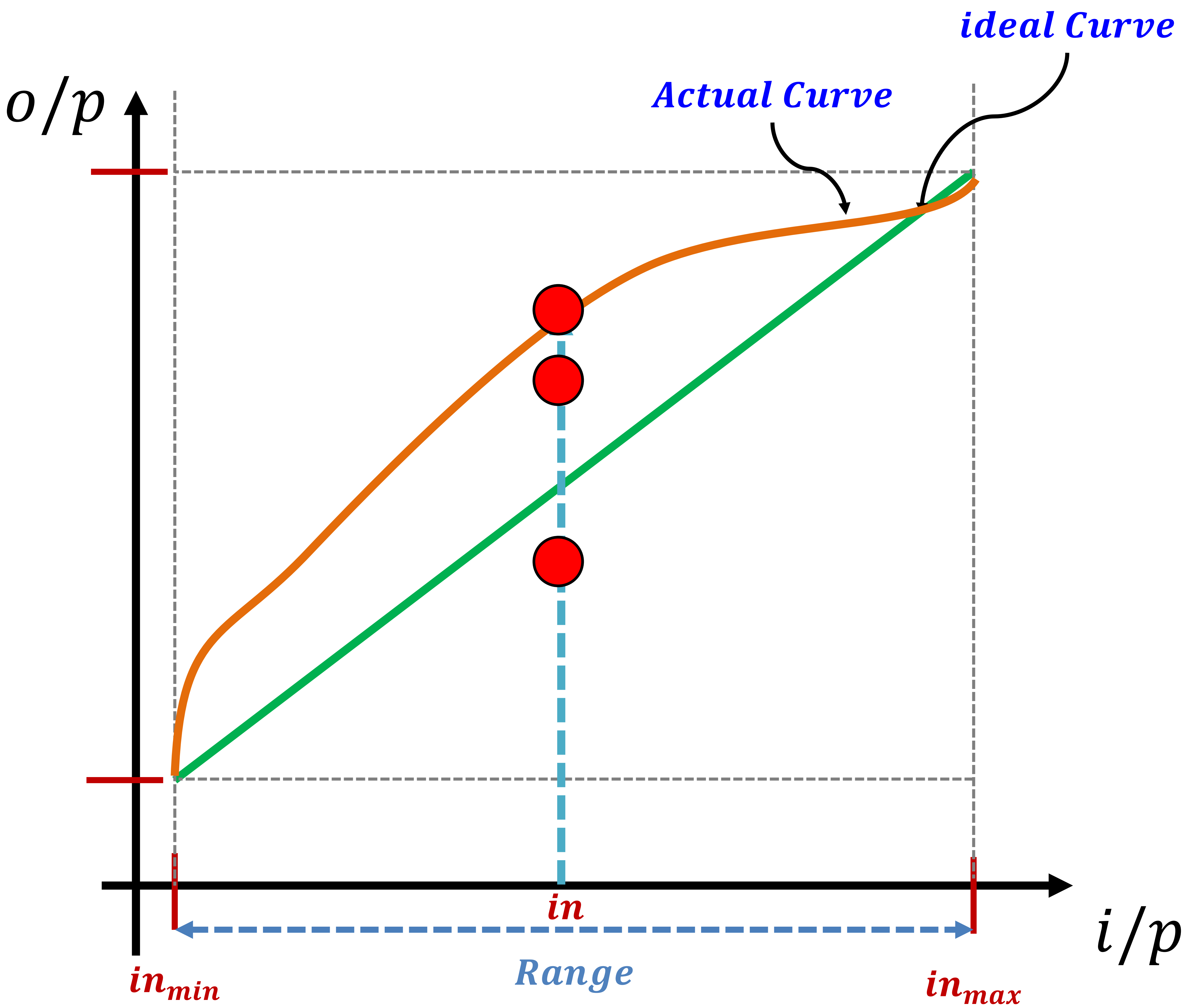
- In any real application, there exist a difference between the actual measurement acquired from the sensor, and the ideal value of the state measured.

$$\varepsilon_n = Out_{n,ideal} - Out_{n,actual}$$



Sensor Characteristics: *Accuracy*

- The accuracy of a sensor refers to how closely its output matches the actual value of the property being measured.
- Sensor accuracy is a critical factor in many applications.



Sensor Characteristics: *Accuracy*

- To be able to **assess the quality** of a specific measurement, the **accuracy of the n^{th} measurement** can be calculated as:

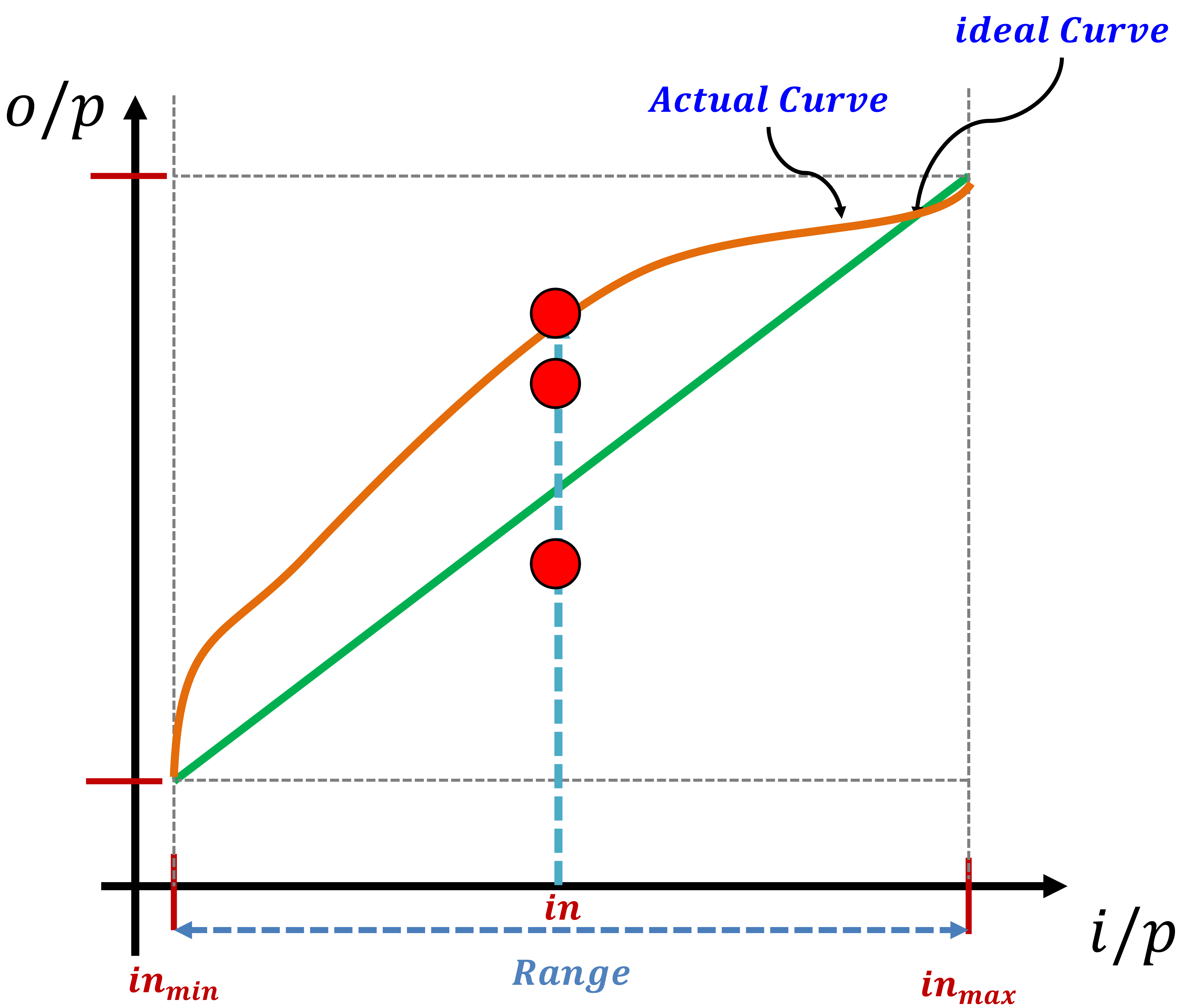
$$Accuracy_n = 1 - \left|\frac{Out_{n,ideal} - Out_{n,actual}}{Out_{n,ideal}}\right|$$

- ***Example:***
  - ➢ Given that the temperature being measured is **actually** $(25° \, C)$.
  - ➢ Given that the sensor provides a **measurement** of $(25.2° \, C)$.
  - ➢ Then the **accuracy** of this measurement is:

$$Acc_i = 1 - \left|\frac{25 - 25.2}{25}\right|$$

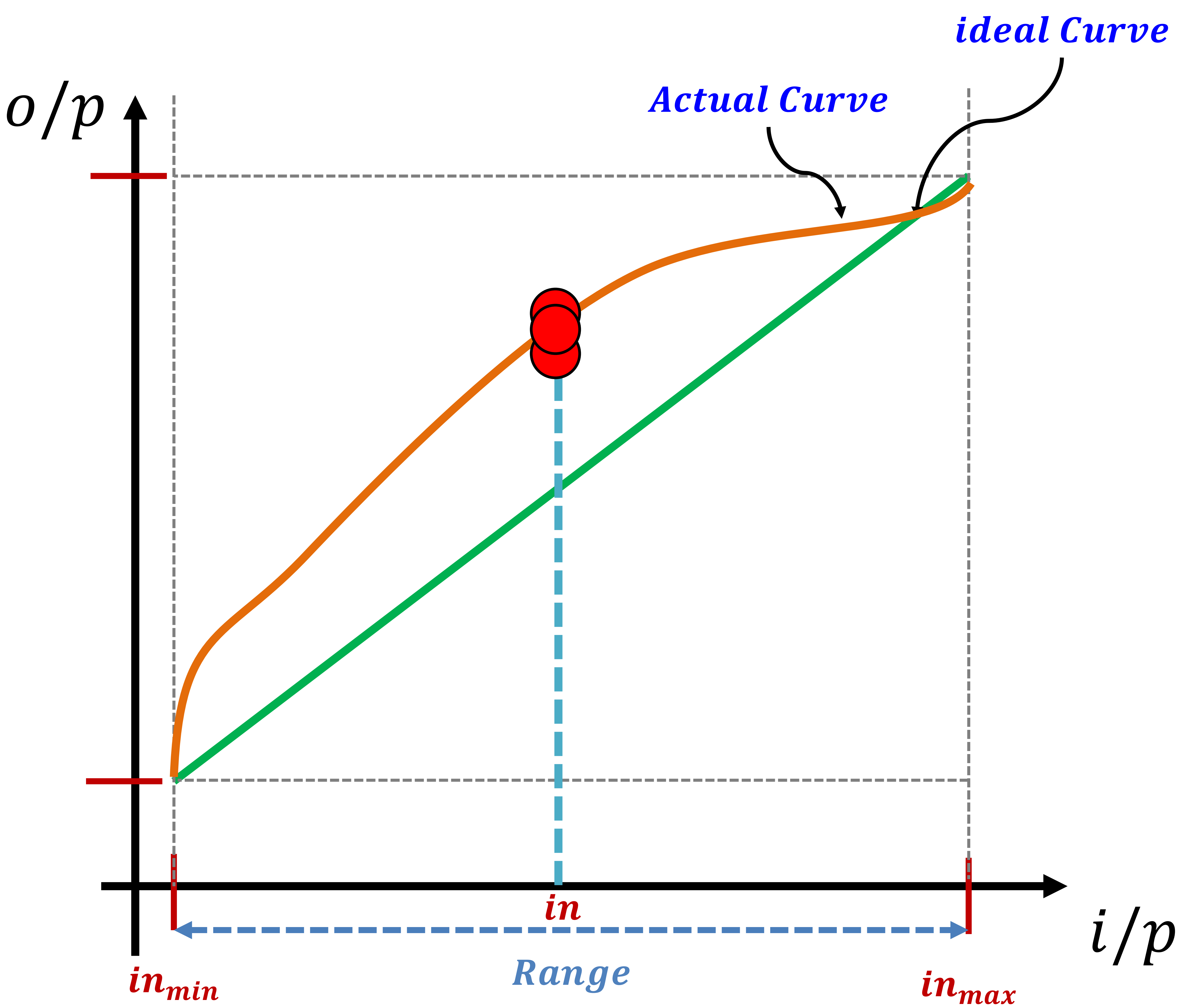
  - ➢ Thus,

$$Acc_i = 1 - \left|\frac{-0.2}{25}\right| = 1 - 0.008 = 0.992 = \mathbf{99.2\%}$$



Sensor Characteristics: *Precision*

- Precision, also known as **repeatability**, indicates **how consistently a sensor produces the same output for repeated measurements of the same input under the same conditions.**
- It quantifies the sensor's ability to provide consistent results.



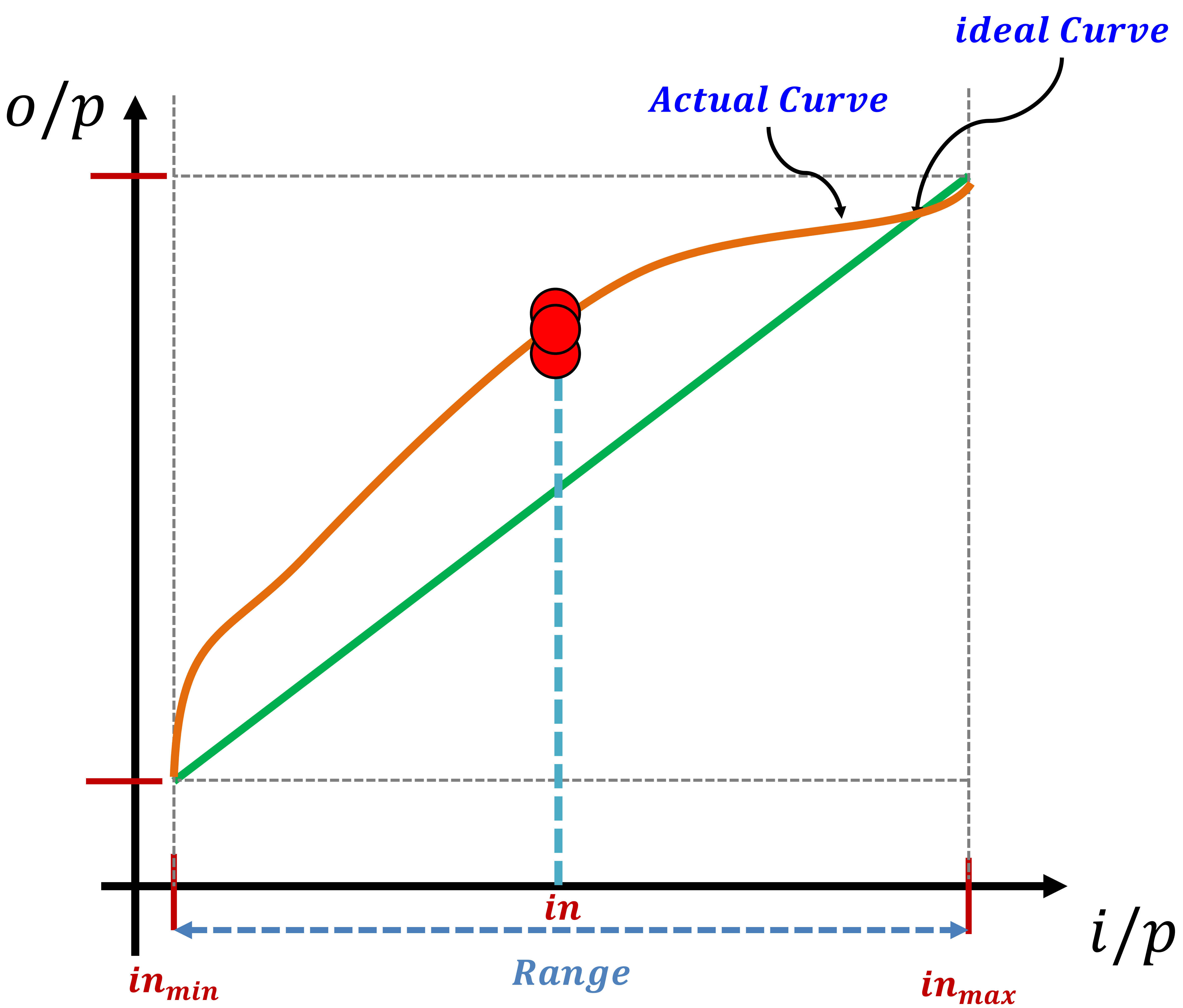
Sensor Characteristics: *Precision*

- To be able to **assess the repeatability** of a specific **measurement**, the **precision of the n^{th} measurement** can be calculated as:

$$\boldsymbol{Precision_n = 1 - \left|\frac{Out_{n,actual} - \overline{Out}}{\overline{Out}}\right|}$$

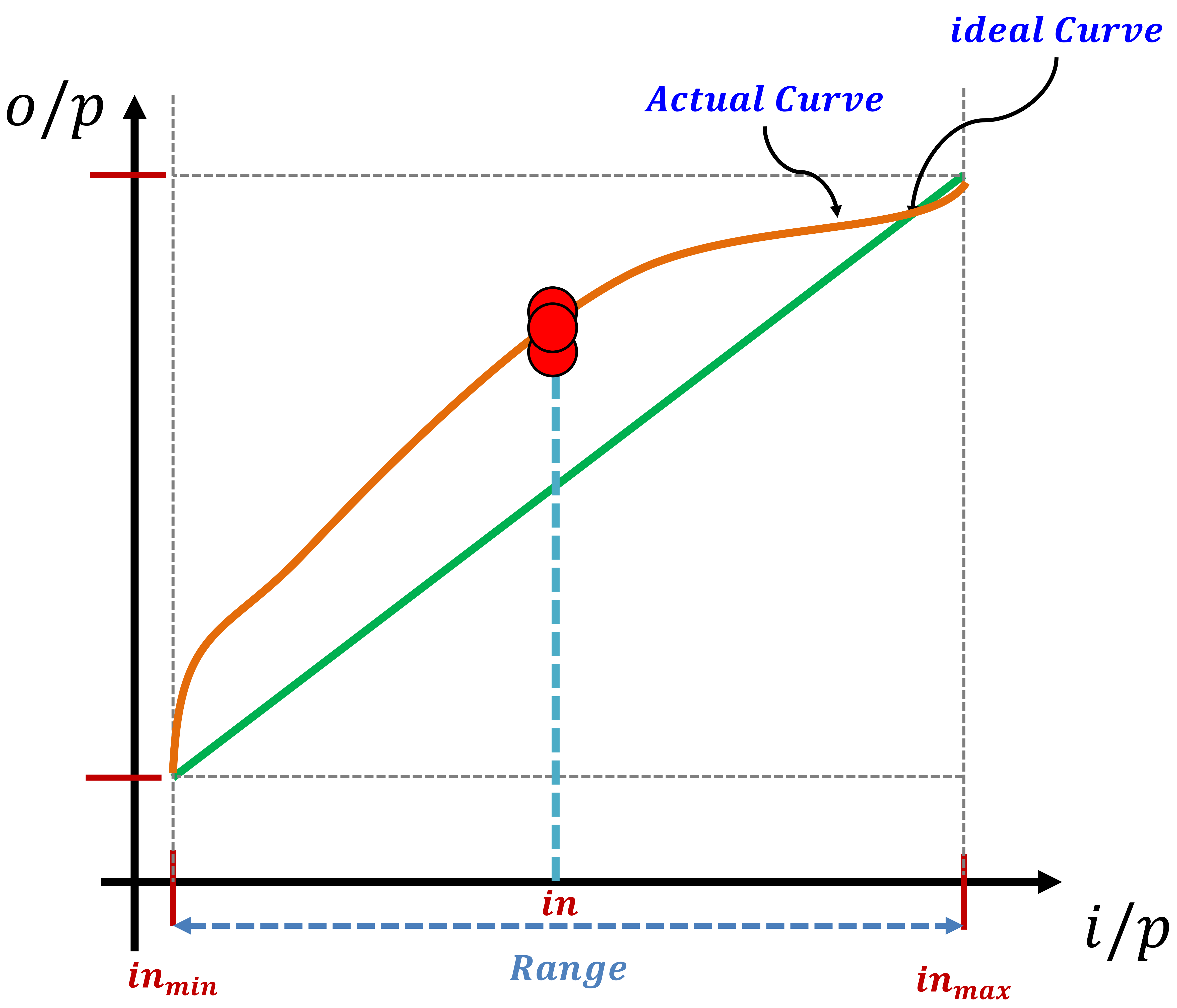
- Where $\overline{Out}$ is the **mean** of different readings, which can be calculated as above and (N) is the **total number** of samples taken in the experiment.

$$\boldsymbol{\overline{Out} = \frac{1}{N}\sum_{n=1}^{N} Out_{n,actual}}$$



Sensor Characteristics: *Precision*

- ***Example:***
  - Given that the temperature being measured is **actually** $(25° \, C)$.
  - Given that the sensor provides a **group of readings** as follows: $[\,25.2, \;\; 24.8, \;\; 25.3, \;\; 24.9, \;\; 25.1]°\,C.$
  - The **average** of these readings is: $\mathbf{25.06°\,C}$
  - Then the **precision** of the 1st measurement is:
  - $Precision_1 = 1 - \left|\frac{25.2-25.06}{25.06}\right|$
  - Thus, $Precision_1 = 1 - \left|\frac{0.14}{25.06}\right| = 1 - 0.0056 = 0.9944 = \mathbf{99.44\%}$



Sensor Characteristics: *Resolution*

- Resolution refers to the **smallest detectable change** in the property being measured.
- **High-resolution** sensors can detect **small changes** with **precision**.

- The sensor **resolution** is highly coupled with the previously discussed concept of **signals**.
- It is also coupled with the **microcontroller** that processes the measured signal by the sensor.
- In order to understand the resolution, let's discuss one important peripheral (interface technique) in any microcontroller which is the **Analog-to-Digital Converter (ADC).**

For Further Inquiries, Please send an email

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Thank you for your attention!

See you next time ☺