NUS National University of Singapore

EE5060
Smart Sensors and Instrumentation

EE5111
Industrial Control and Instrumentation

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Contacts

- You may contact me via

  Phone **+65-89164791** (emergencies)

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- Class WhatsApp group/WeChat group:
  - Maintain communication after class
  - A place for you to discuss anytime, anywhere, and to exchange information (not limited to this module: technical trends, start-up ideas, jobs opportunities, and more…)
  - Remember: I will not be always monitoring the messages in this group.

Continuous Assessment (CA)

Important information:

- Project end time and date: All results must be submitted by **11:59pm, FRIDAY 17-OCT-2021** to LumiNUS (folder: **CA1-submission**).
- Submission: **Report** and **codes** in one zip file with name: **your_NUS_ID.zip**, e.g., A0123456X.zip.
- Please always remain contactable during the semester.
- Format of the report: Use IEEE Templates for Conference Proceedings. **No more than five (≤5) pages** allowed. The template (word/tex) have been uploaded to LumiNUS.

  You may also download it from
  https://www.ieee.org/conferences/publishing/templates.html

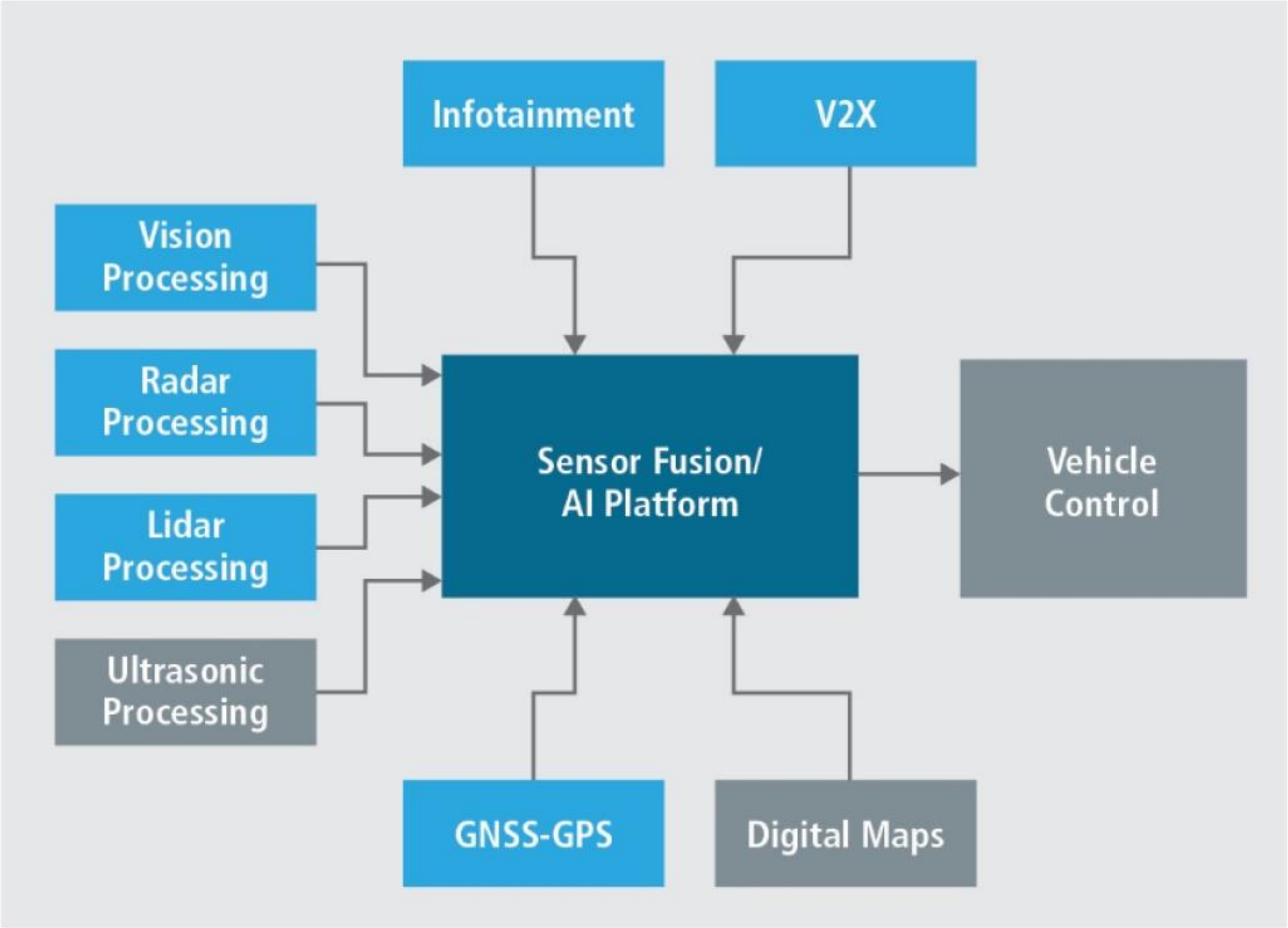
Continuous Assessment (CA)

Important information:

- Written report should contains at least the following:
  1. An abstract that briefly summarizes what you have done and what the results are,
  2. a brief introduction to the project and the problem that you are solving,
  3. derivation of the model (“problem formulation”),
  4. description of the framework and algorithm(s) used
  5. the results,
  6. conclusions and/or a summary,
  7. references (if applicable).

CA: Multi-Sensor Pose Estimation for Autonomous Vehicles

- Background: Sensors on Autonomous Vehicles



CA: Multi-Sensor Pose Estimation for Autonomous Vehicles

- A **pose estimator** tracks vehicle's position and heading. In this project, you are required to design a sensor fusion framework for autonomous vehicle pose estimation.
- The core part of the CA contains:
  system design, problem formulation, estimation method, and results.
  - System design: sensor selection and reasons;
  - Problem formulation: process model (on vehicle's motion) and measurement model (on selected sensors);
  - Estimation method: any approach related to this lecture, or more advanced method if you wish;
  - Results: tracking accuracy, time efficiency, and other metrics based on simulation; You may take this paper and this paper as references.
- More details will be discussed in the future: 2nd and 3rd lecture.
- Start early, start now!

Outline

Introduction

- Intelligent sensor systems

Basics of Sensors and Instrumentation

- Static characteristics and dynamic characteristics
- Basics of Sensing Principles: mechanical sensors, thermal sensors
- Data acquisition

Interfacing and IOT Systems

- Internet-of-Things (IoT) as a control system
- Human-Computer Interfaces (HCI)
- Communications

Learning Objectives

- In this lecture, you are expected to:

1. Describe and explain the basic concepts in sensing and instrumentation;
2. Understand the interfacing and data acquisition of sensors;
3. Have a systematic view on sensing, instrumentation, and IOT systems.

Intelligent Sensor Systems (ISS)

- **System**
  - A combination of two or more elements, subsystems and parts necessary to carry out one or more functions
  - To interact with the real world, a system requires:

  1) **sensors** as inputs devices, 2) **actuators** as output devices, and 3) **processing**

- **Sensor**
  - Device that receives and responds to a stimulus

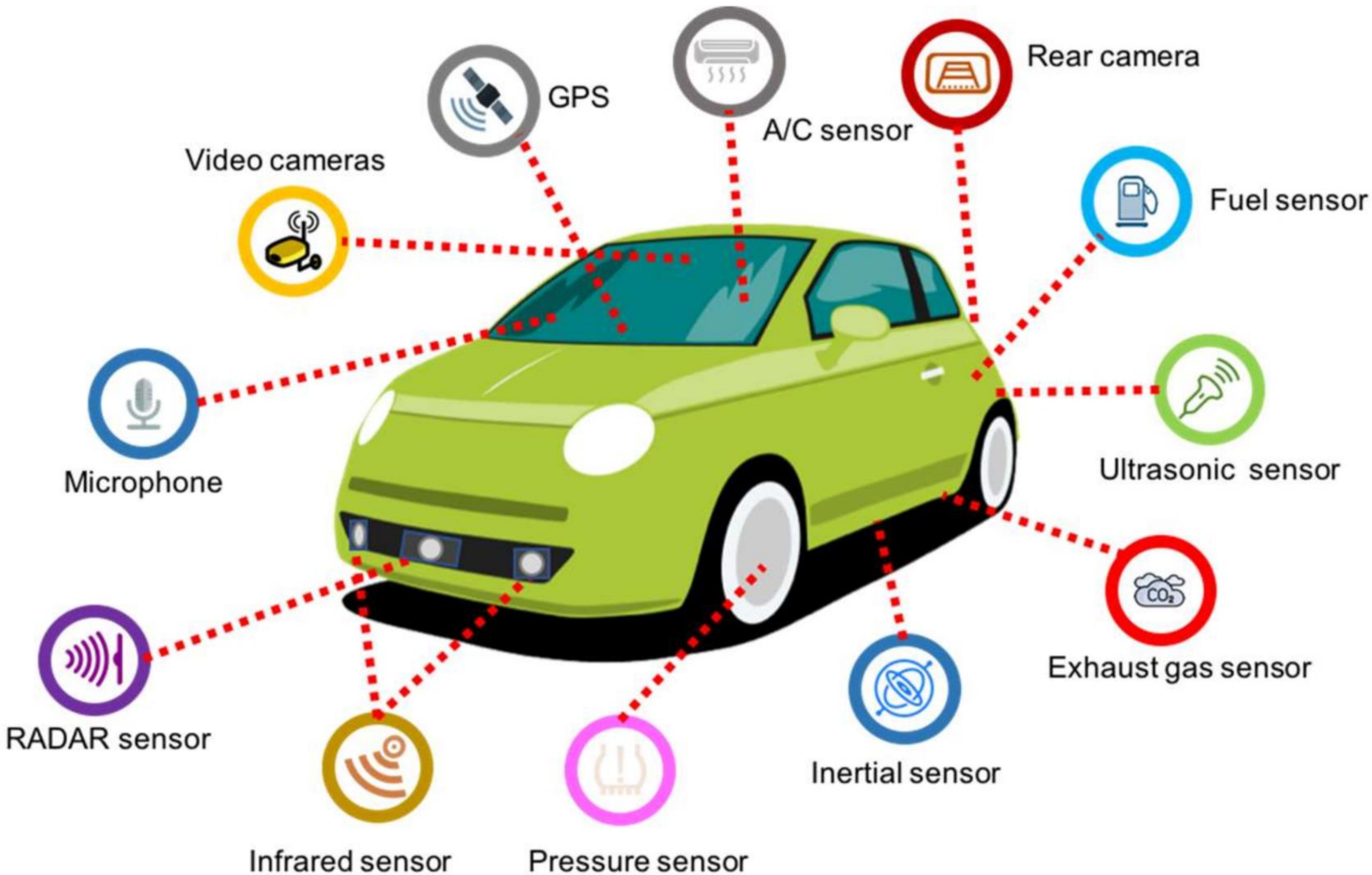
  Stimulus: mechanical, thermal, magnetic, electric, optical, chemical…

  Response: an electrical signal (in most cases)

- **Intelligence**
  - The ability to combine **a priori knowledge** and **measurement**
  - Decision-making / reasoning abilities

Intelligent Sensor Systems (ISS): Example

- **Autonomous vehicles**

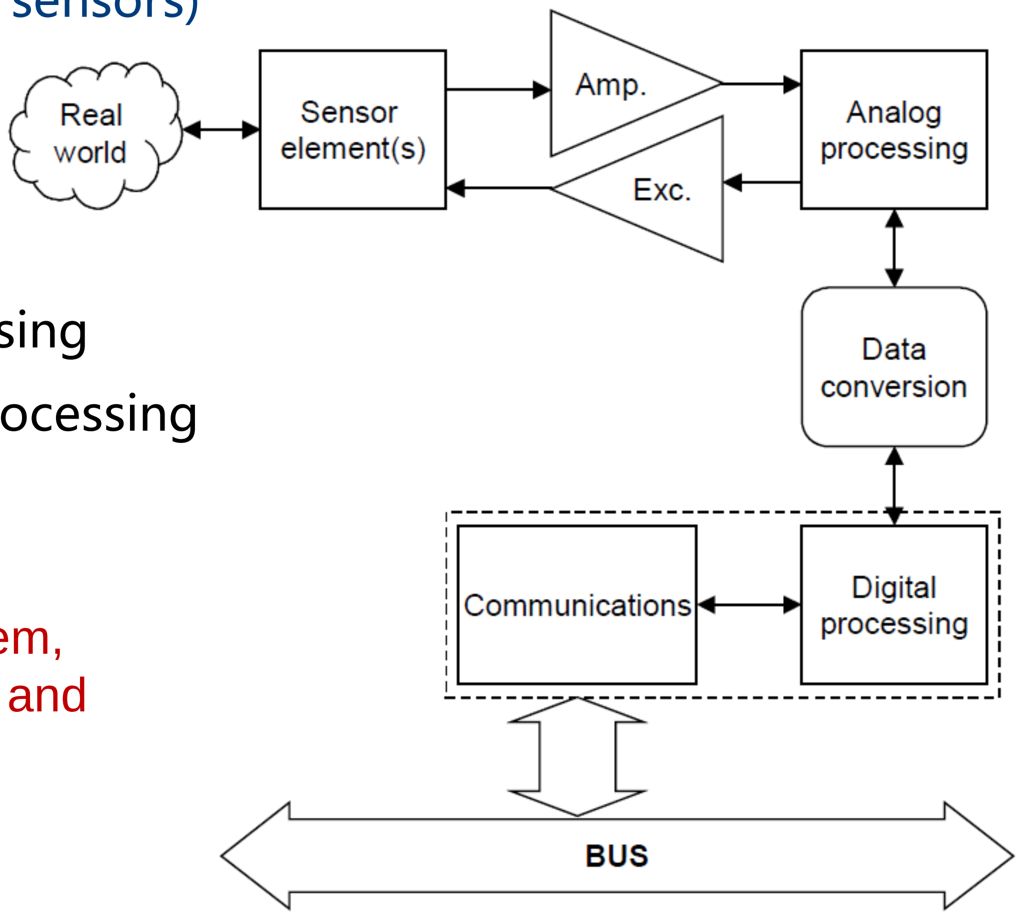


Intelligent Sensor Systems (ISS): Example

- **Your smart phone**

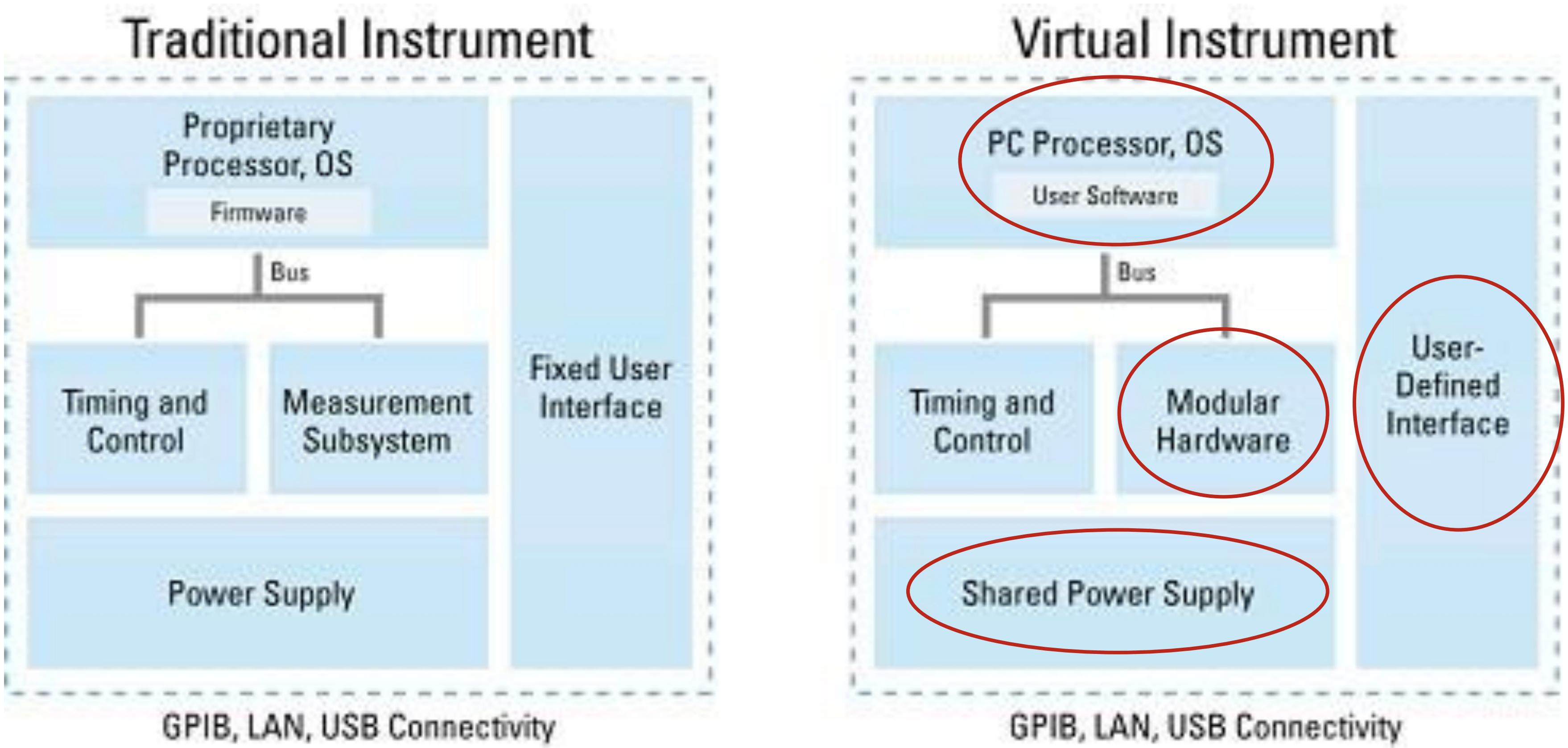
Building Blocks of ISS

- The principal sub-systems within an ISS are
  - Primary sensing element(s)
  - Excitation control (to drive sensors)
  - Amplification
  - Analogue filtering
  - Data conversion
  - Digital information processing
  - Digital communications processing



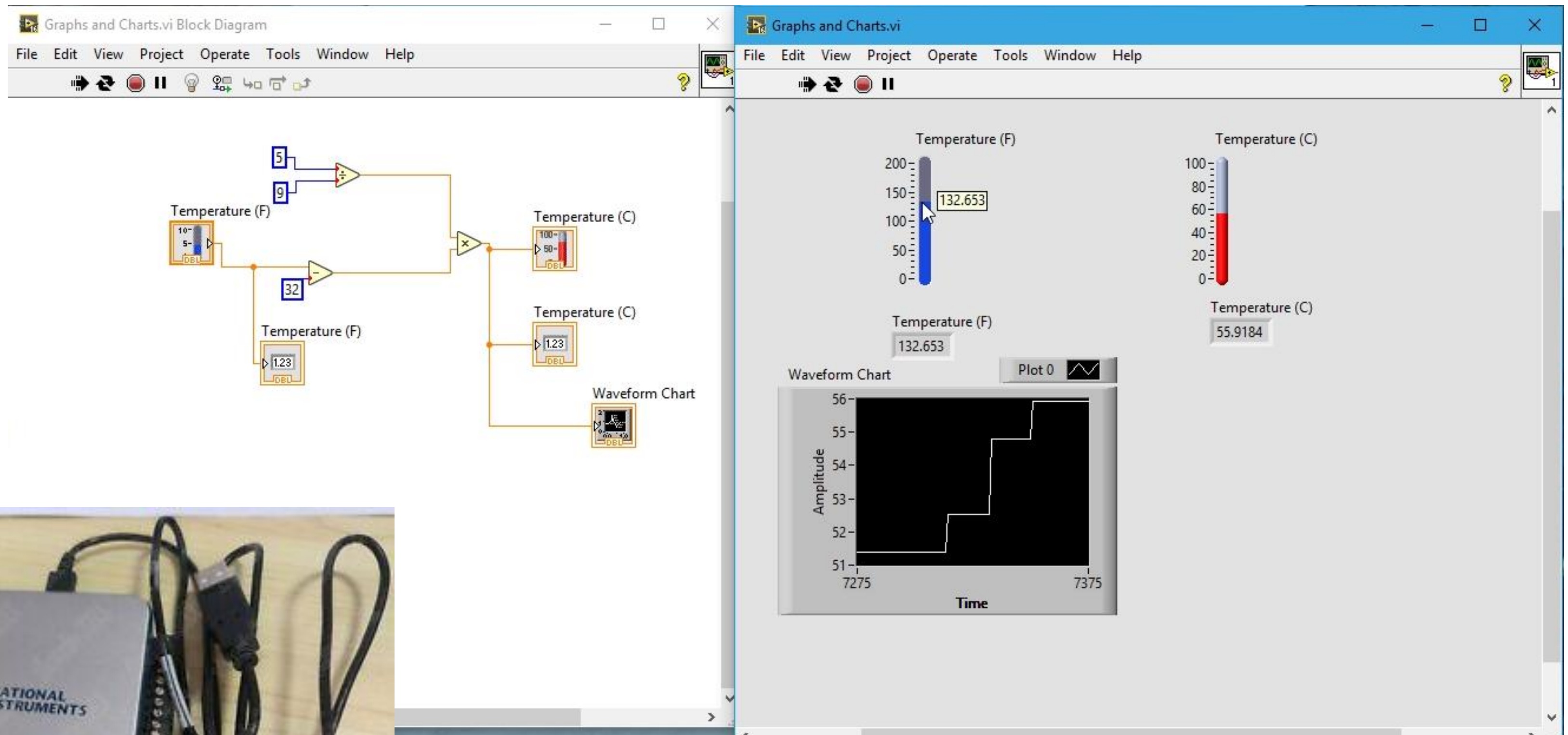
Can we simplify the above system, especially when doing research and prototype development?

Virtual Instrumentation



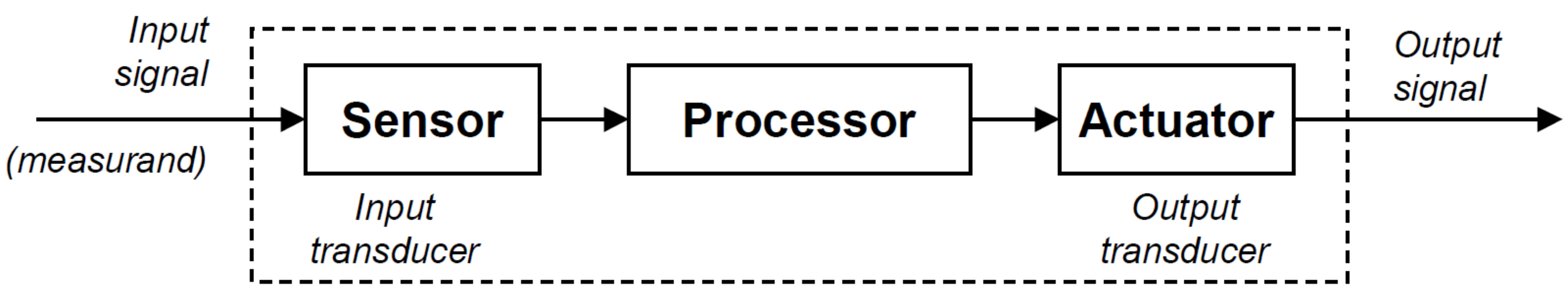
Virtual Instrumentation: Example

- Temperature measurement



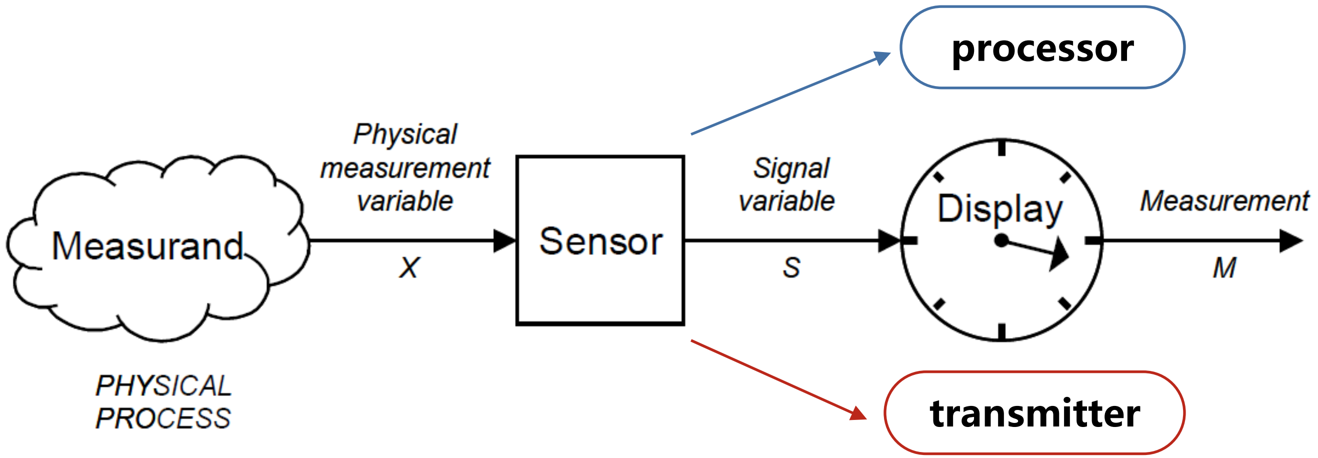
Transducers: Sensors and Actuators

- **Transducer:** A device that converts a signal from one physical form to a corresponding signal having a different physical form
  - Sensor: an input transducer (e.g., a microphone)
  - Actuator: an output transducer (e.g., a loudspeaker)



Measurements

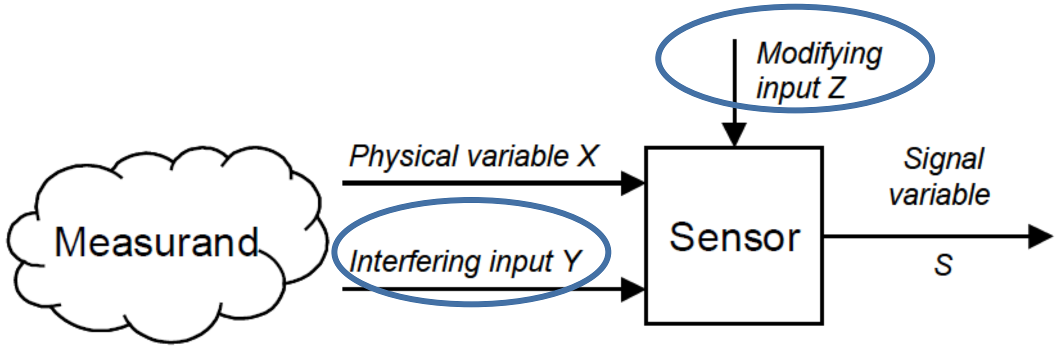
- A simple instrument model



There is no perfect model!

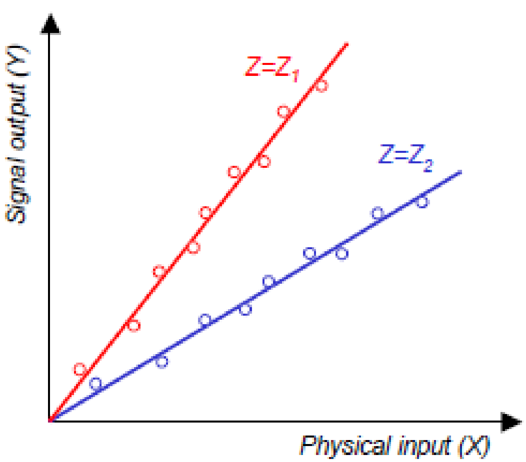
Measurements

- A **practical** instrument model



  - Interfering inputs (Y):
    Quantities to which the Instrument is unintentionally sensitive

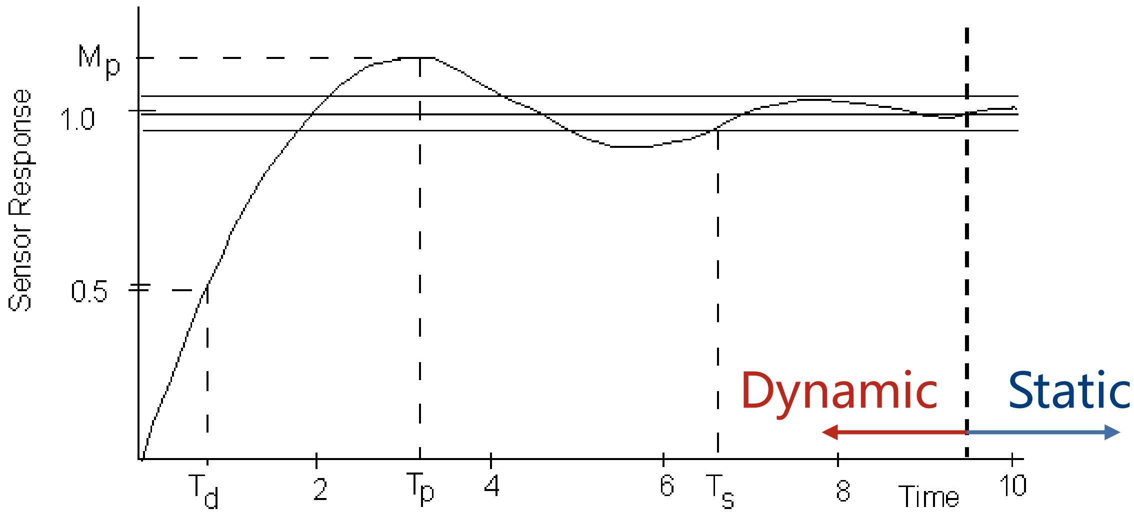
  - Modifying inputs (Z):
    Quantities that cause a change in the input-output relations of the instrument



Sensor Characteristics

- **Static characteristics**
  - The properties of the system after all transient effects have settled to their final or steady state

- **Dynamic characteristics**
  - The properties of the system transient response to an input



Accuracy, Discrimination

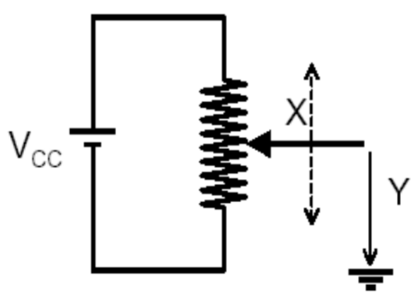
- **Accuracy** is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity.

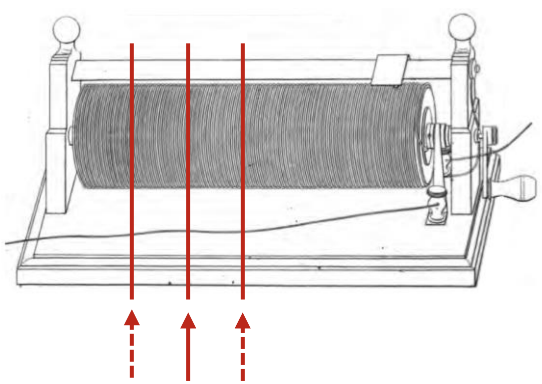
$$\text{ABSOLUTE ERROR} = \text{RESULT} - \text{TRUE VALUE}$$

$$\text{RELATIVE ERROR} = \frac{\text{ABSOLUTE ERROR}}{\text{TRUE VALUE}}$$

- **Discrimination/resolution** is the minimal change of the input necessary to produce a detectable change at the output.

Example: Potentiometer



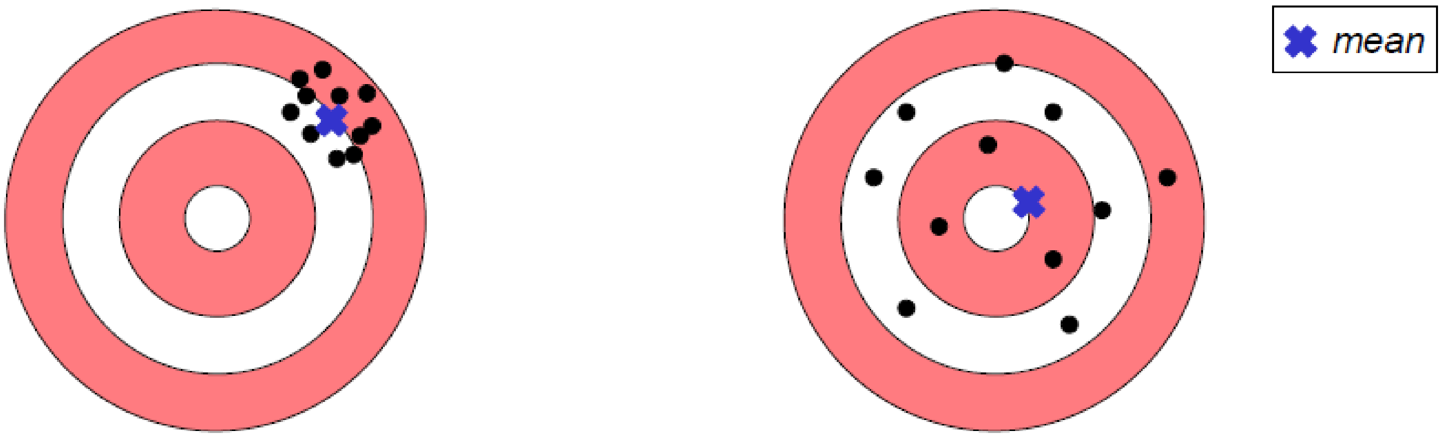


Precision

- **Precision:** The capacity of a measuring instrument to give the same reading when **repetitively** measuring the same quantity under the same prescribed conditions.

precision ≠ accuracy

Which result is more accurate? Which result is more precise?



Result A

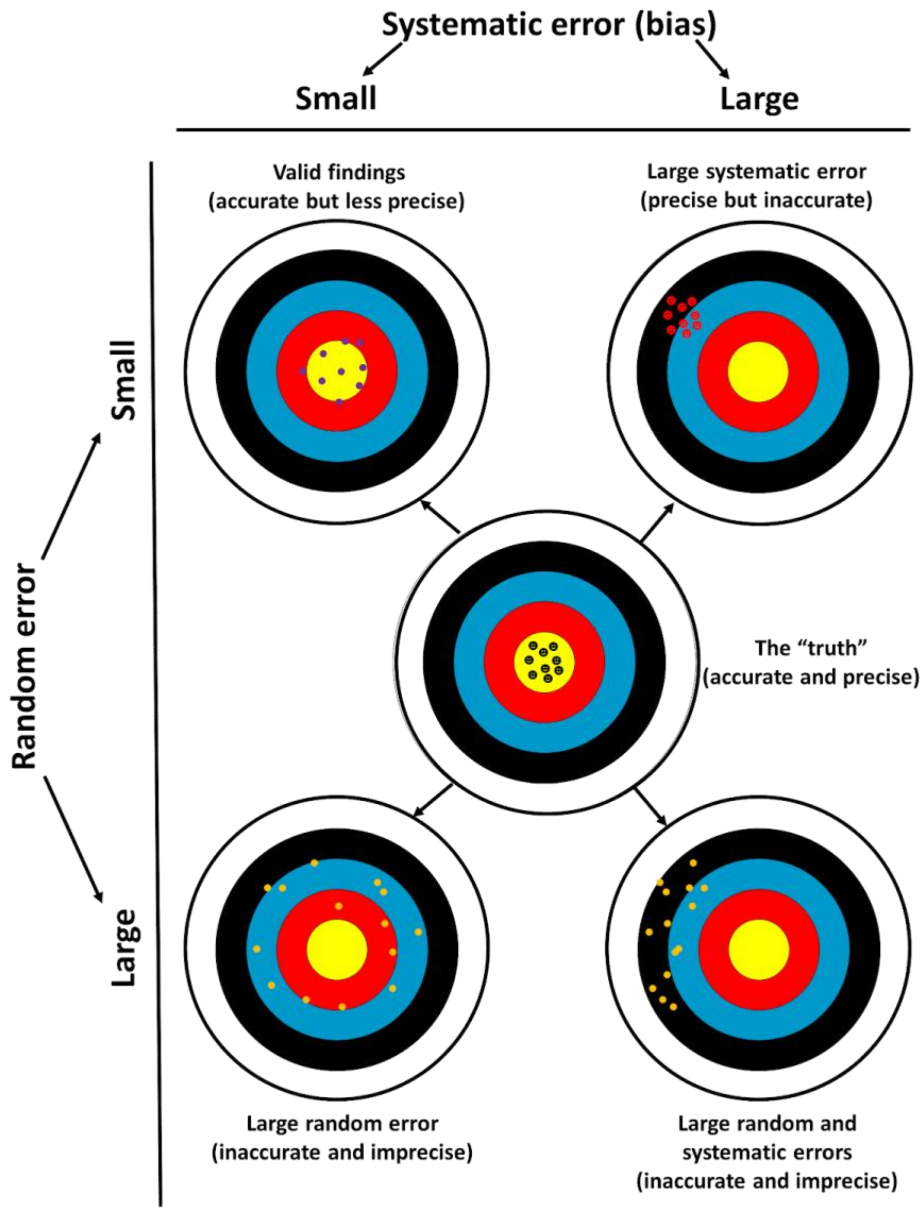
Result B

Accuracy and Errors

- **Systematic errors**
  - Examples: calibration errors, human observation errors (parallax errors), environmental errors (temperature)
  - Systematic errors can be corrected with COMPENSATION methods

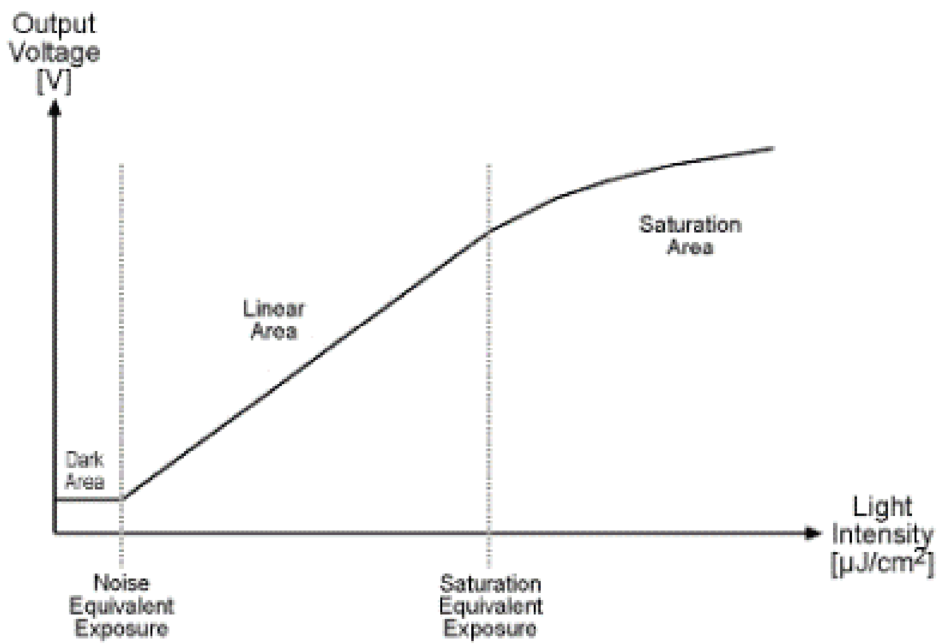
- **Random errors**
  - Also called NOISE: a signal that carries no information
  - True random errors (white noise) follow a **Gaussian distribution**
  - Systematic errors can only be reduced

Accuracy and Errors: Example



More Static Characteristics

- **Input range**
  - The maximum and minimum value of the physical variable that can be measured (i.e., -40C/100C in a thermometer)
  - Output range can be defined similarly
- **Sensitivity**
  - The slope of the calibration curve y=f(x)



Which sensor is better?

Sensor A
sensitivity = 1, noise = 2

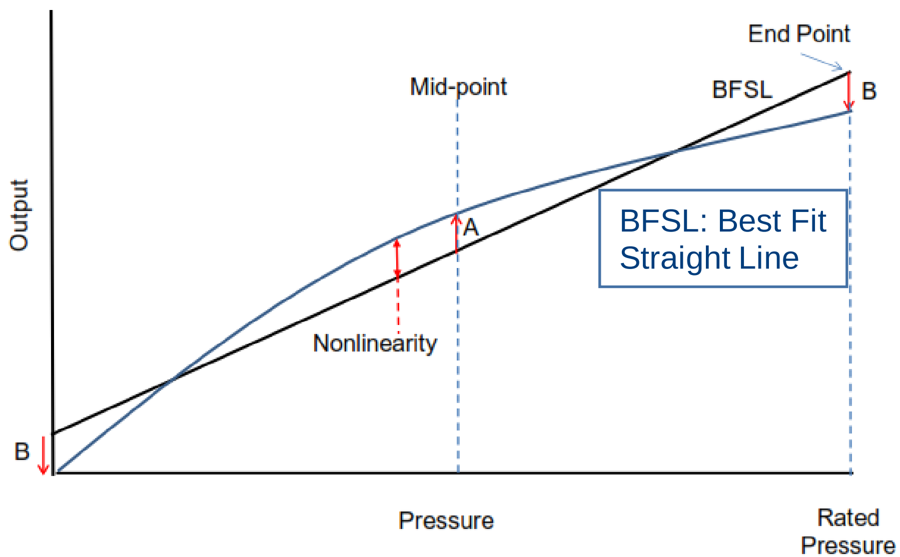
Sensor B:
sensitivity = 2, noise = 5

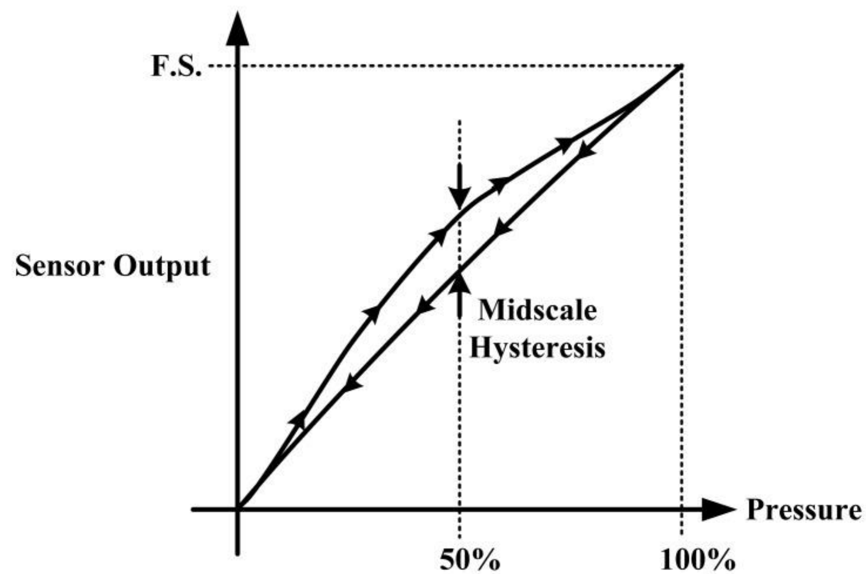
With a GAIN = 2:

Sensor A:
sensitivity = 2, noise = 4

More Static Characteristics

- **Linearity**
  - The closeness of the calibration curve to a specified straight line (i.e., theoretical behavior, least-squares fit)
- **Hysteresis**
  - The difference between two output values that correspond to the same input depending on the trajectory followed by the sensor





Exercise

- 1. Which of the following statements is correct?
  - a) Sensors and actuators are both examples of transducers.
  - b) Sensors and transducers are both examples of actuators.
  - c) Actuators and transducers are both examples of sensors.

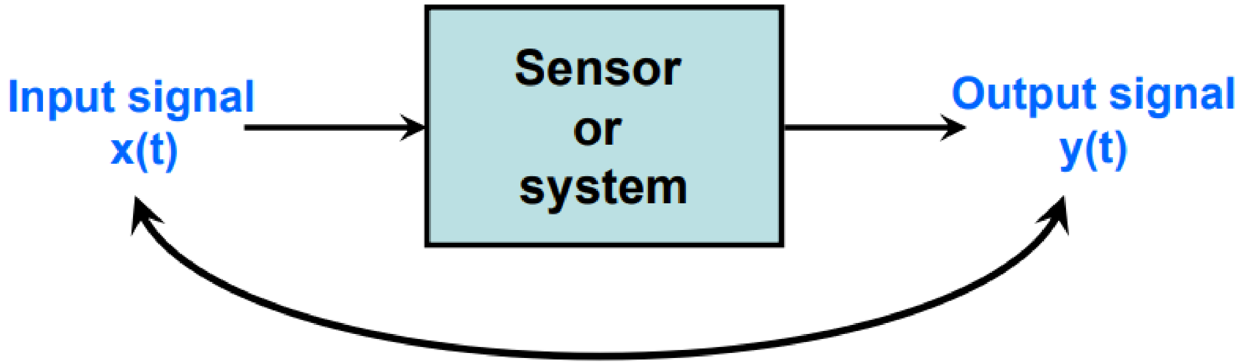
- 2. What term describes the maximum expected error associated with a measurement or a sensor?
  - a) Accuracy.
  - b) Resolution.
  - c) Precision.
  - d) Range.
- **Correct Answers:**

  1. a); 2. a).

Dynamic Characteristics

- How well a sensor respond to **changes** in its input?

Sensor or the measurement system must be able to respond **fast enough** to keep up with the input signals!

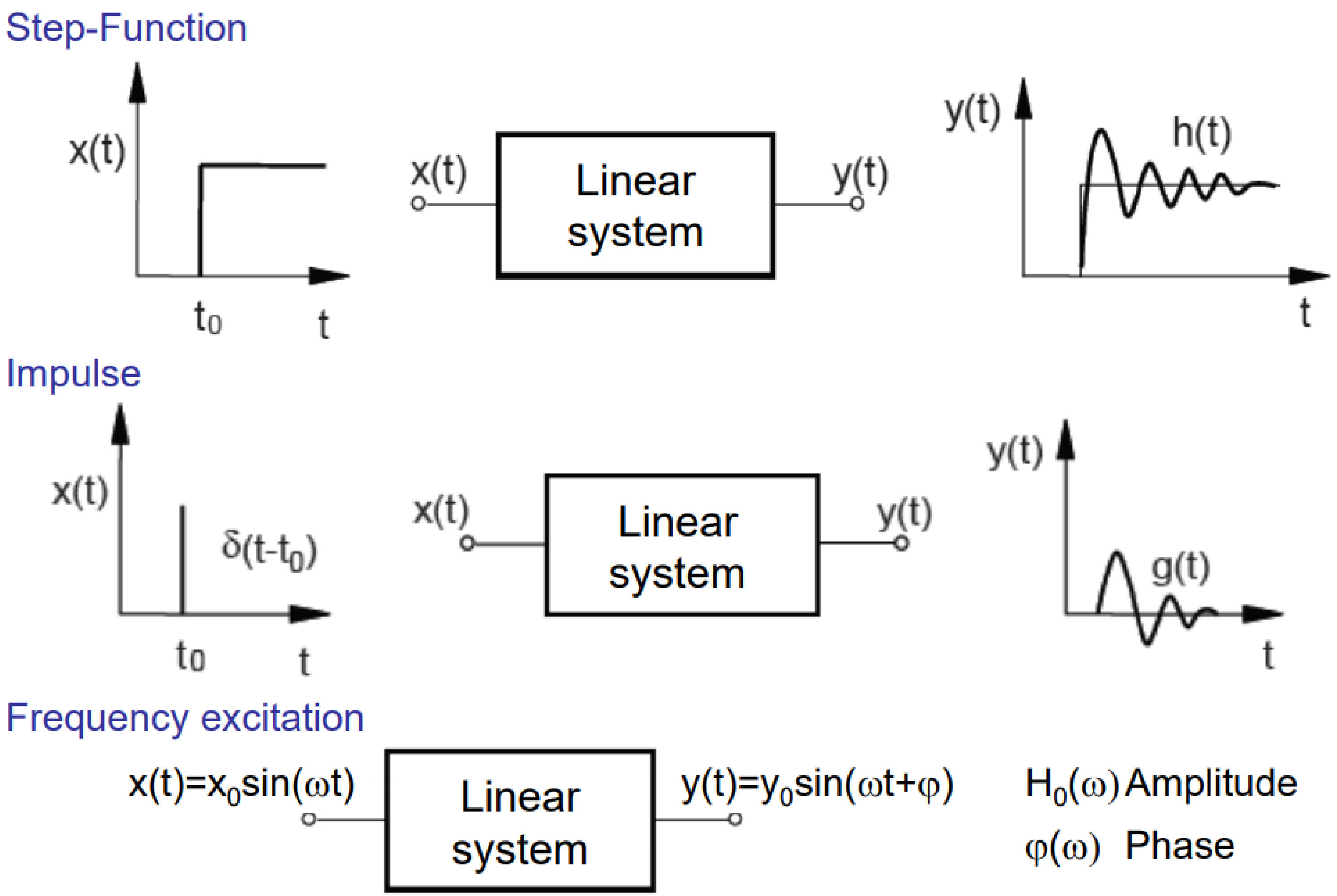


- To simplify the problem, consider **linear area** of the sensor.

We already have the results in **linear system theory!**

Dynamic Characteristics

- The commonly-used input signals are selected as follows:



Dynamic Models

- The dynamic response of the sensor is (typically) assumed to be linear. Therefore, it can be modelled by a constant-coefficient linear differential equation

$$a_k \frac{d^k y(t)}{dt^k} + \cdots a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t)$$

- In practice, these models are confined to zero, first and second order. Higher order models are rarely applied.
- Applying the **Laplace transform** to the sensor model yields

$$L\left[a_k \frac{d^k y}{dt^k} + \cdots a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_o y(t) = x(t)\right]$$

$$\Downarrow$$

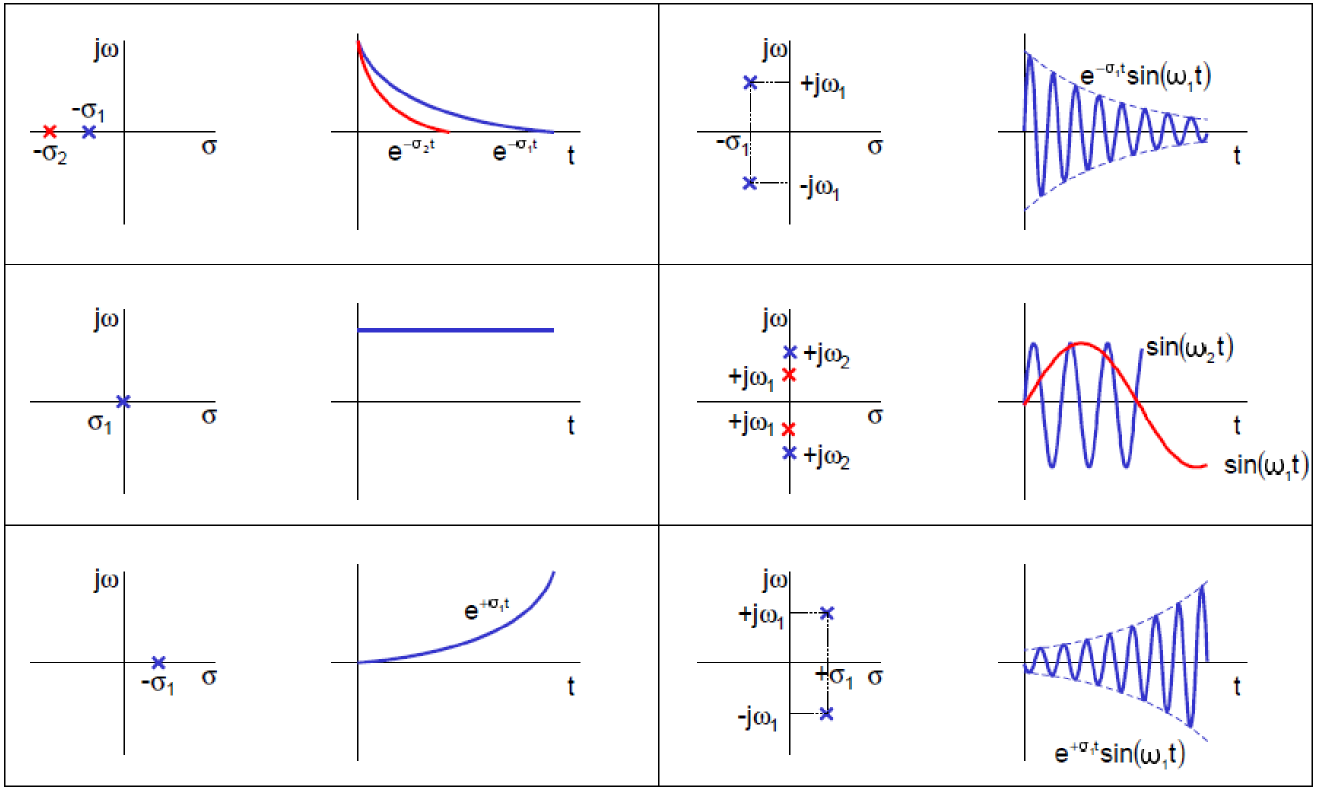
$$\left(a_k s^k + \cdots a_2 s^2 + a_1 s + a_o\right) Y(s) = X(s)$$

$$\Downarrow$$

Transfer function $G(s) = \dfrac{Y(s)}{X(s)} = \dfrac{1}{a_k s^k + \cdots a_2 s^2 + a_1 s + a_o}$

Pole Location and Dynamic Behavior

- The position of the poles of G(s) - zeros of the denominator in the s-plane determines the dynamic behavior of the sensor such as: oscillating components, exponential decays, instability.



Positions of poles and their corresponding time response g(t)

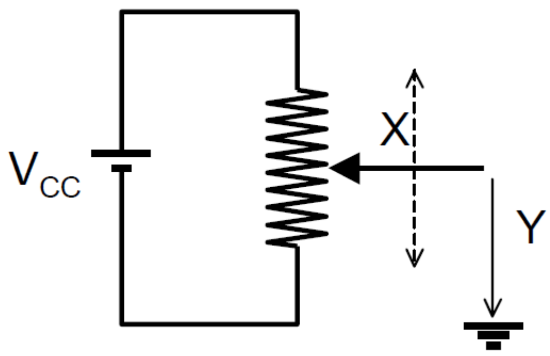
Zero-order Sensors

- Input-output relation

$$y(t) = k \cdot x(t) \Rightarrow \frac{Y(s)}{X(s)} = k$$

- Zero-order is the desirable response of a sensor
  - No delays
  - Infinite bandwidth
  - The sensor only changes the amplitude of the input signal

- No energy-storing elements inside!
- Example: a potentiometer measuring **linear** and **rotary** displacements

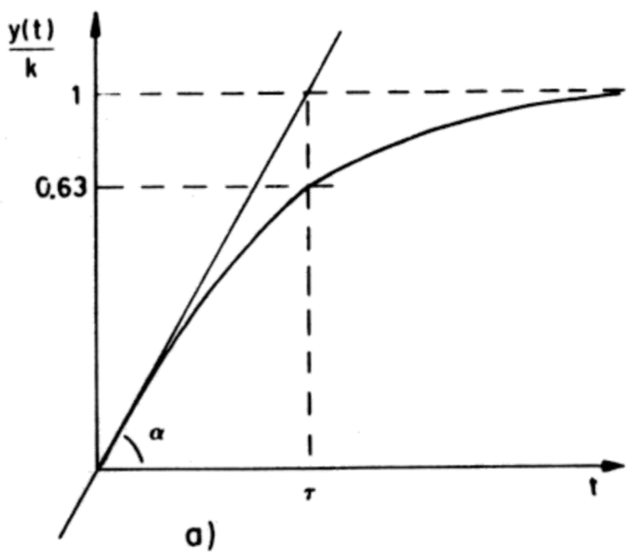


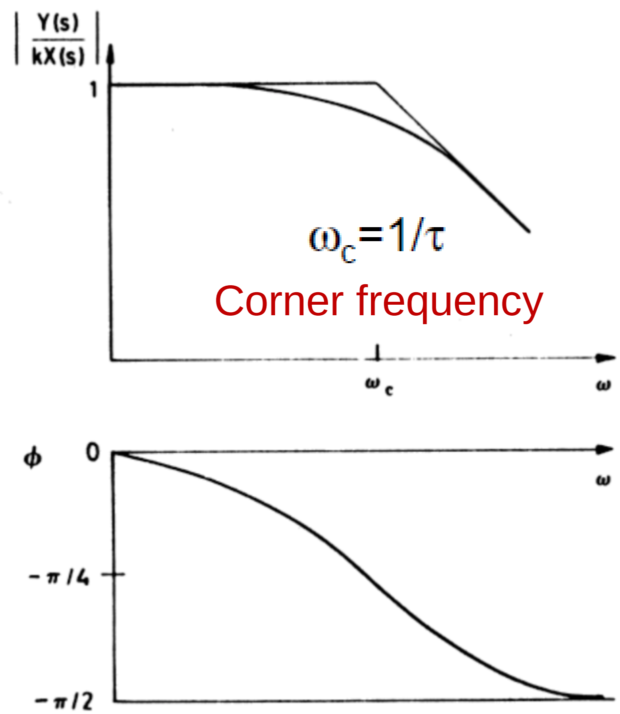
First-order Sensors

- Input-output relation

$$a_1\frac{dy}{dt}+a_0y(t)=x(t)\Rightarrow\frac{Y(s)}{X(s)}=\frac{1}{a_1s+a_0}=\frac{k}{\tau s+1}$$

- First-order sensors have one element that stores energy and one that dissipates it.
- **Step response** and **frequency response**

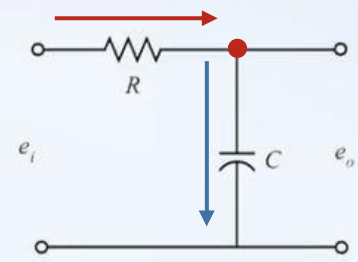




First-order Sensors: Example

- RC circuit:
  - Q = CV
  - I = Q/t

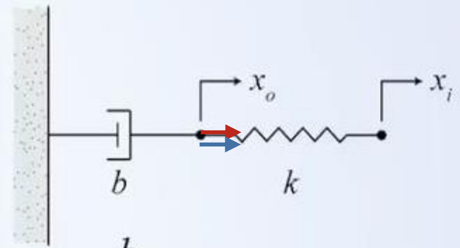
Kirchhoff's current law



$$RC\dot{e}_o + e_o = e_i$$

- Spring-damper:
  - F = -k△x
  - F = -bv

Equal forces



$$\frac{b}{k}\dot{x}_o + x_o = x_i$$

Second-order Sensors

- Input-output relation

$$a_2 \frac{d^2y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y(t) = x(t) \Rightarrow \frac{Y(s)}{X(s)} = \frac{1}{a_2 s^2 + a_1 s + a_0}$$

- Rewrite the transfer function as

$$\frac{Y(s)}{X(s)} = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$\text{with } k = \frac{1}{a_0},\ \zeta = \frac{a_1}{2\sqrt{a_0 a_1}},\ \omega_n = \sqrt{\frac{a_0}{a_2}}$$

static gain

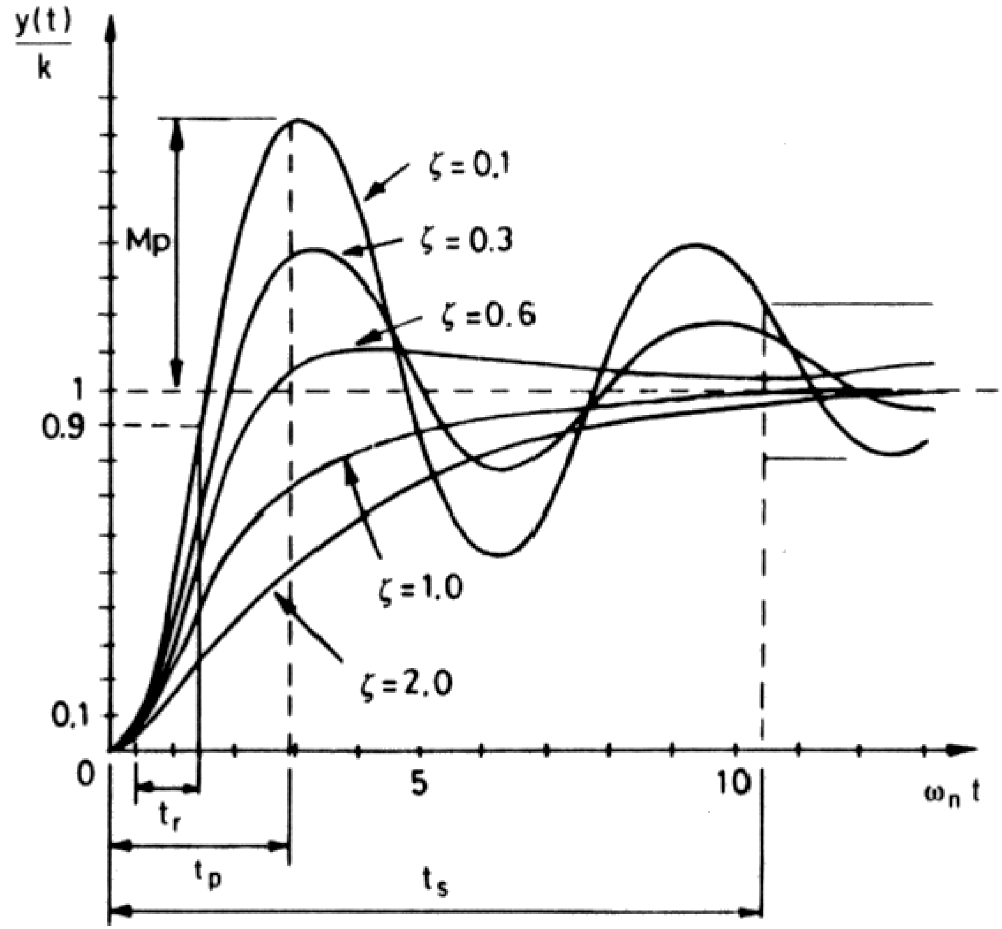
zeta: damping coefficient

omega: natural frequency

Second-order Step Response

- Response types
  - Underdamped ($\zeta<1$)
  - Critically damped ($\zeta=1$)
  - Overdamped ($\zeta>1$)

- Response parameters
  - Rise time (t_r)
  - Peak overshoot (M_p)
  - Time to peak (t_p)
  - Settling time (t_s): 5%/2%



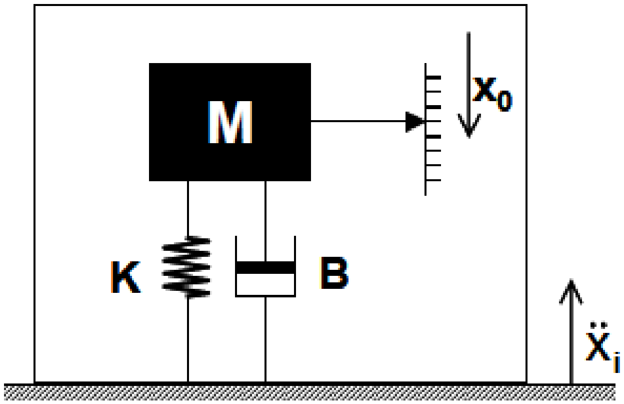
From [PAW91]

Example of Second-order Sensors

- Spring-mass-damping accelerometer
  - Analyse the object M based on Newton's law of motion

  - The equilibrium equation is:

$$M(\ddot{x}_i - \ddot{x}_0) = Kx_0 + B\dot{x}_0$$
$$\Downarrow$$
$$Ms^2X_i(s) = X_0(s)\left[K + Bs + Ms^2\right]$$
$$\Downarrow$$
$$\frac{X_0(s)}{s^2X_i(s)} = \frac{M}{K}\frac{K/M}{s^2 + s(B/M) + K/M}$$



Summary - Introduction, Sensor Characteristics

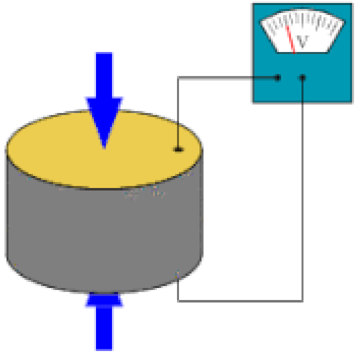
- Introduction of Intelligent Sensor Systems
- Transducers, sensors and measurements
- Static sensor characteristics
- Dynamic sensor characteristics

Sensor Classification Criteria

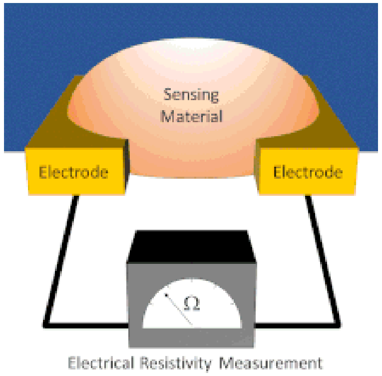
- Sensors can be classified, among others, according to one of the following criteria:
  - Power supply requirements: **Passive** and **active**
  - Nature of the output signal: **Digital** and **analog**
  - Input/output dynamic relationships: **Zero, first, second-order**, etc.
  - Measurand: **Mechanical, thermal, magnetic, radiant, chemical**
  - Physical measurement variable: **Resistance, inductance, capacitance**, etc.

Passive and Active Sensors

- **Passive or self-generating**
  - Directly generate an electrical signal in response to an external stimuli without the need for an external power supply
  - Examples: Thermocouple, Piezoelectric sensors



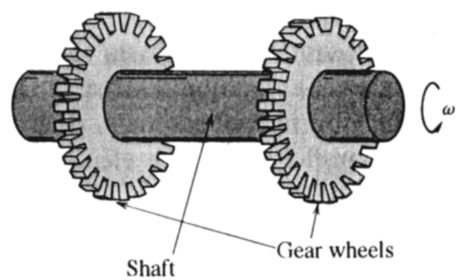
- **Active or modulating**
  - These sensors require external power supply or an excitation signal for their operation
  - Examples: Thermistors, Chemo-resistors

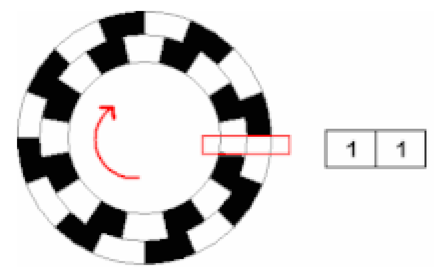


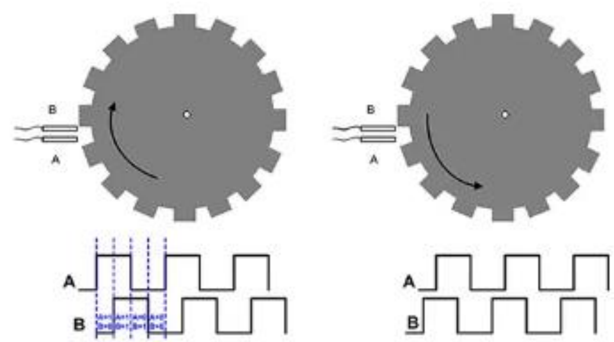
Analog and Digital Sensors

- **Analog sensors**
  - Provide a signal that is continuous in both its magnitude and temporal or spatial content.
  - Most of the physical measurands are analog in nature.
  - Examples: Temperature, displacement, light intensity…

- **Digital sensors**
  - Their output takes the form of discrete steps or states.
  - Digital signals are more repeatable, reliable and easier to transmit.
  - Examples: **Shaft encoder**, contact switch…







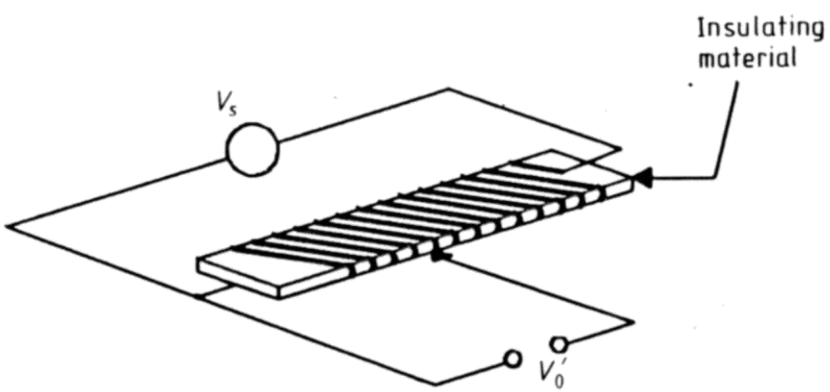
Mechanical Measurands

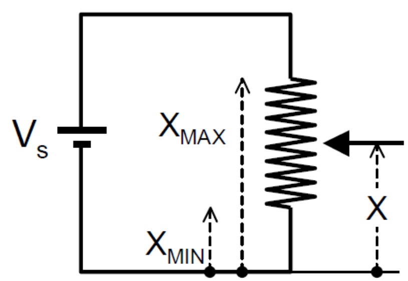
- Displacement
  - Resistive sensors
  - Capacitive sensors
  - Inductive sensors

- Force and acceleration
  - Strain gauges
  - Cantilever beam-based sensors

Resistive Displacement Sensors

- A resistance with a movable contact (a **potentiometer**) may be used to measure linear or rotational displacements
  - A known voltage is applied to the resistor ends
  - The output voltage at the contact is proportional to the displacement
- Notes
  - Non-linearities as a result of **loading effects**
  - Resolution due to limited number of turns per unit distance

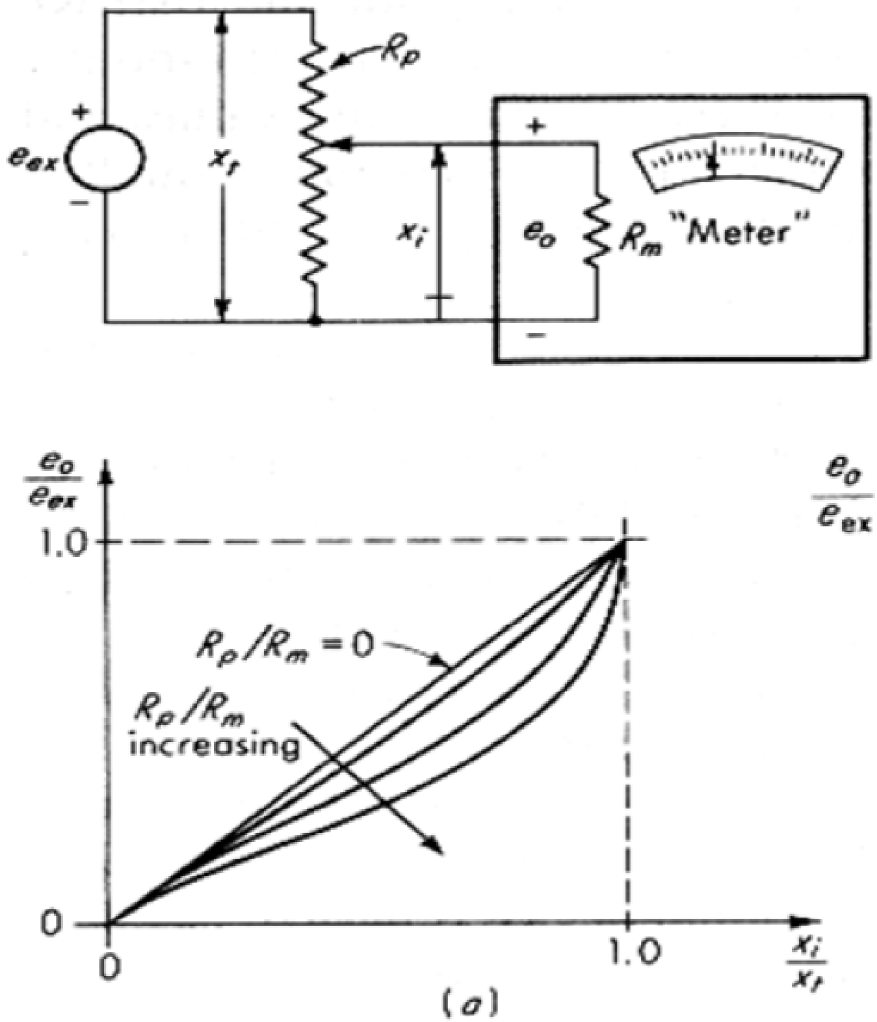




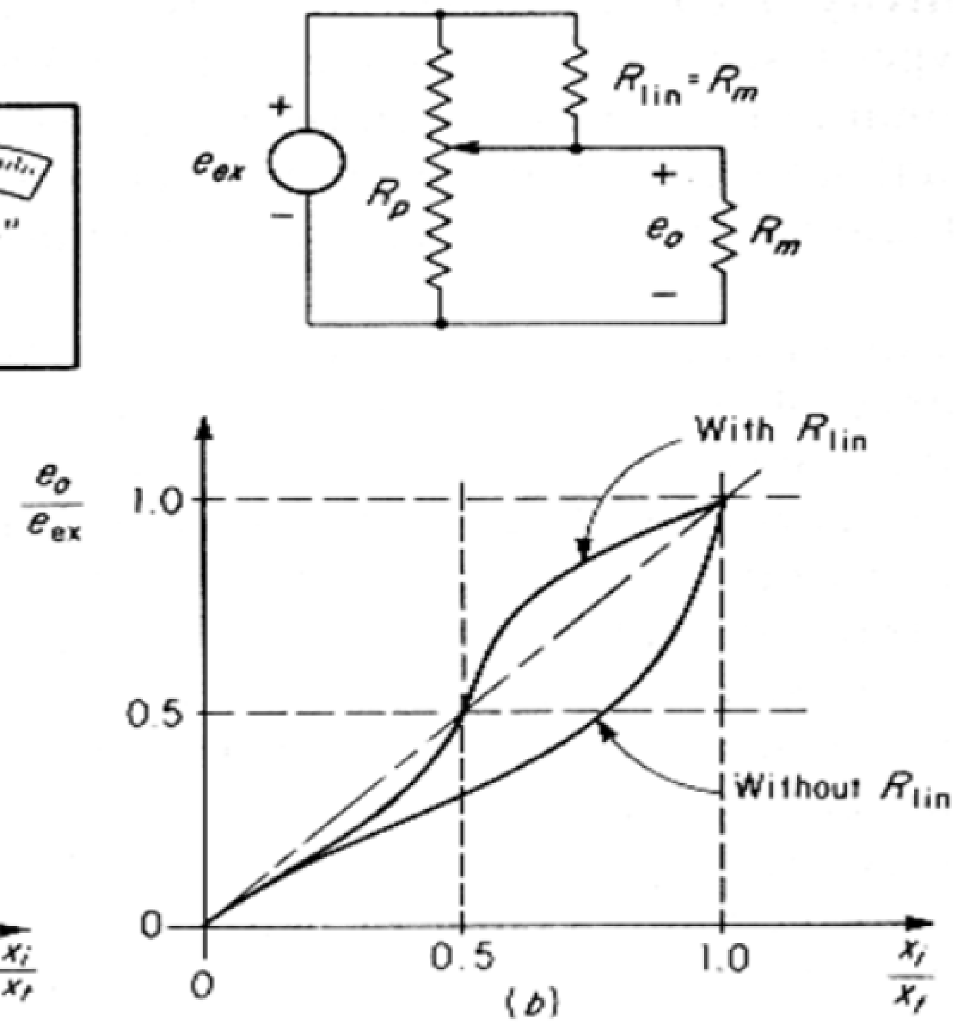
$$V_0 = V_S \frac{X - X_{MIN}}{X_{MAX} - X_{MIN}}$$

Loading Effect in Resistive Displacement Sensors

Loading effect



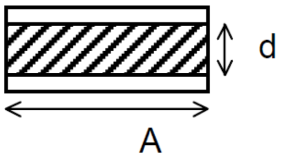
Compensation of loading effect



Capacitive Displacement Sensors

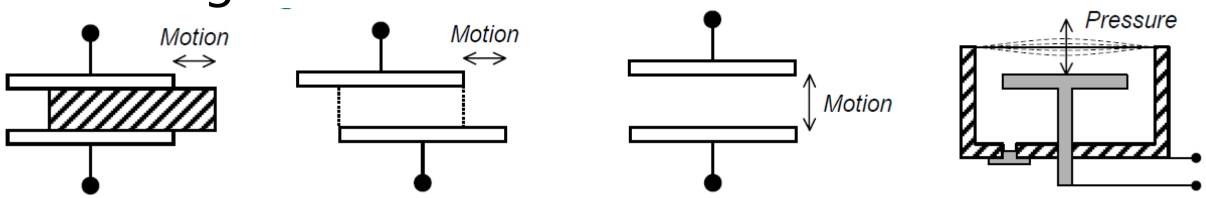
- The capacitance of a parallel plate capacitor is

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$



where d is the separation between the plates, A is the area of the plates, ε_0 is the permittivity of air and ε_r is the relative permittivity of the dielectric.

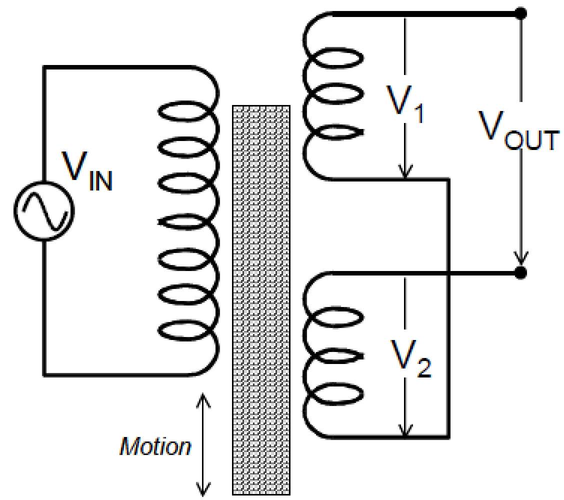
- A moving object is attached to the dielectric or the plates to generate capacitance changes

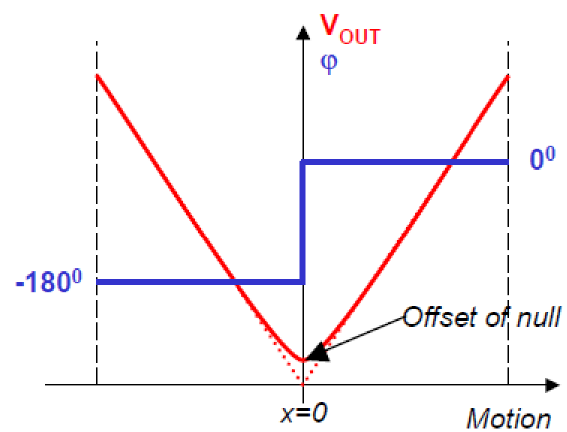


  - Variable distance (d) sensors operate over a range of a few millimeters
  - Cross-sensitivity to temperature and humidity (specially if the dielectric is air)
  - Also commonly used to measure pressure: **microphones**

Inductive Displacement Sensors

- Linear Variable Differential Transformer (LVDT)
  - Motion of a magnetic core changes the **mutual inductance** of two secondary coils relative to a primary coil

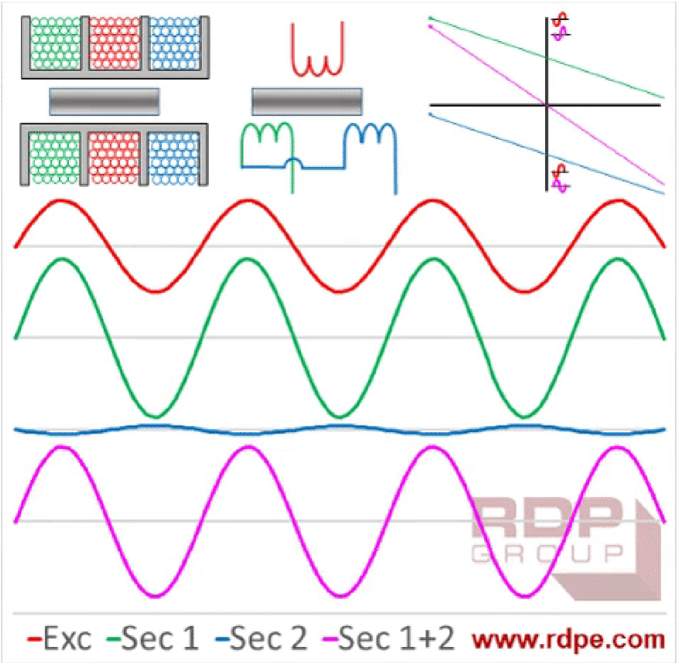


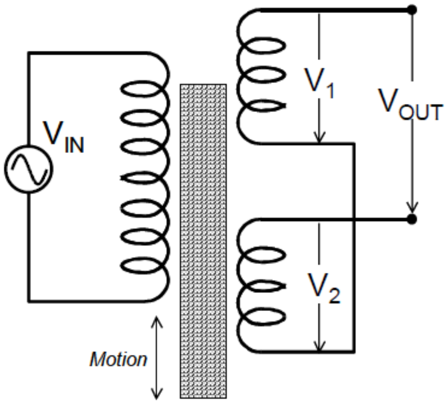


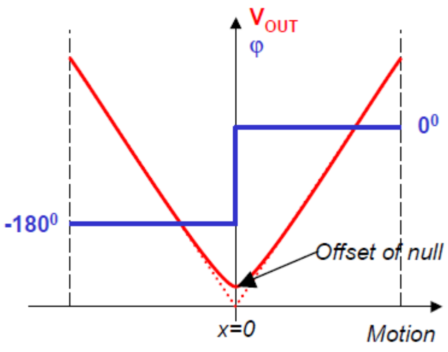
  - Primary coil voltage: $V_S \sin(\omega t)$
  - Secondary coil induced emf: $V_1=k_1 \sin(\omega t+\phi)$ and $V_2=k_2 \sin(\omega t+\phi)$ where k_1 and k_2 depend on the amount of coupling between the primary and the secondary coils, which is proportional to the position of the coil.

Inductive Displacement Sensors

- Linear Variable Differential Transformer (LVDT)
  - Central position: $k_1=k_2 \Rightarrow V_{OUT}=V_1-V_2=0$
  - Displaced x units: $k_1 \neq k_2 \Rightarrow V_{OUT}=(k_1-k_2)\sin(\omega t+\phi)$
  - Positive or negative displacements are determined from the phase of V_{OUT}



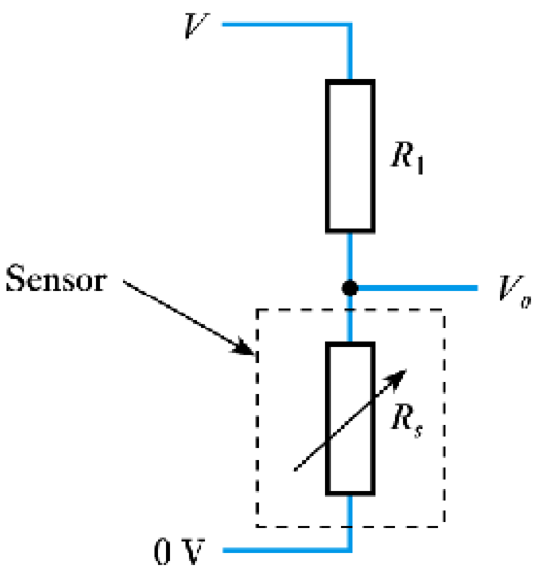




- LVDTs can measure from mm down to μm
- No mechanical wear ensures a long life
- Complete electrical isolation

Exercise

- In the following circuit, if the resistance of the sensor varies linearly with the measured quantity, then the output voltage Vo is also linearly related to the measured quantity. True or False?



- **Correct Answer:**

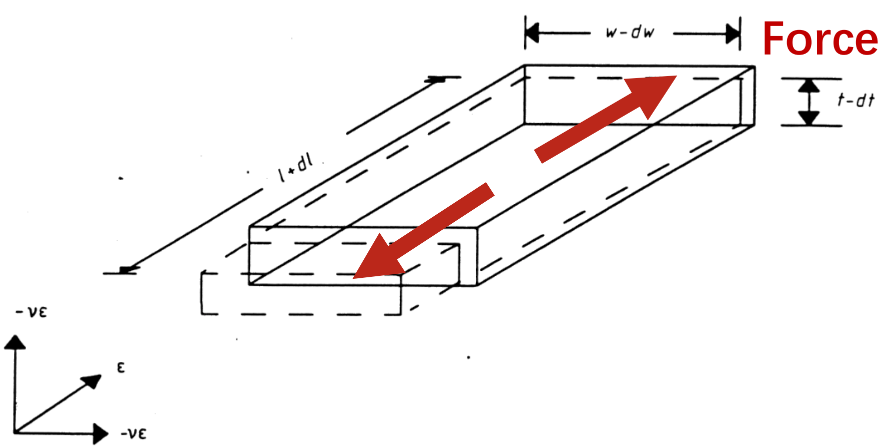
  False. Remember the loading effect.

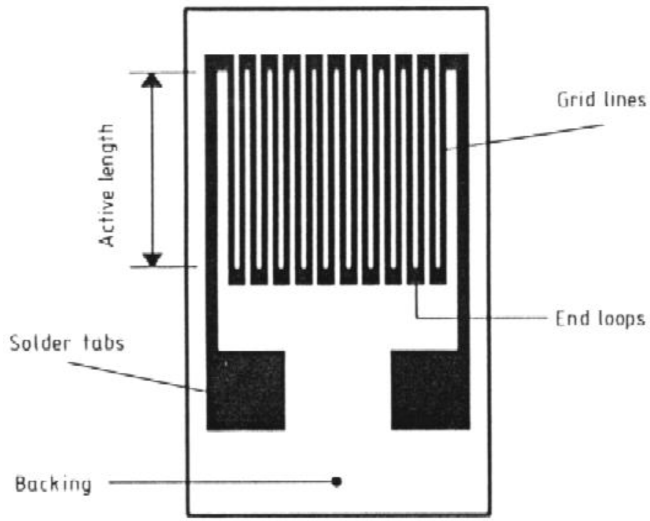
Strain Gauges

- **Piezo-resistive effect**: resistance changes with stress.
- The resistance R of a strip of material of length L, cross-sectional area A and resistivity ρ is

$$R=\rho L/A$$

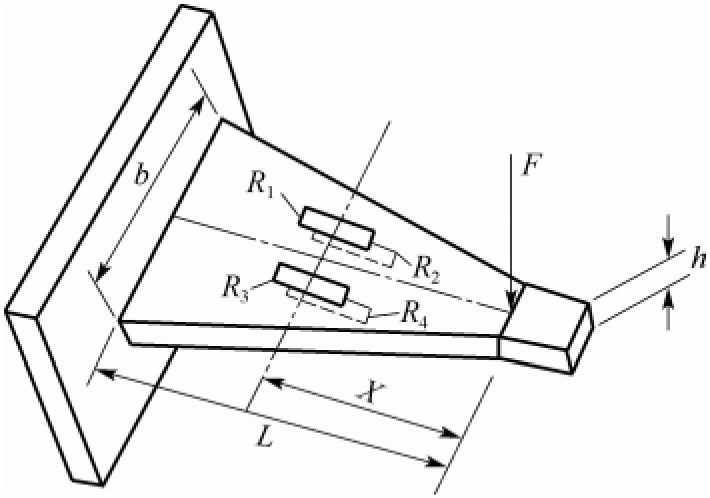
  - Metal foil gauges: R change mainly because of the **geometric shape**.
  - Semiconductor gauges: R change mainly because of the **piezo-resistivity**.



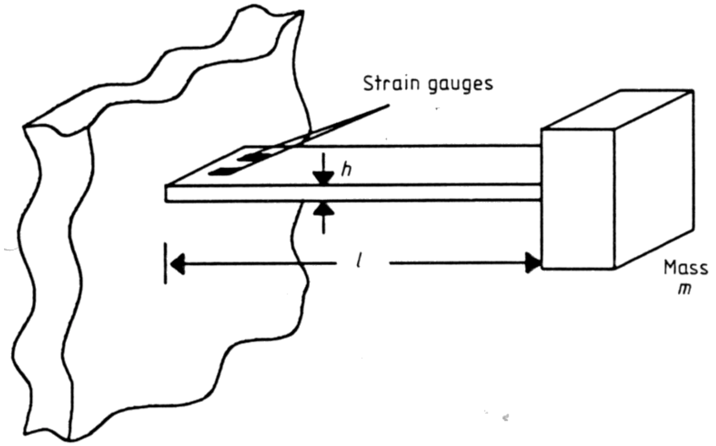


Force and Acceleration Sensors

- Force sensors
  - Both compressive and tensile strains that can be easily measured in a **bridge arrangement.**

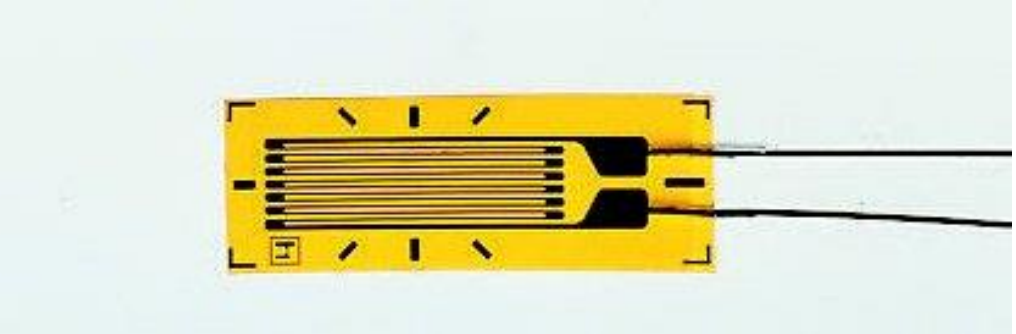


- Acceleration sensors
  - Spring-mass-damper accelerometer: Covered previously
  - Cantilever-beam with strain gauges
    - Mass is attached to the end of the cantilever
    - Dampening is usually performed with viscous fluids or permanent magnets



Exercise

- The image below shows a strain gauge. With the device oriented as shown, what is the direction of sensitivity of the device?



  - a) Perpendicular to the plane of the device.
  - b) Vertical.
  - c) Horizontal.

Correct Answer:

c) Horizontal.

Temperature Sensors

- Thermoresistive sensors
  - Resistive Temperature Devices (RTD)
  - Thermistors
- Thermoelectric sensors
  - The Seebeck effect
  - Thermocouples
- P-N junction sensors

Thermoresistive Sensors

- Resistance changes in accordance with temperature.

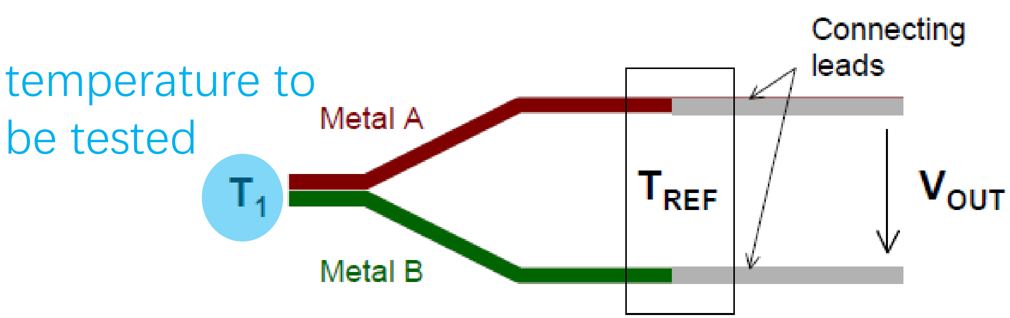
Resistance Temperature Detectors (RTDs)	Thermistors (“thermally sensitive resistor”)
The material is a **metal**: Platinum, Nickel, Copper typically used	The material is a **semiconductor**
Positive temperature coefficients	Typically have **negative** temperature coefficients (NTC thermistors)

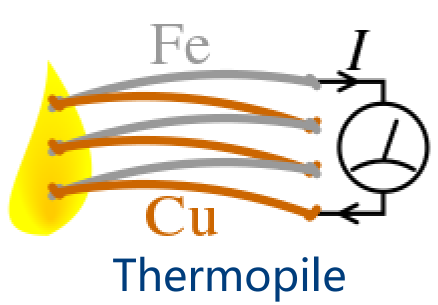
$$R_T = R_0\left[1 + \alpha_1 T + \alpha_2 T^2 + \cdots \alpha_n T^n + \right] \cong R_0\left[1 + \alpha_1 T\right]$$

$$R_T = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

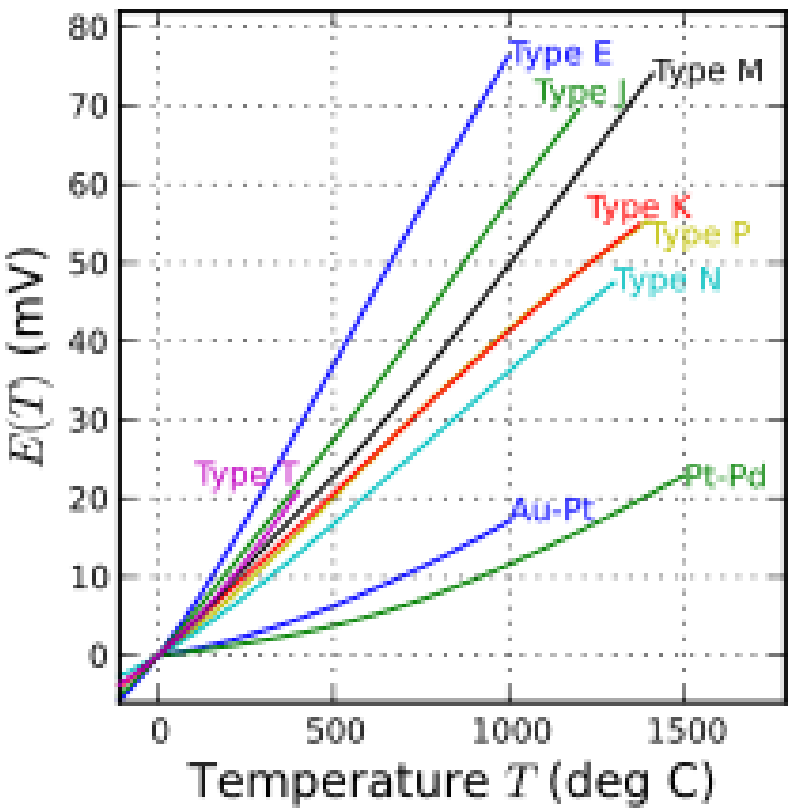
Thermoelectric Sensors

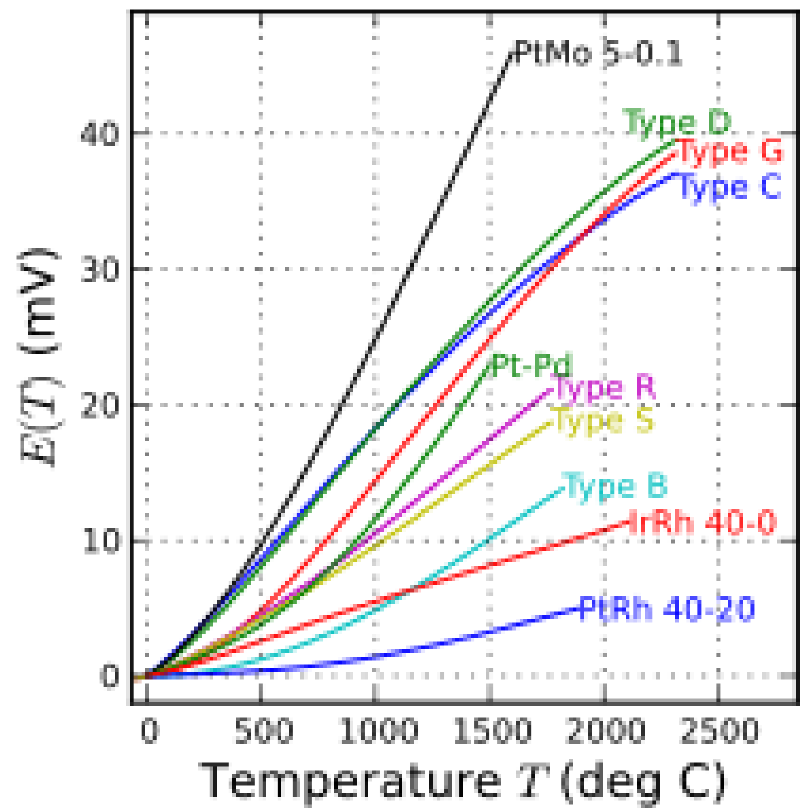
- **The Seebeck effect**
  - The Seebeck effect is the electromotive force (emf) that develops across two points of an electrically conducting material when there is a temperature difference between them.
- **Thermocouples**
  - Based on the Seebeck effect
  - Open ends must be kept at a constant reference temperature T_{REF}
  - Thermopile can provide larger output voltage: used for **precise measurement** or **power generation**.





Thermoelectric Sensors





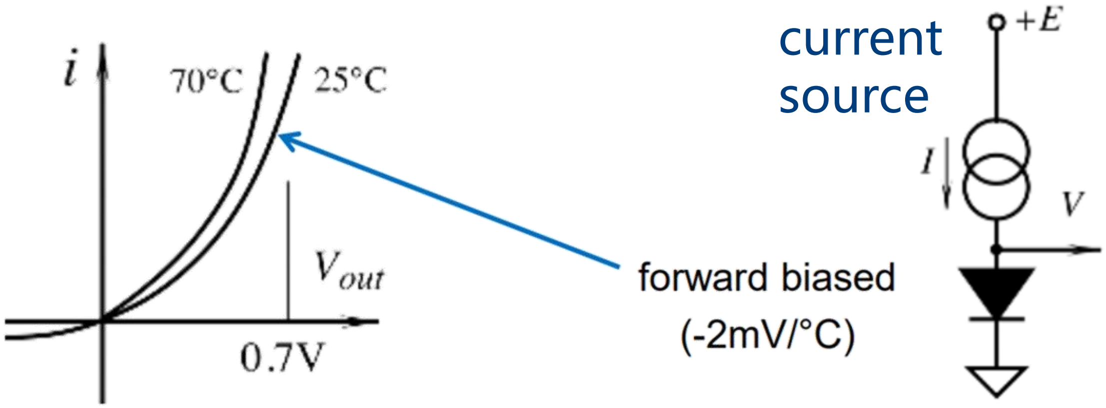
Characteristic functions for thermocouples

intermediate-temperature types

high-temperature types

P-N Junction Sensors (IC Sensors)

- Principle
  - Semiconductor p-n junction in diodes have temperature dependency
- Voltage depends on
  - Temperature
  - Current



Stable, temperature independent current source needed!

P-N Junction Sensors (IC Sensors)

example - LM35Z from national semiconductors

- sensor output

$$V_{out} = V_0 + aT$$

- sensitivity

$$a = 10\,mV/^{\circ}C$$

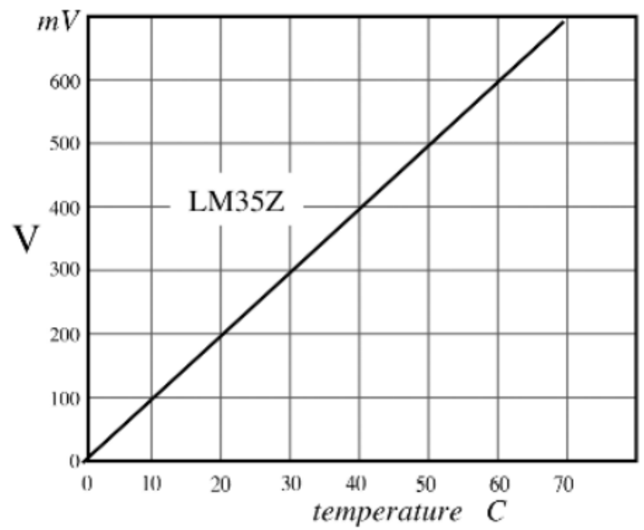
- ideal sensor would have no offset voltage

$$V_0 = 0$$

- part-to-part variations cause

$$V_0 = \pm 10mV$$

$$a = [9.9\,mV/^{\circ}C, 10.1\,mV/^{\circ}C]$$



RTDs vs. Thermocouples vs. IC Sensors

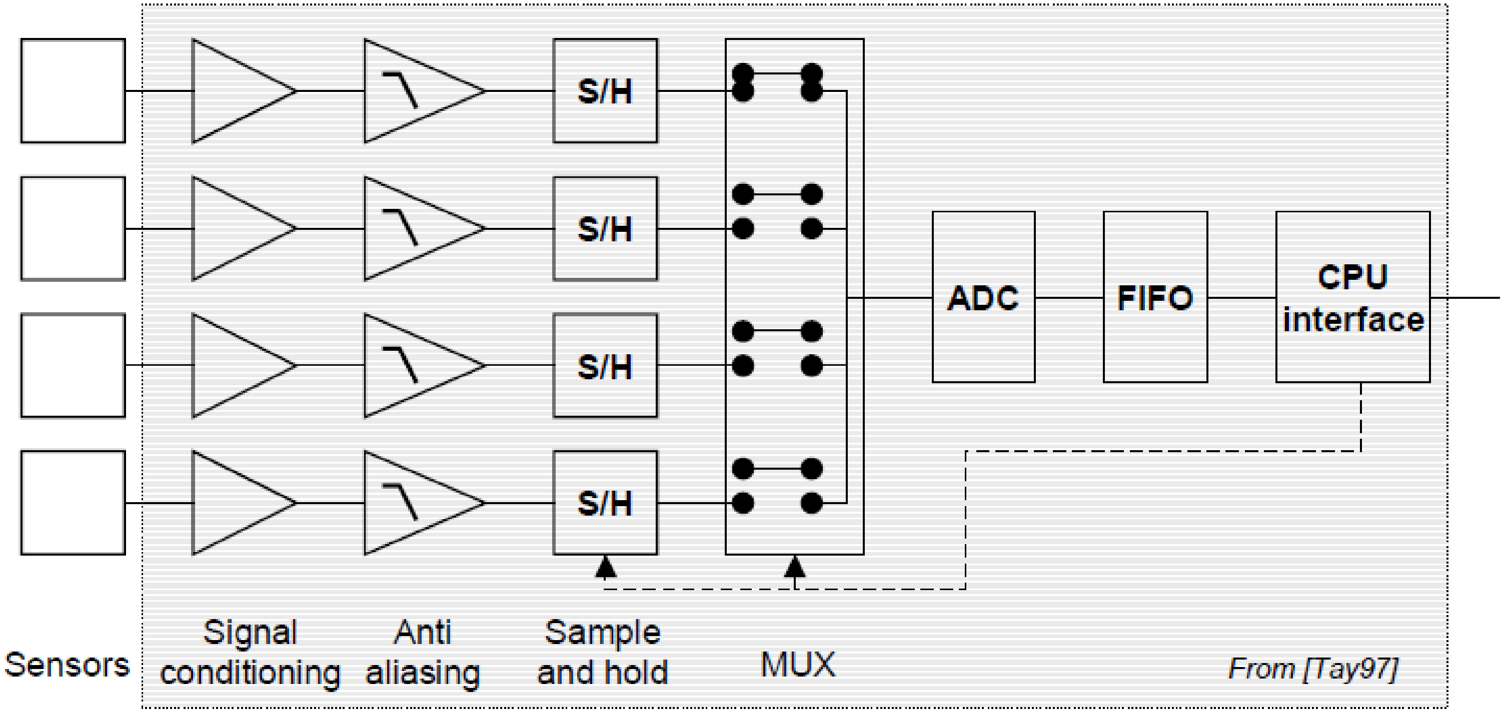
	THERMOCOUPLES	RTD	IC
ACCURACY	Limits of error wider than RTD or IC Sensor	Better accuracy than thermocouple	Best accuracy
RUGGEDNESS	Excellent	Sensitive to strain and shock	Sensitive to shock
TEMPERATURE	-400 to 4200° F	-200 to 1475° F	-70 to 300° F
DRIFT	Higher than RTD	Lower than TC	
LINEARITY	Very non-linear	Slightly non-linear	Very linear
RESPONSE	Fast dependent on size	Slow due to thermal mass	Faster than RTD
COST	Rather inexpensive except for noble metals TCs, which are very expensive	More expensive	Low cost

Summary – Basics of Sensing Principles

- Sensor classification: various criteria
- Mechanical sensors: measuring displacement, force, and acceleration
  - Resistive sensors
  - Capacitive sensors
  - Inductive sensors
  - Strain gauges and Cantilever beam-based sensors
- Thermal sensors
  - Resistive Temperature Devices (RTD)
  - Thermistors
  - Thermocouples
  - P-N junction sensors

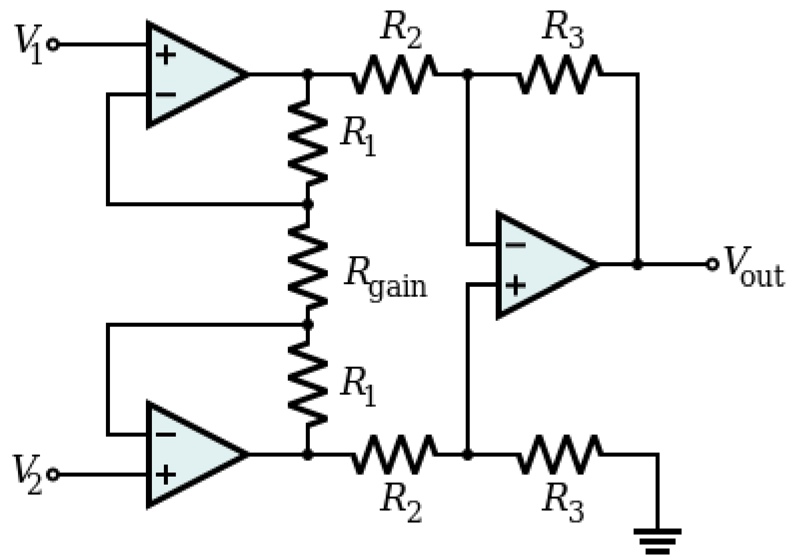
Data Acquisition

- Architecture of data acquisition systems



Signal Conditioning: Instrumentation Amplifiers

- Provide **a large amount of gain for very low-level signals.**

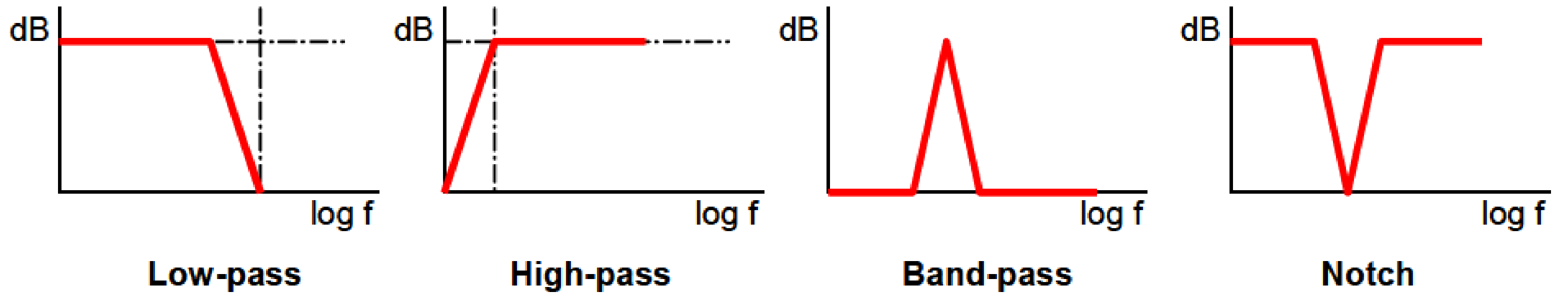


Typical instrumentation amplifier schematic

$$A_v = \frac{V_{\text{out}}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{\text{gain}}}\right)\frac{R_3}{R_2}$$

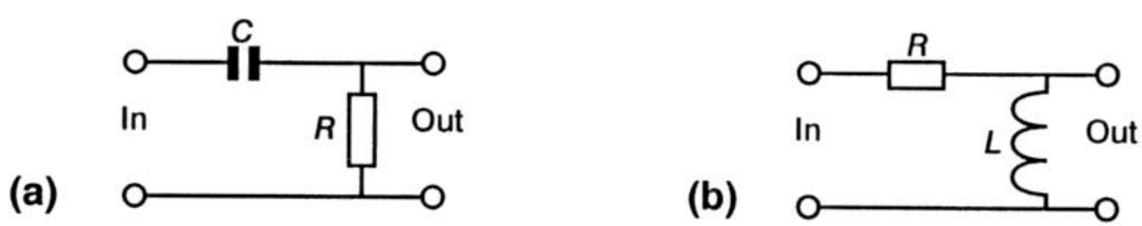
Signal Conditioning: Filters

- Remove **unwanted bandwidths** from a signal.



- Low- and high-pass filters?

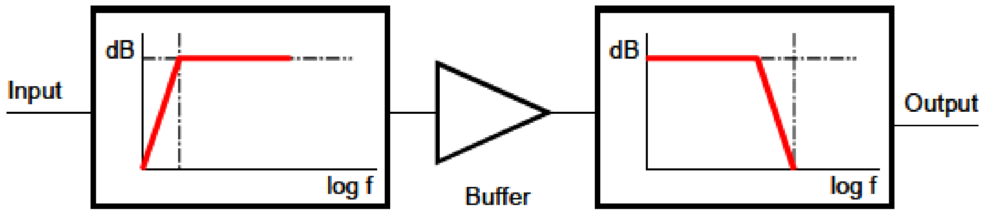
Low pass filters



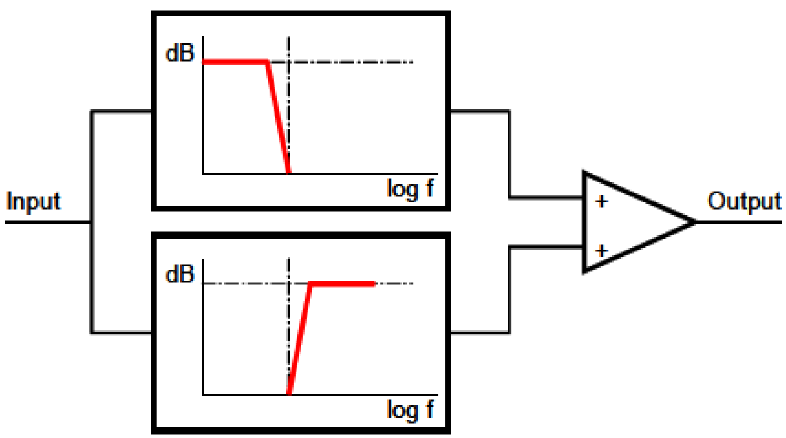
High pass filters

Signal Conditioning: Filters

- How to design a band-pass/band-stop filter?
  - High-pass and low pass in series: band-pass



  - High-pass and low-pass in parallel followed by a summer: band-stop



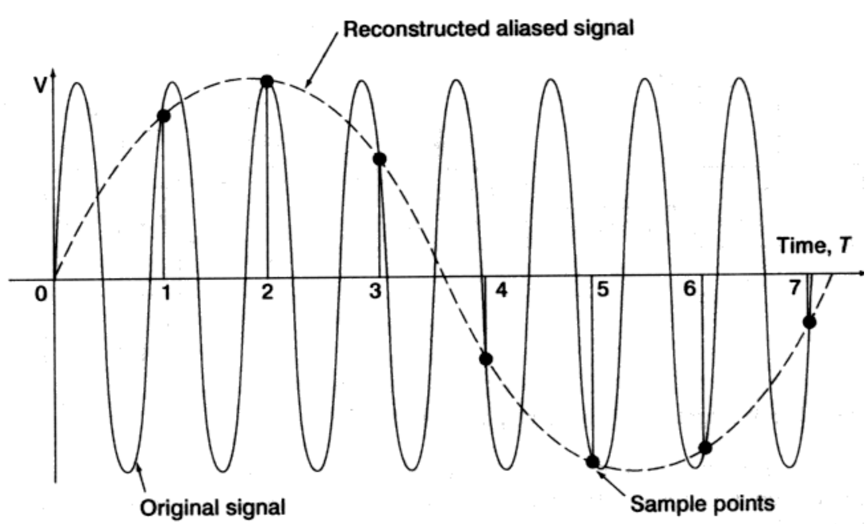
Exercise

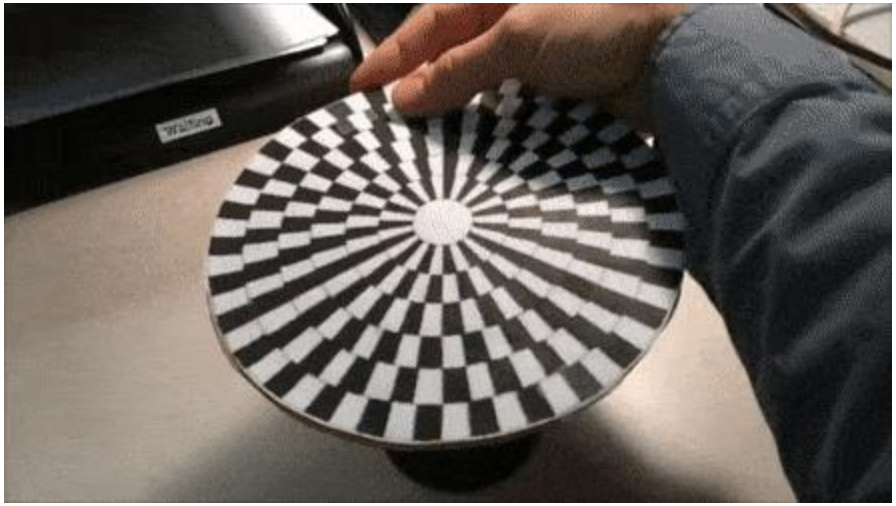
- Besides filtering, integration and derivative could also be used for signal processing. Which of the following statements is correct?
  - a) Integration tends to amplify high-frequency noise present in a signal.
  - b) Velocity can be determined using a position transducer by integrating its output signal.
  - c) Velocity can be determined using a position transducer by differentiating its output signal.
- **Correct Answer:**

  c).

Anti-aliasing

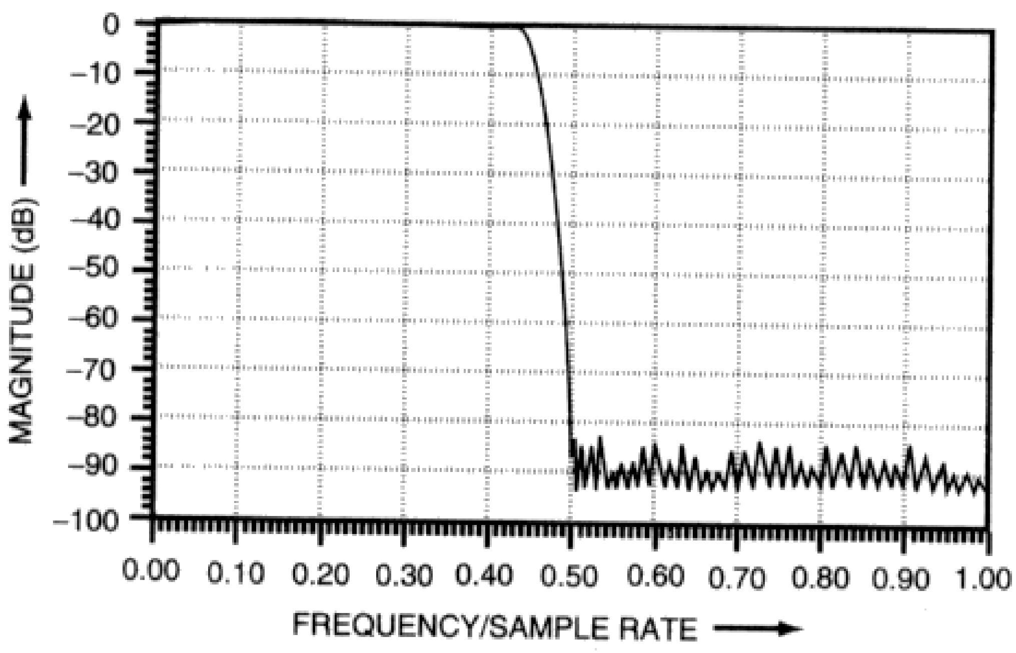
- The sampling theorem
  - You must sample at least twice the rate of the maximum frequency in your signal to prevent aliasing ($F_S \geq 2F_{MAX}$).
  - The sampling rate $F_S \geq 2F_{MAX}$ is called the Nyquist rate.





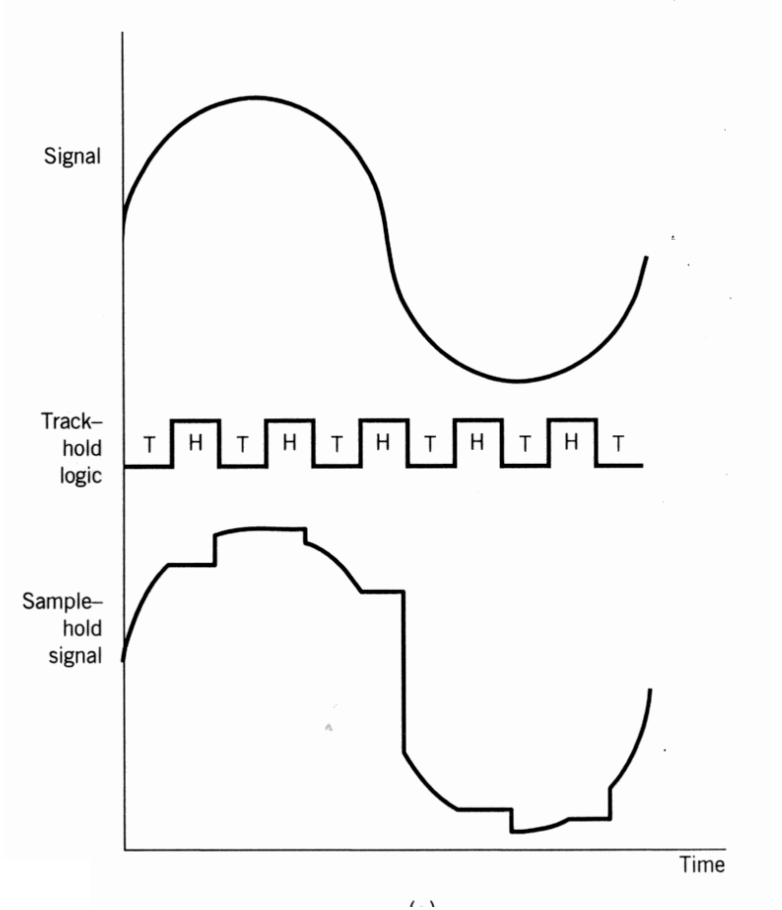
Anti-aliasing

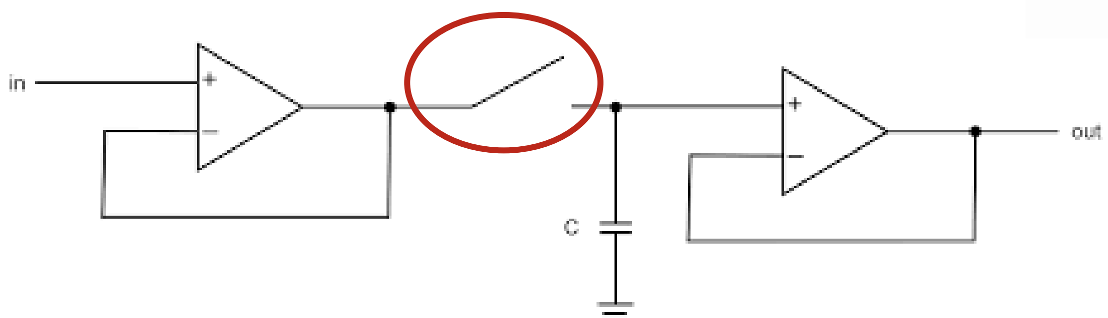
- Anti-aliasing filters
  - A **low-pass filter** designed to filter out frequencies higher than the sampling frequency.



Sample and Hold

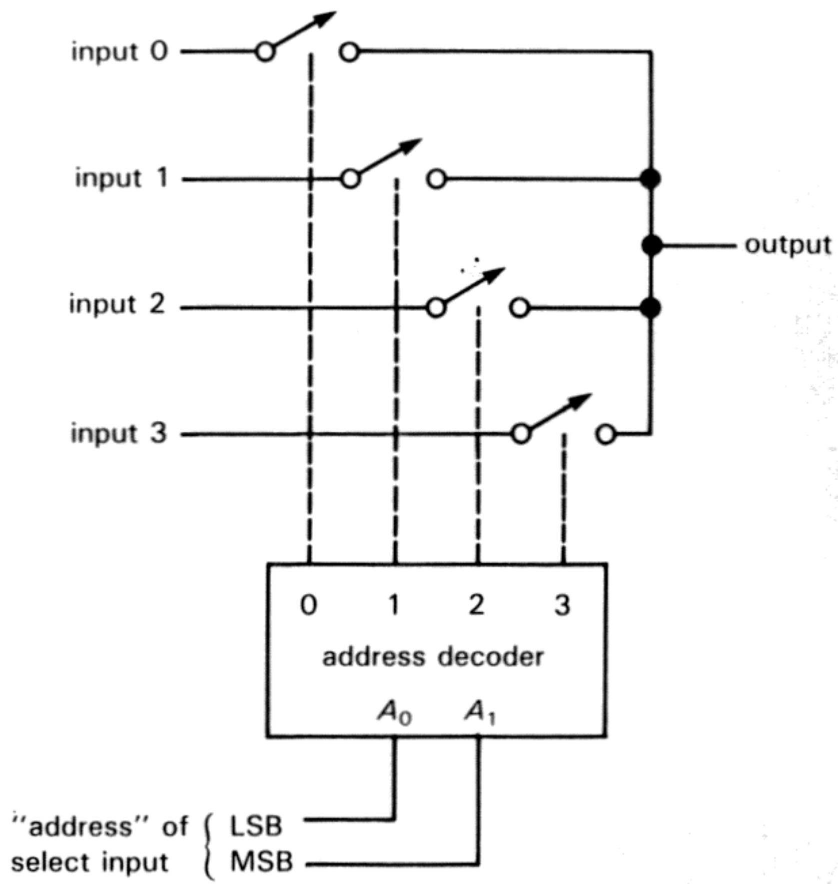
- A Sample and hold (S/H) circuit has two basic operating modes:
  - **Sample mode**: The output follows the input
  - **Hold mode**: The output is held constant until sample mode is resumed
- Why need S/H circuit?
  - To keep the signal constant during ADC conversion.





Multiplexers

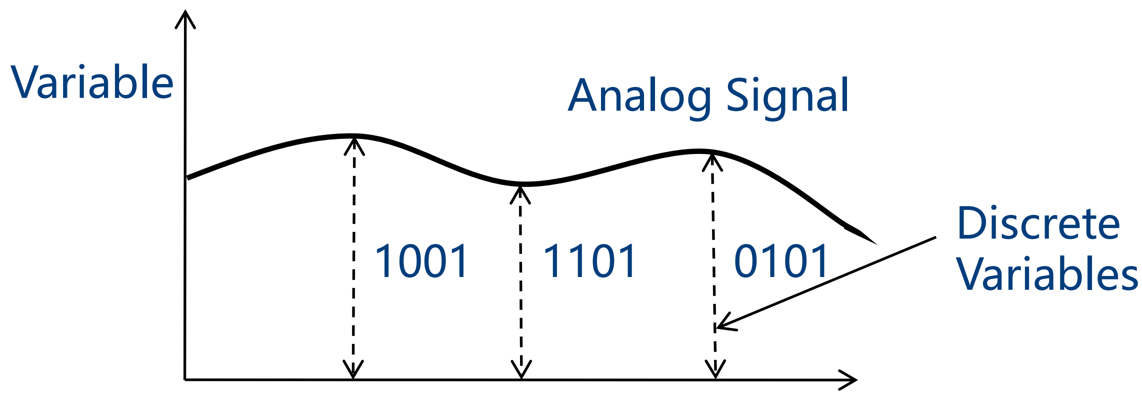
- A multiplexer is a circuit that allows you to select any of several inputs, as specified by digital control signals.



Analog to Digital Conversion (ADC)

1. Sampling – converts the continuous signal into a series of discrete analog signals at periodic intervals
2. Quantization – each discrete analog is converted into one of a finite number of (previously defined) discrete amplitude levels
3. Encoding – discrete amplitude levels are converted into digital code

- Features:
  - Sampling rate
  - Quantization number
  - Resolution
  - Conversion time



Analog to Digital Conversion: Exercise

- The ADC has a 16-bit capacity, and full scale range of 60 V. Determine:
  1. Number of quantization levels?
  2. Resolution?
  3. Quantization error?

Answer:

- Number of quantization levels

  $= 2^{16} = 65{,}536$

- Resolution

  $= 60 / 65{,}536 = \sim 0.00092$ Volts

- Quantization error

  $= 0.00092/2 = 0.00046$ Volts (maximum)

Digital to Analog Conversion (DAC)

- Convert digital values into continuous analogue signal.

$$E_0 = E_{ref}\left\{0.5B_1 + 0.25B_2 + \cdots + \left(2^n\right)^{-1}B_n\right\}$$

where E_0 is output voltage; E_{ref} is reference voltage; B_n is status (0/1) of successive bits in the binary register.

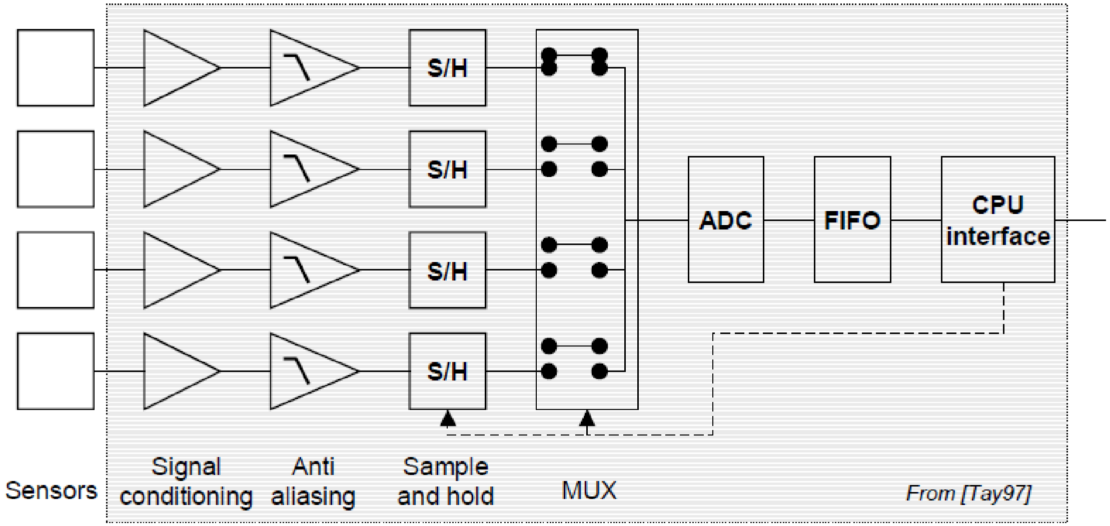
- **Exercise:** A DAC has a reference voltage of 100 V and has 6-bit precision.
  The binary data is 101000.
  Find the output analogue values?

  Answer:

  E_0 = 100{0.5(1)+0.25(0)+0.125(1)+0.0625(0)+0.03125(0)+0.015625(0)}

Summary – Data Acquisition

- Architecture of data acquisition systems
- Modules in data acquisition systems



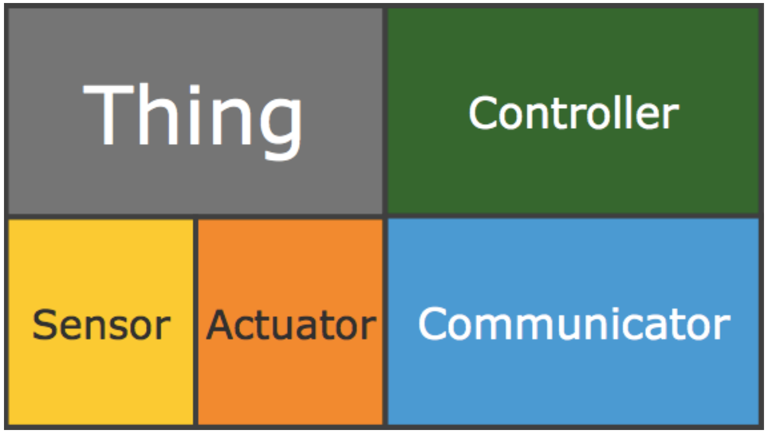
Internet-of-Things (IoT): Introduction

- What is the Internet-of-Things? Watch the video for an example.

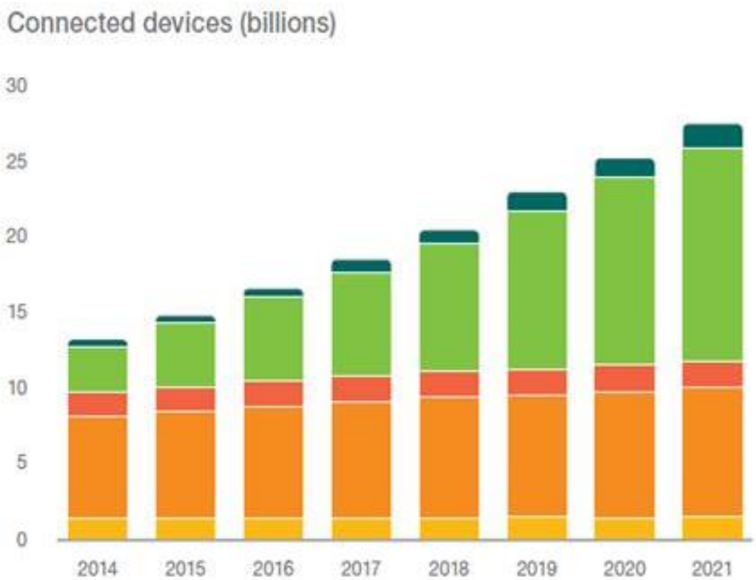
Internet-of-Things (IoT): Introduction

- How does the thermostat work?
  - You are leaving the home: **sense user.**
  - Room temperature is too high/too low: **sense environment/object.**
  - Use the information to make a decision: **process.**
  - Inform user of decision: **communicate.**

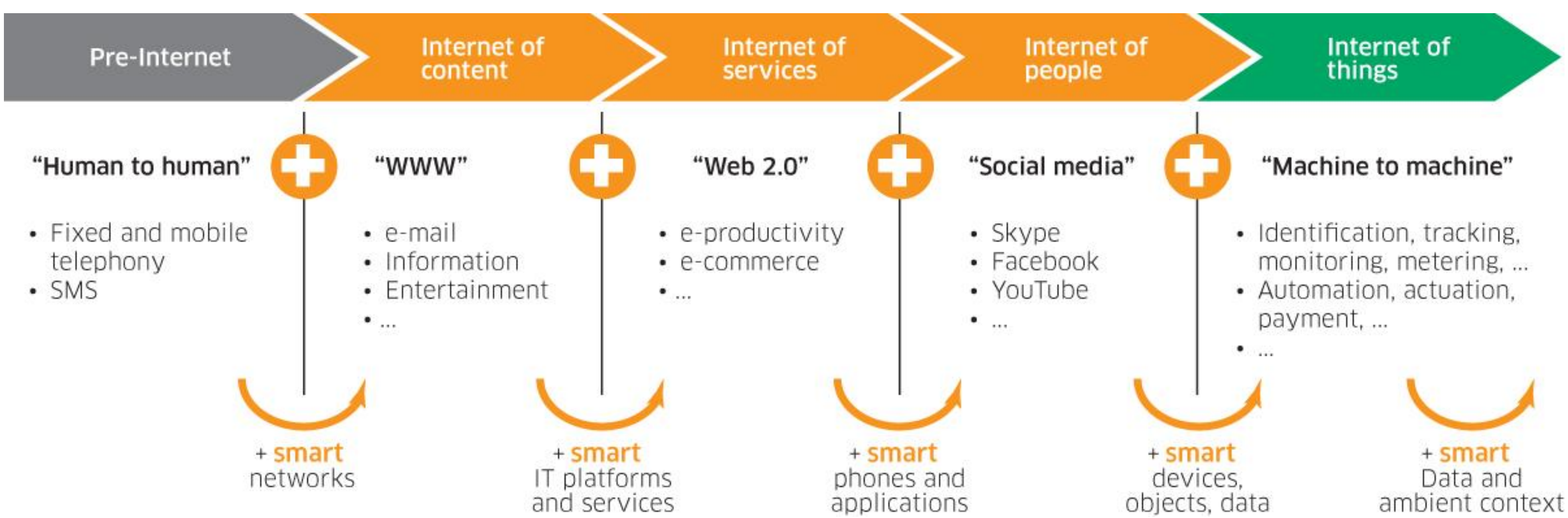
Physical object ("thing")
+
Controller ("brain")
+
Sensors
+
Actuators
+
Networks (Internet)



Internet-of-Things (IoT): Growth and Vision



	15 billion	28 billion	CAGR 2015–2021
Cellular IoT	0.4	1.5	27%
Non-cellular IoT	4.2	14.2	22%
PC/laptop/tablet	1.7	1.8	1%
Mobile phones	7.1	8.6	3%
Fixed phones	1.3	1.4	0%
	2015	2021	



Internet-of-Things (IoT): Issues and Challenges

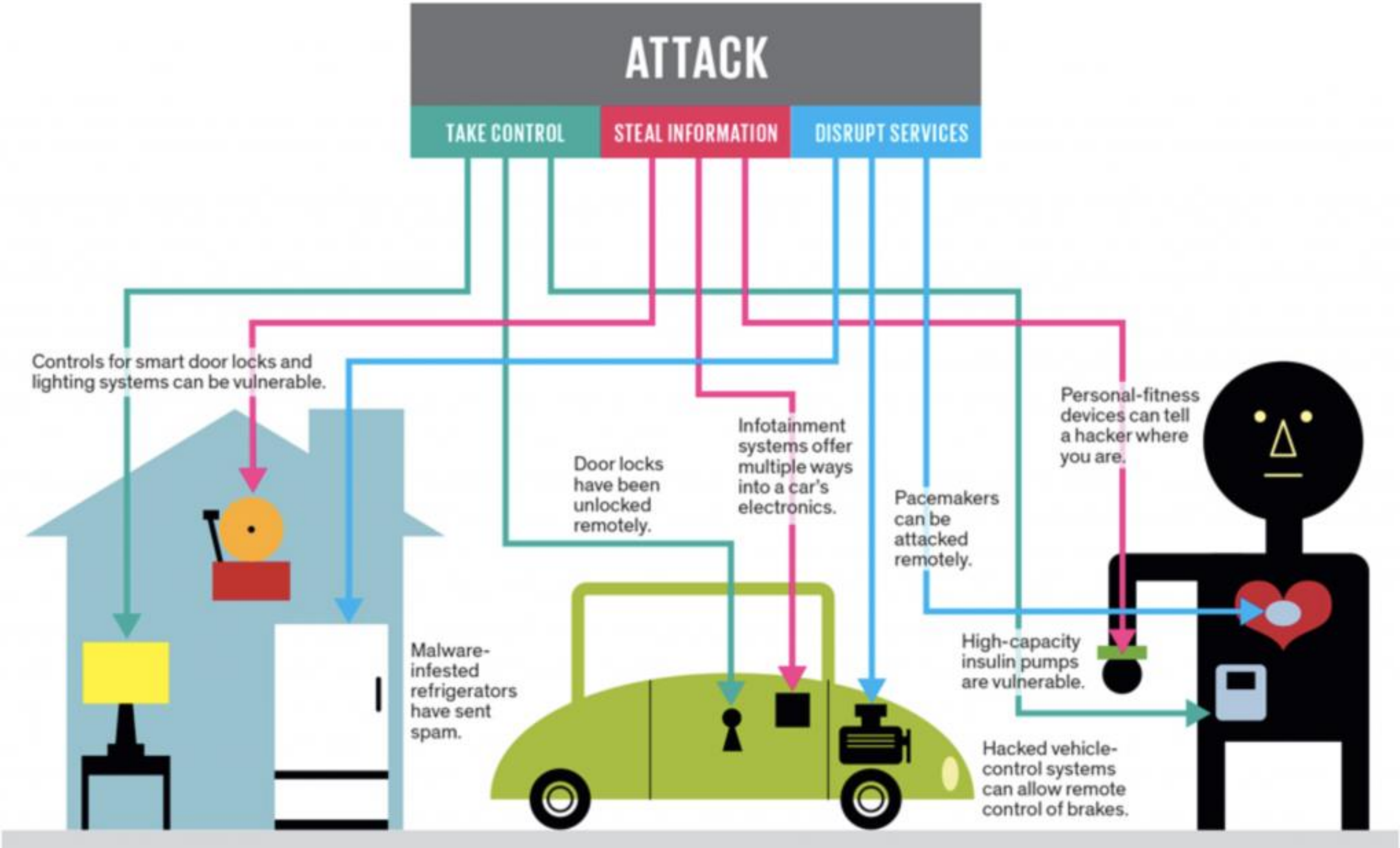
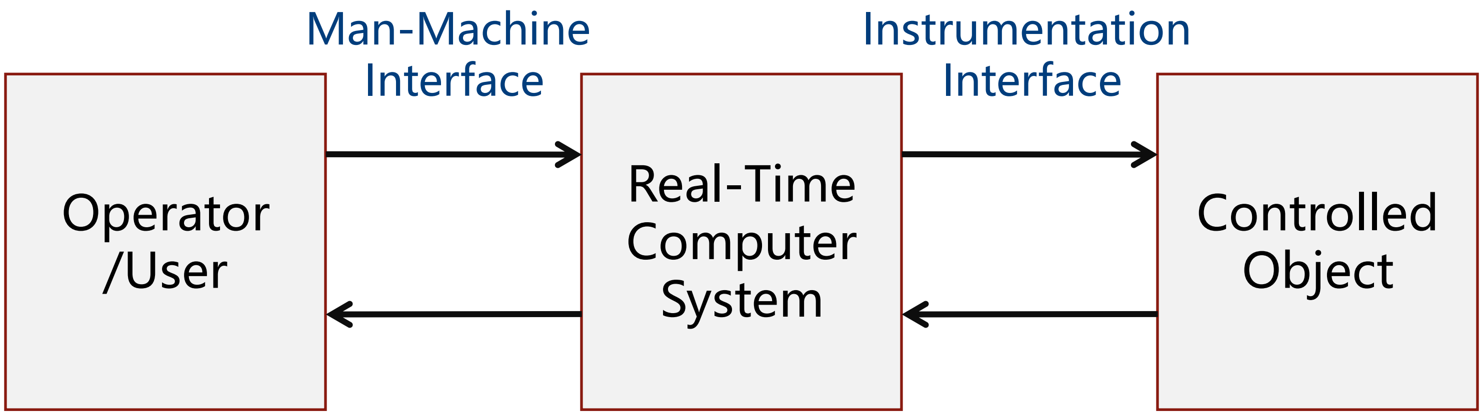


Illustration: J. D. King

Internet-of-Things (IoT) as a Control System

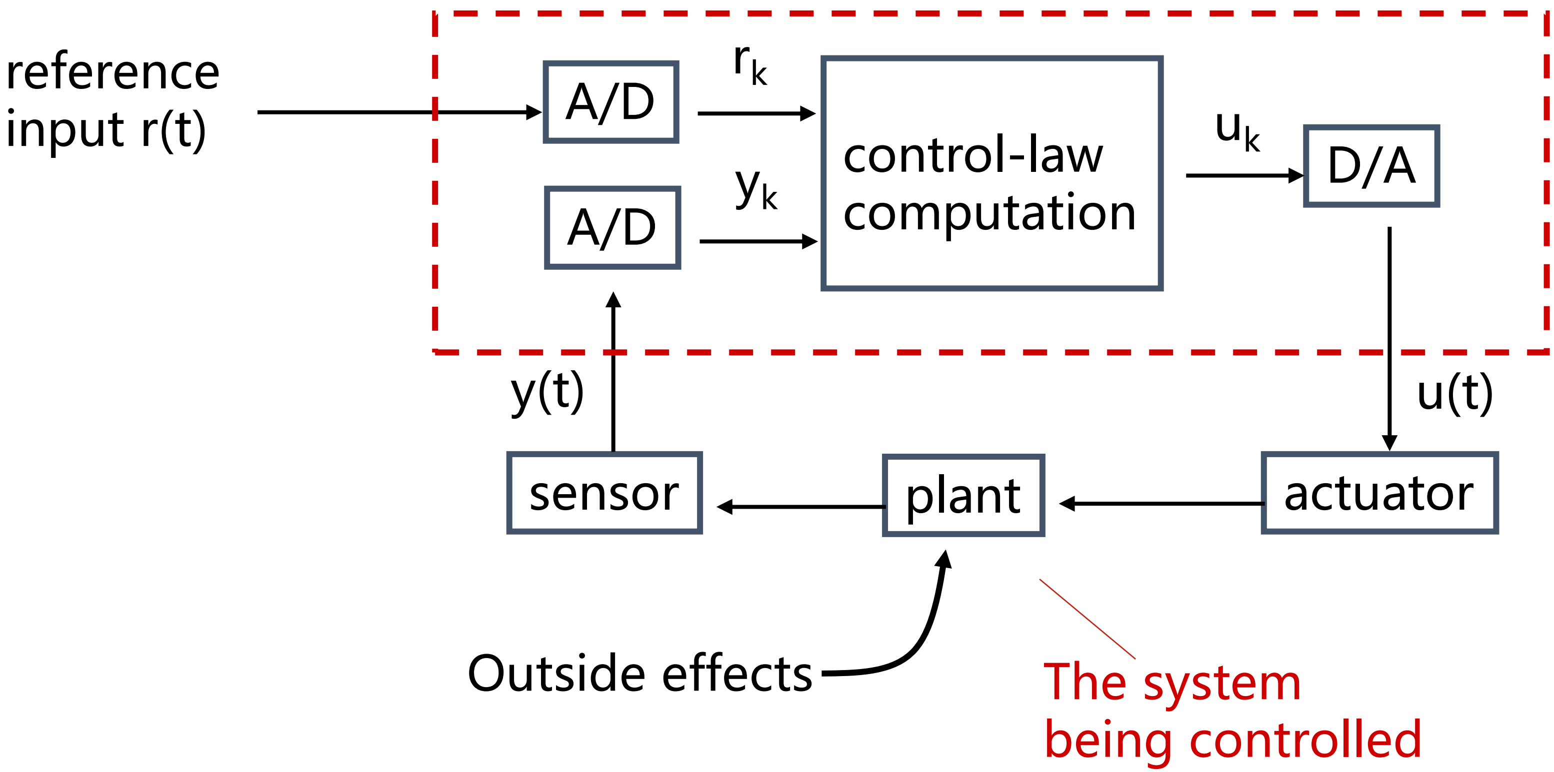
- IOT systems and control systems are similar!



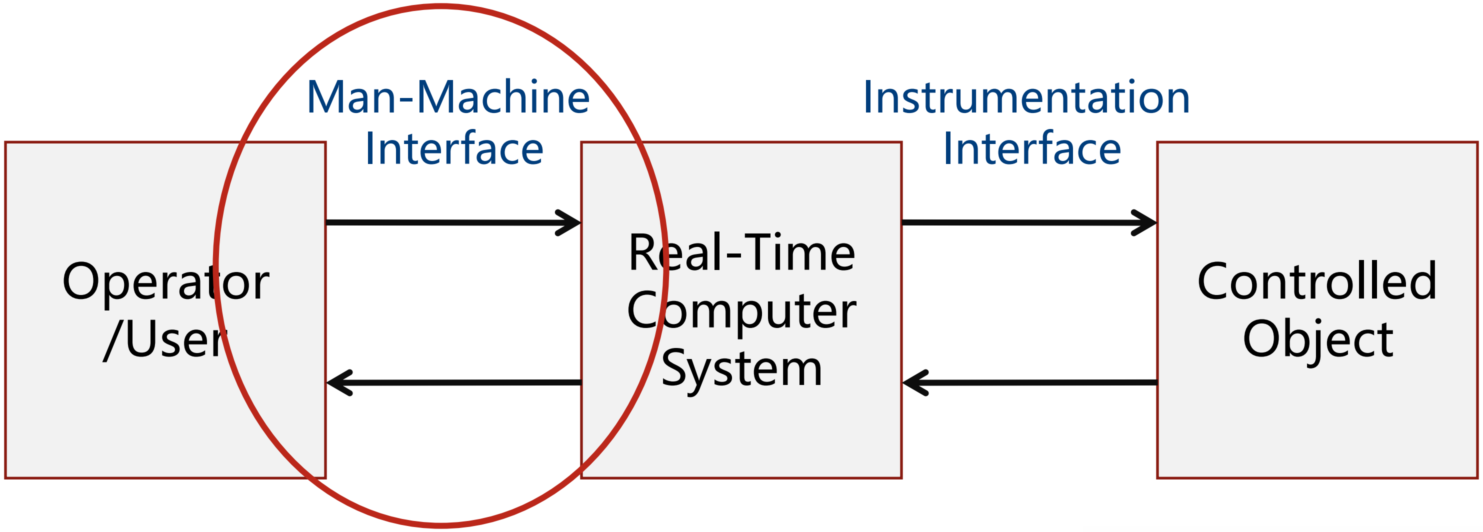
- **Man-machine interface**: input devices, e.g., keyboard and output devices, e.g., display
- **Instrumentation interface**: sensors and actuators that transform between physical signals and digital data

Internet-of-Things (IoT) as a Control System

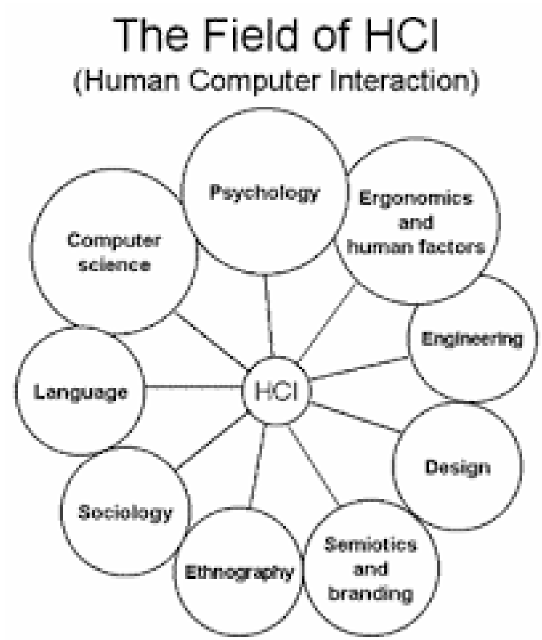
- A simple one-sensor, one-actuator control system:



Human-Computer Interfaces (HCI)



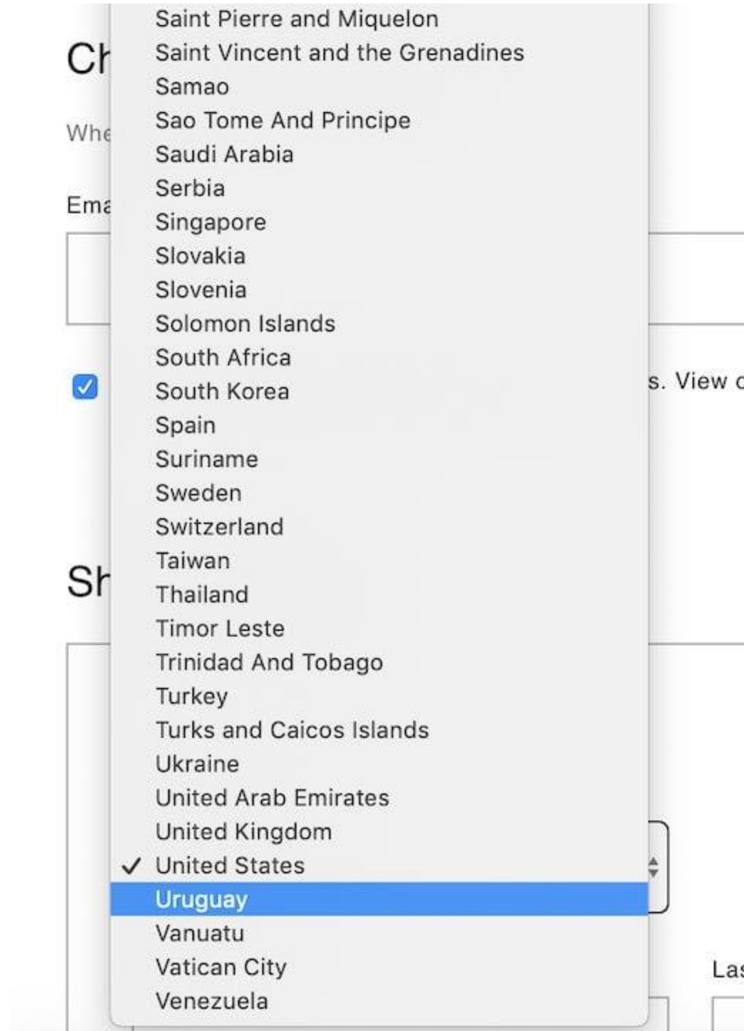
- **Human-computer interaction (HCI)** means the design and the use of computer technology, focused on the interfaces between people (users) and computers.
  - Intersection of **computer science**, **behavioural sciences**, **design**, …



(Bad) Examples of User Interfaces

Pull from which direction?

Illustrative words disappears



Long list without a filter

Why is HCI Important?

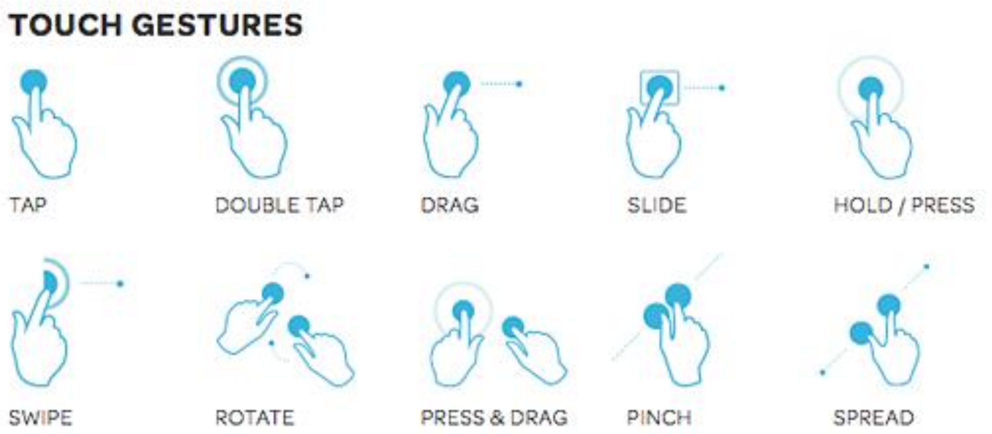
- It can affect
  - Effectiveness
  - Productivity
  - Morale
  - Safety

- Bad interfaces:
  - Confusing
  - Cumbersome
  - Time-consuming
  - Uninformative
  - Lead to errors
  - …

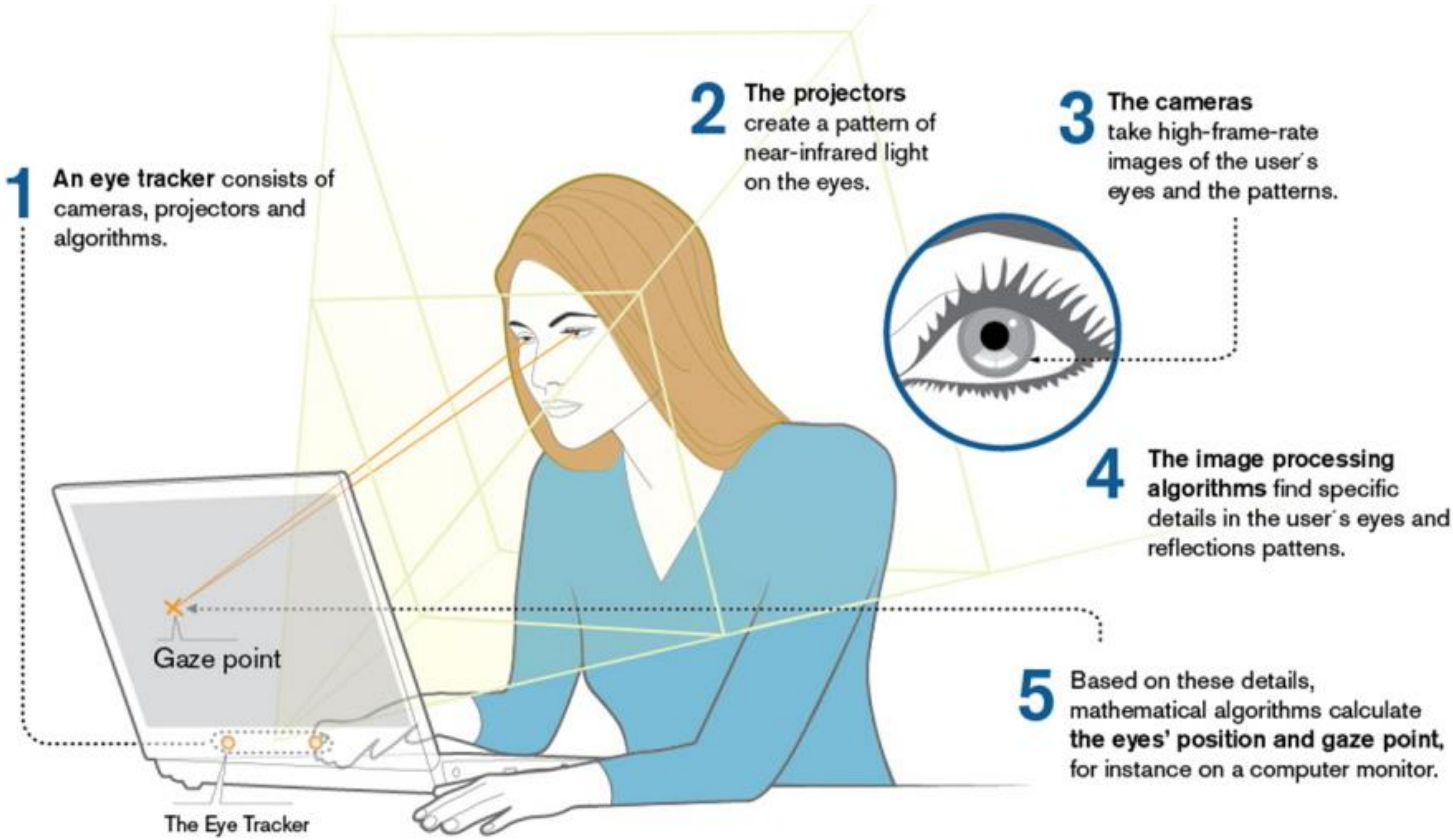
- From now on, try to discuss the interfaces from the following perspectives:
  - Ease-of-Use?
  - Flexibility?
  - Accuracy?
  - Safety?
  - Privacy?

Touch / Gestures as Input

Keyboard or touchscreen?



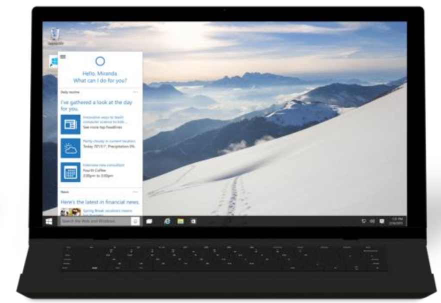
Eye Movement as Input



Speech Input

- Applications:
  - Siri, google assistant, and many more.

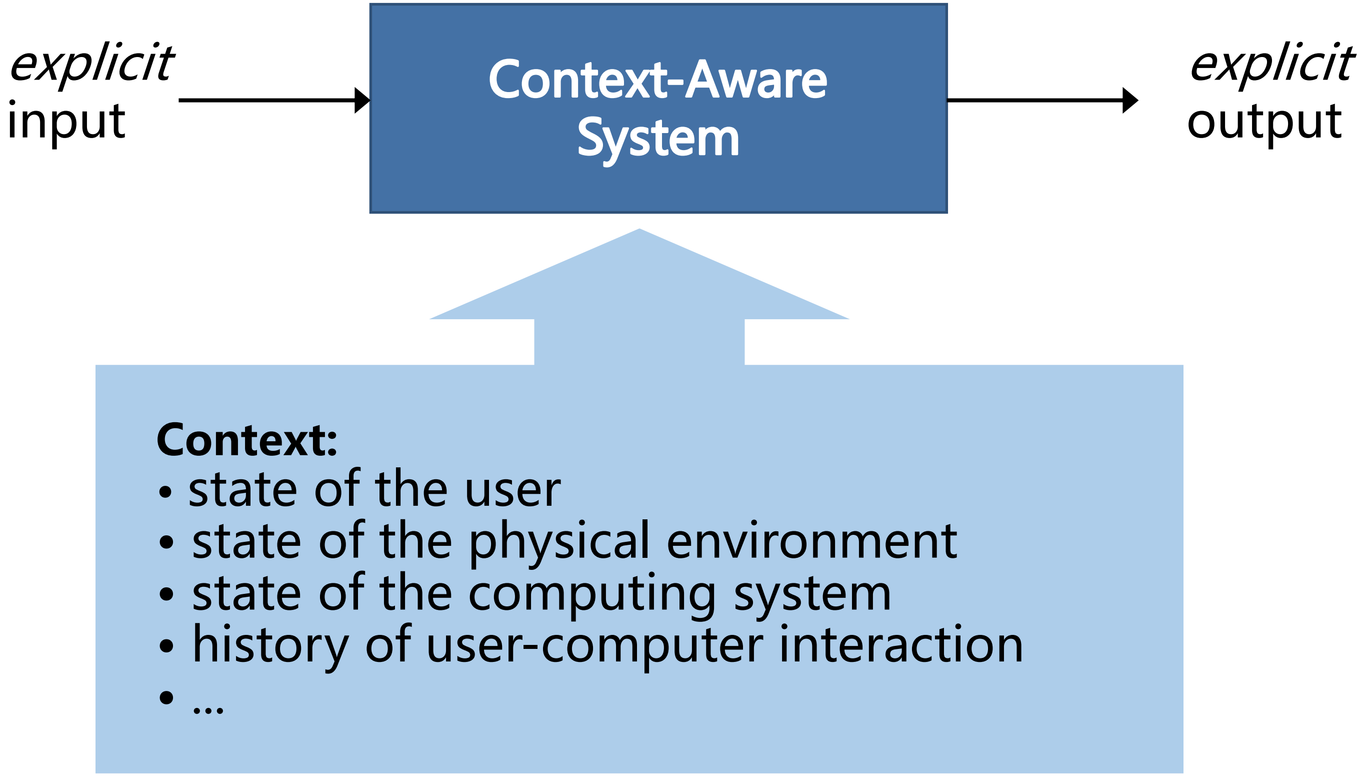




- Difficulties:
  - Noisy environment
  - Body language missed
  - Speaker variability: speed, style, dialects
  - Ambiguity: homophones
  - Context correlation and reasoning

one analysis	alternative analysis
the **tail** of a dog	the **tale** of the dog
the **sail** of a boat	the **sale** of a boat

Trend to Use Context as Implicit Input in HCI



Context Brings Extra Information

Context as Implicit Input in HCI: Examples

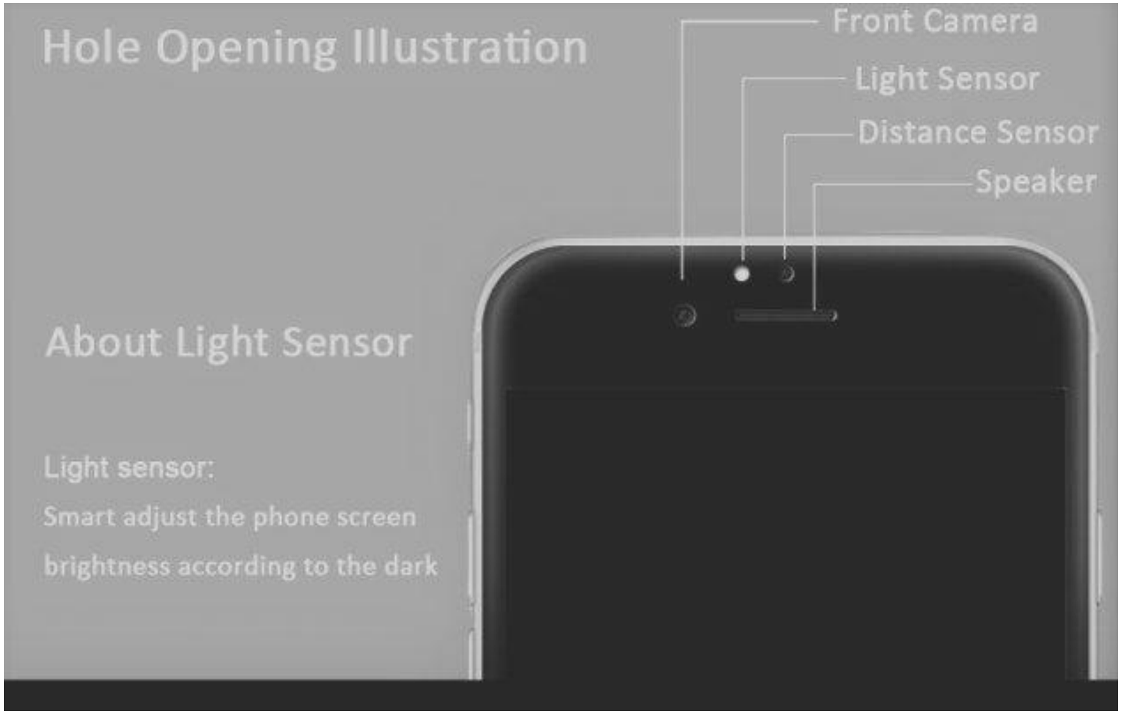
- Example 1
  - Smartphone adjusts the screen to the orientation of the device
  - Apple Watch turns on display if arm lifted/rotated

Orientation is determined by using both a gyroscope and an accelerometer.

Context as Implicit Input in HCI: Examples

- Example 2
  - Phone display adjusts the brightness of the display based on the surrounding area

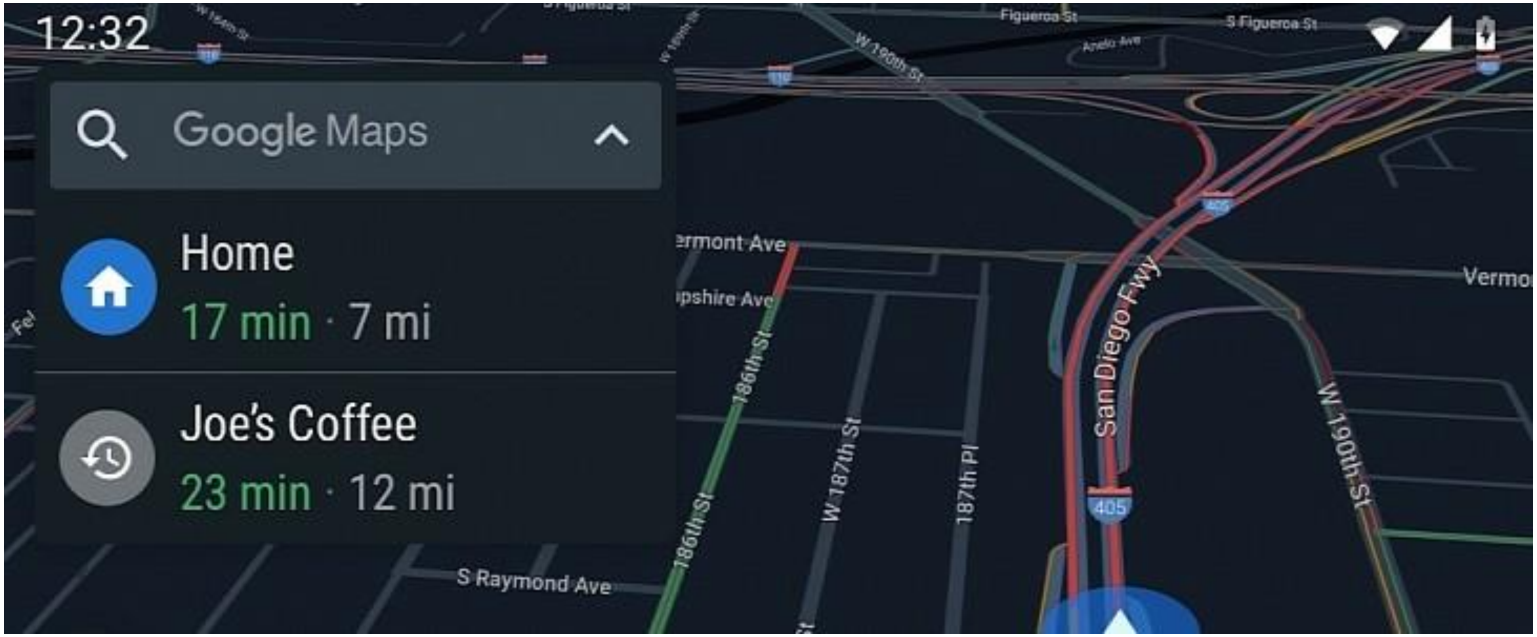
Uses a light sensor.



Context as Implicit Input in HCI: Examples

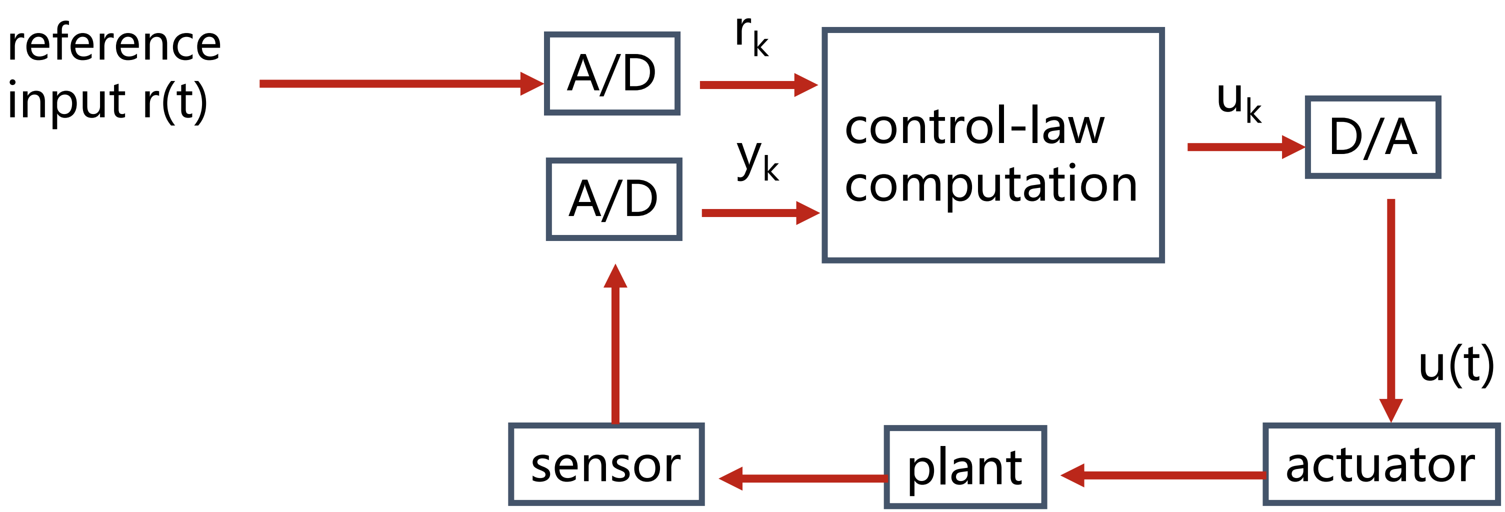
- Example 3
  - Device displays user's location, shows route to a desired destination, find nearby stores, geotag images on social media, etc.

Uses location sensor.



Communications

- **Communications:** Connects devices with each other & the cloud.



Communications

- Communication type:
  - Wireline (e.g., copper wires, optical fibers)
  - Wireless (e.g., RF, IR)

- Popular RF-based communication solutions:
  - IEEE 802.15.1 (Bluetooth)
  - IEEE 802.15.4 (Zigbee)
  - IEEE 802.11 (Wi-Fi)
  - Near Field Communication (NFC), e.g., RFID

Communications: Wireless Characteristics

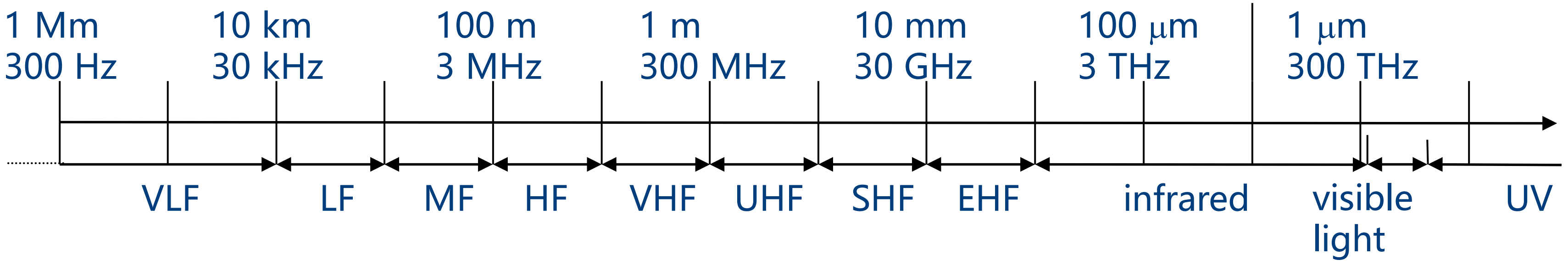
VLF = Very Low Frequency
LF = Low Frequency
MF = Medium Frequency
HF = High Frequency
VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

Frequency and wavelength

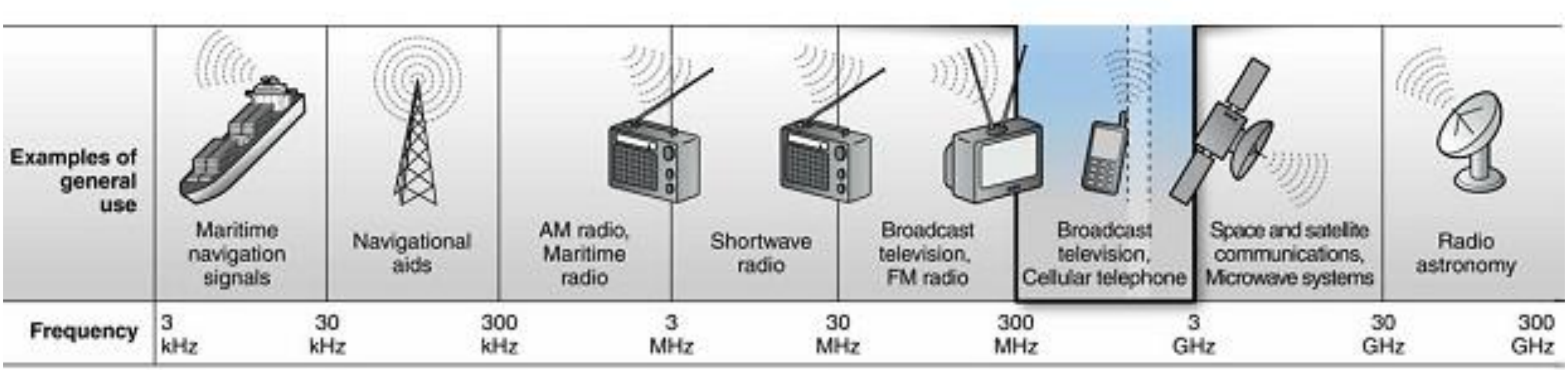
$$\lambda = c/f$$

wavelength λ, speed of light $c \cong 3 \times 10^8$ m/s, frequency f



Frequencies for Mobile Communication

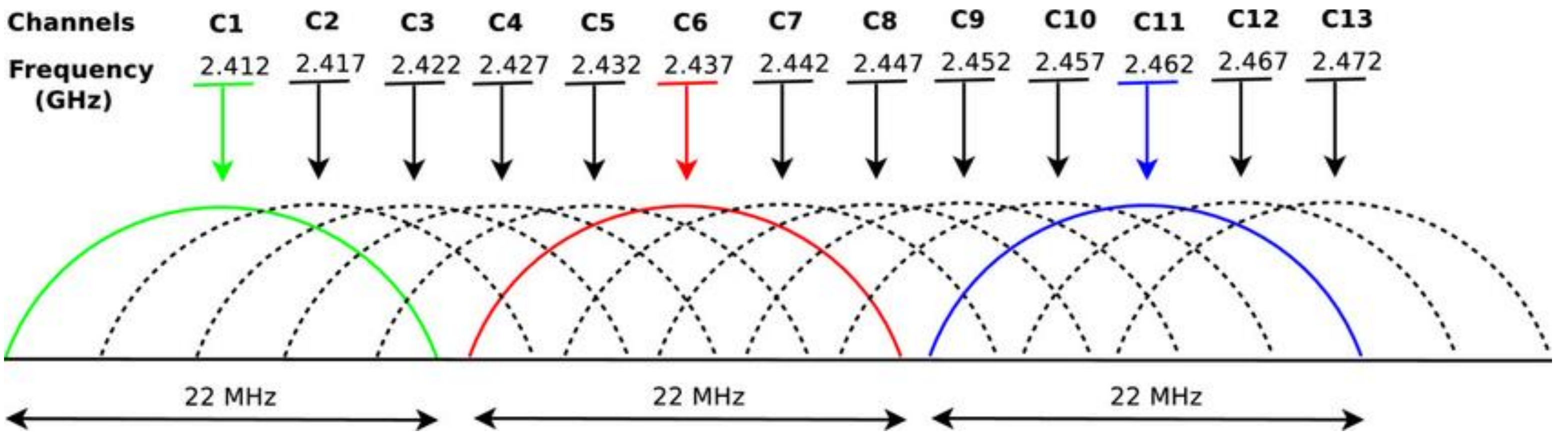
- Low Frequencies:
  - low data rates
  - travel long distances
  - follow Earth's surface
  - penetrate objects and water (submarine communication)
- High Frequencies:
  - high data rates
  - short distances
  - straight lines
  - cannot penetrate objects

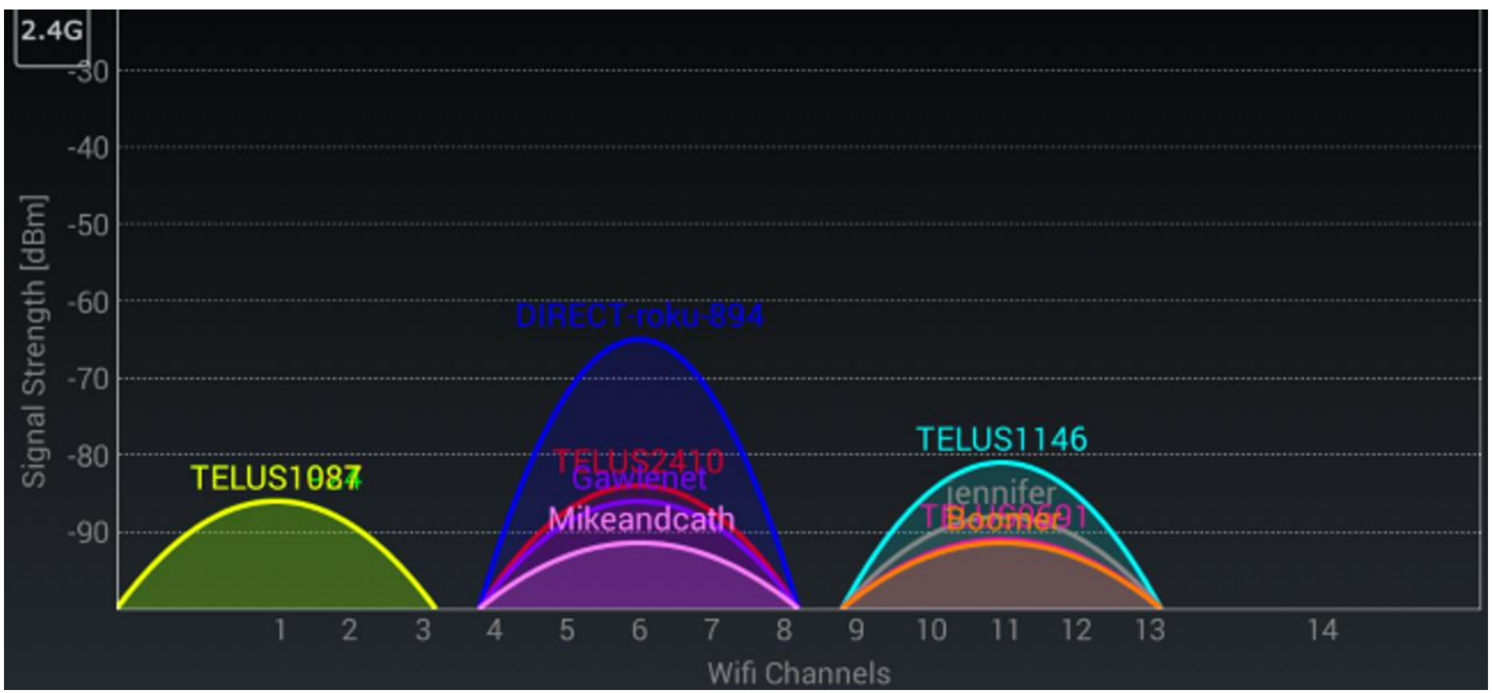


Wi-Fi Standards

802.11 Wireless Standards					
IEEE Standard	**802.11a**	**802.11b**	**802.11g**	**802.11n**	**802.11ac**
Year Adopted	1999	1999	2003	2009	2014
Frequency	5 GHz	2.4 GHz	2.4 GHz	2.4/5 GHz	5 GHz
Max. Data Rate	54 Mbps	11 Mbps	54 Mbps	600 Mbps	1 Gbps
Typical Range Indoors*	100 ft.	100 ft.	125 ft.	225 ft.	90 ft.
Typical Range Outdoors*	400 ft.	450 ft.	450 ft.	825 ft.	1,000 ft.

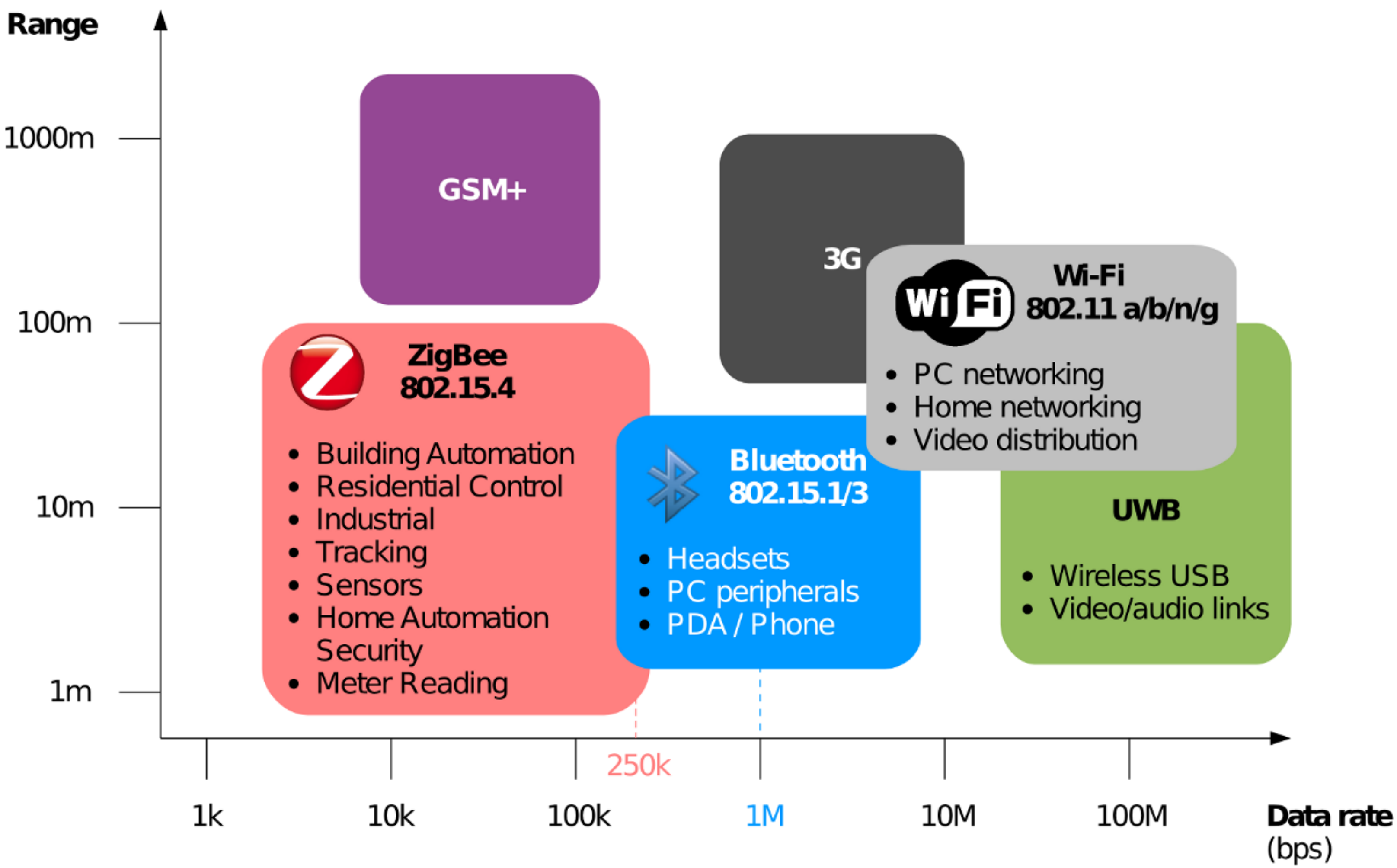
Wi-Fi Channels





Communications: Comparison

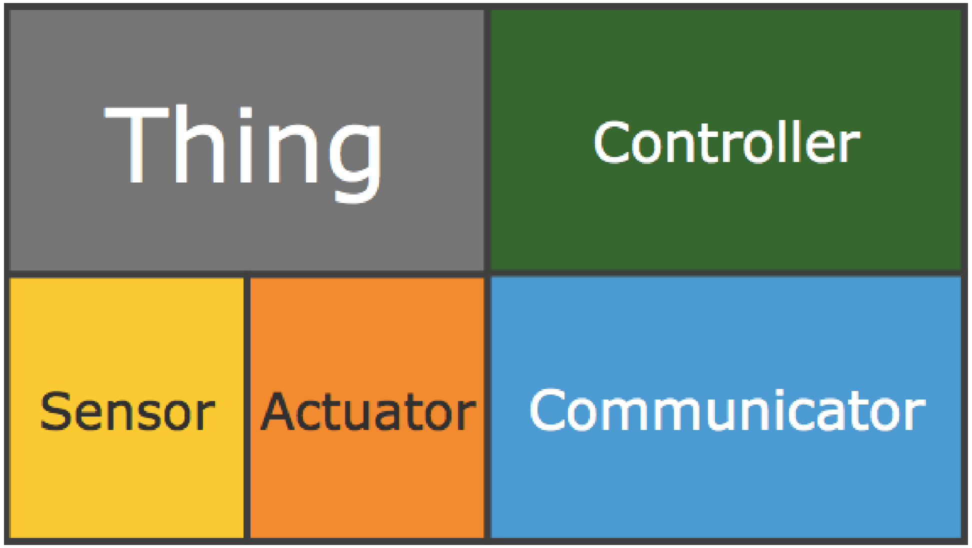
- **Range** vs. **data rate** for different communication methods:



Communications: Example

- Airtags
  - Bluetooth + UWB
  - Bluetooth for rough localization
  - UWB for precise localization

What is not covered?



Summary – IOT Systems

- Introduction
- Internet-of-Things (IoT) as a control system
- Human-Computer Interfaces (HCI)
- Communications

References

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2. Internet of Things (nd.edu)
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4. Chapter 3: Sensors (pearsoned.co.uk)