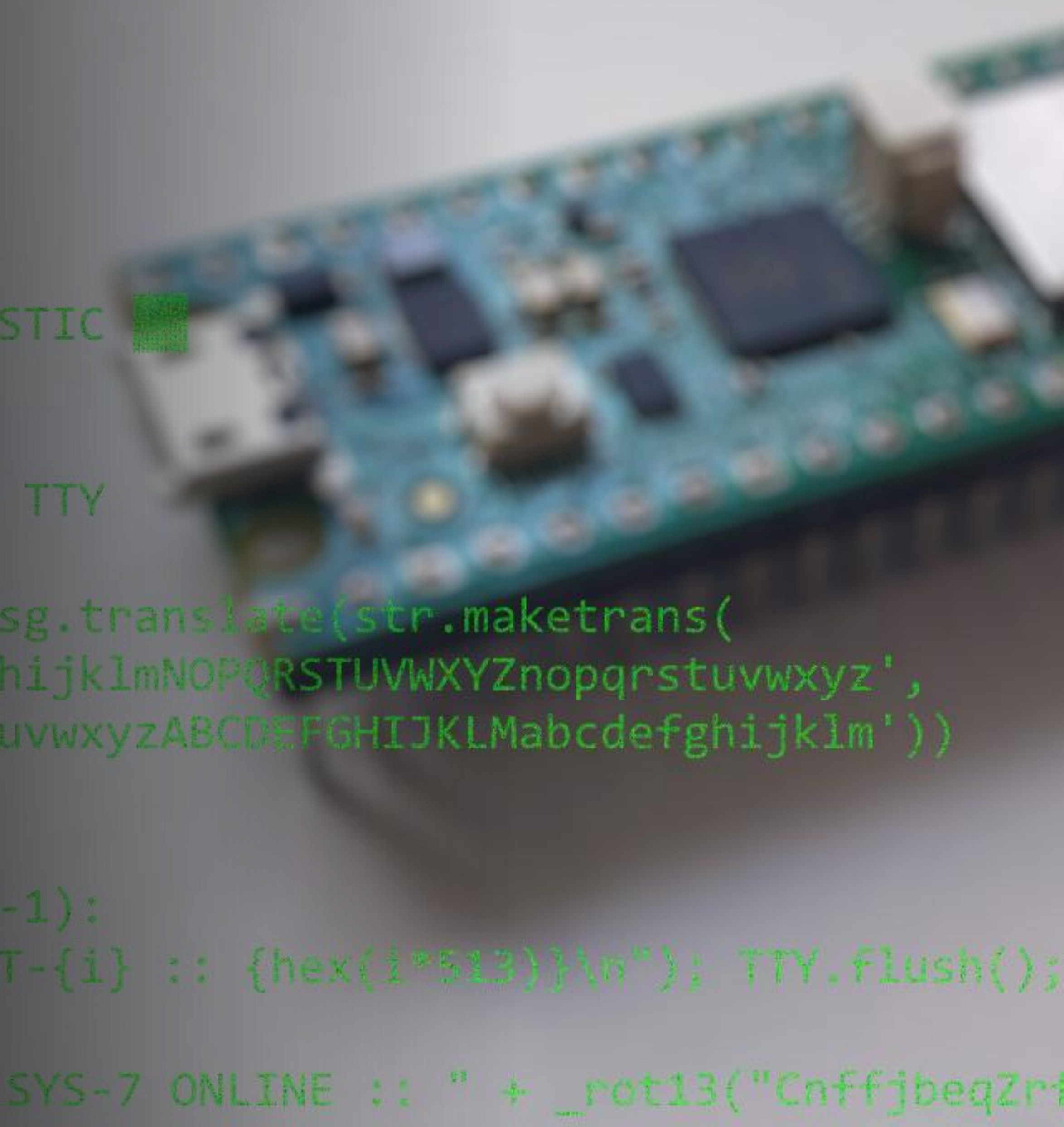
Lecture 4

Design of Data Acquisition Systems

Fjodor van Slooten & Jakup Ratkoceri



Data Acquisition Systems, lecture 4

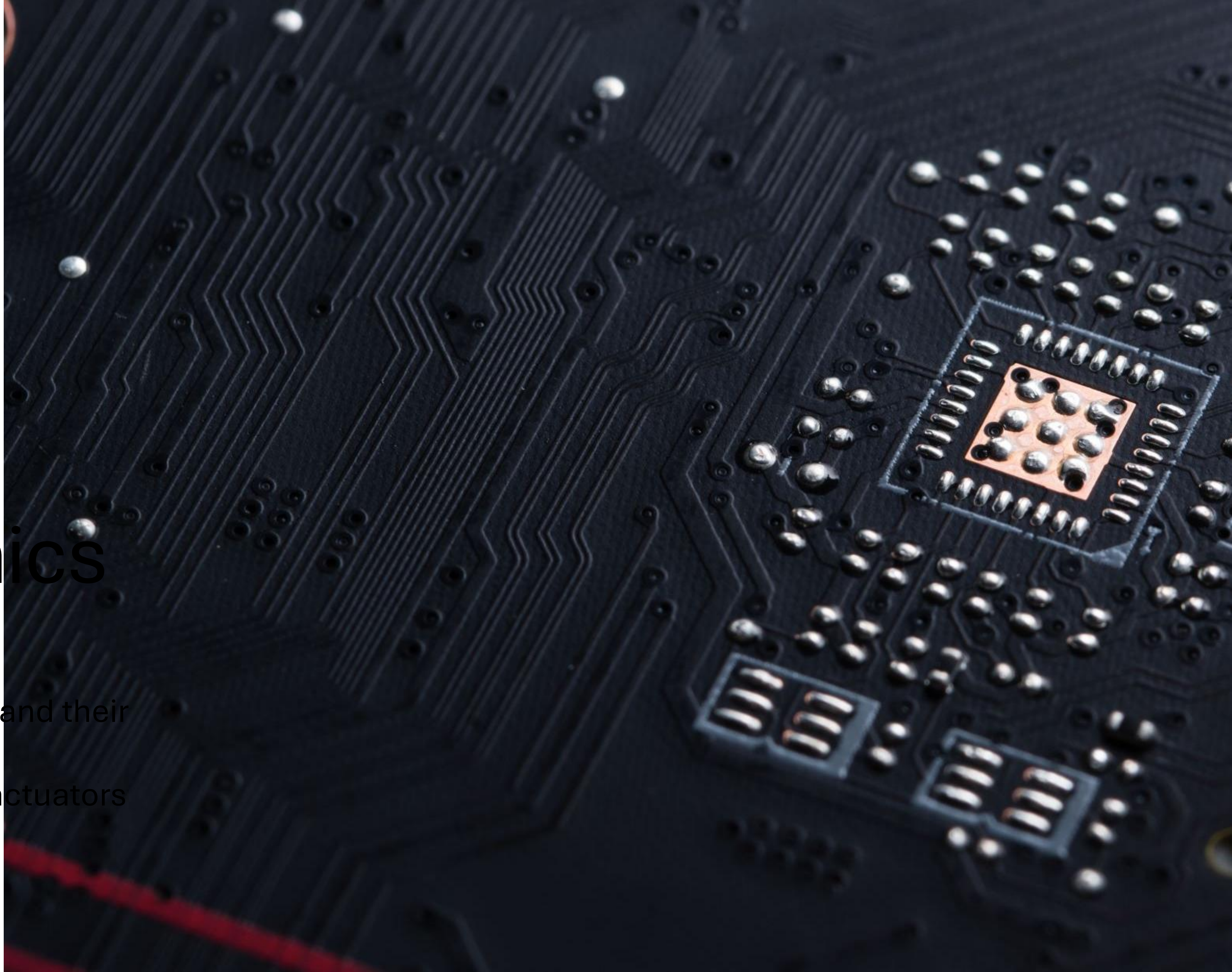
4.1 Microcontroller programming

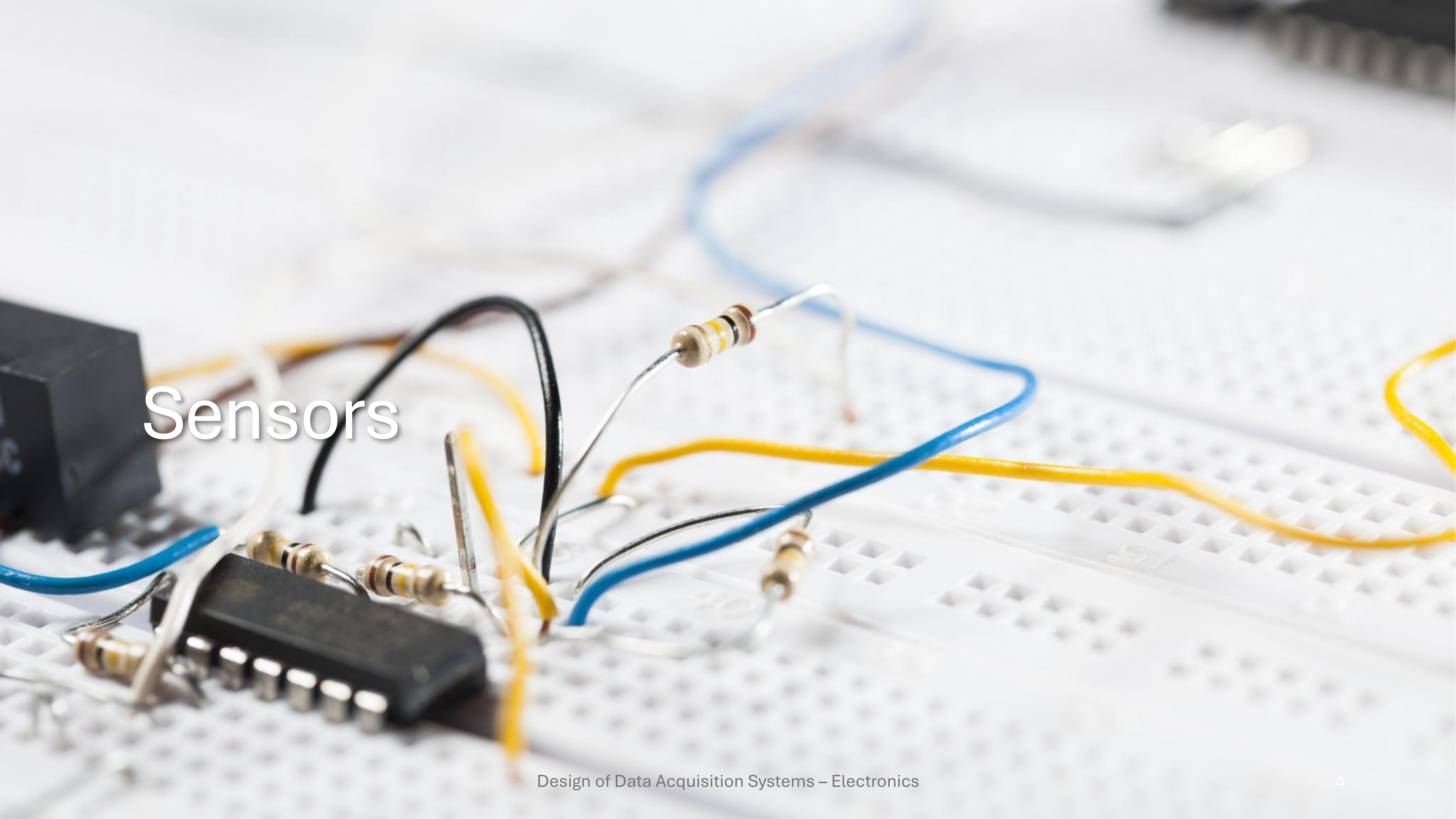
4.2 Interfacing sensors and actuators with microcontrollers. Microcontrollers and Data Acquisition

4.3 Tutorial: Create a sensor that can store data over time (storage can be local or online, providing different levels of challenge)

4.2 Electronics

- Identify types of sensors and their characteristics
- Interfacing sensors and actuators with microcontrollers





Sensors

Controlling sensors & actuators

- Sensors: inputs
- Actuators: outputs (things that move or generate something)

Actuators: light, motor, display, thermal

Measure data, generate data

Sensors and Actuators

Physical property:

- time
- temperature
- position
- angle
- acceleration
- force
- sound

SENSORS

Types Of Sensors - GeeksforGeeks

Sensors and Actuators

Physical property:

- time
- temperature
- position
- angle
- acceleration
- force
- sound

Electrical signal:

- voltage
- current
- (via resistance)
- (via capacitance)
- (via inductance)
- ….

SENSORS

Types Of Sensors - GeeksforGeeks

Sensors and Actuators

Physical property:

- time
- temperature
- position
- angle
- acceleration
- force
- sound

Electrical signal:

- voltage
- current
- (via resistance)
- (via capacitance)
- (via inductance)
- ….

Physical property:

- temperature (by resistor)
- position (by motor)
- force (by e.g. motor)
- sound (by loudspeaker)
- light (by LED, incandescent lamp)

SENSORS

ACTUATORS

Types Of Sensors - GeeksforGeeks

Classification of Sensors

Power Requirement

Active Sensors - Ultrasonic sensor

Passive Sensors- Thermocouple

Feature	Active Sensors	Passive Sensors
Power Source	Require external power to operate	Do not require external power
Signal Generation	Generate their own signal	Detect and respond to external energy
Complexity	More complex and costly	Simpler and generally cheaper
Example	Ultrasonic Sensor (emits and detects sound waves)	Thermocouple (produces voltage from temperature)

Classification of Sensors

Power Requirement

Means of Detection

Electrical
Biological
Chemical
Radioactive

Type	Definition	Example
Electrical	Detects changes in electrical properties (resistance, capacitance, current).	Resistive temperature sensor (RTD)
Biological	Uses biological materials or reactions to detect substances.	Glucose biosensor (enzyme-based)
Chemical	Detects chemical reactions or concentrations of compounds.	pH sensor (measures acidity/alkalinity)
Radioactive	Detects radiation levels or radioactive decay.	Geiger-Müller counter

Classification of Sensors

Type	Definition	Example
Analog Sensors	Provide continuous output signals that vary smoothly with the measured quantity	Temperature sensor (LM35)
Digital Sensors	Provide discrete output signals (e.g., HIGH/LOW, 0/1)	Infrared obstacle sensor, DHT11

Output Type

Analog Sensors
Digital Sensors

Conversion Phenomenon

Classification of Sensors

Type	Definition	Example
Photoelectric	Converts light energy into electrical signals	Photodiode, Solar cell
Thermoelectric	Converts temperature difference into electrical voltage	Thermocouple
Electrochemical	Converts chemical reactions into electrical signals	pH sensor, Fuel cell sensor
Electromagnetic	Converts motion within a magnetic field into electrical output	Induction coil, Electromagnetic flowmeter
Thermoptic	Converts temperature changes into variations in optical properties	Infrared thermometer, Thermal imaging sensors

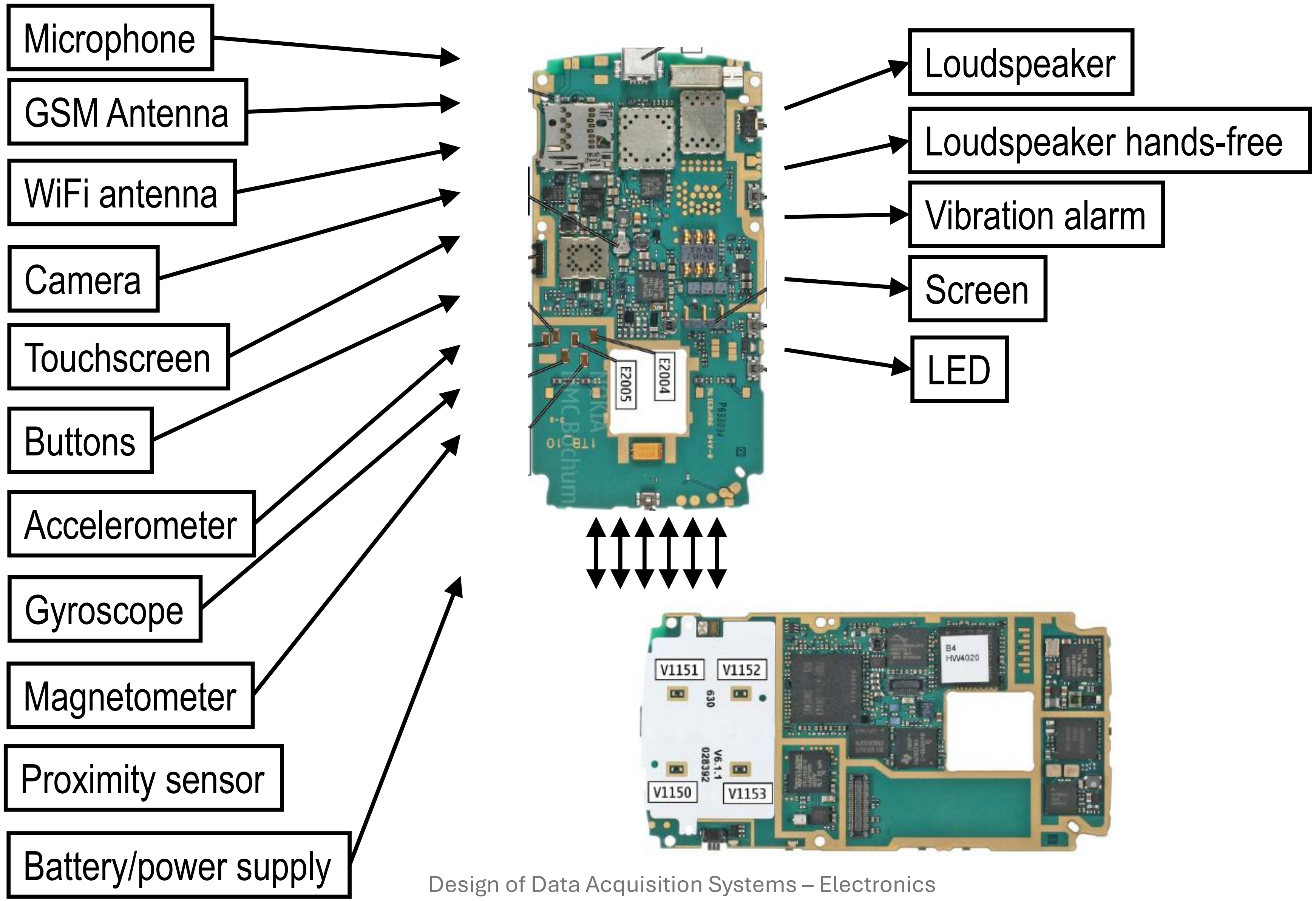
Conversion Phenomenon

Photoelectric
Thermoelectric
Electrochemical
Electromagnetic
Thermoptic

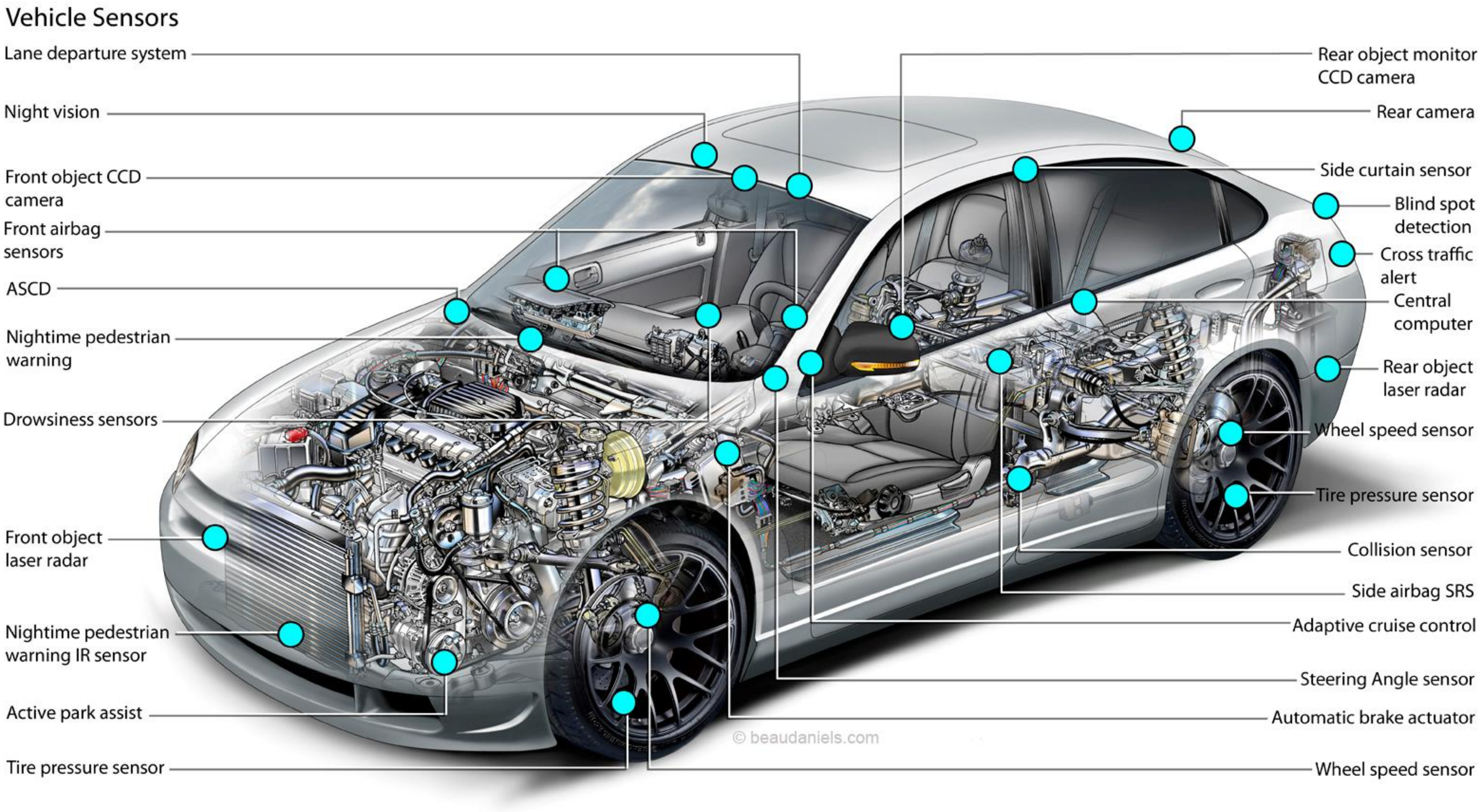
Classification of Sensors

- Power Requirement
- Means of Detection
- Output Type
- Conversion Phenomenon

Sensors/actuators in a smartphone



Sensors & Actuators in a car

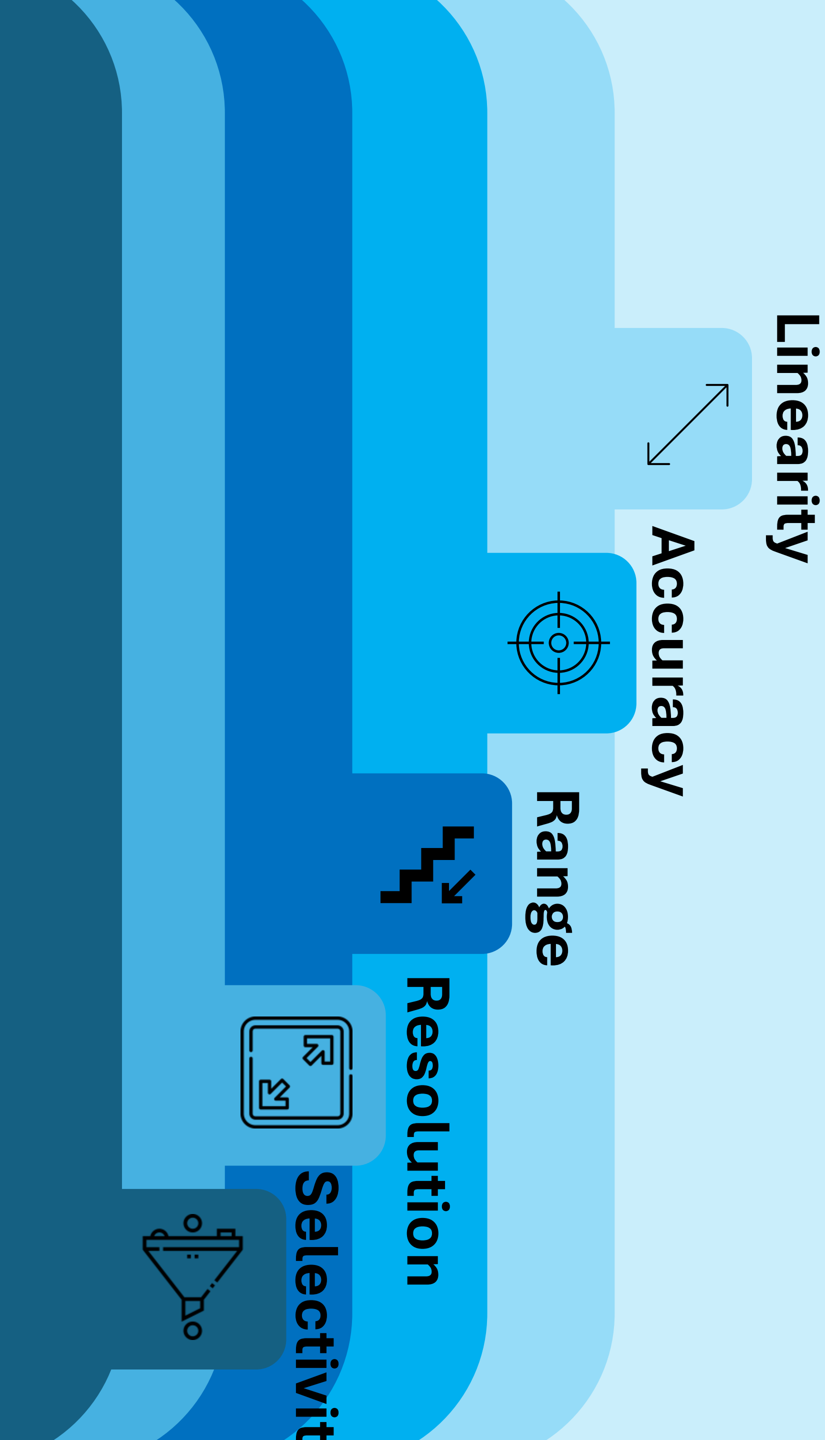


https://www.behance.net/gallery/30157611/Generic-cutaway-car/modules/193881821

- **Sensitivity**
- **Linearity**
- **Accuracy**
- **Range**
- **Resolution**
- **Selectivity**

An **ideal sensor** gives a signal that exactly represents the property to be measured

Unfortunately, **ideal sensor don’t exist**!



Sensitivity

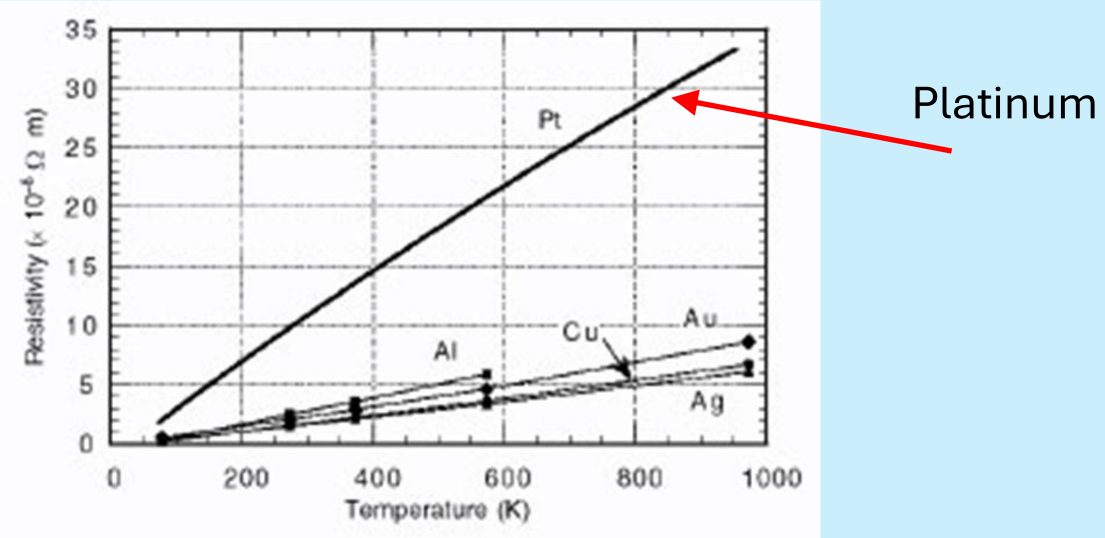
The ratio between the change in the sensor's output signal and the corresponding change in the measured input (stimulus)

Sensitivity: $S = \frac{\delta y}{\delta x}$

δy: How much the sensor's output (voltage, current, signal) changes

δx: How much the physical quantity being measured changes (temperature,

Example: A temperature sensor that changes 10 mV per °C has higher sensitivity than one that changes 1 mV per °C



Linearity

Accuracy

Range

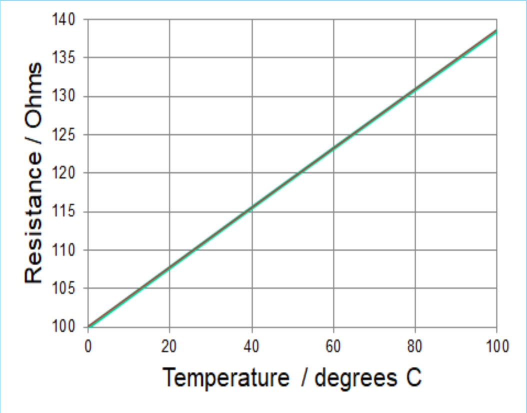
Resolution

Selectivit

How closely the sensor's output follows a straight-line relationship with the input across its measurement range.

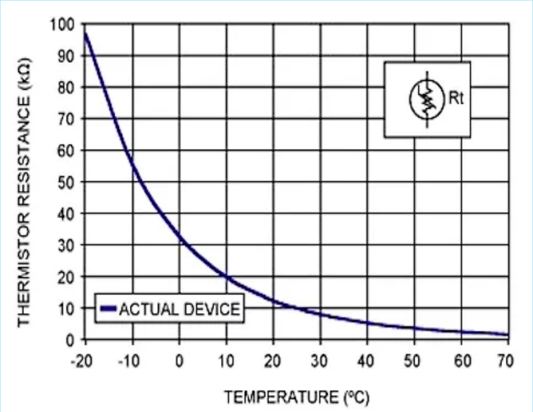
Platinum

- Linear:
- $R(T) = R_0(1 + \alpha T)$
- Low sensitivity (α = 0.00385/°C)



Thermistor (semiconductor):

- Strongly non-linear:
- $R = R_0\, e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$
- Higher sensitivity (≈ -4%/K @ 300K)
- Calibration can still provide accurate values.



https://www.allaboutcircuits.com/technical-articles/introduction-tempe
thermistors-thermocouples-thermometer-ic/

Accuracy

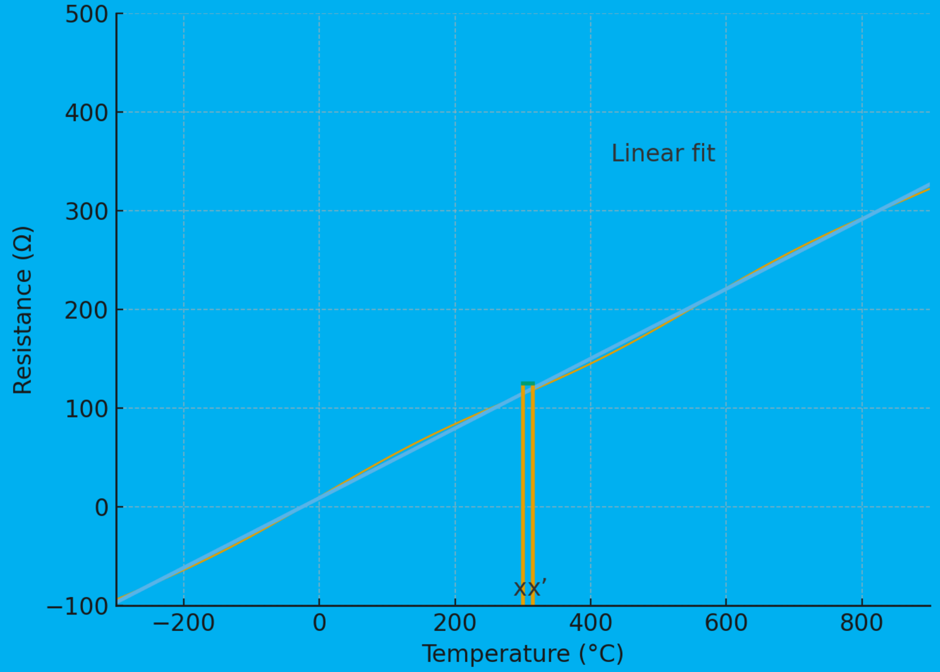
The degree to which the sensor's measurement matches the true (actual) value of the quantity being measured

Influenced by errors such as bias, drift, and non-linearity

Absolute error = $x - x'$

Relative error = $\frac{x-x'}{x}$ [%]

x – *true value*
x' – *measured value*



Range

Resolution

Selectivit

Range

The span of input values a sensor can measure effectively, from the minimum to maximum.

- Some sensors have calibration built-in.
- Holds only in a specific range.
- e.g. LM35 temperature sensor:

Features

- Calibrated directly in °C (Centigrade)
- Linear 10.0 mV/°C scale factor
- 0.5 °C accuracy guaranteeable (at +25 °C)
- Rated for −55 °C to +150 °C range
- Suitable for remote applications
- Low cost due to wafer-level trimming
- Operates from 4 to 30 V
- Less than 60 μA current drain
- Low self-heating: 0.08 °C in still air
- Nonlinearity only ±¼ °C typical
- Low-impedance output: 0.1 Ω at 1 mA load

Resolution

Selectivit

Resolution

The smallest detectable change in the input that the sensor can register in its output.

- Resolution: smallest step size
- ≠ accuracy
- See datasheet of lab multimeters

DC VOLTAGE

Model	Range	Resolution	Accuracy	Overload Protection
72-7765A	400 mV	0.1 mV	± (0.8% + 3)	250 V AC
	4 V	1 mV	± (0.8% + 3)	
	40 V	10 mV		
	250 V	100 mV		

Example: A digital temperature sensor with a resolution of 0.1 °C can distinguish between 25.0 °C and 25.1 °C, but not 25.05 °C.

Selectivity

Selectivity = how little the output changes when something **else** changes.

When a sensor is determined to measure a certain physical quantity in the ideal case it should be fully independent on all other stimuli and not change over time

Examples:

A CO gas sensor that barely reacts to H_2 or humidity is **highly selective** for CO

A color photodiode with a narrowband filter (e.g., 525 nm) is selective to that wavelength

An LM35 temperature sensor should mainly respond to **temperature**, not to supply voltage noise

Integrated temperature sensor

- Some sensors even have integrated A/D conversion.
- e.g. DS18B20:

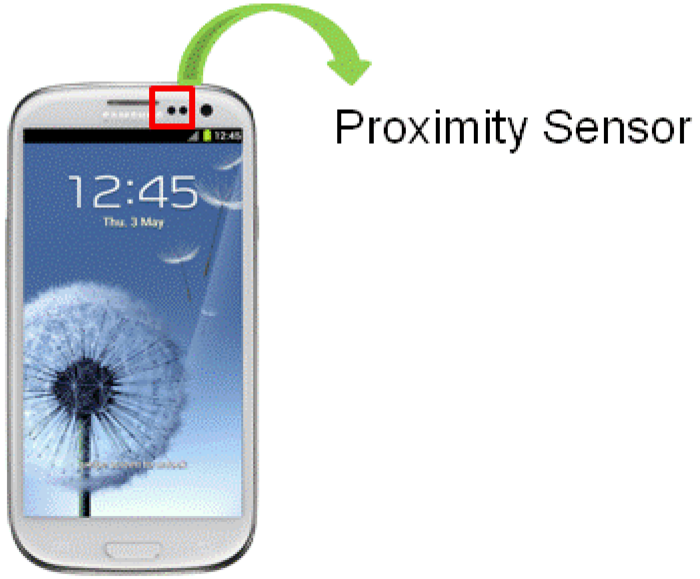
Programmable Resolution 1-Wire Digital Thermometer

Benefits and Features

- Unique 1-Wire® Interface Requires Only One Port Pin for Communication
- Reduce Component Count with Integrated Temperature Sensor and EEPROM
  - Measures Temperatures from -55°C to +125°C (-67°F to +257°F)
  - ±0.5°C Accuracy from -10°C to +85°C
  - Programmable Resolution from 9 Bits to 12 Bits
  - No External Components Required
- Parasitic Power Mode Requires Only 2 Pins for Operation (DQ and GND)
- Simplifies Distributed Temperature-Sensing Applications with Multidrop Capability
  - Each Device Has a Unique 64-Bit Serial Code Stored in On-Board ROM
- Flexible User-Definable Nonvolatile (NV) Alarm Settings with Alarm Search Command Identifies Devices with Temperatures Outside Programmed Limits
- Available in 8-Pin SO (150 mils), 8-Pin µSOP, and 3-Pin TO-92 Packages

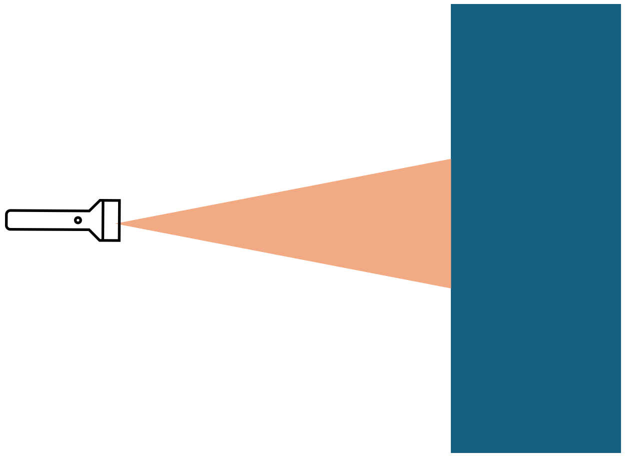
Indirect measurements

- Indirect measurement → measure something related
- Example: Cell phone proximity sensor
  - there's no sensor that measures "proximity".
  - measures reflected light



Proximity detection

- Reflection (indirect) mode:

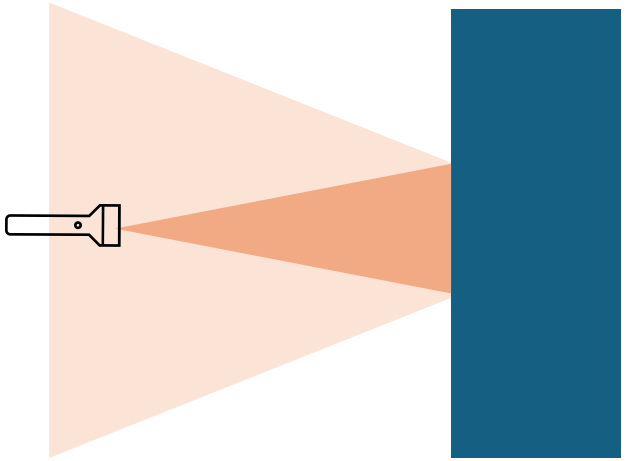


$$I_{received} \propto \frac{1}{x^2}$$

- Contactless distance (proximity) measurement
- Low selectivity: other factors than distance influence measurement

Proximity detection

- Reflection (indirect) mode:



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Proximity detection

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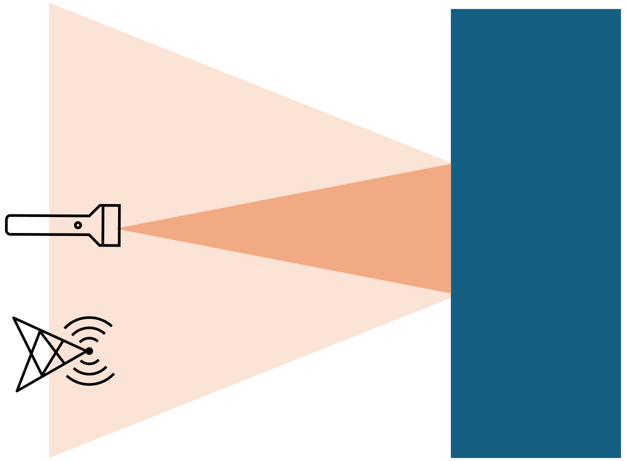

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Proximity detection

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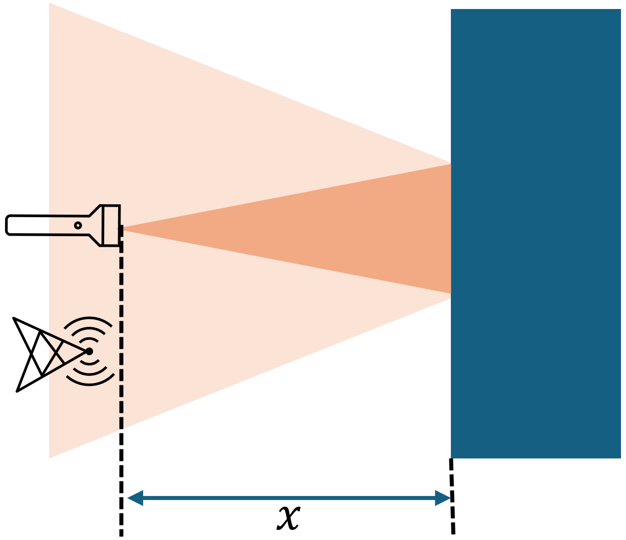


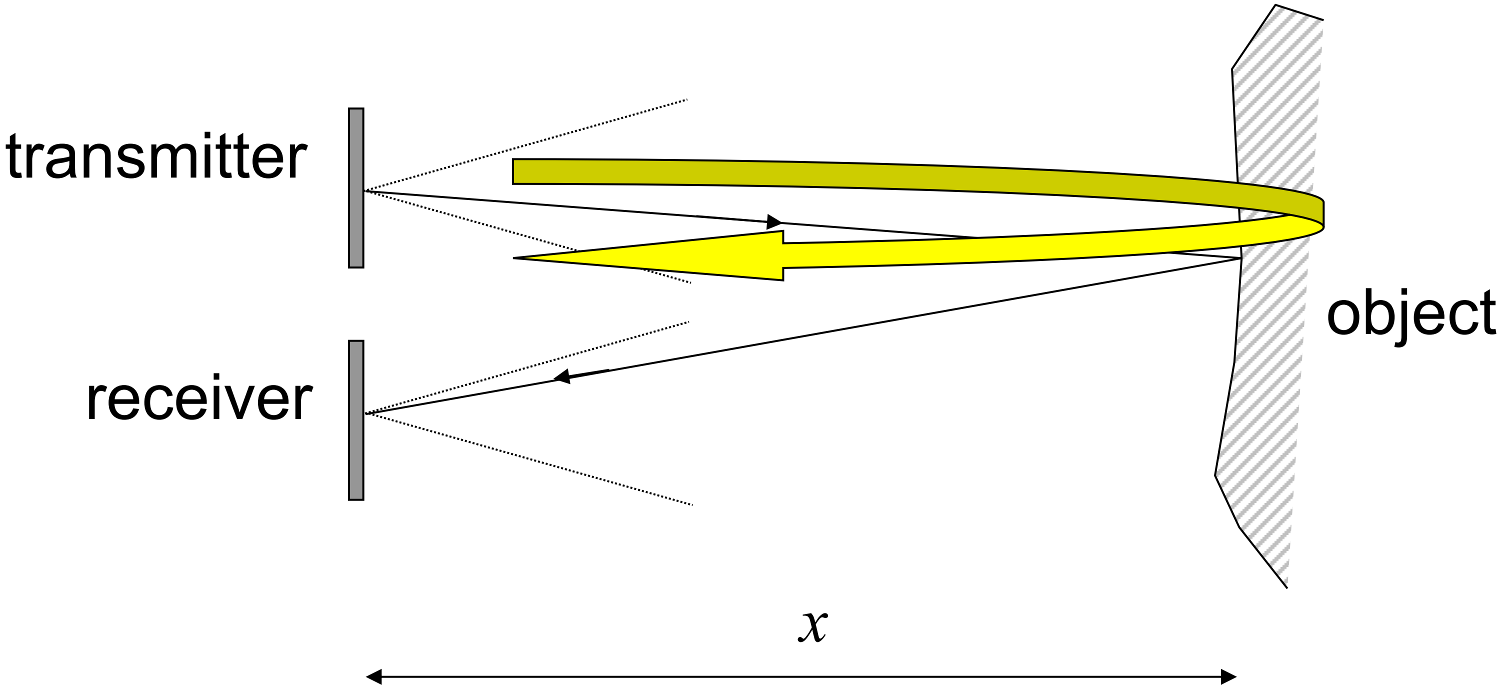
$$I_{received} \propto \frac{1}{x^2}$$

Received intensity

- Contactless distance (proximity) measurement
- Low selectivity: other factors than distance influence measurement

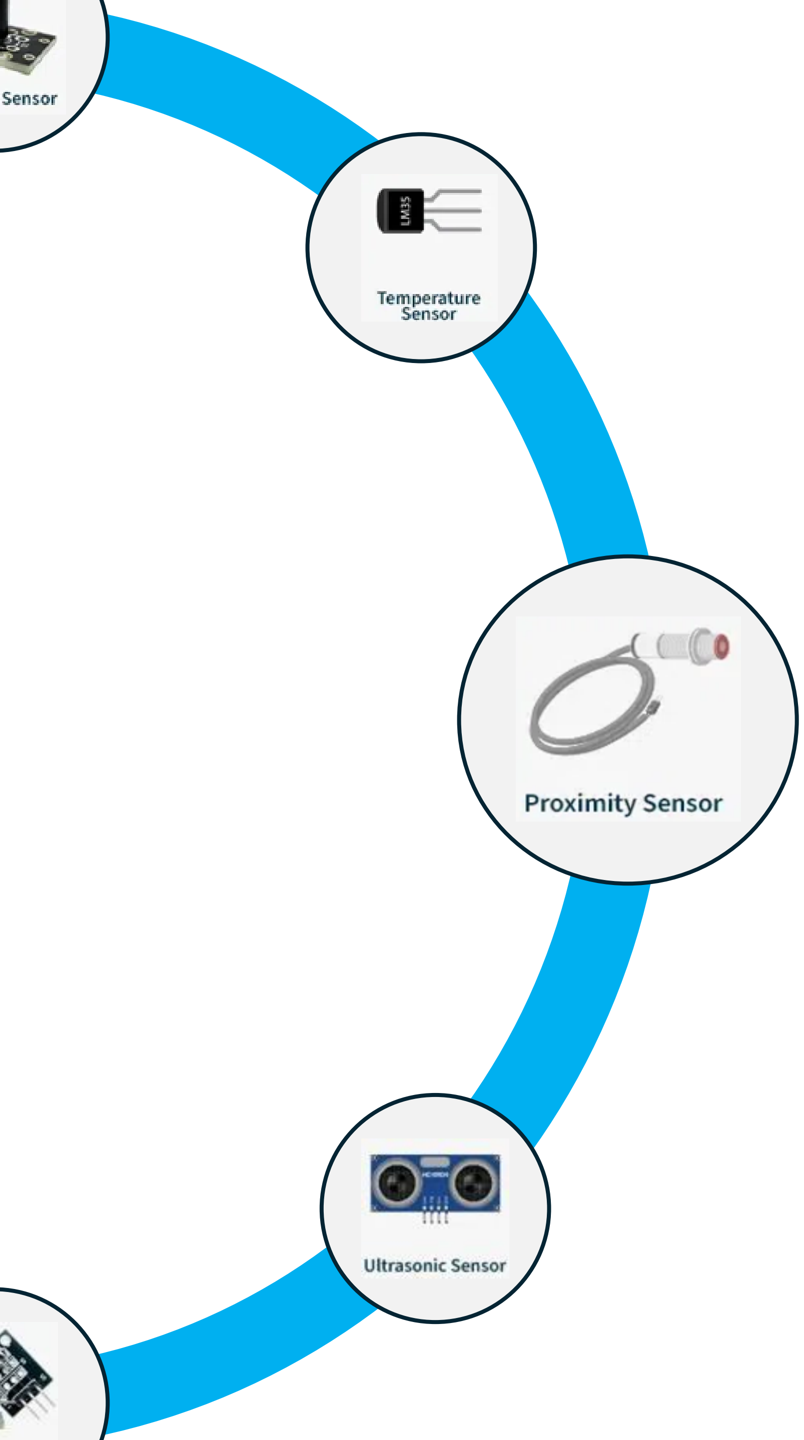
Time-of-flight (TOF)

Time-of-Flight measures **distance** by sending out a wave (sound or light) and timing how long it takes to bounce back from an object.



$$x = \frac{vt}{2}$$

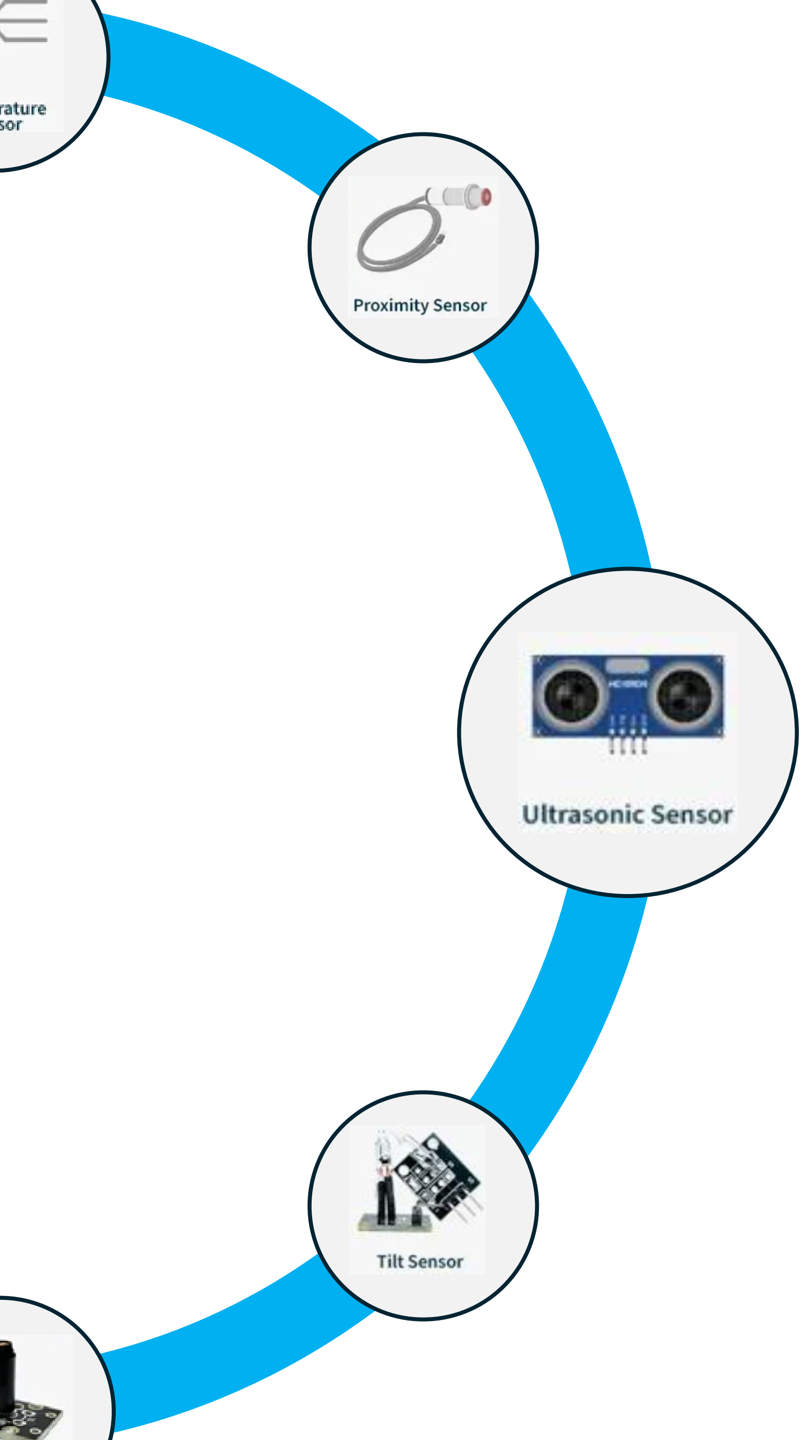
- Better selectivity, but still depends on speed of sound.
- Speed of sound depends on temperature and slightly on humidity, pressure.



Sensors type (some of them)

- Detect presence or distance of an object without contact
- Working principles:
  - IR reflective (LED + photodiode intensity)
  - Ultrasonic (time-of-flight of sound)
  - Inductive (eddy currents; metals only)
  - Capacitive (dielectric change)
  - Laser ToF (light time-of-flight)
- How to compare: Range & resolution, Target material, Response time, Ambient sensitivity, Power, Cost

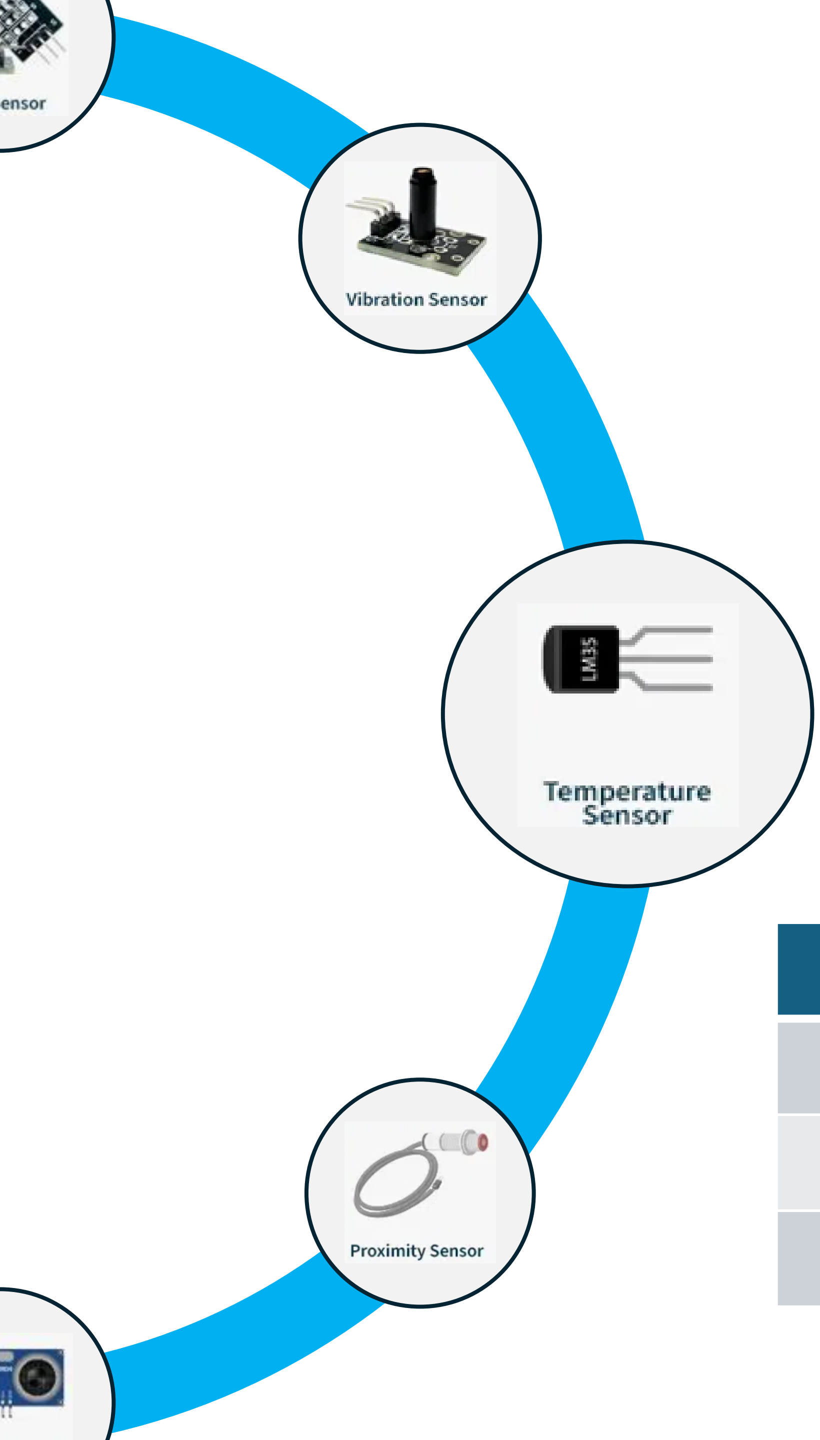
Type	Typical range	Best targets	Pros	Watch-outs
IR reflective	2–80 cm	Reflective surfaces	Cheap, compact	Ambient light, surface color
Ultrasonic	2–400 cm	Any (air path)	Robust to color	Soft/angled surfaces, temp drift
Inductive	0–10 cm	Metals only	Dust/lighting immune	Metal only, short range
Capacitive	0–5 cm	Any incl. liquids	Detects non-metal	Humidity, shielding
Laser ToF	2–200 cm	Most surfaces	High precision	Cost, shiny/black extremes



Sensors type (some of them)

- Detect distance by measuring sound time-of-flight (TOF) at ~40 kHz
- Working principal:
  - Send pulse (40 kHz) → wait for echo; distance $d = (v_s \times t_{echo})/2$
  - Speed of sound $v_s \approx 331 + 0.6 \cdot T(°C)$ m/s → temperature affects result
  - Front-end uses **band-pass filtering** and **threshold** (or **matched-filter/correlation**) to detect the echo reliably
  - Handle **multipath** and multiple echoes (choose first valid echo, apply time gating)
- Limits:
  - Watch for dead-zone, beam angle, temp drift, airflow, cross-talk

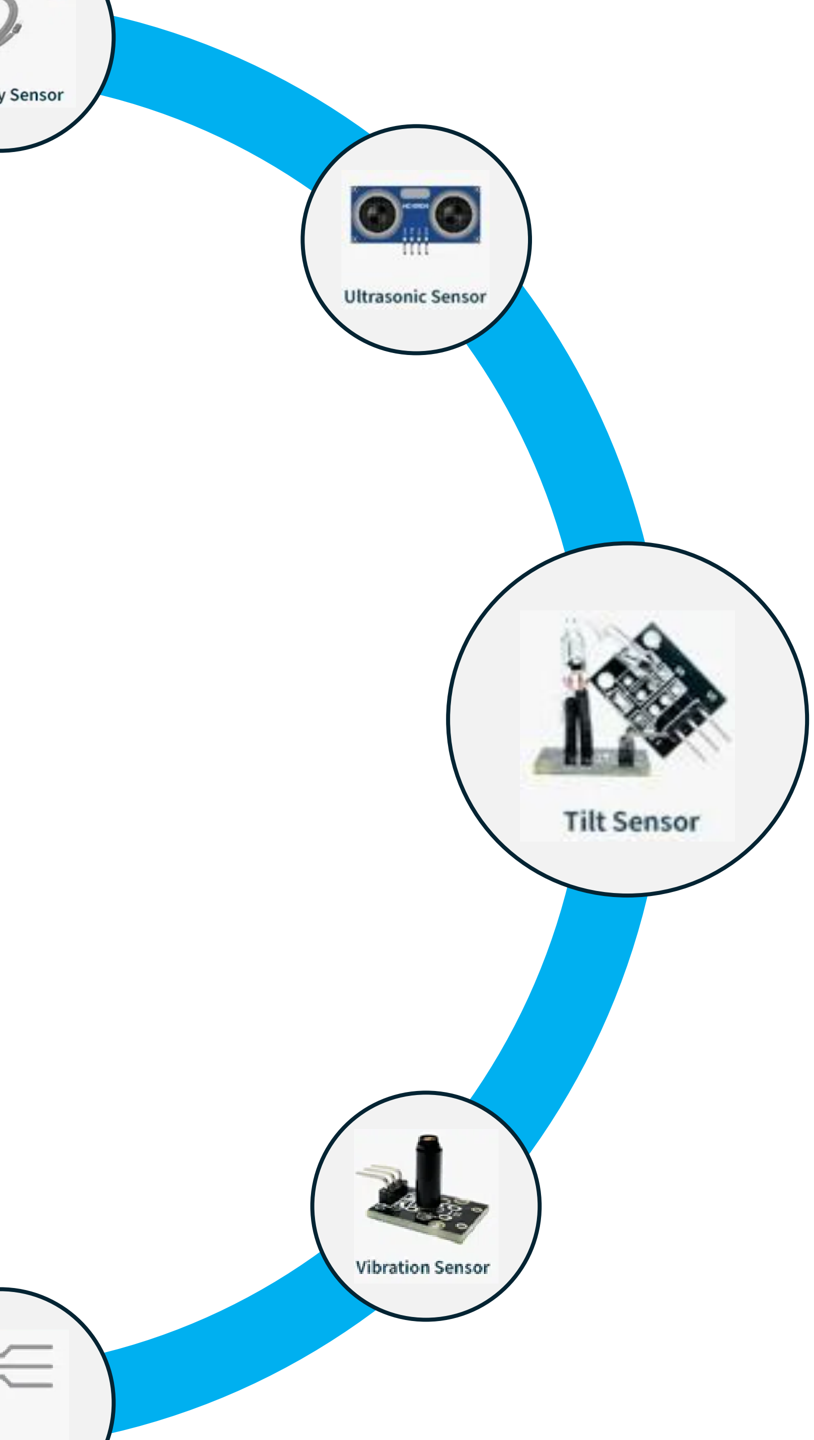
Spec	Typical	Notes
Range	2–400 cm	Dead-zone 2–20 cm
Resolution	1–5 mm	Averaging improves stability
Accuracy	±1% of reading	Temp compensation helps
Beam angle	10–15°	Narrower with tubes/horns
Update rate	10–50 Hz	Higher with shorter windows
Supply	3.3–5.5 V (module-dep.)	Level shifting may be needed
Output	Pulse width (TTL) or I^2C	HC-SR04 vs smart ICs



Sensors type (some of them)

- Convert temperature to resistance or voltage
- Working principles:
  - Thermistor: resistance vs T (nonlinear)
  - RTD (R T Detector): metal resistivity vs T (linear)
  - Silicon IC (LM35/TMP): band-gap voltage vs T
- How to compare:
  - Accuracy & linearity, Range, Self-heating, Interface, Cost

Type	Range	Accuracy	Interface	Notes
NTC Thermistor	−40…125 °C	±0.5…±2 °C	Divider → ADC	Very sensitive, nonlinear
RTD (Pt1000)	−50…500 °C	±0.1…±0.3 °C	Bridge/ADC	Stable, needs excitation
Silicon IC	−40…150 °C	±0.1…±0.5 °C	Analog or I^2C/SPI	Easy; limited high-T



Sensors type (some of them)

What they do

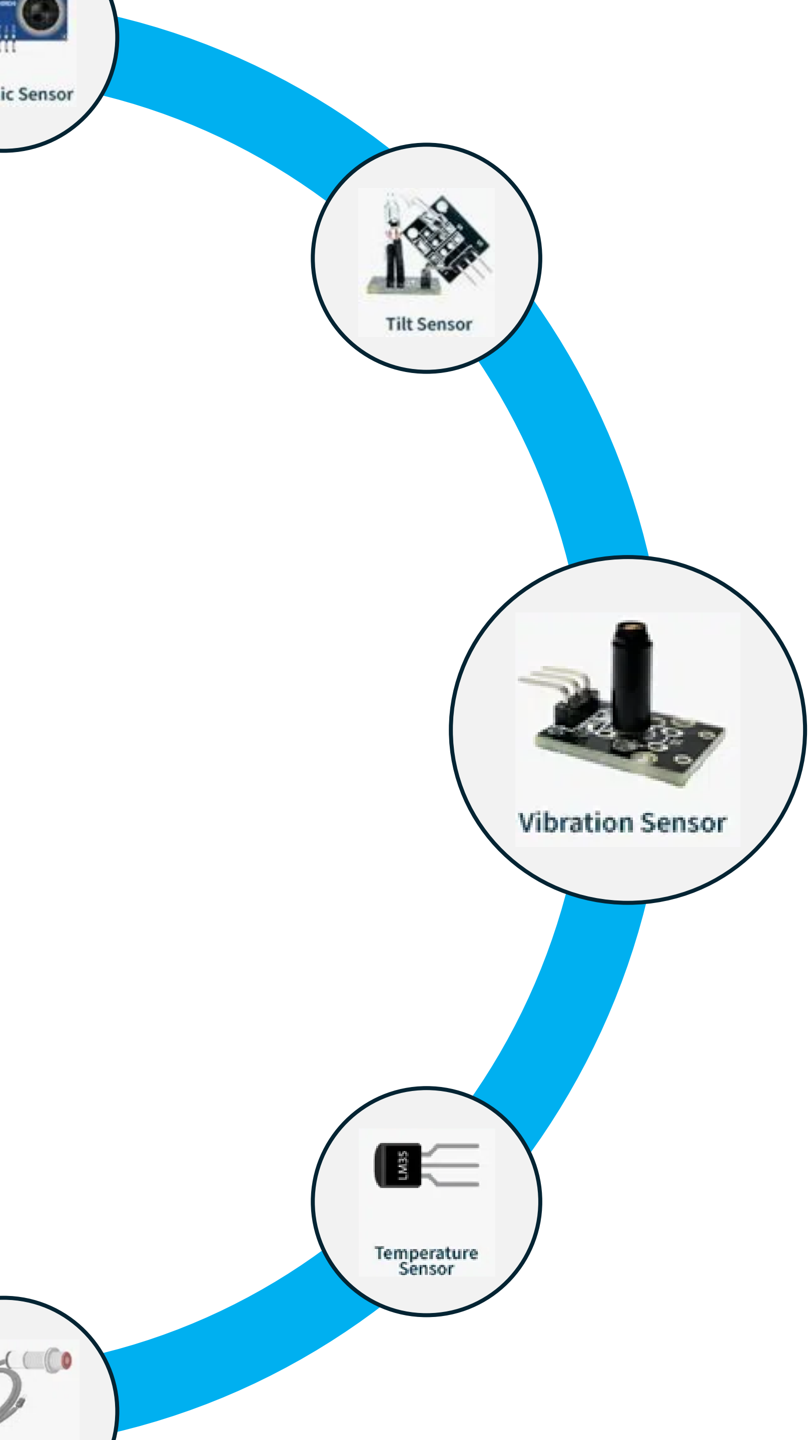
- Detect orientation/tilt angle relative to gravity; some detect simple 'tilted/not-tilted'.

Main types & principles

- Mechanical tilt switch (ball/mercury): conductor closes when tilted past a threshold → digital ON/OFF.
- MEMS (Micro-Electro-Mechanical Systems) accelerometer: proof-mass capacitance changes → read gravity vector → compute angle.
- Electrolytic (bubble) inclinometer: fluid moves over electrodes; differential output ∝ angle.
- IMU (Inertial Measurement Unit) (accel+gyro fusion): combines gravity and angular rate → better dynamic tilt.

How to compare

- Range (±°), resolution, accuracy, response time, dynamic vs static performance, interface, cost, robustness.



Sensors type (some of them)

What they measure

- Vibration as acceleration (g), velocity (mm/s), or displacement (µm).

Main sensor types & principles

- Piezoelectric accelerometer (charge/IEPE): crystal generates charge ∝ acceleration (AC-coupled).
- MEMS capacitive accelerometer: proof-mass capacitance change (DC→kHz).
- Piezoresistive accelerometer: strain-gauge bridge; good for shocks (DC).
- Velocity pickup (geophone/moving-coil): output ∝ velocity (low-freq).
- Eddy-current displacement probe: non-contact shaft displacement (metal).
- Laser vibrometer: optical Doppler, non-contact, very wide bandwidth.

Actuators

Hydraulic

Harness hydraulic power -mechanical functions and operations

Generally - powered by a cylinder or a fluid motor

Mechanical motion is converted into oscillatory, linear, or rotary

Pneumatic

Pneumatic actuators produce two types of motion: rotary or linear

Operated by compressed air or vacuum at high pressure

Low-cost compared to other actuators

Require minimal maintenance.

Electrical

Motor converts electrical energy into mechanical motion

Powered by electricity

Provide high precision control

Widely used in industrial automation

Thermal

Contain thermal-sensitive material that produces linear motion

Operate in response to temperature changes

Commonly used for valves, latches, and switches

Magnetic

Convert electromagnetic energy into mechanical motion

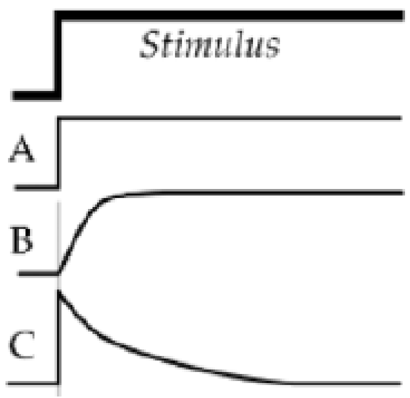
Operate in linear or rotary direction

Enable continuous mechanical operation

Widely used in automotive and aerospace industries

Examples with sensors

A sensor measures a property that suddenly changes (e.g. light being turned on). We measure that property using different sensors. The output signal of three sensors is given. Now we are going to use the sensor to measure a fluctuating or varying signal.



a) Describe for which frequencies the sensors can be used (relative to each other).

b) A student can only affort sensor B and C and has only money to chose one. In the following cases which one would you choose? The timescale in the figures is the same.
   (1) Fire alarm
   (2) Refridgerator temperature
   (3) Parking sensor for cars
   (4) Humidity control for a manufacturing plant
   (5) Counting the amount of cars that pass a cetrain point

Examples (1) with sensors

a) sensor A instantaneously follows the stimulus and is hence ideal and probably expensive. Sensor B has a first order response with an upper limit (so suitable for slower signals) . Senor C has a first order response with a lower cut off (so only suitable at higher frequencies)

b) 1) needs a fast response so C
   2) temperature will most likely change once and stay that way for a long time so B
   3) tricky since you want a collision alarm to sound fast but also keep sounding if the care keeps getting closer to an object. So this means you have to find one that follows B, but the response time is fast enough
   4) When a sensor is in a control loop the sensor and the electronics need to be matched. In a manufacturing plant you do not expect a high frequency change (unless the roof collapses due to a hurricane, but then you have other problems) so B is good.
   5) In this case you are interested in a fast response, you will count peaks. So you need C. It is in this case important that the sensor is fast enough to “reset” to count the next event.

Examples (2) with sensors

Question

Someone wants to determine the distance between a moving robot and a wall with the aid of an acoustic distance measuring system mounted on the robot. At a certain moment, a "time-of-flight" is measured of 12 ms. Calculate the distance to the wall.

Answer

The sound travels to and from the wall, so $x = \frac{1}{2}vt$, with v = 330 m/s (the speed of sound in air) and t the amount of time the sound has travelled (the T.O.F.). This gives $x \approx 2$ m.

Examples (3) with sensors

Question

Which statement about sensors is the most correct one?

A. The sensitivity of a sensor is always linear.
B. Sensors are only sensitive to one physical quantity.
C. A sensor with a high selectivity shows a great sensitivity for the desired physical quantity to be measured relative to other physical quantities in the environment.
D. Sensors are electronic systems.

Answer

A: Most sensors are definitely not linear (for example an LDR). B: Most sensors are sensitive to multiple physical quantities. D: A sensor can be a piece of material, for example a piece of metal to measure temperature. C is correct.

Examples (4) with sensors

Question

A land surveying company uses the indirect time of flight (TOF) method to determine the distance to a building. The propagation speed is 300m/s. It takes 0.5s for the signal to get back to the device. What is the distance?

Answer

0.5 s * 300 m/s = 150 m. The signal travels to and from the building, hence it is the distance divided by two, so 75m.

Examples (5) with sensors

Question

Which of the following statements is the least incorrect?

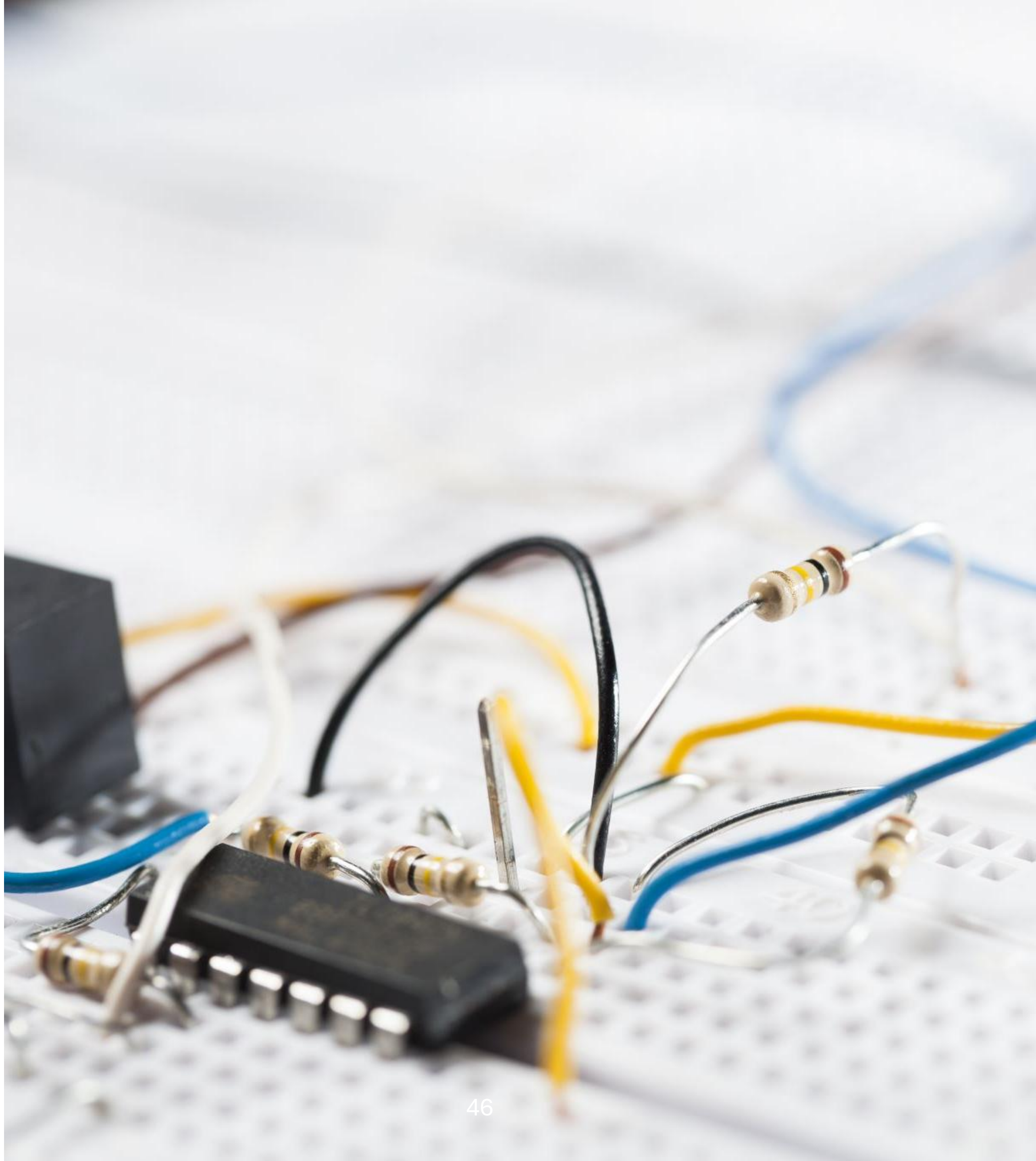
A. Sensors are only sensitive to one physical quantity.
B. Sensors and transducers are both actuators.
C. Some actuators can be used as sensor.
D. Sensors have a linear relation between their output signal and the physical quantity to be measured.

Answer

A: False, most sensors are sensitive to multiple physical quantities. B: False, sensors and actuators are both transducers. D: False, most sensors are not linear at all. C is correct. For example, a loudspeaker can be used as a microphone.

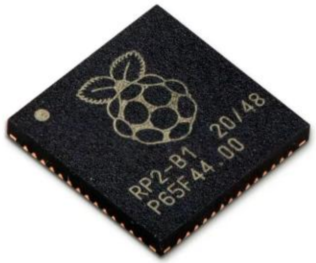
Conclusion

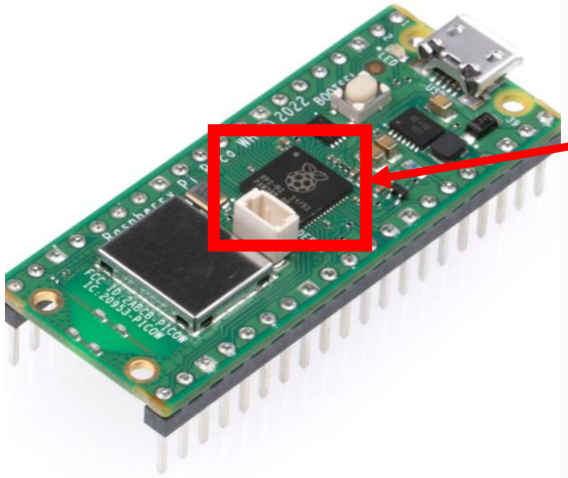
- Sensors and Actuators:
  - Sensors and actuators are the interface between two physical domains.
  - This way electronics can sense or control its surroundings.
  - Sensors are never 100% accurate, so check how much their value can deviate from reality.
  - Acctuators make things happen

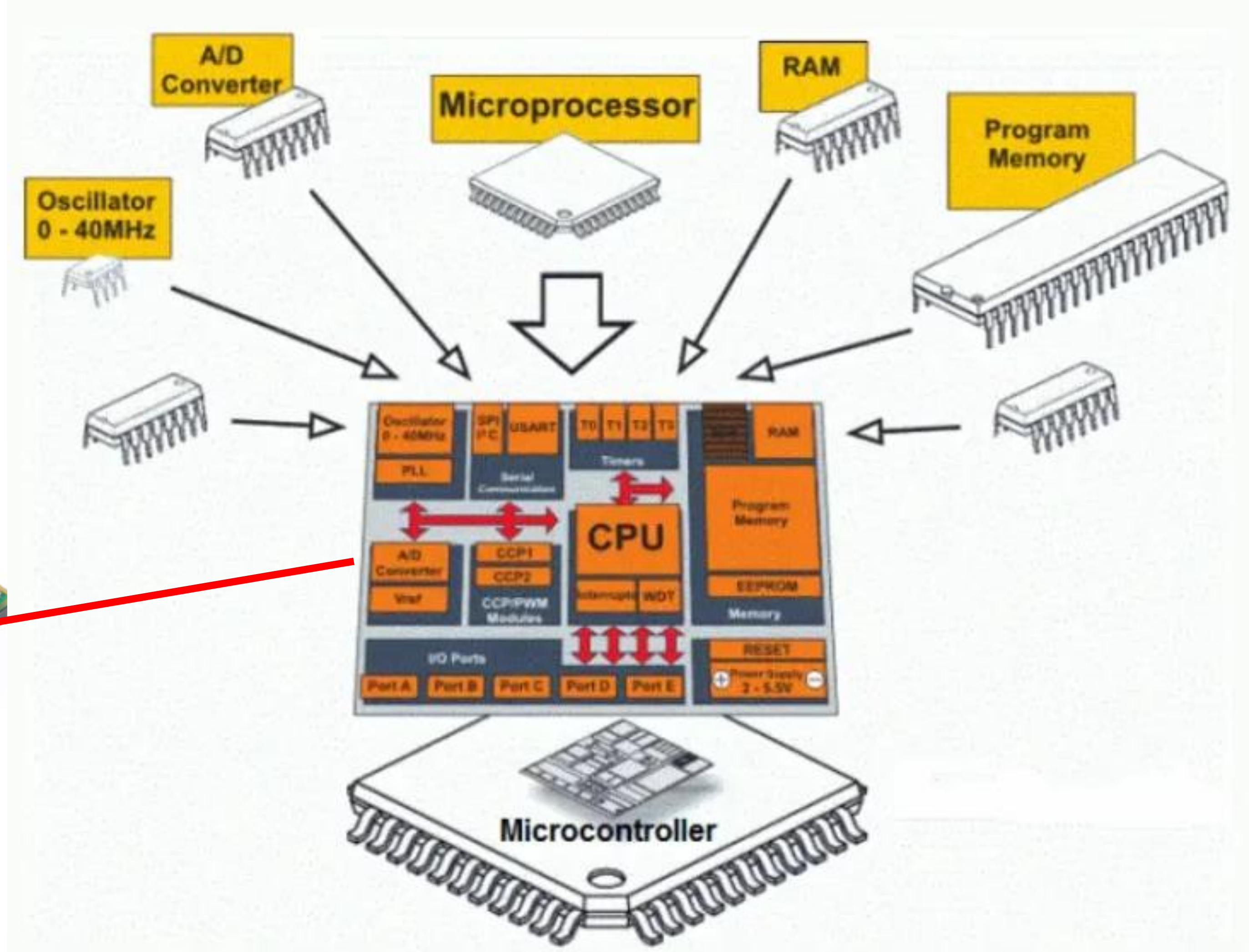


Basics of microcontrollers & architecture

A microcontroller is a self-contained "computer-on-a-chip" that contains a **CPU**, **memory** (RAM and ROM/Flash), and **input/output** (I/O) peripherals on a single integrated circuit.







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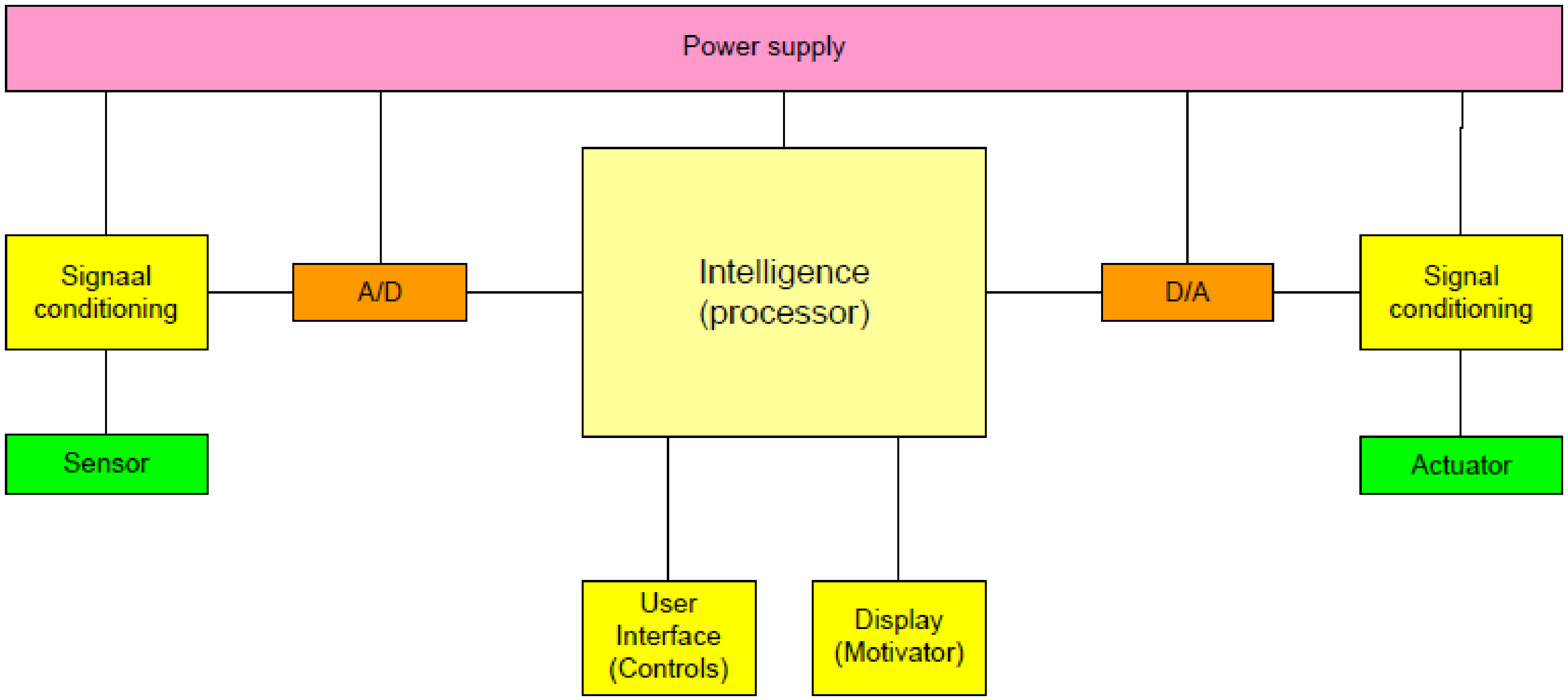
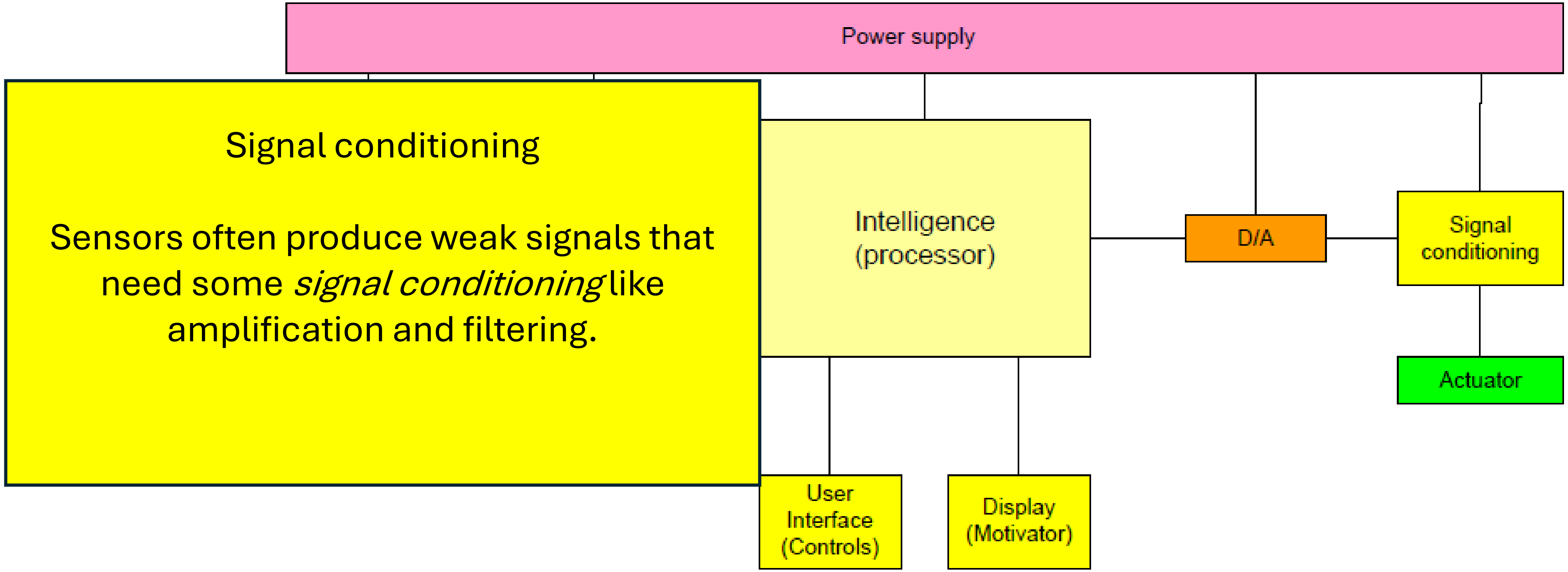


Basics of microcontrollers & architecture

- A microcontroller is a self-contained "computer-on-a-chip" that contains a **CPU**, **memory** (RAM and ROM/Flash), and **input/output** (I/O) peripherals on a single integrated circuit.



Signal conditioning

Sensors often produce weak signals that need some *signal conditioning* like amplification and filtering.

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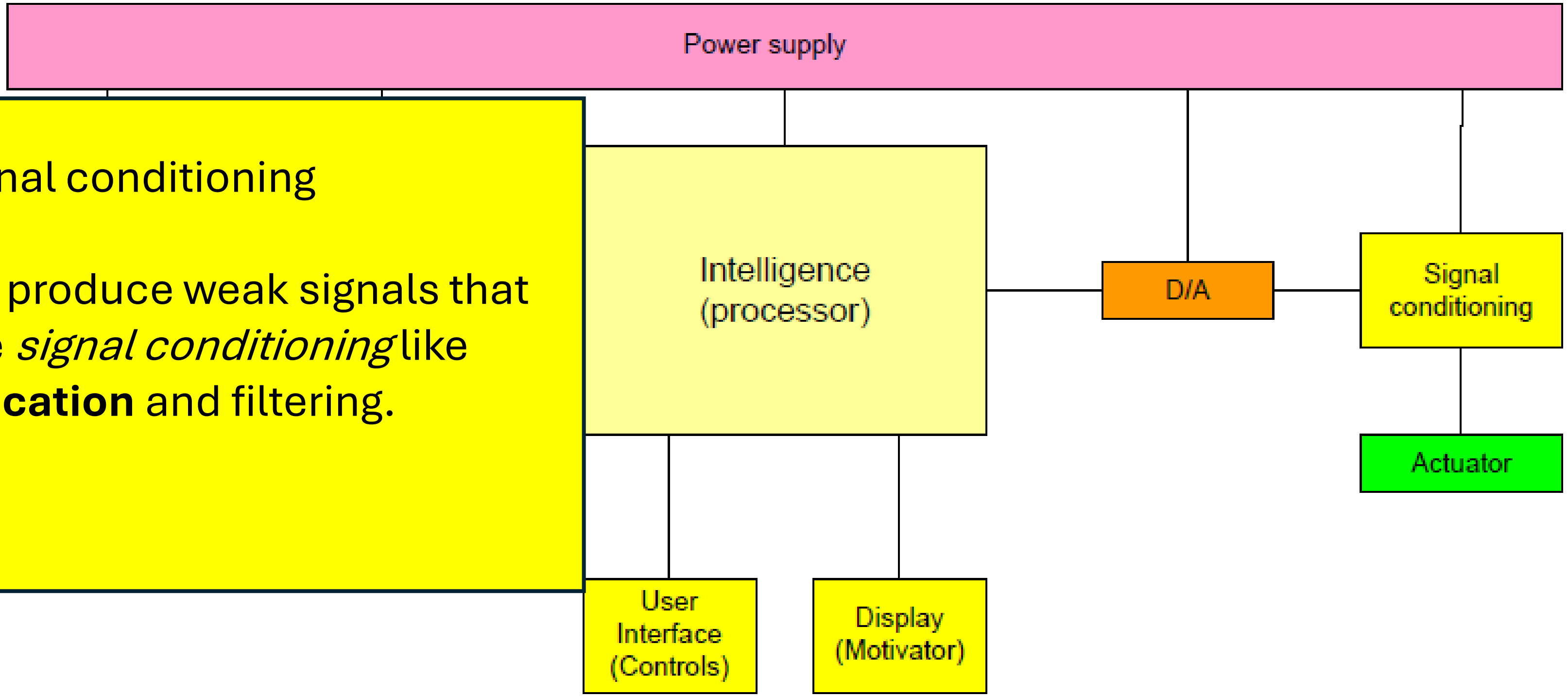

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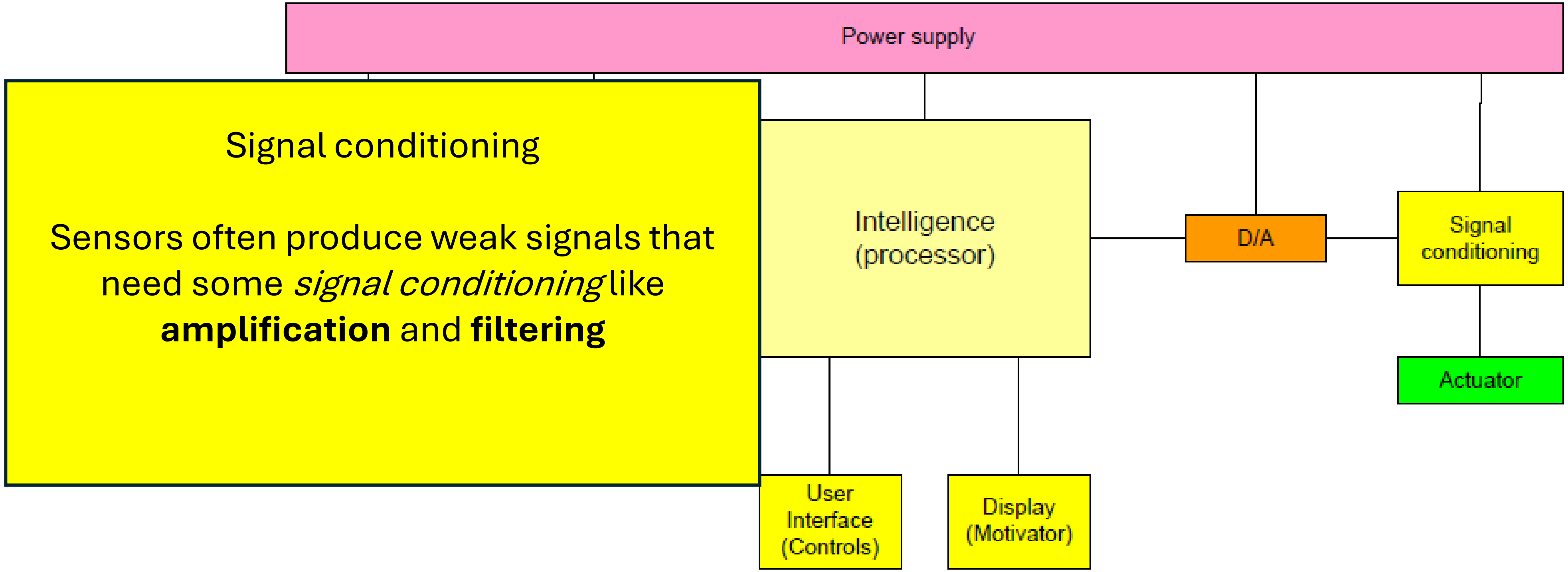

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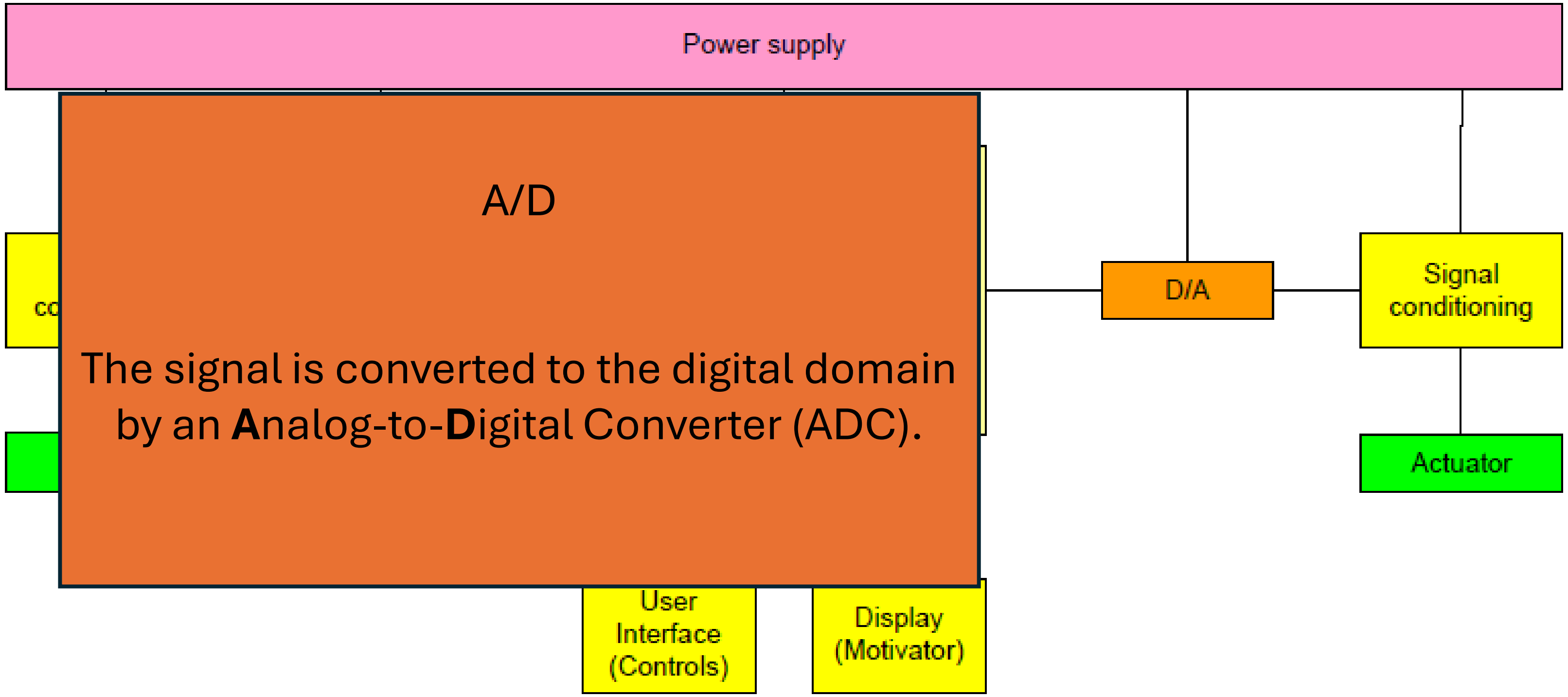
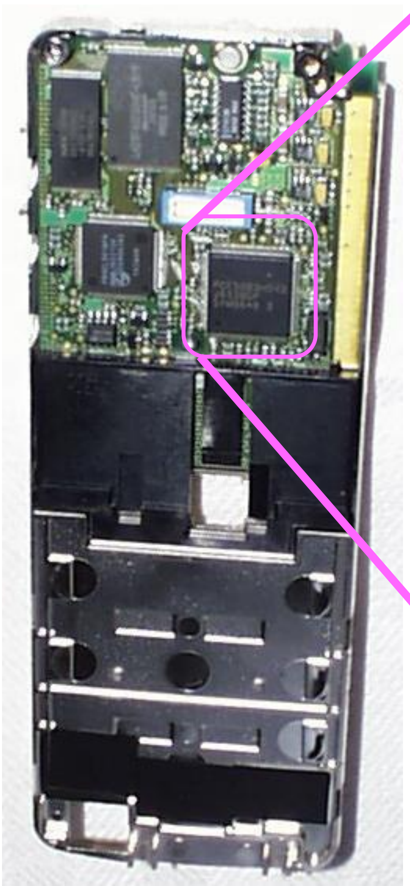
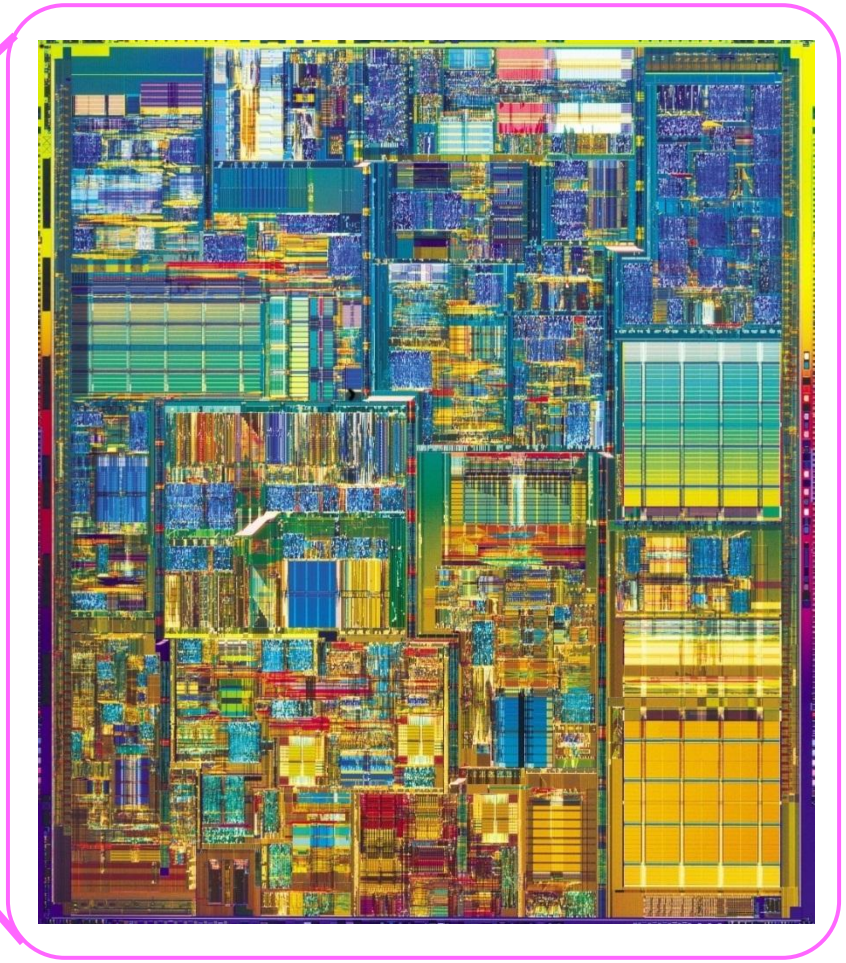


A/D

The signal is converted to the digital domain by an **A**nalog-to-**D**igital Converter (ADC).

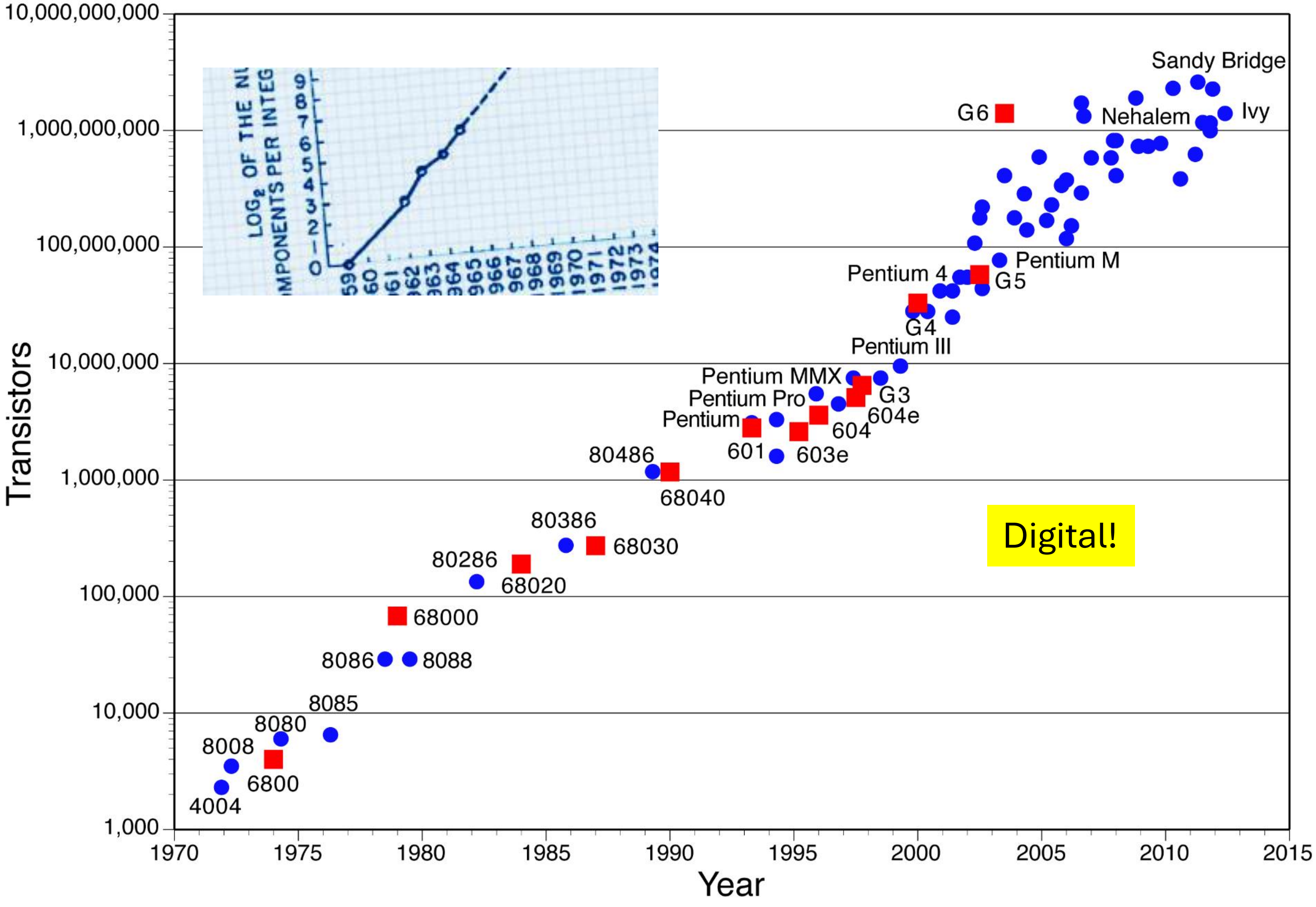
Integrated circuits





Inside a smartphone are 62 microchips with total of 90 billions of nanoscopic transistors

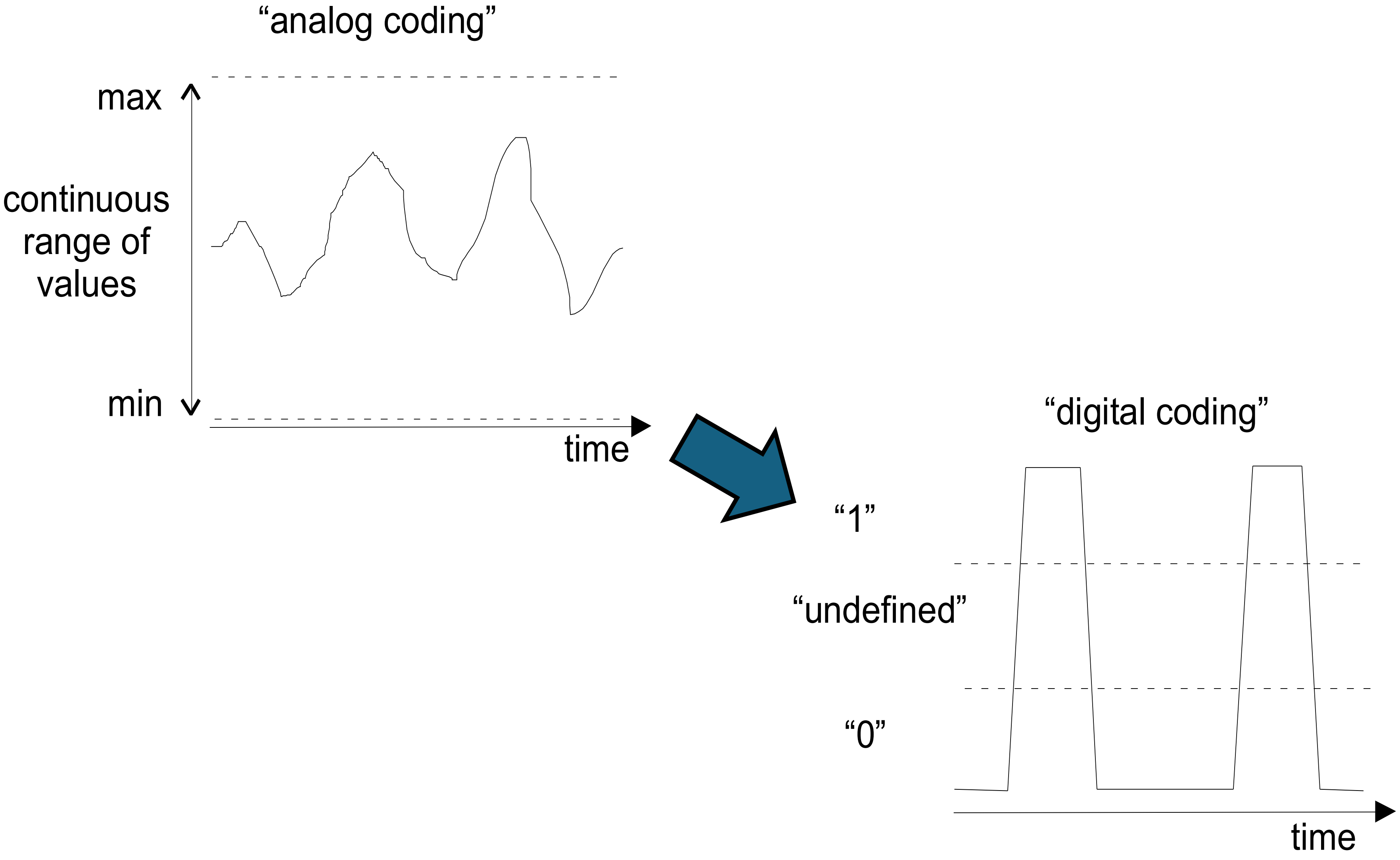
Moore’s Law


Transistors
Year
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
4004
8008
6800
8080
8085
8086
8088
68000
80286
68020
80386
68030
80486
68040
Pentium
601
603e
Pentium Pro
Pentium MMX
604
604e
G3
Pentium III
G4
Pentium 4
G5
Pentium M
G6
Nehalem
Sandy Bridge
Ivy
Digital!

Analog / digital

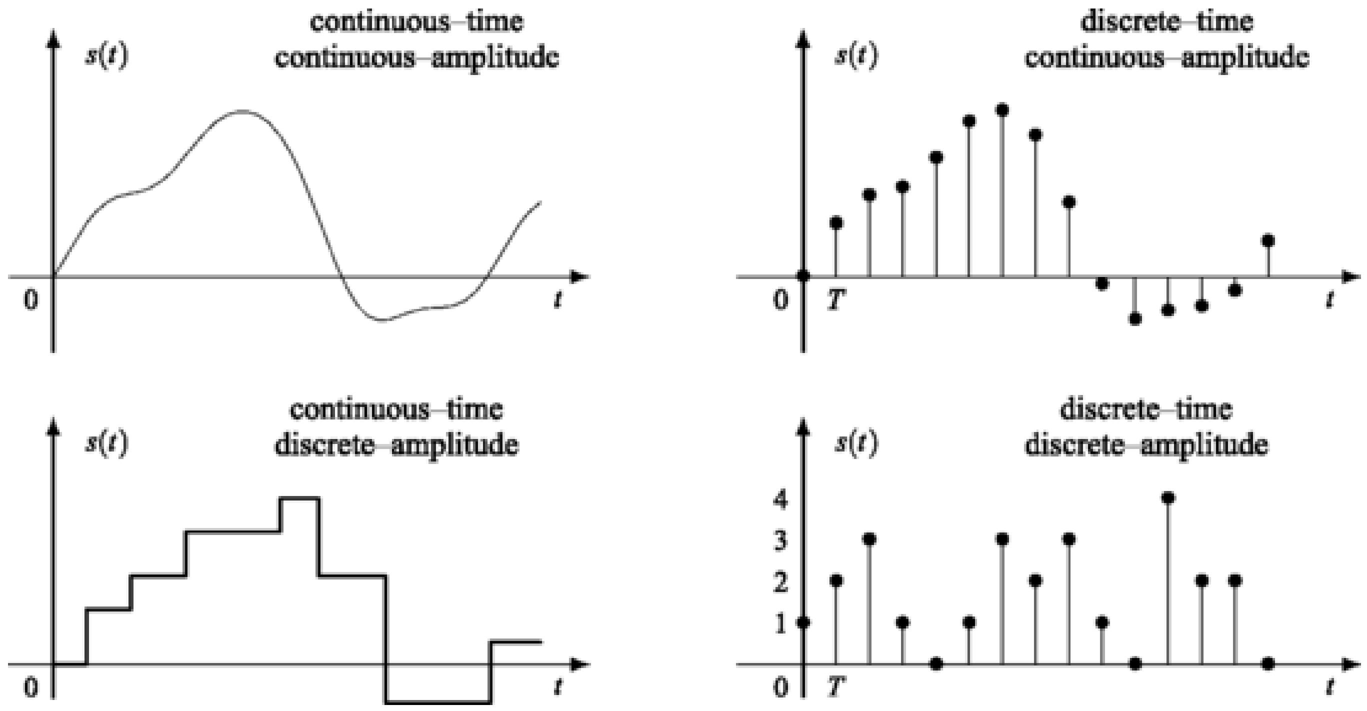
- Most functionality is digital nowadays
  - Signal processing (e.g. filtering, coding, compression)
  - Software
  - Storage (RAM, Flash)
- World = analog
  - Light, sound, temperature, EM fields, etc.
- So convert!
  - ADC (Analog-to-Digital Converter)
  - DAC (Digital-to-Analog Converter)

Analog and Digital



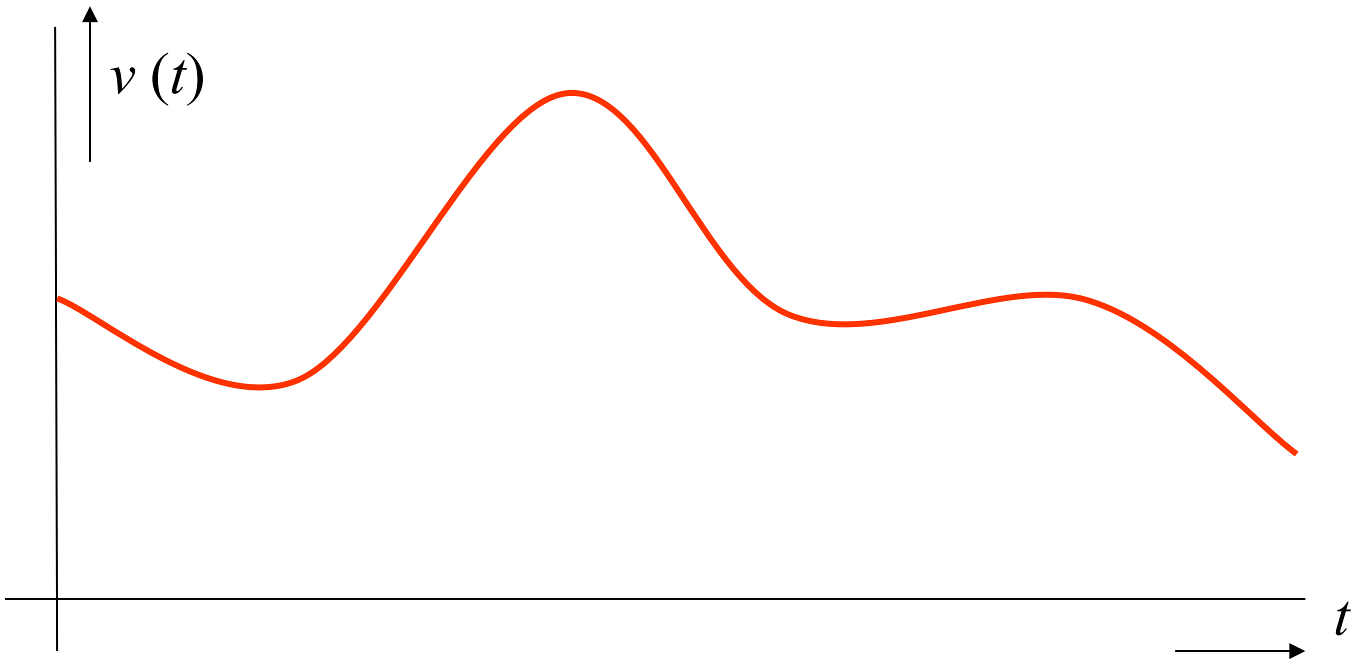
Continuous - Discrete

- Distinction between continuous and discrete signals
- in amplitude and in time
- Four categories:
    - Amplitude continuous and time continuous
    - Amplitude discrete, time continuous
    - Amplitude continuous, time discrete
    - Amplitude discrete and time discrete



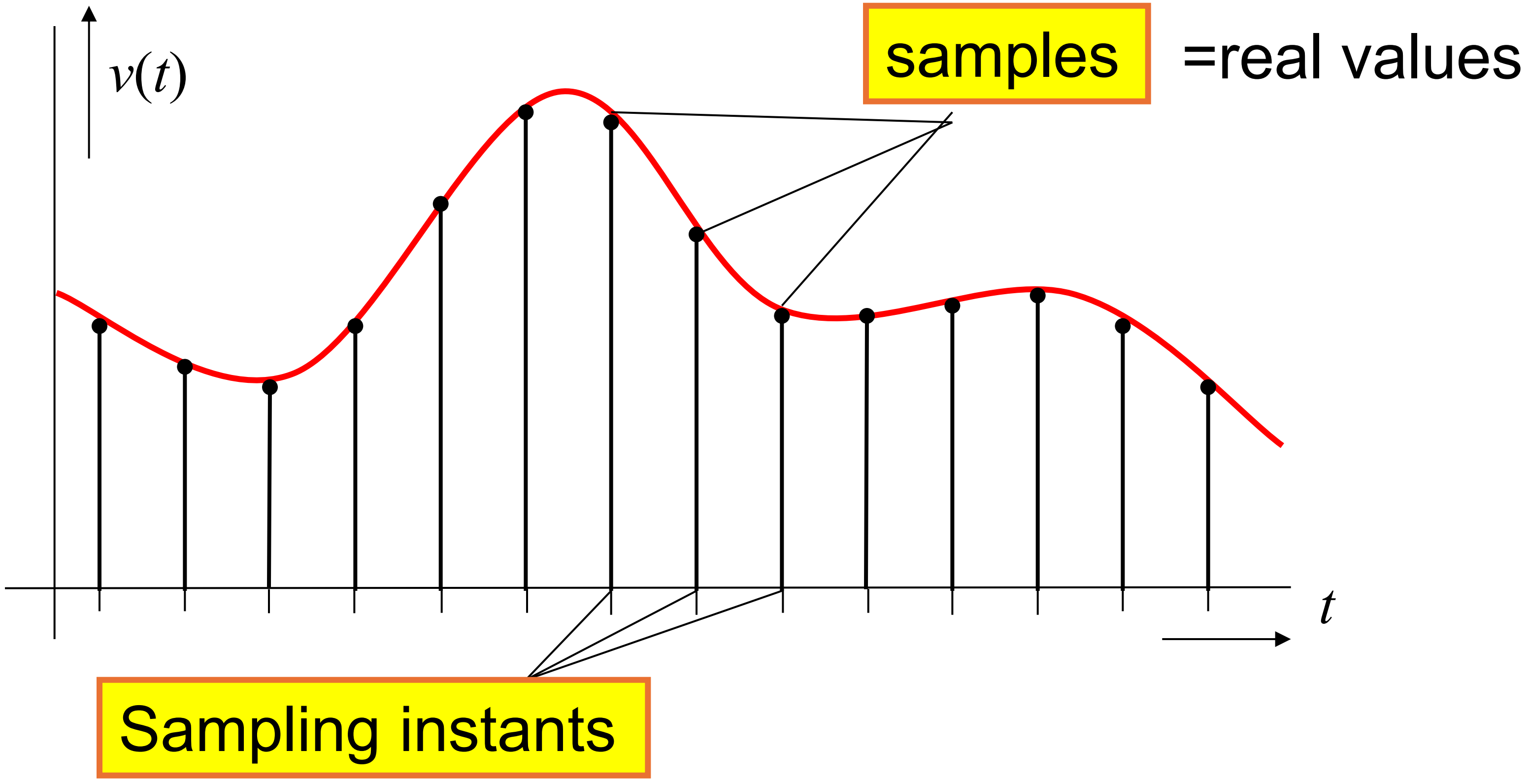
Analog signals

- Continuous in amplitude and time



Sampling

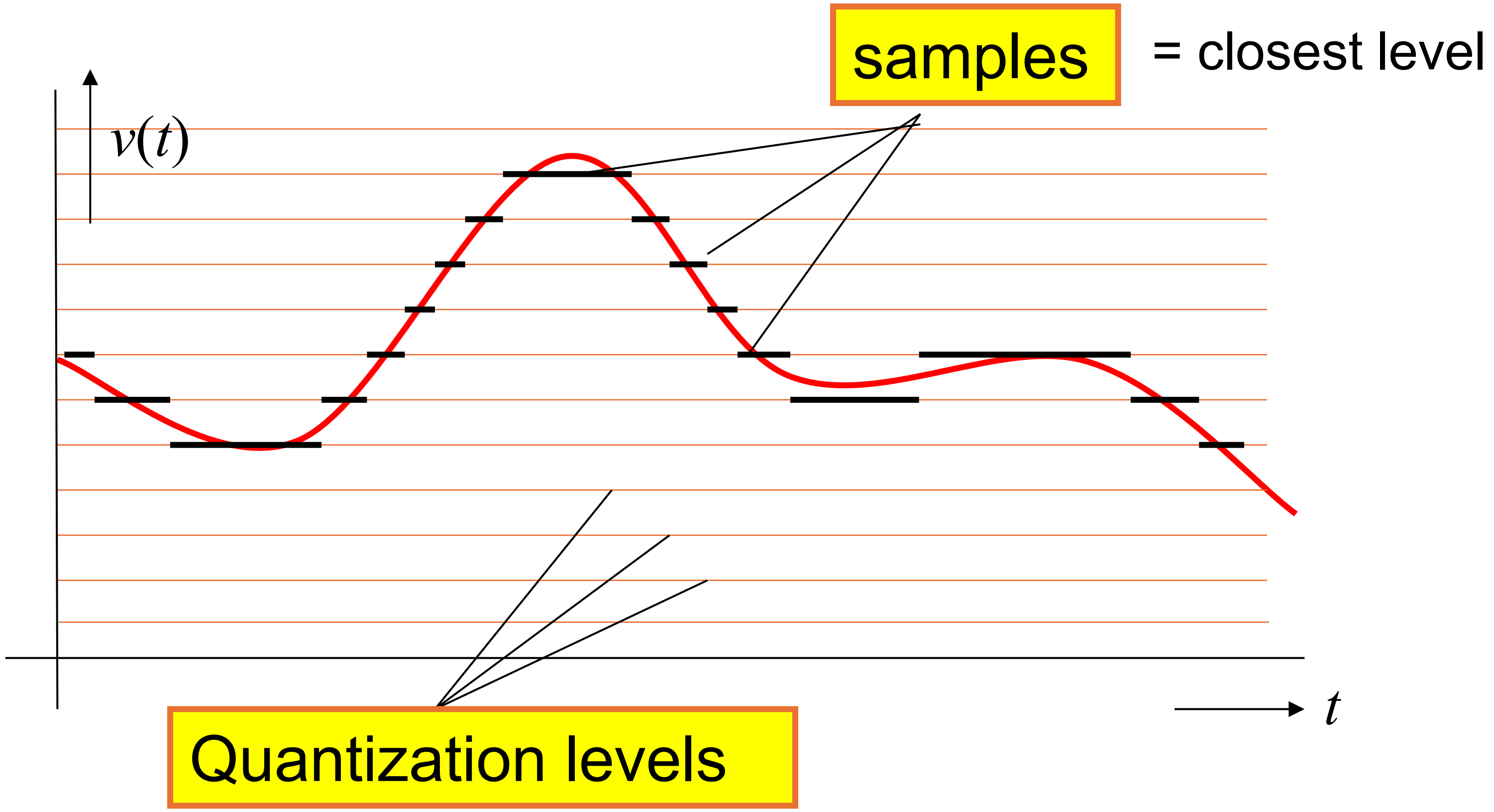
Discrete in time ➔ Sampling



Sampling frequency (fs): how many samples per second.

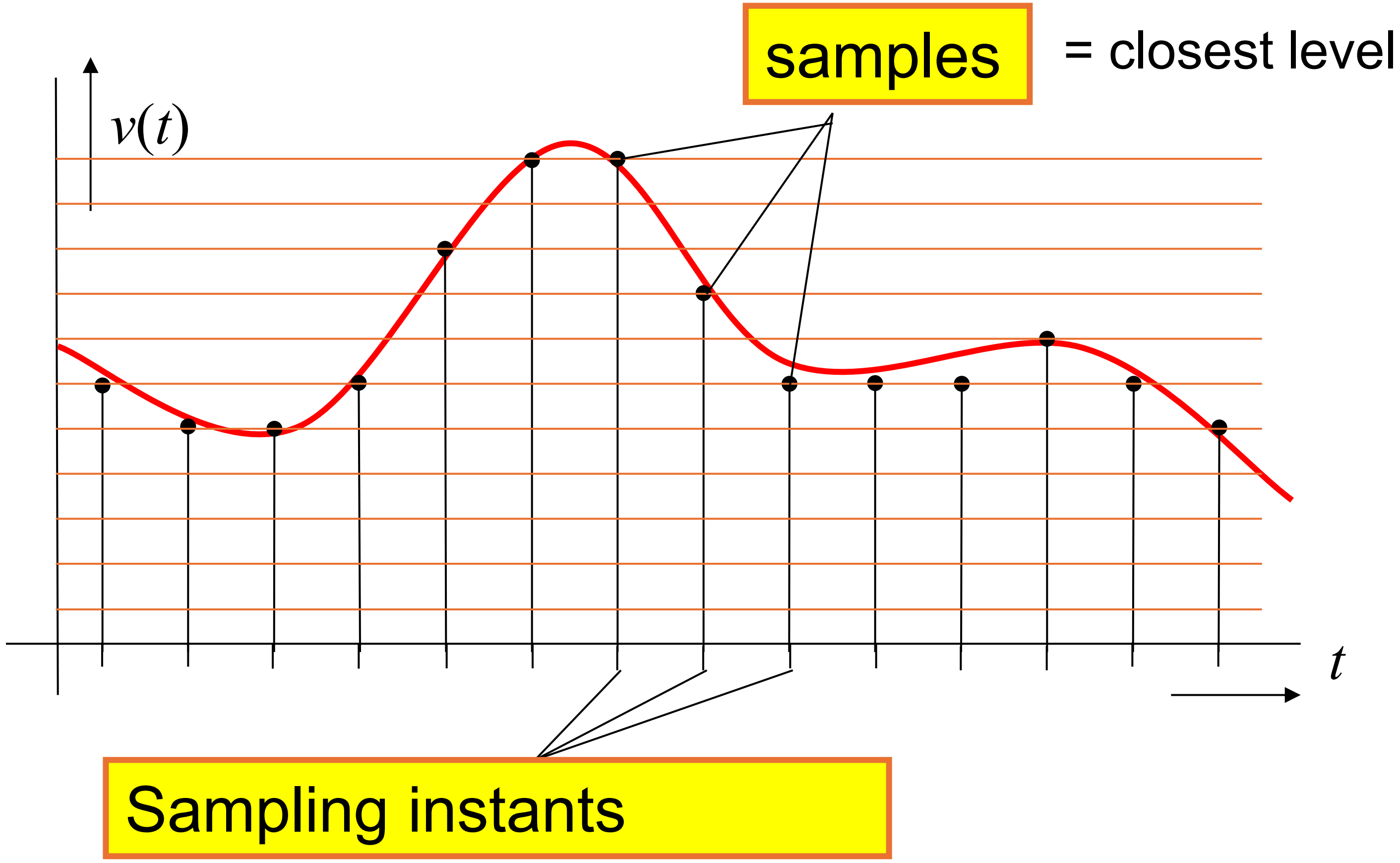
Quantization

Discrete in amplitude ➔quantization



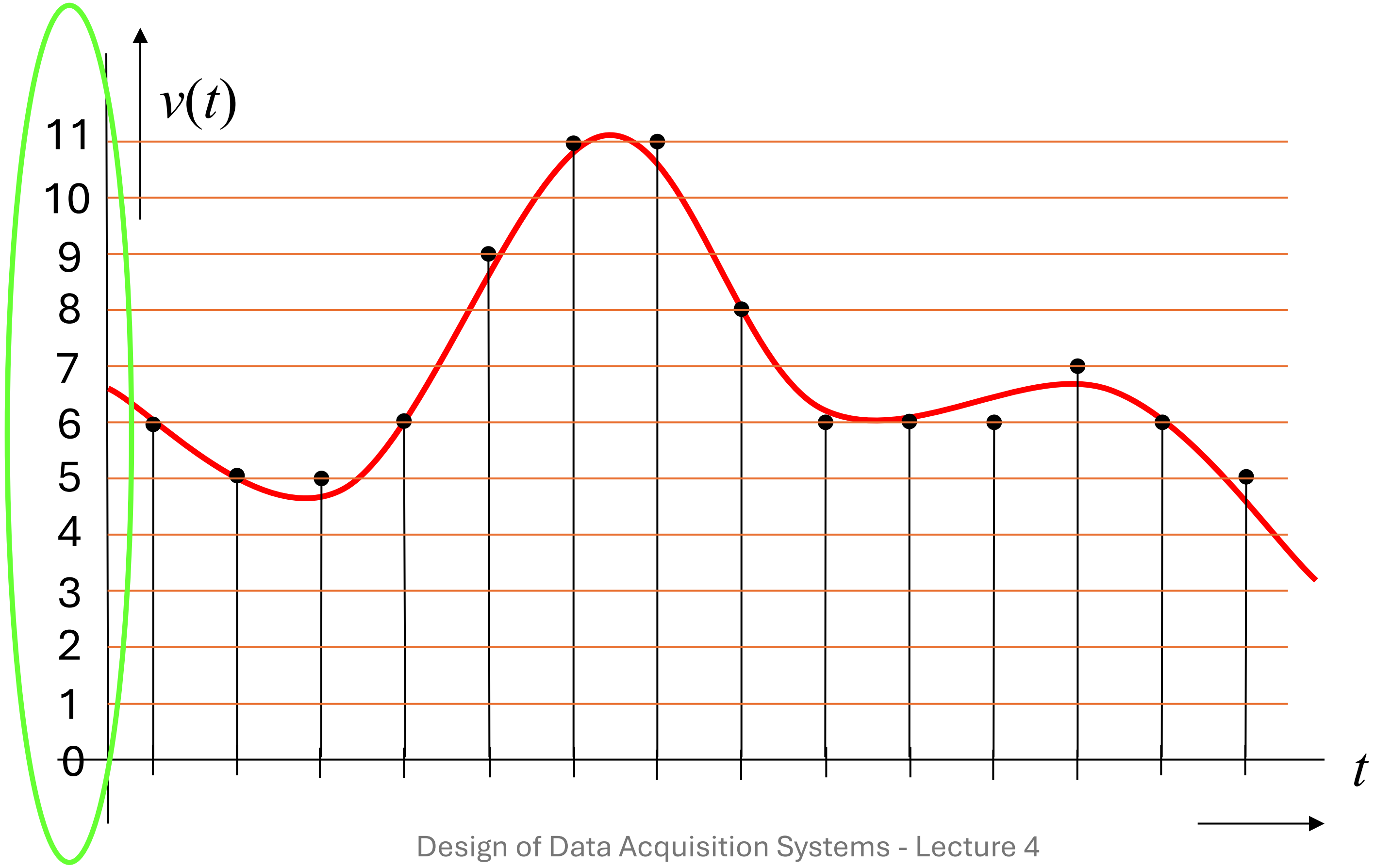
Sampled and quantized

- Discrete in time and amplitude (most common in digital)



Sampled and quantized

- Discrete in time and amplitude
- Now convert to 0s and 1s

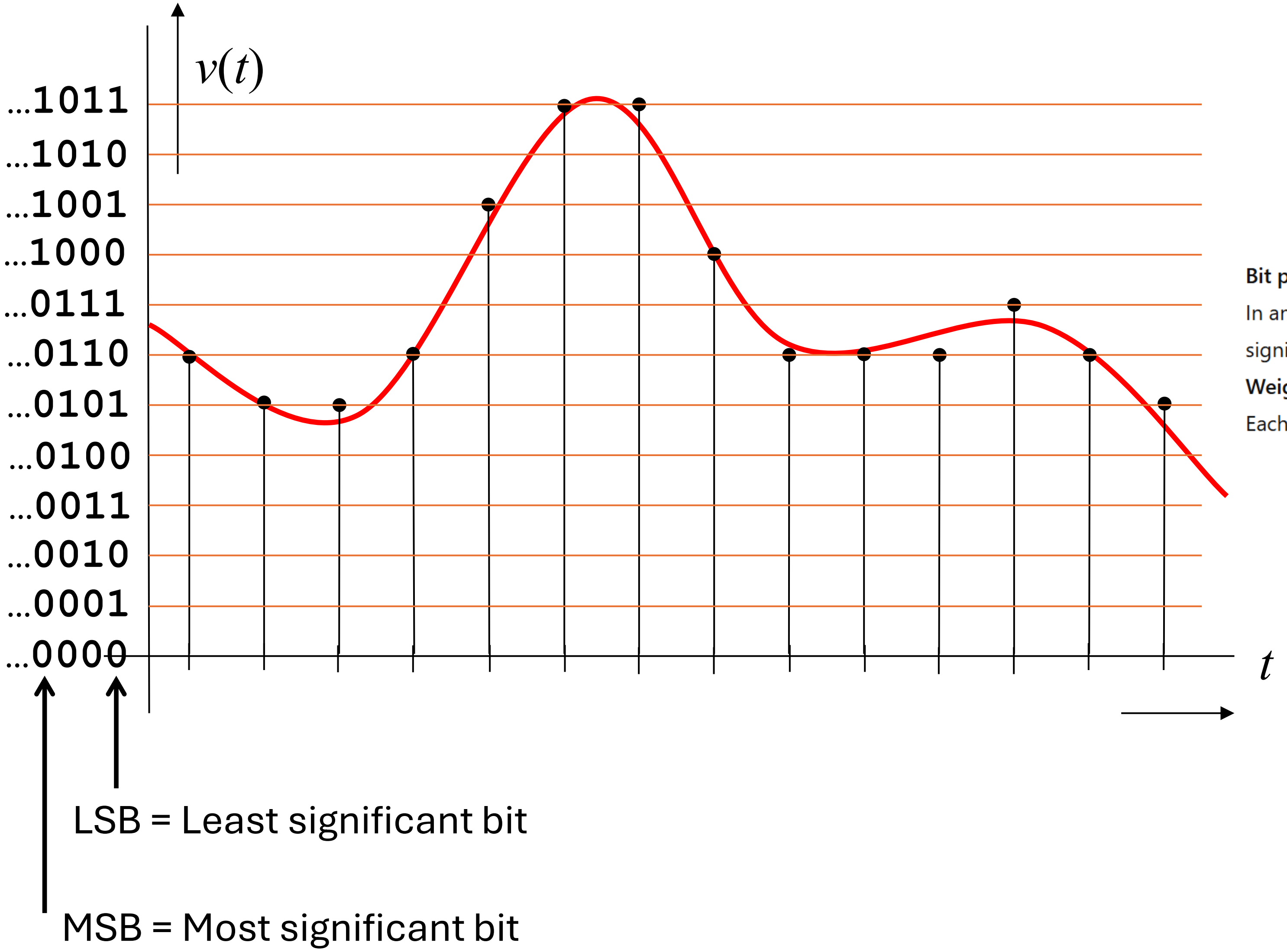


0 and 1

- Decimal → Binary
- For both: when you run out of symbols → restart at 0 and add 1 to the number on the left.

Number	Binary
1	1
2	10
3	11
4	100
…	
9	1001
10	1010
11	1011
…	
99	1100011
100	1100100

ADC output



Bit places are like decimal places, but in base-2.

In an N-bit ADC code $b_{N-1}\, b_{N-2} \dots b_1\, b_0$, the leftmost bit b_{N-1} is the **MSB** (most significant bit) and the rightmost bit b_0 is the **LSB** (least significant bit).

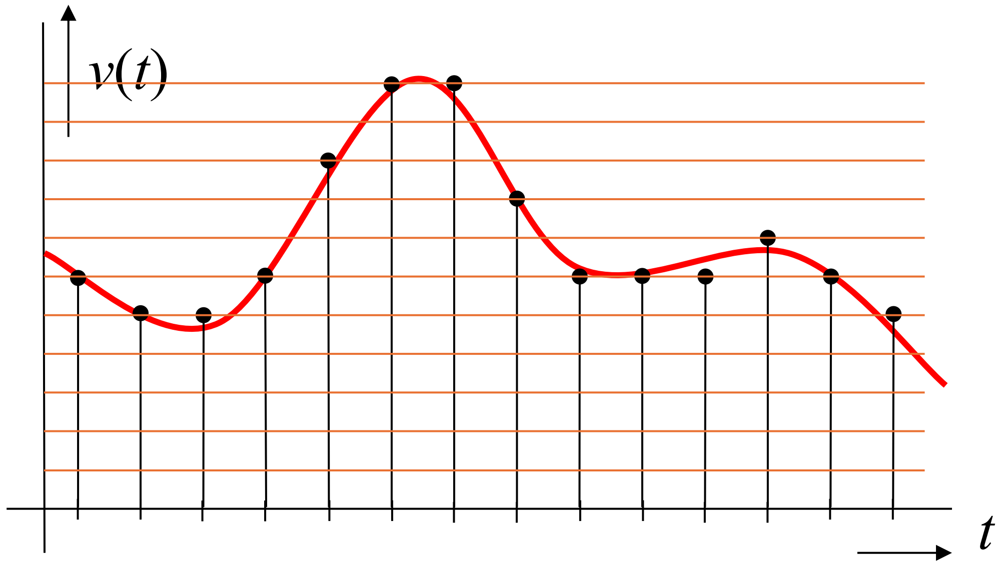
Weights:

Each bit has a weight that's a power of two.

$$\text{Code} = \sum_{k=0}^{N-1} b_k\, 2^k$$

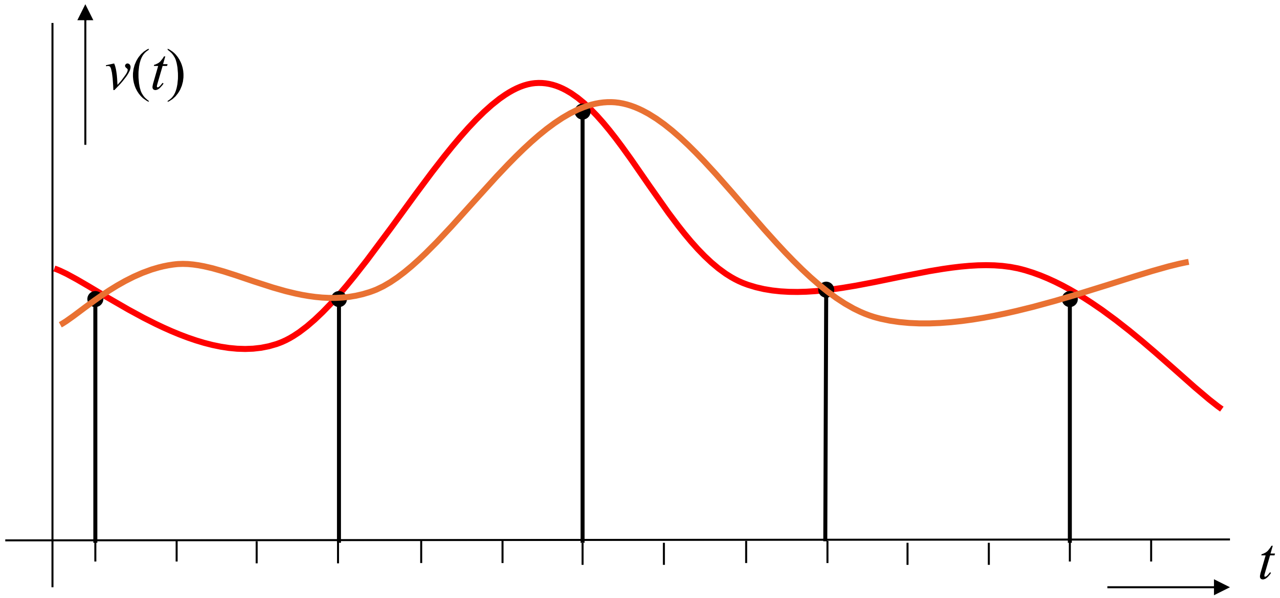
Amplitude resolution

- Quantization must be accurate enough: **rounding causes errors.**
- Example: f_{sample} = 44.1kHz, 16 bits versus 4 bits



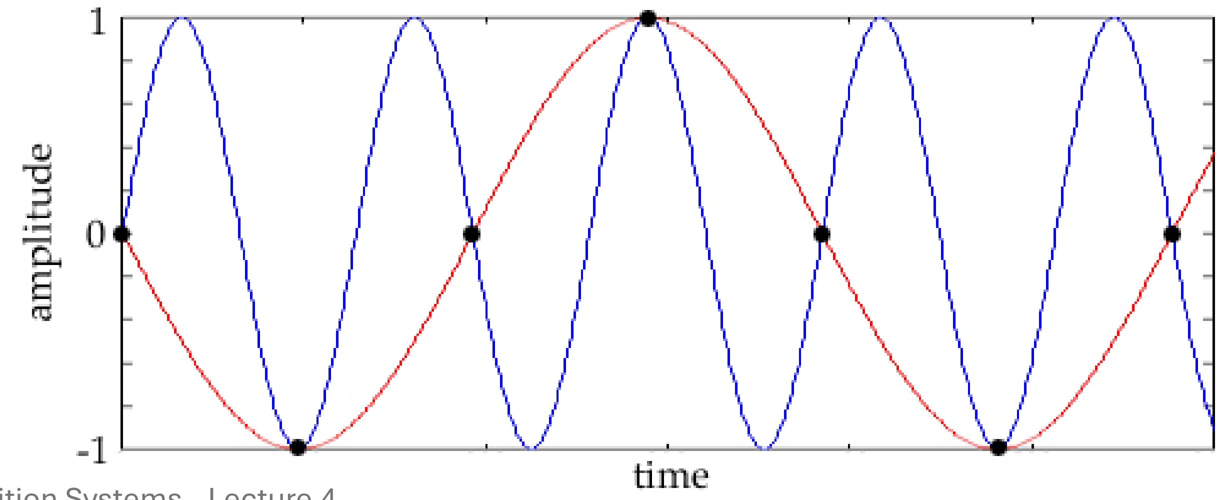
Time resolution

- Sampling frequency must be high enough.
- Nyquist-Shannon theorem: $f_{sample} > 2*f_{signal}$



Aliasing

- **Aliasing:** distortion caused by undersampling.
- If not: aliasing (folding back of frequencies)
- If you sample **too slowly** → **aliasing** happens.
  - High-frequency parts of the signal "fold back" into lower frequencies, distorting the signal.
- If you sample **fast enough** (≥ 2·fmax) → you can **reconstruct the original signal** exactly.



Sampling example

- **Step 1: Signal frequency**

We have a sinusoidal signal with

$$f = 5\ \mathrm{Hz}$$

- **Step 2: Nyquist sampling rate**

The Nyquist theorem says:

$$f_s \geq 2 \cdot f_{max}$$

Here $f_{max} = 5\,\mathrm{Hz}$, so

$$f_s \geq 10\ \mathrm{Hz}$$

At this rate:

- Sample spacing = $T_s = \frac{1}{10} = 0.1\,\mathrm{s}$
- Each cycle of the 5 Hz wave (0.2 s) will get **2 samples** (just enough to reconstruct).

- **Step 3: Good practical sampling**

In practice, we use more than the Nyquist minimum.

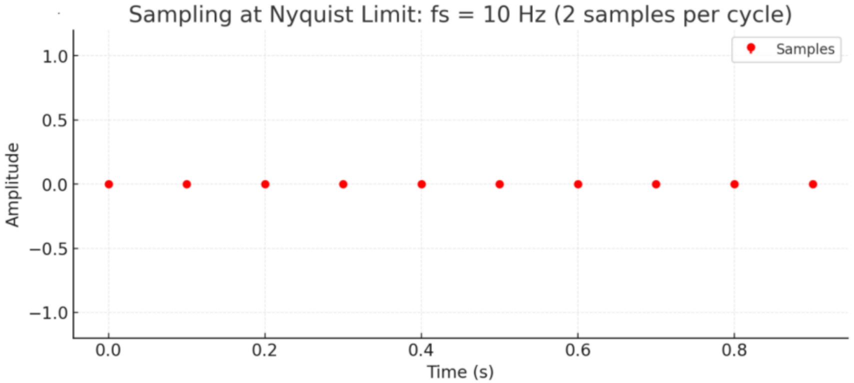
- Example: **20 Hz sampling** → $T_s = 0.05\,\mathrm{s}$.
- Now each 5 Hz cycle (0.2 s) has **4 samples** → better reconstruction.

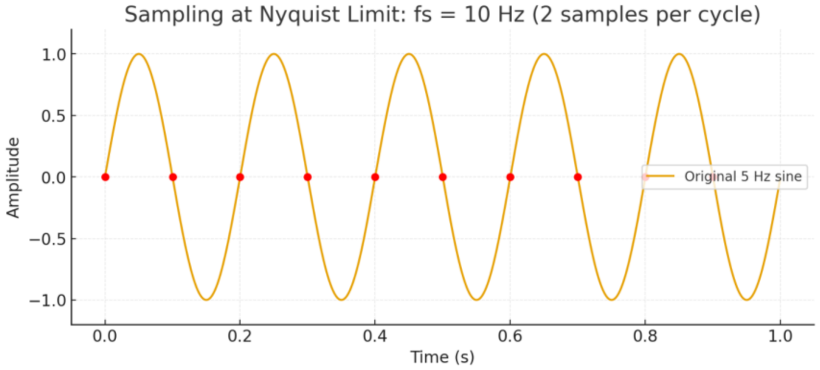
- **Step 4: Undersampling (Aliasing)**

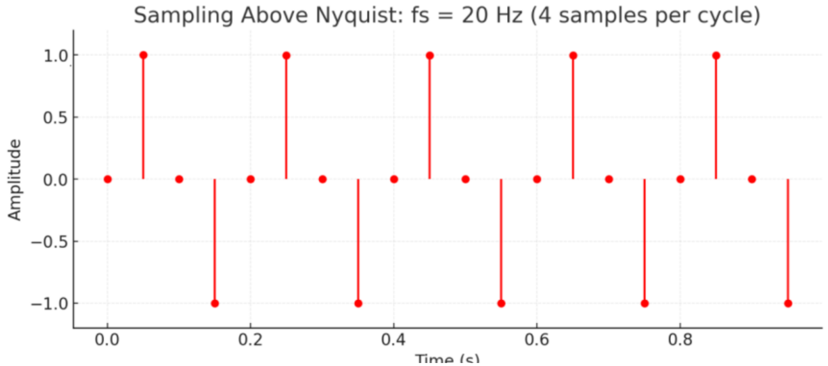
Suppose we sample at **6 Hz** (< Nyquist).

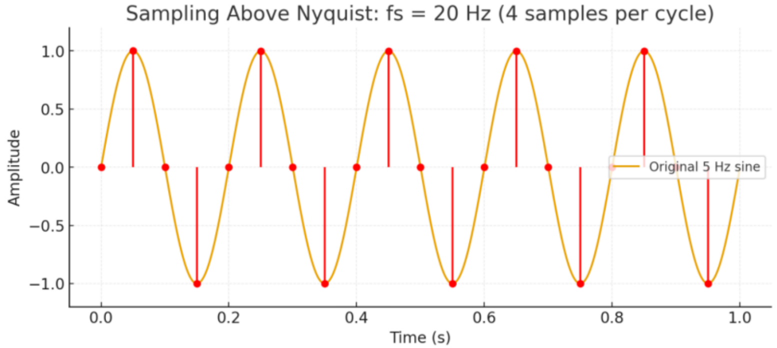
- Sampling interval: $T_s = \frac{1}{6} \approx 0.167\,\mathrm{s}$.
- Instead of 2+ samples per cycle, we only get about 1.2 samples.
- The 5 Hz wave will **look like** a slower sine wave (alias).

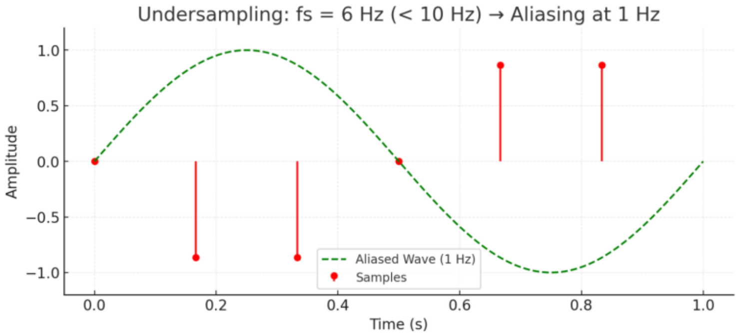
Sampling example

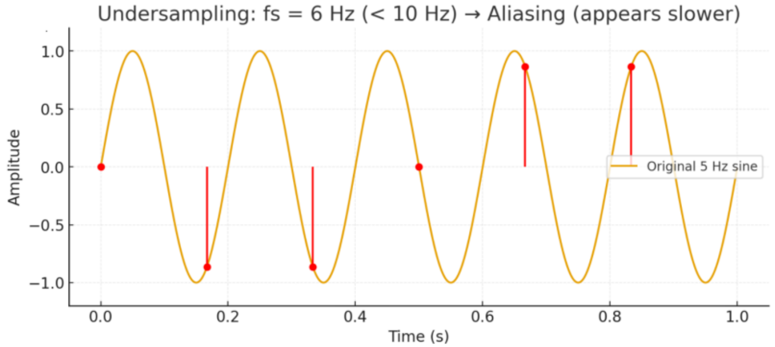




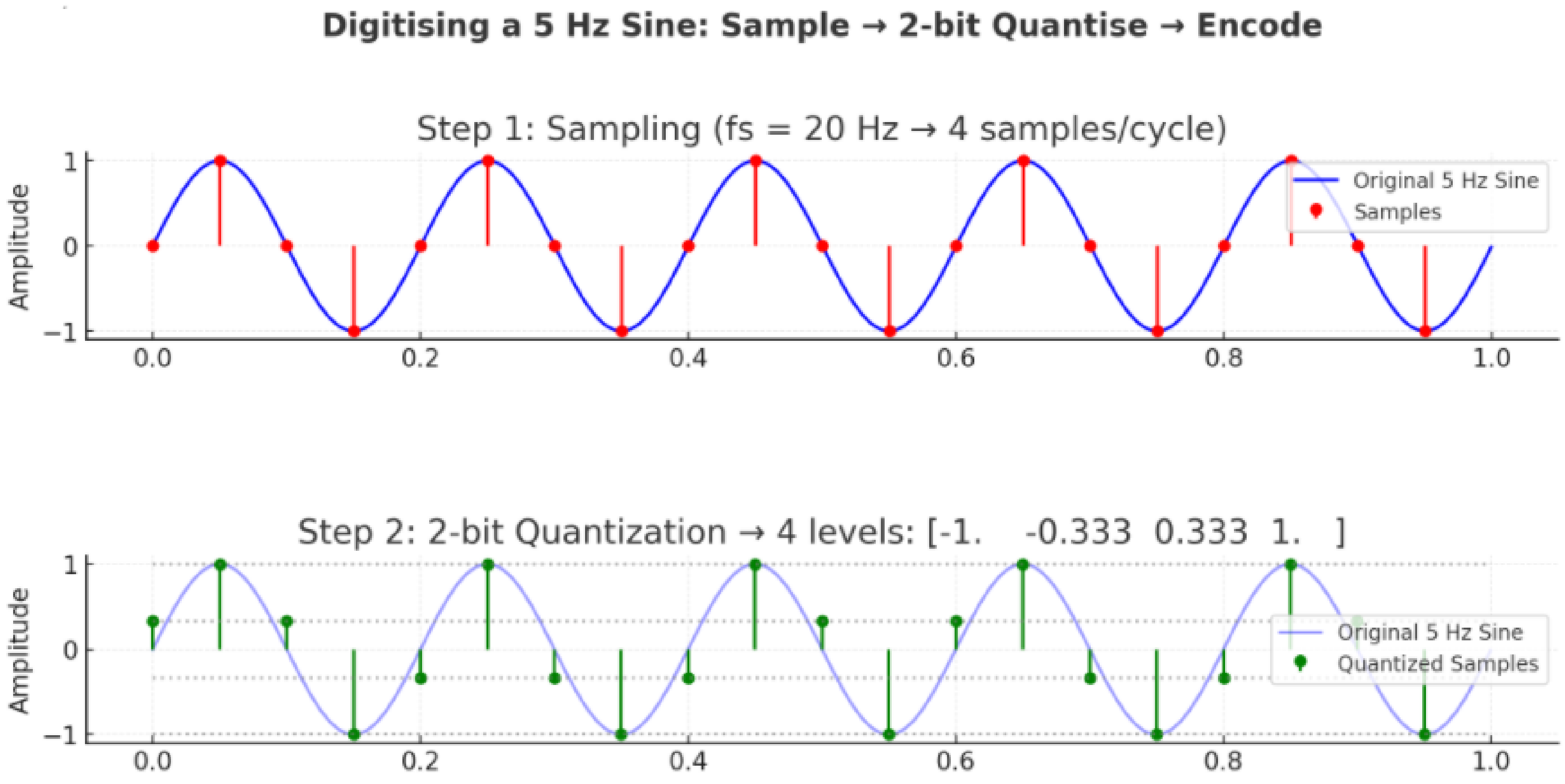








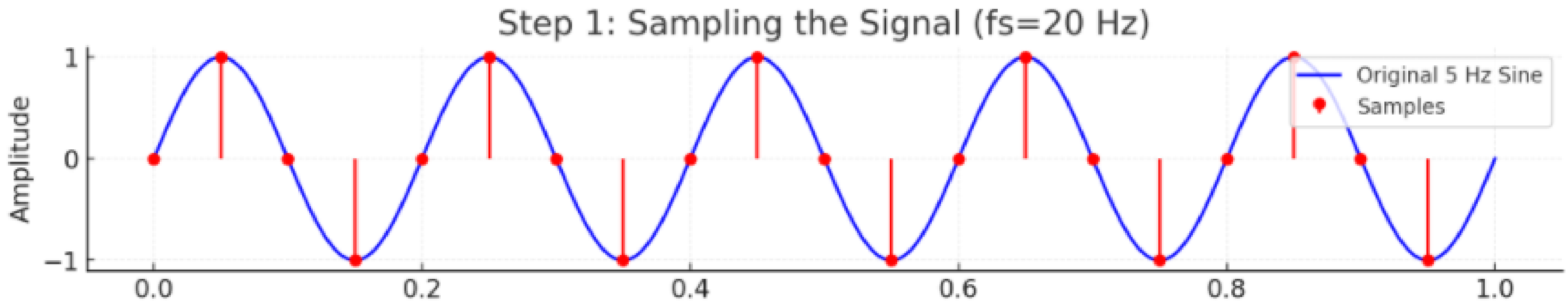
Example

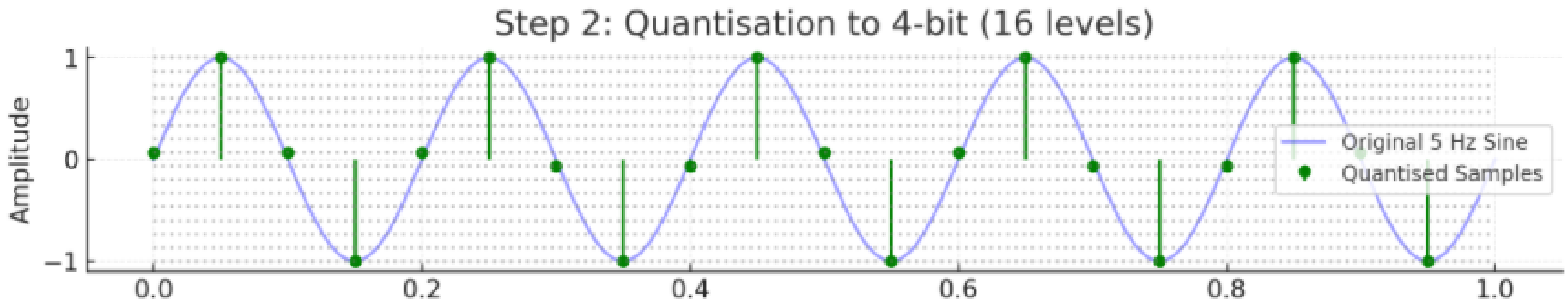


Step 3: 2-bit Binary Encoding and Bitstream

Sample Time (s)	Quantized Value	2-bit Code
0.00	0.333	10
0.05	1.000	11
0.10	0.333	10
0.15	-1.000	00
0.20	-0.333	01
0.25	1.000	11
0.30	-0.333	01
0.35	-1.000	00
0.40	-0.333	01
0.45	1.000	11
0.50	0.333	10
0.55	-1.000	00
0.60	0.333	10
0.65	1.000	11
0.70	-0.333	01
0.75	-1.000	00
0.80	-0.333	01
0.85	1.000	11
0.90	0.333	10
0.95	-1.000	00

Example





Step 3: Binary Encoding (4-bit Codes)

Sample Time (s)	Quantised Value	4-bit Code
0.00	0.067	1000
0.05	1.000	1111
0.10	0.067	1000
0.15	[illegible]	0000
0.20	0.067	1000
0.25	1.000	1111
0.30	-0.067	0111
0.35	-1.000	0000
0.40	-0.067	0111
0.45	1.000	1111
0.50	0.067	1000
0.55	-1.000	0000
0.60	0.067	1000
0.65	1.000	1111
0.70	-0.067	0111
0.75	-1.000	0000
0.80	-0.067	0111
0.85	1.000	1111
0.90	0.067	1000
0.95	-1.000	0000

Time resolution

- Shannon's theorem : $f_{sample} > 2*f_{signal}$
- Signal must be filtered before sampling
- Example: 16 bit samples
    - f_s = 44.1 kHz
    - f_s = 6 kHz (filtered first)
    - f_s = 6kHz (without pre-filter)

Examples (2)

Question

Audio CDs contain a digital representation of sound. The standard sampling frequency for audio is 44.1kHz. What is the reason that a sampling frequency of 44.1kHz is used?

A. 44.1kHz has a sufficiently small quantization error such that we don't hear any noise.
B. 44.1kHz is exactly 882 times 50Hz (frequency of the power grid) such that this hum is filtered.
C. 44.1kHz is just fast enough to properly sample the high frequency components of audio.
D. 44.1kHz contains no higher harmonics which can disturb the signal.

Answer

A: The quantization error has to do with the amount of steps that describe the audio signal which is described by the amount of bits of the digital signal. It has nothing to do with the sampling frequency.
B: There is no reason why the hum would be filtered.
C: This is true, the highest audible frequency is 20kHz (for most people this is lower).
D: This is true. However it is not the answer to the question.

Examples (3)

Question

Which of the following statements is the most correct one?

A. At the sampling frequency of an analog-digital converter, the number of bits is halved compared to the amount of bits for the full scale.
B. At the sampling frequency of an analog-digital converter, the effective value for the analog input voltage decreases to $1/\sqrt{2}$ of the maximum value.
C. The sampling frequency must be at least two times as high as the highest frequency component in the analog signal in order to have a proper digital representation.
D. The number of bits in the digital signal should be higher than the highest frequency component in the analog signal in order to have a proper digital representation of the analog signal.

Answer

A: The number of bits in an AD converter is fixed number. B: the input voltage does not depend on the sampling frequency. C: correct. D: the units do not match, a number cannot be compared to a frequency (the rest of the answer is also total nonsense).

Conclusion

- Analog-to-Digital Converter
  - Samples (makes time discrete)
  - Quantizes (makes amplitude discrete)
  - Codes (describes the value by a binary number)
- No loss of information if:
  - Sampling rate $f_{sample} > 2*f_{signal}$
  - Resolution (number of quantization levels/bits) is high enough.

Examples (1)

Question

The output voltage of an unknown voltage source (source resistance > 0) is measured twice. The first time it is measured with a voltage meter with an input resistance of 1 MΩ. The second time it is measured with an input resistance of 10 MΩ. The measurement results are V_1 and V_2 respectively. Which of the following statements is correct?

A. $V_1 < V_2$
B. $V_1 > V_2$
C. $V_1 = V_2$
D. No statement is possible; the source resistance is unknown.

Answer

Answer A is correct, but it is possible that the source resistance is so small that the difference in voltage is practically not observable.

Examples (2)

Question

We have three different circuits. One with a resistor $R = 1k\Omega$, one with an inductor $L = 10H$ and one with a capacitor $C = 1\mu F$. Each of the circuits has an alternating voltage source with an angular frequency of $\omega = 100$ rad/s. Which of these elements has the largest impedance for this angular frequency?

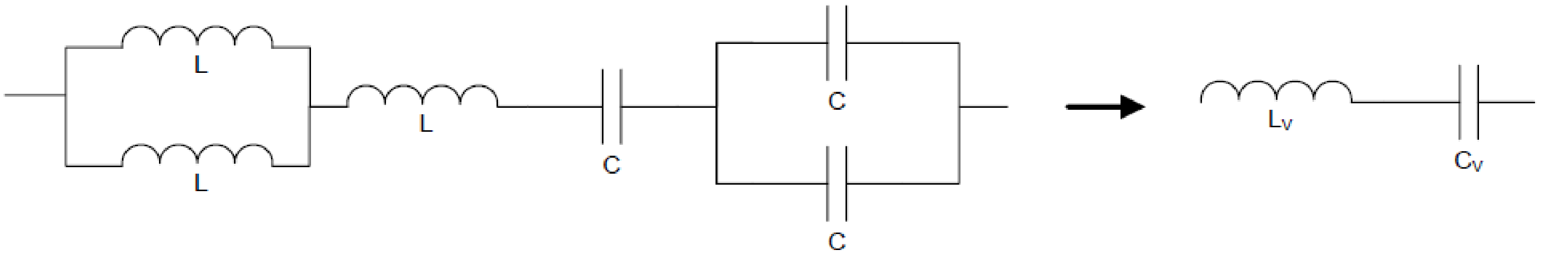
Answer

$Z_R = R = 1k\ [\Omega]$. $Z_L = \omega L = 100\ [rad/s] * 10\ [H] = 1k\ [\Omega]$. $Z_C = 1/(\omega C) = 1/\ (100*10^{-6}) = 10k\Omega$. Therefore, the capacitor has the largest impedance.

Examples (3)

Question

Simplify the following network of three inductors and three capacitors to a network with one total (replacement) inductor L_{tot} and one (replacement) capacitor C_{tot}, and determine the values of L_{tot} and C_{tot}.



Answer

$1/L_{par} = 1/L + 1/L = 2/L \rightarrow 2L_{par} = L \rightarrow L_{par} = 0{,}5L$

$L_{tot} = 0{,}5L + L = 1{,}5L$

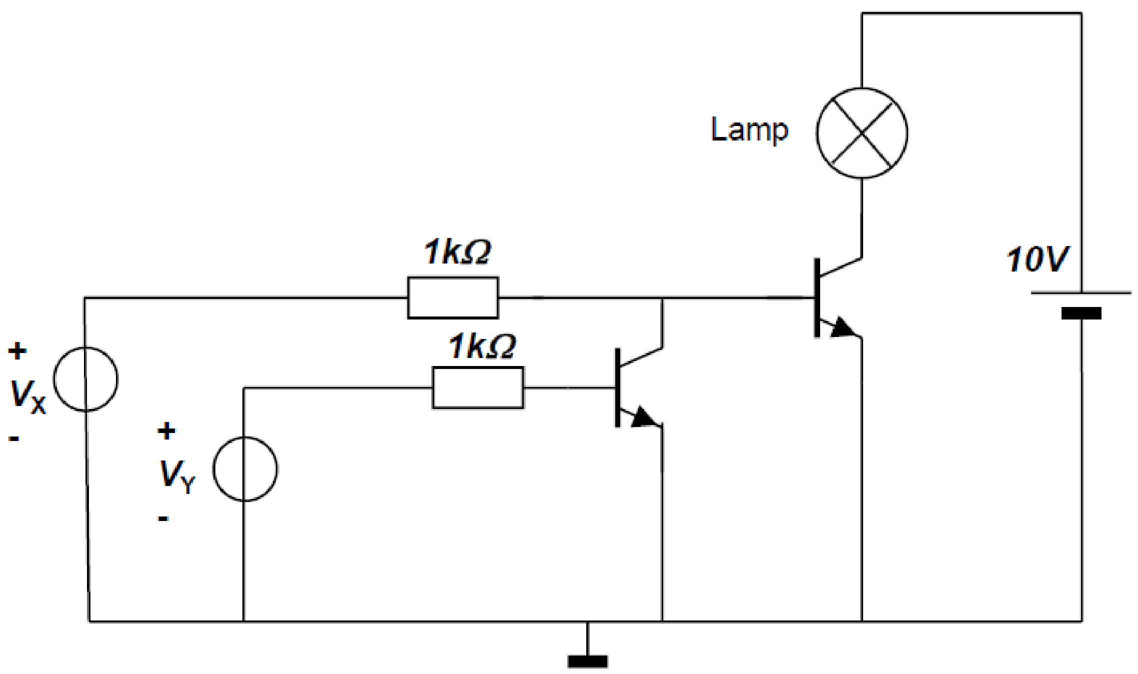
$C_p = C + C = 2C$

$1/C_v = 1/2C + 1/C = 1/2C + 2/2C = 3/2C \rightarrow 1/C_v = 3/2C \rightarrow 3C_v = 2C \rightarrow C_{tot} = 2/3C$

Examples (4) with sensors

Question

Given is the circuit below. Which situation is most likely?



A. V_X = 8V, V_Y = 0V, lamp = off
B. V_X = 7V, V_Y = 0V, lamp = on
C. V_X = 0V, V_Y = 3V, lamp = on
D. V_X = 6V, V_Y = 4V, lamp = on

Answer

The lamp can only be ON if the transistor on the right has a current running through it.
In order for this to happen there needs to be a current going into its base (V_X > 0.6V).
If V_Y is also greater than 0.6V, the current from Vx goes through the 1k resistor and then in to the transistor on the left such that also this transistor has a current running through it.
So, the lamp is only on when Vx > 0.6V and VY < 0.6V. This is only the case in situation B.