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Signals – sensors 4.

Dr. Gyányi Sándor

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What is Transduction?

- Transduction is the conversion of one form of energy into another, which is a key concept in sensor operation.
  - Electrical transduction converts physical parameters (e.g., temperature, pressure) into electrical signals, as in thermocouples and photodiodes.
  - Mechanical-to-electrical transduction occurs in strain gauges, where mechanical stress converts to changes in resistance.
  - Thermal-to-electrical transduction converts heat into electrical signals, as seen in thermocouples.
  - Optical-to-electrical transduction converts light into electrical signals, as in photodiodes and solar cells.
  - Magnetic-to-electrical transduction occurs in Hall effect sensors, where magnetic fields generate voltage.

Sensing Principles Overview

- Sensing principles: electrical, mechanical, thermal, magnetic, optical, and chemical.
  - Electrical: Current, voltage-based sensors (e.g., resistive sensors).
  - Mechanical: Sensors measuring force, displacement, pressure.
  - Thermal: Temperature sensors (e.g., thermocouples).
  - Magnetic: Magnetic field sensors (e.g., Hall effect).
  - Optical: Light sensors (e.g., photodiodes).
  - Chemical: Gas and pH sensors.

Electrical Sensing Principles

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- Electrical sensors detect changes in electrical properties such as resistance, capacitance, or inductance. Examples:
  - Resistive sensors: Potentiometers, strain gauges.
  - Capacitive sensors: Proximity detection.
  - Inductive sensors: Metal detection.

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Mechanical Sensing Principles

- Mechanical sensors measure changes in physical dimensions, such as:
  - Pressure sensors: Measure fluid or gas pressure.
  - Displacement sensors: Measure linear or angular position.
  - Force sensors: Measure applied force (e.g., strain gauges, piezoelectric sensors).

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Thermal Sensing Principles

- Thermal sensors detect temperature changes and include:
  - Thermocouples: Produce voltage in response to temperature.
  - Thermistors: Resistance changes with temperature.
  - Infrared sensors: Detect heat radiation.

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Magnetic Sensing Principles

- Magnetic sensors detect magnetic fields using:
  - Hall effect sensors: Voltage induced by magnetic fields.
  - Magnetoresistive sensors: Resistance changes with magnetic field strength.

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Optical Sensing Principles

- Optical sensors detect light changes and convert them into electrical signals:
  - Photodiodes: Generate current proportional to light intensity.
  - Phototransistors: Light-activated transistors.
  - Optical encoders: Convert light into electrical signals.

Chemical Sensing Principles

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- Chemical sensors detect chemical properties and changes:
  - pH sensors: Measure acidity or alkalinity.
  - Gas sensors: Detect specific gas concentrations (e.g., CO_2, O_2).

Temperature Sensors

- Purpose: to measure overall environmental or a target object’s surface or core temperature.
- Types: Thermocouples, Thermistors, RTDs, infrared sensors.

Thermocouple sensors

- A thermocouple is a temperature sensor that measures temperature based on the voltage difference generated by two different metals when exposed to heat.
- Based on the **Seebeck Effect**: When heat is applied to one of the two conductors or semiconductors, heated electrons flow toward the cooler conductor or semiconductor.
- This voltage can be measured.

Thermistors

- Thermistors are temperature-sensitive resistors whose resistance changes significantly with temperature.
- Typically made from ceramic or polymer materials composed of metal oxides, semiconductor-based sensors are also available.
- It typically has a **negative temperature coefficient (NTC)**, meaning its resistance decreases as temperature increases, however there are PTC-type thermistors.
- They have fast response time, usually the changes are non-linear.
- Operates in a **limited temperature range** (typically -50°C to 150°C).

RTD (Resistance Temperature Detectors)

- An RTD operates based on the principle that the electrical resistance of metals increases linearly with temperature.
- Commonly made from pure metals, most frequently platinum (Pt), though nickel and copper are also used.
- Operates in a **wider temperature range** (typically -200°C to 600°C, though specialized RTDs can go higher).

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Infrared temperature sensors 1.

- **Infrared temperature sensors**, also known as **infrared thermometers** or **pyrometers**, are non-contact temperature measurement devices that detect infrared radiation emitted by objects.
- All objects above absolute zero (-273.15°C or 0 K) emit electromagnetic radiation. The amount and wavelength of the radiation depend on the object's temperature.
- The Stefan–Boltzmann law describes the intensity of the thermal radiation emitted by matter.
- Infrared thermometers detect the intensity of infrared radiation within a specific wavelength range (typically 0.7 to 14 micrometers).

Infrared temperature sensors 2.

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- Infrared temperature sensors consist of two main components: **optics** and a **detector**.
- Infrared radiation is focused onto a detector by lenses made from infrared-transparent materials like **germanium**, **silicon**, **sapphire**, or **calcium fluoride**.
- **Pyroelectric Sensors are using** materials which generate a voltage in response to temperature changes. **Lithium tantalate (LiTaO3)** and **barium strontium titanate (BST)** are common materials.
- Semiconductor-based detectors like **InGaAs (Indium Gallium Arsenide)** or **HgCdTe (Mercury Cadmium Telluride)** are detecting IR directly.

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Infrared temperature sensors 3.

Temperature sensor comparison 1.

Feature	RTDs (Resistance Temperature Detectors)	Thermistors	Infrared Sensors
Operating Principle	Measures temperature by the change in resistance of a pure metal (typically platinum).	Measures temperature by the resistance change in metal oxide with temperature.	Measures temperature by detecting infrared radiation emitted by an object.
Material	Platinum, nickel, or copper	Ceramic, metal oxides	Semiconductor materials, infrared-sensitive photodetectors
Temperature Range	-200°C to +850°C	-100°C to +300°C	-70°C to +3000°C
Response Time	Moderate (typically slower than thermistors)	Fast (due to small size and material properties)	Very fast (non-contact measurement)
Accuracy	High (±0.1°C to ±1°C)	High (±0.1°C within limited range)	Moderate to high (depends on model and calibration)

Temperature sensor comparison 2.

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Feature	RTDs (Resistance Temperature Detectors)	Thermistors	Infrared Sensors
Sensitivity	Moderate (linear response over a wide range)	High sensitivity but non-linear	High sensitivity to infrared radiation
Linearity	Fairly linear response	Non-linear response	Non-linear, typically depends on distance and material properties of the object
Stability	Very stable over time	Can drift over time, especially in extreme conditions	Stability depends on the calibration and environmental factors
Contact/Non-Contact	Contact	Contact	Non-contact (detects radiation from a distance)
Response Time	Moderate (seconds)	Fast (milliseconds)	Very fast (milliseconds to microseconds)

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Displacement sensors

- Displacement sensors measure the **linear** or **angular movement** of an object from a reference point.
- They are used to detect **position**, **distance**, or **movement** of a mechanical part.
- **Linear Displacement:** Measures the straight-line distance moved by an object.
- **Rotational Displacement:** Measures the angular position or rotation of an object.

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Potentiometers

- A potentiometer is a three-terminal resistor with a sliding or rotating contact that provides variable resistance.
- There are 2 types of potentiometers: Rotary Potentiometers and Linear Potentiometers.
- Rotary Potentiometers can be used as rotation-detectors (e.g. gas pedal detection in cars).
- The potentiometer is acting like a voltage divider.

Linear Variable Differential Transformers (LVDTs)

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- An **LVDT** consists of a primary coil, two secondary coils and a movable core.
- When the core moves, it induces a voltage difference in the secondary coils, proportional to the displacement.

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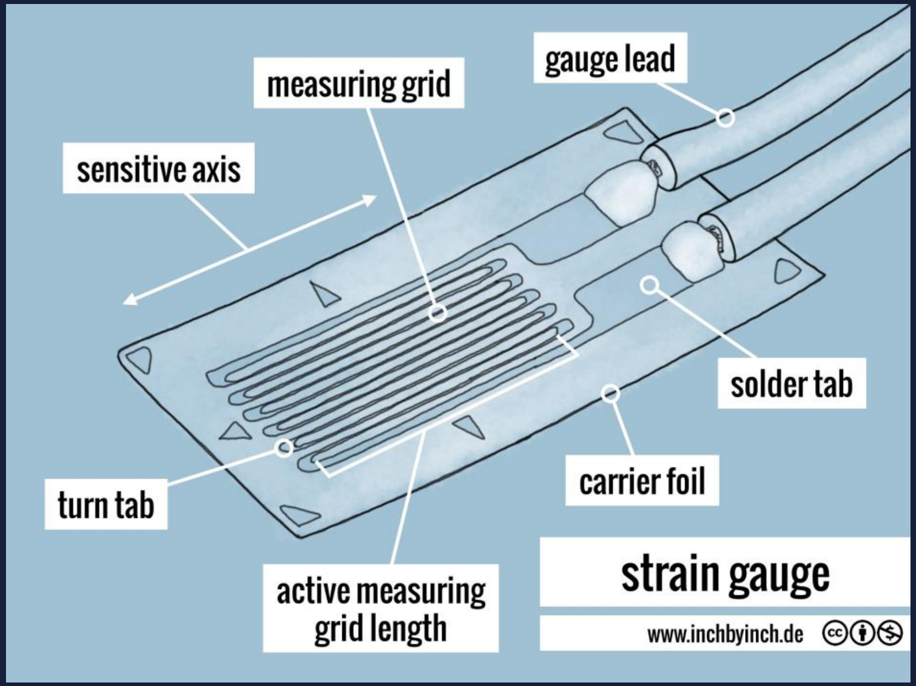
Pressure Sensors

- Usage: indirect force detection, gas or liquid pressure measurements.
- Force can be converted into pressure, therefore a pressure sensor is capable of measuring mass or force.
- Types: Strain Gauge, Piezoelectric, Capacitive.

Strain gauges

- Strain gauges are devices used to measure the strain (deformation) on an object.
- Invented by Edward E. Simmons and Arthur C. Ruge in 1938.
- A typical strain gauge consists of a metallic foil pattern mounted on an insulating flexible backing.
- There are different types of strain gauges, including foil strain gauges, semiconductor strain gauges, and photoelectric strain gauges.



Piezoelectric sensors 1.

- The operation is based on the **piezoelectric effect**, certain materials can generate an electrical charge when subjected to mechanical stress.
- Usually this effect is working on reverse mode too, an electric charge can deform the crystal. This is widely used in precise clock generators (e.g. watches).

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Piezoelectric sensors 2.

- The effectiveness of a piezoelectric sensor largely depends on the material used. Piezoelectric materials can be **natural crystals**, **synthetic ceramics**, or **polymers**.
- Natural crystals: Quartz is the most popular type, however it has low sensitivity.
- Synthetic Piezoelectric Ceramics: Lead Zirconate Titanate (PZT), Barium Titanate (BaTiO3), Lithium Niobate (LiNbO3).
- Piezoelectric Polymers.

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Capacitive pressure sensors

- It has a Ceramic Capacitor Sensitive Diaphragm.
- When the measured pressure (P) acts on the diaphragm, the diaphragm deforms and changes the capacitance.
- An electronic circuit can measure the capacitance.

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Comparison of pressure sensors

Feature	Strain Gauge Sensors	Piezoelectric Sensors	Capacitive Pressure Sensors
Operating Principle	Measures pressure by detecting the strain (deformation) in the material; the strain causes a change in electrical resistance.	Converts mechanical pressure or strain into an electrical charge via the piezoelectric effect.	Measures pressure by detecting changes in capacitance caused by the displacement of a diaphragm between two conductive plates.
Materials	Thin metal foil or semiconductor materials like silicon, bonded to a substrate (often aluminum or steel).	Piezoelectric materials like quartz, PZT (Lead Zirconate Titanate), or PVDF (polyvinylidene fluoride).	Dielectric materials such as air, ceramic, or polymer with conductive metal plates or diaphragms.
Sensitivity	Moderate sensitivity, better suited for static and quasi-static measurements.	High sensitivity to dynamic changes in force or pressure (vibrations, impacts).	Moderate to high sensitivity, particularly in low-pressure ranges; can detect small displacements.

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Proximity Sensors

- Types: Capacitive, Inductive, Ultrasonic, Infrared.
- Purpose: to measure the distance between the sensor and a target object.
- Applications: parking assistants in cars, object detection in manufacturing, touch interfaces.

Capacitive proximity detection

- A capacitive sensor forms an electric field around its sensing face.
- When a target enters this field, it causes a change in capacitance.
- The sensor detects this change and triggers a response.

Inductive sensors

- An inductive proximity sensor detects metal objects using electromagnetic energy without requiring physical contact.
- The sensor's detection range varies depending on the type of metal being sensed.
- Because non-metallic substances like dirt and liquids do not interfere with its function, an inductive proximity sensor can operate effectively in wet or dirty environments.

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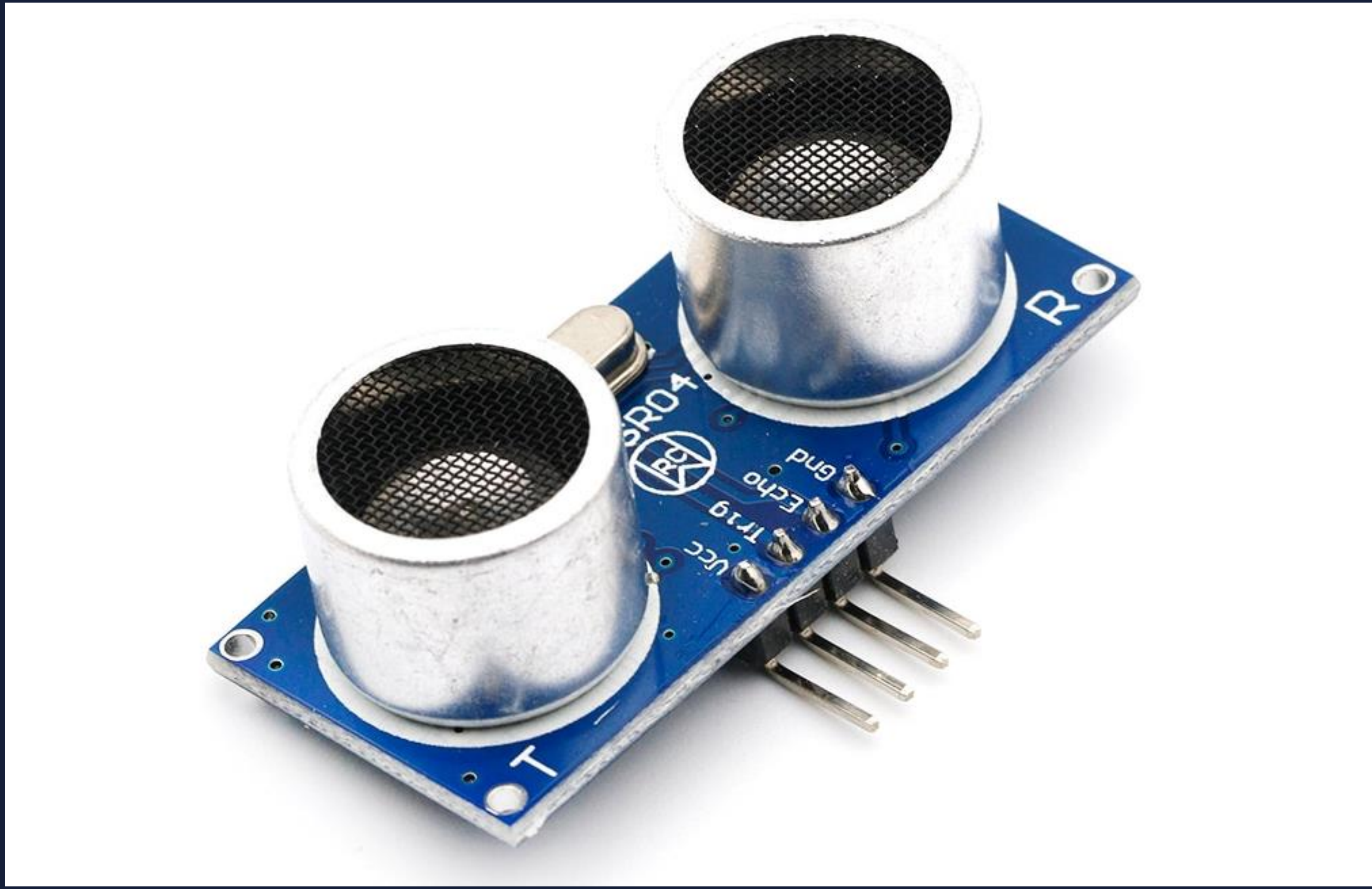
Ultrasonic sensors 1.

- Ultrasonic proximity sensors operate based on the principle of **echo detection.**
- They emit ultrasonic waves (sound waves over 20kHz frequency) and listen for the reflected sound (echo) after it bounces back an object.
- The sensor calculates the round trip time of the sound and calculate the distance based on the speed of sound.
- Ultrasonic sensors can measure both the distance to an object and presence if the object is in the detection range.

Ultrasonic sensors 2.



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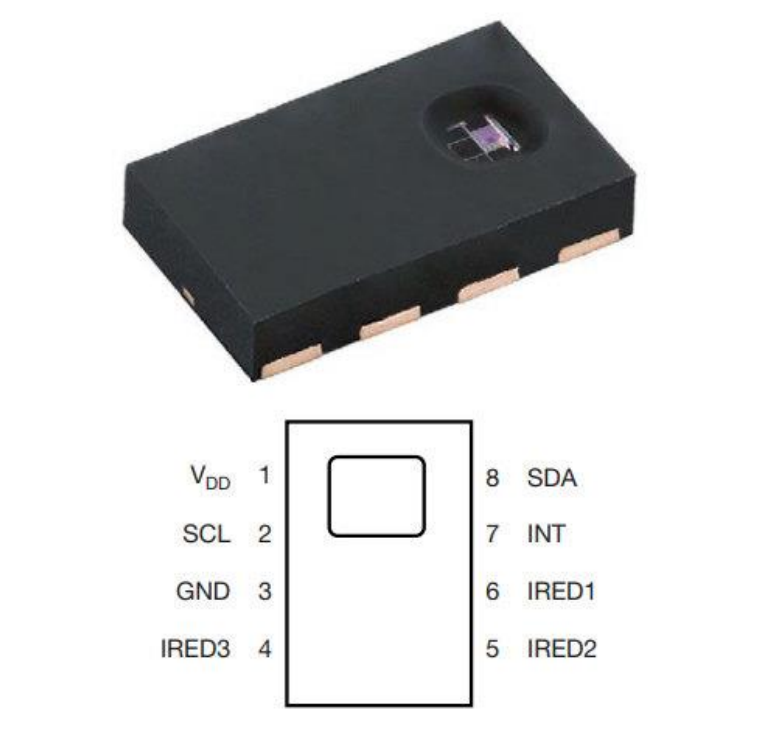
Optical proximity sensors 1.

- Optical proximity sensors use **light emission and detection** to sense the presence of an object within a specific range.
- These sensors are including a light emitting device (usually a LED) and a light detection device (photo LED).
- Infrared light is the most common wavelength.
- Types:
  - **Reflective sensors**: The emitted light hits an object and reflects back toward the sensor.
  - **Through-beam sensors**: The emitted light beam is interrupted when an object passes between the emitter and receiver, breaking the signal.

Optical proximity sensors 2.

- VCNL3036X01 High Resolution Digital Proximity Sensor With I2C Interface



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Proximity sensors comparison

Sensor Type	Detectable Material	Sensing Range	Advantages	Disadvantages
Capacitive Sensor	Metal & Non-metal	Short (3-30mm)	Versatile, non-contact sensing	Sensitive to environment (humidity, dust)
Inductive Sensor	Metal	Short (1-15mm)	High accuracy with metals	Cannot detect non-metals
Ultrasonic Sensor	Solid & Liquid objects	Medium-Long (50mm-10m)	Long-range detection, unaffected by material	Higher cost, slower response
Optical Sensor	Reflective objects	Medium-Long (1mm-10m)	Fast response, long range	Sensitive to dirt, requires line of sight

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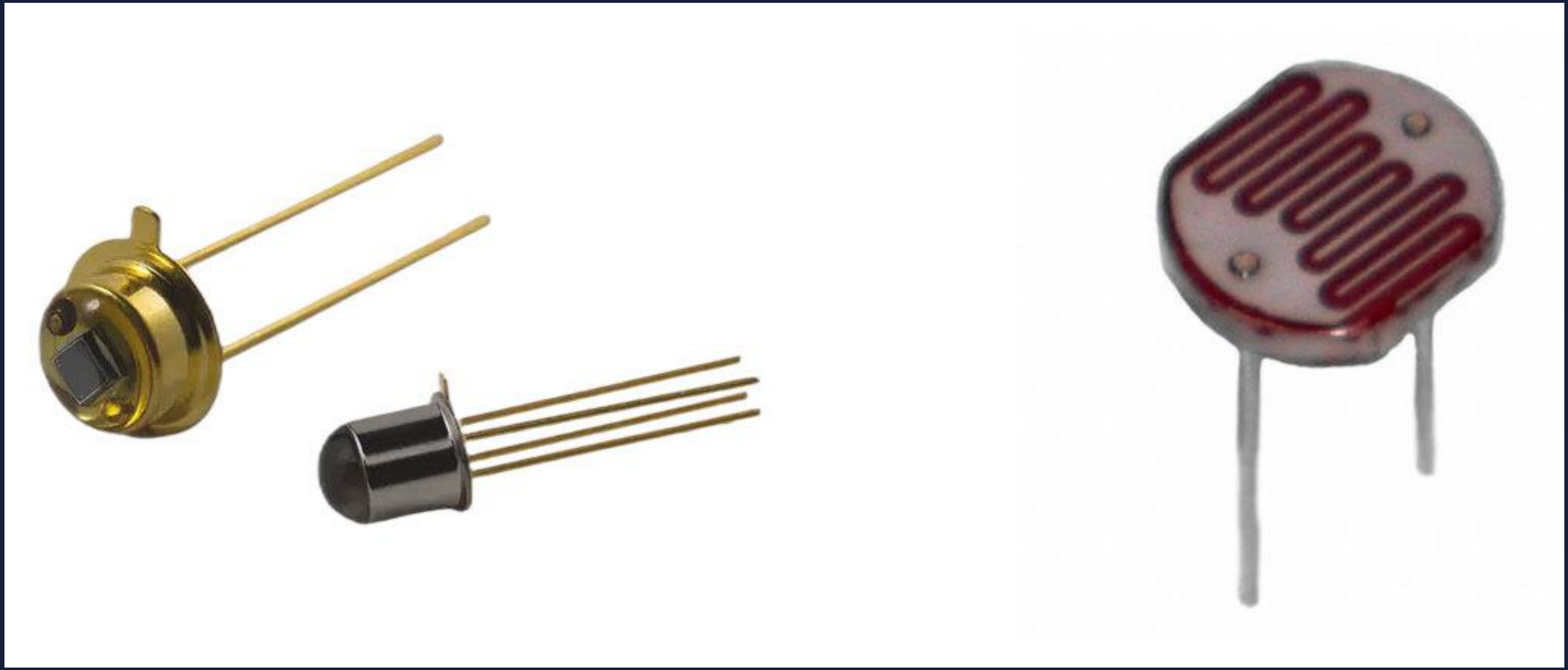
Light Sensors

- Types: Photodiodes, Phototransistors, LDR (Light Dependent Resistor).



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Photodiodes 1.

- A photodiode is a semiconductor device that converts light into an electrical current.
- It operates based on the **photoelectric effect**, where photons of light generate electron-hole pairs in the semiconductor material.
- Two different types:
  - **Photovoltaic Mode:** In this mode, the photodiode generates a voltage when exposed to light.
  - **Photoconductive Mode:** An external reverse bias is applied, increasing the depletion region and making the photodiode more sensitive to light.

Photodiodes 2.

- Practical Applications:
  - Communication: Photodiodes are used in **fiber optic communication** systems.
  - Light detection: Photodiodes are used in **light meters** and **photometers** to measure light intensity.
  - Heart rate and blood oxygen level detection in medical devices: Pulse oximeters measures blood oxygen levels by detecting the absorption of light. Different oxygen levels absorbs different wavelengths.
  - Barcode readers: Photodiodes detects reflected light from barcode patterns.
  - Remote control systems: IR photodiodes are used for detecting the remote controls infrared signals.
  - Photovoltaic diodes can be used for power generation.

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Phototransistors

- A **phototransistor** combines the principles of a photodiode with the amplification ability of a transistor.
- It detects light and in the same time amplifies the electrical signal.
- Higher sensitivity compared to photodiodes.
- Applications are similar to the photodiodes but phototransistors are more sensitive.

LDRs (Light Dependent Resistors)

- An **LDR**, also known as a **photoresistor**, is a light-sensitive resistor whose resistance decreases with increasing light intensity.
- LDRs are made from semiconductor materials like cadmium sulfide **(CdS)**.
- They have non-linear behavior: resistance changes drastically with light intensity.
- They have slow response times.
- LDRs can be used where detection speed is less important (automatic lighting).

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Light sensor comparison

Aspect	Light Dependent Resistor (LDR)	Photodiode	Phototransistor
Operating Principle	Resistance decreases as light intensity increases	Converts light into current via the photoelectric effect	Combines a photodiode with a transistor for signal amplification
Response Time	Slow response to changes in light	Fast response time (microseconds to nanoseconds)	Slower than photodiodes but faster than LDRs
Sensitivity	High sensitivity to ambient light levels	Moderate sensitivity, better in low light conditions	High sensitivity due to internal current amplification
Common Applications	Automatic lighting, light-sensitive alarms	Optical communication, light meters	Infrared receivers, ambient light sensing, optical switches

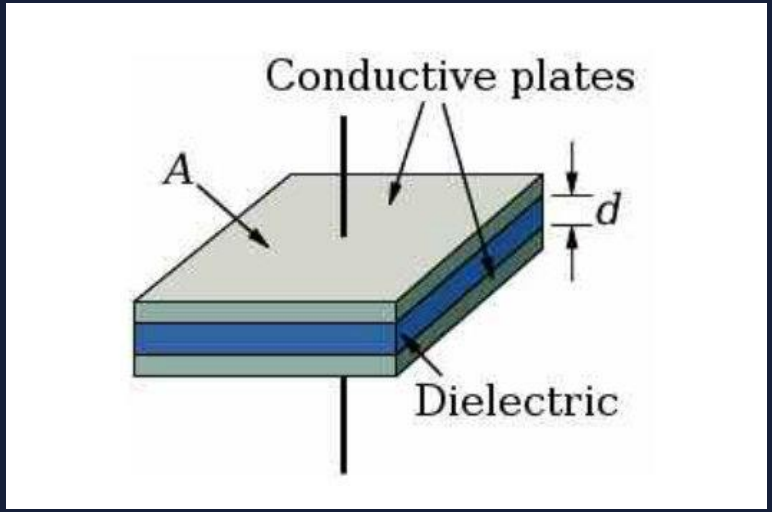
Humidity Sensors

- Humidity is the amount of water in the surrounding air.
- Absolute Humidity (AH): Absolute humidity is the ratio of the mass of water vapor to the volume of air, expressed in grams per cubic meter.
- Relative humidity (RH): Also measures water vapor, but RELATIVE to the temperature of the air. In other words, it is a measure of the actual amount of water vapor in the air compared to the total amount of vapor that can exist in the air at its current temperature.
- Types: Capacitive, Resistive, Thermal Conductivity.

Capacitive humidity sensors

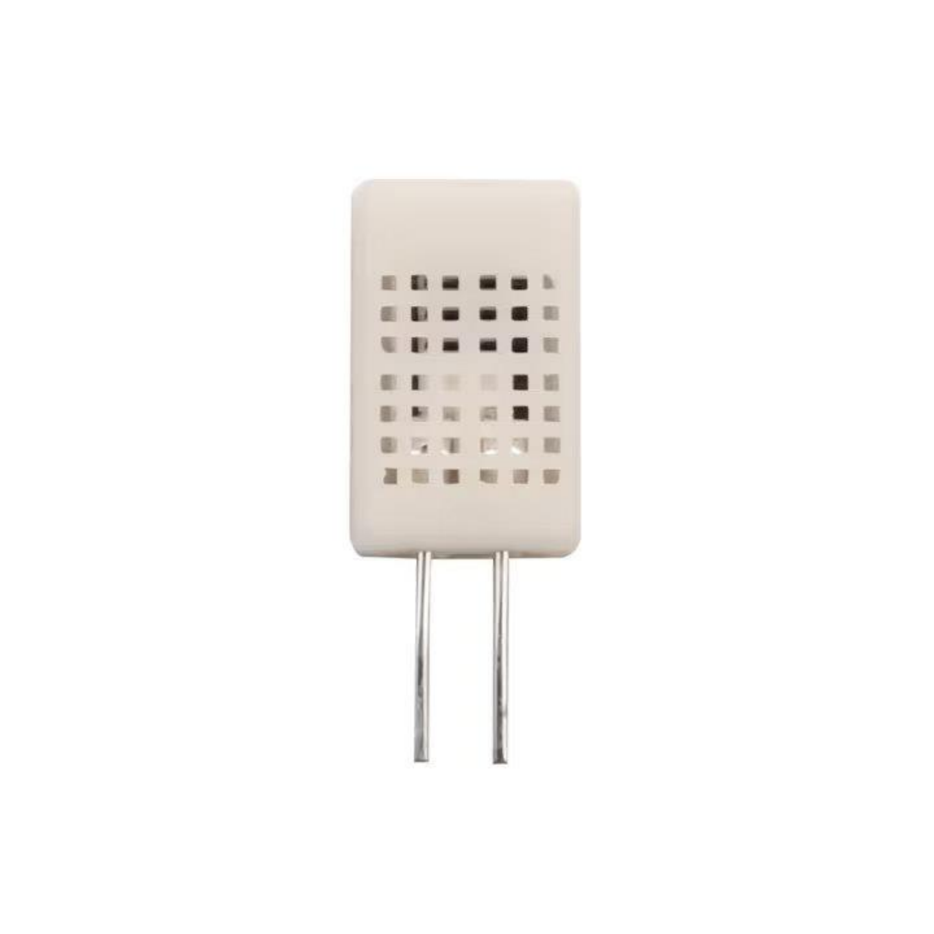
- The humidity sensor is a small capacitor consisting of a hygroscopic (water-absorbing) dielectric material placed between a pair of electrodes.
- Most capacitive sensors use a plastic or polymer as the dielectric material.

https://www.rotronic.com/en-us/humidity_measurement-feuchtemessung-mesure_de_l_humidite/capacitive-sensors-technical-notes-mr



Resistive humidity sensors

- A **resistive humidity sensor** measures the **humidity** of the air by detecting changes in the electrical **resistance** of a hygroscopic material.
- Both capacitive and resistive humidity sensors are measuring relative humidity.



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Thermal Conductivity Humidity Sensors

- The electrical conductivity of dry and wet air is different.
- These sensors measure the absolute humidity (AH) of the air.
- They contain a sealed dry air chamber (reference) and a vented chamber (measured).
- A thermal conductivity humidity sensor consists of two matched negative temperature coefficient (NTC) thermistors.
- As current passes through the thermistors, resistive heating increases their temperatures.
- The sealed sensor dissipates more heat than the exposed sensor, therefore the resistances will be different.

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Comparison table of humidity sensors

Aspect	Capacitive Humidity Sensors	Resistive Humidity Sensors	Thermal Conductivity Humidity Sensors
Operating Principle	Measures changes in capacitance as the dielectric constant changes with humidity.	Measures changes in electrical resistance of a hygroscopic material based on moisture absorption.	Measures changes in thermal conductivity of air due to water vapor content.
Response Time	Fast response time (typically in seconds).	Moderate response time (slightly slower than capacitive).	Relatively slow response time due to thermal mass.
Accuracy and Sensitivity	High accuracy and sensitivity over a wide humidity range.	Good sensitivity, though less accurate in very high humidity environments.	High accuracy in stable environments, but sensitive to temperature changes.
Common Applications	HVAC systems, industrial processes, consumer electronics.	Consumer electronics (humidifiers, dehumidifiers), weather stations.	Industrial drying systems, environmental monitoring, meteorology.

Gas Sensors

- A **gas sensor** is a device that detects the presence or concentration of gases in the air.
- It converts this information into an electrical signal that can be measured and analyzed.
- Gas sensors are used to detect hazardous gases in working or other environments (e.g. Carbon-monoxide, methane, propane).
- Types: Electrochemical, Semiconductor, Infrared, Catalytic.

Electrochemical gas sensors

- Detects gas by generating a current when the target gas reacts with the sensor's electrolyte.
- Main application area is toxic gas detection (CO, H_2S, SO_2).
- Usually they have internal temperature sensor for compensating the measured values.

Semiconductor-based gas sensors

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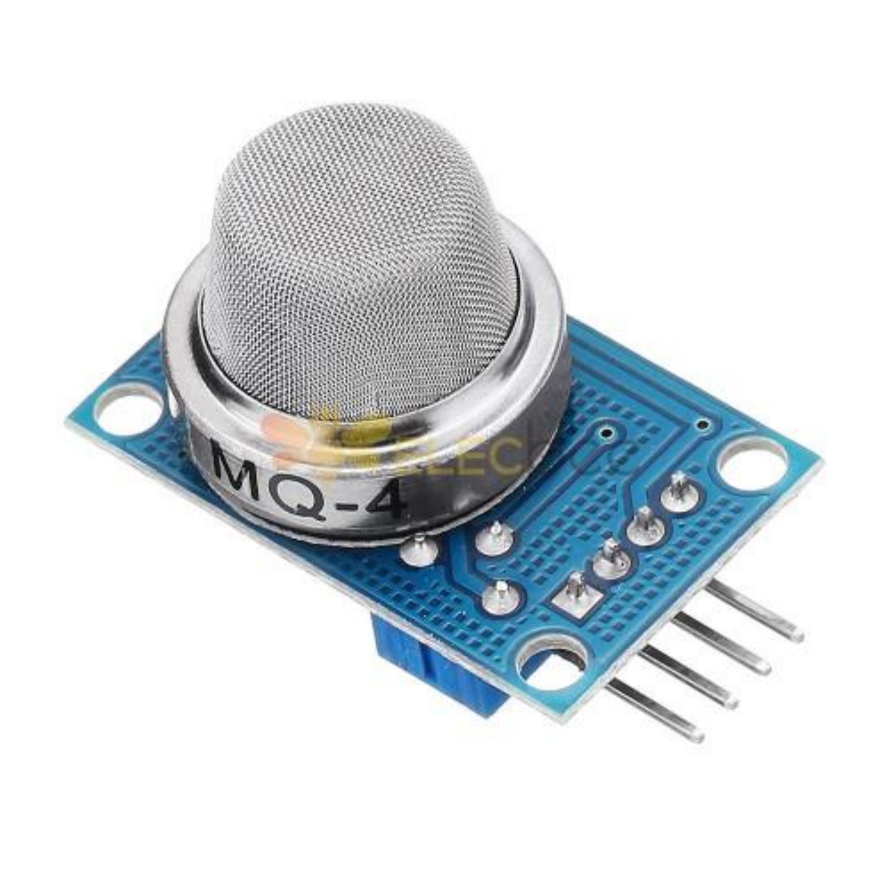
- Changes in resistance occur when gas molecules interact with a metal oxide semiconductor.
- Applications: household gas detectors (methane, propane), air quality monitoring.



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Infrared gas detectors

- Infrared gas detection is a method for detecting combustible hydrocarbon gas with infrared light.
- The detector consists of a source of infrared light, an optical filter to select the proper wavelength and an optical infrared receiver.
- It uses 3.4um infrared wavelength to detect hydrocarbon molecules.
- CO_2 molecules are behaving similarly, this method can be used for Co_2 detection.

Catalytic Bead Gas Sensors

- Detects combustible gases by measuring the heat generated during gas combustion on a catalytic bead.
- Used in industrial environments to detect flammable gases.

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Comparison table for gas sensors

Aspect	Electrochemical Sensors	Semiconductor Sensors	Infrared (IR) Sensors	Catalytic Bead Sensors
Operating Principle	Measures the current produced by a chemical reaction between the gas and electrolyte.	Changes in conductivity occur when gas interacts with a metal oxide semiconductor.	Detects gas by measuring the absorption of infrared light.	Measures heat generated by the combustion of gases on a catalytic bead.
Target Gases	Toxic gases (CO, H2S, SO2)	Combustible gases (CH4, propane)	CO2, CH4, hydrocarbons	Combustible gases (methane, propane)
Key Advantages	High selectivity and sensitivity for specific gases	Cost-effective and detects a wide range of gases	Non-contact detection	Reliable and robust for explosive gas detection
Common Applications	Industrial safety	Household gas detectors	Industrial gas detection	Gas leak detection, industrial safety

Sensor taxonomy by usage

- Sensors can be separated by the usage area:
  - Industrial Automation Sensors.
  - Robotics Sensors.
  - Environmental Monitoring Sensors.
  - Healthcare Sensors.
  - Automotive Sensors.
  - Smart Devices and IoT Sensors.

Industrial Automation Sensors

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- Industrial automation sensors include:
  - Temperature sensors.
  - Pressure and position sensors, used in manufacturing plants and automation systems.

Robotics Sensors

- Robotics sensors allow robots to interact with their environment, including:
  - Gyroscopes: Detecting rotation.
  - Accelerometers: Measuring acceleration.
  - Distance sensors: Detecting obstacles.

Environmental Monitoring Sensors

- Environmental monitoring sensors include:
  - Air quality sensors.
  - Humidity and temperature sensors, used in agriculture, climate control, and pollution monitoring.

Healthcare Sensors

- Healthcare sensors play a crucial role in monitoring vital signs such as:
  - Heart rate sensors.
  - Blood pressure sensors.
  - Glucose monitors.

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Automotive Sensors

- Automotive sensors ensure vehicle safety and efficiency, including:
  - Oxygen sensors for fuel efficiency.
  - Proximity sensors for parking assistance.
  - Tire pressure sensors for safety.

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Smart Devices and IoT Sensors

- IoT sensors are widely used in smart devices, including:
  - Smart thermostats detecting temperature and humidity.
  - Smart security systems using motion sensors.