Process automation

Sensing and Actuating Systems

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Octavian M. Machidon

octavian.machidon@fri.uni-lj.si

Outline

- Introduction to Sensing Systems
- Types of Sensors
- Signal Processing in Sensors
- Industrial Sensor Requirements
- Wiring and Interfacing Sensors
- Position Measurement Systems
- Introduction to Actuating Systems
- Types of Actuators
- Control and Safety
- Practical Applications

Sensing systems

- The basic element of a sensing (measurement) system is a sensor or transducer.
- **Examples:**
  - Position, speed, acceleration
  - Force, torque
  - Pressure
  - Temperature
  - Level
  - Flow
  - Material properties

Actuating systems

- **Structure:**
  - **Actuator**
    - Uses additional power supply to create mechanical movement, depending on the control signal.
  - **Final control element**
    - Mechanical movement causes a change in energy or mass flow in the system, carried out by the final control element (valve, damper).
  - **Position feedback**
    - Response to the control signal depending on the current position of the actuator.
- **Examples:**
  - Valve (fluid flow)
  - Damper (material flow)
  - Electric motor
  - Electro-hydraulic actuating system
  - Electro-pneumatic actuating system

Industrial conditions

- Easy installation and replacement
- Robust connections
- Temperature range:
  - **Commercial**: 0°C to +70°C
  - **Industrial**: -40°C to +85°C
  - **More demanding industrial**: -40°C to +125°C
- Mechanical resistance to shocks and vibrations
- Protection against electromagnetic interference
- Water protection

Industrial Conditions

- **IP Protection Levels (Ingress Protection)**
  - Standard EN60529
  - Two digits
  - Example: IP20, IP55, IP67

Level	Protection from contact with solid foreign objects	Protection from water
0	No protection	No protection
1	Ingress of solid foreign objects, diameter > 50 mm	Vertically falling water
2	Ingress of solid foreign objects, diameter > 12.5 mm	Vertically falling water (15° tilt)
3	Ingress of solid foreign objects, diameter > 2.5 mm	Against spraying water
4	Ingress of solid foreign objects, diameter > 1 mm	Against splashing water
5	Harmful dust deposition inside	Against water jets
6	Dustproof, complete protection against contact	Against powerful water jets
7		Short-term immersion
8		Long-term immersion

Sensor Characteristics

- **Accuracy**
  - How well the measurement matches the actual value of the quantity.
- **Precision**
  - Deviation of the measurement from the average value.
  - The measuring range of the instrument should be as well-suited to the range of measured quantities as possible.
- **Sensitivity**
  - Change in the reading due to a change in the quantity.
- **Resolution**
  - The smallest change in the input quantity that the sensor can detect.
- **Response Time**
- **Hysteresis**
- **Constant Deviation, Drift**
  - Uniform across the entire measuring range, can be corrected by calibration.
- **Scale**
  - Linear dependence of the measured quantity is preferred.
  - It can be quadratic, root-based, logarithmic.
  - Nonlinearity: deviation from the expected dependence (expressed as a percentage of the scale).

Signal processing

Digital Sensors

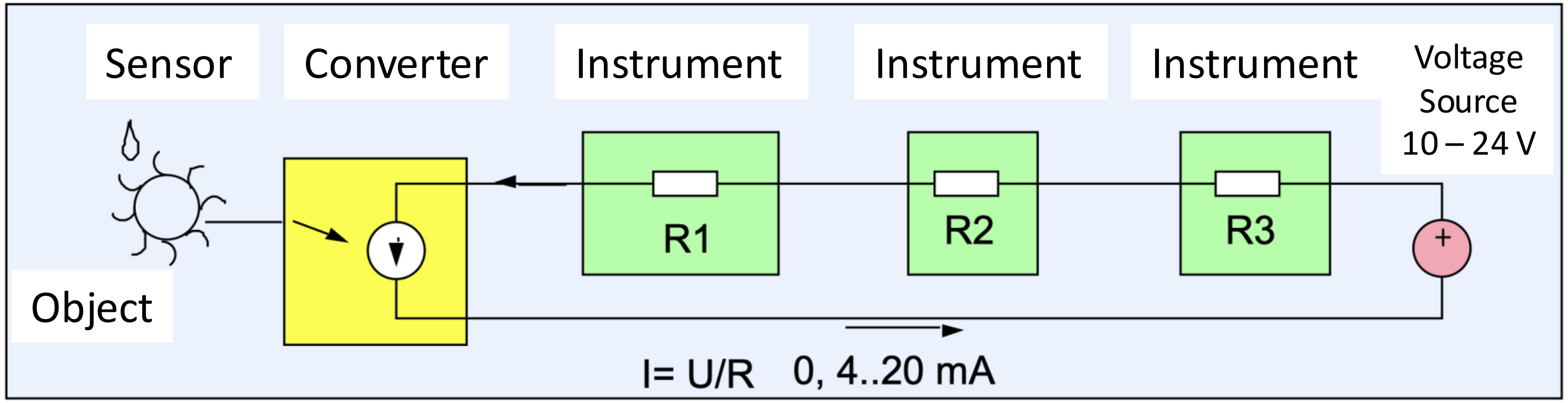
- **Data Acquisition**
  - Setting the operating range
  - Standard levels:
    - 24V relay contacts
    - Output 0..24V, 100mA
- **Processing**
  - Filtering 0..8ms filter
- **Reliability**
  - Deviations are rare

Analog Sensors

- **Data Acquisition**
  - Standardized signals:
    - 0/2..10V, 0/4..20mA
    - Resistive elements
- **Processing**
  - Filtering against 50-60Hz interference and higher harmonics
  - Scaling, linearization, averaging
  - Analog-to-digital conversion
- **Reliability**
  - Interval, limits, integrity
  - Error reporting, diagnostics

Wiring

- Why use 4 to 20 mA measurements?
  - Converters act as current sources, sending currents between 4 and 20 mA, proportional to the measured quantity.
  - The information is transmitted via current, so voltage drop on the wires does not cause errors.
  - Current < 4 mA signals a fault.
  - The number of series-connected loads is limited by the supply voltage.
  - Simple devices can be powered directly via the signal wires.



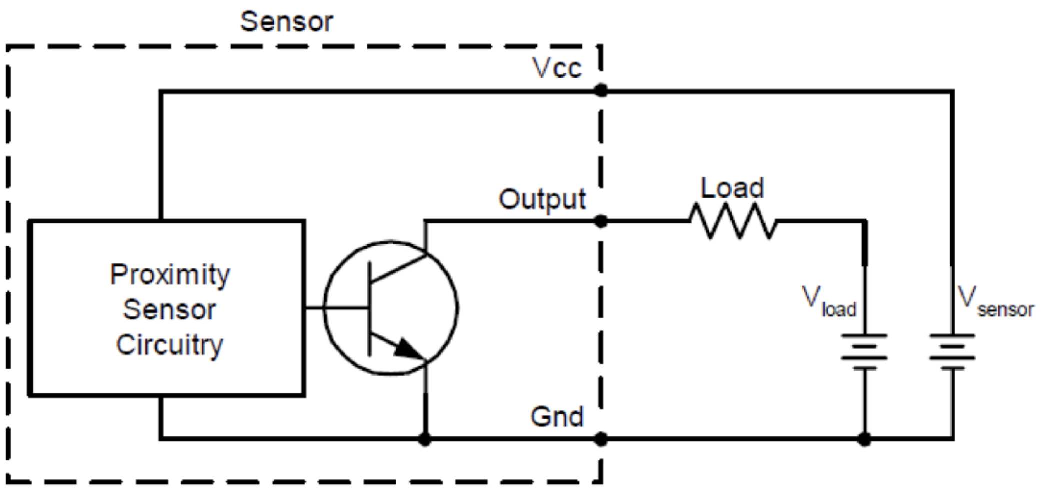
Wiring

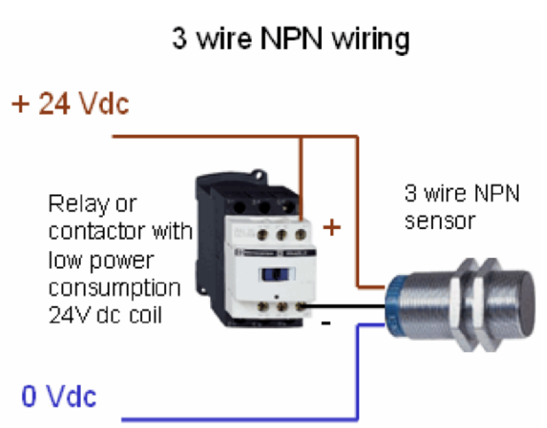
- **Sensor output:**
  - **Normally Open (NO) contact**
    - When the sensor is active, we have a logical 1 at the output.
  - **Normally Closed (NC) contact**
    - The output is always logical 1, which is lost when the sensor becomes active.
- **Type of sensor:**
  - Depends on the type of transistor used: **NPN** or **PNP**.
  - The sensor must be compatible with the input-output card.

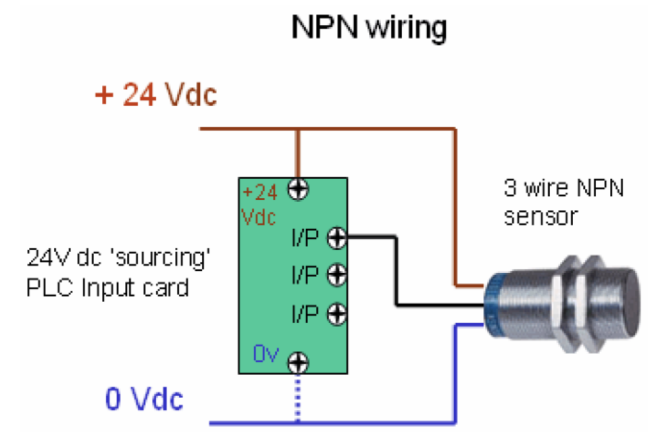
Wiring

NPN Type:

- With voltage at the base, we control the current from the collector to the emitter (indicated by the arrow).
- If the base is at a higher voltage than the emitter, current flows from the collector to the emitter.
- A small amount of current also flows from the base to the emitter.
- **System advantage:** The switching element can operate at a higher voltage than the sensor.
- **Less commonly used.**



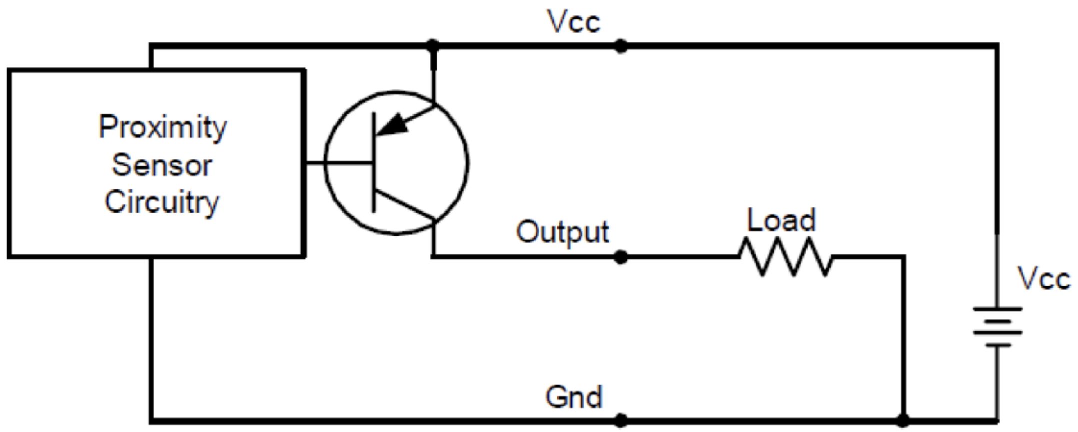


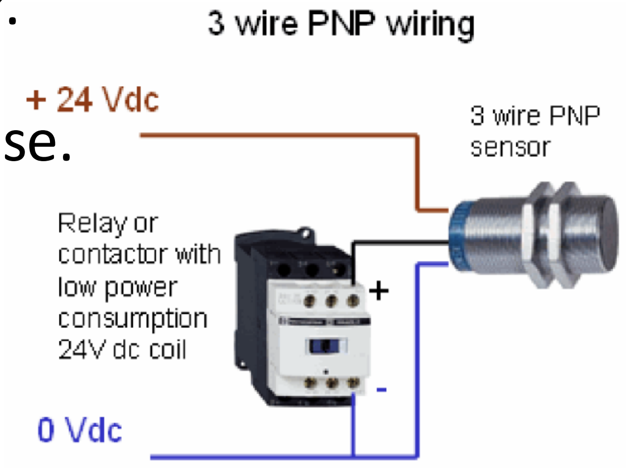


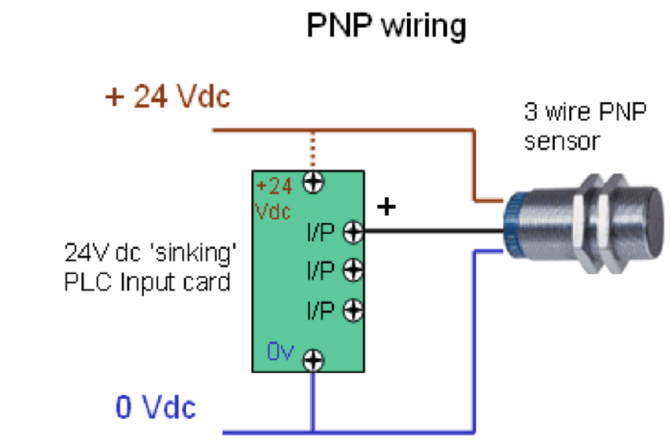
Wiring

PNP Type:

- With voltage at the base, we control the current from the **emitter** to the **collector** (indicated by the arrow).
- If the base is at a lower voltage than the emitter, the current flows from the emitter to the collector.
- A small amount of current also flows from the emitter to the base.
- **Simpler wiring**
- **Most commonly used**





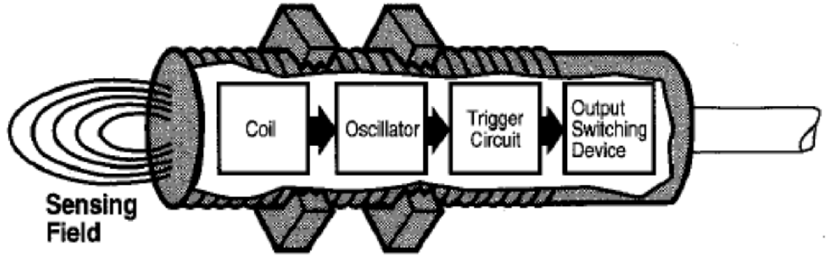


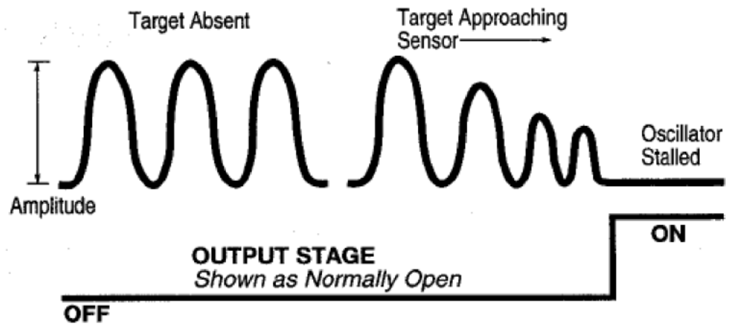
Position sensors

- **Digital Sensors:**
  - Mechanical sensors (limit switches)
  - Optical sensors
  - Magnetic sensors
  - Inductive sensors
  - Capacitive sensors
  - Ultrasonic sensors
- **Analog Sensors:**
  - Potentiometric
  - Capacitive
  - Ultrasonic
  - Transformer-based measurement
  - Optical encoder
  - Resistive strips
  - Piezoelectric sensors

Inductive Sensors

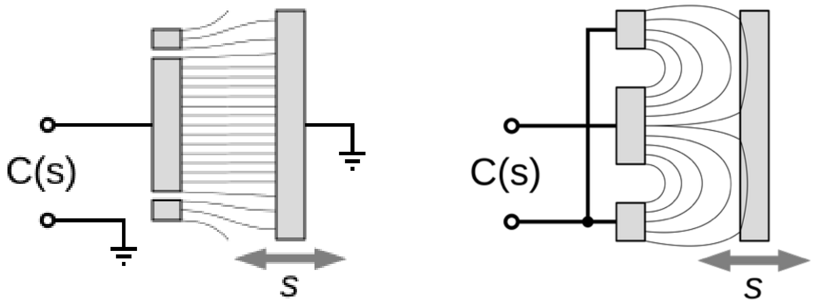
- **Idea:**
  - The inductance of the coil and electrical losses change when metal approaches the sensor.
- **Operating Principle:**
  - Oscillator vibrations create an alternating magnetic field (sensing field) on the coil.
  - The magnetic field extends from the plastic housing of the sensor.
  - When the sensor approaches a metallic object, the alternating magnetic field induces currents in the metal. These currents load the oscillator, reducing its amplitude.
  - When the amplitude drops below a certain threshold, the sensor output switches.

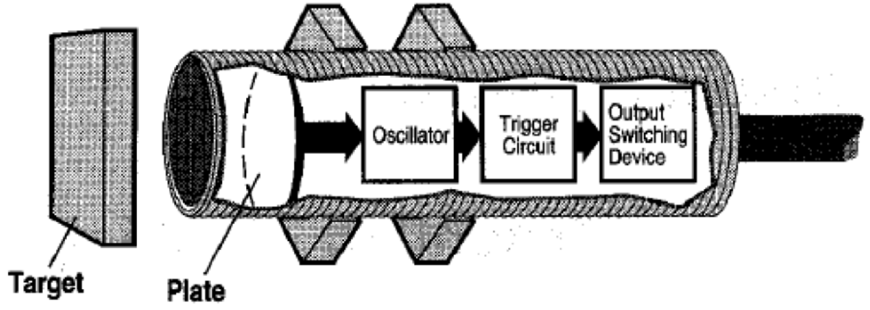


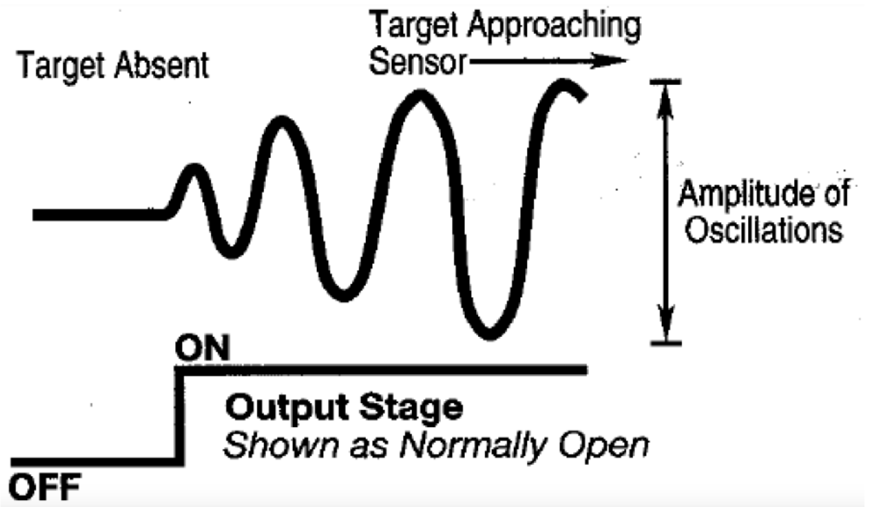


Capacitive sensors

- **Detect changes in the capacitance** of the capacitor in the sensor
  - Suitable for materials with high density
- **Two Types of Capacitive Sensors:**
  - **Conductive (Top Left)**
    - A single capacitor plate is in the sensor, while the object represents the other.
    - The object must be an electrically conductive material.
  - **Dielectric (Top Right)**
    - Two capacitor plates are placed side by side (open capacitor).
    - When an object approaches the capacitor, the change in dielectric increases the capacitance, which increases the amplitude of the oscillator.

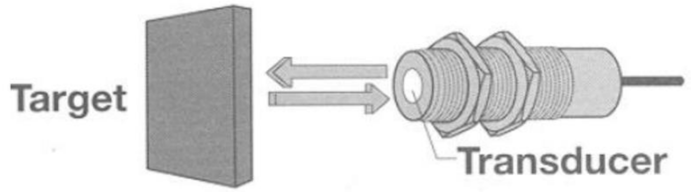


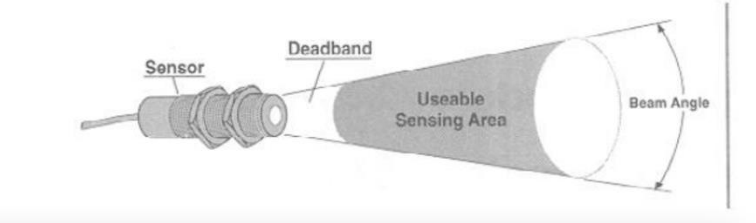




Ultrasonic Sensors

- **Operation:**
  - The sensor emits an ultrasonic signal.
  - If an object is in front of the sensor and within its range, the signal will bounce back to the sensor.
  - When the sensor detects the echo, it can calculate the distance to the object by measuring the time from emission to reception of the signal.
- **Limitations:**
  - **Dead zone at the beginning:** Until the signal is emitted, the receiver cannot start detecting.
  - **Wide angle:** As the object moves away from the sensor, the energy in the echo diminishes, limiting the sensor's maximum range.



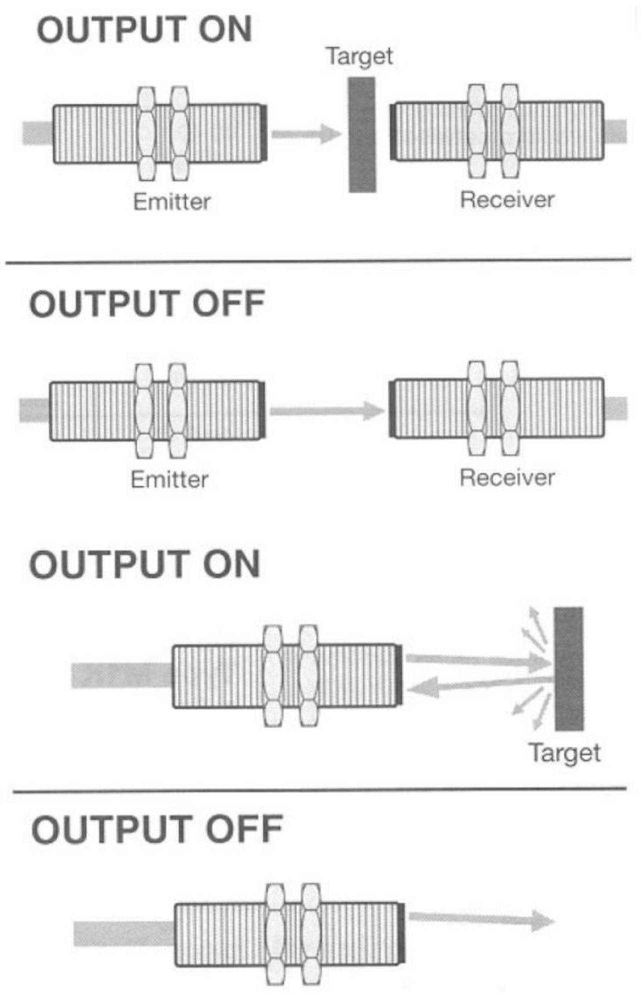


Optical sensors

- **Very popular**
- They detect light, allowing them to sense a wide variety of objects, except for transparent ones.
- Unlike ultrasonic sensors, they work in a vacuum and have a much narrower beam.
- **Different wavelengths of light**:
  - Bulbs with red filters, red LEDs, infrared LEDs, laser beams.
- Emit light in pulses at high frequency; the receiver is tuned to this frequency, eliminating any potential interference from sunlight on the sensor's operation.

Optical sensors

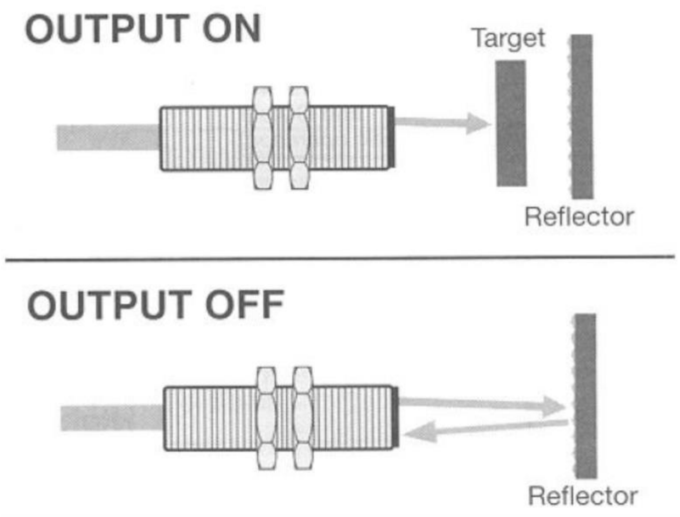
- **Three types:**
  - **Separate emitter and receiver:**
    - Wide operational range.
    - The receiver and emitter are wired separately.
- **Emitter and receiver in the same housing (diffuse-reflective):**
  - Responds to light reflected from the object.
  - Performs poorly on transparent objects or objects where light reflects poorly (e.g., black surfaces).
  - Objects should not have holes, and the surface should be as smooth as possible.
  - **Background suppression:** By adjusting the lens position, we can limit the sensing range.

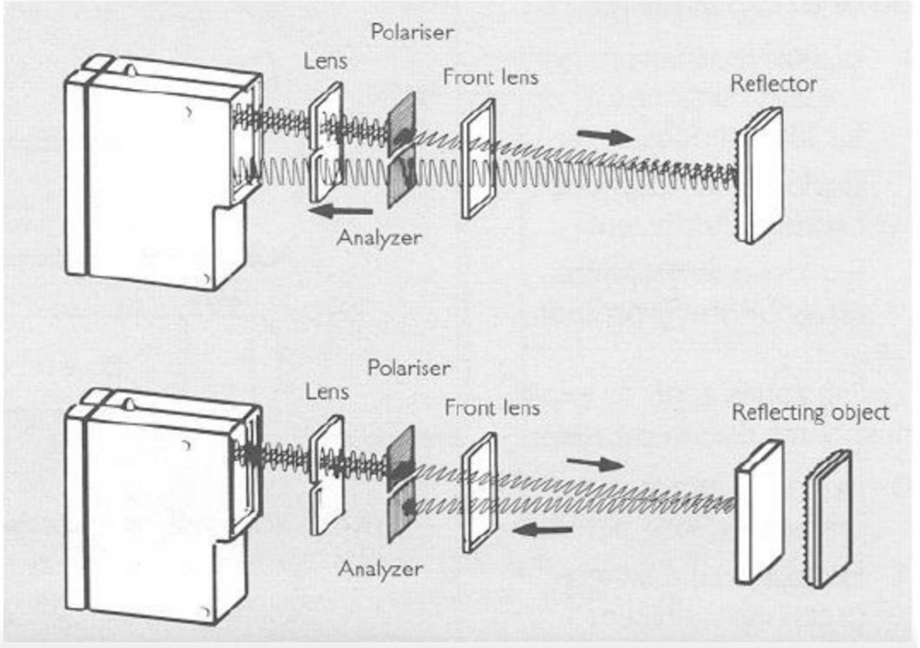


Optical sensors

Three types:

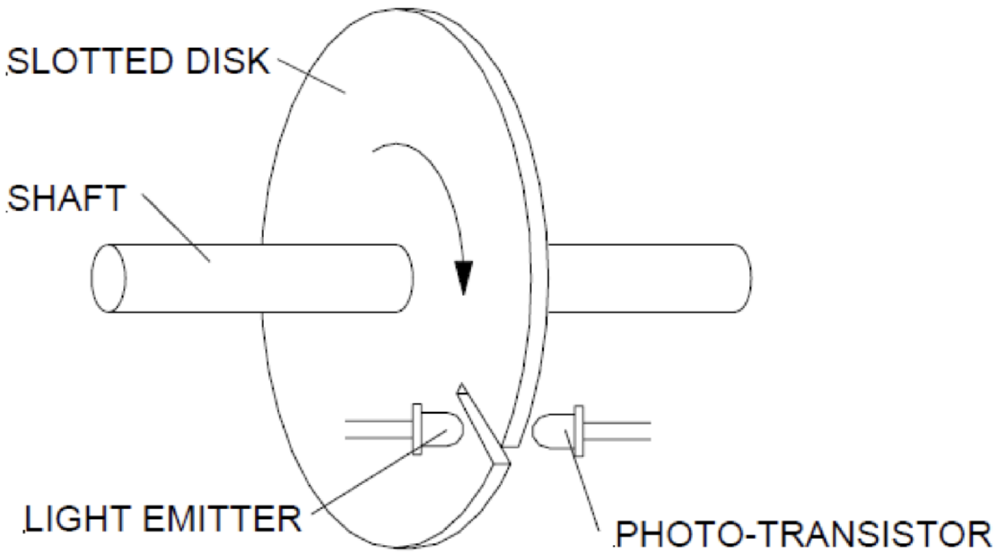
- **Emitter and receiver in the same housing, with a reflector on the opposite side (retro-reflective):**
  - Only the reflector is on the other side.
  - Most complex – ensures no issues with highly reflective objects, as the light is polarized.
  - The receiver and emitter use polarization filters, rotated 90 degrees. The reflector is designed to rotate the light's polarization direction by 90 degrees.
  - **If the light reflects off an object**, the polarization does not change, and the polarized light does not reach the receiver.





Position: optical encoder

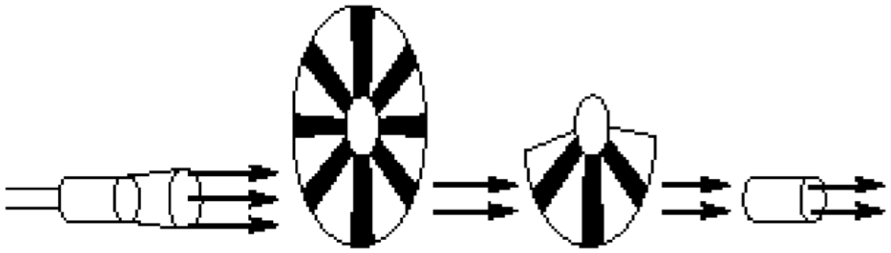
- **Optical pulse generator or encoder**
- **Basic idea: a disk with a slot**
  - Can be used to set the basic position of the machine (homing).
  - Only one measurement per rotation.



Position: optical encoder

Principle:

- **Components:**
  - Directed light source,
  - Slotted disk (transparent | non-transparent),
  - Mask with an inverse pattern,
  - Detector.



- The disk rotates and interrupts the light beam.
- The directed light source and mask are designed for more accurate readings.
  - Only when the transparent areas of the disk and mask align does the light beam reach the detector.

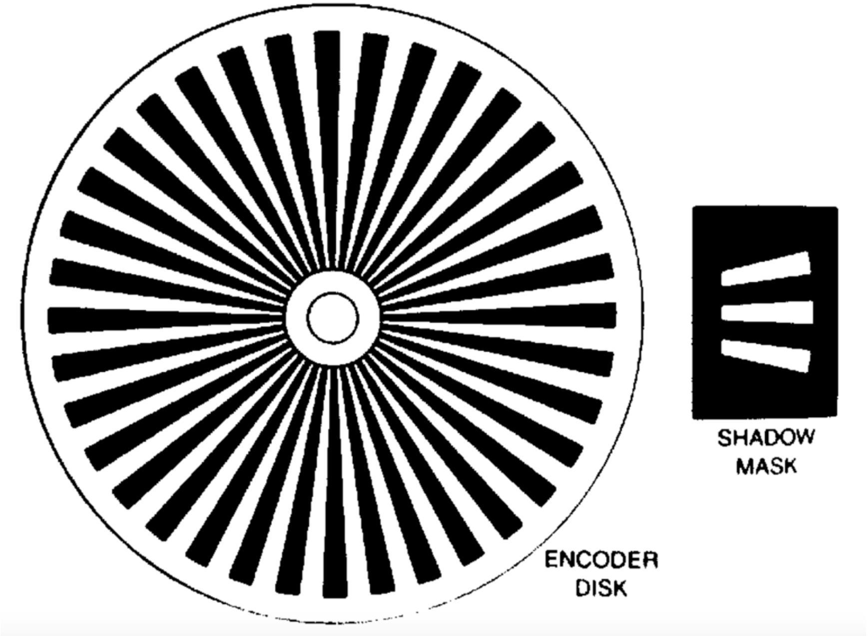
Types:

- **Incremental Encoder:**
  - Generates a pulse for a specific movement, the total movement is determined by summing the pulses.
  - System referencing is necessary during power-up.
- **Absolute Encoder:**
  - The encoder remembers its position even after the system is turned off.

Position: optical encoder

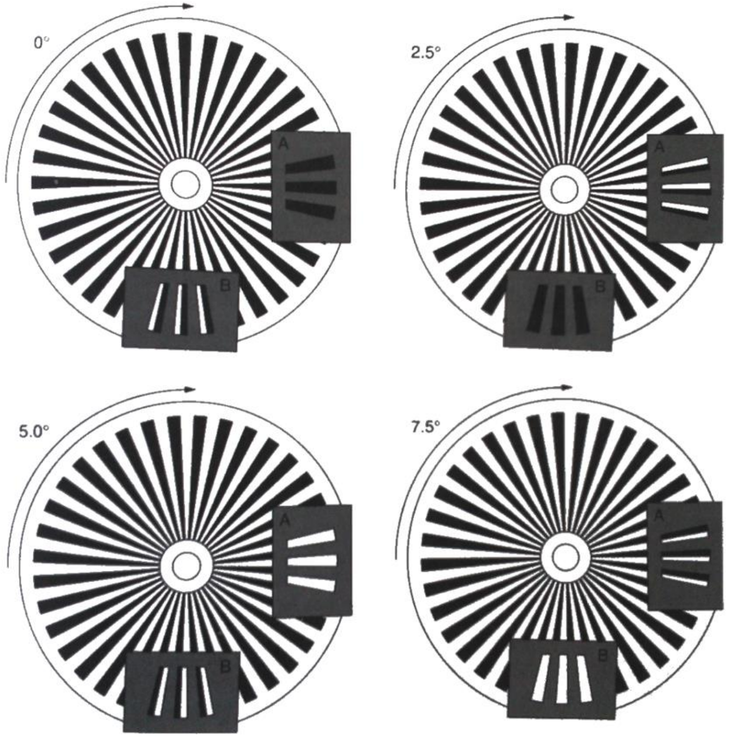
Incremental Optical Encoder

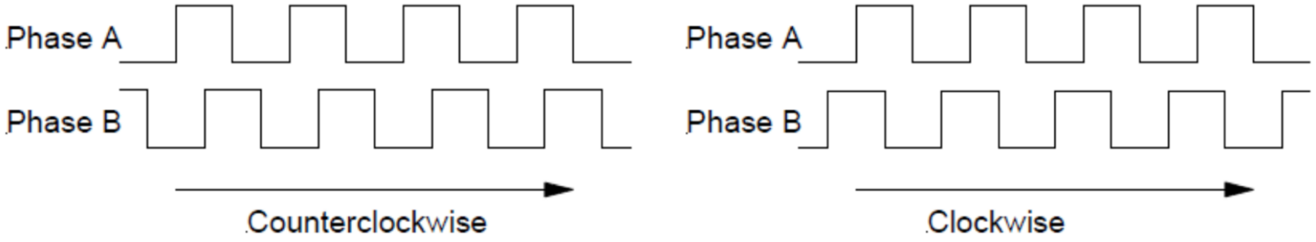
- A disk where dark and transparent areas alternate frequently.
- Since the areas are very close together, it's difficult to accurately align the optical receiver and transmitter, so a mask is used.
- It can generate between **1024 to around 10,000 pulses per revolution**.
- It only detects **relative changes** and not the **absolute position**.
- It can determine the **direction of rotation** (next slide).



Position: optical encoder

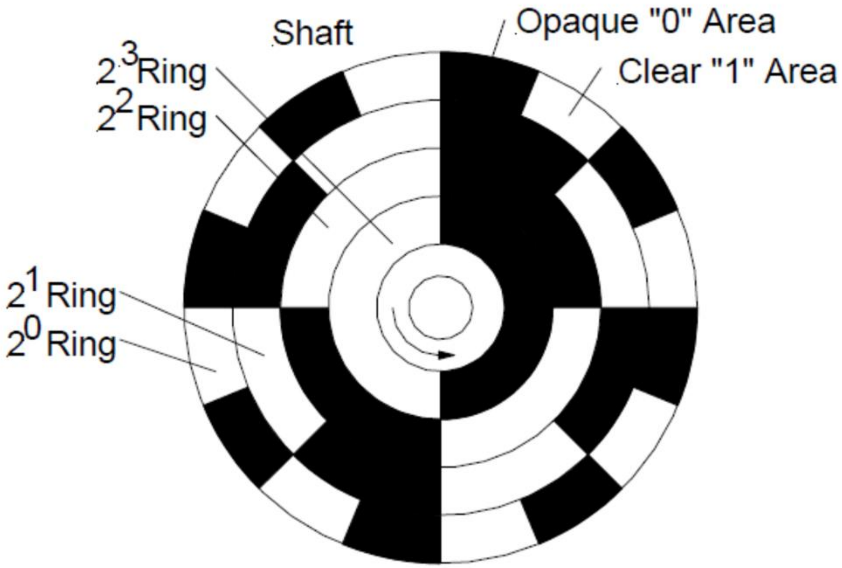
- **Incremental Optical Encoder**
  - Typically, two masks are used, shifted by ¼ of a period – when mask A is fully covered, mask B is half covered.
  - **The direction of rotation:**
    - **A overtakes B**
      (rotation counterclockwise)
    - **B overtakes A**
      (rotation clockwise)





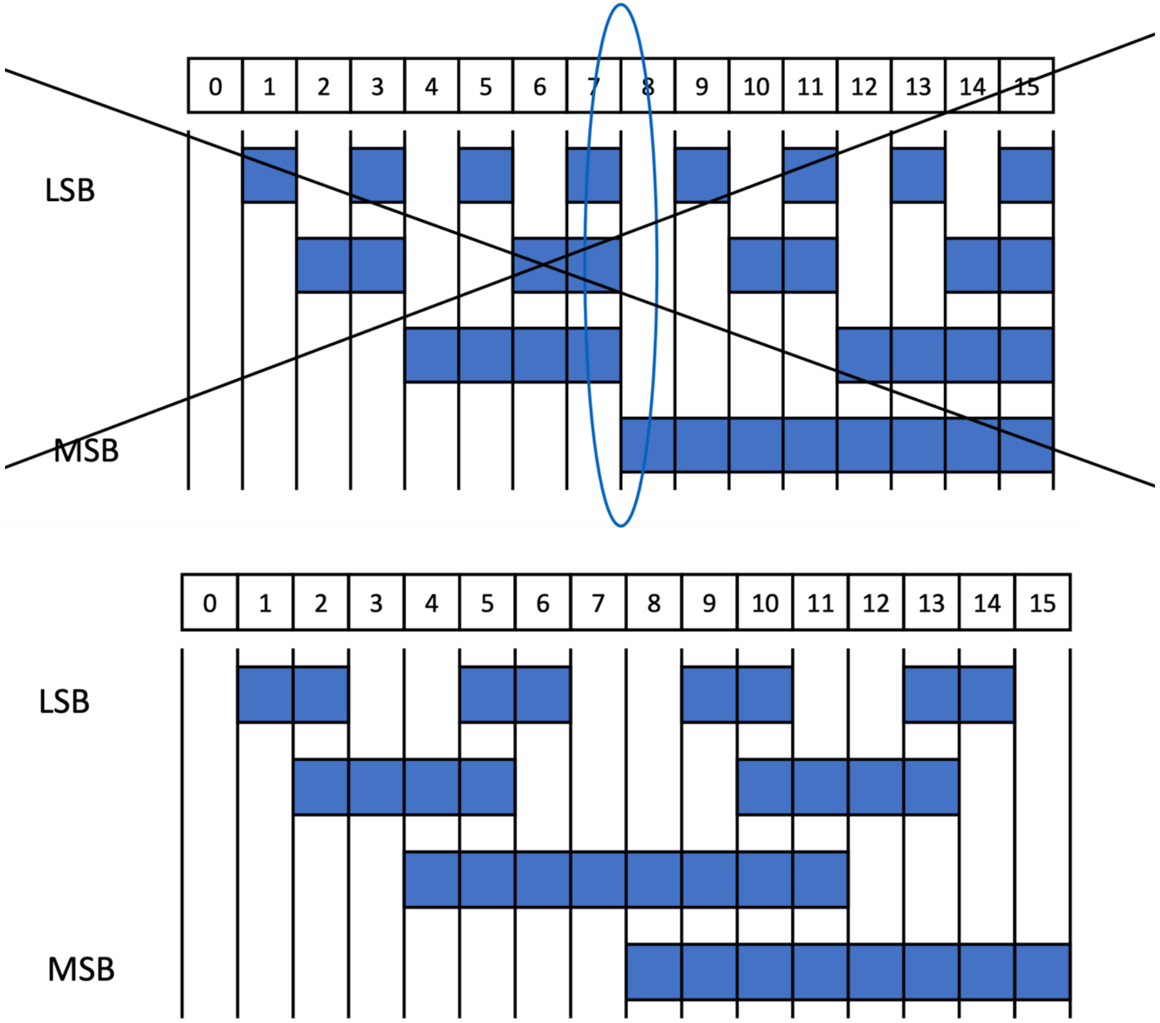
Position: optical encoder

- **Absolute Encoder**
  - Remembers its position even when powered off.
  - Encoding pattern on the disk: binary or Gray code.



Position: optical encoder

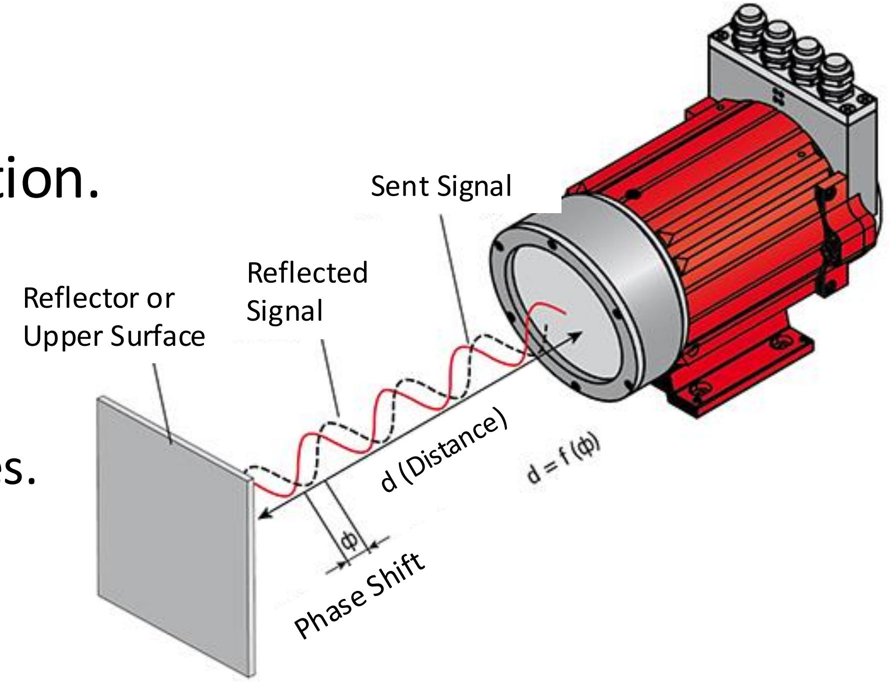
- **Absolute Encoder**
  - Encoding pattern on the disk: binary or Gray code
- **Binary Code**
  - We cannot ensure the simultaneous switching of all sensors.
  - During transitions between states, the value may jump to an unintended intermediate state.
  - Example: 7 → 15 → 8
  - An additional signal is needed to indicate when the value is unreliable.
- **Gray Code**
  - Only one bit changes, values do not jump.



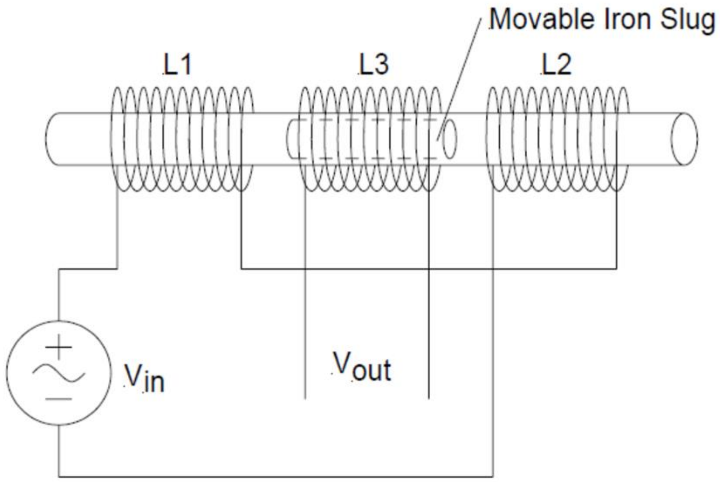
Position: laser

Principle of Phase Shift

- The strength of the emitted signal is sinusoidally modulated.
- Measurement of the phase difference between the received and emitted signals.
- Phase shift: $\phi \propto d \cdot f\_Modulation$
  - The higher the frequency, the greater the resolution.
  - Periodic change in phase shift:
    - The phase shift period is large.
    - The range is increased by taking two measurements at different modulation frequencies.



Position: transformer-based measurement



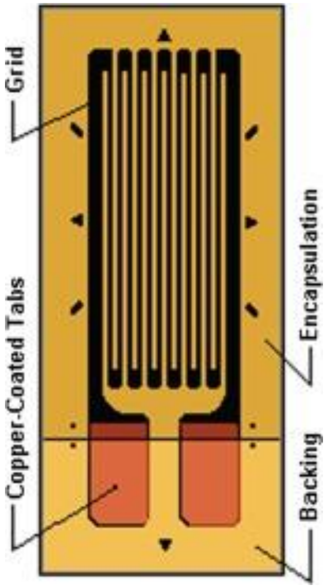
- **Three Coils**
  - **Primary (L1, L2):** They are fixed, and an alternating current flows through them in opposite directions.
  - **Secondary (L3):** It moves.
- **Idea**
  - **L1 and L2** create an equally strong magnetic field, but in opposite directions. As a result, the magnetic field cancels out in L3, which means there is no voltage in L3.
  - If **L3** is slightly moved toward **L2**, due to the change in the magnetic field in L3, a voltage is induced that is in phase with the voltage on L2.
  - Any further movement toward **L2** linearly increases the voltage in **L3**.

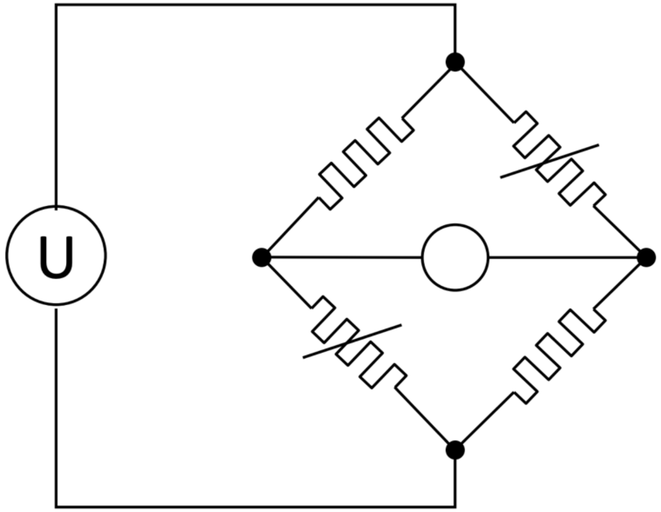
Force

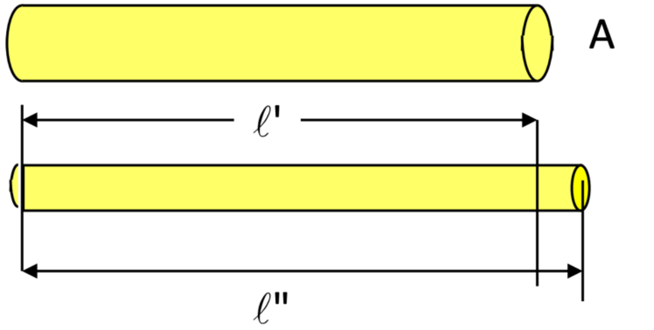
- **Force, Torque, Weight, Pressure**
    - **Measurement of small displacements,** $F=k \cdot x$
    - Strain gauges
    - Piezo-electric transducers
- **Accelerations**
    - Similar to force, measuring small displacements of mass, $F=m \cdot a$

Force: strain gauges

- The resistance of the wire increases with stretching
- Temperature compensation
  - Wheatstone bridge
- Common usage: buildings, bridges, dams





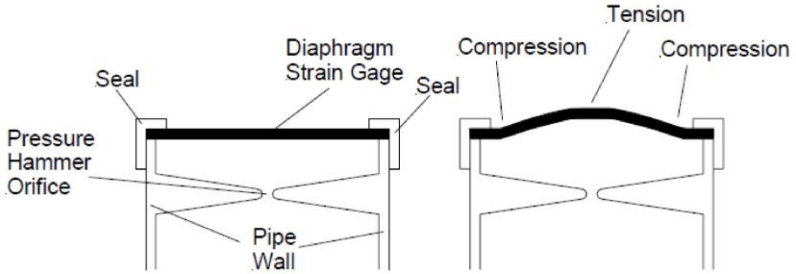


$$R = \rho \frac{\ell}{A} = \rho \frac{\ell^2}{V}$$

V - volume, ρ - constant

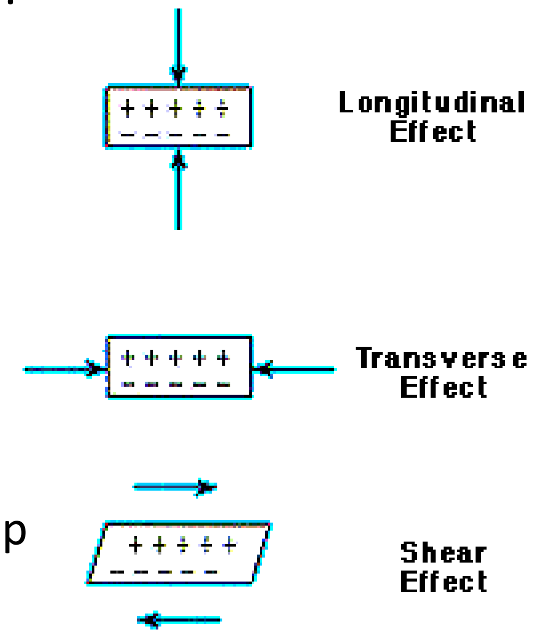
Force: strain gauges

- **Measuring Diaphragm**
  - Cyclically shaped strain gauges
  - When force (pressure) acts on the diaphragm, it stretches in the center and contracts at the edges
  - Connecting the edge and central parts to different points in a Wheatstone bridge strengthens the signal and improves measurements



Force: piezoelectric converters

- **Main Concept:**
  - **Piezoelectric crystals** generate an electric field when they undergo deformation. This can occur through various types of strain, such as:
    - **Longitudinal** (along the axis of force)
    - **Transversal** (perpendicular to the force)
    - **Shear** (sliding force).
- **Static Measurements:**
  - For static measurements, **charge loss** results in a **drop in voltage** over time, which is a characteristic of piezoelectric materials when subject to a constant force.
- **Exceptional Properties:**
  - **High-pressure resistance**: The piezoelectric materials can withstand pressures up to **100 MPa**.
  - **Temperature resistance**: These materials remain functional in environments up to **500°C**.
  - **Nearly constant scale**: They maintain a consistent response across a wide range of temperatures, making them highly reliable for precision measurements.



Temperature

The most frequently measured quantity in industry

Methods of measurement:

- **Bimetal**:
  - Mechanical, discrete, exploits the different thermal expansion of two metals
  - **+** Very cheap, widely used
- **Resistance Temperature Detector (RTD)**:
  - The resistance of the metal increases with temperature
  - **+** Price, robustness, wide temperature range
  - **-** Requires a current source, linearization
- **Thermistor**:
  - The resistance of a semiconductor depends on the temperature
  - **+** Price, sensitivity, wide range, current source
  - **-** Nonlinearity
- **Thermocouple**:
  - Different metals, the voltage is proportional to the temperature difference between the hot and cold junctions
  - **+** Accuracy, high temperatures, point measurement
  - **-** Low voltage, linearization
- **Spectrometer**:
  - Measures IR radiation from appropriate surfaces
  - **+** Highest temperatures, surface temperature, non-contact
  - **-** Price

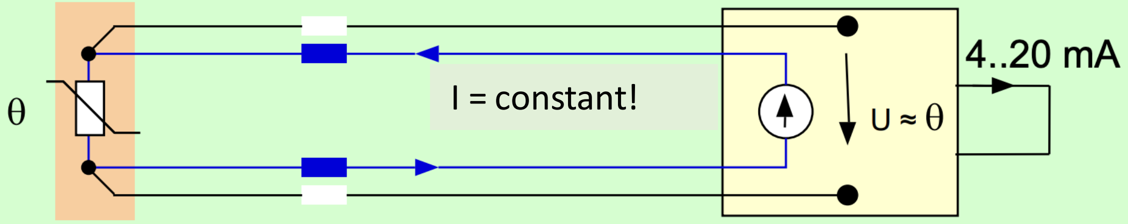
Temperature

- Connection of thermoresistor/thermistor and thermoelement

Thermistor

Material whose resistance depends on temperature

Platinum (Pt 100): resistance of 100 ohms at 0°C

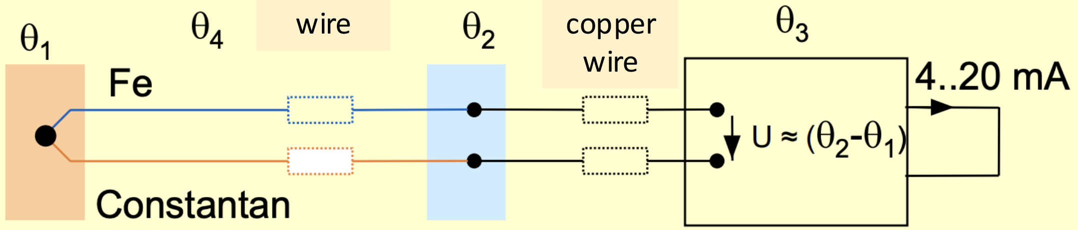


4-wire connection (compensation of voltage drop)
2-wire sensor connection is used in combination with a Wheatstone bridge

Thermocouple

Two metals with different electrical conductivities

Fe-Constantan (Cu/Ni)
Pt/Rh - Pt

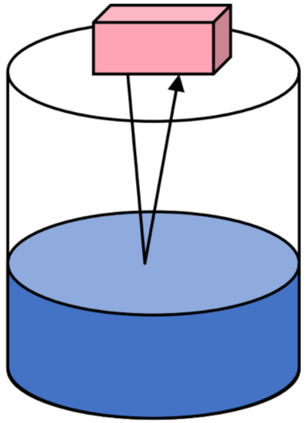


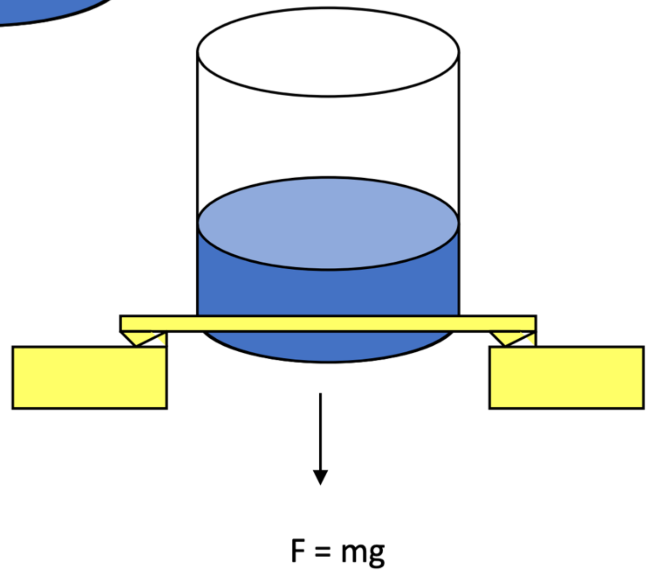
Measured temperature (hot junction)

Reference temperature (cold junction)

Liquid level

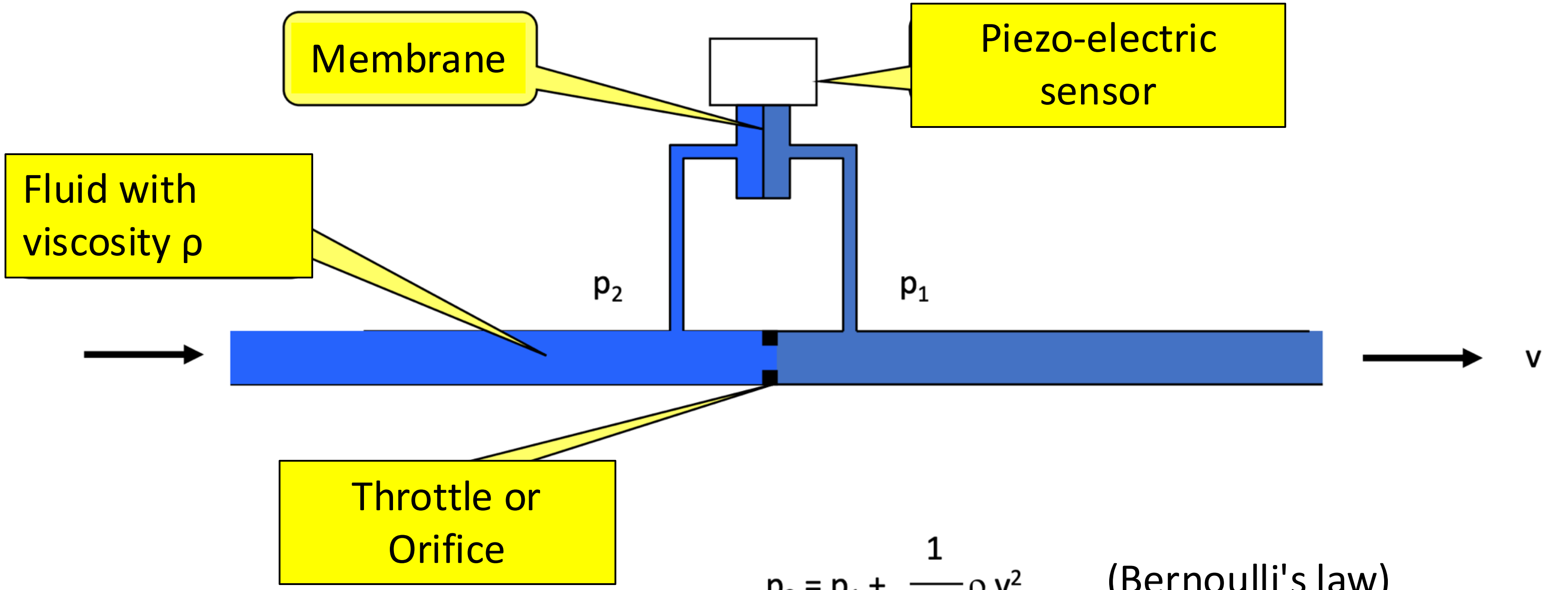
- Pulsed Laser
- Pulsed with Microwaves
- Ultrasonic
- Load Cell (Strain Gauge)
- Capacitive (Non-conductive Liquid)
- Mechanical: Float





Fluid Flow Rate

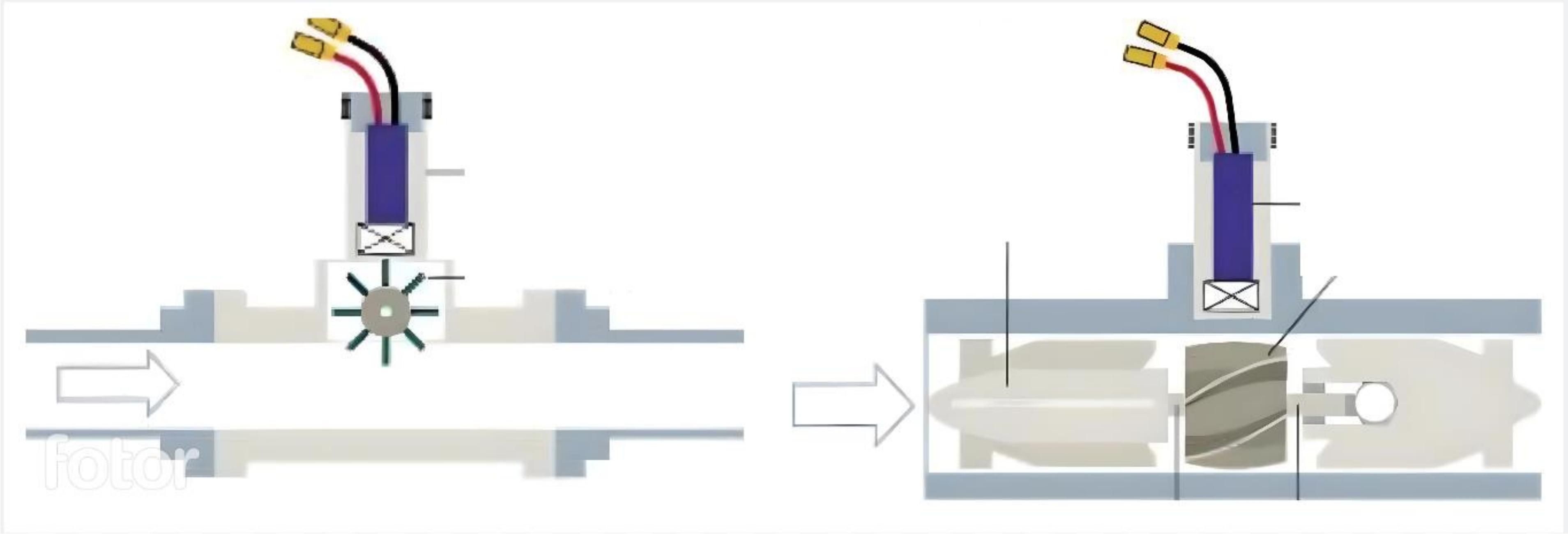
- Measurement of pressure difference



$$p_2 = p_1 + \frac{1}{2} \rho v^2$$ (Bernoulli's law)

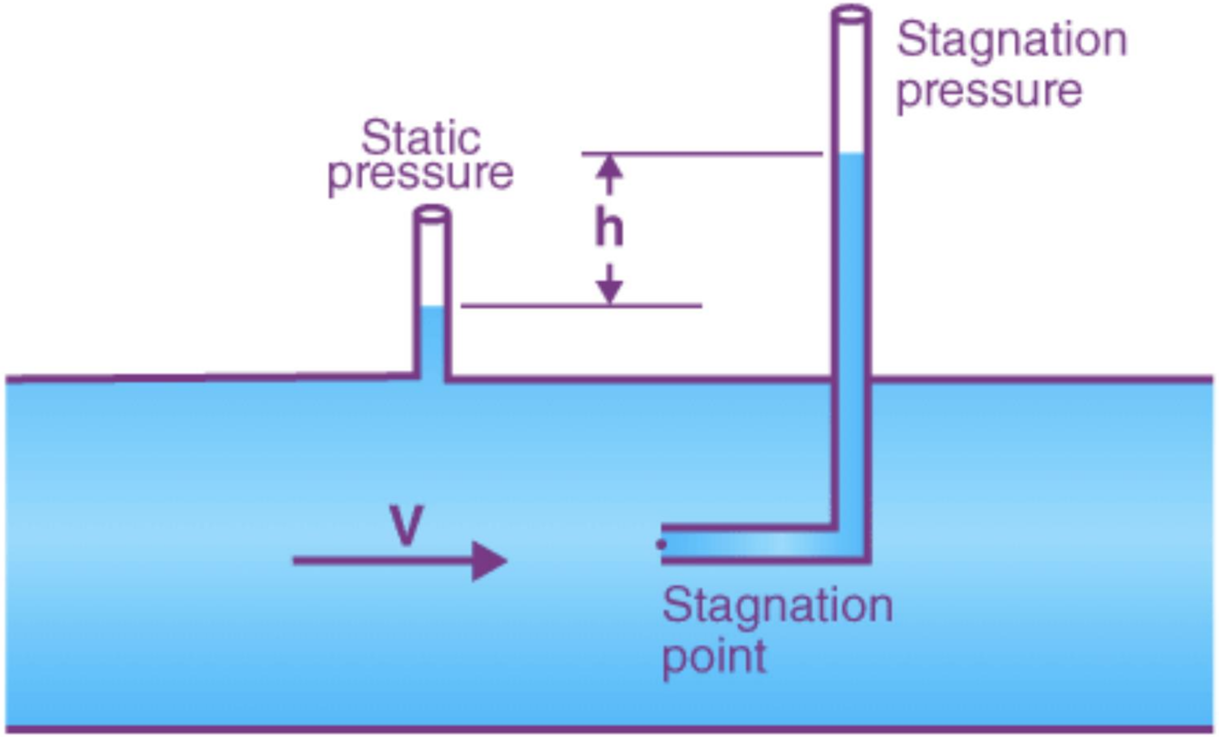
Fluid Flow Rate

Water Wheel **Turbine Meter**

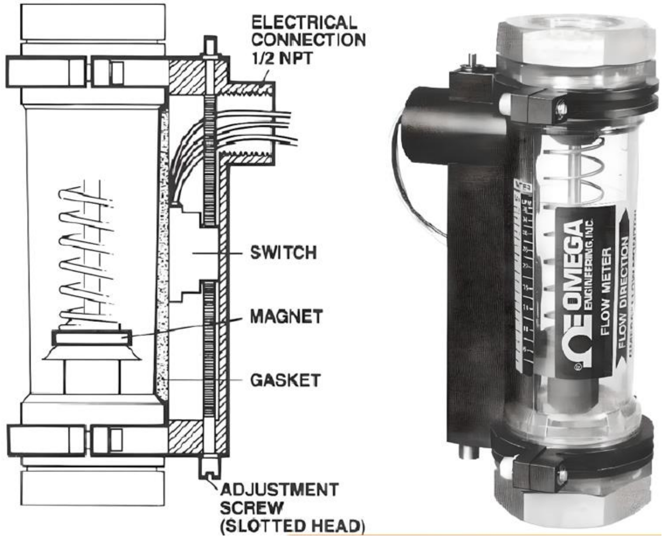


Fluid Flow Rate

- Pitot Tube



Fluid Flow Rate



- **Flow Sensor with Magnetic Switch**
  - It activates when the set value is reached.
  - An obstacle is placed inside the pipe.
  - If the fluid deflects the obstacle enough, the sensor is activated.
- **Thermal Flow Sensor**
  - Measures how much heat the fluid removes from the heater placed in the pipe.
  - Two probes:
    - One is not heated – **reference**, for temperature compensation of the fluid.
    - The other is heated – for determining the speed.
  - Great: no mechanical parts, it doesn't get dirty, suitable for impure fluids.

Actuating Systems

- "Hands" of the control system:
  - Cause changes in energy or material flow in the process.
  - Convert information in the form of standardized signals into appropriate changes in the process.
- Represent 10% of elements in the field.
- Can be binary or analog.
- Controlled by the same electrical signals as sensors, but with much higher power:
  - 4..20 mA, 0..10 V, 0..24 V, ...
- Typical representatives:
  - Electrical contactors and relays
  - Heating elements
  - Pneumatic and hydraulic elements
  - Electric motors

Contactors and Relays

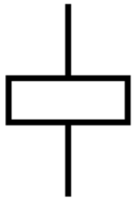
- Electric current flowing through the relay moves the core in the electromagnet, and with the core, also the contacts.
- Difference:
  - Relays are smaller, suitable for lower currents.
  - Contactors have more secondary contacts.
- The oldest method for executing logical functions.
- Today, they are mainly used to adjust voltage and current levels.

Contactors and Relays

- Labelling of relays in diagrams:
  - Normally open contact (NO)

  - Normally closed contact (NC)

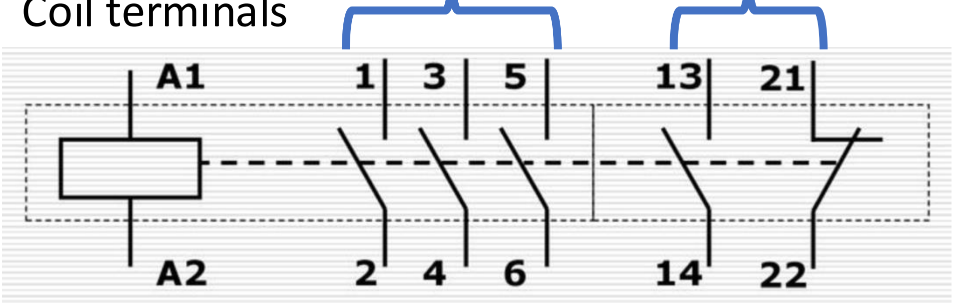
  - Coil



Main contacts

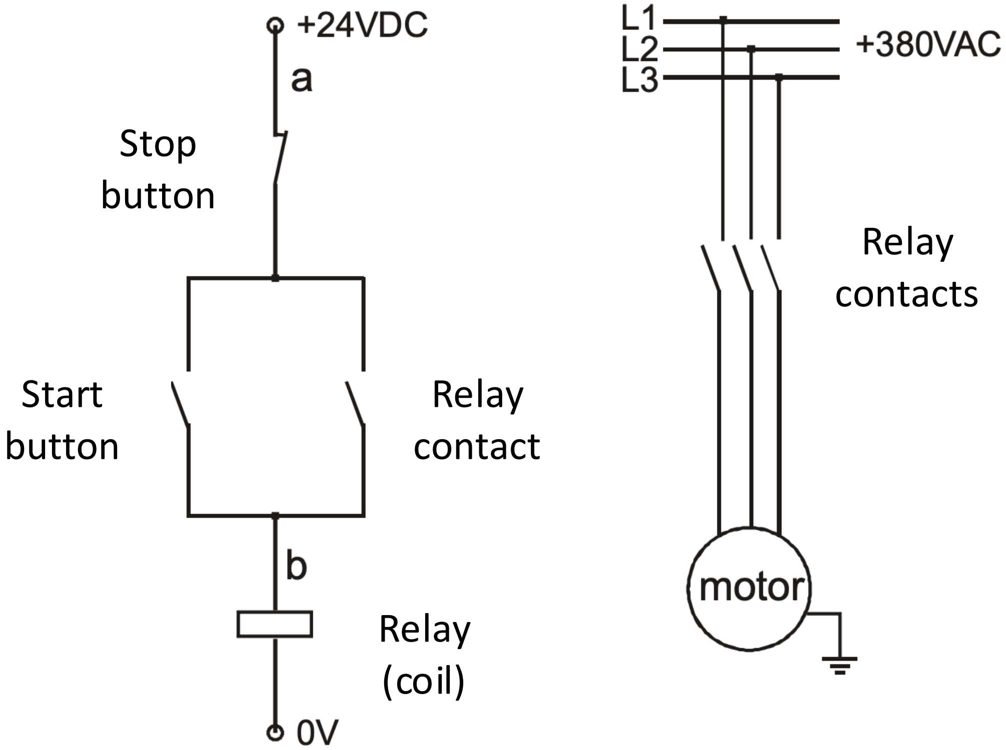
Auxiliary contacts

Coil terminals



Example of usage:

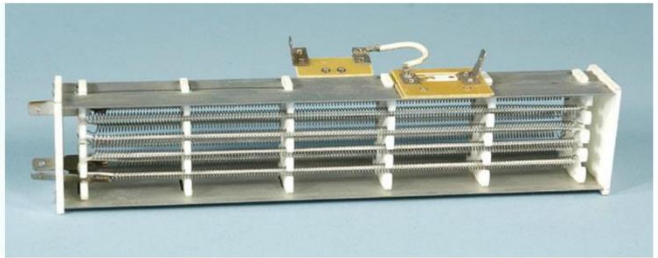
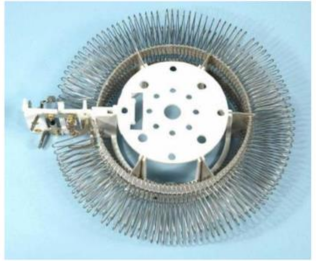
- The motor starts running when the "start" button is briefly pressed.
- The motor stops when the "stop" button is briefly pressed.



Heating elements

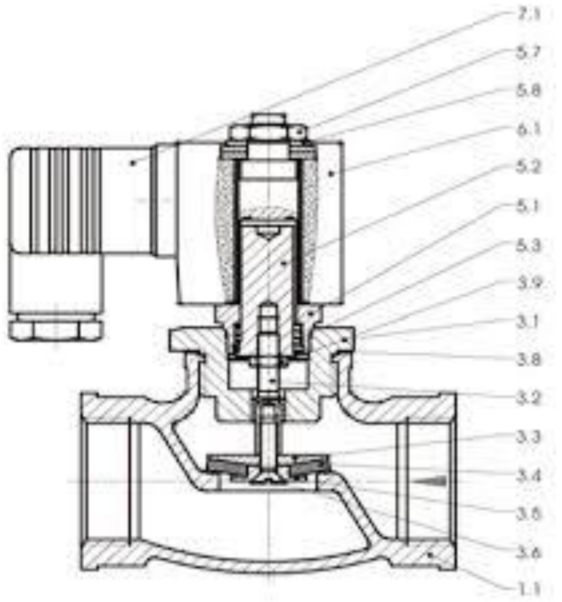
Conversion of electrical energy into heat

- Heating wire
  - Due to the resistance of the material, it heats up when electrical current flows through it.
- Indirect system: heating of a medium, which then heats the devices.


Pneumatic and Hydraulic Elements

- Electromagnetic Valve
- Opening the valve:
  - Electric current flows through the coil winding (6.1), creating a magnetic field.
  - The magnetic field pulls the core (5.2), and along with it, the seal (3.4) moves into the coil.
  - The fluid is free to flow.
- Closing the valve:
  - When the electric current stops flowing through the winding, the fluid itself pushes the seal down and blocks the path.



Electric Motors

Direct Current (DC) Motors (1832):

- Simple change of rotation speed by varying voltage or current.
- Today used where high torques are needed.

Alternating Current (AC) Motors (1888):

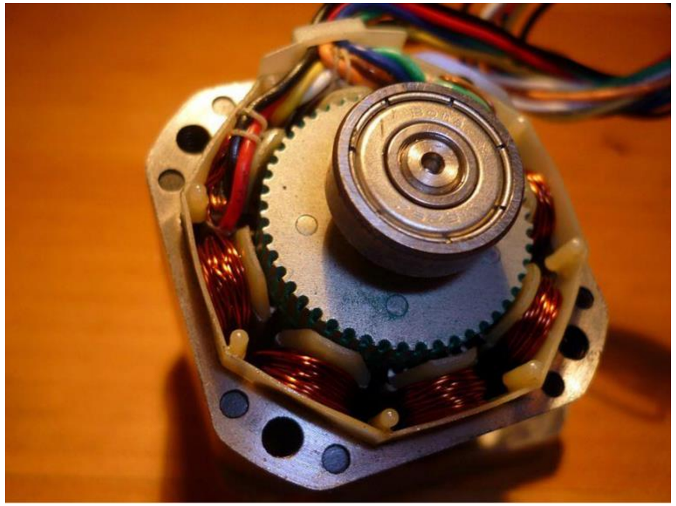
- In the past: rotation frequency was determined by the network frequency, for example, 50 Hz → 2900 rotations per minute.
- Today: increasingly popular, especially with frequency converters that allow the frequency to be changed at will.
- Asynchronous | Synchronous Motors:
  - **A**: Rotor rotates asynchronously with the magnetic field, intentionally lags behind.
  - **S**: Rotor is powered, and the magnetic field matches, with no lag behind the field.

Servo Motors:

- Have an added optical encoder for feedback loops.
- Designed for precise positioning.
- Low rotor inertia → rapid changes in dynamics.

Electric Motors

- Stepper Motors
  - The rotor only rotates once when the control state of the stator is changed.
  - Used in Robotics.
  - Operation
    - The rotor is shaped like a gear.
    - Surrounding it is a set of magnets.
    - When an individual magnet is activated, it pulls the rotor and aligns it with the magnet, causing the rotor to rotate slightly.
    - The magnets are slightly offset, so the activation of the next magnet rotates the rotor slightly again…

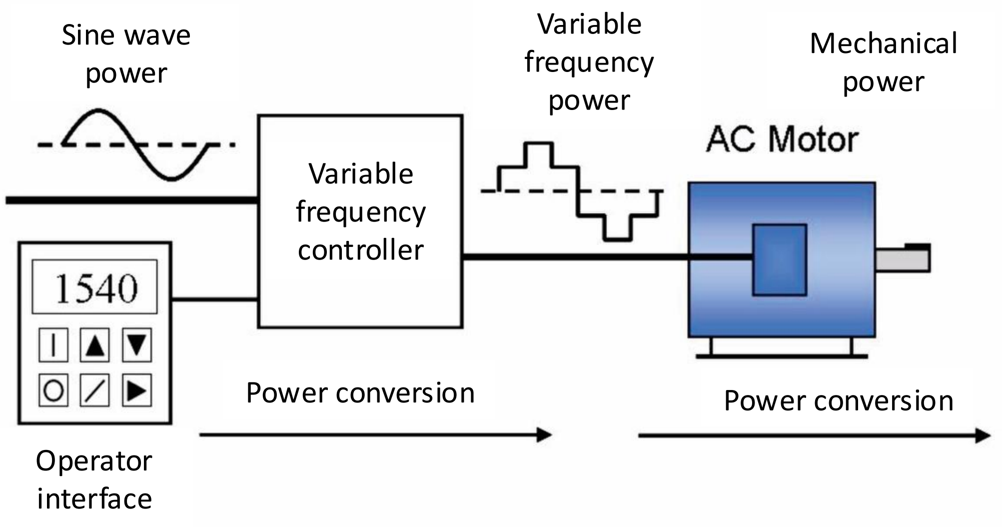


Electric Motors

- Asynchronous Motors
  - Shaft Frequency [1/min]
  - f – frequency of the supply voltage [1/s]
  - p – number of poles
  - f=50 Hz, p=4 (2 pairs), fosi=1500 rpm
  - Shaft speed can be changed by adjusting the supply frequency.

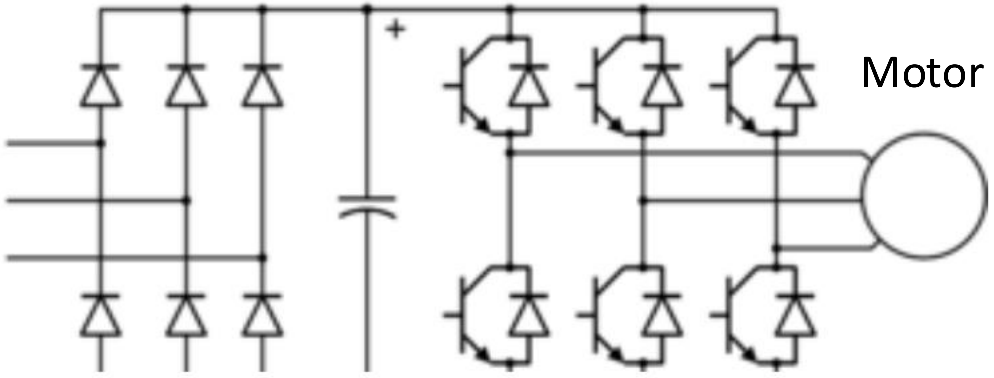
$$f_{osi} = \frac{60 \times f}{p/2}$$

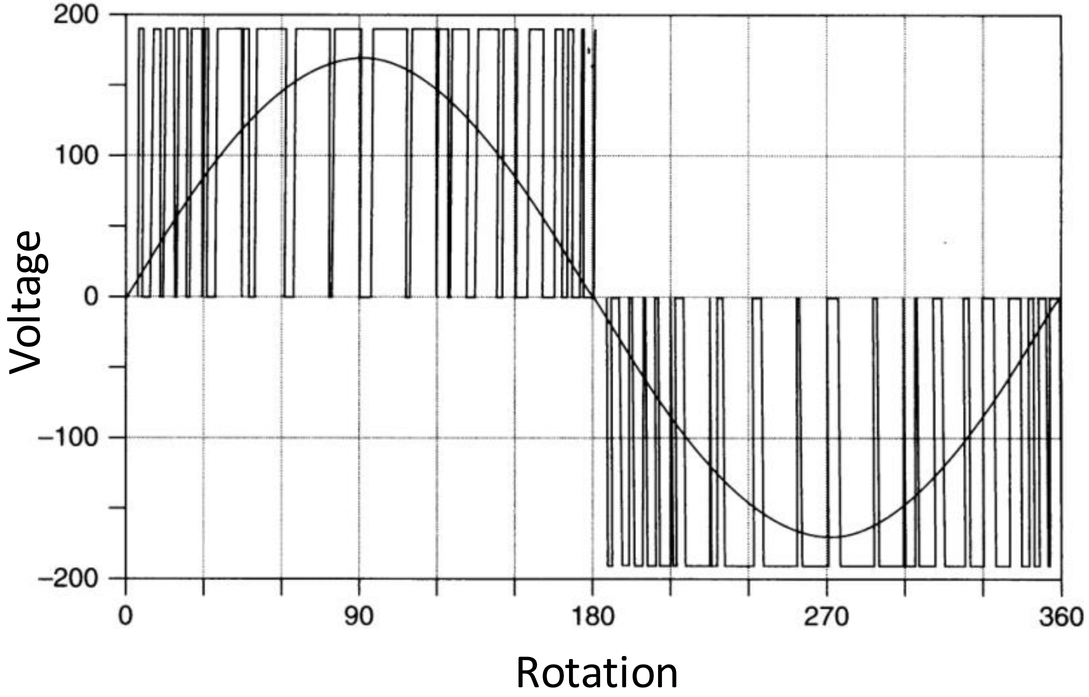
- Frequency Converter
  - Converts alternating voltage to direct current, then based on the required speed of rotation, torque, or power, determines the frequency of the supply voltage.



Electric Motors

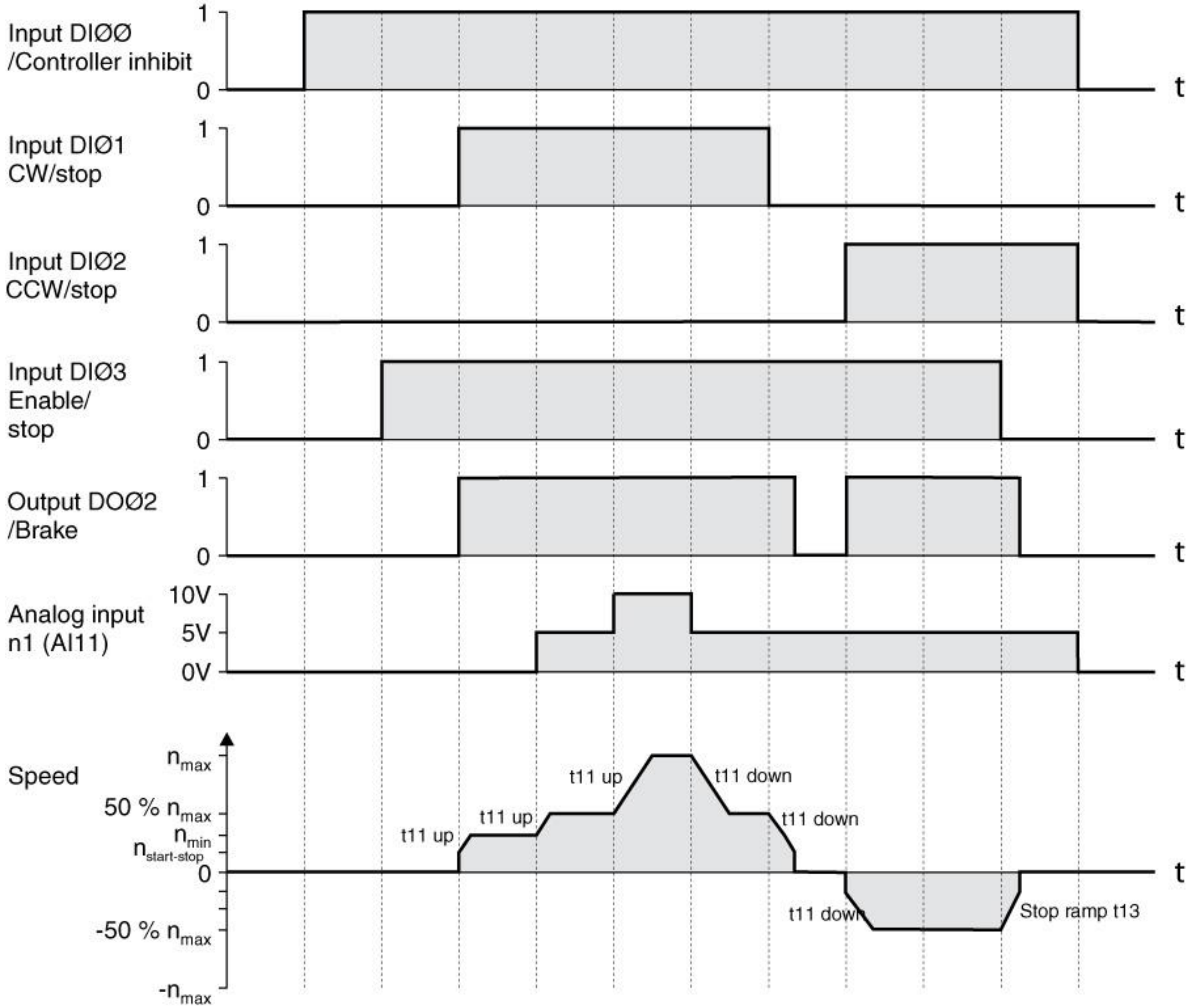
- Frequency Converter
- Structure:
  - DC -> AC
  - IGBT Technology (Insulated Gate Bipolar Transistor)
- Principle of Operation:
  - IGBT switches turn the DC voltage on and off at specific intervals, with pulses of varying length.
  - This generates a variable AC voltage at the output.
  - The voltage must change linearly with the frequency to ensure constant motor power.





Electric motors

- Frequency Converter
  - *Typical control signals and response (motor speed)*



Process automation

Sensing and Actuating Systems

BS UNI studies, Fall semester 2025/2026

Octavian M. Machidon

octavian.machidon@fri.uni-lj.si