ELTE | FACULTY OF INFORMATICS

Embodied Intelligence – L03
Sensors

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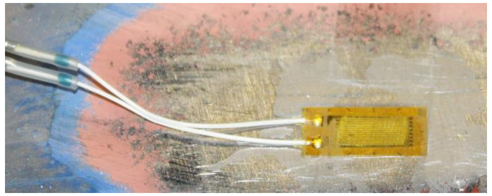
Outline

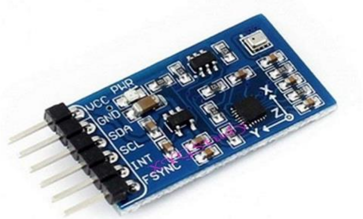
- Basic definitions
- Signals and their properties
- Measuring mechanical quantities
    - Force, torque, position, pressure

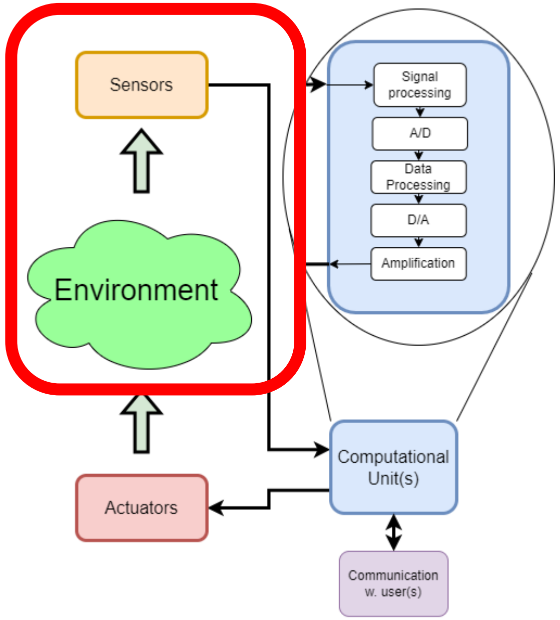
Definitions

What I said on the first lecture?

- In its broader definition, the purpose of a sensor is to ***detect a certain event, process or change in the environment and produce a corresponding output signal***.
- Human sensory inputs:
  - Vision
  - Audio
  - Smelling
  - Taste
  - Tactile
  - Temperature
  - … etc.
  - FUN FACT: We can’t sense wether something is wet or not (no humidity sensors in our skin)

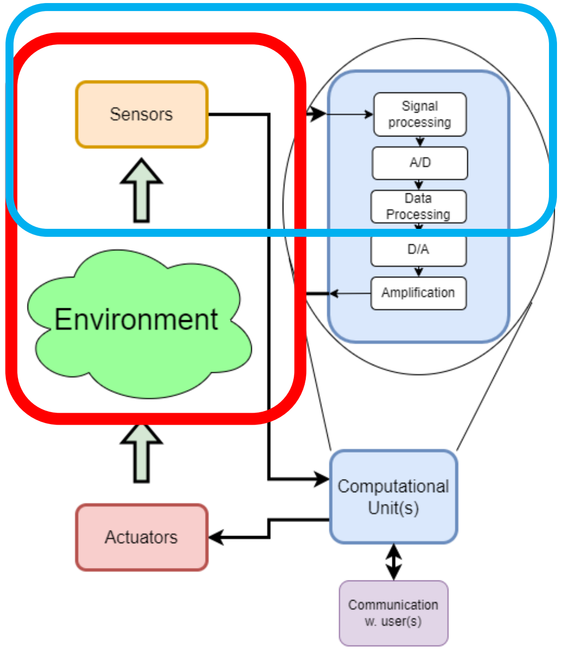






I was not completely honest

- You will see during this lecture that the encirclement was not completely correct.
- Some sensors also do:
  - Signal pre processing
  - Analog/Digital conversion
  - Communication protocols



Communication with the environment

- A subcategory of transducers
- In its broader definition, the purpose of a sensor is to ***detect a certain event, process or change in the environment and produce a corresponding output signal***.

Source: LoTR

Signals - Information

- Information means the quantifiable knowledge content of a communication that is understood to mean.
- It is transmitted by the signal, which is an abstract concept. (Info + Noise = Signal)

Source: LoTR

Signals - Definition

- A signal is a value or change in value of a physical quantity that is capable of acquiring, transmitting or storing information.

This means that, it also needs to be interpretable!

Source: LoTR

Processing unit need to understand the signal

- But this is the topic of the 5th lecture ;)

Source: LoTR

Signals – definition (cont.)

- A signal can be given by a $x = x(t)$ function
- that is interpreted on the $t_0 \leq t \leq t_1$ interpretation domain which can be:
  - Finite
  - Infinite

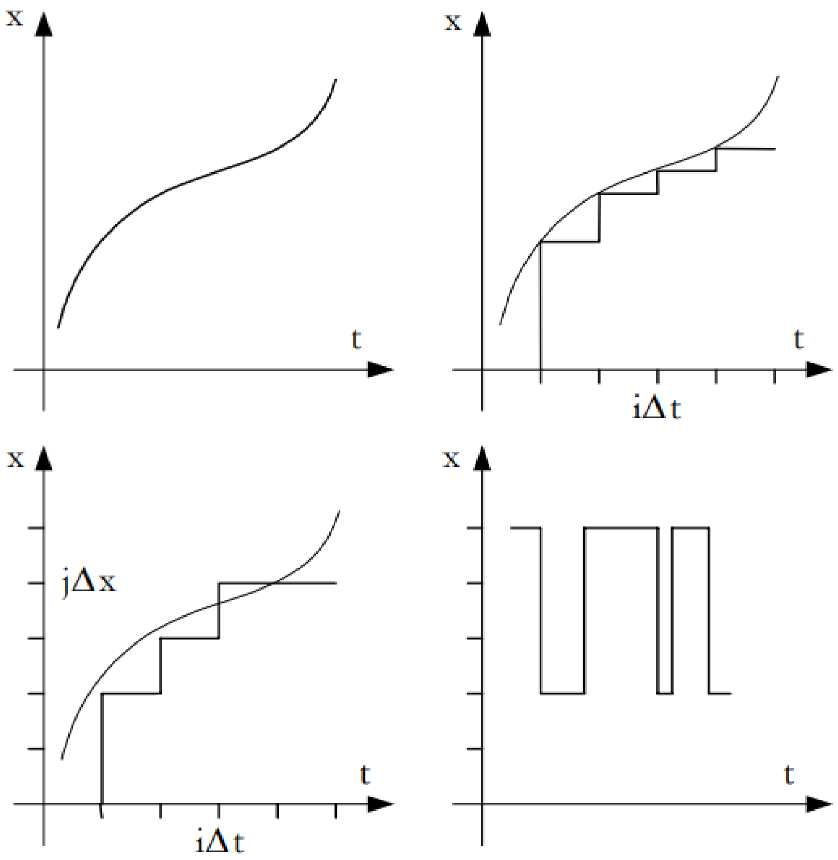
Signals - categorization

- *According to the value*:
  - **Continuous** [i.e.: Any kind of value can appear within a range]
  - **Discrete (Quantified in amplitude)** [i.e.: Only certain values can appear; basically this is the digitalisation]
- *Accorgind to the course of time*:
  - **Continuous** [i.e.: At any given time it can change value]
  - **Discrete (Quantified in time)** [i.e.: It can only change in certain times (like sampling)]

Signals – categorization (cont.)

- Appearance of the information:
  - **Analogue** [i.e.: The information is represented directly in the signal]
  - **Digital** [i.e.: The information is a represented in a discrete value (number)]
- Determination of value:
  - **Deterministic** [i.e.: It can be described with a function]
    - Periodic [e.g.: in cyclic processes]
    - Transient [e.g.: in transient processes]
  - **Stochastic** [i.e.: It can’t be described with a concrete function but with statistical methods]

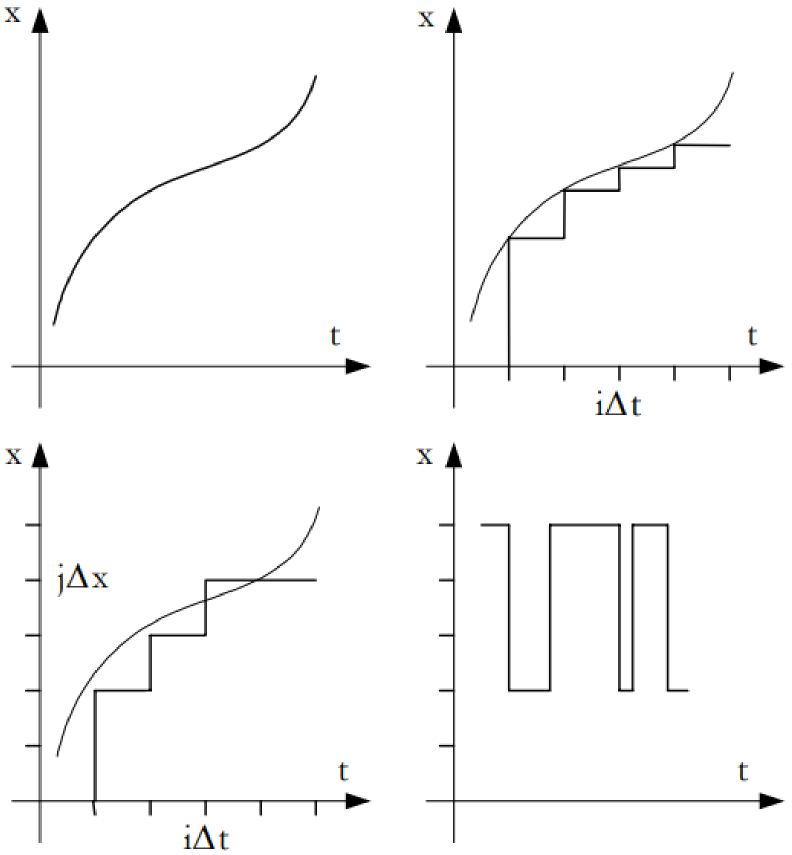
Let’s categorize these signals



Solutions

Continuous (analogue) valued
Continuous in time

Continuous (analogue) valued
Discrete in time



Discrete (digital) valued
Discrete in time

Discrete (digital) valued
Continuous in time

Some important properties of signals

- **Maximum**: $\hat{x} = \max(x(t))$
- **Mean**: $\bar{x} = \frac{1}{T}\int_0^T x(t)dt$
- **RootMeanSquar (effective value):**

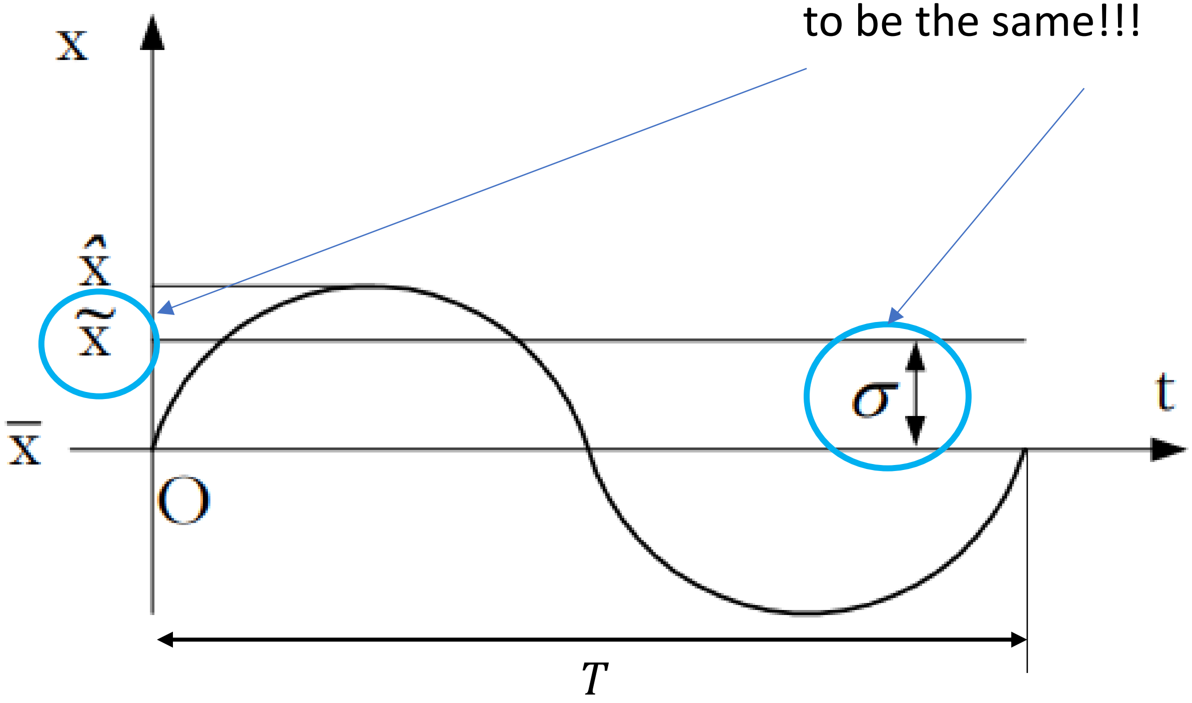
$$\tilde{x} = \left[\frac{1}{T}\int_0^T x^2(t)dt\right]^{\frac{1}{2}}$$

- **Deviation**: $\sigma_x = \left[\frac{1}{T}\int_0^T x^2(t)dt\right]^{\frac{1}{2}}$

Example: $x(t) = A\sin(\omega t), \omega = \frac{2\pi}{T}$

- $\hat{x} = \max\big(x(t)\big) = \mathrm{A}$
- $\bar{x} = \frac{1}{T}\int_0^T x(t)dt = 0$
- $\tilde{x} = \left[\frac{1}{T}\int_0^T x^2(t)dt\right]^{\frac{1}{2}} = \frac{A}{\sqrt{2}}$
- $\sigma_x = \left[\frac{1}{T}\int_0^T x^2(t)dt\right]^{\frac{1}{2}} = \frac{A}{\sqrt{2}}$

Don't necessary needs to be the same!!!



Sensors

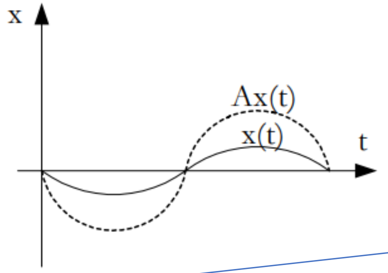
- According to wether they emit energy during the measurement:
  - Active (yes) [CCD, thermocouple, photodiode]
  - Passive (no) [thermistors, photoresistors, resistance strain gauges]

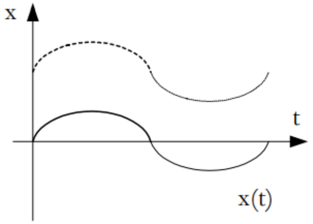
Mostly measured physical quantities

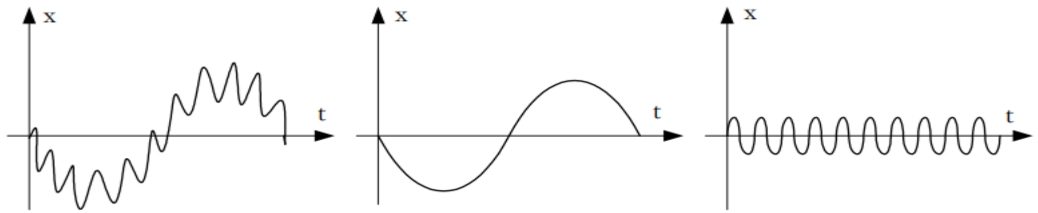
- **Mechanical:** position (absolute/relative), velocity, acceleration, angular position/velocity/acceleration, force, torque, pressure …
- **Thermal:** temperature, heat flux, radiation …
- **Electrical (magnetic):** charge, voltage, current, magnetic induction, flux …
- **Optical:** light intensity, wavelength …

Most of the times the signal from the sensor is not sufficient for processing

- We need signal conditioning (not exhaustive list):
  - Amplification
  - Imput coupling
  - Filtering
  - Electrical isolation
  - Linearization
  - Attenuation
  - …







Lowpass filtering   Highpass filtering

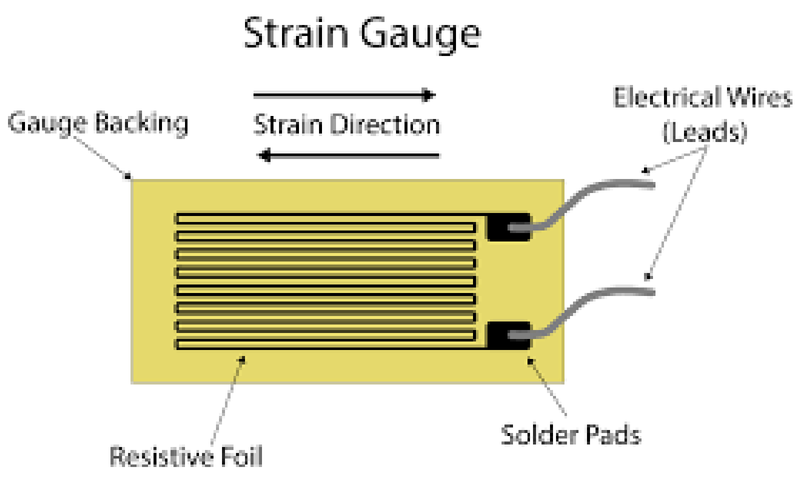
Sensors - MUSTs

- Unambiguous and reproducible signal
- Output is only influenced by the input
- A linear relationship between input and output. (weak requirement)
- Do not affect the measured system. (theoretically)
- Immunity to external disturbances. (mostly theoretically)
- The output signal can be normalized.

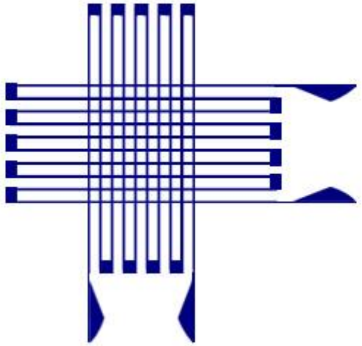
Measuring mechanical quantities

Measurement of deformation

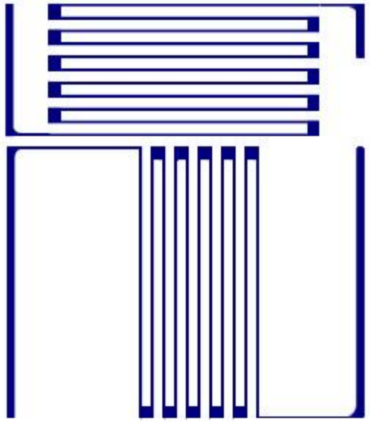
- Why measure?
  - Deformation of solid bodies on mechanical stress
    - Force measurement
    - Torque measurement
- Applications:
  - Material testing
  - Assessment/surveilance of constuctional elements of devices during load
  - Measurement of force
  - Measurement of weight



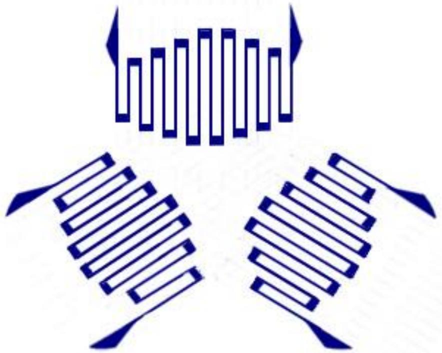
Some usual types



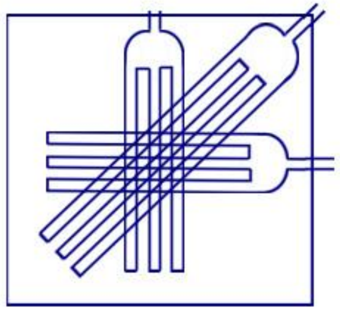
Two-Element, 90 Degree Planar (Shear) Rosette Strain Gauge



Two-Element 90 Degree Planar Rosette Strain Gauge



Three Element, 60 Degree Delta Rosette strain Gauge

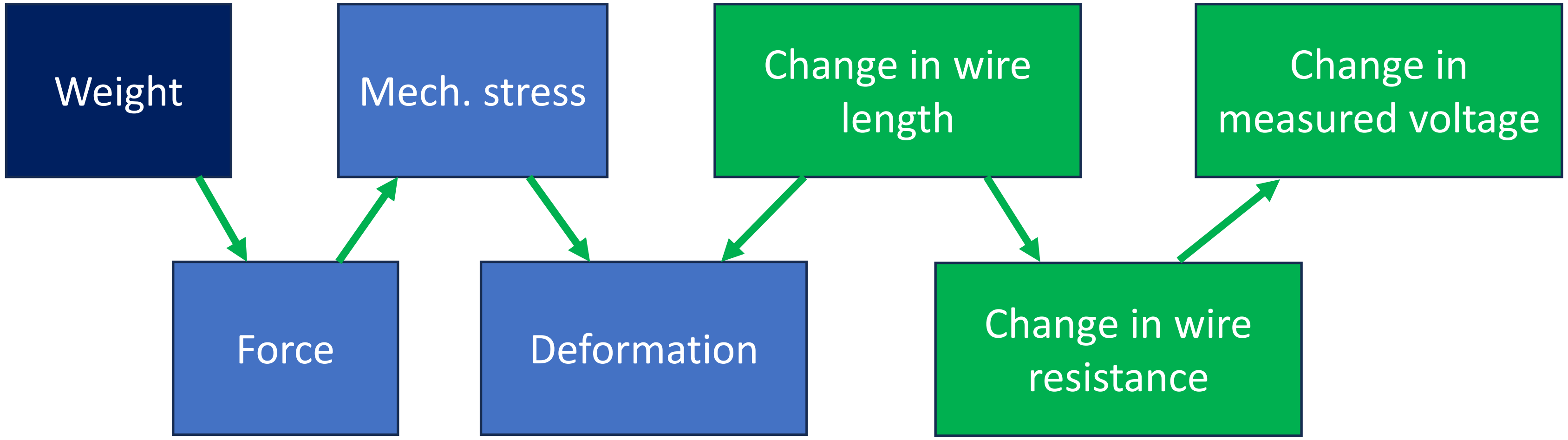


Three Element, 45 Degree Planar Rectangular Rosette Strain Gauge

www.InstrumentationToday.com

Roadmap

- Let’s say we want to measure weight.
- We need to measure it indirectly



Physical background of the measurement

- Weight → Force (simplified):

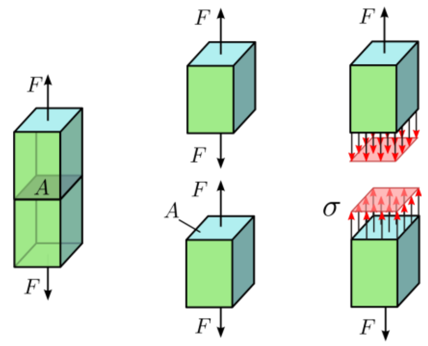
$$F_N = m \cdot g_e$$

where: $\boldsymbol{F_N}$ – normal force; $\boldsymbol{m}$ – mass;
$\boldsymbol{g_e}$ – gravitational coefficient (Earth; 9.817 m/s^2)

- Force → Mech. stress (Uniaxial normal case)

$$\sigma = \frac{F}{A}$$

where: σ – mechanical stress; F – force applied;
A – normal scrossection's area of the body



- Mech. Stress → Length difference (Hook's law):

$$\sigma = E \cdot \varepsilon = E \cdot \frac{\Delta L}{L}$$

Physical background of the measurement (cont.)

- Resistance of a wire:

$$R = \rho \frac{l}{A} = \rho \frac{l}{r^2 \pi}$$

where: *R* - resistance; *ρ* -resistance coefficient; *L* -length of the wire; *A* -Area of the wire

- … (On the next slide for extra)
- Gauge – factor (ratio between the legth change and resistance change):

$$g = \frac{\mathrm{dR/R}}{dl/l} \approx 1 + 2\nu \approx 2$$

Gauge factor (extra)

$$dR \cong \frac{\partial R}{\partial \rho} d\rho + \frac{\partial R}{\partial l} \, dl + \frac{\partial R}{\partial r} \, dr \rightarrow dR \cong \frac{l}{r^2 \pi} d\rho + \frac{\rho}{r^2 \pi} dl + 2 \frac{\rho l}{r^3 \pi} dr$$

$$dR \cong \frac{R}{\rho} d\rho + \frac{R}{l} \, dl + 2 \frac{R}{r} \, dr \rightarrow \frac{dR}{R} \cong \frac{d\rho}{\rho} + \frac{dl}{l} + 2 \frac{dr}{r}$$

Poisson factor: $\frac{dr}{r} = -\nu \frac{dl}{l}$

$\frac{dR}{R} \cong \frac{d\rho}{\rho} + \frac{dl}{l} \, (1 + 2\nu) \rightarrow g = \frac{dR/R}{dl/l} \approx 1 + 2\nu \approx 2 \;\; (\nu = 0.5)$

Problem with the measurement of the resistance change

- Let's consider the following (~typical case):
- Measure maximum weight: 100kg [let be a steel measuring body with $A = 5\,mm^2$, ($E = 2 \cdot 10^5 \frac{N}{mm^2}$, elastic modulus), typical resistance strain gauge: R = 120 Ω]
- $F_N = 1000\,N \;\rightarrow \sigma = \frac{1000\text{ N}}{5\,mm^2} = 200\,\frac{N}{mm^2} \rightarrow \varepsilon_{max} = 0.001$
- $\frac{dR}{R} = g \cdot \varepsilon_{max} = 0.002 \;\rightarrow dR = g\varepsilon R = 0.002 \cdot 120\,\Omega = \mathbf{0.24\,\Omega}$

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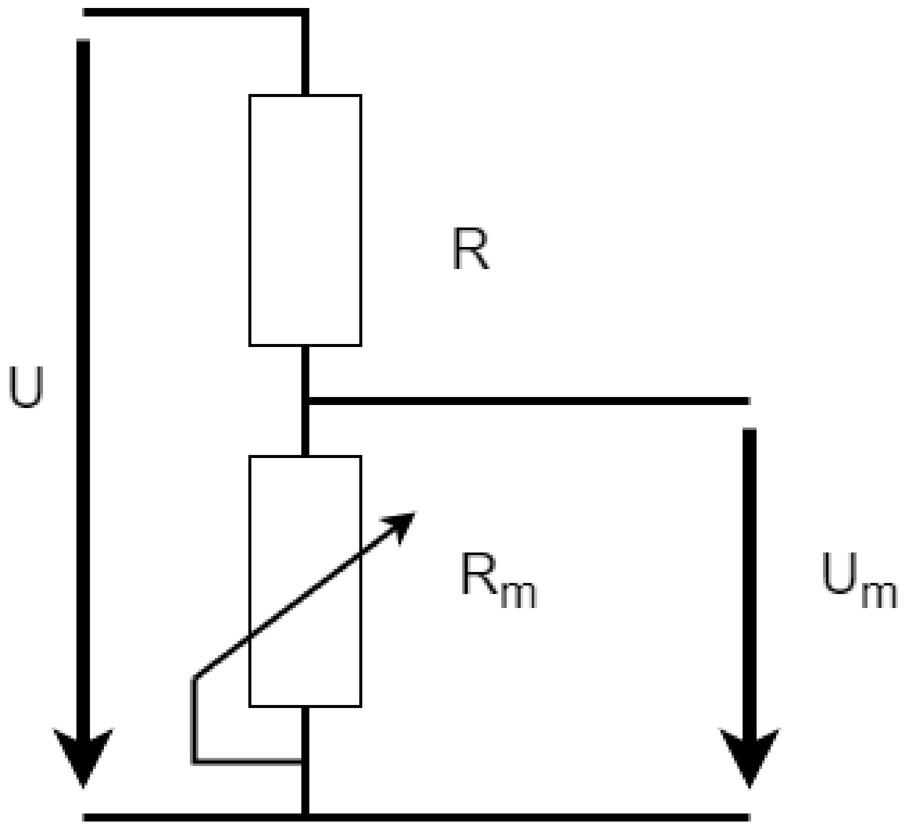
Too small change in resistance, what should we do??

How would we do this, if the difference was not too small

$$U_m = U\frac{R_m}{R + R_m}$$

- We can't use big **U** and small **R**, because of practical reasons.

($P = UI^2 \rightarrow$ this will be converted to heat!!!)

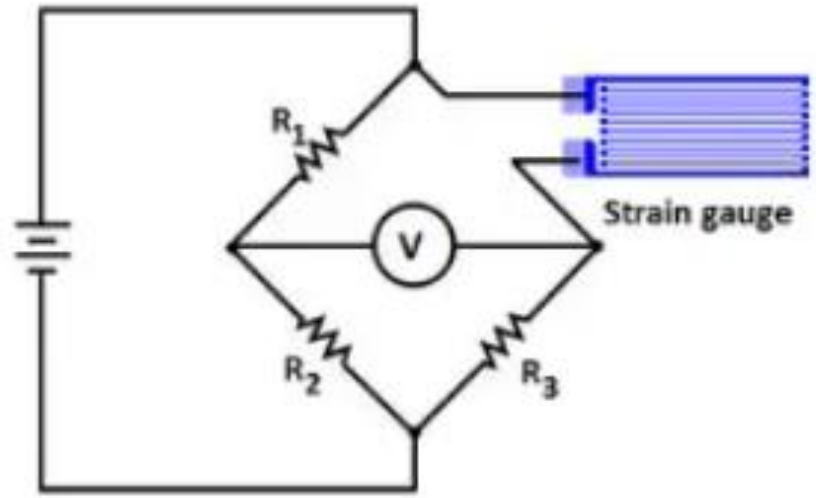


Measuring precisely small resistance changes

- Wheatstone bridge

$$U_{measured} = U \frac{Rg\varepsilon}{2(2R + Rg\varepsilon)}$$

(if $R_1 = R_2 = R_3$)



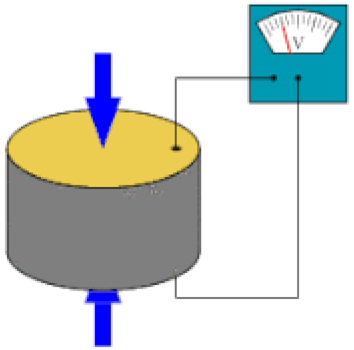
Measuring weight - summary

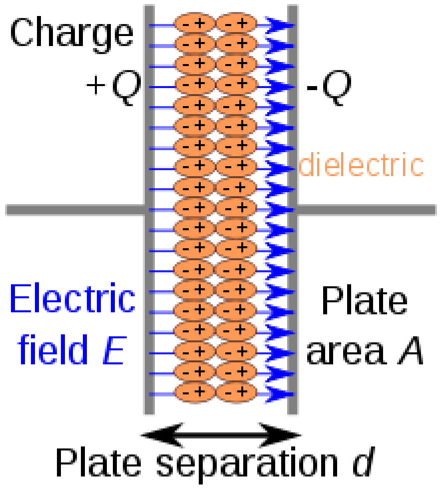
- Think about:
  - So simple thing to measure
  - So complicated measuring principle (but cheap!!! Only we need to use our brain with the calculations)
  - We had a lot’s of simplifications (now!!)
  - We did not processed the signal yet (5th lecure)
  - We did not made our system robust against:
    - Thermal disturbances
    - Electromagnetic disturbances (induction in the wiring)
    - etc …

Measuring linear force/pressure/acceleration

- For (only) dinamical effects we can use Piezzo sensors

- Physical background:
  - In crystalline materials without a symmetry centre, deformation (elastic deformation) leads to the formation of electric dipoles because the positive and negative charge centres separate or the length of the existing dipoles changes. On the opposite faces of the crystal, due to the ordering of the dipoles caused by mechanical stress, electric charges of opposite sign accumulate, creating an electric potential. When the deforming force changes direction, the sign is reversed, and the electric field and voltage change sign.

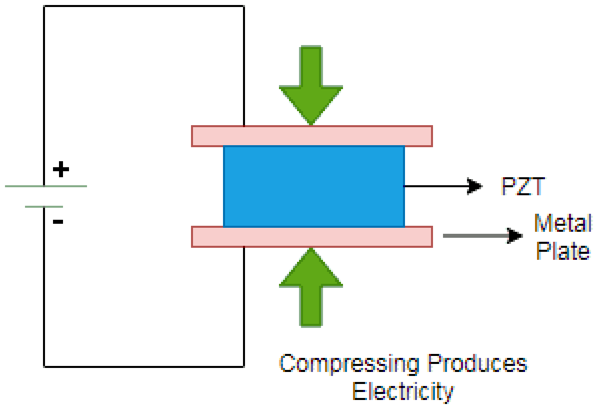




We use some tricks

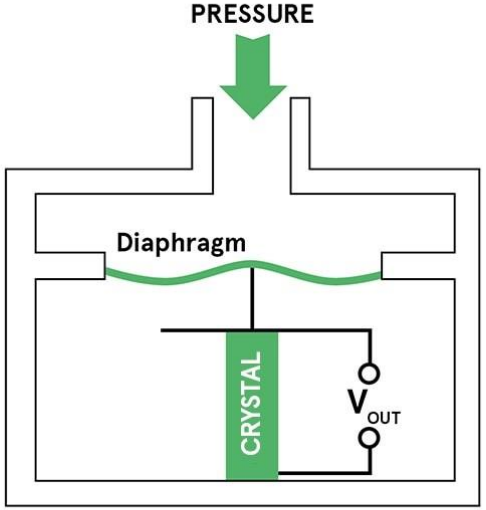
Force

$$F$$



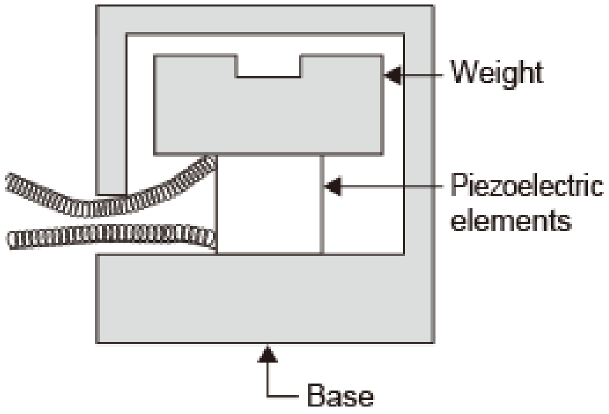
Pressure

$$F = P \cdot A$$



Acceleration

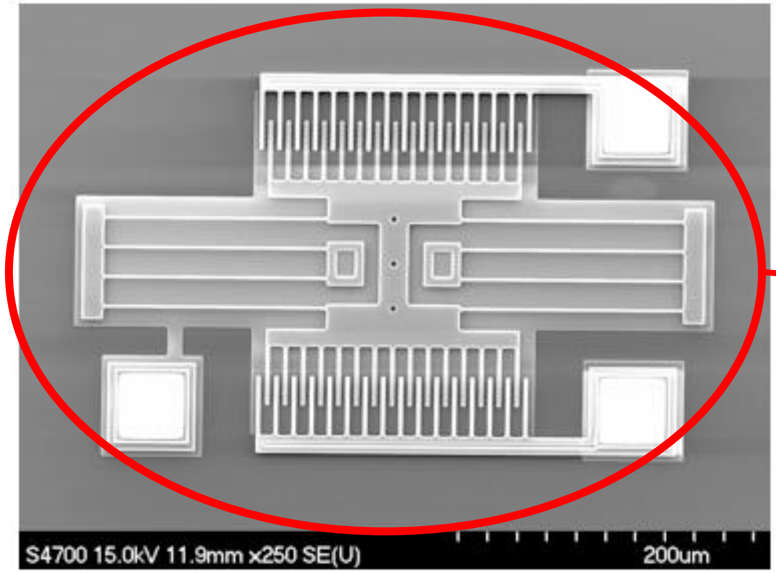
$$F = m * a$$

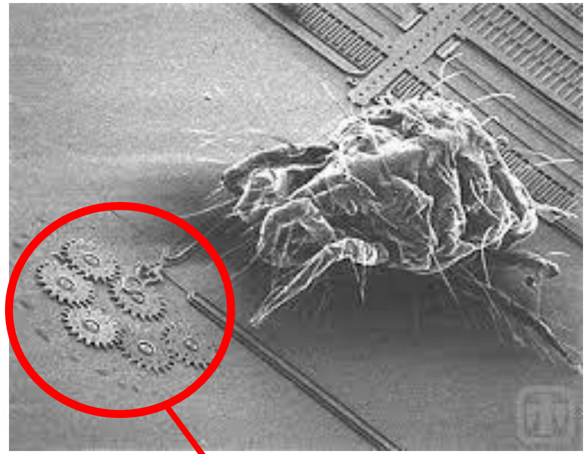


Measuring acceleration with capacitive sensors

- CMOS MEMS technology
- Able to measure statical effects
- Cheap
- Precise and robust

- IMU’s accelerometer

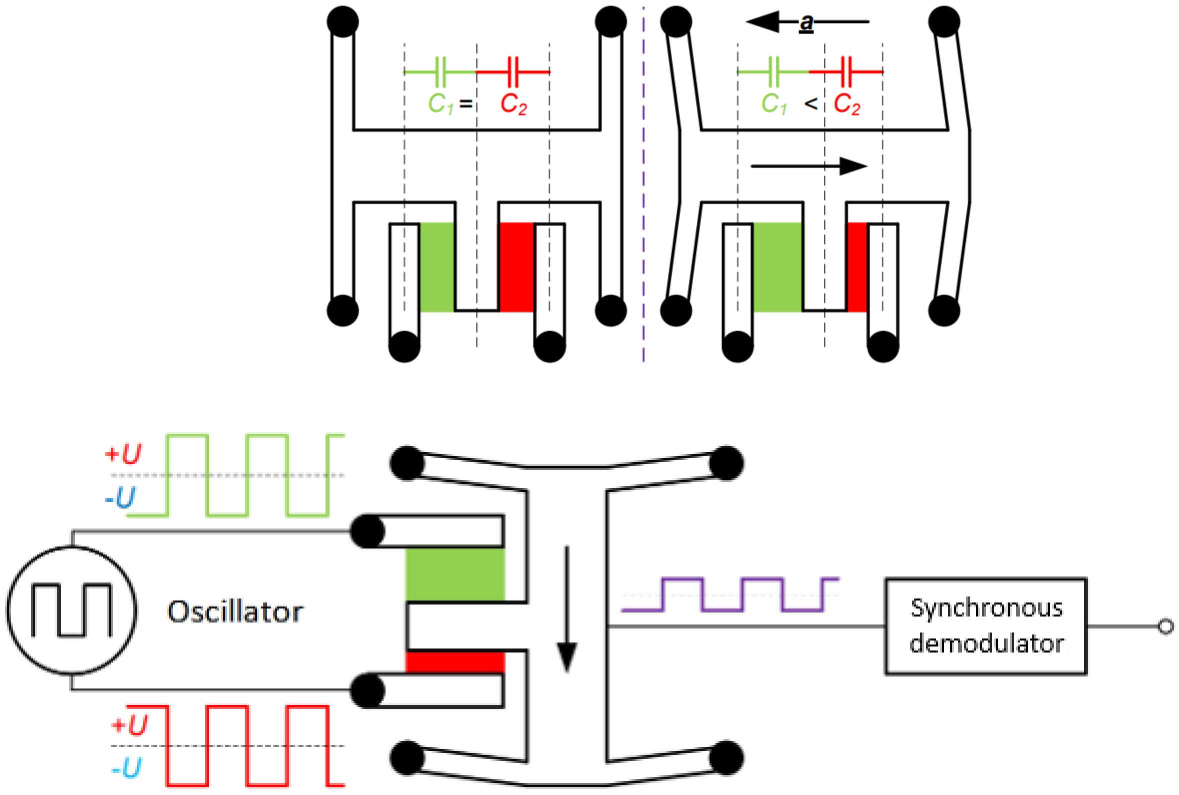




1-100 micrometer

Measuring acceleration with capacitive sensors (cont.)

- Principle of differential capacity
- With a (usually built in) signal generator and demodulator modul we can determine the capacitors value → acceration

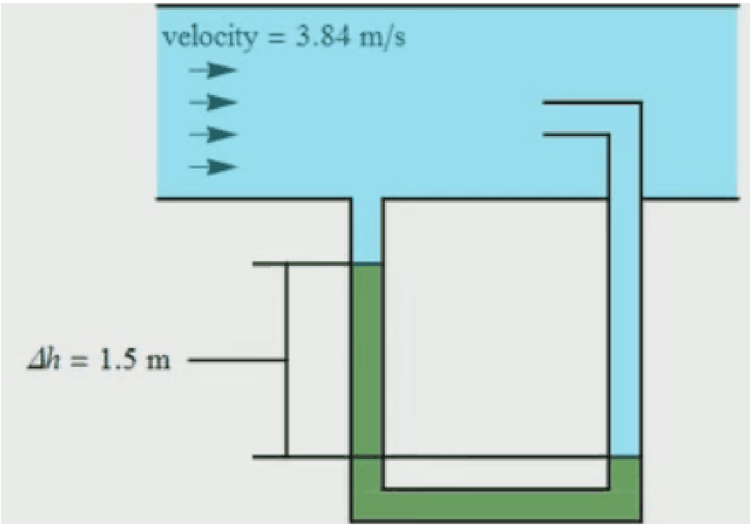


Measuring waterflow (or gases)

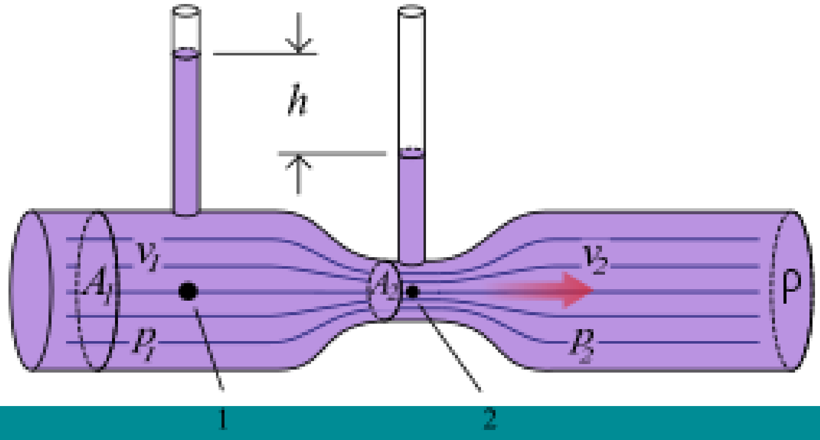
- We can have several different methods for this
  - Pitot – pipe
  - Venturi – pipe
  - Ultrasound based
  - Doppler effect based

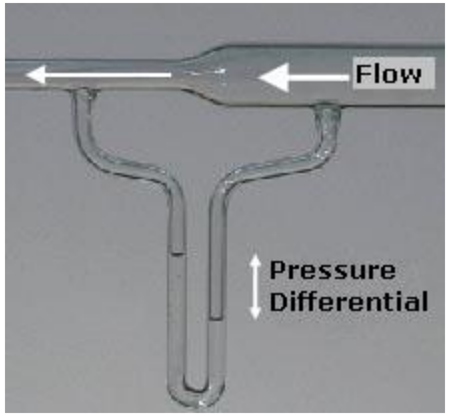
Pitot pipe and Venturi pipe – Invasive measurements

- There will be a difference in the pressure at the tubes edge and the middle



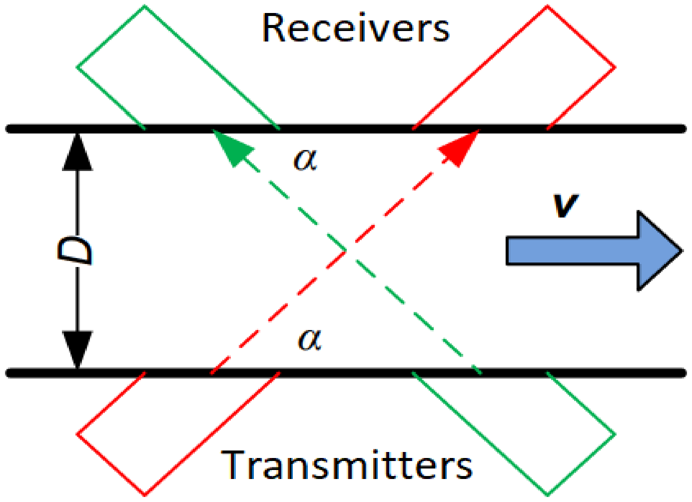
- We measure at the edge of the pipe
- We make a pipe that has different diameters (causing a waterflow difference)





Non-invasive measurement with ultrasound

- With two ultrasound transmitter – receiver pair
  - One in the same direction
  - One in the oposit direction
- The signals are sent in different (but known) times



$$t_{sd} = \frac{D}{\sin\alpha\cdot(c + v\cdot\cos\alpha)}$$

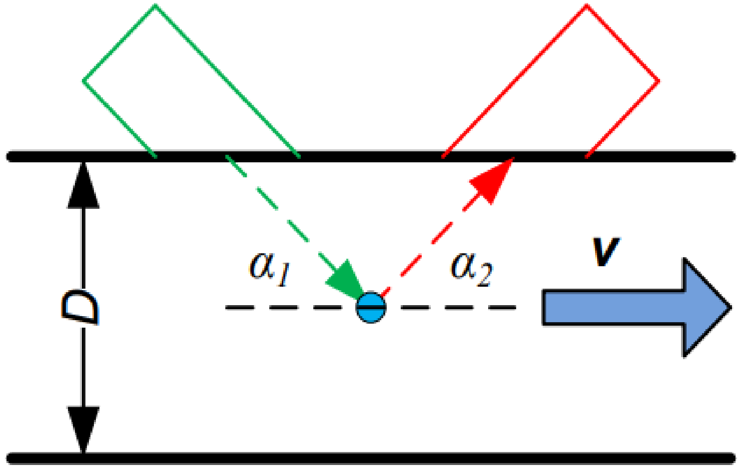
$$t_{od} = \frac{D}{\sin\alpha\cdot(c + v\cdot\cos\alpha)}$$

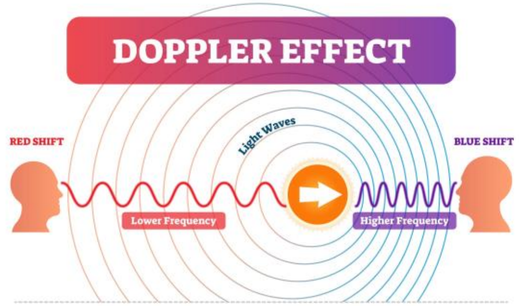
$$\boldsymbol{\Delta t \approx \frac{2\cdot Dv\cdot\cos\alpha}{c^2}}$$

Precise measurement of time is inevitable (speed of sound in water 1500 m/s)

Non-invasive measurement with Doppler's effect

- Same method how the velocity of other galaxies are measured
- The frequency of a wave is changing during the relative motion between a wave source and its observer.
- Static receiver and transmitter BUT the medium is not static!





$$f_{receiver} = \frac{c + v_{receiver}}{c + v_{transmitter}} \cdot f_{transmitter}$$

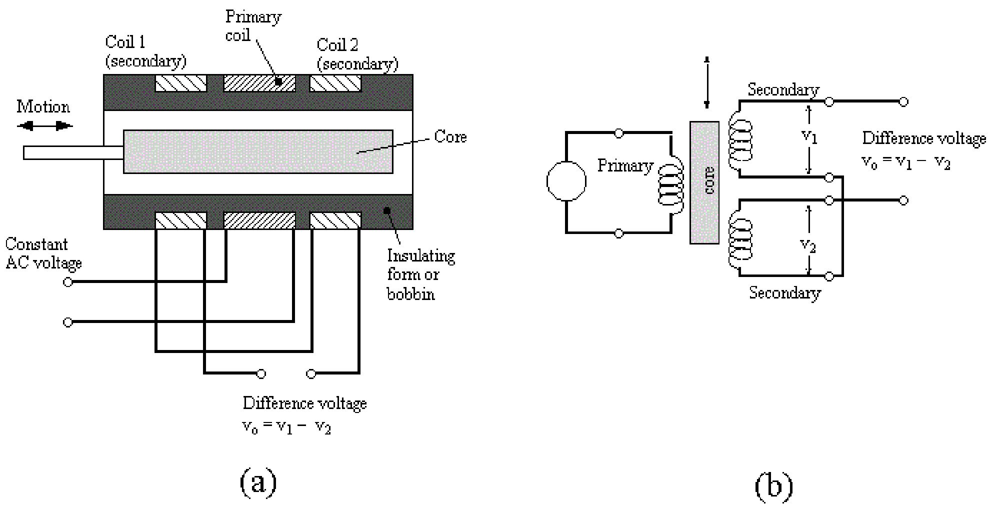
Measuring linear position and displacement

- LVDT
- Hall effect
- (double) Integration of the acceleration

Linear Variable Differential Transformer - LVDTs

- Voltage transformer's principle
- Core is ferromagnetic and moving
- Reliable
- Accurate
- Vibrations, stress testing actuation (feedback)

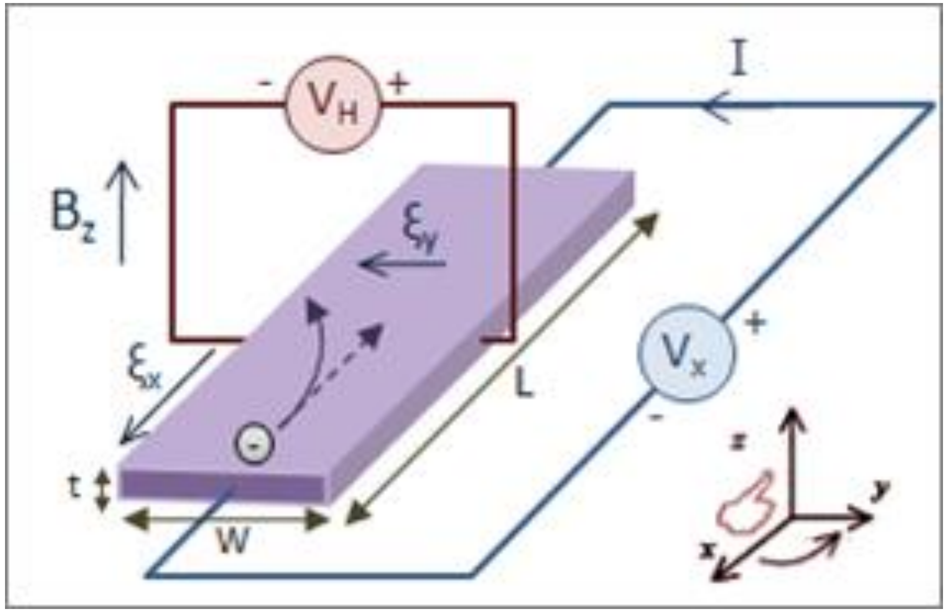
Linear Variable Displacement Transducer (LVDT)



A good presentation of the principle: YouTube

Hall effect transducers

- Hall effect:
  - If a magnetic field is applied perpendicular to the direction of electric current, an electric field is set up, which is perpendicular to both the direction of electric current and the applied magnetic field.
- Measurement of magnetic field or current. Proxemity.Contactless
- Wheel speed sensors – RPM, switches, proximity sensors

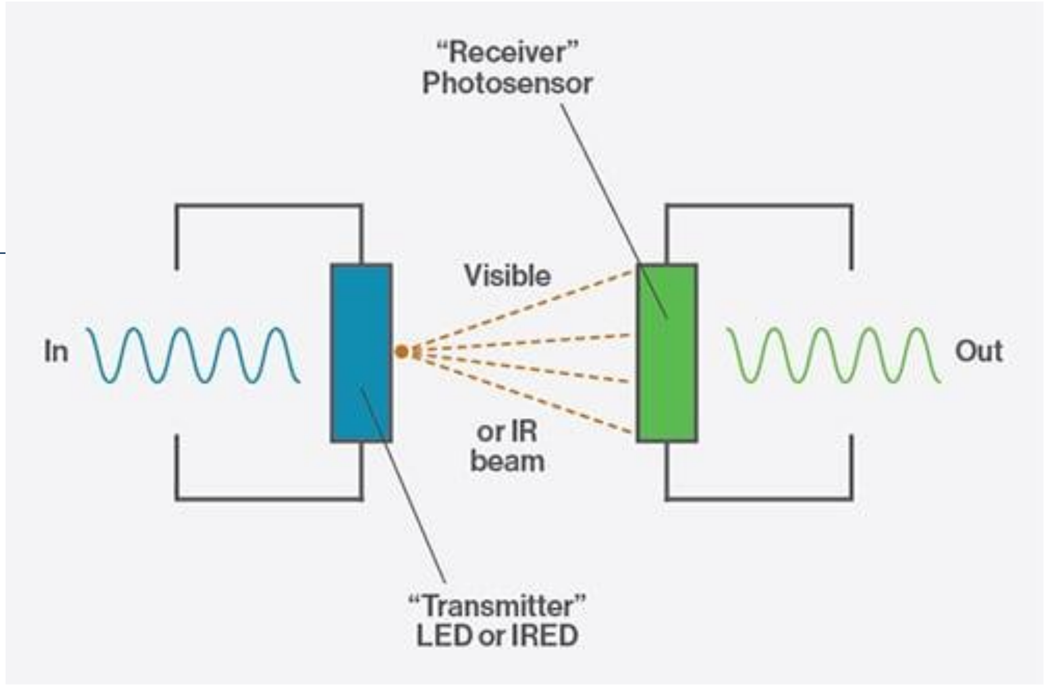


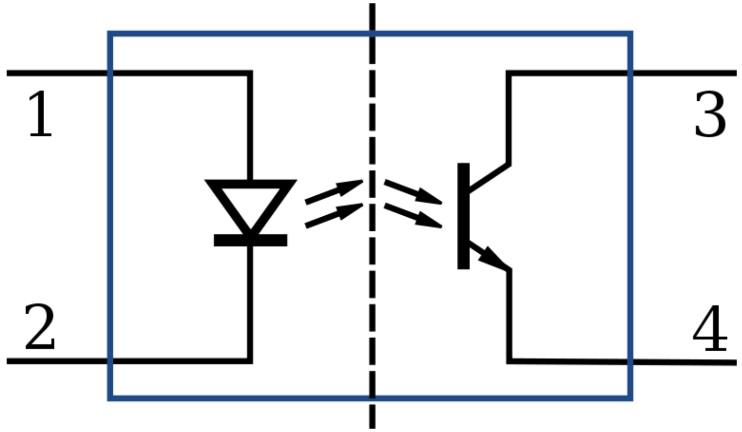
Measuring rotational movements

- Optical encoders
- Hall-sensors
- Resolvers

Optical encoders

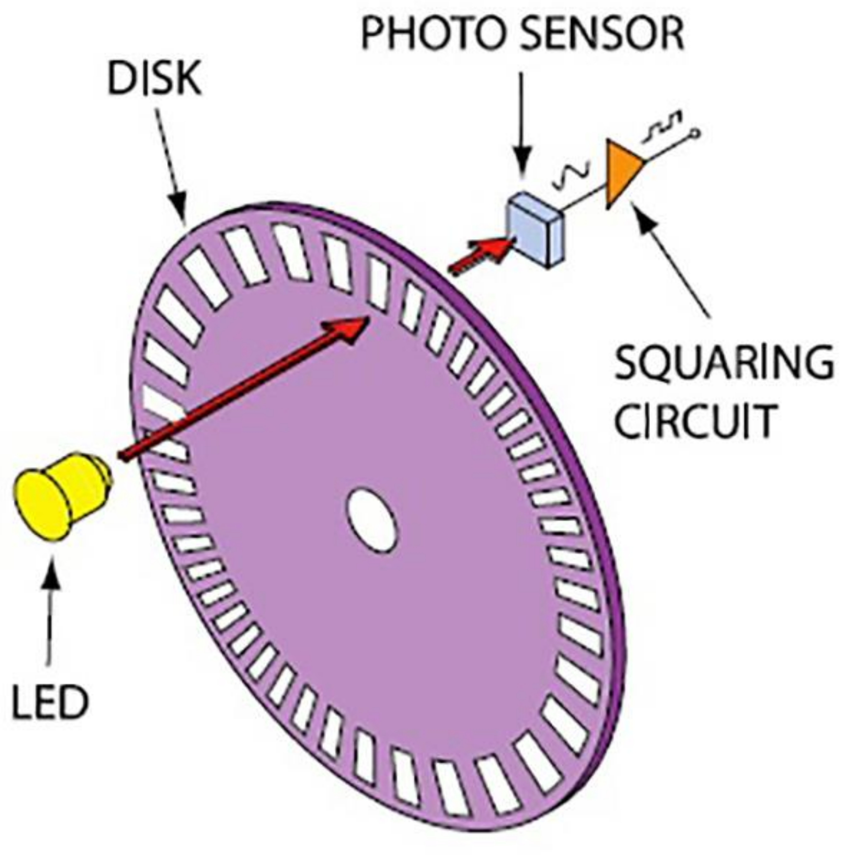
- Transmission optocoupler
  - LED + Phototransistor
- Usually used for electrical decoupling of signals
- With a modification we can use this device for measuring revolut movements





Optical encoders (cont.)

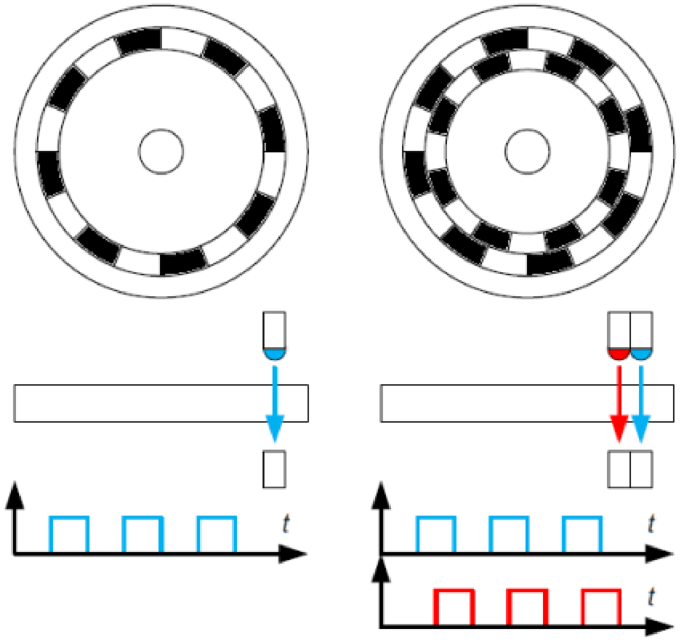
- Putting a disk with holes between the light source and receiver
- The disc is attached to the moving part of the measured device (motor)



Incremental encoder

Optical encoders (cont.) – Incremental encoders

- 1 circle of holes - movement
- If we need to know the direction
- 2 cirle with two receivers (or two receivers in different position)
  - Based on the phase shift we can determine the direction



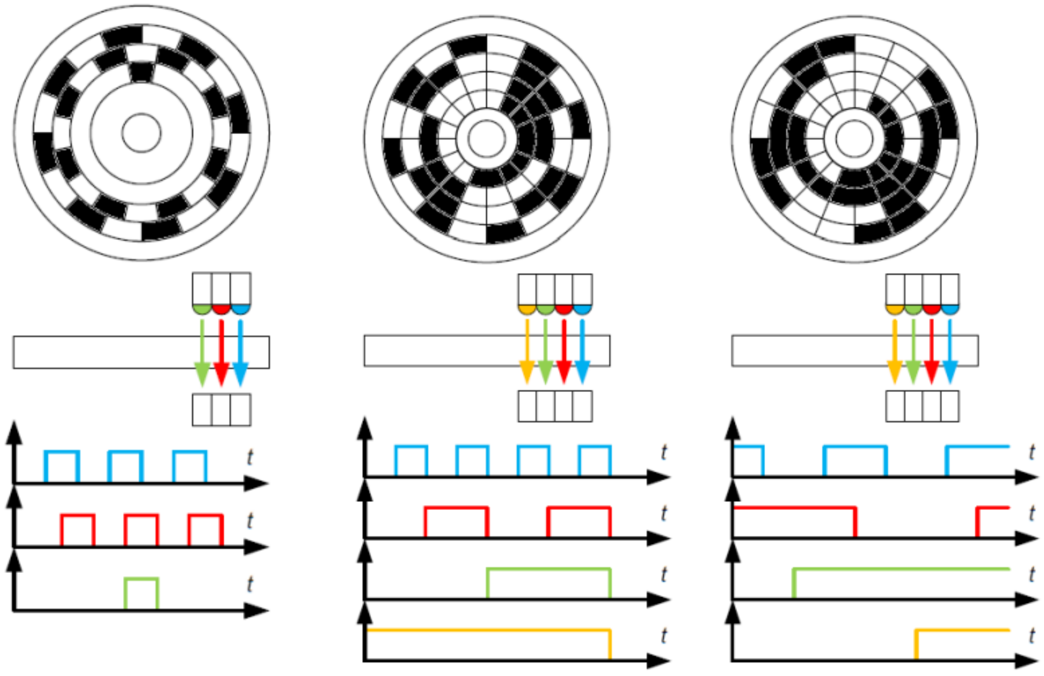
Absolute or incremental

- Sometimes we need to have the absolute position of the moving part (precise movements, even after a shutdown).
- In older scanners the solution was simple (incremental + switch):
  - Move to one direction on the slide (usually the same direction)
  - UNTIL EndSwitch is pusched
  - You are at the 0 point, You can start to count the steps You made

Optical encoders (cont.) – Absolute encoders

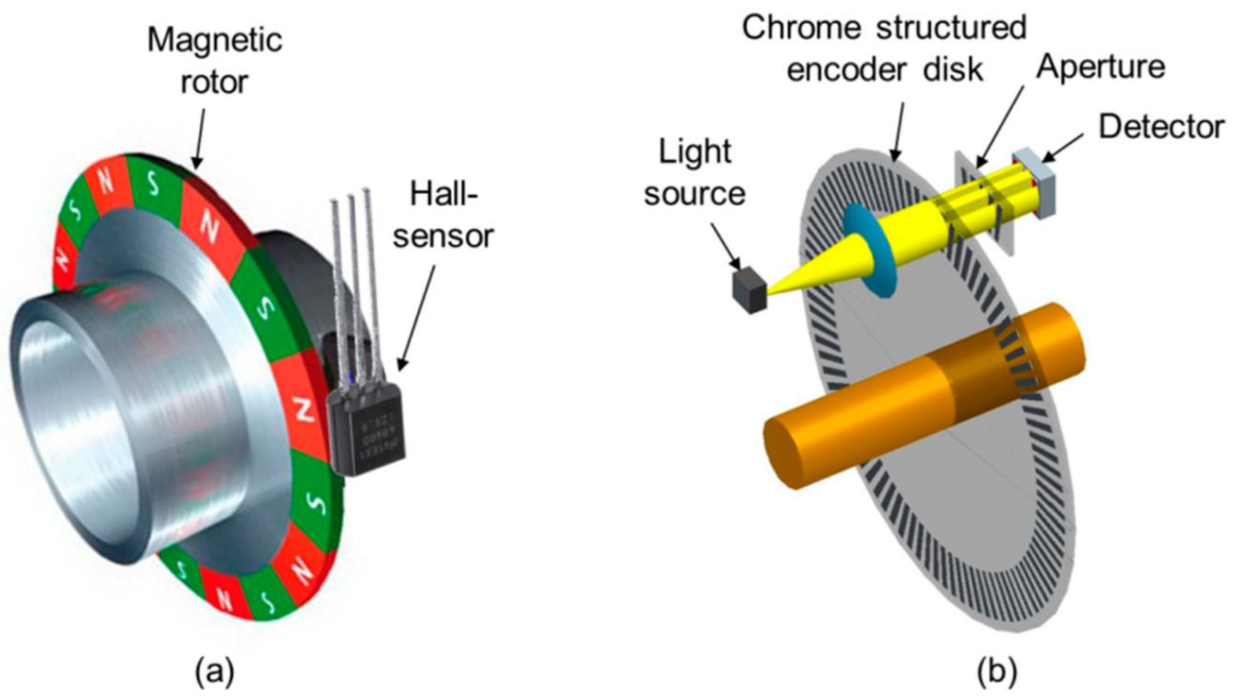
- More expensive
- 3 circle is needed (at least)
- We can use binary or Gray-coded

- Gray-code = at any given time only one bit will change



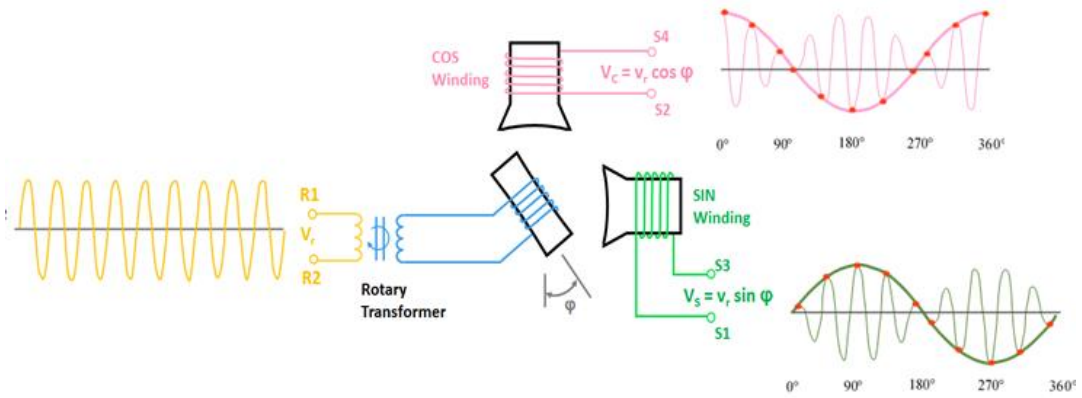
Hall-sensors

- We can use magnets + Hall sensor instead of optocouple



Resolver

- LVDT's pair for rotational movements
- Output: Absolute rotational position
- Originally for military applications were developed (robustness in harsh conditions)
- 2 stationary windings (sin and cos)
- Rotary transformer



From the ratio of the measured voltages and their phase we can calculate the angle of the rotating part.