Proximity, displacement and level sensors

Industrial control

KOVÁCS Gábor
gkovacs@iit.bme.hu

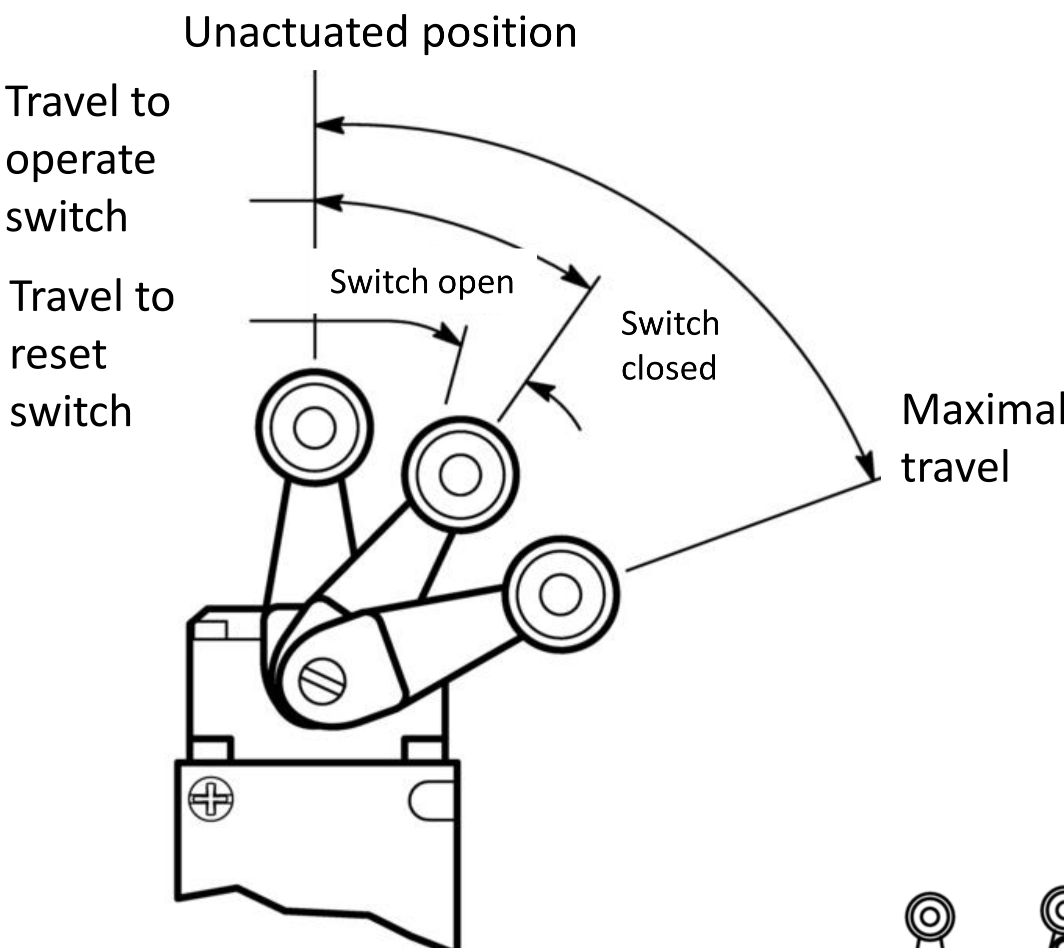
Proximity sensors

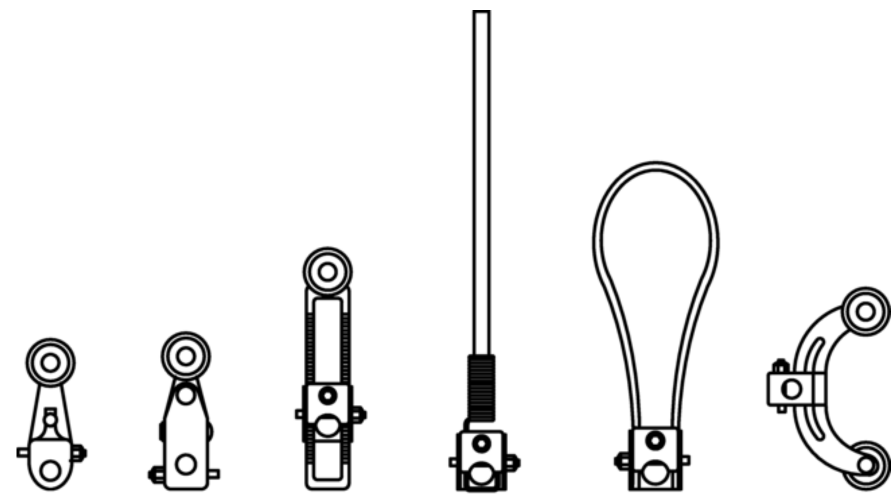
- Proximity sensors (proximity switches) report whether an object is present at a given location
- Used mainly in the field of factory automation

Limit switches

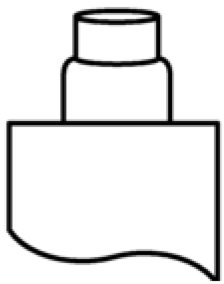
- The approaching objects activates a mechanical switch
- Various constructions
- NO (Normally Open), NC (Normally Closed) and NO/NC switches with both configurations

Side rotary limit switch

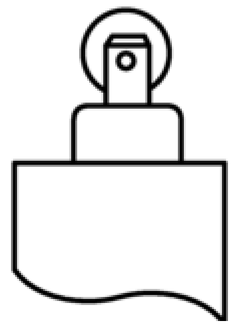




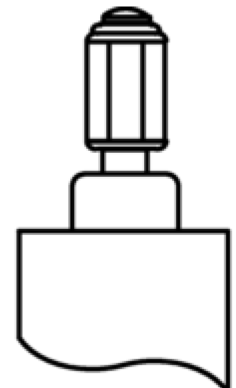
Side / Top Push limit switches



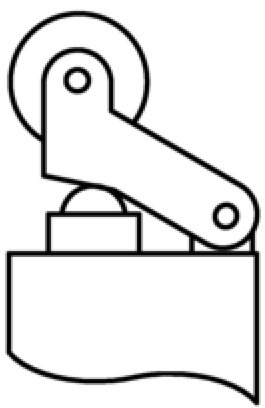
Top Push Rod



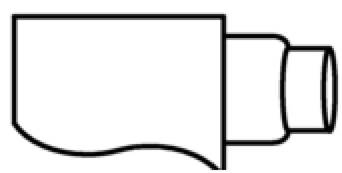
Top Push Roller



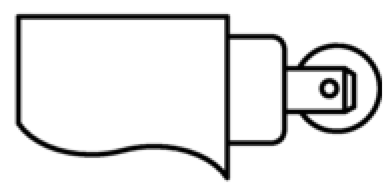
Adjustable Top Push Rod



Roller Lever Push



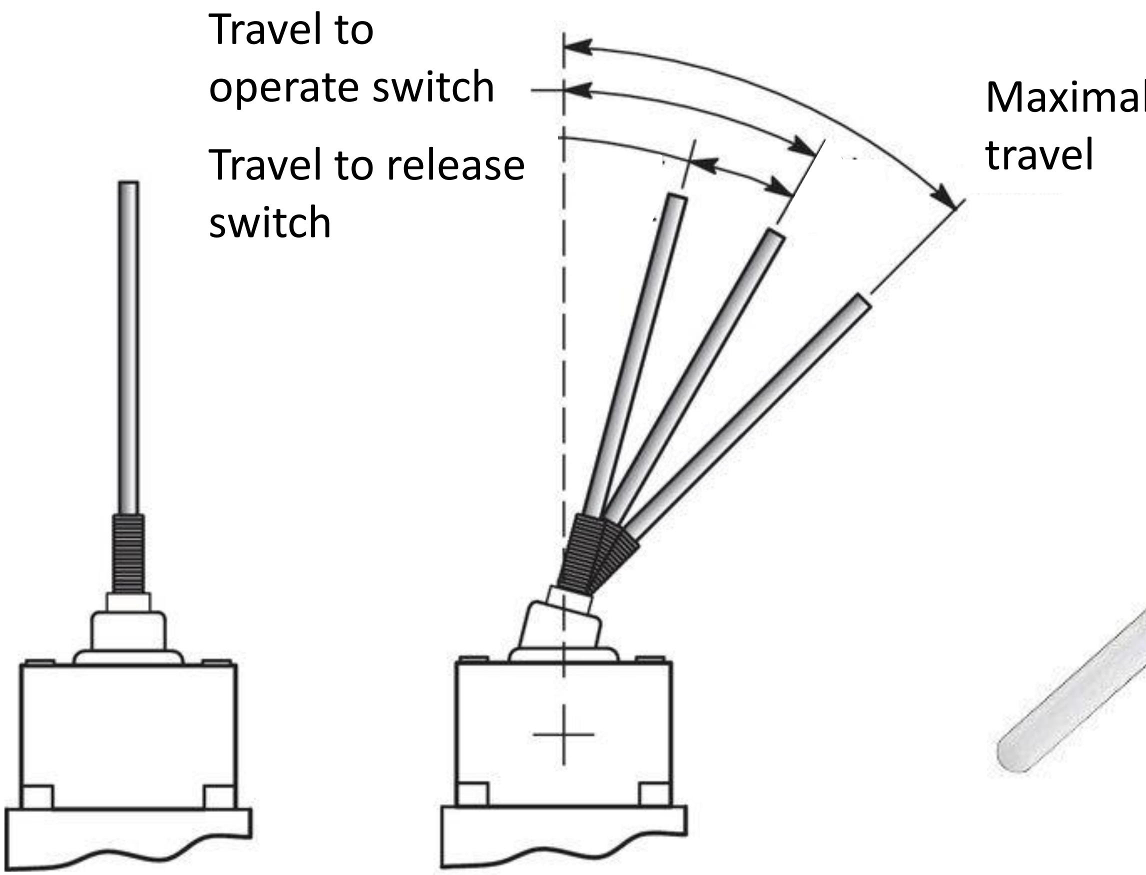
Side Push Rod



Side Push Roller

Wobble Stick limit switches

(cat whisker)



Idle position

Switches when actuated to any direction

Limit switches

+ simple construction
+ low cost
+ insensitive to environmental effects
+ insensitive to noise
+ able to switch any signal (AC, DC, high voltage)

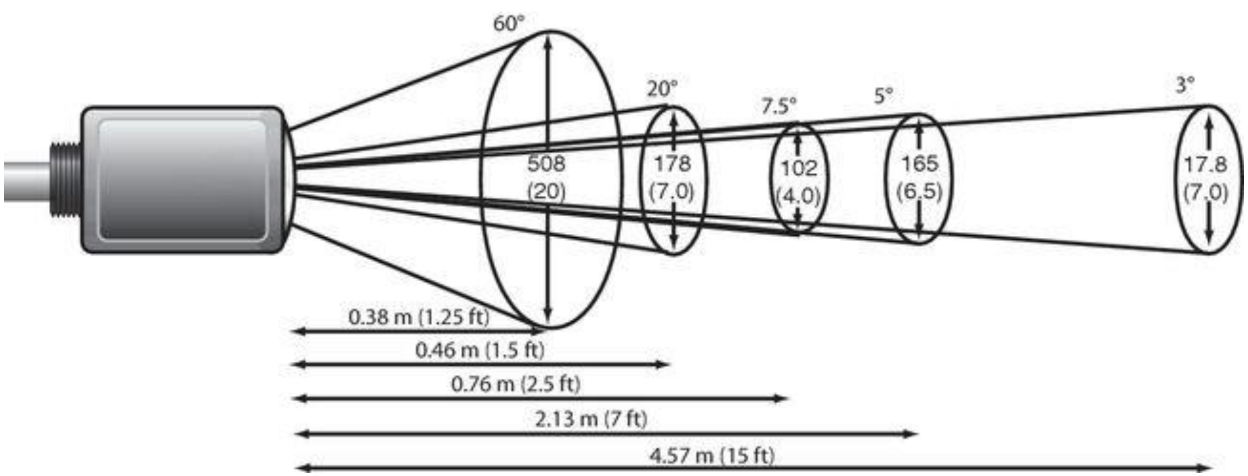
− need of mechanical contact with the object
− might influence significantly the motion of the object
− short lifespan
− need regular maintenance

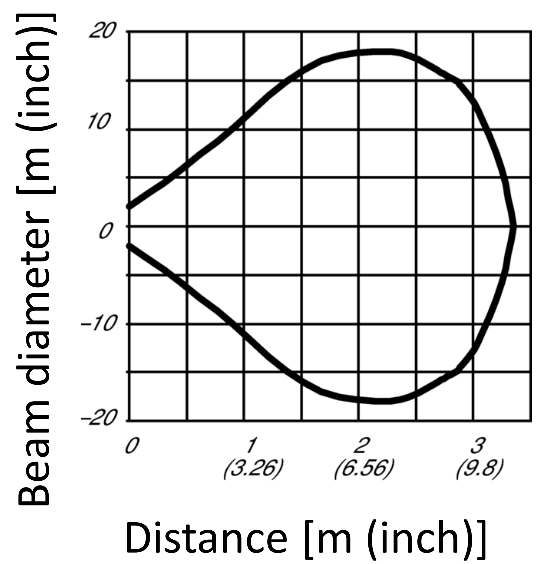
Photoelectric proximity sensors

- Light source: LED
  - Infrared or visible light (generally red)
  - laser
  - modulation (PWM) to prevent overheating
- Receiver: light sensor
  - photo diode or photo transistor
  - spectral sensitivity matched to the light source
- Optics
  - both at source and sensor side

Sensitivity

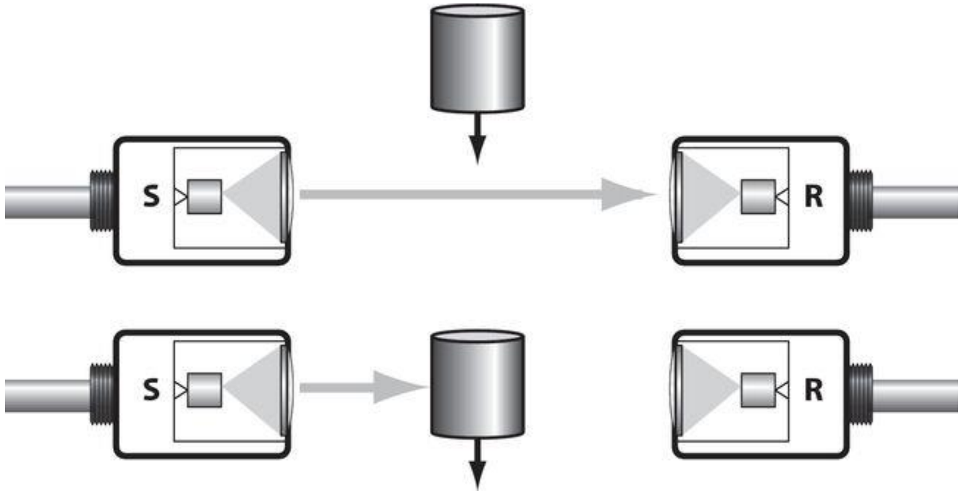
- Sensitivity depends on the shape of the beam
- Shape of the beam can be changed by the lens used at source and receiver sides

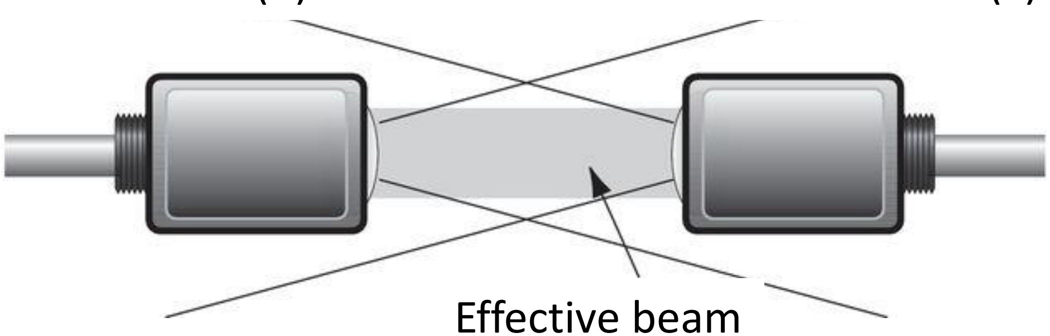




Through beam arrangement

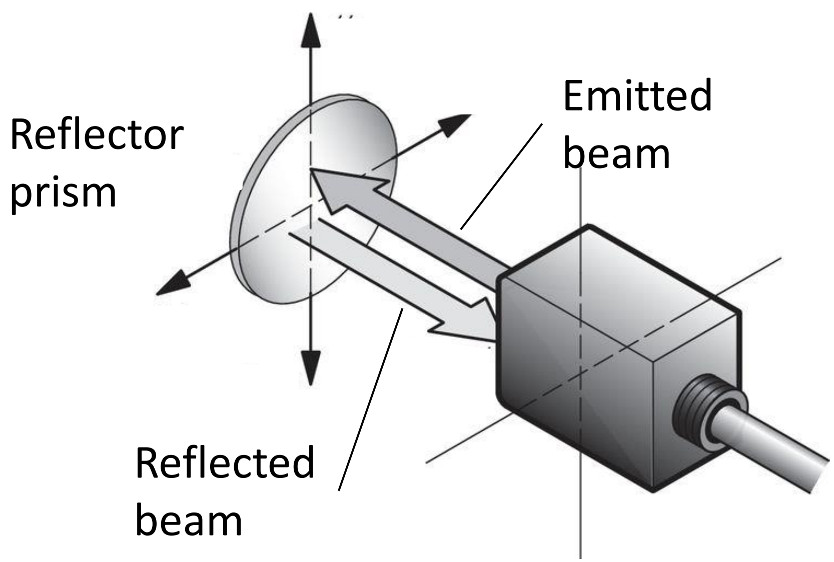
- Light source (S) and receiver (R) in distinct housings
- Allows long-distance sensing
- Providing appropriate field of view might be difficult

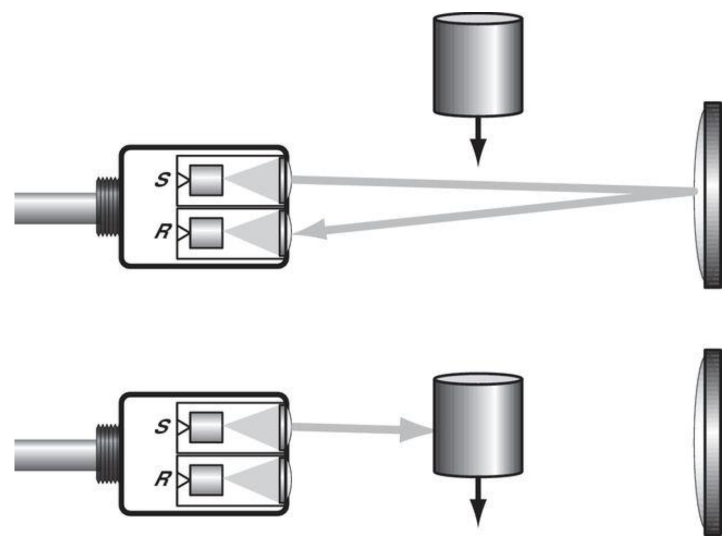




Retroreflective arrangement

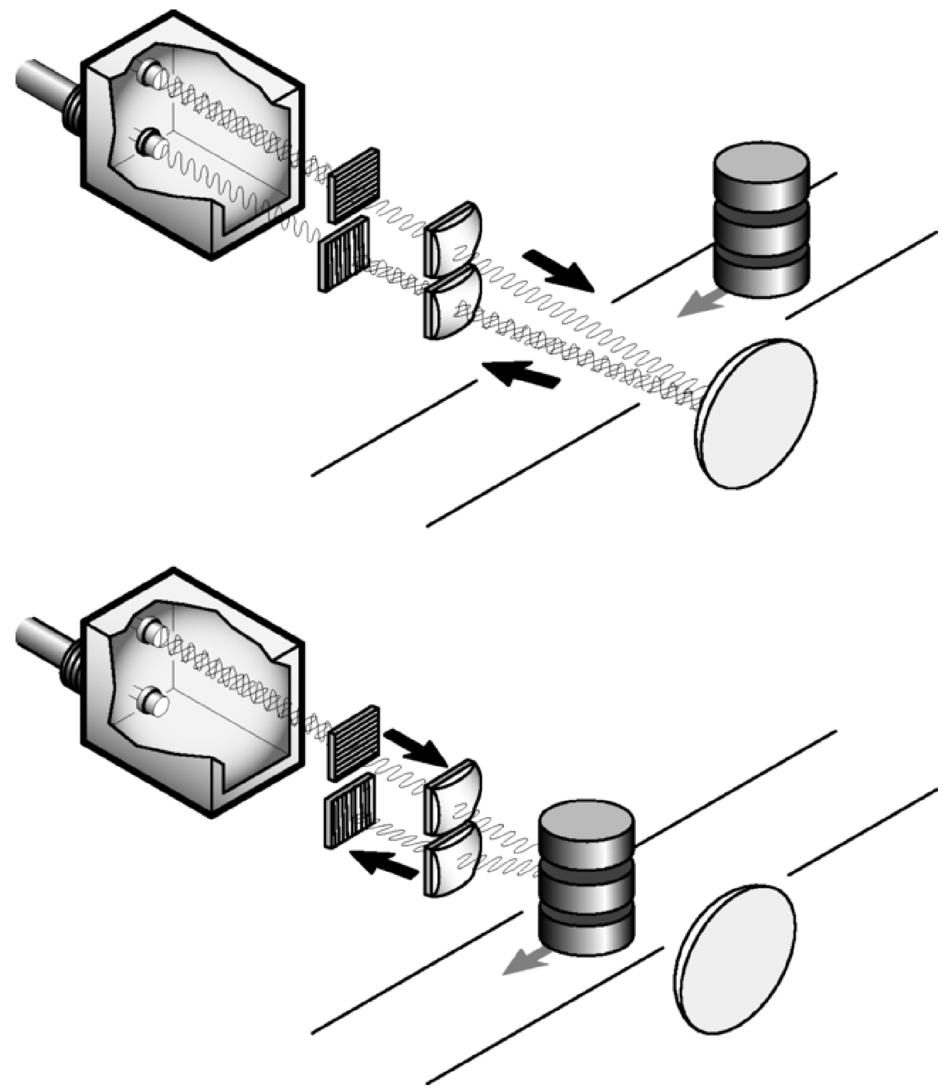
- Source and receiver installed inside the same housing
- Light reflector facing the sensor ($\pm 15°$)
- Lower cost, easier cabling
- Operation might be perturbed by shiny (reflective) objects





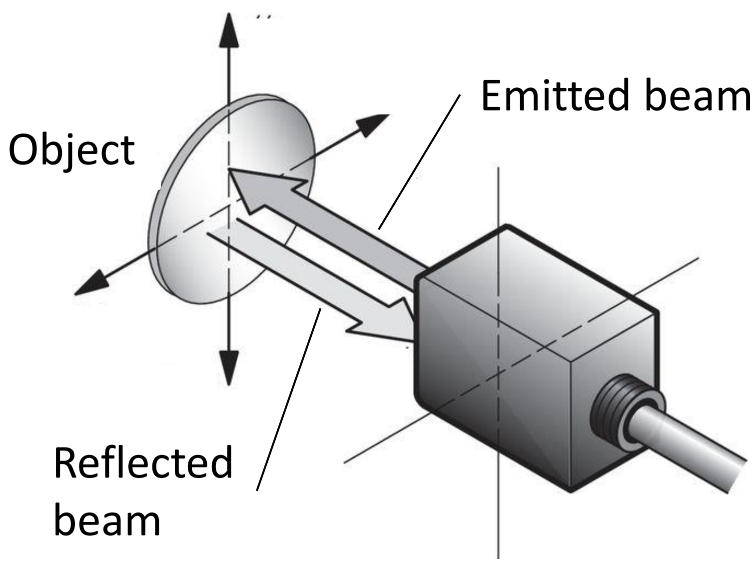
Retroreflective arrangement with polarizing reflector

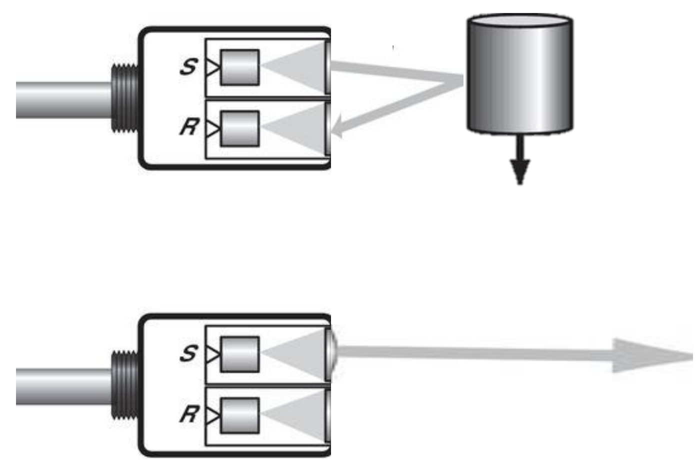
- Polarizing filters with perpendicular polarization located at source and receiver sides
- Special prism: changes polarity of the beam
- Shiny objects reflect beams with similar polarization, hence do not perturb sensing



Diffuse-reflective arrangement

- Source and receiver located at the same housing
- Receiver senses light reflected by the object itself
- Detection range is short, depends on the surface of the object
- Low reliability





Photoelectric proximity sensors

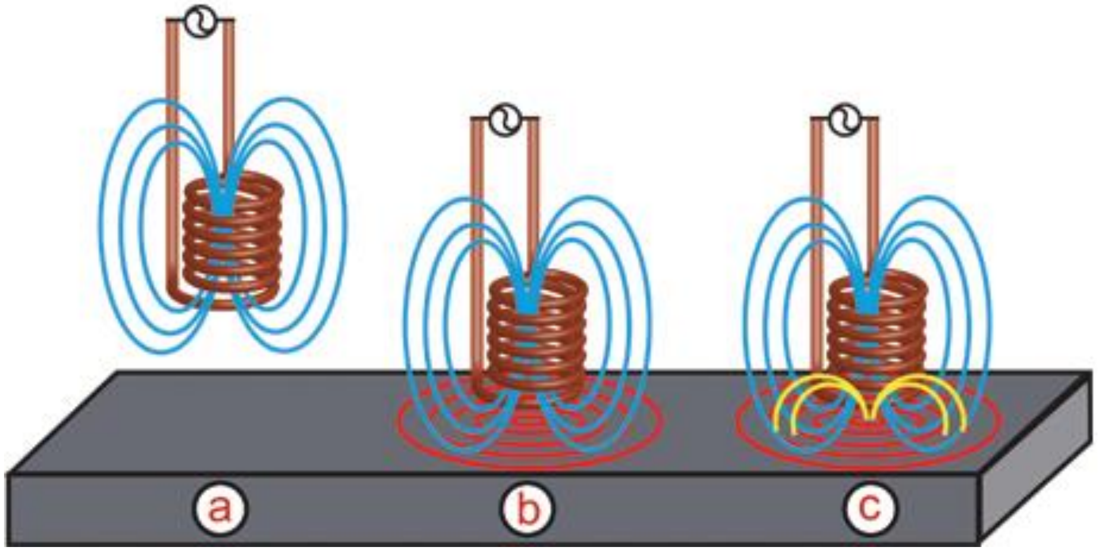
- \+ simple structure
- \+ non-contact operation
- \+ low cost
- \+ insensitive to noise
- \+ direct digital output
- \+ wide measurement range

- − sensitive to environmental conditions
- − sensitive to lighting conditions
- − needs maintenance (cleaning)

Inductive proximity sensors

Eddy current

- Eddy current is inducted within conductors by changing the magnetic field
- Eddy current is induced by Lorentz force
- According to Lenz's law, eddy current creates a magnetic field opposing the change of magnetic field which has induced it

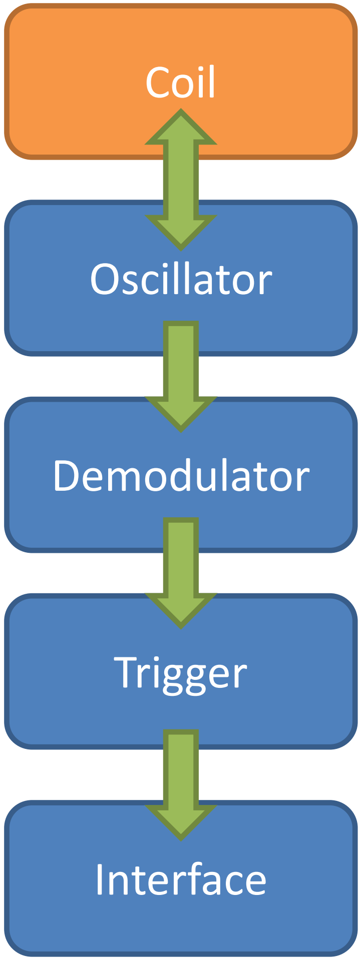


Eddy current

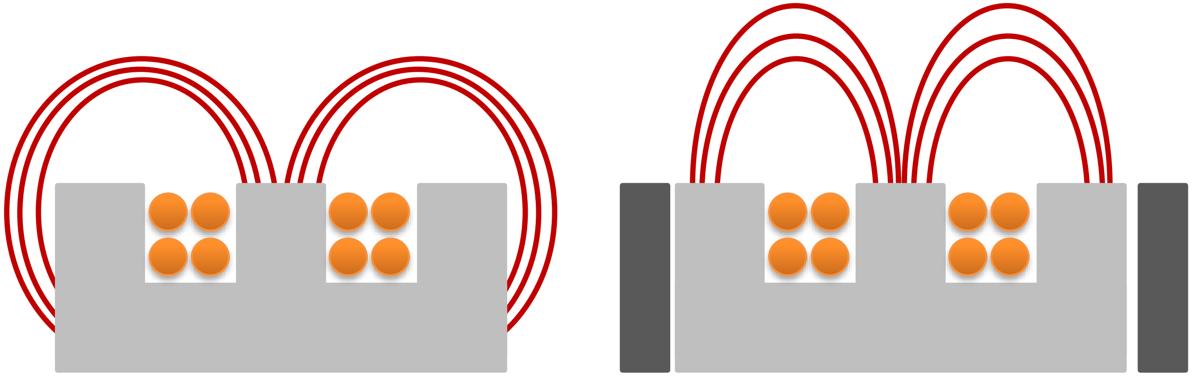
- Magnitude of current depends on
  - magnitude of magnetic force
  - frequency of magnetic field
  - resistivity of the conductor
  - temperature

- Eddy current affects the generating field: causes resistive loss

Inductive proximity sensors



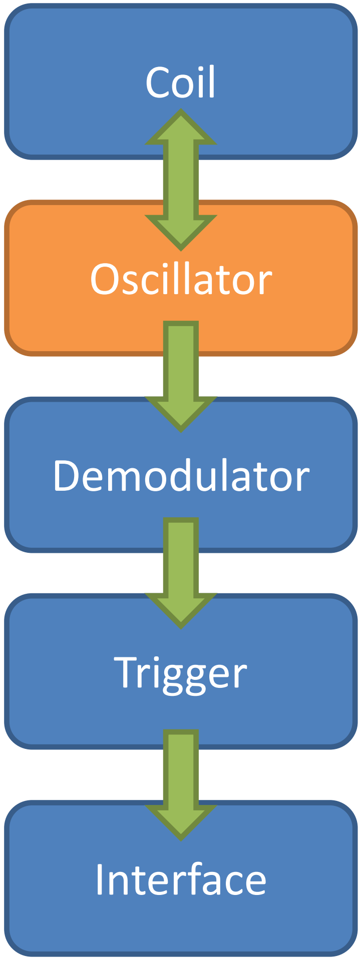
- Magnetic field is generated by a coil
- Coil might be shielded or unshielded



Unshielded coil

Shielded coil

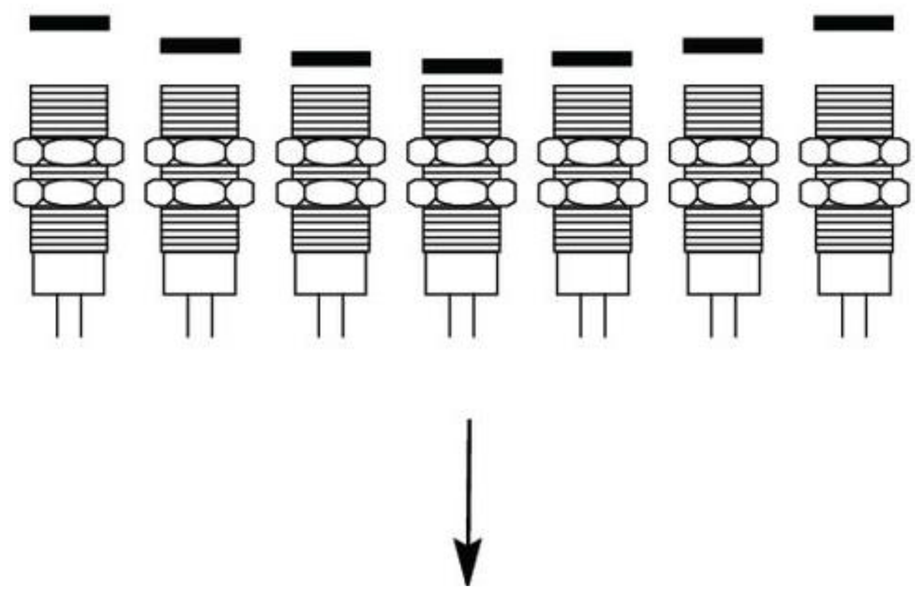
Inductive proximity sensors



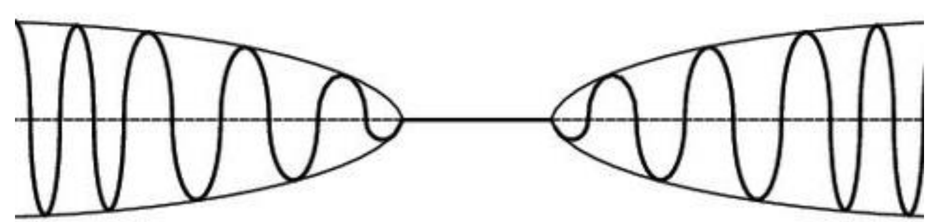
- Coil supplied by an oscillator
- LC/RLC oscillator
- Sine waveform

Principle of operation

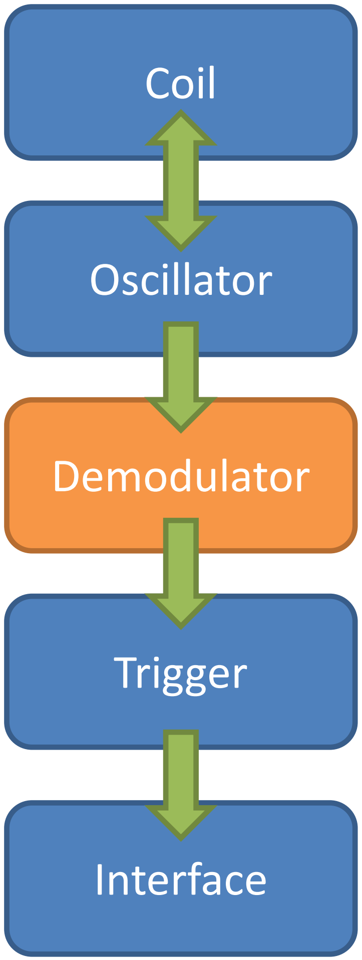
- A conductor approaches the electromagnetic field of the coil
- Eddy current is induced in the conductor
- Eddy current acts as a resistive load in the oscillator
- Damping of oscillator increases
- Frequency and magnitude of oscillator output decrease, finally the oscillator halts



Output of the oscillator



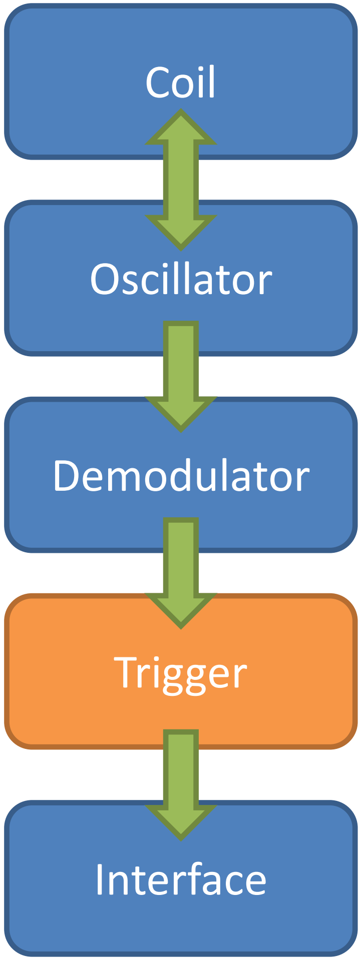
Inductive proximity sensors



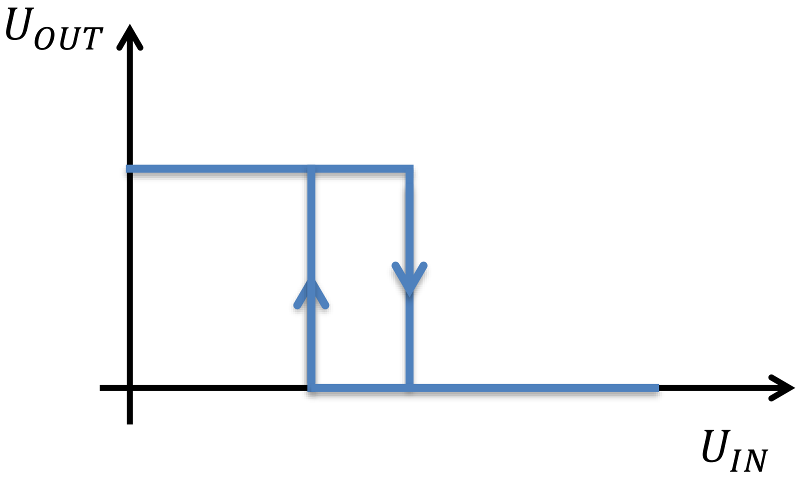
- Demodulator transforms the AC output of the oscillator to DC output

- Parts of the demodulator
  - rectifier
  - low-pass filter

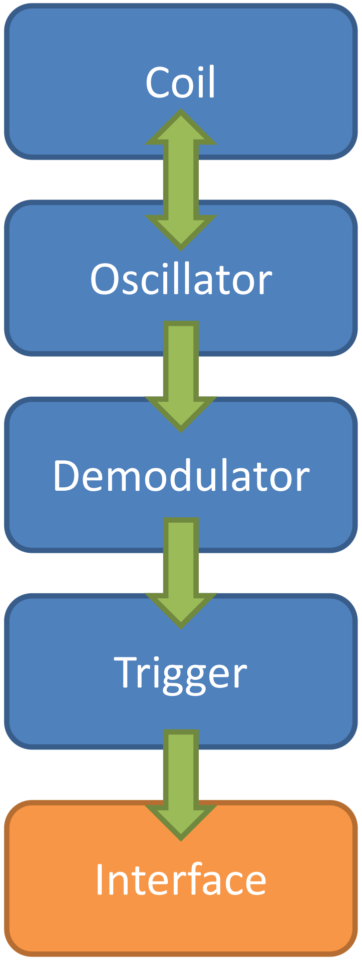
Inductive proximity sensors



- Trigger circuit converts output of the demodulator to a Boolean signal
- Hysteresis characteristics provided by a Schmitt-trigger circuit



Inductive proximity sensors



- Provides supply for other components
- Interfaces trigger output
- Optional analog output (very rare)

Sensitivity of inductive proximity sensors

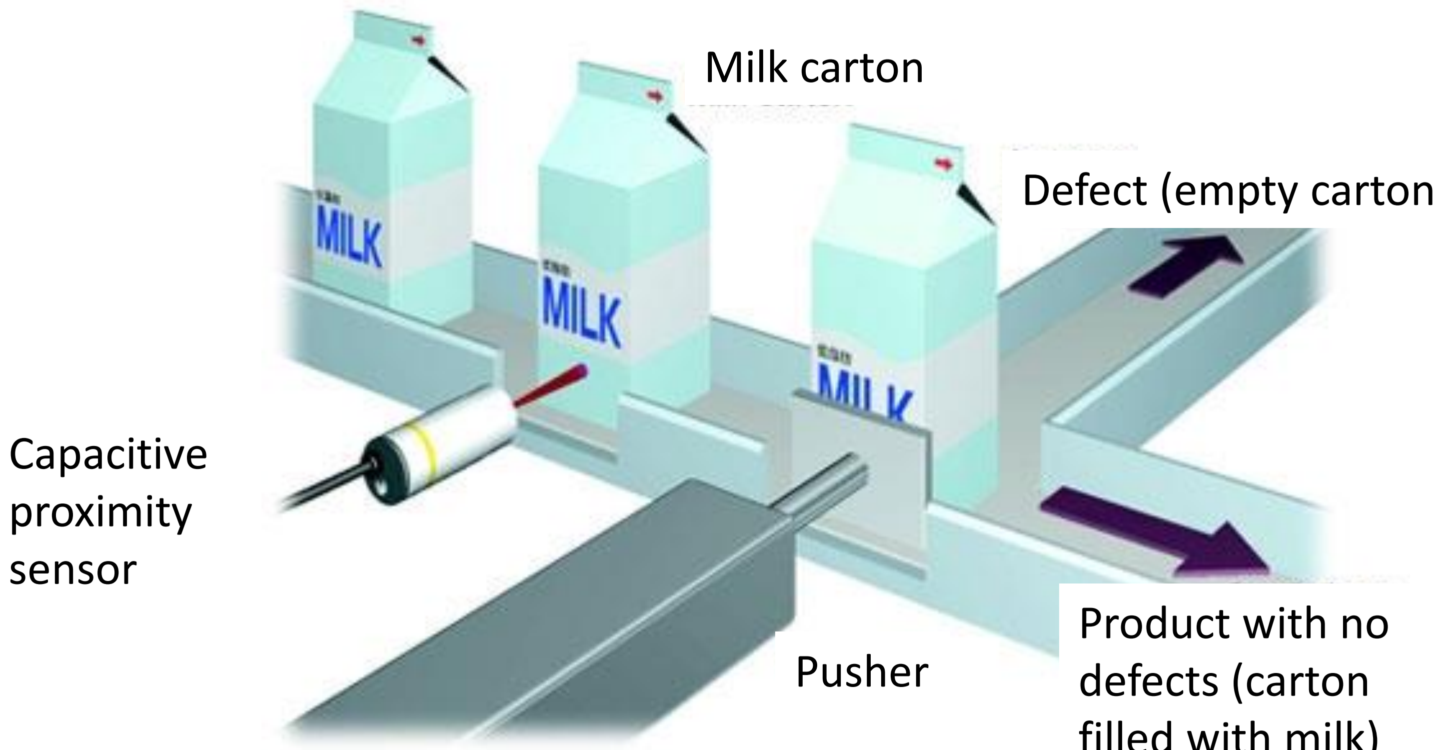
- Sensitivity depends on
  - frequency of excitation (2kHz – 10MHz)
  - shielding
  - material of object to be sensed
- Sensing distance is generally given for steel, for other materials a correction coefficient is used
  - stainless steel: 0.9
  - bronze: 0.5
  - copper: 0.4
- Rule of thumb: use half of the value indicated by the datasheet
- Sensing distance: 1-100 mm (rule of thumb: approximately equals to the diameter of the sensor)

Inductive proximity sensors

- \+ contactless sensing
- \+ long lifespan
- \+ insensitive to most environmental effects
- \+ mid-range sensing distance
- \+ low cost

- − **able to sense conductive objects only**
- − sensitive to disturbance caused by metallic objects in its proximity

Capacitive proximity sensors

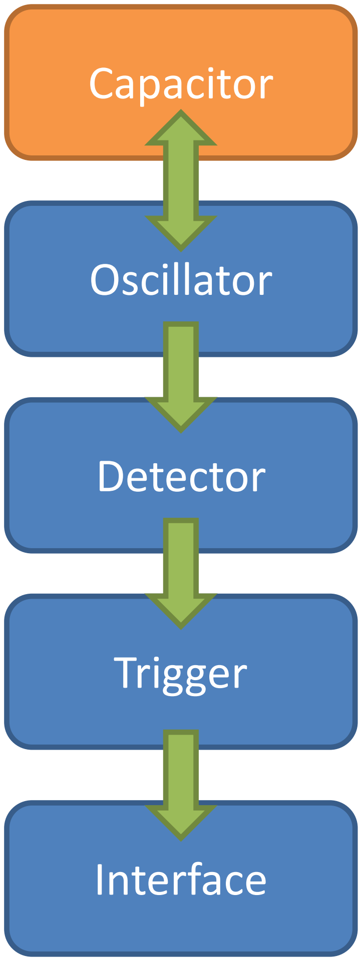


Capacitive proximity sensors

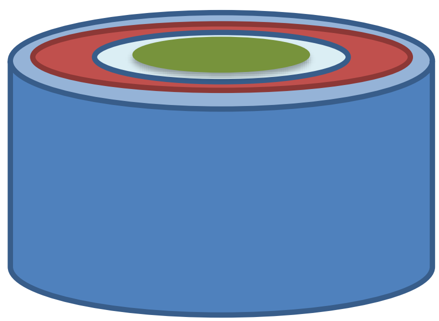
- Principle of operation: change of capacitance due to change of dielectric between the plates

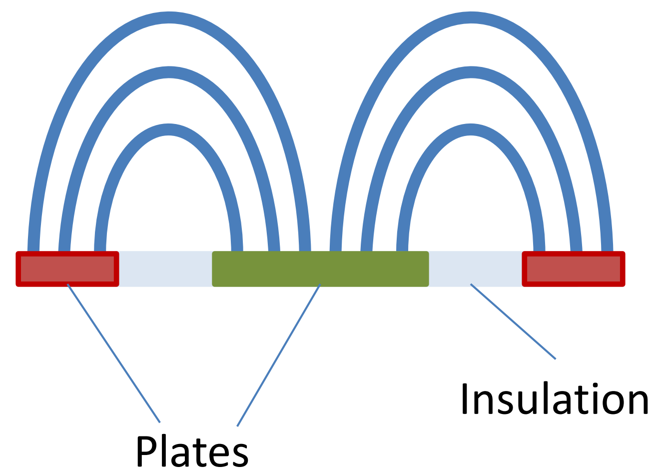
- Output of sensor depends on
  - distance of the object
  - size of the object
  - material of the object
  - environmental effects

Capacitive proximity sensors

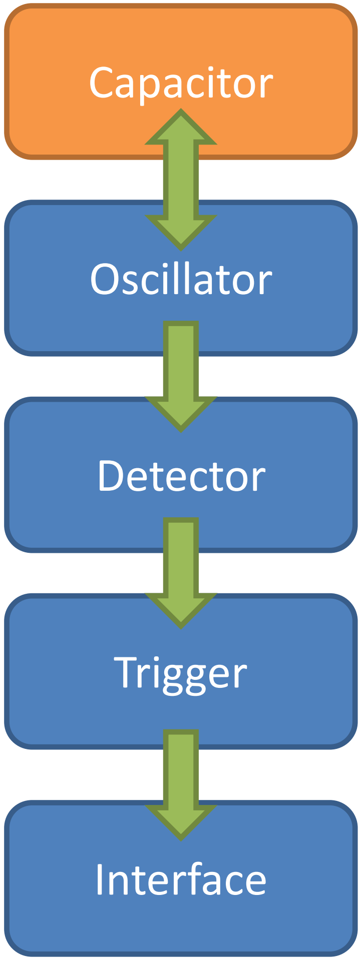


- Plates of the capacitor located at the tip of the sensor
- Shielded or unshielded plates

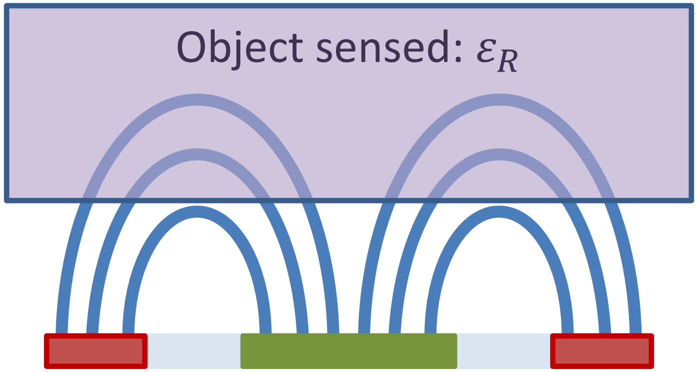




Capacitive proximity sensors

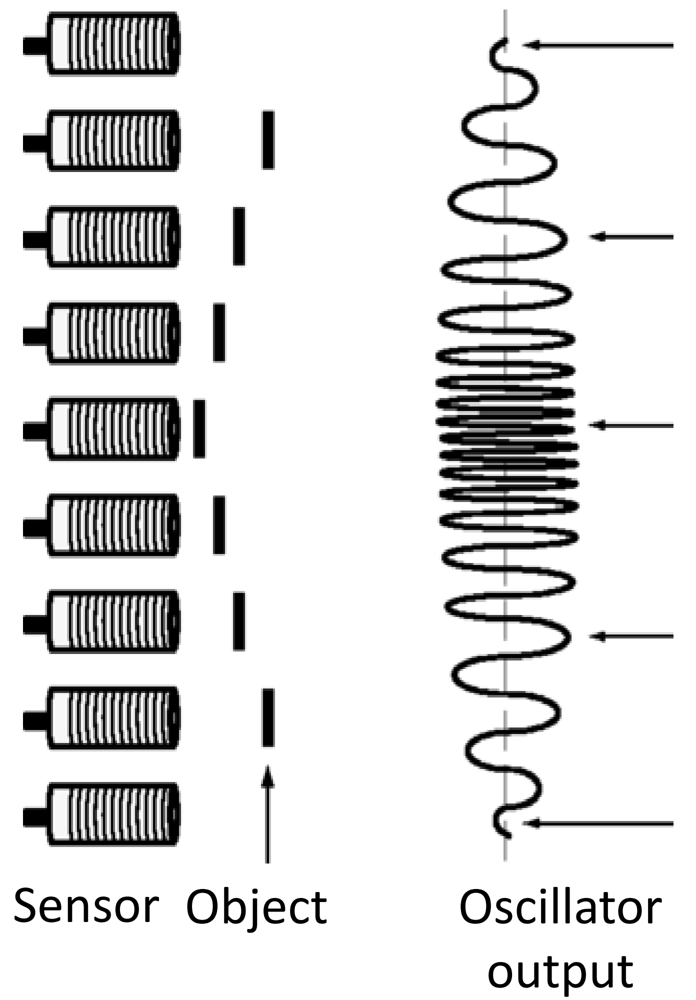


- Capacitor is part of an RC oscillator
- Capacitance is increased if field lines cross field with higher dielectric constant

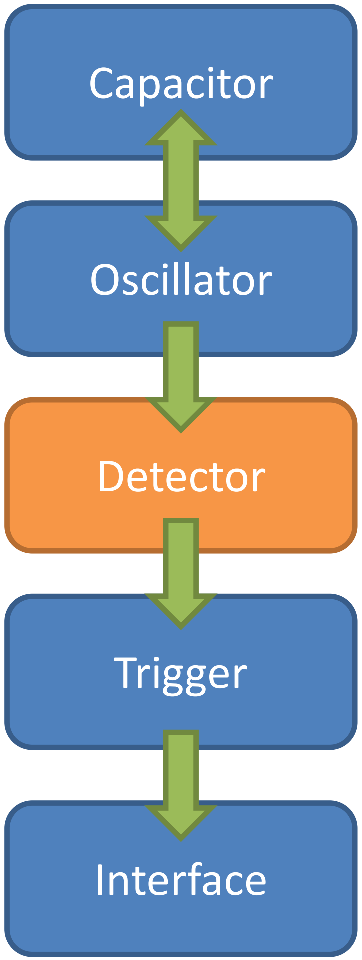


Principle of operation

- Capacitance of the capacitor is nearly zero if no object is present in its proximity, i.e. the oscillator does not operate
- Capacitance increases as the object approaches the sensor
- Increasing capacitance increases frequency and magnitude of oscillator output

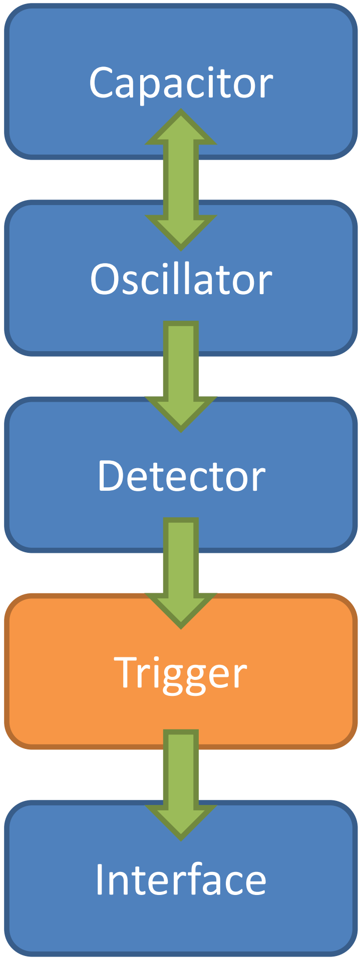


Capacitive proximity sensors



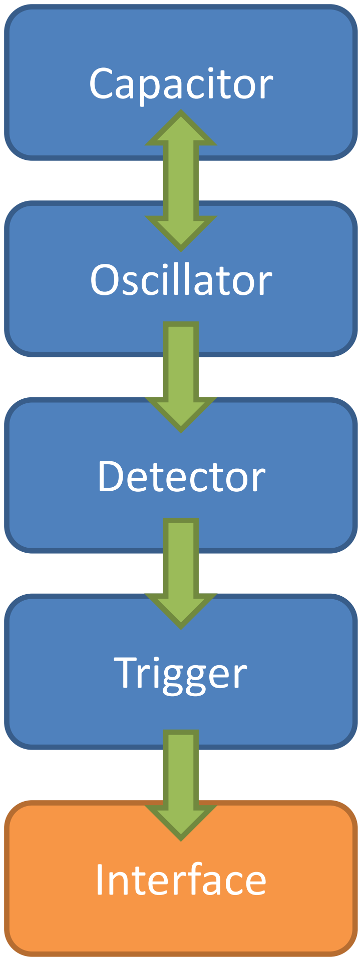
- Detector converts the AC output of the oscillator to a DC output
- Applicable detector circuitry
  - rectifier + low-pass filter
  - frequency – voltage converter
  - direct frequency output (rare)

Capacitive proximity sensors



- Trigger: based on DC voltage or comparation of frequency
- Hysteresis
- Trigger level is commonly adjustable (adjusting to material)

Capacitive proximity sensors



- Power supply for other components
- Interfacing trigger output
- Optional analog output (rare)

Capacitive proximity sensors

- \+ non-contact sensing
- \+ able to sense both conductive and non-conductive objects
- \+ long lifespan
- \+ able to “see through” some material (e.g. milk carton)

- − limited sensing range (2-20mm)
- − sensitive to environmental conditions (e.g. humidity)
- − higher cost
- − not applicable for sensing fast moving objects

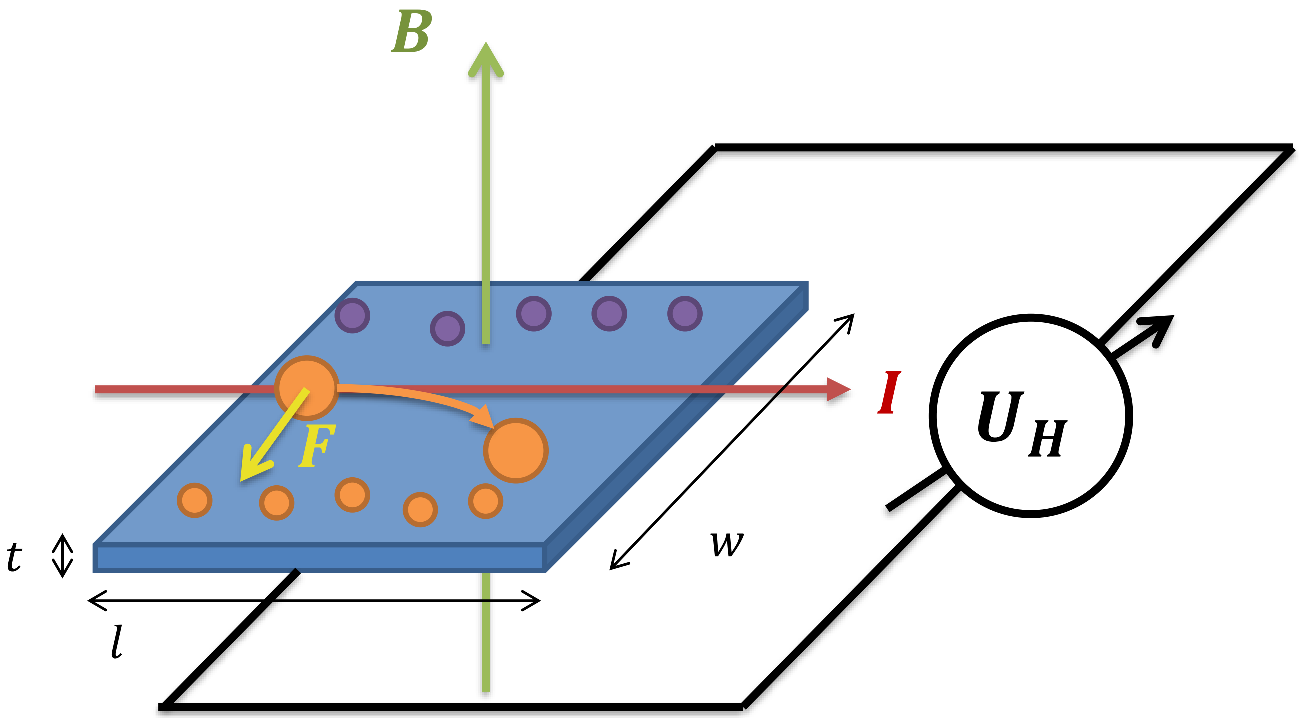
Magnetic proximity switches

- Sensing based on permanent magnetic properties of the object
- Contactless sensing, even from outside a hermetically sealed component

Reed switch

- Reed switch (Reed relay)
  - overlapping ferromagnetic contacts inside a sealed capsule filled with inert gas
  - contacts are closed if magnetic field is applied
  - able to switch limited power only
  - limited switching frequency and lifespan

Hall effect



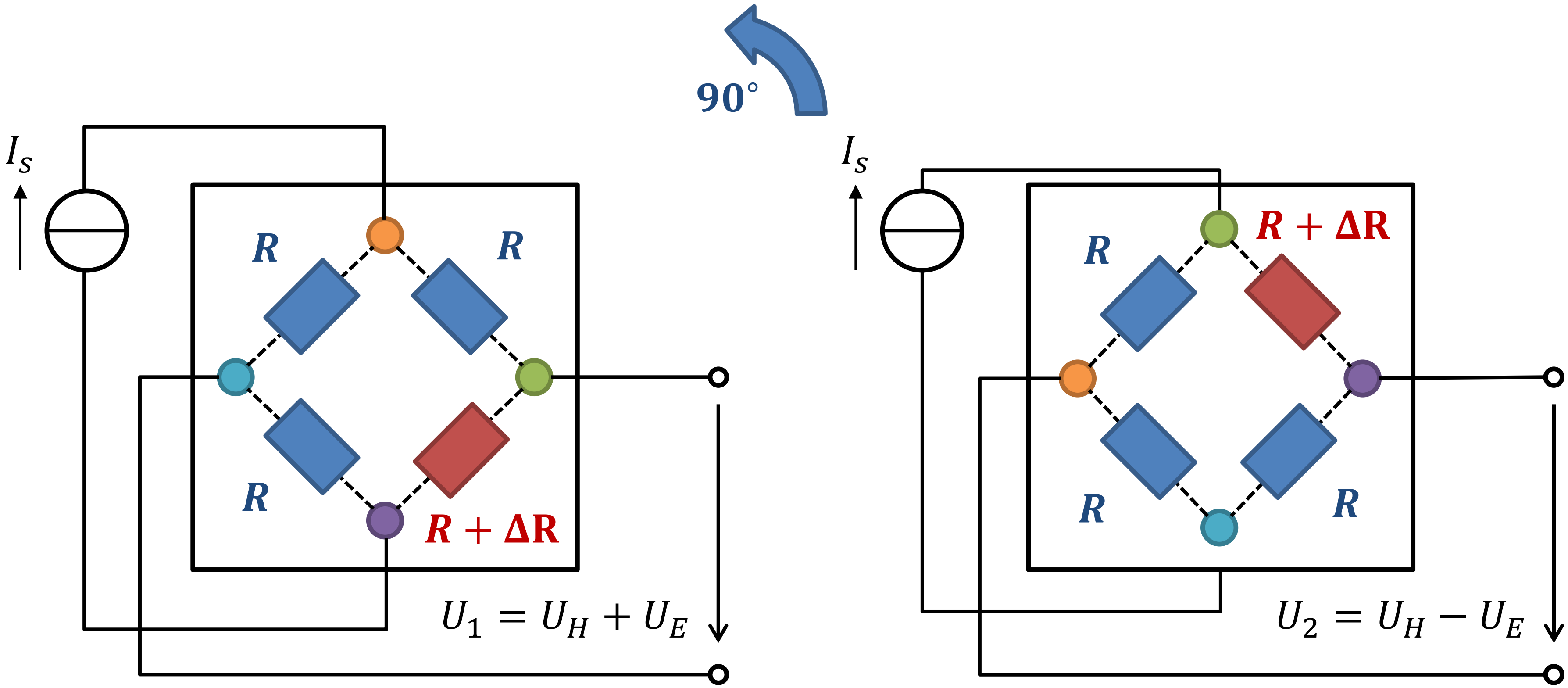
- Lorentz force:
  $F = q(E + v \times B)$
- $E = \frac{U_H}{w}$
- $v = \frac{l}{T}$
- $I = \frac{Q}{T}$
- $Q = l \cdot w \cdot t \cdot n \cdot e$
- $\boldsymbol{U_H = -\frac{IB}{n \cdot t \cdot e}}$
- $\boldsymbol{R_H = -\frac{1}{nte}}$
- $\boldsymbol{U_H = R_H I B}$

- n: charge carrier density
- e: elementary charge

Hall effect sensor
(Hall sensor)

- Simple semiconductor plate
- Problems
  - temperature dependence
  - piezoresistive effect originating from mechanical stress
- Offset error
  - added to the Hall voltage, value is unknown
  - the sensor might be considered as a bridge, i.e. offset can be thought as result of an unbalanced bridge

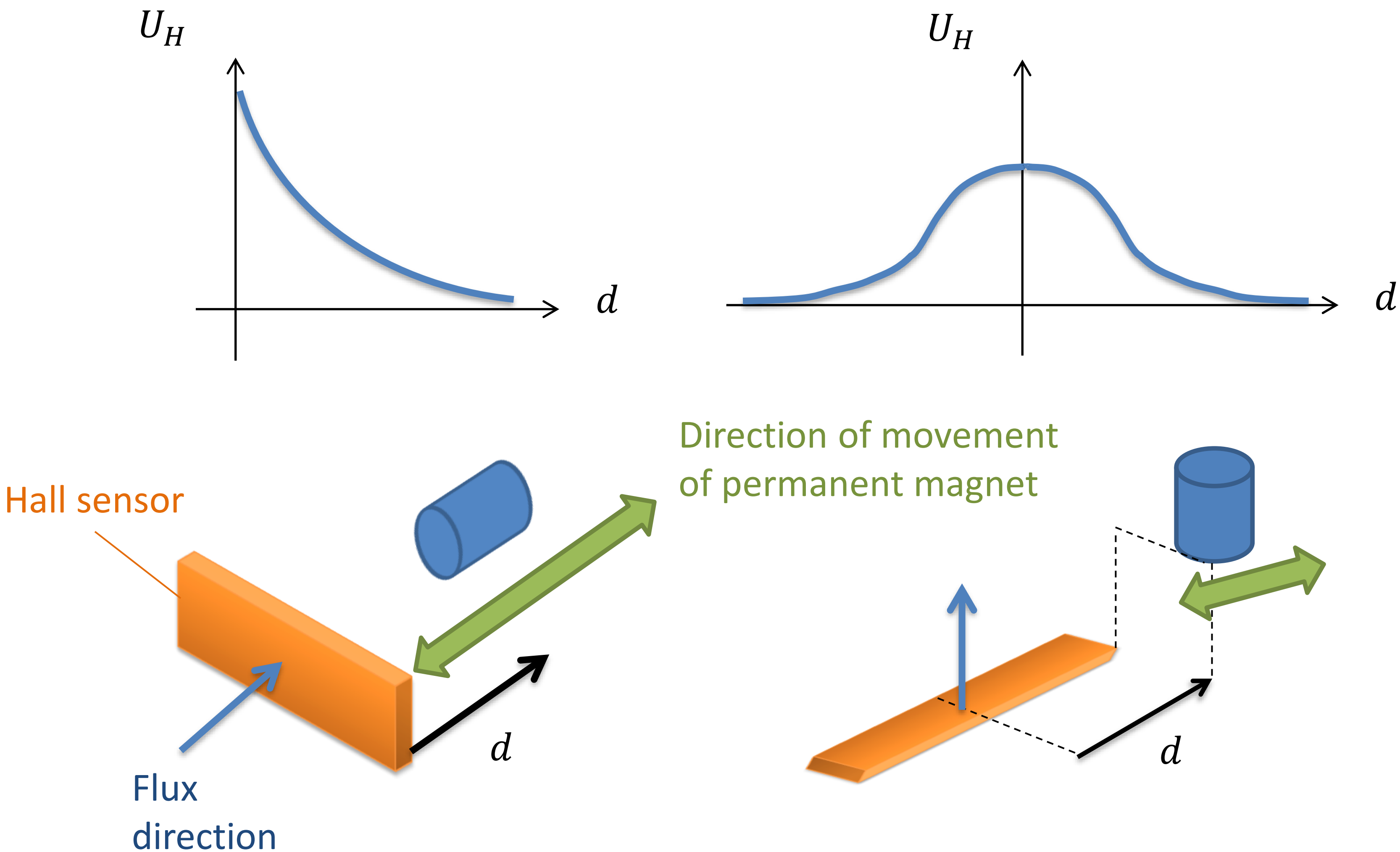
Compensation of offset error



$$U_1 + U_2 = 2U_H$$

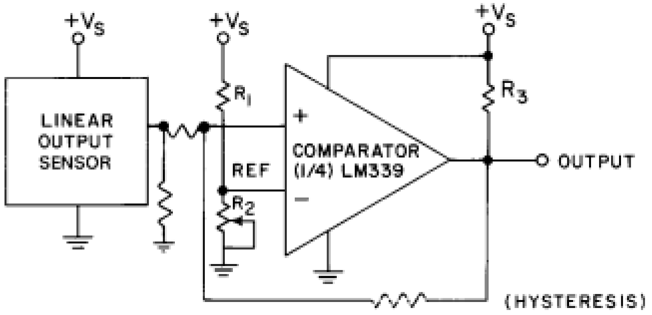
By using two Hall sensors rotated by 90° the offset error can be compensated.

Hall sensor in unipolar magnetic field

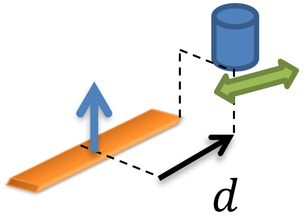


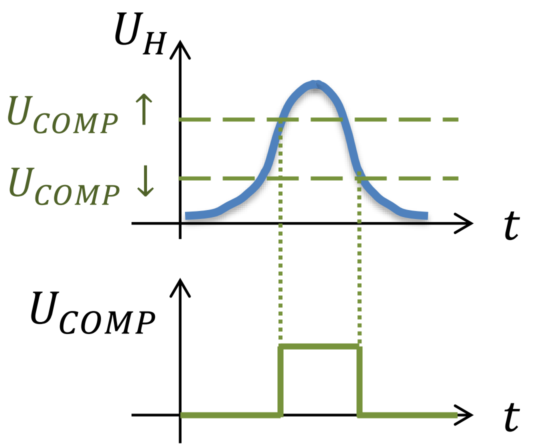
Typical applications of Hall sensors

- Proximity switch
  - hysteresis comparator
  - permanent magnet located on the moving object



- Measurement of discrete positions
  - multiple Hall sensors located along the path
  - used in incremental encoders





Magnetic proximity sensors

+ simple and robust construction
+ contactless sensing
+ simple interfacing
+ very low cost

− low sensing range (20mm)
− needs the use of a permanent magnet

Displacement sensors

- Displacement: change of location
  - translational (linear) – change of position, displacement
  - rotational – change of orientation, rotation
  - rotation can be related to displacement along the circumference of a circle – sensing principles are the same

Units - displacement

- Meter - m
  - SI base unit
  - defined by the speed of light
  - easy-to-use unit

- Imperial units
  - inch (’’) – 1’’= 2.54 cm
  - foot (’) – 1’=12’’ = 0.3048m
  - yard (yd) – 1yd = 3’ = 91,4 cm

Units - rotation

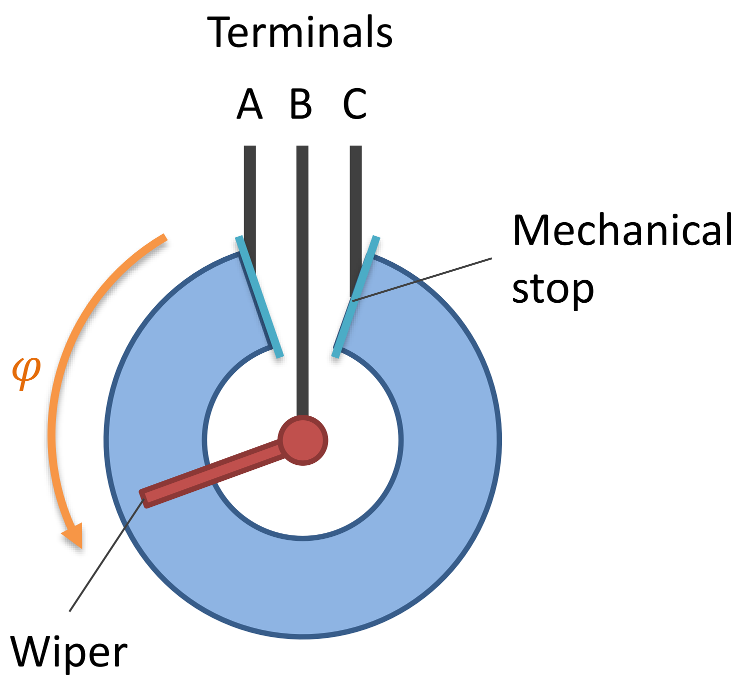
- Rotation
  - radian– rad
  - degree – °
  - minute of arc – 1’ = 1/60 °
  - second of arc – 1’’ = 1/60 ’

- Revolution
  - radians/sec
  - Revolution Per Minute (RPM) – $1\ \mathrm{RPM} = \frac{2\pi}{60}\frac{\mathrm{rad}}{\mathrm{sec}}$

Resistive displacement sensors

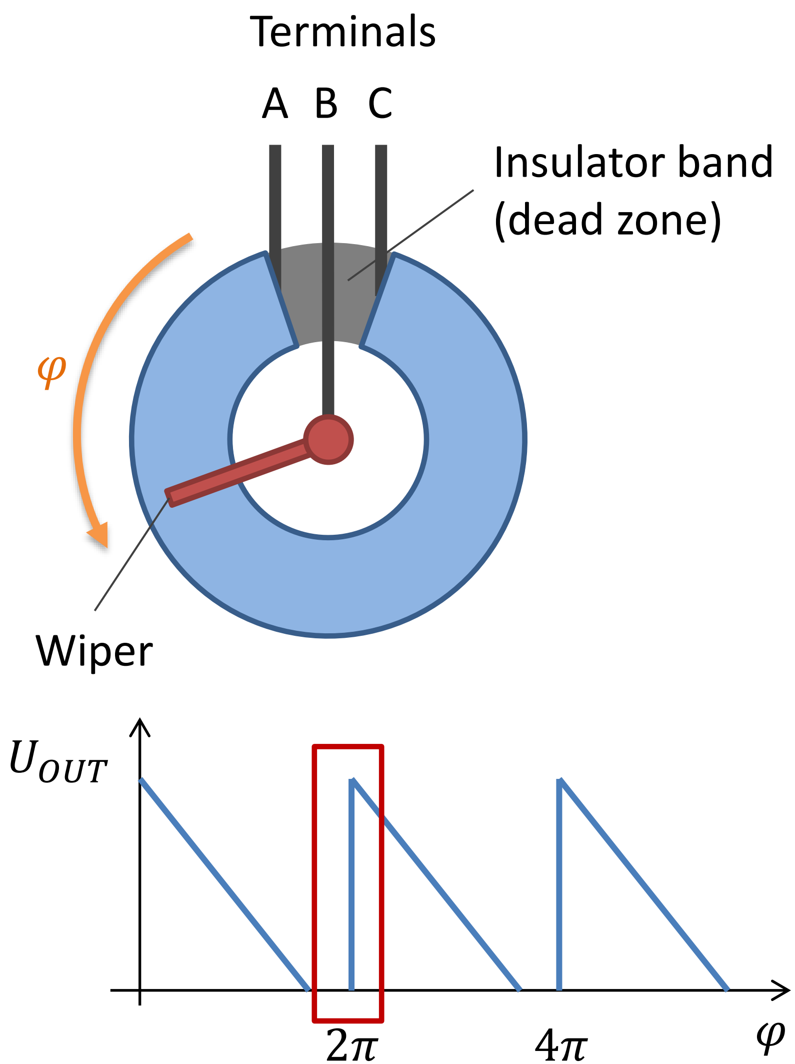
- Wiper moving on a resistive track
- Resistance depends on the displacement
- Well-known, mature technology

Rotary potentiometer



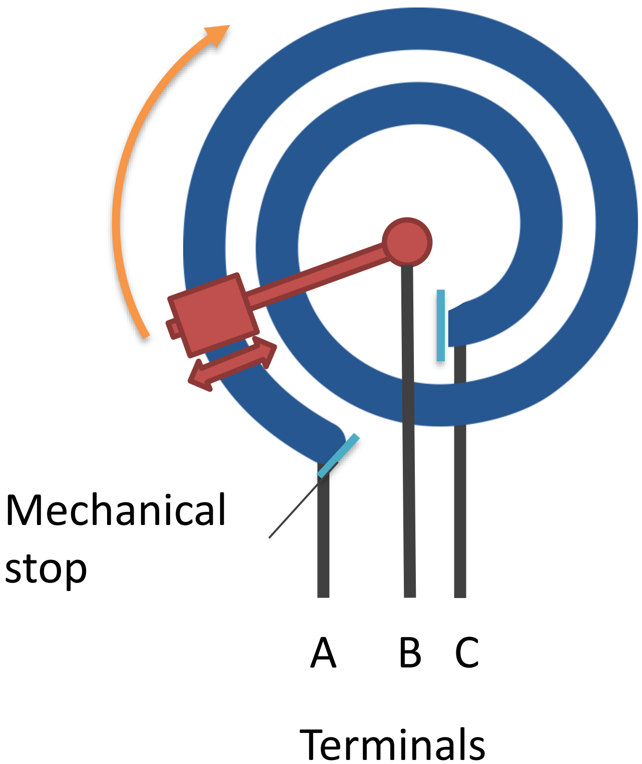
- Resistance depends on the angular position of the wiper
- Linear characteristics (other functions, e.g. logarithmic can also be realized)
- Resistance increases in CW or CCW direction, depending on the connection of terminals

Multi-turn rotary potentiometer



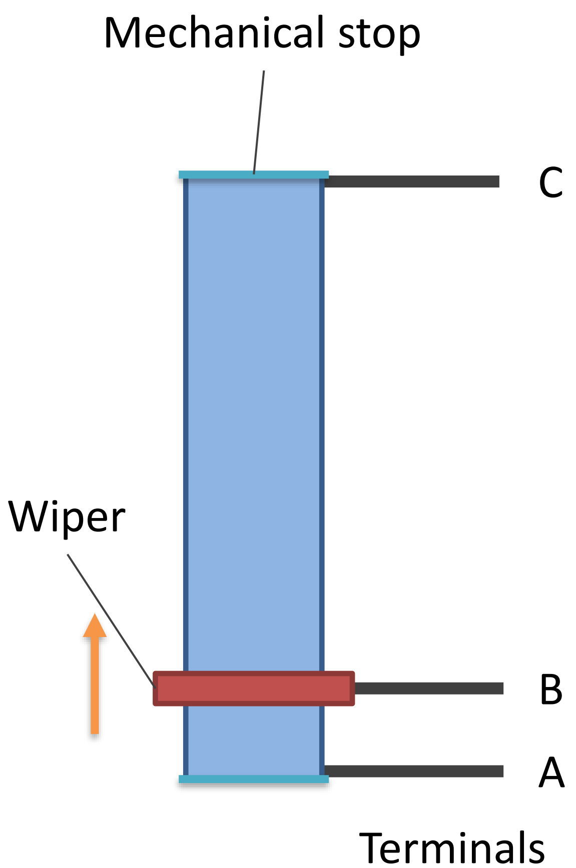
- Mechanical stops are not installed, revolution of wiper is not limited
- Dead zone of insulator band: infinite resistance – zero voltage
- Rising or falling edge when passing the insulator – resistor border
- Number of full revolutions can be measured by counting the edges
- Problem: no reference position, absolute measurement within one single revolution only

Helical potentiomener



- Wiper moves on a helical resistive track
- Multiple full revolutions
- Linear characteristics
- Number of revolutions is limited
- Provides absolute angular position (not only within one single revolution)

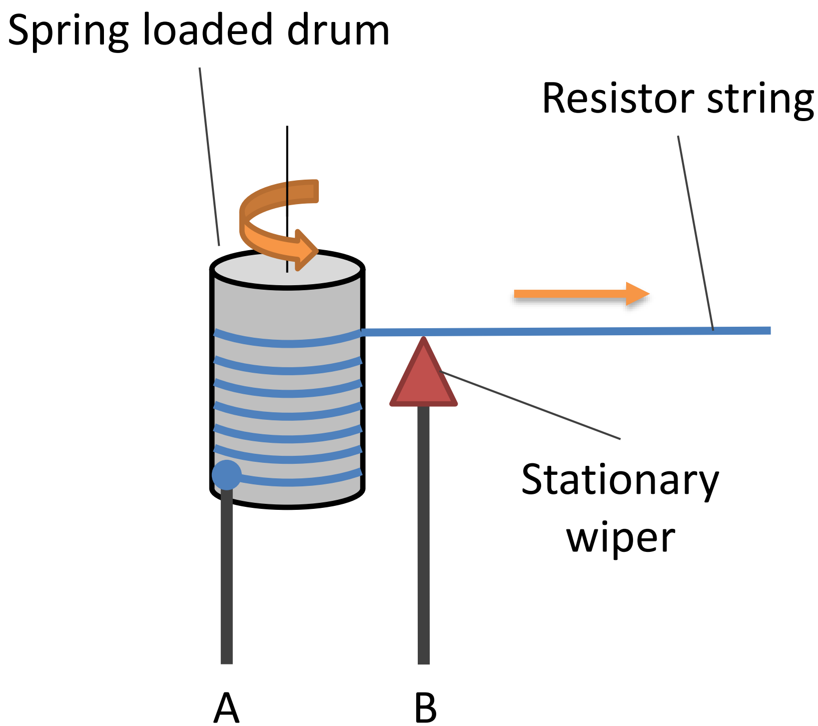
Linear potentiometer



- Resistance depends on translational position
- Linear characteristics (other functions, e.g. logarithmic can also be realized)
- Measurement range up to 400mm

String potentiomenter

(yo-yo pot)



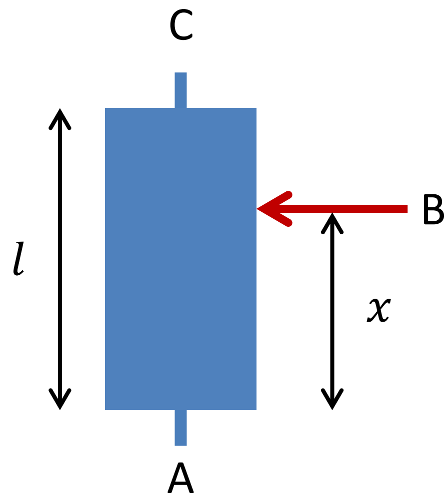
- Wiper is stationary, resistance depends on the length of resistor string on the drum
- Measurement range up to 100m

Resistive elements

- Wire-wound potentiometers
  - limited resolution
  - high power
- Film potentiometers
  - unlimited resolution
  - limited power
  - sensitive to environmental effects
- Cermet: ceramic-metal composite
  - unlimited resolution
  - high power, low noise
  - sensitive to environmental effects
- Carbon composite
  - low cost
  - highly sensitive to environmental effects

Wire-wound potentiometer

Displacement measurement with potentiometers



- Total resistance (ρ: resistivity of a conductor of given cross-section $[\Omega/\mathrm{m}]$):

$$R_0 = R_{AC} = \rho l$$

- Resistance component related to displacement:

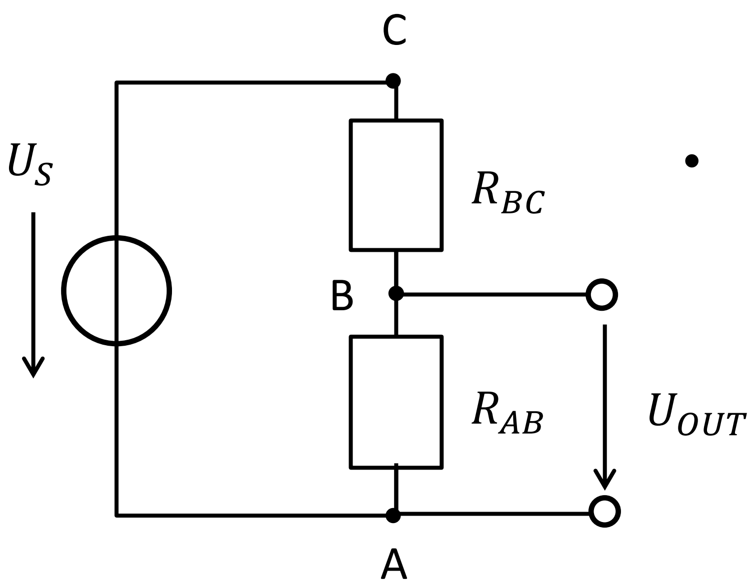
$$R = R_{AB} = \rho x$$

$$\Rightarrow \boldsymbol{\frac{R}{R_0} = \frac{x}{l}}$$

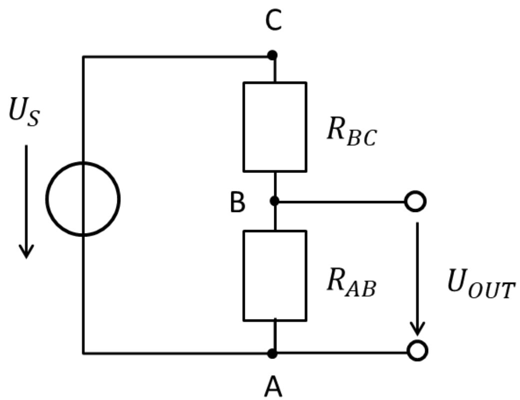
- Output voltage:

$$U_{OUT} = U_{AB} = \frac{R_{AB}}{R_{AB} + R_{BC}} U_S = \frac{R}{R_0} U_S$$

$$\boldsymbol{U_{OUT} = \frac{x}{l} U_S}$$



Thermal and mechanical effects



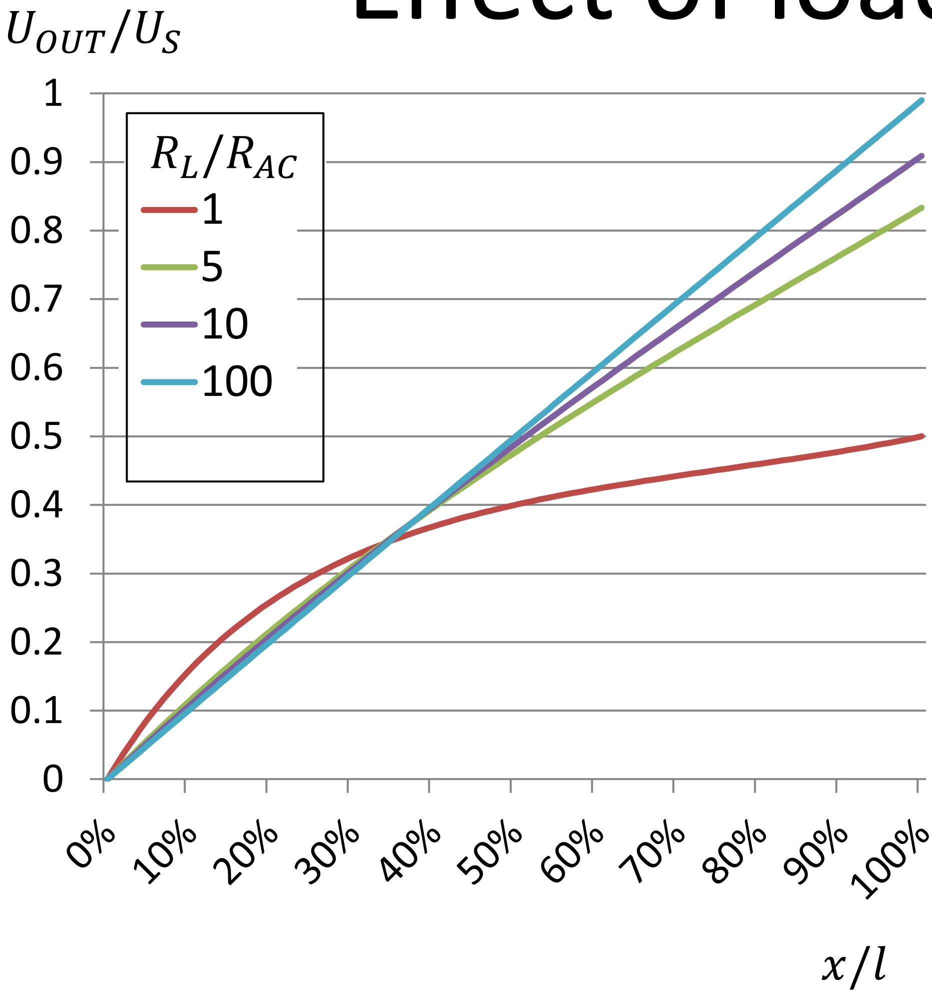
$$U_{OUT}\Big|_{\vartheta=\vartheta_0,\varepsilon=0} = \frac{R_{AB}}{R_{AB}+R_{BC}}U_S = \frac{R_{AB}}{R_{AC}}U_S = \frac{x}{l}U_S$$

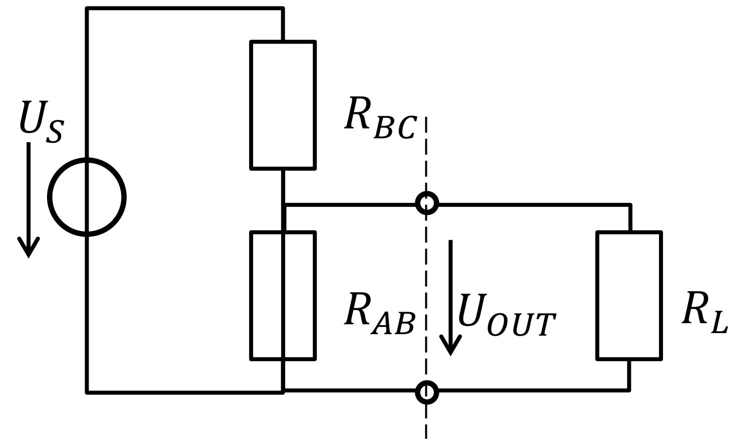
Effect of temperature change and mechanical stress:

$$U_{OUT} = \frac{\rho_0(1+g\varepsilon)(1+\alpha\Delta\vartheta)x}{\rho_0(1+g\varepsilon)(1+\alpha\Delta\vartheta)l}U_S = \frac{x}{l}U_S$$

Output voltage is independent of mechanical stress and temperature.

Effect of load resistance





- $U_{OUT} = \dfrac{\frac{R_{AB}R_L}{R_{AB}+R_L}}{R_{BC}+\frac{R_{AB}R_L}{R_{AB}+R_L}} U_S$
- $R_L \gg R_{AC}$: $U_{OUT} \approx \dfrac{R_{AB}}{R_{AB}+R_{AC}} U_S$

Apply infinite load resistance: use an amplifier

Resistive displacement sensors

- Significant problem: mechanical contact
  - friction – inhibits the displacement to be measured
  - hysteresis (backlash)
  - sensitivity to vibration

- Lifespan: 1-10 million cycles
  - 1 cycle / second
  - 86400 cycles / day
  - 10 million cycles ≈ 115 days!

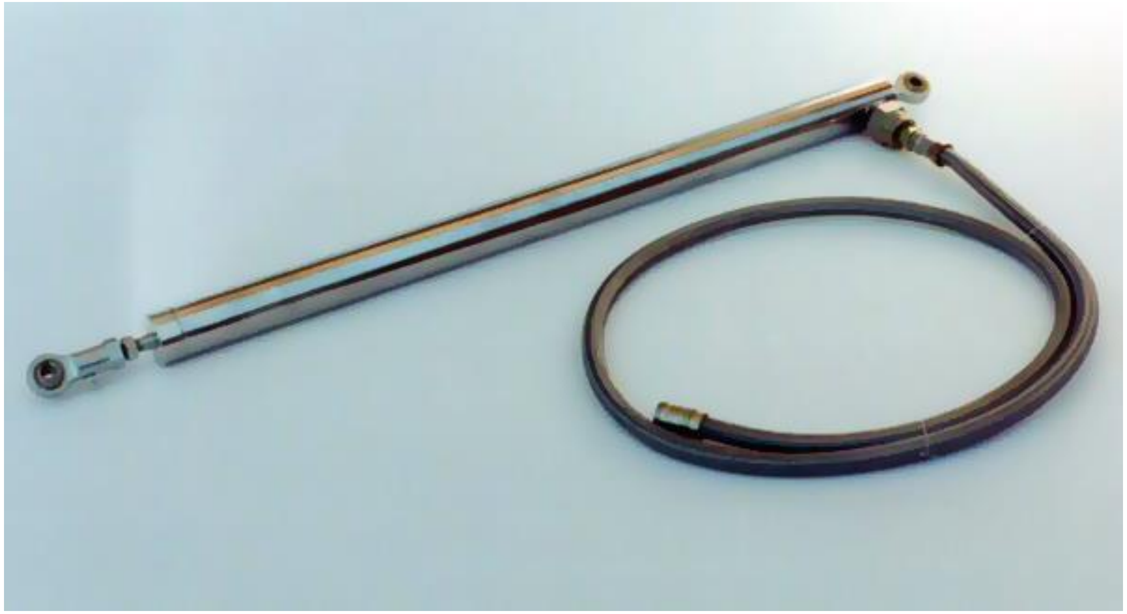
Resistive displacement sensors

+ simple structure
+ low cost
+ insensitive to electromagnetic noise
+ simple circuitry

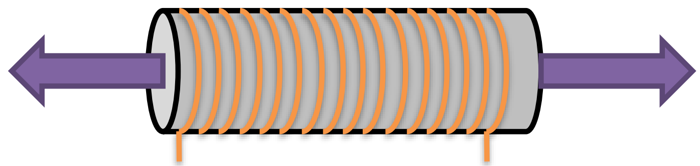
− mechanical contact
− backlash
− short lifespan
− low accuracy

Inductive displacement sensors

- Principle of operation: electromagnetic inductivity
- Contactless measurement
- Wide measurement range

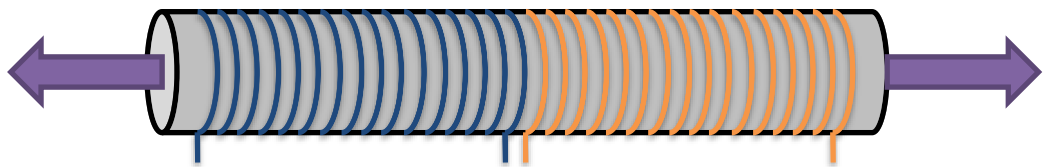


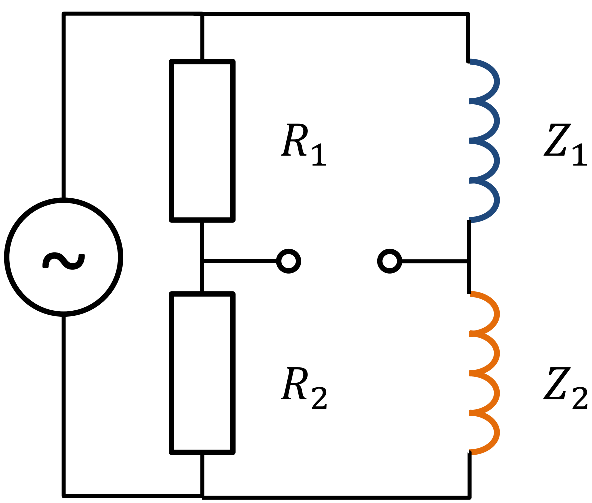
Linear variable inductor



- Inductivity of the coil depends on the position of ferromagnetic core
- Change of inductivity can be measured
- Problems: nonlinearity, significant thermal error, low sensitivity

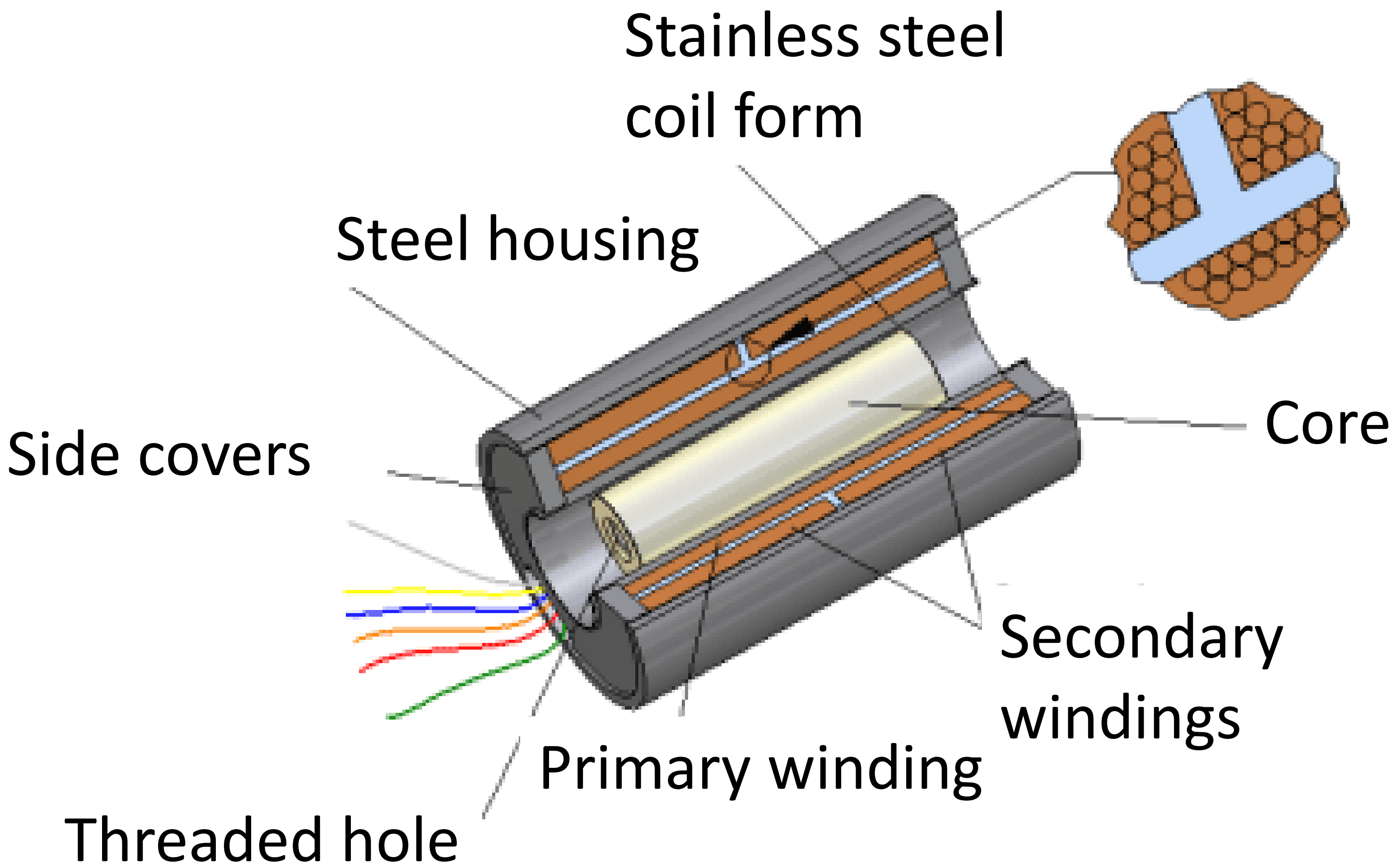
Linear variable inductor



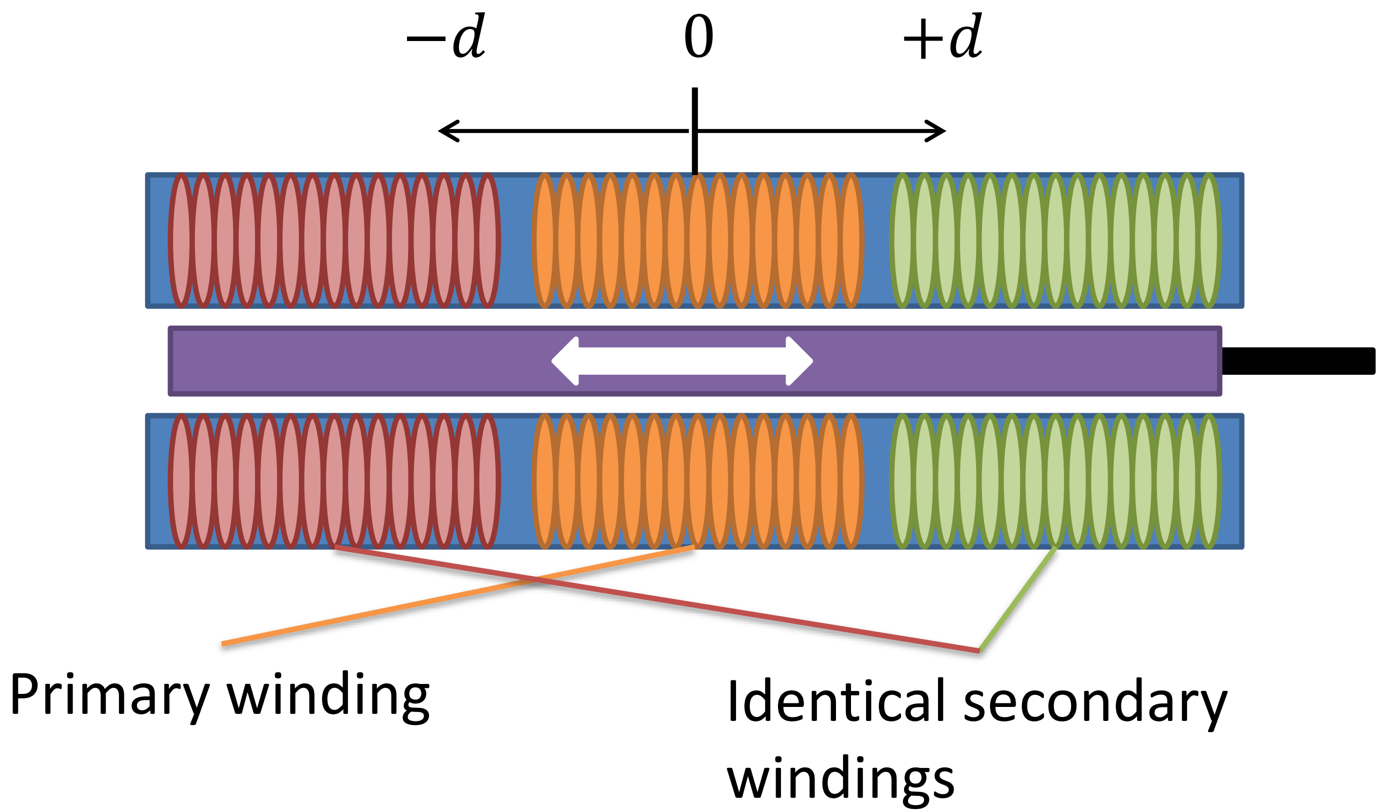


- Sensitivity can be by a bridge circuit
- Wide linear range with careful selection of elements
- Simple structure
- Significant thermal error
- Accuracy up to 1%

Linear Variable Difference Transducer - LVDT



Linear Variable Difference Transducer - LVDT

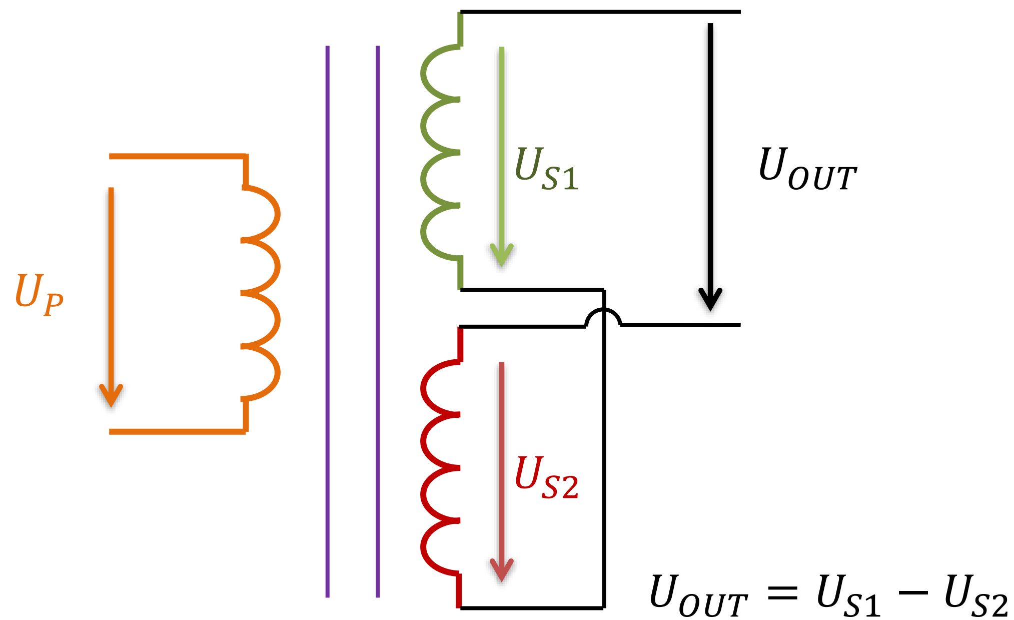


LVDT

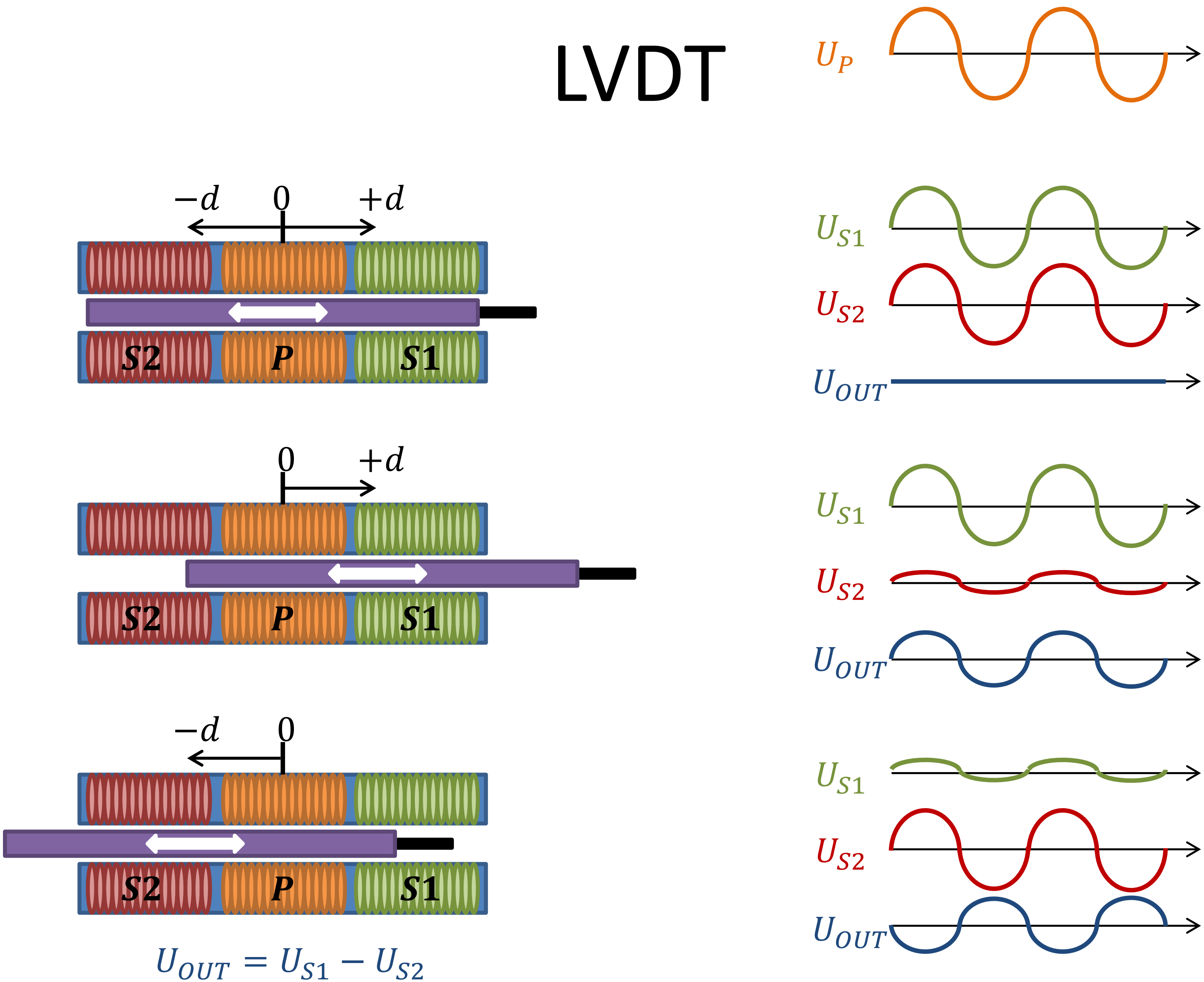
- $U_P = U\sin(\omega t)$
- $U_{S1} = \frac{N_1}{N} U\sin(\omega t)$
- $U_{S2} = \frac{N_2}{N} \mathrm{U}\sin(\omega t)$

N : number of turns of primary winding

N_1, N_2: effective number of turns of secondary windings



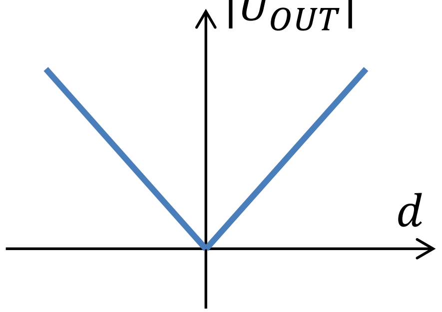
LVDT

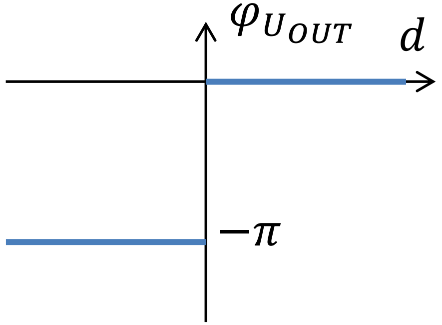


U_P
$-d$ 0 $+d$
$S2$ P $S1$
U_{S1}
U_{S2}
U_{OUT}
0 $+d$
$S2$ P $S1$
U_{S1}
U_{S2}
U_{OUT}
$-d$ 0
$S2$ P $S1$
U_{S1}
U_{S2}
U_{OUT}
$U_{OUT} = U_{S1} - U_{S2}$

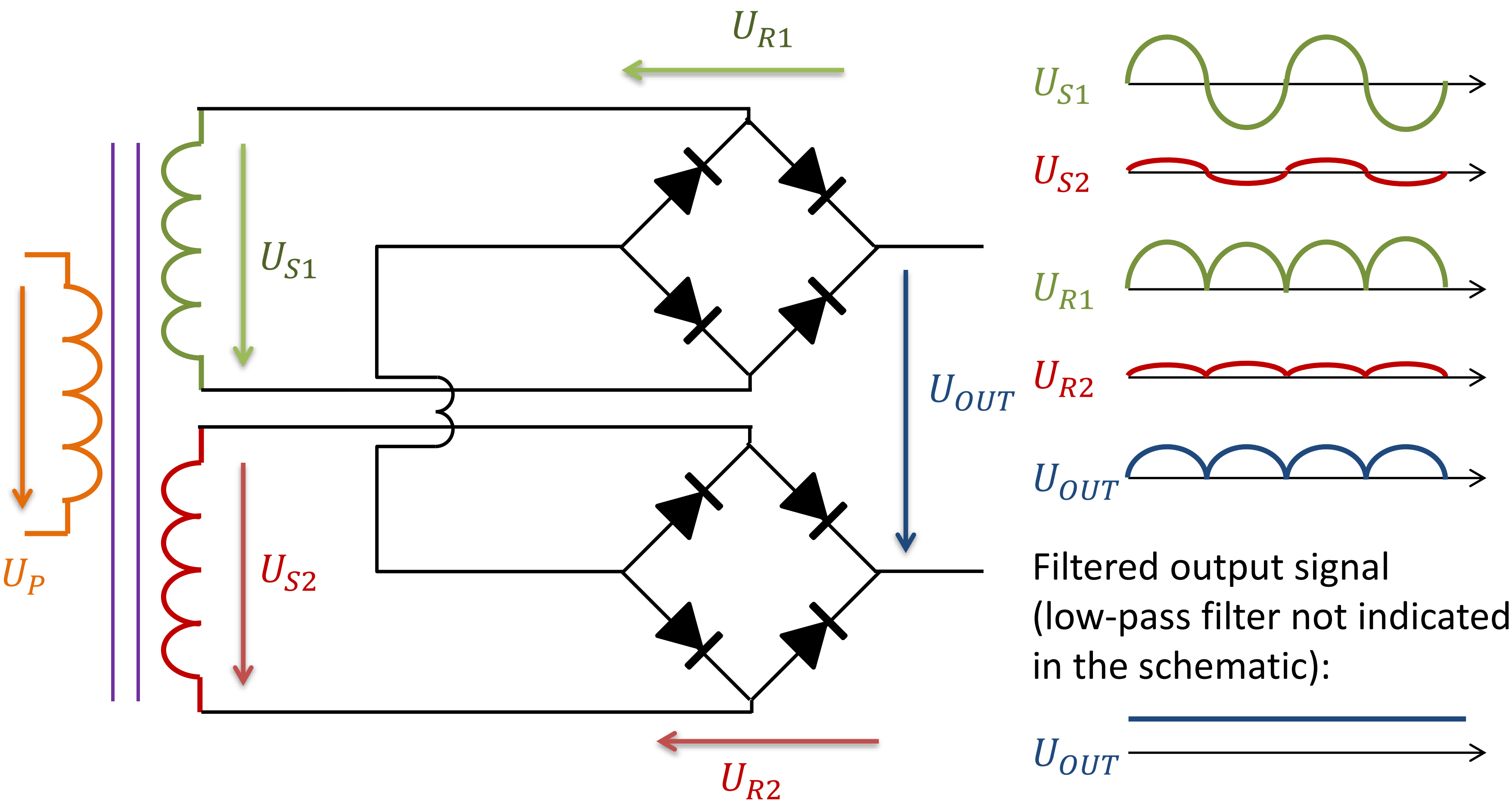
LVDT

- Center position
  - $N_1 = N_2 \Rightarrow U_{OUT} = 0$
- Positive displacement
  - $N_1 > N_2 \Rightarrow U_{OUT} = \frac{N_1 - N_2}{N} U \sin(\omega t) > 0$
- Negative displacement
  - $N_1 < N_2 \Rightarrow U_{OUT} = \frac{N_1 - N_2}{N} U \sin(\omega t) < 0$
  - $U_{OUT} = -\frac{|N_1 - N_2|}{N} U \sin(\omega t) = \frac{N_1 - N_2}{N} U \sin(\omega t - \pi)$
- Output voltage (phase relative to primary coil)
  - $|U_{OUT}| = \frac{|N_1 - N_2|}{N} U$
  - $\varphi_{U_{OUT}} = \begin{cases} 0 \text{ if } d \geq 0 \\ -\pi \text{ if } d < 0 \end{cases}$





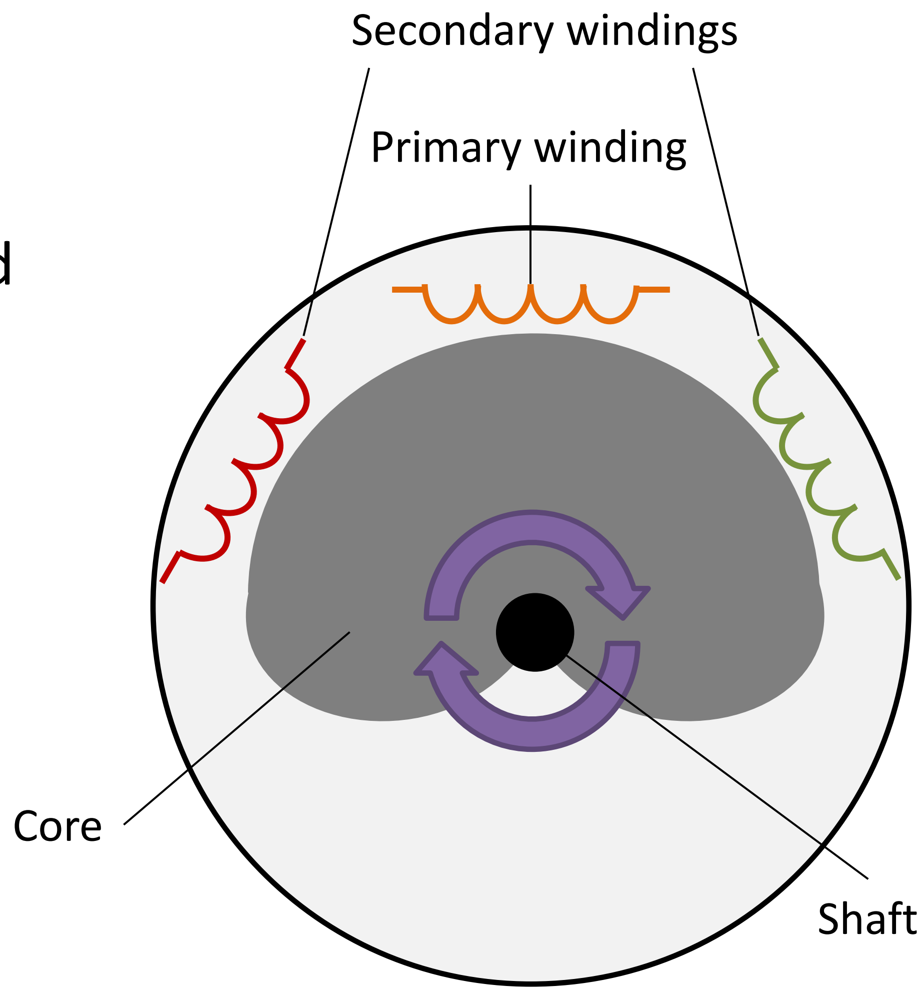
LVDT with phase-sensitive detector



Directions of rectified voltages U_{R1} and U_{R2} are opposing!

Rotary Variable Difference Transformer

- Principle of operation similar to LVDT
- Specially engineered core and windings
- Limited input range (up to $\pm 40°$)



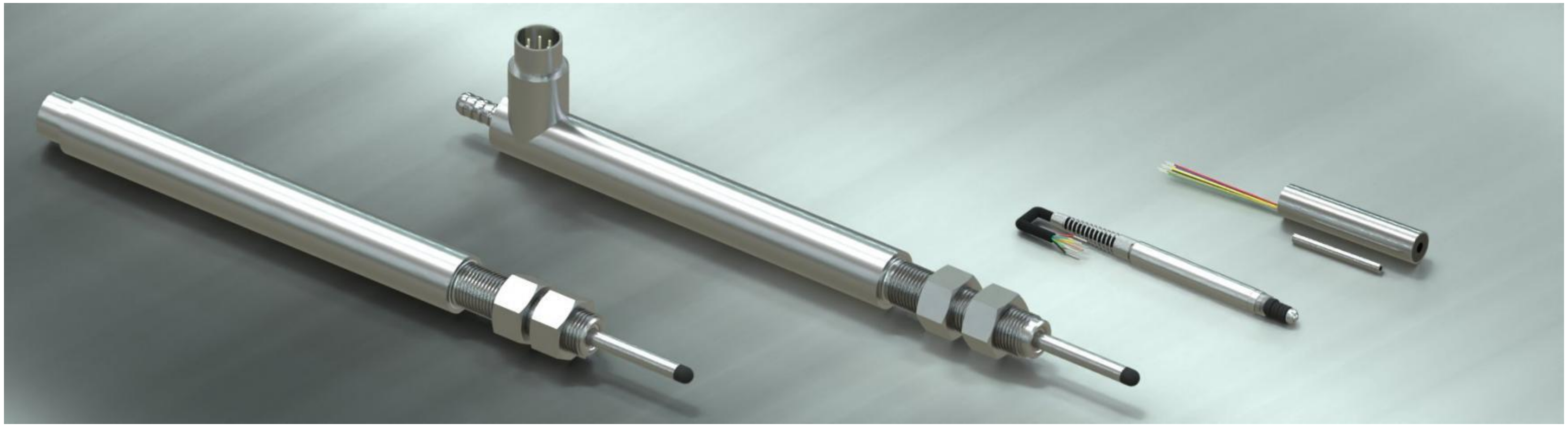
LVDT - excitation

- LVDT needs AC excitation
- Common setup: DC supply + oscillator
- Excitation frequency
  - faster displacements need higher excitation frequency
  - frequency range: 50Hz – 10kHz
  - typical range of excitation frequency: 250Hz-1kHz
  - for slow motions utility frequency might also be applied (50Hz)

LVDT

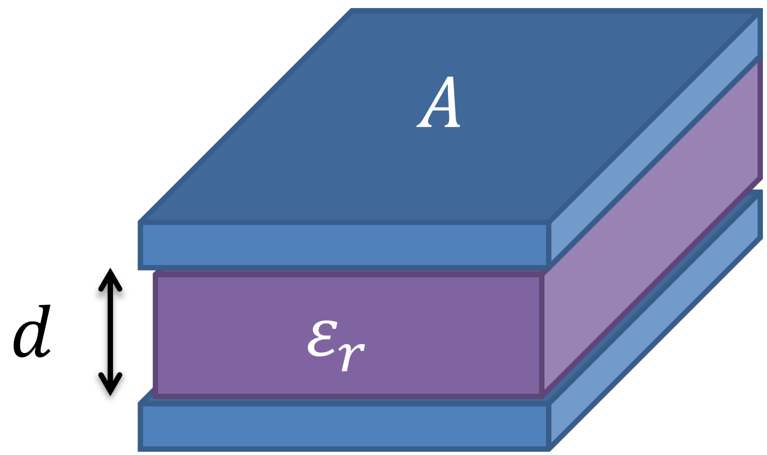
+ robust construction
+ contactless measurement
+ 0.2 - 0.5% accuracy
+ insensitive to vibration
+ unlimited resolution

– need of AC excitation
– complex signal conditioning circuitry
– limited linear input range (below 500mm)



Capacitive displacement sensors

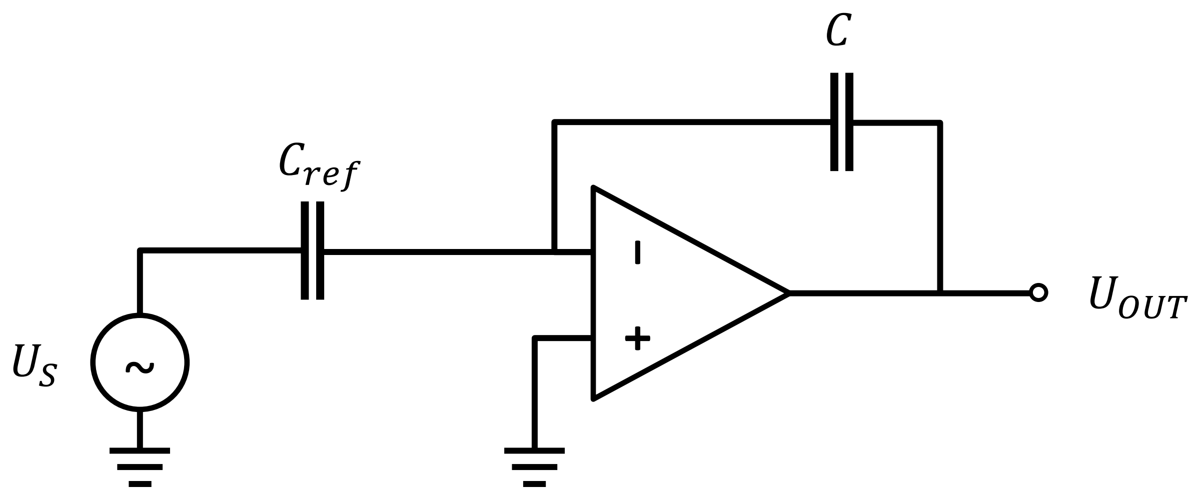
Capacitive displacement sensors



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

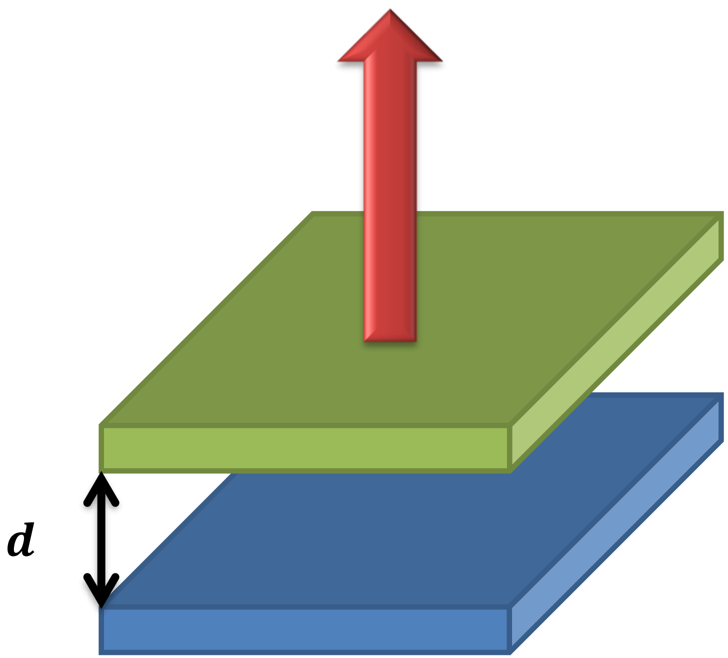
- ε_0: vacuum permittivity
- ε_r: relative permittivity of the dielectric
- A: effective area of electrodes
- d: distance of electrodes

Capacitance measurement



- $U_{OUT} = -U_S \frac{Z}{Z_{ref}} = -U_S \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C_{ref}}} = -U_S \frac{C_{ref}}{C}$
- Capacitance relative to a reference capacitor can be measured
- Problems: thermal effects, need of an exact reference capacitor

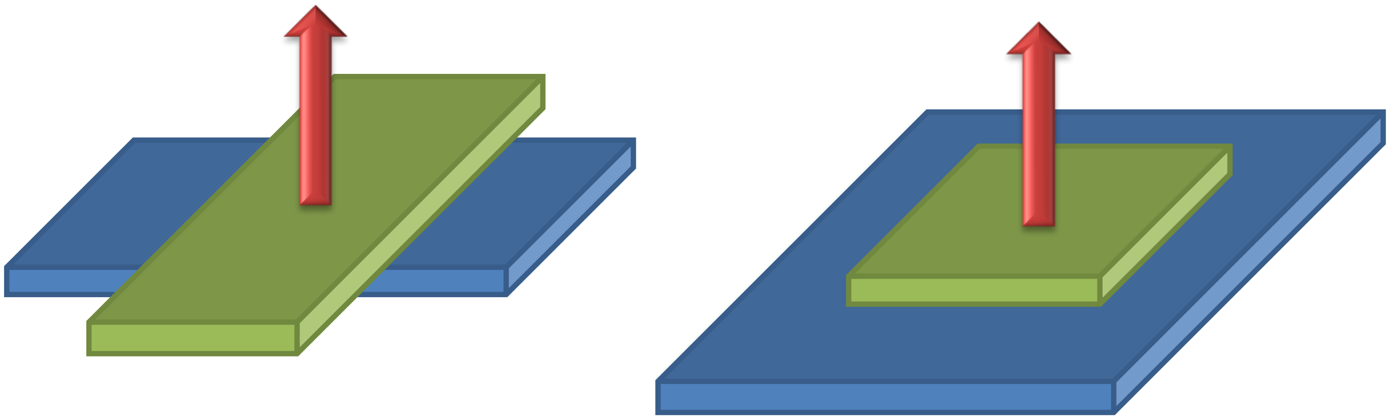
Measurement based on the distance of electrodes



- Capacitance:
  - $C = \frac{\varepsilon A}{\boldsymbol{d}}$
  - nonlinear function of distance
- Impedance:
  - $Z = \frac{\boldsymbol{d}}{j\omega\varepsilon A}$
  - linear function of distance

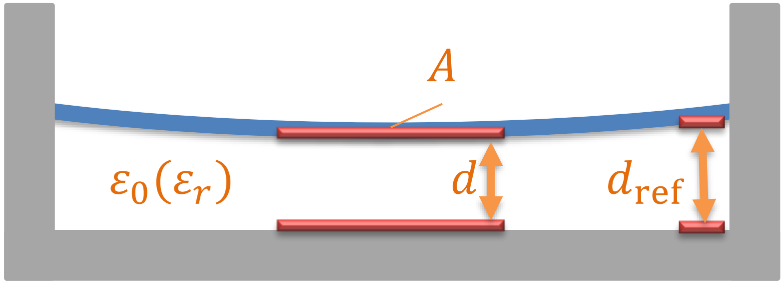
Measurement based on the distance of electrodes

- Problems
  - tilt of plates
  - displacement in X and Y directions – solution: overlapping plates

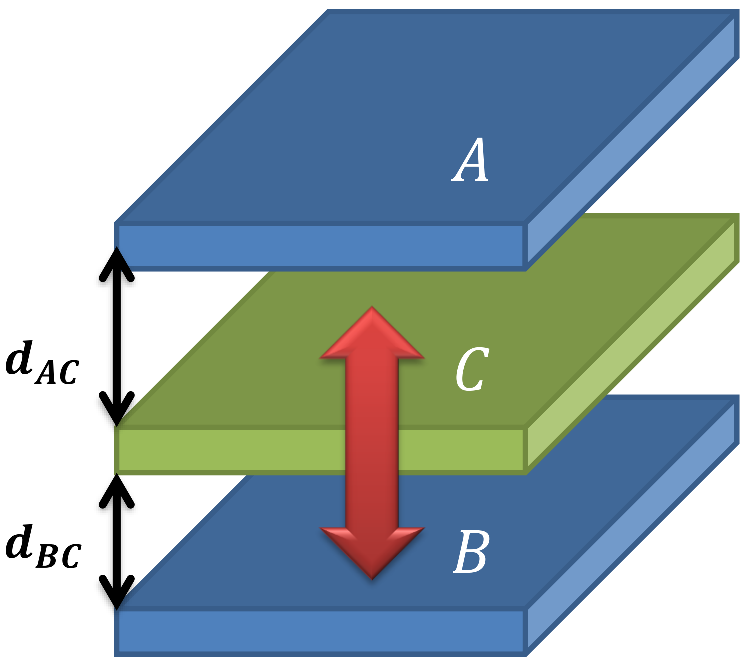


Typical application

Force and pressure sensors



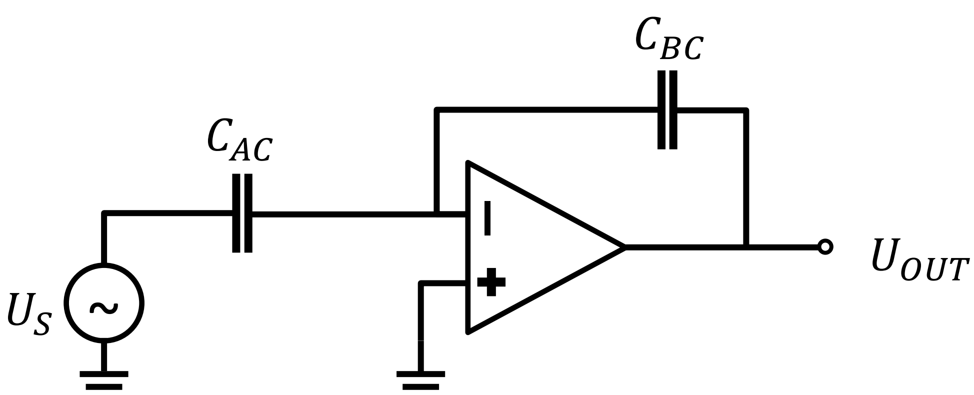
Three-plate setup



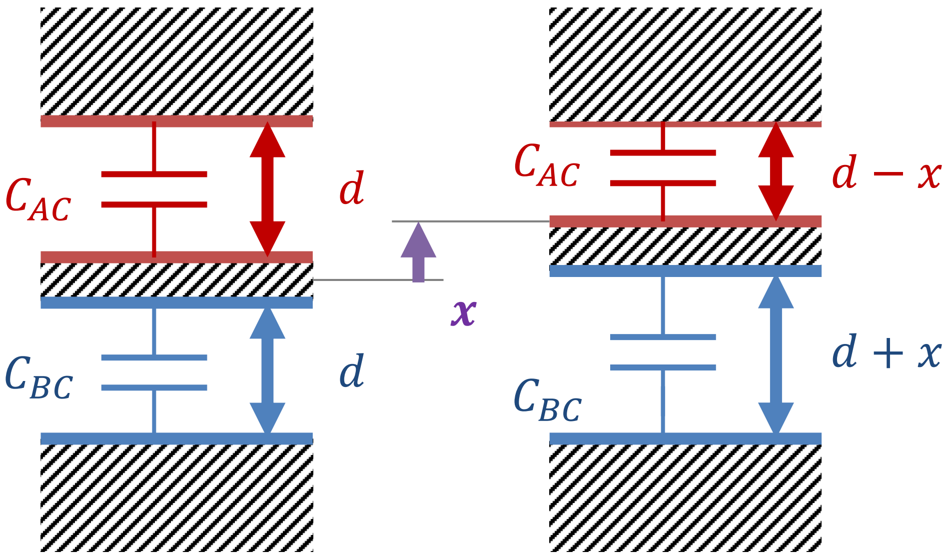
- Capacitance:
  - $C_{AC} = \frac{\varepsilon A}{d_{AC}}$
  - $C_{BC} = \frac{\varepsilon A}{d_{BC}}$

- Output voltage:

$$U_{OUT} = -U_S \frac{C_{AC}}{C_{BC}} = -U_S \frac{d_{BC}}{d_{AC}}$$

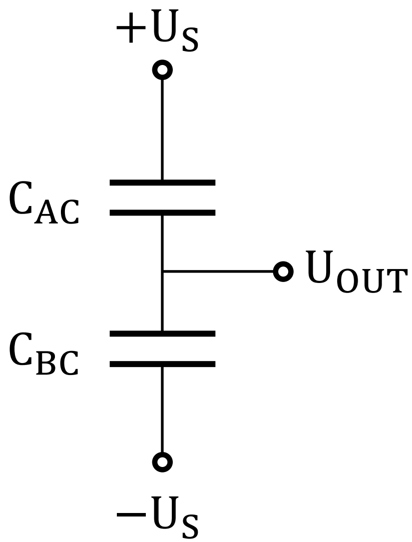


Three-plate setup



- Area of plates and permittivity of the dielectric are the same for both capacitors
- $C_{AC} = \frac{\varepsilon A}{d - \boldsymbol{x}}$
- $C_{BC} = \frac{\varepsilon A}{d + \boldsymbol{x}}$

Differential measurement



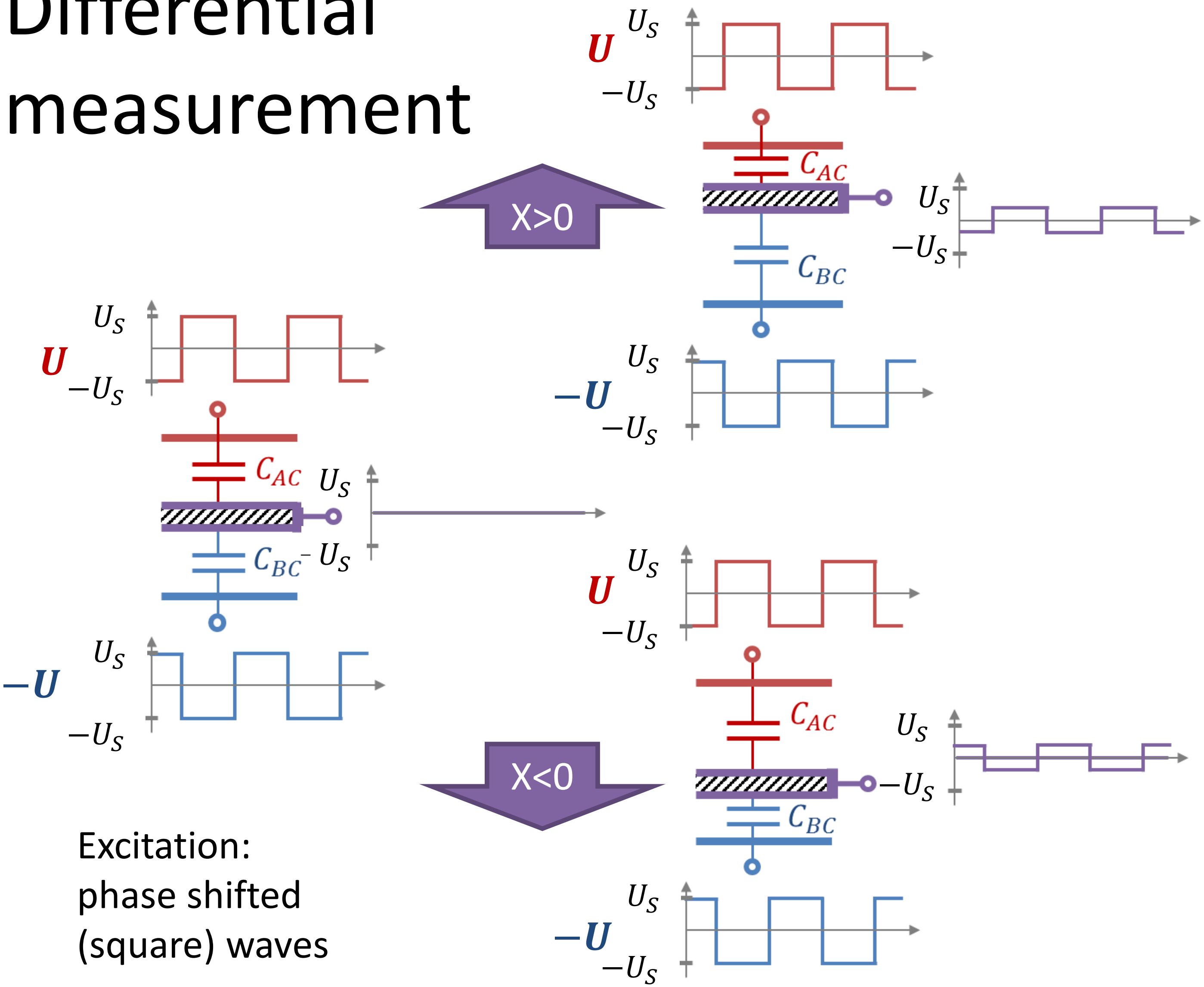
$$U_{OUT} = -U_S + \left(U_S - (-U_S)\right)\frac{Z_{BC}}{Z_{AC}+Z_{BC}} =$$

$$= U_S\left(2\frac{Z_{BC}}{Z_{AC}+Z_{BC}} - 1\right) = U_S\ \frac{Z_{BC}-Z_{AC}}{Z_{BC}+Z_{AC}} =$$

$$= U_S\frac{\frac{1}{C_{BC}}-\frac{1}{C_{AC}}}{\frac{1}{C_{BC}}+\frac{1}{C_{AC}}}$$

$$\boldsymbol{U_{OUT}} = U_S\frac{\dfrac{d+x}{\varepsilon A} - \dfrac{d-x}{\varepsilon A}}{\dfrac{d+x}{\varepsilon A} + \dfrac{d-x}{\varepsilon A}} = U_S\frac{(d+x)-(d-x)}{(d+x)+(d-x)} = \boldsymbol{U_S}\frac{\boldsymbol{x}}{\boldsymbol{d}}$$

Differential measurement



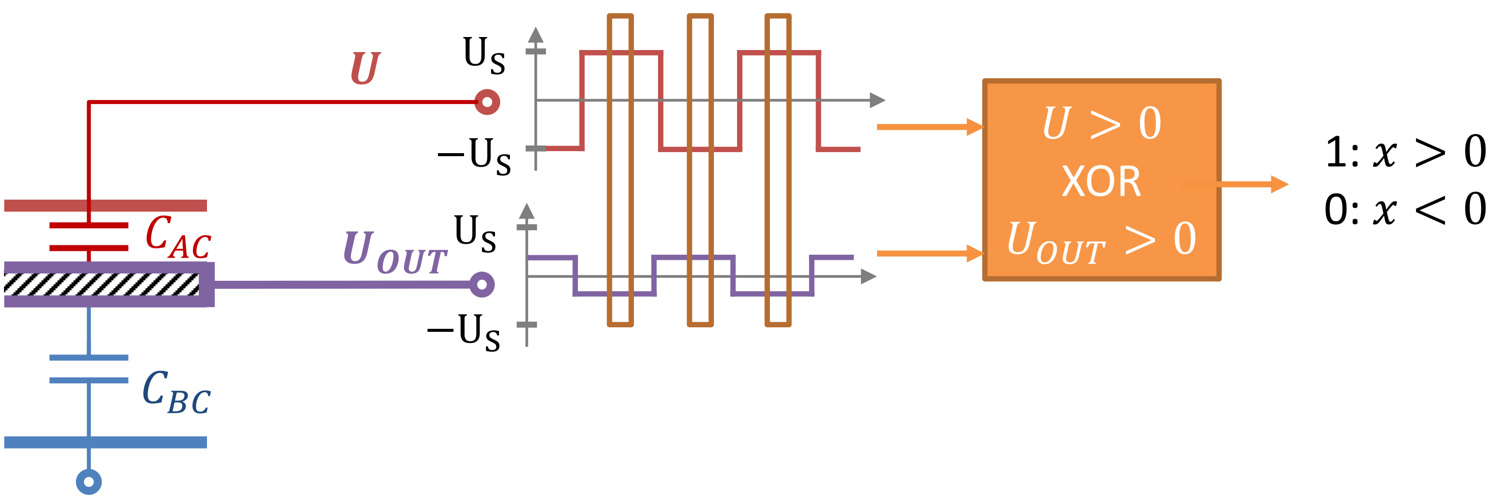
$$|U_{OUT}| = U_S \frac{|x|}{d}$$
$$\varphi_{U,U_{OUT}} = 0°$$

$$|U_{OUT}| = U_S \frac{|x|}{d}$$
$$\varphi_{U,U_{OUT}} = -180°$$

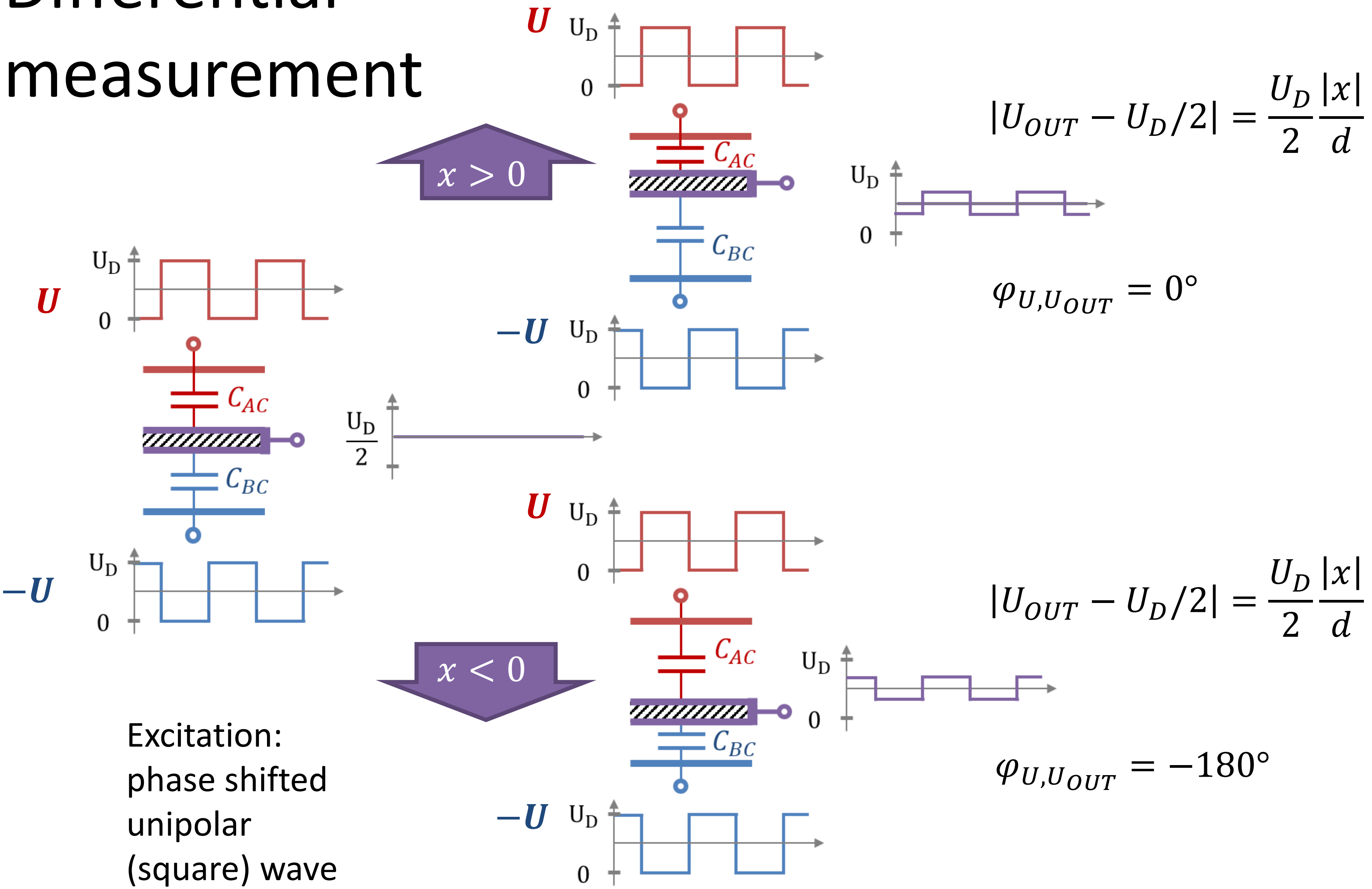
Excitation:
phase shifted
(square) waves

Differential measurement

- $|U_{OUT}| = U_S \frac{x}{d}$ - peak detector / rectifier
- $\varphi_{U,U_{OUT}} = \begin{cases} -180° & : x > 0 \\ 0° & : x < 0 \end{cases}$ - phase detector (XOR)



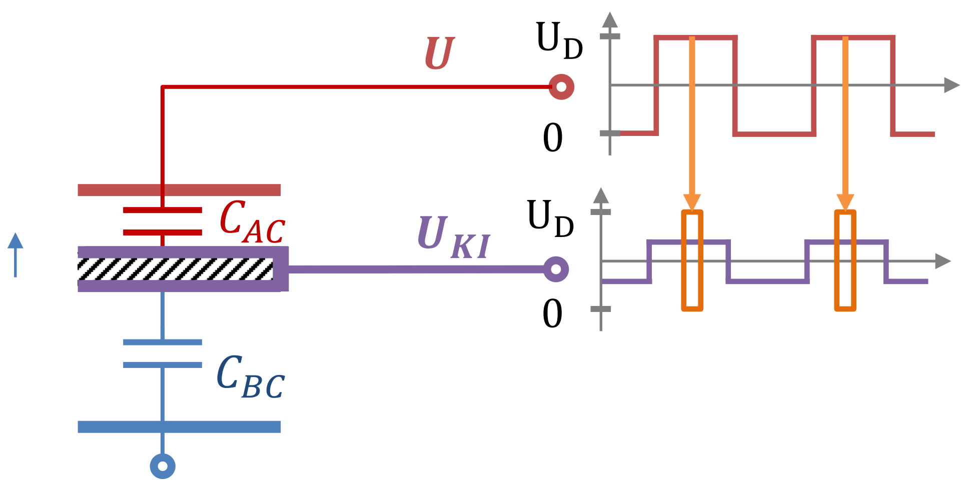
Differential measurement



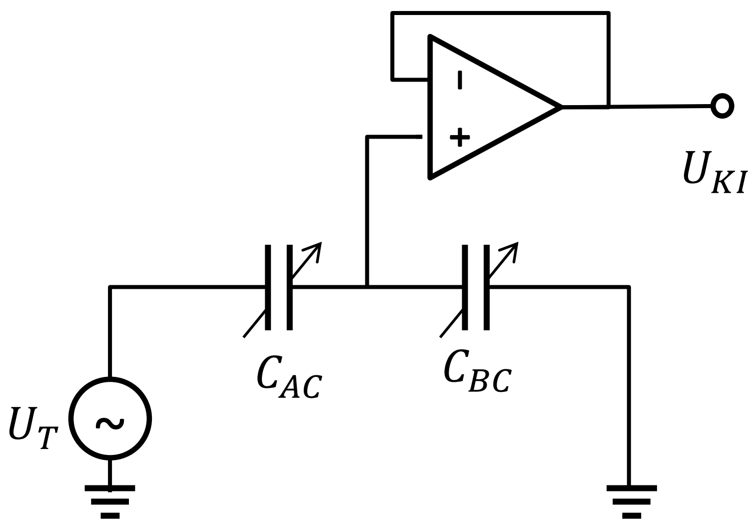
Excitation: phase shifted unipolar (square) wave

Differential measurement

- Sampling according to the period of the square wave
- Consider an N bit ADC with reference voltage U_D:
  - magnitude of displacement: $\left|\frac{x}{d}\right| = \left|Y - \frac{2^N - 1}{2}\right|$
  - direction of displacement: $\mathrm{sgn}(Y - \frac{2^N - 1}{2})$



Differential measurement: capacitive divider circuit

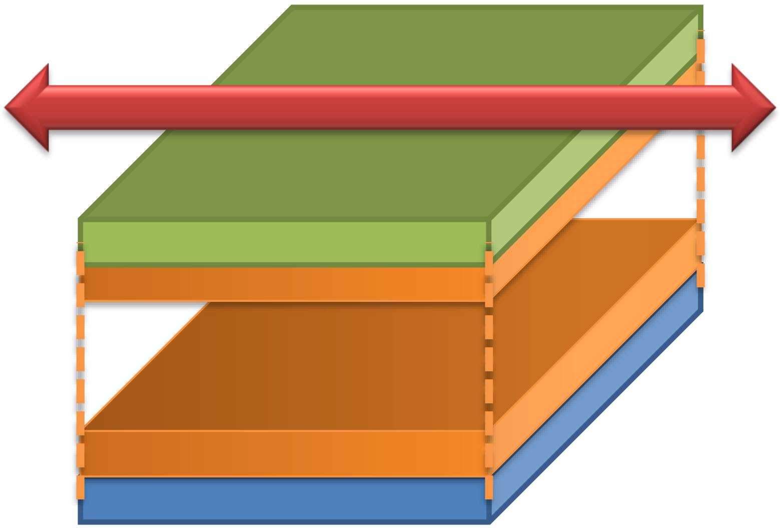


$$\boldsymbol{U_{KI}} = U_T \frac{Z_{BC}}{Z_{AC} + Z_{BC}} =$$

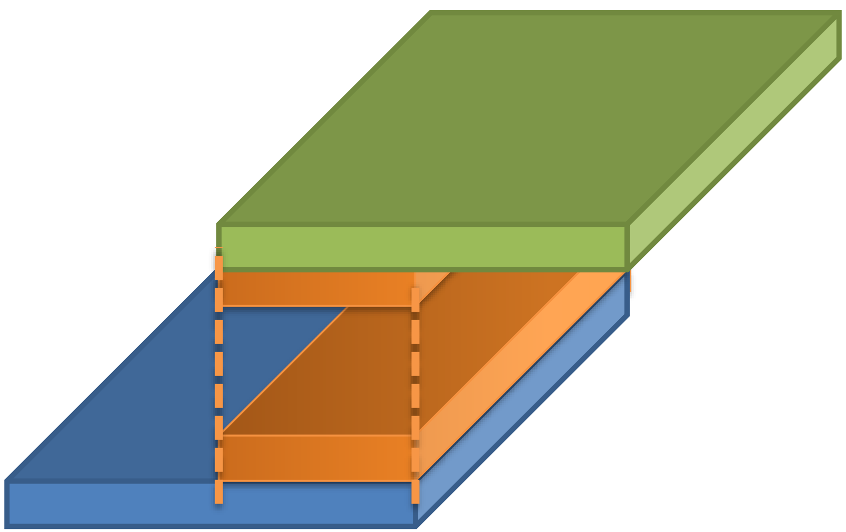
$$= U_T \frac{\frac{1}{j\omega}\frac{d+x}{\varepsilon A}}{\frac{1}{j\omega}\frac{d-x}{\varepsilon A} + \frac{1}{j\omega}\frac{d+x}{\varepsilon A}} =$$

$$= U_T \frac{d+x}{2d} = \boldsymbol{\frac{U_T}{2}\left(1 + \frac{x}{d}\right)}$$

Measurement based on effective area of plates

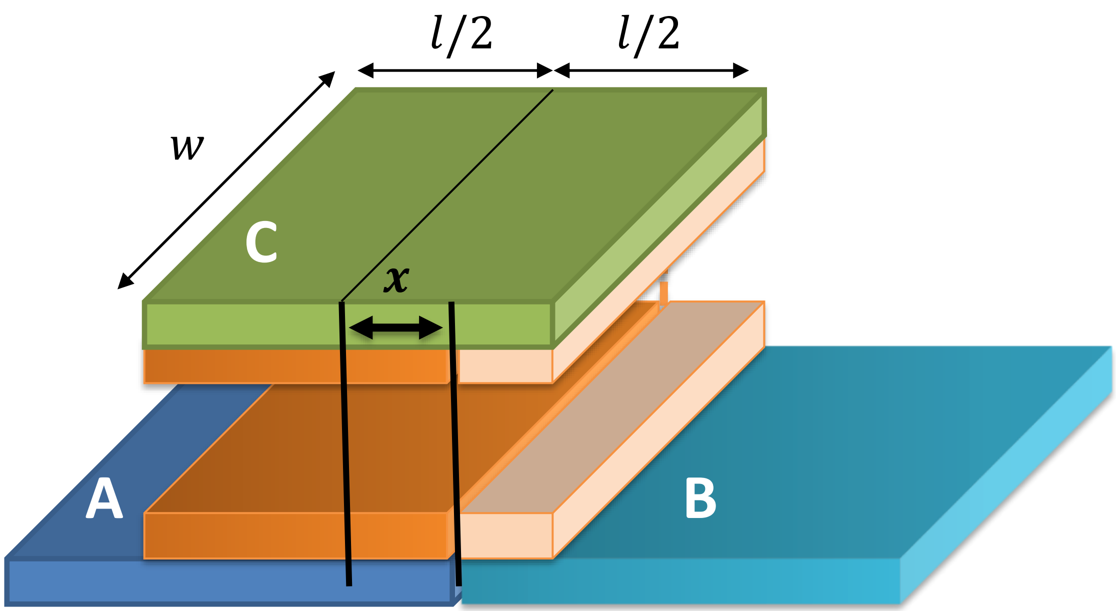


- Capacitance:
  - $C = \frac{\varepsilon \boldsymbol{A}}{d}$
  - linear function of displacement



- Impedance
  - $Z = \frac{d}{j\omega\varepsilon \boldsymbol{A}}$
  - nonlinear function of displacement

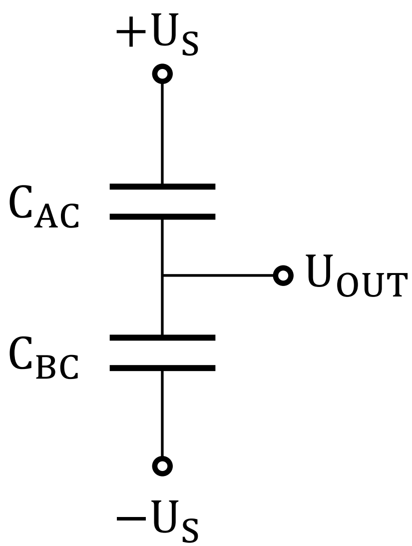
Three-plate setup



- $A_{AC} = (l/2 + x)w$
- $A_{BC} = (l/2 - x)w$
- $d_{AC} = d_{BC}$
- $\varepsilon_{AC} = \varepsilon_{BC}$

$$\frac{C_{AC}}{C_{BC}} = \frac{A_{AC}}{A_{BC}} = \frac{l/2 + x}{l/2 - x}$$

Differential measurement



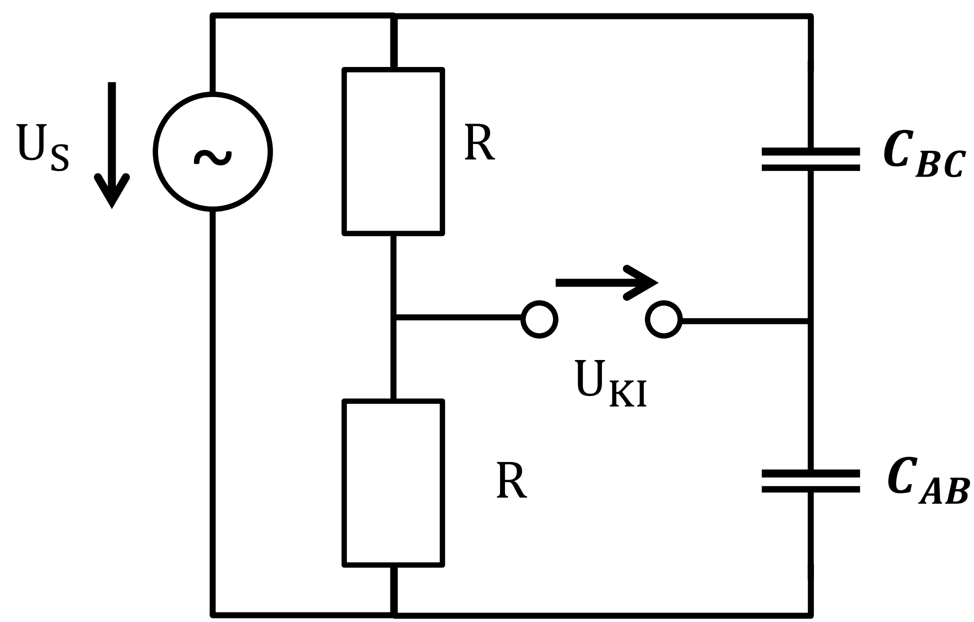
$$U_{OUT} = -U_S + \left(U_S - (-U_S)\right)\frac{Z_{BC}}{Z_{AC}+Z_{BC}} =$$

$$= U_S\left(2\frac{Z_{BC}}{Z_{AC}+Z_{BC}} - 1\right) = U_S\,\frac{Z_{BC}-Z_{AC}}{Z_{BC}+Z_{AC}} =$$

$$= U_S\frac{\frac{1}{C_{BC}} - \frac{1}{C_{AC}}}{\frac{1}{C_{BC}} + \frac{1}{C_{AC}}} = U_S\frac{C_{AC}-C_{BC}}{C_{AC}+C_{BC}}$$

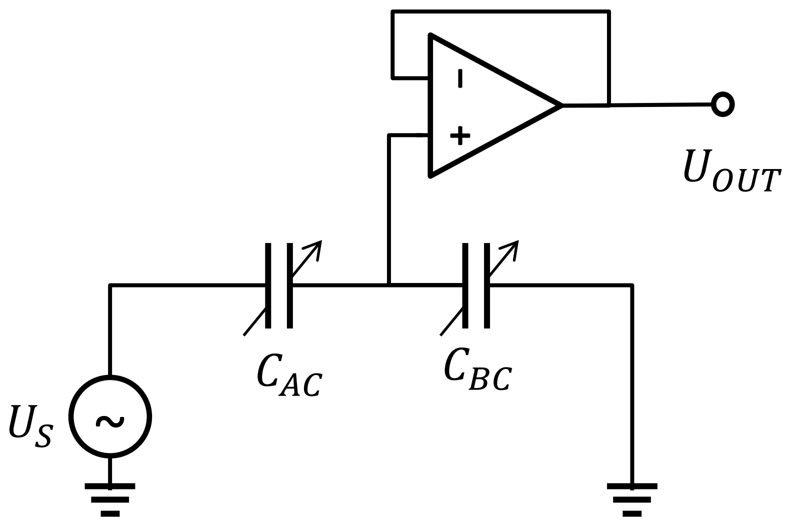
$$\boldsymbol{U_{OUT}} = U_S\frac{\frac{\varepsilon\left(\frac{l}{2}+x\right)w}{d} - \frac{\varepsilon\left(\frac{l}{2}-x\right)w}{d}}{\frac{\varepsilon\left(\frac{l}{2}+x\right)w}{d} + \frac{\varepsilon\left(\frac{l}{2}-x\right)w}{d}} = U_S\frac{\left(\frac{l}{2}+x\right)-\left(\frac{l}{2}-x\right)}{\left(\frac{l}{2}+x\right)+\left(\frac{l}{2}-x\right)} = \boldsymbol{2U_S\frac{x}{l}}$$

AC bridge



$$\boldsymbol{U_{OUT}} = U_S \frac{C_{AB} - C_{BC}}{C_{AB} + C_{BC}} = U_S \frac{\varepsilon dw\big((l/2 + x) - (l/2 - x)\big)}{\varepsilon dw\big((l/2 + x) + (l/2 - x)\big)} = \boldsymbol{2U_S \frac{x}{l}}$$

Capacitive divider



$$\boldsymbol{U_{OUT}} = U_S \frac{Z_{BC}}{Z_{AC} + Z_{BC}} =$$

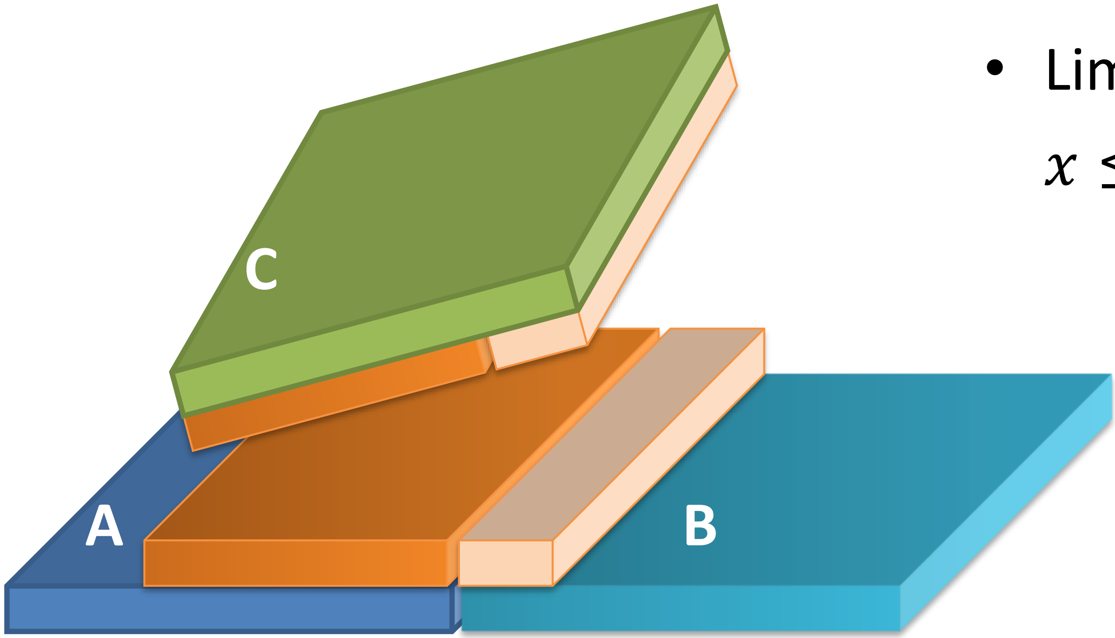
$$= U_S \frac{\frac{1}{j\omega C_{BC}}}{\frac{1}{j\omega C_{AC}} + \frac{1}{j\omega C_{BC}}} =$$

$$= U_S \frac{C_{AC}}{C_{AC} + C_{BC}} =$$

$$= U_S \frac{l/2 + x}{l/2 + x + l/2 - x} =$$

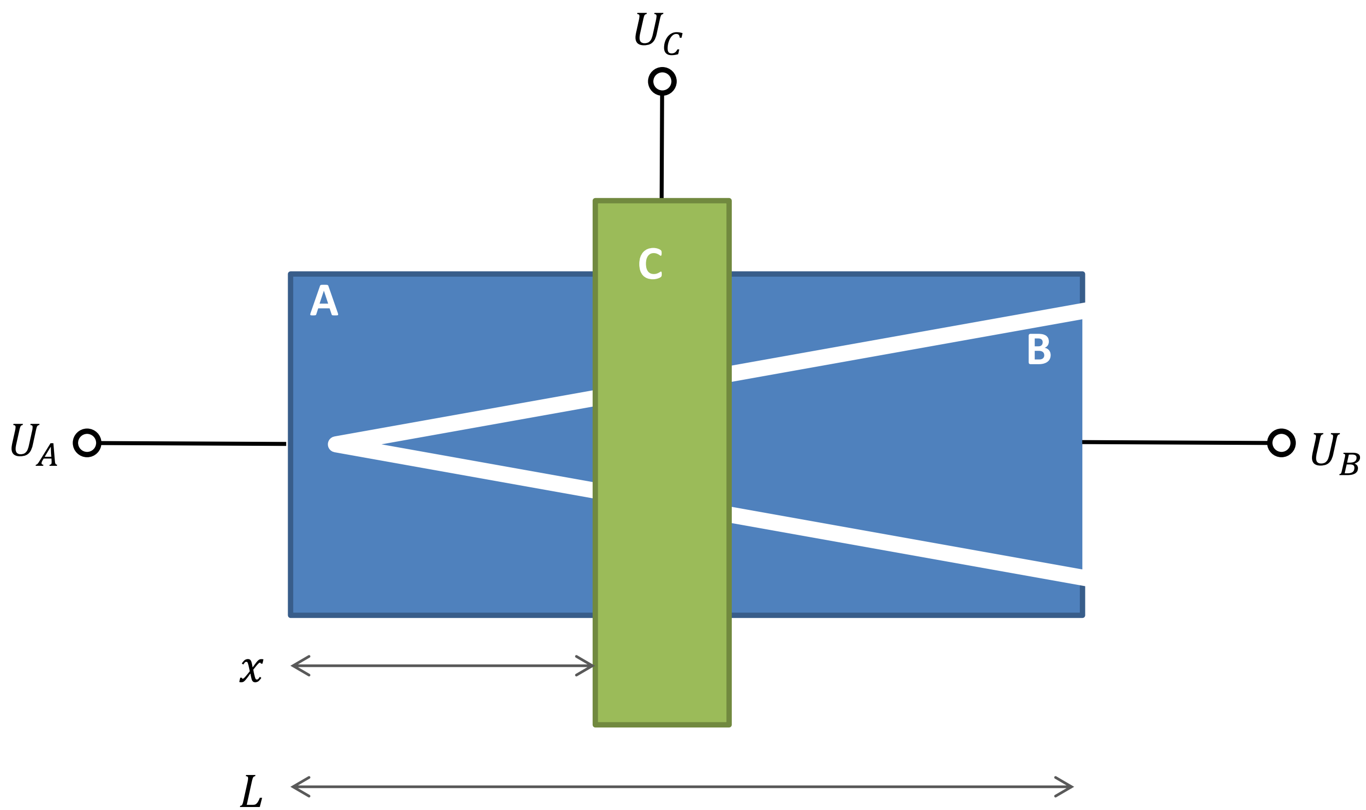
$$= \boldsymbol{U_S \left(\frac{1}{2} + \frac{x}{l}\right)}$$

Problems with three-plate setup



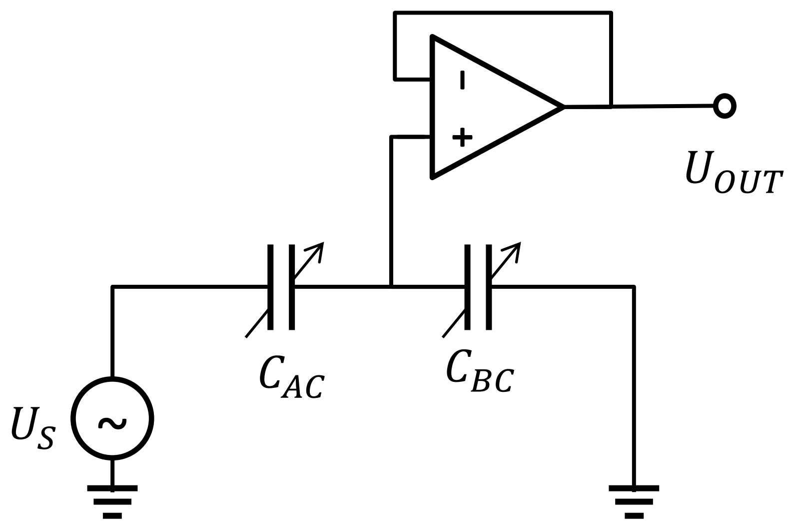
- Tilt, rotation and displacement of the moving plate
- Limited measurement range: $x \leq \frac{l}{2}$

Three-plate setup – V shaped plates



- Insensitive to tilt and rotation
- If $U_A = \sin \omega t$, $U_B = 0$ then U_C is nearly linear between the end-points

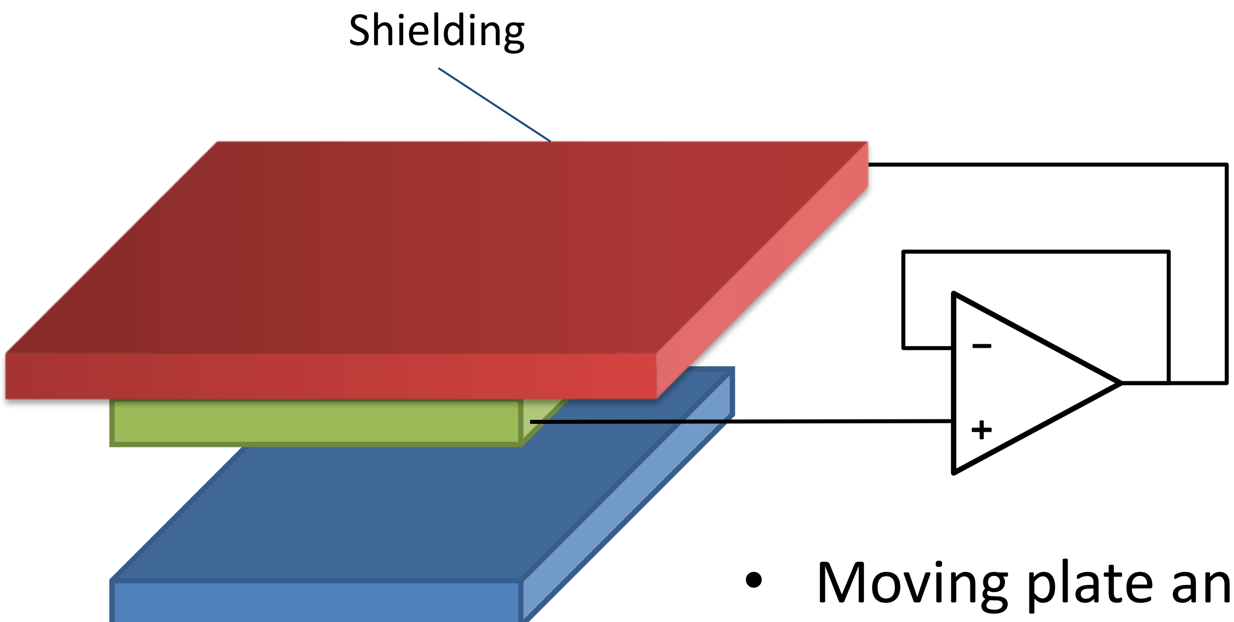
V shaped plates – capacitive divider



$$U_{OUT} = U_S \frac{C_{AC}}{C_{AC}+C_{BC}} \approx cU_S \frac{L-x}{L} = cU_S\left(1-\frac{x}{L}\right),$$

where c is a device-specific constant

Shielding of capacitive sensors



- Moving plate and shielding shares the same potential
- No current flows between them
- Decreases stray capacitance significantly

Capacitive displacement sensors

- \+ contactless measurement
- \+ insensitive to environmental effects and vibration
- \+ errors below 0.1%
- \+ accuracy below $1\mu m$

- − sensitive to electromagnetic noise
- − limited measurement range (0-10mm)
- − high cost

Encoders

Encoder types

- Linear encoder
  - measures displacement along a straight line
  - well-known extremal positions (limits)
  - absolute position at limits can be measured easily (e.g. by limit switches)

- Rotary encoder
  - measures angular position (revolution)
  - absolute position can be measured in a range of $360°$ (one revolution)
  - within one revolution the operation is identical to a linear encoder

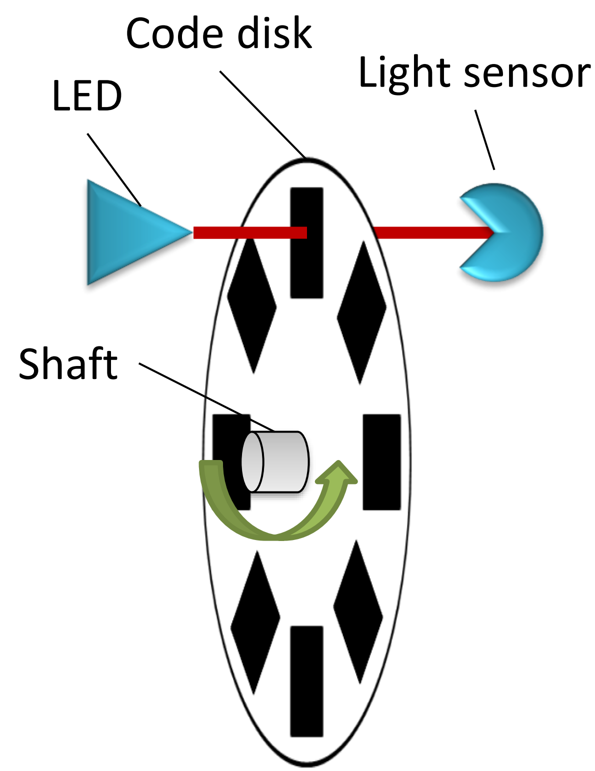
Encoder types

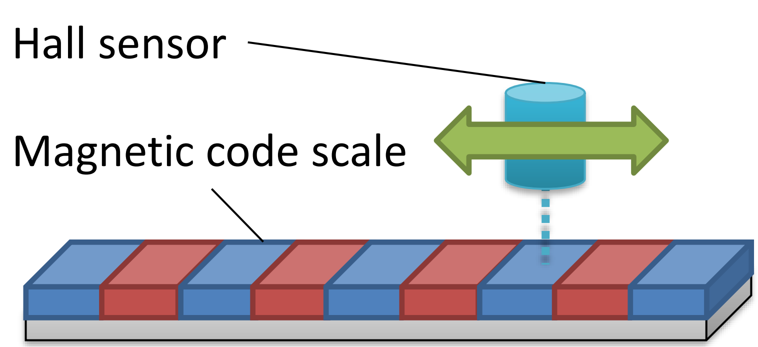
- Absolute encoder
  - measures absolute position

- Incremental encoder
  - measures relative displacement
  - relative position can be obtained by summing displacements
  - only relative position can be measured

Principle of operation

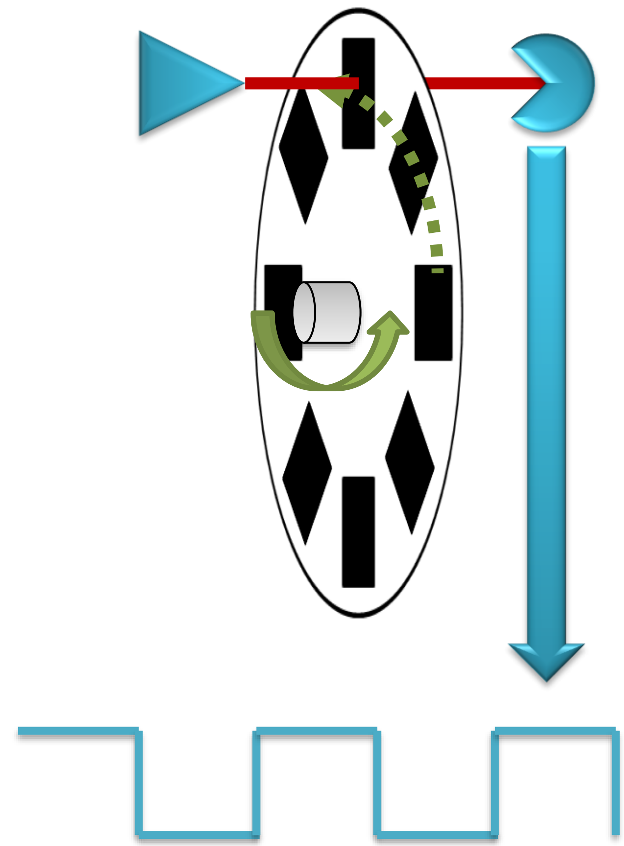
- Disk (rotary encoder) or scale (linear encoder) with well-distinguishable bands
- Bands might be
  - magnetic / non-magnetic
  - transparent / non-transparent
  - white or reflective / black
- Sensor element sensing bands
  - magnetic (Hall-effect)
  - through-beam photoelectric sensor
  - reflective photoelectric sensor





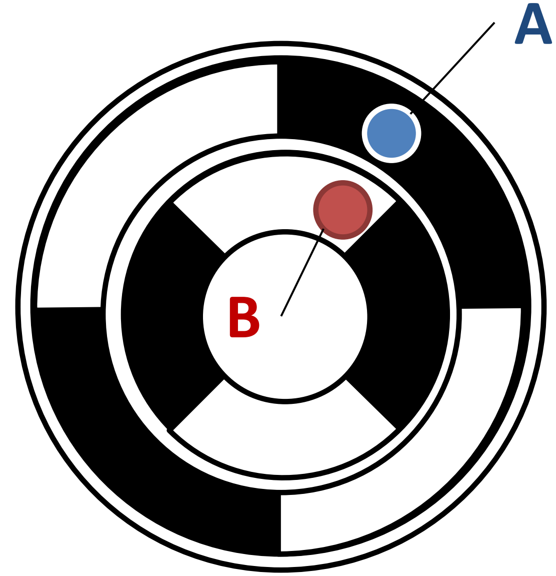
Incremental encoder

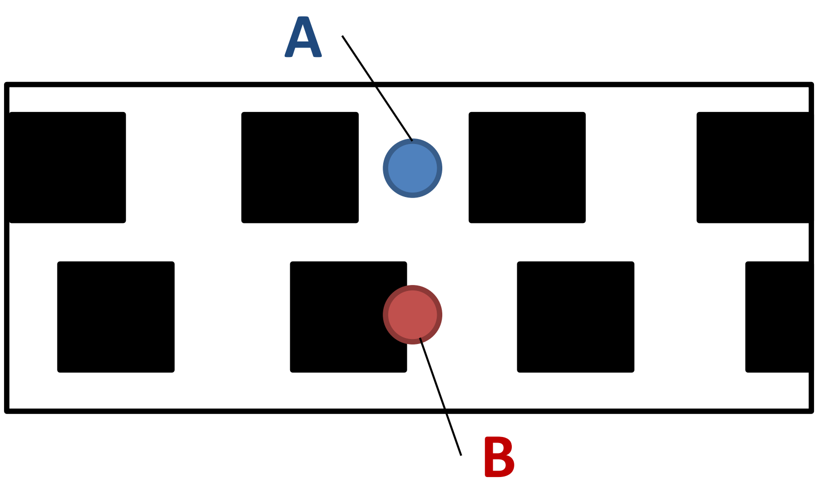
- Output signal is a square wave when passing series of varying bands (magnetic / non-magnetic, light / dark etc.)
- Angular position relative to power-up can be determined by counting the edges of the square signal
- If n pairs of bands are present then the angular displacement corresponding to an edge is $360°/n$
- Resolution can be improved to $360°/2n$ by counting both rising and falling edges
- However, there is no way to determine the direction of rotation



Quadrature encoders

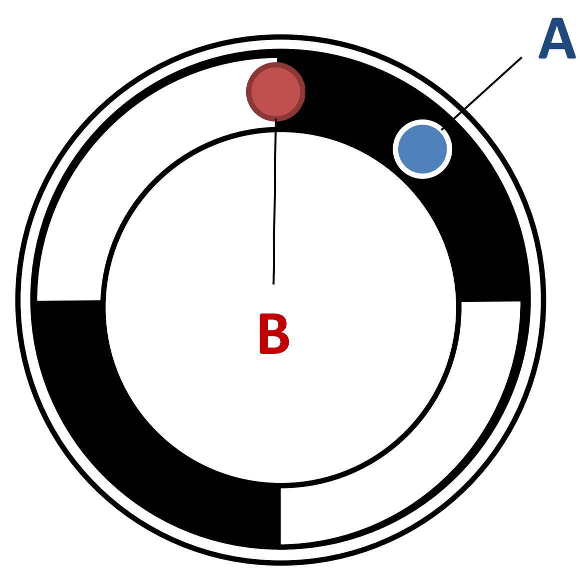
- Use an other series of bands with a quarter-phase shift ($360/4n°$ for quadrature encoder)
- Two sensors (A and B) above the two series of bands located diagonally
- Resolution can be increased by a factor of 4 if both edges of both signals are counted
- Direction of displacement can be detected by the phase shift of signals A and B

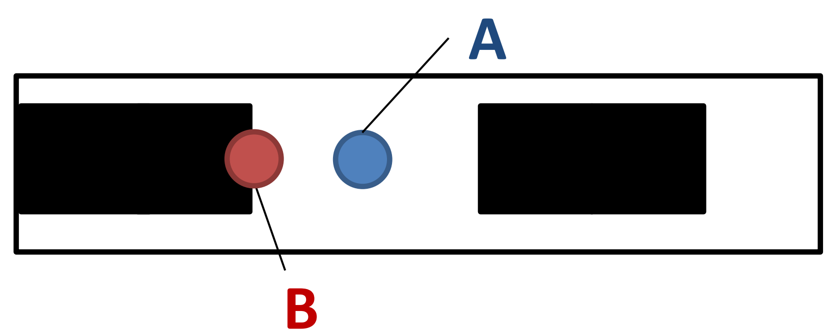




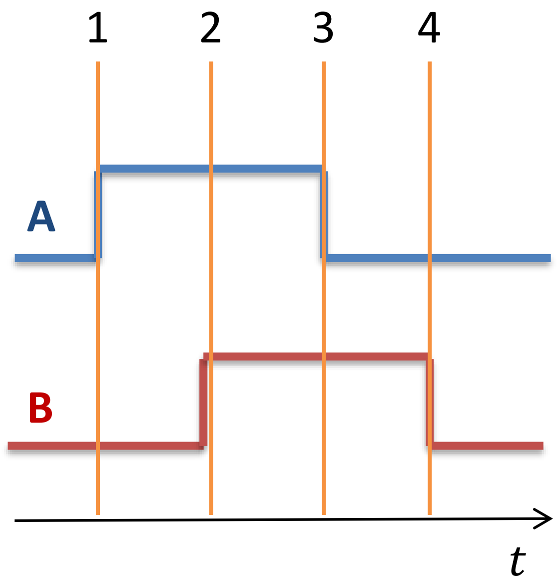
Quadrature encoder – Alternative setup

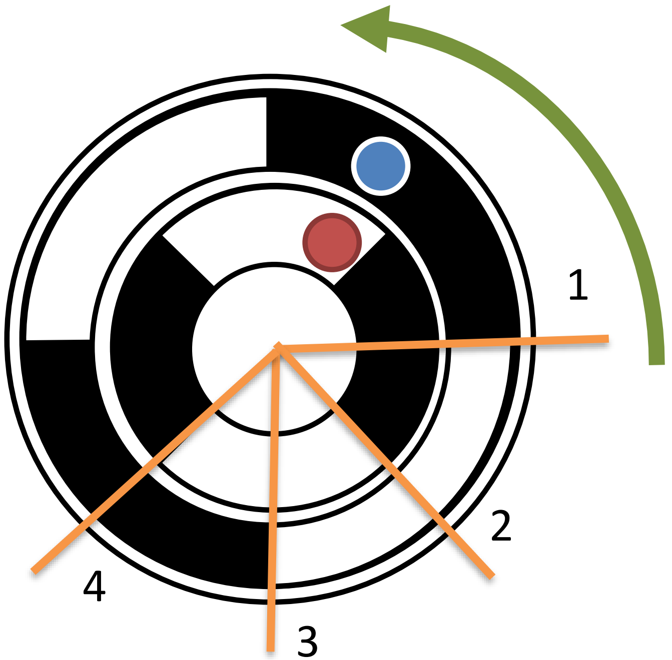
- Use one single series of bands but place the two sensors (A and B) according to quarter-phase shift ($360/4n°$ for rotary encoders)
- Resolution can be increased by a factor of 4 if both edges of both signals are counted
- Direction of displacement can be detected by the phase shift of signals A and B

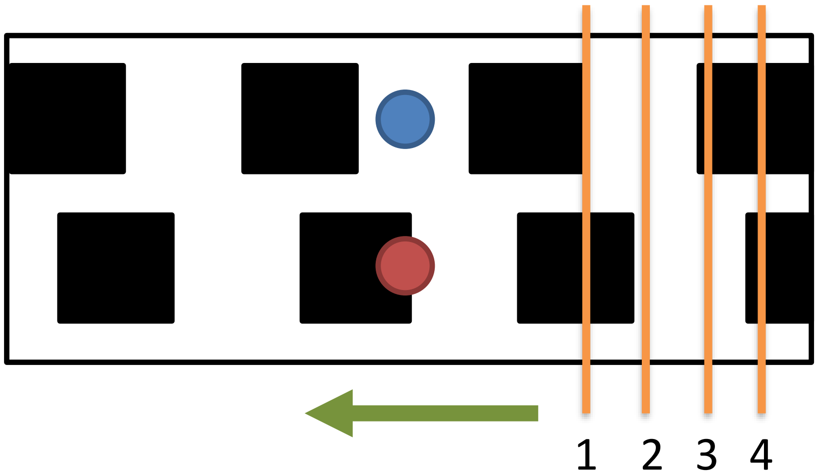




Direction of displacement



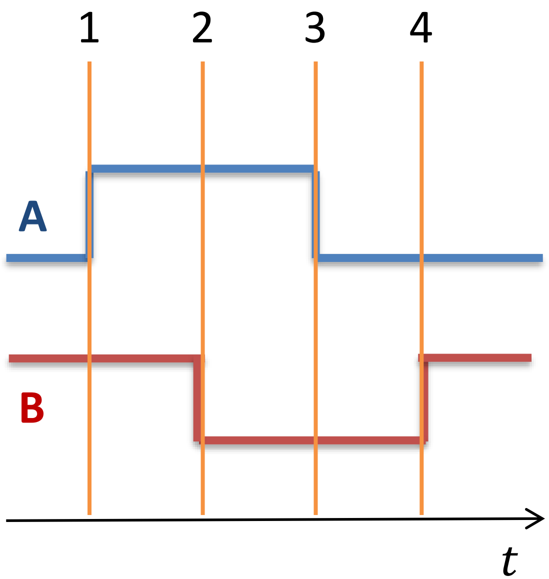


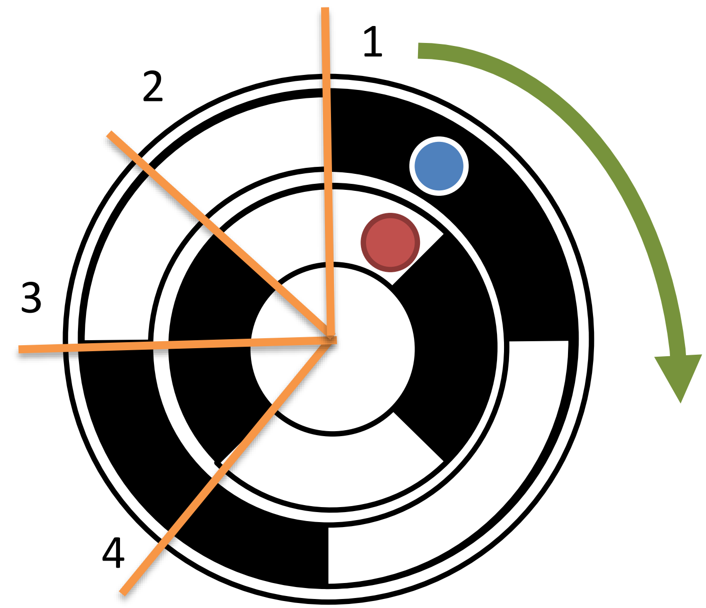


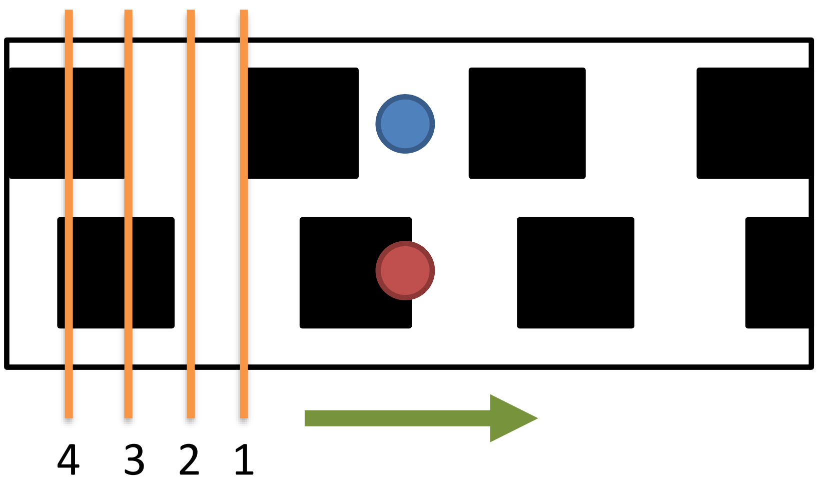
Counter-clockwise rotation / negative displacement:

- rising edge of B during high level of A, rising edge of A during low level of B
- levels of A and B differ after an edge of A, levels of A and B are the same after edge of B

Direction of displacement





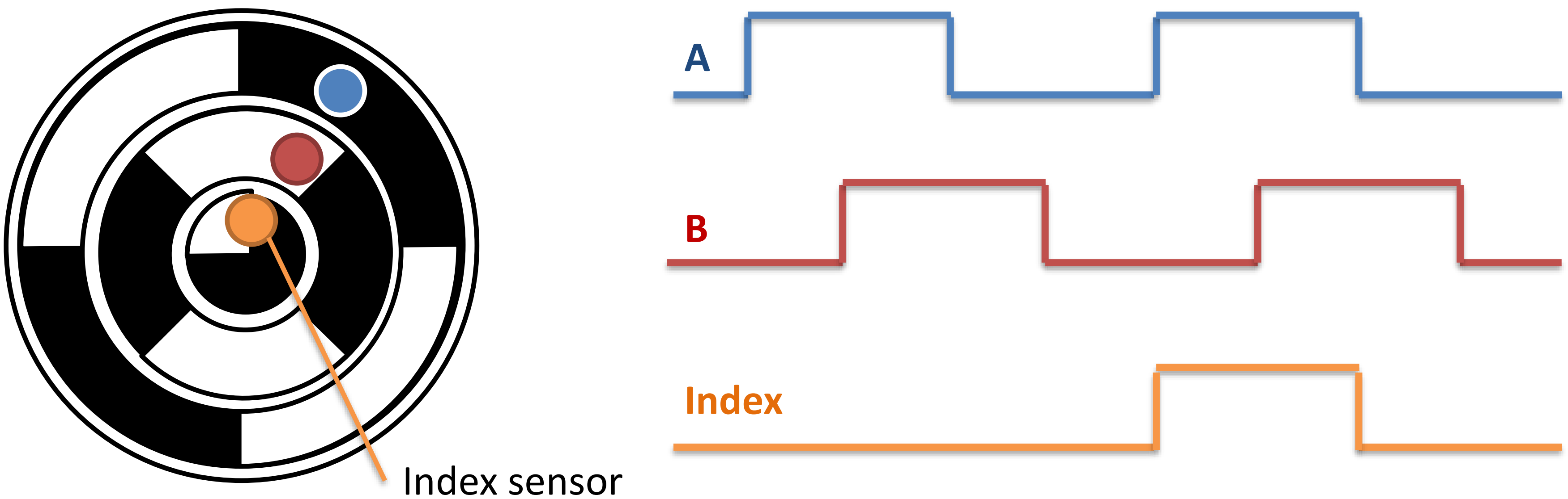


Clockwise rotation / positive displacement:

- rising edge of B during low level of A, rising edge of A during high level of B
- levels of A and B are the same after an edge of A, levels of A and B differ after an edge of B

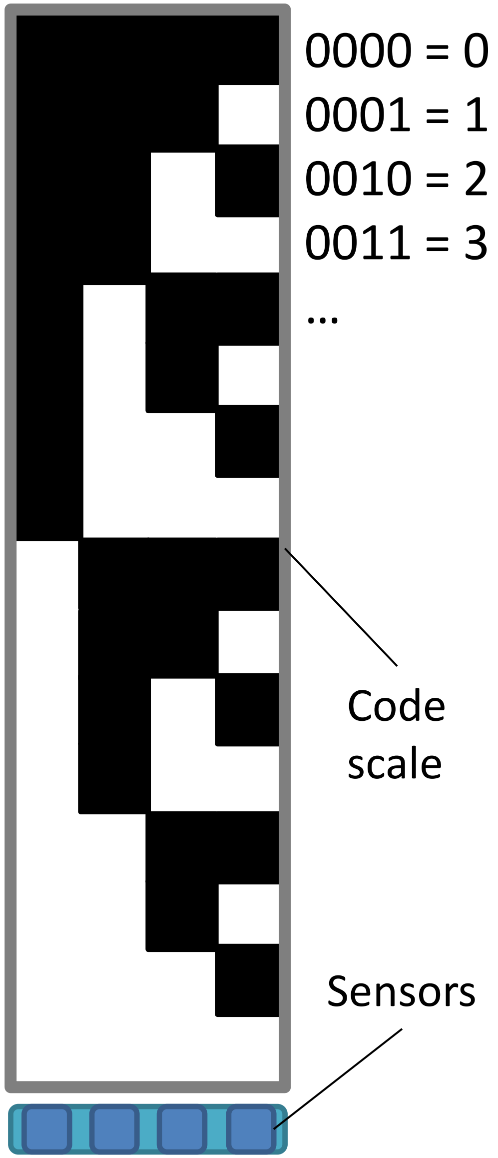
Index channel of rotary encoder

- Extra band on the disk: index channel (*Z channel*)
- One single band of positive value along the circumference
- Index pulse (null pulse) allows absolute position measurement within one revolution



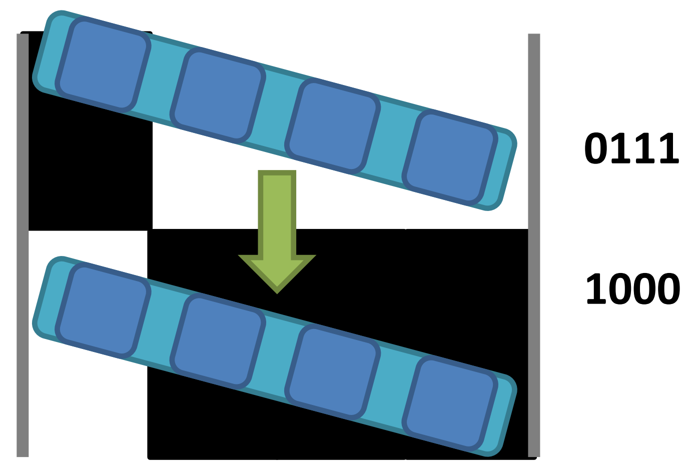
Absolute encoders

- Absolute encoders use more than two series of bands
- All bands together represent a binary coded number
- Each number represents an absolute position
- The more channels the better resolution (e.g. 1/256 for 8 channels)



Absolute encoders

- Problem: transient behavior
- If change of signals is not fully synchronized, transient false readings appear
- Solution: use such an encoding which ensures that only one single channel changes its value (Gray code)

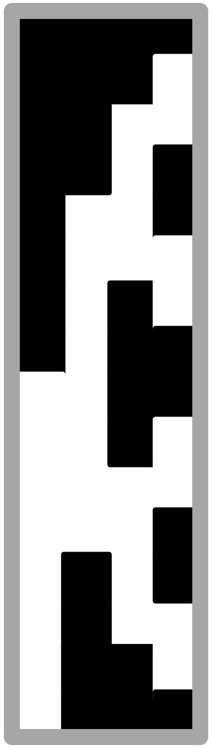


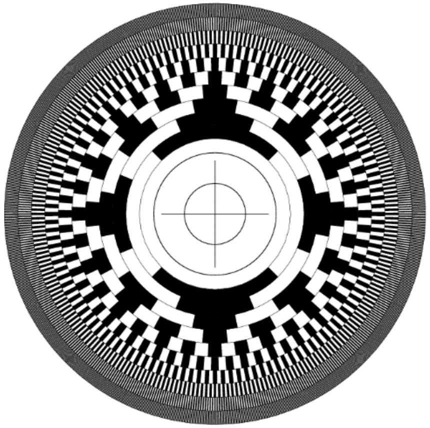
0111
0110
0100
0000
1000

False readings

Gray code

Decimal	Binary	Gray
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111
11	1011	1110
12	1100	1010
13	1101	1011
14	1110	1001
15	1111	1000



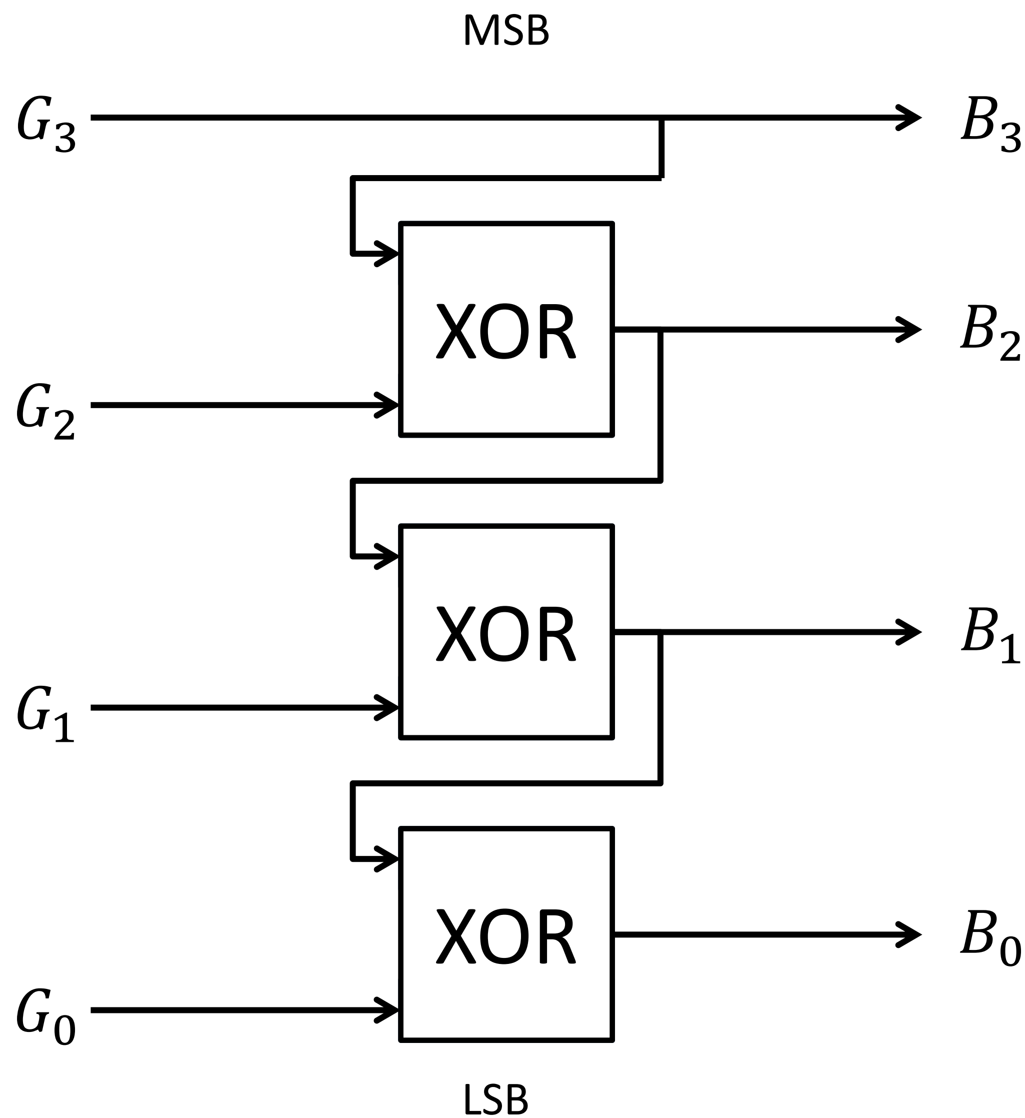


Gray-binary conversion

- MSB:
$$B_n = G_n$$

- Further bits:
$$B_k = G_k \oplus B_{k+1}$$

- Look-up tables might also be used (much faster for high bit count)



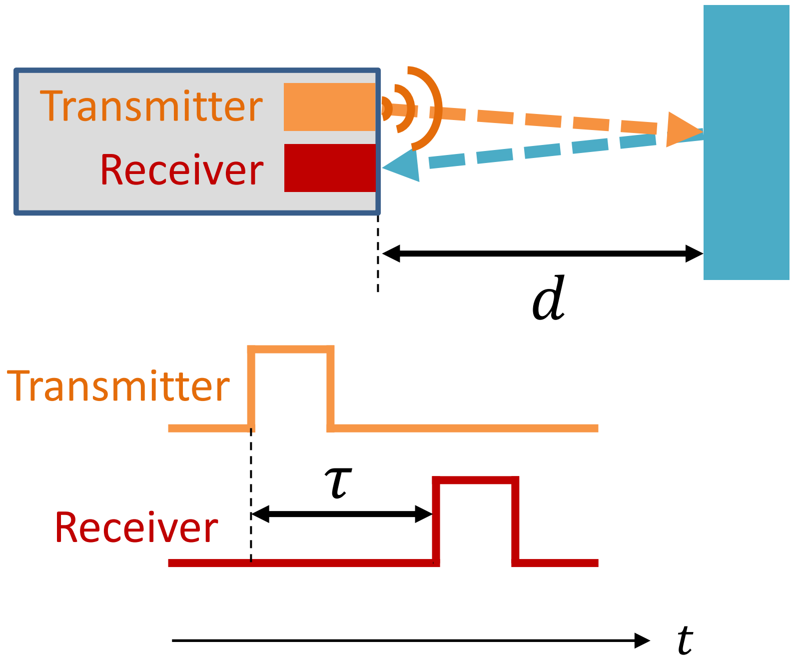
Encoders

+ contactless sensing
+ insensitive to electromagnetic noise
+ high accuracy
+ direct digital output

− limited resolution
− relative encoders provide no absolute information
− sensitive to vibration and mechanical disturbance

Ultrasonic displacement sensors

- The transmitter emits an ultrasonic pulse
- Ultrasonic wave is reflected by the object and detected by the receiver
- The time between the emission and detection is measured (*time of flight, ToF*)

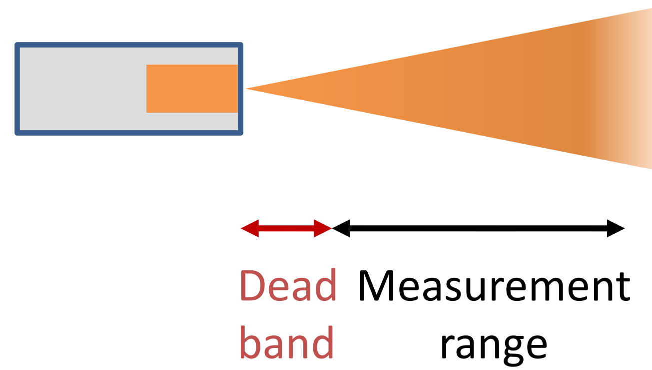


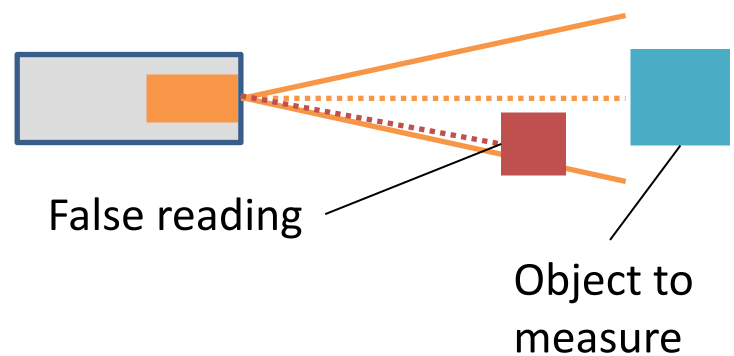
$$d = \frac{\tau v}{2}$$

v: speed of sound

Ultrasonic displacement sensors

- Wide measurement range (up to 10m)
- Dead band near the sensor
- Measurement range depends on the surface and material of the object
    - highest for dense objects with surface perpendicular to the sensor
    - lowest for objects made of soft material, of high temperature or with surface diffusing sound waves
- Large angle of measurement
    - mostly a drawback
    - might be beneficial for some applications





Ultrasonic displacement sensors

- Resolution: cca. measurement range / 4000
- Problem: noise
  - moving average filter with 3-5 samples
  - side effect: cca. 100ms of lag
- Dependence of the speed of sound of the environmental temperature might cause a significant error

Temperature	Reading without temperature compensation	Reading with temperature compensation
$20°C$	$1000\ mm$	
$-25°C$	$1077\ mm$	$1015\ mm$
$70°C$	$915\ mm$	$985\ mm$
Error	$\pm 8.5\%$	$\pm 1.5\%$

Pepperl+Fuchs UB1000 ultrasonic displacement sensor

Ultrasonic displacement sensors

- Ultrasonic sensors might also be used as proximity switches
  - displacement sensor with binary output
  - through-beam or retroreflective displacement sensor

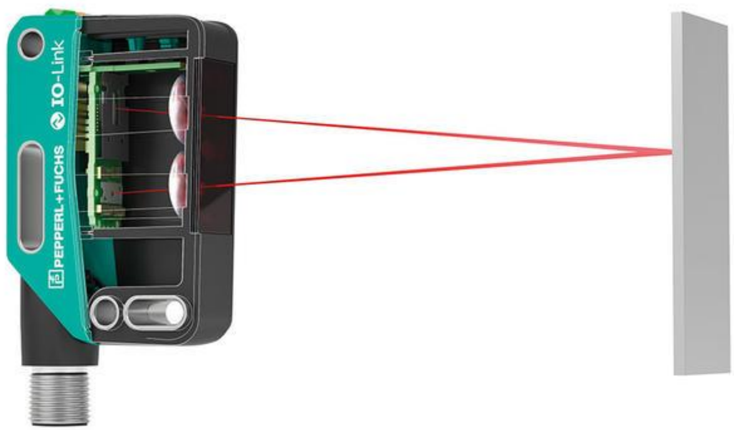
- Output
  - analogue (current / voltage)
  - Boolean (proximity switch mode)
  - digital (field bus)

Ultrasonic displacement sensors

+ contactless sensing
+ insensitive to lighting and pollution
+ wide measurement range

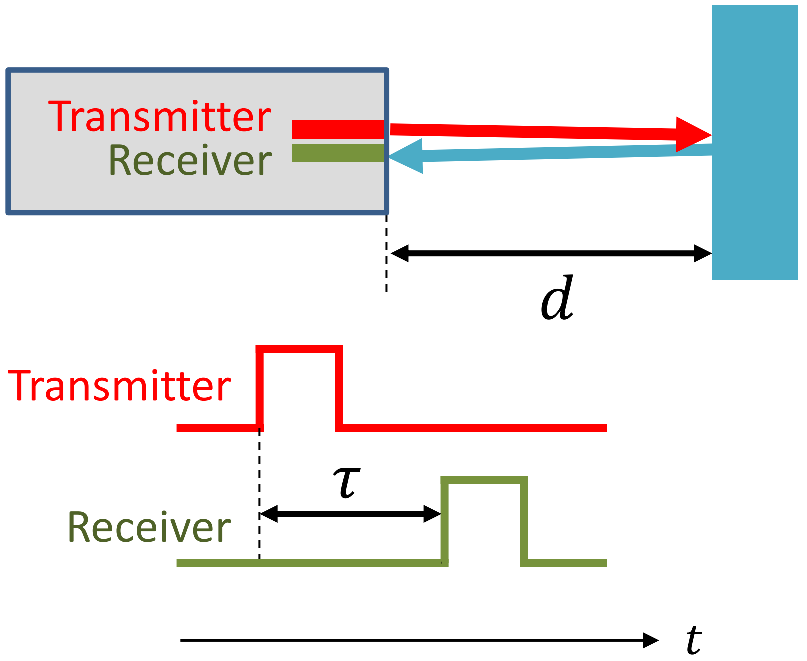
− high cost
− large response time
− significant temperature effects
− wide angle of measurement is commonly a cause of error

Laser displacement sensors



Pulse mode

- Transmitter emits a high-power laser pulse
- The laser beam is reflected by the object and detected by the receiver
- Time between the emission and detection is measured (*time of flight, ToF*)
- Emission of pulses with a frequency up to 10kHz

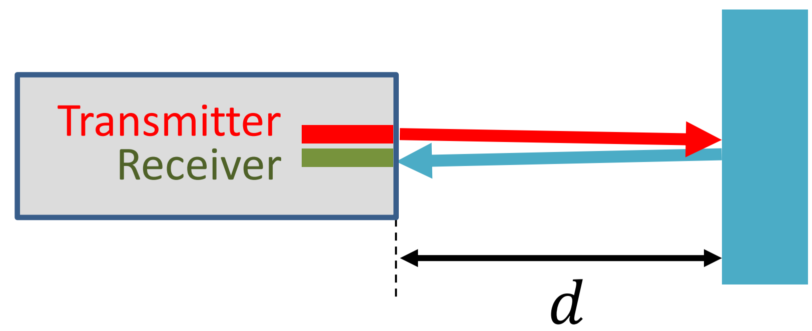


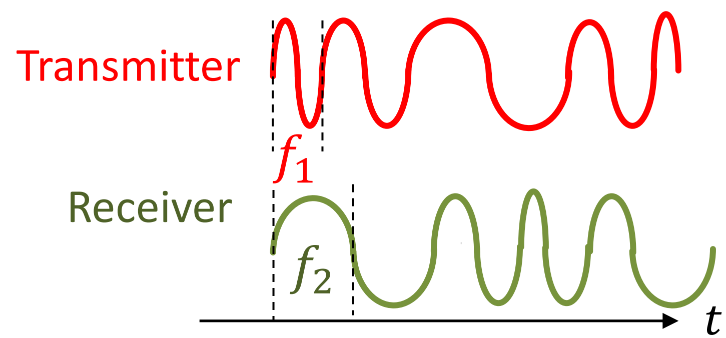
$$d = \frac{\tau c}{2}$$

c: speed of ligth

Frequency modulated mode

- Transmitter emits a continuous laser wave with modulated frequency
- Beam reflected by the object is detected by the receiver
- Time of flight can be measured by the frequency shift between the emitted and received wave
- Needs complex signal processing circuitry
- Reflection of the low-intensity, continuous wave depends on the material and surface of the object

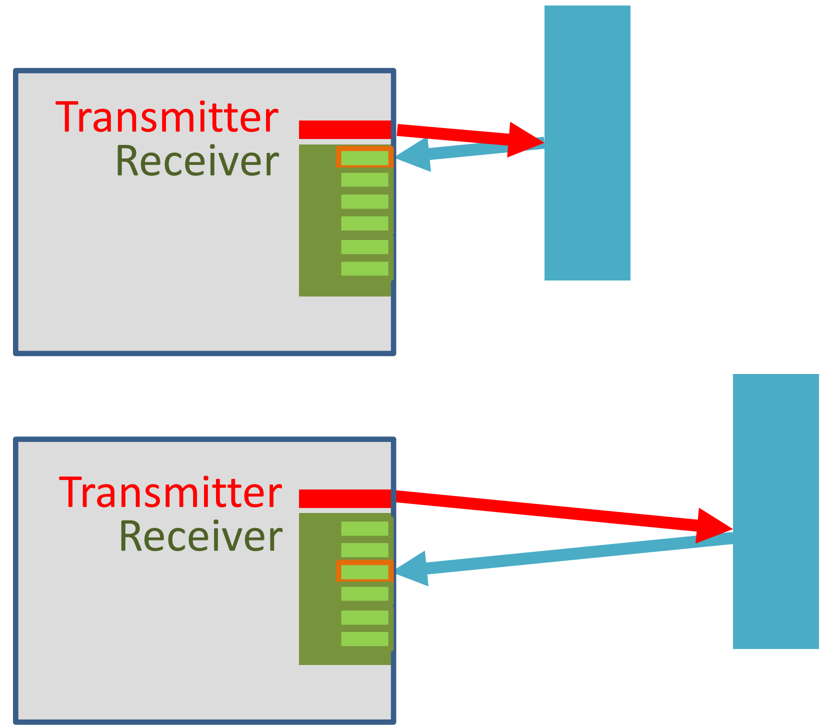


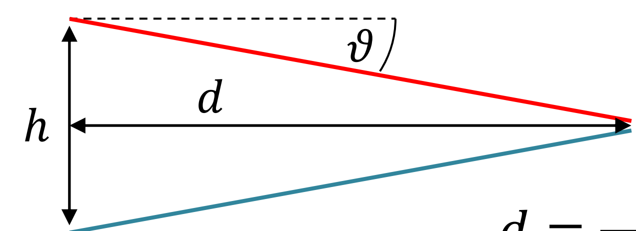


$$d \propto |f_1 - f_2|$$

Triangulation

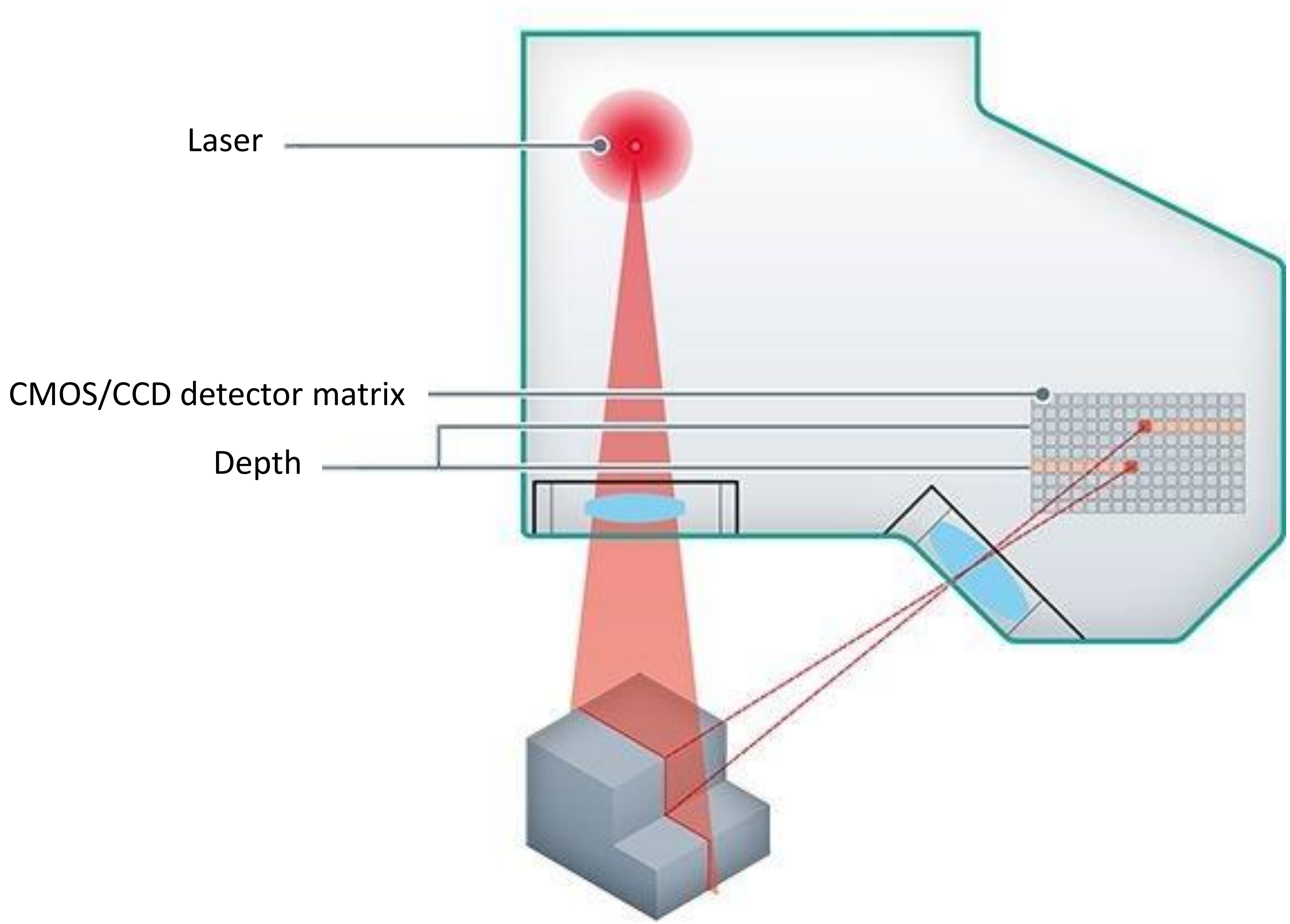
- The laser beam is detected by an element of the receiver detector line/matrix (CCD/CMOS) depending on the distance of the object
- Distance can be measured by the distance of the detector element
- Needs complex, high-resolution receiver and optics





$$d = \frac{h}{2\tan\vartheta}$$

Laser triangulation



Laser displacement sensors

+ contactless measurement
+ extremely high measurement range (up to 100m)
+ accuracy below 1%
+ insensitive to environmental temperature

- high cost
- needs complex signal processing electronics
- certain models are sensitive to lighting and surface of the object

Level sensors

Level sensors

- Products to sense
  - pure liquid
  - impure liquid
  - slurries
  - powder, bulk solid
  - interfaces

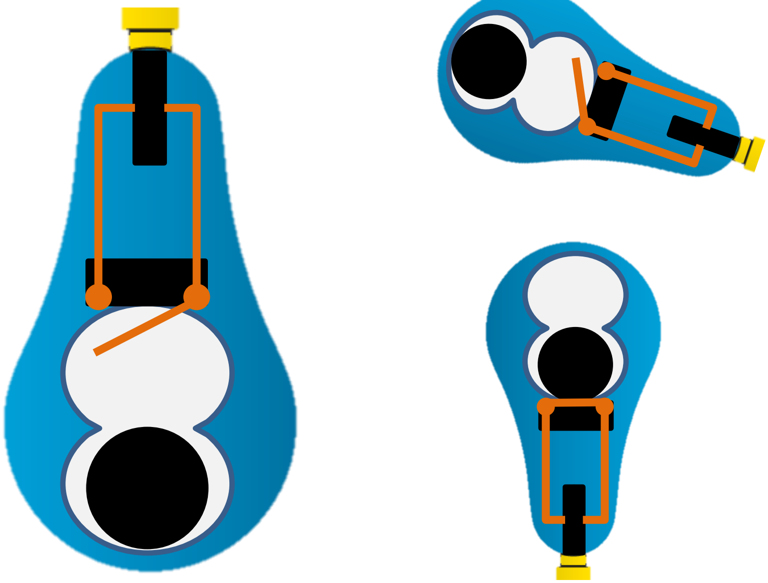
- Extreme conditions
  - high temperature
  - corrosive products
  - explosion hazard
  - floating solid particles

Level switches

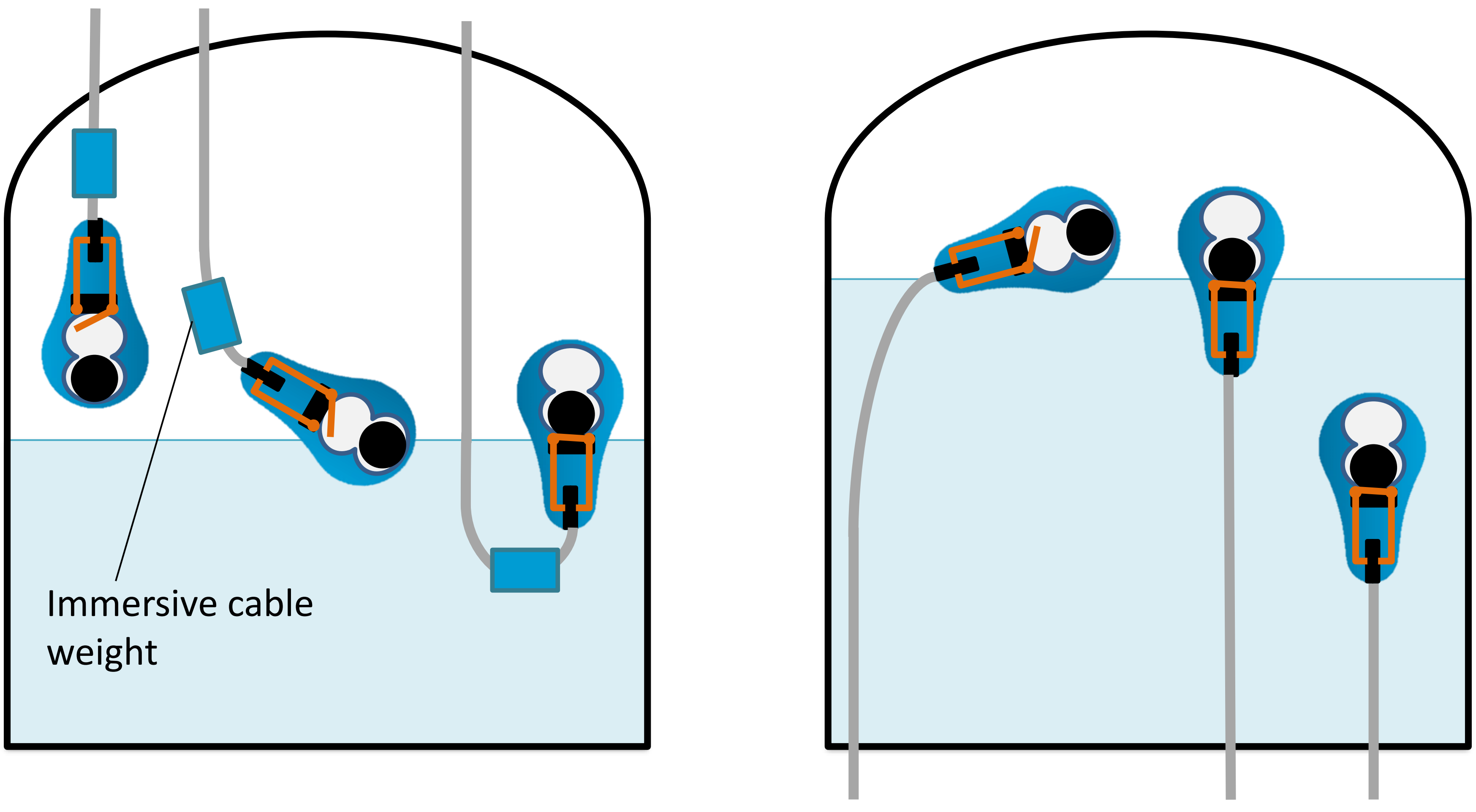
- Sensors with Boolean output
- Switch when the level reaches a given point
- Various forms
- Used mainly for alarm and simple level control (e.g. hysteresis control)

Float switch

- Hermetically sealed plastic housing
- Mechanical switch opened/closed depending on orientation
- Capable of switching high power signals



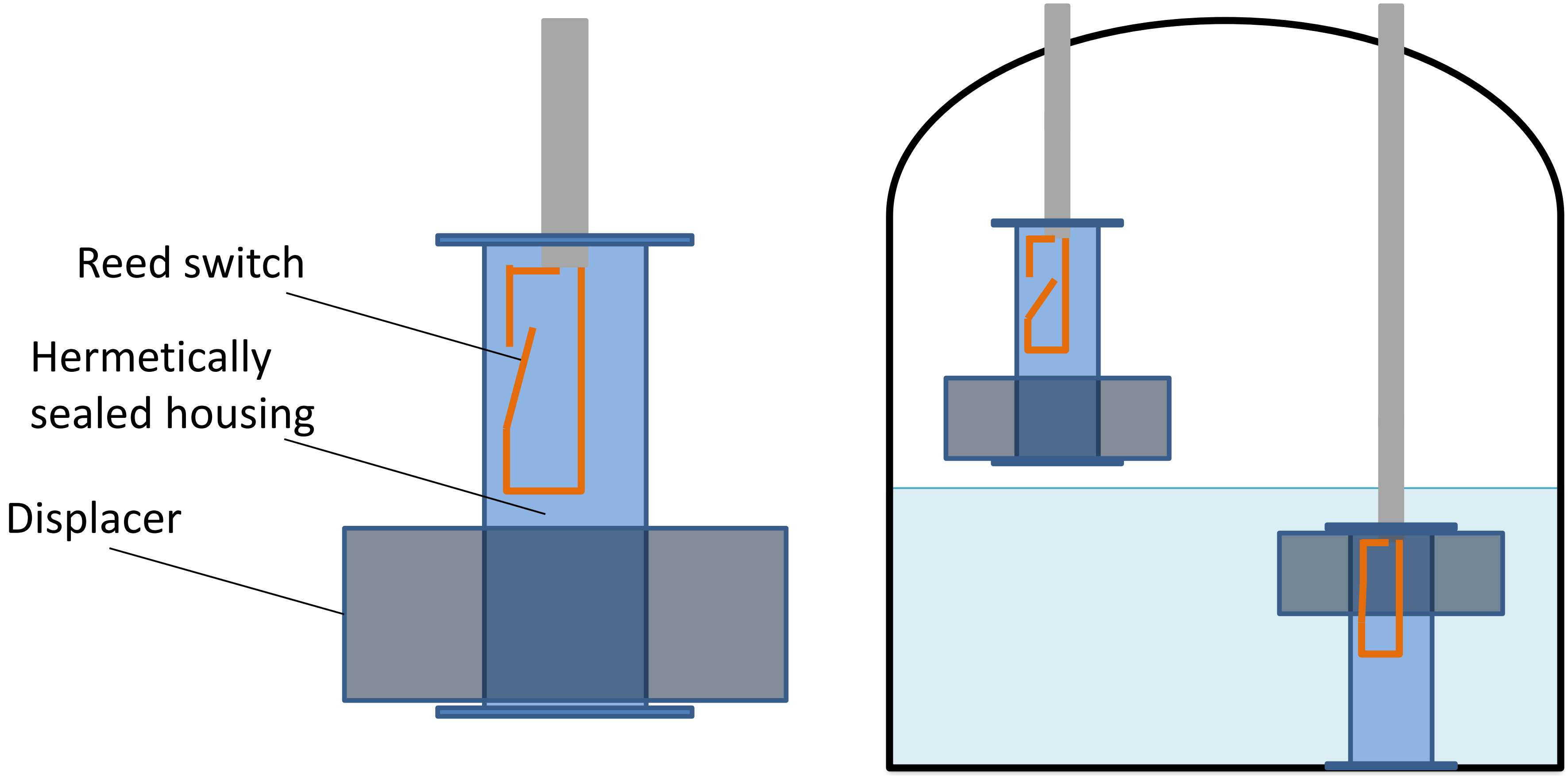
Application of float switches



Displacer switch

- Switching device: Reed switch
  - overlapping ferromagnetic contacts in glass or ceramic tube filled with inert gas
  - contacts close if magnetic field is applied
  - able to switch low-power signals only
- Conductive parts are hermetically sealed
- Reed switch operated by magnetic displacer

Displacer switch



Displacer switches

Direction of installation
- horizontal
- vertical

Installation location
- side
- top
- bottom

Mounting
- internal
- external
- floating

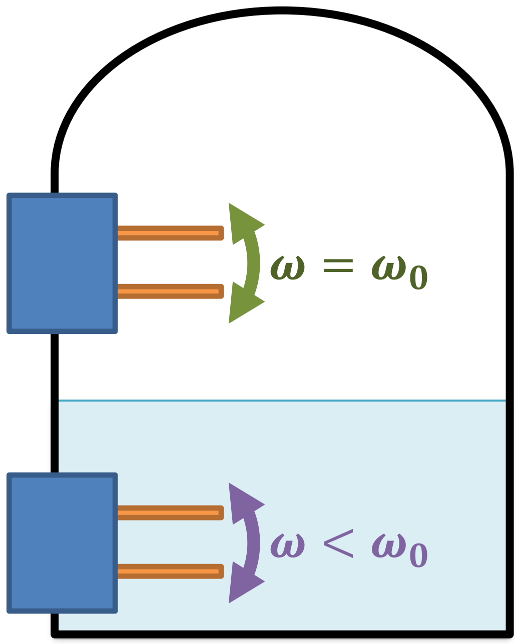
Float and displacer level switches

+ very simple design
+ reliable sensing
+ robust
+ able to operate in high pressure and high temperature environment
+ low cost

– immersed transducer
– immersed wiring (float switches)
– sensitive to solid dust
– might stuck in viscous fluids
– able to sense liquid level only

Vibrating fork level switch

- Fork resonates at its natural frequency in air
- Dense medium changes the resonant frequency
- Frequency depends on density (the higher the density the lower the frequency)
- Less sensitive to product coating due to resonation



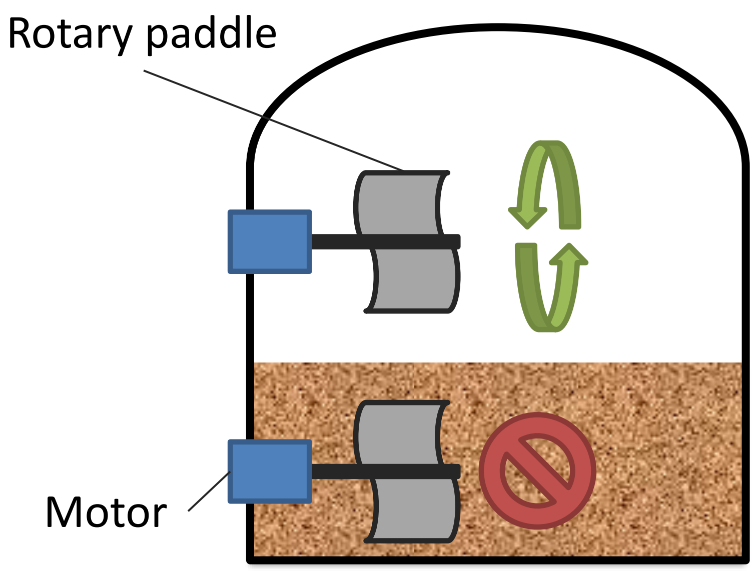
Vibrating fork level switch

- \+ no moving parts
- \+ able to operate at high temperature and high pressure
- \+ insensitive to flow, bubbling, parameter change of product

- − higher cost (compared to float and displacer switches)
- − immersed transducer
- − viscous liquids might form coating which changes the mass of the fork
- − able to sense liquid level only

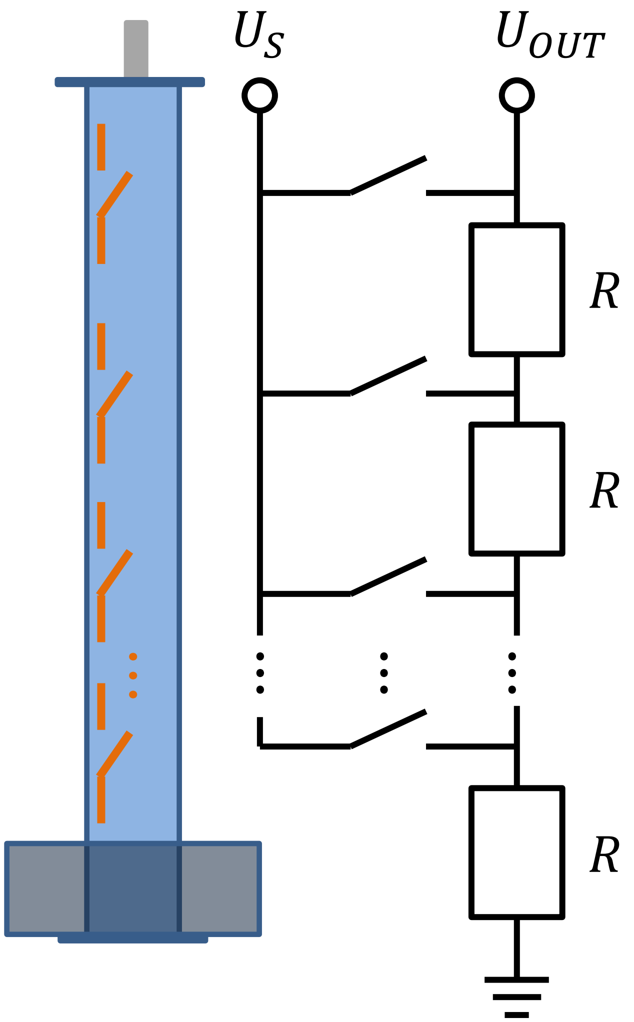
Rotary paddle level switch

- Level sensing for solid products (e.g. sand)
- Paddle rotated by low-speed and low-torque electric motor
- If the level reaches the sensor, the motor stalls
- Level sensing based on stall detection



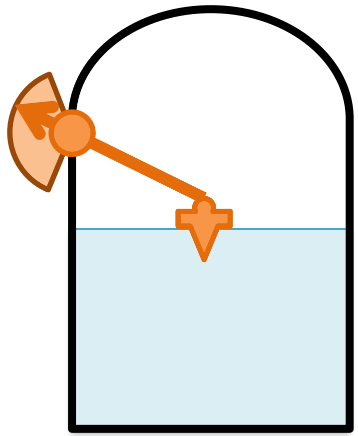
Discrete level sensor

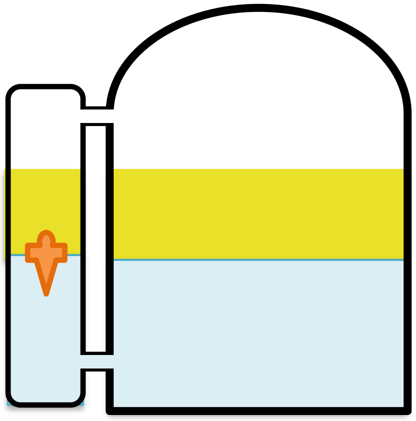
- Vector of discrete level switches (commonly displacer switches)
- Switches rungs of a resistor ladder, i.e. provides discrete output voltage levels for distinct liquid level ranges
- Limited resolution only



Displacer level sensors

- Task: measure the position of a buoyant displacer
- Electrical parts need to be sealed from the measured material
- Key: suitable transducer converting mechanical displacement to an other effect
- Problems: interfacing, disturbance effect of submerged displacer
- Advantage: interface levels can be measured with an appropriate displacer





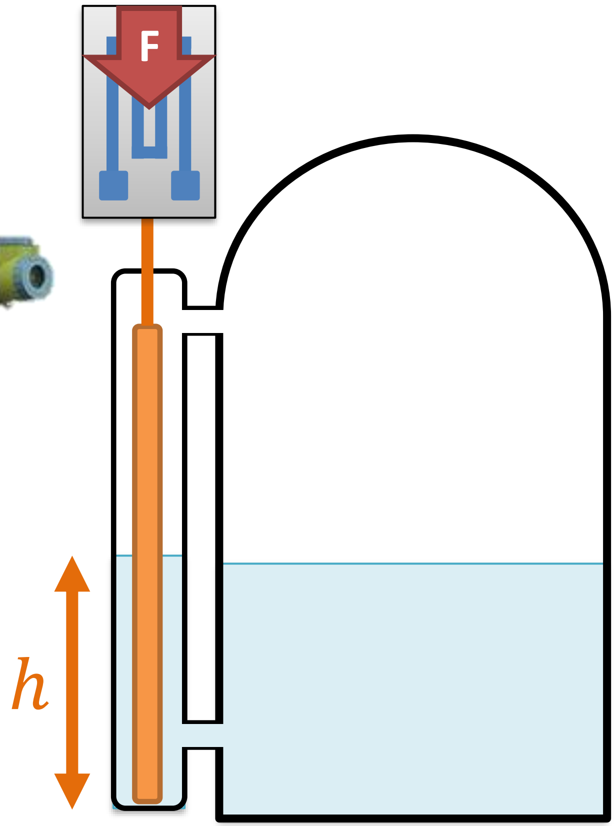
Lift force level sensor

- Lift force acting on a mass: $F_{lift} = \rho g V' = \gamma V'$
  - ρ: medium (fluid) density
  - g: standard gravity
  - V': submerged volume
  - γ: medium (fluid) specific weight
- Measured force:

$$F = mg - F_f = mg - \rho g V'$$

- Level:

$$V' = Ah \Rightarrow h = \frac{mg - F}{\rho g A}$$



Lift force level sensor

+ able to operate at high temperature and high pressure
+ able to operate if emulsion layers are present

- immersed transducer
- can be used if density of medium is constant and known exactly
- needs calibration
- high maintenance need
- limited measurement range (5m)
- able to measure liquid level only
- sensitive to coating, might get stuck

Hydrostatic pressure

- Hydrostatic pressure: $P = \rho g h = \gamma h$

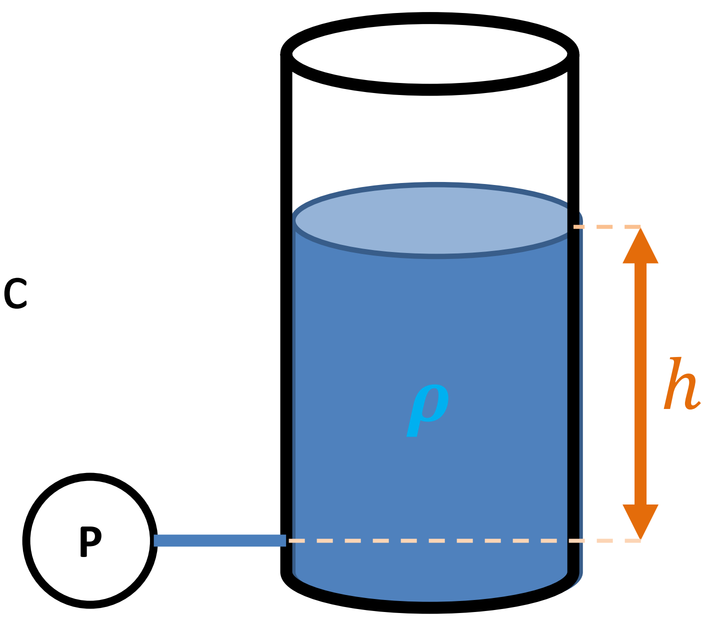
  ρ: medium (liquid) density

  h: height of liquid column (level)

  g: standard gravity

  γ: specific weight of medium

- Gauge pressure (relative to atmospheric pressure)
- Applies for open vessels only



Hydrostatic pressure in closed vessels

- Hydrostatic pressure:

$$P = \rho g h + P_v = \gamma h + P_v$$

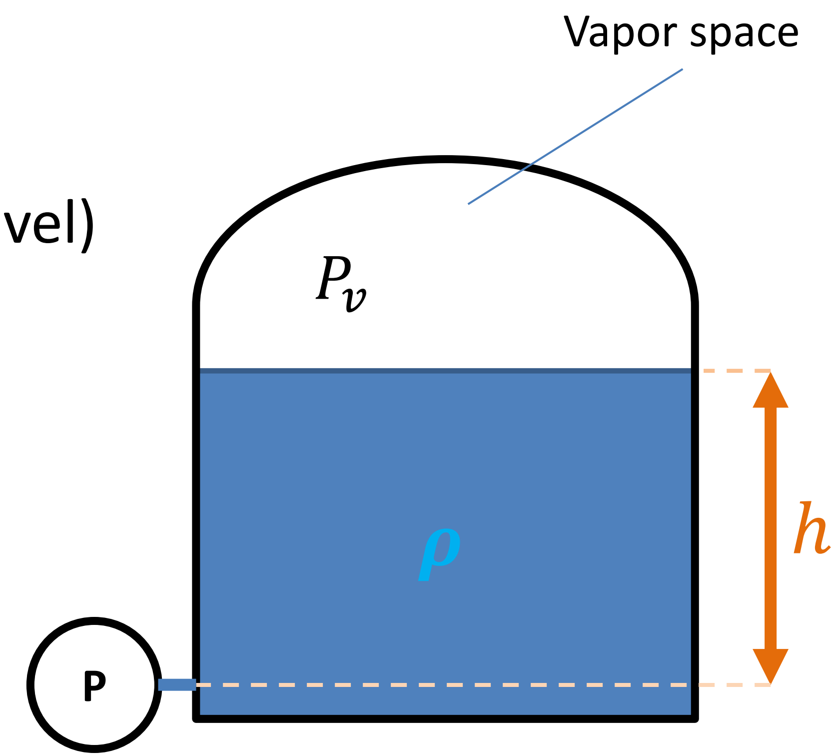
ρ: medium (liquid) density

h: height of liquid column (level)

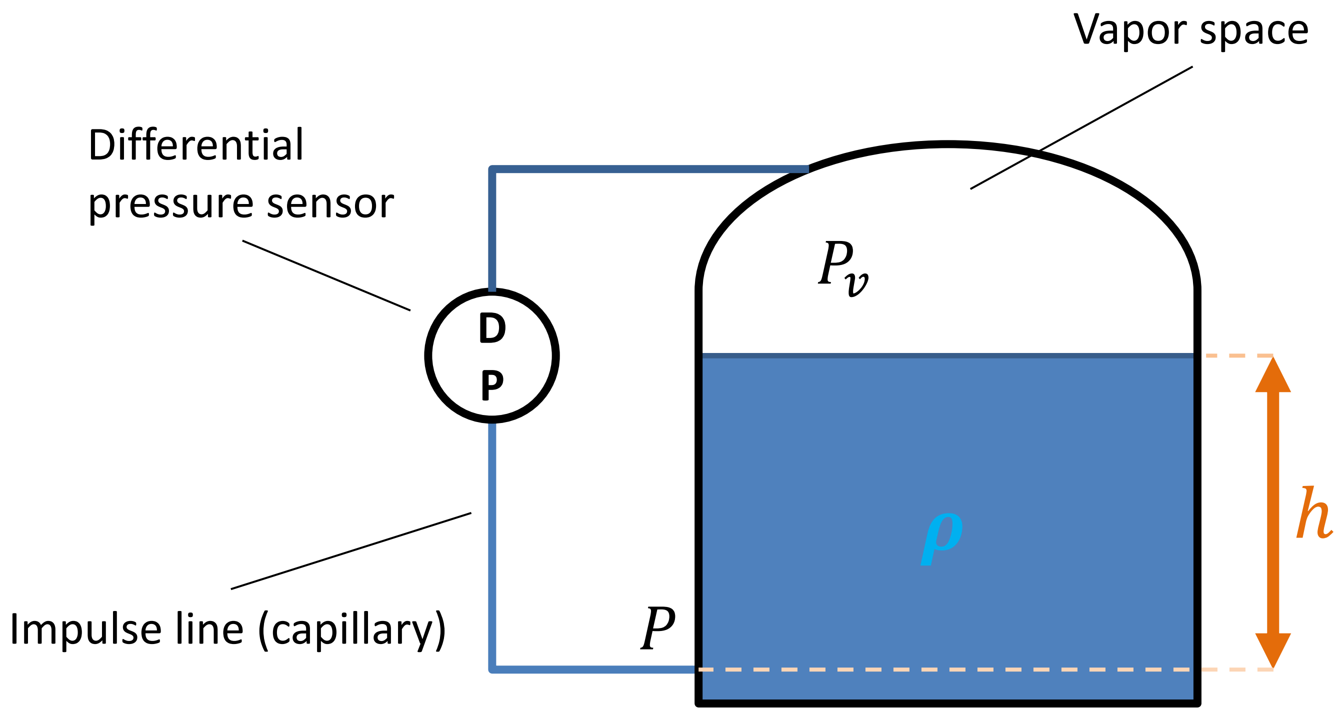
g: standard gravity

P_v: vapor space pressure

γ: specific weight of medium



Differential pressure (dp) level sensors



$$P_d = P - P_v = (\rho g h + P_v) - P_v = \rho g h = \gamma h$$

$$h = \frac{P_d}{\rho g} = \frac{P_d}{\gamma}$$

Measurement of product with unknown density

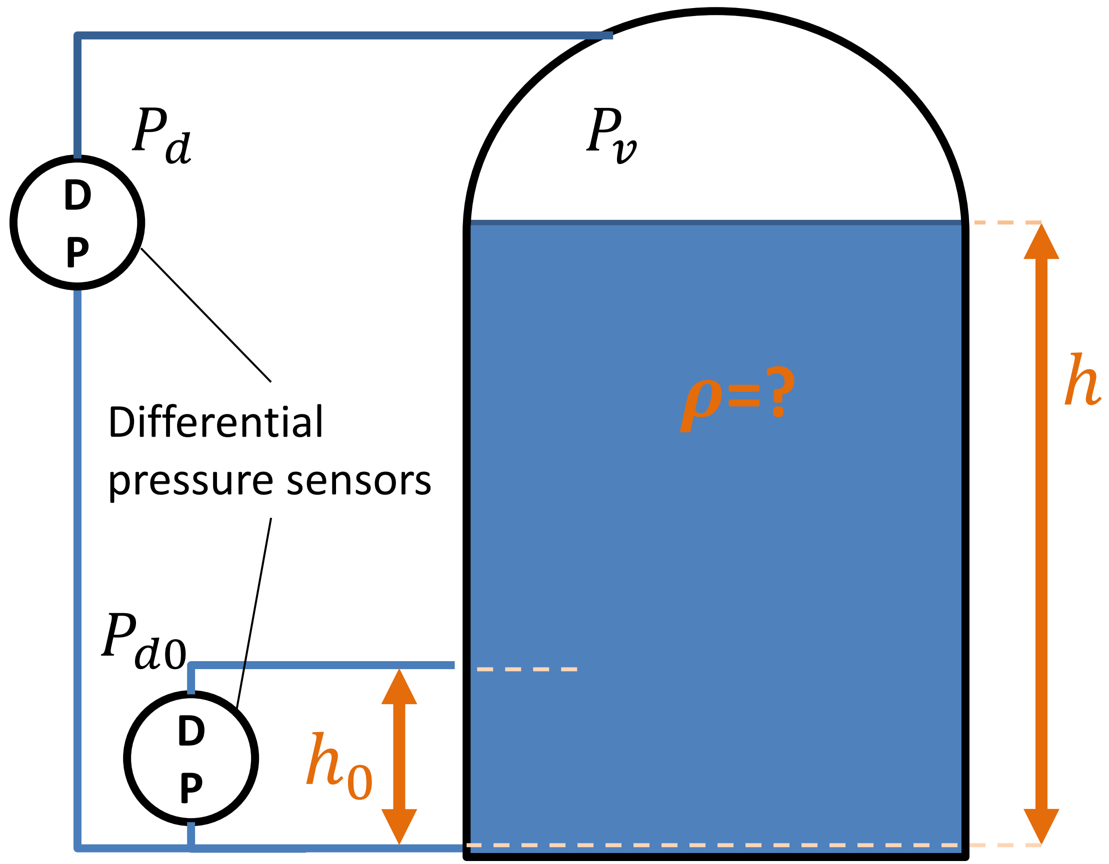
- $P_d = (\rho g h + P_v) - P_v = \rho g h = \gamma h$
- $P_{d0} = (\rho g h + P_v) - (\rho g (h - h_0) + P_v) = \rho g h_0 = \gamma h_0$

- h_0 is known exactly

- $\boldsymbol{\frac{P_d}{P_{d0}} = \frac{h}{h_0} \Rightarrow}$

$$\boldsymbol{\Rightarrow h = h_0 \frac{P_d}{P_{d0}}}$$

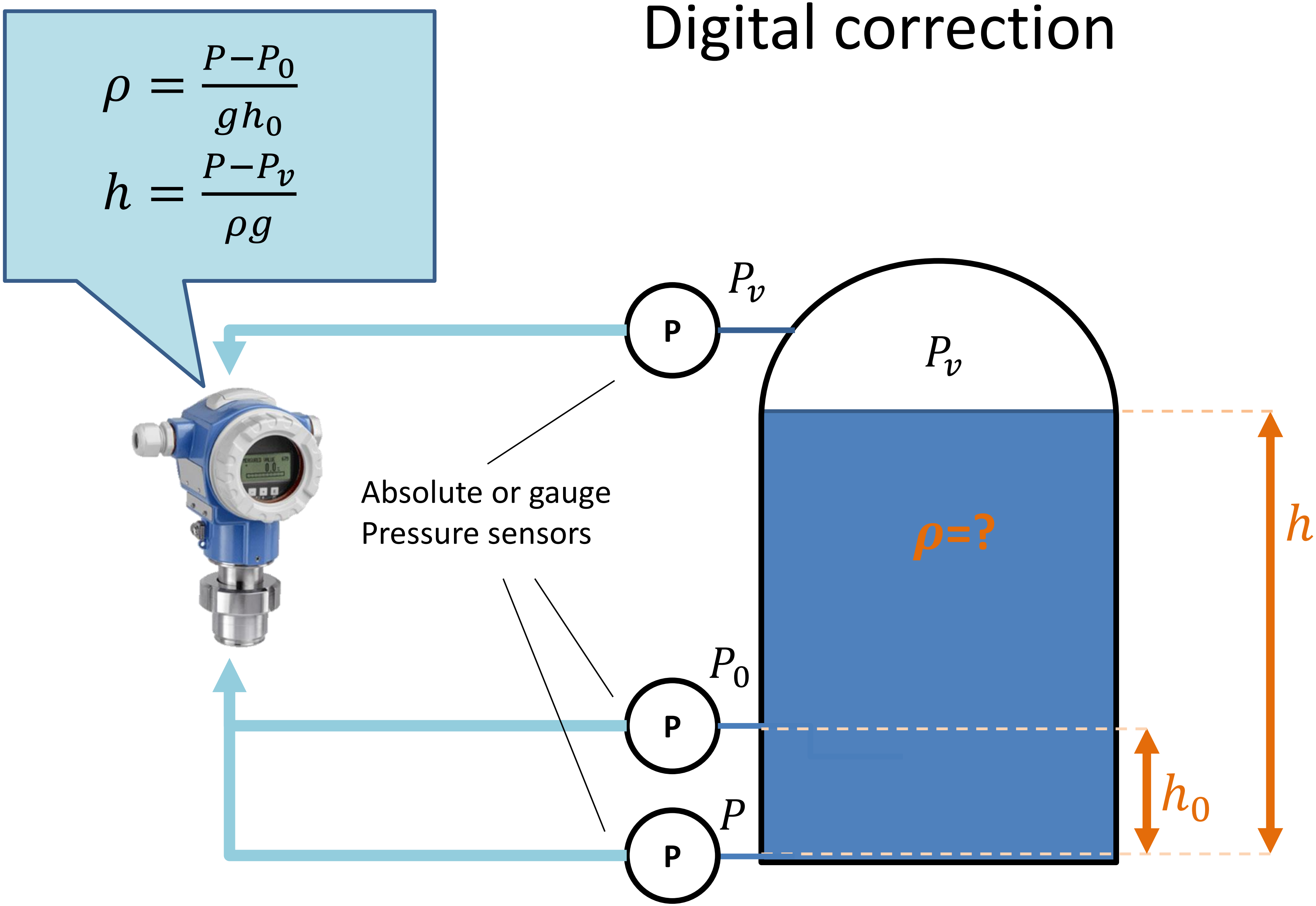
Applies to levels higher than h_0 only!



Problems of differential pressure level sensors

- Large vessels need long impulse lines or capillaries
- Impulse lines might clog
- Significant thermal expansion of product in impulse lines
- Danger of freeze of product in impulse lines

Digital correction

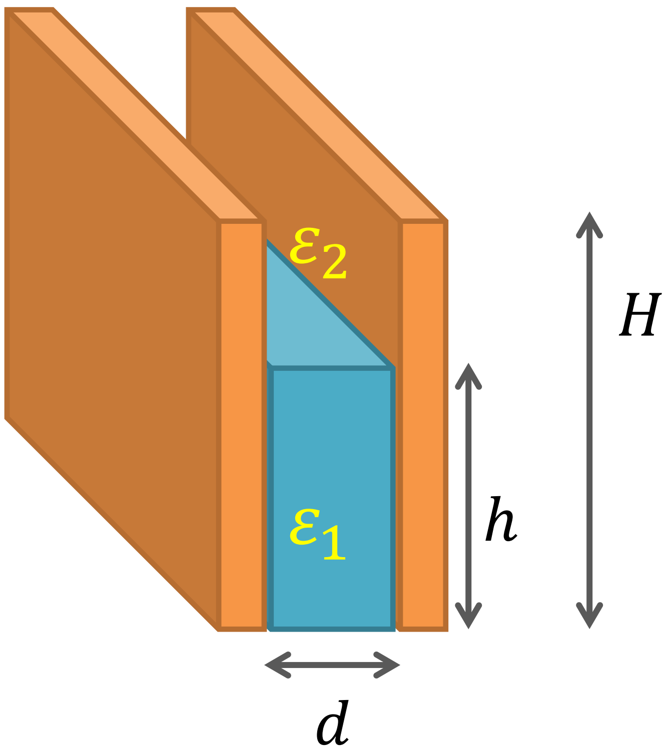


Differential pressure level sensors

- \+ able to operate in high temperature and high temperature environment
- \+ wide measurement range
- \+ no immersed part
- \+ sensing principle independent from the geometry of the vessel
- \+ able to measure level of any liquid or slurries
- \+ able to measure interface levels
- \+ insensitive to turbulence and foaming

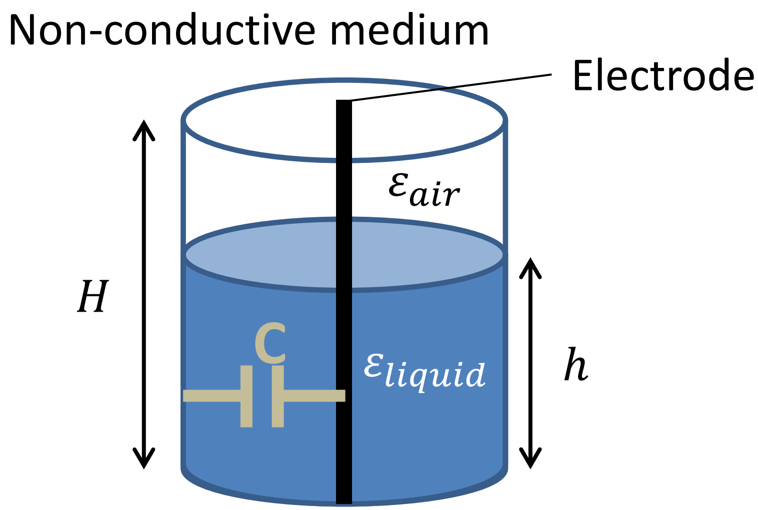
- − density dependence of simple setups
- − unable to measure solidifying material (e.g. paper mache)
- − thermal expansion in impulse lines can cause significant error
- − able to sense liquid and slurry level only

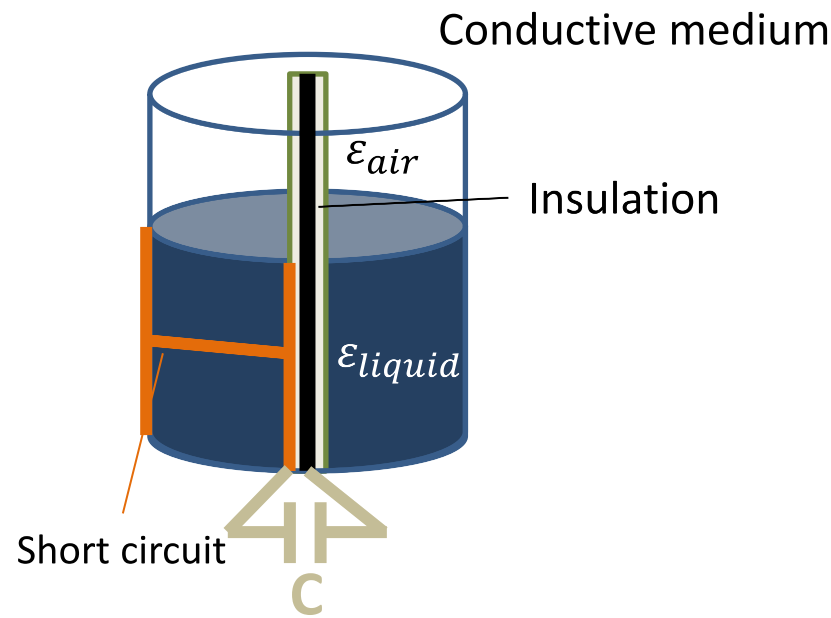
Capacitance level sensors



- $C = \frac{\left(\varepsilon_1 \frac{h}{H} + \varepsilon_2 \frac{H-h}{H}\right)A}{d}$
  - ε_1: permittivity of medium (liquid)
  - ε_2: permittivity of air or inert gas
  - h: level of medium
  - H: total height of vessel
  - A: area of electrodes
  - d: distance of electrodes

Capacitive level sensors

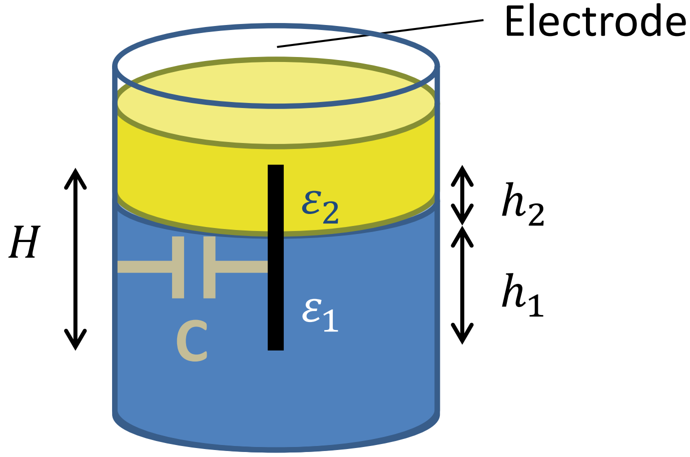




- Calibration:
  - $C_{empty} = C|_{h=0} = H\varepsilon_{air}\alpha$
  - $C_{full} = C|_{h=H} = H\varepsilon_{liquid}\alpha$
- Measurement:
  - $C = \alpha\left(h\varepsilon_{liquid} + (H-h)\varepsilon_{air}\right) = \frac{\mathrm{h}}{\mathrm{H}}\mathrm{C}_{\mathrm{full}} + \mathrm{C}_{\mathrm{empty}} - \frac{\mathrm{h}}{\mathrm{H}}\mathrm{C}_{\mathrm{empty}} = \mathrm{C}_{\mathrm{empty}} + \frac{\mathrm{h}}{\mathrm{H}}(\mathrm{C}_{\mathrm{full}} - \mathrm{C}_{\mathrm{empty}})$
  - $h = H\frac{C - C_{empty}}{C_{full} - C_{empty}}$

Interface measurement

Non-conductive media



- Calibration:
  - $C_1 = C|_{h_1=H} = H\varepsilon_1\alpha$
  - $C_2 = C|_{h_2=H} = H\varepsilon_2\alpha$

- Measurement:
  - $C = \alpha(h_1\varepsilon_1 + (H - h_1)\varepsilon_2) =$
    $= \frac{\mathrm{h}_1}{\mathrm{H}}\mathrm{C}_1 + \mathrm{C}_2 - \frac{\mathrm{h}_1}{\mathrm{H}}\mathrm{C}_2 = \mathrm{C}_2 + \frac{\mathrm{h}_1}{\mathrm{H}}(\mathrm{C}_1 - \mathrm{C}_2)$
  - $h_1 = H\frac{C - C_2}{C_1 - C_2}$

Capacitive level sensors

+ able to operate in wide temperature and pressure range
+ wide measurement range
+ no moving parts
+ able to measure liquids, slurries and solids
+ able to measure interfaces
+ limited cost

− requires site calibration (and frequent recalibration)

− change in permittivity of the medium causes measurement error

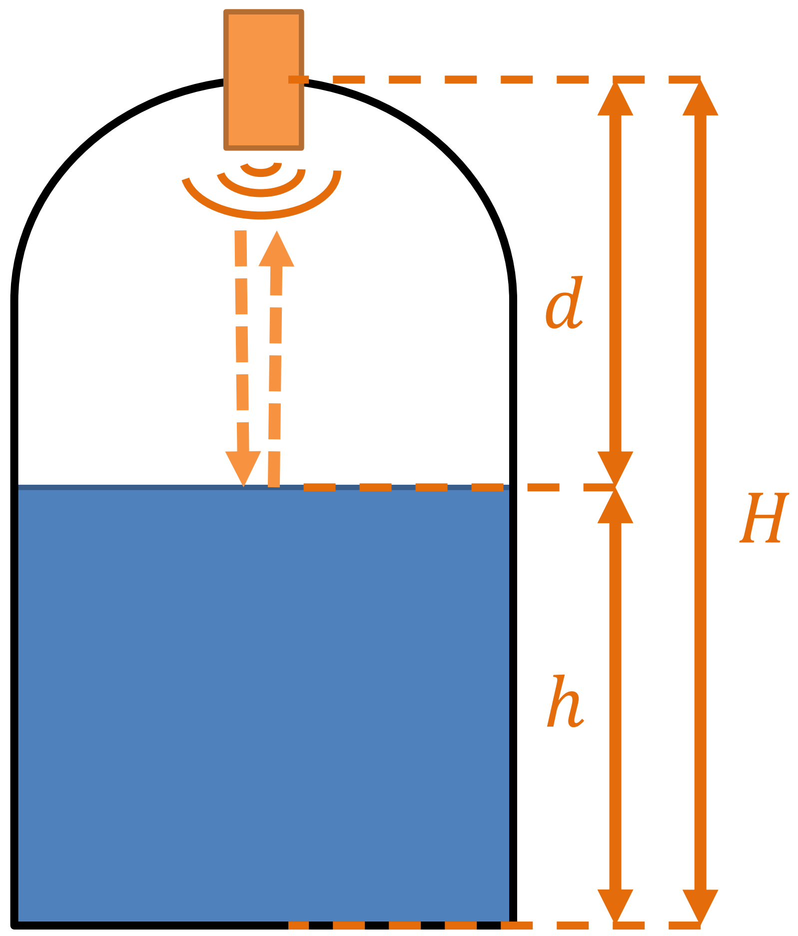
− coating of electrodes causes measurement error

Ultrasonic level sensors

- Ultrasound source located at the top of the vessel
- Ultrasonic waves reflected by the surface of the medium
- Level calculated from the time elapsed between emitting an ultrasonic package and receiving the reflection (time of flight measurement)

Ultrasonic level sensors

- $\tau = \frac{2d}{v}$,
  where v is the speed of sound
- $d = \frac{\tau v}{2}$
- $h = H - d$
- H can be measured during installation (empty vessel)



Ultrasonic sensors - problems

- Reflection
  - significant foam or vapor forming causes measurement error
  - significant turbulence causes measurement error
  - waves reflected by obstacles inside the vessel (agitator, pipes etc.) might cause measurement error
  - measurement range is limited by beam angle

- Wave propagation
  - vacuum in vapor space makes measurement impossible
  - speed of sound depends on temperature (needs digital compensation)

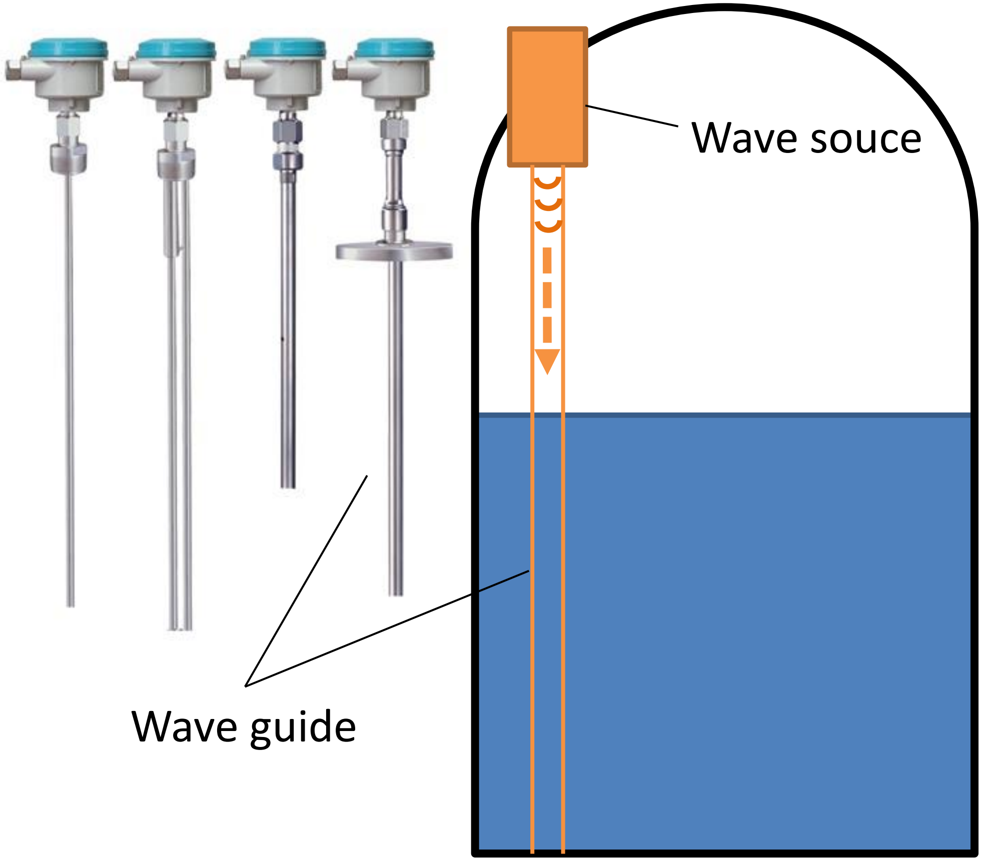
Ultrasonic level sensors

- \+ contactless measurement without moving parts
- \+ wide measurement range
- \+ insensitive to parameter changes of the medium
- \+ able to measure liquids, solids and slurries
- \+ easy installation

- − high cost
- − narrow temperature and pressure range
- − properties of product surface (foam, vapor, turbulence) influence accuracy
- − need of complex electronics

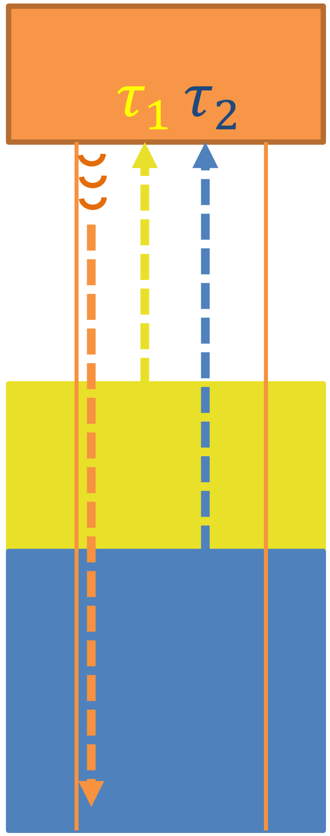
Guided wave radar (GWR) sensors

- Microwave pulses propagate from the top of the vessel towards the bottom inside the wave guide
- Wave guide prevents dispersion of waves
- A part of waves is reflected from the surface of medium
- Measurement of level based on time of flight



Interface measurement

- Parts of radar waves are reflected by the top surface
- Parts of remaining waves are reflected by the interface
- Difference of times of flight indicates level of the interface



Non-contacting radar level sensors

- Directed radar waves propagate freely from the top of the vessel without a wave guide
- Impulse mode radar
  - emission of short pulses
  - time of flight measurement
- Frequency modulated mode radar (FMCW)
  - continuous emission of waves with slowly varying frequency
  - mixing emitted wave with the reflected one
  - time of flight calculated from the difference of frequencies

Radar level sensors

+ partially/fully contactless
+ no moving parts
+ wide measurement range
+ insensitive to parameter changes of the medium
+ able to measure liquids, slurries and solids
+ easy installation

– high cost
– low dielectric constant products might absorb radar waves
– coating in wave guide
– installation of wave guides might be difficult
– obstacle inside the vessel might cause error (in case of non-contacting types)

Other principles for level sensing

- Level sensing based on weight (force) measurement
- Nuclear level sensors
- Conductivity sensors
- Laser level sensors