EE1320: Measurement Science

Lecture 2: Sensors

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April 26, 2013

Course program 2013

week	date	topic
4.1	Tu 23/4	#1 intro measurements and meas. systems
	Fr 26/4	#2 sensors
4.3	Tu 7/5	#3 sensor readout and signal conditioning
4.4	Tu 14/5	#4 instrumentation amplifiers
	We 15/5	intermediate test
4.5	Tu 21/5	#5 analog-to-digital converters
4.6	We 29/5	#6 measurement instruments I
4.7	Tu 4/6	#7 measurement instruments II
	We 5/6	intermediate test
4.8	Tu 11/6	tutorial
4.11	We 3/7	final exam

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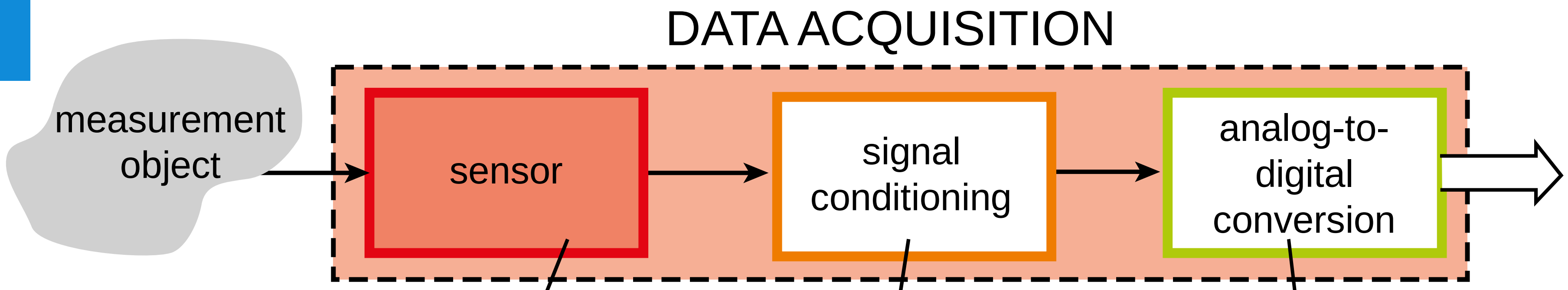
Last time…

- **Measuring** = determining the value of a certain quantity
  - measurement requires international standards
  - calibration is needed for traceable, comparable measurements
  - every measurement is subject to measurement uncertainty

- **Measurement system**: converts quantity to be measured x into usable output signal y (often electrical, digital)
  - Characterized by transfer $y = H(x)$ with sensitivity $H'(x)$
  - Deviation transfer can lead to measurement errors:
    non-linearity, ambiguity, cross sensitivity, finite resolution

- Don't forget to **practice!**
  Answers to the exercises can be found on BlackBoard

Structure of a measurement system



lecture 5: A/D convertors

transduction of information from a (non-electrical) domain to the electrical domain

lecture 2: sensors

- amplification
- buffering (impedance transformation)
- filtering
- signal conversion (e.g. R → V)

lecture 3/4: sensor readout & instrumentation amplifiers

Today: Sensors

- General properties and classification

- Resistive sensors
- Capacitive sensors
- Inductive sensors
- Thermoelectric sensors
- Piezoelectric sensors
- Semiconductor sensors

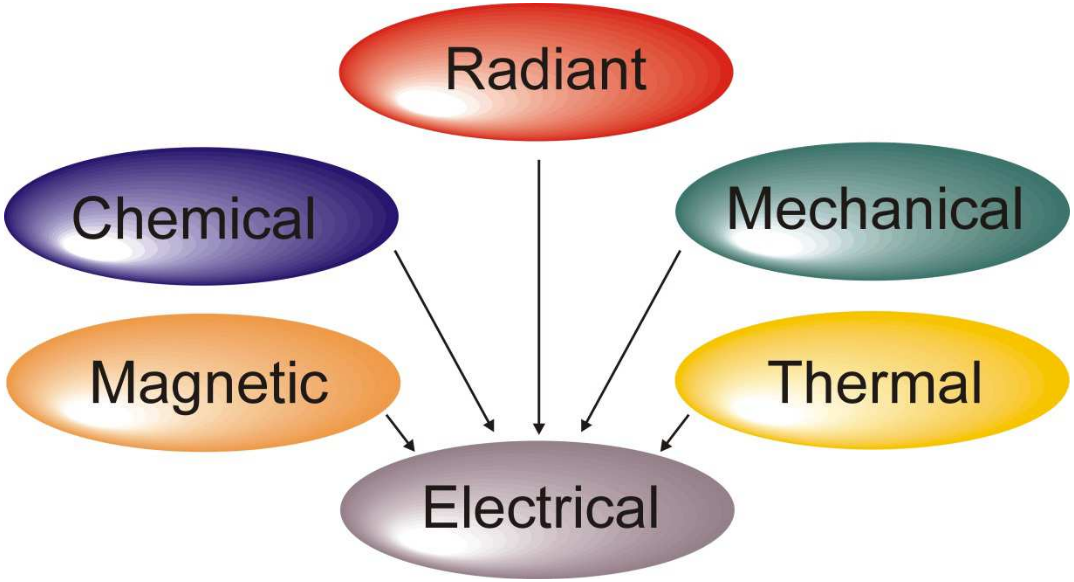
Wednesday 1/5: EPO-2 just-in-time training capacitive sensors

Wednesday 8/5: EPO-2 just-in-time training inductive sensors

Overview study material

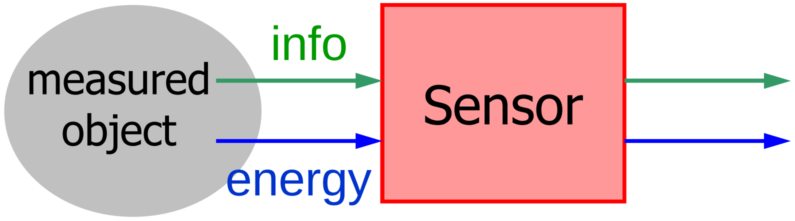
General properties and classification	slides
Resistive sensors	Regtien 7.2.1
Capacitive sensors	7.2.3
Inductive sensors	7.2.2
Thermoelectric sensors	7.2.4
Piezoelectric sensors	7.2.5
Semiconductor sensors	9.1.1 en 9.1.2

Sensors



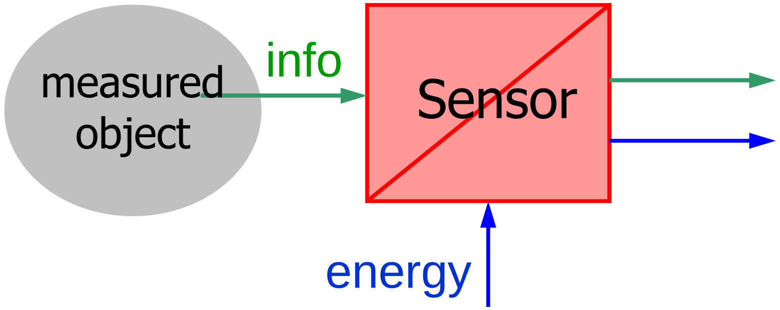
- Transduction of non-electrical signals to electrical signals
- Ideal sensor:
  - imposes no load on the source
  - does not add noise
  - is selective: only sensitive to relevant information

Self-generating vs. modulating



self-generating

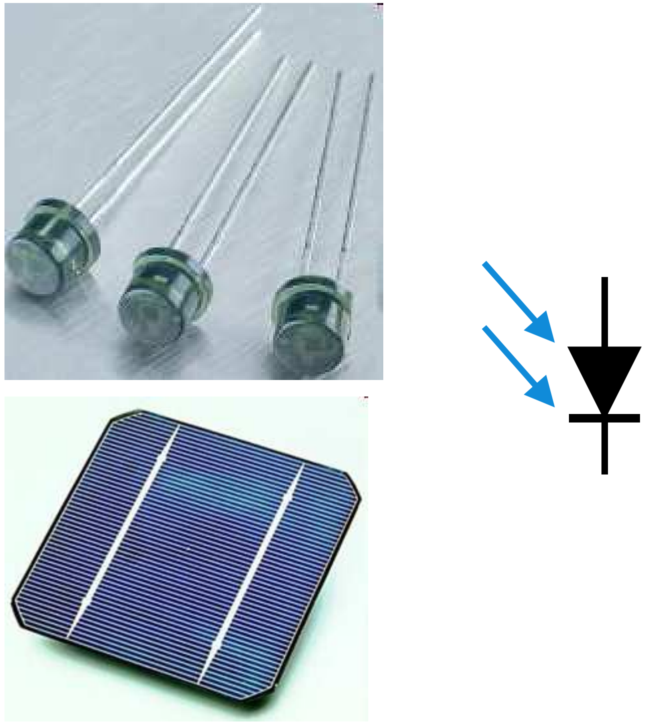
information and energy drawn from the measured object
+ minimal sources of error (e.g. no offset)
– load is imposed on the source



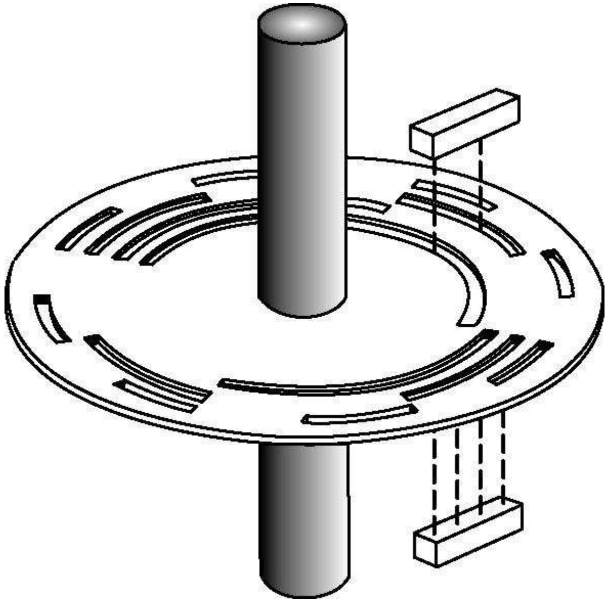
modulating

information of measured object modulates energy transfer from external auxiliary source
+ minimal load on source
– extra sources of error

Self-generating vs. modulating

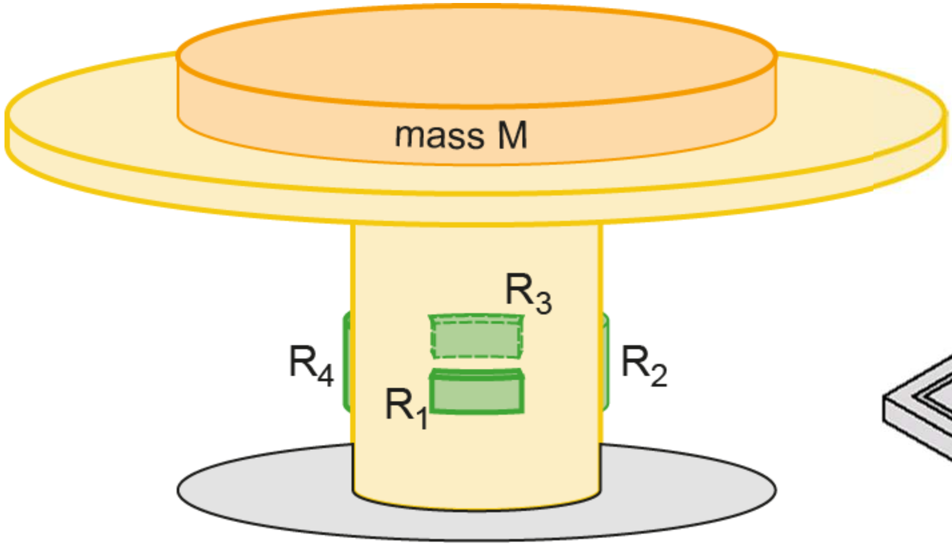


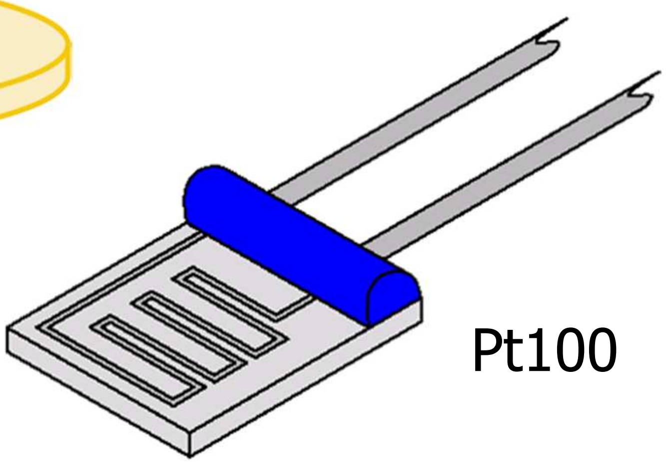
Photodiode, solar cell



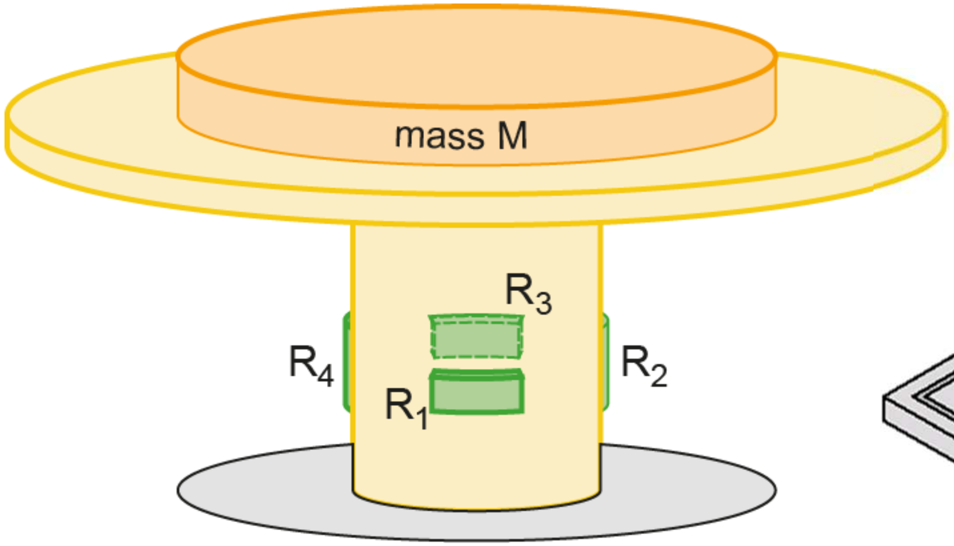
optical
angle encoder

Self-generating or modulating?

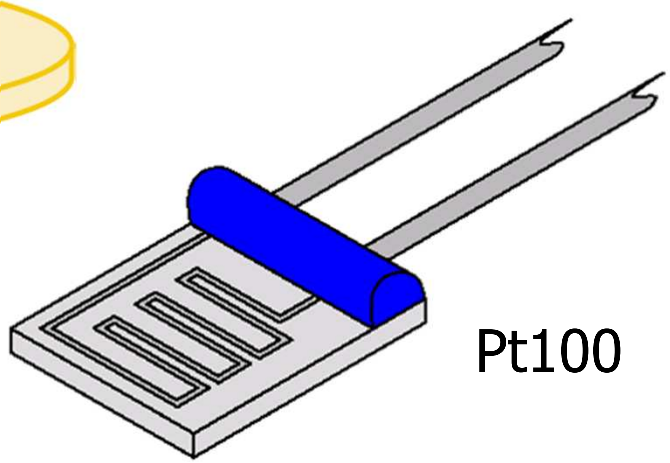




Self-generating or modulating?



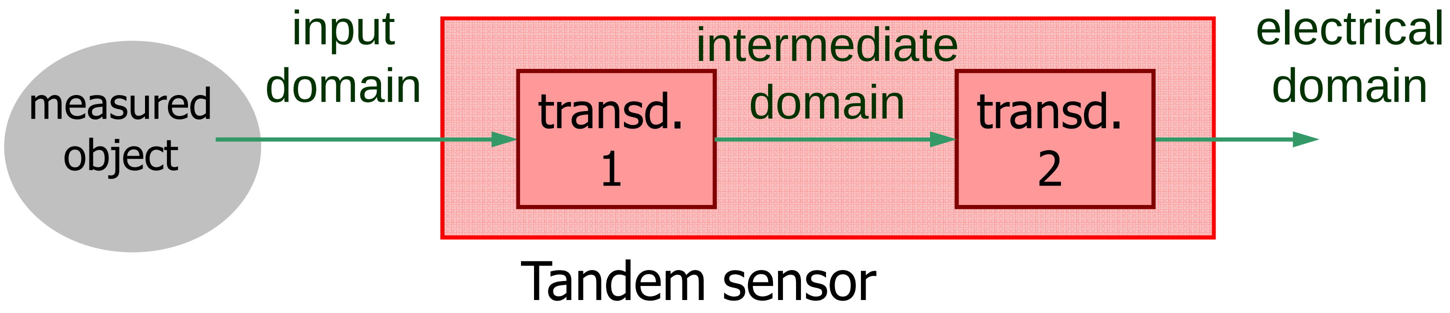
Modulating



Modulating

Tandem transducers

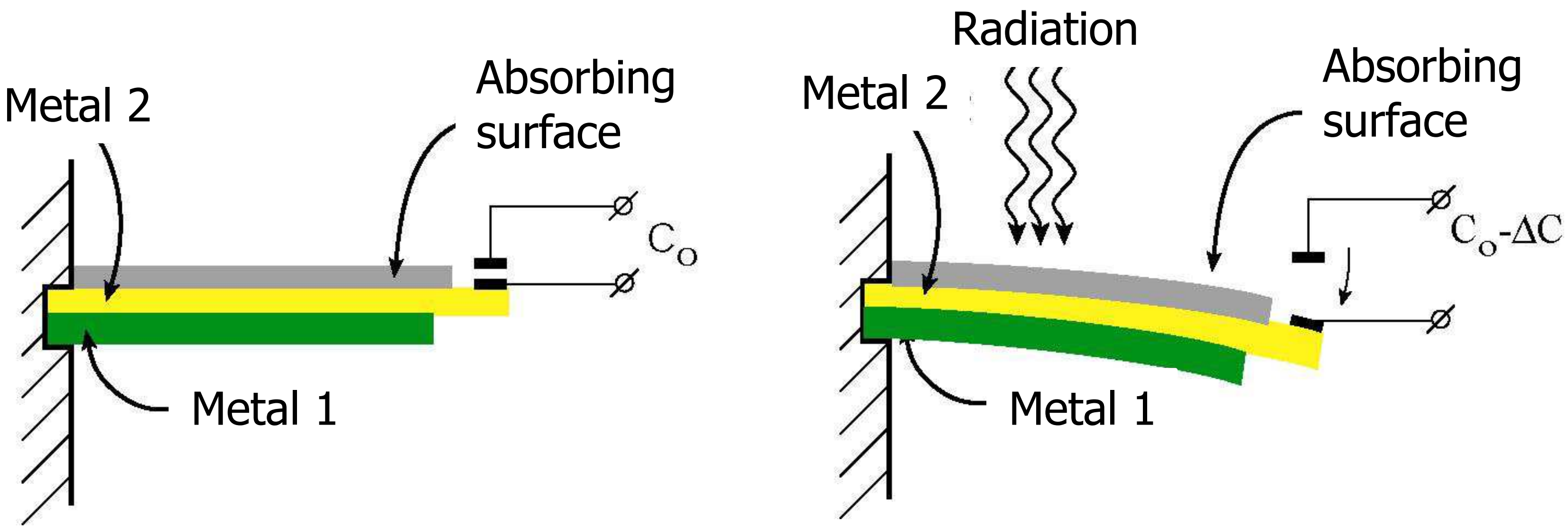
- Transduction consisting of one or more intermediate steps



- Besides the input domain and the output domain (electrical), at least one other (non-electrical) intermediate domain

Tandem transducers

- Example: radiation sensor with bi-metal and capacitive readout



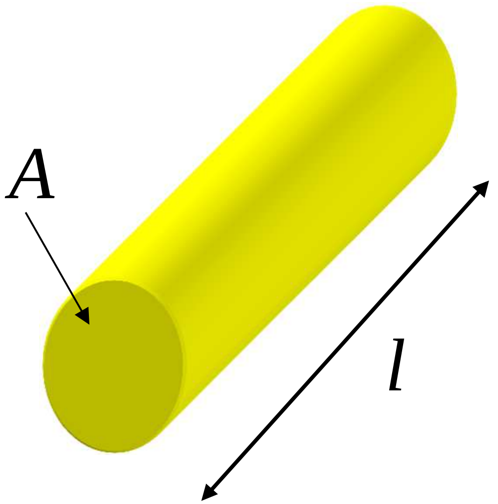
Resistive sensors

- Resistance of a wire-shaped conductor:

$$R = \rho \frac{l}{A} \quad [\Omega]$$

material

geometry

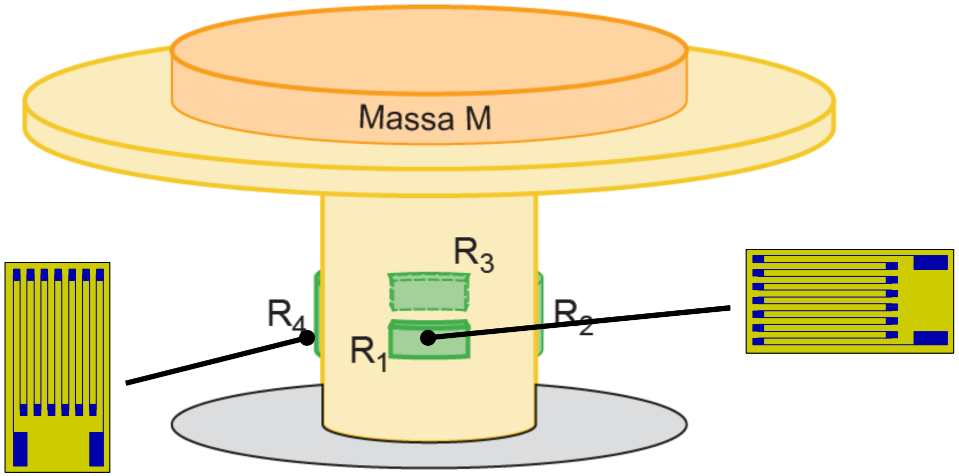


ρ = resistivity [Ωm]

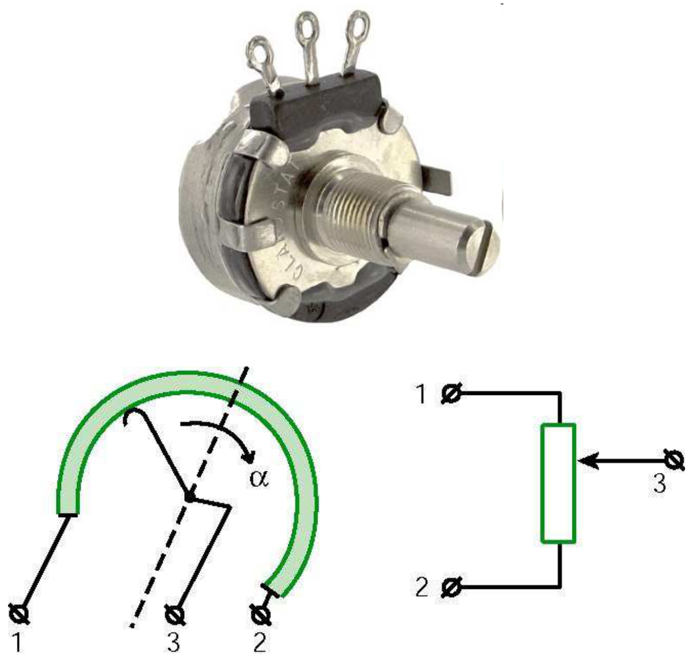
σ = 1/ρ = conductance

Resistive sensors: mechanical

- Examples:



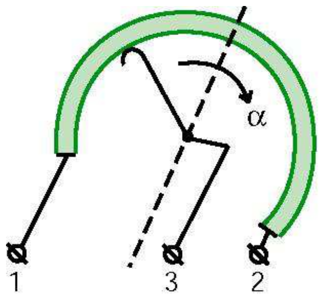
weighing scale with strain gauges
(see lecture 1)

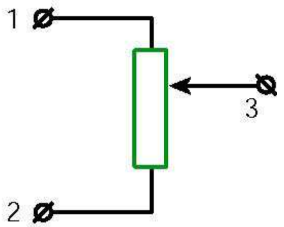


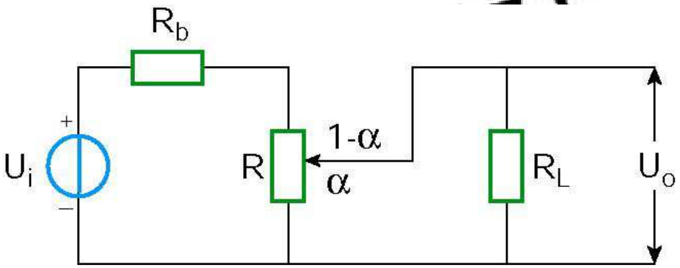
angular displacement sensor
based on a potentiometer

Regtien 7.2.1.3, 7.2.1.4

Readout of a potentiometric sensor

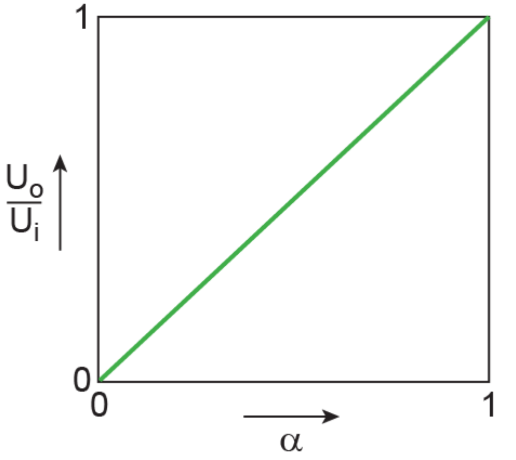






- Ideal sensor: $R_b = 0$, $R_L \to \infty$

$$\frac{U_o}{U_i} = \frac{\alpha \cdot R}{R} = \alpha$$



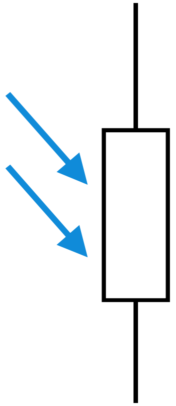
- Say $R_L \to \infty$, but $R_b \neq 0$.
  What kind of transfer error will this yield?

Regtien 5.1.3

Resistive sensors: LDR

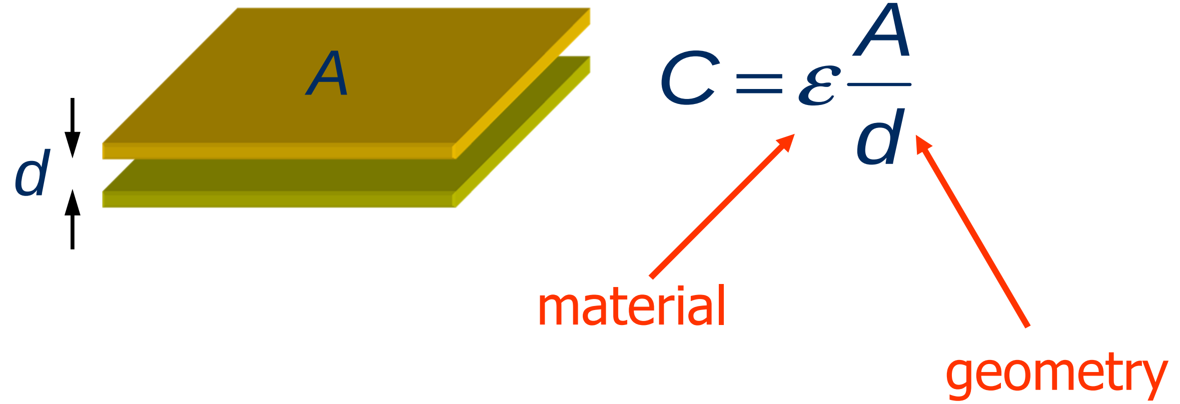
Light dependent resistor (LDR), or photoconductor

- High-resistivity semiconductor (typically CdS)
- Light ⇒ more free charge carriers ⇒ lower resistance
- Not very accurate, but very sensitive:
  - dark resistance on the order of 10^6 Ω
  - resistance at high light intensity on the order of 10^2 Ω
- Spectral sensitivity can be adjusted from UV via visible light to infrared, depending on the application



Capacitive sensors

- Parallel-plate capacitor:



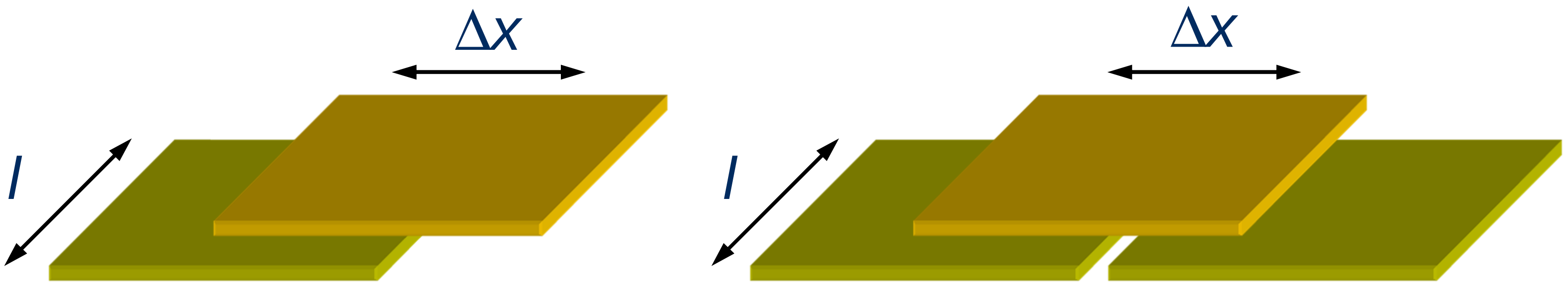
$$C = \varepsilon \frac{A}{d}$$

$\varepsilon = \varepsilon_0\, \varepsilon_r$ = permittivity or dielectric constant [F/m]

$\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m = permittivity of vacuum

Capacitive displacement sensors

- Lateral displacement:



single

$$\frac{\Delta C}{C} = \frac{\Delta A}{A} = \frac{l \cdot \Delta x}{A}$$

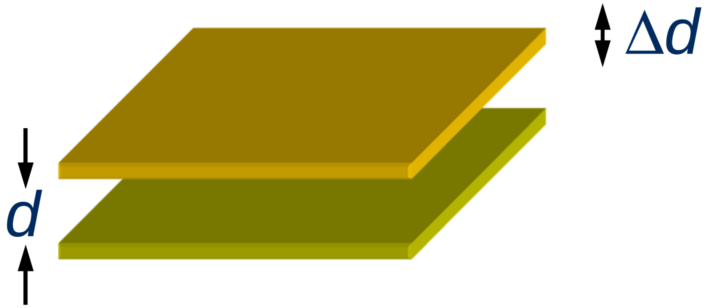
differential

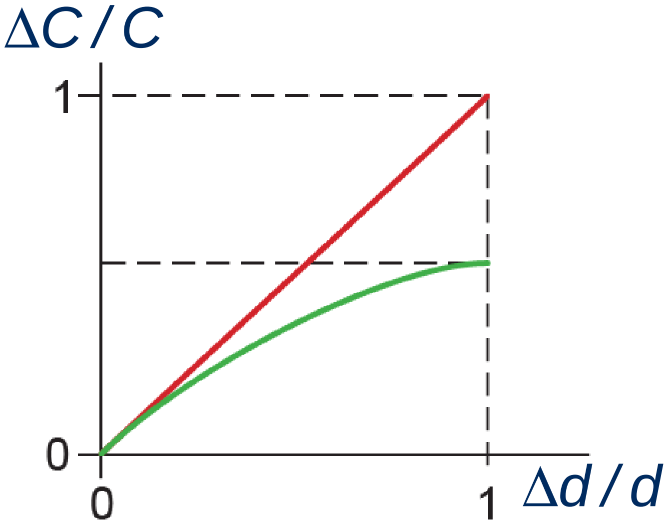
$$\Delta C_1 = -\Delta C_2$$

Capacitive displacement sensors

- Vertical displacement:

$$\frac{\Delta C}{C} = \frac{\Delta d}{d + \Delta d} \approx \frac{\Delta d}{d}$$



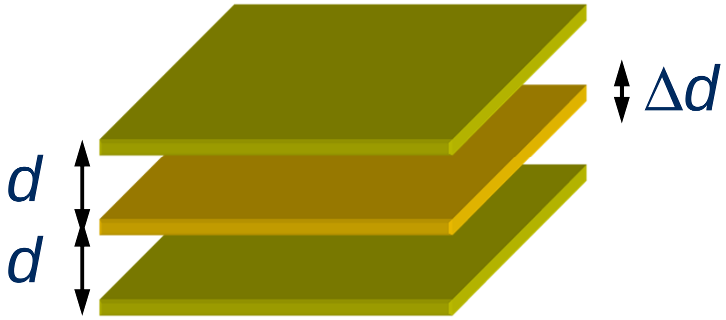


- Systematically non-linear transfer
- Linear approximation will quickly result in large errors!

- How can we make this sensor more linear???

Capacitive displacement sensors

- Vertical displacement – differential:



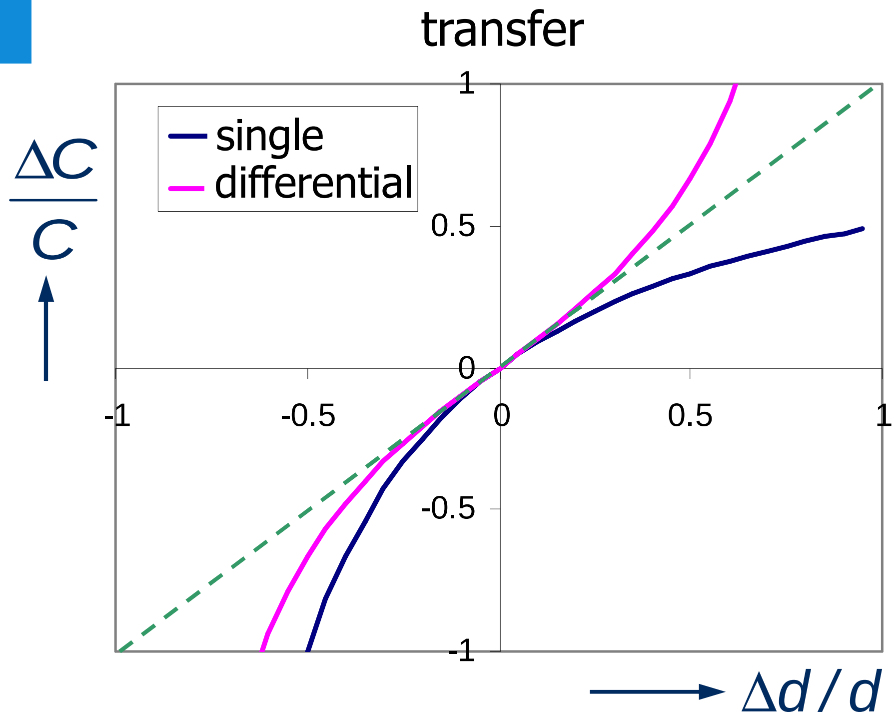
$$\frac{\Delta C_1}{C_1} = \frac{\Delta d}{d_1 + \Delta d} \qquad \frac{\Delta C_2}{C_2} = -\frac{\Delta d}{d_2 - \Delta d}$$

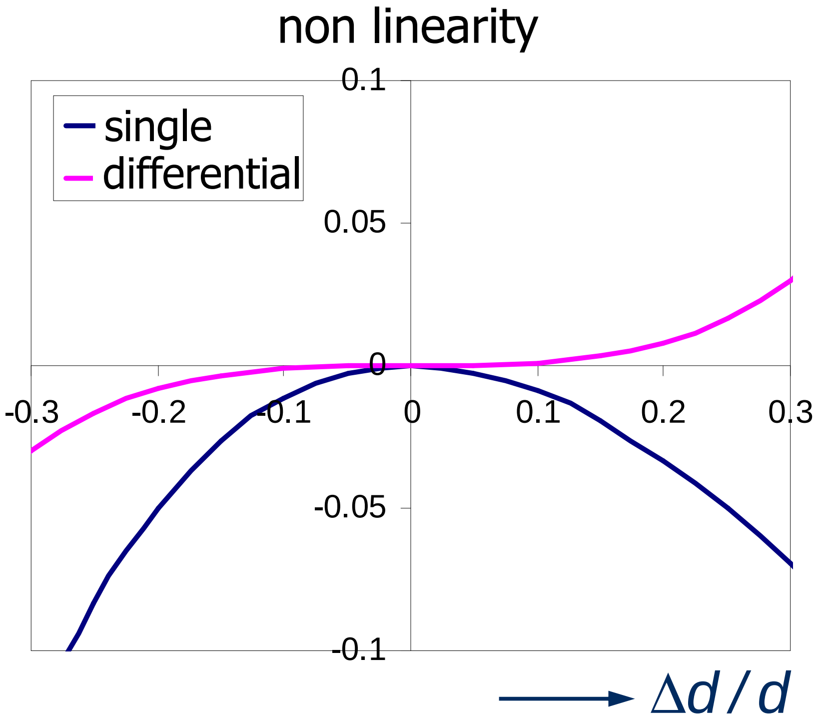
$$\frac{\Delta C_1}{C_1} - \frac{\Delta C_2}{C_2} = \frac{\Delta d}{d + \Delta d} + \frac{\Delta d}{d - \Delta d}$$

$$= 2\frac{\Delta d}{d}\left(\frac{1}{1 - \boxed{\Delta d^2 / d^2}}\right)$$

- Error term scales with $(\Delta d / d)^2$ instead of $\Delta d / d$
  $\Rightarrow$ much smaller for small $\Delta d / d$

Capacitive displacement sensors

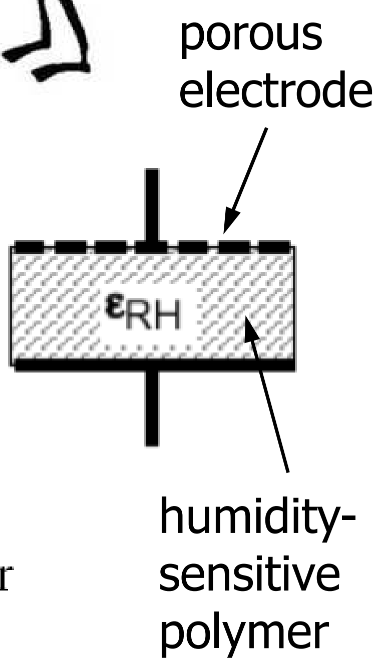




- **Generally:** differential approaches eliminate even-order non linearities (quadratic, fourth-order, etc.)

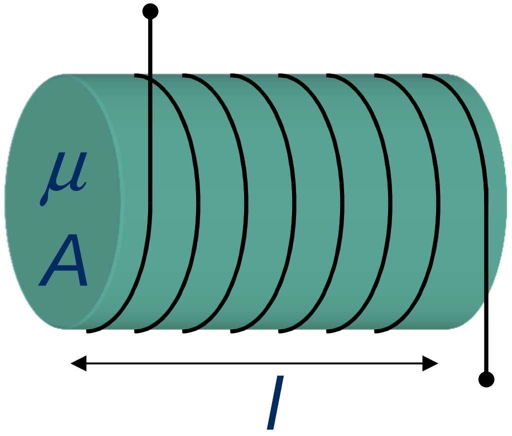
Capacitive humidity sensor

Parameter	Conditions	Value
Nominal capacitance	$\phi = 55\%$, $T = 25$ °C	330 pF
Nominal sensitivity	$20\% \leq \phi \leq 95\%$, $T = 25$ °C	0.80 pF/%
Cross sensitivity to temperature	$5\ °C \leq T \leq 70\ °C$	0.16 pF/°C
Long-term reproducibility	$T = 25$ °C	<0.2 %/jaar



What is the maximum measurement error one year after calibration in the temperature range of 10 °C to 45 °C?

Inductive sensors



$$L = \mu \cdot n^2 \cdot \frac{A}{l}$$

material

windings

geometry

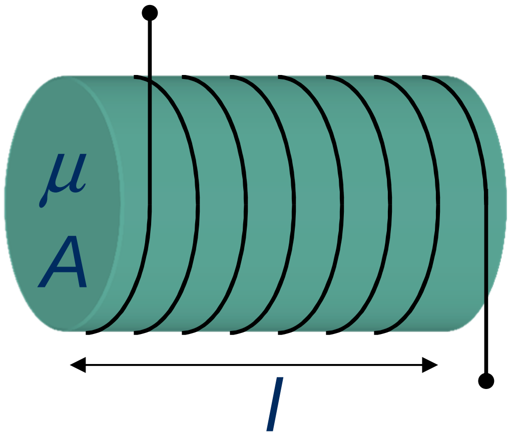
approximation valid for a long, thin coil
(diameter << length)

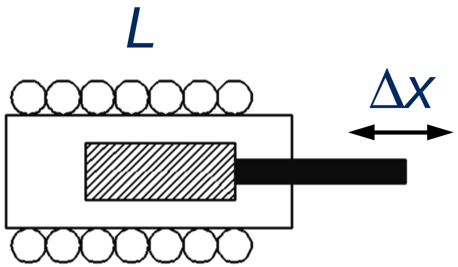
$\mu = \mu_0\,\mu_r$ = permeability [H/m]

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m = permeability of vacuum

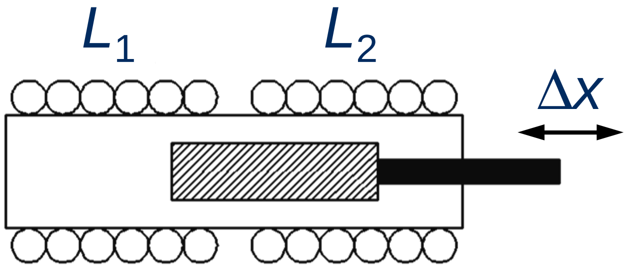
Inductive displacement sensor

- Adjustable coil
  - coil with movable core
    ⇒ μ changes
  - Disadvantage: limited linearity
- Differential ⇒ better linearity





single

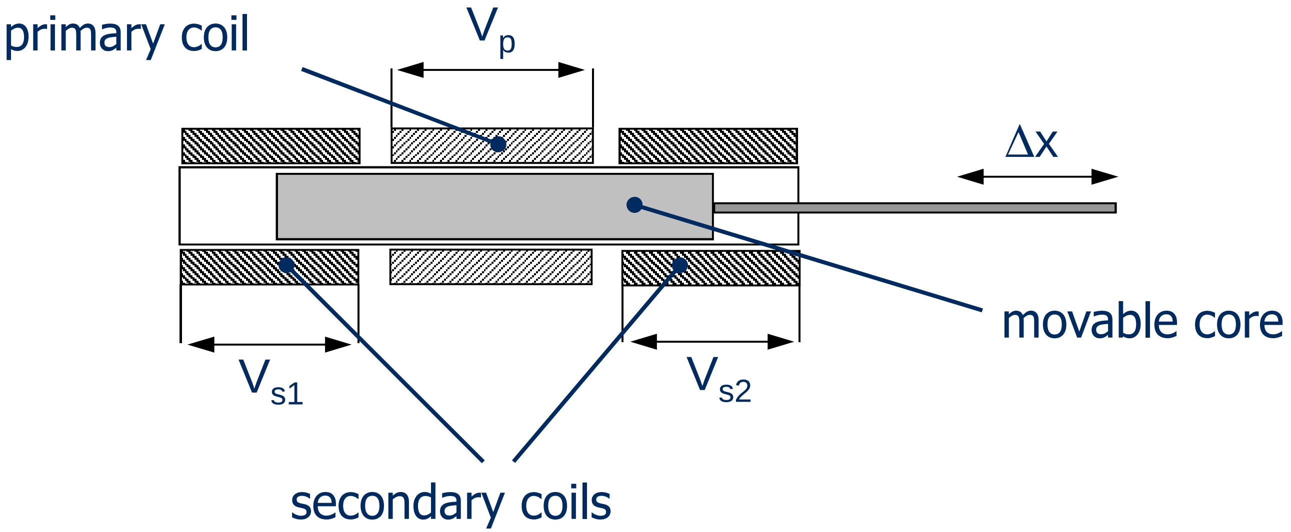


differential

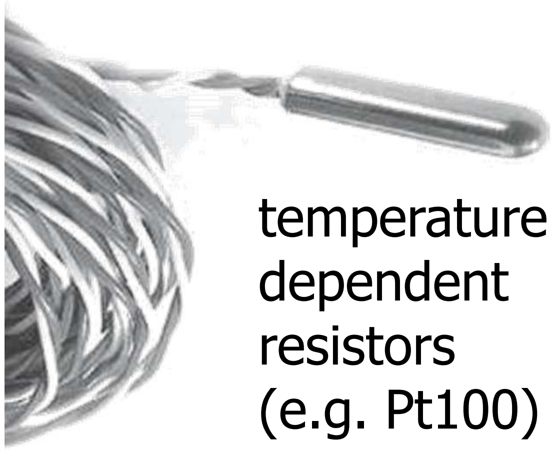
$$L = \mu \cdot n^2 \cdot \frac{A}{l}$$

Inductive sensors: LVDT

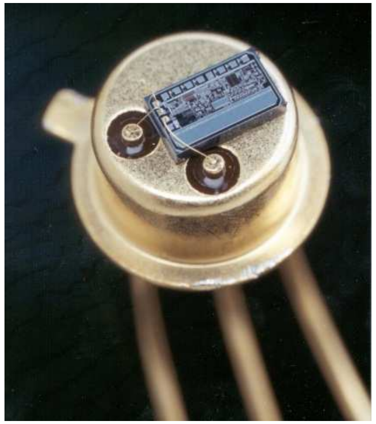
- LVDT = "Linearly-variable differential transformer"
  -- How would that work??



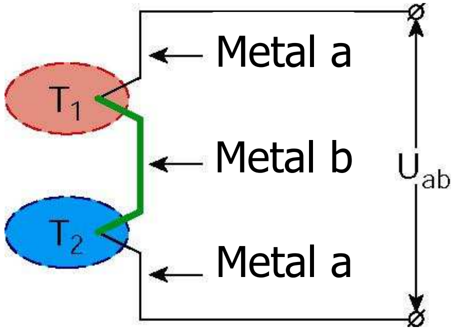
Thermal sensors



temperature dependent resistors (e.g. Pt100)



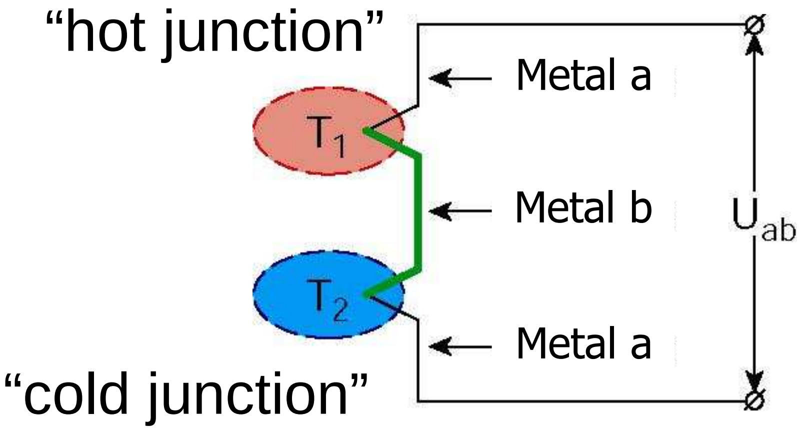
pn-junction temperature sensors



thermoelectric sensors

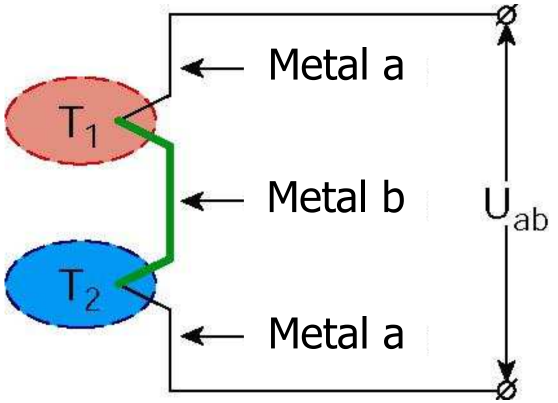
Thermocouples

- Measure temperature **difference** between two junctions of different (semi)conductors
- Self-generating effect
  $\Rightarrow$ intrinsically offset-free
- Suitable for a broad temperature range (up to 2800 K)
- For absolute temperature measurement, T_2 must be stabilized (e.g. at 0 °C) or measured with another temperature sensor



$$U_{ab} = \alpha_{ab} \cdot (T_1 - T_2)$$

Thermocouples



$$U_{ab} = \alpha_{ab} \cdot (T_1 - T_2)$$

- Based on the Seebeck effect:
  Fermi level $E_F(T)$ is temperature dependent
  $\Rightarrow \Delta T \rightarrow \Delta E_F \rightarrow \Delta U$

- Seebeck coefficient:

$$\alpha = \frac{1}{q} \cdot \frac{dE_F}{dT}$$

- Thermocouple:

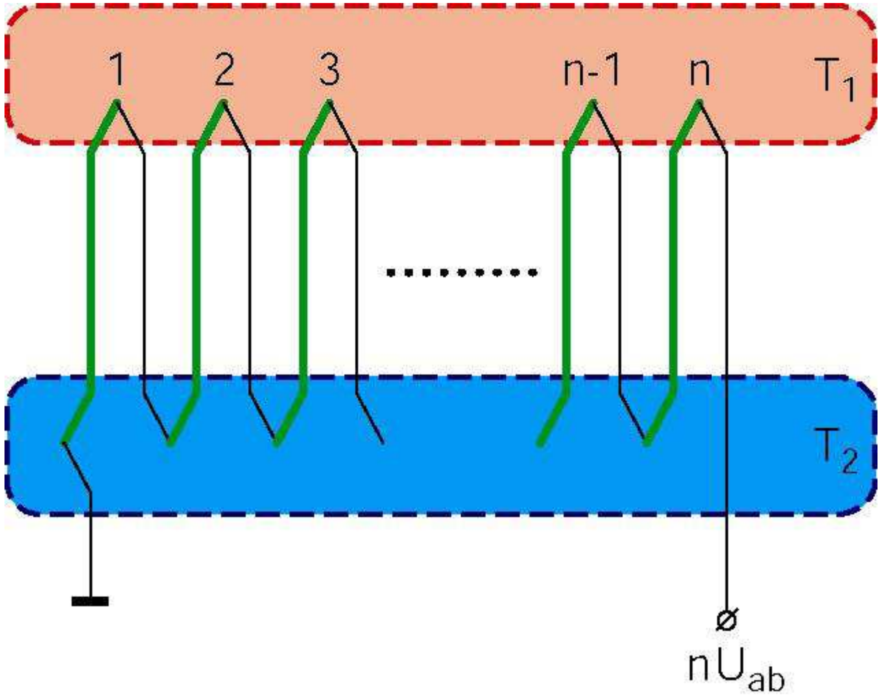
$$\alpha_{ab} = \alpha_a - \alpha_b$$

Material combination	**Sensitivity (at 0˚C) [μV/K]**	**Temp. range [˚C]**
Iron / constantan (type J)	45	0..760
Copper / constantan (type T)	35	-100..370
Chromel / alumel (type K)	40	-200..1350
Platinum / platiunum+rhodium	5	0..1500

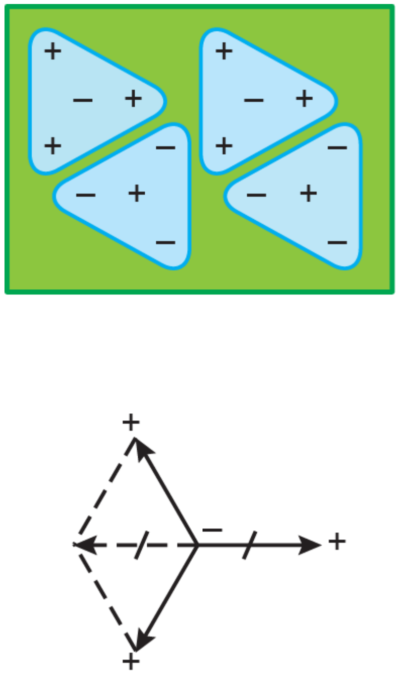
Thermopile

- Series connection of *n* thermocouples
  ⇒ *n* times larger sensitivity

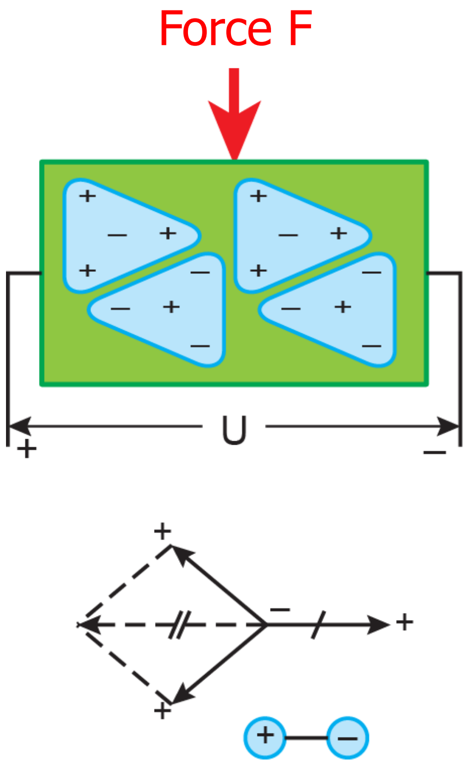
- But also:
  - *n* times larger impedance
  - larger thermal conductance (heat loss) between the hot and cold junctions



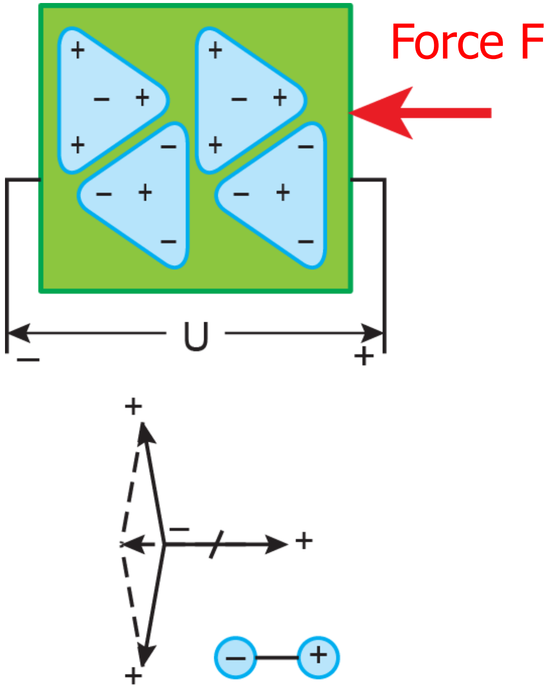
Piezoelectric effect



No load: no polarization charge



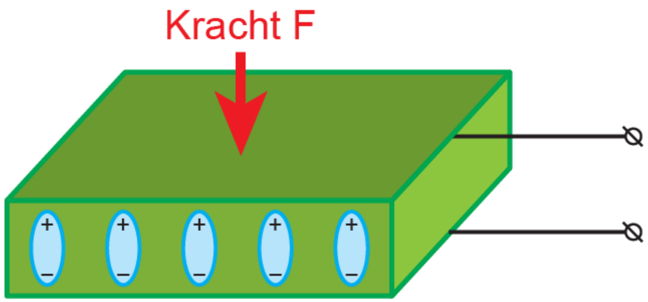
Transverse piezoelectric effect



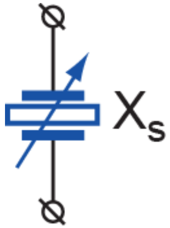
Longitudinal piezoelectric effect

Piezoelectric sensors

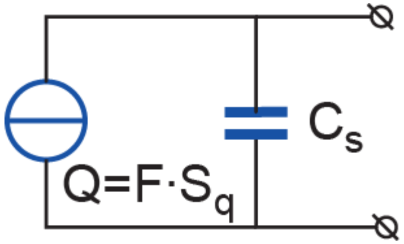
- Piezoelectric crystal:
  - force $F \rightarrow$ polarization charge $Q = S_q \cdot F$
  - Charge sensitivity S_q: typically 2 .. 100 pC/N
- Two readout approaches:
  - Voltage: Q on sensor capacitance $C_s \Rightarrow$ open voltage $U_s = Q / C_s$
  - Charge: connect sensor to charge amplifier



Piezoelectric crystal



Symbol

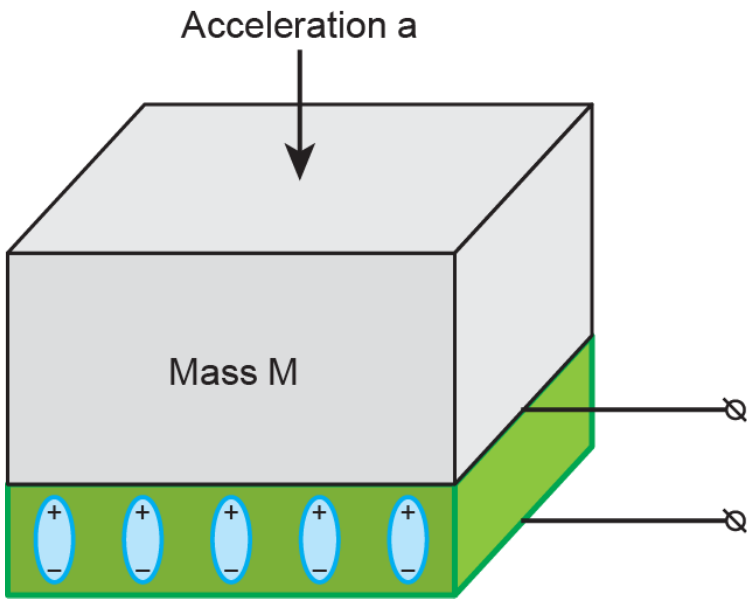


Simple model

Readout of a piezoelectric accelerometer

- Test mass M exerts a force $F = M \cdot a$ on a piezoelectric crystal
- Resulting polarization charge $Q = S_q \cdot F$ is integrated on C_f

$$\Rightarrow U_o = \frac{S_q \cdot M}{C_f} \cdot a$$



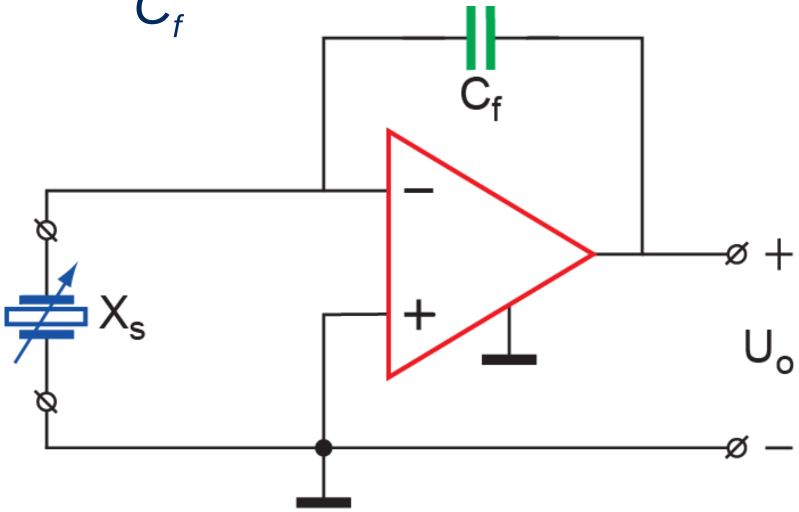
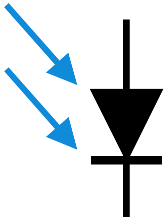
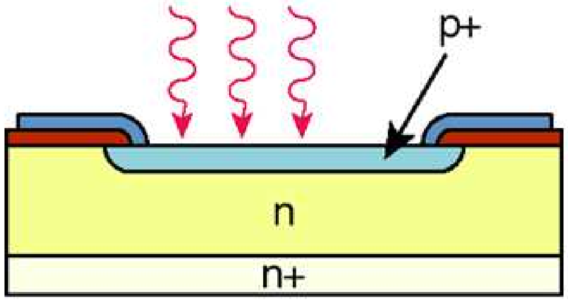


Photo diode

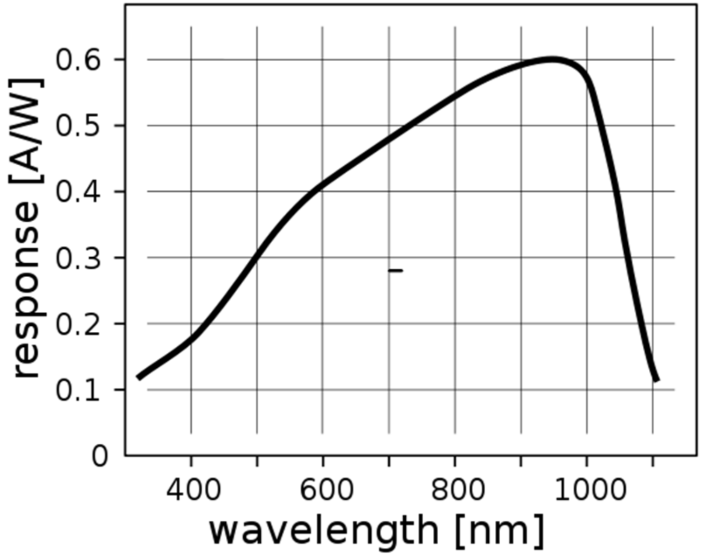


$$E = h \cdot \nu = \frac{h \cdot c}{\lambda}$$



- Photons lead to a photocurrent I_{ph}
- Characteristic properties:
  - spectral sensitivity R [A/W]
  - dark current I_{dark}
  - quantum efficiency η [%]: electrons / photon

Typical sensitivity of a Si photodiode



Regtien 9.1.2

Summary

- Sensors allow transduction to the electrical domain
  - self-generating / modulating
  - direct / tandem transduction
- Examples:
  - Resistive: thermistor, potentiometer, strain gauge
  - Capacitive: displacement, acceleration, humidity
  - Inductive: displacement, distance
  - Thermoelectric: thermocouples
  - Piezoelectric: force, acceleration
  - Semiconductor: photodiode

What’s next?

- Study:
  - Regtien sections 7.2, 9.1.1 en 9.1.2
- Practice:
  - See exercises on Blackboard!
- Questions, things unclear? Let me know!
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Next time: sensor readout