LET271

- measurement system → info about PHY value of some variable of interest
- single mechanical unit : in glass mercury thermometer ↔ modern measurement systems
SMHI → autonomous - digital.
- Elements of measurement systems.
  - sensors : PHY-EL → amplifier : make signal "bigger", improve SNR
→ filter : remove high-freq noise → AD converter : make measurement digital
digital signal processing → extract desired info, (LabView)
(also - determine accuracy of measurements through tools from statistics.

→ course requires familiarity with many fields!
→ it prepares you for the job :)

Before this, intro about

- who am I? Who are the TA?
- how does the course work? Course PM + pingpong.
- Feedback from previous years.

Sensors

Lecture 1 cheat-sheet

PHY ⟶ EL

many kinds → differences in range accuracy and price!

Passive sensors →

- ~~need external voltage source~~
- el. parameter ~~properties~~ change (with PHY phenomena)
  - resistance
  - capacitance
  - inductance
- ~~one need~~ external voltage needed
- E.g.

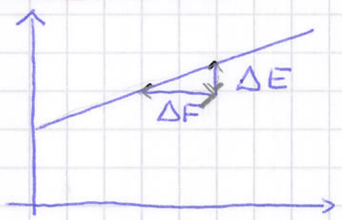
Active sensors

- generate energy (that depends on PHY phenomena)
- ~~E.g., thermocouples, piezoelectric sensors~~

Example	Active	Passive
Temperature	Thermocouple (voltage)	Thermistor (resistence)
Force	piezo-electric crystal (charge)	strain gauge (resistance)

Linear sensors

Electrical quantity E



PHY quantity

F

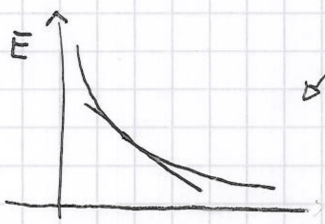
$$E = k \cdot F + c$$

$$k = \frac{\Delta E}{\Delta F}$$ sensor constant (↑ ☺)

TPS: if they costed the same, would you choose a sensor with high or low sensor constant?

If sensor is nonlinear

$$k = \frac{dE}{dF}$$ at a given point (local sensitivity)



e.g. thermistor.

(we can linearize it over a small range - LAB 2 and 4).

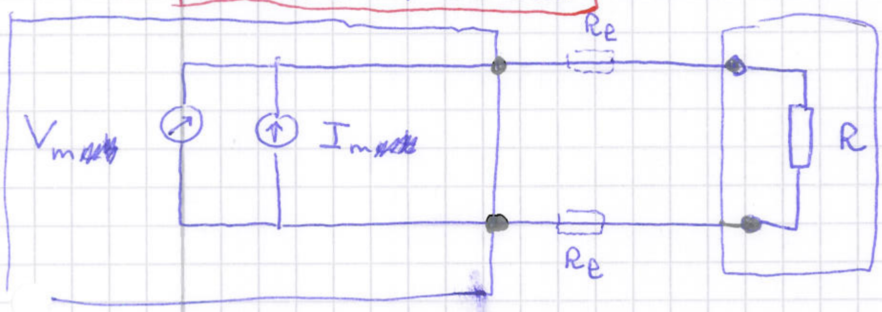
Resistive sensor

- passive
- resistance changes with PHY → Challenge: how do we measure it?

↓

Easiest approach: digital multimeter!

2-wire method



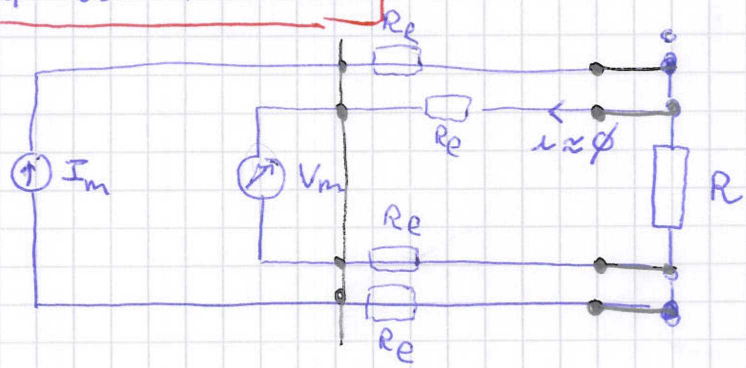
digital multimeter

$$R_m = \frac{V_m}{I_m} = R$$

- if R is small and/or wires are long

$$R_m = \frac{V_m}{I_m} = R + 2R_e$$

4-wire method

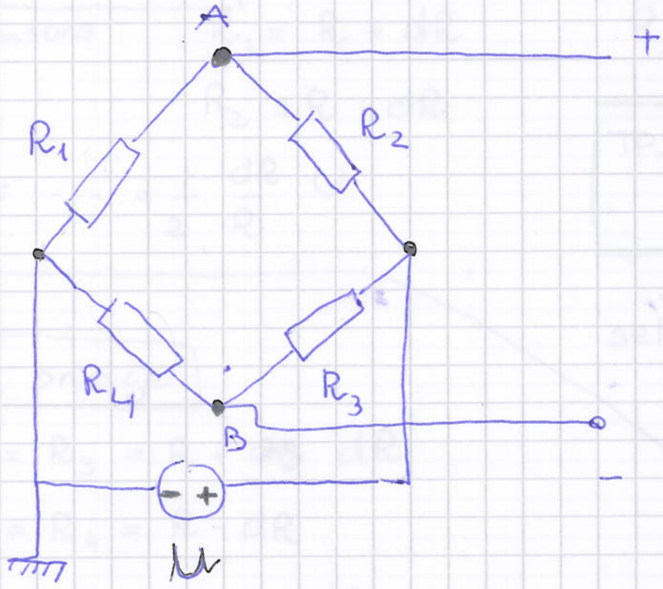


$$\frac{V_m}{I_m} = R$$

See in the labs that using 2w instead of 4w results in error in measuring temperature of a couple of degrees!

Wheatstone bridge

→ more accurate method to measure resistances (for resistive sensors)
↳ (than digital multimeter)



voltage divider

$$U_b = V_A - V_B = \frac{R_1}{R_1 + R_2} U - \frac{R_4}{R_3 + R_4} U$$

Leave this formula on	→	$= \dfrac{R_1 R_3 - R_2 R_4}{(R_1+R_2)(R_3+R_4)} U$

$\frac{1}{4}$ - bridge

nominal resistance

response to physical phenomenon

$R_1 = R + dR$, $dR \ll R$

$R_2 = R_3 = R_4 = R$

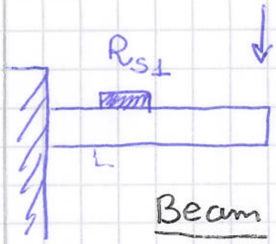
$$U_b = \frac{(R+dR)\cancel{R} - R^{\cancel{2}}}{(R+dR+R)(2\cancel{R})} U = \frac{dR}{4R + 2dR} U \approx \frac{1}{4} \frac{dR}{R} U$$

$(R \gg dR)$

Note: $U_b = 0$ if $R_1 = R_2 = R_3 = R_4 = R$

Sensor constant $\dfrac{U_b}{dR} = \dfrac{U}{4R}$

TPS → be creative! more beams? more sensors?

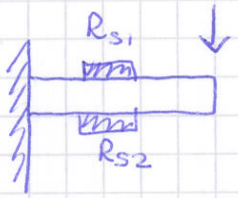


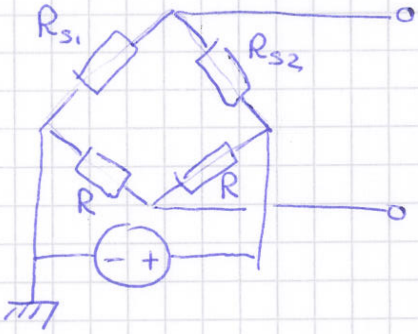
$R_S = R + dR + dR_T$ variations (the beam expands as temperature increases)

temperature variations may cause strain

~~...~~ ⇒ false reading

Solution ?

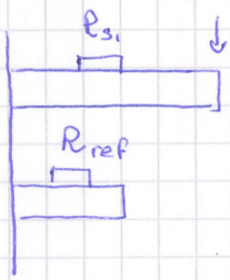




temp - $\begin{cases} R_{S_1} = R + dR_T \\ R_{S2} = R + dR_T \end{cases}$ – temperature dilatation ⇒ $U_b = \emptyset$

force $\begin{cases} R_{S_1} = R + dR \\ R_{S2} = R - dR \end{cases}$ $U_b \approx \frac{1}{2} \frac{dR}{R} U$

Alt. solution



$\frac{1}{4}$ bridge

$R_1 = R_{S1}$

$R_2 = R_{ref}$

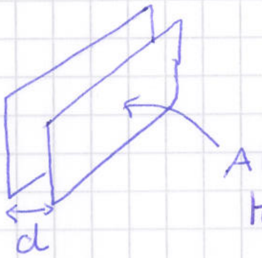
Problem detailed in this page:

- I want to measure the load on a beam.
- I use a straingauge: problem → I get resistance variations also because of temperature variations

Note: why do the reference resistances do not change as well with temperature?

- They may not be in contact with the beam or of a different material

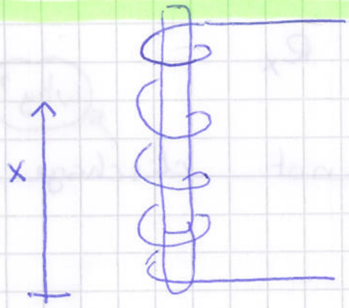
Capacitive sensors



$$C = \varepsilon \frac{A}{d}$$, ε: dielectric constant

to change capacitance
- change d { pressure, acceleration }
- change ε { moisture, liquid level }

Inductive sensor



$L = L(x)$ → to change inductance

coil ; iron core

Measure changes of C or L
- wheatstone bridge (alternating current)
- oscillator

Piezoelectric sensors

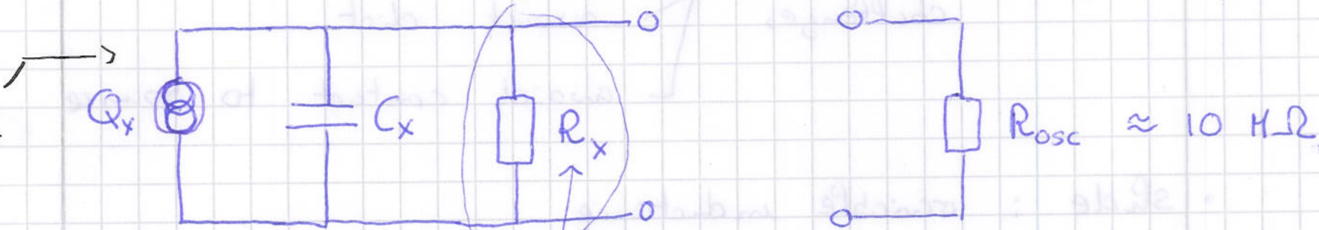
- slide

SLIDE

$Q_x = k \cdot F$ (draw later) $k = 2,3 \cdot 10^{-12}$ As/N for quartz

sensor costant

equivalent circuit



$$V = \frac{Q_x}{C_x}$$

isolation resistance $(10^{12}\ \Omega)$

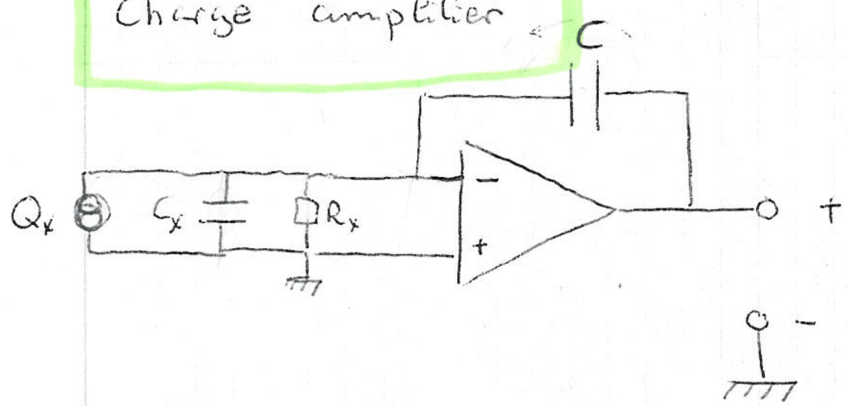
$\tau = C_x R_x \approx 1\,s$

SHOW DATA SHEET

Example : $C_x = 1pF$, $R_x = 10^{12}\ \Omega$ $R_{osc} = 10^{7}\ \Omega$

$\tau = C_x (R_x // R_{osc}) = 10\ \mu s$ (~~1s without~~

Charge amplifier



$$U = -\frac{Q_x}{C} = -\frac{k}{C} F$$

- independent of C_x and R_x
- ~~ideal opamp~~ ~~C does not discharge~~ (why?)
- τ improved!

Position sensors

- slide: strain gauges (milling cutter - fräsmaskiner)
- slide: potentiometer
  - material: wire (low accuracy) / carbon/ plastic film (high accuracy)
  - mechanical challenges: keep slider in contact / avoid dirt / avoid contact to bounce
- slide: variable inductance

Differential transformer

$V_S = \sin(\omega t)$ primary windings

Ka, Kb depend on position iron core

$V_A = K_a \sin(\omega t)$
$V_B = K_b \sin(\omega t)$
secondary windings

Get position from amplitude & phase

$\Rightarrow V_O = (K_a - K_b)\sin(\omega t)$

~~Charge amplifier~~

Accelerometer

- widely used
  - vibration in turbines
  - inertial navigation system
  - consumer electronics
  - vulcanology

- ~~often provide~~ measurements as multiples / fraction of ~~the standard accelerate of~~ free fall $g = 9{,}81\ m/s^2$

- slide : accelerometer [up to 1000 g crash tests]

- slide : piezo-electric sensor
  - smaller

Pressure sensors

bälg

slide : bellows , bosch → piezo resistive sensor.

Level sensors

slide : floating objected

slide : pressure sensor ~~on~~ and capacitive sensor

Flow sensors

Venturi

- speed increase → preassure decreases

- flow proportional to $\sqrt{P_1 - P_2}$

Temperature sensors

sensors based on

- resistance change
- thermoelectric effect
- sensitivity of semiconductor devices.

Resistance thermometer

- use material whose resistance changes with temperature.

$$R = R_0 (1 + \gamma T)$$

material constant: γ

resistance at 0°C: R_0

temperature in °C: T

Pt : $\gamma = 3{,}85 \cdot 10^{-3}$ $[°C^{-1}]$

Ni : $\gamma = 6{,}75 \cdot 10^{-3}$ $[°C^{-1}]$

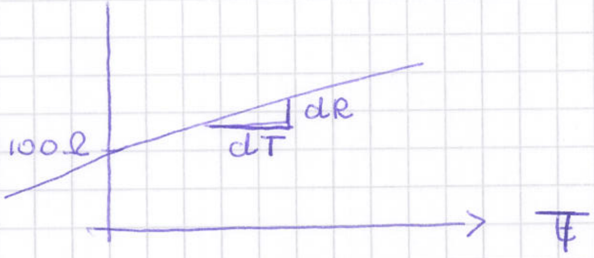
- Pt-100 most used (high melting point, linear response, does not age)

R_0 $\rightarrow$ $R = 100 (1 + 3.85 \cdot 10^{-3}\ T)$

$$= (100 + 0{,}385 \cdot T)\ \Omega$$

R

$$k = \frac{dR}{dT} = 0{,}385 \ \frac{\Omega}{°C}$$

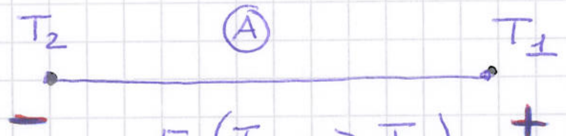


$T \in (-200°, 800°)$

- $\boxed{\text{slide}}$: sensor constant
- cost : 80SEK

Thermocouples

- useful outside Pt-100 range
- Seeback effect :

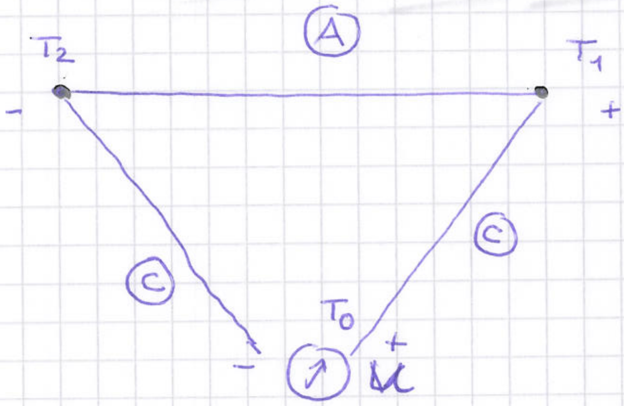


$E_A(T_2 \to T_1)$ electromotive force (emf)

$= -E_A(T_1 \to T_2)$

  - voltage depends on material and on (T_1, T_2)
  - relation nonlinear

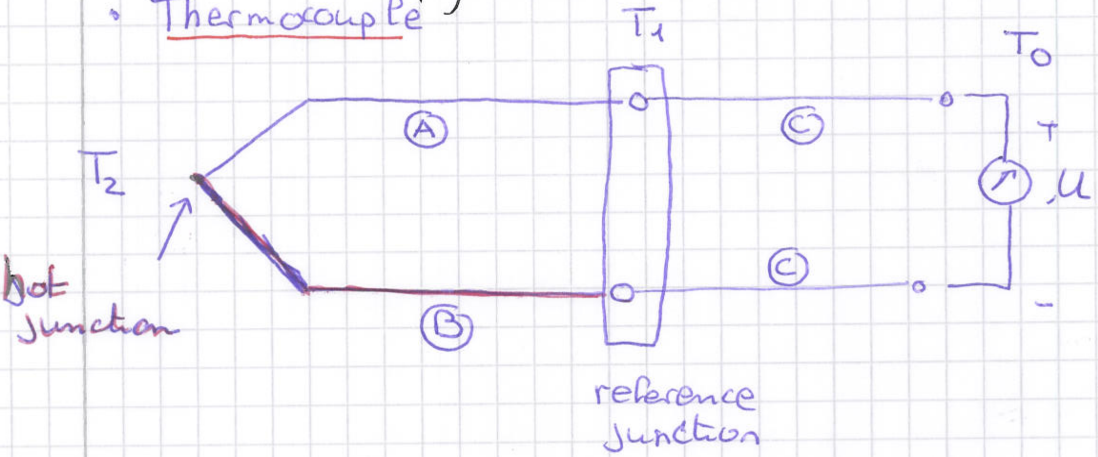
- ~~implements~~
- in practice we need to measure it using cables



$$U = E_C(T_0 \to T_2) + E_A(T_2 \to T_1) + E_A(T_1 \to T_0)$$

- problem : U depends on T_0 and C !

- Thermocouple solves this issue !



(10) $$U = \cancel{E_C(T_0 \to T_1)} + E_B(T_1 \to T_2) + E_A(T_2 \to T_1) + \cancel{E_C(T_1 \to T_0)}$$

$$= E_A(T_2 \to T_1) - E_B(T_2 \to T_1) = E_{AB}(T_2 \to T_1)$$

- high dregree of pureness : cost ↑ with length
- chromel / alumen $-250° \leftrightarrow 900°$ Type K
- copper / constantan $-200° \leftrightarrow 400°$ Type T
- platinum / platinum - rhodium $-50° \leftrightarrow 1600°$ Type S

150 SEK for small thermocouple

show table

$$E_{AB}(T_2 \to \emptyset) \quad \text{type - T thermocouple}$$

what if T_1

- $T_1 \neq 0°C$?

$$E_{AB}(T_2 \to T_1) = E_A(T_2 \to T_1) - E_B(T_2 \to T_1)$$

$$= E_A(T_2 \to 0) + E_A(\emptyset \to T_1)$$

$$- E_B(T_2 \to \emptyset) - E_B(\emptyset \to T_1)$$

$$= \underbrace{E_{AB}(T_2 \to \emptyset)}_{\text{Table}} - \underbrace{E_{AB}(T_1 \to \emptyset)}_{\text{Table}}$$

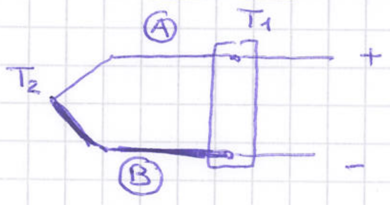
Solutions of problems with thermocouples in book not correct !

- Note : course approx. in book (do not use it)

Book: App B

$$E_{AB}(T_2 \to T_1) \approx E_{AB}((T_2 - T_1) \to \emptyset).$$

Example



$T_1 = 25°C$

$U = -1,51$ mV

$$U = E_{AB}(T_2 \to T_1) = E_{AB}(T_2 \to \emptyset°) - \underbrace{E_{AB}(T_1 \to \emptyset°)}_{0,992 \text{ mV}}$$

$$\Rightarrow E_{AB}(T_2 \to \emptyset°) = U + E_{AB}(T_1 \to \emptyset°)$$

$$= -1.51 + 0.992 \text{ mV} = -0,518 \text{ mV}$$

$\Rightarrow T_2 = -14°C$

With book approx.

$U \approx E_{AB}(T_2 - T_1 \to \emptyset) \Rightarrow T_2 - T_1 = -41°C$

$T_2 = -16°C$

Thermistors

- semiconductor ~~theci~~ technology
- negative temperature coeff. (NTC)
- nonlinear

$$R_T = R_0 \, e^{\alpha/T}$$

R_0 = resistance at $0°C$ ← $273°K$

$\alpha : [K]$

R_{25} given in specs smb.

$$\Rightarrow R_{25} = R_0 \, e^{\alpha/298} \Rightarrow R_0 = R_{25} \, e^{-\alpha/298}$$

$$\Rightarrow R_T = R_{25} \, e^{(\alpha/T - \alpha/298)}$$

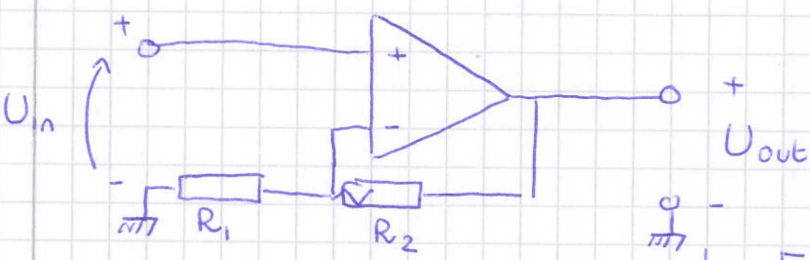
+ cheap (7 SEK)	− nonlinear
+ quick	− requires calibration
+ possible to integrated (semiconductor)	− limited range ($-40°C \leftrightarrow 125\ °C$)

- ~~Bosch pressure sensor~~
- ~~slide linearity error~~

~~before at the beginning of lecture~~

Amplifier

- slide : block diagram
- amplification with op. amp.



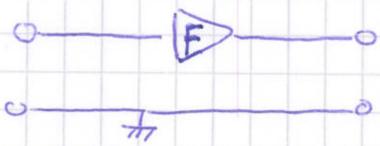
noninverting amplifier

$$U_{out} = \left(1 + \frac{R_2}{R_1}\right) U_{in}$$

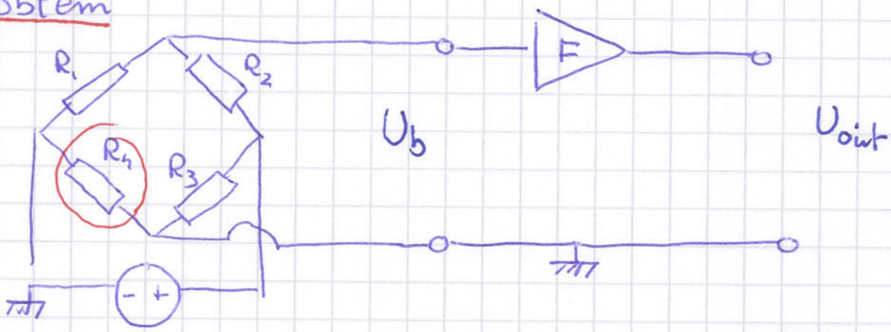
- $F = \frac{U_{out}}{U_{in}}$: gain
- measured in dB

$$F = 20 \log_{10} \frac{U_{out}}{U_{in}}$$

F [linear]	F [dB]
100	40
10	20
2	6
$\sqrt{2} \approx 1.4$	3
1	0
0.5	-6
0.1	-20
0.01	-40



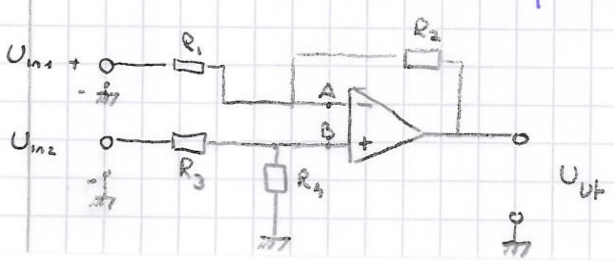
Problem



TPS does it work ?

R_4 shortcutted.

- Solution : OP-AMP in subtractor configuration
  - low input impendance / low gain. + sensitive → to common mode signal



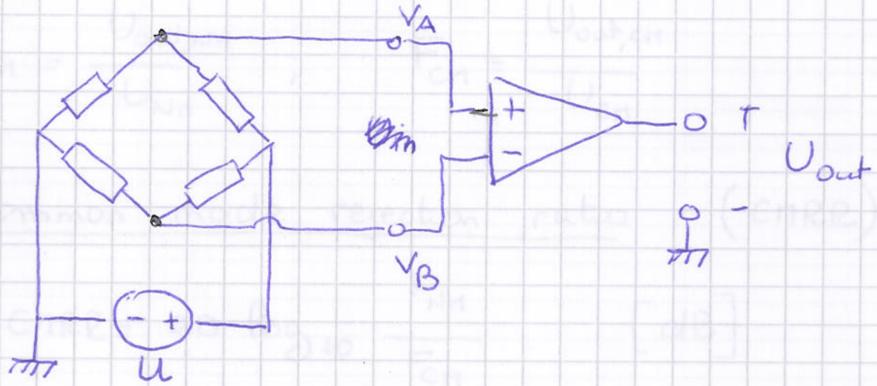
If $R_3/R_4 = R_1/R_2$

$$\Rightarrow U_{out} = \frac{R_2}{R_1}\left(U_{in1} - U_{in2}\right)$$

Solution : $\boxed{\text{instrumentation amplifiers}}$

- op amp subtractor + 2 op-amp as input buffers
  - ⇒ high input impedance
  - ⇒ high common mode rejection

- same symbol as op-amp !



SHOW DATA SHEET.

normal mode

- $\boxed{U_{NM}} = V_A - V_B$ (desired signal ... small)

common mode

- $U_{CM} = \dfrac{V_A + V_B}{2}$ (undesired signal ... large).

E.g. $U = 5V \Rightarrow U_{NM} \approx 25mV$, $U_{CM} \approx 2.5V$ } 10^3 !

- Problem : amplifiers sensitive to both U_{NM} and U_{CM}

$$\boxed{U_{out} = F_{NM}\, U_{NM} + F_{CM}\, U_{CM}}$$

F_{NM} = normal mode gain

F_{CM} = common mode gain

- we want $F_{NM} \gg F_{CM}$; ← OK with instrumentation amplifier