EE1320: Measurement Science

Lecture 4: Instrumentation Amplifiers

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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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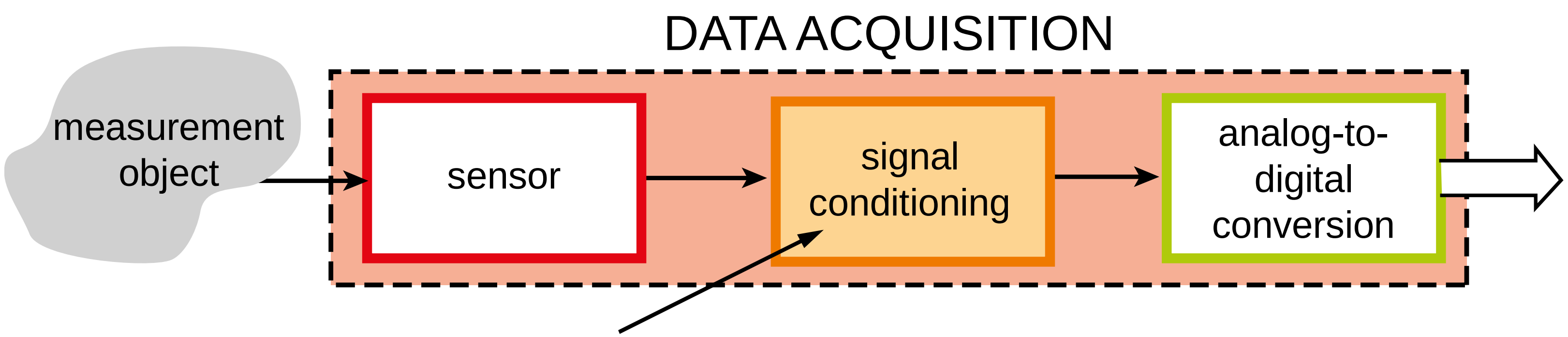
Last time… signal conditioning



- Signal conditioning needed to adjust output signal of the sensor to the input of the ADC

- Opamps are suitable building blocks for sensor readout
  - non-inverting amplifier, transimpedance amplifier, inverting amplifier, charge amplifier

- Opamp non-ideal properties influence the transfer and sometimes have to be compensated for
  - offset voltage, bias current, offset current

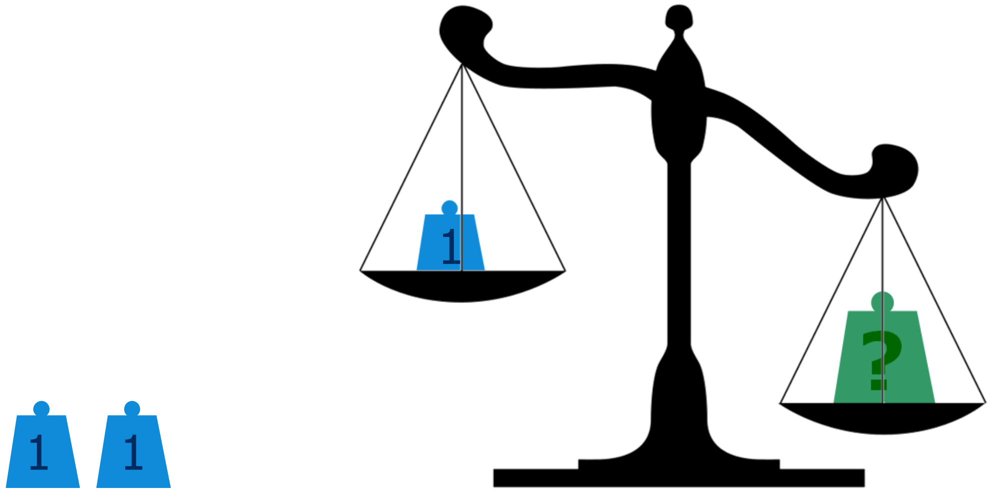
Today: bridge circuits and instrumentation amplifiers

- Bridge circuits with resistors
- Differential and common-mode signals
- Common-mode rejection
- Opamp difference amplifier
- 3-opamp instrumentation amplifier

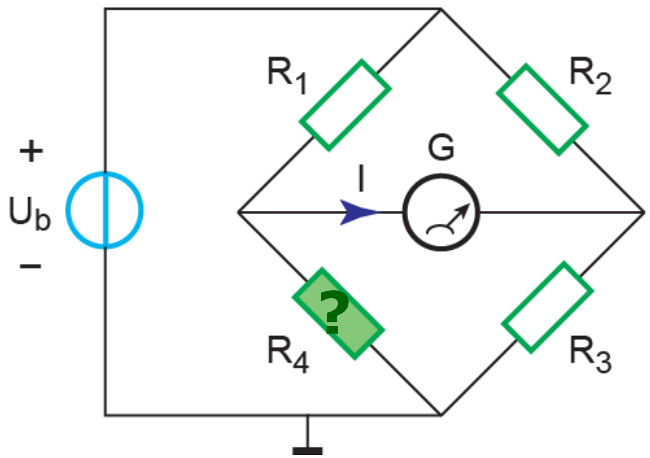
Overview study material

- Slides: Wheatstone bridge
- Regtien 1.2: common-mode rejection
- Regtien 12.1.4, 12.1.5: difference- en instrumentation amplifiers

Balance measurements



The Wheatstone bridge

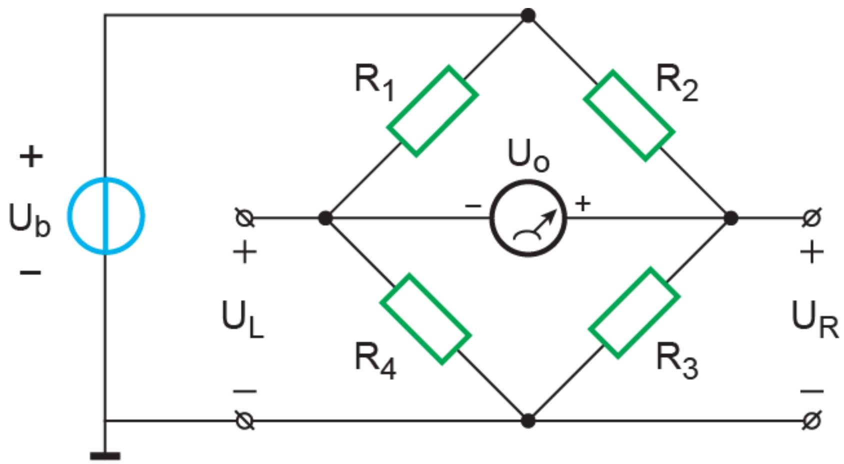


Sir Charles Wheatstone
(1802 – 1875)

- Known resistors R_1, R_2, R_3
  Unknown resistor R_4
- Galvanometer G measures current I due to unbalance
- Point of balance ($I = 0$) if $\frac{R_1}{R_4} = \frac{R_2}{R_3} \Rightarrow R_4 = \frac{R_1 R_3}{R_2}$

The Wheatstone bridge

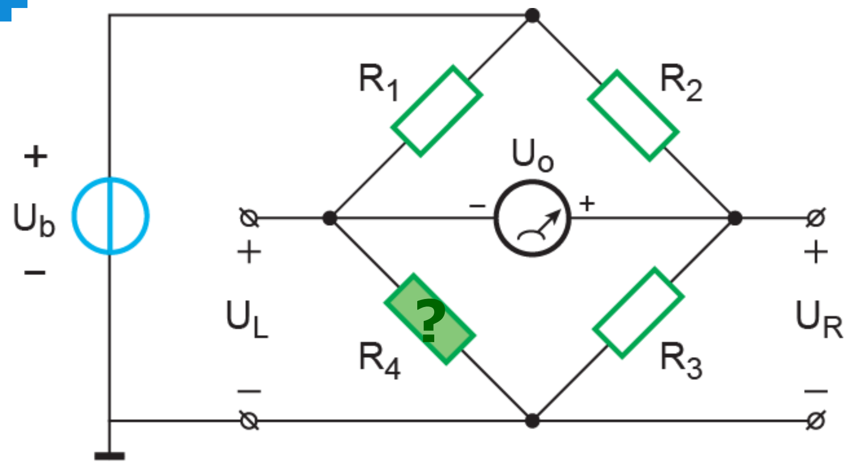
- With voltage readout



- Left divider: $U_L = \frac{R_4}{R_1 + R_4} U_b$
- Right divider: $U_R = \frac{R_3}{R_2 + R_3} U_b$
- Output voltage:

$$U_o = U_R - U_L$$
$$= \frac{R_1 R_3 - R_2 R_4}{(R_2 + R_3)(R_1 + R_4)} \cdot U_b$$

The Wheatstone bridge

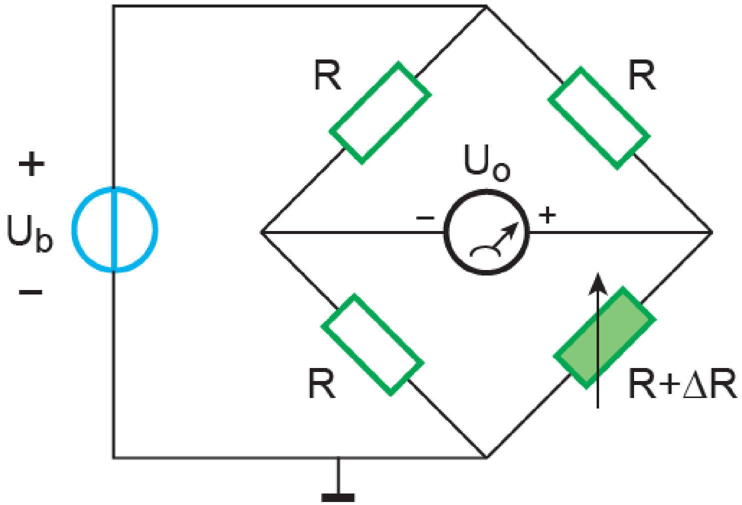


$$U_o = U_R - U_L$$
$$= \frac{R_1R_3 - R_2R_4}{(R_2+R_3)(R_1+R_4)} \cdot U_b$$

- Balance measurement: let $R_2 = R_3 = R \Rightarrow \quad U_o = \frac{R_1 - R_4}{2(R_1+R_4)} \cdot U_b$

$$U_o > 0 \Rightarrow R_4 < R_1 \qquad U_o < 0 \Rightarrow R_4 > R_1$$

Resistive sensor in a Wheatstone bridge



$$U_L = \frac{1}{2} U_b$$

$$U_R = \frac{R + \Delta R}{2R + \Delta R} U_b \cong \frac{1}{2}\left(1 + \frac{\Delta R}{2R}\right) \cdot U_b$$

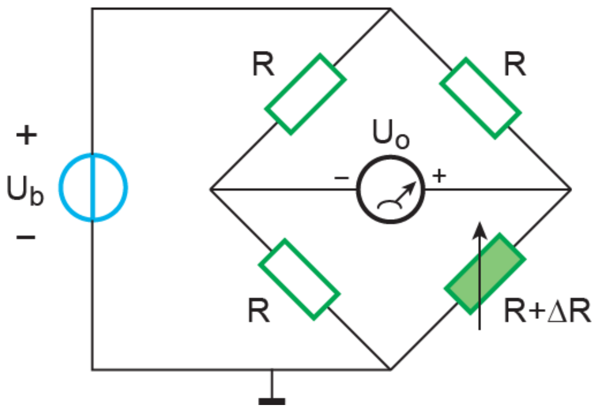
$$U_o = U_R - U_L \cong \frac{\Delta R}{4R} U_b$$

$$\Rightarrow \frac{U_o}{U_b} \cong \frac{\Delta R}{4R}$$

- **Ratiometric** measurement: U_o measured relative to U_b
  (U_o / U_b) is measure for ΔR / R
- Absolute value of U_b is not important!

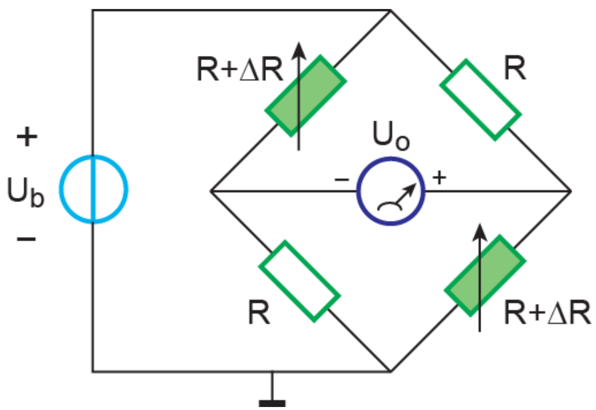
Bridge configurations

quarter bridge



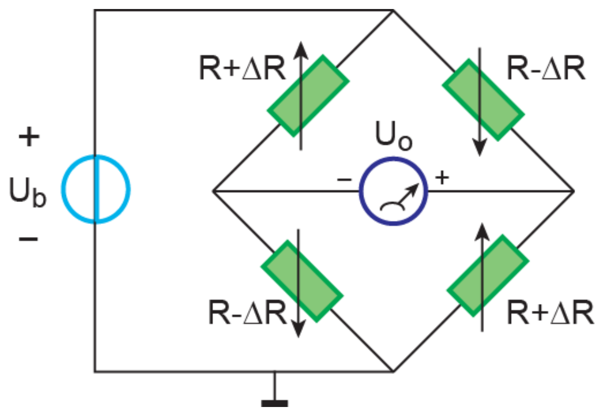
$$\frac{U_o}{U_b} \cong \frac{\Delta R}{4R}$$

half bridge



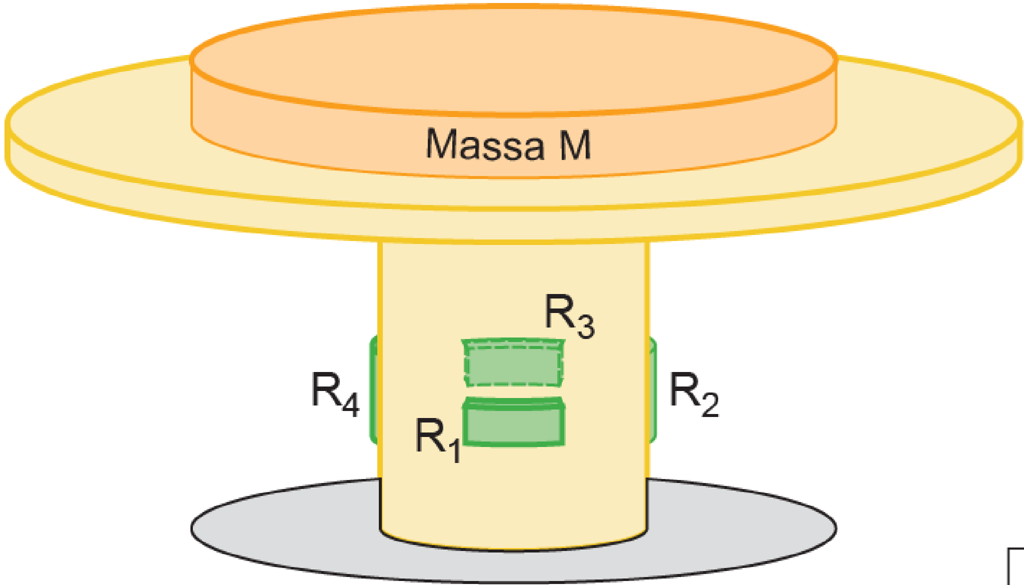
$$\frac{U_o}{U_b} \cong \frac{\Delta R}{2R}$$

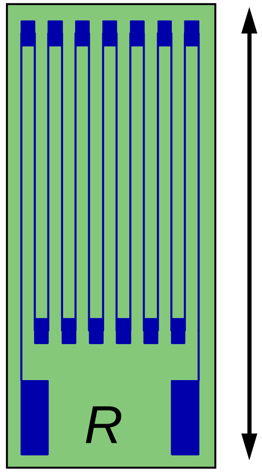
full bridge



$$\frac{U_o}{U_b} \cong \frac{\Delta R}{R}$$

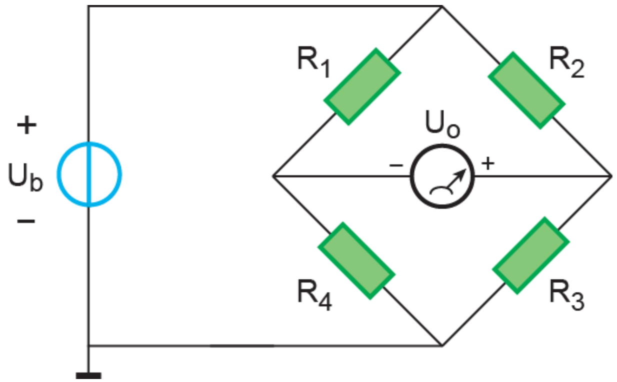
Example bridge configurations:
weighing scale with strain gauges



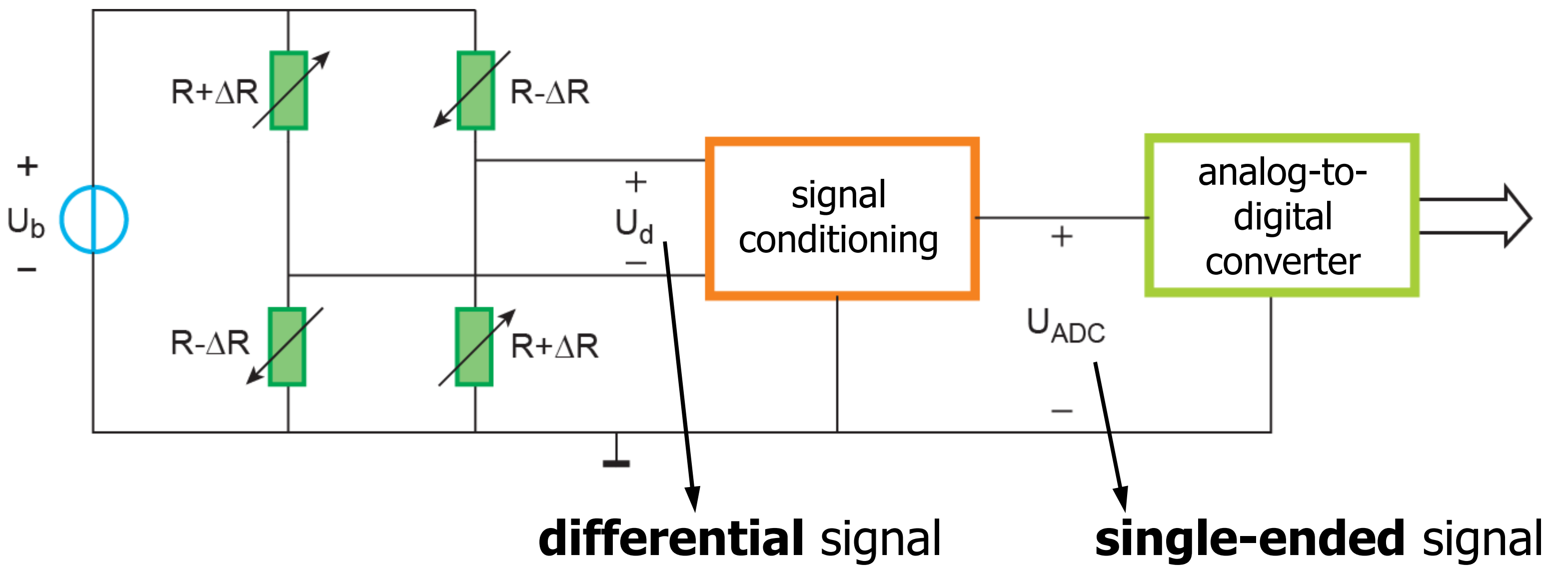


$$\frac{\Delta R}{R} = k \cdot \frac{\Delta L}{L}$$

- quarter, half, full?
- Temperature effect?

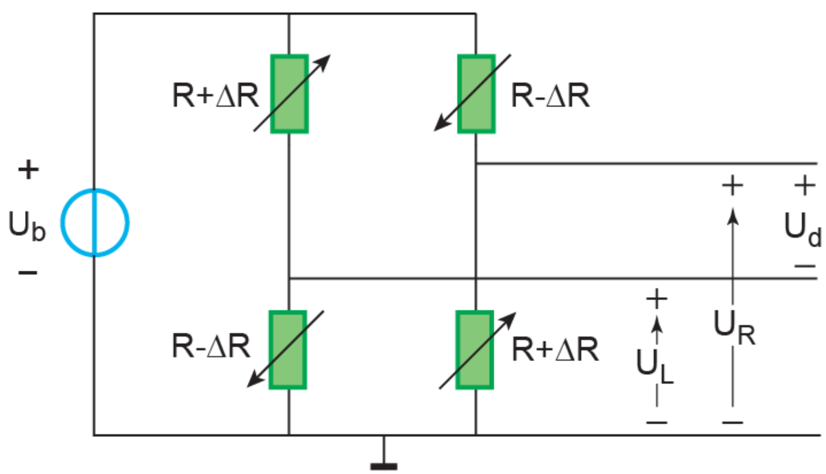


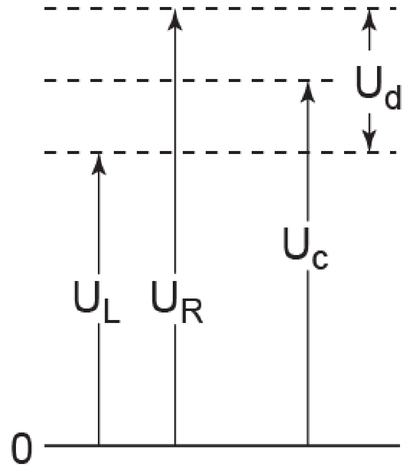
Readout of bridge circuits



- Here, signal-conditioning takes care of:
  - converting the differential signal to a signal referenced to ground (*single-ended* signal)
  - amplification
  - readout of the bridge without significantly loading it

Differential and common-mode signals





- Differential signal: $U_d = U_R - U_L = \dfrac{\Delta R}{R} U_b$
- Common-mode signal: $U_c = \dfrac{U_R + U_L}{2} = \dfrac{U_b}{2}$
- $U_L = U_c - \dfrac{U_d}{2} \qquad U_R = U_c + \dfrac{U_d}{2}$

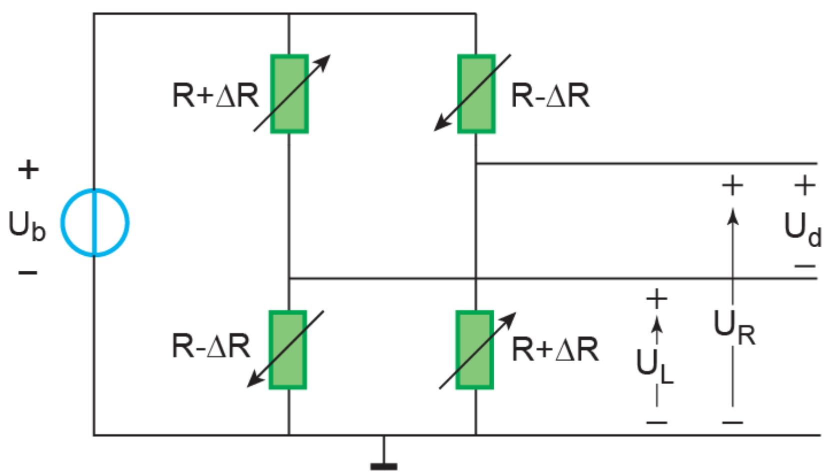
Differential and common-mode signals

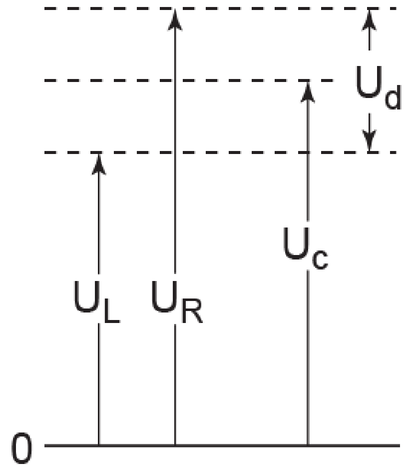
- $U_L = 1$ V $U_d =$
  $U_R = 4$ V $U_c =$

- $U_L = -4$ V $U_d =$
  $U_R = 2$ V $U_c =$

- $U_c = 3$ V $U_L =$
  $U_d = 1$ V $U_R =$

Differential and common-mode signals





- Differential signal is often **much** smaller than common-mode signal:

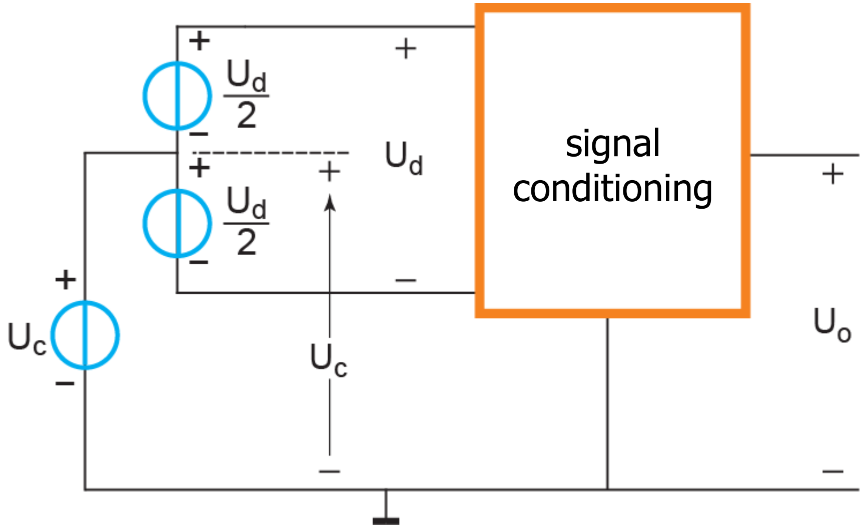
For example: $U_b = 1\,\text{V},\ \Delta R / R = 1\% \Rightarrow$

$$U_d = \frac{\Delta R}{R} U_b = 10\,\text{mV}$$

$$U_c = \frac{U_b}{2} = 0.5\,\text{V}$$

50x

Common-mode en differential amplification



- Differential signal U_d is the information-carrying signal of interest and has to be amplified:

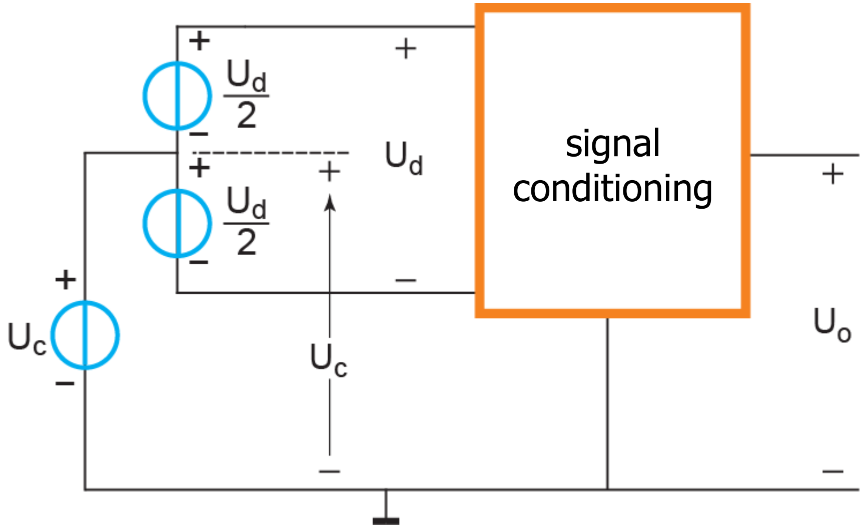
$$U_o = G_d \cdot U_d$$

- Common-mode signal U_c should *not* contribute to output signal

- In practice: output *is* dependent on U_c: $U_o = G_d \cdot U_d + G_c \cdot U_c$

  $\Rightarrow$ finite **common-mode rejection**

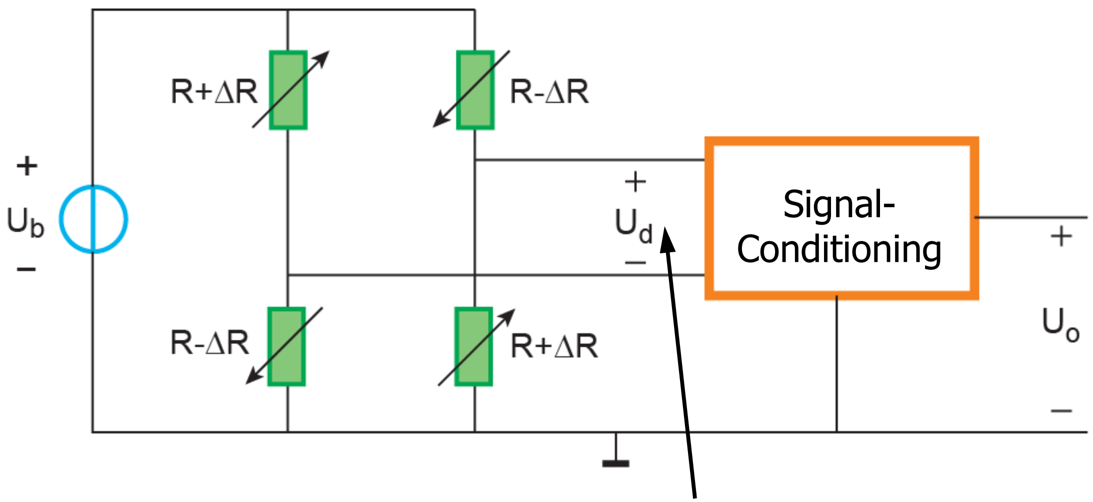
Common-mode rejection ratio (CMRR)



- $U_o = G_d \cdot U_d + G_c \cdot U_c$
- CMRR: $H = \frac{G_d}{G_c} = \frac{dU_o / dU_d}{dU_o / dU_c}$

- Often expressed in dB: $20 \cdot {}^{10}\log(|H|)$ [dB]
- Example: a CMRR of H = 1000 (60 dB) means that ΔU_d = 1 mV and ΔU_c = 1 V give an equal contribution ΔU_o to the output

Importance of a high CMRR



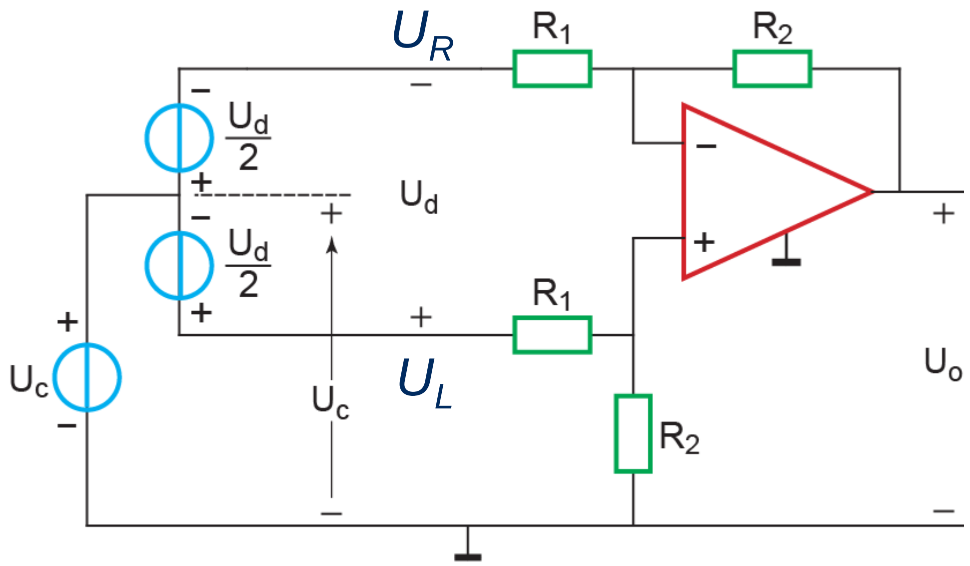
$$H = \frac{G_d}{G_c} = \frac{dU_o / dU_d}{dU_o / dU_c}$$

small differential signal U_d on a **large** common-mode signal U_c

- Determine how high the CMRR must be such that: ΔU_o due to U_c is smaller than ΔU_o due to $\Delta R / R = 1\%$

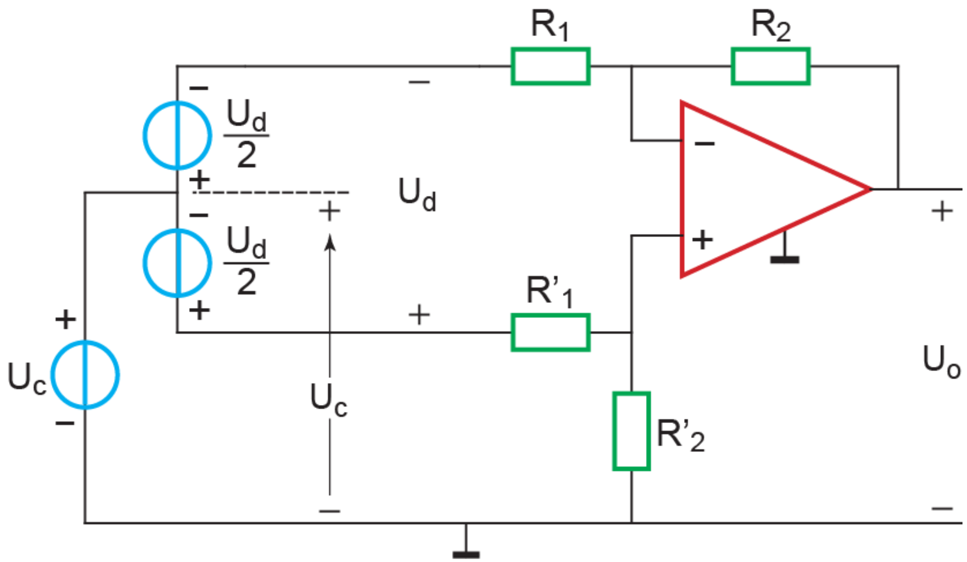
Difference amplifier

- Can be used to amplify a voltage difference



- Determine the differential gain $G_d = U_o / U_d$

Limitations of difference amplifiers



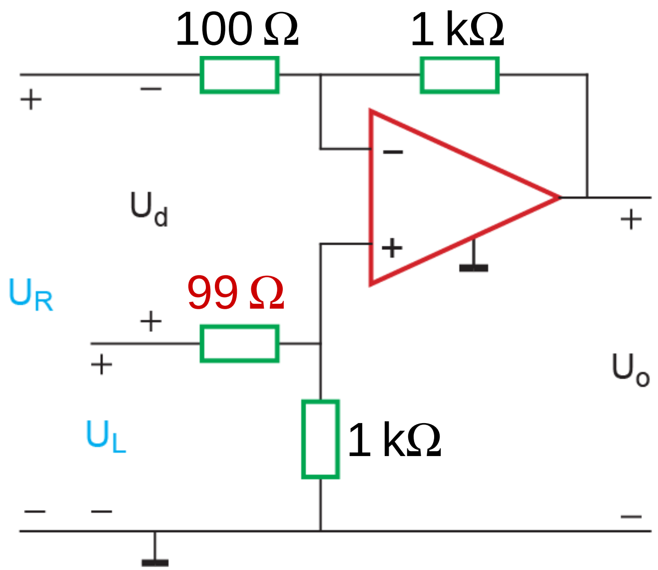
- Resistors impose a load on the source
- Practical resistors have tolerances:

⇒ $R'_1 \neq R_1$, $R'_2 \neq R_2$

⇒ inverting and non-inverting transfer is not exactly equal

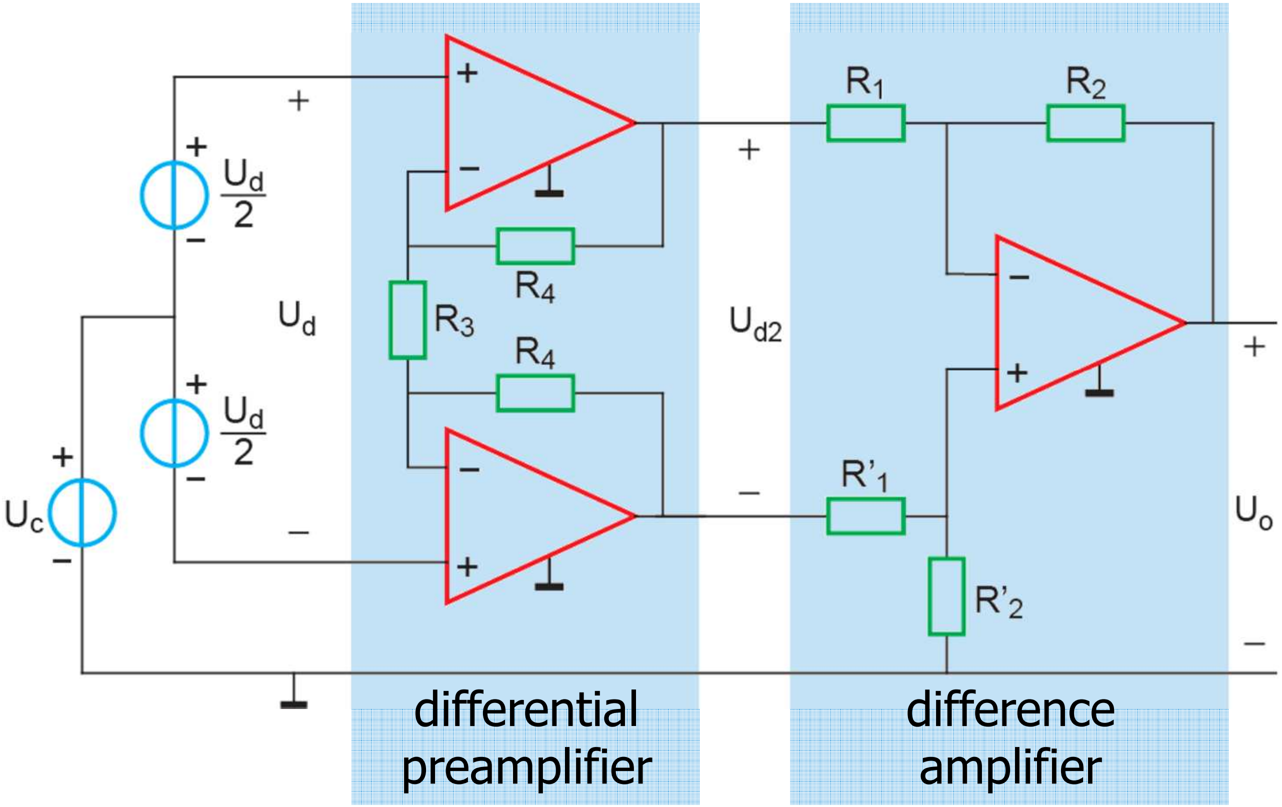
⇒ output is influenced by U_c !!

Example: determine the common-mode rejection of a difference amplifier



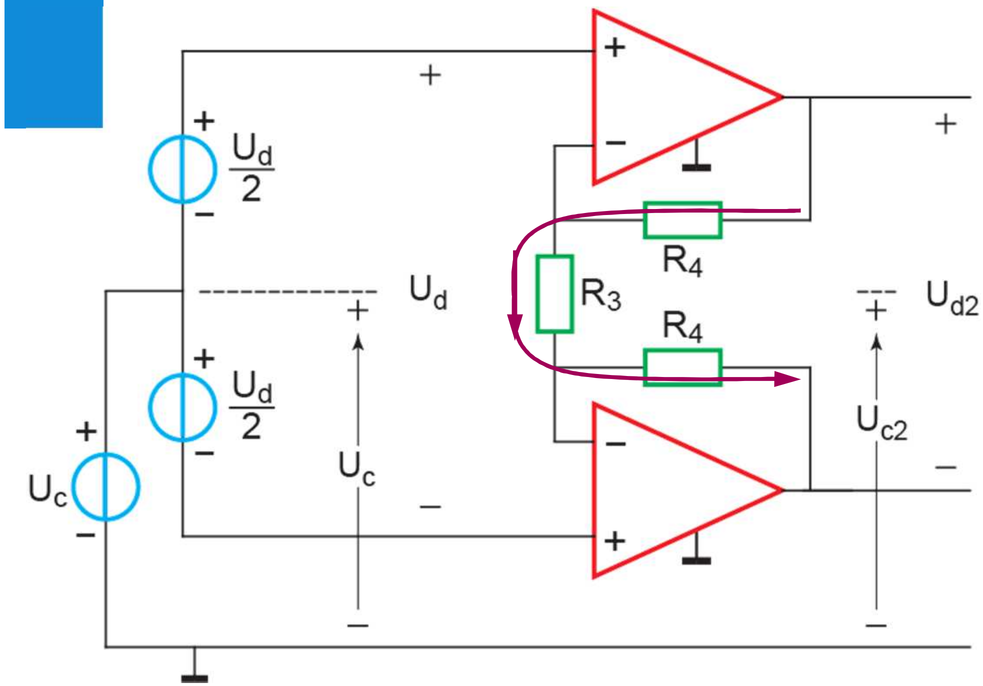
- **Common-mode rejection ratio** $H = \frac{G_d}{G_c} = \frac{dU_o / dU_d}{dU_o / dU_c}$ **= ???**

3-opamp instrumentation amplifier



Advantages:
- higher CMRR than differential amplifier
- higher input impedance (does not load source)

3-opamp instrumentation amplifier



- Virtual grounds opamps ⇒

$$U(R_3) = U_d \Rightarrow I(R_3) = \frac{U_d}{R_3}$$

- This current flows through resistors R_4 ⇒

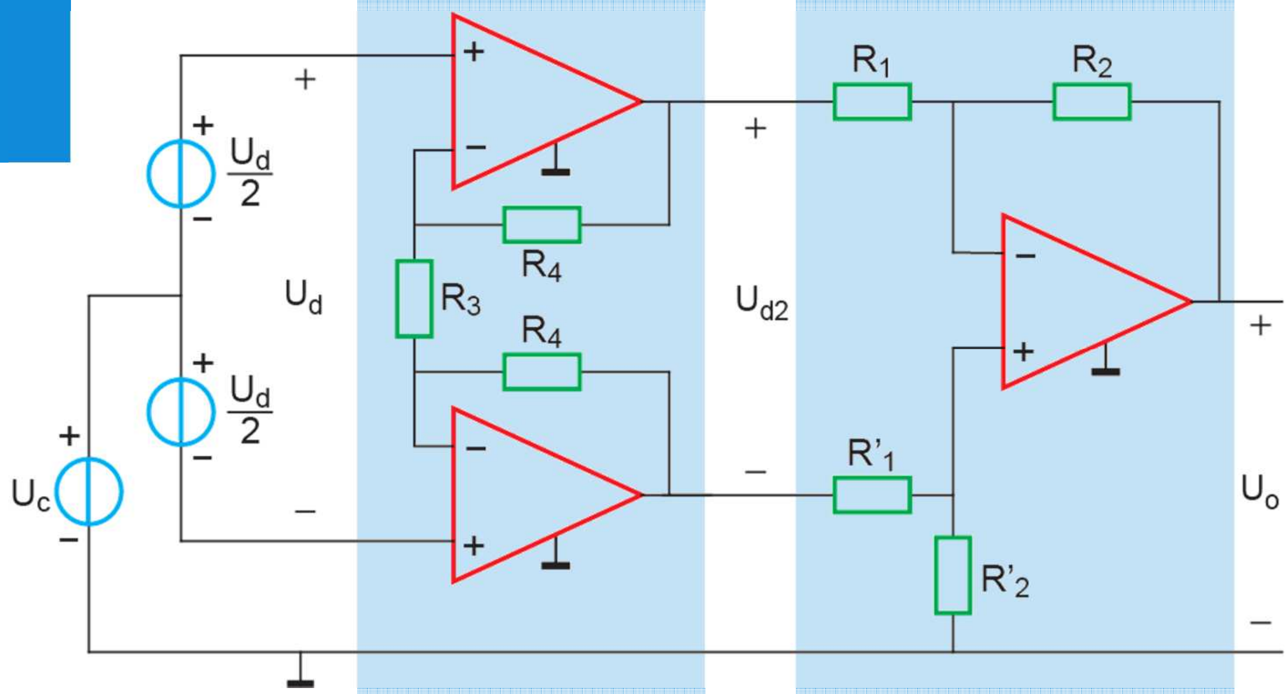
$$U_{d2} = \frac{R_3 + 2R_4}{R_3} U_d = G_{dd} \cdot U_d$$

- So, differential voltage is **amplified** by a factor G_{dd}

- Common-mode voltage at output **equals** that at input:

$$U_{c2} = U_c$$

3-opamp instrumentation amplifier



differential amplification

$$G_{dd} = \frac{R_3 + 2R_4}{R_3}$$

difference amplifier

$$G_d = \frac{R_2}{R_1} \quad G_c \cong \frac{\Delta R}{R}$$

- total gain:

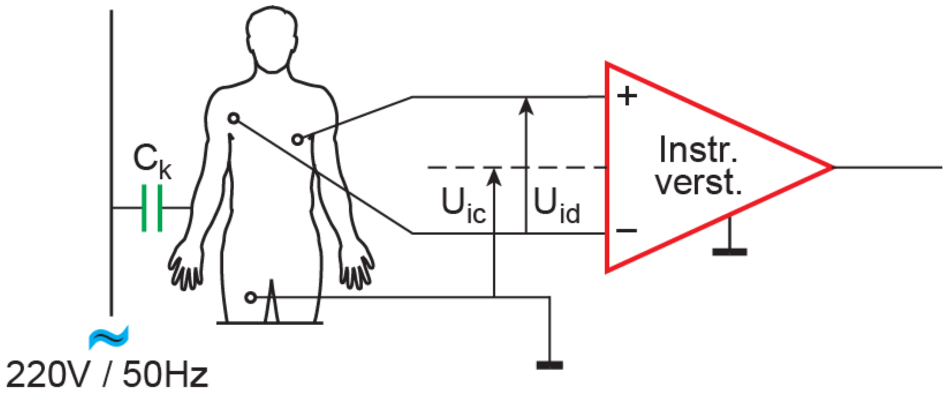
$$G_{d,tot} = \frac{R_3 + 2R_4}{R_3} \cdot \frac{R_2}{R_1}$$

- total CMRR:

$$H_{tot} = G_{dd} \frac{G_d}{G_c}$$

- So, CMRR is G_{dd} times better than that of only a difference amplifier!

Example: bio-potential measurement with an instrumentation amplifier



- ECG signal:
  U_{id} ~ 10 μV,
  DC – 100 Hz
- Interference: capacitively coupled line voltage:
  U_{ic} ~ 1 mV,
  50 Hz

- Distortion in frequency range ECG signal ⇒ filtering is not possible
- But: distortion is mostly common-mode signal ⇒
  use instrumentation amplifier with sufficiently high CMRR

Summary

- Wheatstone bridge: balance measurement of resistive sensors, mostly suitable for small $\Delta R/R$
- Differential signals of interest (such as output bridge circuit) often superimposed on (unwanted) common-mode signal
- Common-mode rejection ratio (CMRR): measure of the degree to which an amplifier suppresses the common-mode signal
- Opamp differential amplifier: amplifies differential voltage, but
  - input resistors load the source
  - tolerances of components limit the achievable CMRR
- 3-opamp instrumentation amplifier
  = differential preamplifier + difference amplifier
  - Less load on the source: high input impedance
  - CMRR increases with gain of the preamplifier

What's next?

- Study:
  - Regtien sections 1.2, 12.1.4, 12.1.5

- Practice:
  - See the exercises on Blackboard!

- Questions, things unclear? Let me know!

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Next time:
analog-digital convertors