EE1320: Measurement Science

Lecture 3:
Sensor Readout and Signal Conditioning

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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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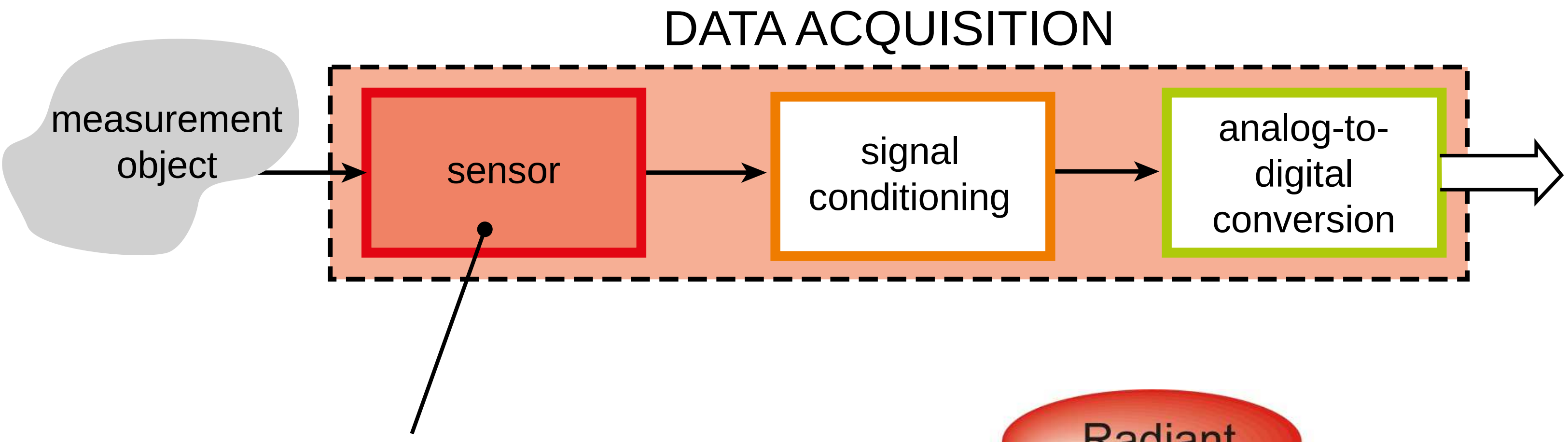
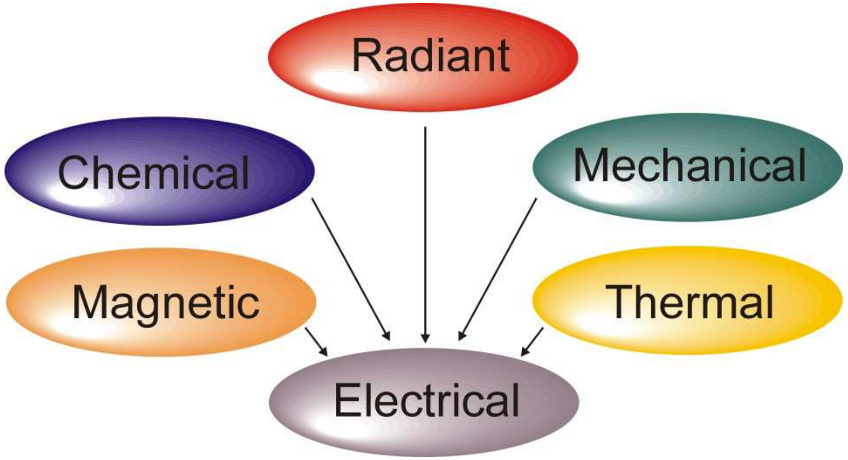
Last time…
Sensors

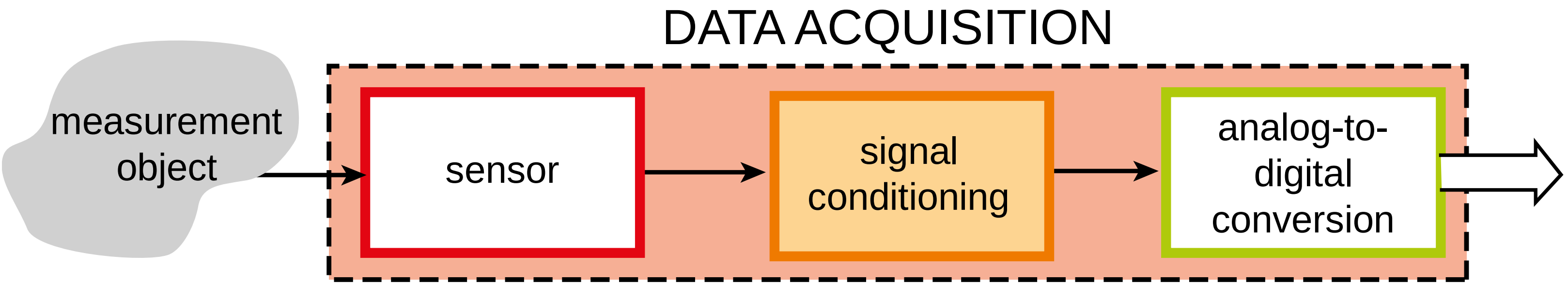


transduction of information from a (non-electrical) domain to the electrical domain

- self generating / modulating
- direct / tandem transduction



Today: sensor readout and signal conditioning



- Why signal conditioning?
- Readout of
  - thermocouples with a non-inverting amplifier
  - photodiodes with a transimpedance amplifier
  - capacitive sensors with a charge amplifier
- Additionally: effects of non-ideal properties of opamps

Overview study material

- Regtien 12 (except 12.1.4, 12.1.5):
  - Properties of opamps and basic opamp circuits (recap)
  - Non-ideal properties of opamps

- Regtien 13.1.1, 13.1.2
  - Integrator en differentiator

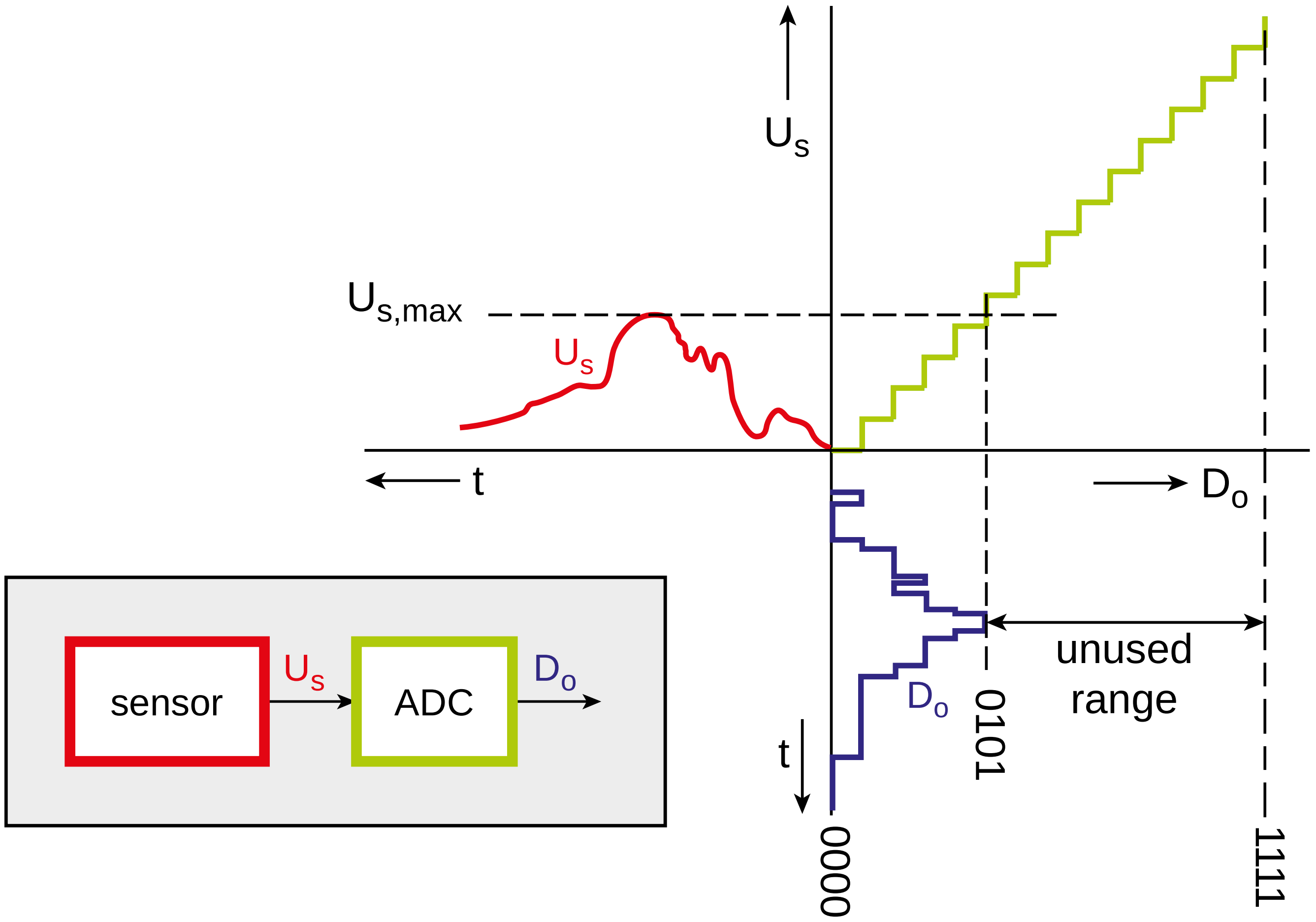
- Regtien 5.2: Signal models – equivalent error sources

Importance of signal conditioning

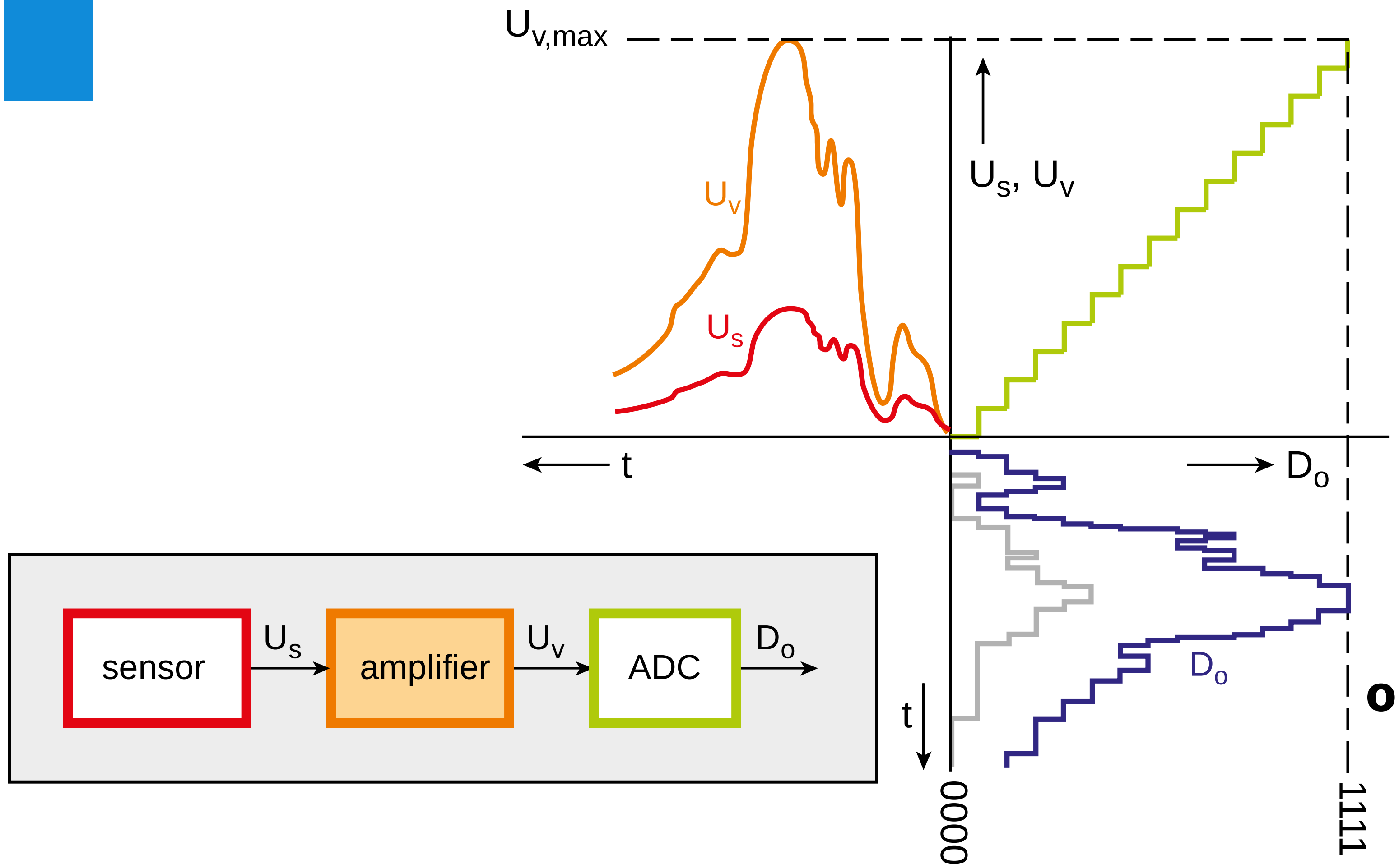
- Output signal of sensors is often not suitable for ADC input
  - too small - input range ADC not used effectively
  - too sensitive - load of sensor by ADC yields errors
  - too much interference / noise - ADC saturates without filtering
  - wrong format - e.g. resistive sensor on voltage-input

- Signal conditioning adapts the sensor signal to the ADC
  - amplification (scaling)
  - buffering
  - filtering
  - conversion

Importance of signal conditioning
- without scaling

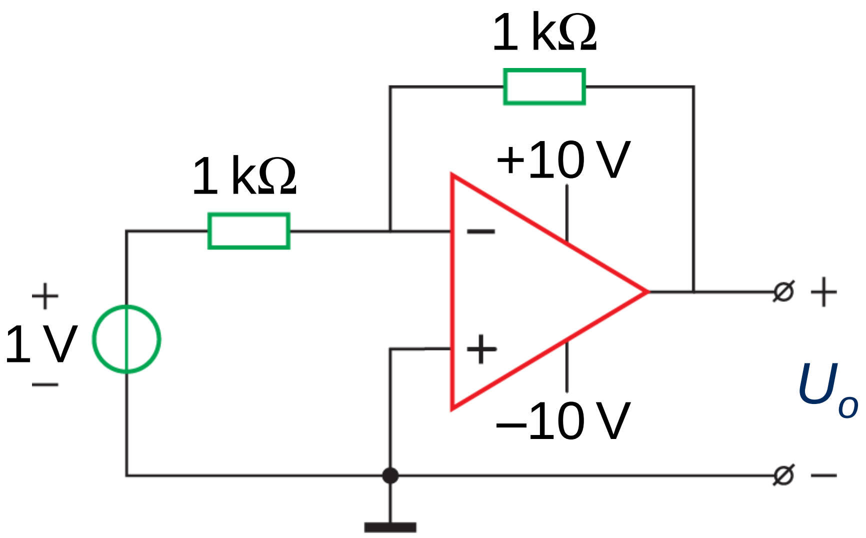


Importance of signal conditioning
- with scaling



How?
often using
opamp circuits!

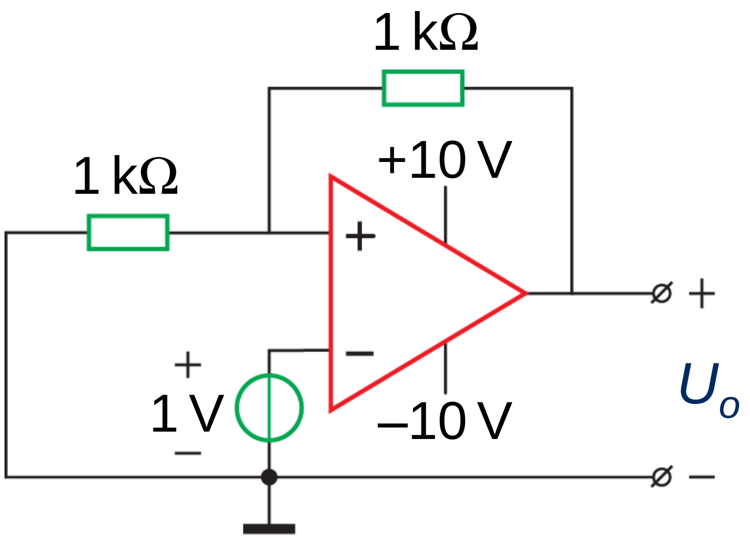
Opamps – remember them?



The output voltage U_o is:

A	–1 V
B	2 V
C	–2 V
D	–10 V

Opamps – remember them?



The output voltage U_o is:

A	1 V
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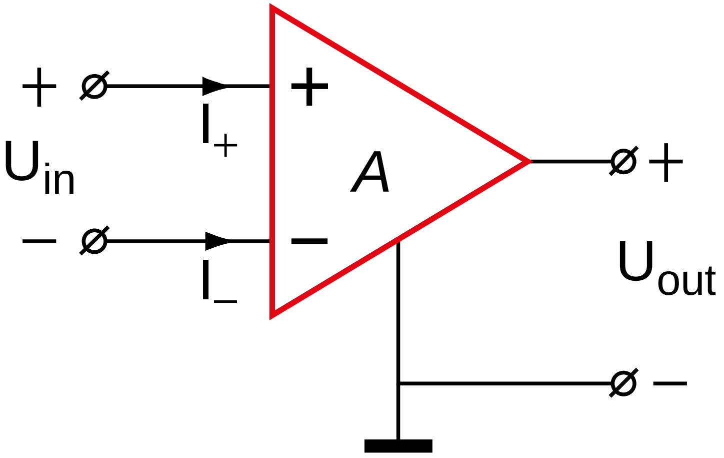
Opamp – ideal behavior



- Amplifies differential input voltage with very high (ideally infinite) gain *A*

$$U_{out} = A \cdot U_{in} = A \cdot \left(U_+ - U_-\right)$$

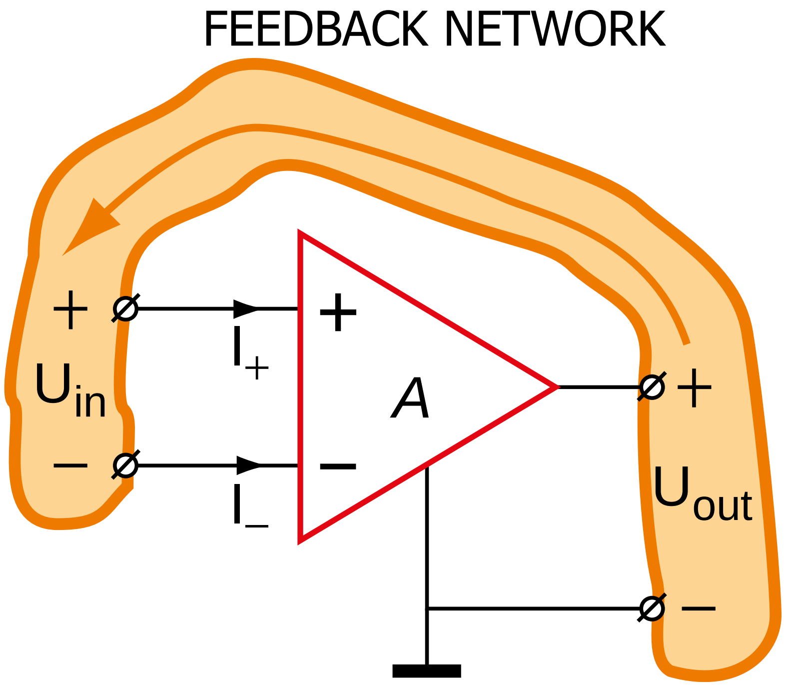
$$A \to \infty$$

- Input currents are zero:

$$I_+ \to 0$$

$$I_- \to 0$$

Opamp – ideal behavior



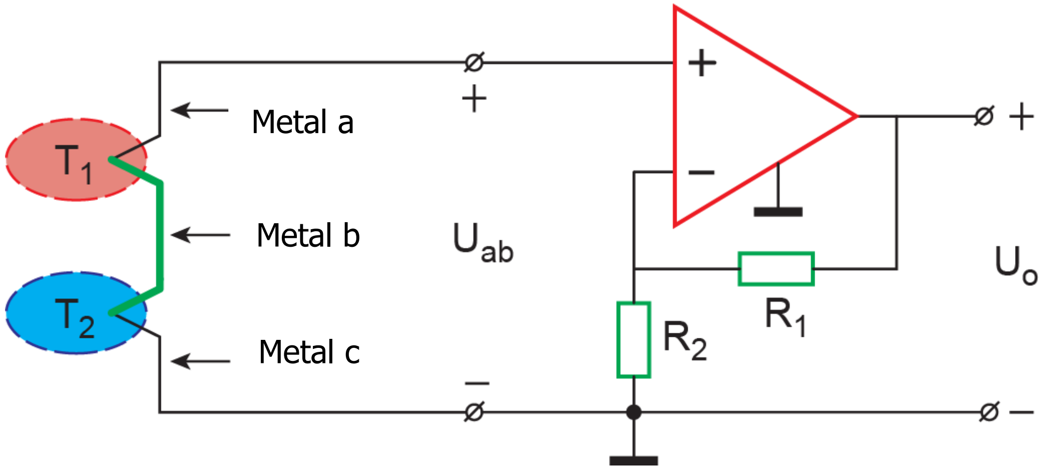
- Feedback network (with passive components) determines transfer
- Stable negative feedback ⇒ $U_{in} \to 0$ ("virtual ground")
- Zero-conditions at the input:

$$U_{in} = U_{+} - U_{-} \to 0$$

$$I_{+} \to 0$$

$$I_{-} \to 0$$

Thermocouple readout using a non-inverting amplifier



- Thermocouple senses temperature difference:

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

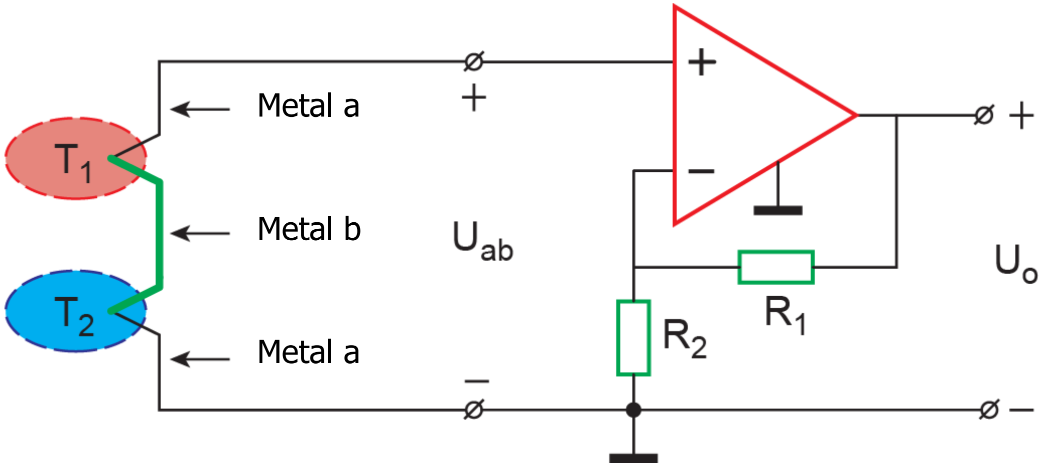
- Sensitivity determined by Seebeck coefficients α_a and α_b:

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

- Example: chromel/alumel ("type K" thermocouple)

$$\alpha_{ab} = 40\ \mu\mathrm{V/K}$$

Thermocouple readout using a non-inverting amplifier



- Given:
  - measurement range
    $0 \leq T_1 - T_2 \leq 100\,\mathrm{K}$
  - ADC input range
    $0 \leq U_o \leq 1\,\mathrm{V}$
  - chromel/alumel couple
    $\alpha_{ab} = 40\,\mu\mathrm{V/K}$

- Determine the required gain

$$G = \frac{1\,\mathrm{V}}{40\,\mu\mathrm{V/K} \cdot 100\,\mathrm{K}} = 250$$

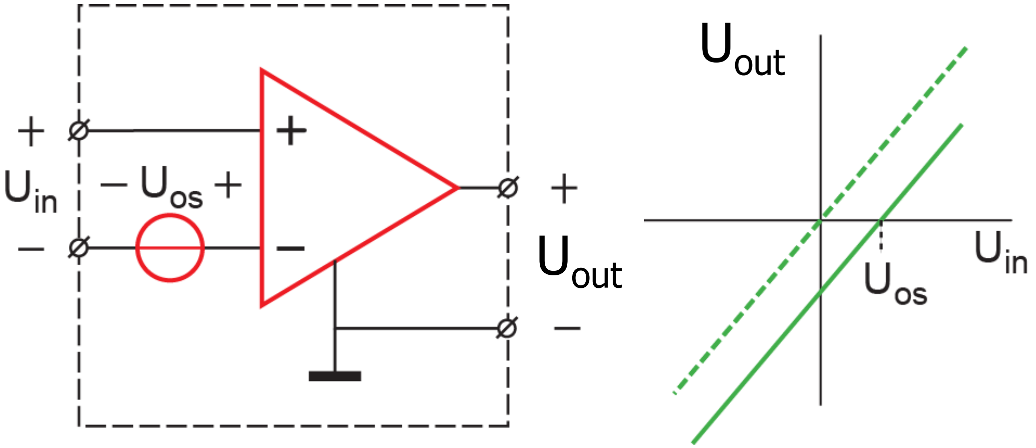
- Dimension the resistors

$$G = \frac{R_1 + R_2}{R_2}$$

e.g. $R_1 = 249\,\mathrm{k}\Omega$,
$R_2 = 1\,\mathrm{k}\Omega$

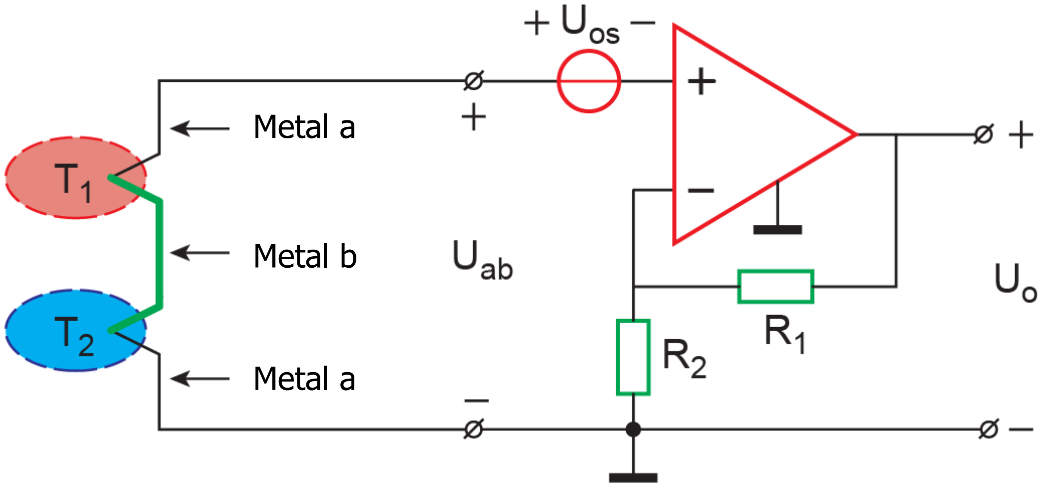
Opamp offset voltage

- Ideal opamp: $U_{out} = 0$ when $U_{in} = 0$
- Actual opamps have an **offset**: $U_{out} = 0$ at $U_{in} \neq 0$
- **Offset voltage U_{os}**: input voltage U_{in} for which $U_{out} = 0$



typical values:
- standard opamp: ±1 mV
- precision opamp: < ±10 µV

Thermocouple readout with offset



- Given:
  - opamp offset voltage

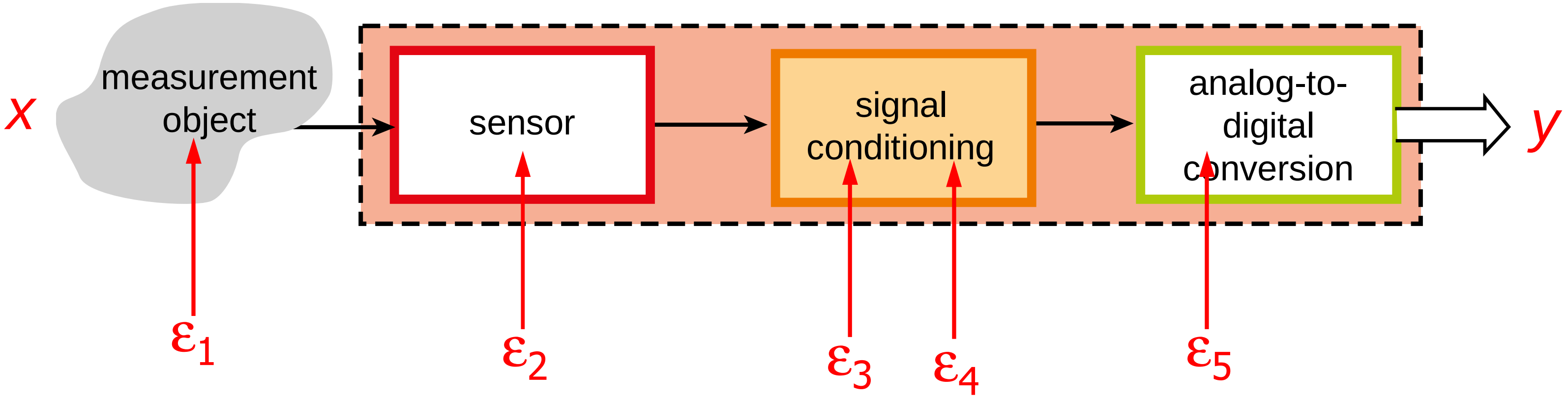
    $|U_{os}| < 1\ \text{mV}$
  - chromel/alumel couple

    $\alpha_{ab} = 40\ \mu\text{V/K}$

- Determine the maximum measurement error due to the offset voltage

Combining sources of error

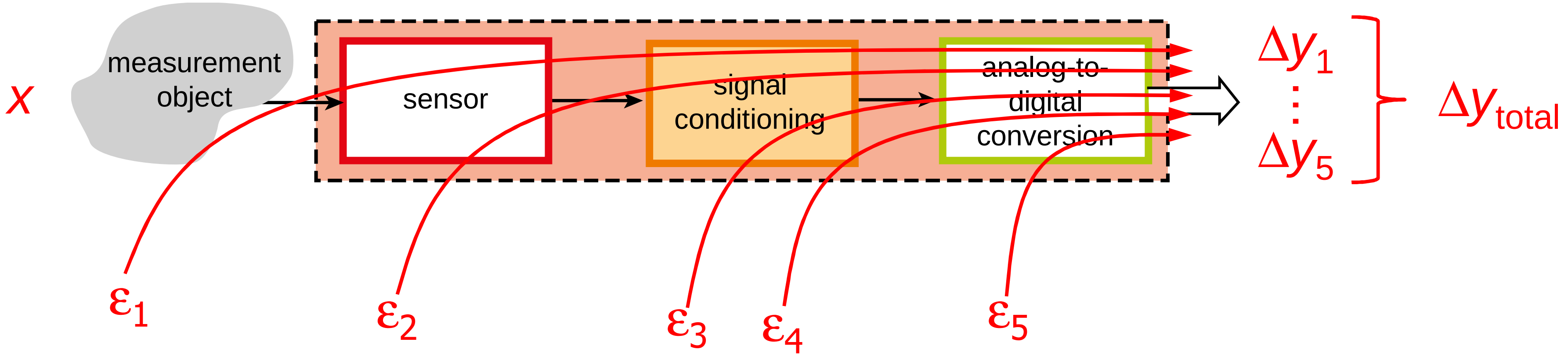
- Sources of error can occur at many positions in the chain



- For instance: offset, distortion, crosstalk, cross sensitivity
- How to determine their combined effect on the measurement?

Combining sources of error

- Determine the effect of the individual sources on the output



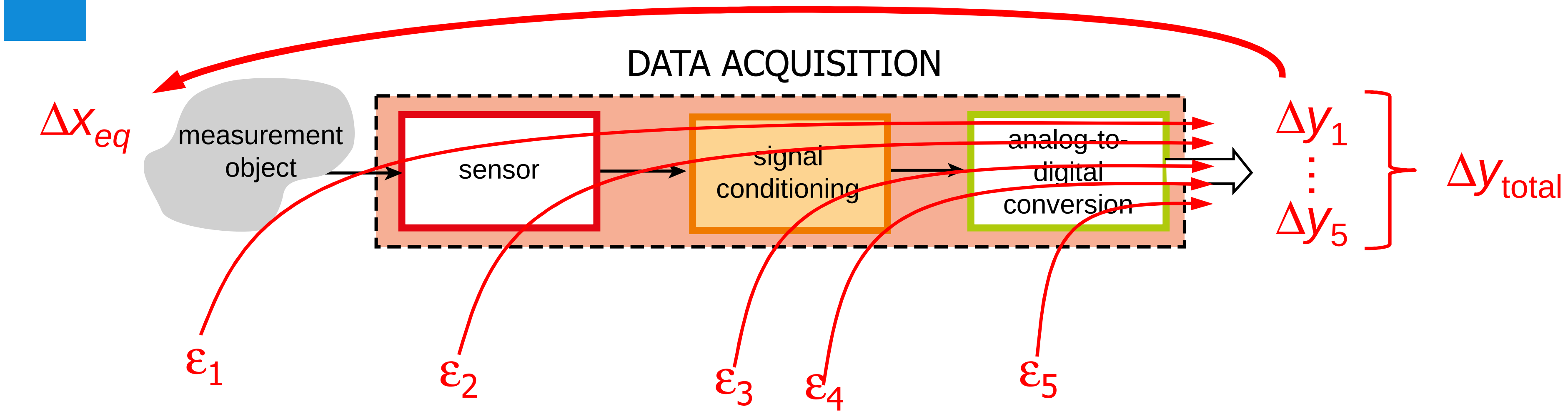
- If the system is linear (or can be linearized), then:

$$\Delta y_{total} = \sum \Delta y_i$$ for systematic sources of error (e.g. offset)

$$\Delta y_{total}^2 = \sum \Delta y_i^2$$ for uncorrelated stochastic sources of error (e.g. noise)

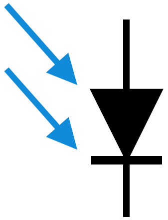
Equivalent sources of error

- Translate the output-referred error back to the input

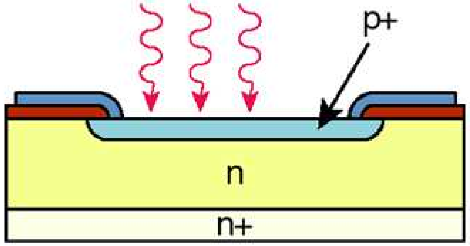


- Δx_{eq} is called the <u>equivalent input error</u>
- Example: what's the effect of ε_3 on the measurement?
  - Determine output error due to $\varepsilon_3 \Rightarrow \Delta y_3$
  - Translate this back to the input $\Rightarrow \Delta x_{eq,3}$
  - ε_3 causes an equally large error as an error $\Delta x_{eq,3}$ at the input would

Photo diode



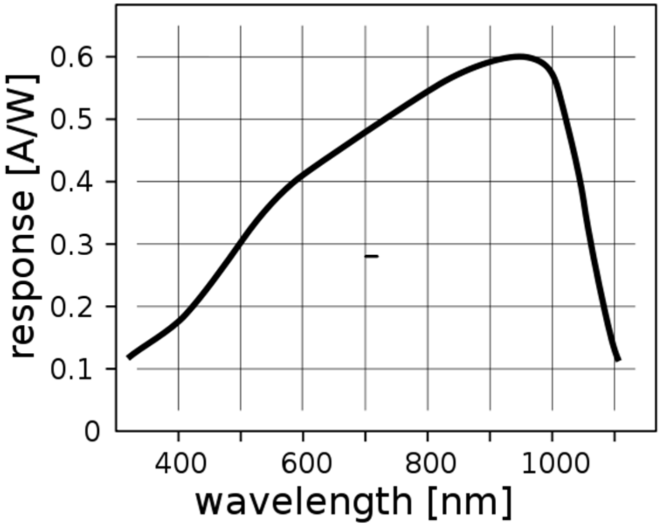
$$E = h \cdot \nu = \frac{h \cdot c}{\lambda}$$



- Photons lead to a photocurrent I_{ph}

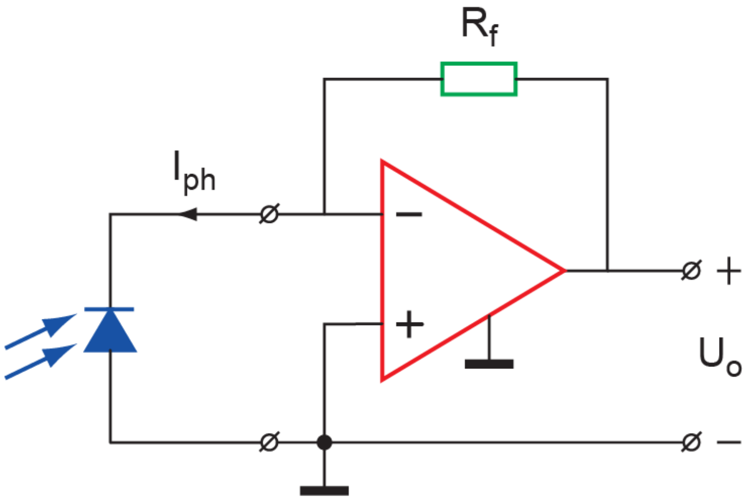
- Characteristic properties:
  - spectral sensitivity R [A/W]
  - dark current I_{dark} [A]
  - quantum efficiency η [%]: electrons / photon

Typical sensitivity
of a Si photodiode



Regtien 9.1.2

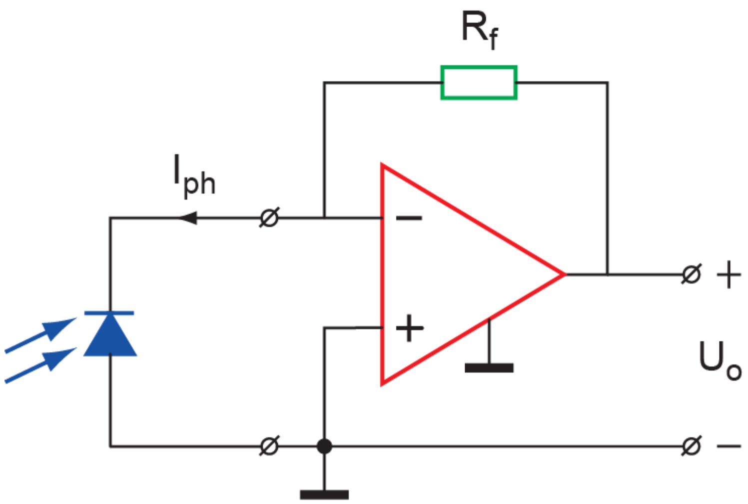
Photodiode readout using a transimpedance amplifier



- transimpedance amplifier = current-voltage converter

$$U_o = R_f \cdot I_{ph}$$

Photodiode readout using a transimpedance amplifier

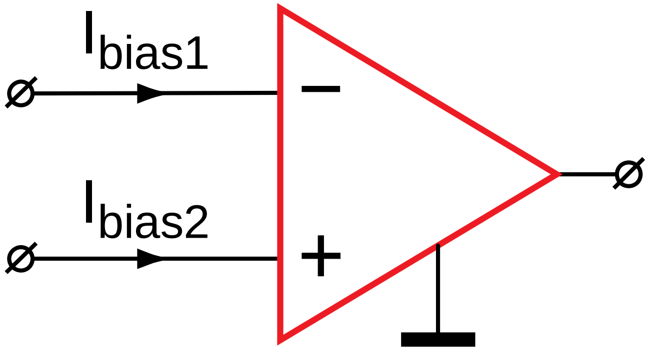


- Given:
  - spectral sensitivity
    $R_{spec} = 0.5$ A/W
  - sensitive area
    $A = 1\ \text{mm}^2$
  - light intensity range
    $0 \leq P \leq 1\ \text{W/m}^2$
  - ADC input range
    $0 \leq U_o \leq 1$ V

- Determine the required feedback resistance

Opamp offset current and bias current

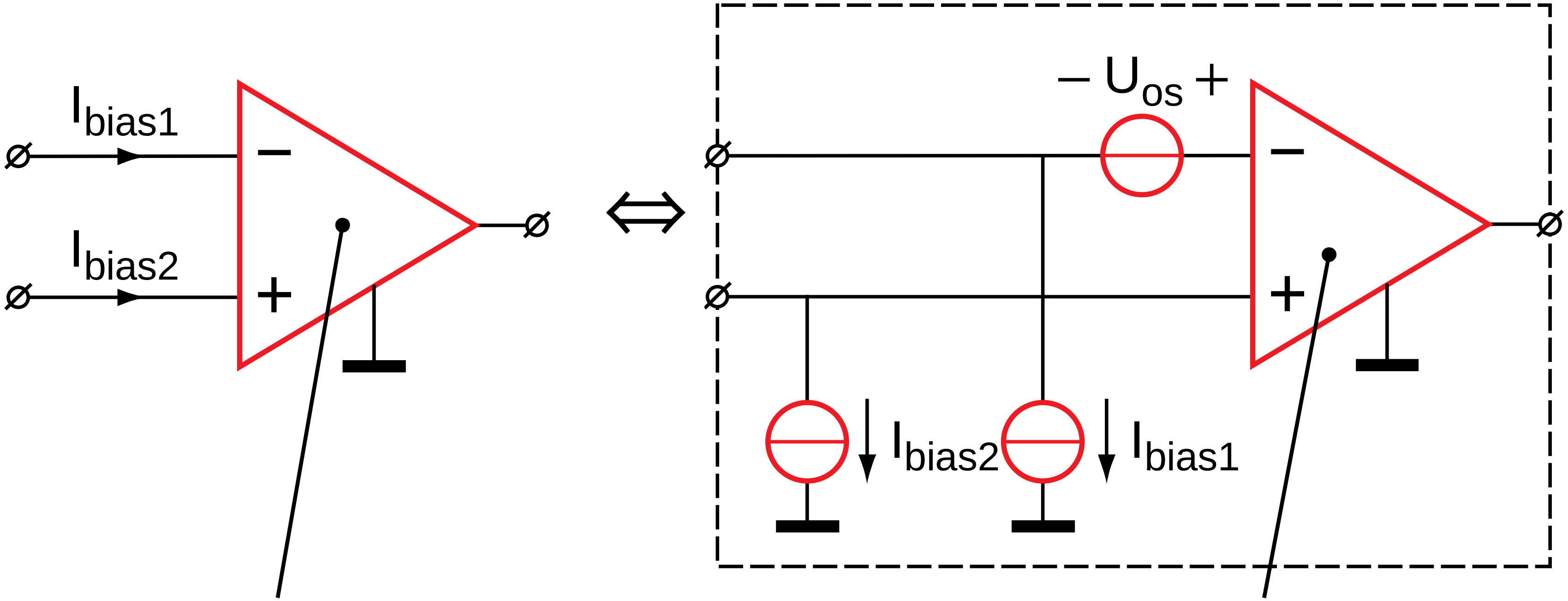
- Ideal opamp: $I_+ \rightarrow 0, \; I_- \rightarrow 0$
- Practical opamps require **bias current** I_{bias}
- Moreover, input currents are not exactly equal:
  offset current: $I_{os} = I_{bias1} - I_{bias2}$



values vary strongly depending on opamp type
- MOS: pA ~ nA
- bipolar: nA ~ μA

often highly temperature dependent!

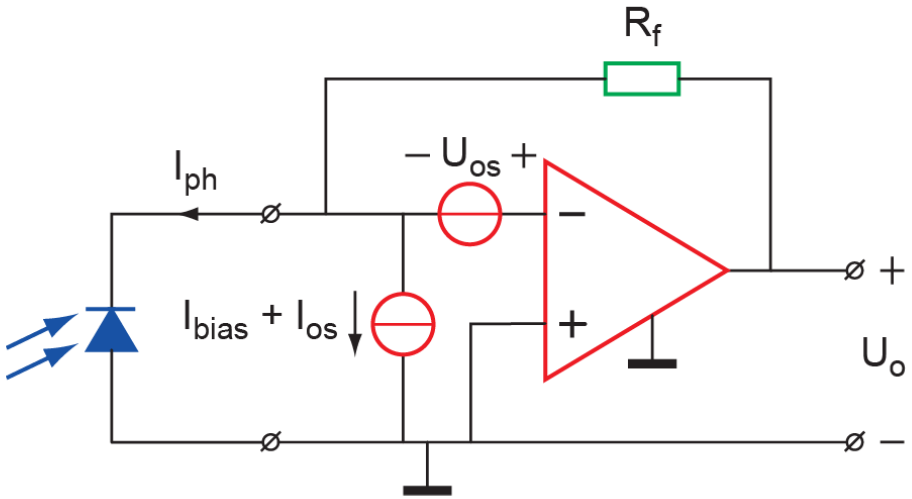
Modeling offset and bias current with equivalent sources



Practical opamp
with offset and
bias currents

Ideal opamp
without offset and
bias currents

Photodiode readout with offset and bias current

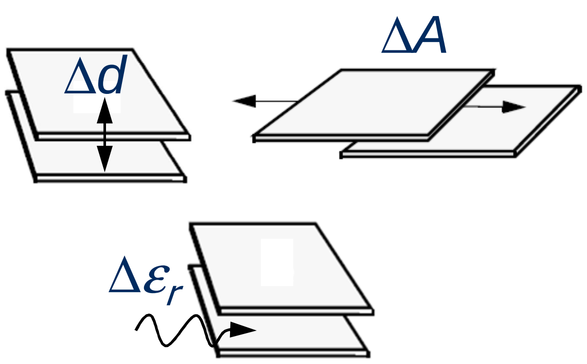


- Determine maximum offset voltage at the output (in mV)
- Determine the equivalent input offset in terms of the photocurrent (in nA)

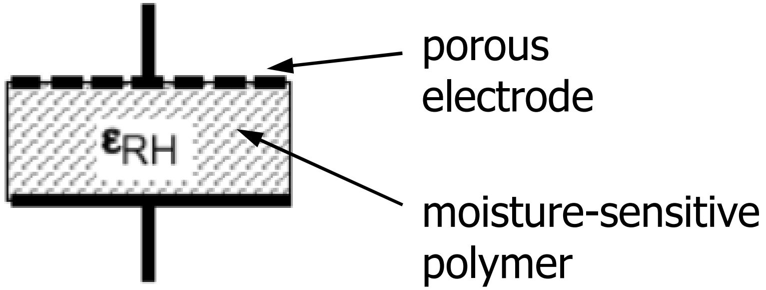
- Given:
  - dark current photodiode
    $I_{dark} \leq 5$ nA
  - opamp offset voltage
    $|U_{os}| < 1$ mV
  - opamp bias current
    $I_{bias} < 10$ nA
  - opamp offset current
    $|I_{os}| < 1$ nA
  - $R_f = 2\text{M}\Omega$

Readout of capacitive sensors using a charge amplifier

- Capacitive sensor: $C_s = \varepsilon_0 \cdot \varepsilon_r \cdot \dfrac{A}{d}$
- C_s changes due to
  - displacement Δd, ΔA
  - change in dielectric constant

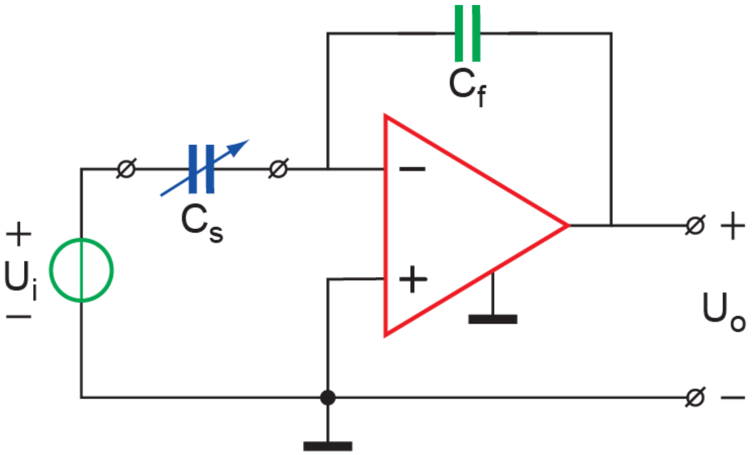


- Example: humidity sensor



Regtien 7.2.3, 20.2.2 (Fig. 20.16)

Readout of capacitive sensors using a charge amplifier



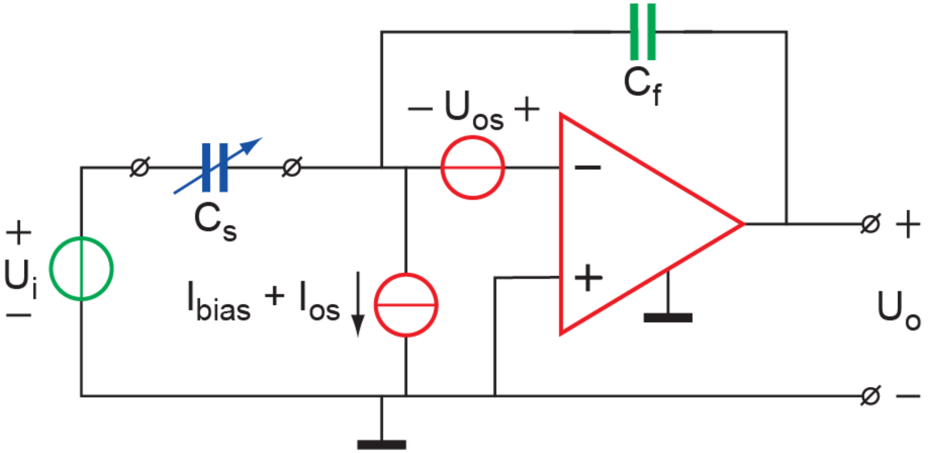
- Charge amplifier
  - resembles an inverting amplifier

- Transfer:

$$U_o = -\frac{Z_f}{Z_s}U_i = -\frac{j\omega C_s}{j\omega C_f}U_i = -\frac{C_s}{C_f}U_i$$

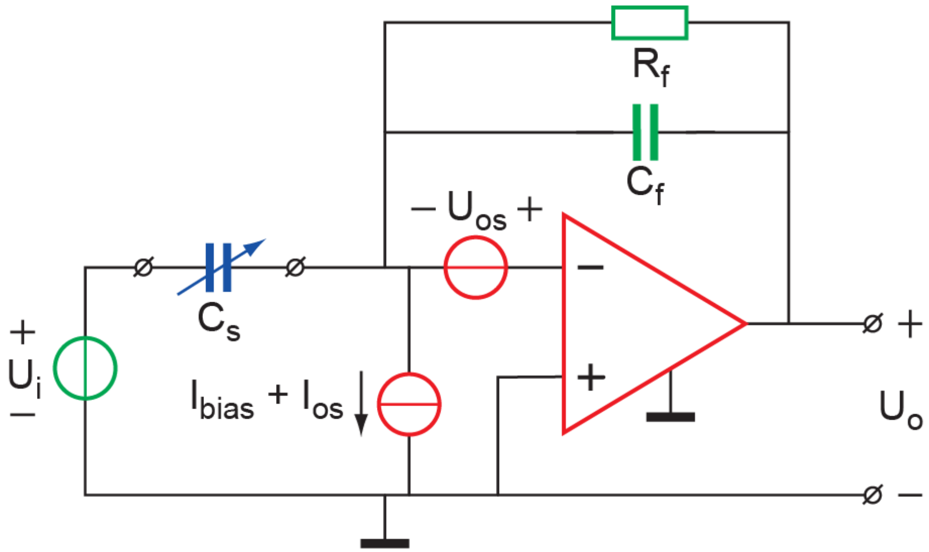
- Requires AC voltage U_i ($\omega > 0$)

Readout of capacitive sensors with offset and bias current



- What is wrong??

Readout of capacitive sensors with offset and bias current



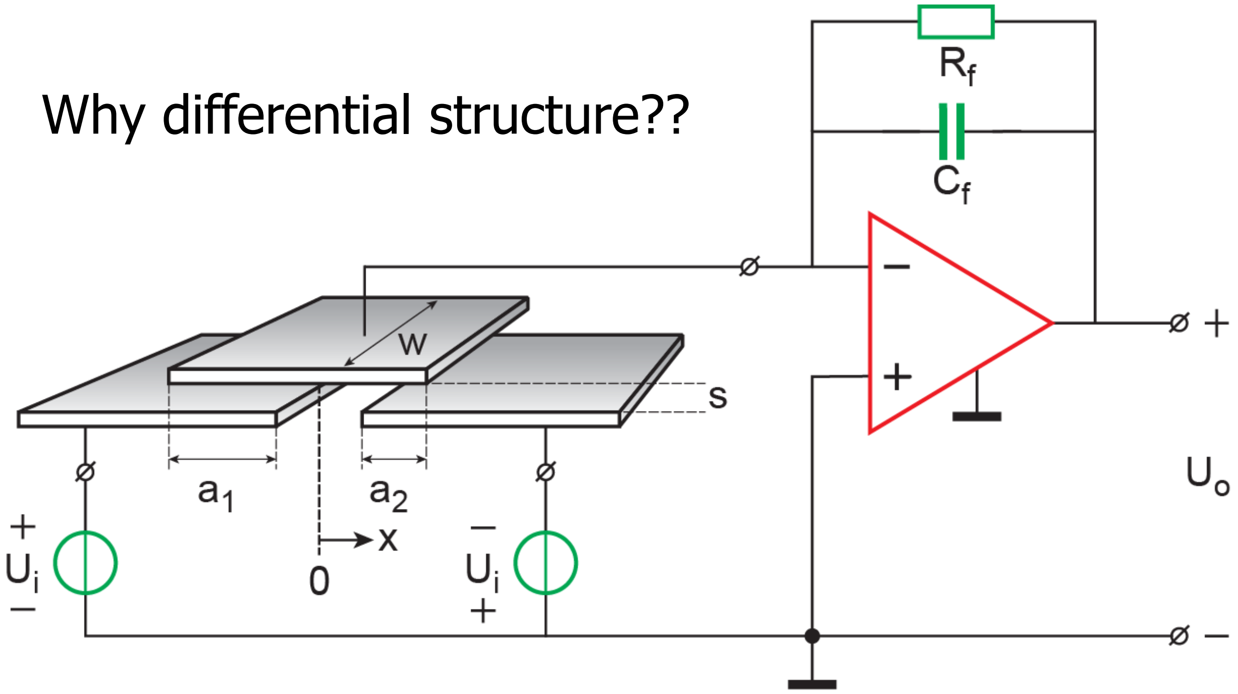
- "Tamed" integrator: feedback resistance R_f
- DC transfer determined by R_f:

$$\Delta U_o = -U_{os} + \left(I_{bias} + I_{os}\right) \cdot R_f$$

- For $\omega > \frac{1}{R_f C_f}$ transfer determined by C_f: $U_o = -\frac{C_s}{C_f} U_i$

Differential readout of capacitive sensors

Why differential structure??



- Differential structure ⇒ $U_o = 0$ for $x = 0$
- Differential structures eliminate offsets and even-order non-linearities.

Summary

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

- Opamps are suitable building blocks for sensor readout
    - non-inverting amplifier (example: thermocouples)
    - transimpedance amplifier (example: photodiodes)
    - charge amplifier (example: capacitive sensors)

- Opamp's non-ideal properties influence the transfer
    - offset voltage, bias current, offset current
    - modeled with equivalent sources at input of opamp
    - can be translated to equivalent input- or output-referred errors

What's next?

- Study:
  - Regtien chapter 12, sections 5.2, 13.1.1, 13.1.2

- Practice
  - See the exercises on Blackboard!

- Questions, things unclear? Let me know!
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Next time: instrumentation amplifiers!