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Lab05: Operational Amplifiers

Practical Example Operational Amplifier (Op-Amp) as Linear Aplifier

1. Audio pre-amplifier (e.g., guitar pedal, microphone preamp).
2. Amplification of sensor signals (temperature, strain gauge, photodiode).
3. Medical equipment such as ECG front-end amplifiers.

Practical Example Op-Amp as Active Filter

1. Active crossover filters in hi-fi and car audio systems.
2. Anti-aliasing filters before ADCs and reconstruction filters after DACs.
3. Noise-reduction filters in measurement and sensor systems.

Golden Rules

Explain the Golden Rules of the operational amplifier.

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Op-Amp zero adjustment without feedback

Build the following circuit in figure 1 with the power supply and a multimeter.

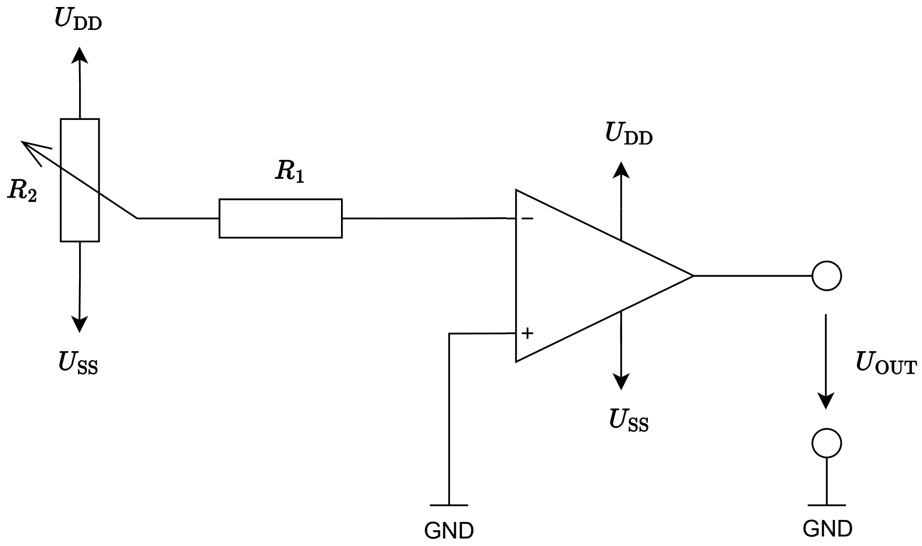

Fig. 1: Zero adjustment

$U_{DD} = 10\ \mathrm{V},\ U_{SS} = -10\ \mathrm{V},\ R_1 = 10\ \mathrm{k\Omega},\ R_2 = 10\ \mathrm{k\Omega}$

Adjust the output of the Op-Amp to zero and describe your results.

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How can the circuit be improved?
Draw an improved version and explain it.

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Inverting Operational Amplifier

Gain of Op-Amp

Build the following circuit in figure 2 with the power supply and a multimeter.

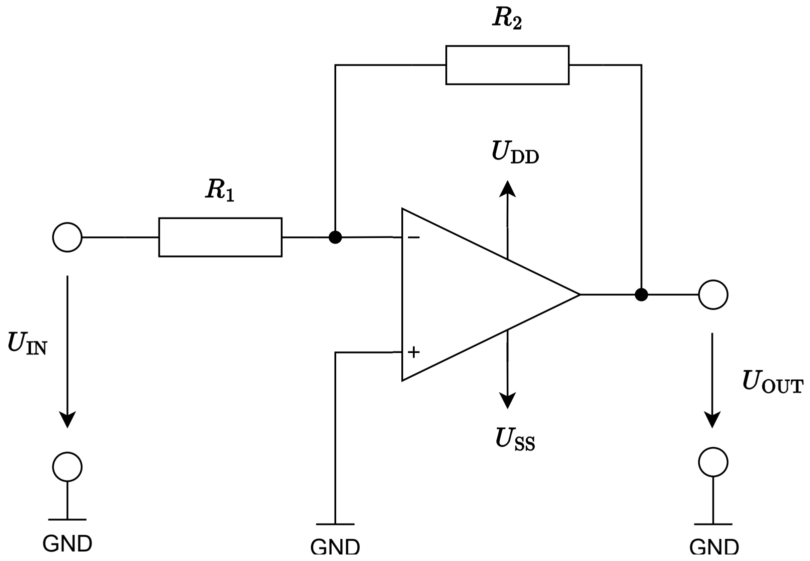

Fig. 2: Inverting Op-Amp

$U_{DD} = 10\ \mathrm{V},\ U_{SS} = -10\ \mathrm{V},\ R_1 = 10\ \mathrm{k\Omega}$

Calculate the necessary value for R_2, so that the output U_{OUT} is +5 V. Use the supply voltage of the operational amplifier for U_{IN}.

$U_{IN} =$

$R_2 =$

Analysis of inverting input currents

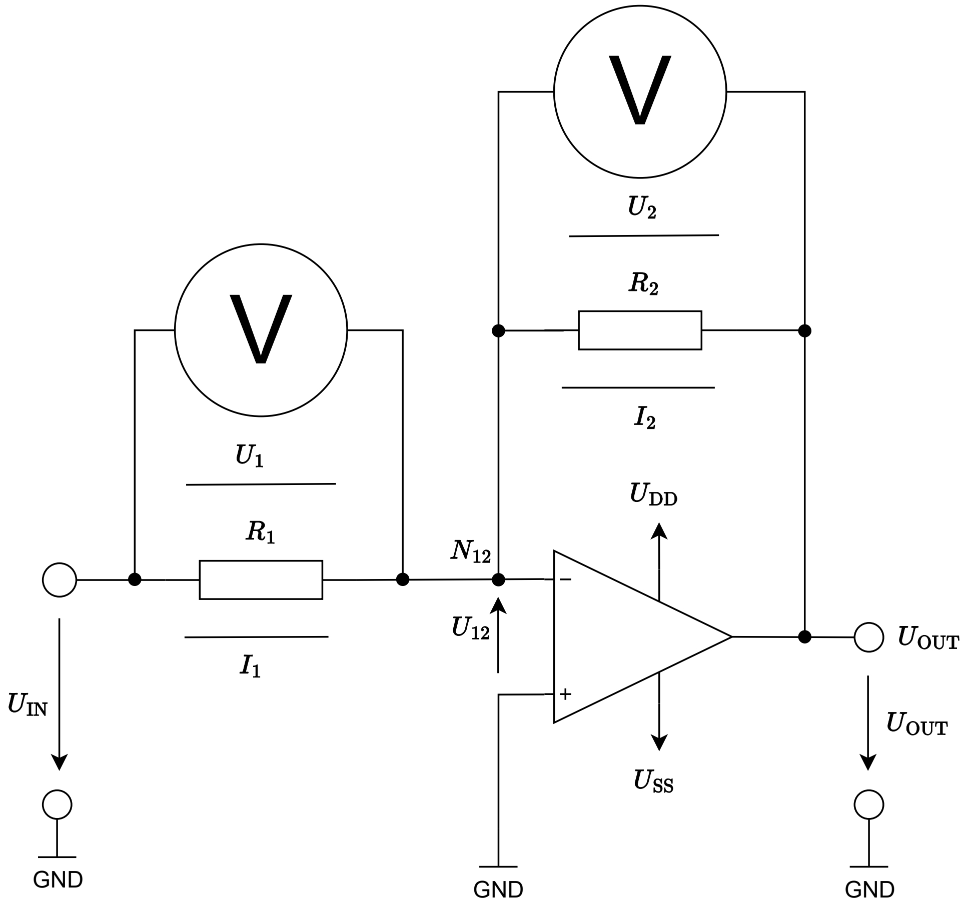

Fig. 3: Inverting Op-Amp: Analysis of currents of the inverting input

$U_{DD} = 10\ \mathrm{V},\ U_{SS} = -10\ \mathrm{V},\ R_1 = 10\ \mathrm{k\Omega}$

Use the values from figure 2 for $U_{IN},\ U_{OUT},\ R_2$.

Complete the arrows in the scematic of the circuit.
Determine the the currents I_1 and I_2 indirectly by measuring the voltage across known resistors and calculate the algebraic sum of the currents at node N_{12} using Kirchhoff's Current Law (KCL).

$U_1 =$

$U_2 =$

$I_1 \ =$

$I_2 \ =$

$I_{\mathrm{N12}} \ =$

Analysis of inverting input voltages

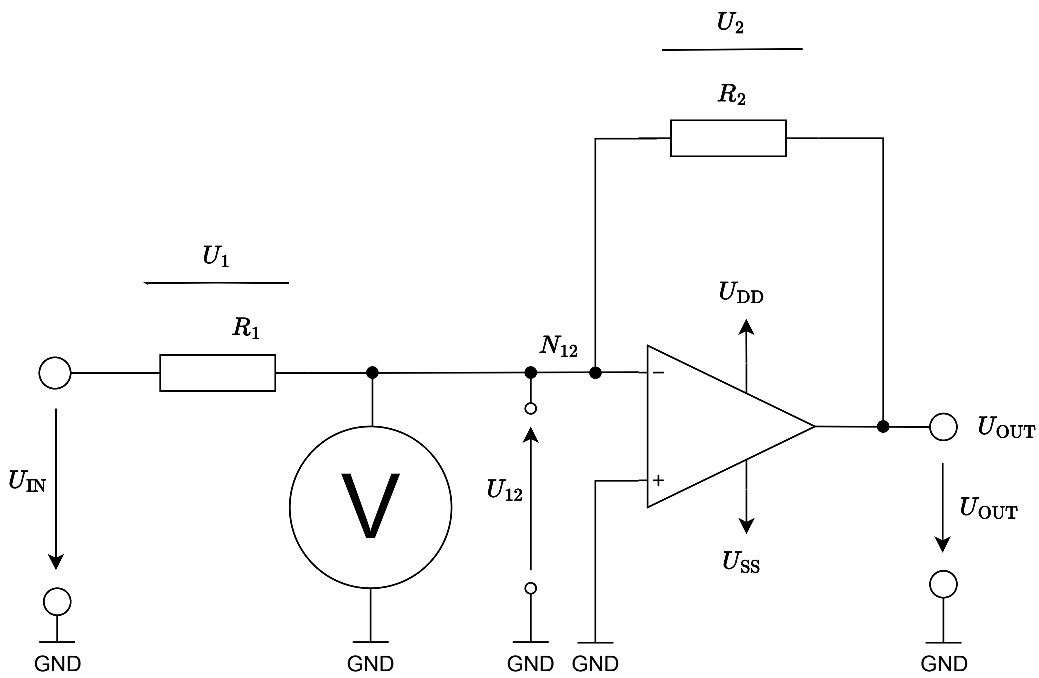

Fig. 4: Inverting Op-Amp: Analysis of virtual GND of the inverting input

$U_{DD} = 10\ \mathrm{V},\ U_{SS} = -10\ \mathrm{V},\ R_1 = 10\ \mathrm{k\Omega}$

Use the values from figure 2 for $U_{IN},\ U_{OUT},\ R_2$.

Complete the reference arrows in the scematic of the circuit.
Take the values for $U_1,\ U_2,\ U_{OUT}$ from figure 3.
Calculate the voltage U_{12} using Kirchhoff's Voltage Law (KVL) within the circuit loop.
Verify your calculated result by measuring U_{12}.

$U_1 =$

$U_2 =$

$U_{OUT} =$

Calculated $U_{12} =$

Measured $U_{12} =$

Analyse the physical significance of the potential at N_{12} relative to GND () (defined as U_{12}) in the context of the operational amplifier's input configuration. What do you observe?

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What happens if you short-circuit R_2 (the feedback resistor)?
Experimentally verify this effect and explain the observed behavior regarding the output voltage.

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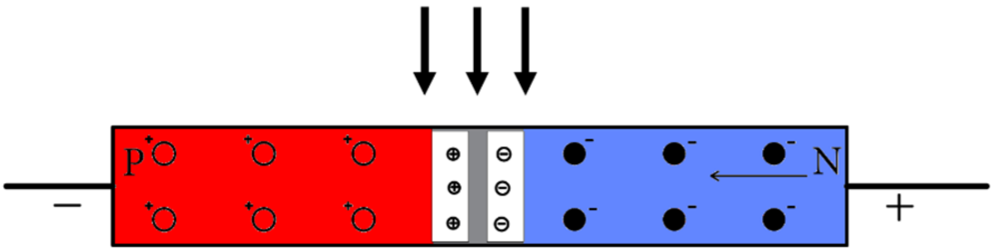
Photodiode as current source

A photodiode is a special type of diode which, **in the absence of light**, exhibits a **current-voltage relationship** very similar to that of a standard diode (see the **dark current** characteristic in the $I-V$ **diagram**).

When illuminated, it generates additional electron-hole pairs within the crystal.



Photodiodes are often operated **in reverse bias**, **where** the charge carriers (electrons and holes) generated by the incident light cause an increased **reverse** current flow (**third quadrant** of the I-V diagram). The higher the light intensity, the greater the reverse current. **Forward bias operation** is also possible, where the photodiode behaves like a solar cell (**first quadrant** of the I-V diagram).

Applications include remote controls (IR range), galvanic isolation (optocouplers), light measurement, positioning, and light barriers.

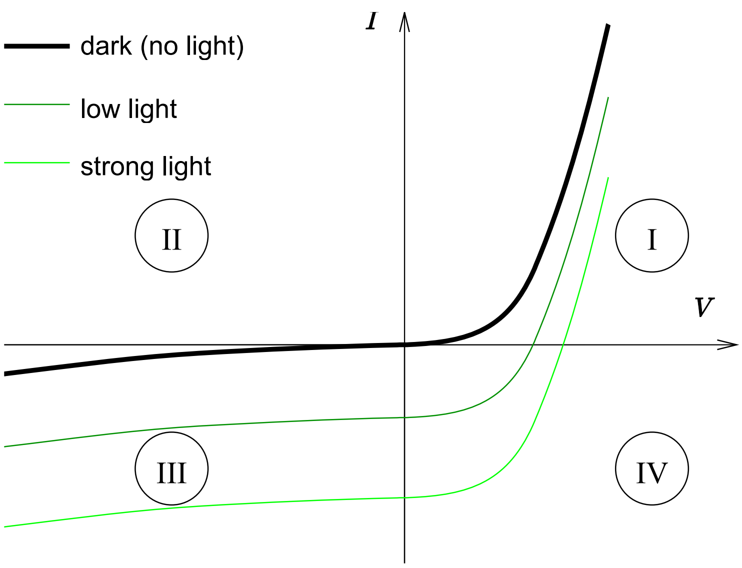


Fig. 5: Inverting Op-Amp: Operating principle of a photodiode

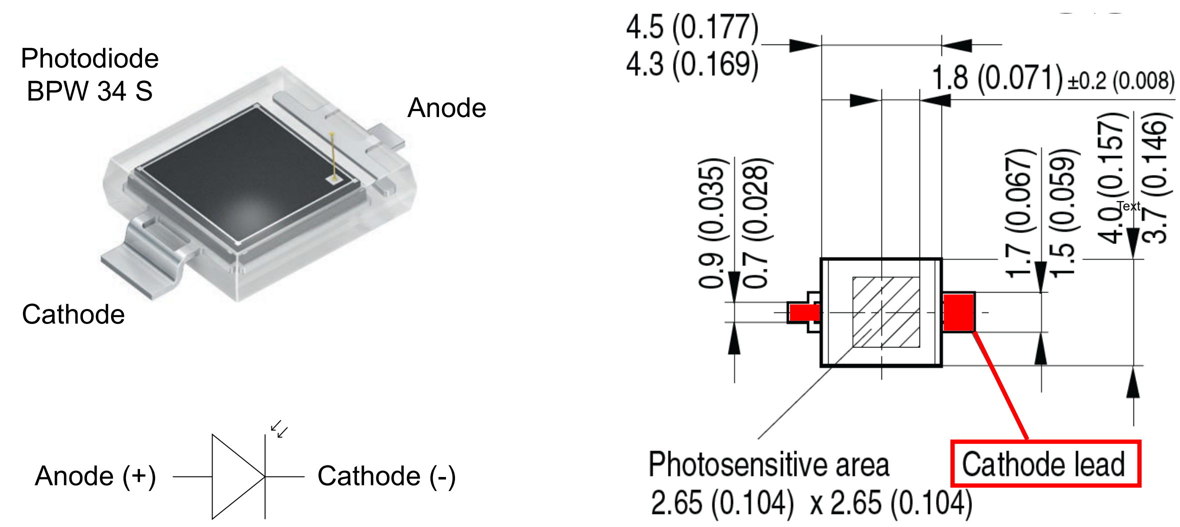
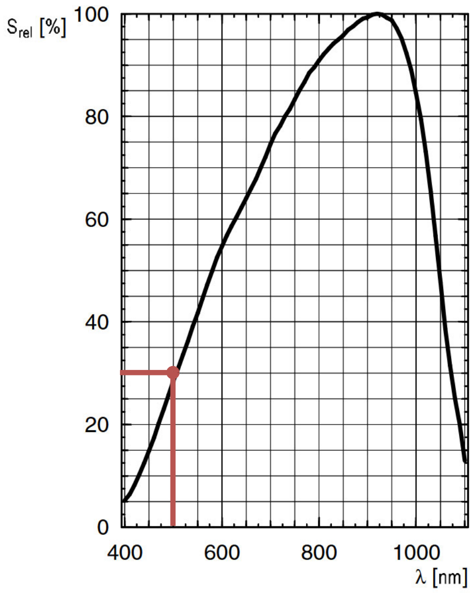
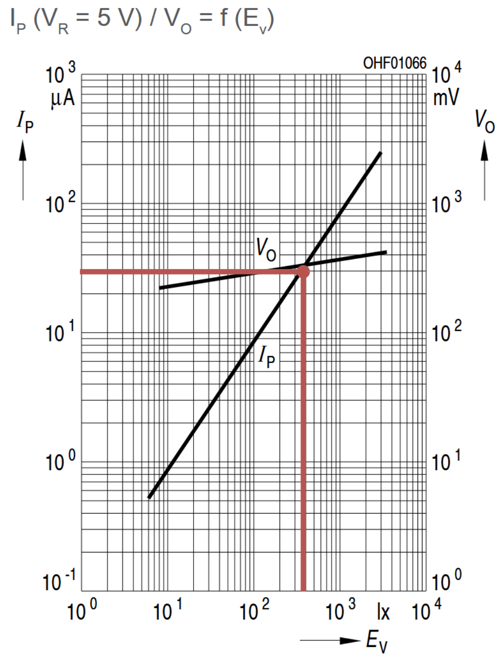


Fig. 6: Inverting Op-Amp: Photodiode BPW 34 S



Sensitivity in % as a function of the wavelength of light



Optocurrent I_P and open-circuit voltage V_O as a function of the illuminance

Fig. 7: Inverting Op-Amp: Diagramms of BPW 34 S

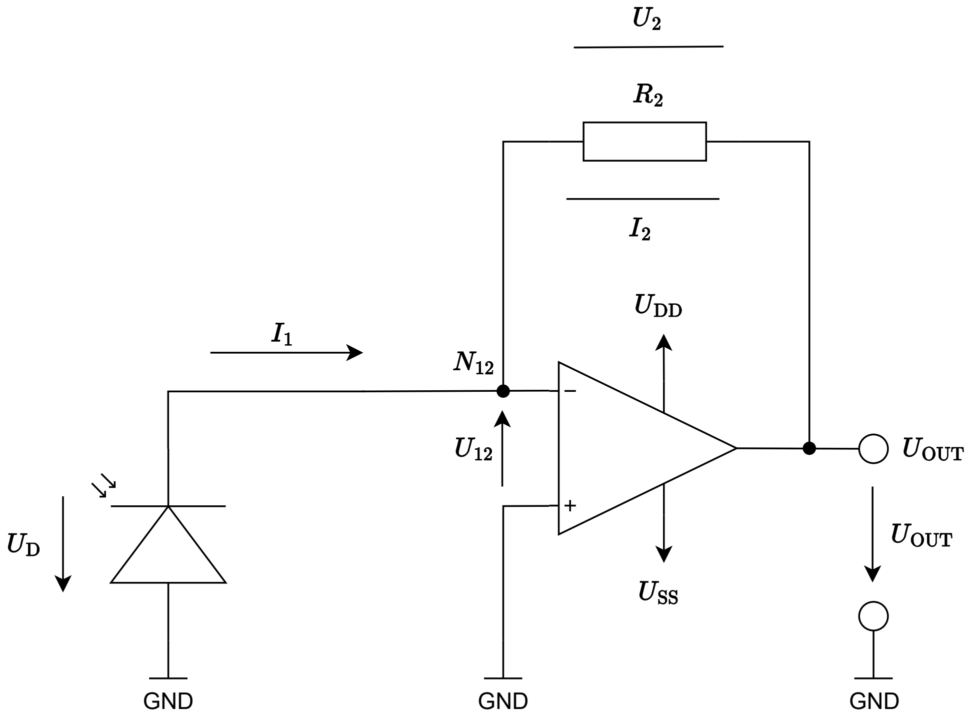


Fig. 8: Inverting Op-Amp: Photo Diode as current source

$U_{DD} = 10 \text{ V}, \; U_{SS} = -10 \text{ V}$

We are assuming a well-lit room with an illuminance of 300 lx, lit by a white LED. White light is a mixture of many wavelengths across the visible spectrum, roughly 380 to 780 nm. For a typical white LED, the spectrum usually comes from a blue LED chip with a peak around 450 nm, plus a broader phosphor emission that spreads across green, yellow, and red wavelengths. For an easier calculation, we take a mean value of 500 nm which is close to the peak value of the blue LED and 300 lx for the illumination. (500 nm is in reality a greenish light and not blue)
The graph in figure 7 shows that the photodiode sensitivity at 500 nm is only 30%. The maximim current (100%) at 300 lx is 30 μA.
We can now estimate the current we would expect from the photodiode at 300 lx:

$$I_1 = 30 \; \mu\text{A} * 0.3 = 9 \; \mu\text{A}$$
$$I_1 \approx 10 \; \mu\text{A}$$

30% of 30 μA is roughly 10 μA.
We will assume a current of 10 μA at 300 lx for our calculations.

Complete the arrows in the circuit diagram in figure 8.

Calculate R_2 so that U_{OUT} = 5 V at 300 lx. Take a resistor from the E6 series that is as close as possible to the calculated value.
Also enter the values for I_1, I_2, U_2 and U_{OUT}.

$I_1 \ =$

$I_2 \ =$

$U_2 \ =$

$U_{\rm OUT} \ =$

$R_2 \ =$

What value would you expect for $U_{\rm D}$ in figure 8 and why?

$U_{\rm D} \ =$

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What value would you expect for U_D at 300 lx when the photodiode is not connected to the Op-Amp or any other electronic component (open-circuit voltage) and why?

$U_\mathrm{D} =$

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Measure or calculate the values given in the table below.

Illumination	U_OUT measuerd	I_1 calculated	I_2 calculated	U_D Op-Amp circuit	U_D open-circuit ***)** measured
dark (cover the photodiode)					
300 lx (room light)					
bright (use torch from mobile phone)					

***)** The photodiode must be disconnected from the Op-Amp circuit

Tab. 1: Photodiode measured and calculated values

Non-inverting Operational Amplifier

Op-Amp as current source

An Op-Amp can not only amplify voltages and currents, it can also act as a current source itself. Here is the schematic of a typical Op-Amp current source:

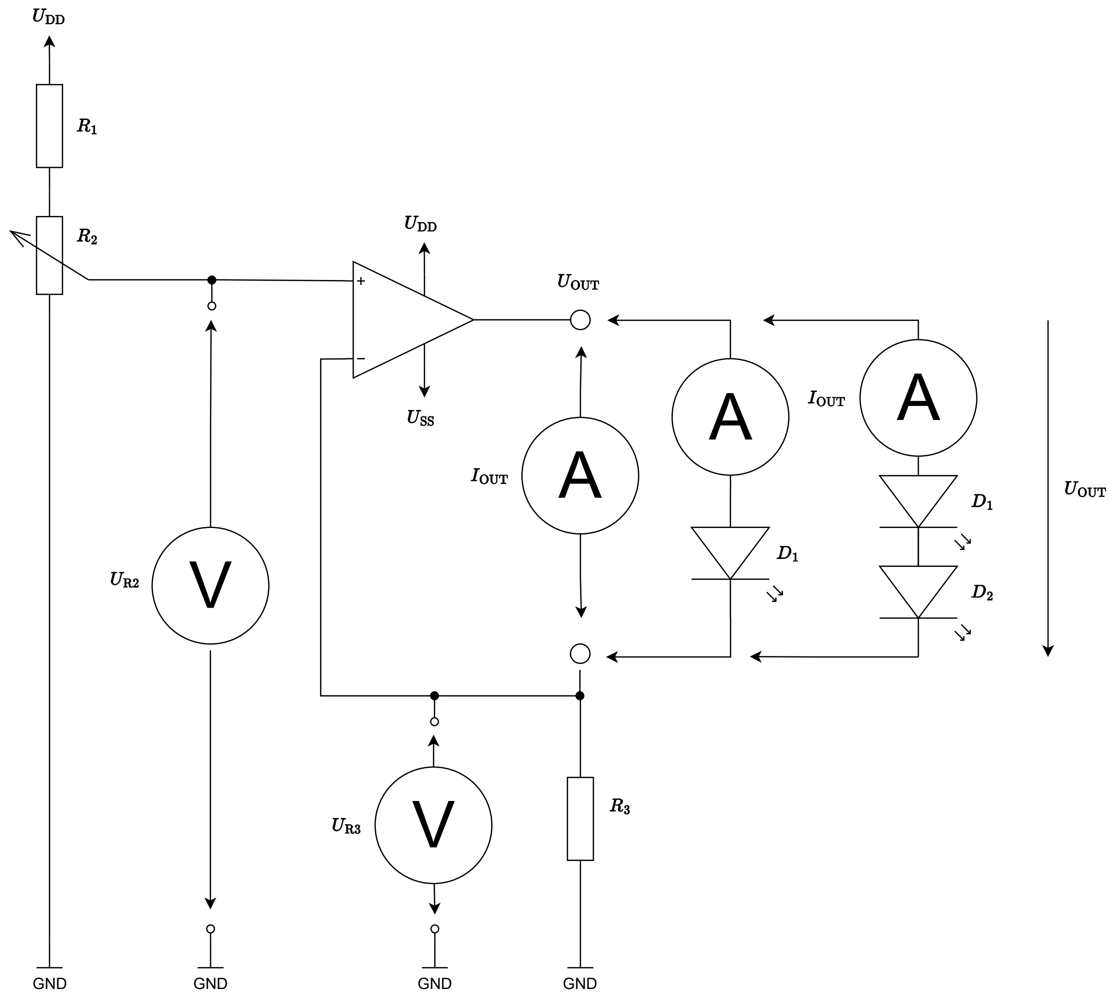

Fig. 9: Non-inverting Op-Amp: current source

$U_{DD} = 10 \text{ V},\ U_{SS} = -10 \text{ V},\ R_1 = 100 \text{ k}\Omega,\ R_2 = 10 \text{ k}\Omega,\ R_3 = 100\ \Omega$

Measure the values given in the table below.

Potentiometer	U_{R2}	U_{R3}	I_{OUT} without diodes	U_{OUT} without diodes	I_{OUT} with D_1	U_{OUT} with D_1	I_{OUT} with D_1 + D_2 in series	U_{OUT} with D_1 + D_2 in series
0%								
50%								
100%								

Tab. 2: Op-Amp as current source: measured and calculated values

Why does the current remain constant at the output of the Op-Amp?
Give a brief explanation of the circuit's operating principle.

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Op-Amp as non-inverting low-pass filter

We can also use an operational amplifier as an active filter. There are two typical circuit configurations: the Sallen-Key circuit, which uses a non-inverting operational amplifier, and the multiple-feedback circuit, which uses an inverting operational amplifier.
We use the Sallen-Key circuit as it is easier to understand and the gain of the operational amplifier can be determined independently of the cut-off frequency.
The cut-off frequency can be calculated using the following formula:

$$f_{\rm c} = \frac{1}{2\pi\sqrt{R_1 \cdot C_1 \cdot R_2 \cdot C_2}}$$

Here is an scematic of an typical low-pass filter using the Sallen-Key circuit:

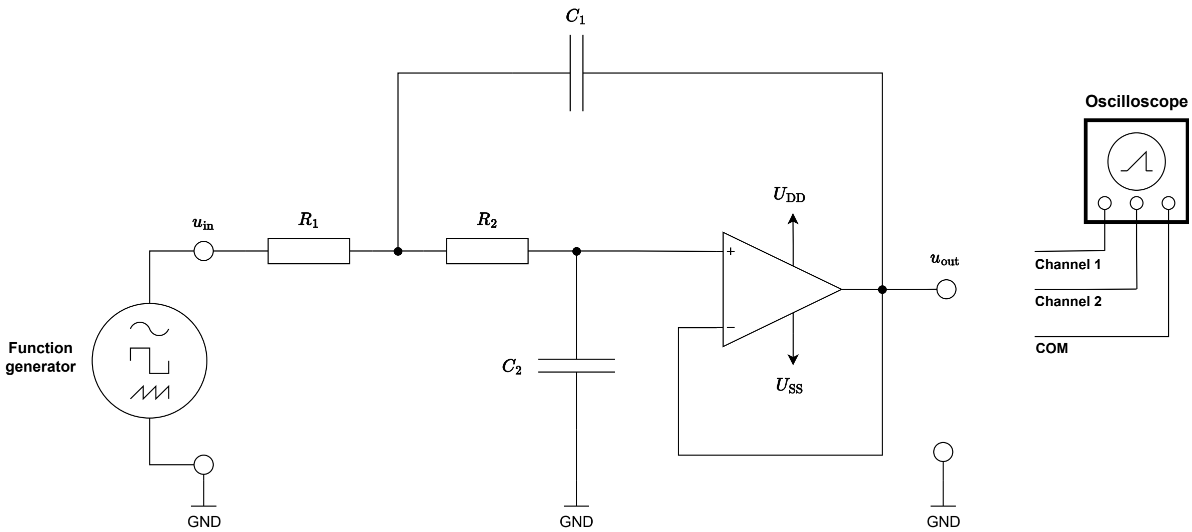

Fig. 10: Non-inverting Op-Amp: Sallen-Key Low-pass filter

$$U_{\rm DD} = 10\ {\rm V},\ U_{\rm SS} = -10\ {\rm V},\ R_1 = 10\ {\rm k\Omega},\ {\rm C}_1 = 10\ {\rm nF},\ R_2 = 15\ {\rm k\Omega},\ C_2 = 4,7\ {\rm nF}$$

Complete the schematic and calcutlate the cut-off frequency of the given circuit.

$f_\mathrm{c} \ =$

What amplification of the filter circuit do you expect and why?

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Measure the values given in the table below.
Use the function generator with a sine wave of 6 V amplitude.
Plot the filter response on the logarithmic graph paper provided.

$\frac{f}{f_\mathrm{c}}$	0,2	0,4	0,6	0,8	1,0	2,0	4,0	6,0	8,0	10,0
$\frac{u_\mathrm{in}}{\mathrm{V}}$ *)	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0	6,0
u_out										

*) Sine wave

Tab. 3: Op-Amp as current source: Frequency Response Data