Block 21 — Op-Amp Basics

Student Group

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Learning objectives

After this 90-minute block, you can

- explain what an operational amplifier (op-amp) is **as a black-box voltage amplifier** with two inputs (inverting / non-inverting) and one output.
- correctly label and use the voltages $U_{\rm p}$, $U_{\rm m}$ and the **differential voltage** $U_{\rm D}$.
- state and apply the **basic equation** of the (idealized) op-amp.
- state and use the **golden rules** (ideal op-amp model)
- distinguish **open-loop gain** $A_{\rm D}=U_{\rm O}/U_{\rm D}$ from **closed-loop / circuit voltage gain** $A_{\rm V}=U_{\rm O}/U_{\rm I}$.
- explain what **feedback** is and clearly differentiate **negative feedback** (stabilizing) from **positive feedback** (reinforcing / potentially unstable).
- describe key **non-ideal** limitations of real op-amps at the qualitative level (finite gain, finite input resistance & bias currents, limited output swing and output current, nonzero output resistance).
- explain the difference between **bipolar** and **unipolar** op-amp power supply and what this implies for the possible output voltage range.

Preparation at Home

Well, again

- read through the present chapter and write down anything you did not understand.
- Also here, there are some clips for more clarification under 'Embedded resources' (check the text above/below, sometimes only part of the clip is interesting).

For checking your understanding please do the following exercises:

- …

90-minute plan

1. Warm-up (10 min):
    1. Hook: audio amplifier clipping example (undistorted vs overdriven waveform/spectrum) → why "ideal amplification" is not automatic.
    2. Recall: what does "amplify a voltage" mean? What would an ideal voltage amplifier look like (voltmeter at input, voltage source at output)?
2. Core concepts & derivations (55–60 min):
    1. Op-amp as a black box + symbols (10–15 min)
        1. Triangle symbol(s), inverting/non-inverting inputs, output, supply rails.
        2. Differential voltage definition $U_{\rm D}=U_{\rm p}-U_{\rm m}$.
    2. Ideal op-amp model (15 min)
        1. Basic equation $U_{\rm O}=A_{\rm D}U_{\rm D}$.

2. Golden rules; interpret each rule physically (input ≈ voltmeter, output ≈ ideal source).
   3. Real op-amp limits (10–15 min)
      1. Output saturation (rails / headroom), finite $A_{\rm D}$, small input currents, limited output current.
      2. Unipolar vs bipolar supply: output range and operating point.
   4. Feedback concept (15 min)
      1. Meaning of feedback; block diagram vs circuit diagram.
      2. Sign convention: positive vs negative feedback.
      3. Big idea: with negative feedback and large $A_{\rm D}$, the **closed-loop gain** becomes mostly set by the feedback network (introduce k and the result $A_{\rm V}\approx 1/k$ as the motivating target; details can be finished in later blocks if needed).
3. Practice (15–20 min):
   1. Quick symbol + sign drills: identify $U_{\rm p}$, $U_{\rm m}$, $U_{\rm D}$, and predict the direction of $U_{\rm O}$ change.
   2. "Golden rules" micro-exercises:
      1. Decide when you may set $U_{\rm p}\approx U_{\rm m}$ and $I_{\rm p}\approx I_{\rm m}\approx 0$.
   3. Feedback classification:
      1. Given a block diagram with $kU_{\rm O}$ fed back, classify as positive/negative feedback and state the qualitative consequence (stabilize vs runaway/oscillate).
4. Wrap-up (5 min):
   1. Summary box: basic equation, golden rules, open-loop vs closed-loop gain, feedback sign.
   2. Common pitfalls checklist (below).

Conceptual overview

1. Think of an op-amp as a **differential voltage sensor + powerful output stage**:
   1. it measures the difference $U_{\rm D}=U_{\rm p}-U_{\rm m}$,
   2. then tries to produce $U_{\rm O}=A_{\rm D}U_{\rm D}$.

1. The "magic" of op-amp circuits comes from **negative feedback**:
   1. with large $A_{\rm D}$, the circuit forces $U_{\rm D}$ to be (almost) zero in normal operation,
   2. so you can treat $U_{\rm p}\approx U_{\rm m}$ and $I_{\rm p}\approx I_{\rm m}\approx 0$ as powerful design rules,
   3. and the **external feedback network** determines the closed-loop behavior (gain, impedance, linearity).

1. Open-loop vs closed-loop is the key separation:
   1. **open-loop gain** $A_{\rm D}$ is huge but poorly controlled,
   2. **closed-loop gain** $A_{\rm V}$ is what we design to be stable, predictable, and useful.

1. Reality check:
   1. real op-amps are limited by supply rails, maximum output current, finite speed, and nonzero input/output resistances.
   2. choosing unipolar vs bipolar supply changes what "zero" and "negative output" even mean in the circuit.

Core content

Introductory example

Acoustic amplifiers, such as those found in mobile phones, laptops, or hi-fi systems, often exhibit an unpleasant characteristic when heavily amplified: the previously undistorted signal is no longer passed on as usual, but clatters. It is distorted in such a way that it no longer sounds pleasant.

For this purpose, you will find an acoustic example with pictures in figure 1 and figure 2 respectively. The bottom of each image shows the time course of the voltage output to a loudspeaker (x-axis: time, y-axis: frequency). The upper picture has three dimensions: It shows in color intensity which frequencies are used at which time. The frequencies in grey areas are not used. If a frequency is shown in red at one point in time, it has a relatively large amplitude.
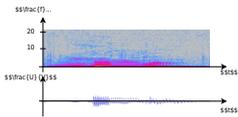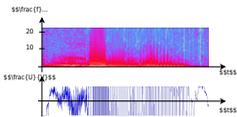
Fig. 1: undistorted signal

hallo.mp3

Fig. 2: overdriven signal

hallo_verzerrt.mp3

$$\frac{f}{...}$$

20
10

$$\frac{U}{V}$$

$$t$$

$$t$$

It can be seen that the distorted signal has large amplitudes in the time course of the voltage as well as a wide distribution of frequencies (= a broad spectrum).
The high frequencies in particular can promote wear of the diaphragm in loudspeakers.

The signal distortion is due to the design of the amplifier, which can only output the maximum possible voltage and otherwise clipping.
The structure of an acoustic amplifier is similar to that of a feedback operational amplifier, as seen in the simulation.

Acoustic amplifiers are usually constructed like operational amplifiers, which will be considered in the following chapters.

Circuit symbols and basic circuitry

This chapter deals with operational amplifiers. One application for these are the measurement of voltages, currents, and resistances.

These values must be determined very precisely in some applications, for example for accurate temperature measurement. In this case, amplification of the measurement signals is useful and necessary.

This amplification is done by measuring amplifiers. Measuring amplifiers have to fulfill some characteristics.
Measurement amplifiers should ..

- ... **not have any feedback effect** on the measured variable.
  An operational amplifier should have the highest possible input resistance. This prevents the voltage to be amplified from collapsing.

- ... have a **high sensitivity**.
  An operational amplifier should have a large differential gain $A_\rm D$.

- ... should show a **defined transmission behavior**, i.e. the output signal should be clearly related to the input signal.
  An operational amplifier concretely should show a linear relationship.

- ... show **good dynamic behavior**.
  The output signal of an operational amplifier should follow the input signal without any time delay.

- ... produce an **impressed output signal**.
  This means that the components at the amplifier output cannot change the output signal.
  An operational amplifier, specifically, should be able to maintain the desired output signal with the necessary current to do so.
  Since the current $I_\rm O$ can become very large (by electronic standards), this means that an operational amplifier must have a low output resistance $R_{\rm O} =\frac{U_{\rm O}}{I_{\rm O}}$.

Fig. 3: Equivalent circuit diagram of an amplifier
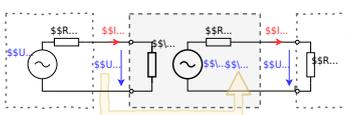
In general, an operational amplifier can be interpreted as a blackbox as in figure 3.
The real interieur is quiet complex and needs an understanding of the transistor, as shown in the

Architecture of the "simple" uA741.

Therefore, these chapter only focusses on the blackbox interpretation.

The circuit symbol of the amplifier is an isosceles triangle, at the apex of which the output signal originates and at the base of which the input signal enters.
In figure 4 you can see different circuit symbols:

Fig. 4: Circuit Symbols of Amplifiers

$$U_\rm I$$ $$U_\rm O$$ $$U_\rm m$$ $$\infty$$ $$U_\rm p$$ $$U_\rm O$$

(1) (2)

$$U_\rm n$$ $$U_\rm n$$ $$U_{\rm sp}$$
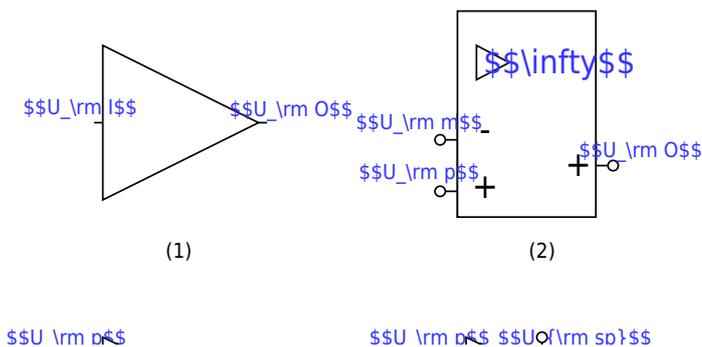
- Circuit symbol (1):
  In block diagrams (not to be confused with circuit diagrams) this circuit symbol is used for general amplifiers. In block diagrams in interaction from an output back to the input exist, except there is an explicit path shown.

- Circuit symbol (2):
 According to DIN EN 60617, this circuit diagram is to be used for operational amplifiers. It indicates with the infinity sign the ideally infinitely high amplification. in the following this symbol is not used, because it is not used in all international circuits and tools.

- Circuit symbol (3):
  The circuit symbol (3) is the most commonly used symbol for an operational amplifier. On the left is the **inverting input** with voltage $U_{\rm m}$ (minus) and the **non-inverting input** with $U_{\rm p}$ (plus). The output with voltage $U_{\rm O}$ is shown on the right.

- Circuit symbol (4):
  The circuit symbol (4) is additionally drawn with the supply voltages $U_{\rm sp}$ (supply plus) and $U_{\rm sm}$ (supply minus). Power is provided from the supply for the output voltage of the operational amplifier.

- Circuit symbols (5) and (6):
  these symbols show **no** operational amplifier. These symbols show the NOT gate and the tri-state gate. Unfortunately, the representation of these digital components in various circuits is not unlike the operational amplifier. An example of this is the transceivers[1] SP3481 or SP3485. If digital input values are considered, assuming that the circuit symbol does not represent an operational amplifier.

Notice: opamp input

Fig. 5: Voltages at the operational amplifier
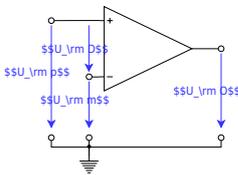
The inputs of the operational amplifier are designated as **inverting input** $U_\rm m$ and **non-inverting input** $U_\rm p$.

The voltage $U_{\rm D} = U_{\rm p} - U_{\rm m}$ is called the differential voltage (see figure 5).

Basic Equation / Golden Rules

The operational amplifier is a voltage amplifier. It simply measures on one side the voltage (like a voltmeter) and provides an amplified voltage on its output (like a voltage source).
Thus, for the ideal case, the input resistance must be infinite (like for a voltmeter) and the output resistance $R_{\rm O}=0$ (like for a voltage source).

The figure 6 shows an ideal voltage amplifier.
This is characterized by the following properties:

- **Input resistance**:
  The input side is drawn in the figure.
  The resistance given here is the differential resistance $R_{\rm D}$ where the differential voltage $U_{\rm D}$ drops.
  Therefore, $R_{\rm D} \rightarrow \infty$ is valid. Thus, the input currents $I_\rm p \rightarrow 0$ and $I_\rm m \rightarrow 0$.

- **Output resistance**, **Basic equation**:
  On the output side, $R_\rm O=0$ gives that $U_{\rm O} = A_{\rm D}\cdot U_\rm D$.

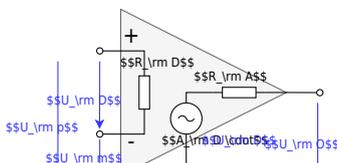This is the basic equation of the amplifier circuit.
Ideally, the op-amp amplifies linearly, as indicated in the equation. Specifically, for a differential voltage of $0 ~\rm V$, the output voltage is $0 ~\rm V$.

- **Differential Gain**:
  $A_\rm D$ is very large.
  Ideally, the following applies: $A_ \rm D \rightarrow \infty$

Fig. 6: Operational amplifier equivalent circuit

Remember: basic equation and golden rules

1. The output voltage depends on the differential voltage via the differential gain: $U_{\rm O} = A_{\rm D} \cdot U_\rm D$.
   This is the **basic equation** of the amplifier circuit.
2. The **golden rules** of the ideal amplifier are:
   1. The differential gain goes to infinity: $A_\rm D \rightarrow \infty$
   2. The input resistance goes to infinity: $R_\rm D \rightarrow \infty$
   3. The output resistance is 0: $R_\rm O = 0$

In figure 7 a simulation of an ideal amplifier is shown. The input source specifies the voltage to be amplified.
The idealized amplifier with an differential gain of 400'000 has the connections for input and output voltage are drawn in. On the right side, a resistor is provided as load; this can be varied via a switch.

Fig. 7: Ideal Amplifier

In the simulation some characteristics of an amplifier can be seen:

1. Ideally, no current flows into the amplifier on the input side.
2. The current on the output side depends on the connected load. If the load resistance is reduced with the help of the switch, the current increases. The amplifier thus tries to maintain the desired voltage.
3. On the output side of the amplifier, the current can flow in either direction.
   The amplifier adjusts the current so that the amplified voltage $U_A=\pm 4.0~\rm V$ can be measured at the output.

Real operational amplifier

These rules have different limits in the real amplifier:

- Output voltage $\boldsymbol{U_{\rm O} = A_{\rm D} \cdot U_{\rm D}}$:
  - The output voltage can only follow the input voltage as far as the power supply allows.
    In real operational amplifiers, only so-called **rail-to-rail** operational amplifiers can exploit the range down to a few $100~\rm mV$ to $U_\rm S$.
    Other operational amplifiers have an **output limit**, which is $1 \ldots 2~\rm V$ below the supply voltage.
  - If the supply voltages are not symmetrical ($U_{\rm sm} \neq -U_{\rm sp}$), then the characteristic also shifts.
  - The ideal operational amplifier produces the same output voltage $U_{\rm O}=A_{\rm D} \cdot U_{\rm D}$ as long as $U_{\rm D} = U_{\rm p} - U_{\rm m}$ is the same.
    For the real operational amplifier with fixed $A_{\rm D}$, output voltage $U_{\rm O1}$ for $U_{\rm D1}=5~\rm V - 4.9~V$ is different from $U_{\rm O2}$ for $U_{\rm D2}=0.1~\rm V - 0~V$.

- Differential gain $\boldsymbol{A_\rm D}$:
  The differential gain is usually between $A_\rm D = 20'000 \ldots 400'000$.

- Input resistance $\boldsymbol{R_\rm D}$:
  For real operational amplifiers, the input resistance $R_\rm I > 1 M\Omega$ and the input current $|I_\rm p|$ or $|I_\rm m|$ is less than $1~\rm µA$.

- Output resistance $\boldsymbol{R_\rm O}$:
  In real operational amplifiers, the output resistance $R_\rm O$ is usually a few Ω and limited by a maximum current (in the range of a few tens of $\rm mA$ to a few $\rm A$)

The simulation shows a **(simulated) real amplifier**. The input source has a high internal resistance. This means it has a high impedance and can only supply a small amount of current.
The amplifier with a differential gain of 400'000 has - besides the connections for input and output voltage - also connections for the supply voltage drawn in.
On the right side, a resistor is provided as load; this can be varied via a switch.

In the simulation some properties of an amplifier can be seen:

1. On the input side, a small current flows into the amplifier.
2. The current on the output side depends on the connected load. If the load resistance is reduced with the help of the switch, the current increases.
   The amplifier thus tries to maintain the desired voltage.
3. The amplifier can output current as well as absorb current.
   The current on the output side flows in and out of the amplifier through the supply voltage connections.
4. The simulation is based on a real amplifier. This has a small deviation from the expected value $U_{\rm O}=\pm 4.0~\rm V$ at the output voltage.

Voltage Supply of the Operational Amplifier

The op-amp needs an additional voltage supply to be able to actively output more power.
This two supplies are also called **rails**. In general, the rails are drawn on top and on below the triangular shape of the op-amp.

For the voltage supply of the operational amplifier, a distinction is made between unipolar and bipolar:

With the **bipolar voltage supply**, the same voltage levels but with different signs are applied to both supply terminals in terms of magnitude.
This allows the output voltage $U_{\rm O}$ of the amplifier to point in either direction.
The power supply must be designed in such a way that it can provide both voltages. A differential voltage of $U_{\rm D}=0$ also results in an output voltage of $U_{\rm O}=0$.

With the **unipolar power supply**, the negative supply terminal is connected to the ground.
As a result, the output voltage $U_{\rm O}$ of the amplifier can only take on non-negative values.
In this case, the supply can be provided by a single voltage source (e.g., a battery).
With a differential voltage of $U_\rm D=0$, the output voltage is $U_{\rm O}=\frac{1}{2}\cdot U_{\rm sp}$.

The op-amps in the simulation replicate real op-amps in some respects: The differential gain is $A_\rm D = 100'000$.
The transfer characteristics $U_{\rm O}(U_\rm D)$ show proportional behavior only when the output value is smaller in magnitude than the supply voltage $|U_{\rm sp}|=|U_{\rm sm}|=5~\rm V$ (not shown).
The modulation limits and the differential gain can be changed in the simulation via "Edit component" (double click).

Fig. 8: unipolar and bipolar supply

Feedback

One of the fundamental principles of control engineering, digital technology, and electronics is **feedback**.
A feedback is given when the output value of a system is routed back as to its input.
Here, the output voltage of the operational amplifier fed back to the input.

In addition, there is another tool for control engineering, digital systems, and electronics: the **block diagram** or signal flow diagram.

Up to now, only circuit diagrams have been used so far. With circuit diagrams there is an interaction of all components due to Kirchhoff's rules.

Furthermore, voltage differences or current can be measured over all components.

The block diagram is different. It shows individual blocks linked into a chain of cause-and-effect. In general, no reaction of the effect on the cause is assumed. Causes and effects can be voltages or currents, which are then written on the respective connecting arrow.

The block diagram does not claim to conserve energy or charge but serves to provide an overview of the effects and interrelationships. Thus Kirchhoff's rules are usually not applicable there.

figure 9 shows a block diagram of a feedback amplifier consisting of an ideal voltage amplifier with differential gain $A_\rm D$ drawn in the center. The output voltage $U_\rm O$, reduced by the factor k, is fed back via a feedback element. The circle symbol with the arithmetic symbols (in the block diagram on the left) shows how the incoming values must be offset against each other. The value $k \cdot U_\rm O$ is thus subtracted from the input value $U_\rm I$ in the indicated block diagram.

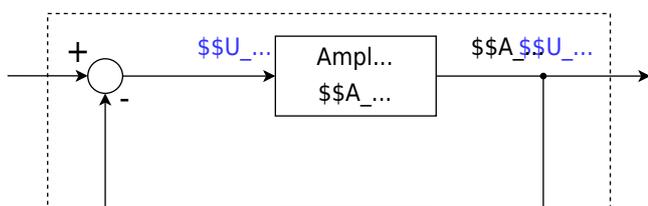Fig. 9: Block diagram of an amplifier with feedback

Fig. 8: unipolar and bipolar supply

There is a big advantage of a real amplifier in negative feedback:
The voltage gain $A_\rm V$ of the whole system depends in this case only negligibly on the differential gain $A_\rm D$ (assuming $A_\rm D$ is very large).

In this case, the voltage gain is:

$$A_{\rm V}=\frac {1}{k + \frac {1}{A_{\rm D}}} $$

$$\boxed{ A_{\rm V}=\frac {1}{k} \quad \Bigg|_{A_{\rm D} \rightarrow \infty} }$$

To avoid oscillation of the whole system, the amplifier must contain a delay element.
This is present in the real amplifier in such a way that the output voltage $U_\rm O$ cannot change infinitely fast. [2].

Note: feedback, positive feedback, negative feedback

Feedback (German: **Rückkopplung**) refers to the return of part of the output signal of an amplifier.

With **positive feedback** (German: **Mitkopplung**), output signal is partially routed back with a positive sign.
The output value $U_{\rm O}$ therefore always increases the input value $U_{\rm D}$.

With **negative feedback** (German: **Gegenkopplung**), output signal is partially routed back with a negative sign.
The output value $U_{\rm O}$ therefore always attenuates the input value $U_{\rm D}$.

Note: Gain factors

The **differential gain** or **open-loop gain** $\boldsymbol{A_\rm D}$ (German: Differenzverstärkung) refers only to the input and output voltage of the inner amplifier: $$A_{\rm D}=\frac{U_\rm O}{U_\rm D}$$ This gain is the amplification without external feedback.
It is also called open-loop gain.

The **voltage gain** $\boldsymbol{A_\rm V}$ refers to the input and output voltage of the whole circuit with feedback: $$A_{\rm V}=\frac{U_\rm O}{U_\rm I}$$ It is also called closed-loop gain.

[1] transmitter and receiver, meaning transmitter-receiver, or interface adapter
[2] That a voltage change can only take place in a finitely long time is also true for the input voltage. However, this cannot be influenced by the amplifier, but is

externally specified.

Common pitfalls

- **Mixing up the inputs:** confusing the inverting input $U_{\rm m}$ (minus) with the non-inverting input $U_{\rm p}$ (plus). A wrong sign flips the whole behavior.
- **Wrong differential voltage:** forgetting that $U_{\rm D} = U_{\rm p} - U_{\rm m}$.
- **Using the golden rules outside their valid context:**
    1. $U_{\rm p} \approx U_{\rm m}$ is only justified when the op-amp is in **linear operation** with **negative feedback** and not saturated.
    2. $I_{\rm p} \approx I_{\rm m} \approx 0$ is an idealization; real input bias currents may matter in high-impedance circuits.
- **Assuming unlimited output voltage:** the output is limited by the **supply rails** (and headroom). Once saturated, linear equations break.
- **Confusing open-loop and closed-loop gain:** $A_{\rm D}$ (open-loop) is huge and device-dependent; $A_{\rm V}$ (closed-loop) is what the feedback network sets.
- **Ignoring supply type:** unipolar supply does **not** allow negative output voltages (without a mid-supply reference). Many textbook sketches silently assume bipolar rails.
- **Assuming unlimited output current:** real op-amps have output current limits; too-small load resistance causes clipping/distortion.
- **Treating block diagrams like circuit diagrams:** block diagrams show cause–effect; Kirchhoff's laws do not automatically apply inside blocks.
- **Misclassifying feedback sign:** feeding output to the inverting input is typically **negative feedback**, while to the non-inverting input is typically **positive feedback** (depending on the network).

Learning Questions

- Explain the difference between the unipolar and bipolar power supply of an opamp.
- Draw a sketch for bipolar and one for unipolar power supply.
- What are the advantages and disadvantages of unipolar and bipolar supply in opamp?
- What are the golden rules?
- What is the basic equation of the opamp?

Exercises

Exercise 1.3.2 Calculations for negative feedback

Fig. 11: Block diagram of a feedback amplifier
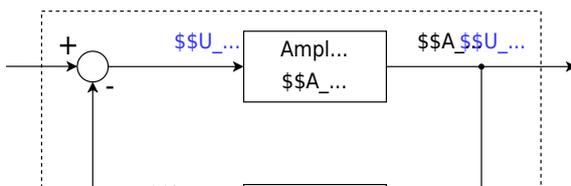
For the principle of negative feedback, the adjacent block diagram was given in the script. Here $A_\rm D$ is the so-called differential gain, i.e. the gain of the difference between the input voltage $U_\rm I$ and the feedback voltage.

1. Derive the voltage gain $A_\rm V$ as a function of the differential gain $A_\rm D$ and the feedback factor k. Note that $A_{\rm V} = {{U_\rm O}\over{U_\rm I}} = f(A_{\rm D}, k)$ and give the derivation.
2. What is the voltage gain $A_\rm V$ for an ideal differential gain ($A_\rm D \rightarrow \infty$)?
3. Find the voltage gain $A_\rm V$ for feedback $k = 0.001$ with differential gain $A_{\rm D1} = 100'000$ and $A_{\rm D2} = 200'000$.
   Real differential amplifiers, more precisely operational amplifiers, are considered in more detail in Chapter 3. Two operational amplifiers of the same type can have noticeably different values in the differential gain, e.g., due to specimen scattering, aging, or temperature drift.
   Looking at the result from $A_{\rm D1}$ and $A_{\rm D2}$, what can be said about such a variation of a large differential gain value by, say, $50~\%$?
4. State how the voltage gain behaves for the following feedback parameter k with an ideal differential gain and correctly assign the following statements (some are not needed, some are needed more than once):
   (A) Positive feedback,
   (B) Negative feedback,
   (C) Damping,
   (D) gain,

(E) voltage gain equals open-loop gain,
(F) $U_{\rm O} = U_{\rm I}$,
(G) $U_{\rm O} = - U_{\rm I}$,
(H) gain equal 0.

1. $k < -0$
2. $k = 0$
3. $0 < k < 1$
4. $k = 1$
5. $k > 1$

Exercise 21.1 — Op-amp basics: symbols and signs

- Given an operational amplifier symbol, label the following quantities:
    1. non-inverting input voltage $U_{\rm p}$,
    2. inverting input voltage $U_{\rm m}$,
    3. output voltage $U_{\rm O}$,
    4. (if present) the supply voltages $U_{\rm sp}$ and $U_{\rm sm}$.

- For each case below, state whether the output voltage $U_{\rm O}$ initially moves **upwards** or **downwards** (assume linear operation):
    1. $U_{\rm p}$ increases slightly over $U_{\rm m}$.
    2. $U_{\rm m}$ increases slightly over $U_{\rm p}$.
    3. $U_{\rm p} = U_{\rm m}$.

- Compute the differential voltage: $U_{\rm D}$ for $U_{\rm p} = 2.1\,\rm V$ and $U_{\rm m} = 2.0\,\rm V$.

- Using a differential gain of $A_{\rm D} = 200{'}000$, compute the **ideal** output voltage $U_{\rm O}$.
- Explain briefly why this output voltage cannot be realized in practice when the op-amp is powered from supply rails of $\pm 5\,\rm V$.

Exercise 21.2 — Differential vs single-ended thinking

An op-amp has $A_{\rm D}=150{'}000$ and is powered from $\pm 12\,\rm V$.

1. Compute $U_{\rm O}$ for $U_{\rm p}=1.002\,\rm V$ and $U_{\rm m}=1.000\,\rm V$ (ideal equation).
2. Decide whether the result is physically possible.
3. Explain why even very small differences between $U_{\rm p}$ and $U_{\rm m}$ are sufficient to drive the output into saturation in open-loop operation.

Exercise 21.3 — Unipolar supply and output biasing

An op-amp operates from a unipolar supply $0\,\rm V$ to $9\,\rm V$.

1. What output voltage corresponds to "zero differential input" in a typical unipolar configuration?
2. Why is this value often chosen close to $U_{\rm S}/2$?

3. Describe one practical consequence if the output is biased too close to one supply rail.

Exercise 21.4 — Unipolar supply and virtual ground intuition

An op-amp uses a unipolar supply $0\,\rm V \dots 10\,\rm V$.
If you want to amplify a small sinus signal centered around $0\,\rm V$, why is it a problem to connect it directly to an input?

Exercise 21.5 — Classify feedback (fast diagnosis)

- For each statement, mark **true/false** and correct the false ones:
    1. Feeding back a fraction of the output to the inverting input always creates negative feedback.
    2. With negative feedback and large $A_{\rm D}$, the op-amp tends to keep $U_{\rm D}$ close to 0.
    3. Positive feedback generally stabilizes the operating point and improves linearity.
    4. If the output is saturated at a rail, $U_{\rm p} \approx U_{\rm m}$ must still be true.
- For each configuration below, classify the feedback as positive or negative (assume resistive feedback networks):
    1. Output fed through a divider to $U_{\rm m}$, $U_{\rm p}$ driven by the input source.
    2. Output fed through a divider to $U_{\rm p}$, $U_{\rm m}$ driven by the input source.

Exercise 21.6 — Saturation and clipping reasoning

An op-amp is powered from $\pm 5\,\rm V$ (bipolar). The output swing is limited to about $\pm 4\,\rm V$.

1. If $U_{\rm D}=+50\,\mu\rm V$ and $A_{\rm D}=200{,}000$, compute the ideal $U_{\rm O}$. Is saturation expected?
2. Repeat for $U_{\rm D}=+10\,\rm mV$.
3. Explain in one sentence why clipping produces distortion in audio signals.

Exercise 21.7 — Input bias currents (qualitative + estimate)

A sensor with source resistance $R_{\rm S}=1\,\rm M\Omega$ drives the non-inverting input.
The real op-amp dows not only show an internal resistance, but also a small current source on the input pins.
This input bias current is in this exercise $I_{\rm B}=200\,\rm nA$.

1. Estimate the voltage error at the input caused by $I_{\rm B}$ flowing through $R_{\rm S}$.
2. Explain when such an error matters and when it is negligible.

Exercise 21.8 — Output current limit and load selection

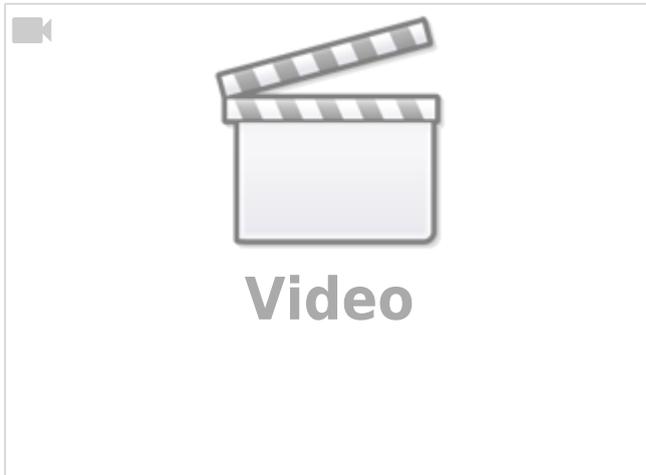A real op-amp can supply at most $I_{\rm O,max}=20\,\rm mA$.

It is intended to drive a load resistor $R_{\rm L}$ from an output voltage of $U_{\rm O}=3\,\rm V$.

1. What is the minimum $R_{\rm L}$ to avoid exceeding the output current limit?
2. If $R_{\rm L}$ is smaller than this value, what happens to the output waveform for a sine input?

Bonus: If the op-amp can also sink $20\,\rm mA$, does that change your answer to (a)?

Embedded resources

What is an operational amplifier?

From: