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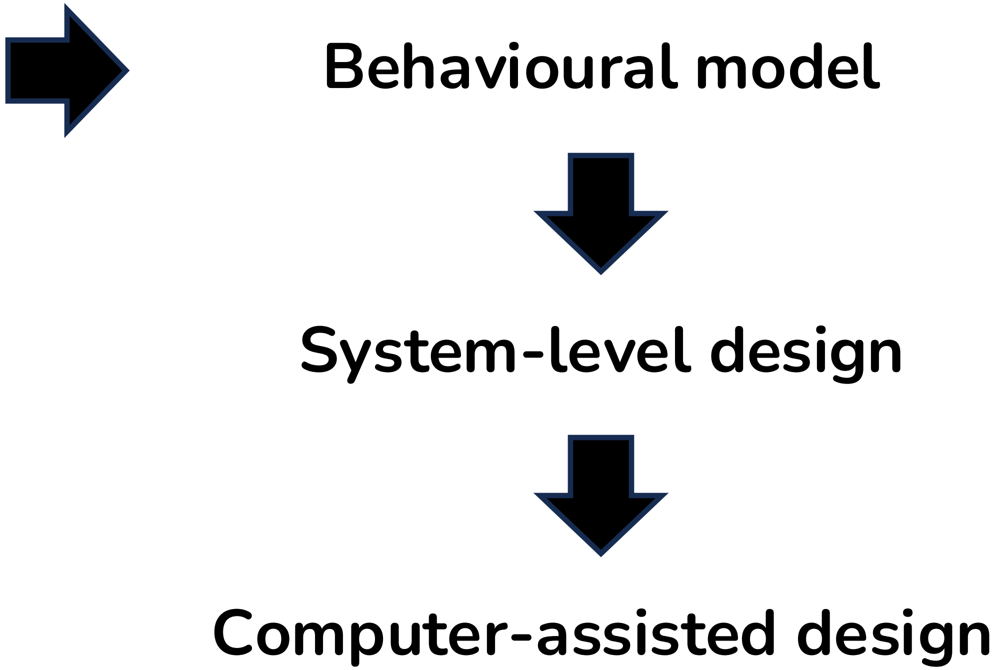
Test circuits – Measuring component specifications

Lecture #5
Electronic measurements
Alessandro Pozzebon

Electronic Components Testing

- **Component specifications**
  - Performances
  - Power consumption
  - Operating limits
- **Digital circuits**
  - Boolean algebra
- **Analog circuits**
  - Blocks model



Behavioural model

System-level design

Computer-assisted design

Electronic Components Testing

- **Measurements** ➡ **Extract relevant component data**

- **Specifications** (maximum and minimum values)

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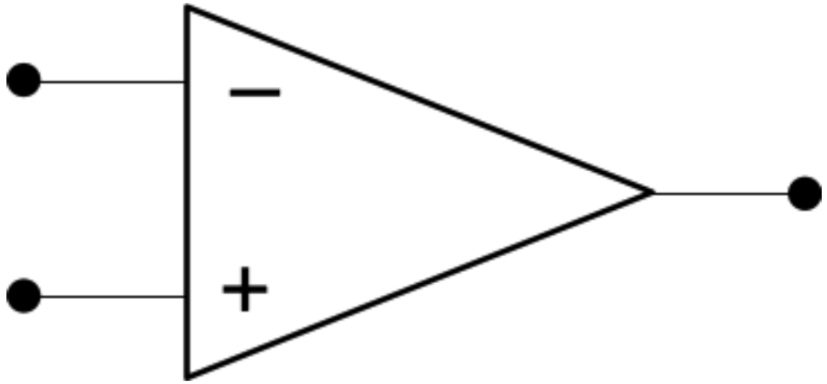
- Results of measurements

- Test circuits:
    - Create suitable operating conditions for the **Device Under Test (DUT)**
    - Enable test signals to be accurately measured

Operational Amplifier

- Single, ground-referenced output and two differential inputs called, respectively, inverting (–) and non-inverting (+) inputs



- **Voltage gain** is infinite (very large in practice, order of 10^5 or more)
- **Input impedance** is infinite (order of 10^8 Ω)
- **Output impedance** is null (a few Ω in practice)

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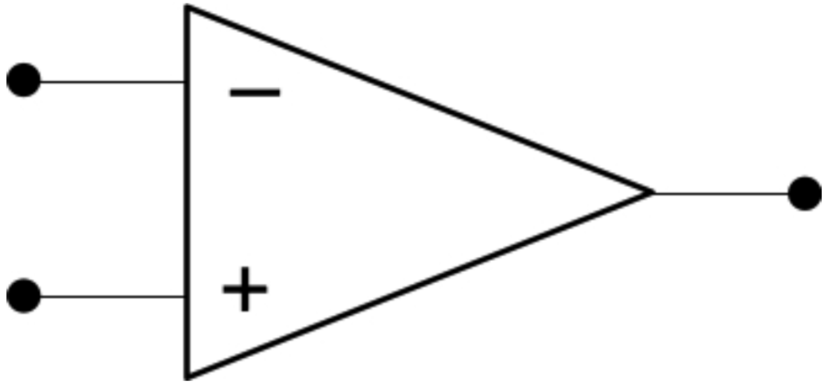
Operational Amplifier

- **Current drawn by the inputs** is zero, since input impedance is infinite
- Since output voltage must be finite and voltage gain is close to infinite, the **two inputs** may be assumed to be equipotential for most practical purposes
- Any intensity of **output current** can be obtained, since output impedance is negligible



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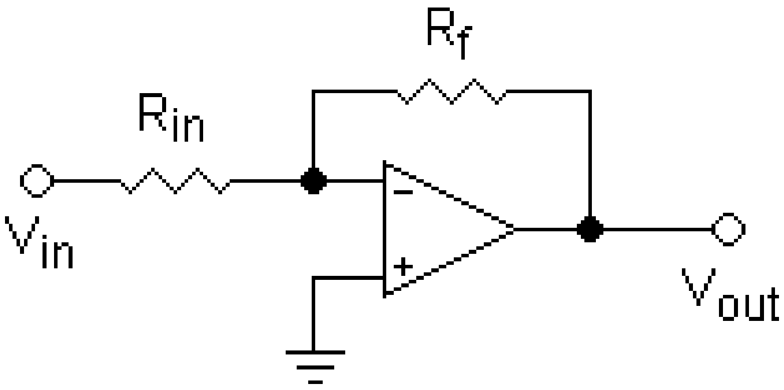
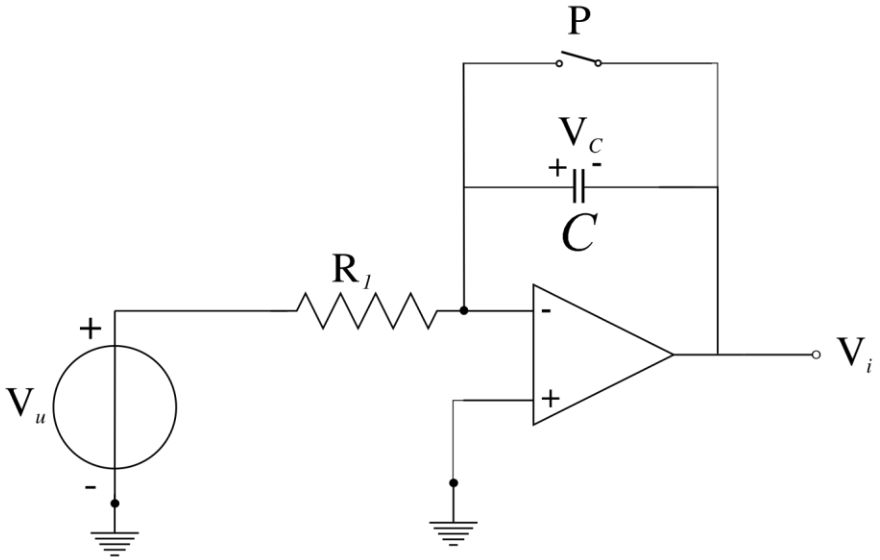
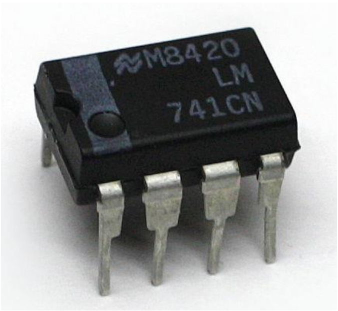
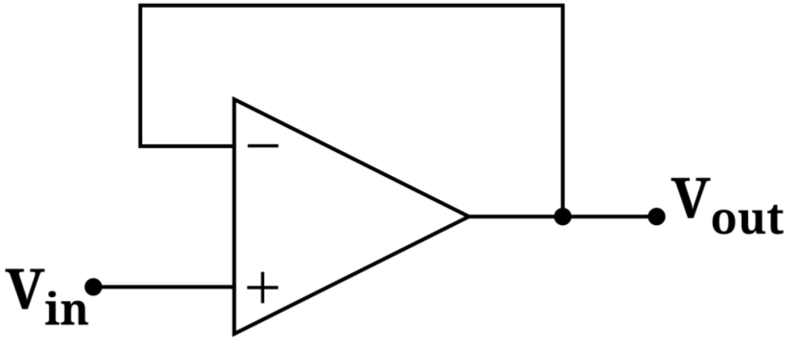
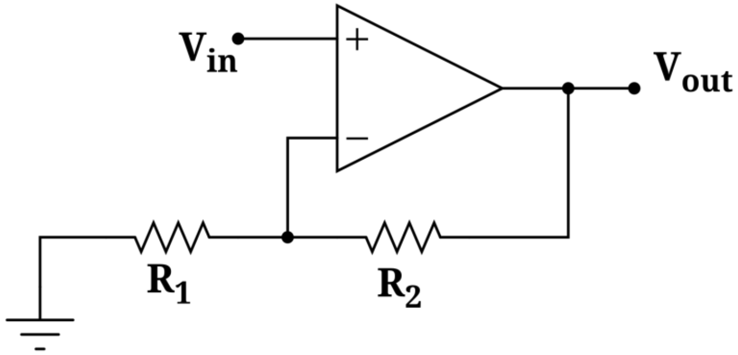
Operational Amplifier





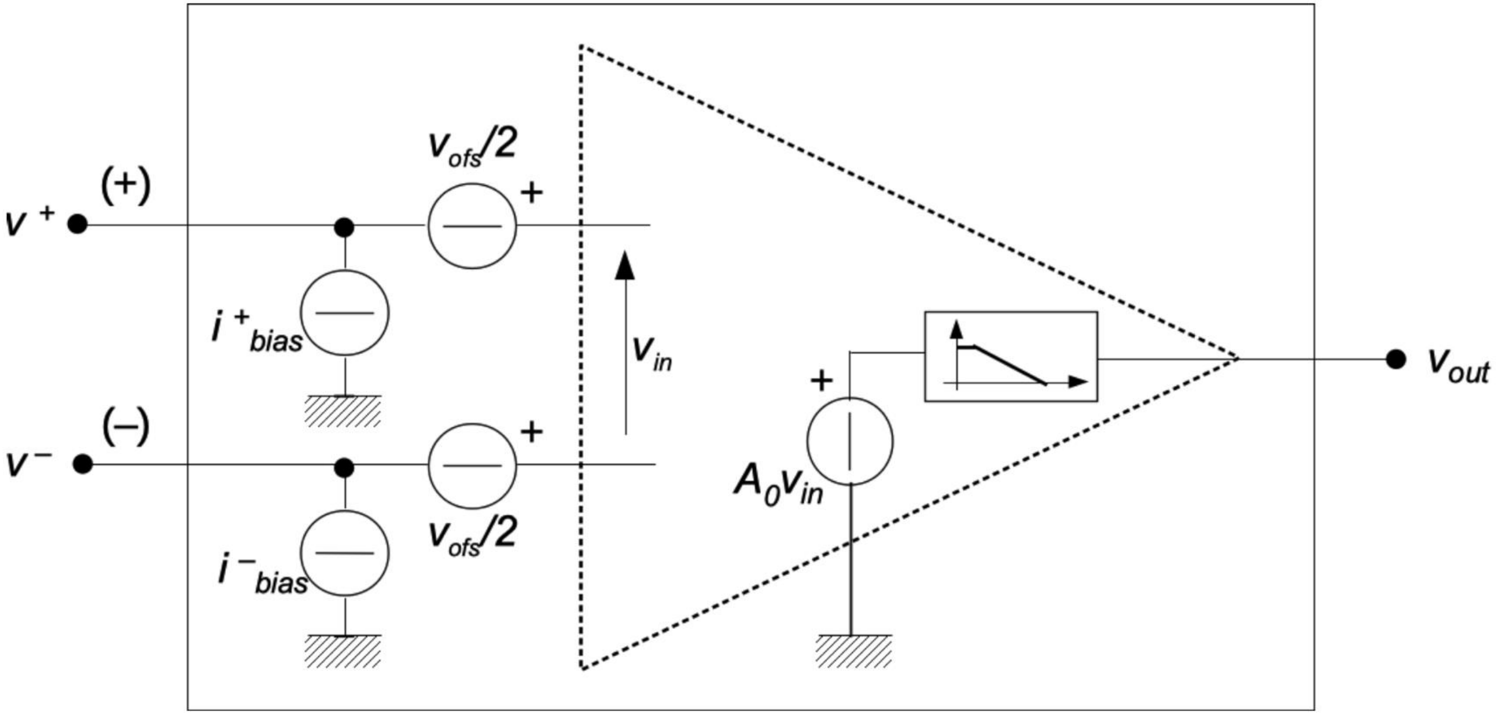






Real operational amplifier

- **Voltage sources** at the input → OpAmp **offset voltage**
- **Current sources** at the input → **Bias currents** through the input terminals
- Voltage-controlled **voltage source** → **Finite gain**
- **Frequency-dependent block** → Low-frequency pole → **Frequency response**



SPICE macromodel

Operational Amplifier Measurements

- **Extremely high gain**

Difficult to be measured due to the very large difference between input and output voltage levels

Suitable feedback configurations

Effects of the test circuit on the measured device

- **Open-loop gain**

$$G_{ol}(f) = \frac{A_0}{1 + j2\pi f T_1}$$

- A_0 DC gain
- T_1 low frequency pole time constant

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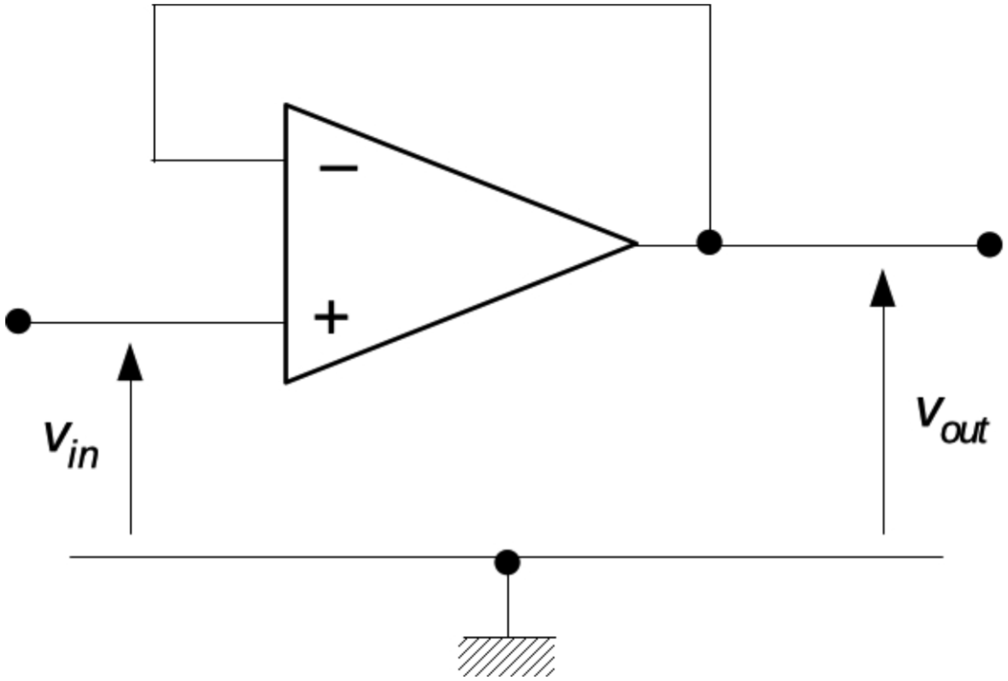
Unit-gain bandwidth

- **Voltage-follower configuration**

$$G_{vf}(f) = \frac{G_{ol}(f)}{1 + G_{ol}(f)} \cong \frac{1}{1 + j2\pi f \frac{T_1}{A_0}} =$$

$$= \frac{1}{1 + j\frac{f}{f_T}}$$

$$f_T = \frac{A_0}{2\pi T_1} = A_0 f_{ol}$$

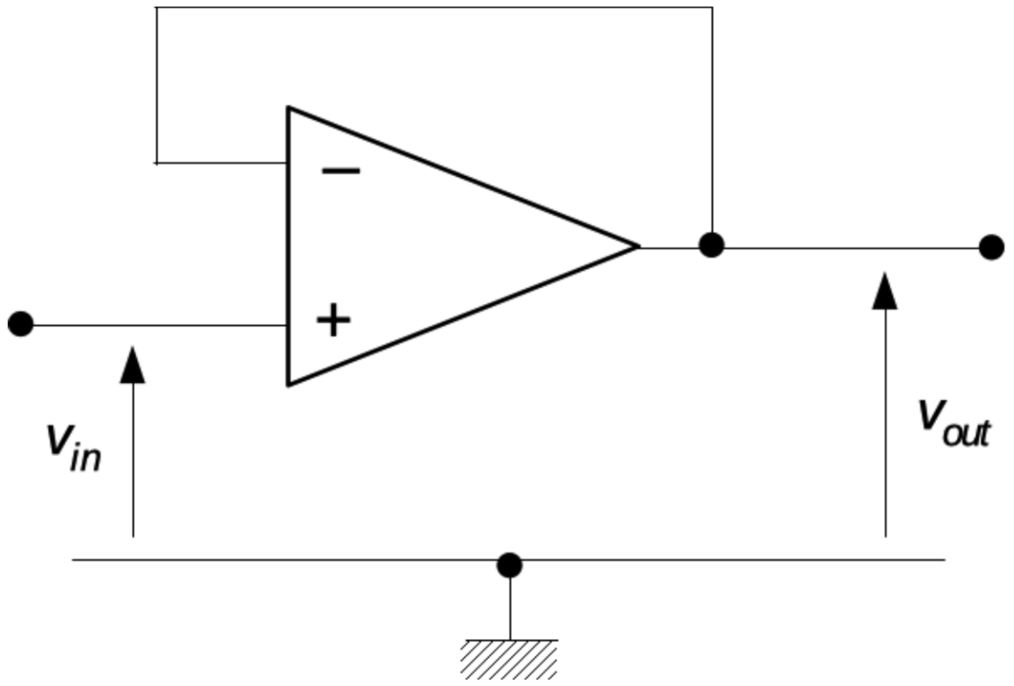


- f_{ol} **unit-gain bandwidth**
  - Typically, in the order of MHz

Unit-gain bandwidth measurement

- Frequency at which measured gain is 3 dB less than DC gain
- DC gain = 1
- Ratio of output to input voltage = $\frac{1}{\sqrt{2}} \cong 0.707$

- **Sinewave generator**
- **Two-channel oscilloscope** (voltage follower input and output)



Unit-gain bandwidth measurement

- Bias currents
- Voltage offsets

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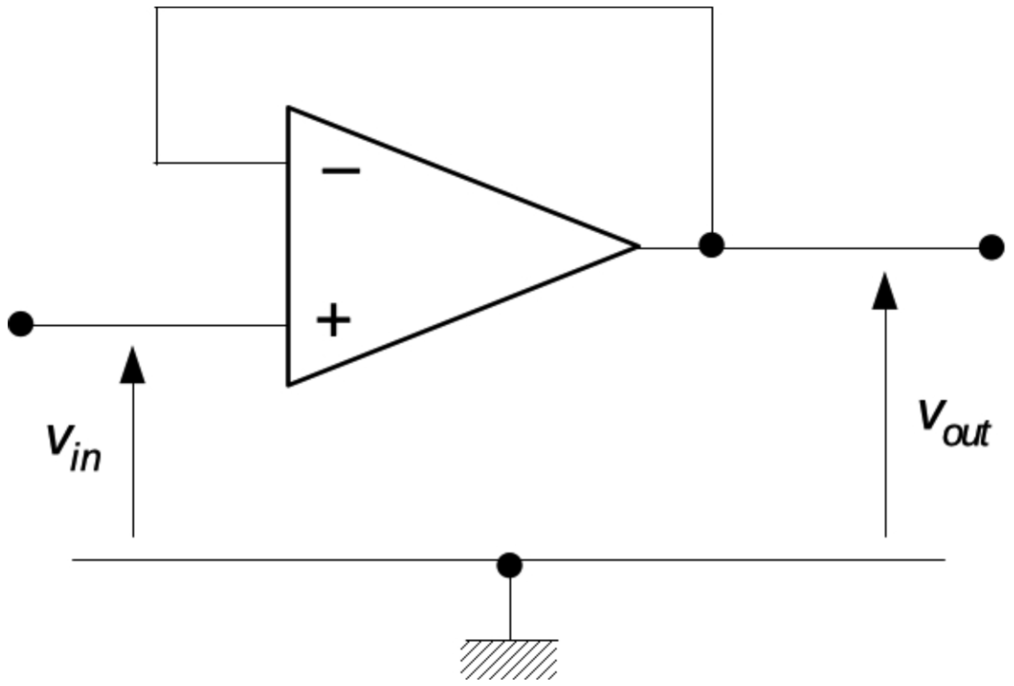
Significant output voltage offset

(non-zero mean value)

- Peak-to-peak or RMS voltage
- AC coupling (both channels)



Open-loop gain

- Input-output measurement with sinewave input at different frequencies

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High gain makes measurements hard

Input wave should be in the μV range

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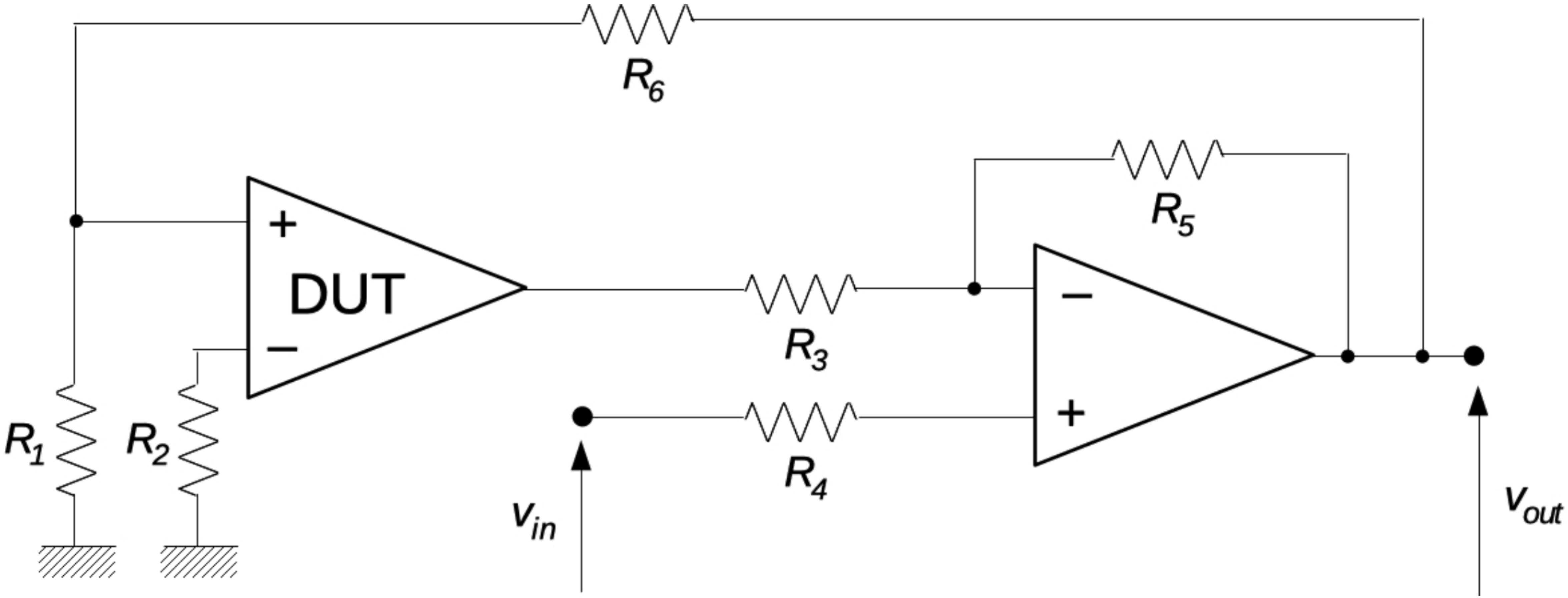
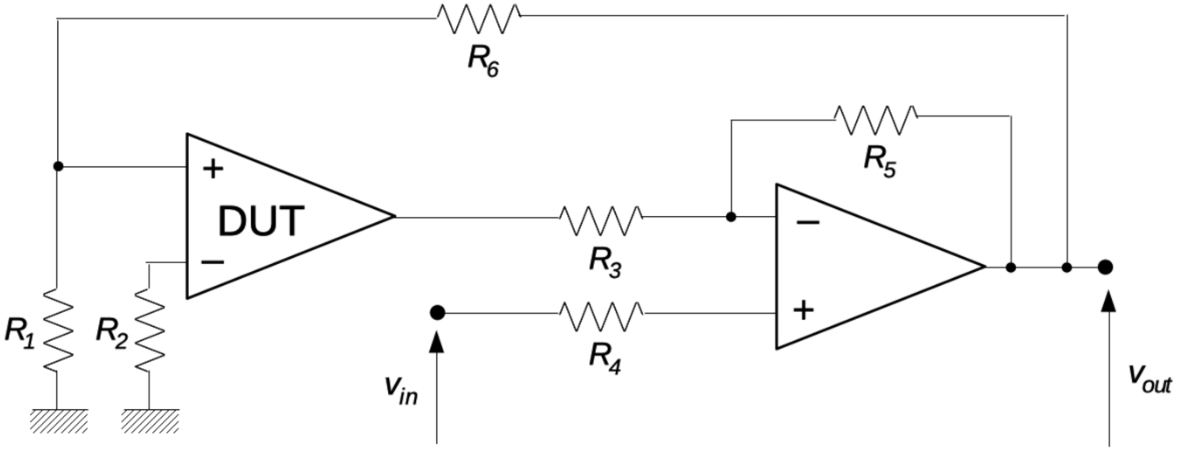
Feedback loop with an additional OpAmp

Open-loop gain measurement



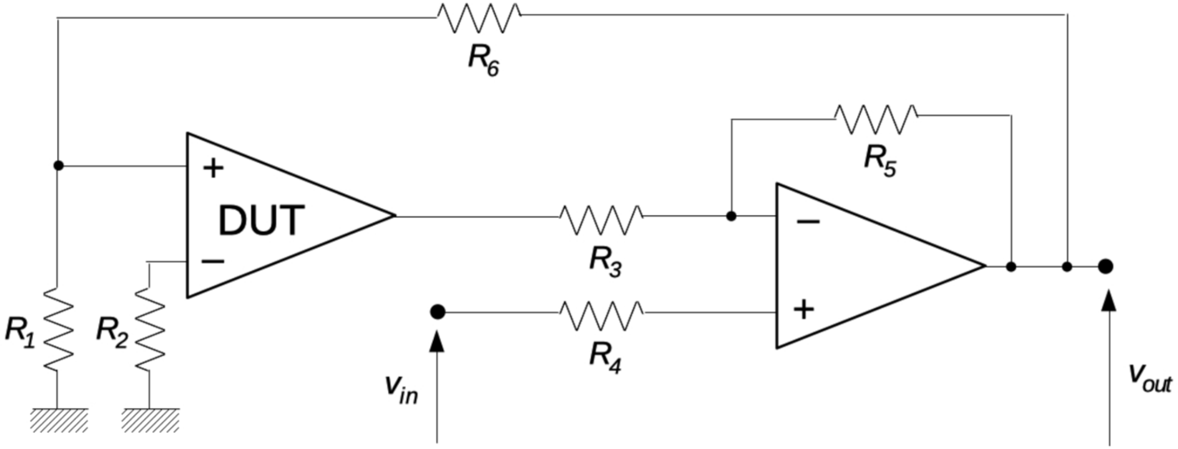
Open-loop gain measurement

- v_{in} sent to the auxiliary OpAmp non-inverting input through R_4
- DUT output to the inverting input through R_3
- $\boldsymbol{R_3 = R_4}$ to get a balanced differential input for the auxiliary OpAmp
- $\boldsymbol{R_1 = R_2}$ to balance the effect of the DUT bias currents



Open-loop gain measurement

- The inner feedback loop provides the gain
- $R_5 \gg R_3$
- The outer loop acts as a voltage divider to bring **a fraction of $\boldsymbol{v_{out}}$ to the non-inverting input** of DUT
- $v_{DUT_{in}} = v_{out}\frac{R_1}{R_1+R_6}$
- $\boldsymbol{R_6 \gg R_1}$



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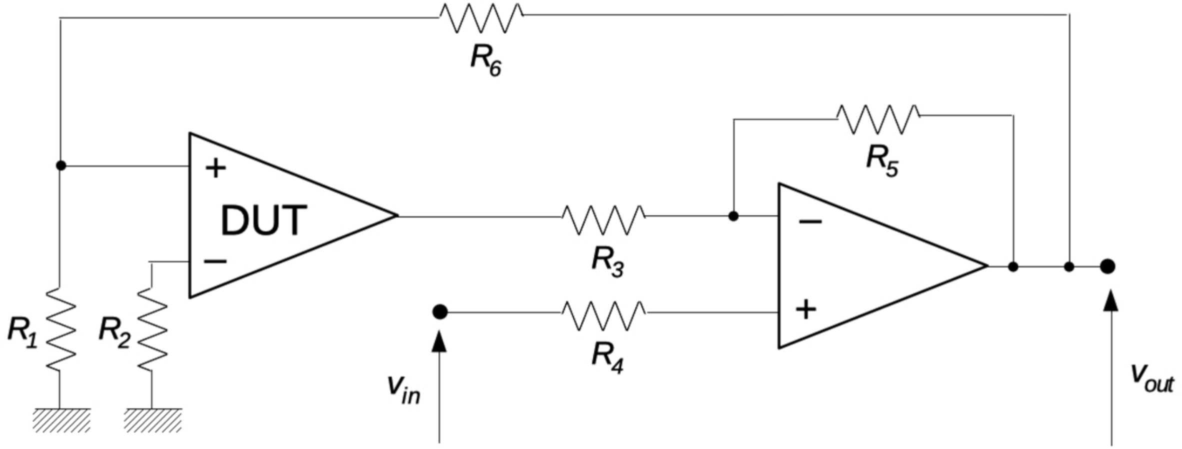
Open-loop gain measurement

- $v_{DUT_{out}} = v_{in}$
- DUT gain = $\frac{v_{DUT_{out}}}{v_{DUT_{in}}} = \frac{v_{in}}{v_{out}\frac{R_1}{R_1+R_6}}$
- Actual R_1 and R_6 values should be **measured**



R_1	R_2	R_3	R_4	R_5	R_6
47 Ω	47 Ω	100 Ω	100 Ω	47 kΩ	47 kΩ

Frequency Response

PROCEDURE

1. **Connect a power supply** to the test circuit and power it up
2. **Connect the waveform generator** to the test circuit and to an oscilloscope input channel, so that the test sinewave can be measured (using a 'T' coaxial connector). Set an appropriate waveform amplitude
3. Using a coaxial cable with suitable wire clips (or "banana" plugs), **acquire the test circuit output** and send it to an oscilloscope input channel
4. **Determine a set of frequencies** where the DUT gain is to be determined and repeat the measurement at each frequency

Frequency Response

TIPS

- **Low frequency pole**

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- **No AC coupling** (attenuation)

- **Noisy v_{out} signal**

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- **RMS(AC)** measurement function instead of peak-to-peak
- **Averaging** acquisition mode (Stable trigger)

Gain and Phase Shift

Measurement outputs

- Amplitude of the test circuit input sinewave v_{in}
- Amplitude of the test circuit output sinewave v_{out}
- Delay τ of the output sinewave from the input sinewave

DUT GAIN

$$G[\mathrm{dB}] = 20\log_{10}\frac{v_{in}}{v_{out}\dfrac{R_1}{R_1+R_6}}$$

DUT PHASE

$$\Delta\phi = -\tau\cdot 2\pi[\mathrm{rad}] = -\tau\cdot 360[\mathrm{degrees}]$$

- Test circuit input corresponds to the DUT output, while test circuit output provides the DUT input

Test circuit analysis

Limitations

- Deviations from nominal **resistance values**

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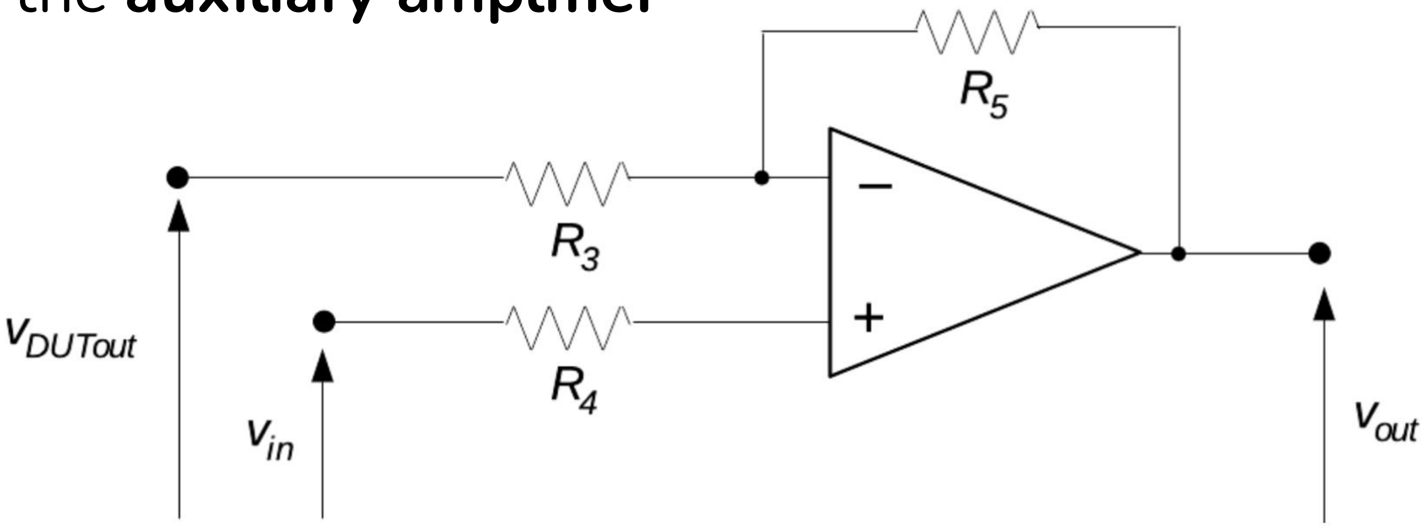
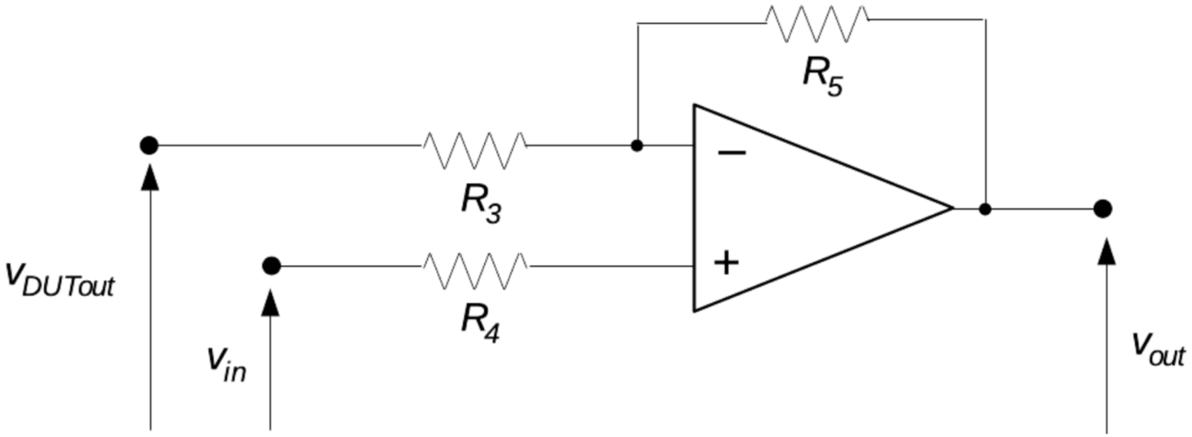
- tolerance limits are not critical, since the measured operational amplifier gain is quite large

- Behaviour of the **auxiliary amplifier**



Test circuit analysis

- Behaviour of the **auxiliary amplifier**



- Input-output relationship:

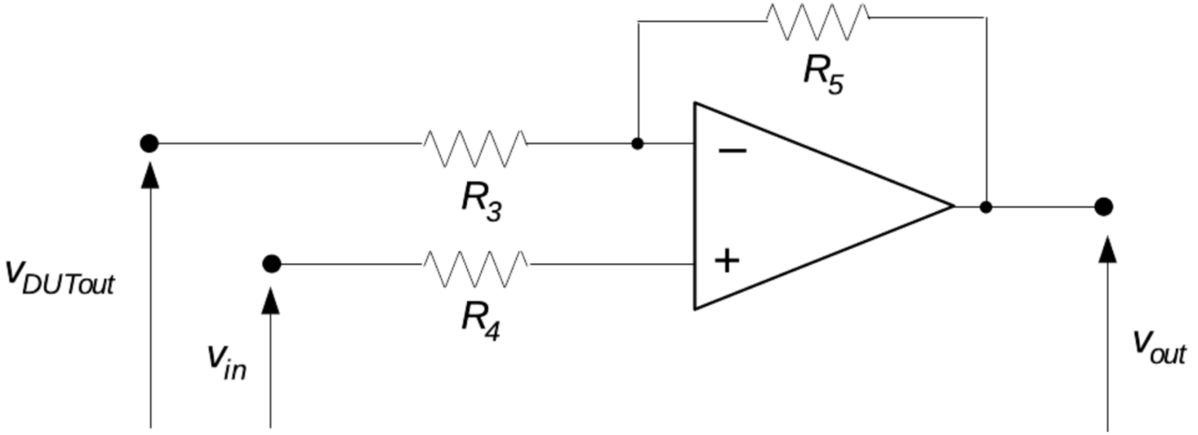
$$v_{out} = \frac{R_5 + R_3}{R_3} \cdot \left(v_{in} - \frac{R_5}{R_5 + R_3} v_{DUTout} \right)$$

- Open-loop gain of the auxiliary amplifier:

$$f_{T_2} = \frac{A_{0,2}}{2\pi T_2}$$

Test circuit analysis

- Behaviour of the **auxiliary amplifier**



- New input-output relationship:

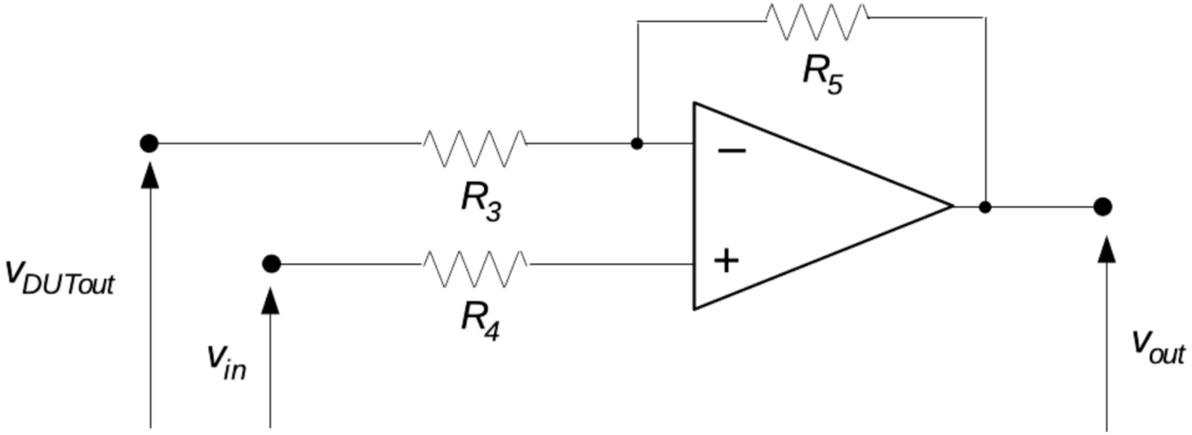
$$v_{out} = \frac{1}{1 + j\frac{f}{f_T} \cdot \frac{R_5 + R_3}{R_3}} \cdot \left[\frac{R_5 + R_3}{R_3} \cdot \left(v_{in} - \frac{R_5}{R_5 + R_3} v_{DUT_{out}} \right) \right]$$

- Test circuit amplifier is **band-limited**

$$f_{Aux} = \frac{f_{T_2}}{\frac{R_5+R_3}{R_3}} \text{ with } \frac{f_{T_2}}{A_{0,2}} < f_{Aux} < f_{T_2}$$

Test circuit analysis

- Numerical example:
- $f_{T_1} = f_{T_2} = 1\ \mathrm{MHz}$
- $A_0 = 10^5$
- $\frac{R_5+R_3}{R_3} \cong 5 \cdot 10^3$



- Low frequency pole at 10 Hz
- Auxiliary cut-off frequency at 2 kHz

- v_{out} is attenuated → DUT gain increases

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