Electronics for Physicists

Analog Electronics

Chapter 4; Lecture 08

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KIT, Winter 2023/24

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Chapter 4

Operational Amplifiers

- OpAmp Basics
- Simple Circuits: Feedback etc.
- OpAmp Circuits I
- Realistic OpAmps
- OpAmp Circuits II

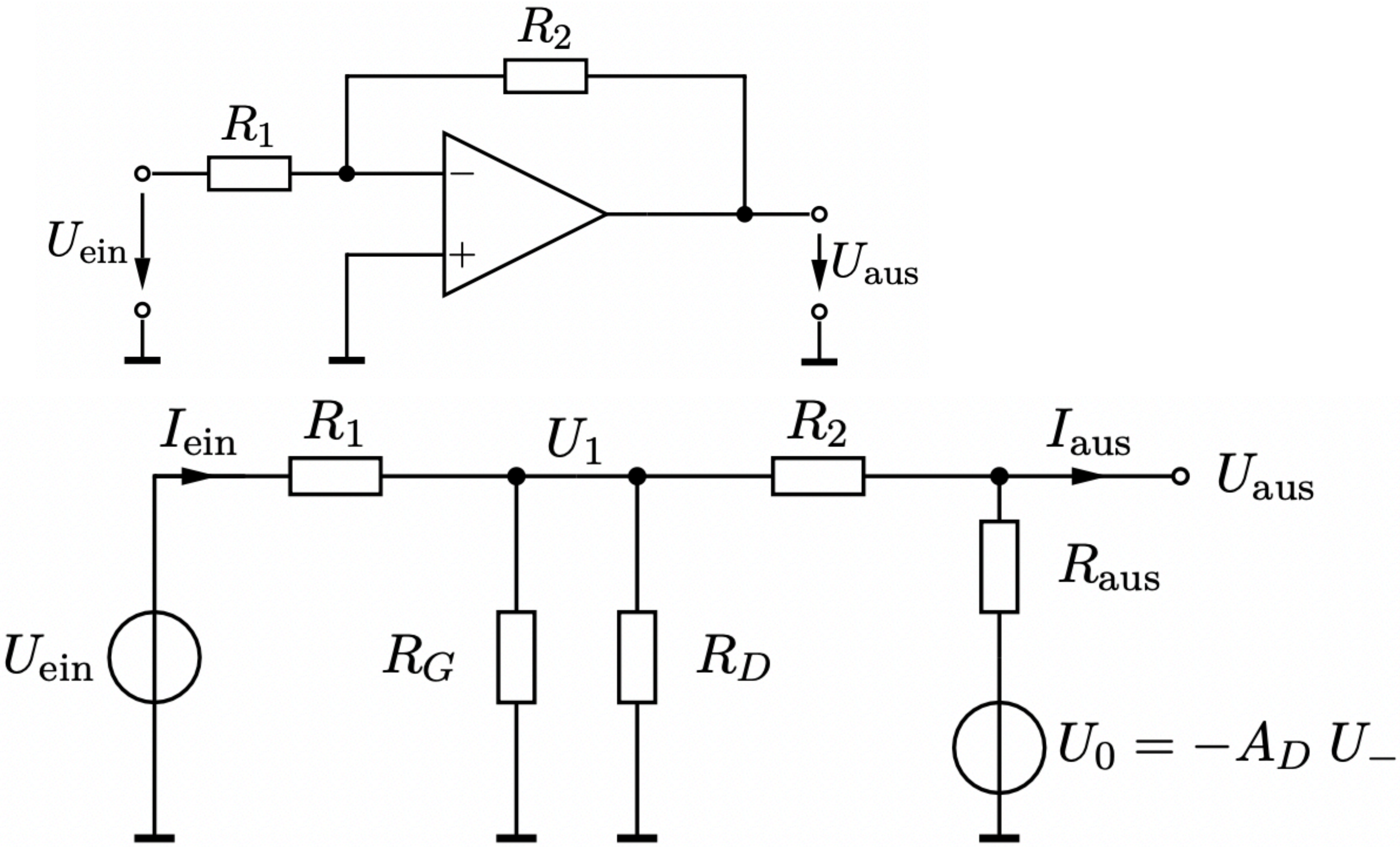
Overview

A more general View of Feedback

In: Chapter 4: Operational Amplifiers

Equivalent Circuit

Inverting Amplifier



Input Impedance?

Output Impedance?

Definitions:

$$Z_{ein} = \frac{dU_{ein}}{dI_{ein}}$$

for open output $I_{aus} = 0$

$$Z_{aus} = \frac{dU_{aus}}{dI_{aus}}$$

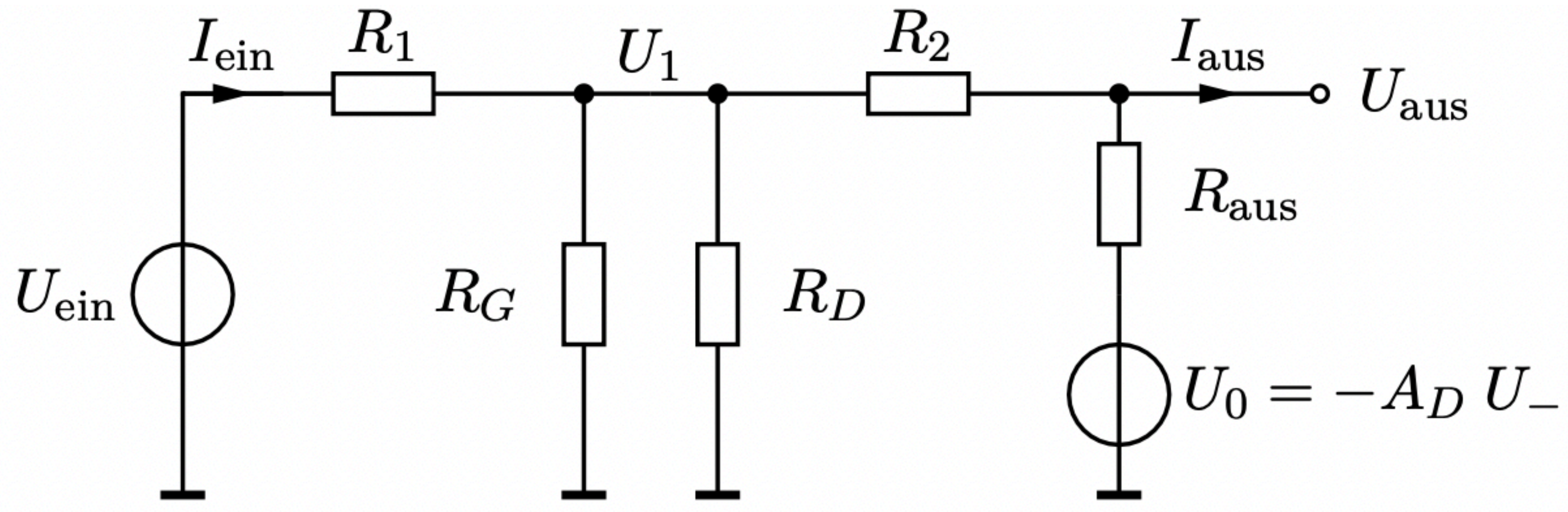
short circuit on input

$U_{ein} = 0$

$U_- = U_1$ Voltage on inverting input

Equivalent Circuit

Inverting Amplifier



$$I_{ein} = \frac{U_{ein} - U_-}{R_1}$$

$(R_2 + R_{aus}) = R$

can be calculated with superposition principle, assuming $R_G \gg R_D \gg R_1, R_2$

\- not done in detail here -

$$U_- = U_{ein}\frac{R}{R_1 + R} - A_D U_- \frac{R_1}{R + R_1} \quad \Rightarrow \quad U_- = U_{ein}\frac{R}{R + R_1 + R_1 A_D}$$

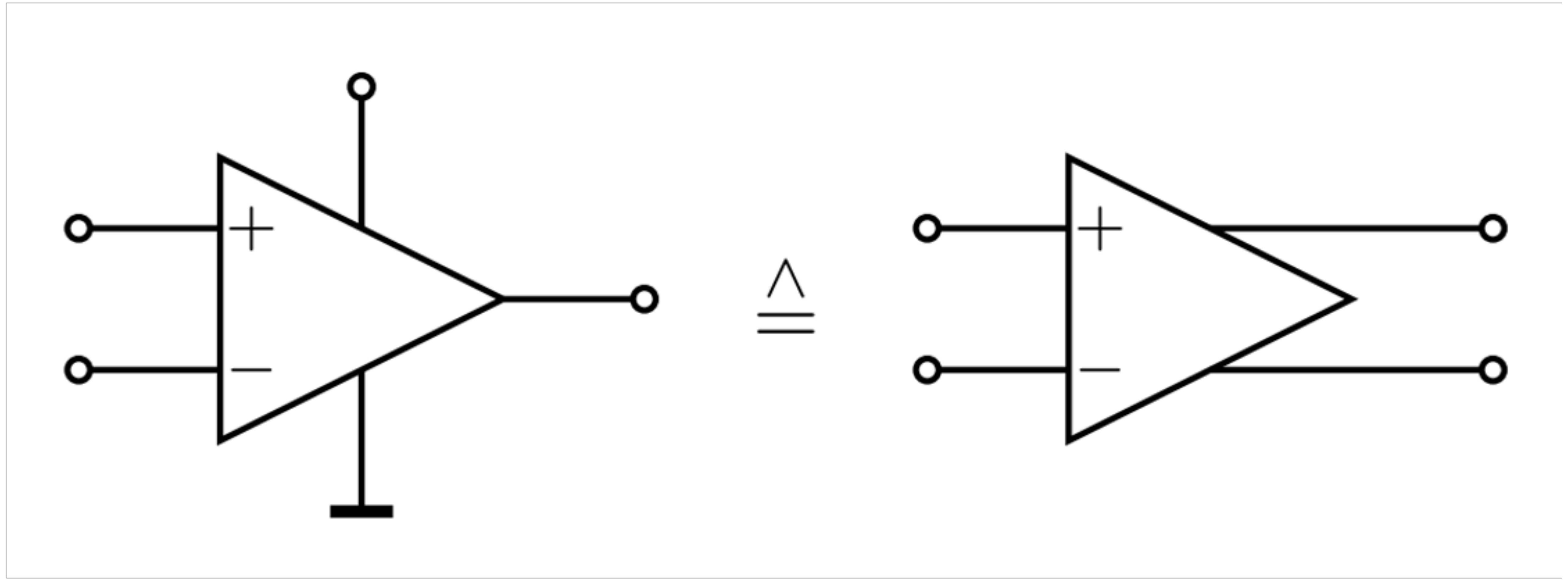
A_D is very large. Consequence: $U_- \ll U_{ein}$ => ~ 0 V (“virtual mass”), see 1st Golden Rule. Results in: $Z_{ein} = R_1$

Reminder: $Z_{ein} = \frac{dU_{ein}}{dI_{ein}}$

More general Perspectives on Feedback

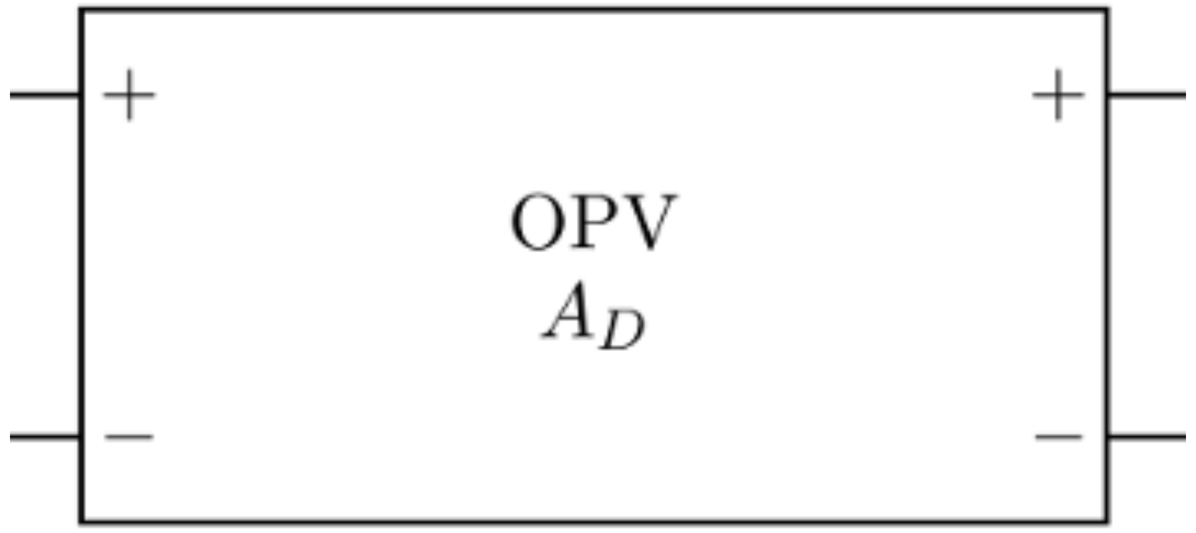
Control Loop

- Here: Assume an OpAmp with differential input and output

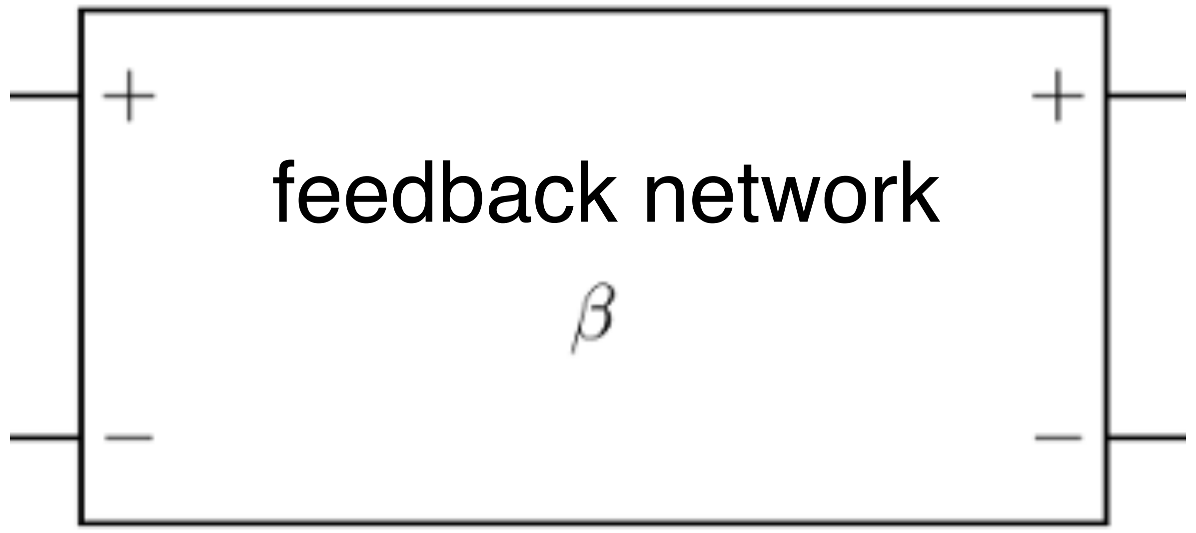


The components:

OpAmp with
differential gain A_D

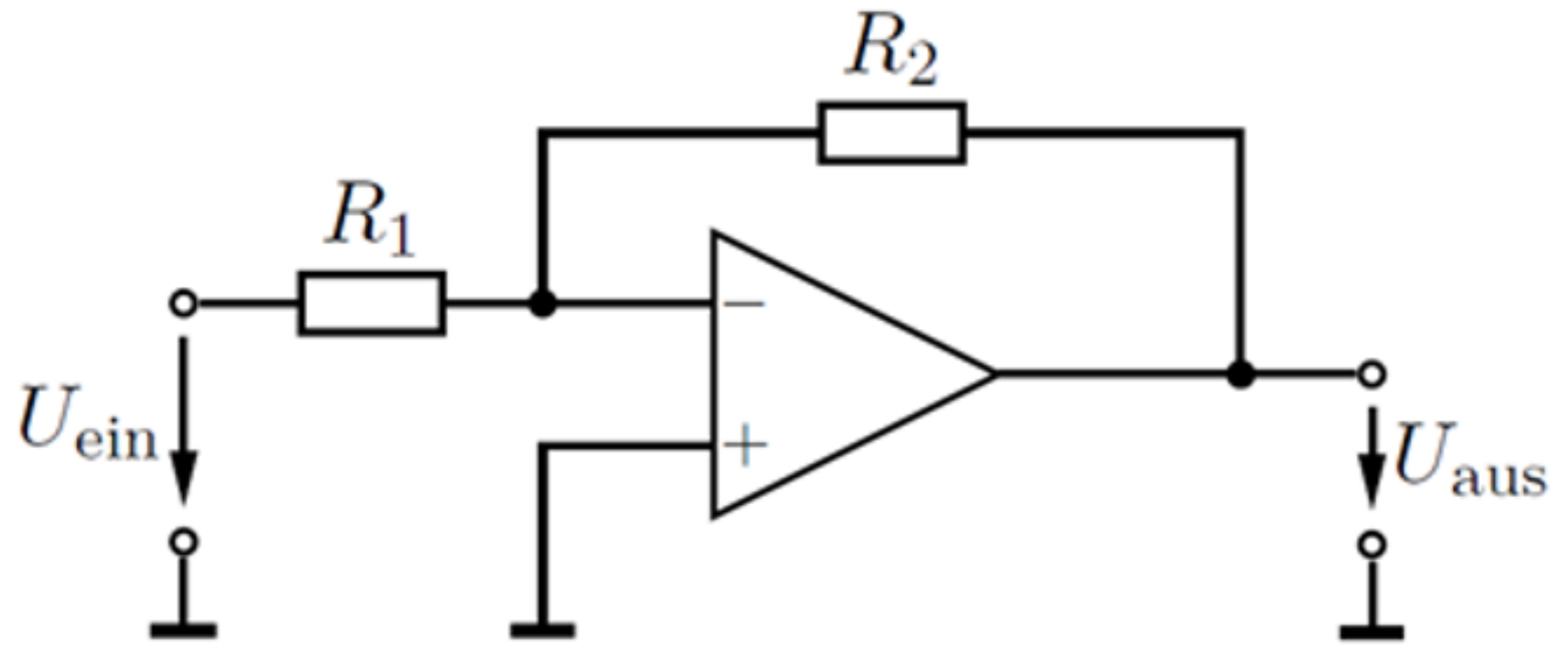


Feedback Network



More general Perspectives on Feedback

Inverting Amplifier

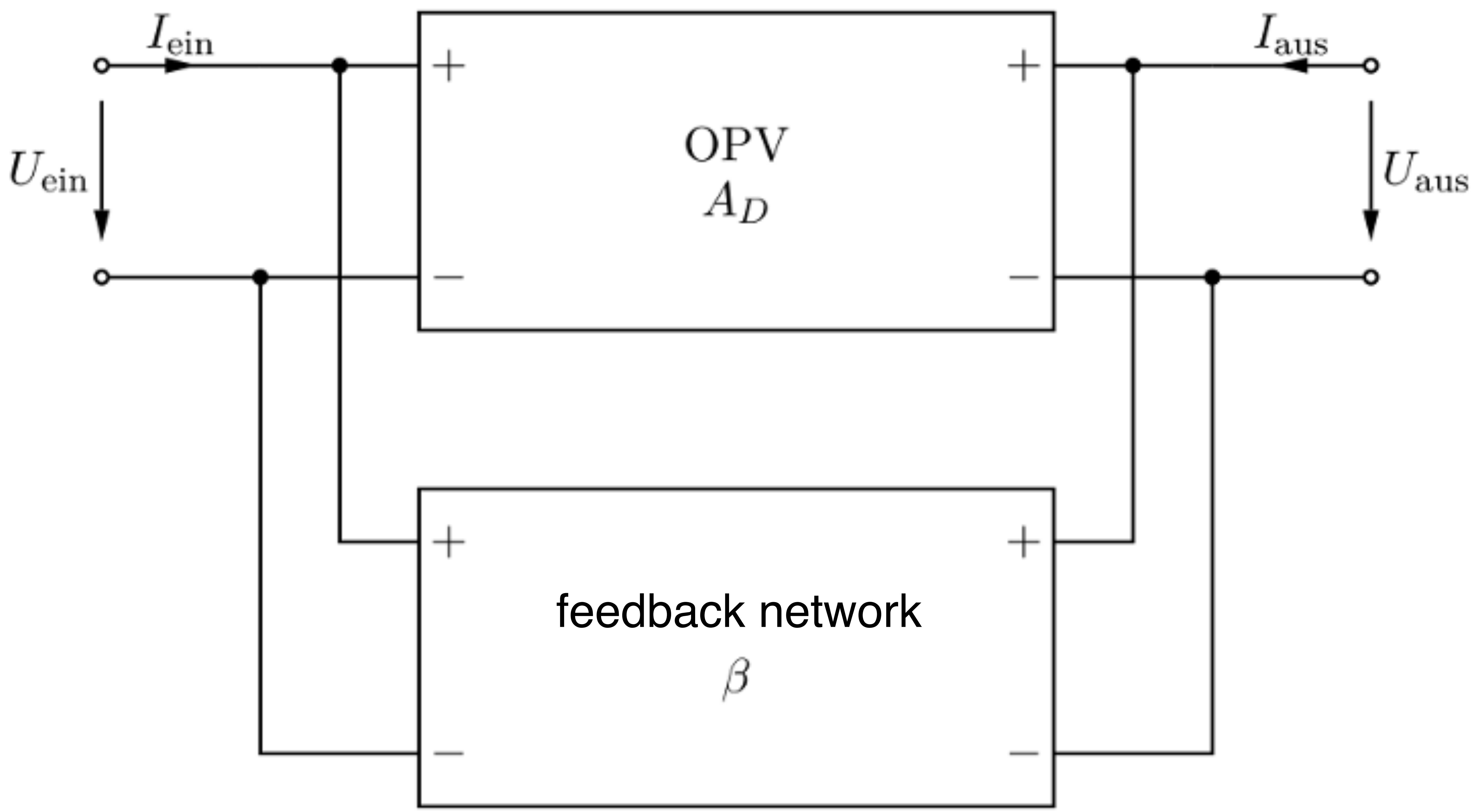


$I_{ein} = U_{ein}/R_1$ (since $U_- = 0$)

Gain: $A = U_{aus}/U_{ein}$, or

$$A = \frac{dU_{aus}}{dI_{ein}}$$

"current-voltage feedback"

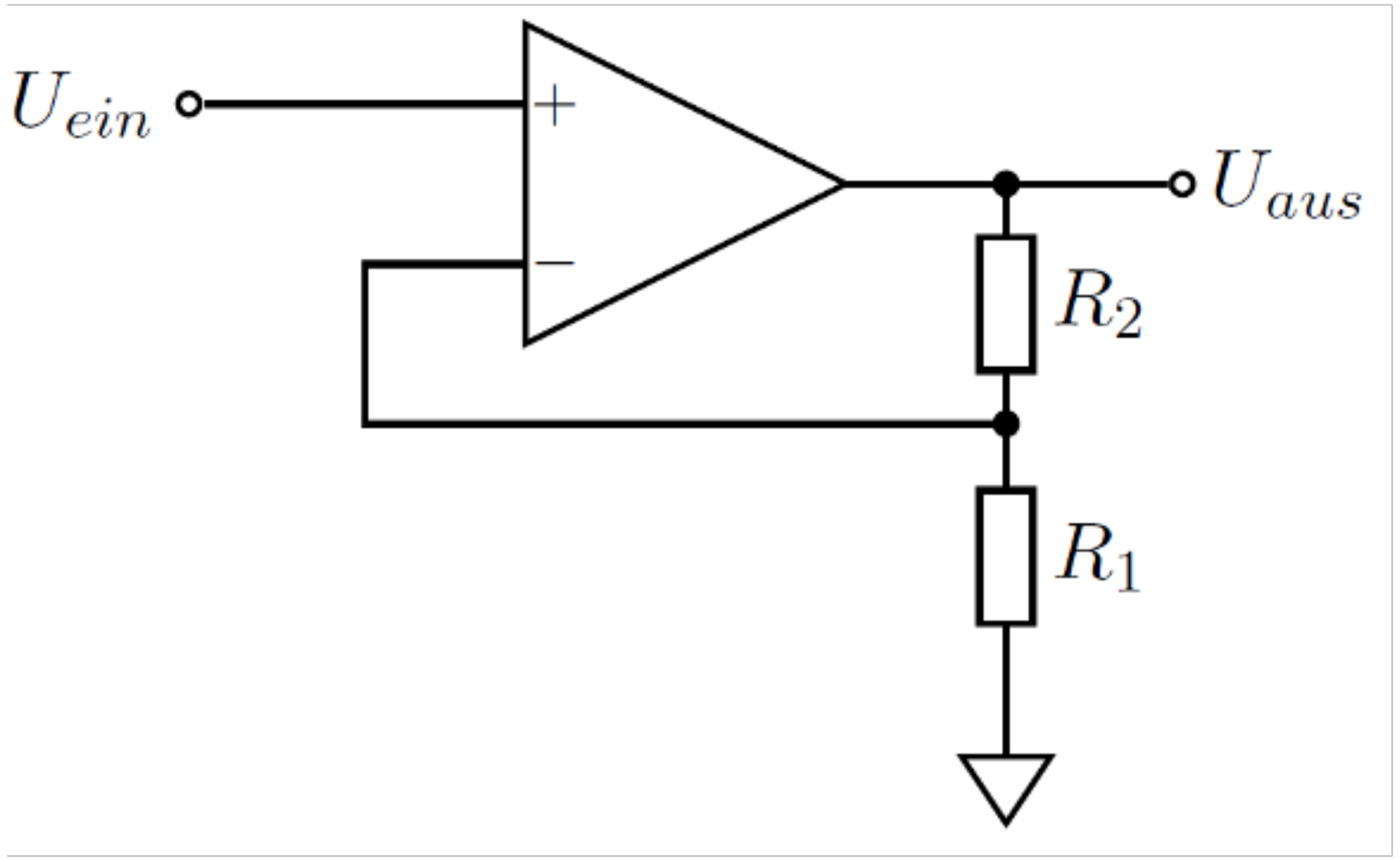


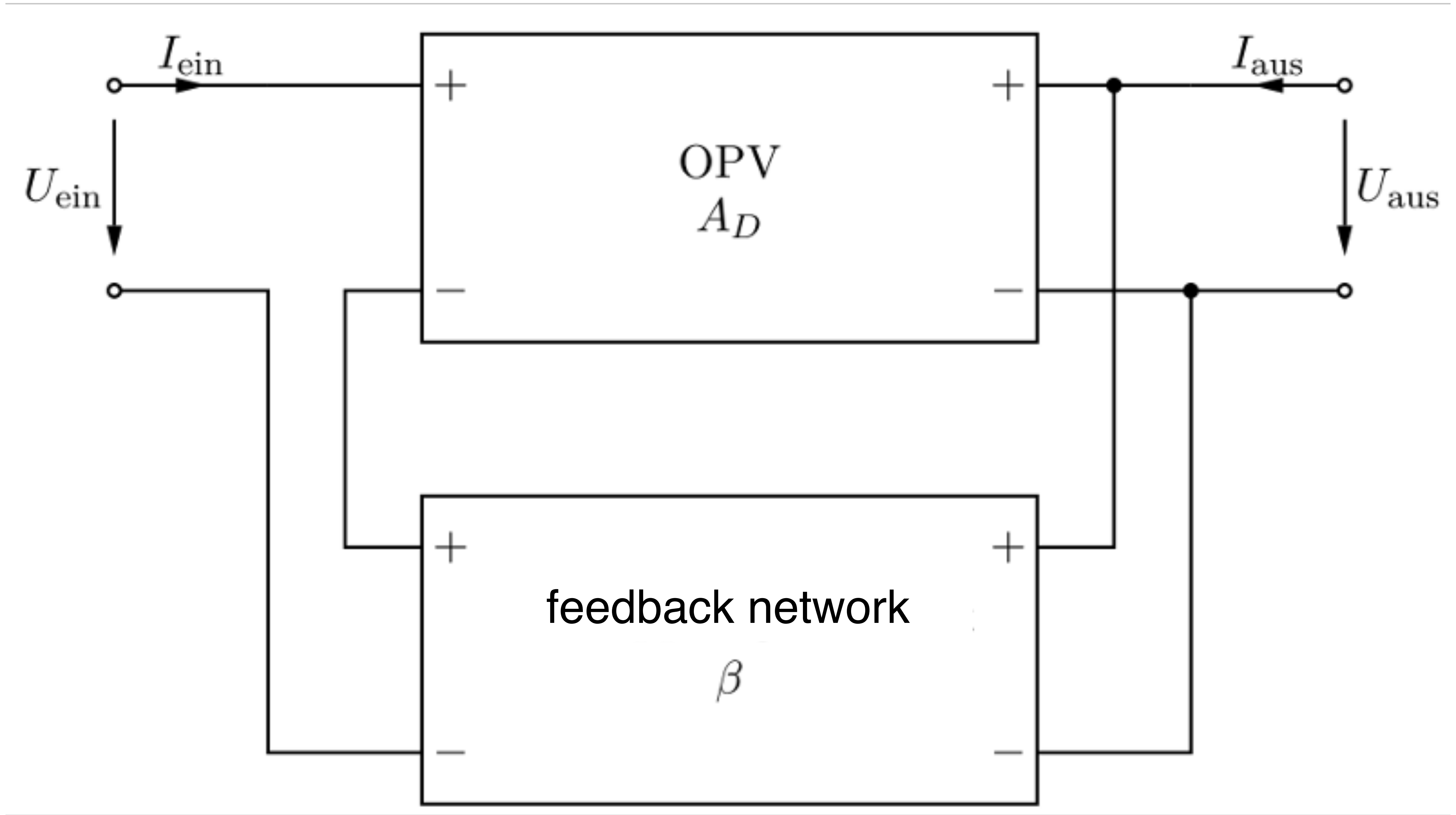
OpAmp parallel ("shunt") on input and output of the feedback network: "shunt - shunt"

The feedback reduces input and output impedance.

More general Perspectives on Feedback

Non-inverting Amplifier





gain: $A = U_{aus}/U_{ein}$, or

$$A = \frac{dU_{aus}}{dU_{ein}}$$

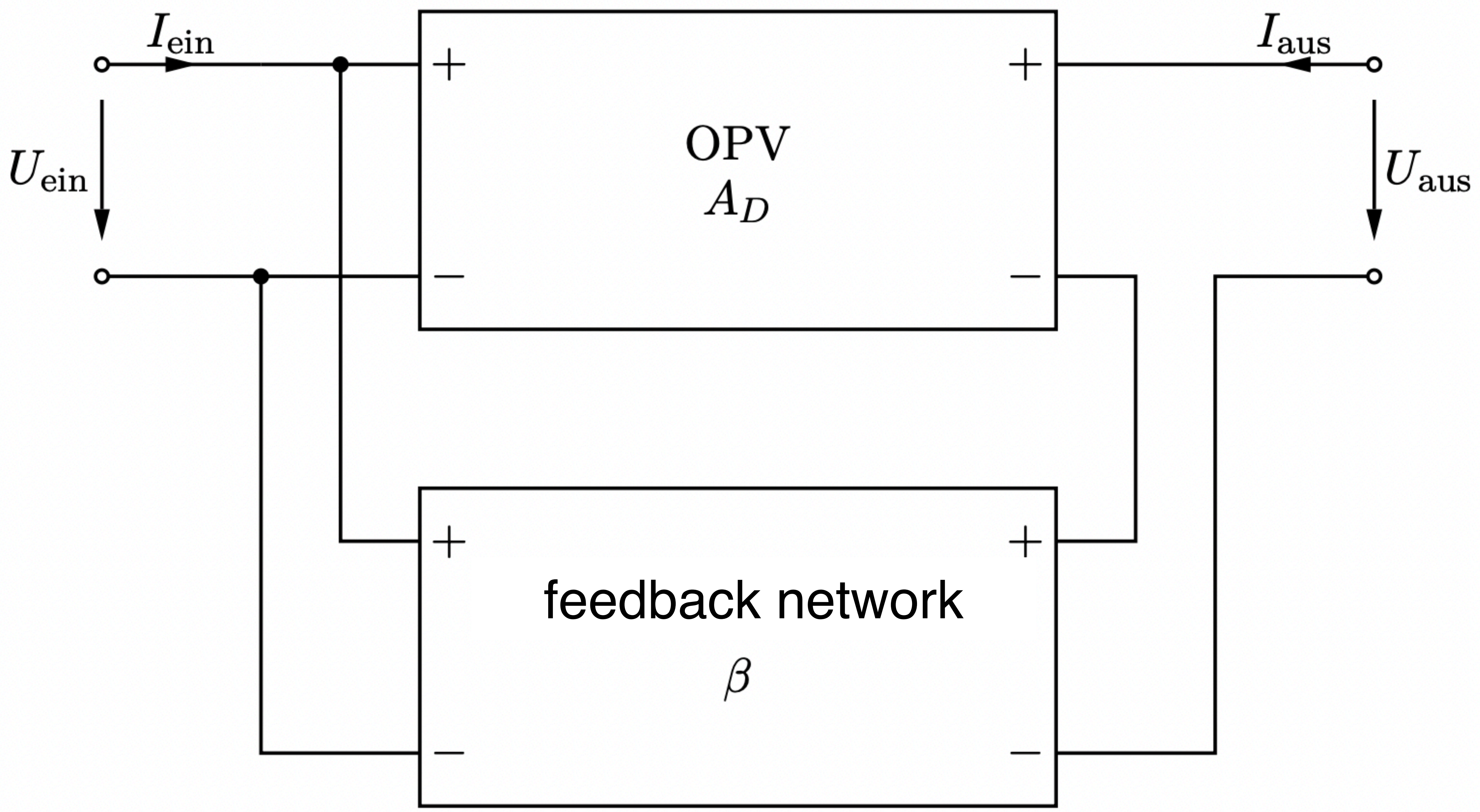
"voltage amplifier"

OpAmp in series ("series") on input, parallel ("shunt") on output of the feedback network : "series - shunt"

The feedback increases input impedance, reduces output impedance.

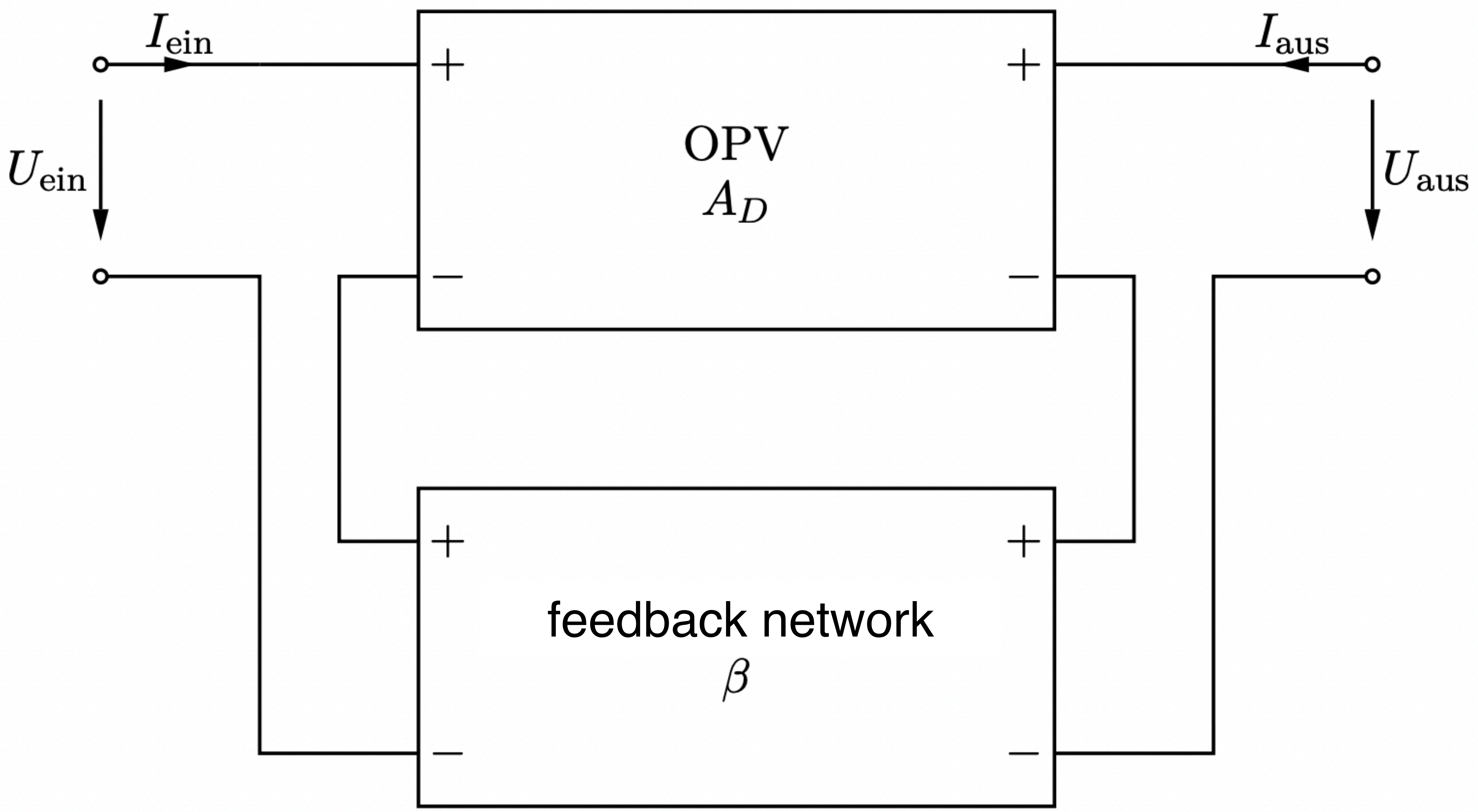
More general Perspectives on Feedback

Additional Options



OpAmp in parallel ("shunt") on input, in series ("series") on output of feedback network: "shunt - series"

low input impedance, high output impedance:
Current-Current feedback
Current amplifier / current source



"series-series"
High input and output impedance:
Voltage-current feedback
"Transconductance amplifier"

Feedback: Summary

General View

Amplifier	Type	Gain	R_{ein}	R_{aus}
non-inverting amplifier (series-shunt)	voltage to voltage	$\frac{A_D}{1+\beta\, A_D}$	$(1+\beta\, A_D)\ R_{ein}$	$\frac{R_{aus}}{1+\beta\, A_D}$
inverting amplifier (shunt-shunt)	current to voltage	$\frac{A_D}{1+\beta\, A_D} \approx -R_2$	$\frac{R_{ein}}{1+\beta\, A_D}$	$\frac{R_{aus}}{1+\beta\, A_D}$
current amplifier (shunt-series)	current to current	$\frac{A_D}{1+\beta\, A_D}$	$\frac{R_{ein}}{1+\beta\, A_D}$	$(1+\beta\, A_D)\ R_{aus}$
transconductance amplifier (series-series)	voltage to current	$\frac{A_D}{1+\beta\, A_D}$	$(1+\beta\, A_D)\ R_{ein}$	$(1+\beta\, A_D)\ R_{aus}$

A_D: open loop gain

βA_D: loop gain

R_{ein}, R_{aus}:
input / output impedance w/o feedback

Feedback: Summary

General View - For Reference with German Terms

Verstärker	Typus	Verstärkung	R_{ein}	R_{aus}
Nicht-invertierender OPV (series-shunt)	Spannung zu Spannung	$\frac{A_D}{1+\beta\,A_D}$	$(1+\beta\,A_D)\;R_{\text{ein}}$	$\frac{R_{\text{aus}}}{1+\beta\,A_D}$
Invertierender OPV (shunt-shunt)	Strom zu Spannung	$\frac{A_D}{1+\beta\,A_D} \approx -R_2$	$\frac{R_{\text{ein}}}{1+\beta\,A_D}$	$\frac{R_{\text{aus}}}{1+\beta\,A_D}$
Stromverstärker (shunt-series)	Strom zu Strom	$\frac{A_D}{1+\beta\,A_D}$	$\frac{R_{\text{ein}}}{1+\beta\,A_D}$	$(1+\beta\,A_D)\;R_{\text{aus}}$
Transkonduktanz-verstärker (series-series)	Spannung zu Strom	$\frac{A_D}{1+\beta\,A_D}$	$(1+\beta\,A_D)\;R_{\text{ein}}$	$(1+\beta\,A_D)\;R_{\text{aus}}$

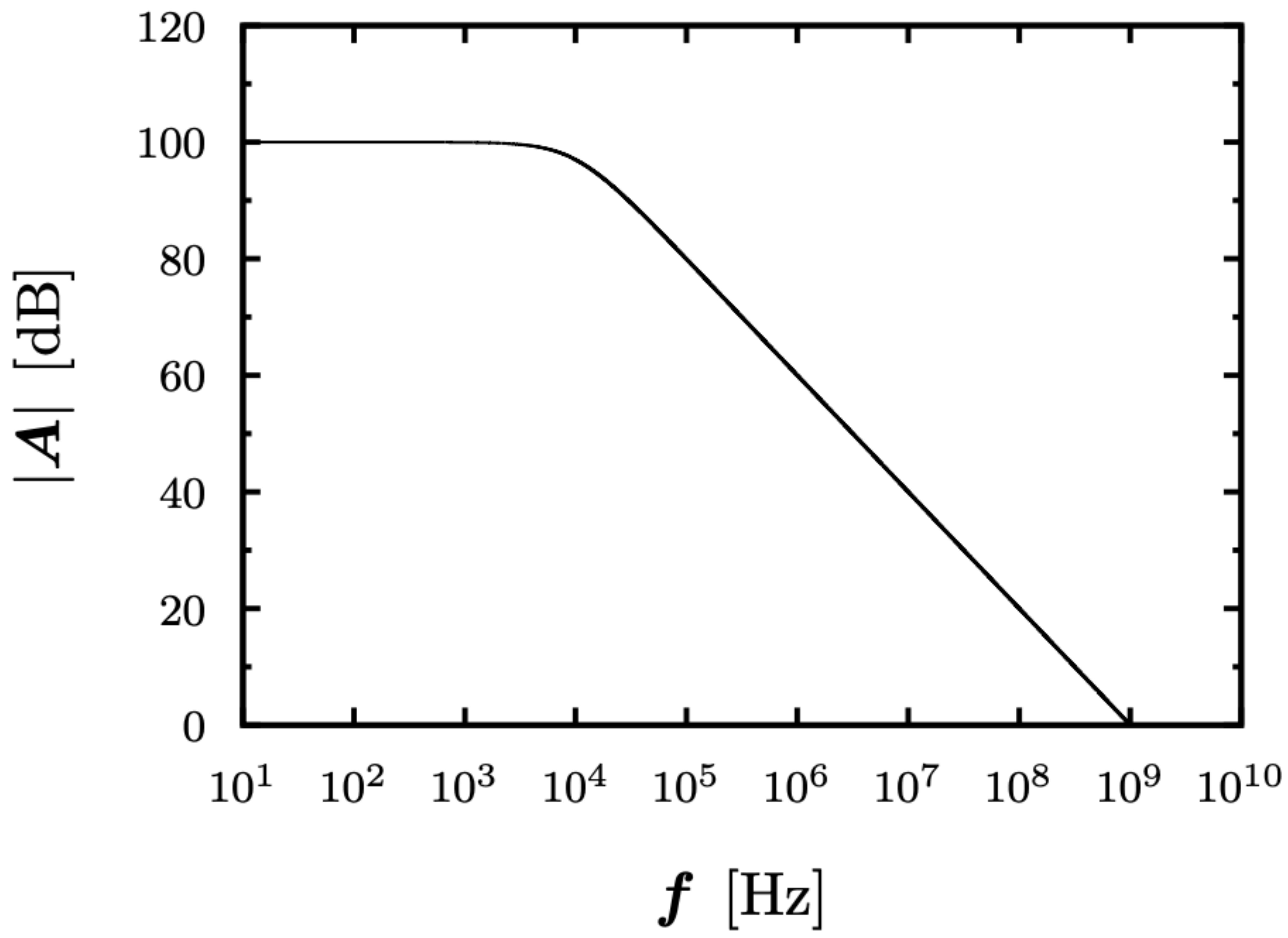
A_D: Leerlauf-Verstärkung

βA_D: Schleifen-verstärkung

R_{ein}, R_{aus}: Eingangs- / Ausgangs-Impedanz ohne Rückkopplung

Frequency Behavior of OpAmps

- Typically: Gain decreases with frequency, often as for a simple low pass



Gain drops significantly beyond cutoff frequency (“Grenzfrequenz) f_g

$$\underline{A}_D = \frac{A_{D_0}}{1 + j\frac{f}{f_g}}$$

Cutoff frequency = equal imaginary and real component of gain (see Chapter 02, Bode Plots)

What happens when feedback is introduced?

Reminder:

$$A = \frac{U_{aus}}{U_{ein}} = \frac{K_F\,A_D}{1 + K_R\,A_D} \approx \frac{K_F}{K_R}$$

Frequency Behavor with negative Feedback

Non-inverting Amplifier

- Gain with feedback ($K_F = 1$):

$$\underline{A} = \frac{\underline{U}_{aus}}{\underline{U}_{ein}} = \frac{\underline{A}_D}{1 + K_R\,\underline{A}_D}$$

adding frequency dependence:

$$\underline{A} = \frac{\frac{A_{D_0}}{1 + j\frac{f}{f_0}}}{1 + K_R\frac{A_{D_0}}{1 + j\frac{f}{f_0}}}$$

results in:

$$\underline{A} = \frac{A_{D_0}}{1 + j\frac{f}{f_g} + K_R\,A_{D_0}} \approx \frac{A_{D_0}}{j\frac{f}{f_g} + K_R\,A_{D_0}}$$

For low frequencies $f \ll f_g$ $\quad \underline{A} \approx \frac{1}{K_R}$ $\quad$ (frequency independent)

For high frequencies $f \gg f_g$ $\quad \underline{A} \approx \frac{A_{D_0}}{j\frac{f}{f_g}}$ $\quad$ and $\quad \underline{A}_D \approx \frac{A_{D_0}}{j\frac{f}{f_g}}$

Frequency Behavor with negative Feedback

Non-inverting Amplifier

- More interesting: The region between the extremes

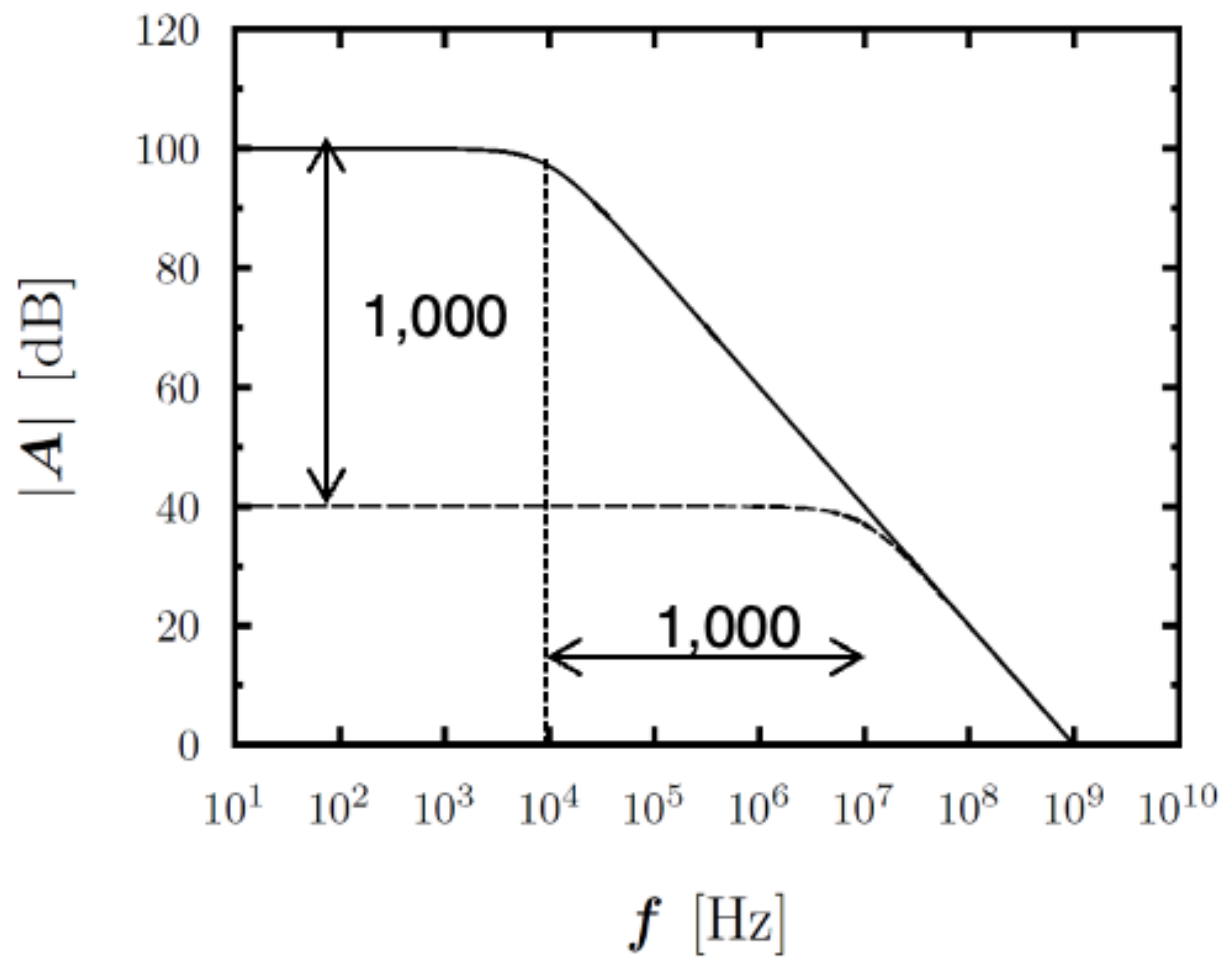
Cutoff frequency = equal imaginary and real component of gain

$$\underline{A} \approx \frac{A_{D_0}}{j\frac{f}{f_g} + K_R A_{D_0}}$$ resulting in $$f_{g,FB} = f_g K_R A_{D_0}$$

feedback increases the cutoff frequency of the amplifier!

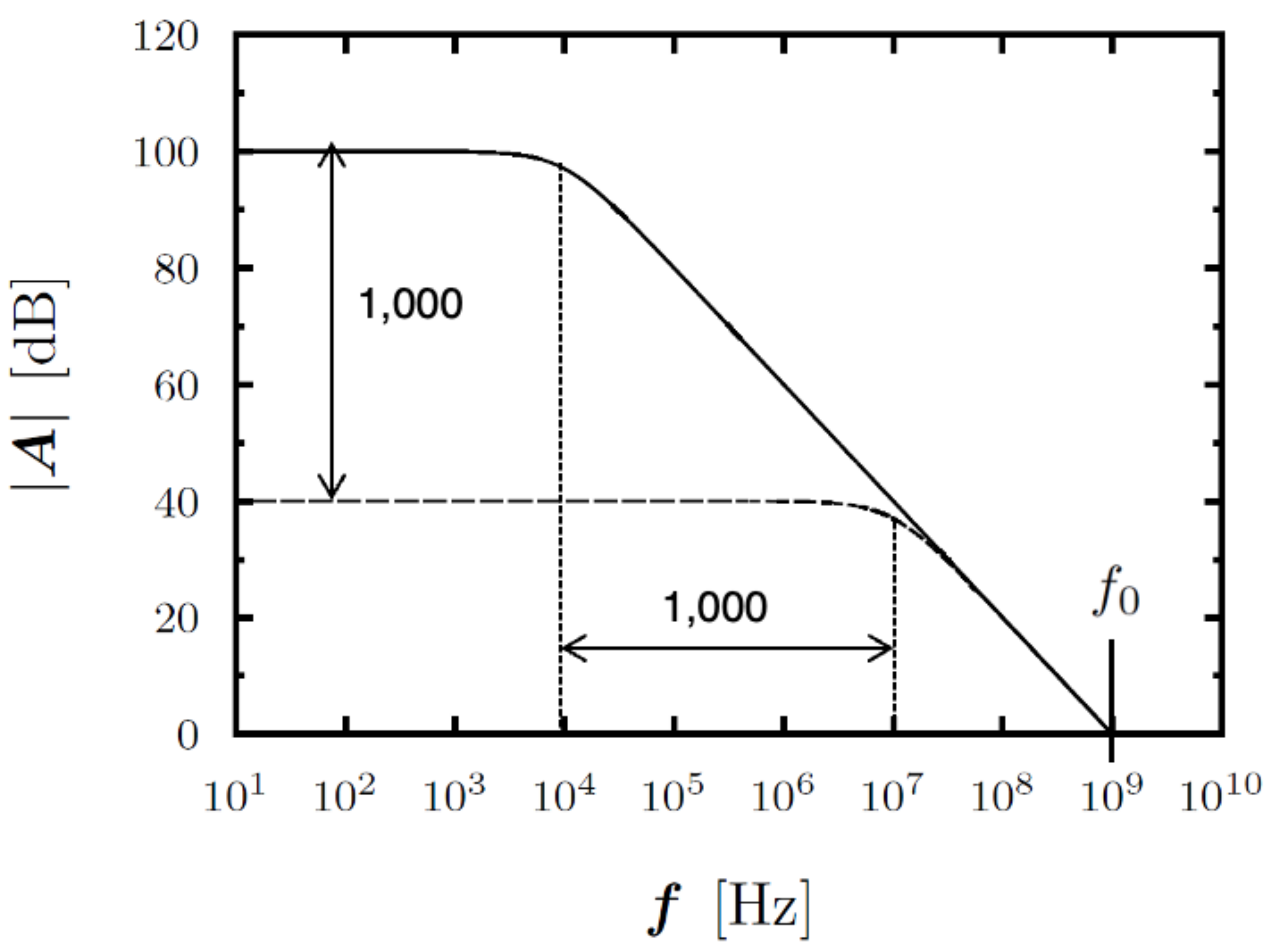
by $\frac{\text{open-loop gain } A_{D0}}{\text{closed-loop gain } 1/K_R}$

=> Lower gain => Higher cut-off frequency.



Frequency Behavor with negative Feedback

Gain Bandwidth Product



- Bandwidth of the amplifier: Region of (relatively) constant frequency-independent gain.

You can trade gain vs bandwidth:
Bandwidth increases by the same factor as gain is reduced.

"Gain-Bandwidth-Product GBP":

$$A_{D_0} \cdot f_g = \frac{1}{K_R} \cdot f_{g,FB} = \frac{1}{K_R} \cdot f_g K_R A_{D_0} = f_0$$

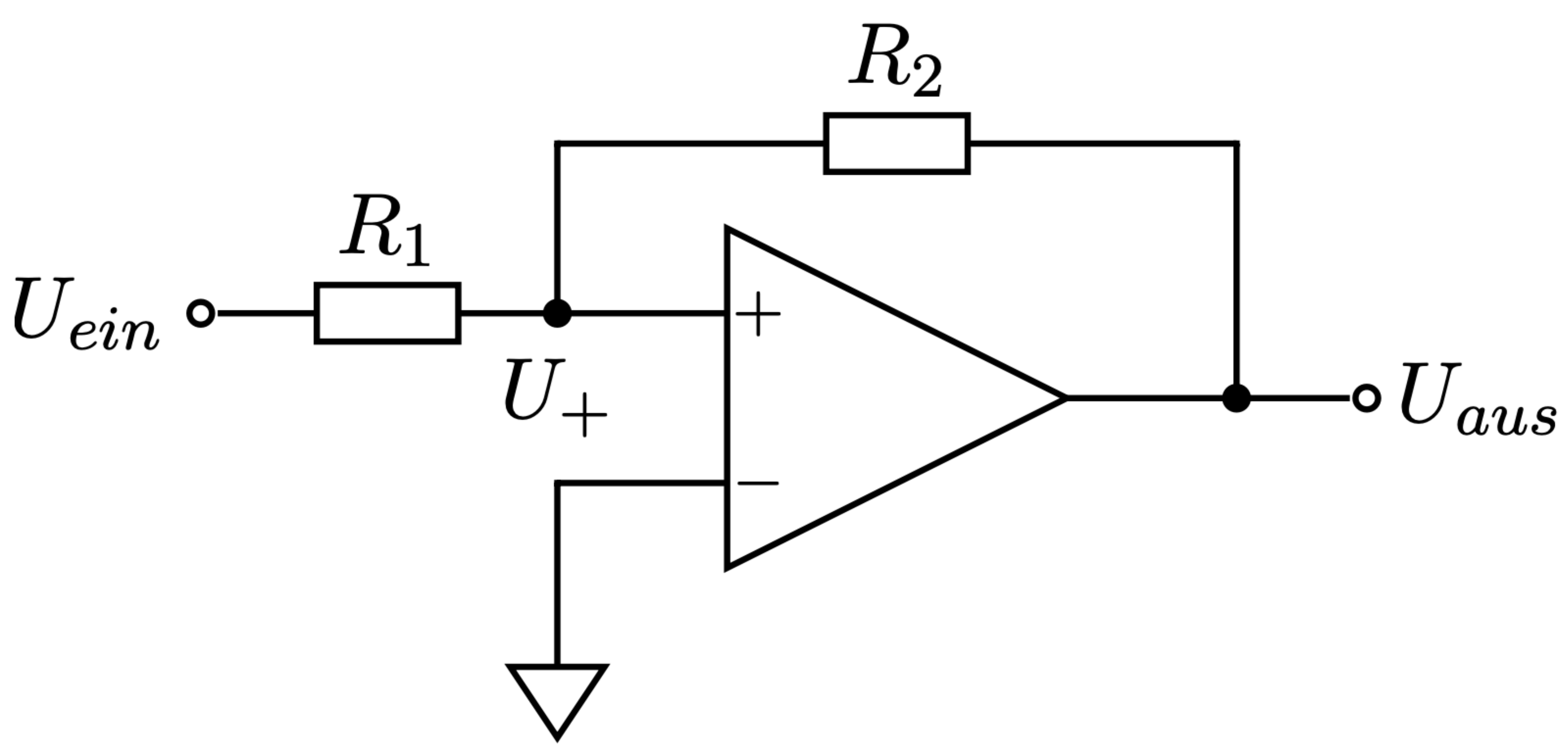
w/o feedback with feedback

OpAmp Circuits - Part II

In: Chapter 4: Operational Amplifiers

- A wide range of applications, in particular in telecommunication, audio, …
  Desired: high frequency stability, low deviations from target waveform (distortions), …

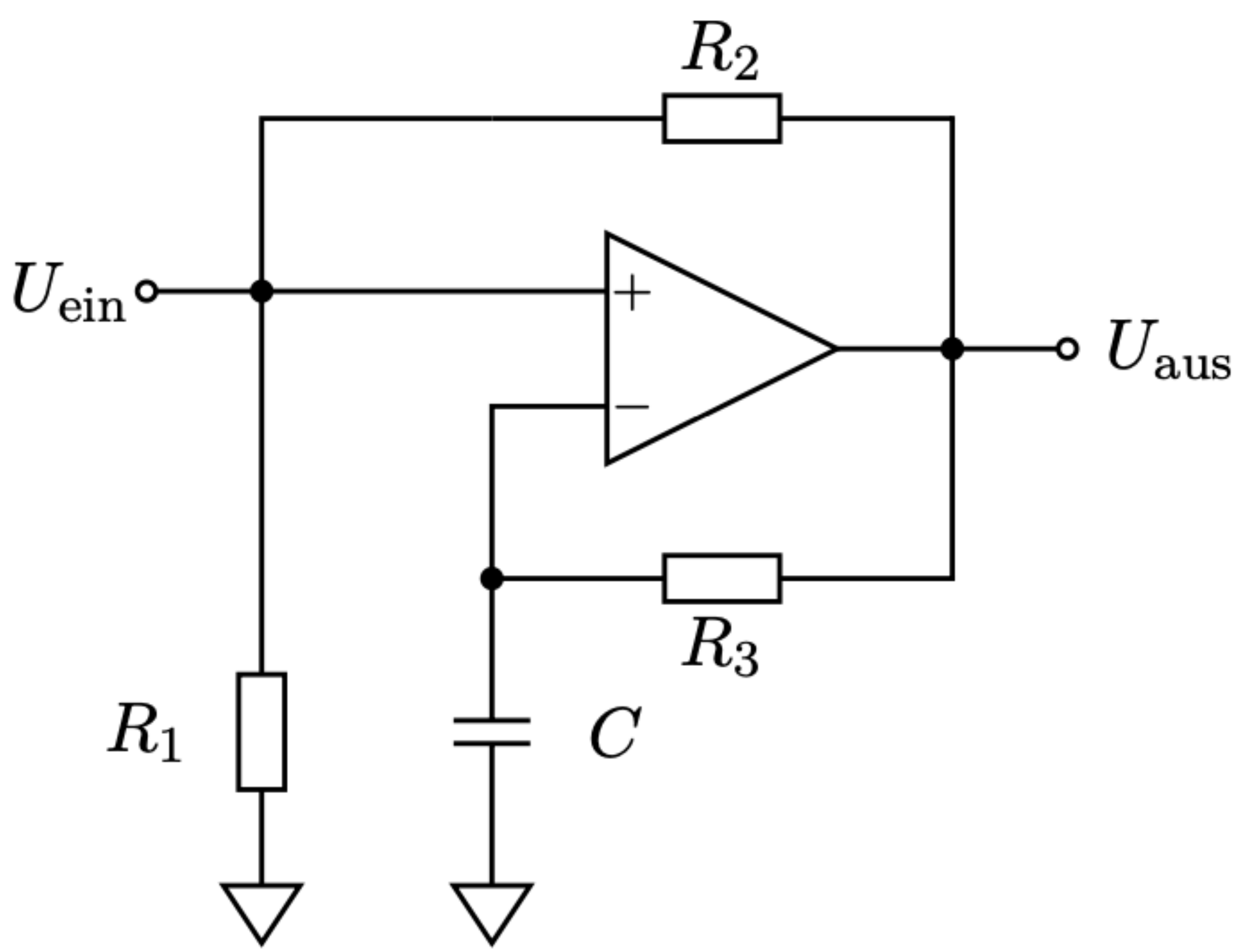
Reminder: Schmitt Trigger

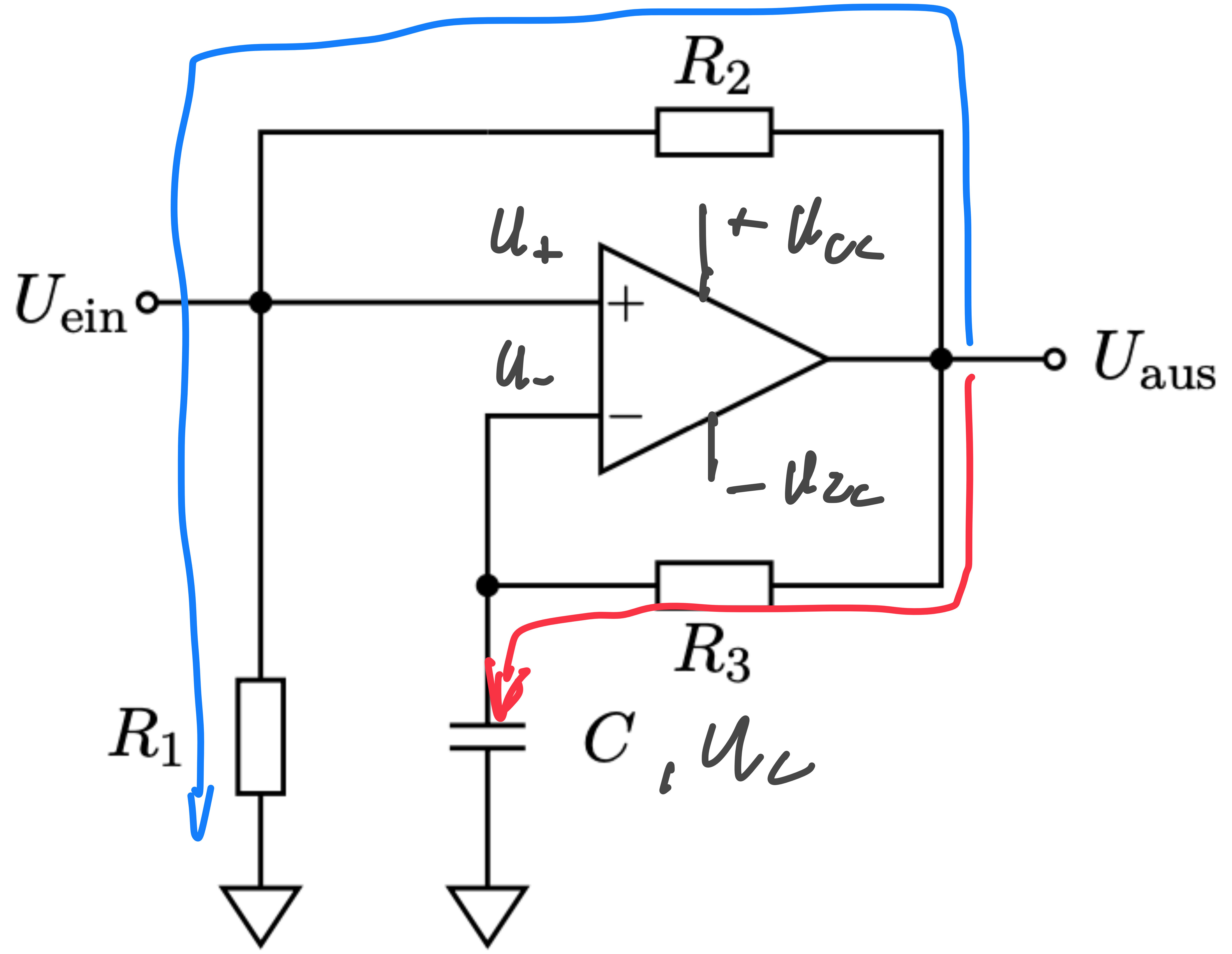


Two states:
$+U_{CC}$, $-U_{CC}$

How do I get this thing to oscillate?

Extension of feedback to both inputs





Starting point $t=0$

$U_{aus} = 0V$ $U_C = 0V$

→ U_{ein} positive

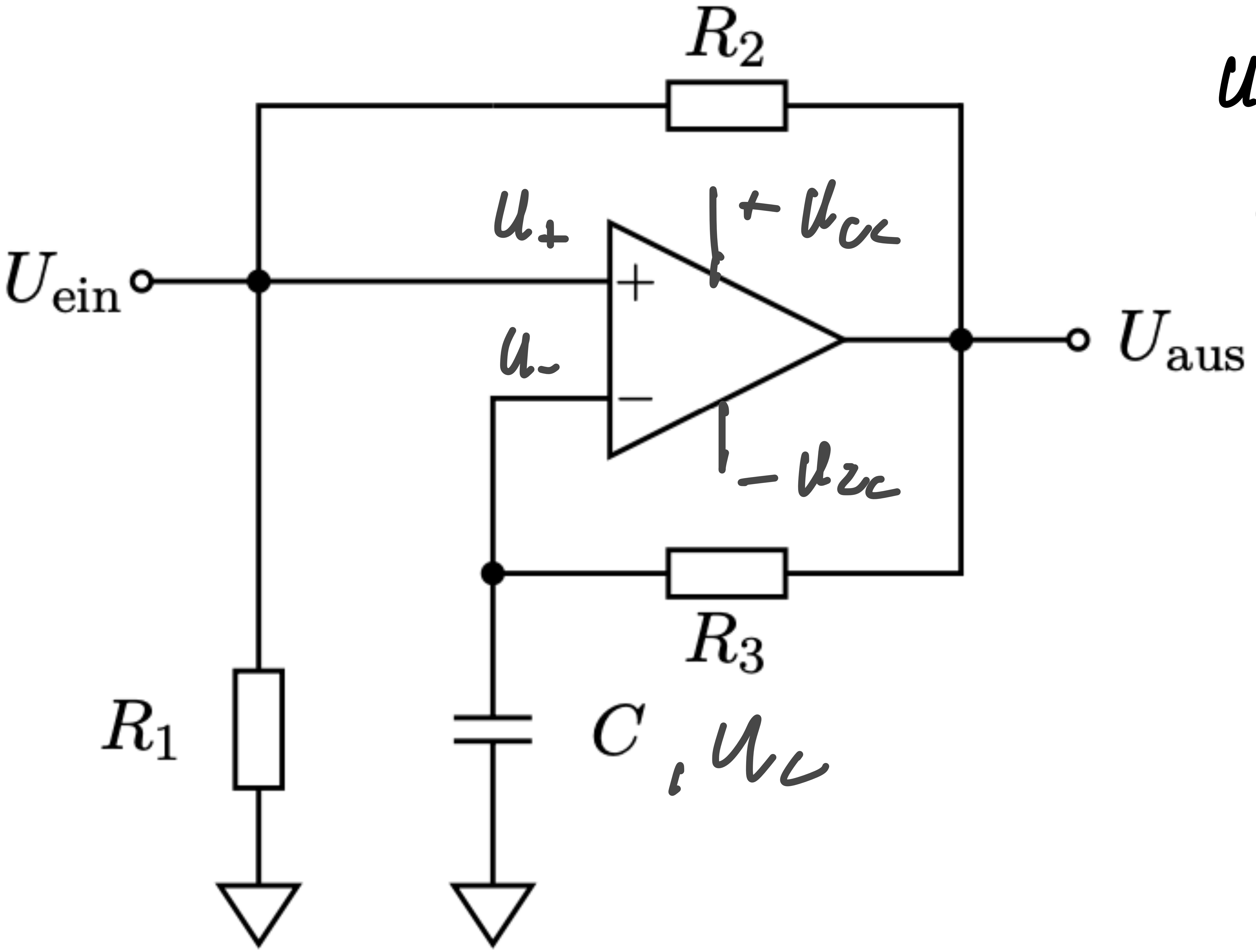
↳ $U_{aus} = +U_{cc}$

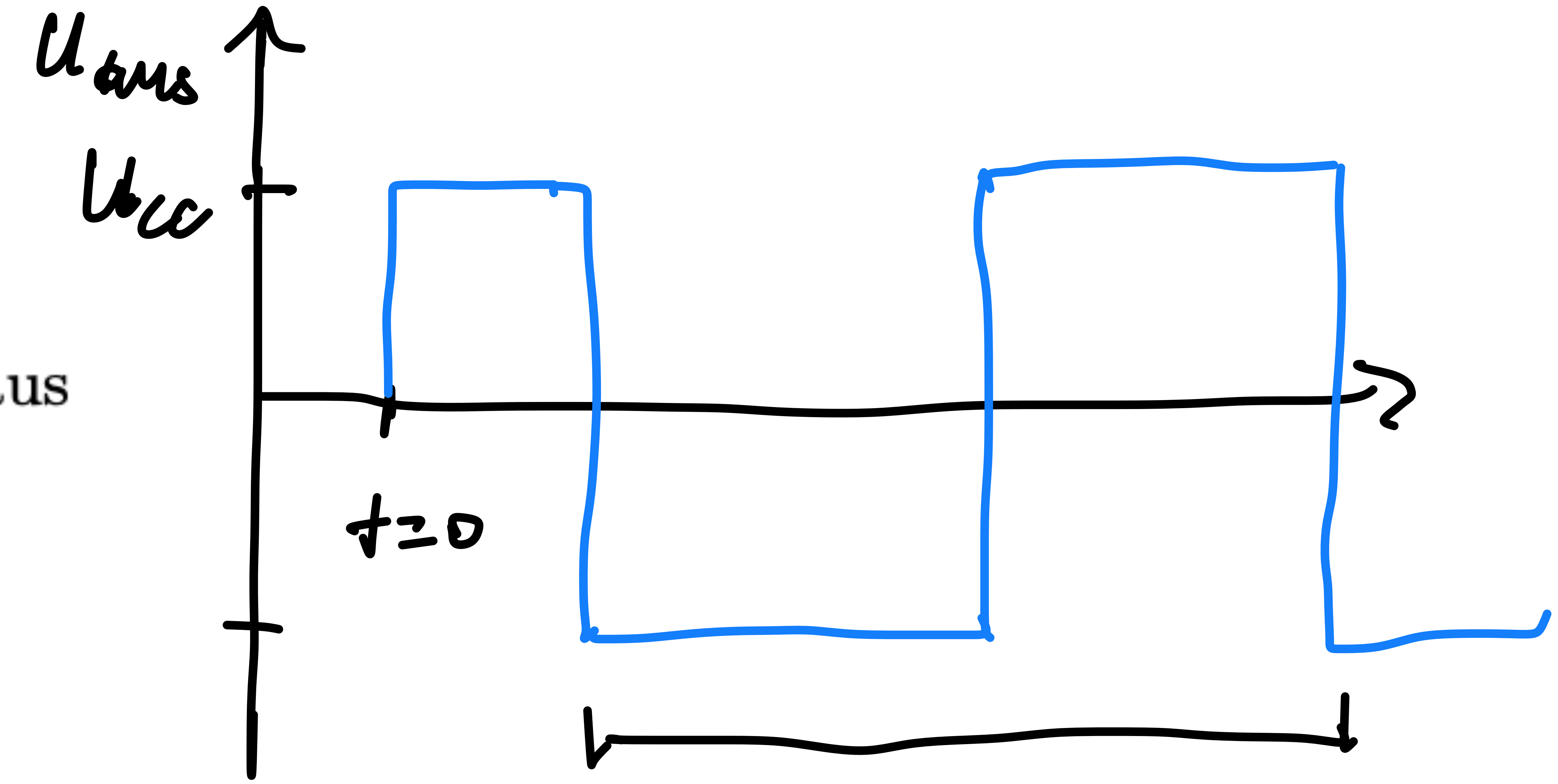
↳ C is charged via R_3

Resulting in:

$$U_+ = U_{cc} \cdot \frac{R_1}{R_1+R_2}$$

$$U_- = U_C = U_{cc}\left(1-e^{-\frac{t}{R_3 C}}\right)$$





Period

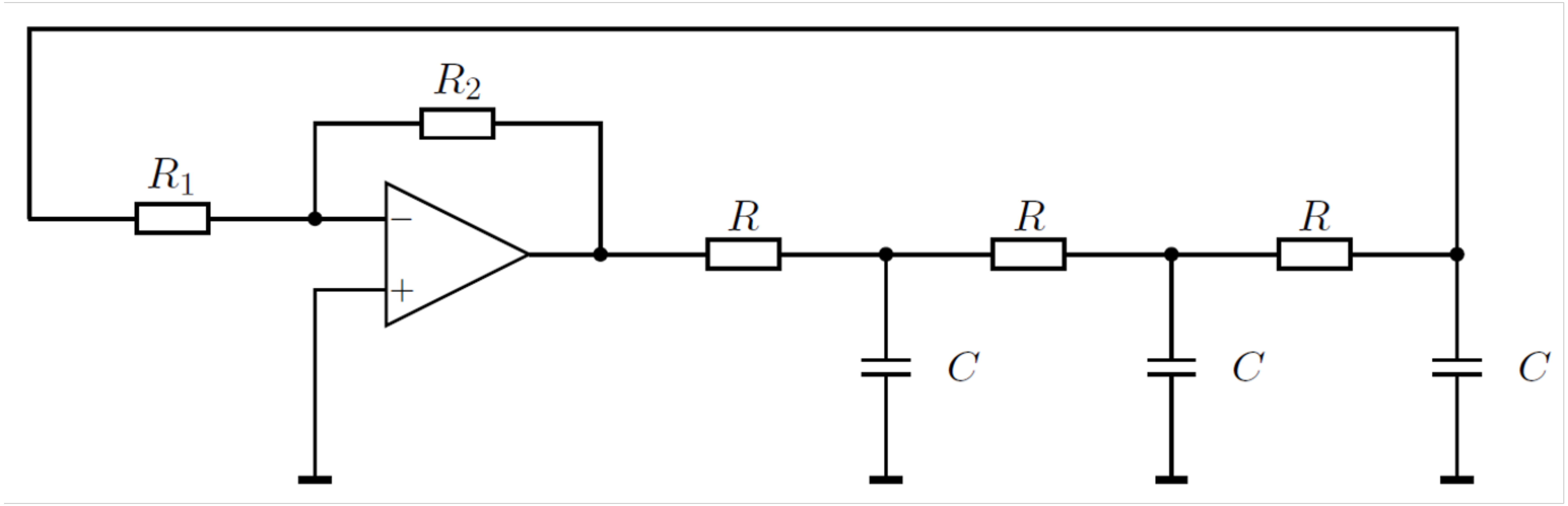
$$T = 2 R_3 C \ln\left(\frac{2R_1 + R_2}{R_2}\right)$$

Phase Shift Oscillator

Phasenschieber-Oszillator

- In general: How can stable, harmonic oscillations be achieved?

Oscillation condition: $U_{aus}(t) = U_{aus}(t+T)$

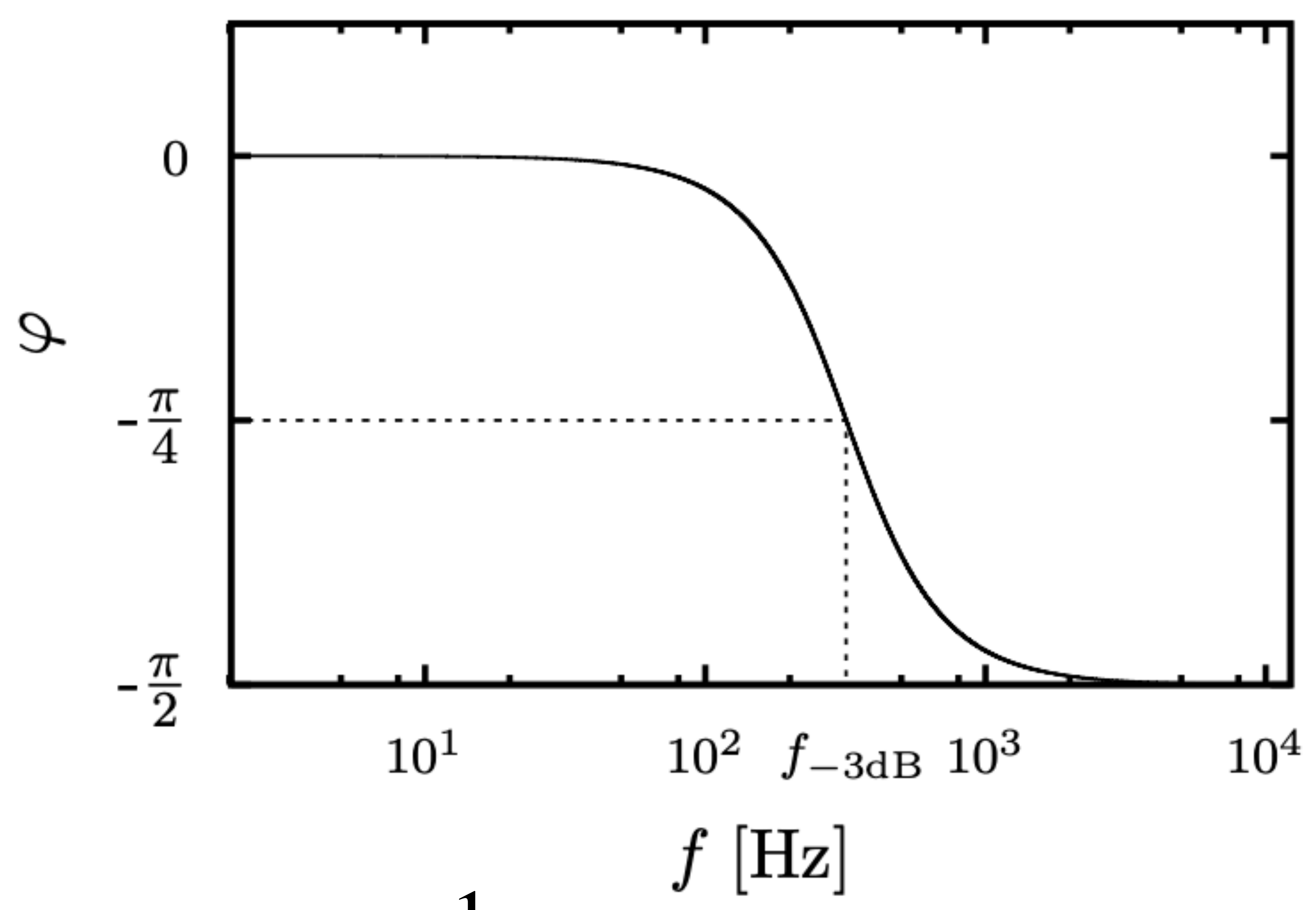


OpAmp with negative feedback, 3 low passes.

Frequency Dependence of Low Pass

Short Recall of Chapter 2

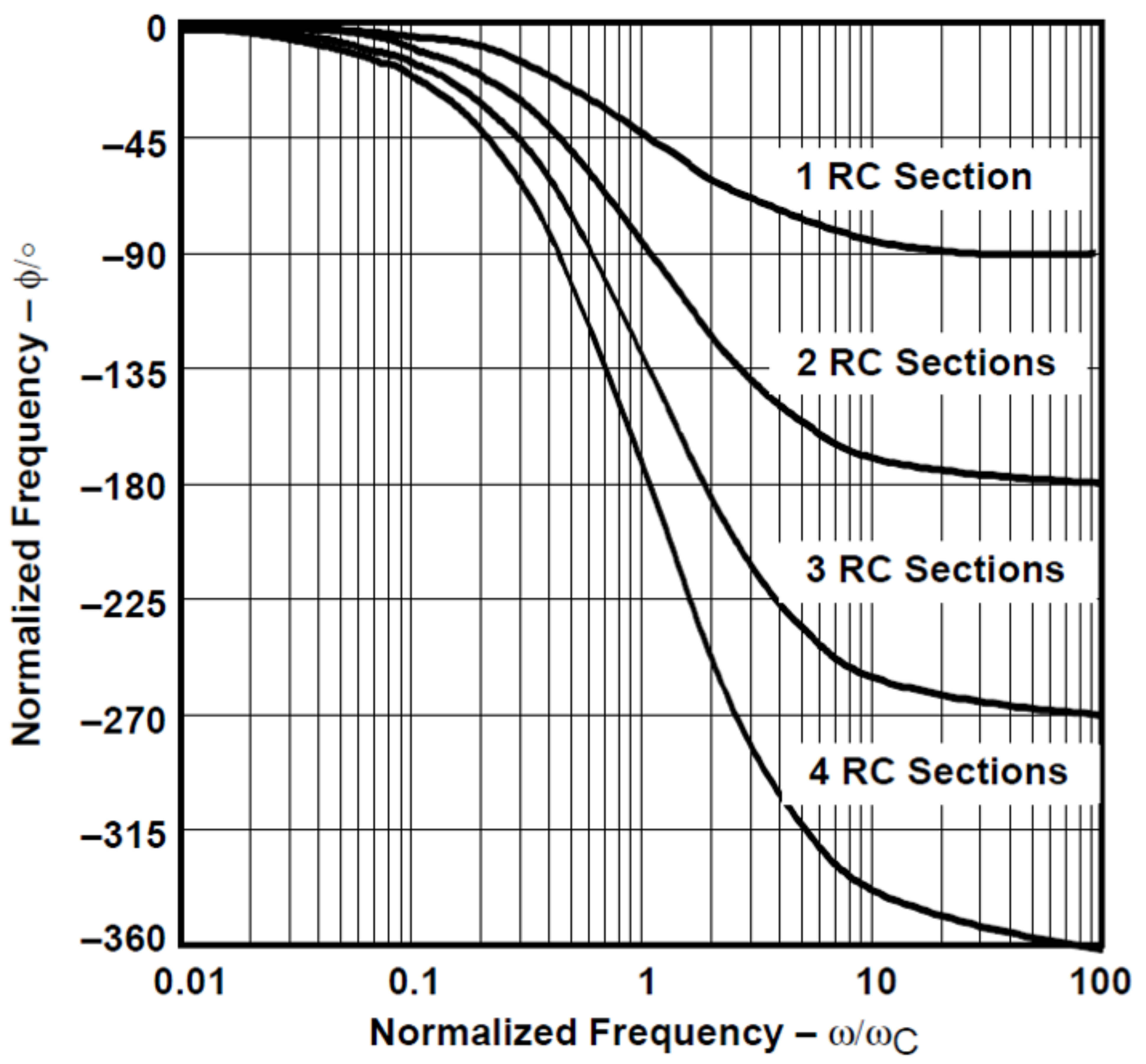
- Bode plot of low pass:



$$Z = \frac{1}{\sqrt{1 + (\omega RC)^2}} \qquad \tan \varphi = -\omega RC$$

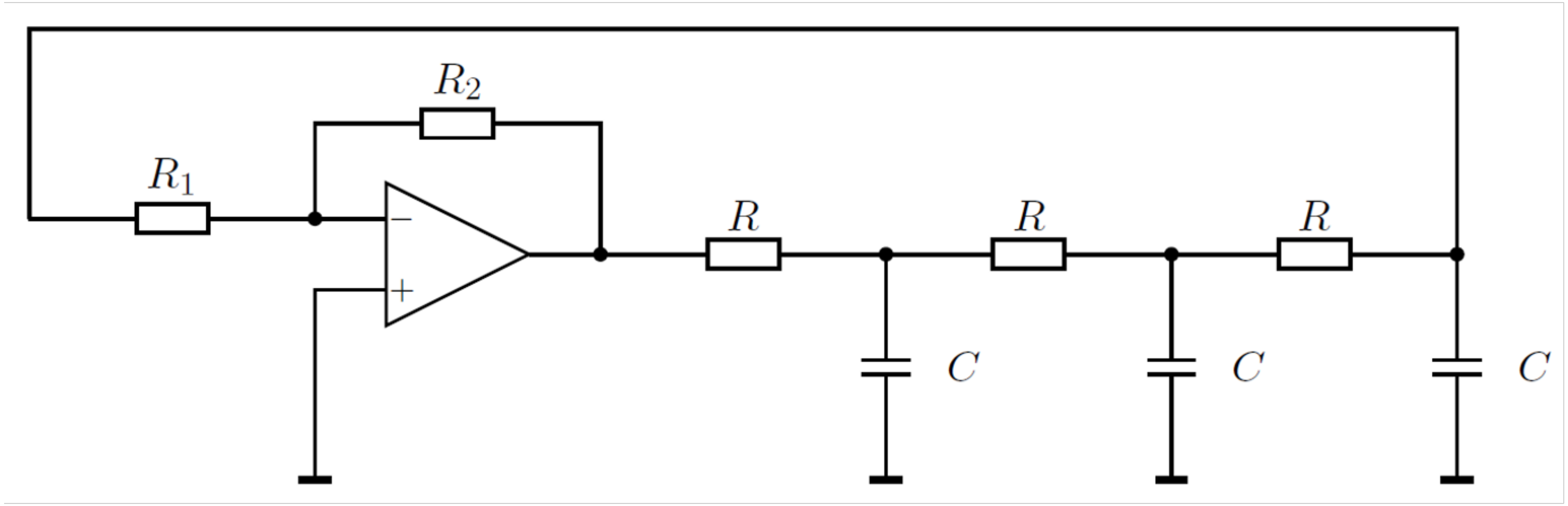
between 0 and 90 degrees phase shift

combination of multiple low passes



Phase Shift Oscillator

Phasenschieber-Oszillator



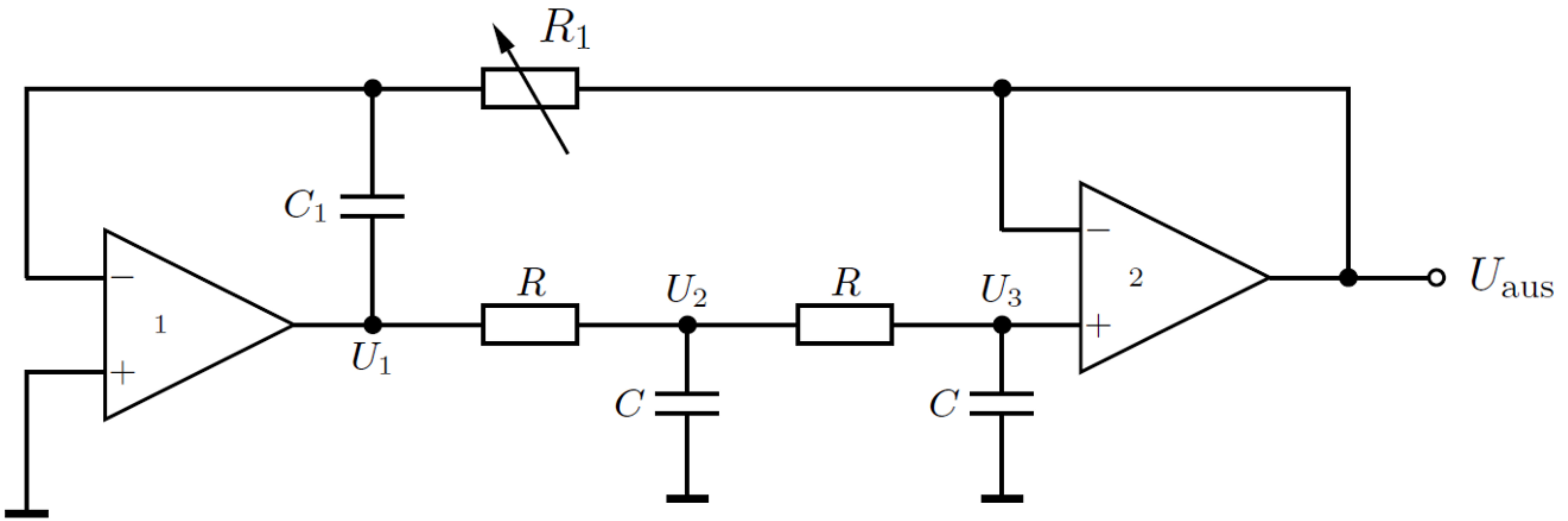
- Without external input: Oscillation for phase shifts of +- 360 degrees
- Resonance frequency depends on RC (here ω = 1.73/RC - 60 degrees per low pass)

$U_{aus}(T) = -K_R\, A_D\, U_{aus}(t=0) = +U_{aus}(t=0\_$

Feedback network K_R contributes 180 degrees , inverting amplifier another 180 degrees.

Phase Shift Oscillator

In the Practical Course



- One integrator (OpAmp 1), two low passes, one voltage buffer
  - Adjustable via R1

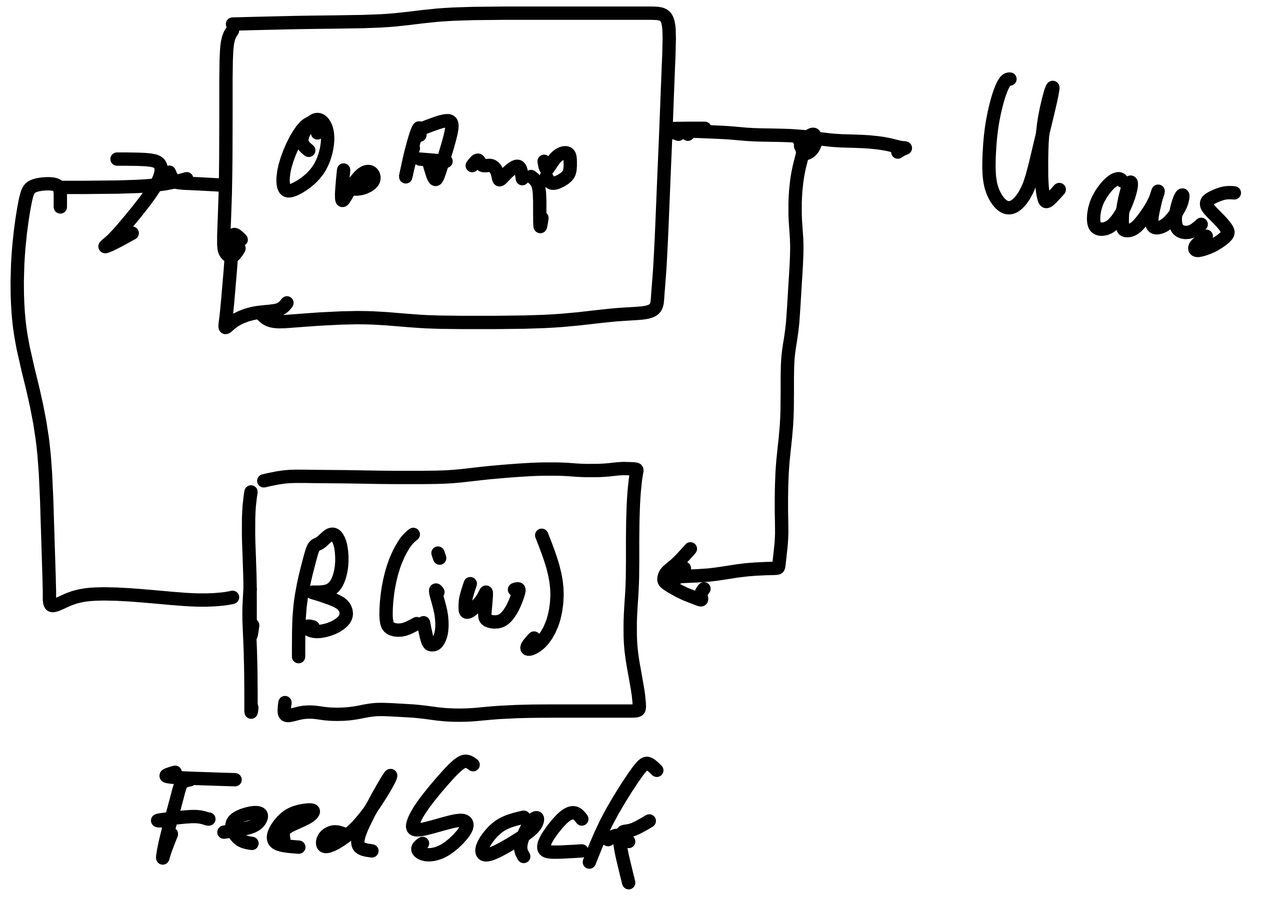
Here: No further details - see practical course!

Oscillation Conditions

General Considerations

- Gain of an OpAmp-based amplifier with negative feedback:

$$A = \frac{U_{aus}}{U_{ein}} = \frac{A_D}{1 + \beta A_D}$$



- 3 scenarios:
  - Loop gain $|\beta A_D| >> 1$:
    Strong feedback, low gain:
    -> stable behavior

$$A = \frac{A_D}{1 + \beta A_D} \approx \frac{1}{\beta}$$

  - Loop gain $|\beta A_D| << 1$:
    Weak feedback, very high gain $A \sim A_D$
    -> stable behavior (not ideal for “normal” amplifiers, but ok as trigger, comparator, …)
  - Loop gain $|\beta A_D| \sim 1$: Here it depends on the phase!
    For $\beta A_D \sim 1$: similar to weak feedback,
    $\beta A_D \sim -1$: Oscillation (***Barkhausen Criterion***)

    Here extreme gain (A diverges), also without further input.

Not good for amplifiers!

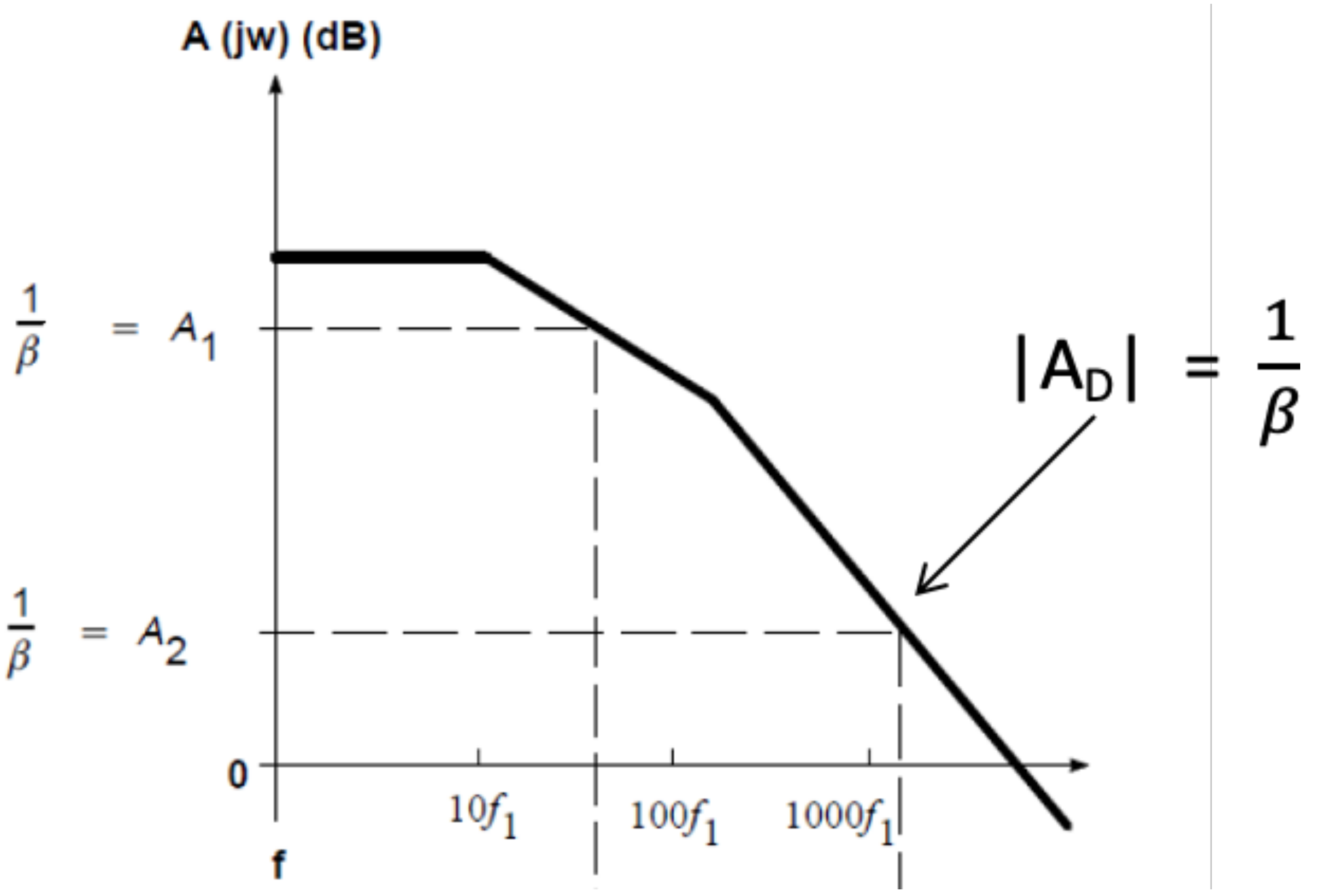
$$U_{aus}(T) = -\beta\, A_D\, U_-(t=0) = -\beta\, A_D\, U_{aus}(t=0) = +U_{aus}(t=0)$$

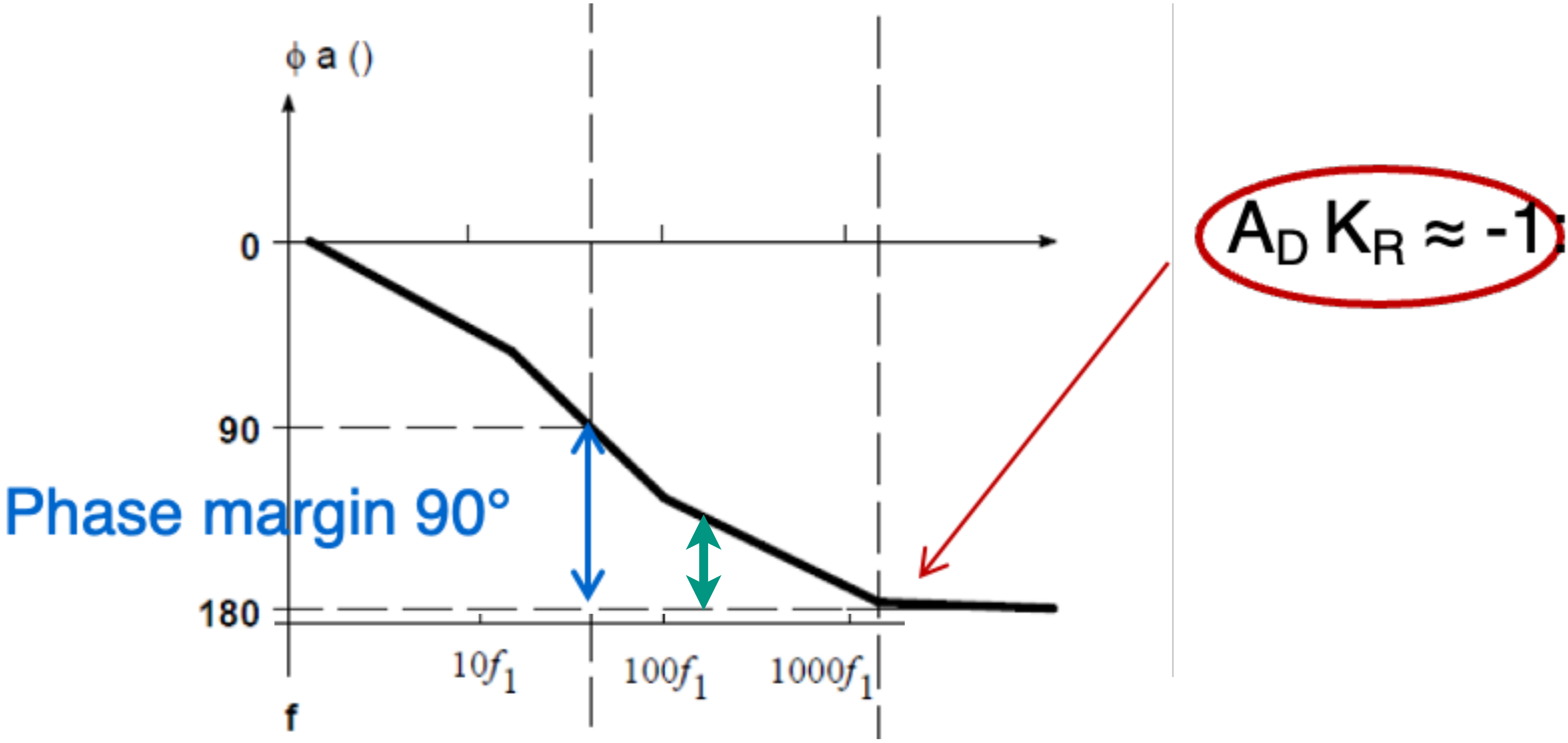
Phase Margin of Amplifiers

Phasenreserve

- Since gain and phase shift change with frequency amplifiers can always enter the “danger zone” under certain conditions.

Simplified representation via Bode Plots:





In general: A phase margin of 45 degrees is considered “safe”.

Defines the maximum usable range in frequency.

OpAmps - A first Conclusion

- OpAmps have many other applications - some examples still later in the lecture, such as DC-DC converters

Electronics for Physicists

Analog Electronics

Chapter 5; Lecture 08 Part II

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Chapter 5

Transistors - Basics

- Bipolar Transistors Introduction
- Basic Transitor Circuits

Overview

Bipolar Transistors Introduction

In: Chapter 5: Transistor Basics

Transistors

One of the greatest Inventions of the 20th Century

- The basis of all modern microelectronics:
  An active component - switching and amplification of voltages and currents, can also act as adjustable resistor.
  The basic building block of digital logic.

  Concept of the field effect transistor (FET) already introduced in 1925 (Patent Lilienfeld, 1925) - technical capabilities back then not sufficient for implementation.

  First functional transistor: 1947 by Bardeen, Brattain, Shockley (Bell Labs): Bipolar transistor

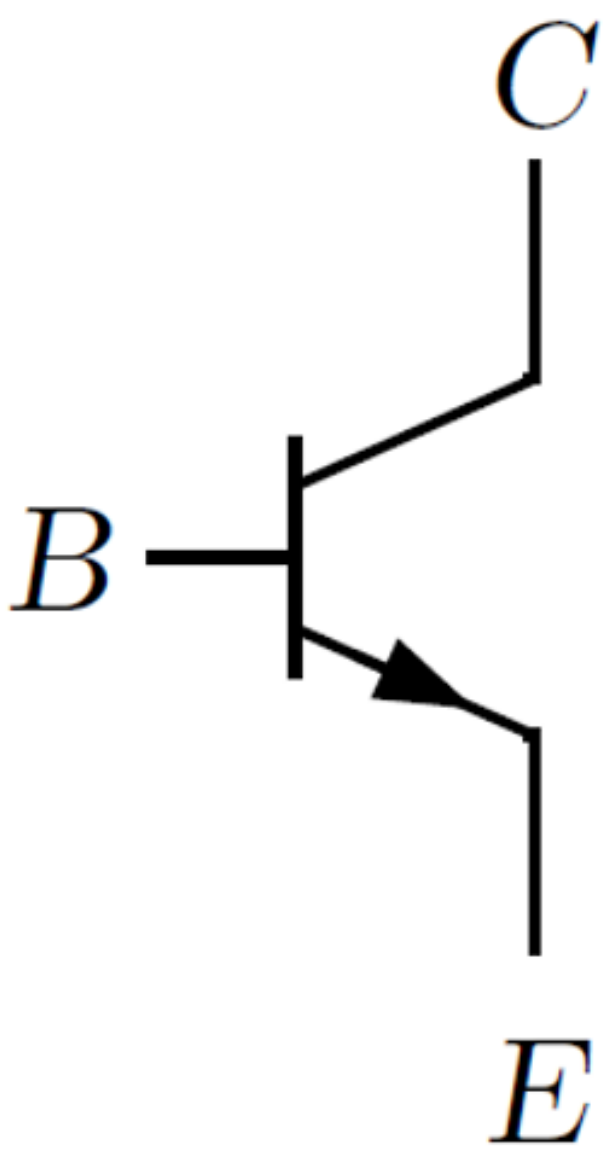
Nobel Prize 1956

Transistor Types

- Bipolar transistor (BJT)
- Field effect transistors:
  - Junction Field Effect Transistor (JFET)
  - Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

collektor / Kollector

base / Basis

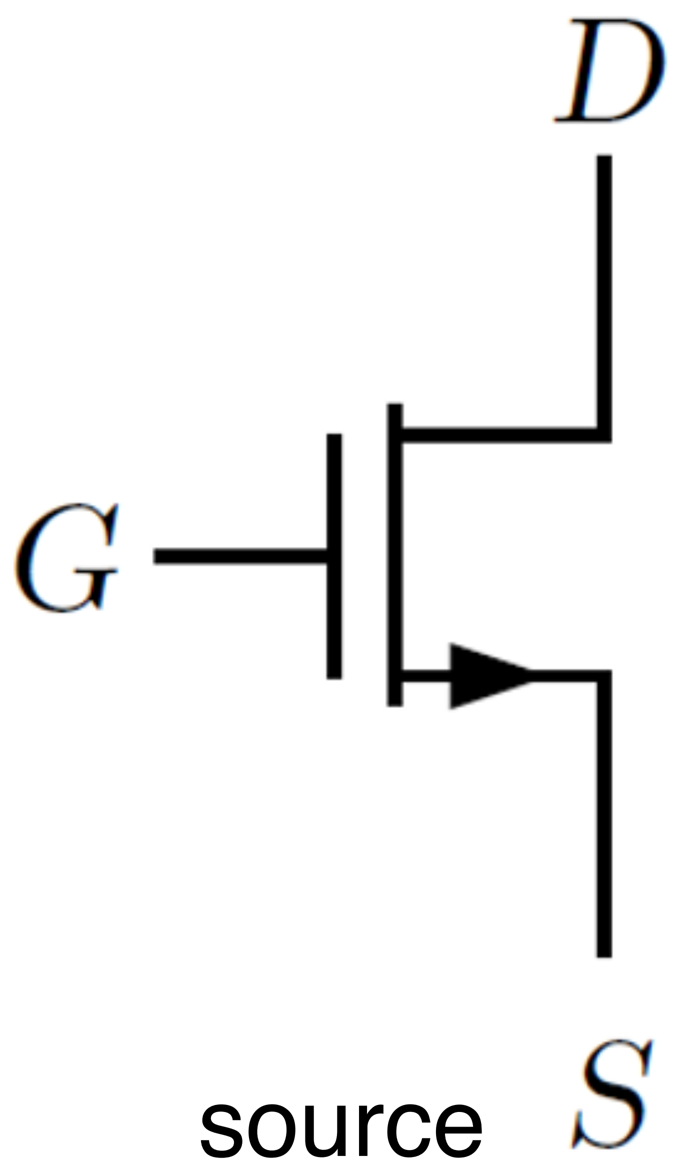


emitter

npn BJT

drain

gate



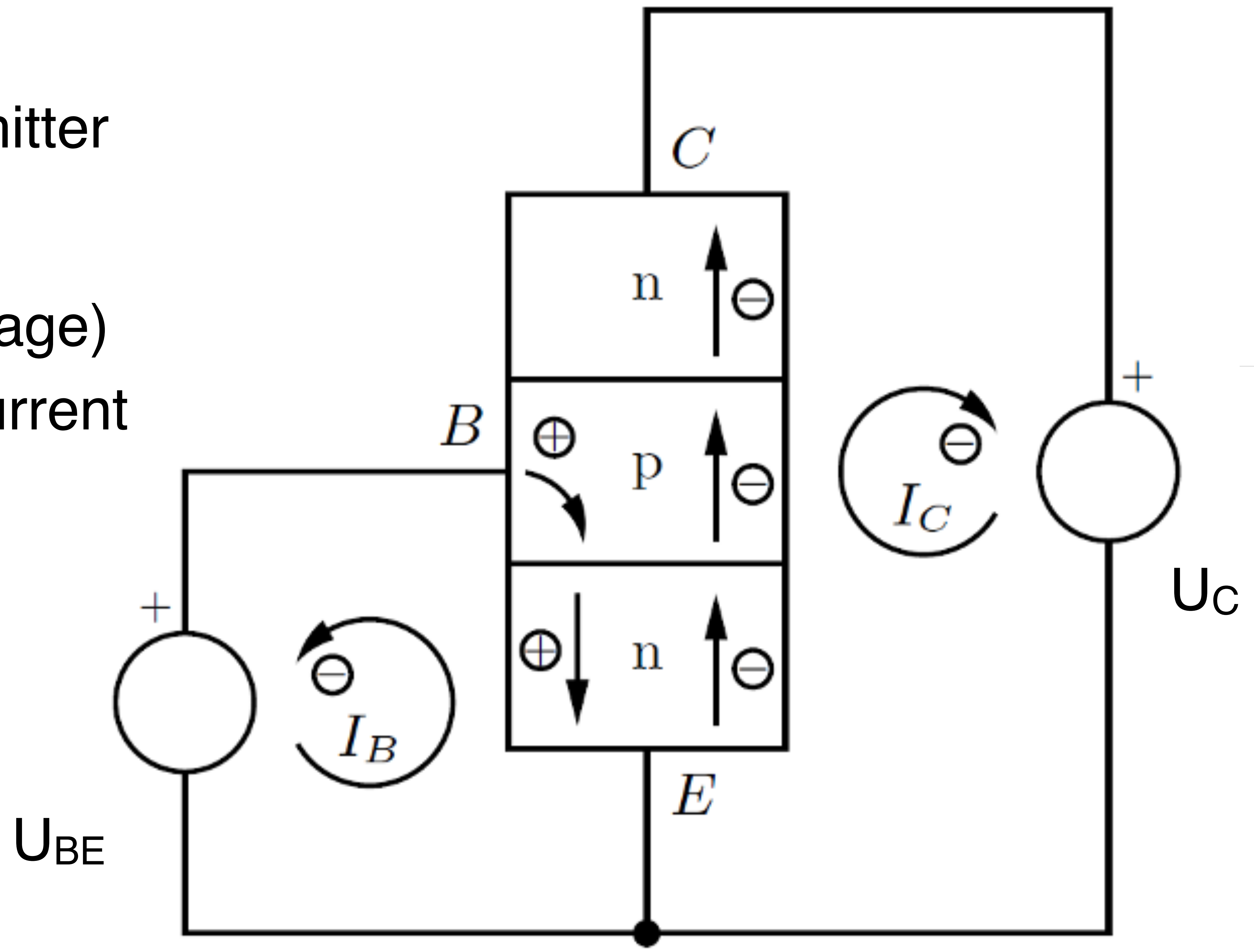
source

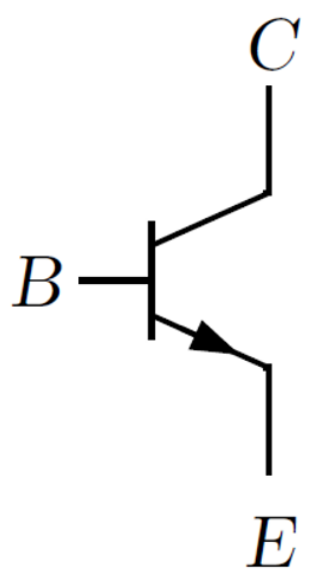
NMOS MOSFET

(in principle the body (“Substrat”) as 4th connection) npn transistor

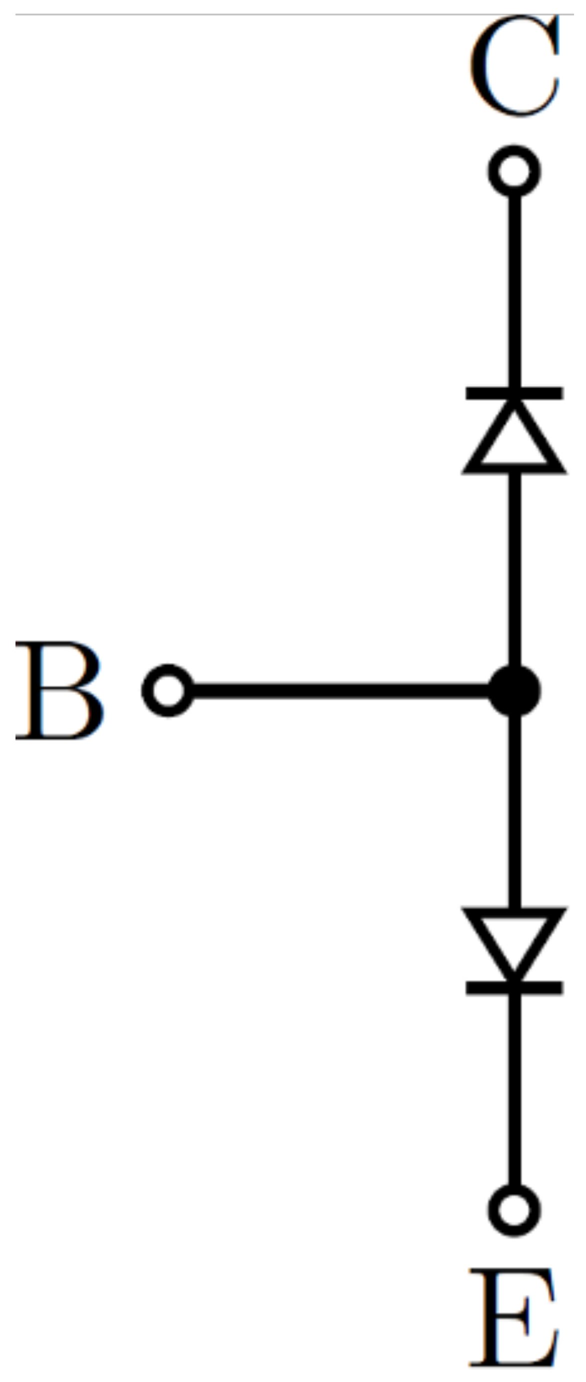
Collector-base-emitter

base current (voltage)
drives collector current





=>



Normally: $U_B > U_E$

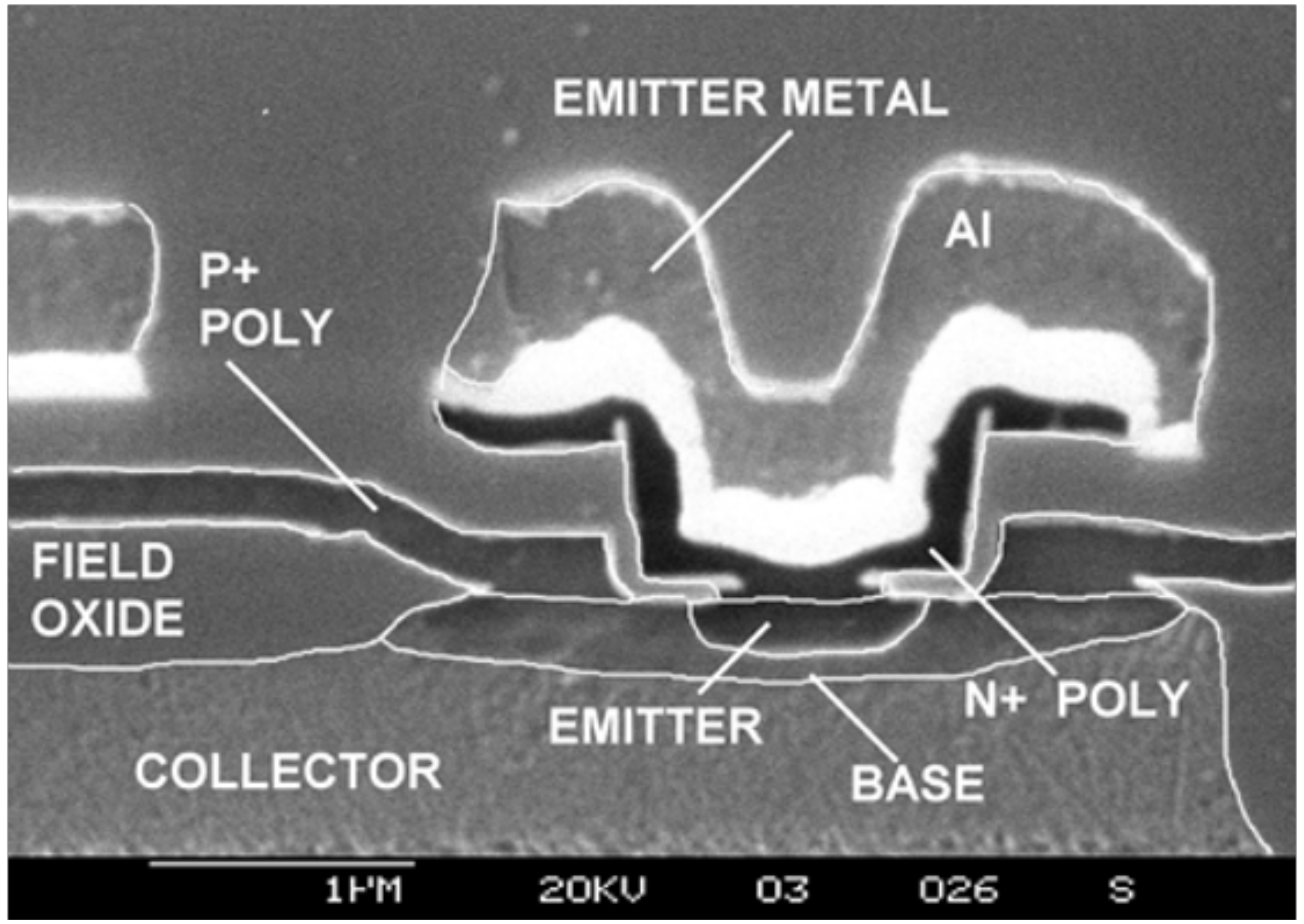
For $U_C > U_B$: collector current:
Electrons from E to B
enable current from E to C

Thin base layer:
< diffusion length of charge carriers

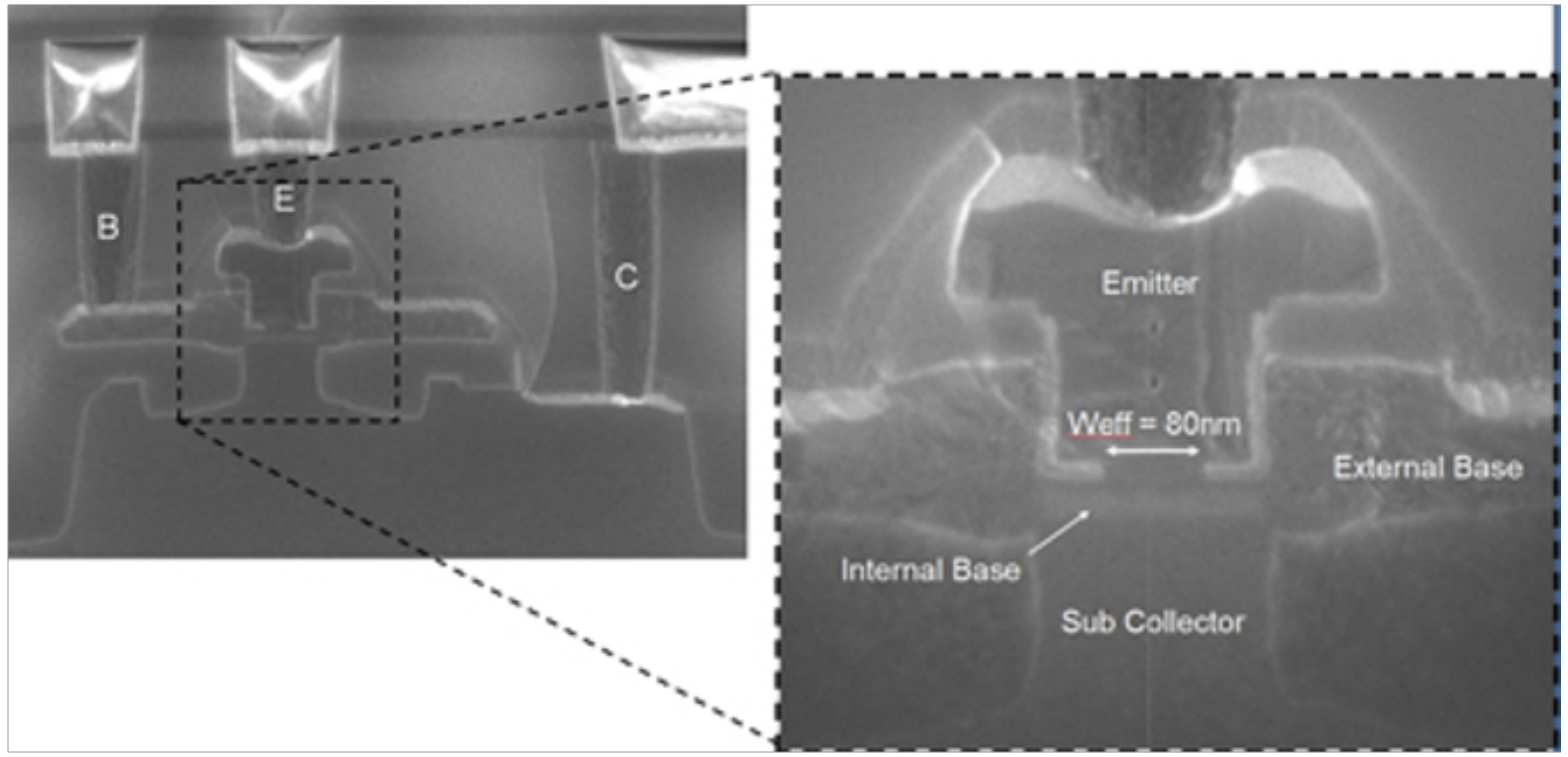
$$\frac{I_C}{I_B} \sim \frac{N_{D_{Emitter}}}{N_{A_{Basis}}} \gg 1$$

The bipolar Transistor

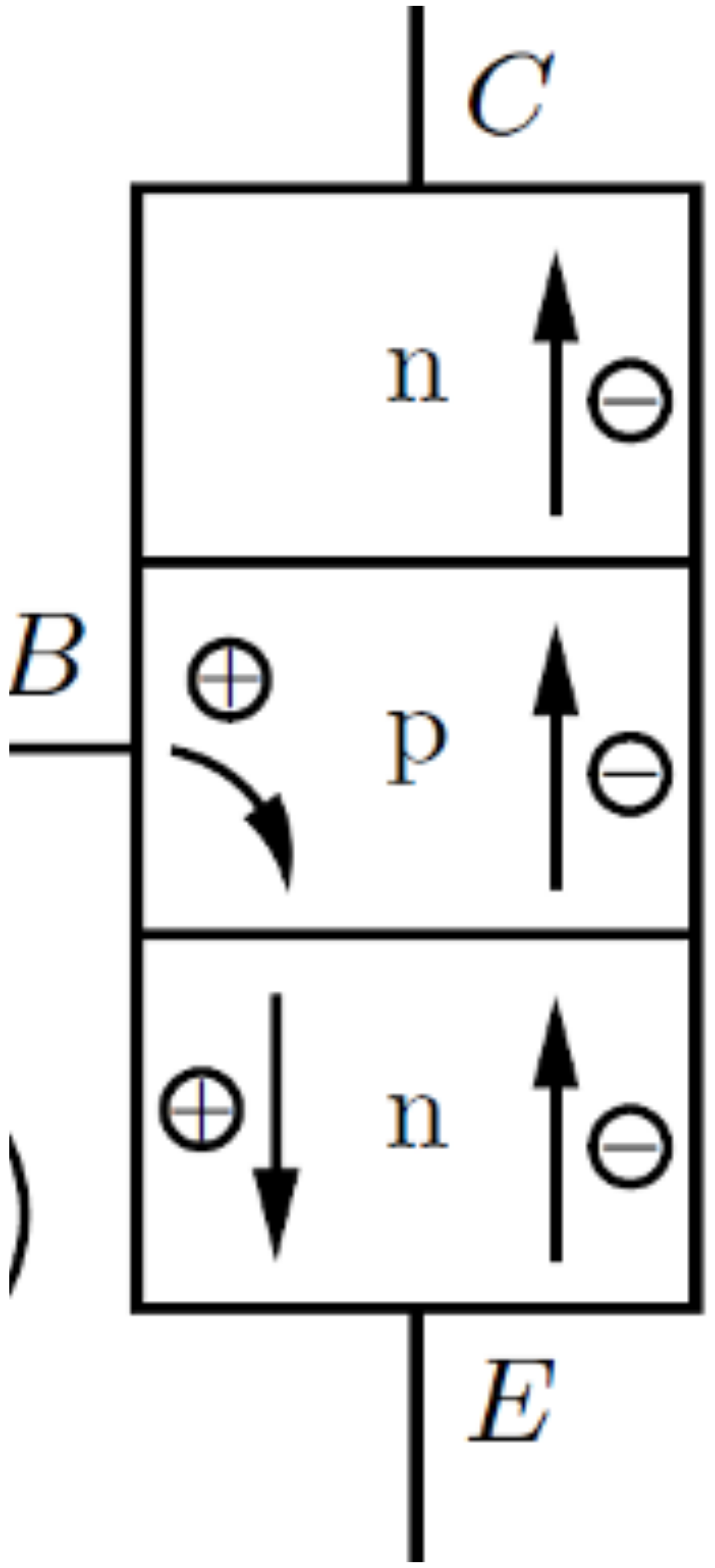
Under the Microscope



Source: Raytheon

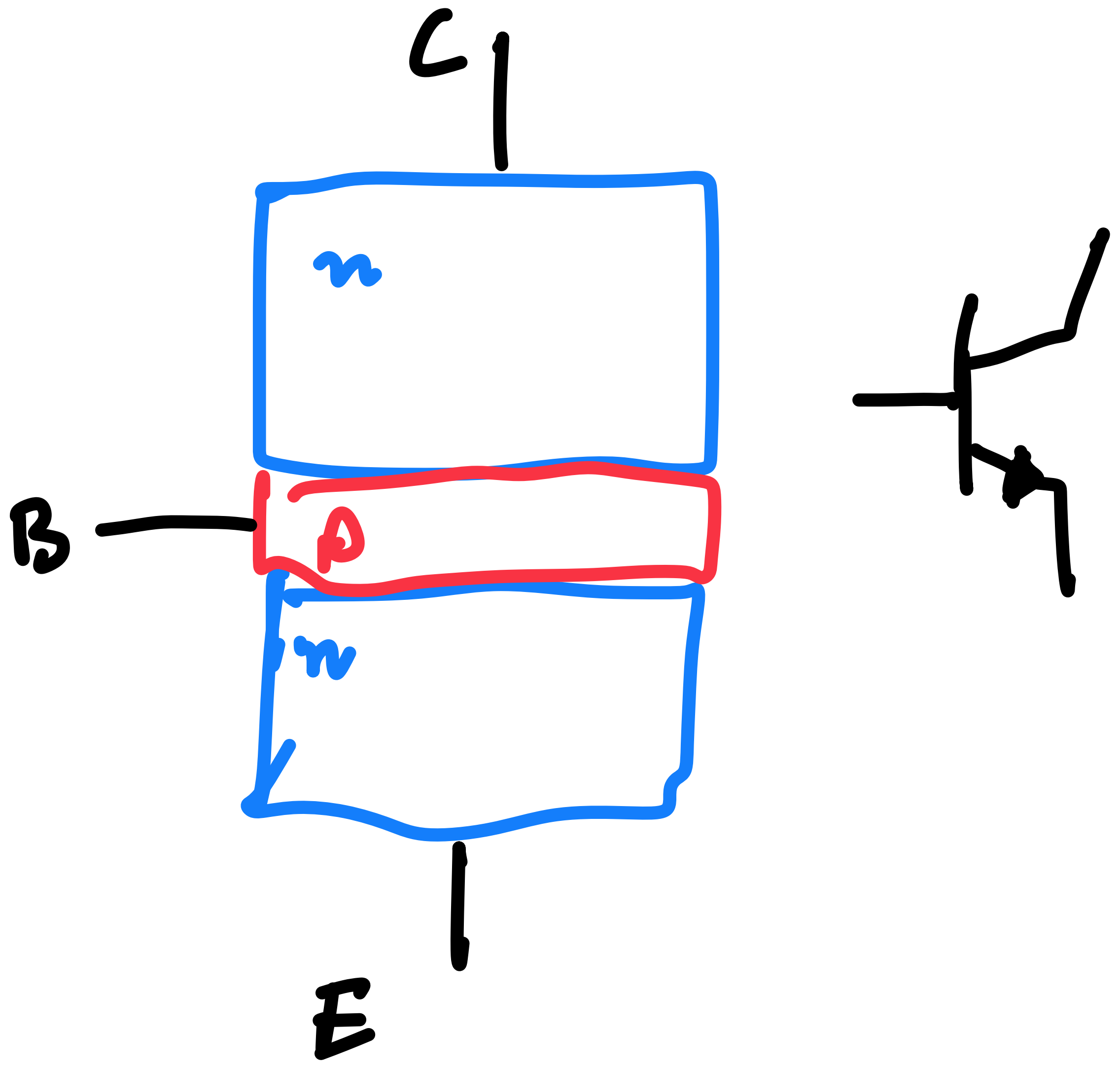


Source: IMEC

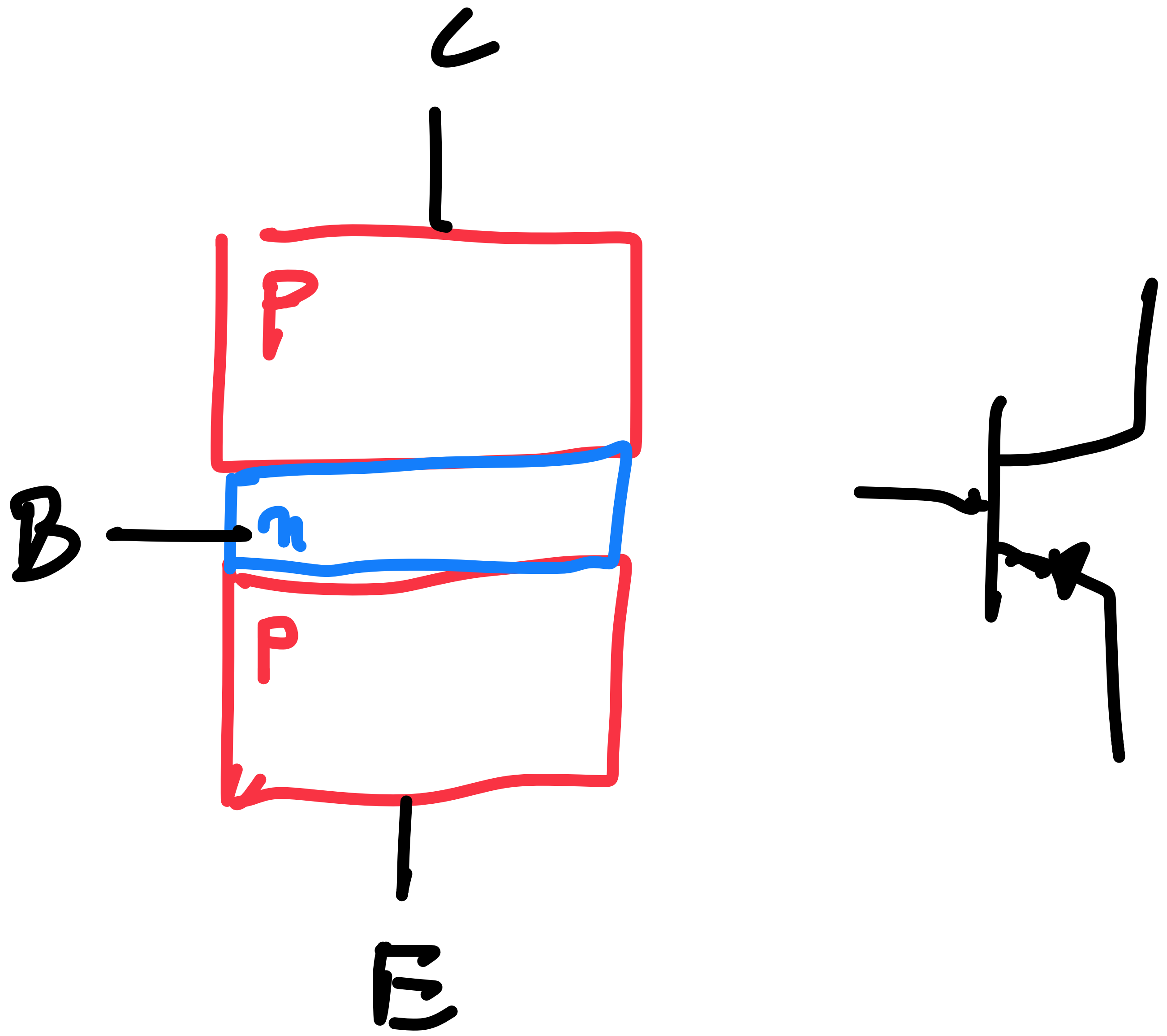


The bipolar Transistor

npn and pnp



npn



pnp

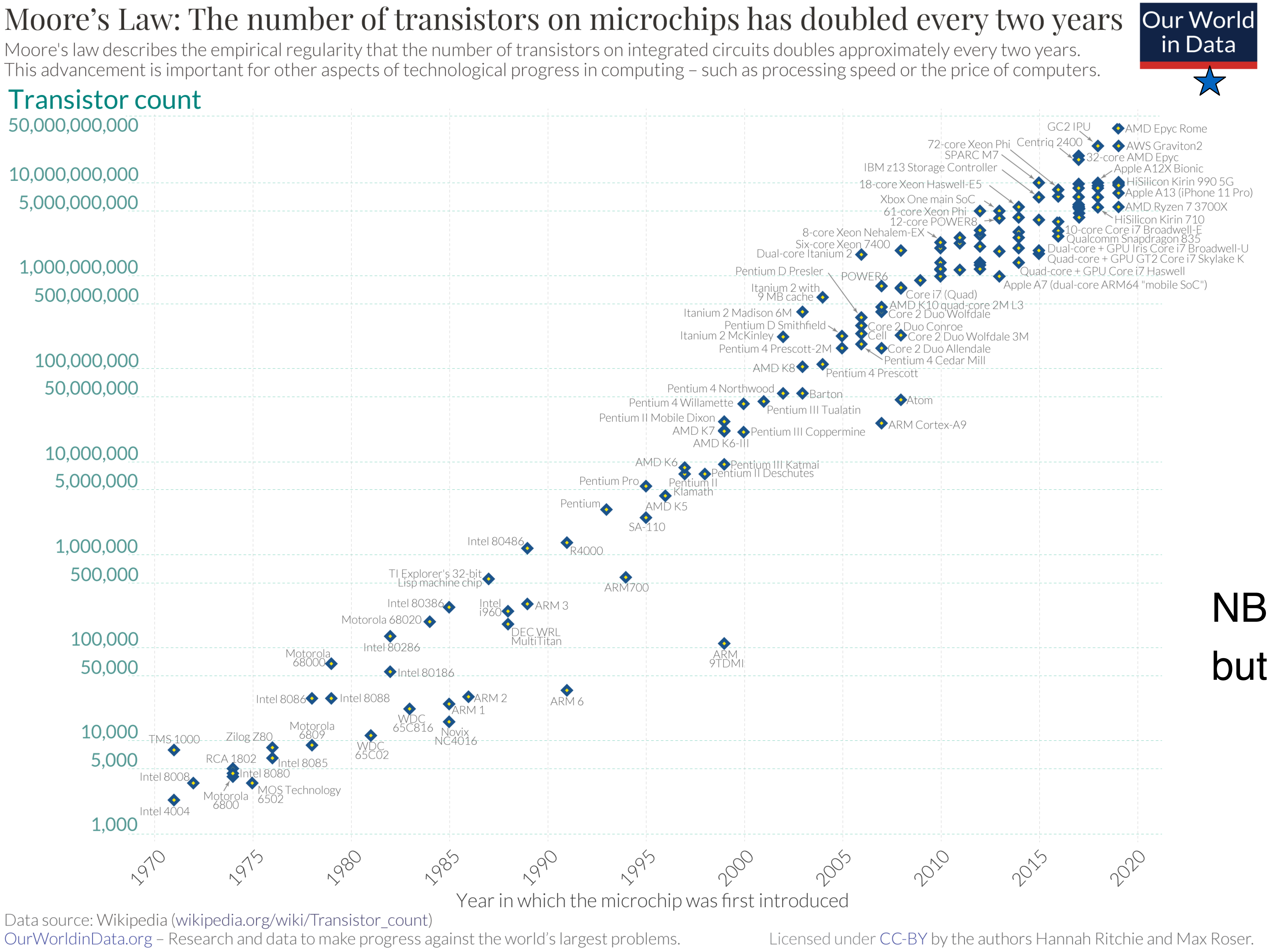
- Same principle, swapped voltage sign:
  - npn: Positive base voltage U_{BE} results in a collector current I_C (via electrons)
  - pnp: Negative base voltage U_{BE} results in a collector current I_C (via holes)

=> Due to hole-driven currents a pnp-transistor has long switching times.

npn are the by far more common transistors.

Moore’s Law

The Microelectronics Revolution



Apple M3 Max (2023)

92 G transistors

NB: These are not BJTs, but FETs

Next Lectures:

Analog 09 - Chapter 05 - Tuesday, December 19

Digital - Thursday, December 21

Time Plan for Next Lectures

A few Changes coming up!

Calender Week	Tuesday	Thursday
45	07.11. **Analog**	09.11. **Digital**
46	14.11. **Analog**	16.11. **Digital**
47	21.11. **Digital**	23.11. **Analog**
48	28.11. **Digital**	30.11. **Digital**
49	05.12. **Digital**	07.12. **Analog**
50	12.12. **Digital**	14.12. **Analog**
51	19.12. **Analog**	21.12. **Digital**
2	09.01. **Analog**	11.01. **Analog**
3	16.01. **Digital**	18.01. **Digital**
4	23.01. **Analog**	25.01. **Digital**
5	30.01. **Analog**	01.02. **Digital**
6	06.02. **Analog**	08.02. **Digital**
7	13.02. **Analog**	15.02. **Digital**

Electronics for Physicists

Analog Electronics

Frank Simon
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