Electronics for Physicists

Analog Electronics

Chapter 5; Lecture 10

Frank Simon
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09.01.2024

Karlsruhe Institute of Technology

KIT, Winter 2023/24

Institute for Data Processing and Electronics

Chapter 5

Transistors - Basics

- Bipolar Transistors Introduction
- Basic Transitor Circuits

Overview

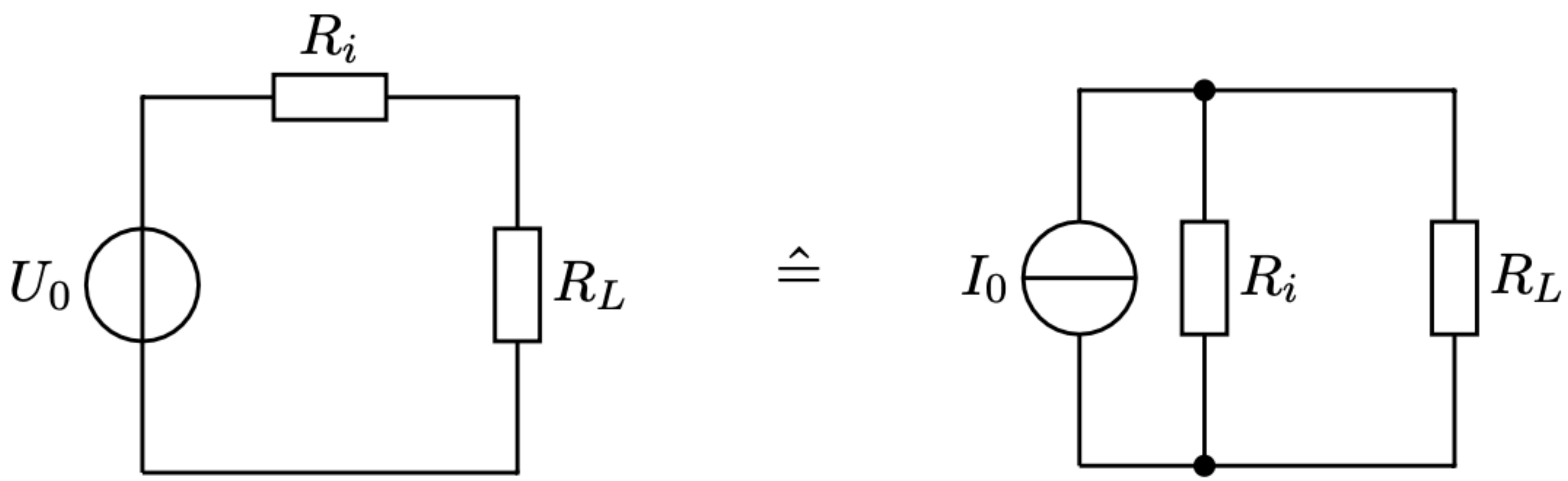
Basic Transistor Circuits - Cont’d

In: Chapter 5: Transistor Basics

Current Source

With a single Transistor

- Reminder:



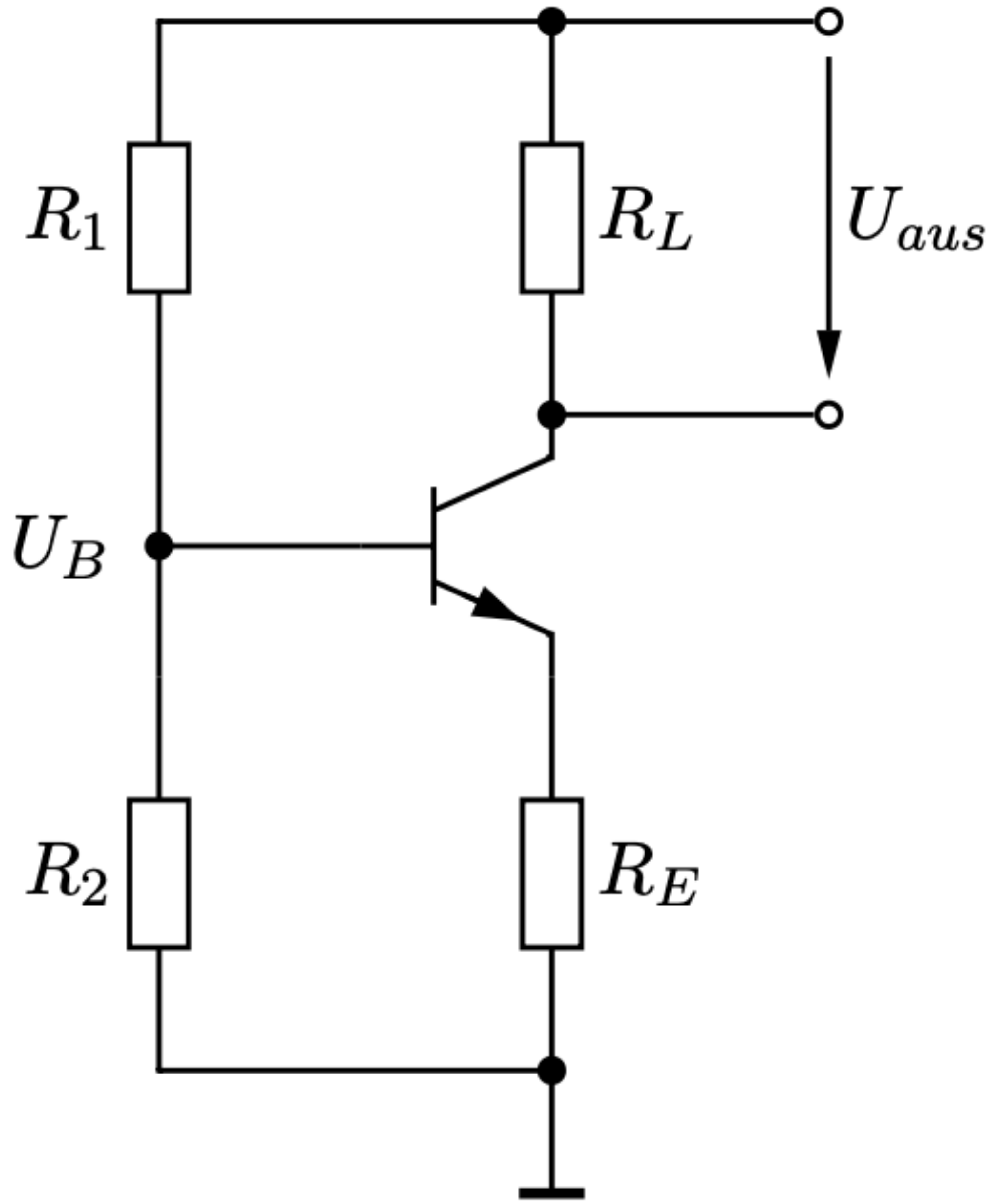
Northon Theorem (Chapter 1):

A circuit (and, with that, also a voltage source) can also be represented by a current source with corresponding internal resistor R_i.

Current Source

With a single Transistor

- The more practical solution: Resistor R_i of voltage source replaced by transistor!
  - Working point adjusted such that differential internal impedance dU_{aus}/dI_{aus} is large (as desired for current sources)



$$I_L = I_C \approx I_E = \frac{U_E}{R_E} \approx \frac{U_B - 0,7\,\mathrm{V}}{R_E}$$

With that: R_1 and R_2 define U_B, and in turn I_L

Transistor behavior makes I_L independent on R_L:

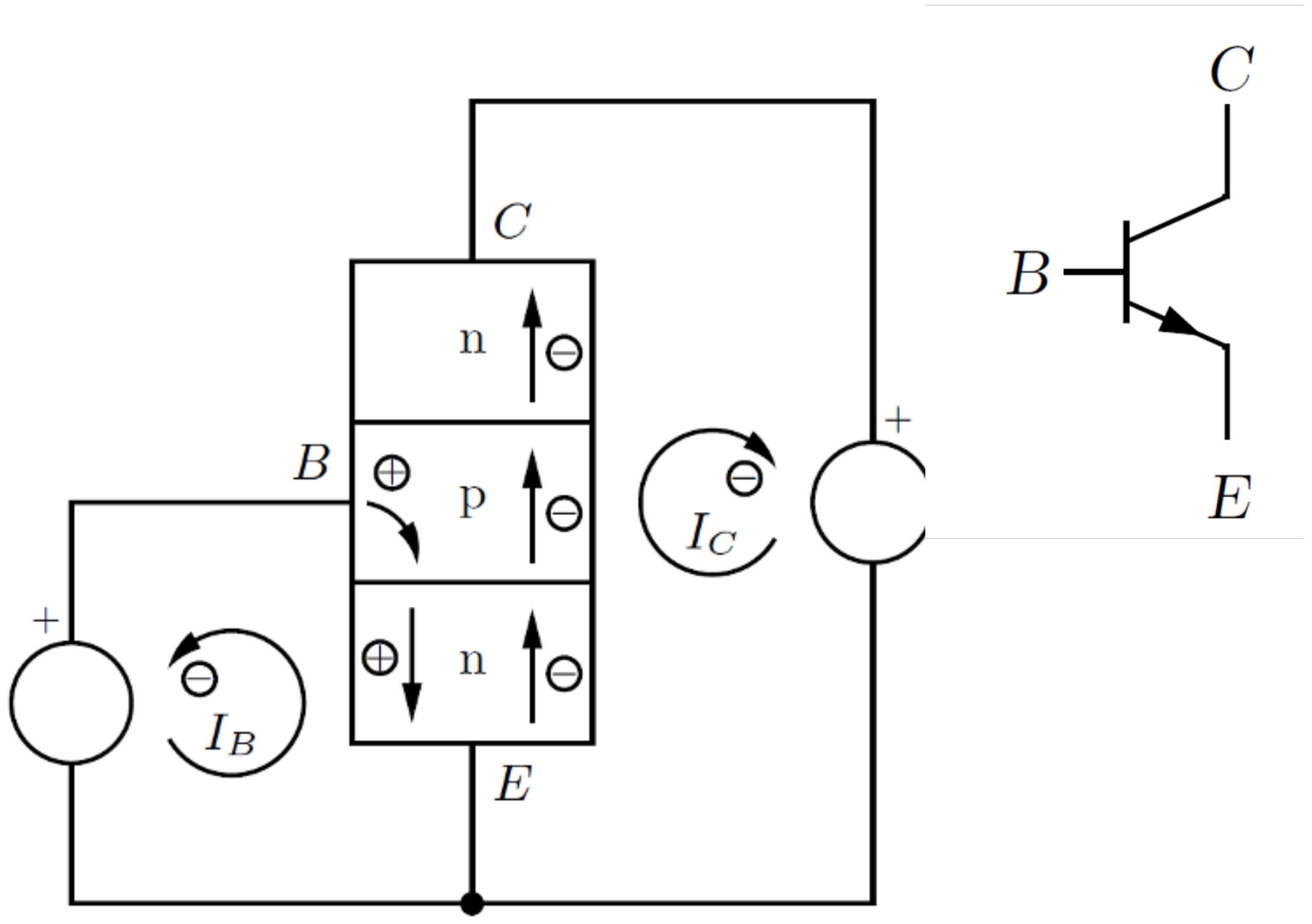
$$I_L = \frac{U_{CC} - U_C}{R_L} \quad \text{und} \quad I_L = I_C = \beta\, I_B$$

Also relevant: temperature dependence

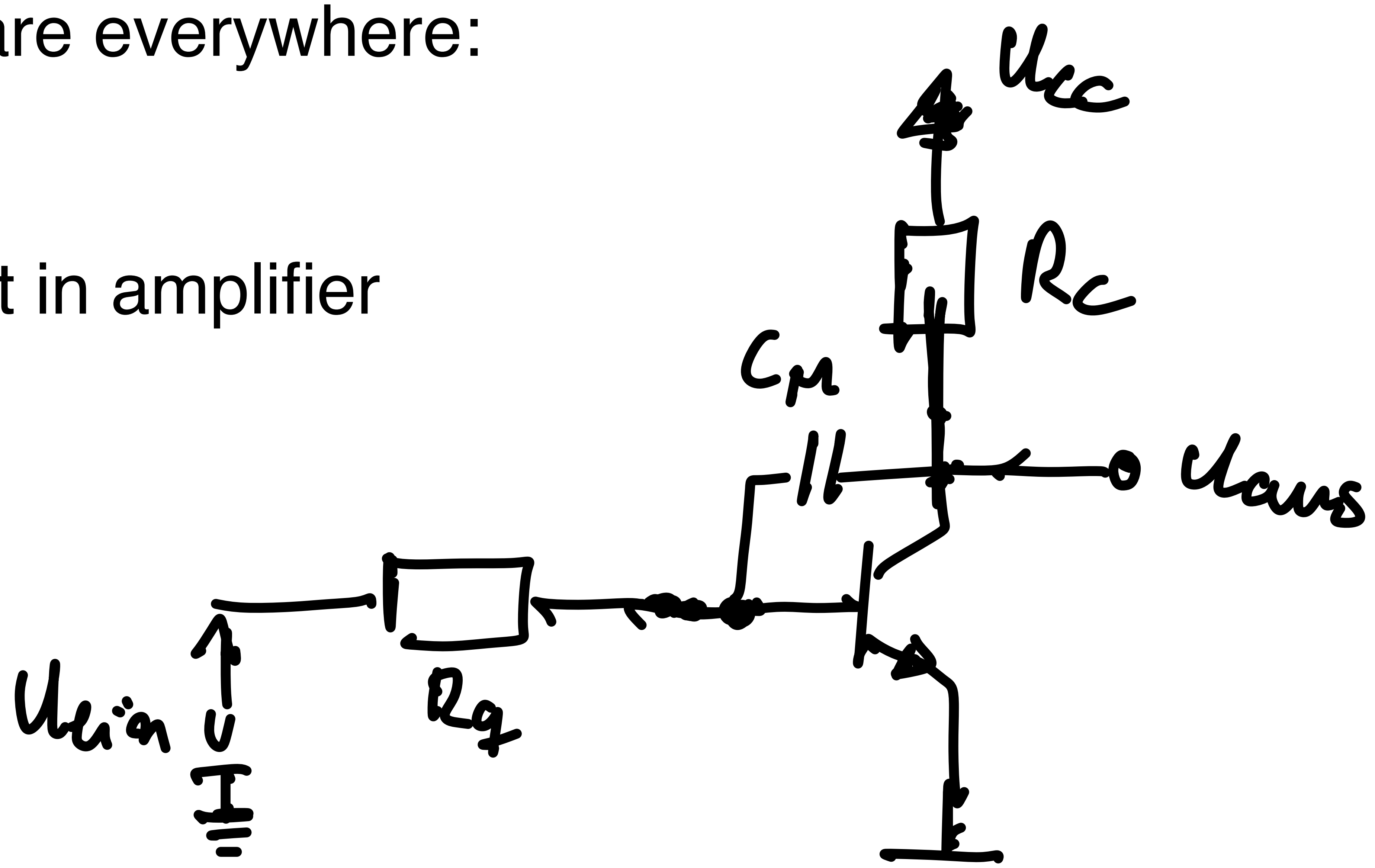
$$\frac{dI_{aus}}{dT} = -\frac{1}{R_E}\frac{dU_{BE}}{dT} \approx \frac{2}{R_E}\frac{\mathrm{mV}}{\mathrm{K}}$$

The Miller Effekt

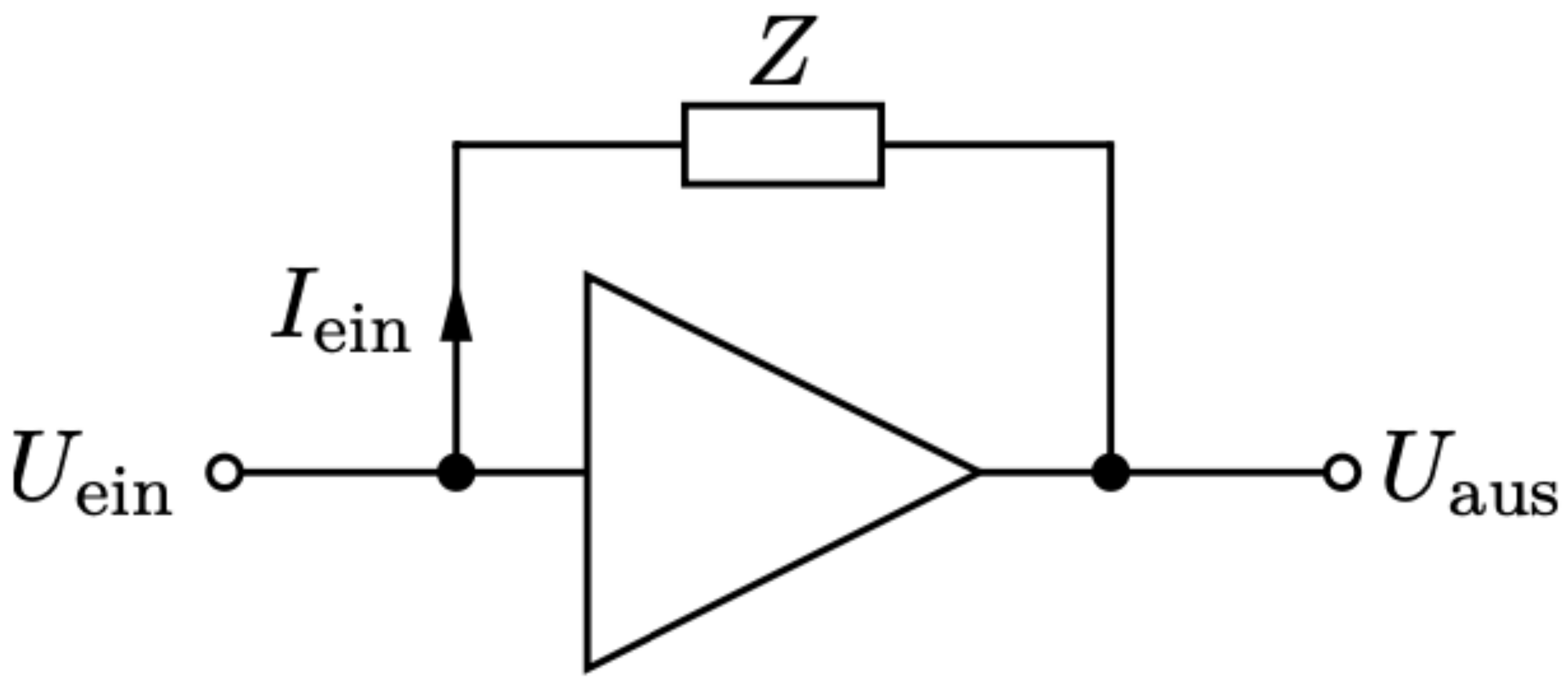
- Capacitances change frequency dependence - and they are everywhere:



Main impact in amplifier circuits:

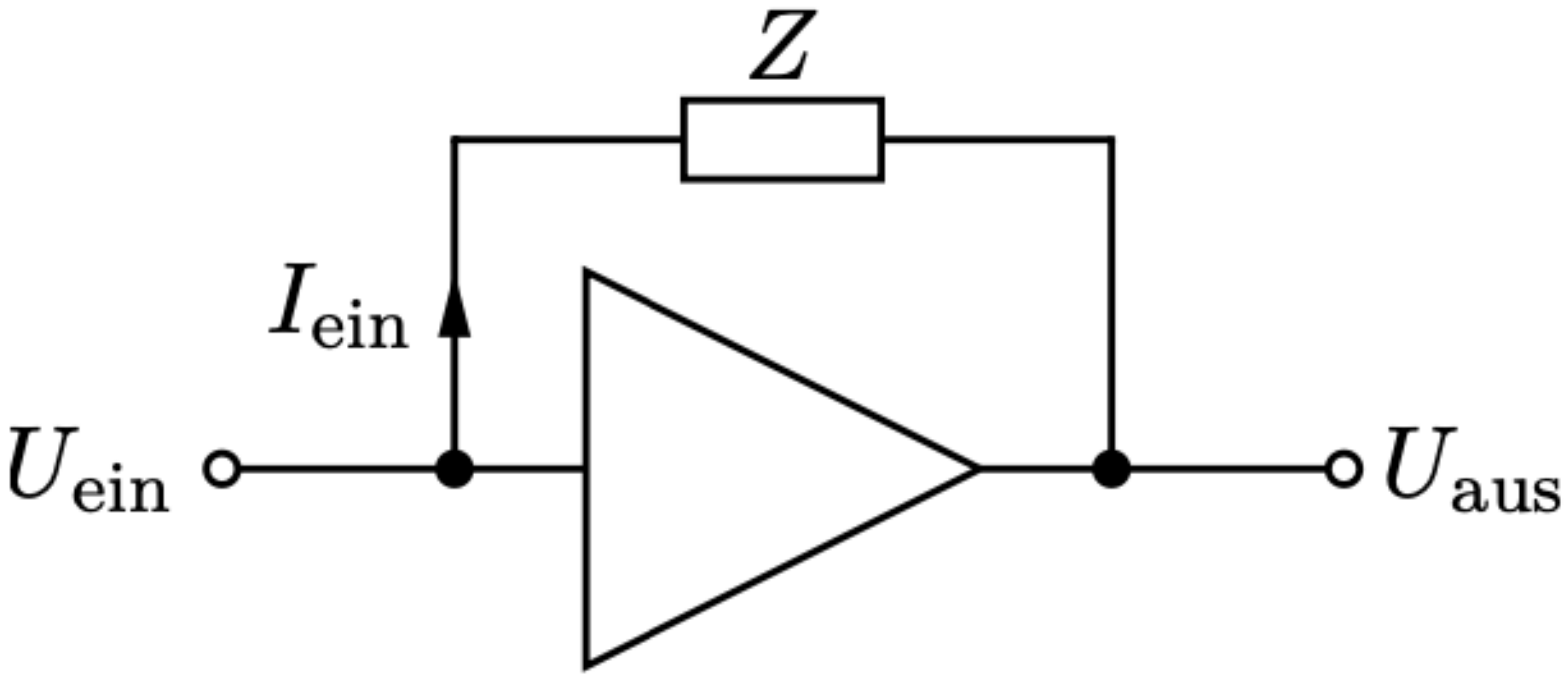


Here: Considering an amplifier with negative feedback.



The Miller Effect

Inverting Amplifier



- The impact of feedback

$$I_{ein} = \frac{U_{ein} - U_{aus}}{Z} = \frac{U_{ein} + A\,U_{ein}}{Z} = U_{ein}\,\frac{A+1}{Z}$$

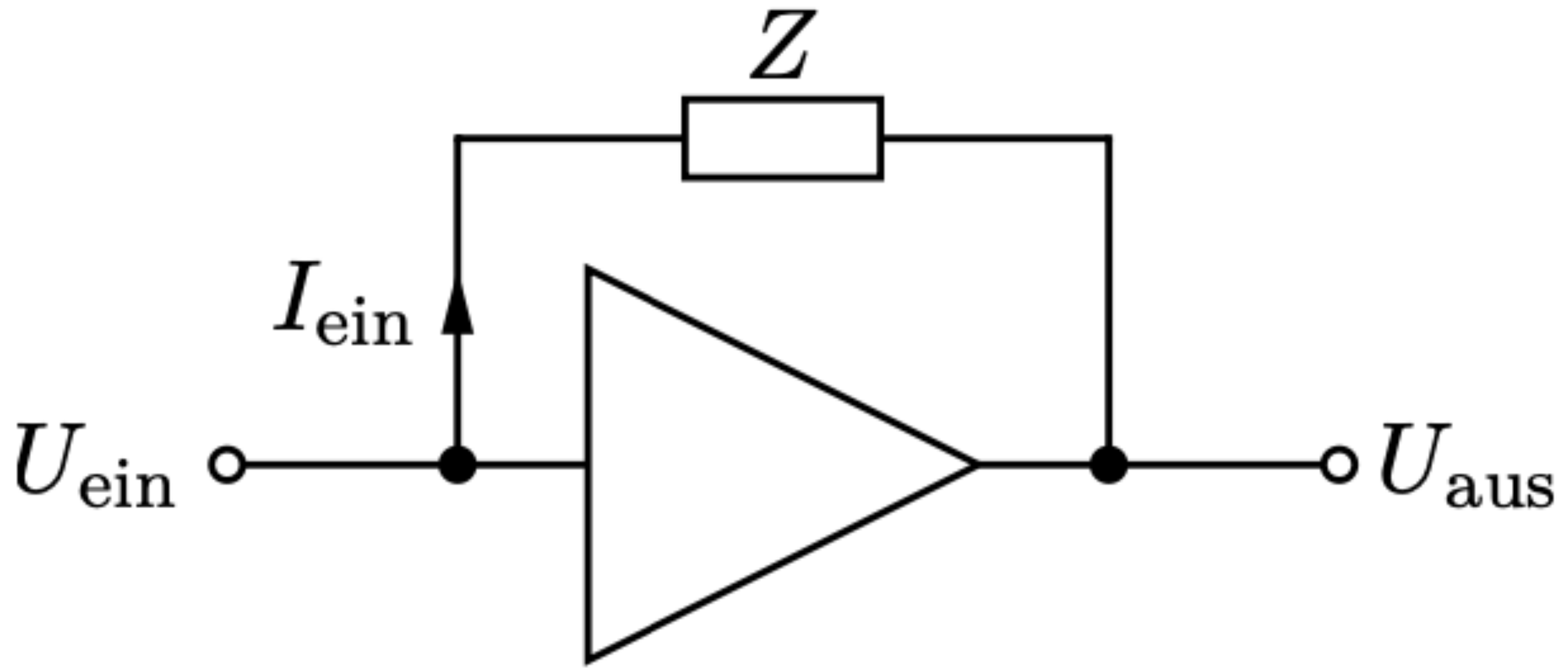
(A: gain of the circuit)

With this: input impedance of the circuit:

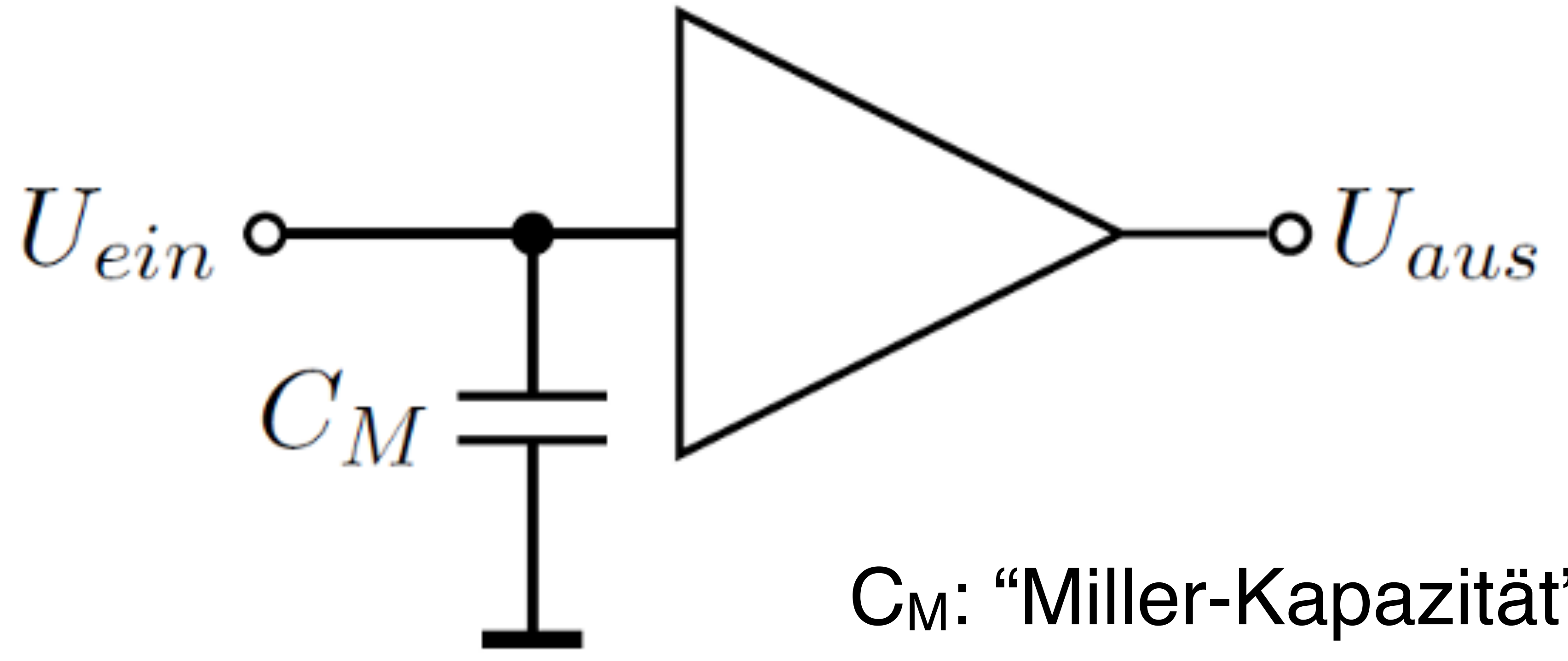
$$Z_{ein} = \frac{dU_{ein}}{dI_{ein}} = \frac{Z}{A+1}$$ and $$Z = \frac{1}{j\omega C}$$ => $$Z_{ein} = \frac{1}{j\omega C\,(A+1)}$$

The Miller Effect

Inverting Amplifier



$$Z_{ein} = \frac{1}{j\omega C\,(A+1)}$$



C_M: “Miller-Kapazität”

Consequences:

- Reduction of input impedance
- Effective increase of input capacitance by gain factor: Often several orders of magnitude (from a few pF to many)

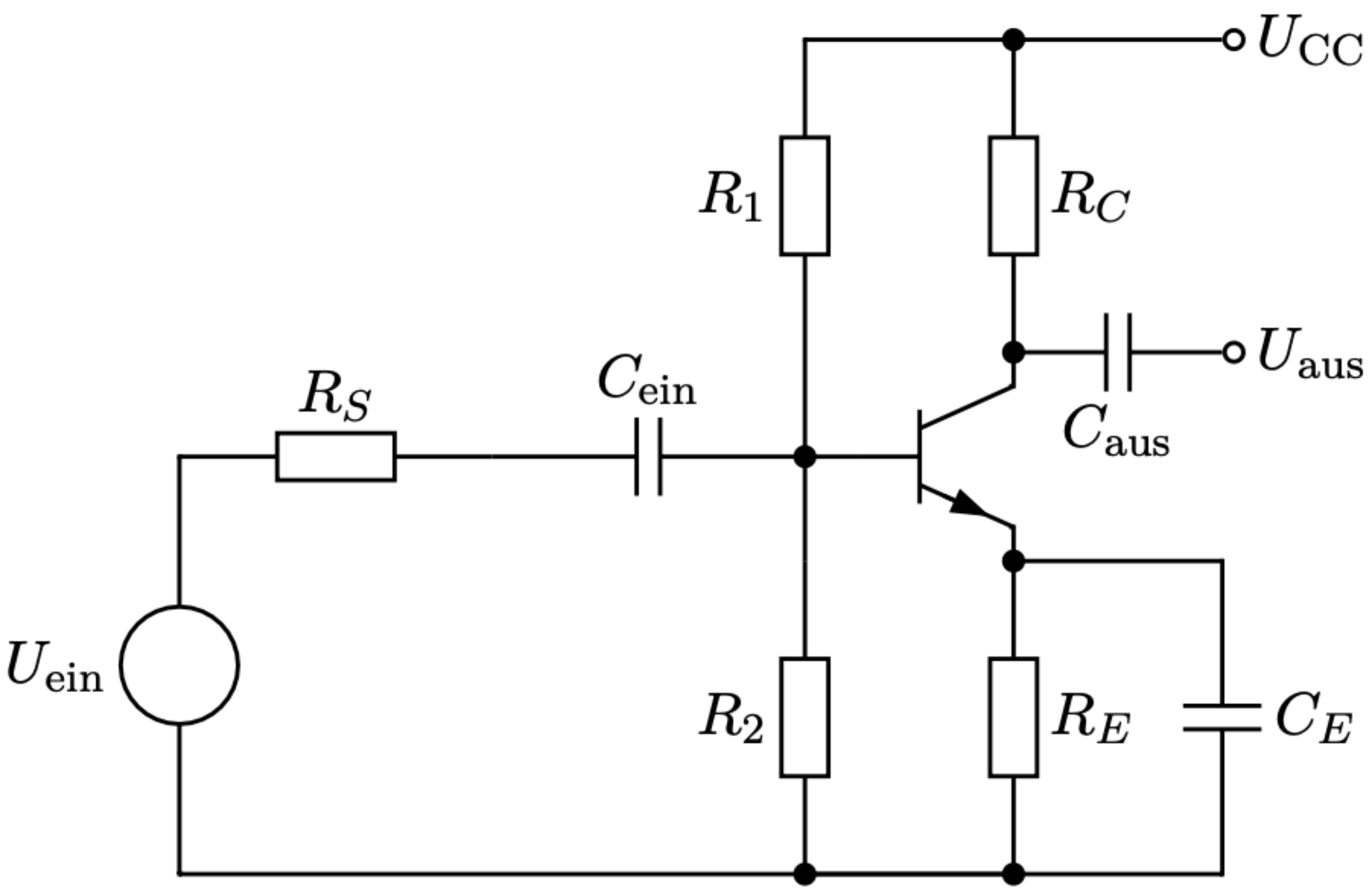
Result: Low pass with time constant $\tau = R_s C_M$

R_S: internal resistance of signal source

=> “slow down” of the amplifier

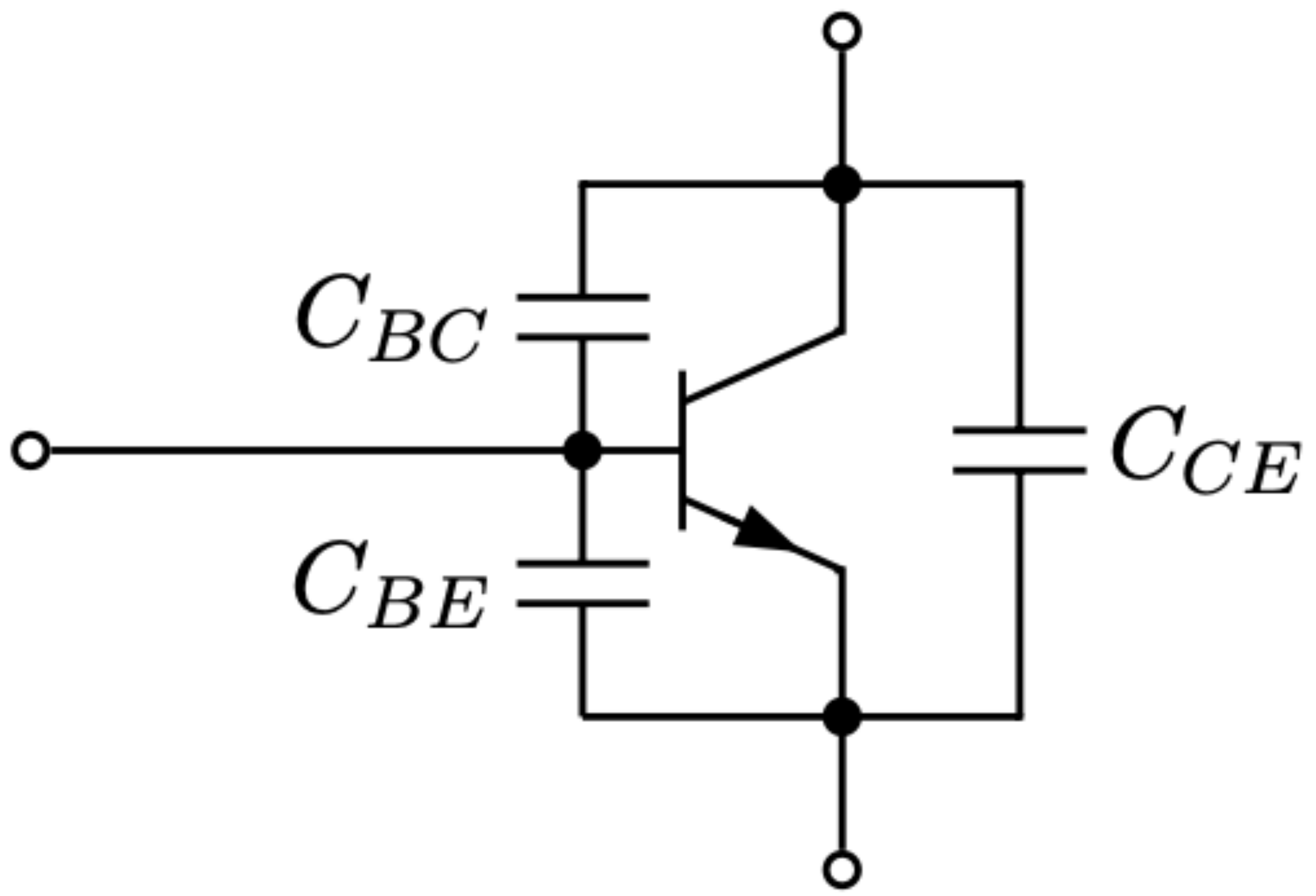
Frequency Dependence of Amplifiers

1-Transistor Amplifier



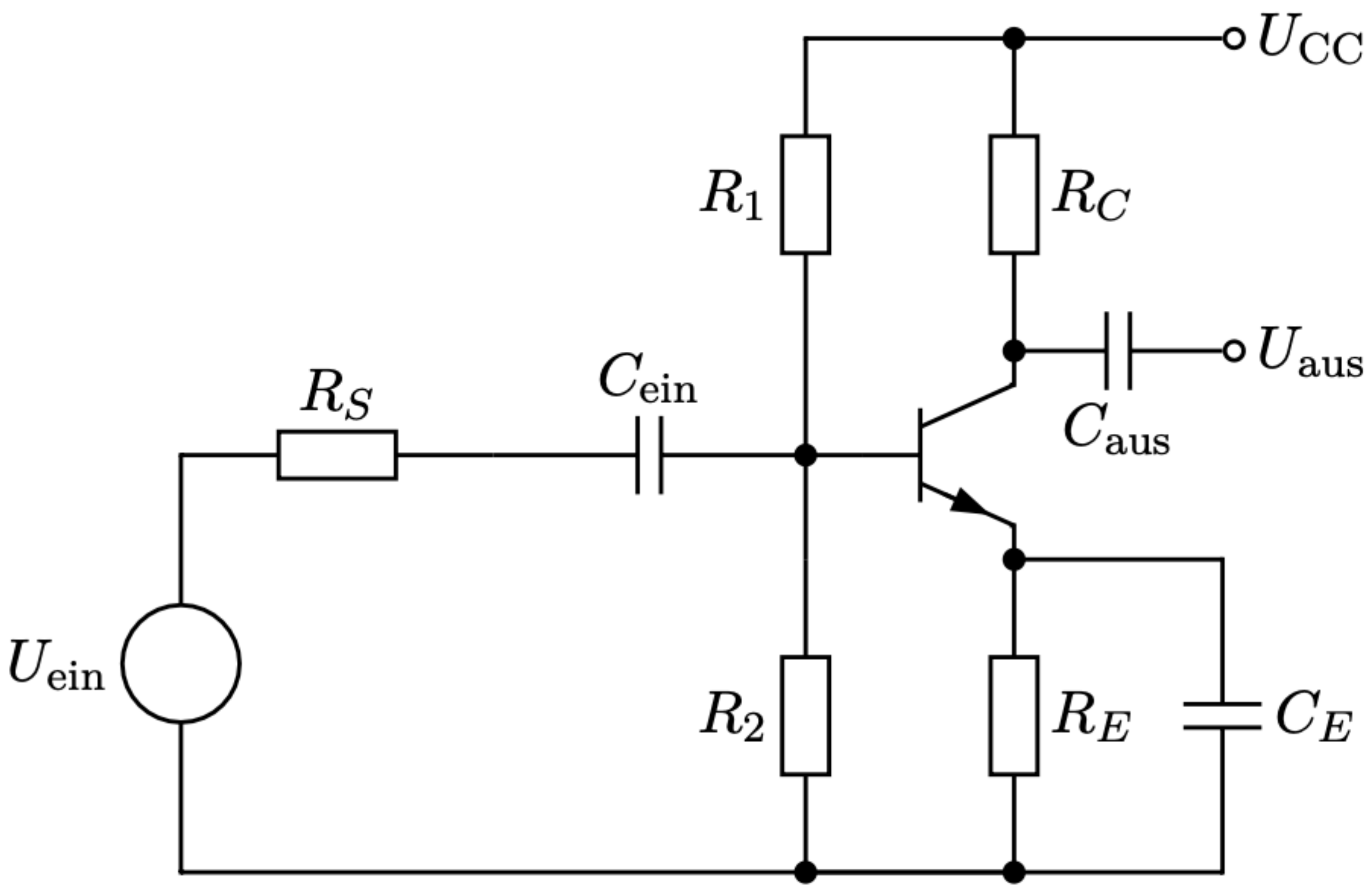
- Illustration (of a few) capacitances in a typical common emitter amplifier

On top: internal capacitances of the transistor



normally small compared to “external” capacitances

But: Miller effect for C_{BC}!



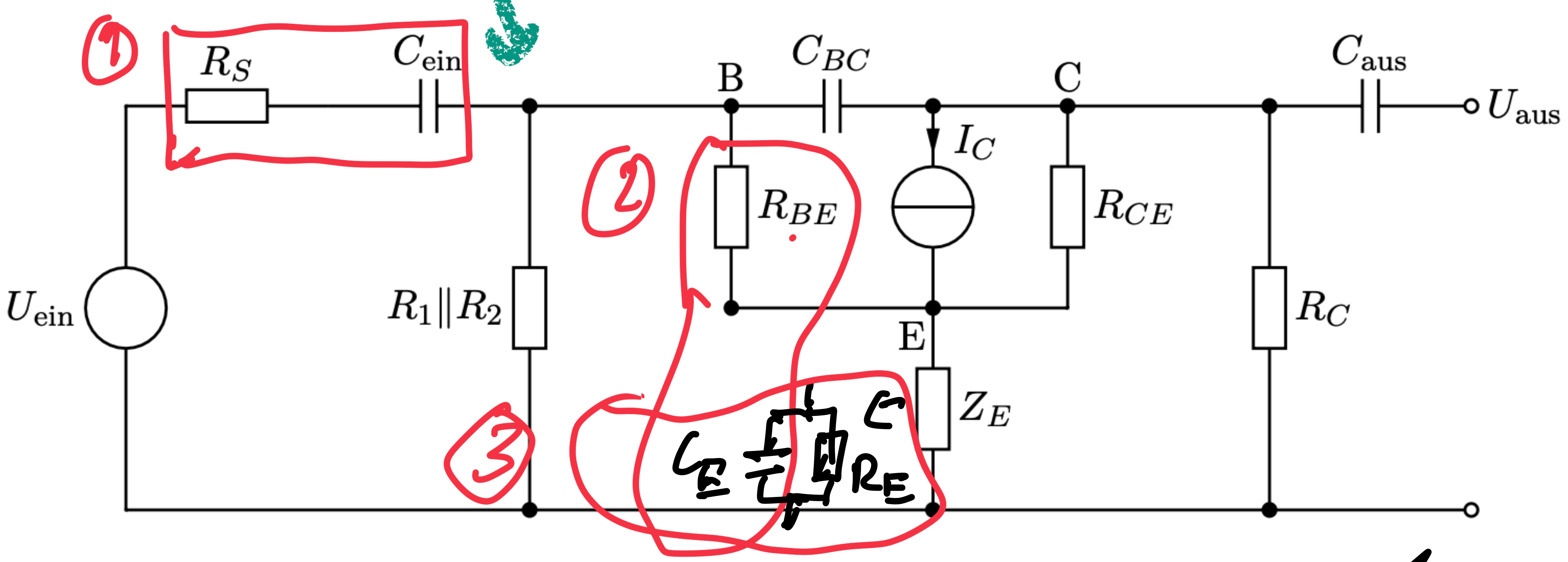
(1) High pass: f_1

(2) Low pass: f_2

(3) High pass: f_3

- Different critical frequencies due to external and internal capacitances and resistors.

Small-signal equivalent circuit

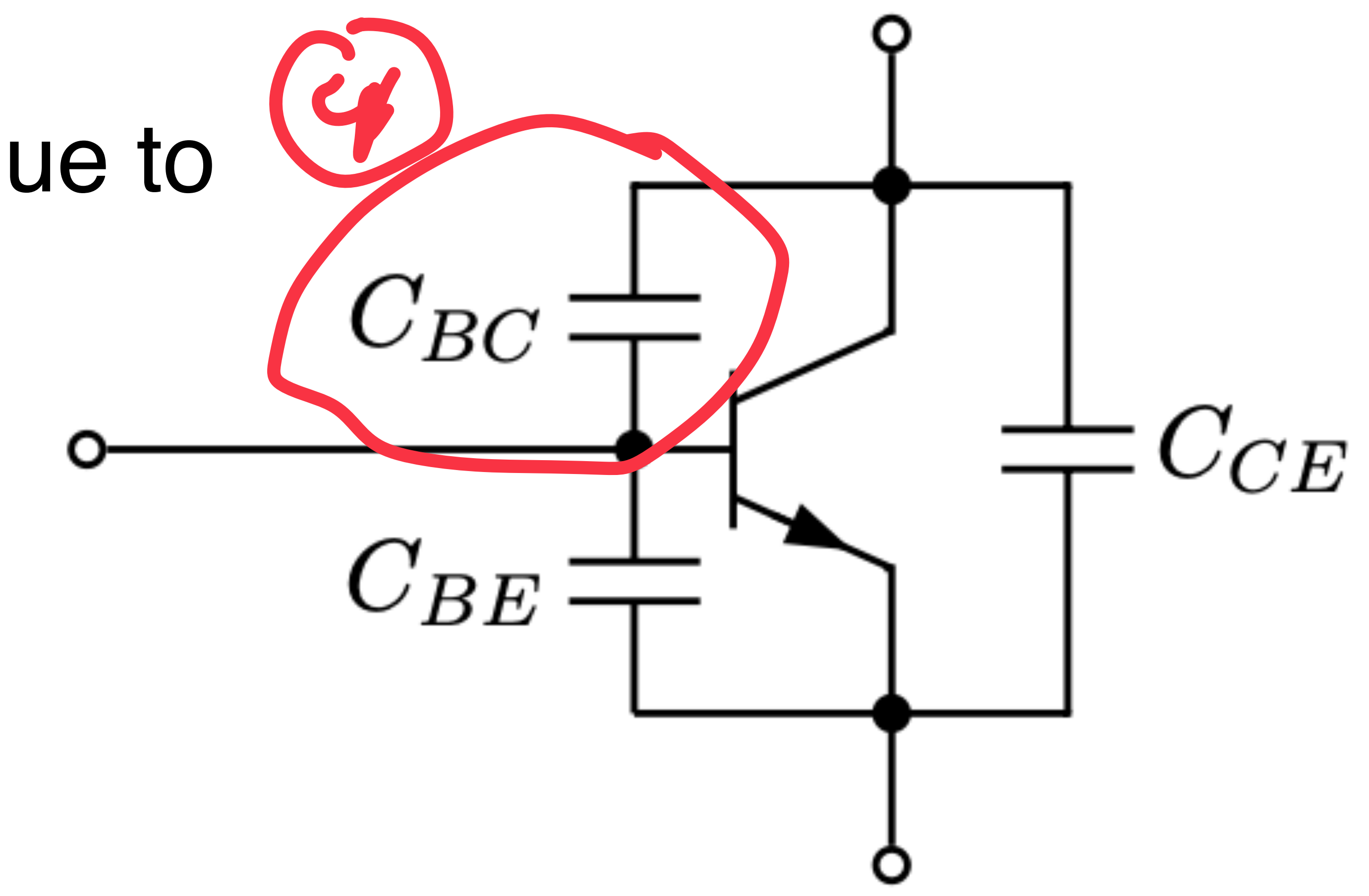


$$Z_E \mathrel{\hat{=}} R_E \parallel \frac{1}{j\omega C_E}$$

Frequency Dependence of Amplifiers

1-Transistor Amplifier

(4) Low pass due to Miller effect



Results in:

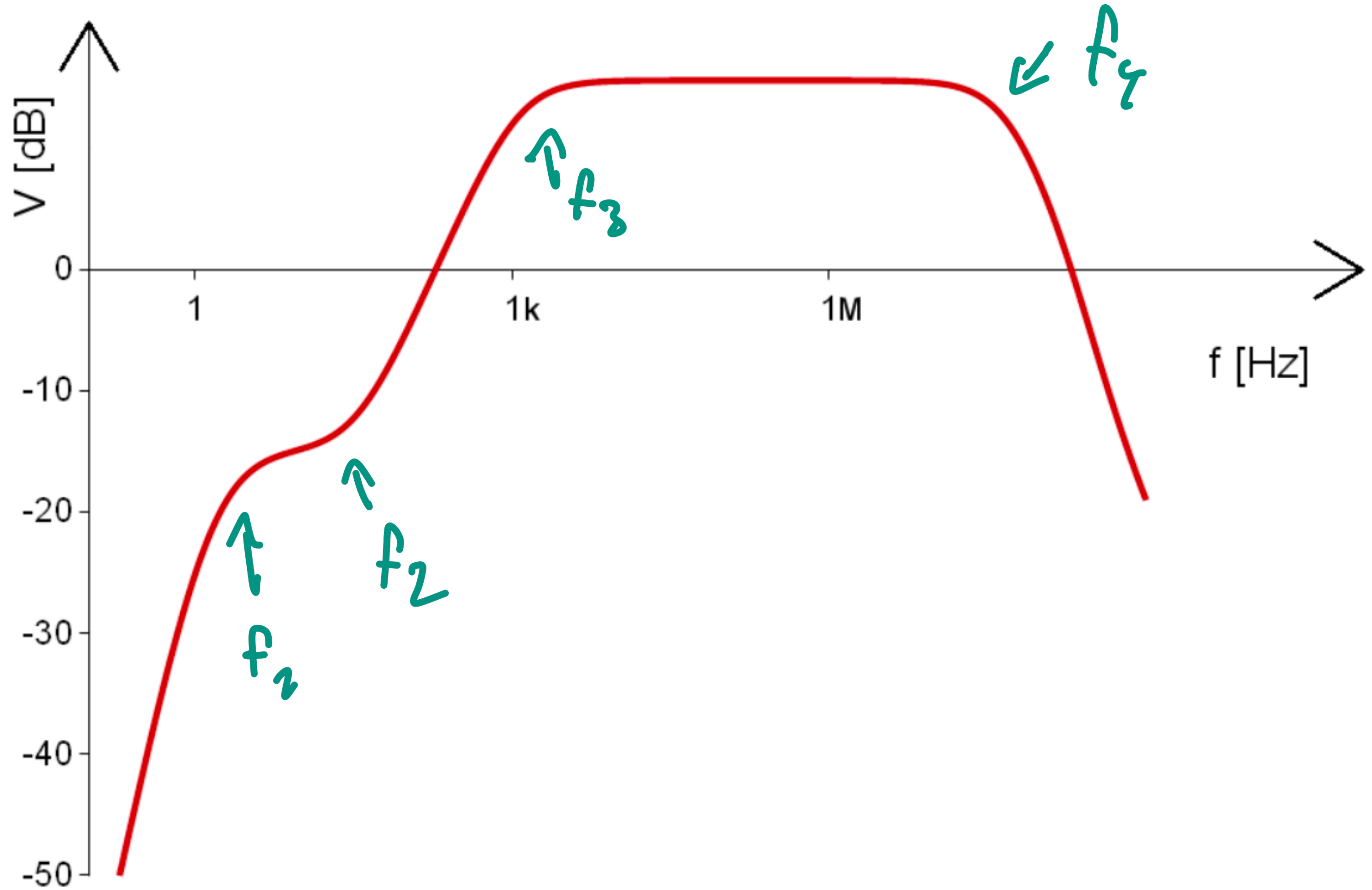
(1): High pass on input - f_1

(2): Low pass on input/emitter - f_2

(3): High pass in feedback - f_3

(4): Low pass between base and collector - f_4

- Different critical frequencies due to external and internal capacitances and resistors.



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Chapter 6; Lecture 10 Part II

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Chapter 6

2-Transistor Circuits

- Current Mirrors
- Amplifier Circuits

Overview

Current Mirrors

In: Chapter 6: 2-Transistor Circuits

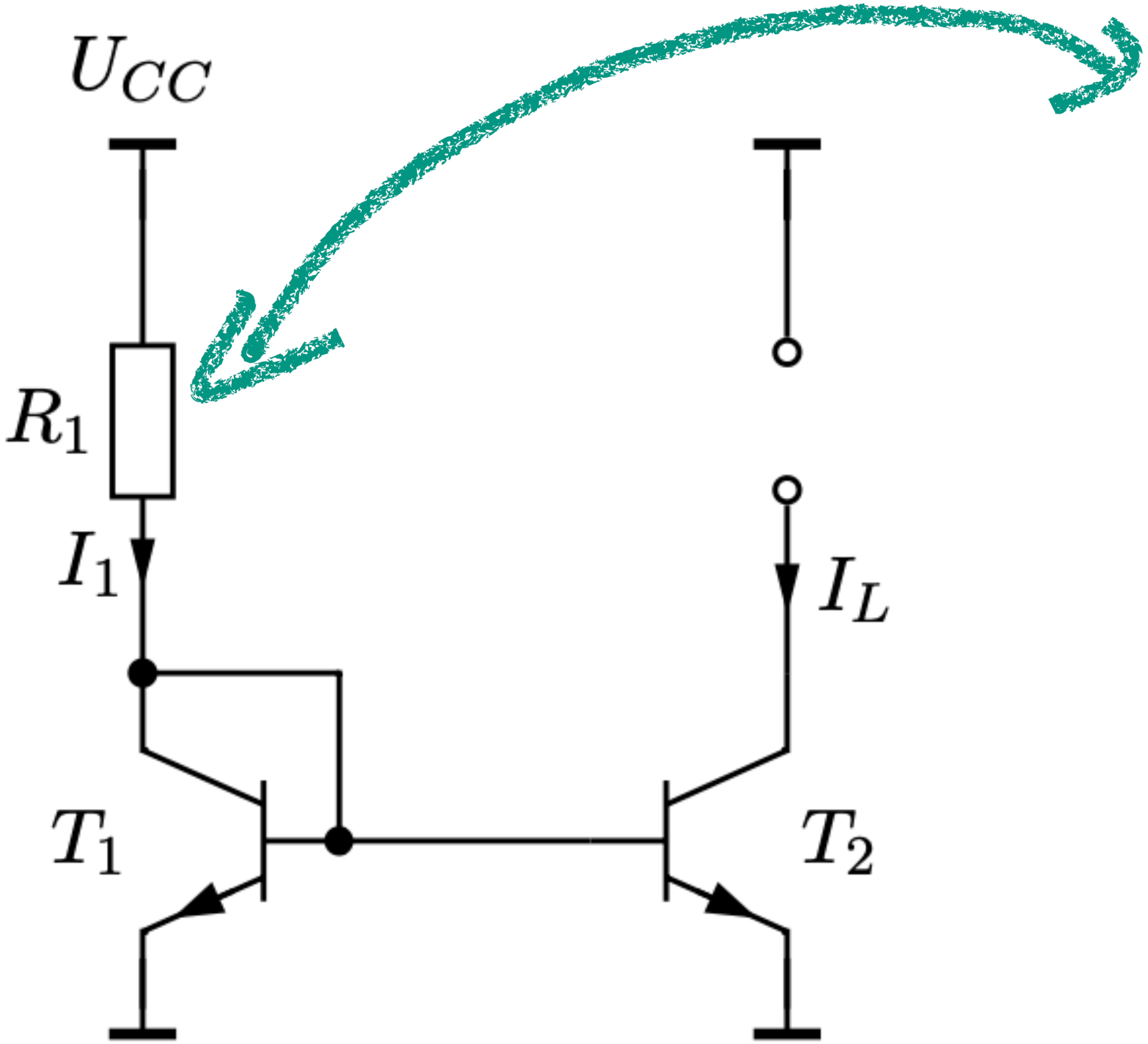
Current Mirrors - Introduction

Stromspiegel

- A circuit which can derive a current from a reference current:
  A ***current-driven current source***
  - Copying or scaling (multiplying, dividing) of the input current
- Applications:
  - Bias currents for transistor circuits to set working points
  - Active loads
  - “Copy” of current signals for different circuit elements …
- Desired properties:
  - Linearity: Output current precisely follows input current
  - High output impedance (= good current source)
  - Large dynamic range (depending on application)

Current Mirror

With Resistor



Defines the current:

T_1: B and C connected => diode (BE)!

defines: $I_1 = \frac{U_{CC} - 0.7\,\mathrm{V}}{R_1}$

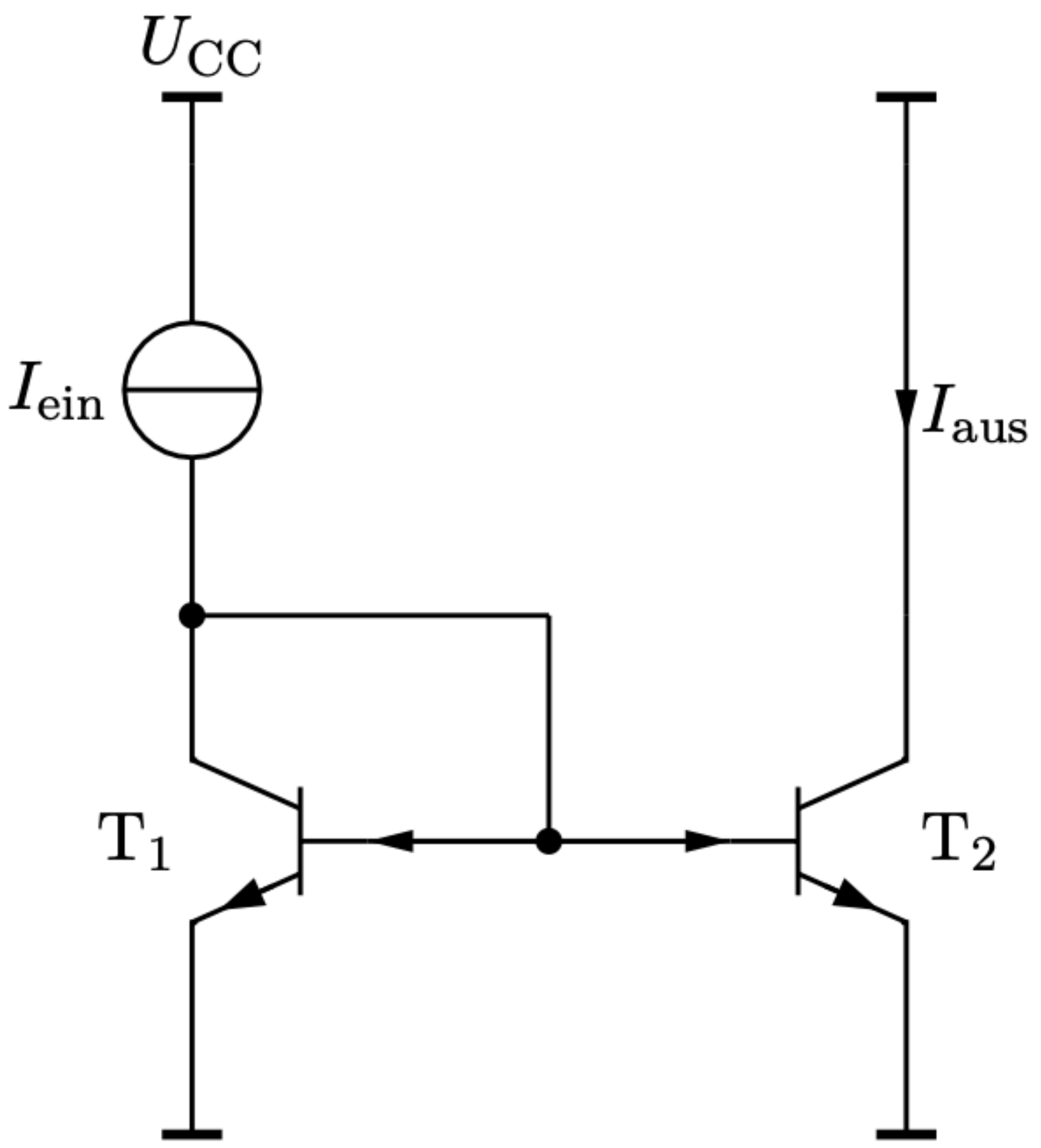
In addition: $U_{BE1} = U_{BE2}$

Remember (Ch 5): $I_C = \beta I_S \left(e^{\frac{U_{BE}}{U_T}} - 1\right)$

=> For identical transistors T_1 and T_2:
Same collector current I_C

And: $I_{C1} = I_1 - I_{BE1} - I_{BE2}$

resulting in: $I_L = I_1 - 2\,I_{BE}$



- Here: With current source instead of resistor - the more general application.
  - Identical consideration!

$$I_{aus} = I_{C2} = I_{ein} - 2\,I_{BE} = I_{ein} - 2\frac{I_C}{\beta}$$

Consequences:

U_L is defined by R_L - within the limits set by the operational parameters of the transistors: $U_L = U_{CC} - U_{CE2}$

U_{CE2} has to be within the active region, not in the saturation region (Ch 5: > ~ 0.2 V)

Current Mirror

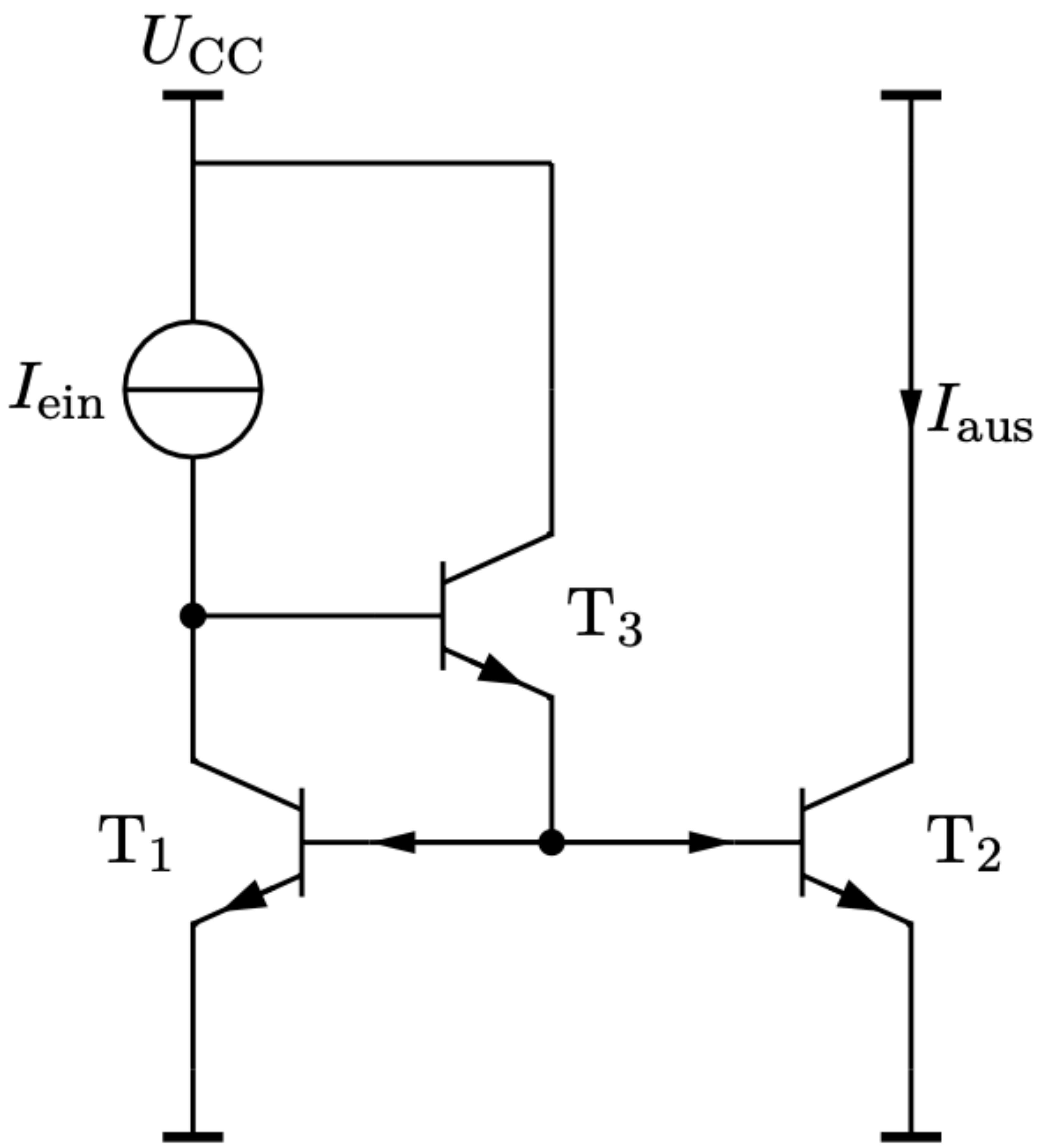
With Base Current Compensation

- Can we get closer to $I_{aus} = I_{ein}$?
  Requires the compensation for the "lost" base current.

  Possible with one additional transistor:
  $I_{E3} = I_{B1} + I_{B2}$

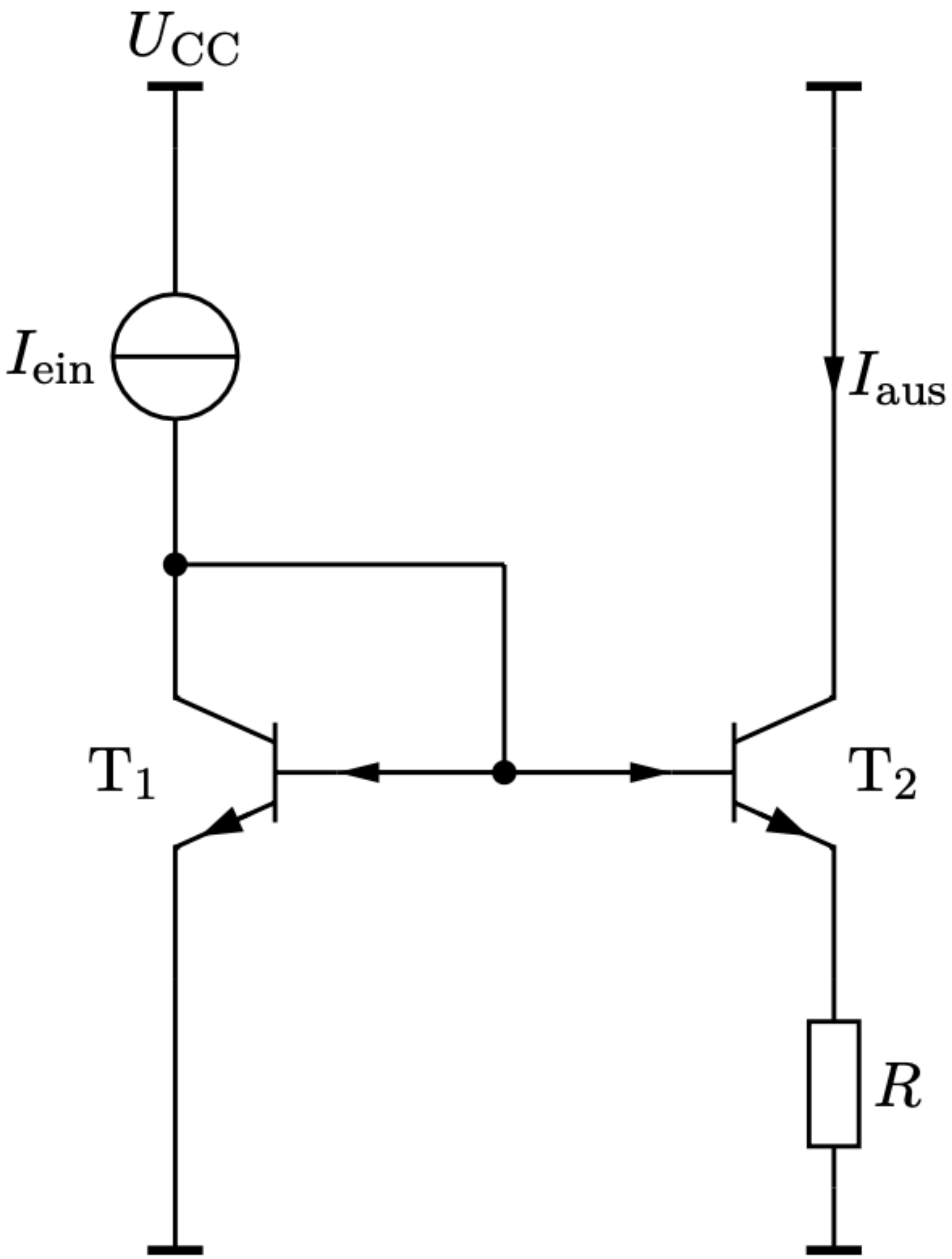
  There remains a small "current loss" due to the base current of the 3rd transistor:

$$I_{B3} = \frac{I_{B1} + I_{B2}}{\beta_3}$$



Widlar Current Mirror

For small Currents



- One additional resistor R on the "output arm"

How it works:

$U_{BE1} = U_{BE2} + I_{aus}R$ (neglecting I_{BE2} through R)

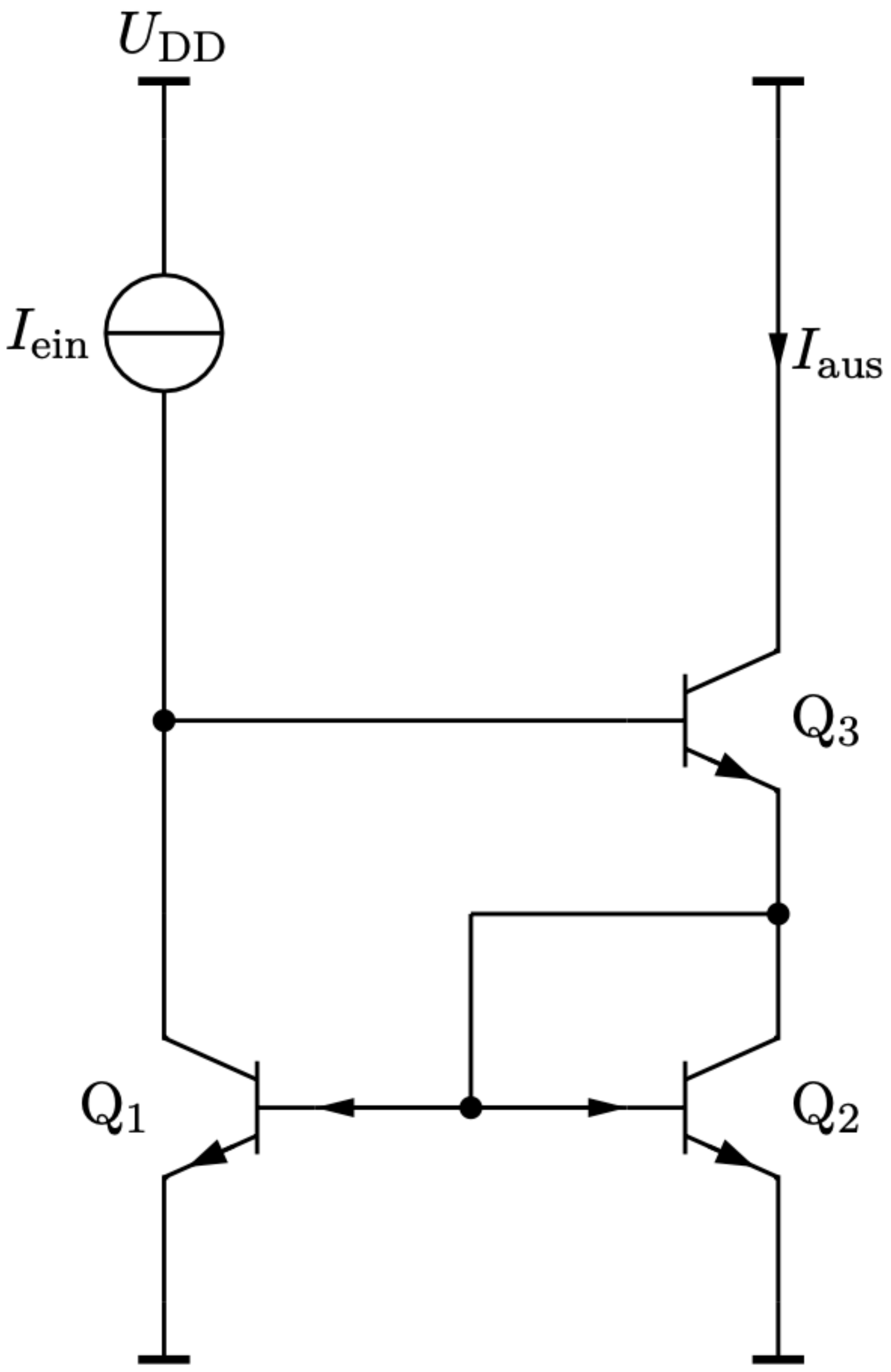
Shockley equation: $I_{BE} \approx I_S \, e^{\frac{U_{BE}}{U_T}}$ => $U_{BE} \approx U_T \, ln \frac{I_C}{\beta I_S}$

$I_C = \beta \, I_{BE}$ (gain)

results in: $I_{aus} = \frac{U_T}{R} \, ln \frac{I_{ein}}{I_{aus}}$ (no analytic solution, is solved analytically)

Wilson Current Mirror

A frequent Solution



- Same principle as for the current mirror with base current compensation - here in the “output arm”:
  Transistor 3 provides the base current for T1 und T2

Amplifiers - Part 1

In: Chapter 6: 2-Transistor Circuits

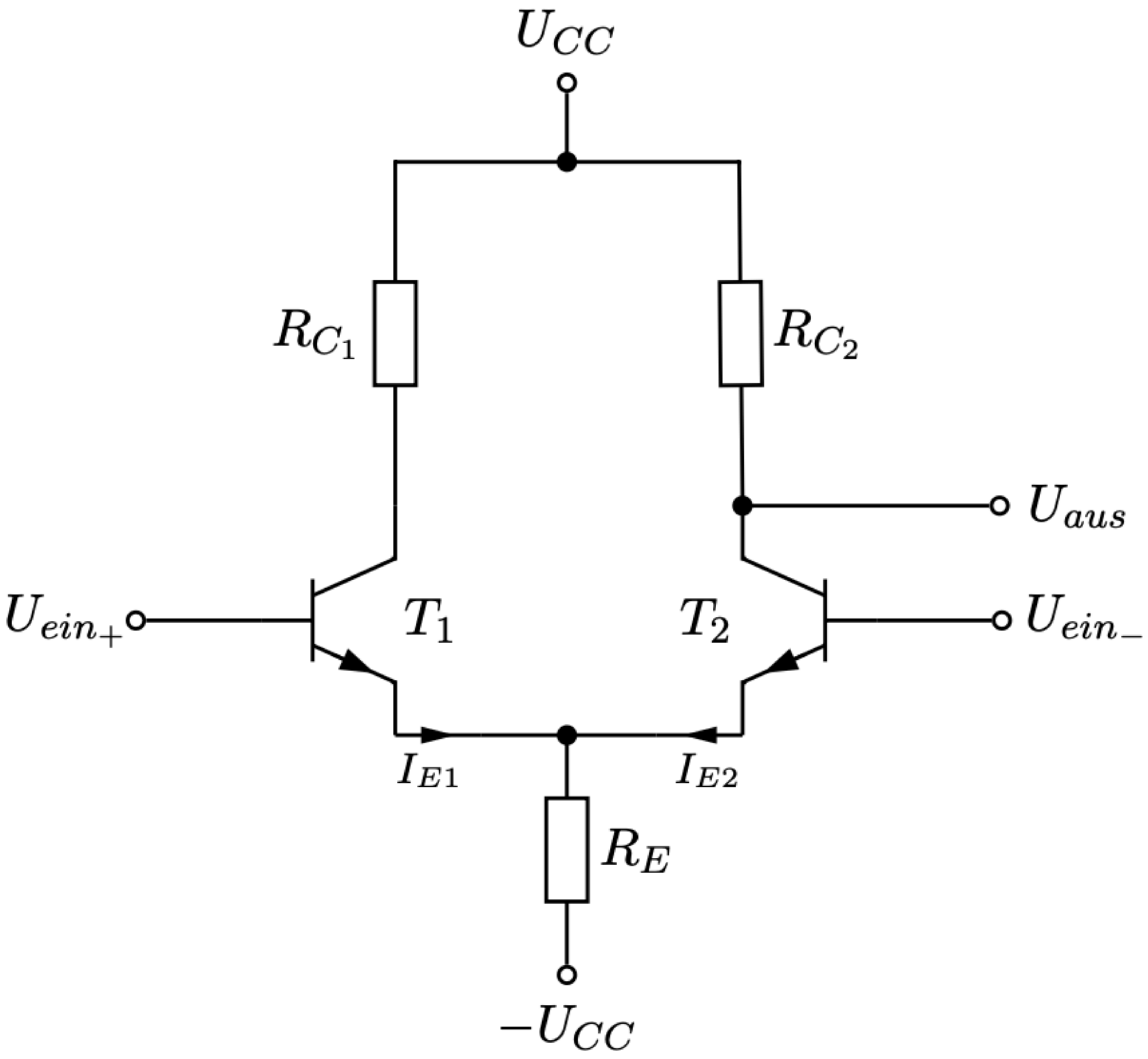
Verstärkereigenschaften

Der ideale Verstärker

- Large gain
- High input impedance
- Low output impedance
- Large bandwidth
- Good linearity
- Low noise
- Low power
- Small temperature dependence

Differential Amplifier

Differenzverstärker



- Used (for example) as input stage of op amps

- Differential input: U_{ein+}, U_{ein-}
- One output U_{aus}
- Two coupled common emitter amplifiers normally: $R_{C1} = R_{C2} = R_C$

To understand the circuit: Consider input as:

- $U_D = U_{ein+} - U_{ein-}$
- $U_{Gl} = (U_{ein+} + U_{ein-})/2$

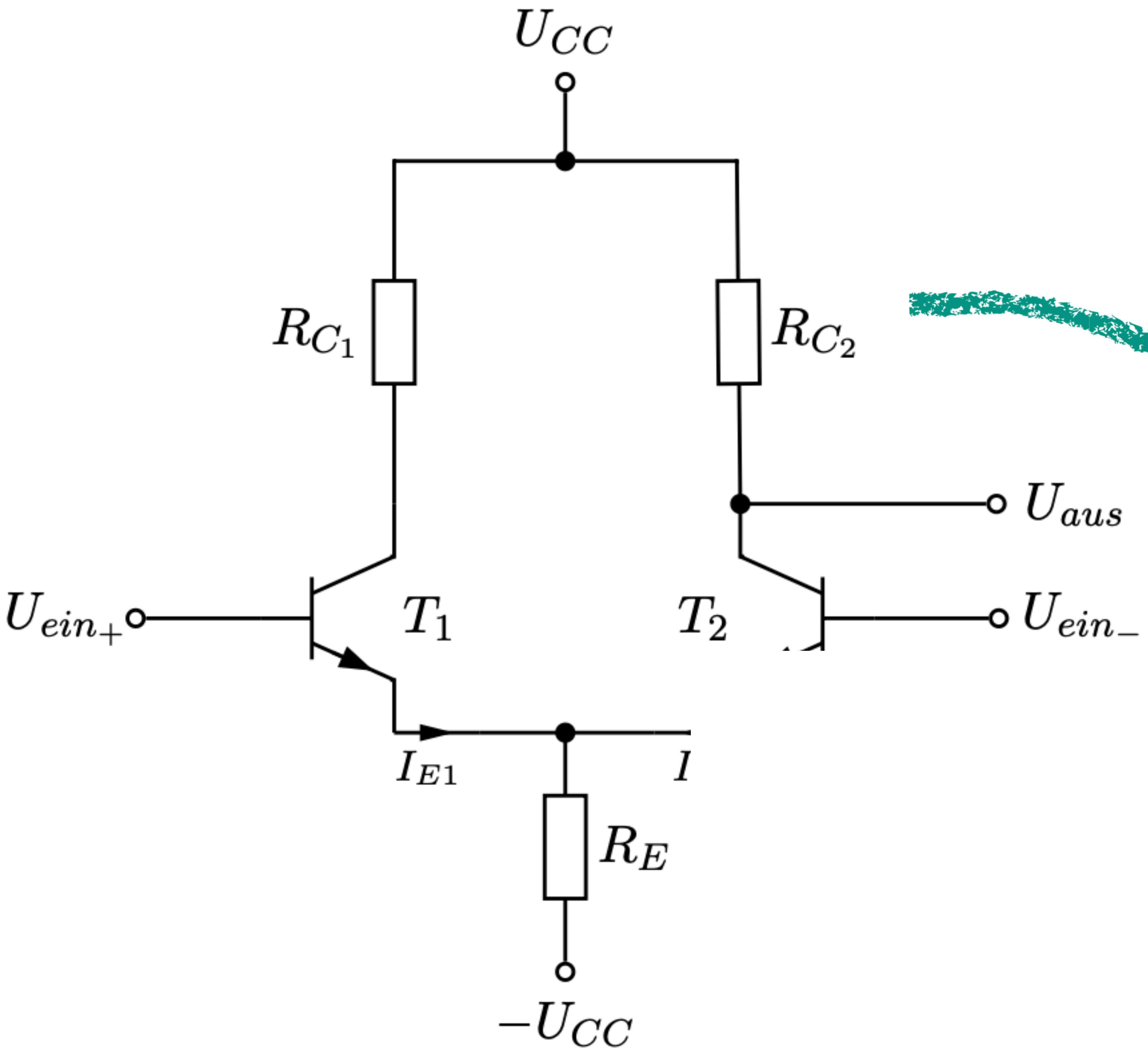
Results in:

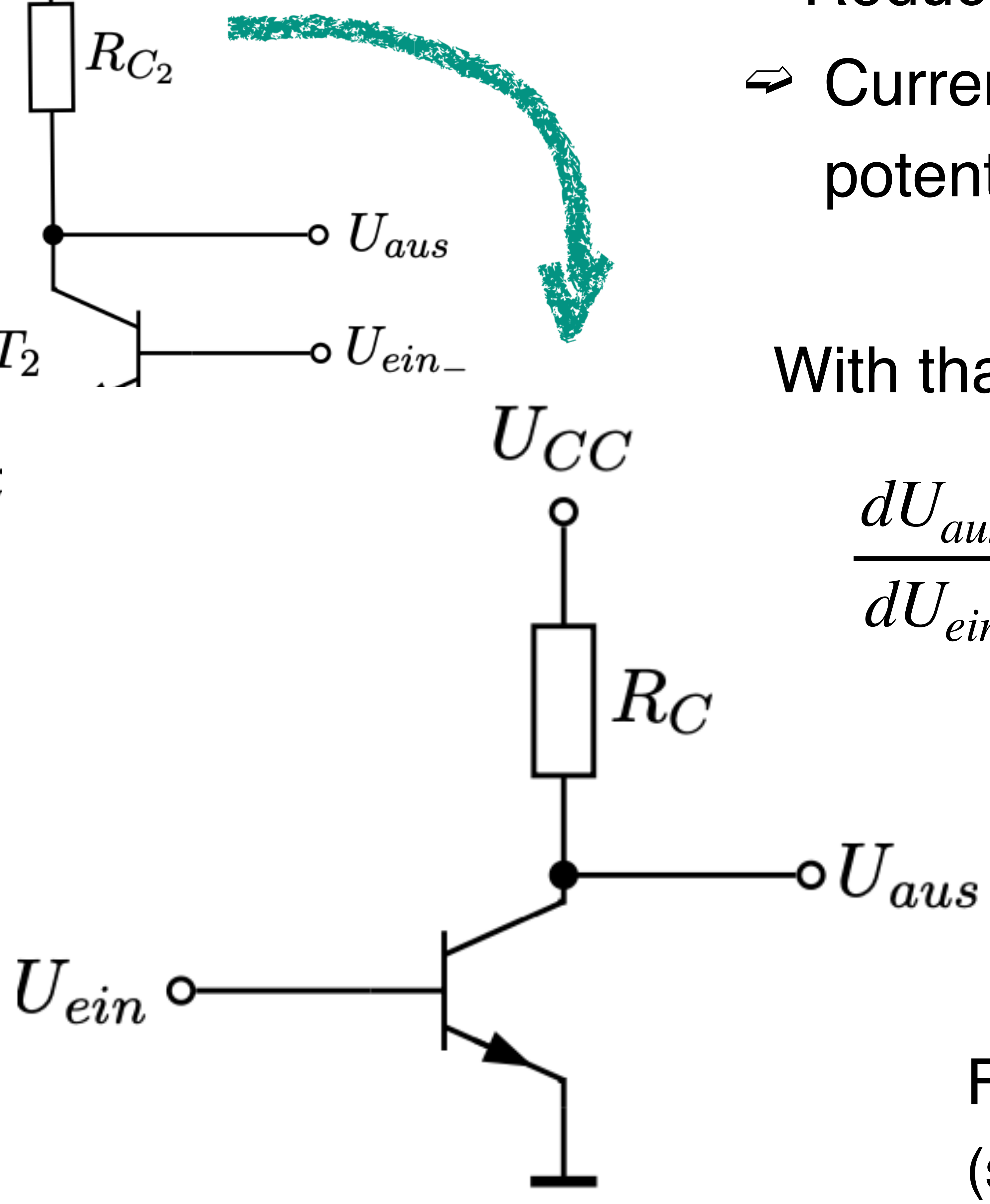
$$U_{ein+} = U_{Gl} + \frac{U_D}{2}$$

$$U_{ein-} = U_{Gl} - \frac{U_D}{2}$$

Differential mode amplification

Differenzverstärkung





- Consider the differential voltage:
  - Increasing U_{ein+} increases the current in arm 1
  - Reducing U_{ein-} reduces current in arm 2

  ➩ Current sum remains constant, common emitter potential remains unchanged

With that: Behavior as the common emitter amplifier (Ch 05):

$$\frac{dU_{aus}}{dU_{ein}} = -R_C S$$

In differential amplifier: Output on “negative” arm, and only half of the differential signal: only half of the current

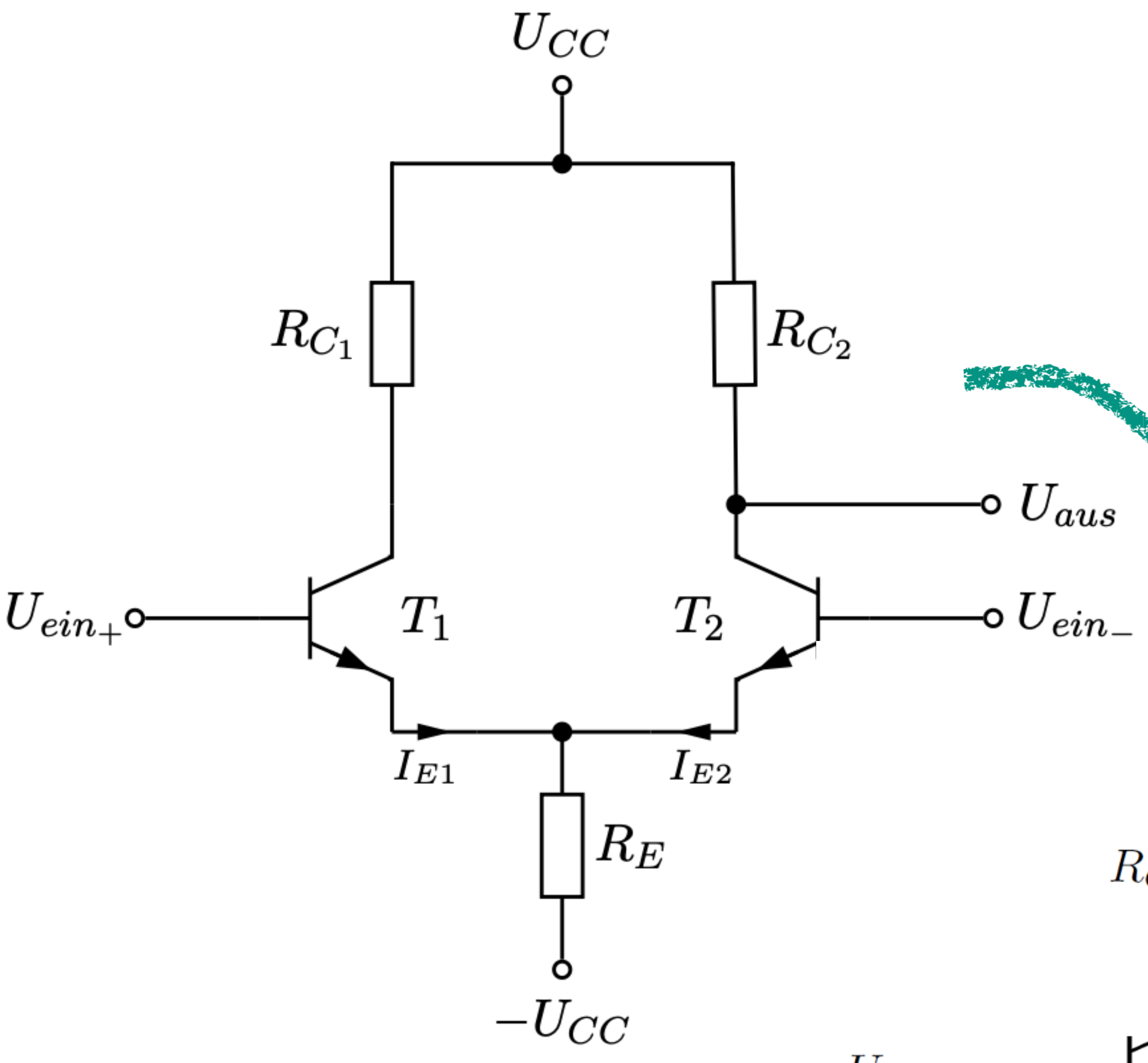
$$V_D = \frac{dU_{aus}}{dU_D} = R_C \frac{S}{2} = R_C \frac{I_C}{4U_T}$$

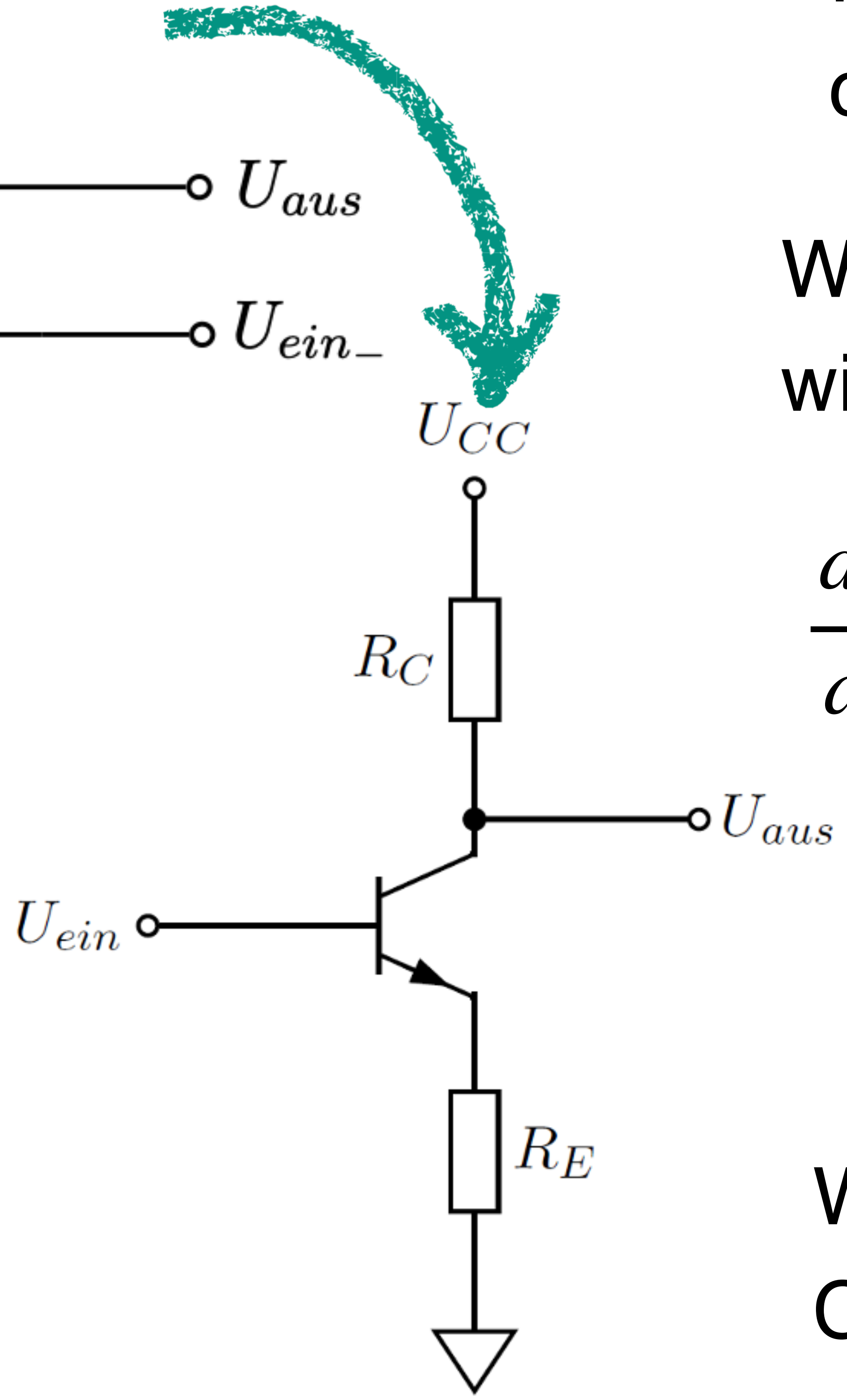
From Ch 05:
(single transistor)

$$S = \frac{dI_C}{dU_{BE}} = \beta \frac{dI_B}{dU_{BE}} = \frac{\beta}{R_{BE}} = \frac{\beta I_B}{U_T} = \frac{I_C}{U_T}$$

Common Mode Amplification

Gleichtaktverstärkung





- Consider the common mode voltage:
  - U_{ein+} and U_{ein-} increase together
  - ➯ Current increases by equal amounts in both arms. Results in a change of voltage on emitters due to higher current through R_E . Here U_E is not constant!

With that: Behavior as common emitter amplifier with current feedback (Ch 5):

$$\frac{dU_{aus}}{dU_{ein}} = -\frac{R_C}{R_E}$$

In differential amplifier: Output on “negative” arm, and only half of the differential signal: only half of the current

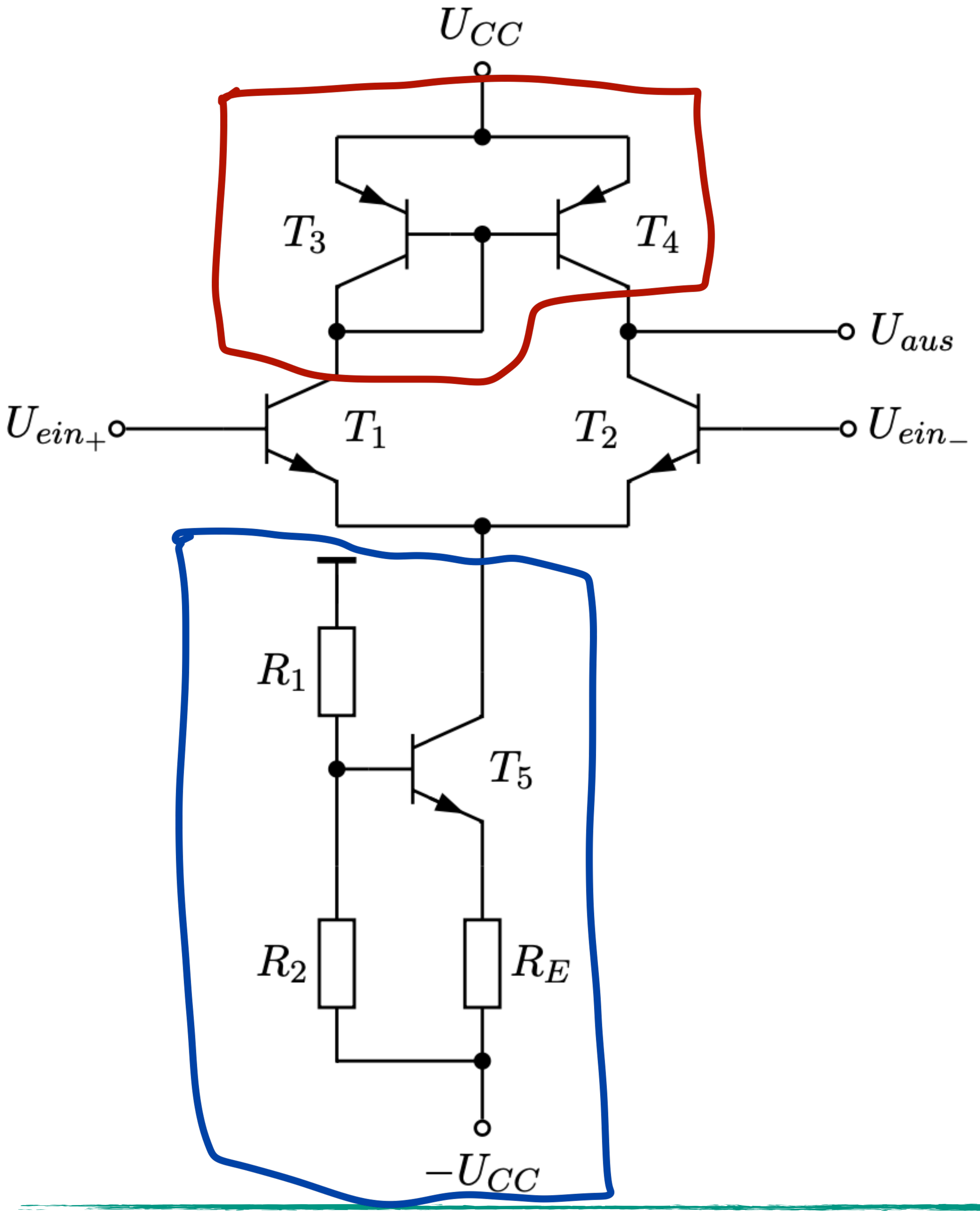
$$V_G = \frac{dU_{aus}}{dU_G} \approx -\frac{R_C}{2\,R_E}$$

With result from previous slide: Common-mode suppression

$$\left|\frac{V_D}{V_G}\right| = SR_E$$

Differential Amplifiers

More Sophistication: Additional Transistors



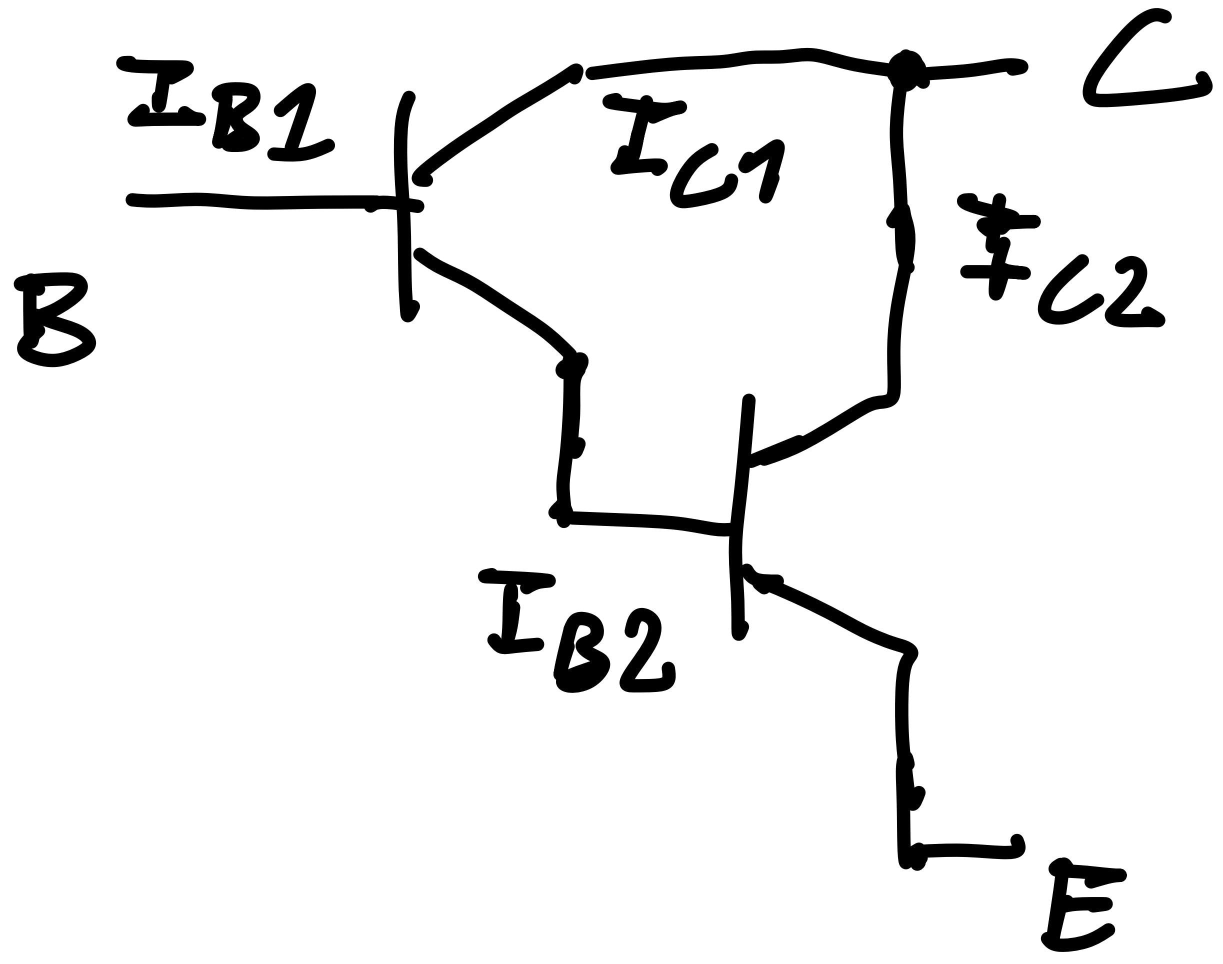
- A simple improvement of the differential amplifier:

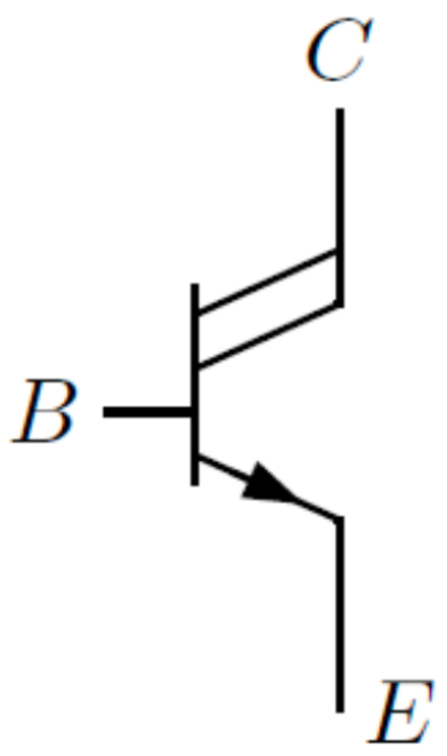
  - Current mirror instead of R_C (current source with two identical outputs): Significant increase of gain (both V_D and V_G): Effective increase of R_C
    NB: Current mirror consisting of pnp-transistors so that the voltages fit.

  - Current source instead of R_E:
    Common mode amplification decreases with increasing R_E: Current source with high internal resistance improves behavior.

The Darlington Transistor

Two Transistors in one





- Invented 1952 by Sidney Darlington (Bell Labs)
- Often available as dedicated component (2 transistors on one chip, integrated in one package)

$I_{C1} = \beta_1 I_{B1} \qquad I_{C2} = \beta_2 I_{B2}$

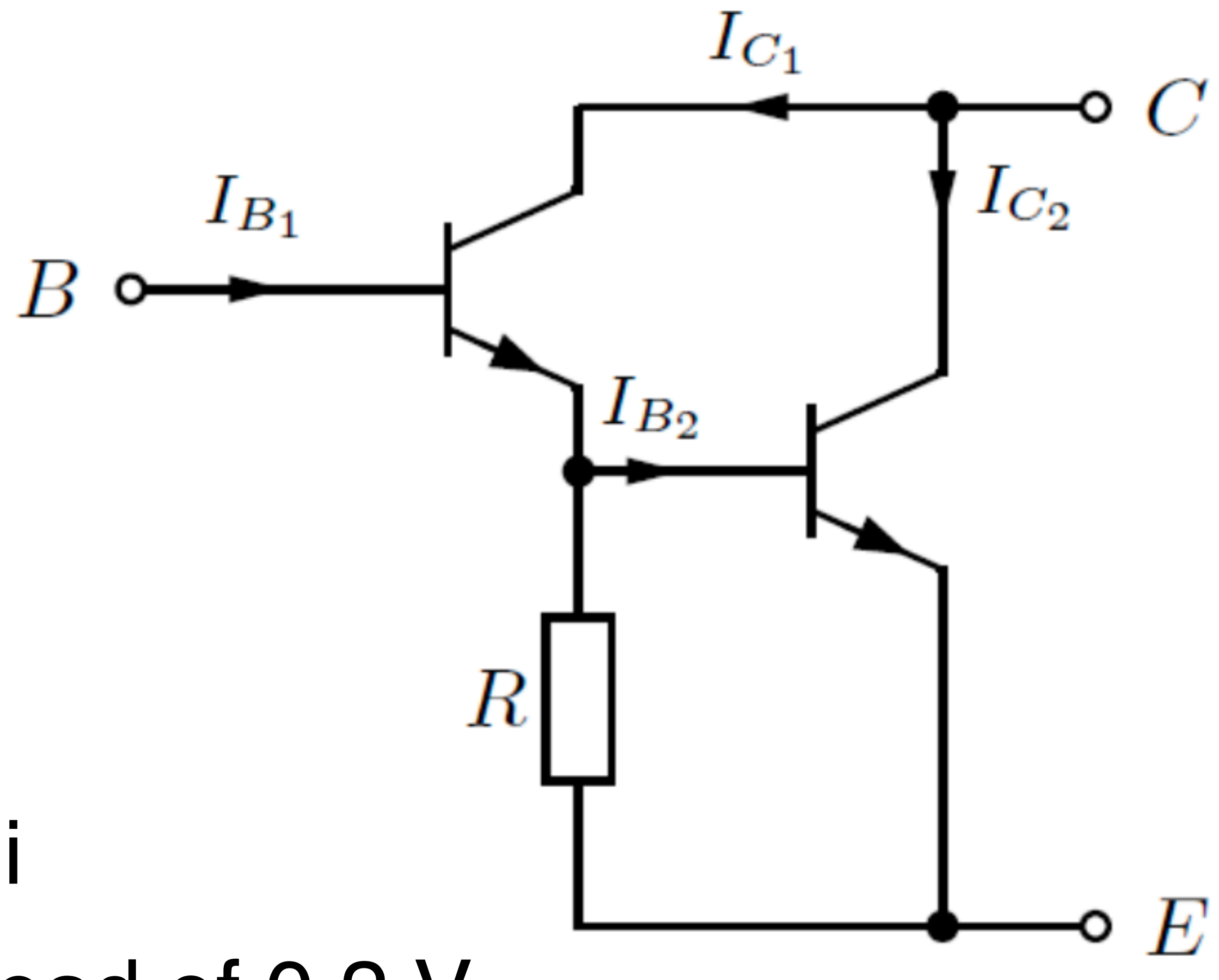
=> $I_{C2} = \beta_2(I_{C1} + I_{B1}) = \beta_2(\beta_1 + 1)I_{B1}$

Gain ~ $\beta_1\beta_2$

But also:

- Doubling of base-emitter voltage: 1.2 - 1.4 V for Si
- Increased collector-emitter-voltage -> ~ 0.9 V instead of 0.2 V to reach the active region: Higher power losses
- And: slower switching, larger phase shift

Common modification: Resistor at the 2nd transistor



Speeds up switching, but costs gain.

Don't choose R too small: I_{B2} and U_{B2} have to be sufficiently large to switch the 2nd transistor.

Next Lectures:

Digital - Thursday, January 11, Tuesday, January 16 and Thursday, January 18

Analog 11 - Chapters 06, 07 - Tuesday, January 23, 2024

Time Plan for Next Lectures

A few Changes coming up!

Karlsruhe Institute of Technology

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. **Digital**
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. **Analog**
7	13.02. **Analog**	15.02. **Digital**

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