Vorlesung 3

- Rückkopplung – nichtinvertierender Verstärker
- Impedanzen und RK
- Integrator (Millereffekt)
- Bode-Diagramm und Stabilität (Nyquistkriterium)
- **CMOS Circuit Design, Layout, and Simulation**, R. Jacob Baker, John Wiley & Sons, 2008

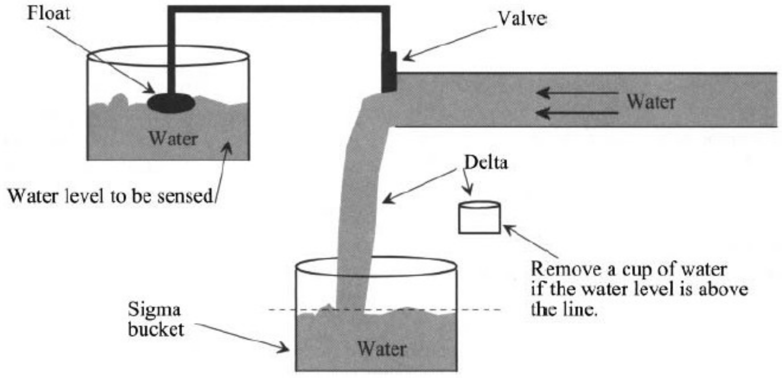
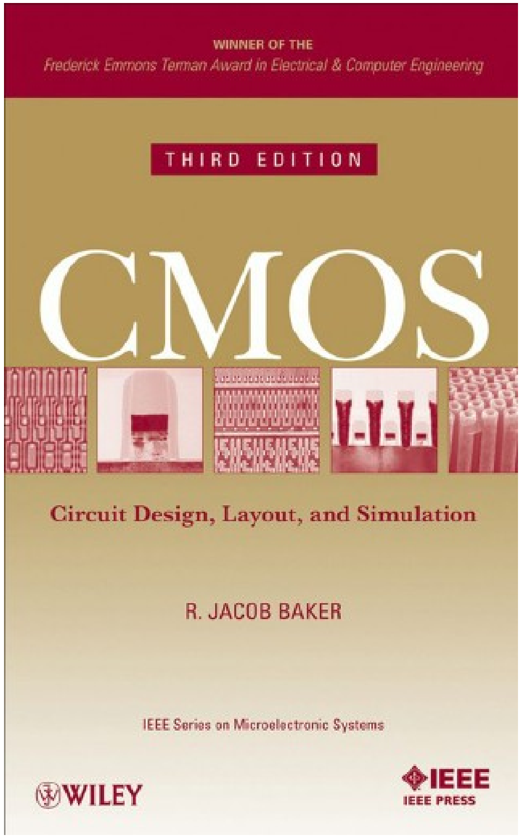
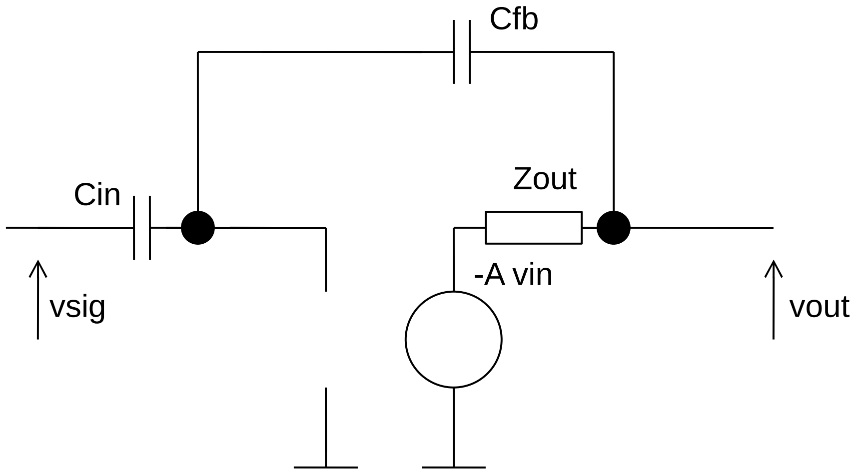


Figure 17.2 Changing the water height (pressure or voltage) into a water flow (current) using the float and valve. The delta comes from the difference in the number of cups we remove from the bucket with the water we add to the bucket. The sigma (sum) is the storage of the difference in the bucket.



Rückkopplung

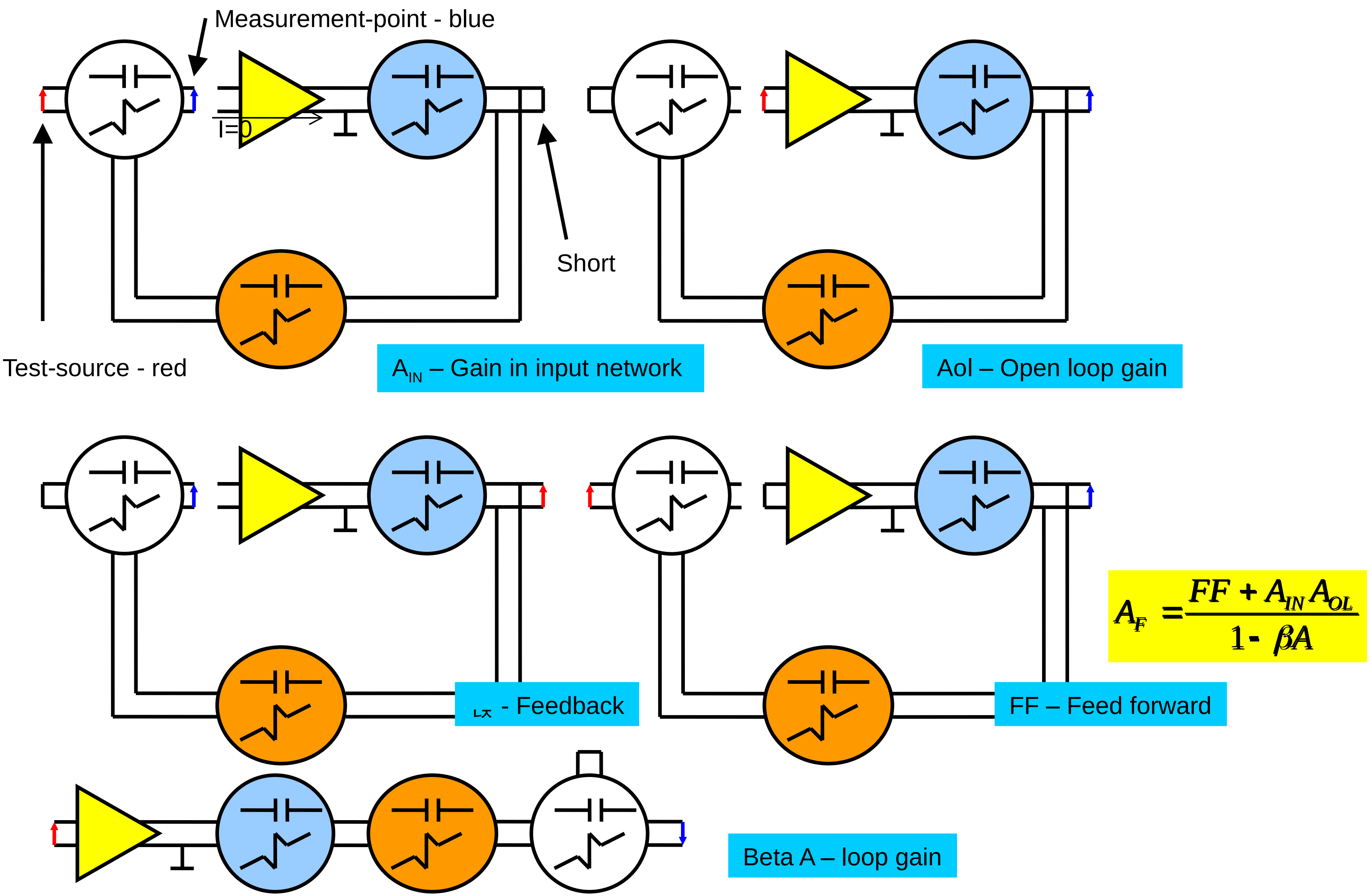
- Af – Kreisverstärkung (Verstärkung mit RK)
- FF – feed forward (Vorwärtsverstärkung)
- Ain – Verstärkung im Addierer
- Aol – open loop gain (Leerlaufverstärkung)
- bA – Schleifenverstärkung

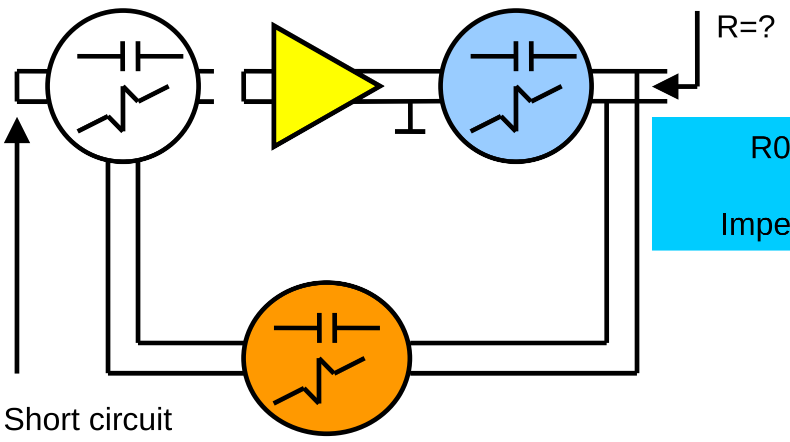


$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

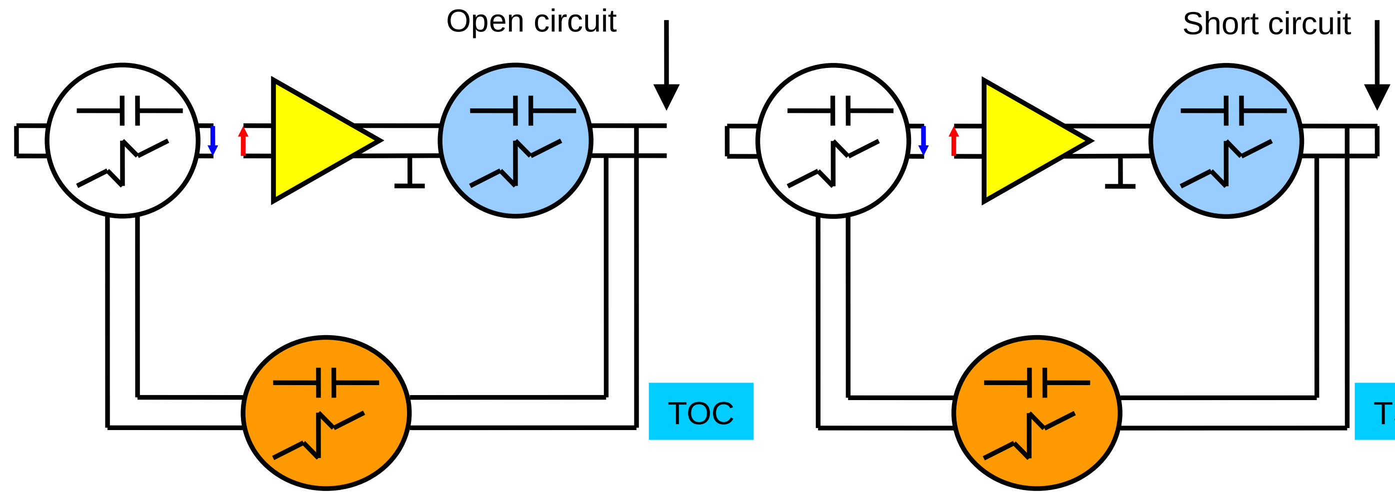
$$\beta A = \beta \cdot A_{OL}$$

Verstärkung mit Rückkopplung





R0 – dead gain output impedance
Impedanz ohne Verstärker

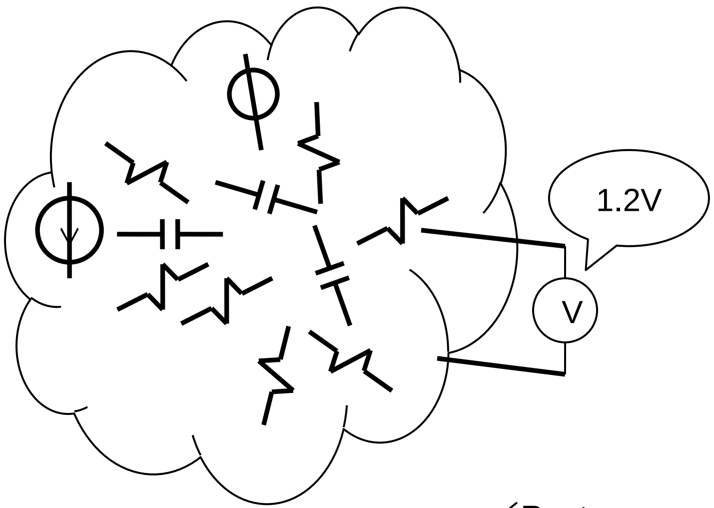


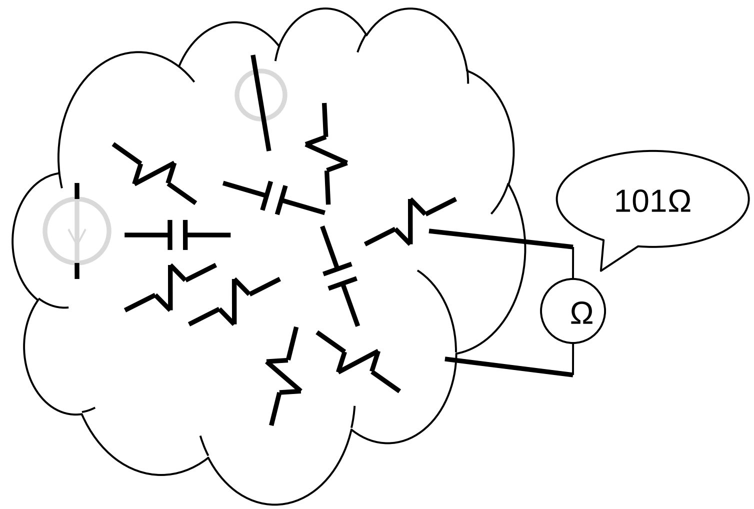
TOC

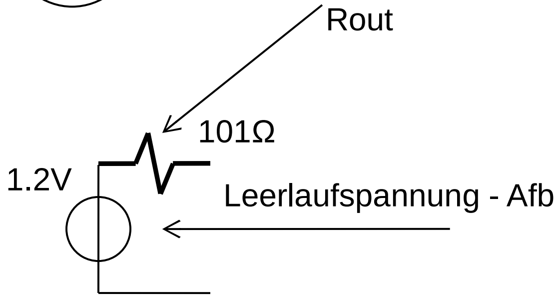
TSC

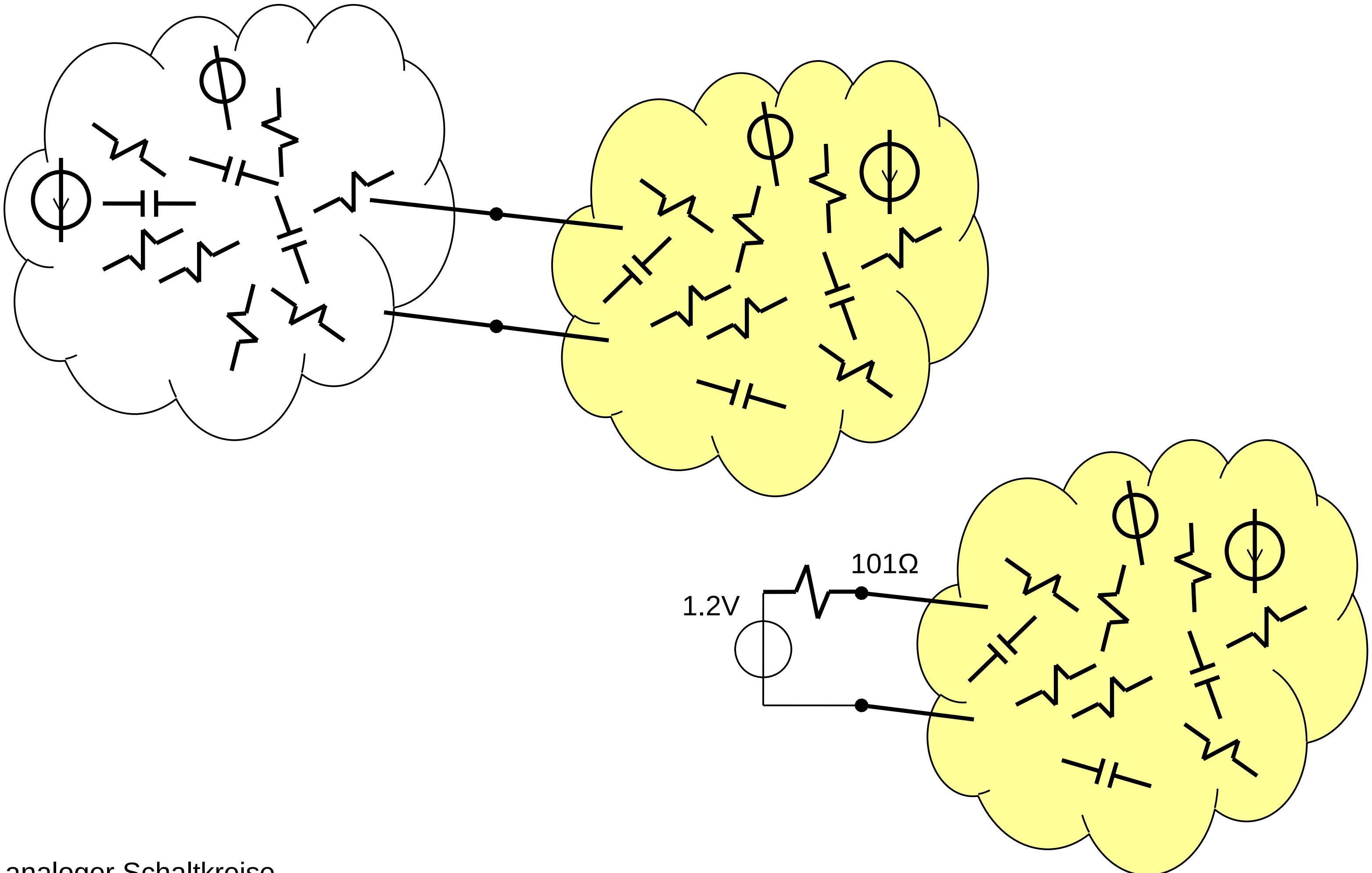
Loop gains

$$R_{OUT} = R_0 \frac{1 - \beta A_{SC}}{1 - \beta A_{OC}}$$

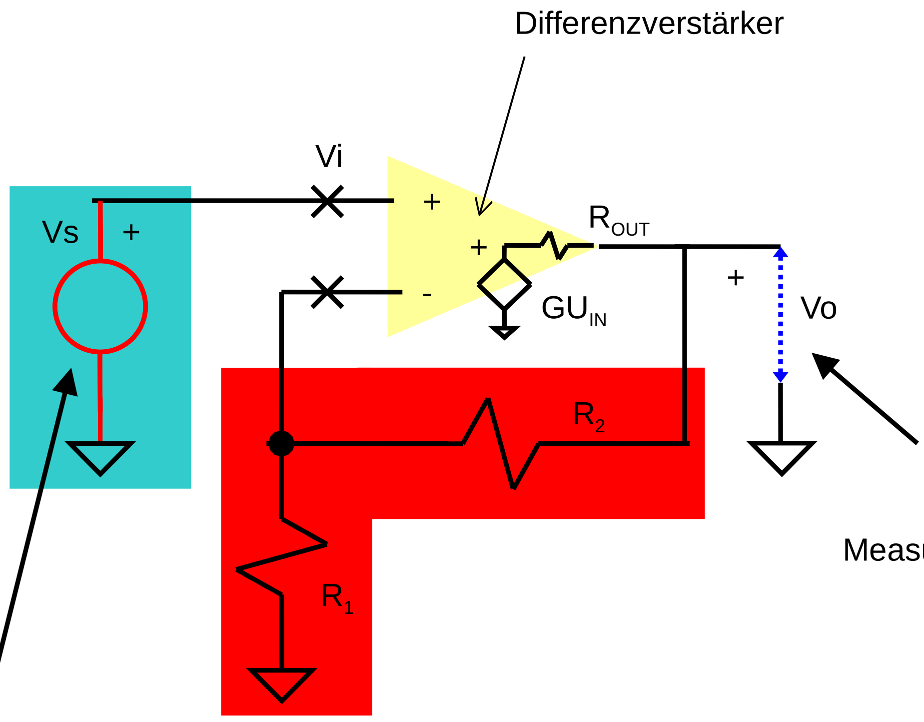

1.2V
V

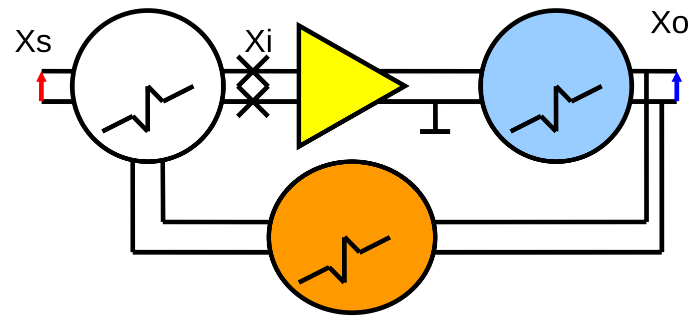

101Ω
Ω


Rout
101Ω
1.2V
Leerlaufspannung - Afb


101Ω
1.2V

Noninverting amplifier

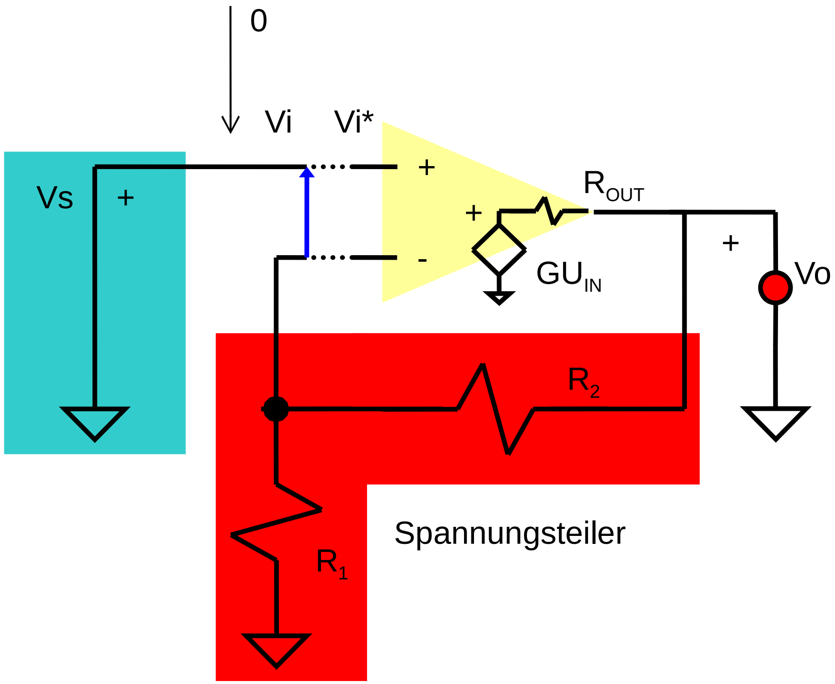


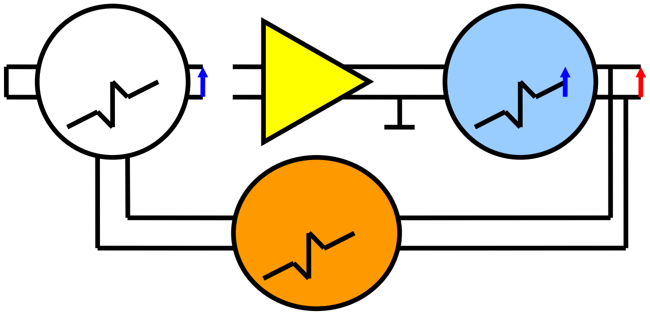


Measured signals are in blue

Independent sources are in red

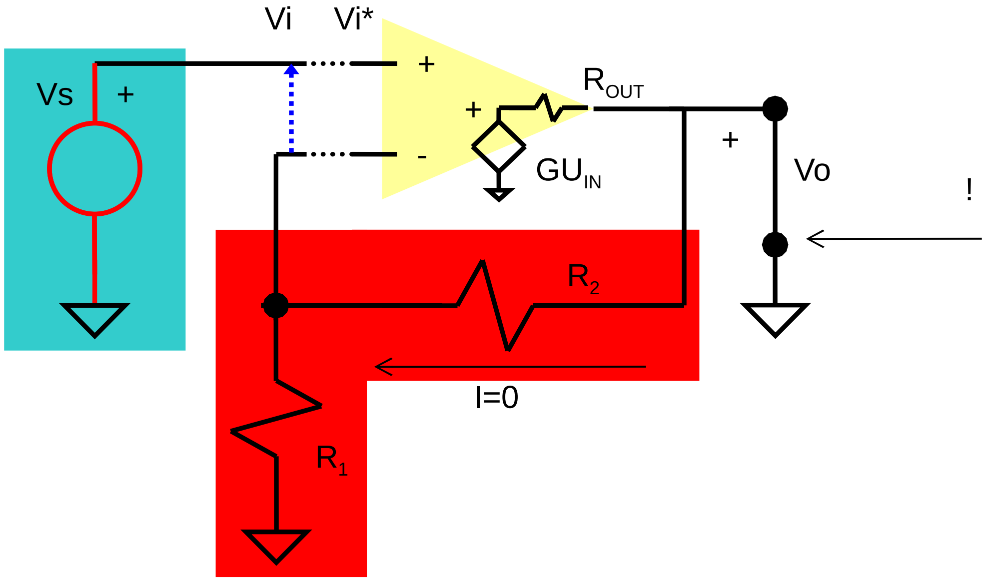
$$A_F = \frac{FF + A_{IN} A}{1 - \beta A} \rightarrow \frac{A_{IN}}{-\beta}$$

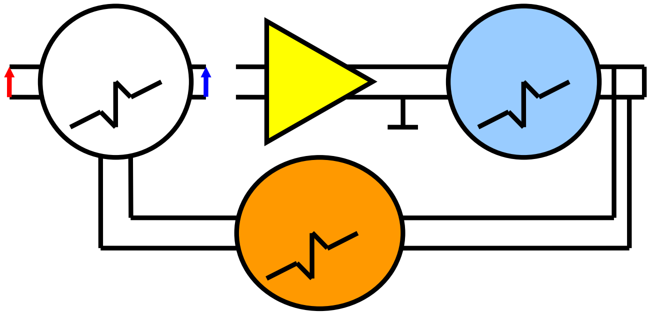




$$\beta = -\left.\frac{V_i}{V_o}\right|_{V_s=0}$$

$$\beta = -\frac{R_1}{R_1 + R_2}$$

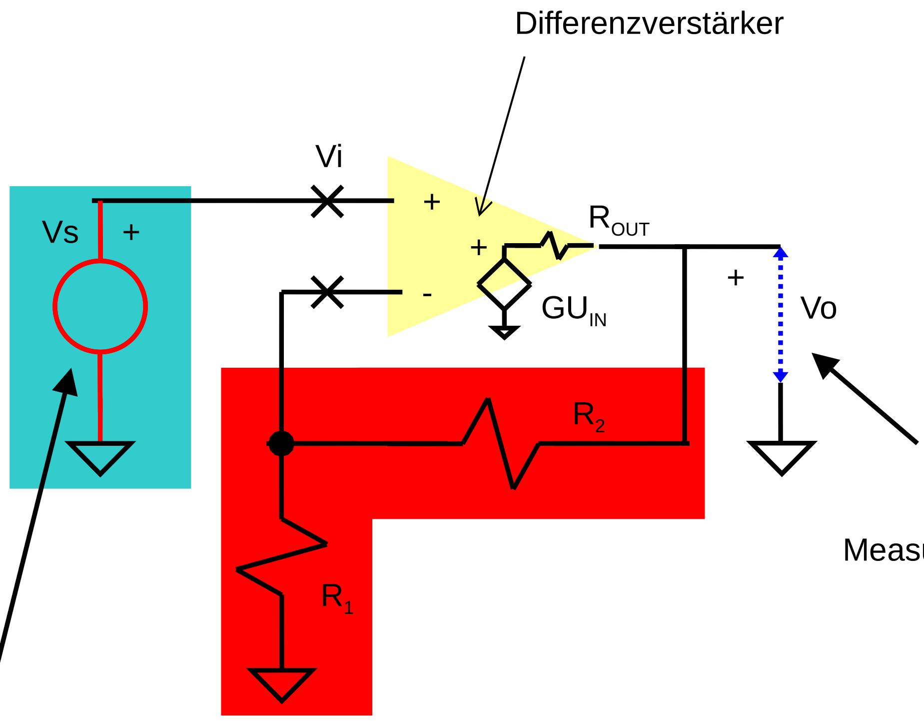


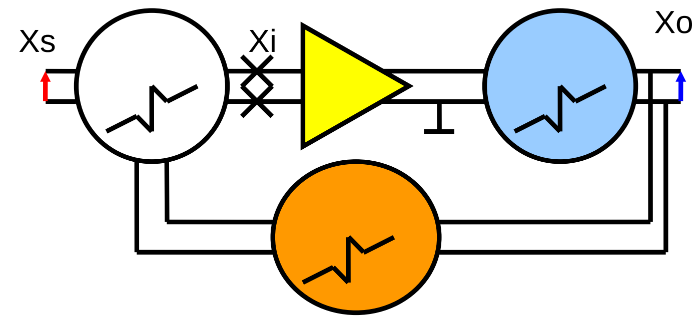


$$A_{IN} = \frac{V_i}{V_s}\bigg|_{V_o=0}$$

$$A_{IN} = 1$$

A_FB



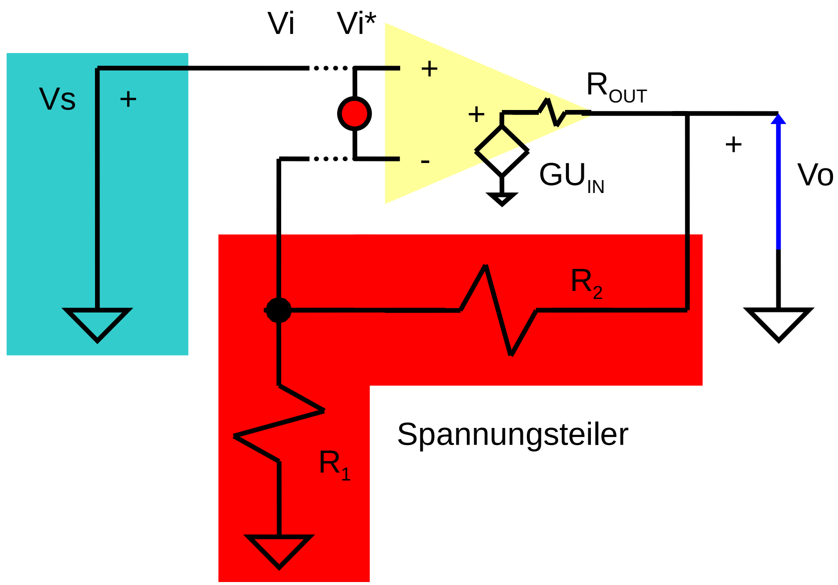


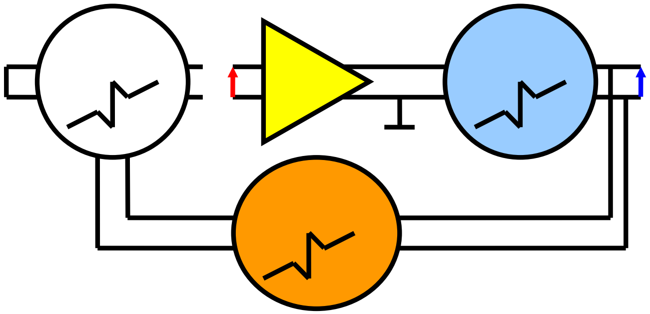
Measured signals are in blue

Independent sources are in red

$$A_F = \frac{FF + A_{IN}A}{1 - \beta A} \rightarrow \frac{A_{IN}}{-\beta} = \frac{R_1 + R_2}{R_1}$$

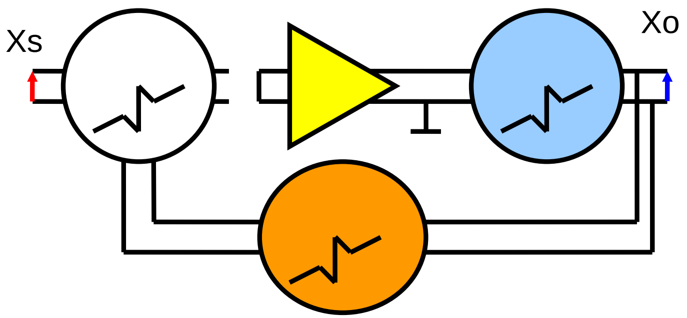
Open loop gain

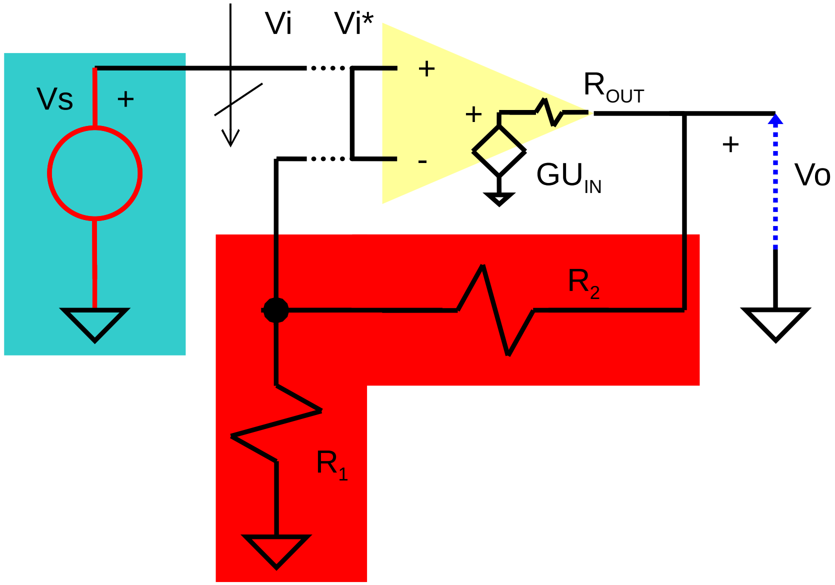




$$A = \left.\frac{V_o}{V_i^*}\right|_{V_s=0}$$

$$A = G\,\frac{R_1 + R_2}{R_1 + R_2 + R_{OUT}}$$

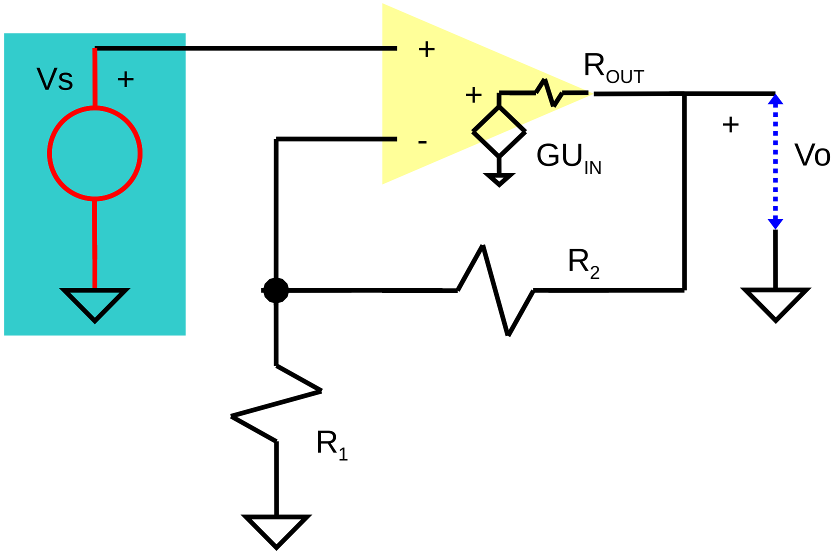




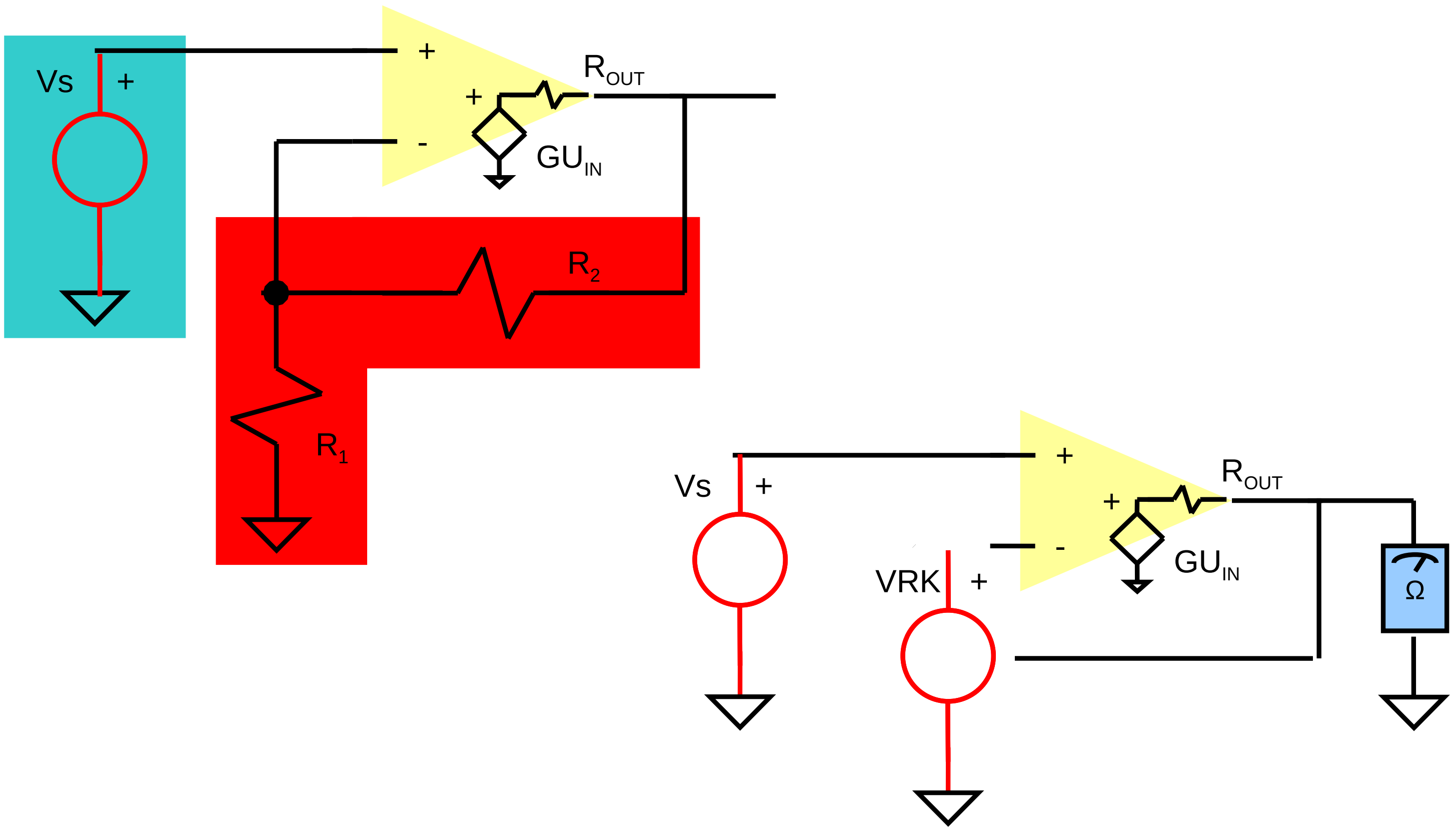
$$FF = \left.\frac{V_o}{V_s}\right|_{V_i^* = 0}$$

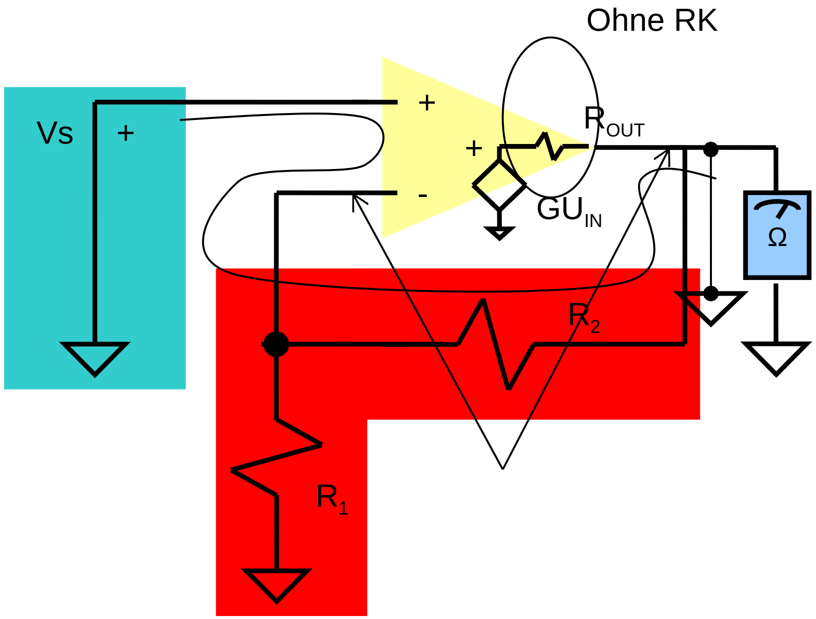
$$FF = 0$$

$$A_F \equiv \frac{X_O}{X_S} = \frac{FF + A_{IN}A}{1-\beta A} = \frac{\dfrac{R_1+R_2}{R_1+R_2+R_{OUT}}G}{1+\dfrac{R_1+R_2}{R_1+R_2+R_{OUT}}\dfrac{R_1}{R_1+R_2}G} \approx \frac{R_1+R_2}{R_1}$$

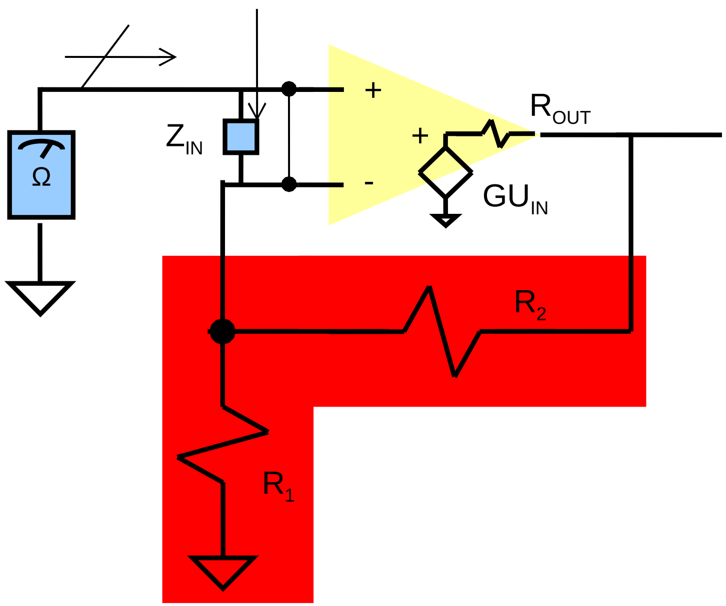


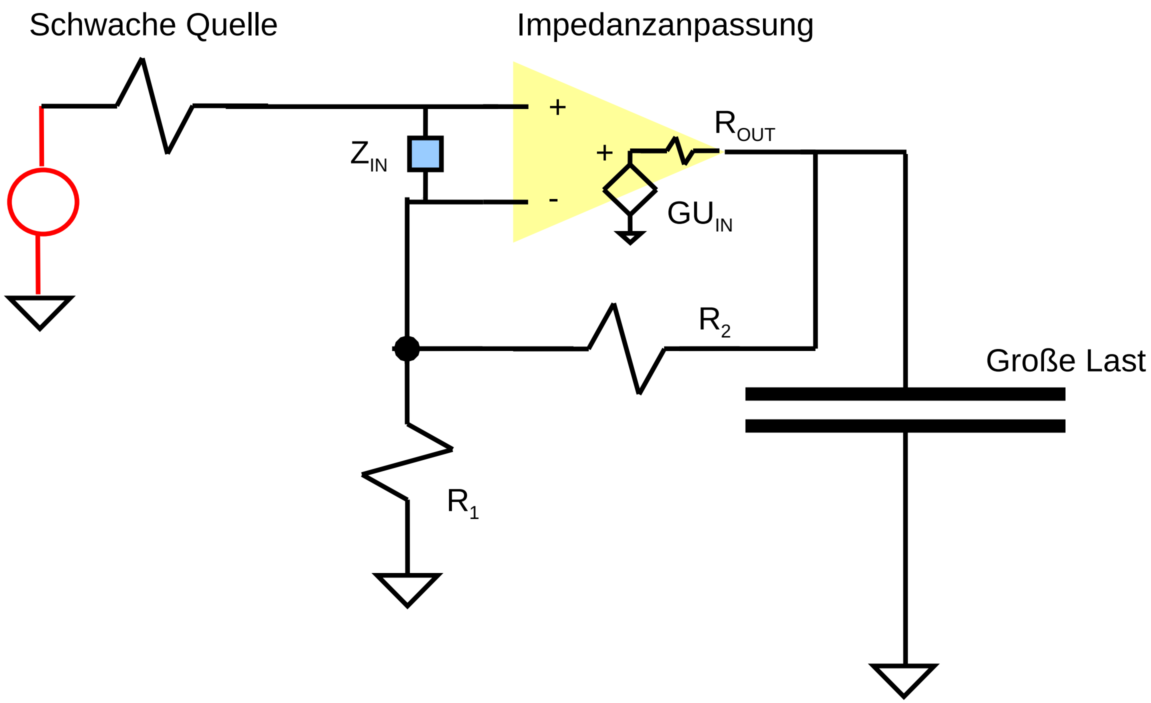
Non-inverting amplifier output resistance


Vs
+
+
-
+
ROUT
GUIN
R2
R1
Vs
+
+
-
+
ROUT
GUIN
VRK
+
Ω



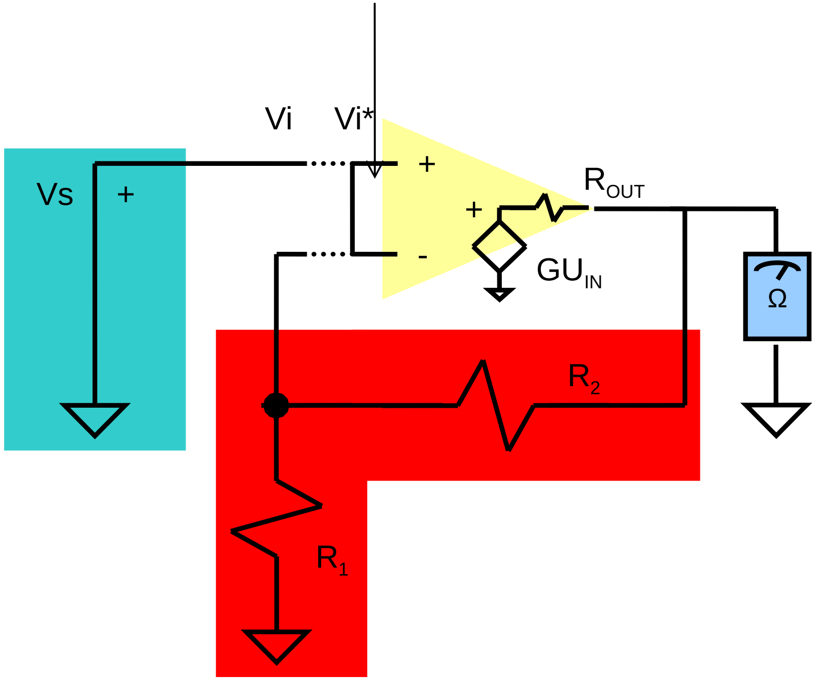
Ohne RK
Vs
+
+
-
+
R_{OUT}
GU_{IN}
Ω
R_2
R_1

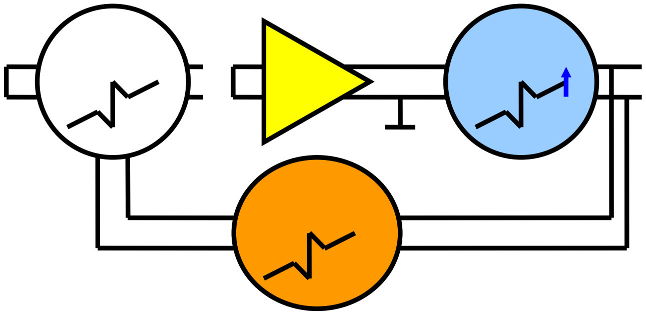

Ω
Z_IN
+
-
+
R_OUT
GU_IN
R_2
R_1



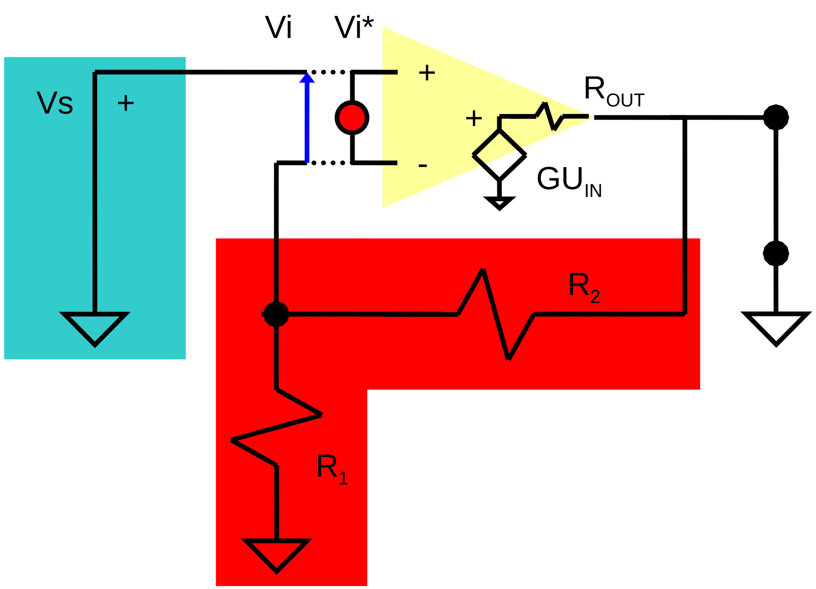
Schwache Quelle
Impedanzanpassung
+
-
+
Z_{IN}
R_{OUT}
GU_{IN}
R_2
R_1
Große Last

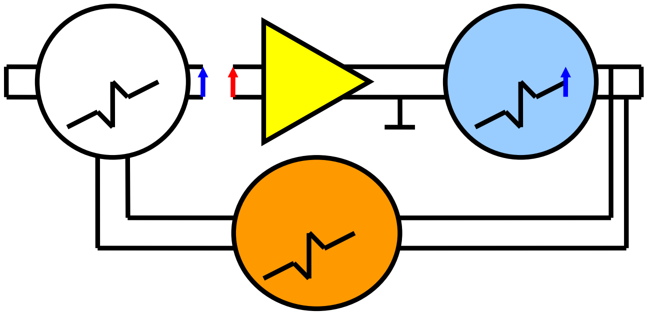
R_{OUT} without amplifier





$$R_{OUT\,0} = R_{OUT} \parallel (R_1 + R_2)$$

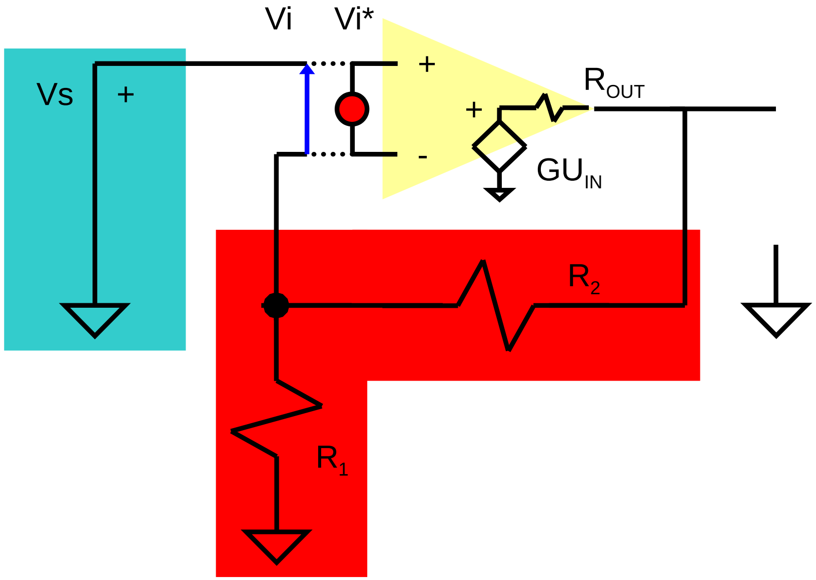


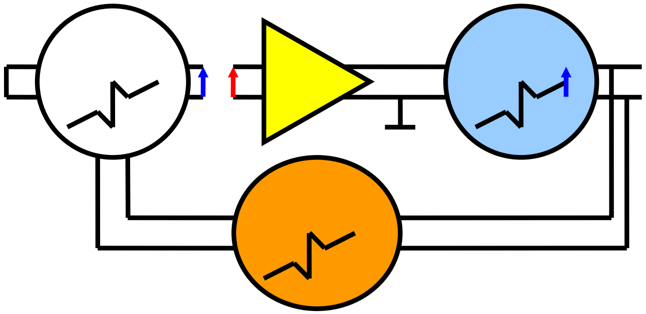


$$\beta A_{sc} = -\left.\frac{V_i}{V_i^*}\right|_{V_s=0}$$

$$\beta A_{sc} = 0$$

Open-circuit loop gain

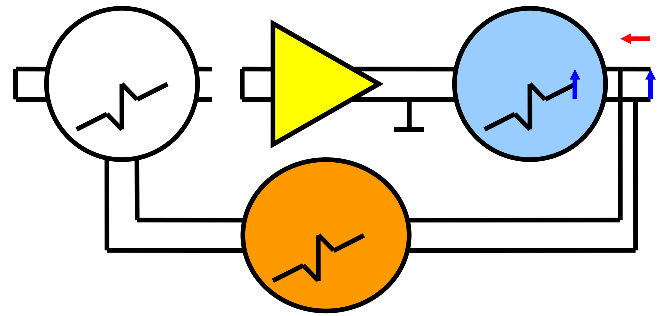


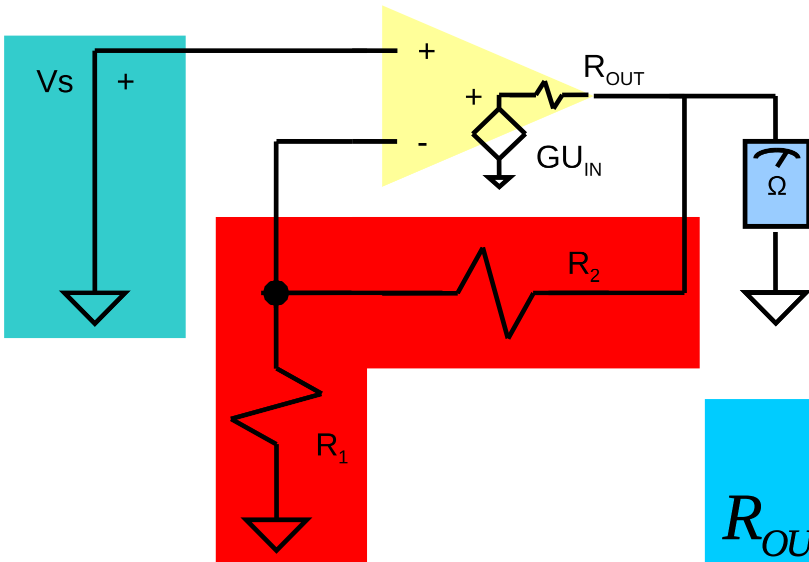


$$\beta A_{oc} = -\left.\frac{V_i}{V_i^*}\right|_{V_s=0}$$

$$\beta A_{oc} = -G\frac{R_1}{R_1 + R_2 + R_{OUT}}$$

R_{OUT} with feedback



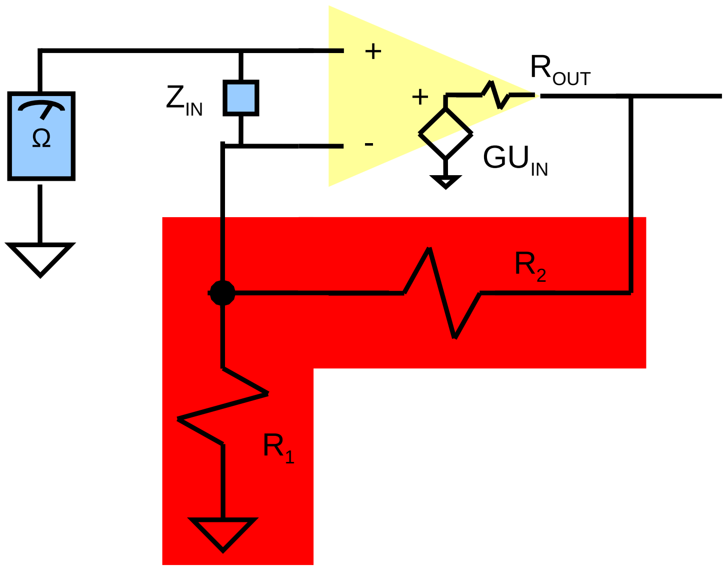


$$R_{OUTFB} = \frac{R_{OUT} \parallel (R_1 + R_2)}{1 + G \dfrac{R_1}{R_1 + R_2 + R_{OUT}}} \prec R_{OUT}$$

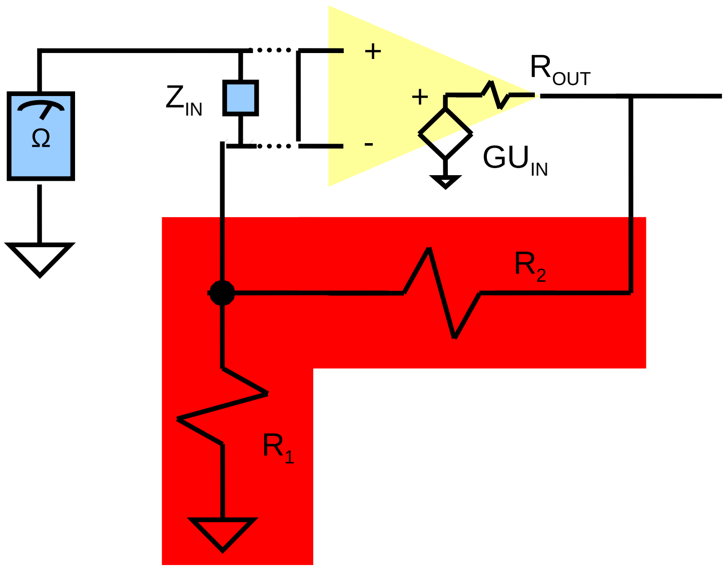
$$R_{OUT} \prec R_1, R_2 \qquad R_{OUTFB} \sim \frac{R_{OUT}}{G\beta}$$

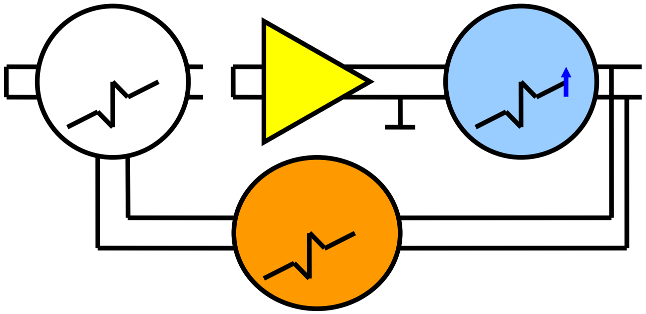
10,100 für präzise Verstärkung

Non-inverting amplifier input resistance



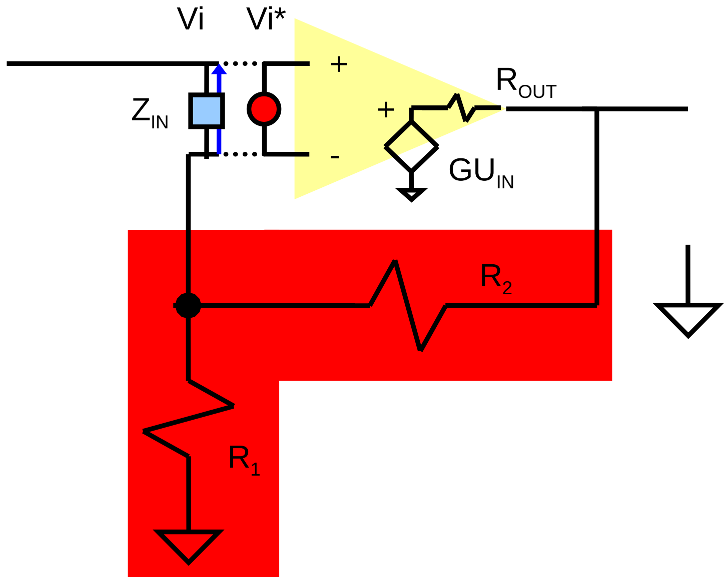
+
-
+
Ω
Z_{IN}
R_{OUT}
GU_{IN}
R_2
R_1

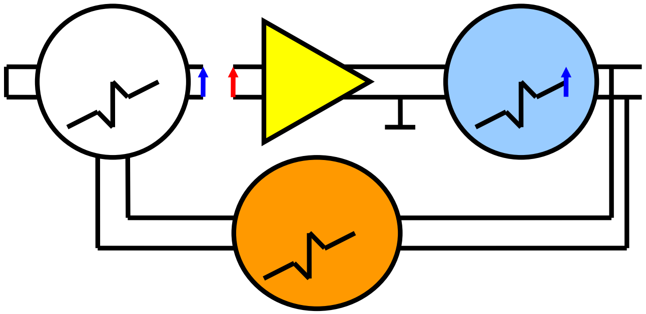




Annahme Zin klein

$$Z_{IN0} = Z_{IN} + (R_1 \| R_2) \sim R_1 \| R_2$$

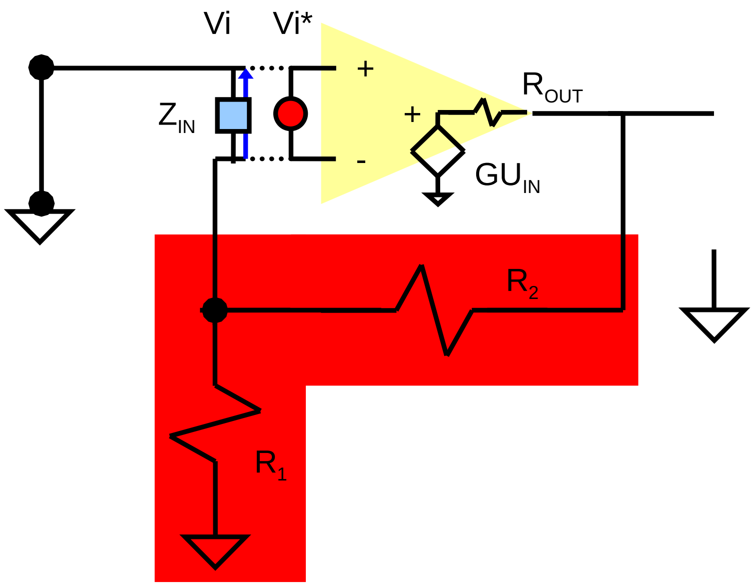


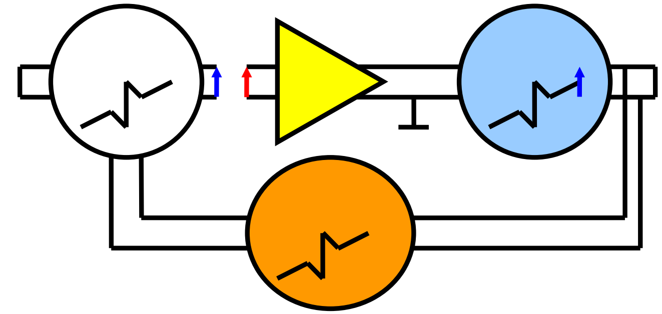


$$\beta A_{oc} = -\left.\frac{V_i}{V_i^*}\right|_{V_s=0}$$

$$\beta A_{oc} = 0$$

Short-circuit loop gain

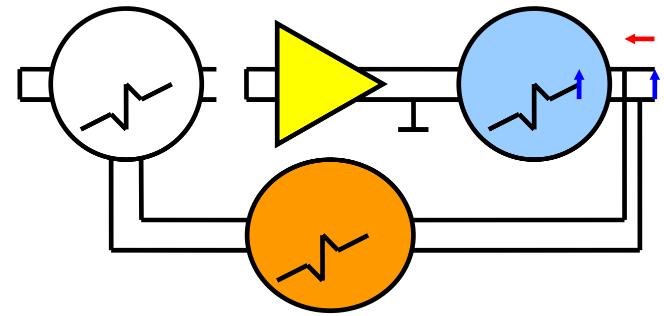


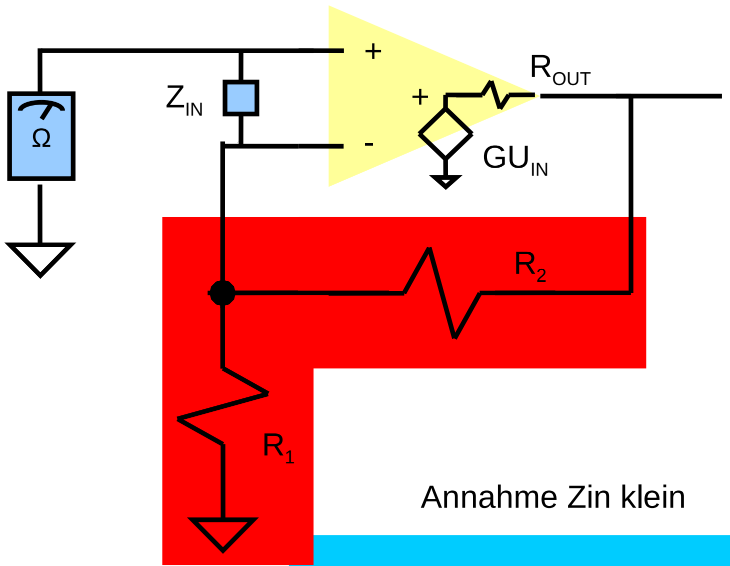


$$\beta A_{sc} = -\left.\frac{V_i}{V_i^*}\right|_{V_S=0}$$

$$\beta A_{oc} \sim -G\frac{R_1 \,||\, R_{IN}}{R_1 \,||\, R_{IN} + R_2}$$

Z_{IN} with feedback



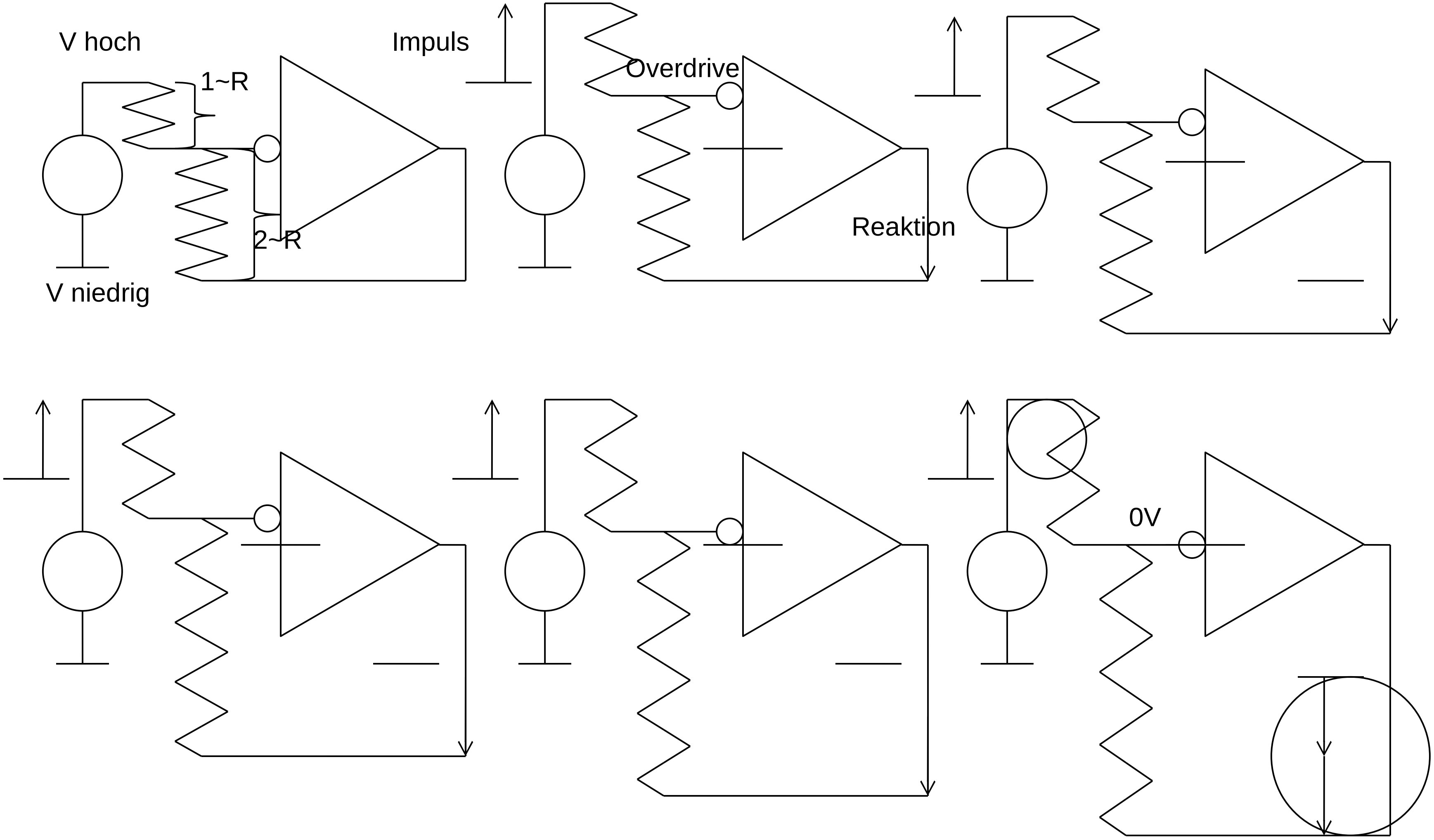


Beta A

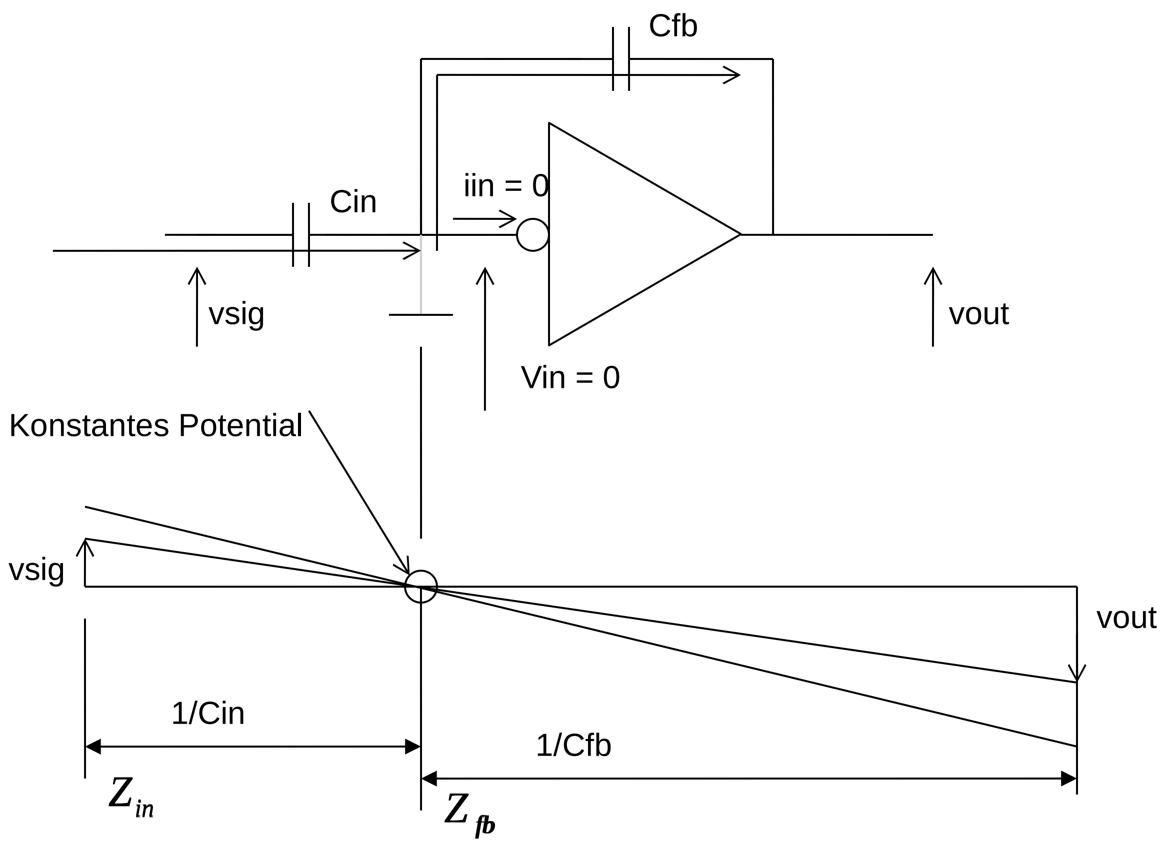
Annahme Zin klein

$$Z_{INFB} \simeq R_1 \,\|\, R_2\left(1+G\frac{Z_{IN}}{R_2}\right) = \frac{R_1}{R_1+R_2} G Z_{IN} >> Z_{IN}$$

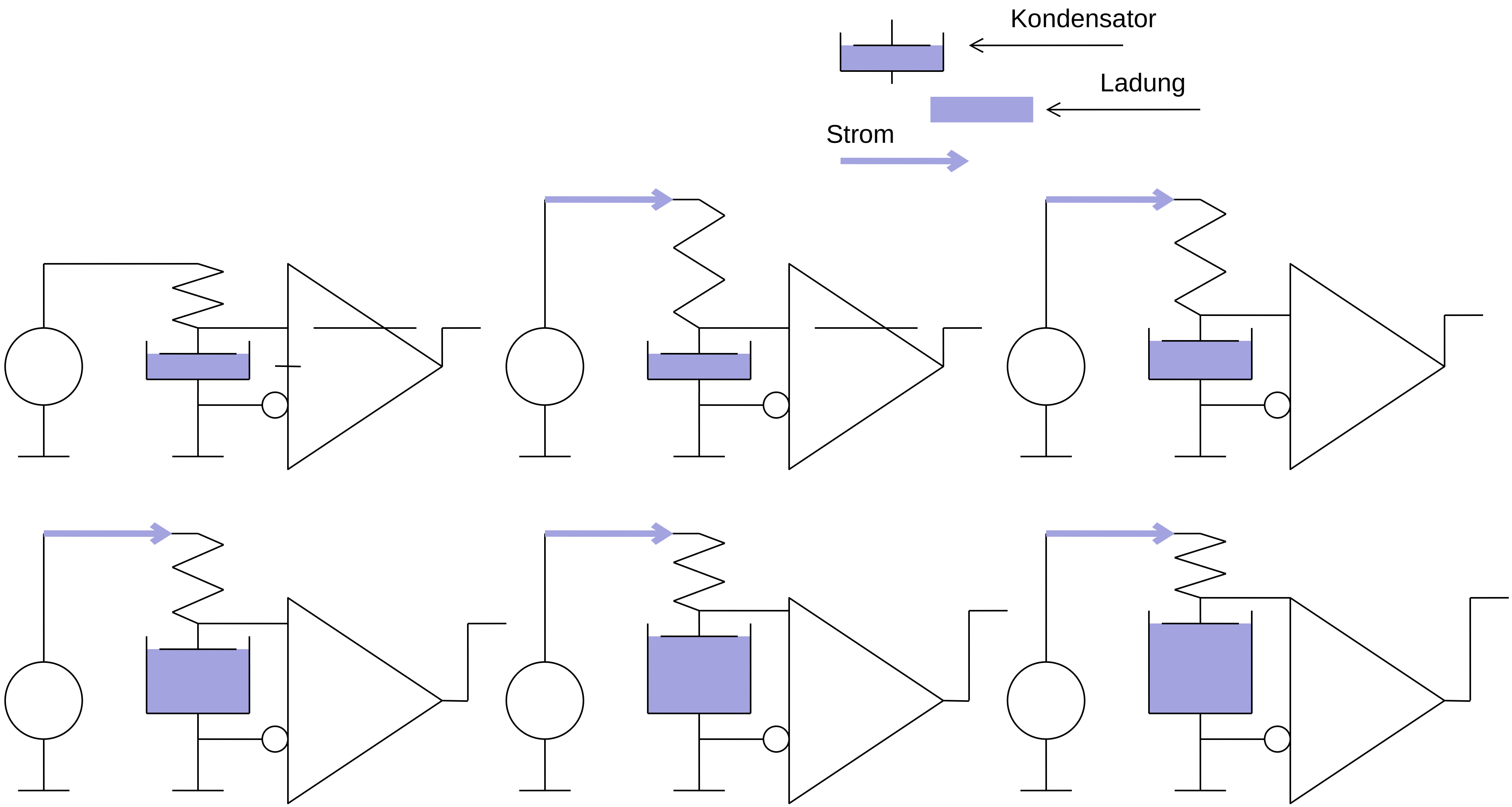
- Die Verstärkung mit Gegenkopplung ist nur durch die Stärke der Gegenkopplung bestimmt



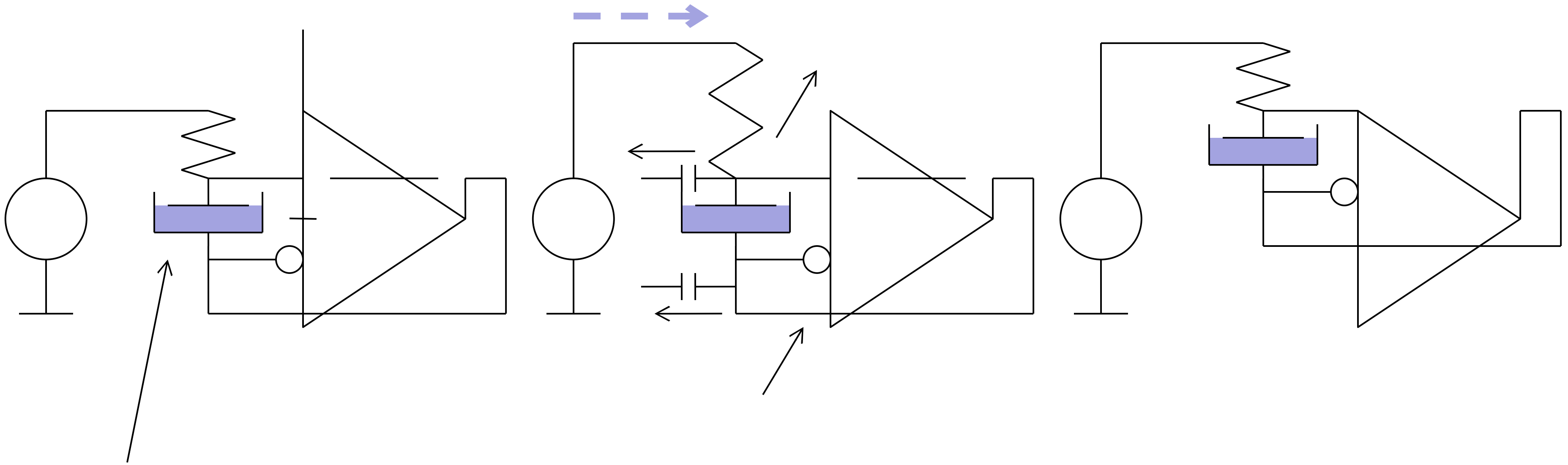
- Virtuelle Masse am Eingang des Verstärkers



- Eingangsimpedanz ohne RK

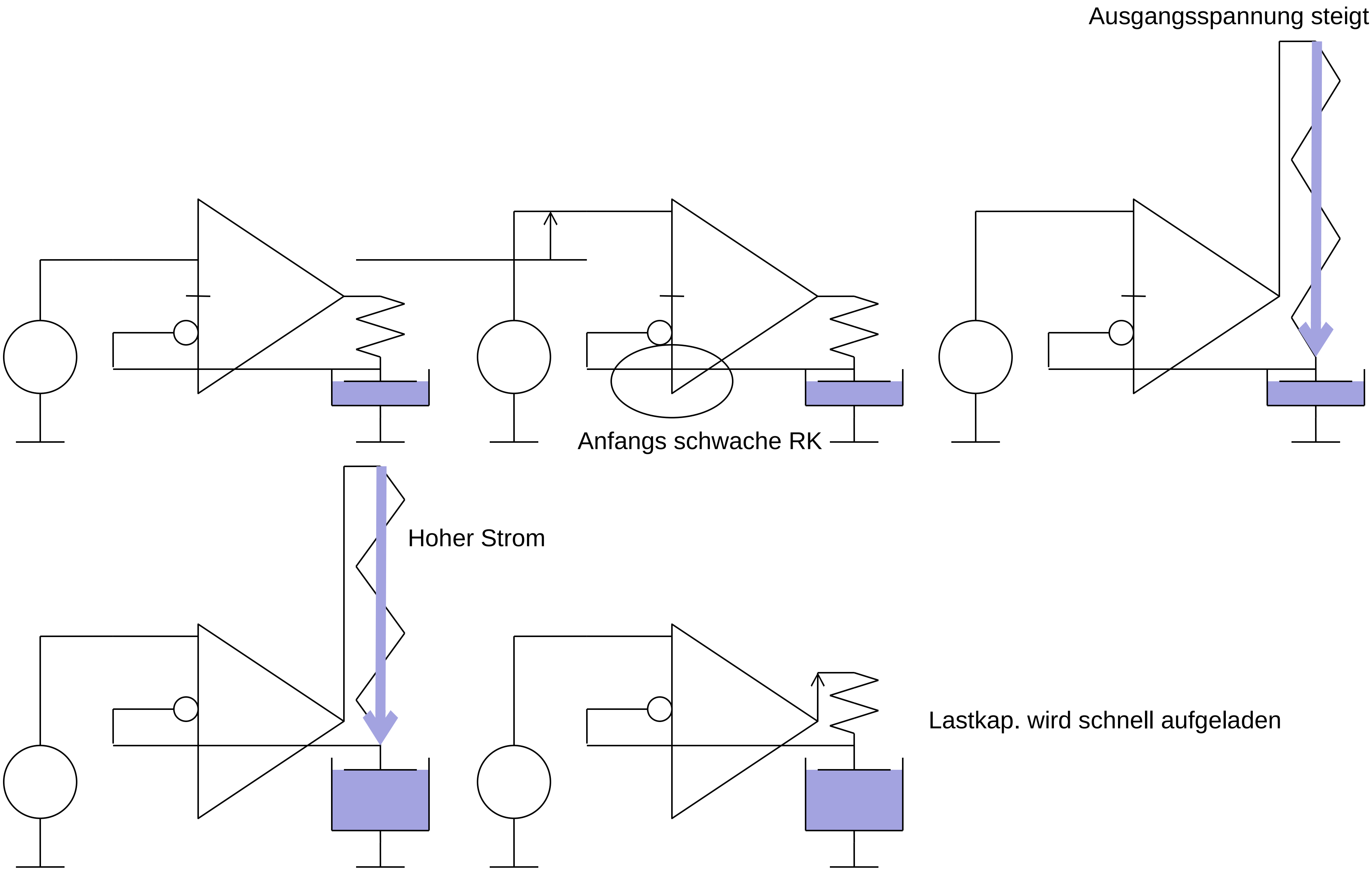


- Eingangsimpedanz mit RK



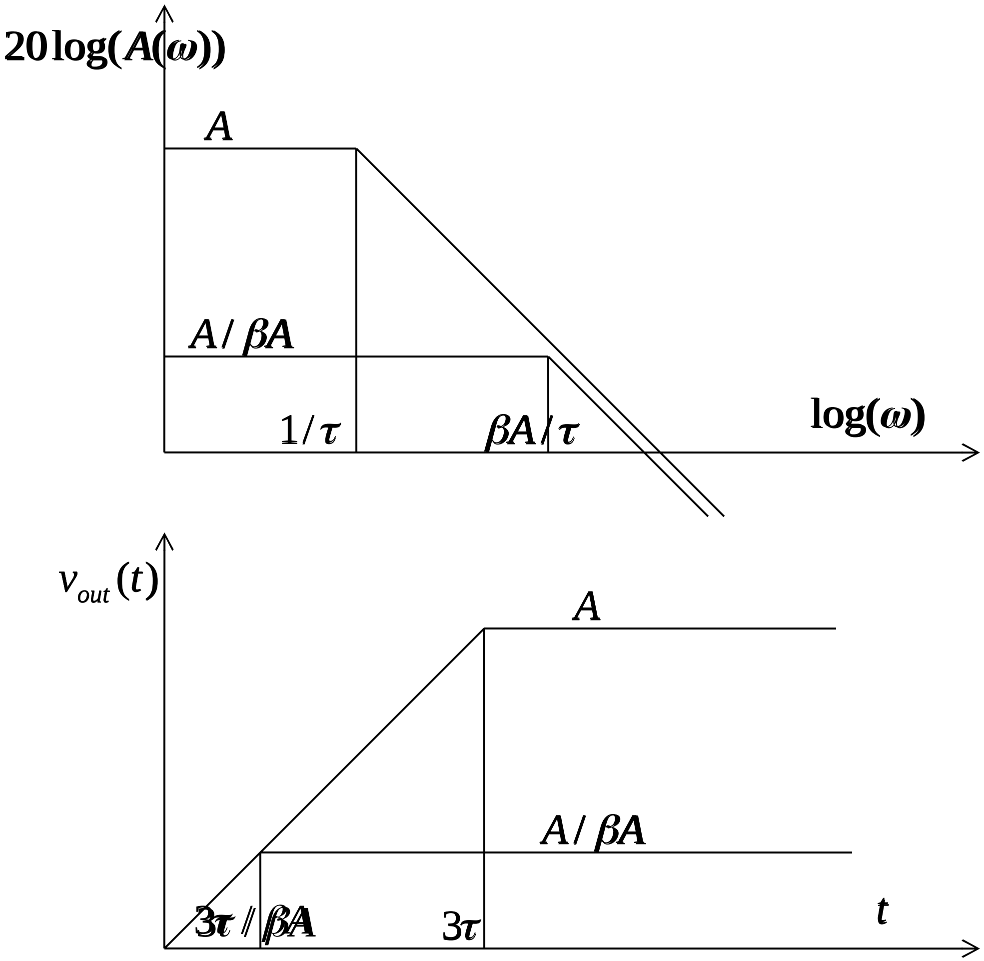
Kondensator zwischen +-
Ladung Konstant

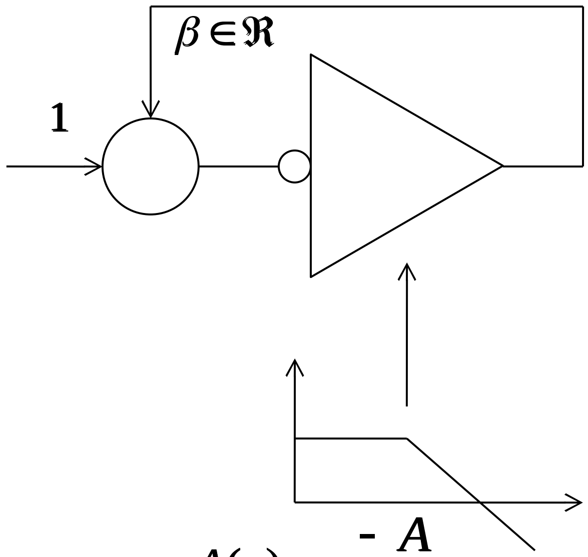
- Ausgangsimpedanz mit RK



Integrator

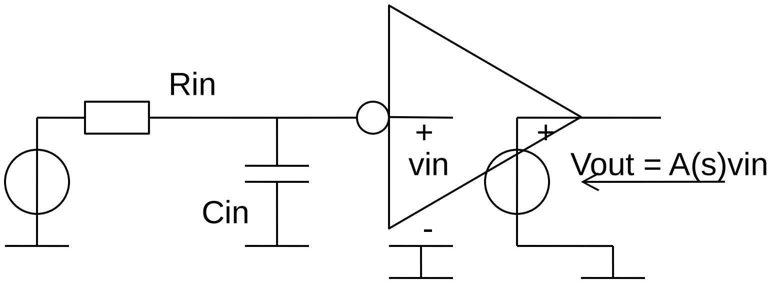
- Einfluss von RK: Zeitkonstante wird kleiner



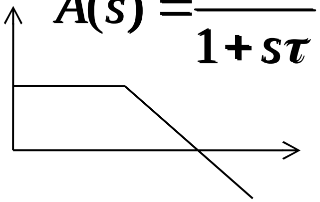


$$A(s) = \frac{-A}{1+s\tau}$$

- Anfang: Verstärker ohne RK

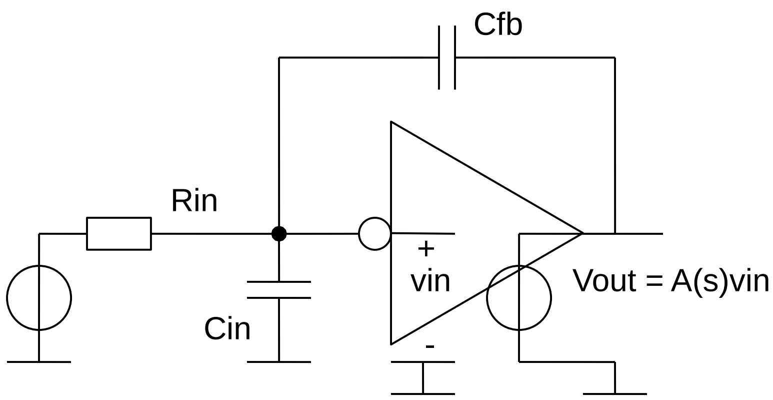


$$A(s) = \frac{-A}{1+s\tau}$$



$$H(s) = -\frac{1}{(1+sR_{IN}C_{IN})(1+s\tau)}A$$

- Verstärker mit kapazitiver RK



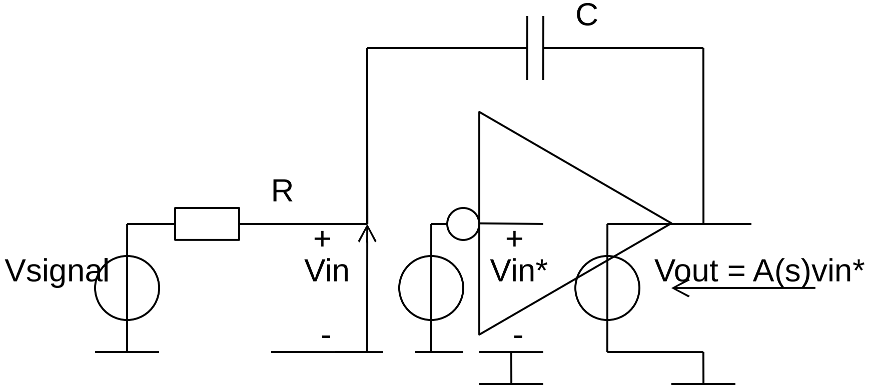
$$H(s) = -\frac{1}{(1+s?)(1+s?)}A$$

- Feedback Analyse

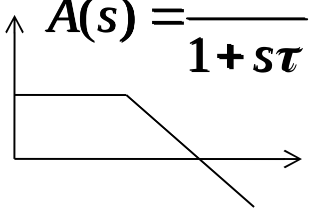
$$A_{OL} = A(s)$$

$$A_{IN} = \frac{1}{1 + sRC}$$

$$\beta A = \frac{sRC}{1 + sRC} A_{OL} = \frac{sRC}{1 + sRC} A(s)$$



$$A(s) = \frac{-A}{1 + s\tau}$$



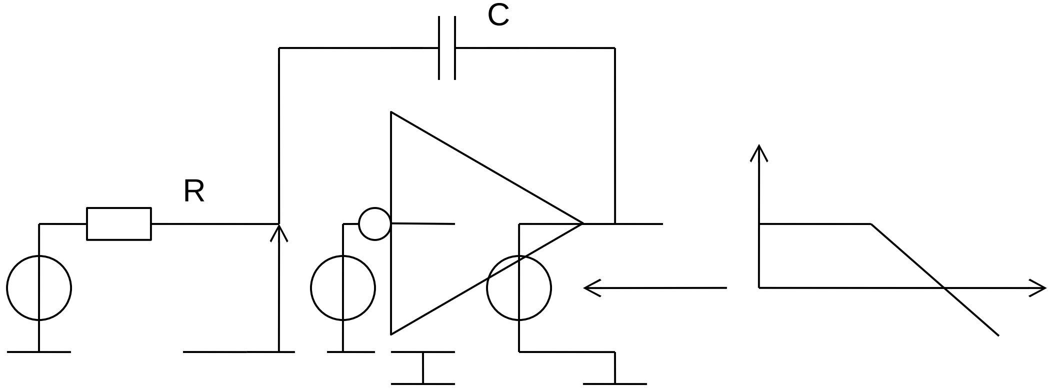
$$H(s) = -\frac{1}{(1 + s?)(1 + s?)} A$$

Feedback-Analyse (2)

- Verstärkung mit RK

$$A_{FB}=\frac{A_{IN}A_{OL}}{1+\beta A_{OL}}=\frac{A(s)\,\dfrac{1}{1+sRC}}{1-A(s)\,\dfrac{sRC}{1+sRC}}$$

$$A_{FB}=\frac{-\dfrac{A}{1+s\tau}\,\dfrac{1}{1+sRC}}{1+\dfrac{A}{1+s\tau}\,\dfrac{sRC}{1+sRC}}$$



Feedback-Analyse (3)

- Zeikonstanten

$$A_{FB} = \frac{-\frac{A}{1+s\tau}\frac{1}{1+sRC}}{1+\frac{A}{1+s\tau}\frac{sRC}{1+sRC}} \longrightarrow A_{FB} = \frac{-A}{(1+s\tau)(1+sRC)+sARC}$$

$$A_{FB} = \frac{-A}{1+s\tau+sRC+sARC+s^2RC\tau}$$

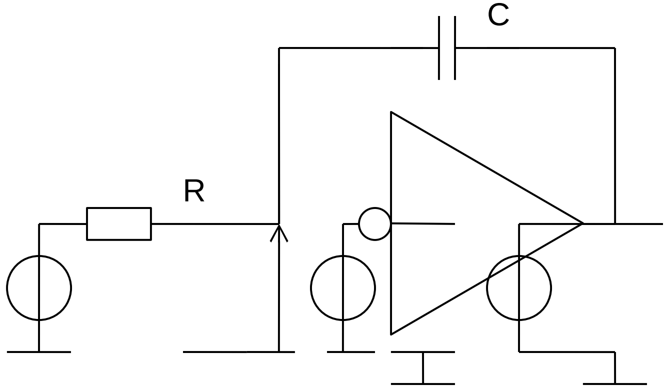
klein klein Groß Groß für HF

$$A_{FB} = \frac{-A}{1+sARC+s^2RC\tau}$$

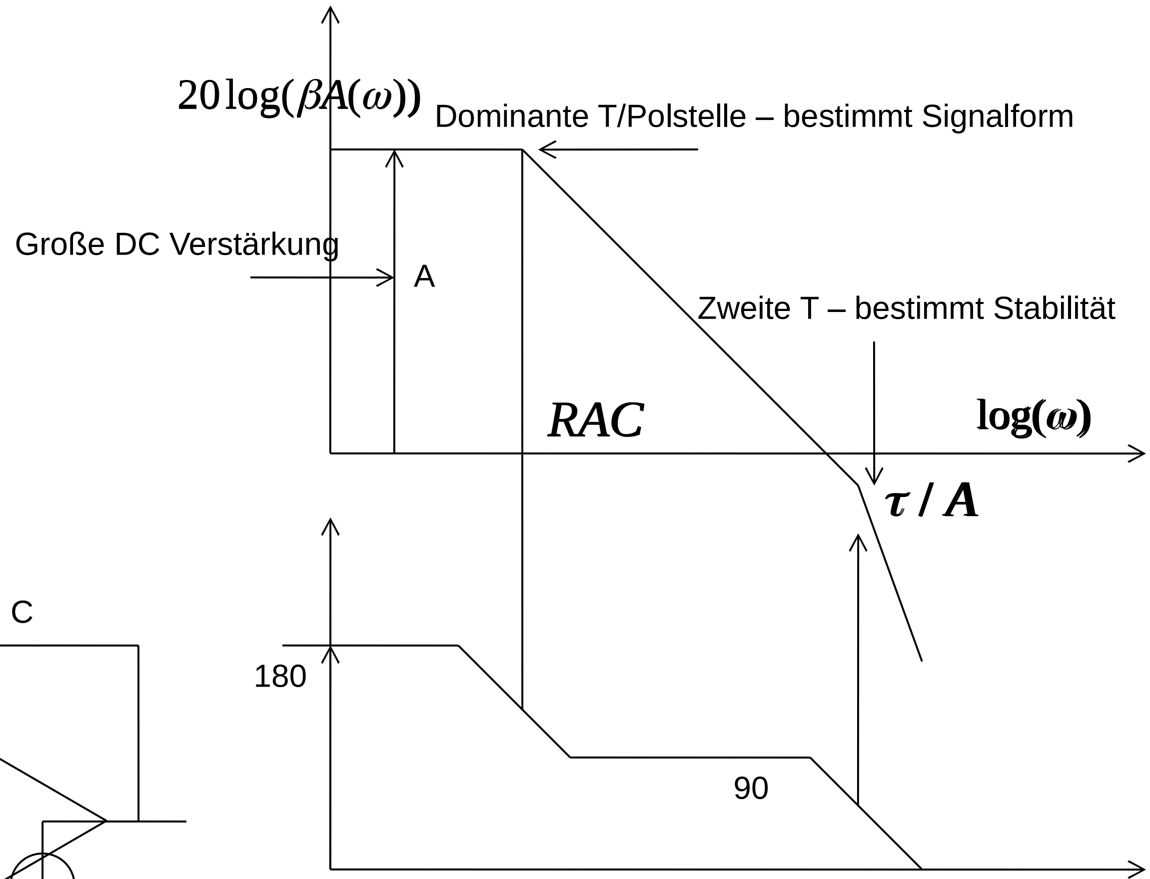
$$A_{FB} = \frac{-A}{(1+sARC)(1+s\frac{\tau}{A})}$$

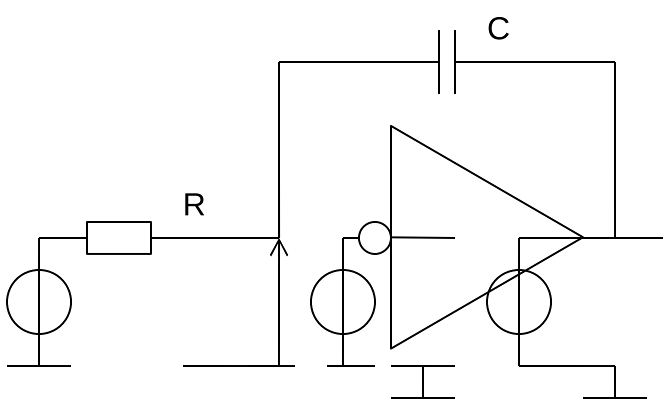
Große T-Const

Kleiner als ohne RK



- Zeitkonstanten



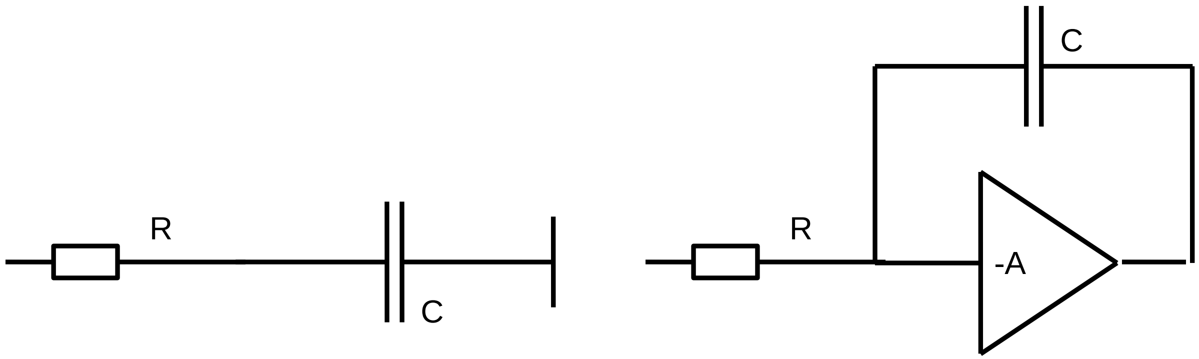


$$A_{FB} = \frac{-A}{(1+sRAC)(1+s\frac{\tau}{A})}$$

Große T-Const

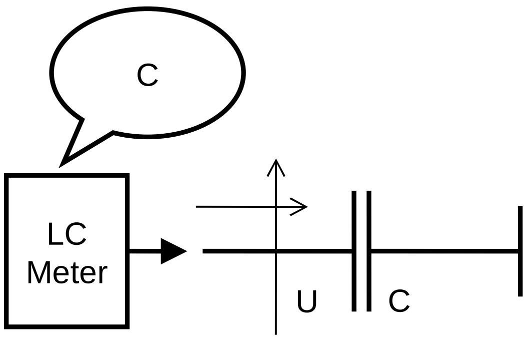
Kleiner als ohne RK

Multiplikation von Cfb



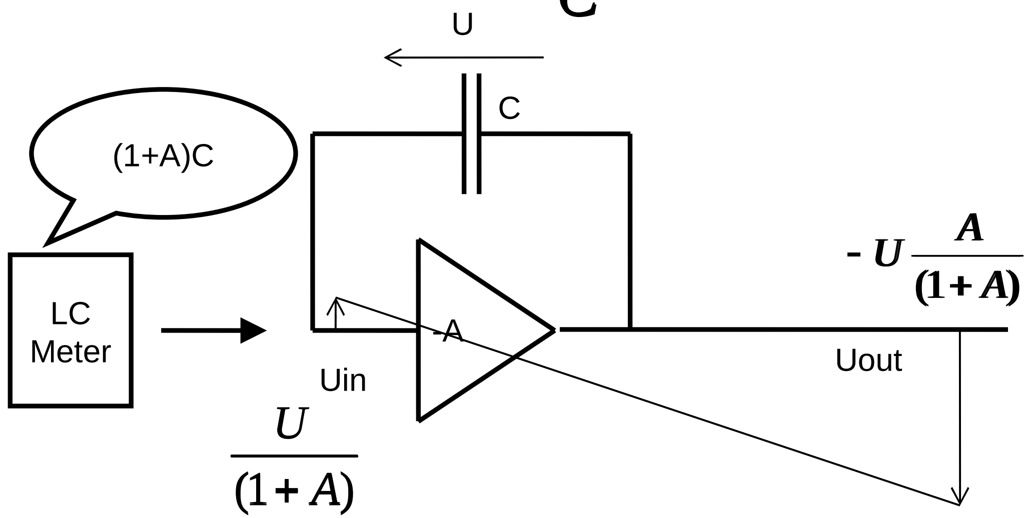
T = RC

T = R*AC

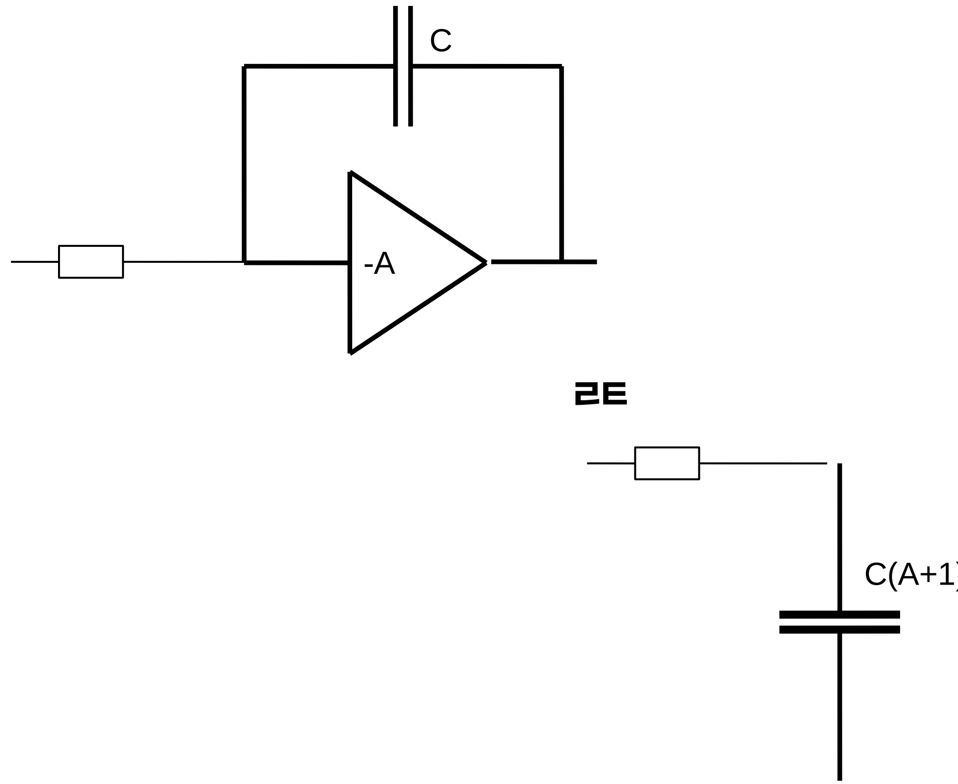


$$U = \frac{1}{C} TI$$

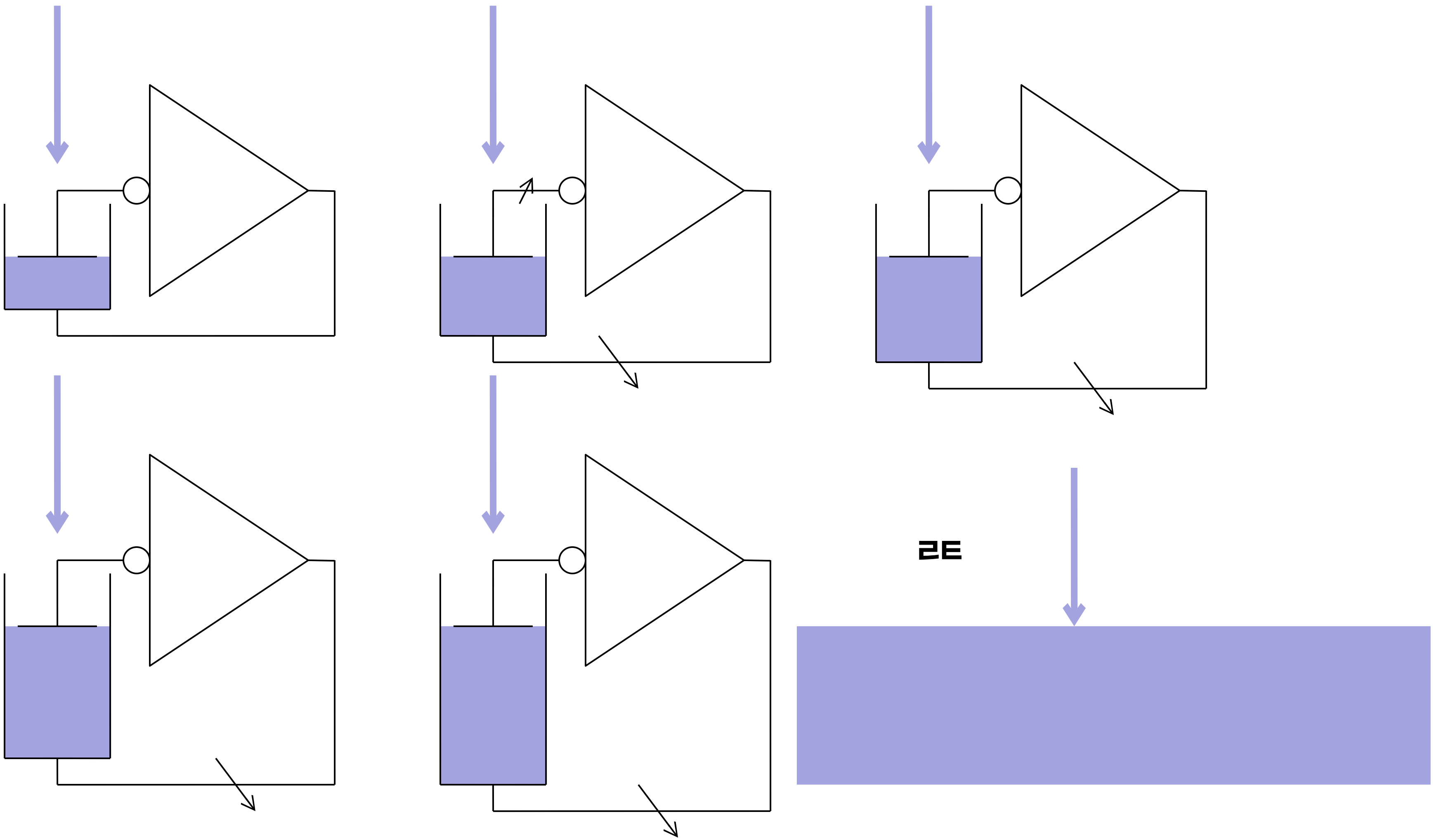
$$U = \frac{1}{C} TI$$



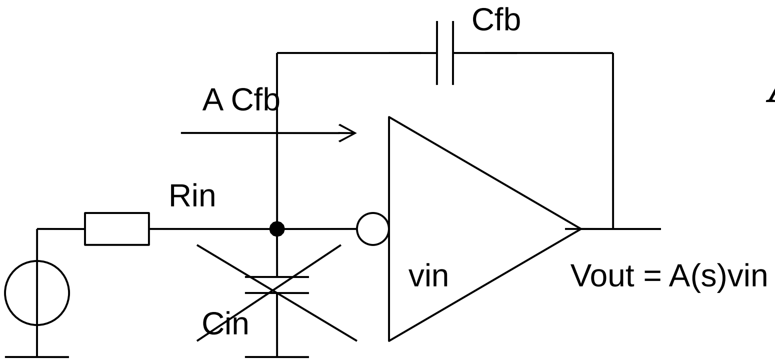
Millereffekt



Millereffekt



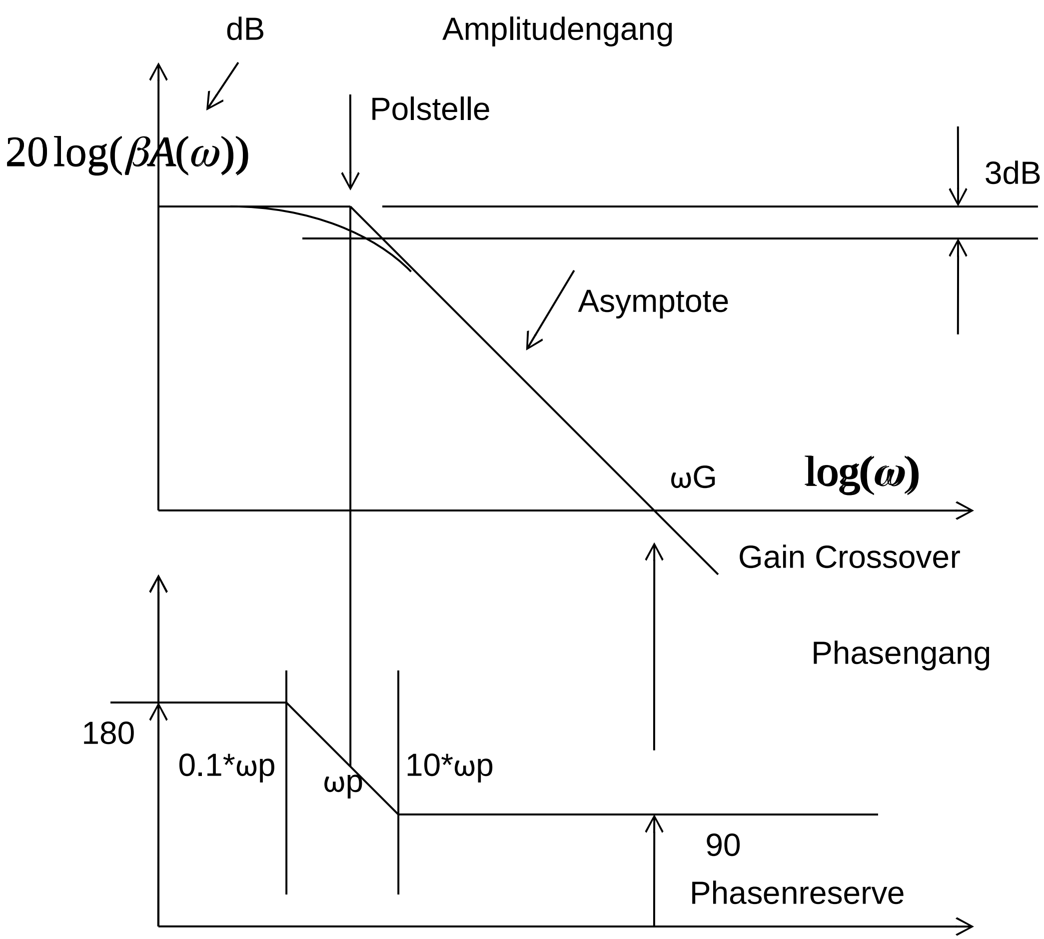
- Integrator



$$A_{FB} = \frac{-A}{(1+sRAC)(1+s\frac{\tau}{A})} \rightarrow -\frac{1}{sRC}$$

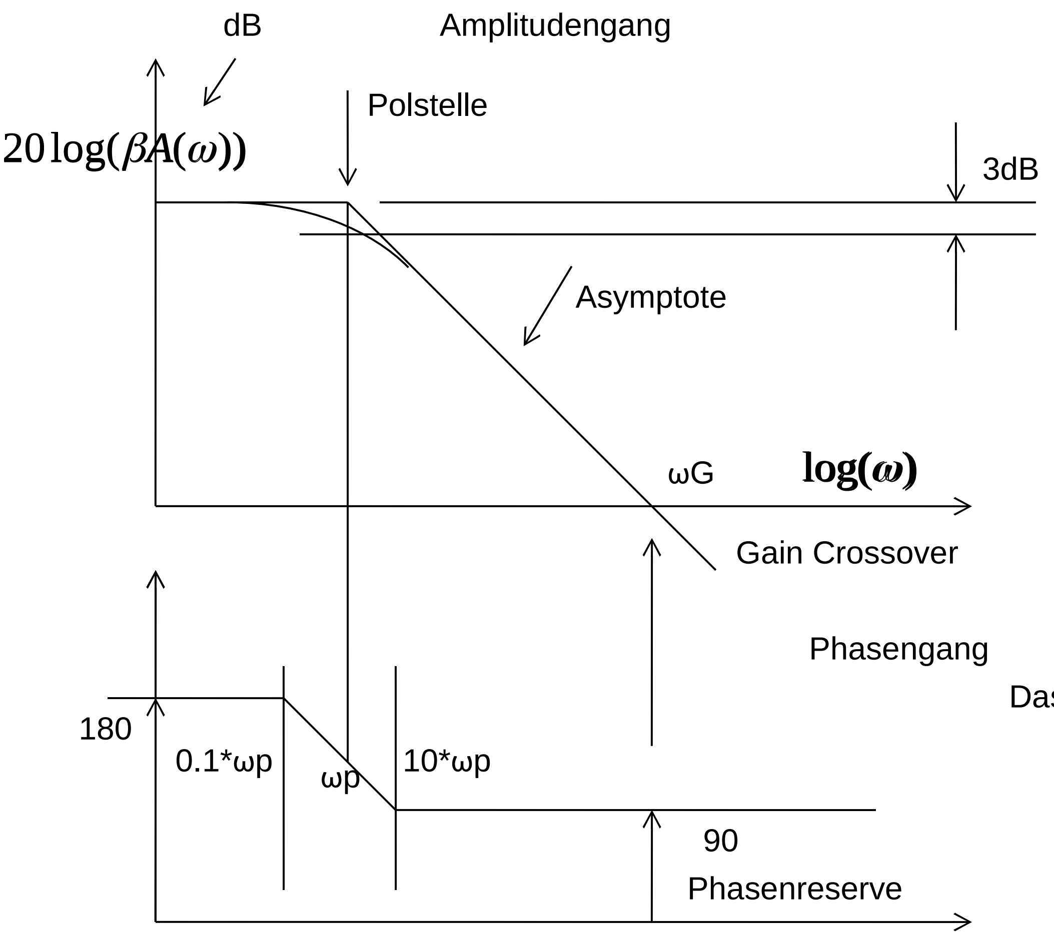
Bode-Diagramm und Stabilität

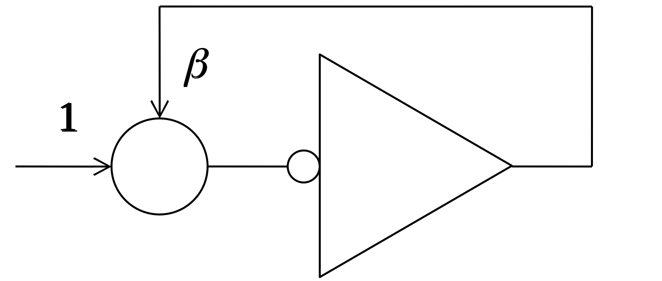
- Bode Diagramm



Stabilität (Nyquistkriterium)

- System ist stabil wenn die Phasenreserve > 0 (Phasenänderung < 180)





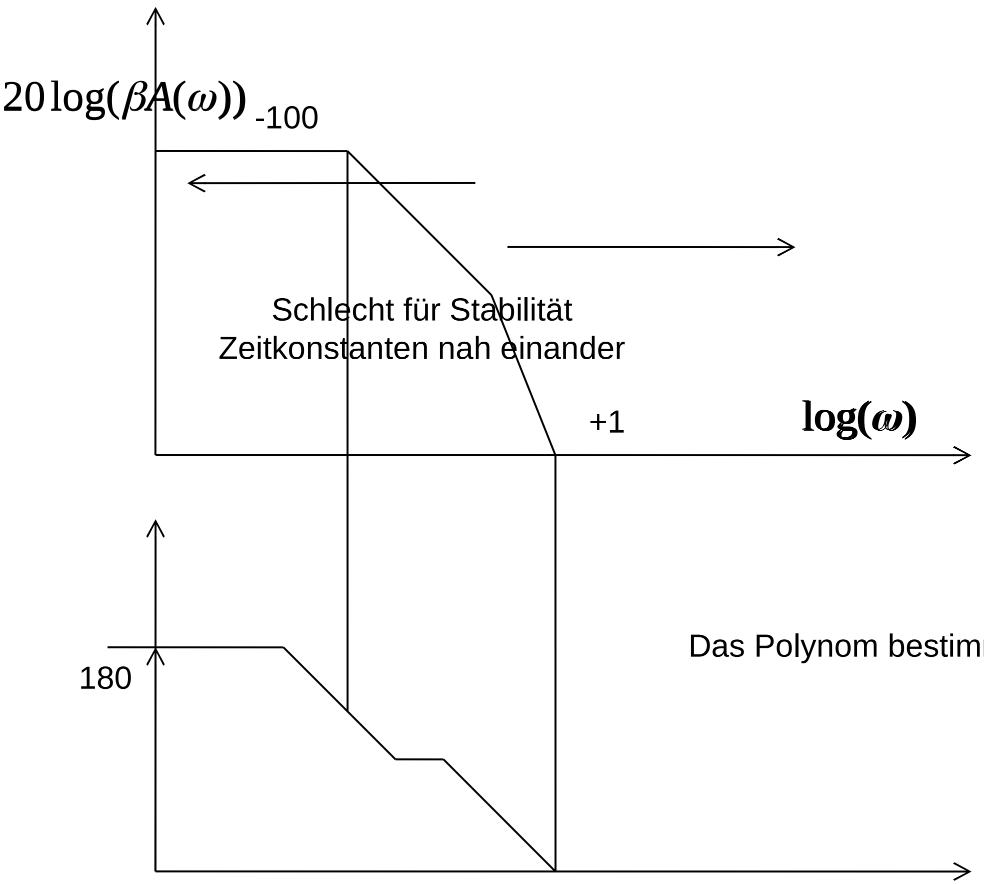
$$A_F = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

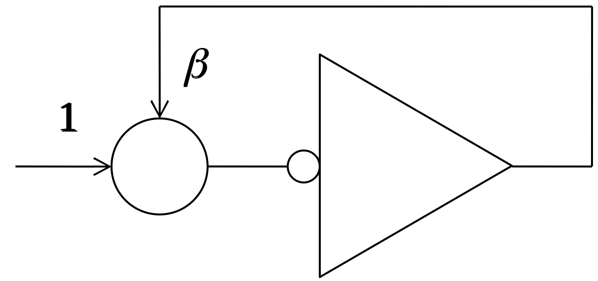
Das Polynom bestimmt Eigenverhalten des Systems

$$v(t) = \sum_i c_i \exp(\lambda_i t)$$

Instabil

- Phasenänderung = 180 -> Oszillator





$$A_F = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

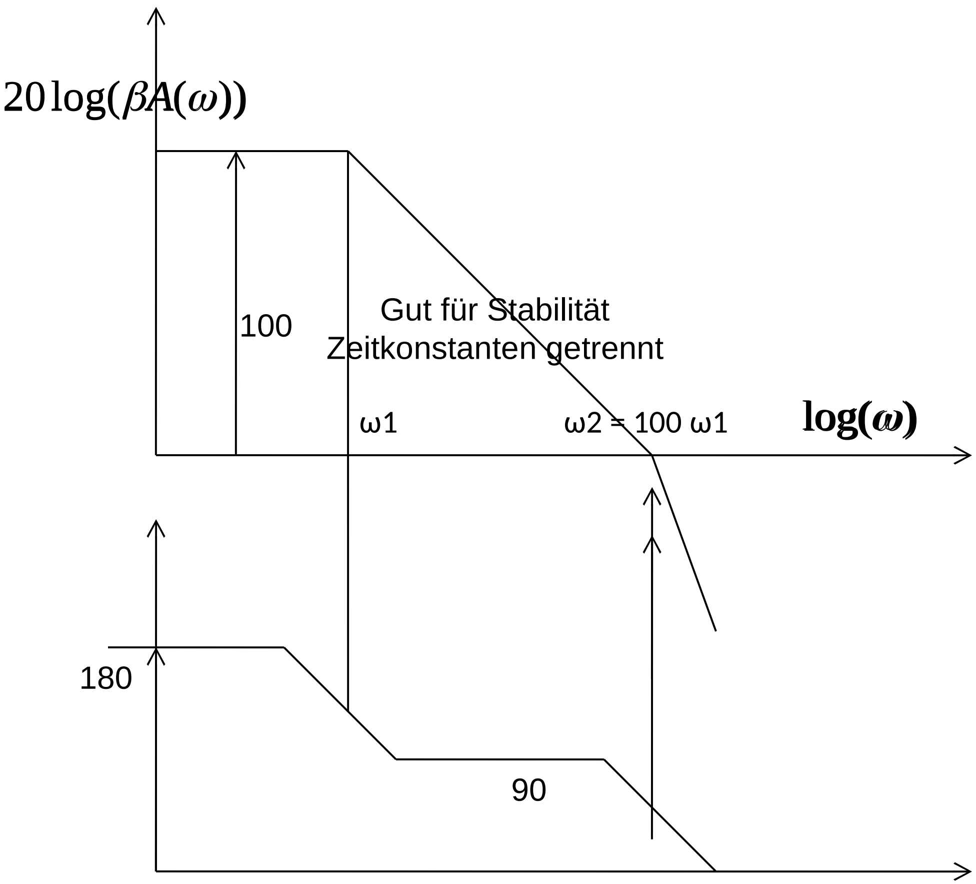
Das Polynom bestimmt Eigenverhalten des Systems

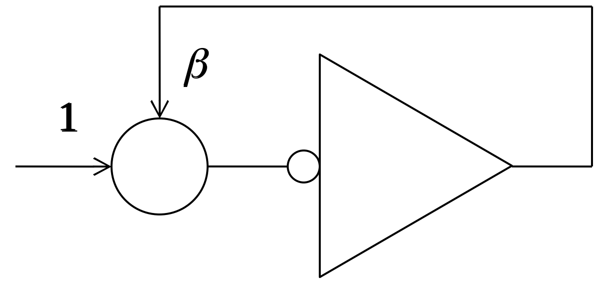
1-1

$$v(t) = \sum_i c_i \exp(\lambda_i t)$$

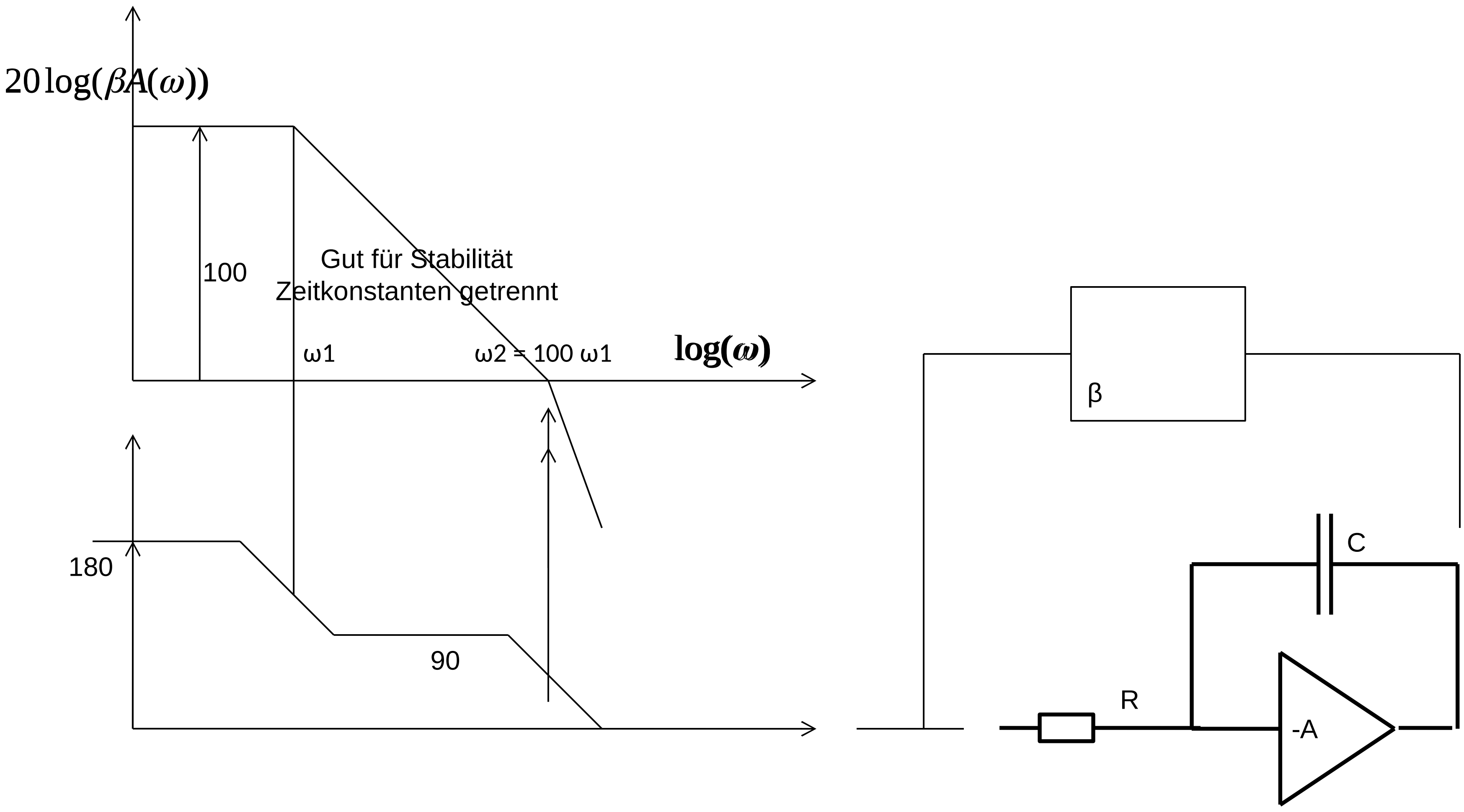
Stabil

- Phasenreserve 45°
- Beispiel: beta A = 100, die zweite Zeitkonstante soll 100 kleiner sein als die dominante T





$$A_F = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$



$20\log(\beta A(\omega))$
100
Gut für Stabilität
Zeitkonstanten getrennt
ω1
ω2 = 100 ω1
$\log(\omega)$
180
90
β
C
R
-A

Zusammenfassung

- Rückkopplung – nichtinvertierender Verstärker
- Impedanzen und RK (Beispiel Nichtinvertierender Verstärker)
- Rin wird höher, Rout niedriger
- Integrator (Millereffekt)
- Kapazität wird multipliziert
- Bode-Diagramm und Stabilität (Nyquistkriterium)
- System ist stabil wenn Phasenreserve > 0
- Trennung von Zeitkonstanten ist gut für Stabilität