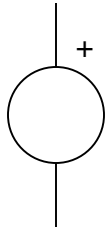


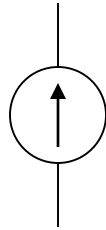
Design analoger Schaltkreise

Vorlesung 2

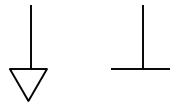
- Spannungsquellen, Stromquellen
- Masse und Versorgungsspannung



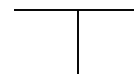
Spannungsquelle
Vdc, vpulse, vsin



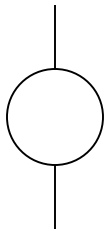
Stromquelle



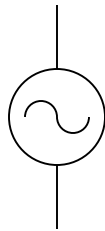
Masse
gnd, gnda



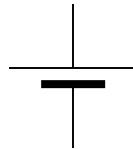
Versorgungsspannung
vdd, vdda



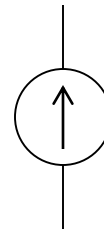
Spannungsquellen



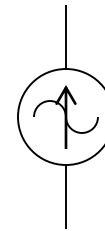
Kleinsignal



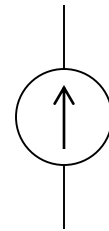
DC



Stromquellen

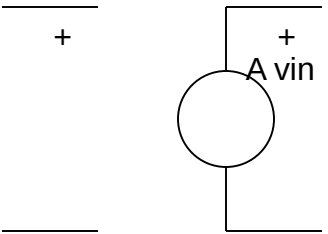
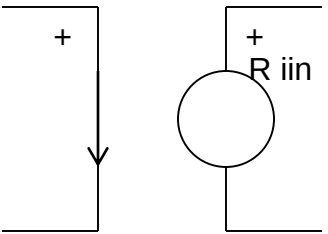
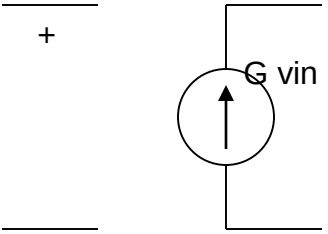
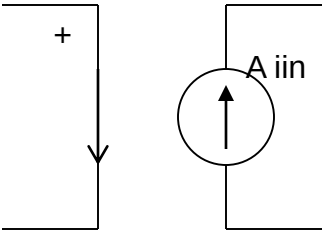


Kleinsignal

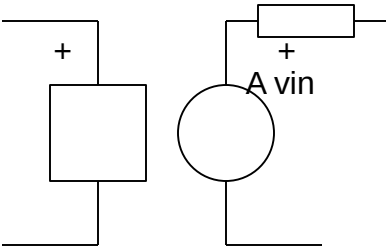
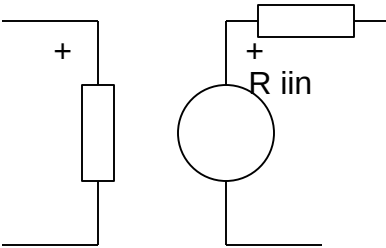
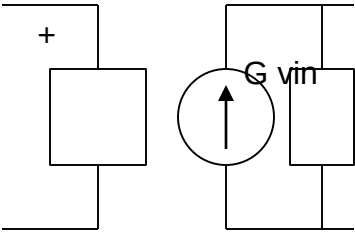
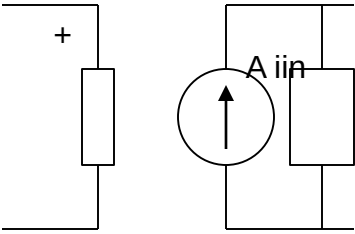


DC

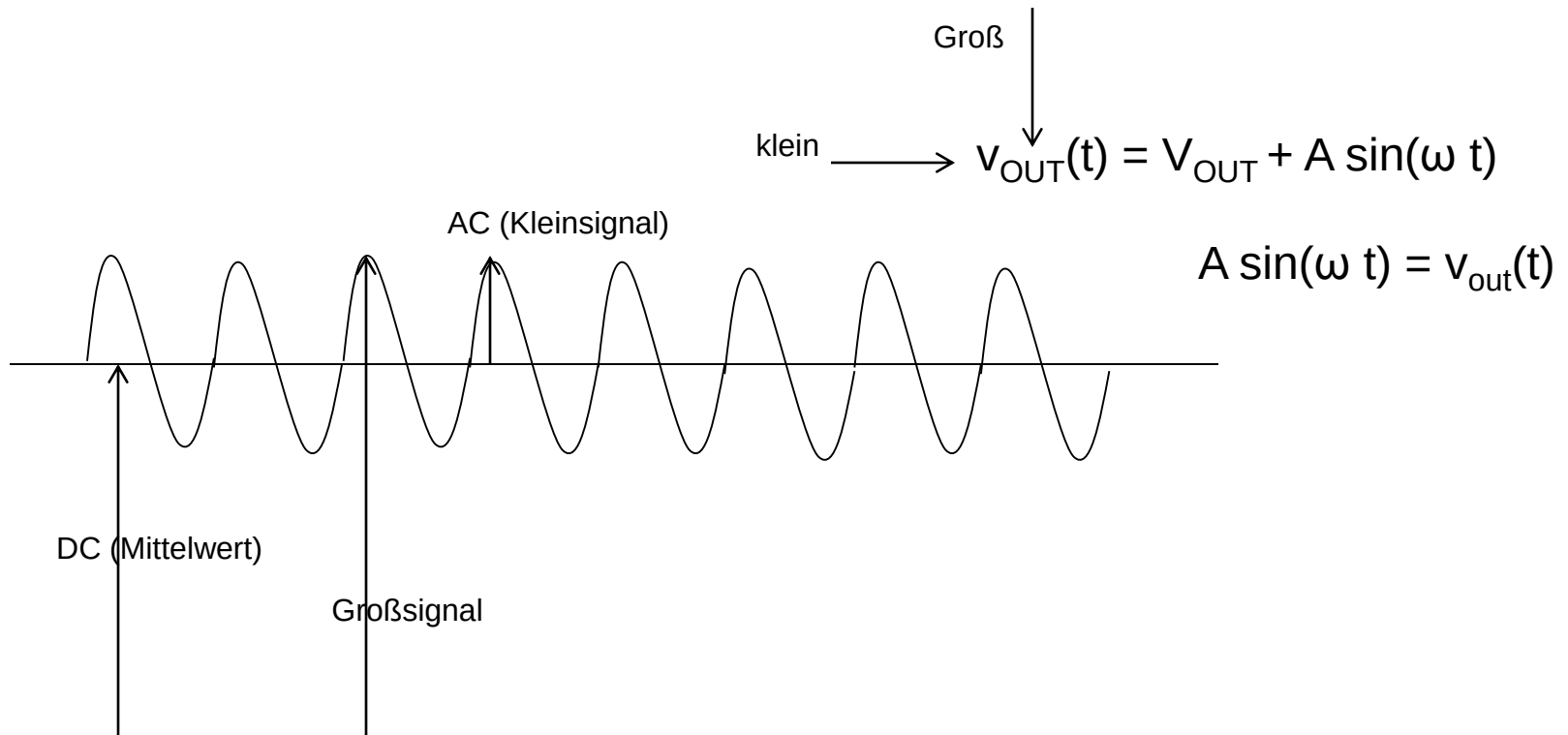
- Gesteuerte ideale Spannungsquellen und Stromquellen

 Spannungsverstärker (V-V) OPAMP	 Transimpedanzverstärker (I-V) Sensor-Signal Verstärker	Ausgang Spannung
 Transkonduktanzverstärker (V-I) MOSFET	 Stromverstärker (I-I) BJT	Ausgang Strom
Eingang Spannung	Eingang Strom	

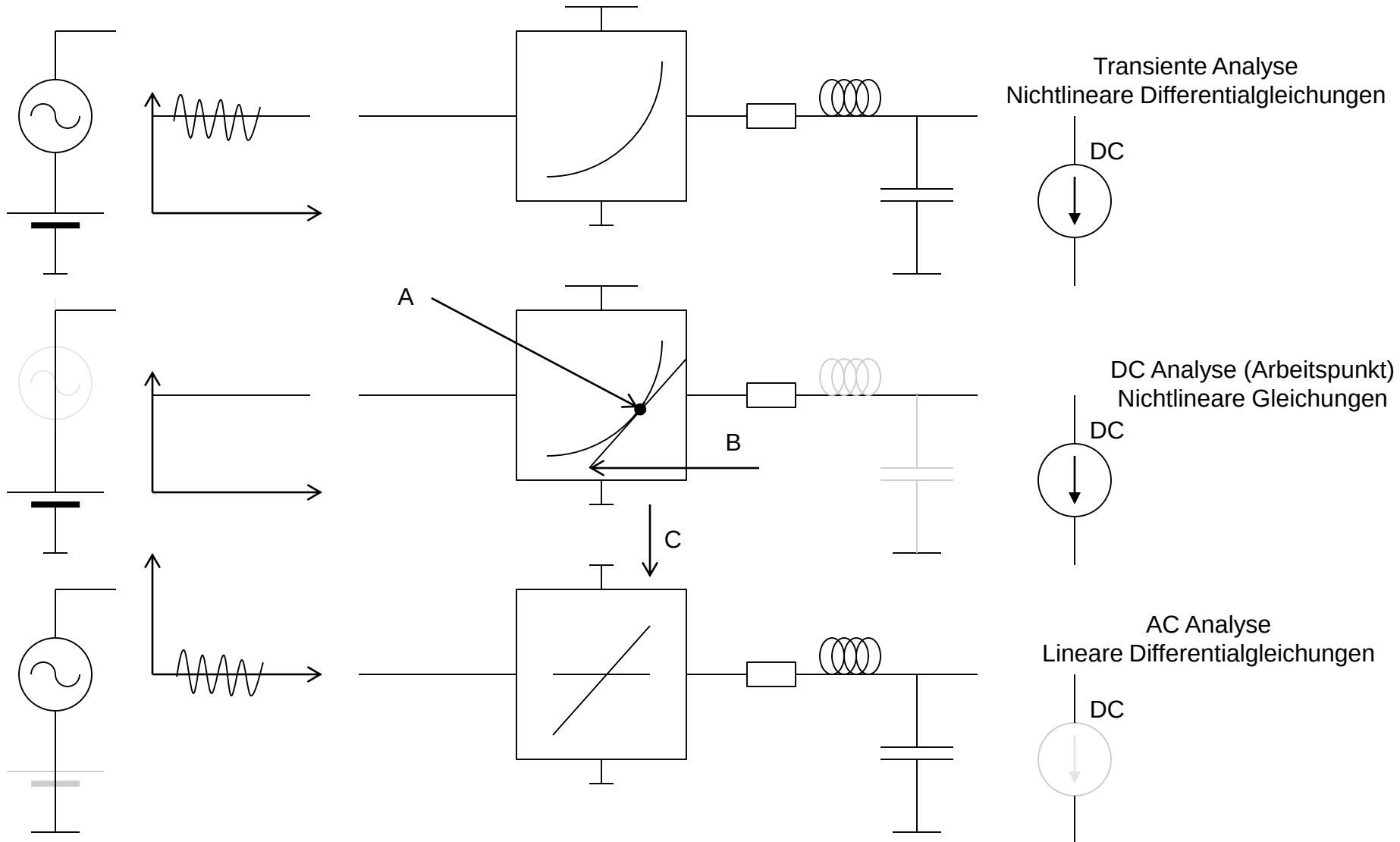
- Gesteuerte reale Spannungsquellen und Stromquellen

 Spannungsverstärker (V-V) OPAMP	 Transimpedanzverstärker (I-V) Sensor-Signal Verstärker	Ausgangsimpedanz klein Bitte nicht kurzschliessen (Sonst Strombegrenzung)
 Transkonduktanzverstärker (V-I) MOSFET	 Stromverstärker (I-I) BJT	Ausgangsimpedanz groß Nicht offen lassen (Sonst Spannungsbegrenzung)
Eingangsimpedanz groß Voltmeter	Eingangsimpedanz klein Ampremeter	

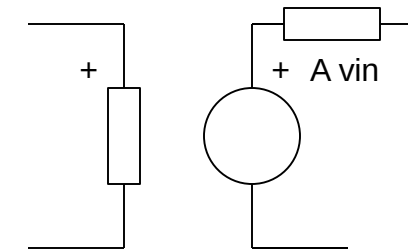
- AC DC



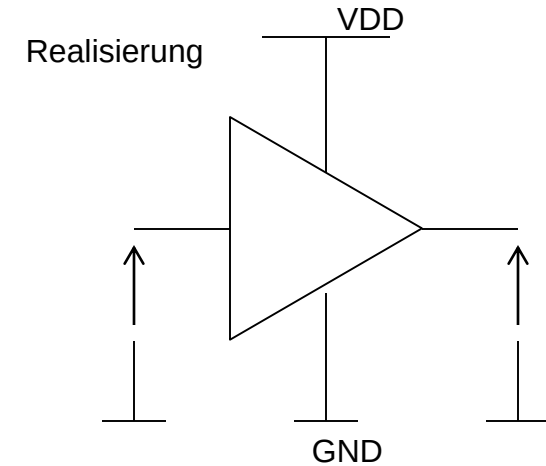
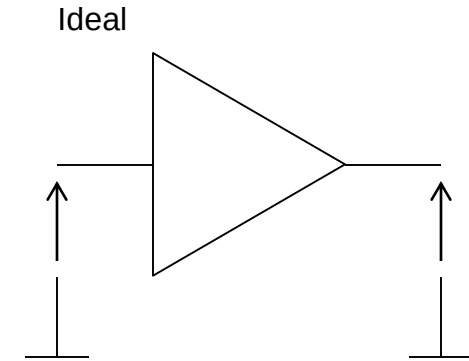
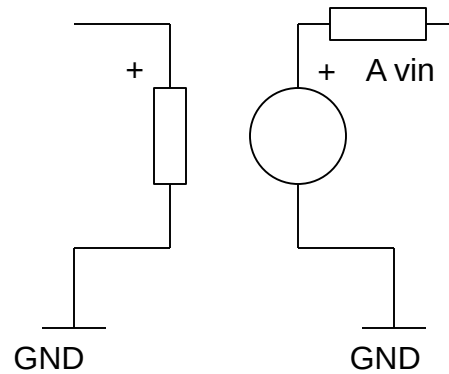
- Klein- und Großsignalmodelle



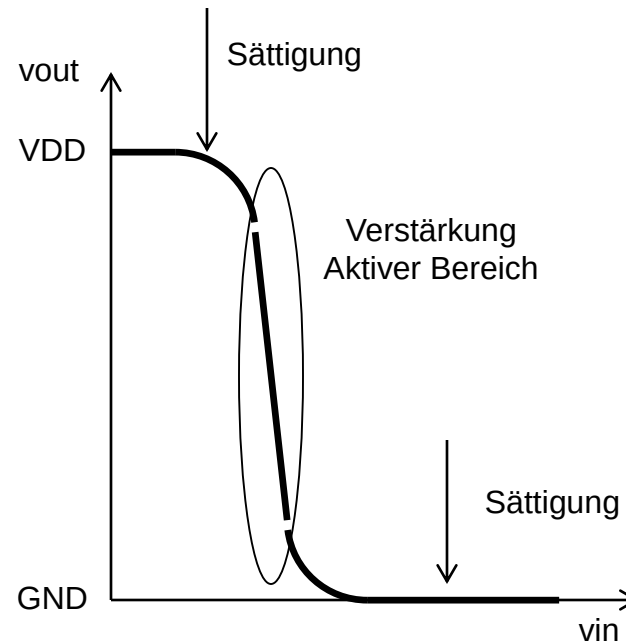
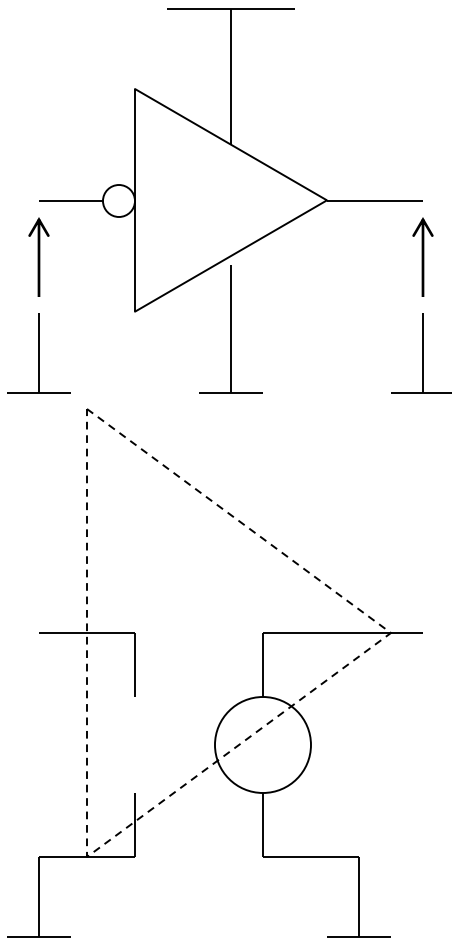
- Verstärker
- Einfachste Variante - Single-Ended Verstärker



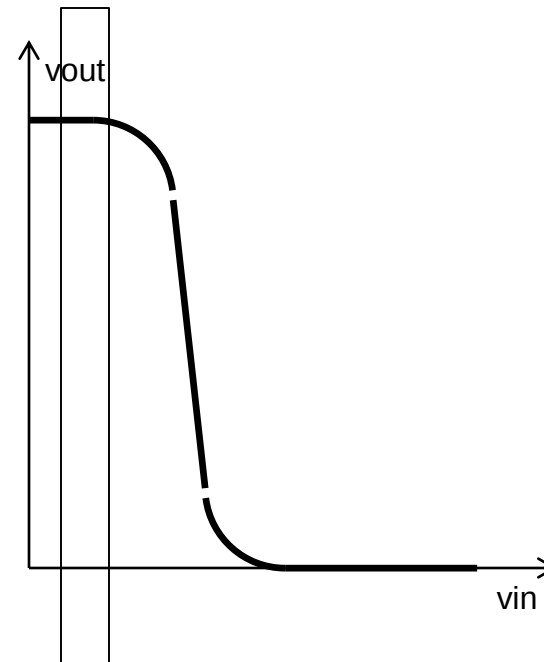
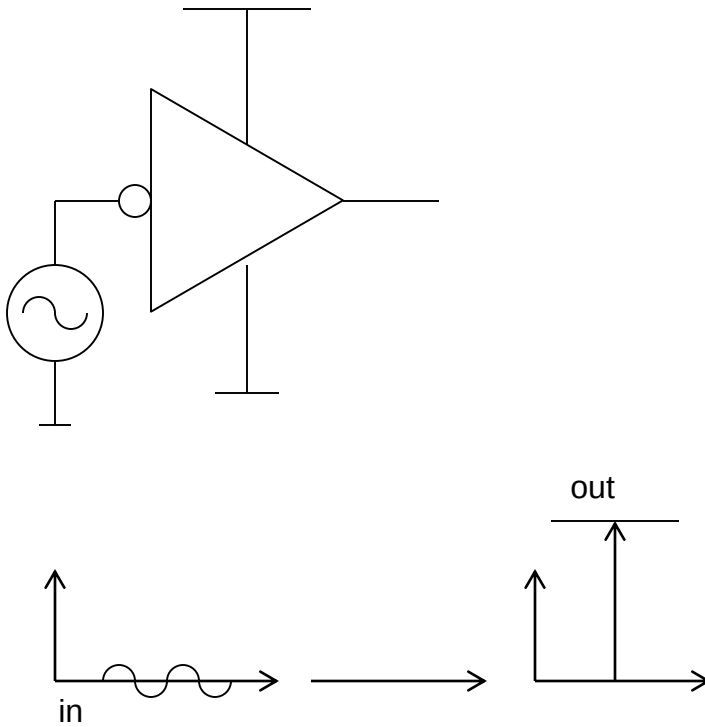
Spannungsverstärker



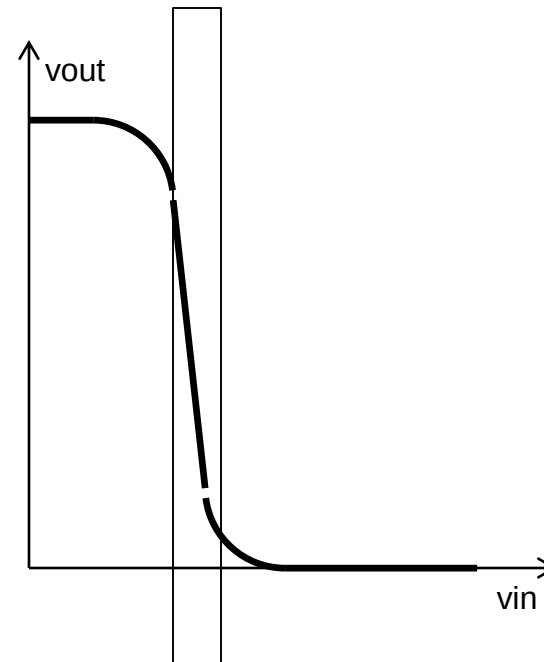
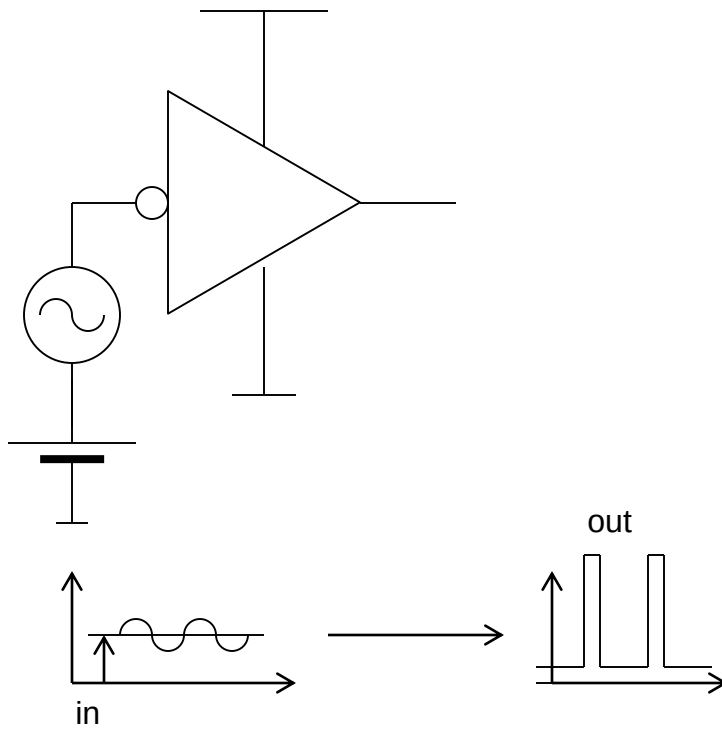
- $v_{out} = f(v_{in})$
- Annahmen: $Z_{out} = 0$, $Z_{in} = \text{unendlich}$



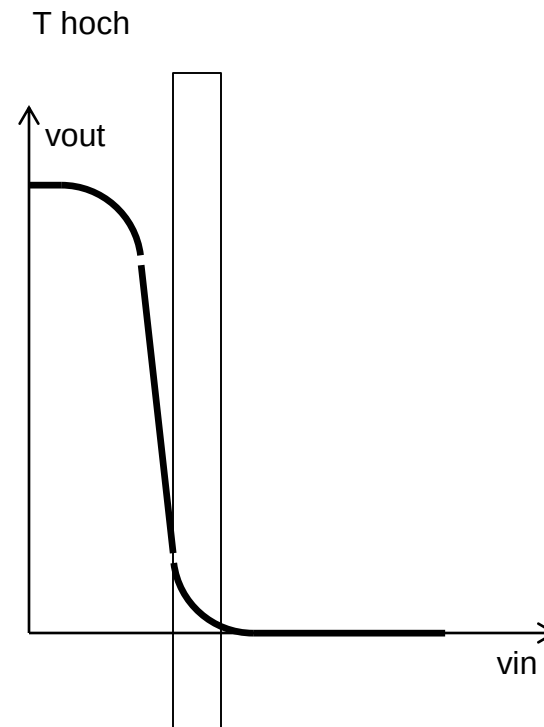
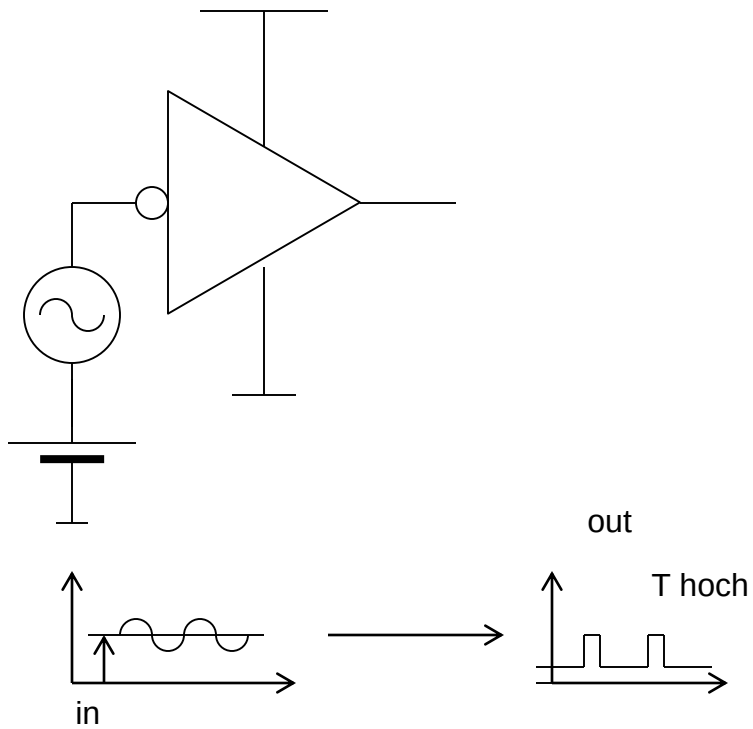
- Verstärker



- Verstärker



- Verstärker



- Gegenkopplung
- Design of Analog CMOS Integrated Circuits (B. Razavi)

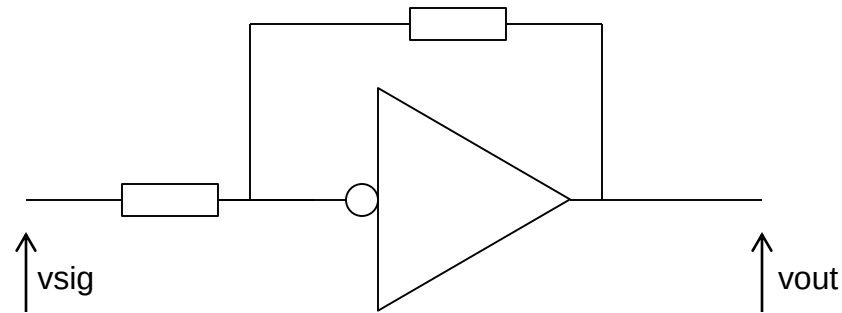
Feedback

On a mild August morning in 1921, Harold Black was riding the ferry from New York to New Jersey, where he worked at Bell Laboratories. Black and many other researchers had been investigating the problem of nonlinearity in amplifiers used in long-distance telephone networks, seeking a practical solution. While reading the newspaper on the ferry, Black was suddenly struck by an idea and began to draw a diagram on the newspaper, which would later be used as the evidence in his patent application. The idea is known to us as the negative feedback amplifier.

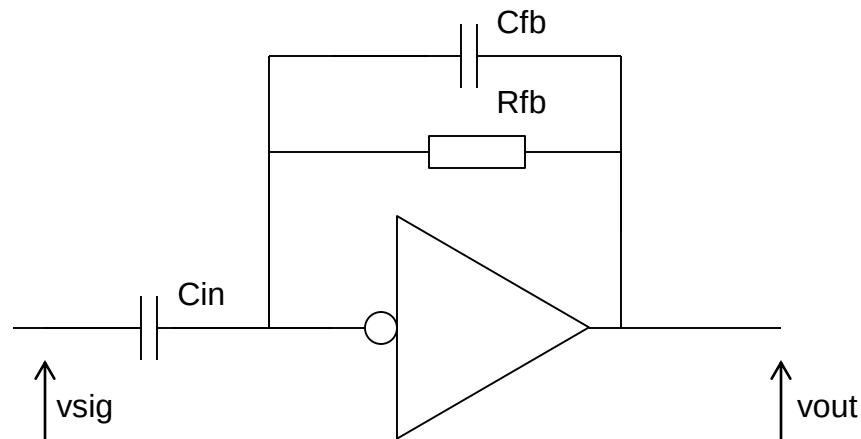
Feedback is a powerful technique that finds wide application in analog circuits. For example, negative feedback allows high-precision signal processing and positive feedback makes it possible to build oscillators. In this chapter, we consider only negative feedback and use the term feedback to mean that.

We begin with a general view of feedback circuits, describing important benefits that result from feedback. Next, we study four feedback topologies and their properties. Finally, we examine the effects of loading in feedback amplifiers.

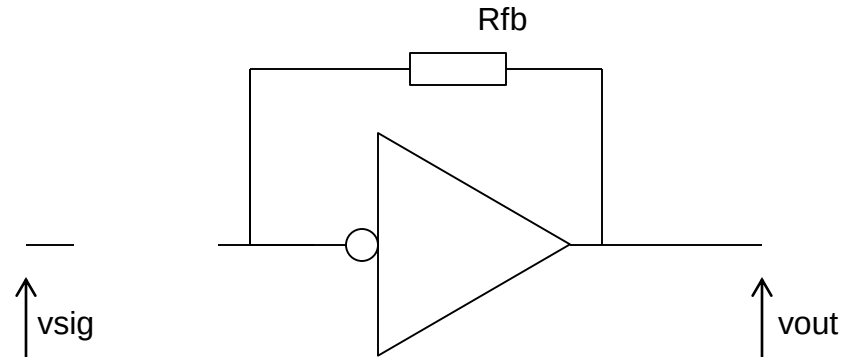
- Gegenkopplung
- Beispiel: Invertierender Verstärker
- Realisierung mit R (diskret)



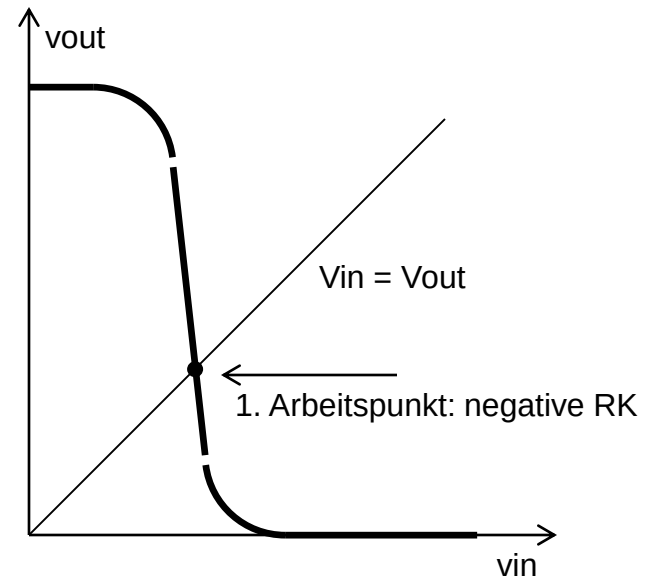
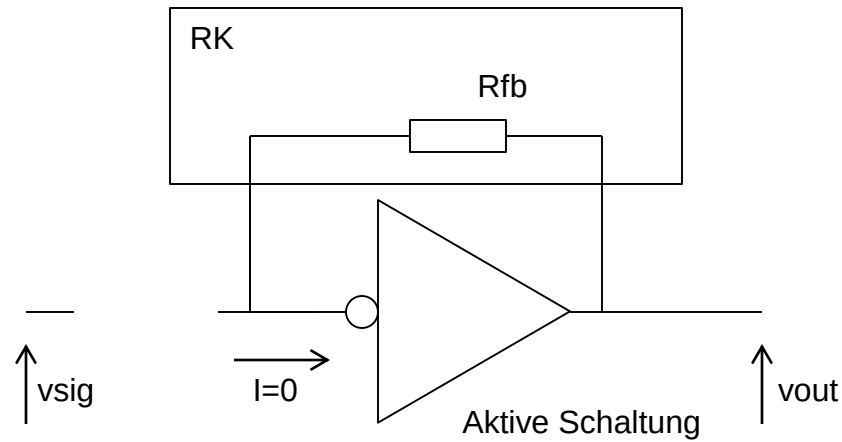
- Gegenkopplung
- Beispiel: Invertierender Verstärker
- Realisierung mit C (IC)
- „Starke“ resistive (ohmsche) Gegenkopplung für DC Spannungen
- Schnelle und „schwache“ kapazitive Rückkopplung für AC Signale
- Arbeitspunkt ist stabil
- AC Signale werden verstärkt



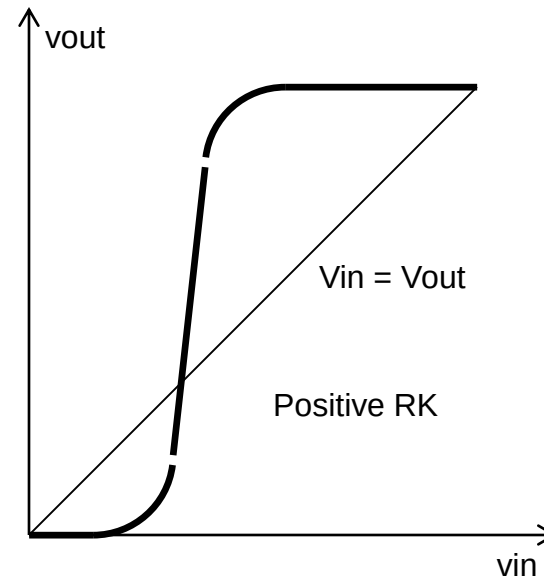
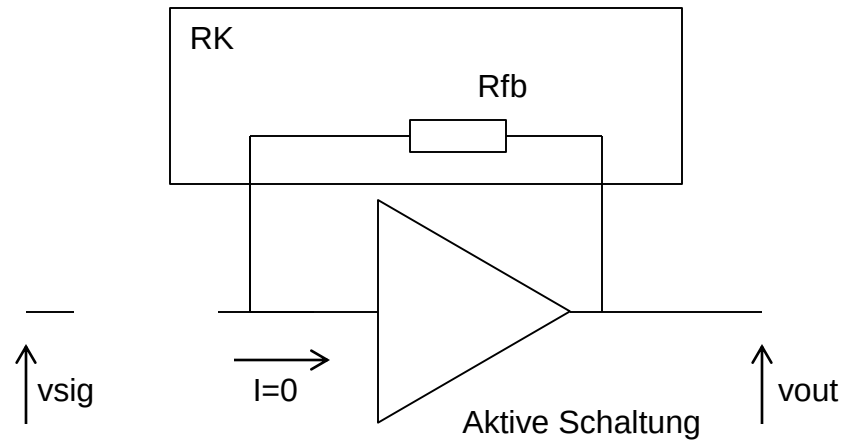
- DC Analyse
- C sind weg



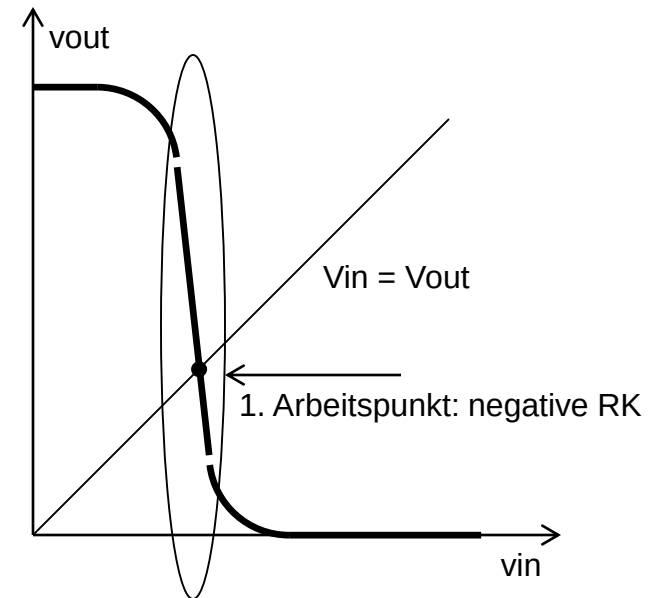
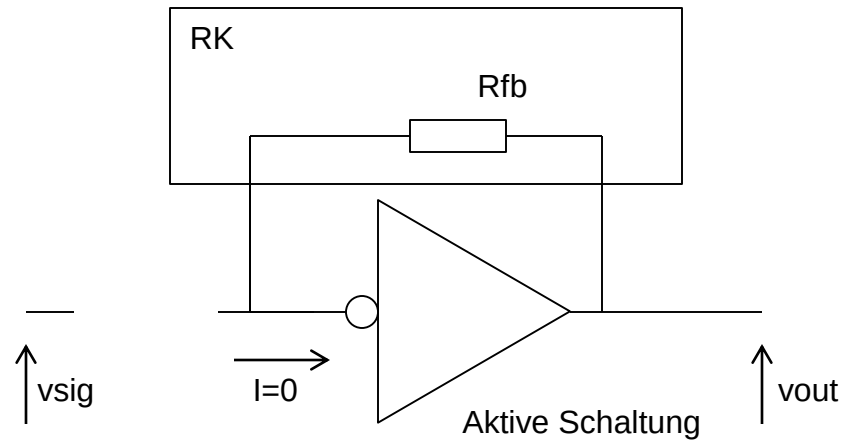
- DC



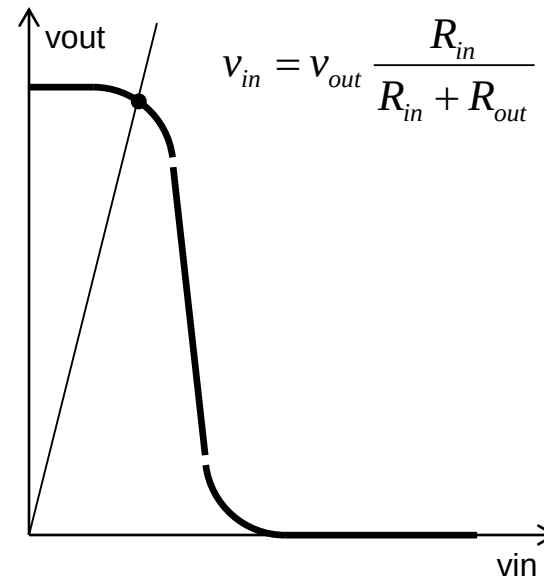
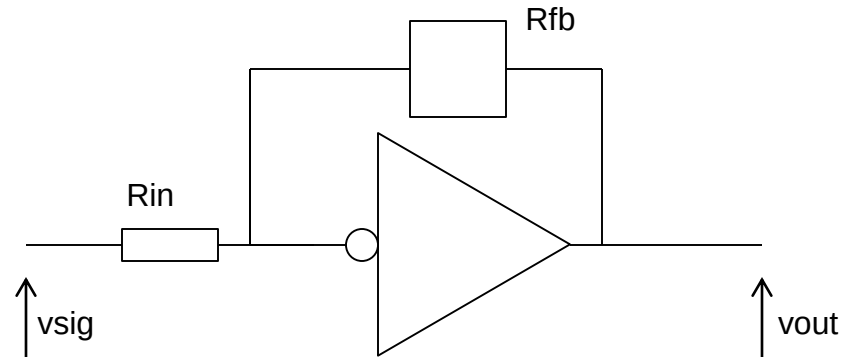
- RAM Zelle



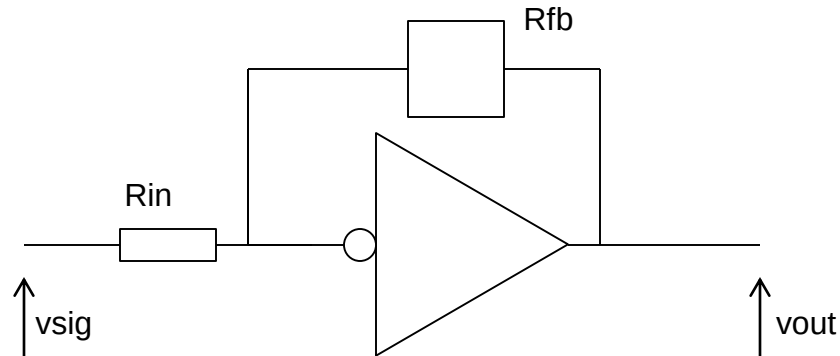
- DC



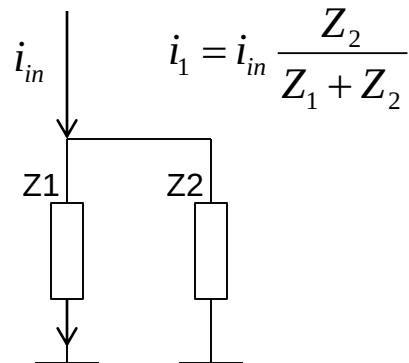
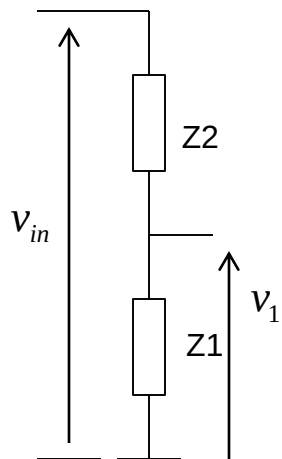
- Gegenkopplung ist falsch dimensioniert



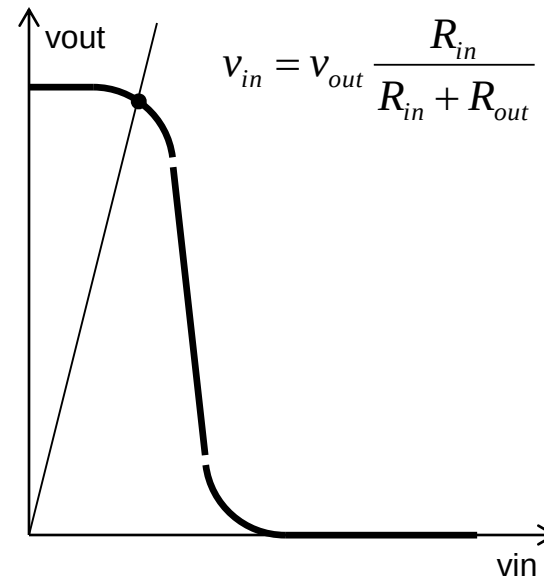
- Spannungs- und Stromteiler



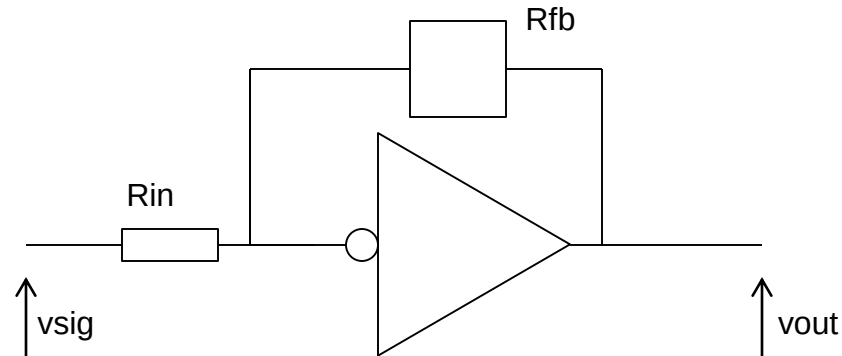
$$v_1 = v_{in} \frac{Z_1}{Z_1 + Z_2}$$



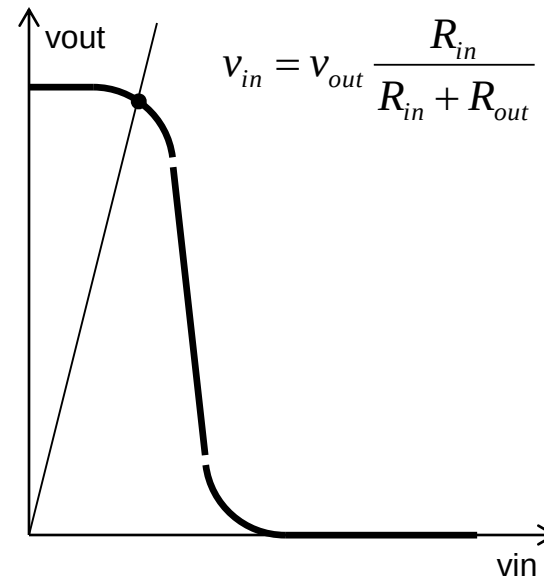
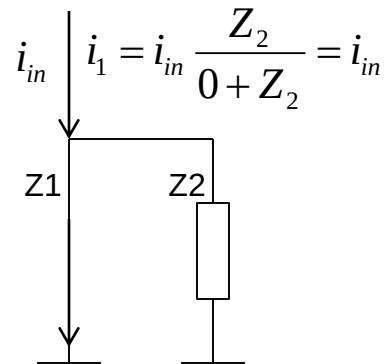
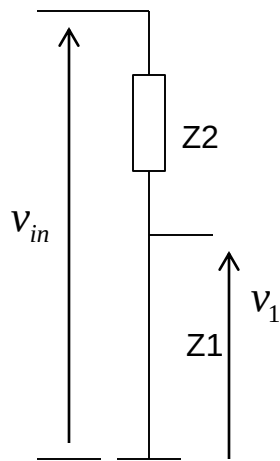
$$i_1 = i_{in} \frac{Z_2}{Z_1 + Z_2}$$



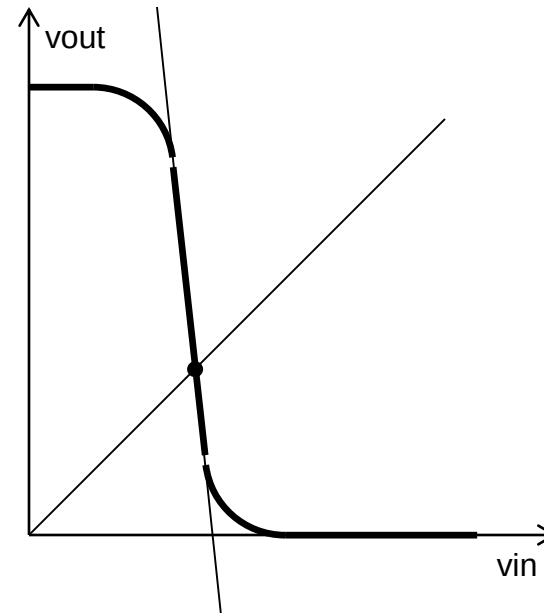
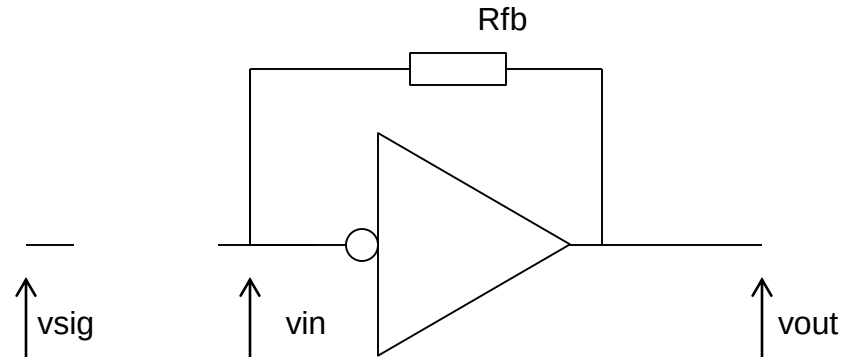
- Spannungs- und Stromteiler



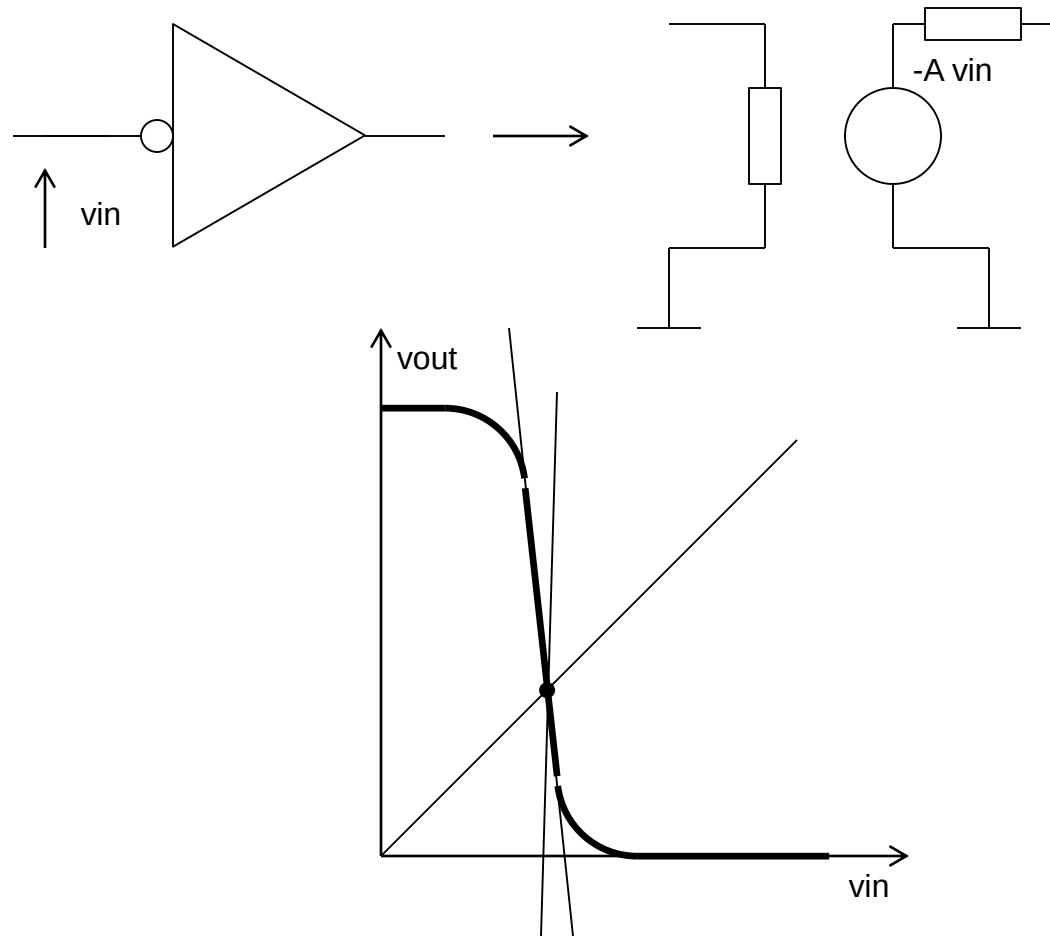
$$v_1 = v_{in} \frac{0}{Z_1 + Z_2} = 0$$



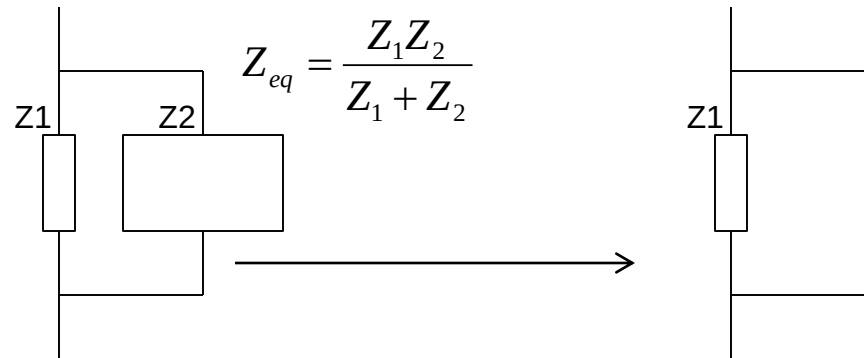
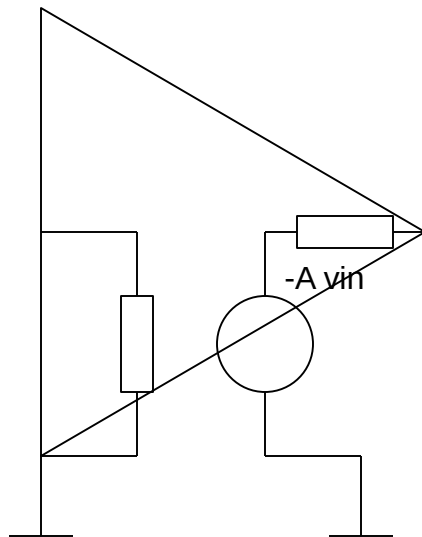
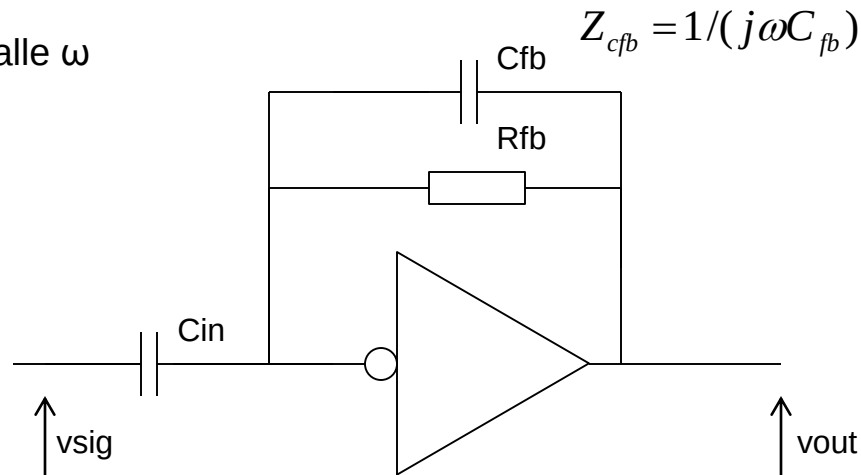
- Kleinsignalanalyse



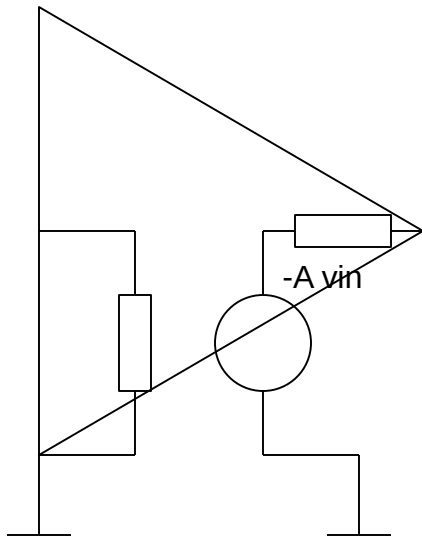
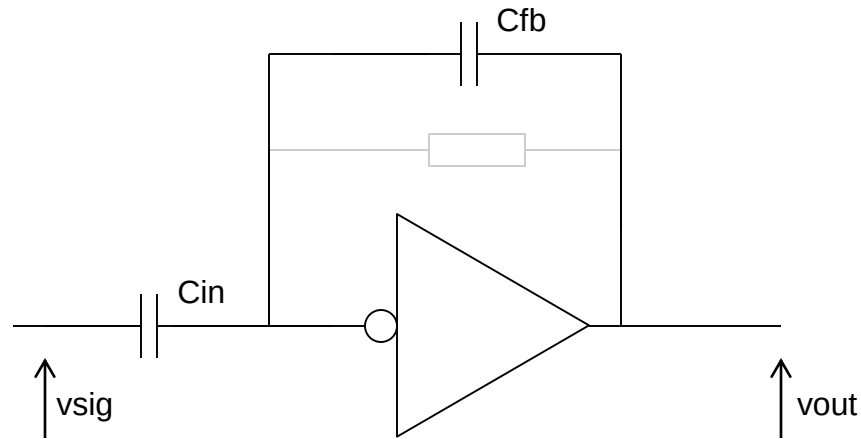
- Kleinsignalanalyse
- R_{out} , R_{in} unendlich



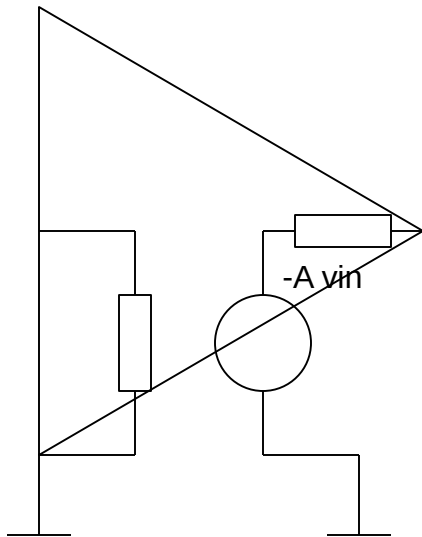
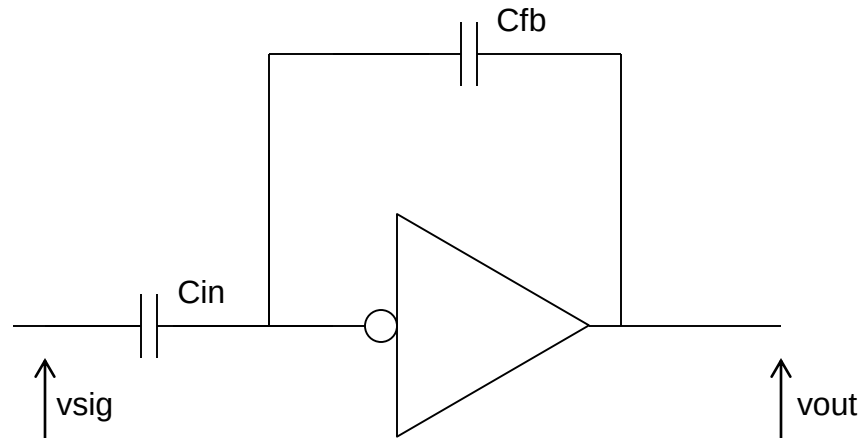
- R_{fb} ist groß
- Z_c ist klein für alle ω



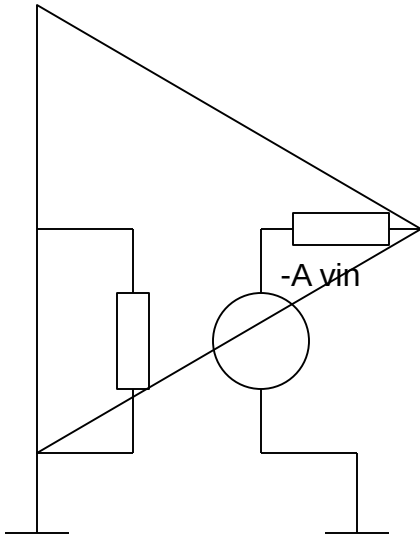
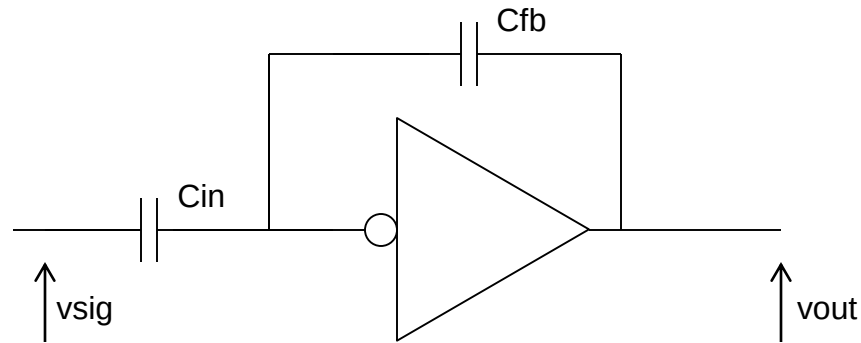
- Gegenkopplung



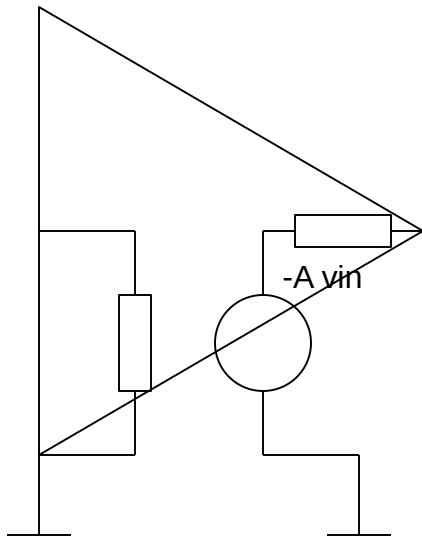
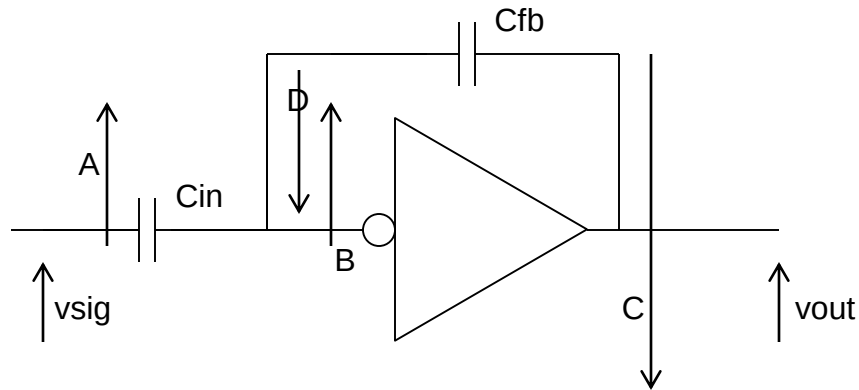
- Gegenkopplung



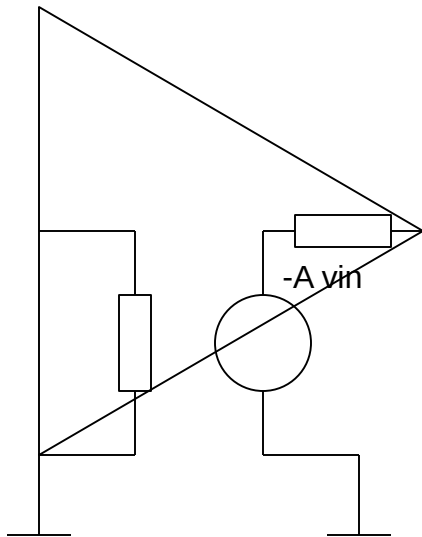
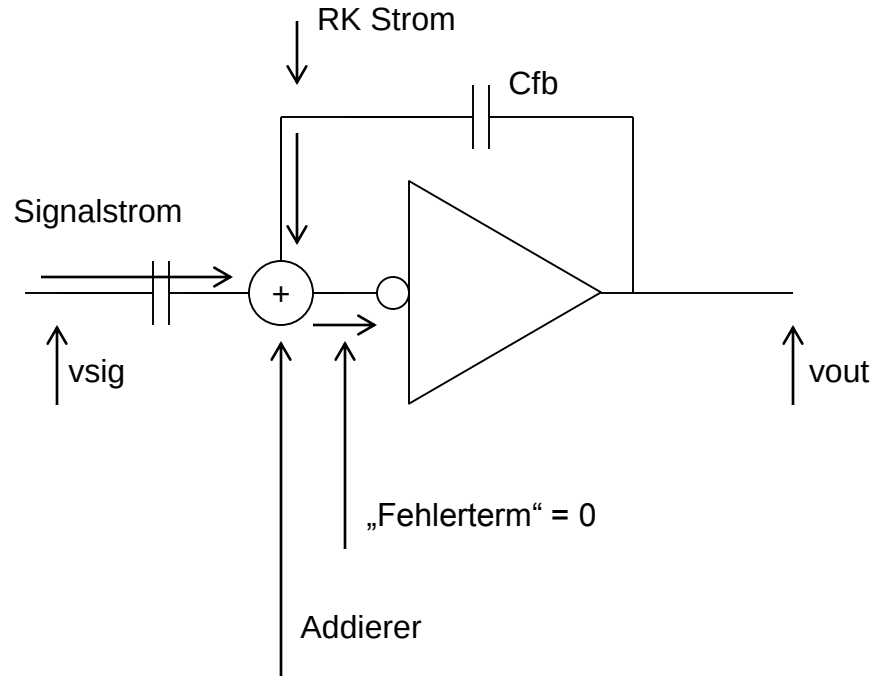
- Gegenkopplung



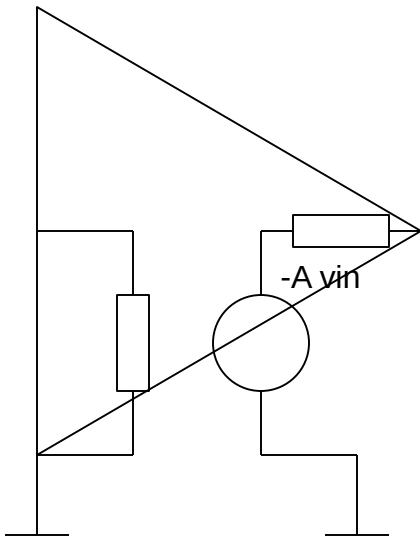
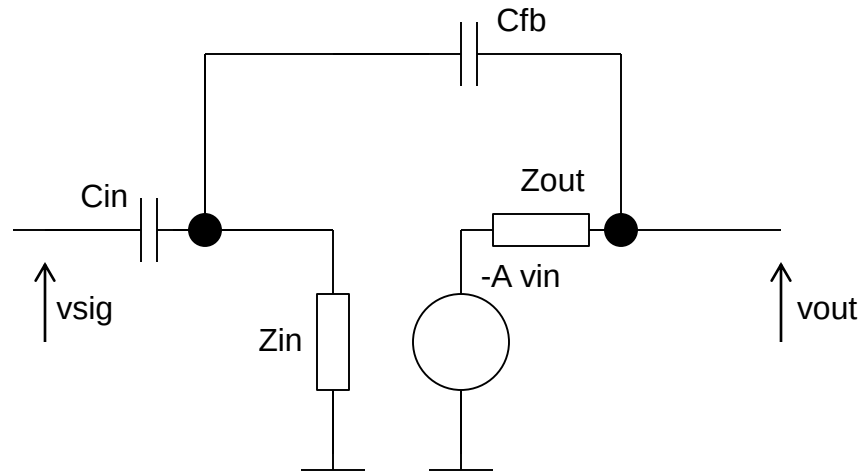
- Rückkopplung ist negativ



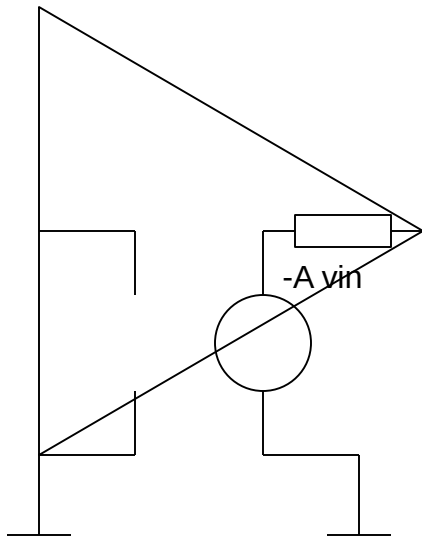
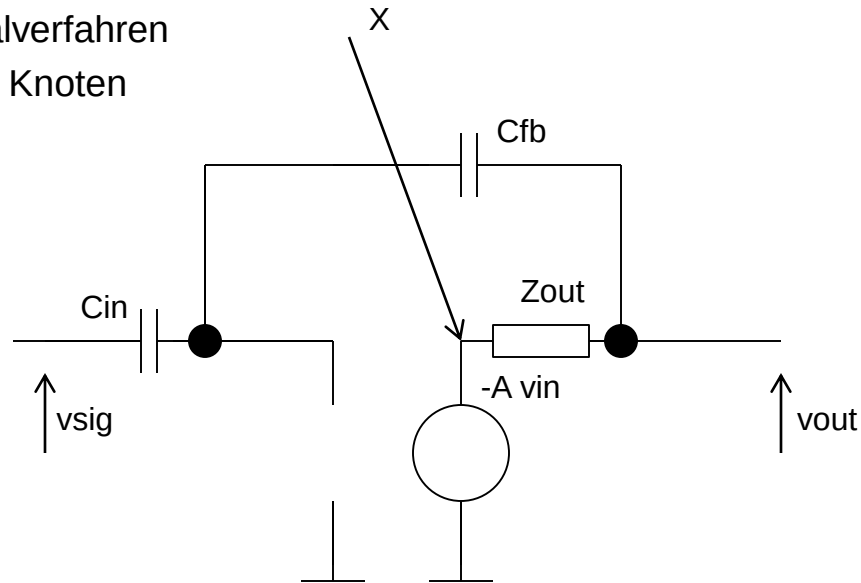
- V-I Rückkopplung



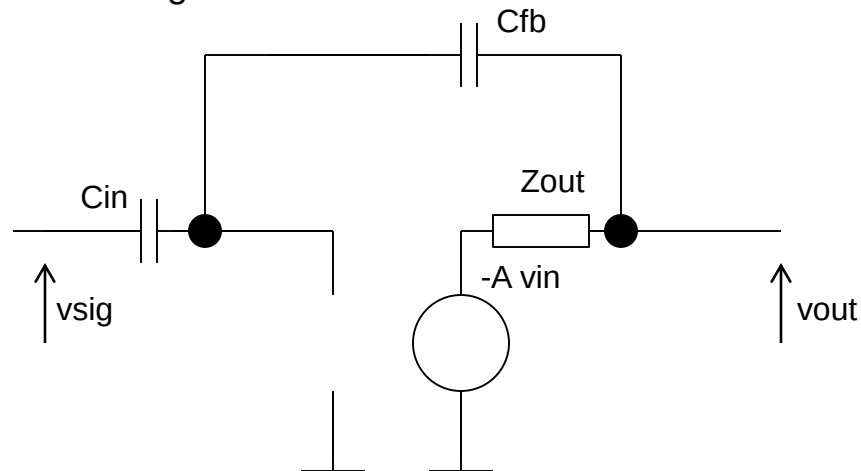
- Gegenkopplung



- Lösung
- Knotenpotentialverfahren
- 2 unabhängige Knoten



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

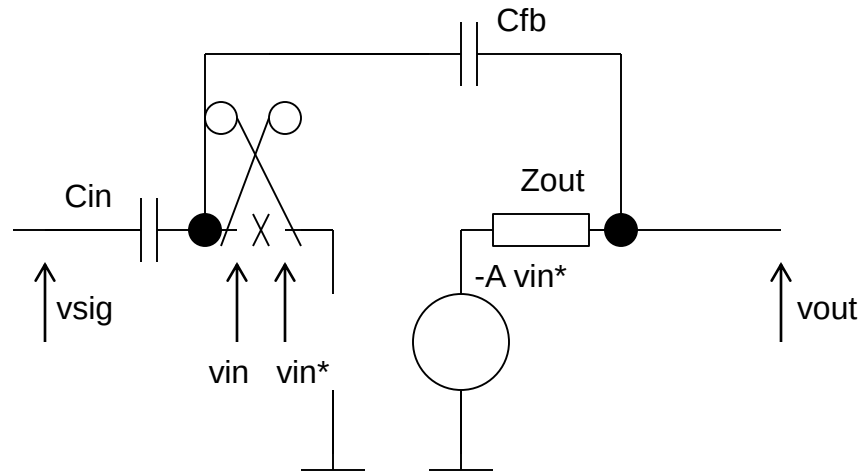


„Wichtige“ Formel (wird später bewiesen)

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

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

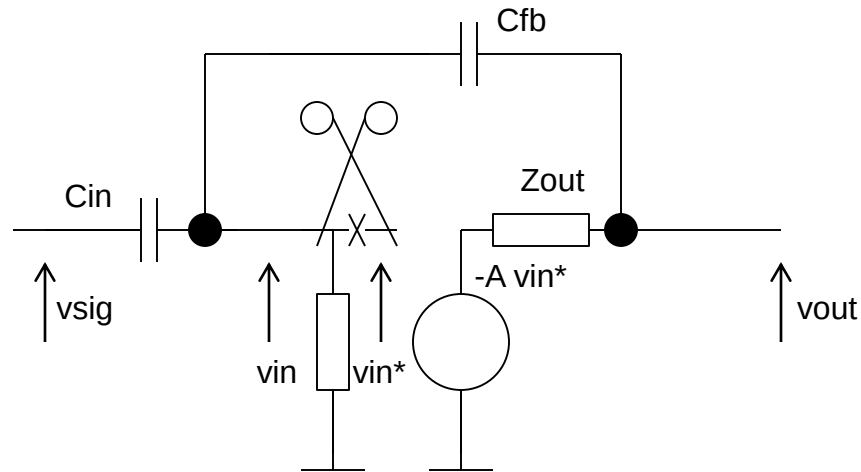
- Rückkopplung wird in einem passenden Punkt unterbrochen



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

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

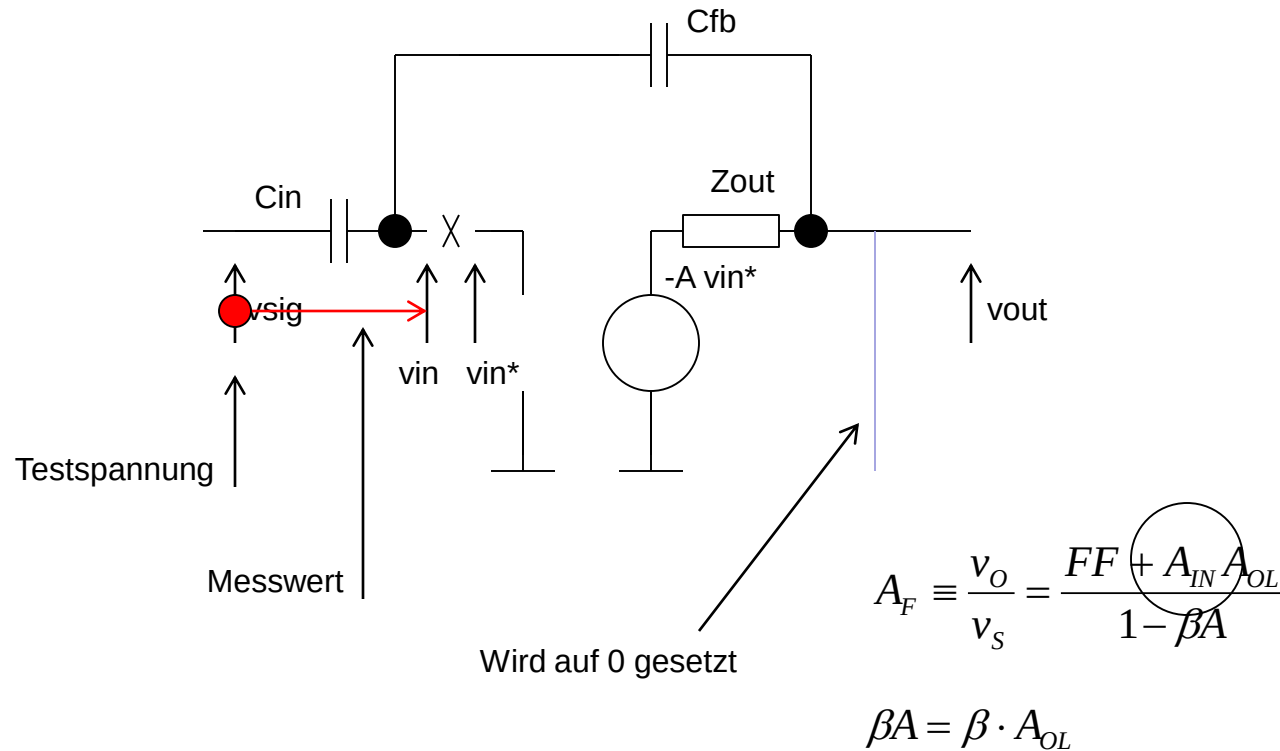
- Rückkopplung wird in einem passenden Punkt unterbrochen
- Variante mit R_{in}



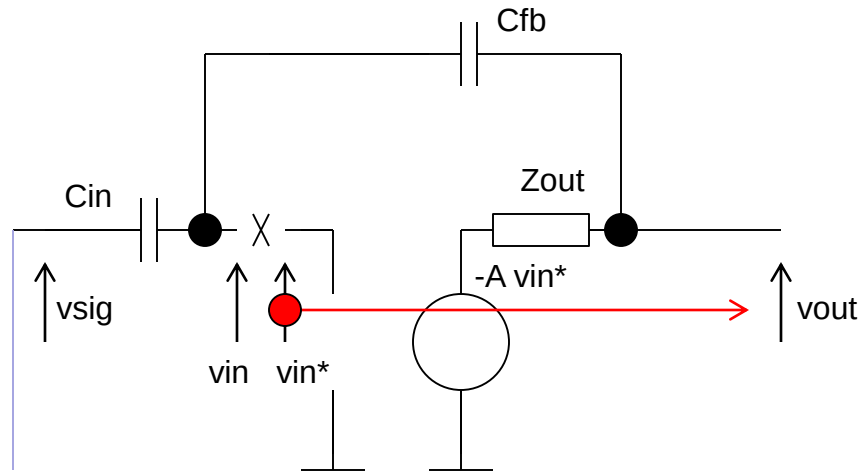
$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

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

- Ain (Definition) – Verstärkung im Addierer



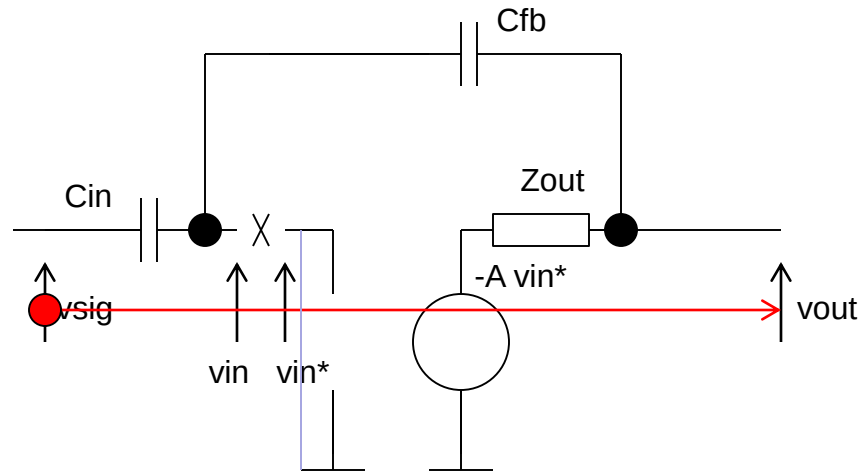
- Aol (Definition) – open loop gain (Leerlaufverstärkung)



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

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

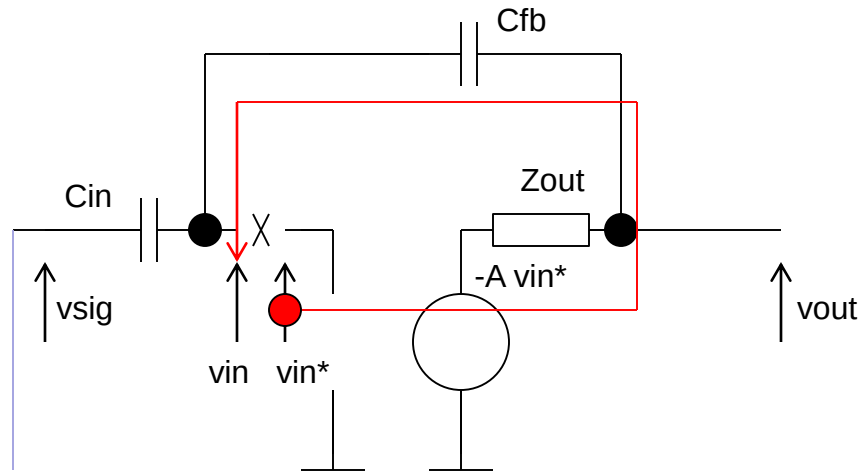
- FF (Definition) – feed forward (Vorwärtsverstärkung)



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

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

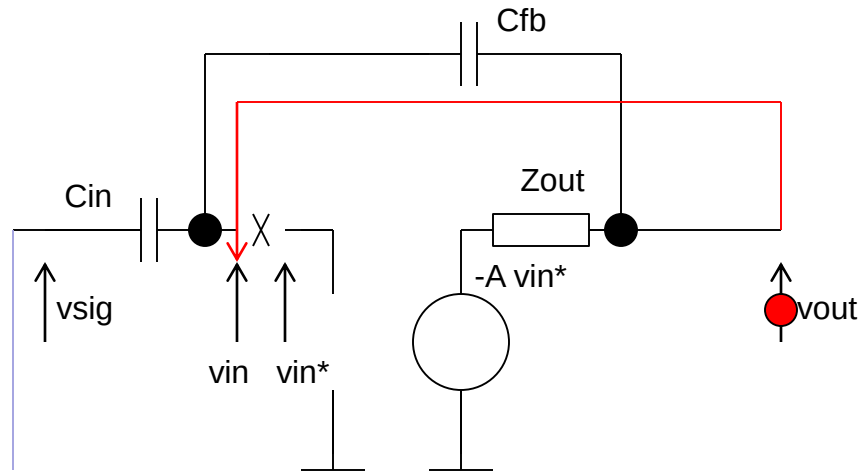
- betaA (Definition) – Schleifenverstärkung



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

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

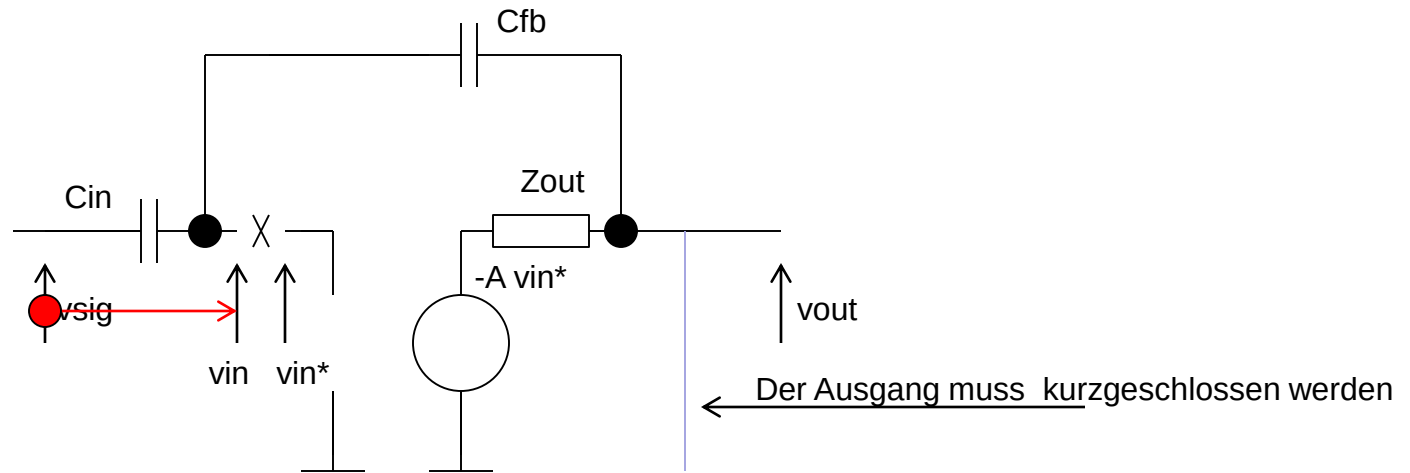
- Beta (Definition) – Rückkopplung



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

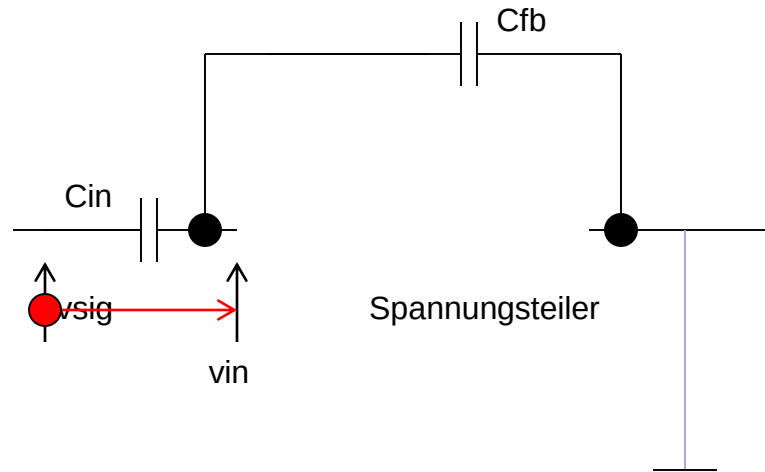
$$\beta A = \beta \cdot A_{OL}$$

- Ain (Berechnung)



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

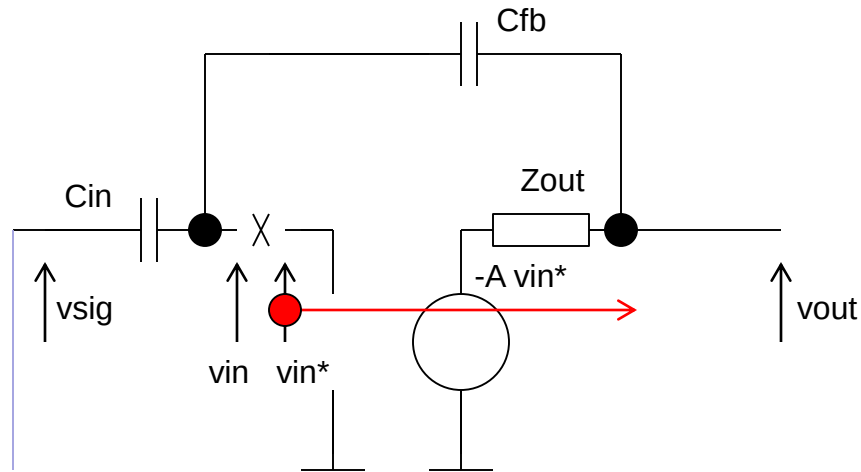
- Ain (Berechnung) - vereinfacht



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

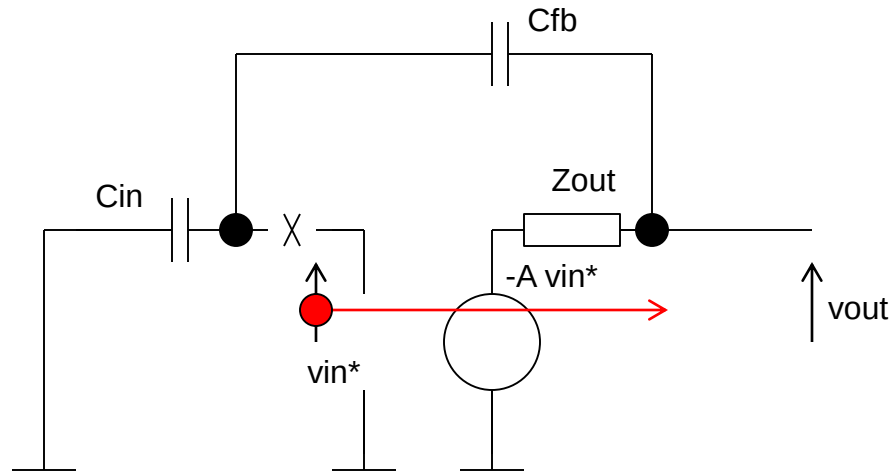
$$v_{in} = \frac{Z_{FB}}{Z_{FB} + Z_{IN}} v_{sig} \quad A_{IN} = \frac{Z_{FB}}{Z_{FB} + Z_{IN}}$$

- Open loop gain (Berechnung)



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

- Open loop gain (Berechnung)



Verstärker und Spannungsteiler

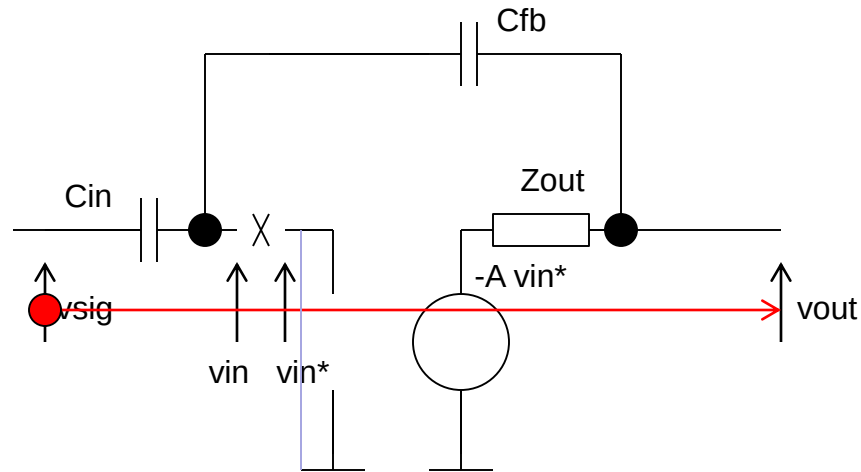
$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

$$v_{out} = -A \frac{Z_{FB} + Z_{IN}}{Z_{FB} + Z_{IN} + Z_{OUT}} v_{in}^* \quad A_{OL} = -A \frac{Z_{FB} + Z_{IN}}{Z_{FB} + Z_{IN} + Z_{OUT}}$$

$$Z_{out} = 0 \rightarrow A_{OL} \approx -A$$

Es ist leicht die Rechnung zu vereinfachen
In Summen können kleinere Größen vernachlässigt werden

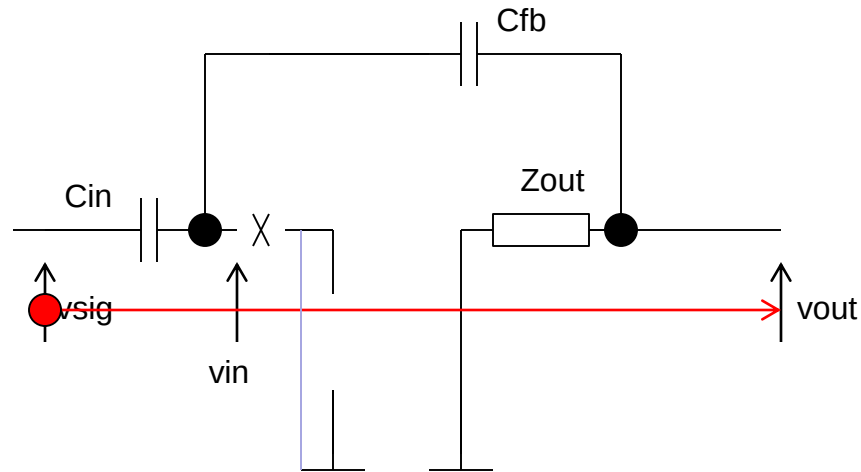
- Feed forward (Berechnung)



Verstärker wird ausgeschaltet

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

- Feed forward (Berechnung)



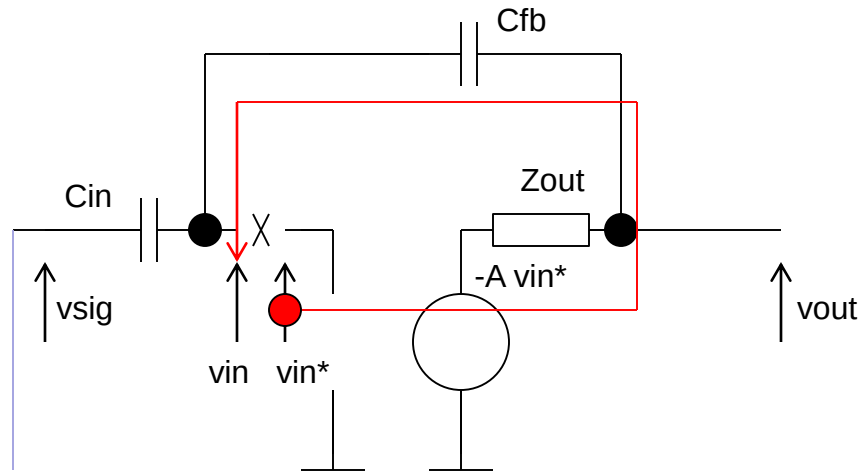
$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

$$v_{out} = \frac{Z_{OUT}}{Z_{FB} + Z_{IN} + Z_{OUT}} v_{sig}$$

$$FF = \frac{Z_{OUT}}{Z_{FB} + Z_{IN} + Z_{OUT}}$$

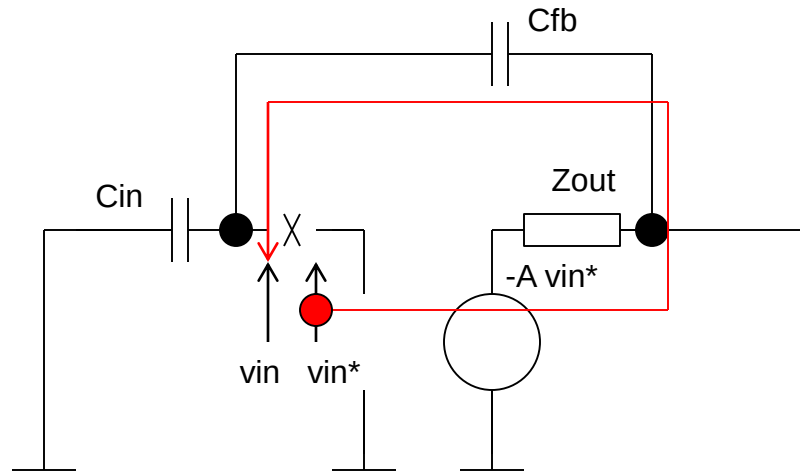
$$Z_{OUT} = 0 \rightarrow FF \approx 0$$

- Schleifenverstärkung (beta A) (Berechnung)



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

- Schleifenverstärkung (beta A) (Berechnung)



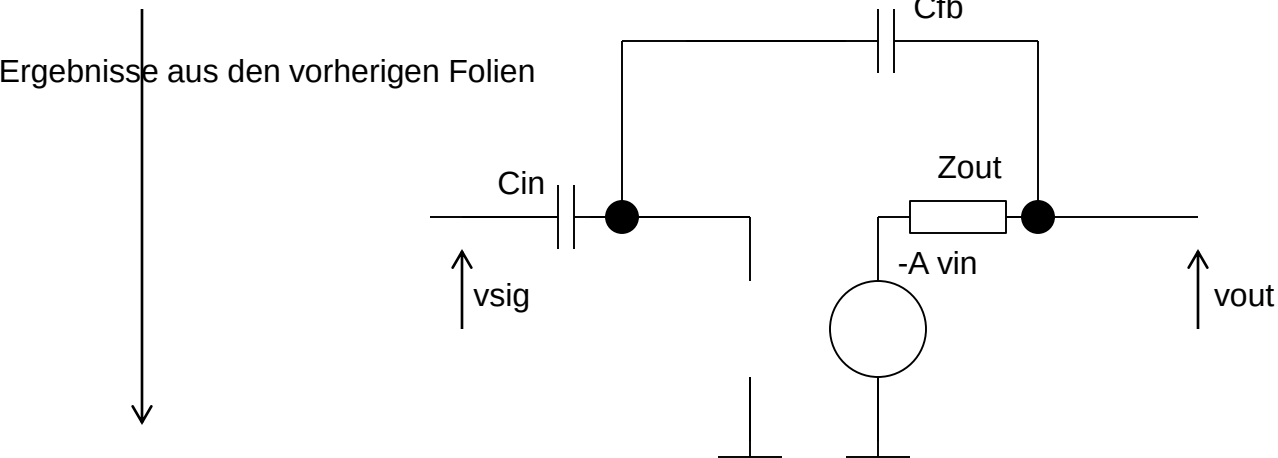
$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

$$v_{in} = -A \frac{Z_{IN}}{Z_{FB} + Z_{IN} + Z_{OUT}} v_{in}^*$$

$$\beta A = -A \frac{Z_{IN}}{Z_{FB} + Z_{IN} + Z_{OUT}}$$

$$Z_{OUT} = 0 \rightarrow \beta A \approx -A \frac{Z_{IN}}{Z_{FB} + Z_{IN}}$$

- Zu Schluss: Verstärkung mit Rückkopplung
- Annahme: $R_{out} = 0$



Die „wichtige“ Formel

$$A_{IN} = \frac{Z_{FB}}{Z_{FB} + Z_{IN}}$$

$$A_{OL} \approx -A$$

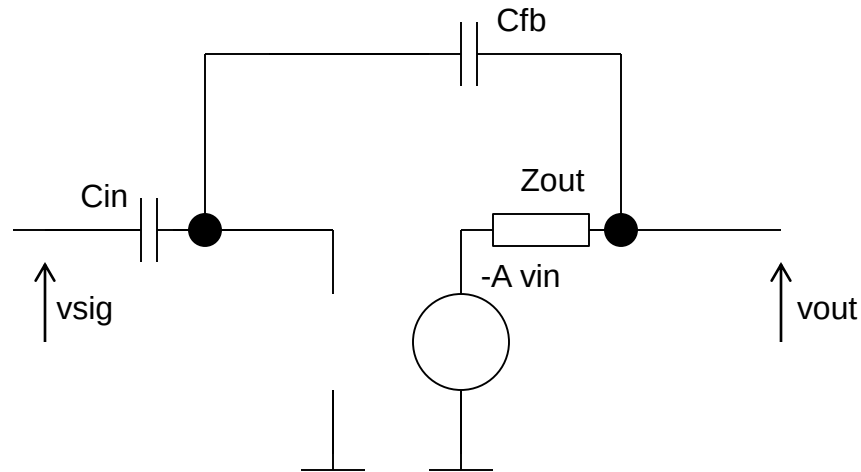
$$FF \approx 0$$

$$\beta A \approx -A \frac{Z_{IN}}{Z_{FB} + Z_{IN}}$$

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

$$A_F \equiv \frac{v_O}{v_S} = \frac{-A \frac{Z_{FB}}{Z_{FB} + Z_{IN}}}{1 + A \frac{Z_{IN}}{Z_{FB} + Z_{IN}}} = \frac{-A \frac{C_{IN}}{C_{FB} + C_{IN}}}{1 + A \frac{C_{FB}}{C_{FB} + C_{IN}}}$$

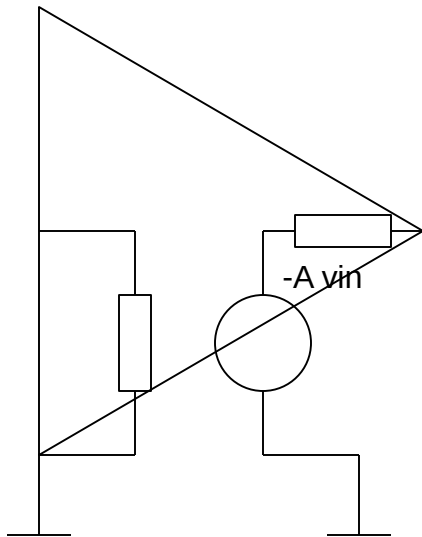
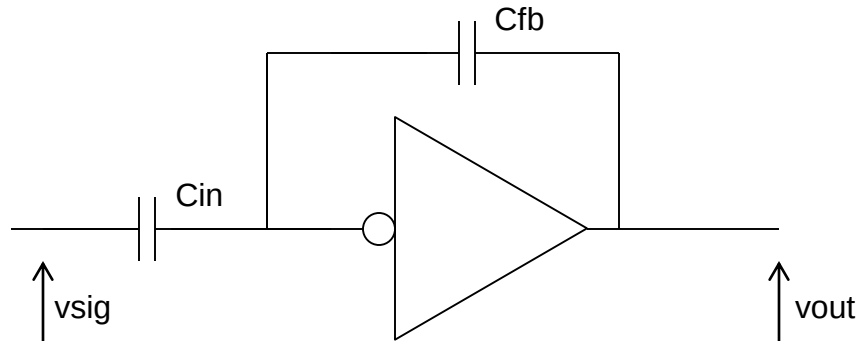
- Übliche Annahme $|\beta A| \gg 1$



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

$$A_F = \frac{-A \frac{C_{IN}}{C_{FB} + C_{IN}}}{\cancel{1} + A \frac{C_{FB}}{C_{FB} + C_{IN}}} \approx -\frac{C_{IN}}{C_{FB}}$$

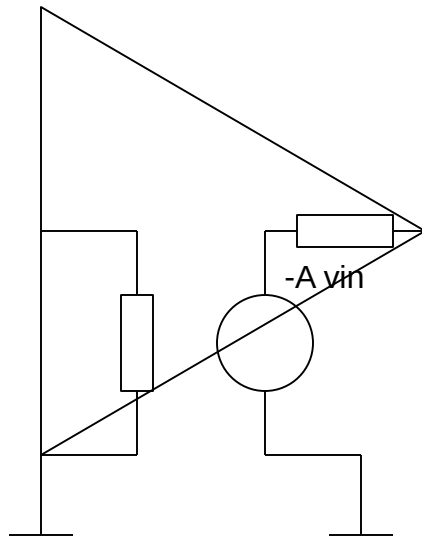
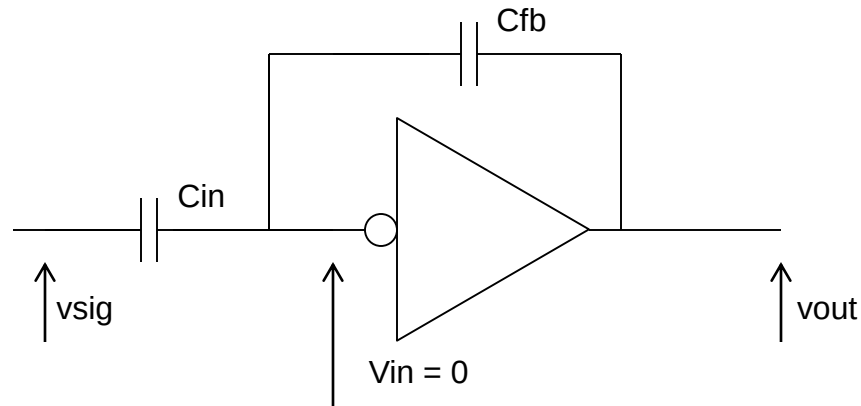
- Verstärkung mit RK (AF) hängt von A nicht ab!
- Gut denn: A ist schwer zu kontrollieren und temperaturinstabil
- Verstärkung mit RK (AF) hängt nur von passiven Komponenten (C) ab
- Passive Komponenten haben bekannte Eigenschaften – insbesondere Kondensatoren
- Desensibilisierung von Verstärkung
- Verstärkung mit RK ist reduziert um βA
- $\Rightarrow$ Verstärkung ist kleiner aber stabiler



$$A_F \approx -\frac{C_{IN}}{C_{FB}}$$

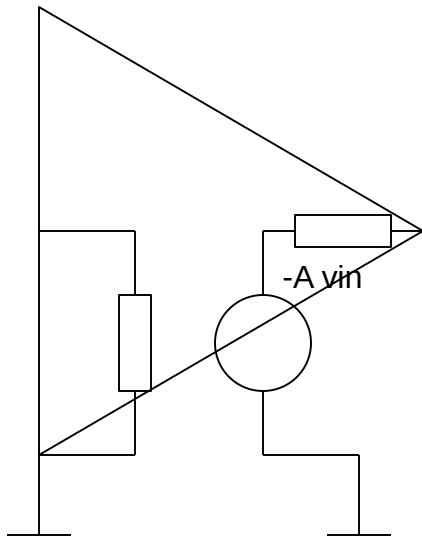
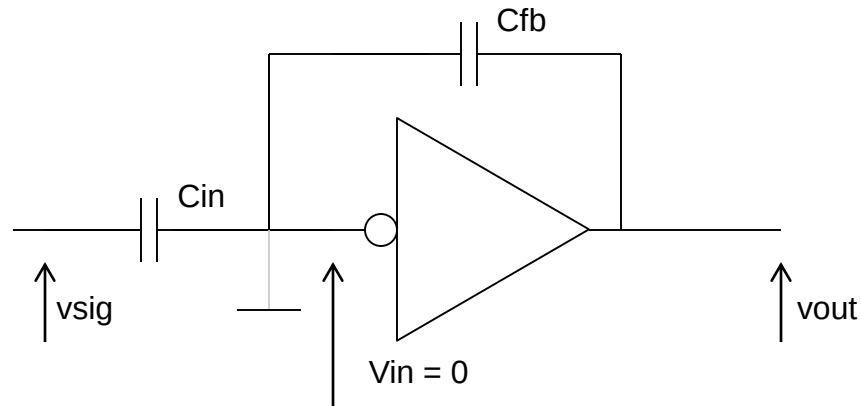
$$A_F \approx \frac{A_{IN} A_{OL}}{\beta A} = \frac{A_{IN}}{\beta}$$

- Spannung am Eingang des Verstärkers ~ 0
- Warum: Eingang = Ausgang/A – Annahme βA groß



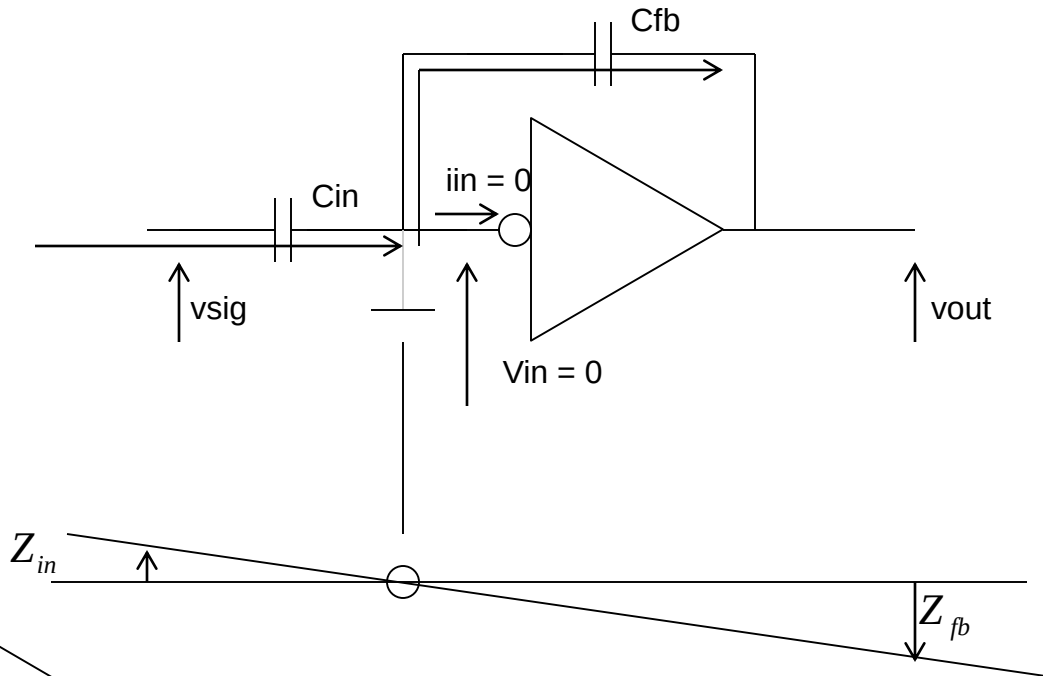
$$A_F = -A \frac{C_{IN}}{C_{FB} + C_{IN}} \approx -\frac{C_{IN}}{C_{FB}} \quad v_{in} = \frac{C_{IN}}{C_{FB} + C_{IN}} v_{sig} = \frac{C_{IN}}{\beta A}$$

- Virtuelle Masse

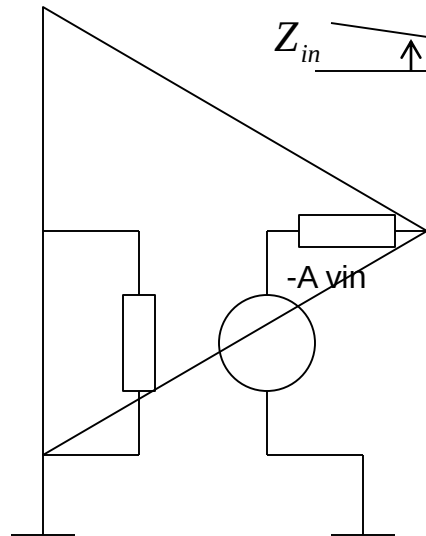


$$A_F \approx -\frac{C_{IN}}{C_{FB}}$$

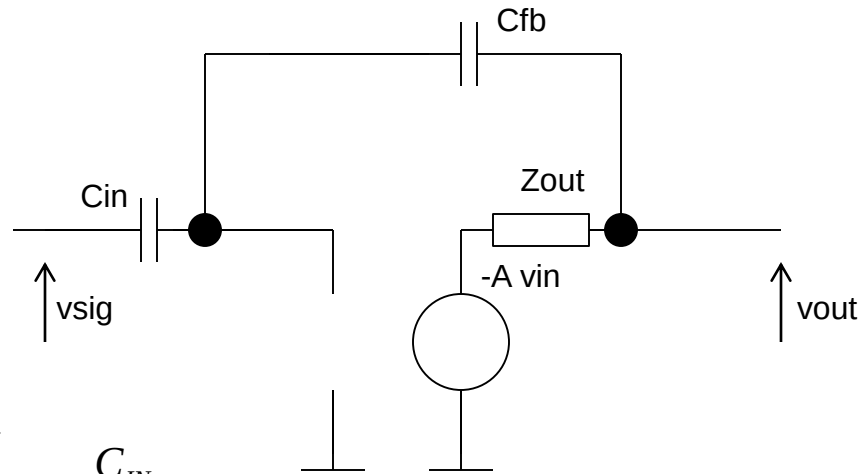
- Virtuelle Masse
- Annahme $v_{in} = 0$ vereinfacht die Rechnungen, sie ist aber manchmal problematisch
- Virtuelle Masse $\rightarrow$ Fehlerterm = 0, gute Regelung



$$A_F \approx -\frac{C_{IN}}{C_{FB}}$$



- Wie groß soll A sein?
- Annahme: $A_{fb} = 10 \rightarrow 10\% A > 100, 1\% A > 1000$
- Aktive Verstärkung soll mindestens 1-2 Größenordnungen höher als A_{fb} sein

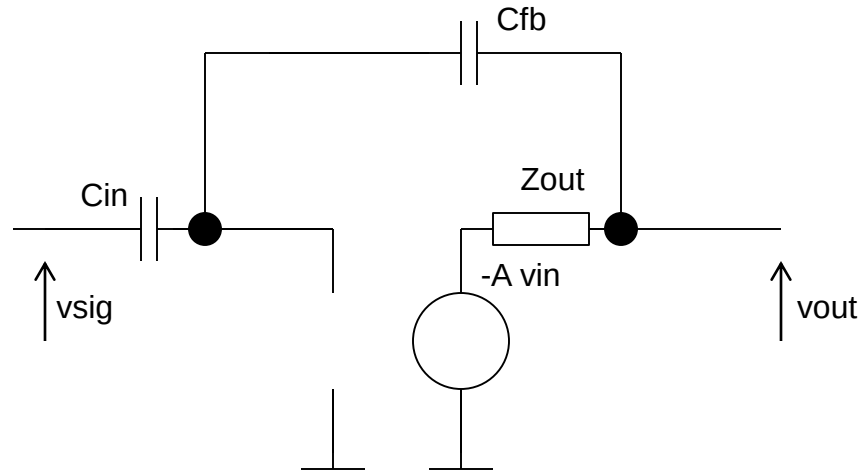


$$A_F = \frac{-A \frac{C_{IN}}{C_{FB} + C_{IN}}}{1 + A \frac{C_{FB}}{C_{FB} + C_{IN}}} \approx -\frac{C_{IN}}{C_{FB}}$$

$$\frac{C_{IN}}{C_{FB}} = 10$$

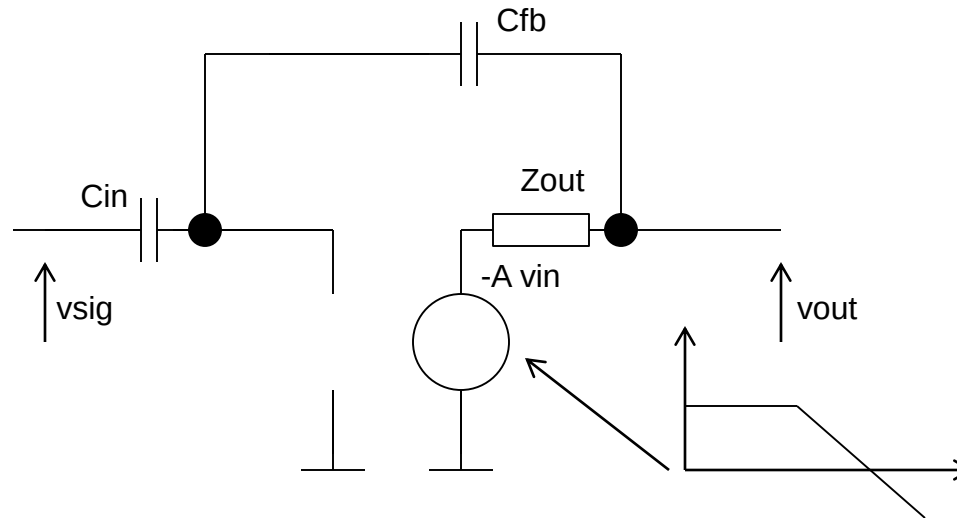
$$A \frac{C_{FB}}{C_{FB} + C_{IN}} \gg 1 \quad A \gg 1 + \frac{C_{IN}}{C_{FB}} \approx \frac{C_{IN}}{C_{FB}} = A_F$$

- Wie groß soll A sein?
- Annahme: $A_{fb} = 10 \rightarrow 10\% A > 100, 1\% A > 1000$
- Aktive Verstärkung soll mindestens 1-2 Größenordnungen höher als A_{fb} sein
- Trade off zwischen Genauigkeit (beta A groß) und Verstärkung (beta klein)

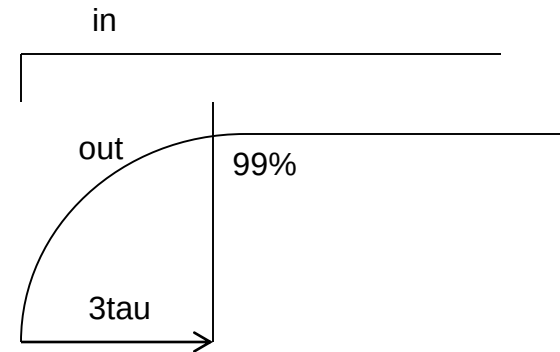


$$A_F = \frac{-A \frac{C_{IN}}{C_{FB} + C_{IN}}}{1 + A \frac{C_{FB}}{C_{FB} + C_{IN}}} = -\frac{C_{IN}}{C_{FB}} \frac{1}{(C_{IN} / C_{FB} + 1) / A + 1} = A_F \frac{1}{A_F / A + 1}$$

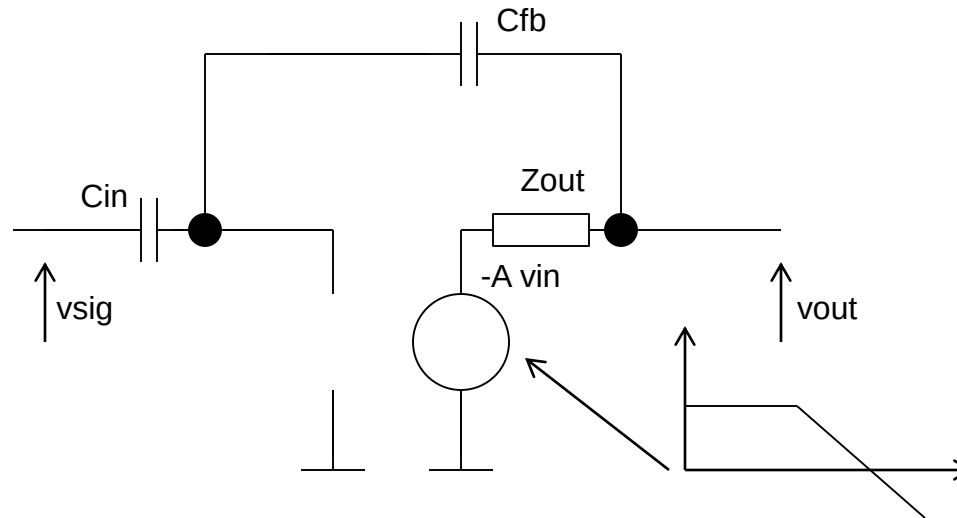
- AC Analyse mit RK
- **RK verändert die Zeitkonstanten**
- Wandelt Kondensatoren in Induktivitäten um



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



- Verstärkung mit einer Zeitkonstante

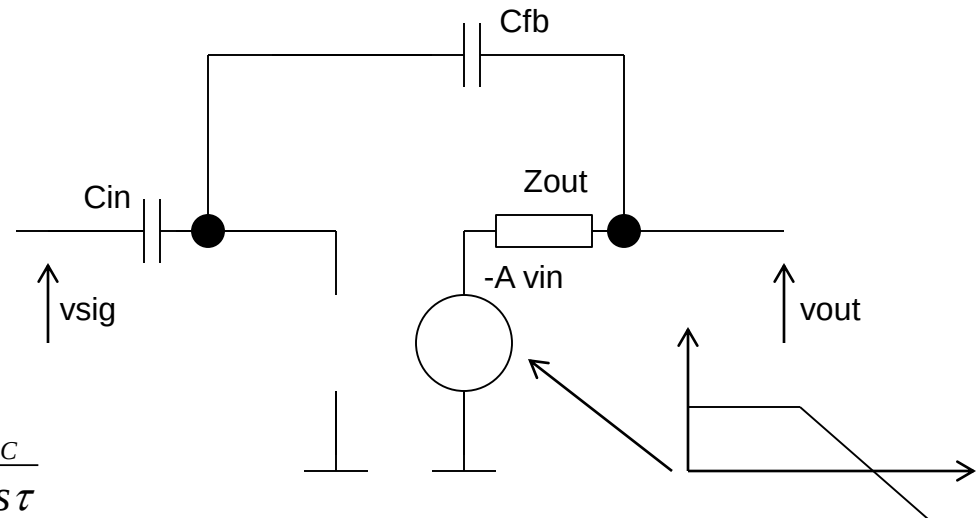


$$A_F = \frac{-A \frac{C_{IN}}{C_{FB} + C_{IN}}}{1 + A \frac{C_{FB}}{C_{FB} + C_{IN}}} = \frac{c_1 A}{1 + c_2 A} \leftarrow A(s) = \frac{A_{DC}}{1 + s\tau}$$

$$A_F(s) = \frac{c_1 A_{DC} / (1 + s\tau)}{1 + c_2 A_{DC} / (1 + s\tau)} \longrightarrow A_F(s) = A_{F0} \frac{1}{\left(1 + \frac{s\tau}{(1 + c_2 A_{DC})}\right)}$$

$$A_{F0} = \frac{c_1 A_{DC}}{1 + c_2 A_{DC}}$$

- Zeitkonstante um $1 + \text{bata } A$ kleiner
- Verstärkung ebenfalls um $1 + \text{bata } A$ kleiner
- Bandbreite definiert als $B = 1/(t * 2\pi)$
- Produkt Verstärkung * Bandbreite ist konstant.

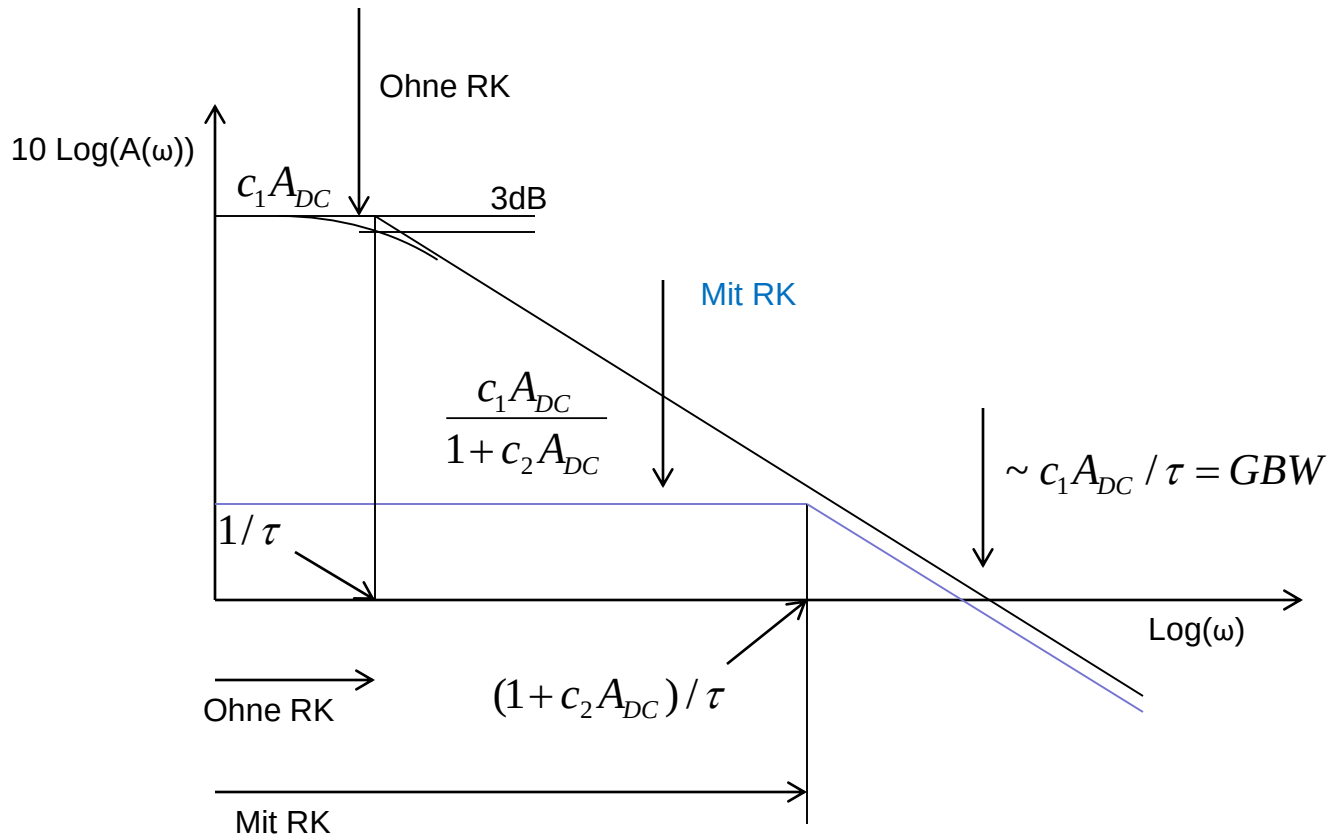


$$A_F = \frac{-A \frac{C_{IN}}{C_{FB} + C_{IN}}}{1 + A \frac{C_{FB}}{C_{FB} + C_{IN}}} = \frac{c_1 A}{1 + c_2 A} \leftarrow A(s) = \frac{A_{DC}}{1 + s\tau}$$

$$A_F(s) = \frac{c_1 A_{DC} / (1 + s\tau)}{1 + c_2 A_{DC} / (1 + s\tau)} \longrightarrow A_F(s) = A_{F0} \frac{1}{\left(1 + \frac{s\tau}{(1 + c_2 A_{DC})}\right)}$$

$$A_{F0} = \frac{c_1 A_{DC}}{1 + c_2 A_{DC}}$$

- Verstärkung * Bandbreite ist konstant
- Eine Art Desensibilisierung von A, weniger gegenüber Frequenz empfindlich



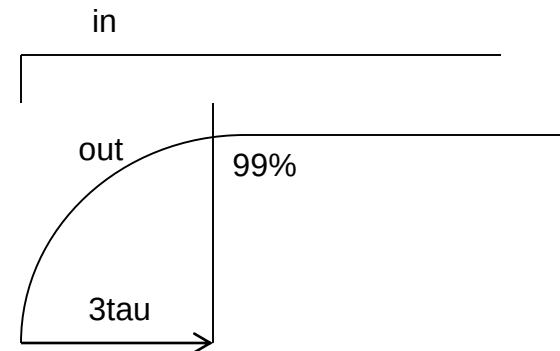
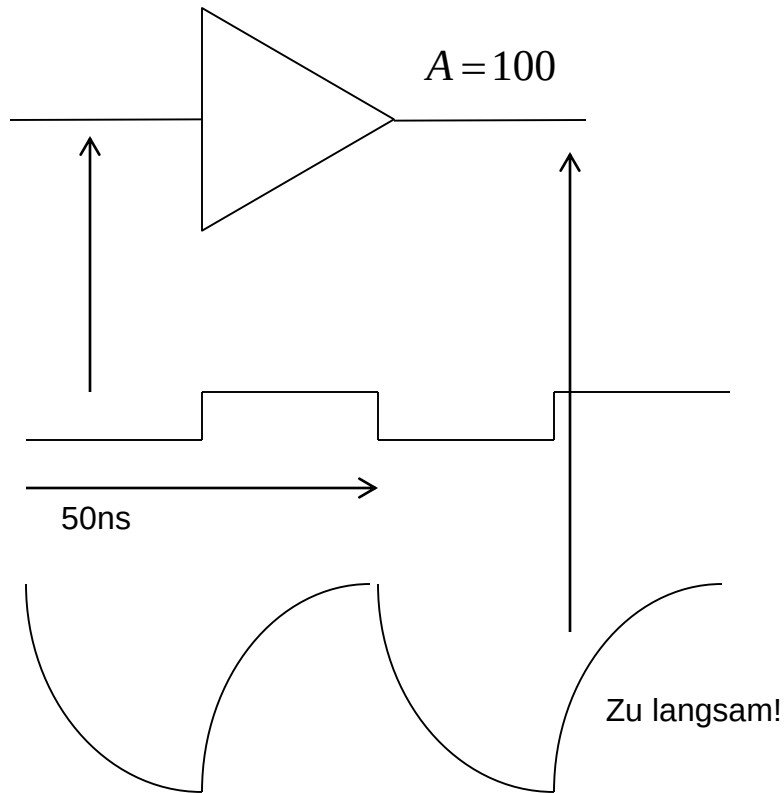
- Beispiel
- Wir möchten 20MHz Taktsignal 100x verstärken, haben nur langsame Verstärker

Bandbreite

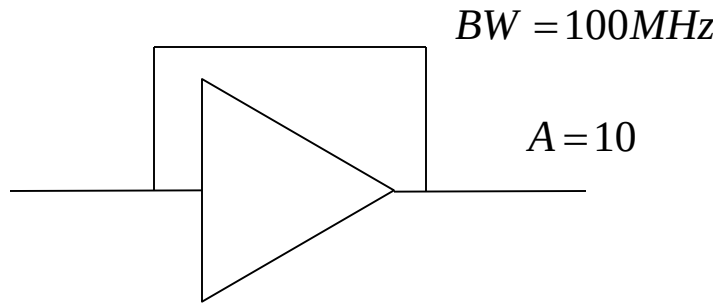
Kreisfrequenz

Dominante Zeitkonstante

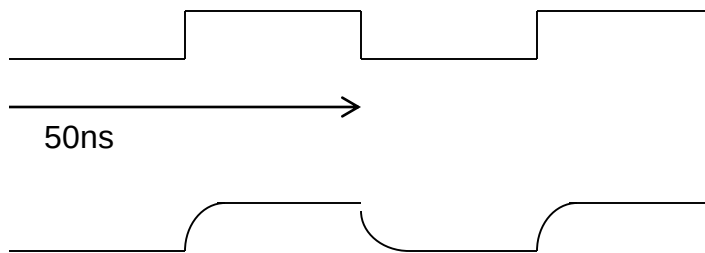
$$BW = 10\text{MHz} \quad \omega_{BW} = 2\pi \cdot 10\text{MHz} \quad \tau = 1/\omega_{BW} = 1/(2\pi \cdot 10\text{MHz}) \approx 16\text{ns}$$



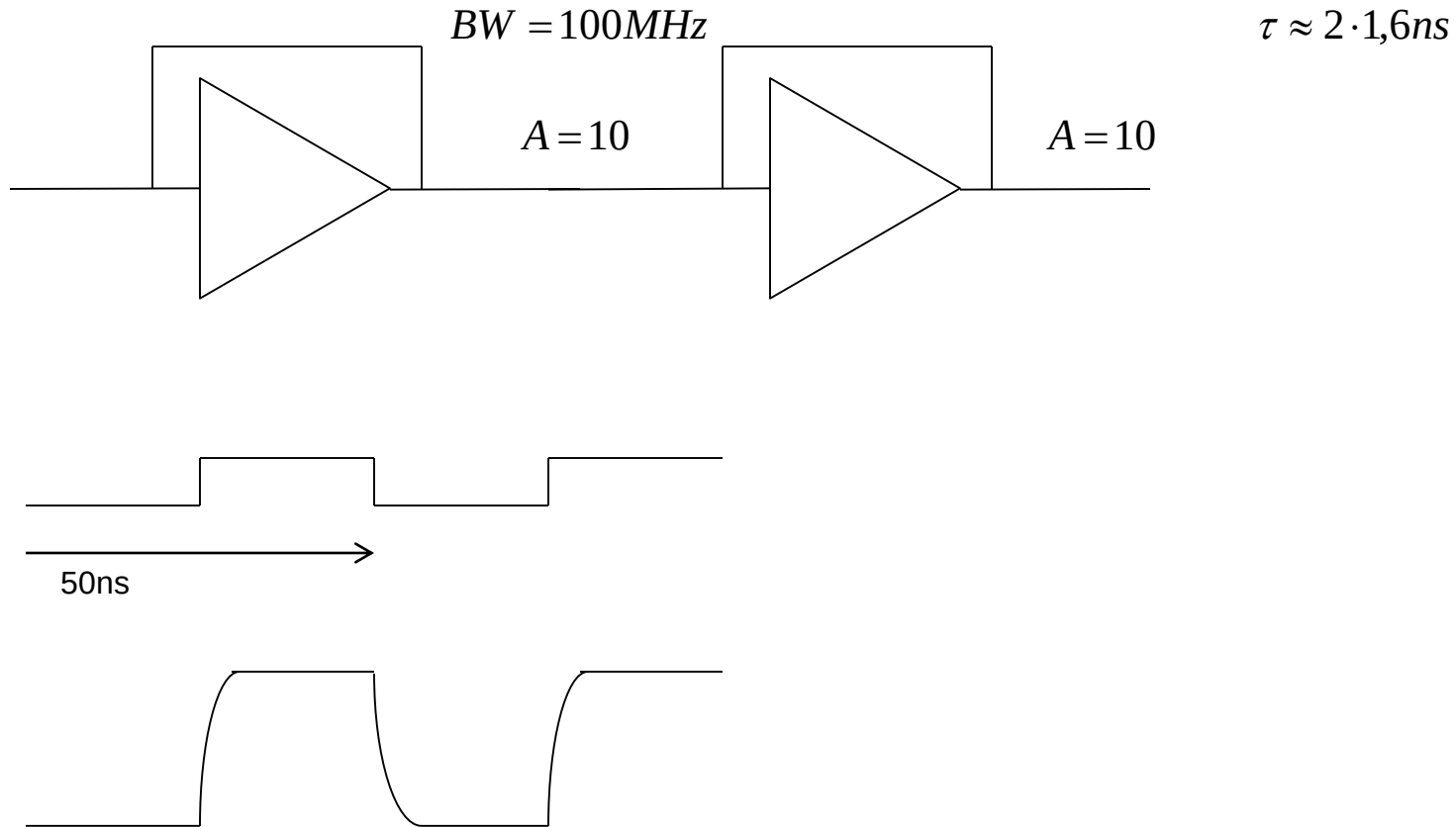
- 1. Idee: Gegenkopplung



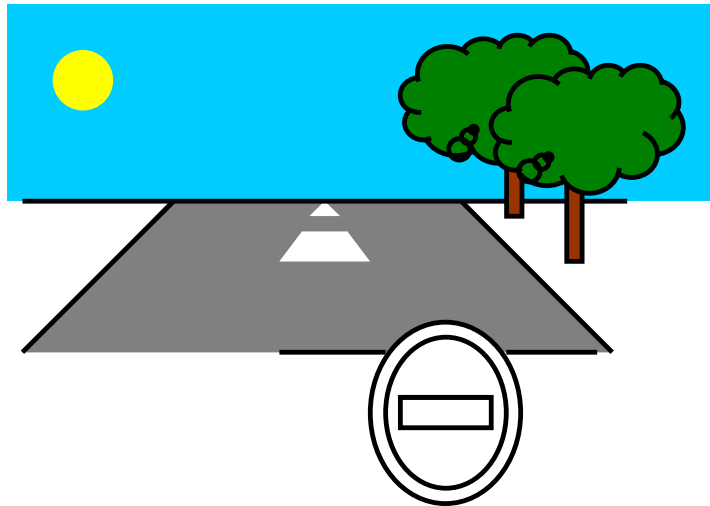
$$\tau = 1/(2\pi \cdot 100\text{MHz}) \approx 1,6\text{ns}$$



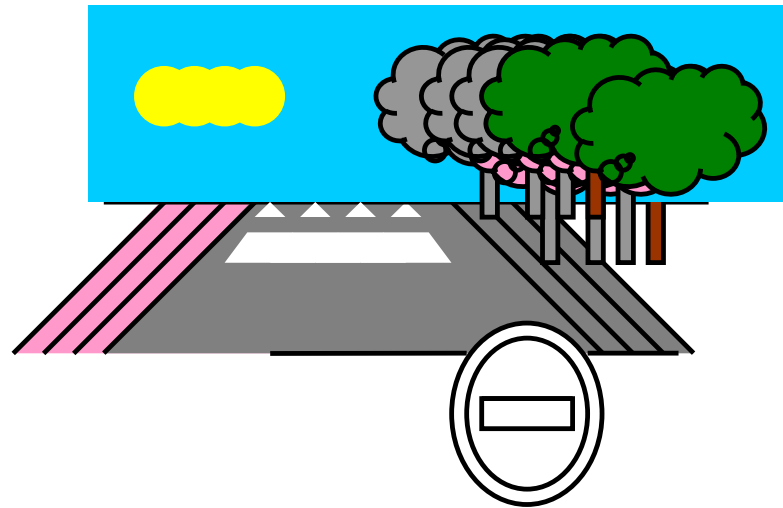
- 2. Idee: Kaskade



- Rückkopplung
 - Elektronik: Ein Teil des Ausgangssignals wird verwendet um Eingangssignal zu beeinflussen
 - Regelung des Systems – negative Rückkopplung

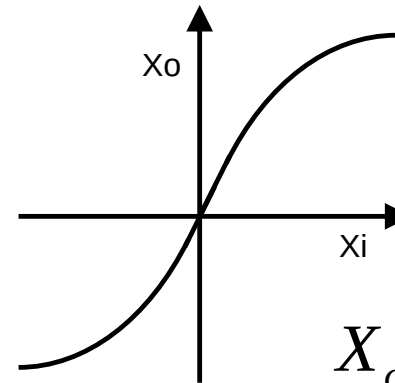
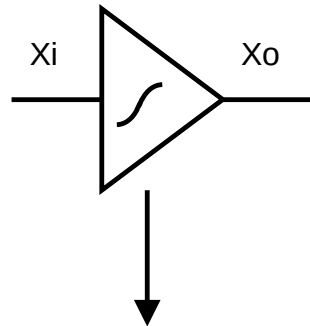


- Rückkopplung in Elektronik
- Vorteile
 - Desensibilisierung für **Prozessparameter** und Temperatur
 - **Bandbreite** wird höher
 - **Linearität** besser
 - Eingangs- und Ausgangsimpedanzen können angepasst werden.
- Nachteile
 - Verstärkung wird kleiner - zeitkonstanten
 - Gefahr vor **Schwingungen**
 - Millereffekt



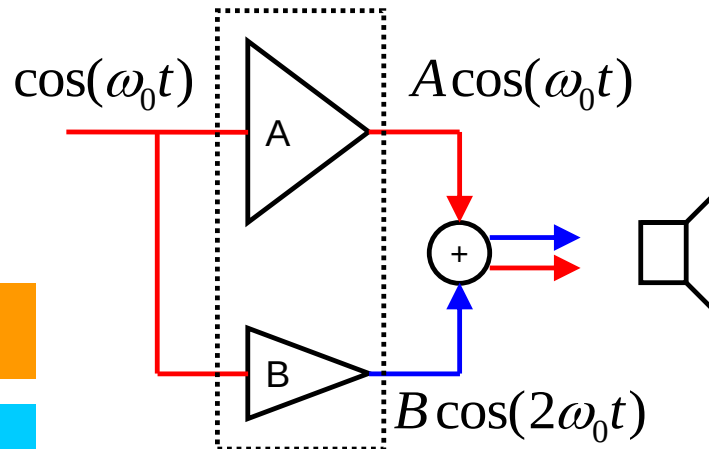
- Backup Folien

Verstärker mit schlechter Linearität



$$X_o = AX_i + BX_i^2 + \dots$$

Reihenentwicklung

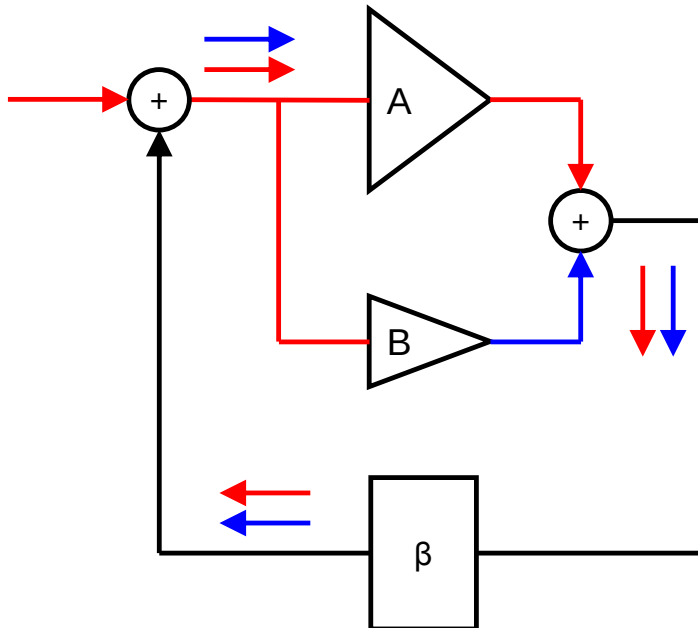


Rot -
Grundfrequenz

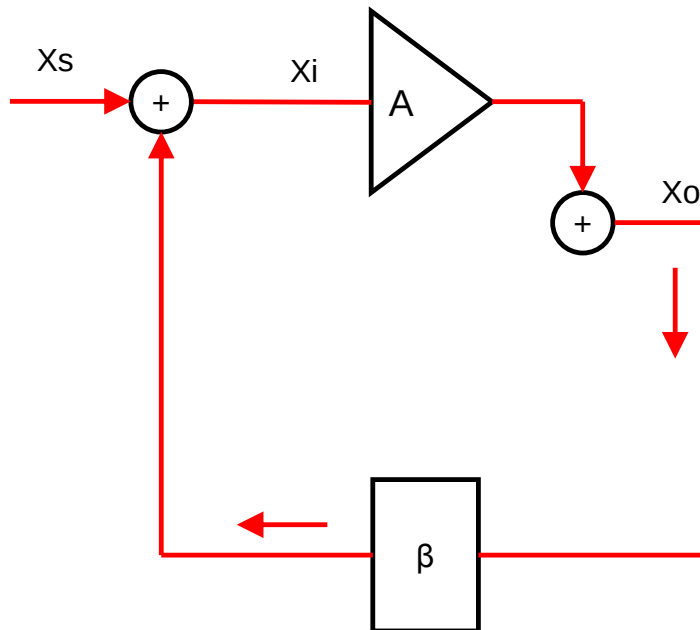
Blau – Die
Oberwelle

Harmonic Distortion
(harmonische
Verzerrung)

$$HD \equiv \frac{B}{A}$$



Nur erste Obewelle



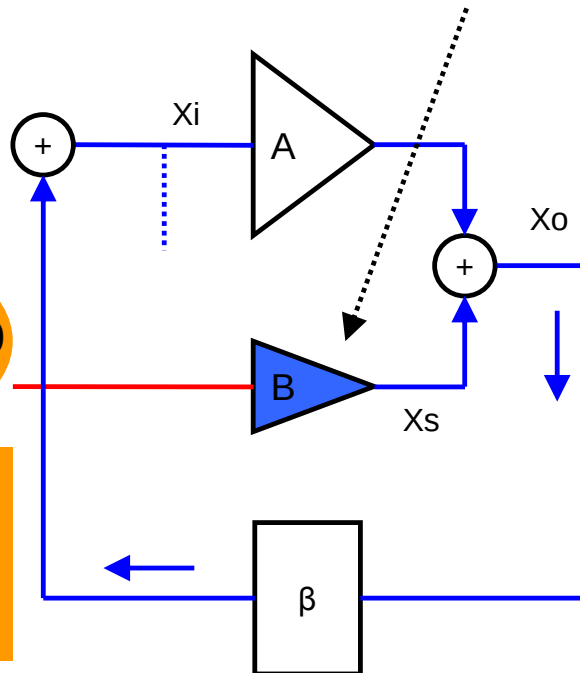
$$X_o = \frac{A}{1+T} X_s$$

$$X_s = \cos(\omega_0 t)$$

$$X_o = \frac{A}{1+T} \cos(\omega_0 t) \quad T = \beta A$$

$$X_i = \frac{1}{1+T} \cos(\omega_0 t)$$

Quelle für die 1. Oberwelle



$$\frac{1}{1+T} \cos(\omega_0 t)$$

Eingang für diese Quelle ist Ergebnis von der letzten Folien

$$X_s = \frac{B}{1+T} \cos(2\omega_0 t)$$

$$X_o = \beta A X_o + X_s$$

$$X_o = \frac{X_s}{1+T}$$

$$X_o = \frac{B}{(1+T)^2} \cos(2\omega_0 t)$$

$$X_{oges} = \frac{A}{1+T} \cos(\omega_0 t) + \frac{B}{(1+T)^2} \cos(2\omega_0 t)$$

Mit RK $HD = \frac{B}{A} \frac{1}{1+T}$

Ohne RK war $HD = \frac{B}{A}$