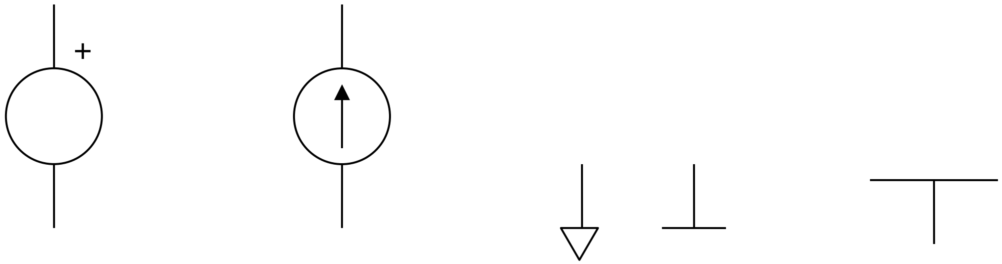
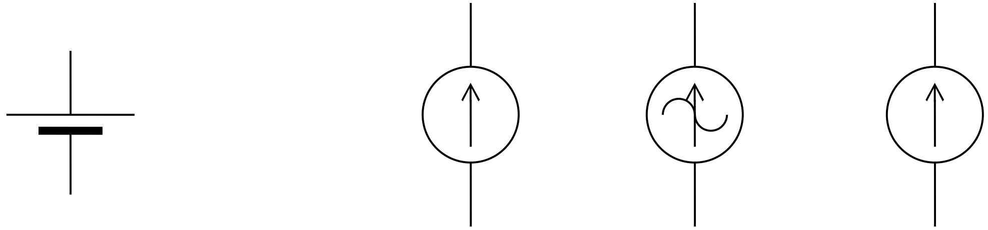
Design analoger Schaltkreise
Vorlesung 2

- Spannungsquellen, Stromquellen
- Masse und Versorgungsspannung



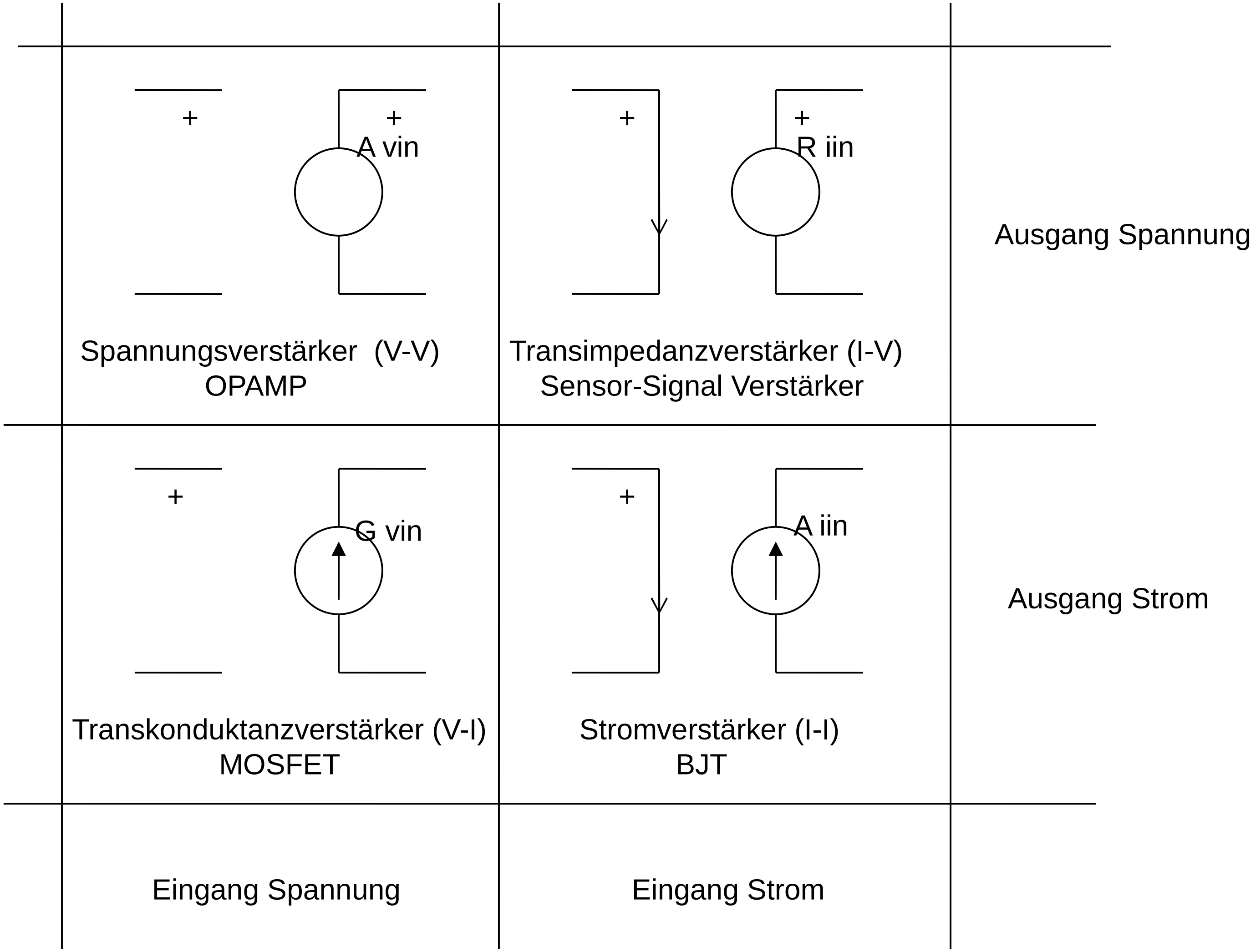
Spannungsquelle | Stromquelle | Masse | Versorgungsspannung

Vdc, vpulse, vsin | gnd, gnda | vdd, vdda



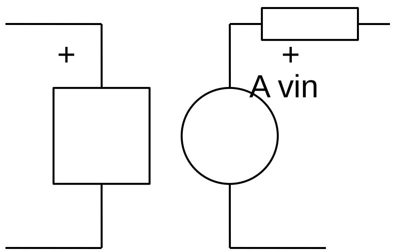
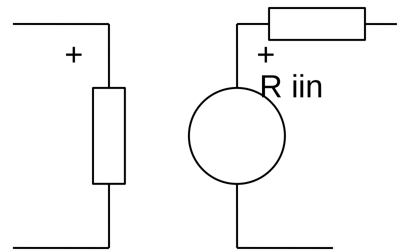
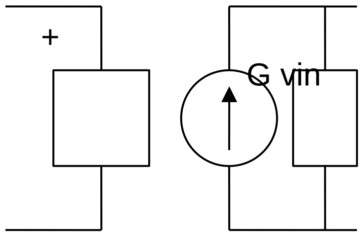
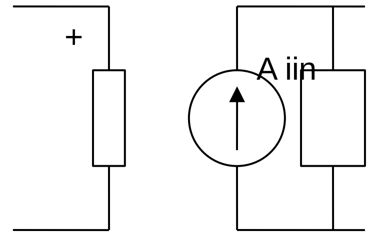
Spannungsquellen | Kleinsignal | DC | Stromquellen | Kleinsignal | DC

- Gesteuerte ideale Spannungsquellen und Stromquellen



Gesteuerte Quellen

- Gesteuerte reale Spannungsquellen und Stromquellen

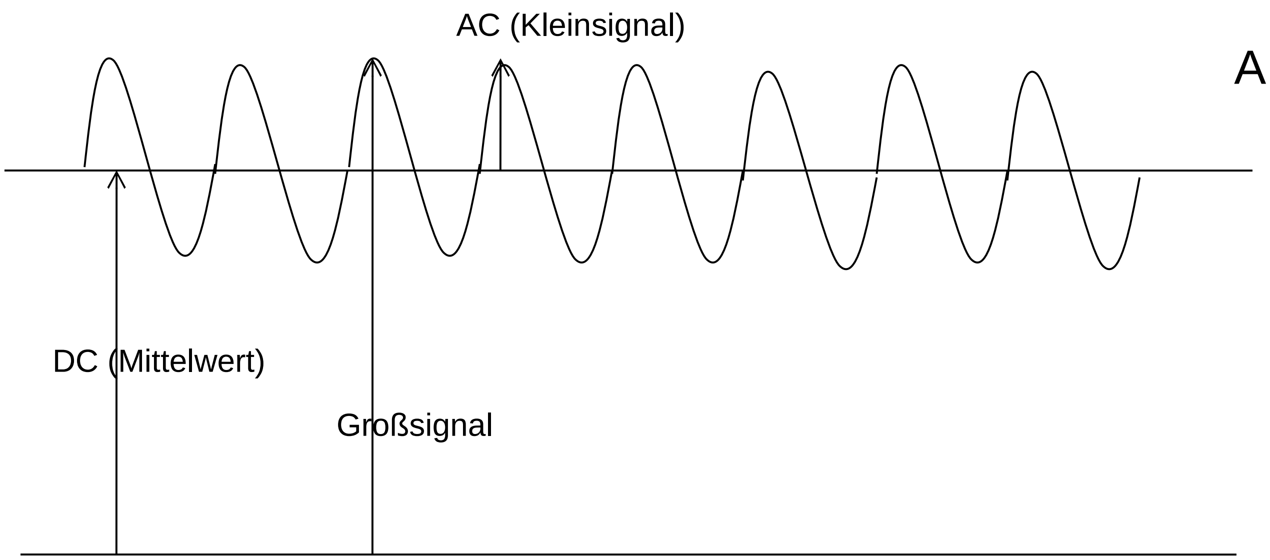
 Spannungsverstärker (V-V) OPAMP	 Transimpedanzverstärker (I-V) Sensor-Signal Verstärker	Ausgangsimpedanz klein Bitte nicht kurzschiessen (Sonst Strombegrenzung)
 Transkonduktanzverstärker (V-I) MOSFET	 Stromverstärker (I-I) BJT	Ausgangimpedanz groß Nicht offen lassen (Sonst Spannungsbegrenzung)
Eingangsimpedanz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

- AC DC

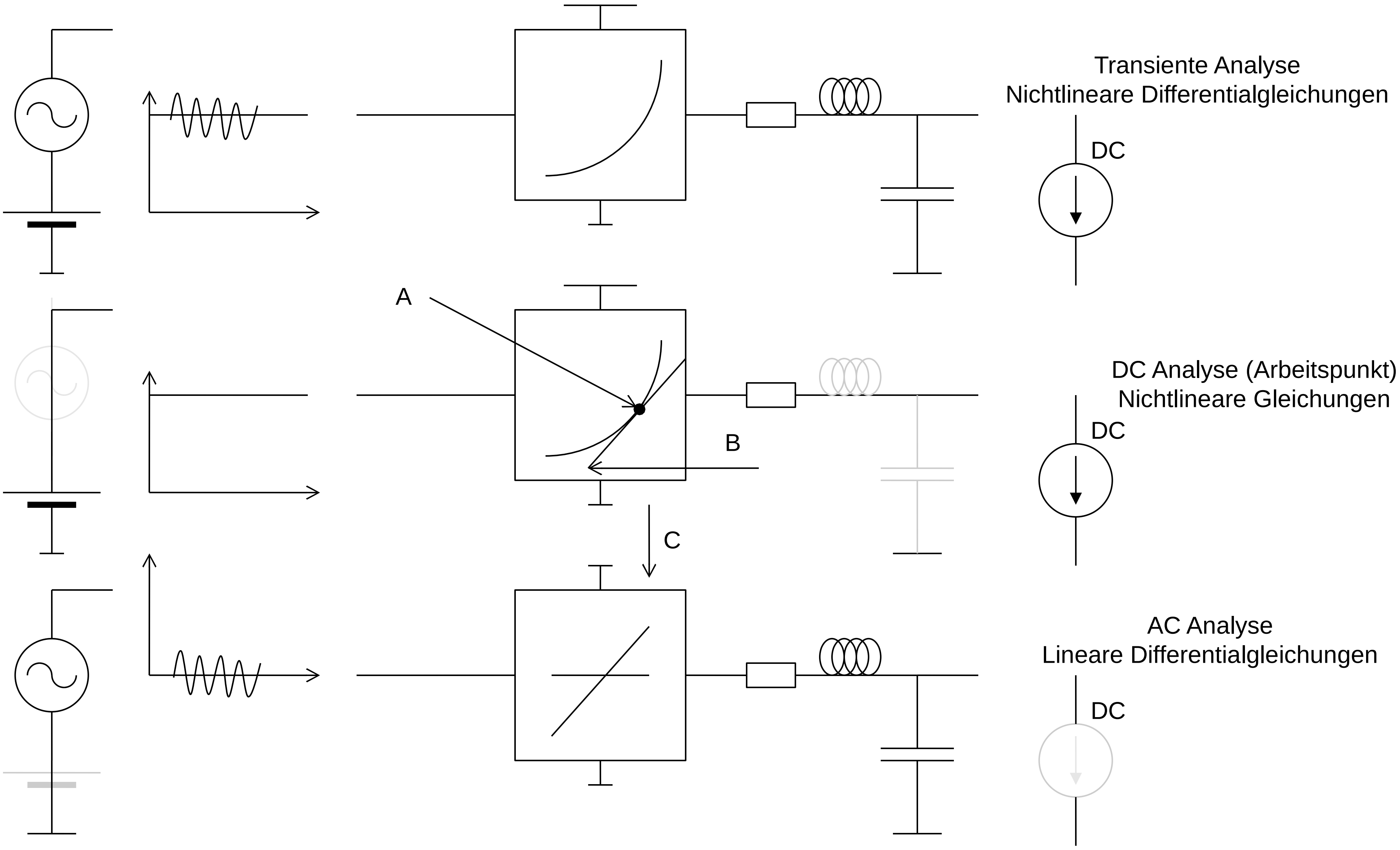
Groß

klein → $v_{OUT}(t) = V_{OUT} + A \sin(\omega\, t)$

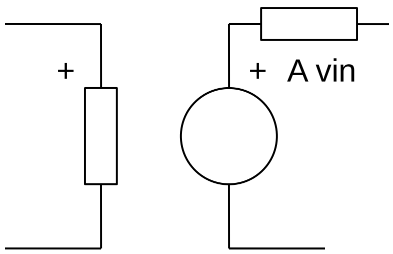
$A \sin(\omega\, t) = v_{out}(t)$



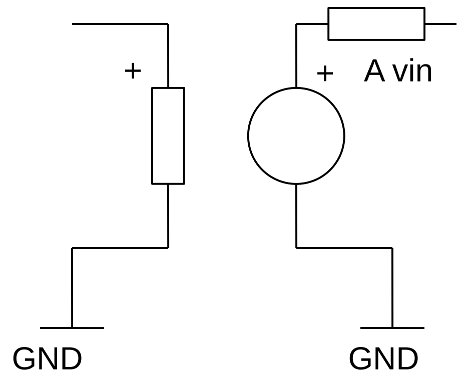
- Klein- und Großsignalmodelle



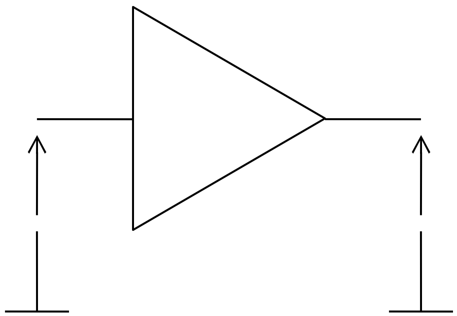
- Verstärker
- Einfachste Variante - Single-Ended Verstärker



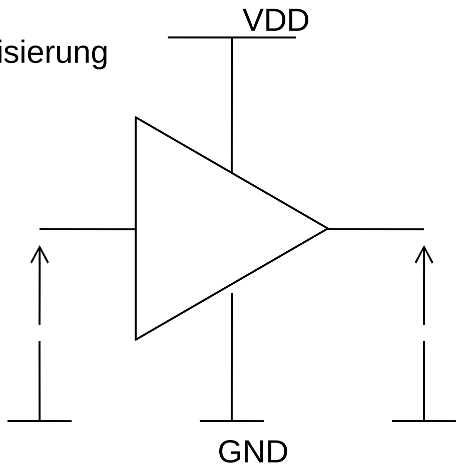
Spannungsverstärker



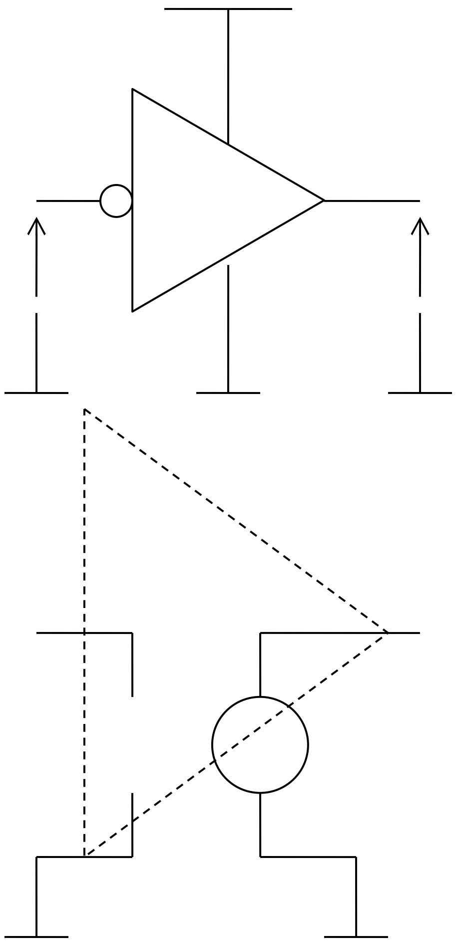
Ideal

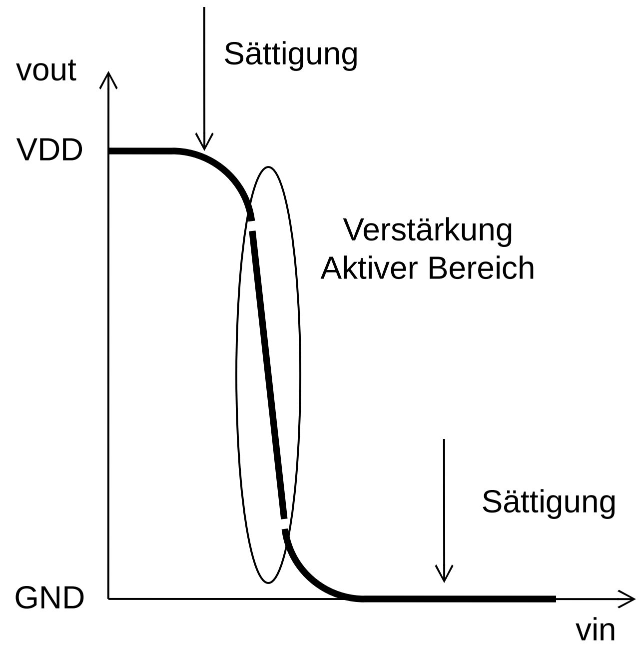


Realisierung

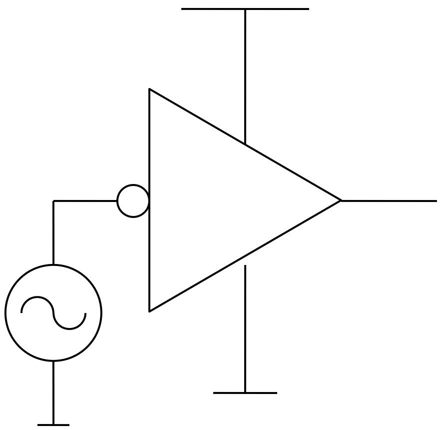


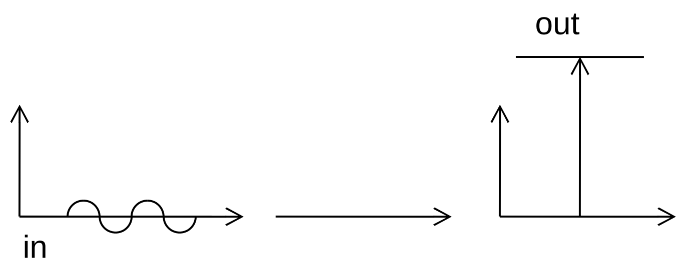
- vout = f(vin)
- Annahmen: Zout = 0, Zin = unendlich

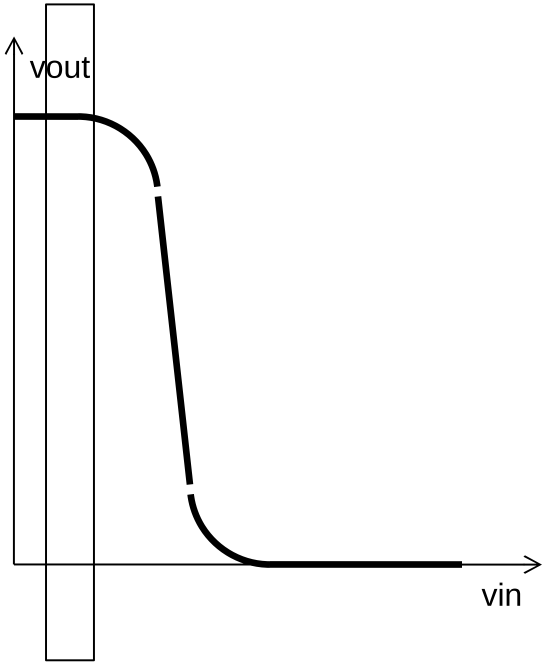




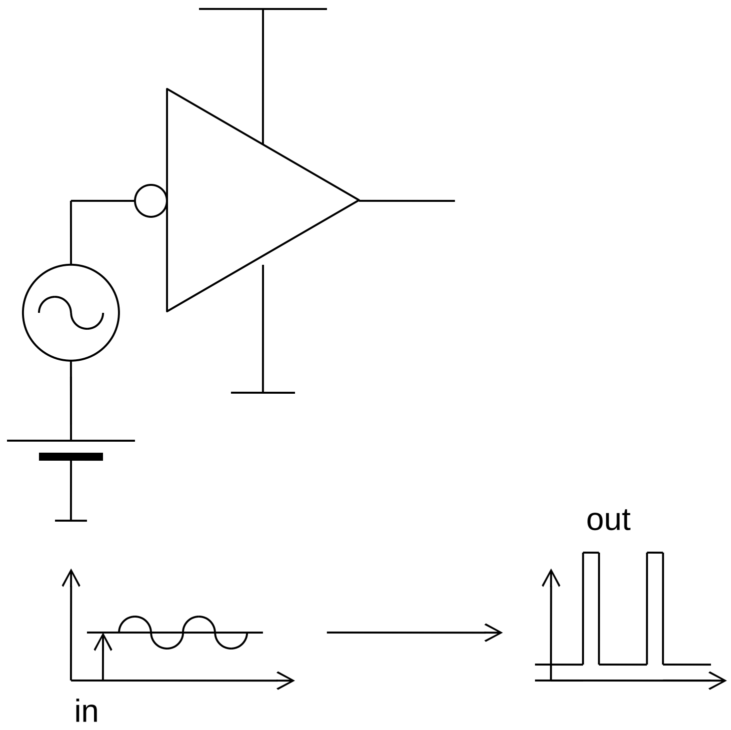
- Verstärker

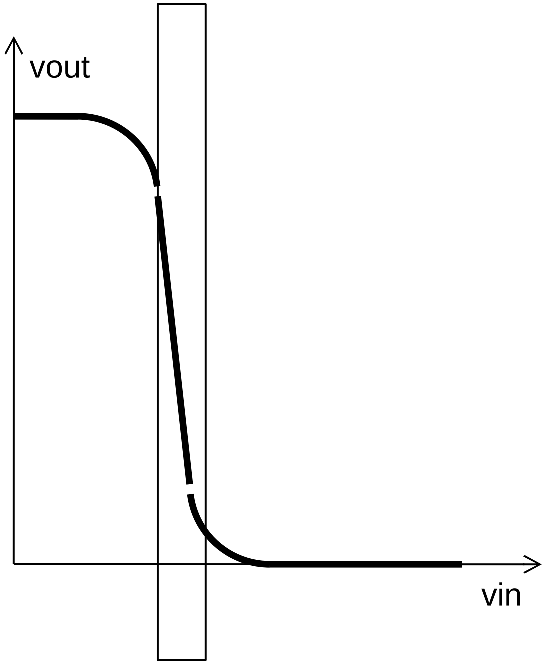




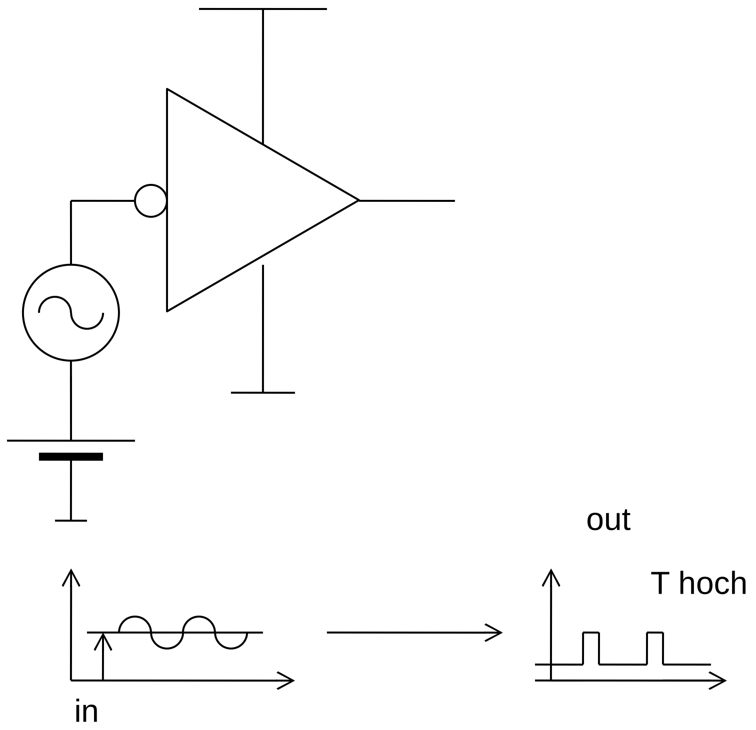


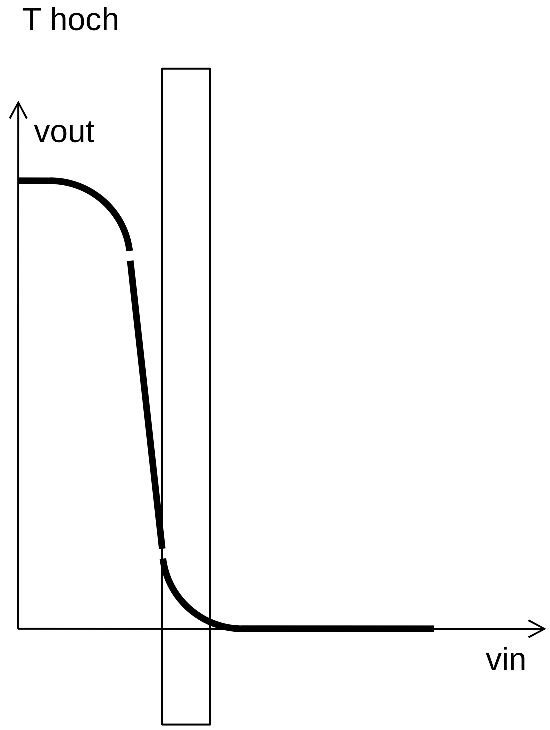
- Verstärker





- Verstärker





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

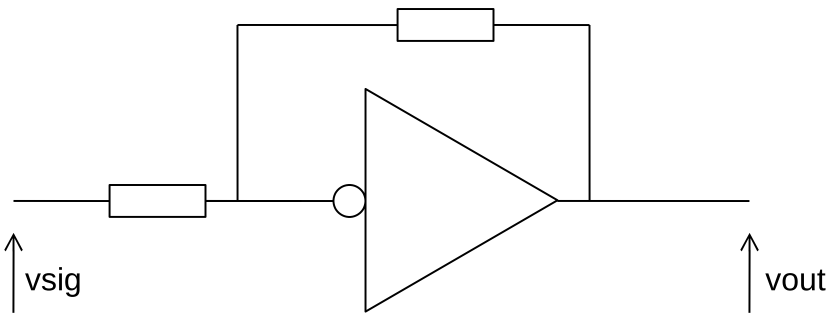
Feedback

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.

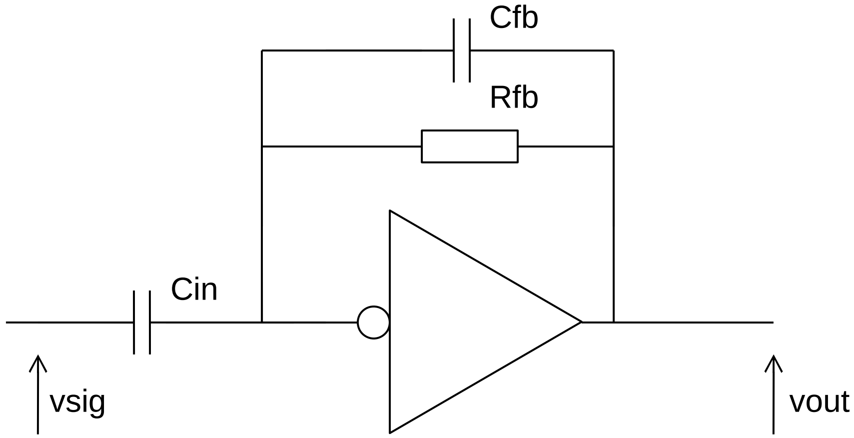
Feedback is a powerful technique that finds wide application in analog circuits. For example, negative feedback allows high-precision signal processing and positive feedback makes it possible to build oscillators. In this chapter, we consider only negative feedback and use the term feedback to mean that.

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)

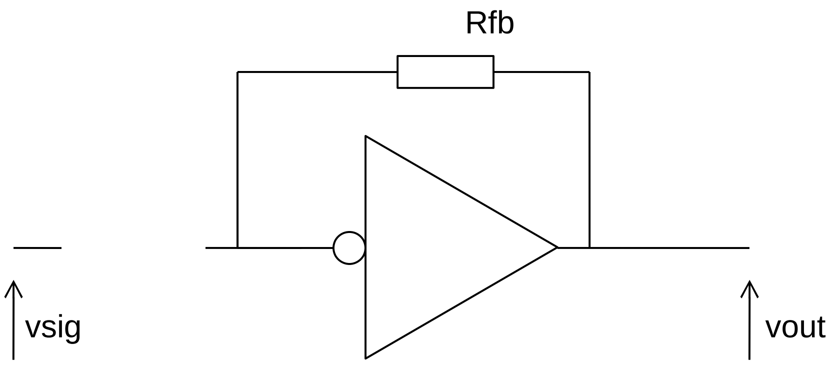


- Gegenkopplung
- Beispiel: Invertierender Verstärker
- Realisierung mit C (IC)
- „Starke“ resistive (ohmsche) Gegenkopplung für DC Spannungen
- Schnelle und „schwache“ kapazitive Rückkopplung für AC Signale
- Arbeitspunkt ist stabil
- AC Signale werden verstärkt

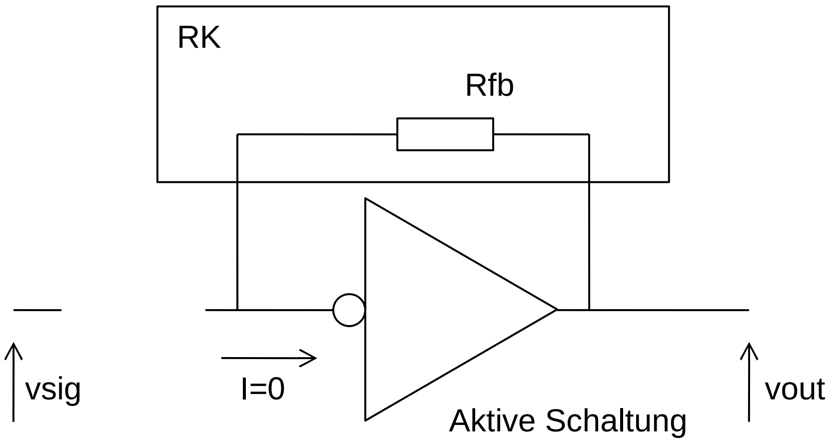


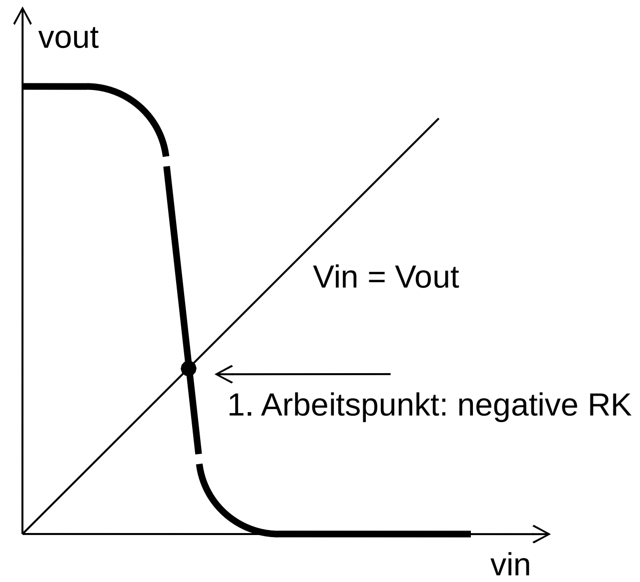
Invertierender Verstärker DC 1

- DC Analyse
- C sind weg

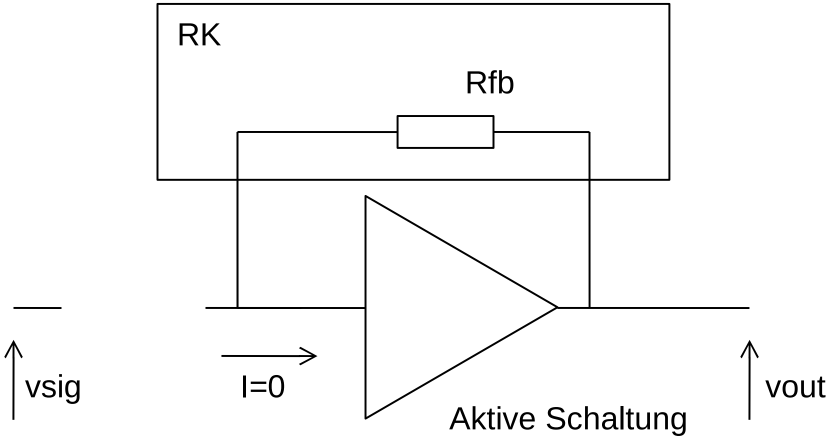


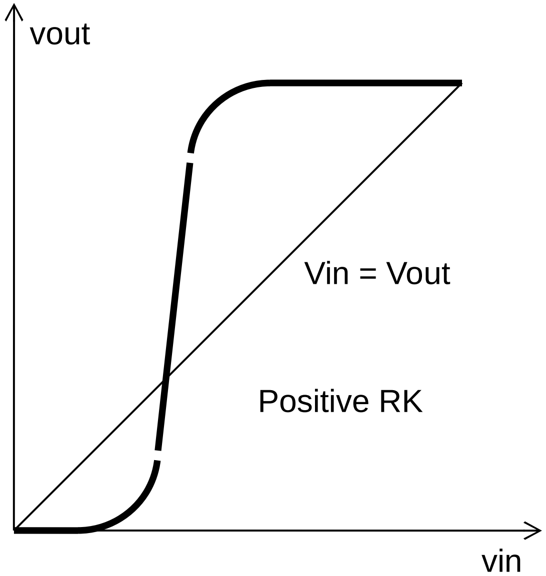
- DC


RK
Rfb
vsig
I=0
vout
Aktive Schaltung

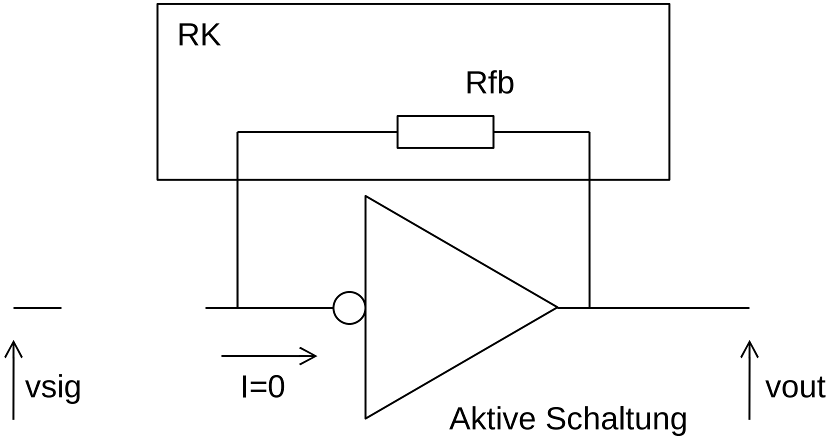

vout
Vin = Vout
1. Arbeitspunkt: negative RK
vin

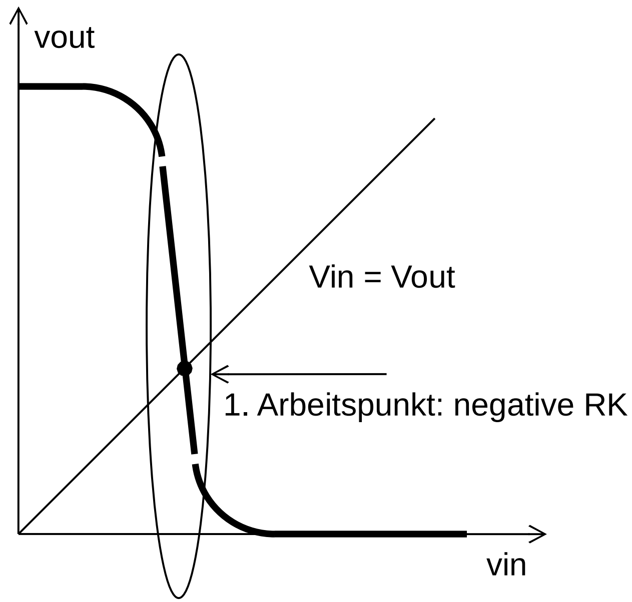
- RAM Zelle


RK
Rfb
vsig
I=0
Aktive Schaltung
vout

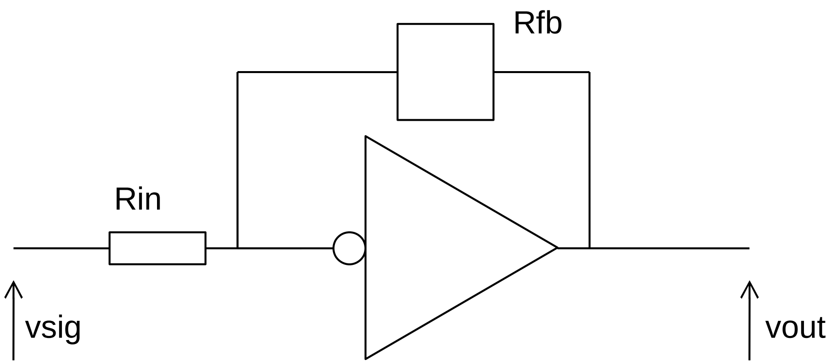

vout
Vin = Vout
Positive RK
vin

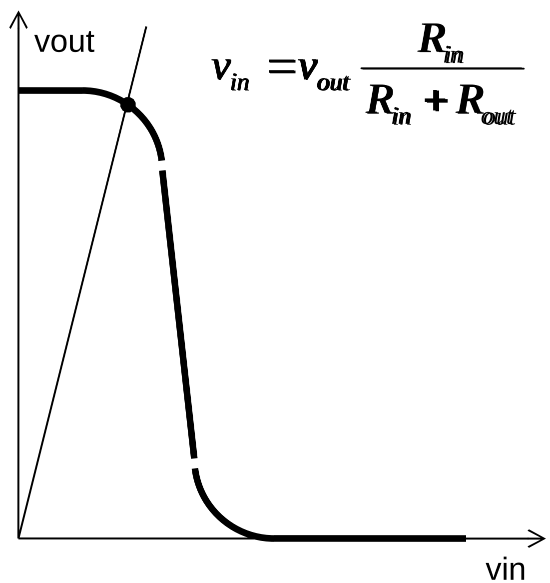
- DC


RK
Rfb
vsig
I=0
Aktive Schaltung
vout


vout
Vin = Vout
1. Arbeitspunkt: negative RK
vin

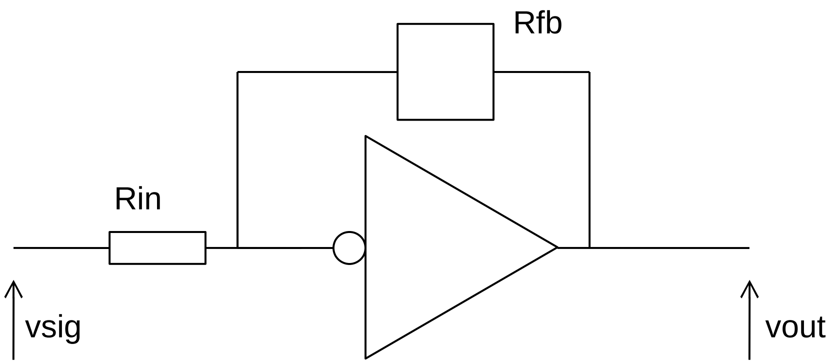
- Gegenkopplung ist falsch dimensioniert



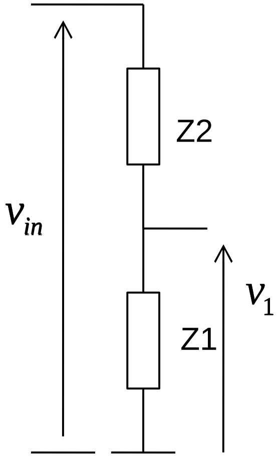


$$v_{in} = v_{out} \frac{R_{in}}{R_{in} + R_{out}}$$

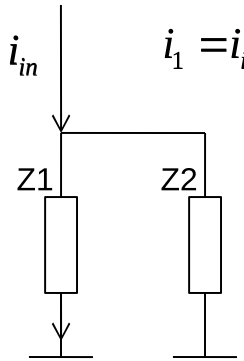
- Spannungs- und Stromteiler

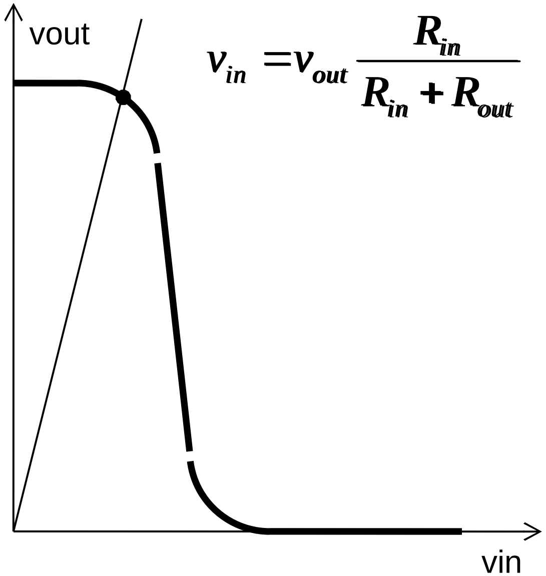


$$v_1 = v_{in} \frac{Z_1}{Z_1 + Z_2}$$



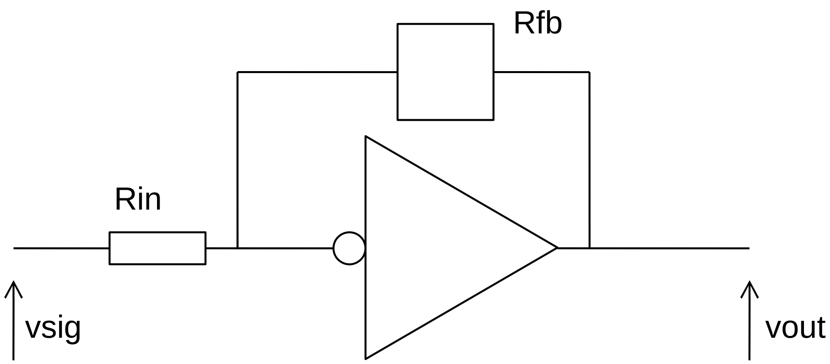
$$i_1 = i_{in} \frac{Z_2}{Z_1 + Z_2}$$



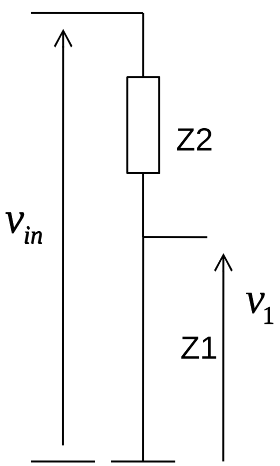


$$v_{in} = v_{out} \frac{R_{in}}{R_{in} + R_{out}}$$

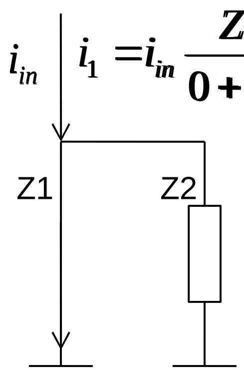
- Spannungs- und Stromteiler



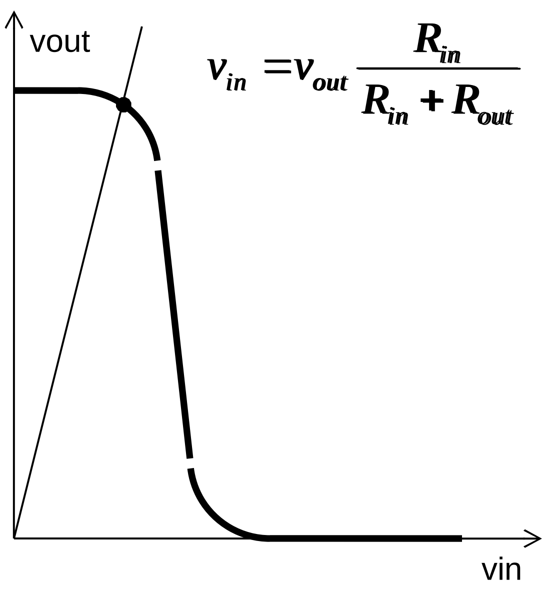
$$v_1 = v_{in}\frac{0}{Z_1 + Z_2} = 0$$



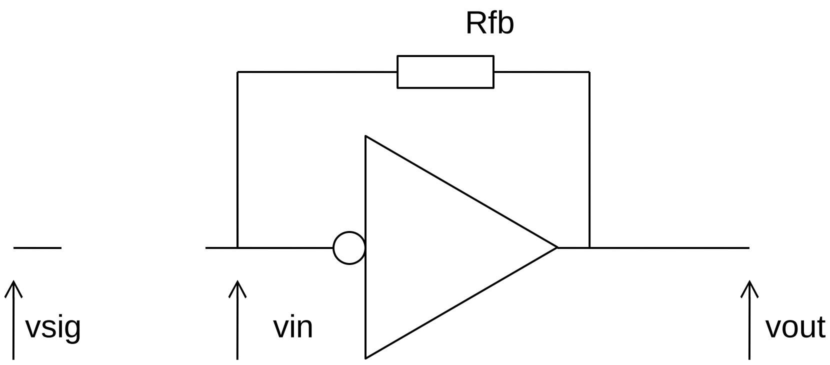
$$i_1 = i_{in}\frac{Z_2}{0 + Z_2} = i_{in}$$

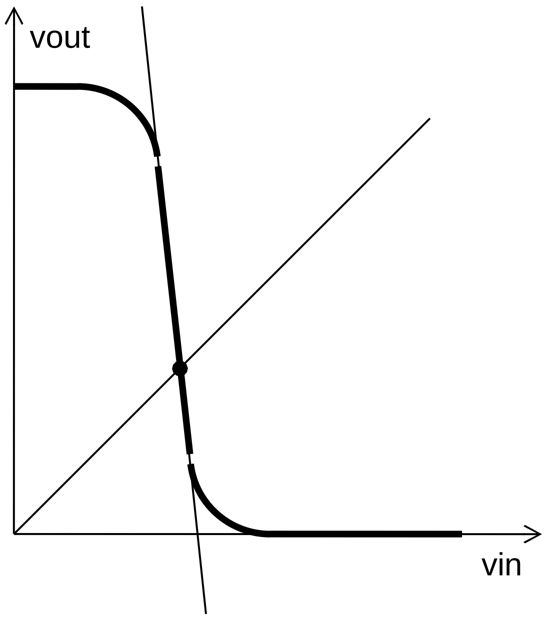


$$v_{in} = v_{out}\frac{R_{in}}{R_{in} + R_{out}}$$

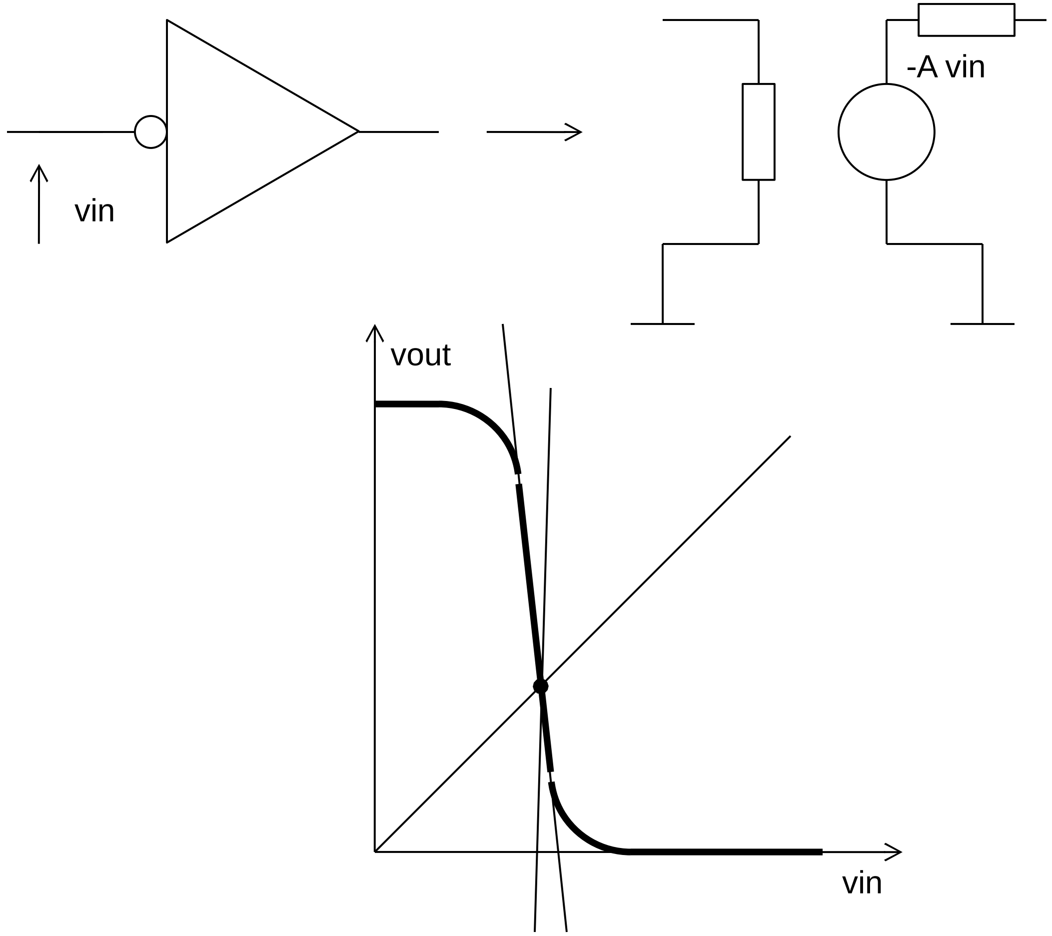


- Kleinsignalanalyse



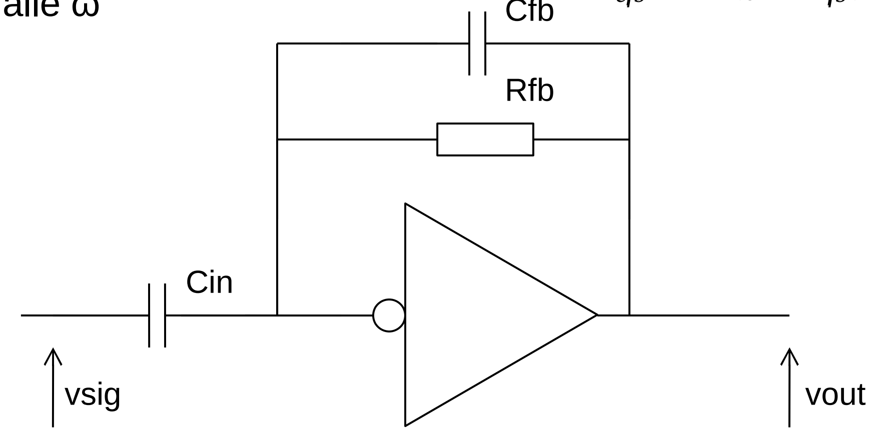


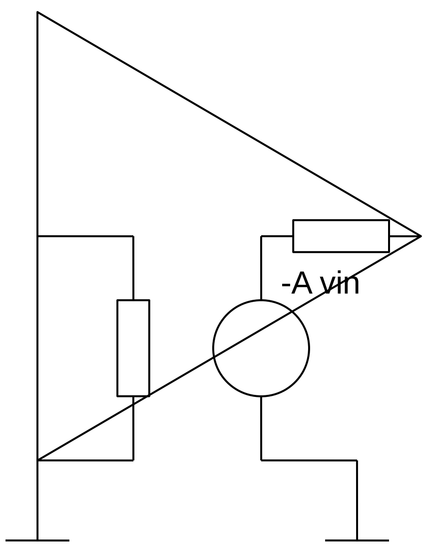
- Kleinsignalanalyse
- Rout, Rin unendlich



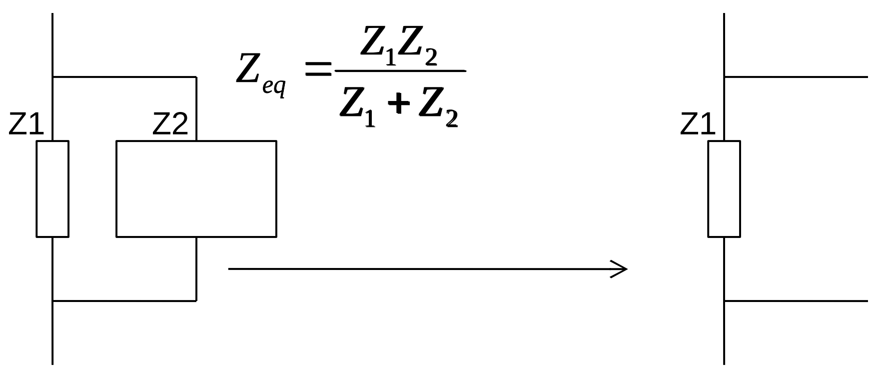
- Rfb ist groß
- Zc ist klein für alle ω

$$Z_{cfb} = 1/(j\omega C_{fb})$$

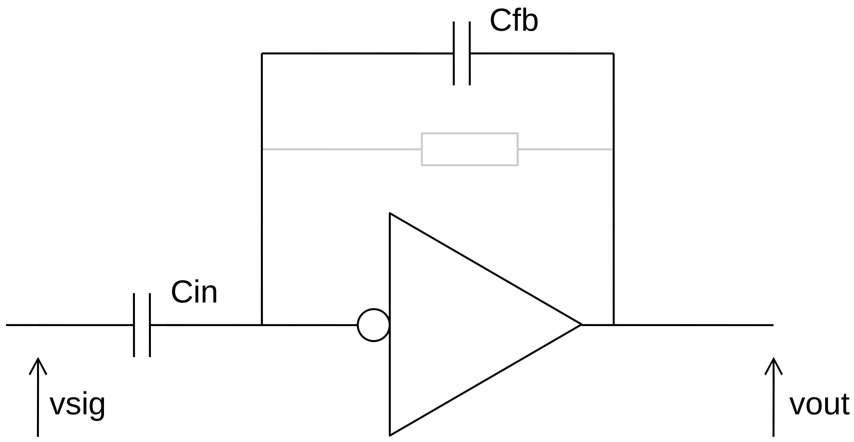


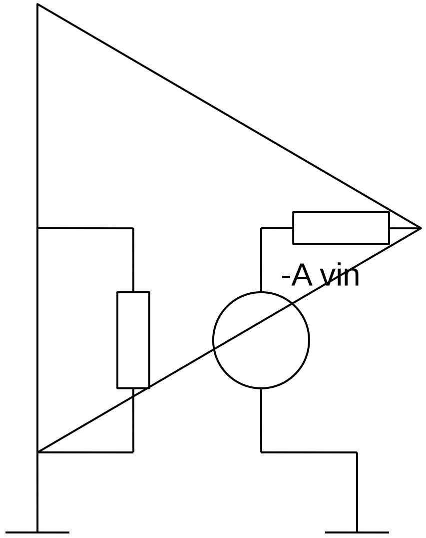


$$Z_{eq} = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

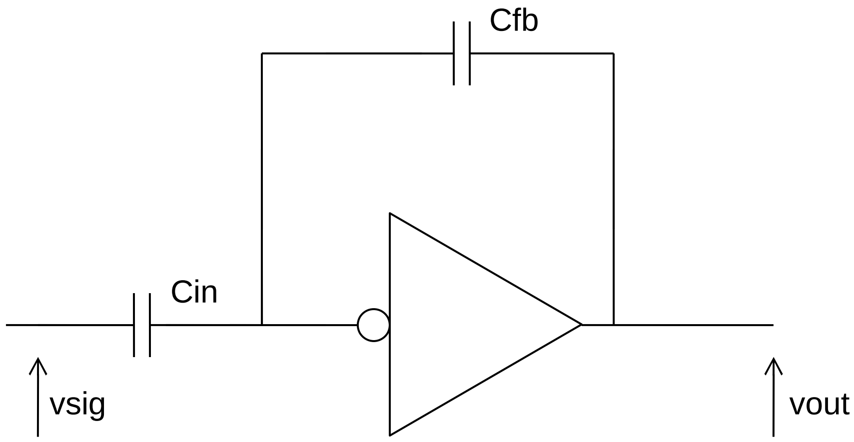


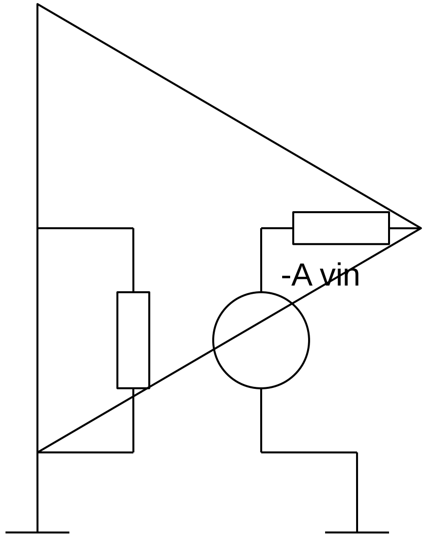
- Gegenkopplung



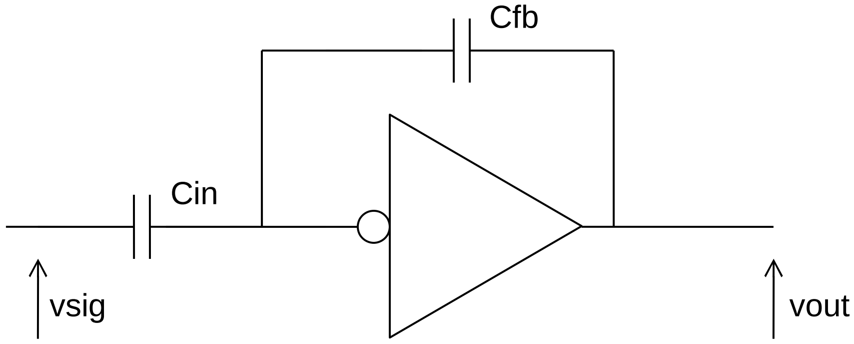


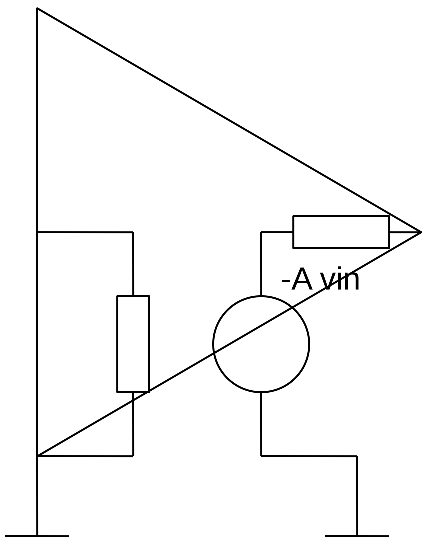
- Gegenkopplung



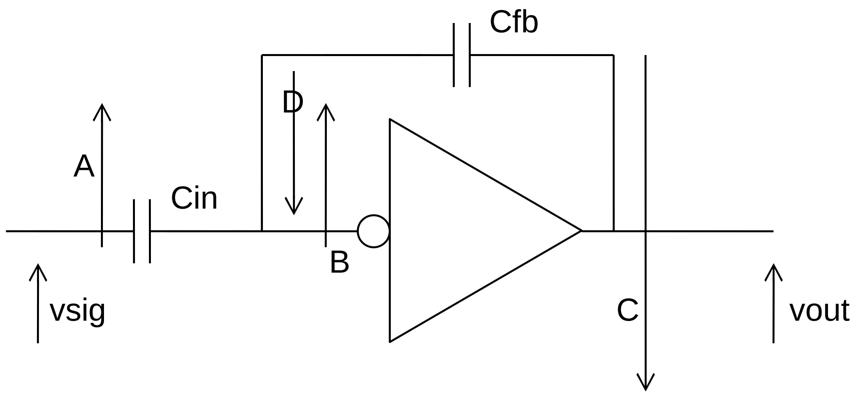


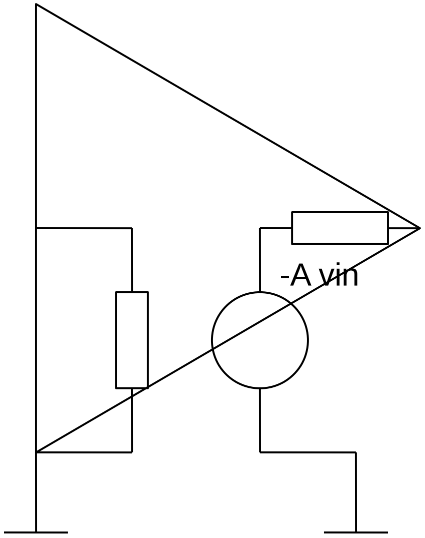
- Gegenkopplung



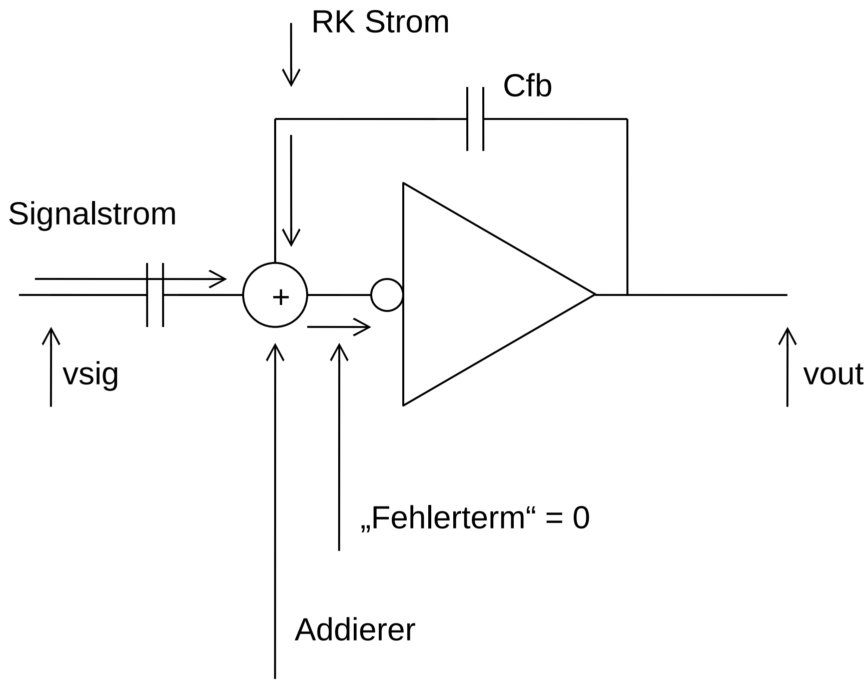


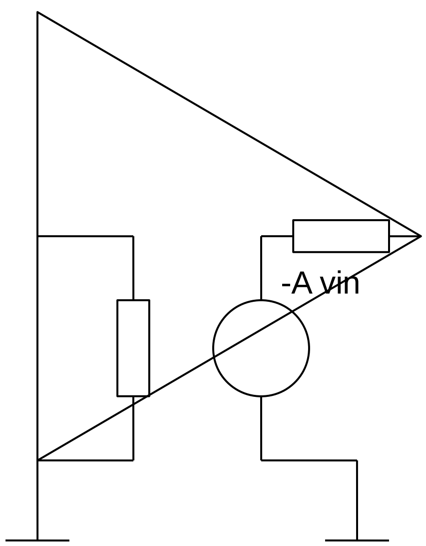
- Rückkopplung ist negativ



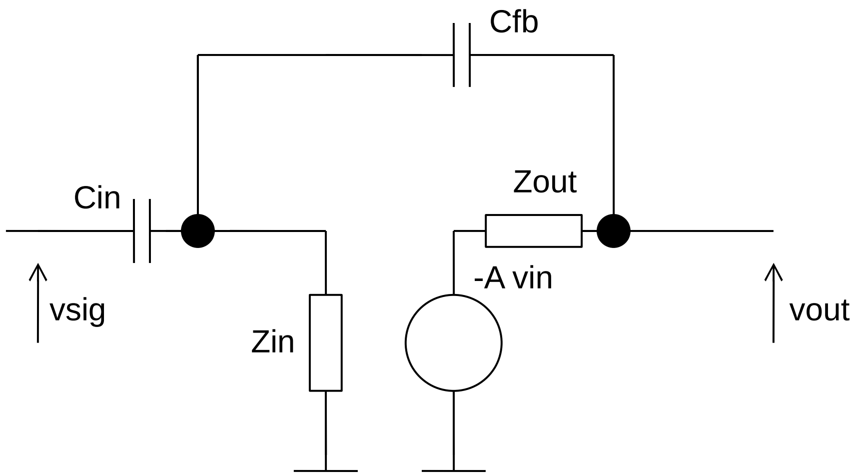


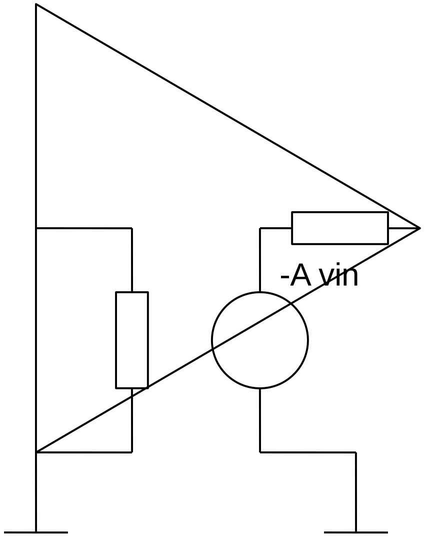
- V-I Rückkopplung



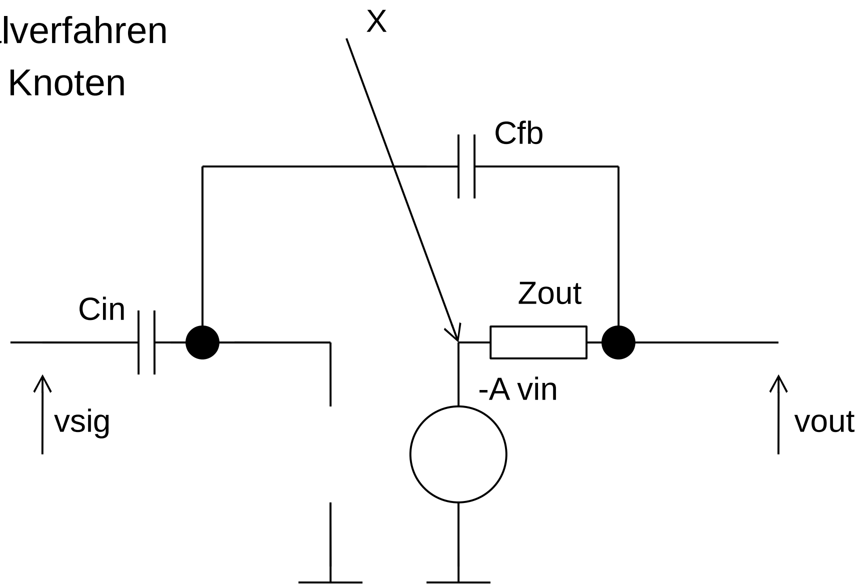


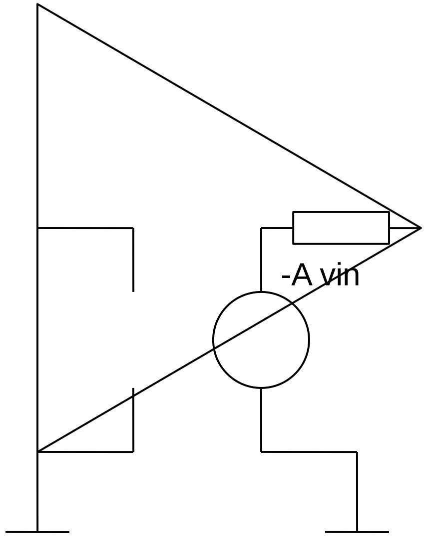
- Gegenkopplung



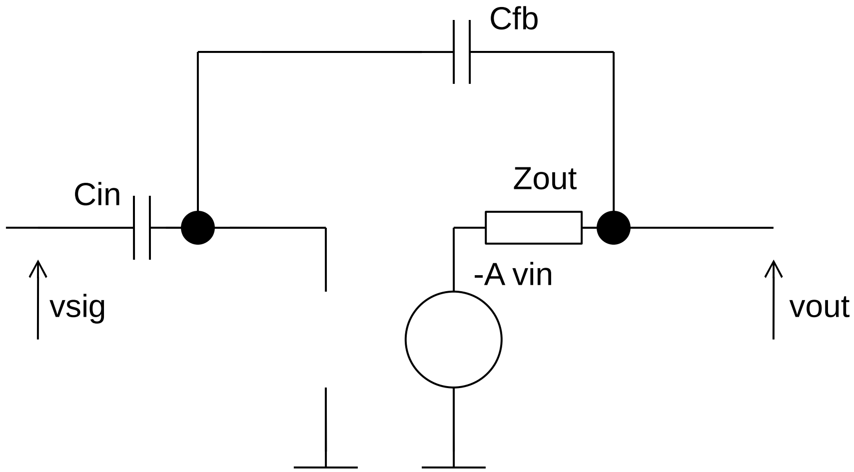


- Lösung
- Knotenpotentialverfahren
- 2 unabhängige Knoten





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

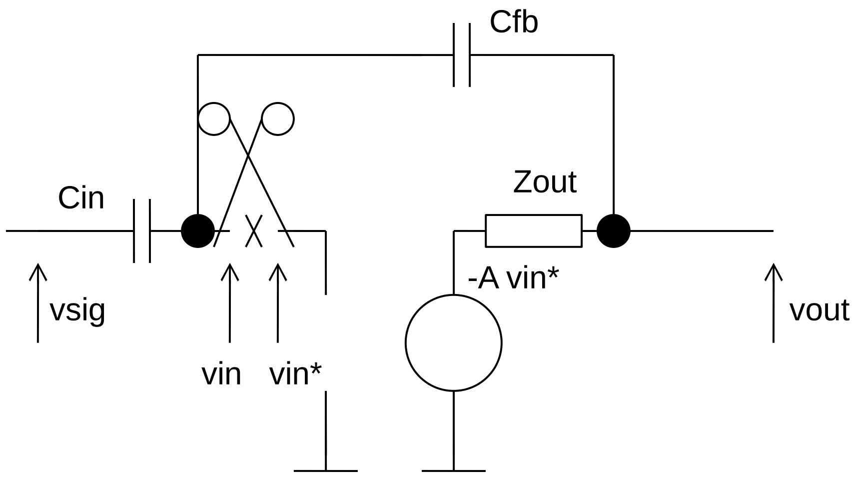


„Wichtige“ Formel (wird später bewiesen)

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

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

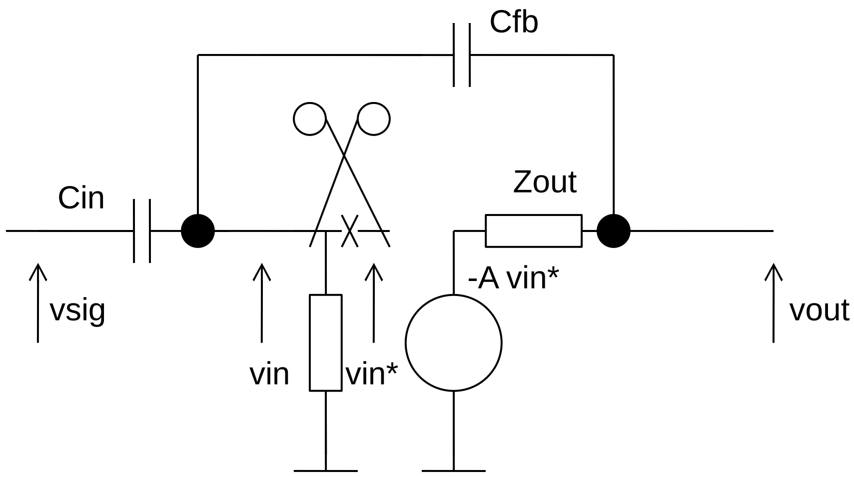
- Rückkopplung wird in einem passenden Punkt unterbrochen



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

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

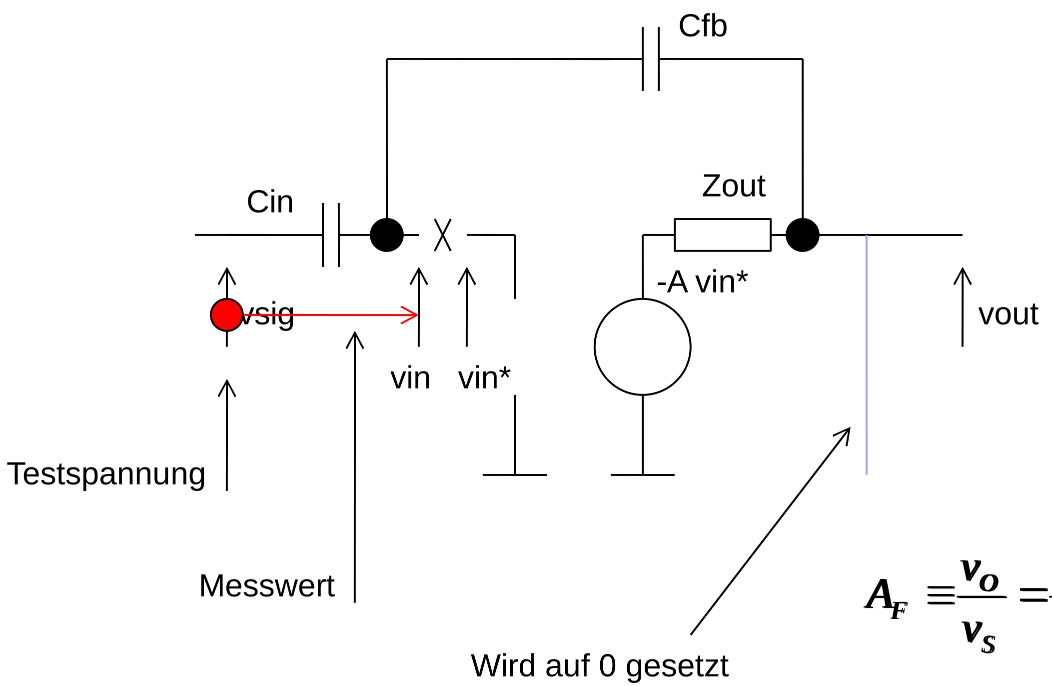
- Rückkopplung wird in einem passenden Punkt unterbrochen
- Variante mit Rin



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

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

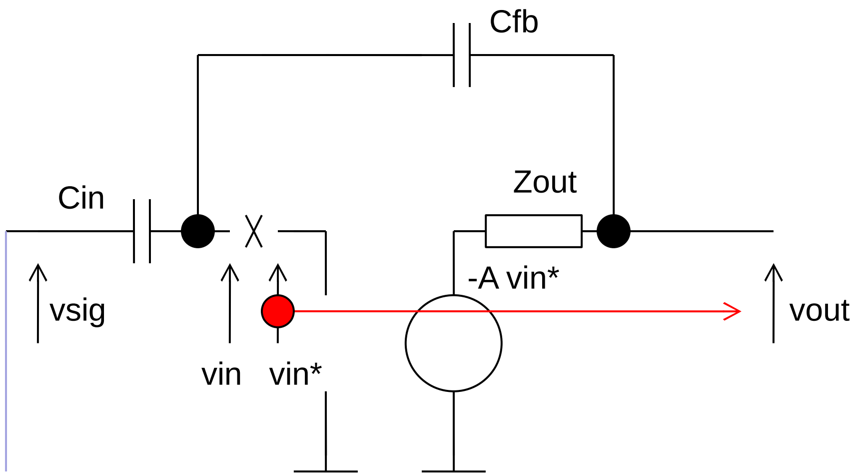
- Ain (Definition) – Verstärkung im Addierer



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

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

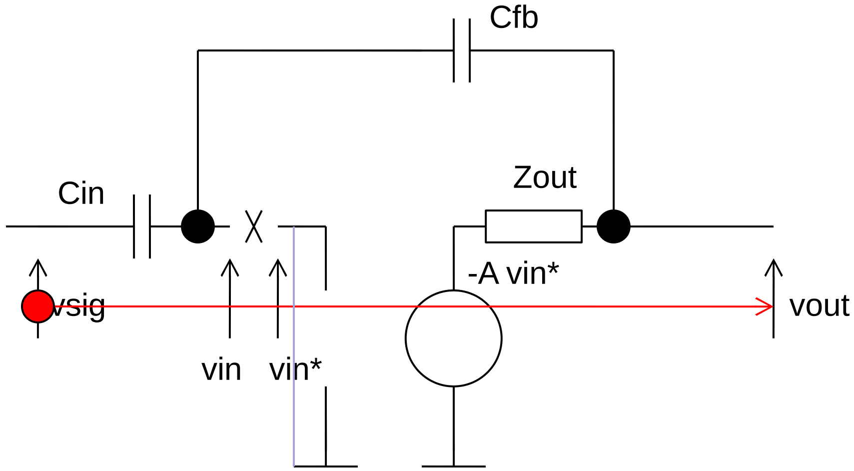
- Aol (Definition) – open loop gain (Leerlaufverstärkung)



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

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

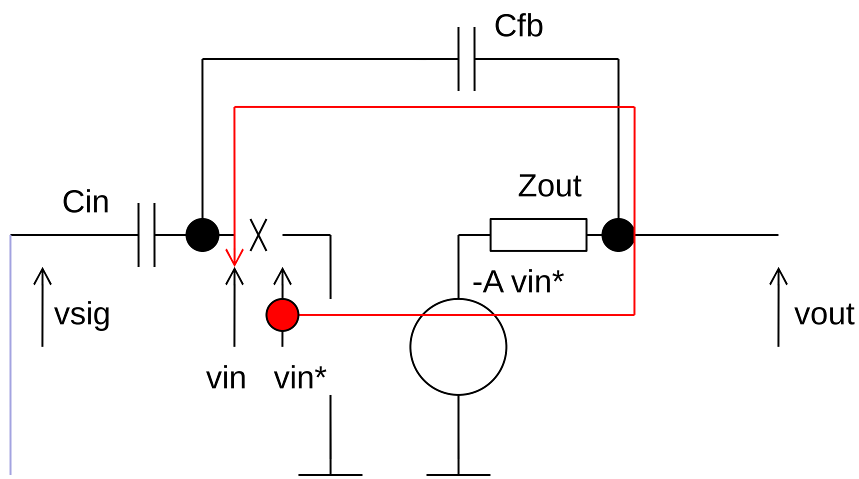
- FF (Definition) – feed forward (Vorwärtsverstärkung)



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

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

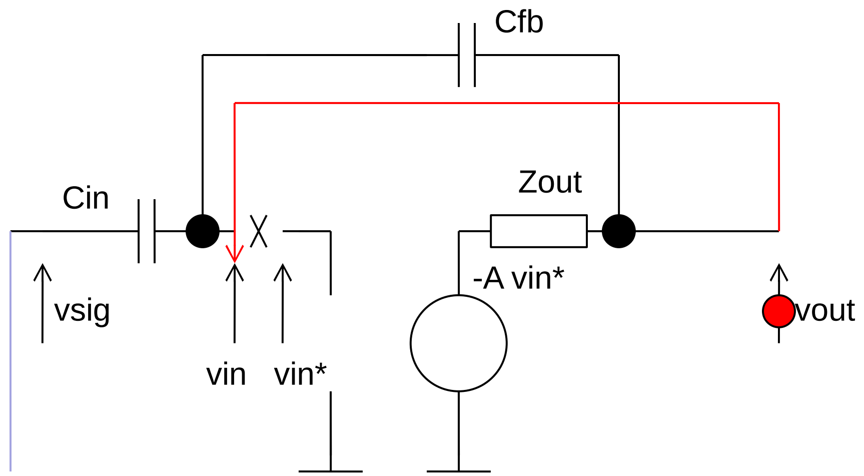
- betaA (Definition) – Schleifenverstärkung



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

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

- Beta (Definition) – Rückkopplung

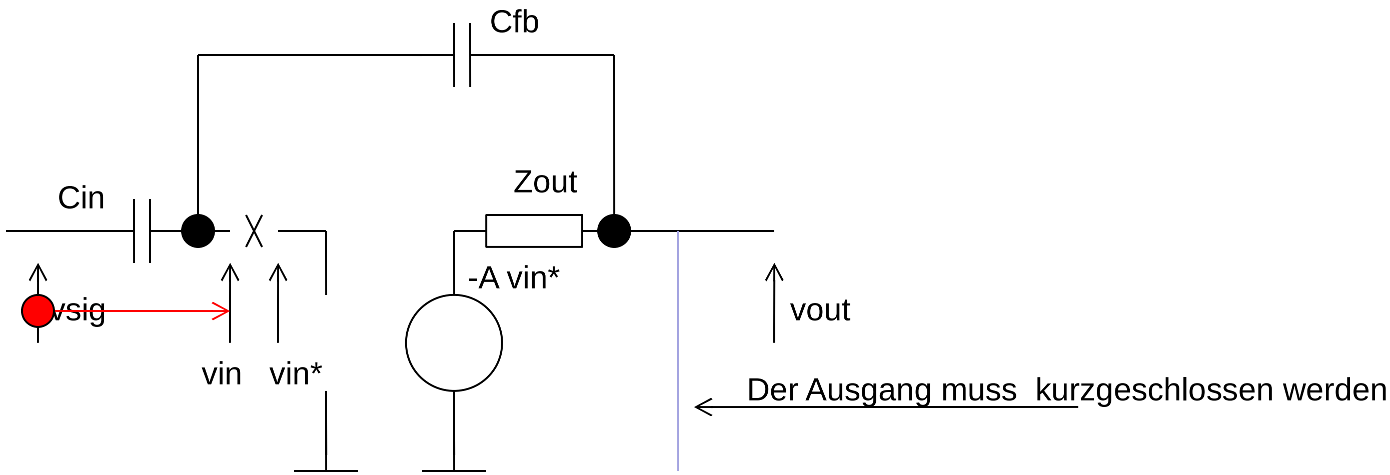


$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

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

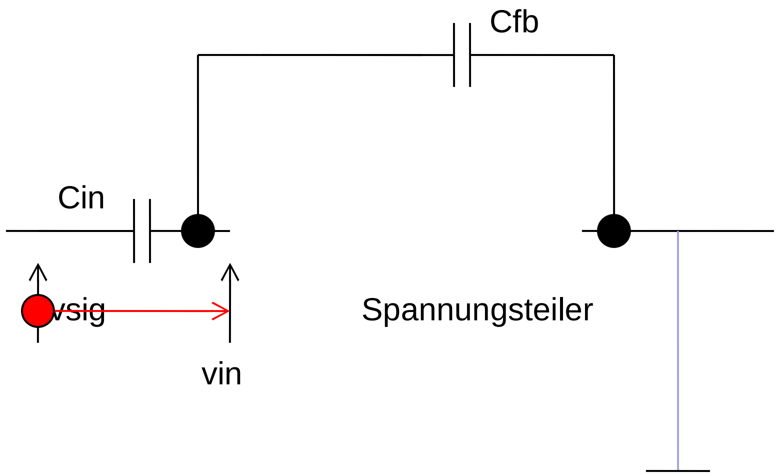
Ain – Berechnung

- Ain (Berechnung)



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

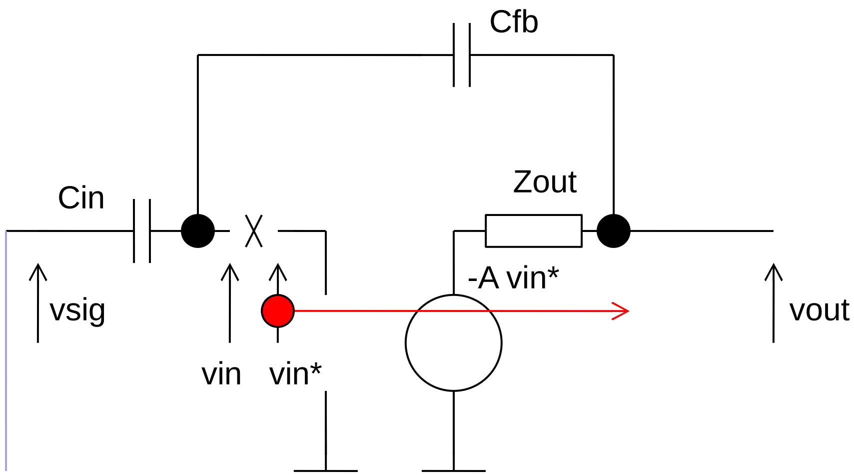
- Ain (Berechnung) - vereinfacht



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

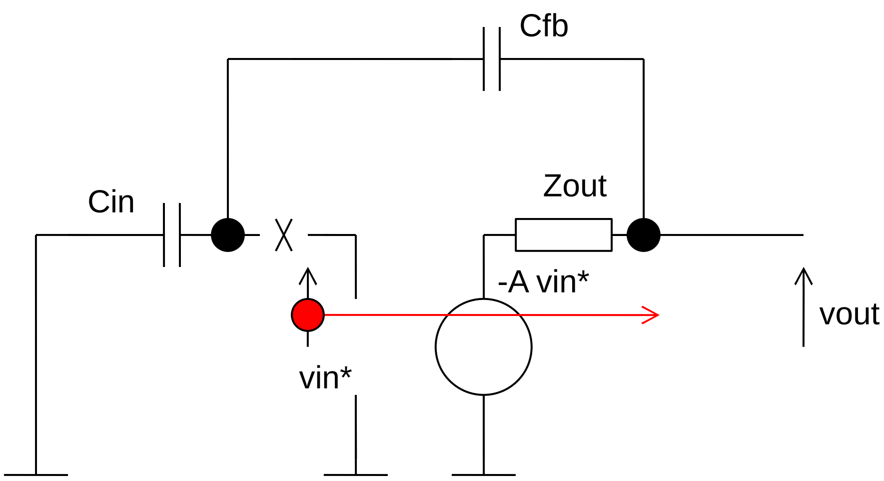
$$v_{in} = \frac{Z_{FB}}{Z_{FB} + Z_{IN}} v_{sig} \qquad A_{IN} = \frac{Z_{FB}}{Z_{FB} + Z_{IN}}$$

- 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

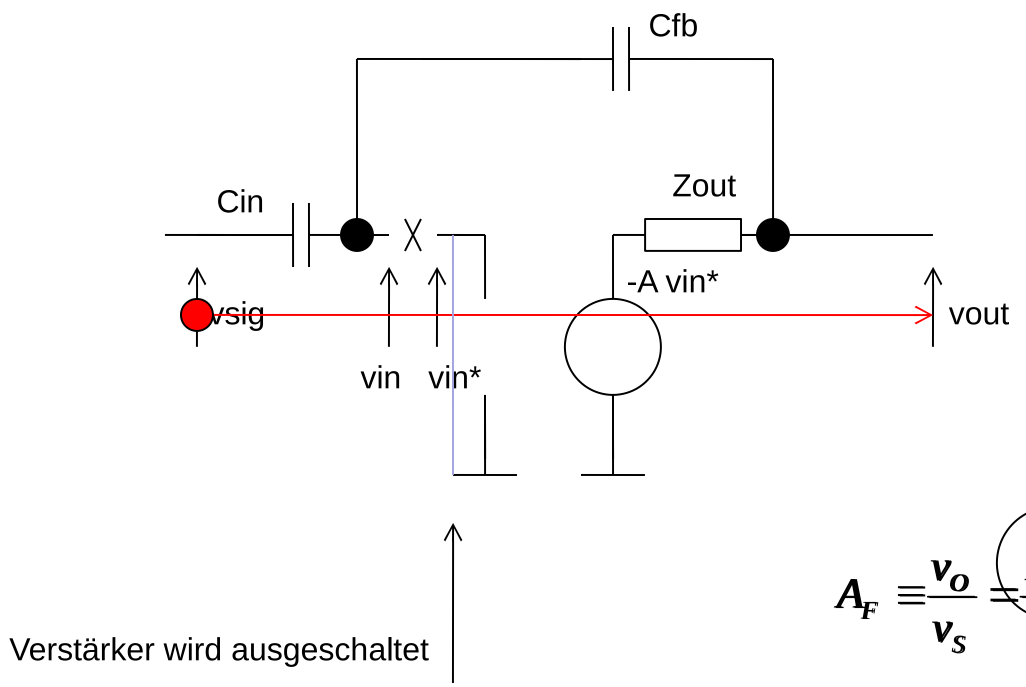
$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

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

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

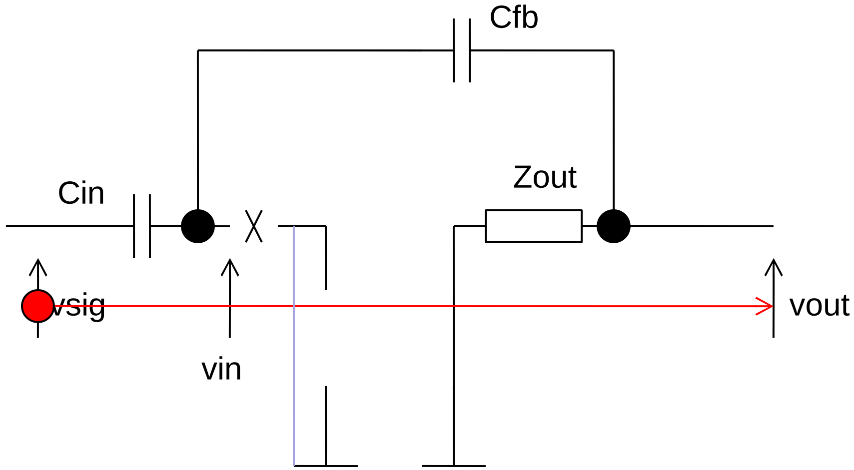
Es ist leicht die Rechnung zu vereinfachen
In Summen können kleinere Größen vernachlässigt werden

- Feed forward (Berechnung)



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

- Feed forward (Berechnung)

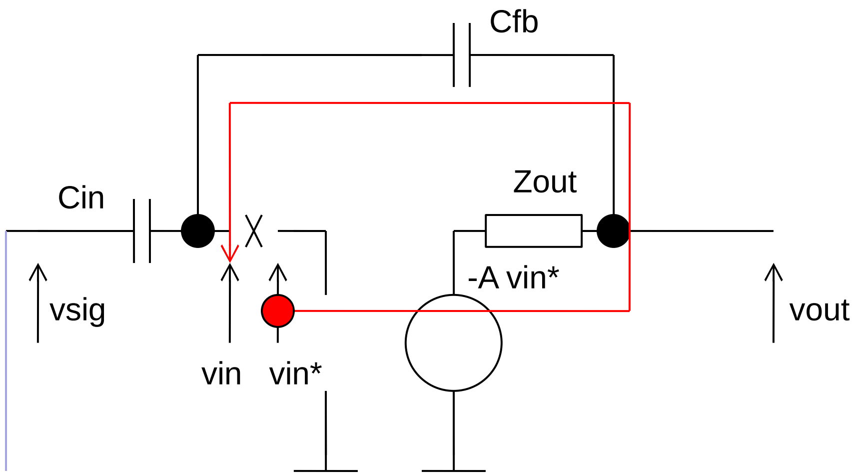


$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A}$$

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

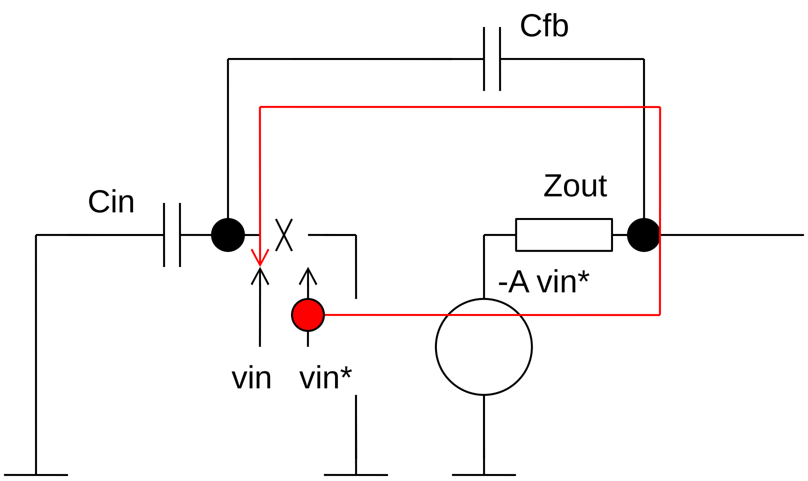
$$Z_{OUT} = 0 \rightarrow FF \approx 0$$

- 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)



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

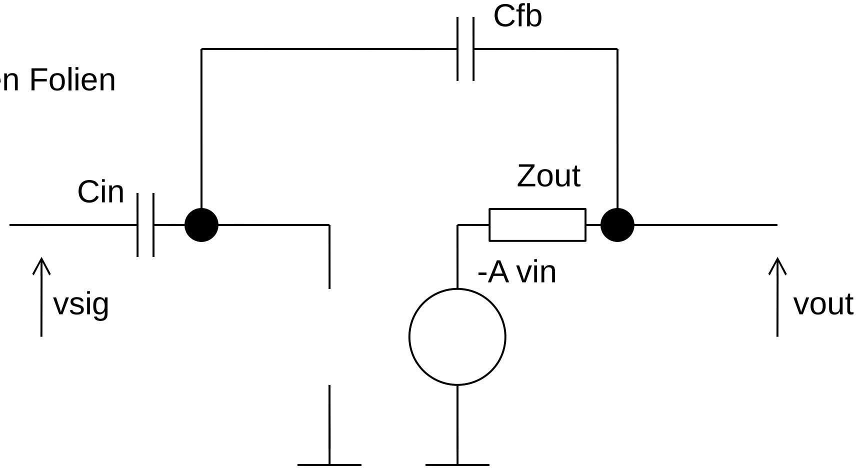
$$v_{in} = -A \frac{Z_{IN}}{Z_{FB} + Z_{IN} + Z_{OUT}} v^*_{in} \qquad \beta A = -A \frac{Z_{IN}}{Z_{FB} + Z_{IN} + Z_{OUT}}$$

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

Verstärkung mit Rückkopplung

- Zu Schluss: Verstärkung mit Rückkopplung
- Annahme: Rout = 0

Ergebnisse aus den vorherigen Folien



Die „wichtige" Formel

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

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

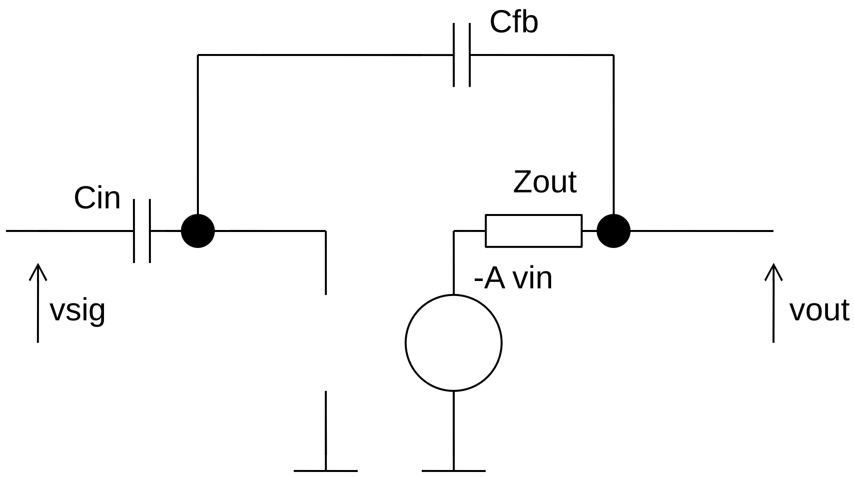
$$A_{OL} \approx -A$$

$$FF \approx 0$$

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

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

- Übliche Annahme |betaA| >> 1

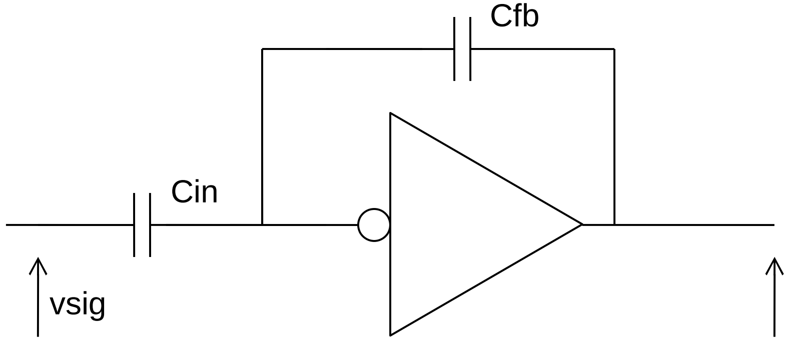


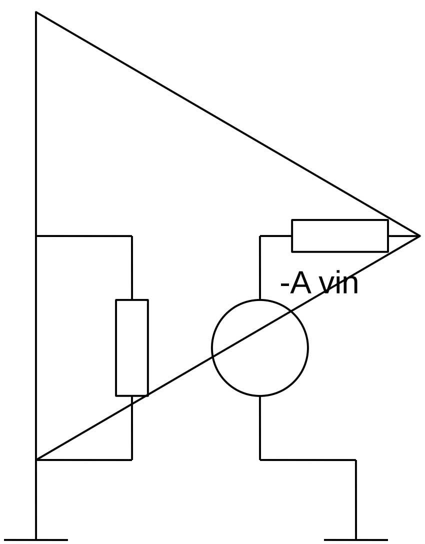
$$A_F \equiv \frac{v_O}{v_S} = \frac{FF + A_{IN} A_{OL}}{1 - \beta A} \approx \frac{A_{IN} A_{OL}}{\beta A} = \frac{A_{IN}}{\beta}$$

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

Desensibilisierung

- 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 betaA
- => Verstärkung ist kleiner aber stabiler



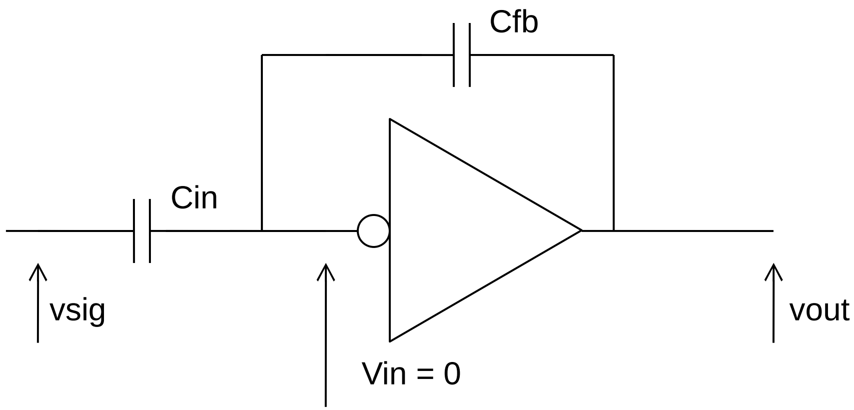


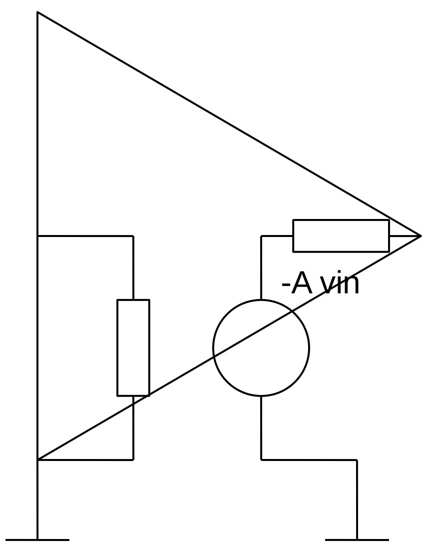
$$A_F \approx -\frac{C_{IN}}{C_{FB}}$$

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

Virtuelle Masse 1

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

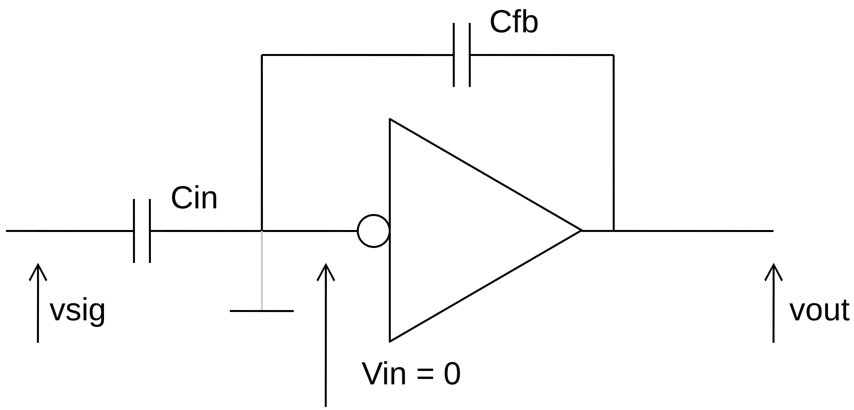


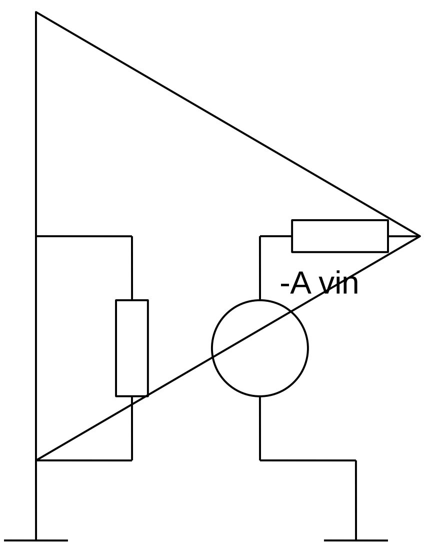


$$A_F = \frac{-A\frac{C_{IN}}{C_{FB}+C_{IN}}}{1+A\frac{C_{FB}}{C_{FB}+C_{IN}}} \approx -\frac{C_{IN}}{C_{FB}}$$

$$v_{in} = \frac{\frac{C_{IN}}{C_{FB}+C_{IN}}}{1+A\frac{C_{FB}}{C_{FB}+C_{IN}}} v_{sig} = \frac{\frac{C_{IN}}{C_{FB}+C_{IN}}}{\beta A}$$

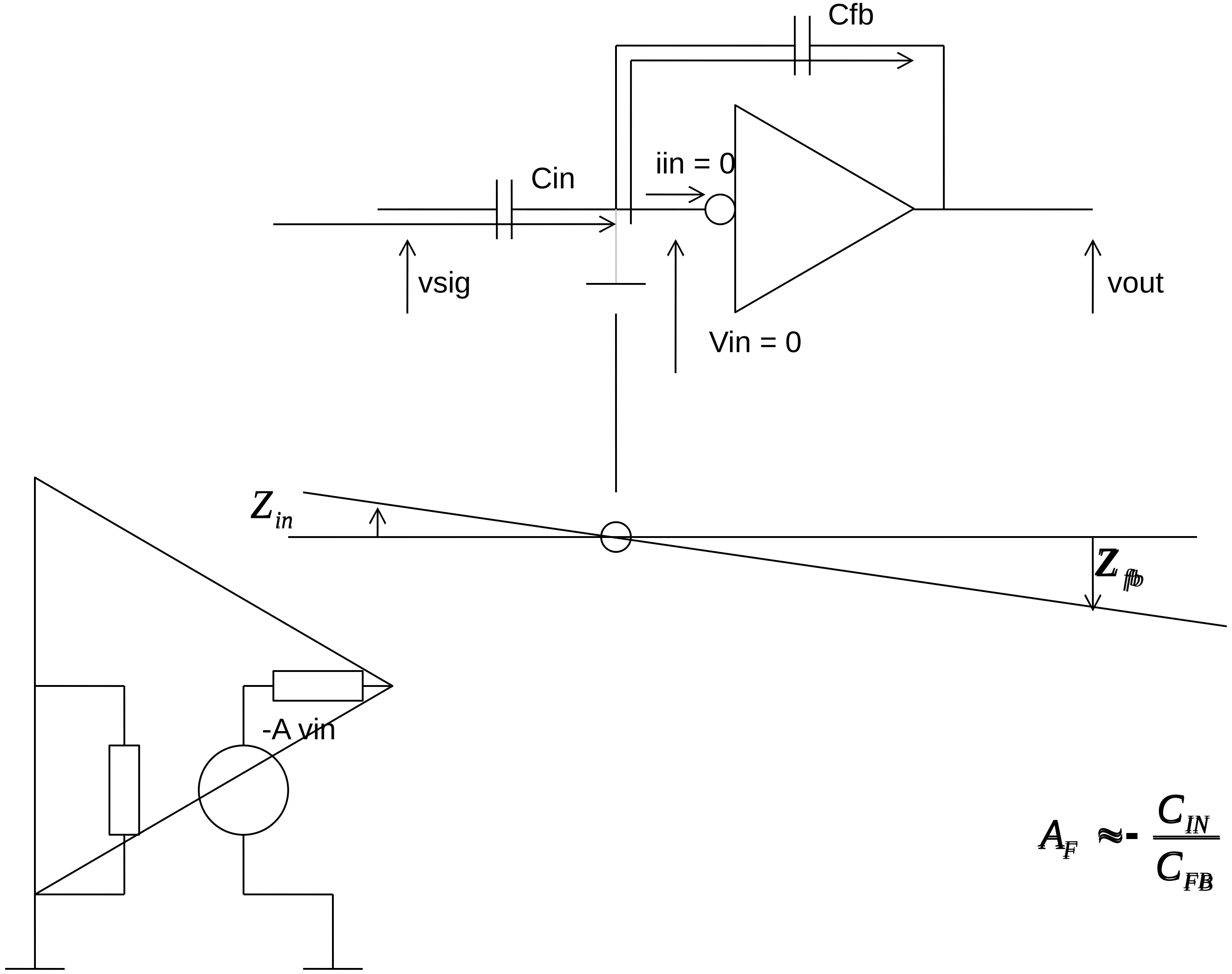
- Virtuelle Masse





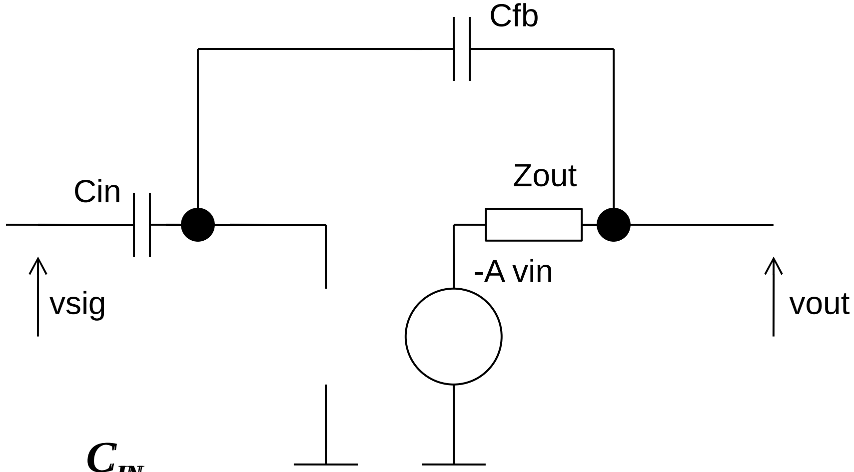
$$A_F \approx -\frac{C_{IN}}{C_{FB}}$$

- Virtuelle Masse
- Annahme vin = 0 vereinfacht die Rechnungen, sie ist aber manchmal problematisch
- Virtuelle Masse -> Fehlerterm = 0, gute Regelung



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

- Wie groß soll A sein?
- Annahme: Afb = 10 -> 10% A > 100, 1% A > 1000
- Aktive Verstärkung soll mindestens 1-2 Größenordnungen hoher als Afb sein



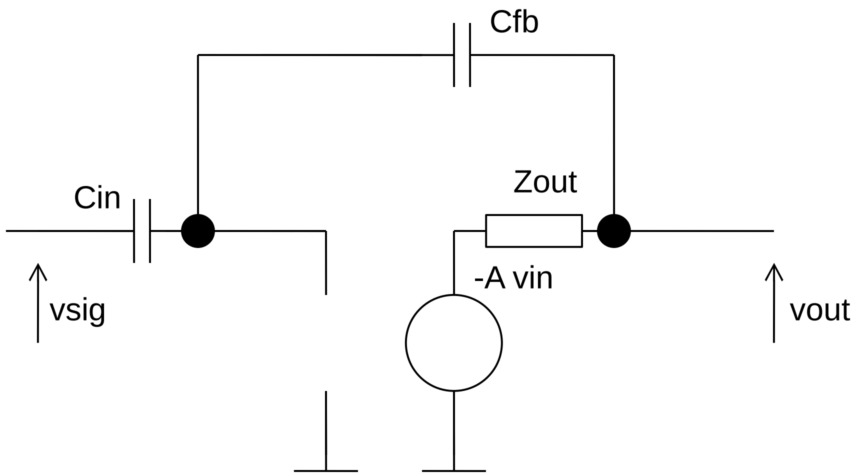
$$A_F = \frac{-A\frac{C_{IN}}{C_{FB}+C_{IN}}}{1+A\frac{C_{FB}}{C_{FB}+C_{IN}}} \approx -\frac{C_{IN}}{C_{FB}}$$

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

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

Dimensionierung von A 2

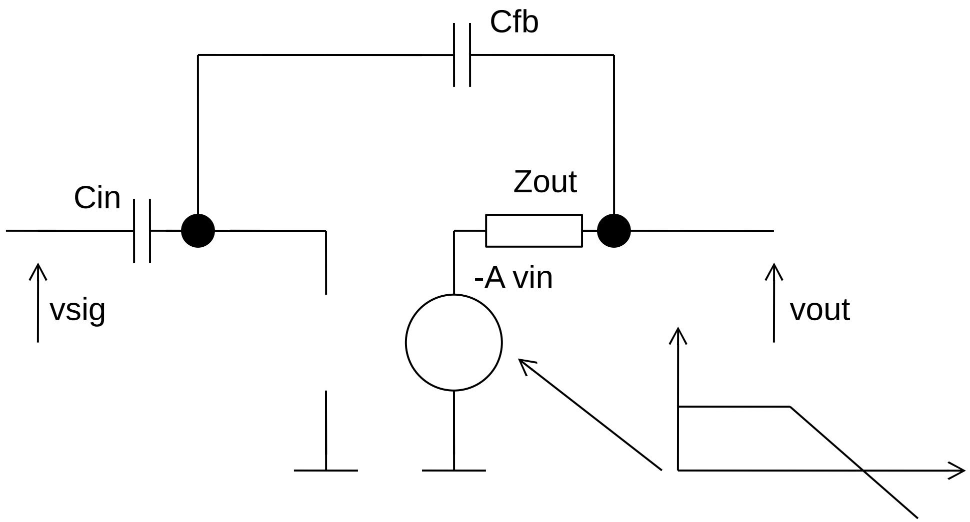
- Wie groß soll A sein?
- Annahme: Afb = 10 -> 10% A > 100, 1% A > 1000
- Aktive Verstärkung soll mindestens 1-2 Größenordnungen hoher als Afb sein
- Trade off zwischen Genauigkeit (beta A groß) und Verstärkung (beta klein)



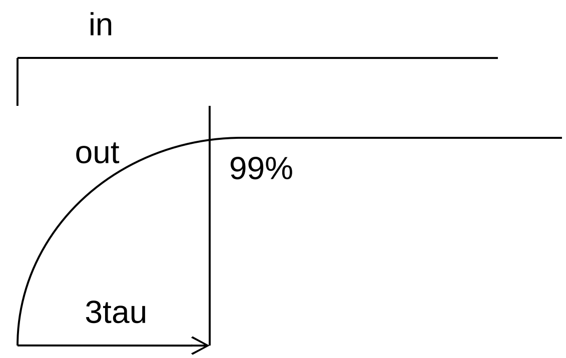
$$A_F = \frac{-A\dfrac{C_{IN}}{C_{FB}+C_{IN}}}{1+A\dfrac{C_{FB}}{C_{FB}+C_{IN}}} = -\frac{C_{IN}}{C_{FB}}\frac{1}{(C_{IN}/C_{FB}+1)/A+1} = A_F\frac{1}{A_F/A+1}$$

Gegenkopplung und Zeitkonstante 1

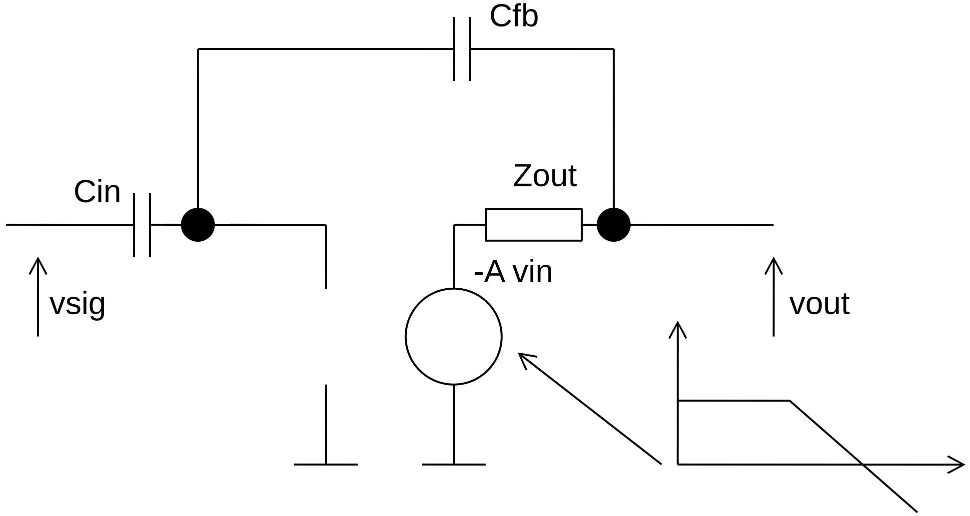
- AC Analyse mit RK
- RK verändert die Zeitkonstanten
- Wandelt Kondensatoren in Induktivitäten um



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



- Verstärkung mit einer Zeitkonstante



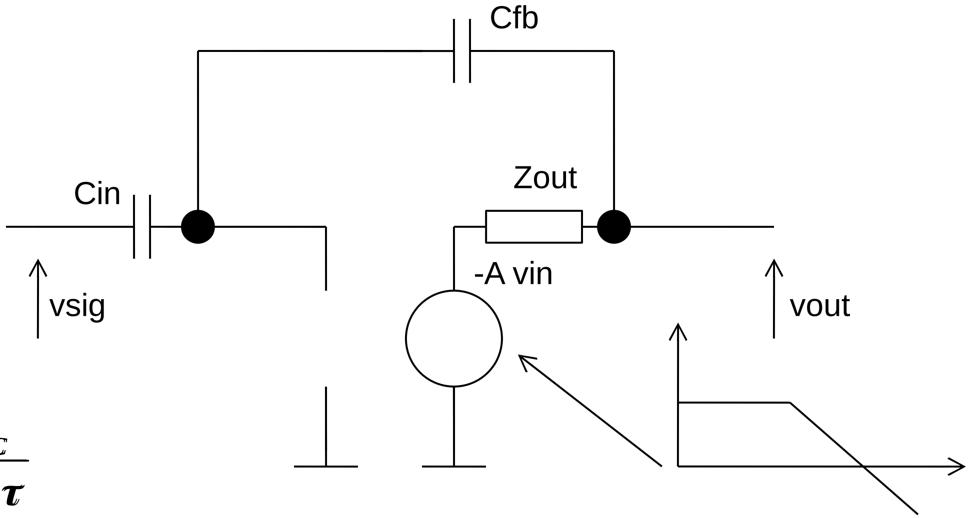
$$A_F = \frac{-A\frac{C_{IN}}{C_{FB}+C_{IN}}}{1+A\frac{C_{FB}}{C_{FB}+C_{IN}}} = \frac{c_1 A}{1+c_2 A} \longleftarrow A(s) = \frac{A_{DC}}{1+s\tau}$$

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

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

Gain-Bandwidth Produkt 1

- Zeitkonstante um 1+ bata A kleiner
- Verstärkung ebenfalls um um 1+ bata A kleiner
- Bandbrite definiert als B = 1/(t * 2Pi)
- Produkt Verstärkung * Bandbreite ist konstant.



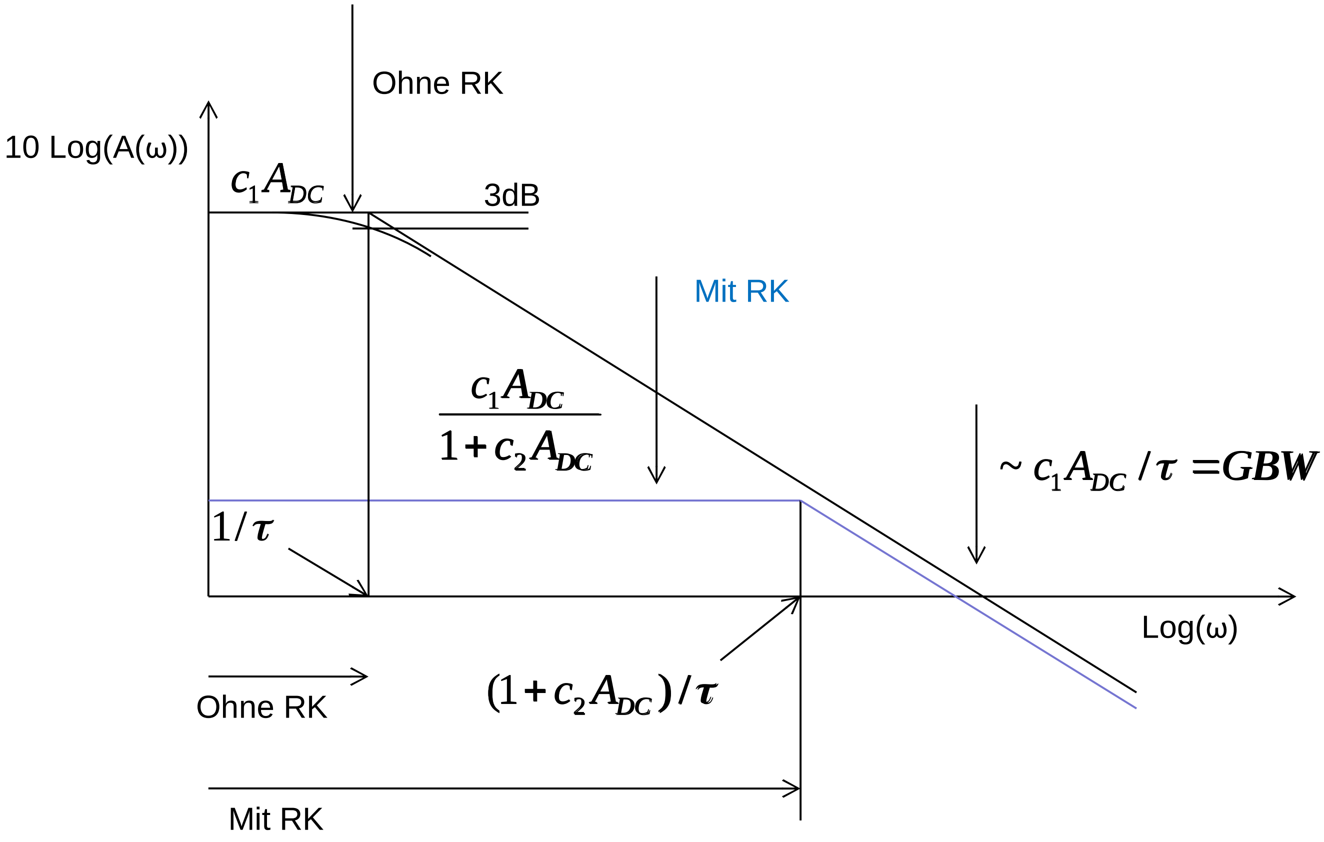
$$A_F = \frac{-A\frac{C_{IN}}{C_{FB}+C_{IN}}}{1+A\frac{C_{FB}}{C_{FB}+C_{IN}}} = \frac{c_1 A}{1+c_2 A} \longleftarrow A(s) = \frac{A_{DC}}{1+s\tau}$$

$$\downarrow$$

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

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

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

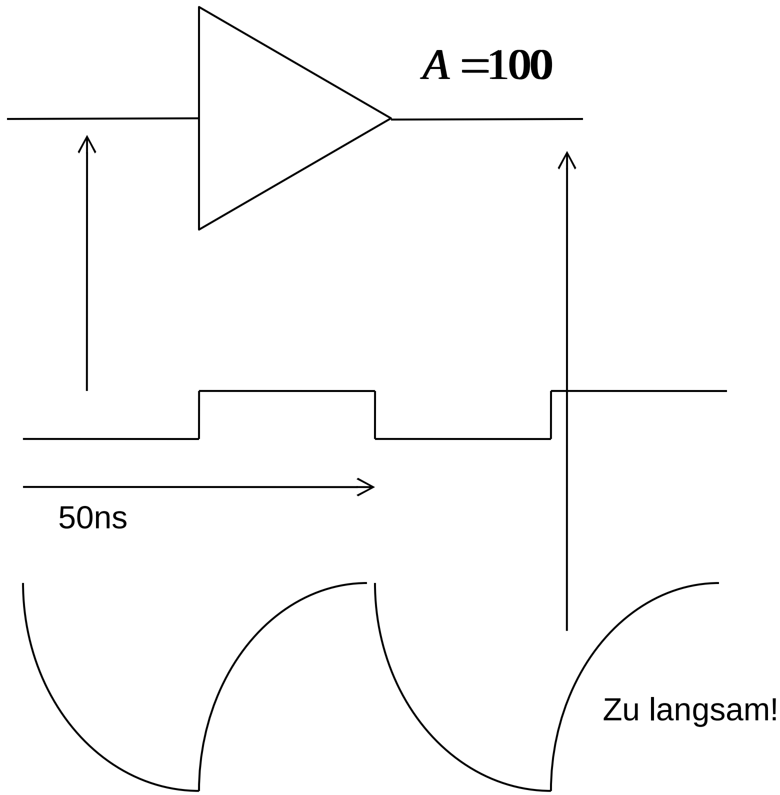


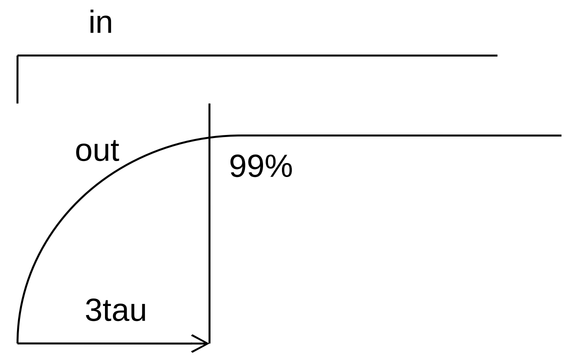
- Beispiel
- Wir möchten 20MHz Taktsignal 100x verstärken, haben nur langsame Verstärker

Bandbreite — Kreisfrequenz — Dominante Zeitkonstante

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

$A = 100$



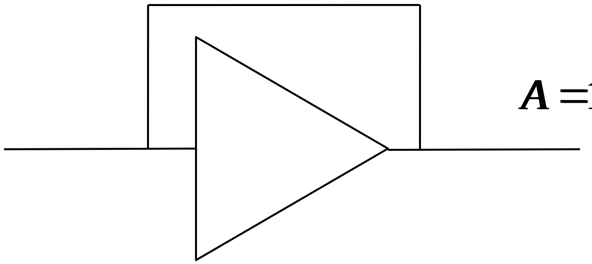


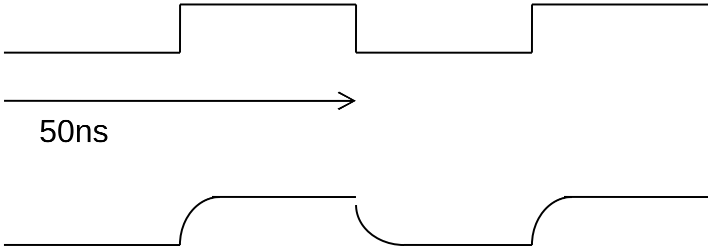
- 1. Idee: Gegenkopplung

$$BW = 100MHz$$

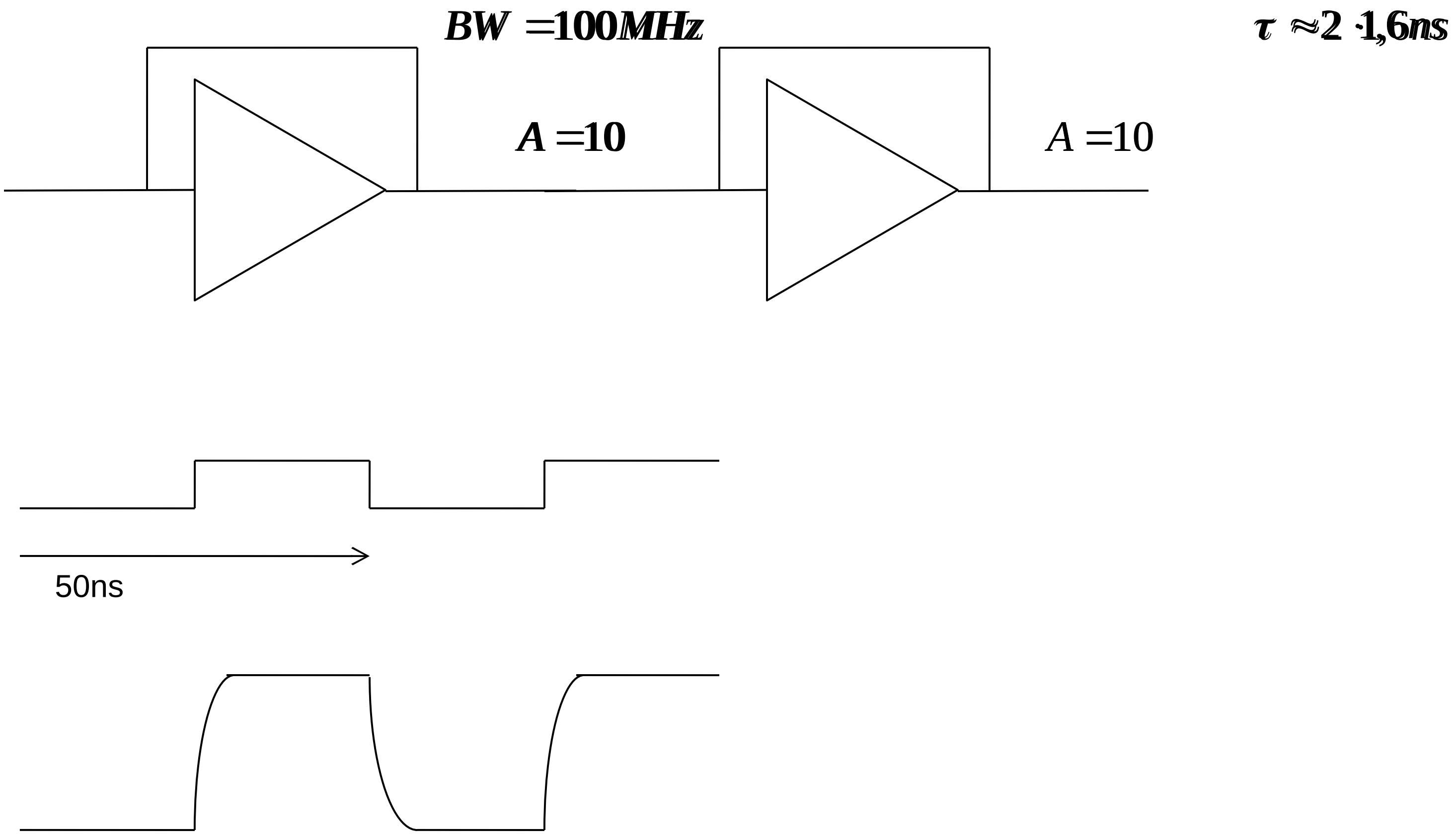
$$\tau = 1/(2\pi \cdot 100MHz) \approx 1{,}6ns$$

$$A = 10$$

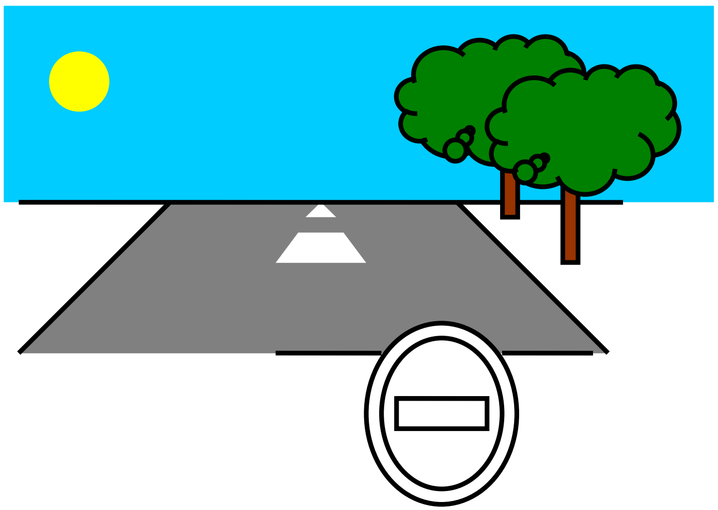




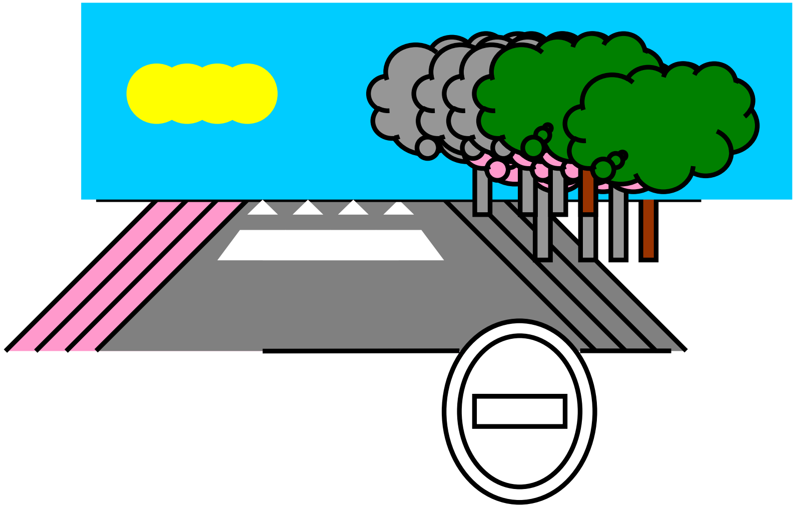
- 2. Idee: Kaskade



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

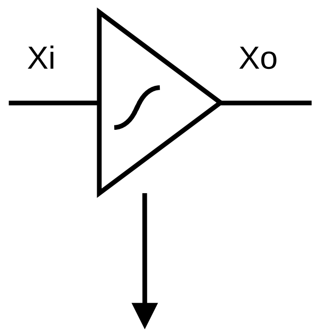


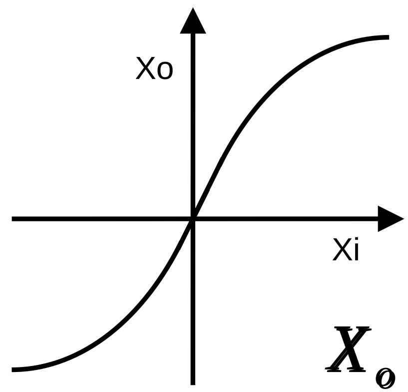
- Rückkopplung in Elektronik
- Vorteile
  - Desensibilisierung für Prozessparameter und Temperatur
  - Bandbreite wird höher
  - Linearität besser
  - Eingangs- und Ausgangsimpedanzen können angepasst werden.
- Nachteile
  - Verstärkung wird kleiner - zeitkonstanten
  - Gefahr vor Schwingungen
  - Millereffekt



- Backup Folien

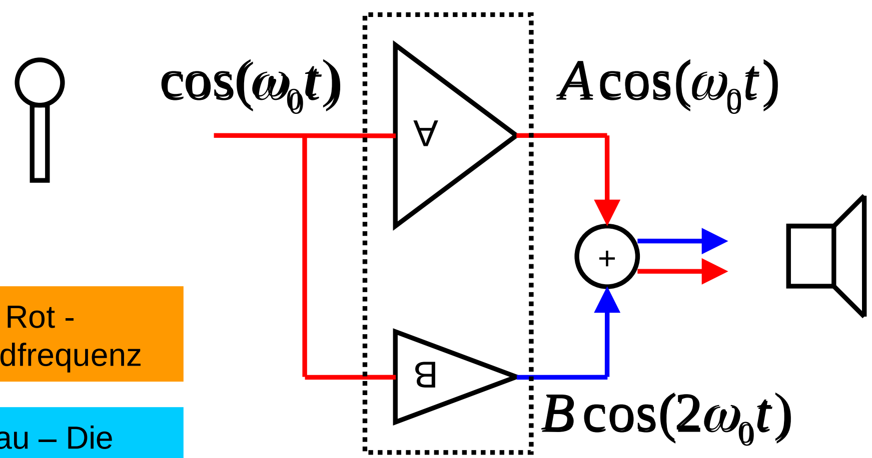
Verstärker mit schlechter Linearität





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

Reihenentwickung

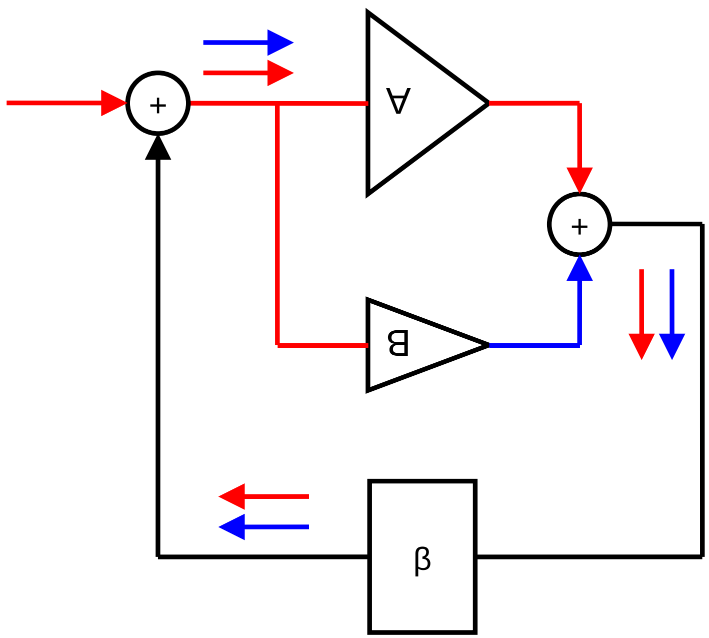


Harmonic Distortion (harmonische Verzerrung)

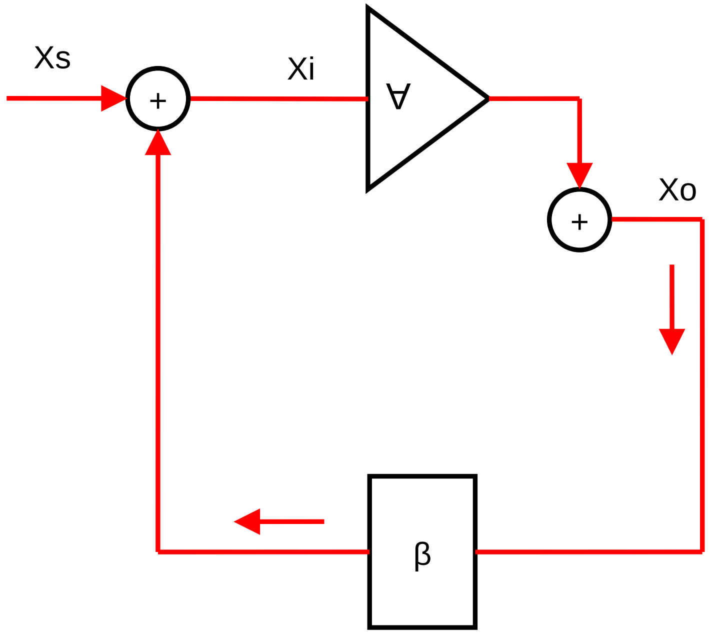
$$HD \equiv \frac{B}{A}$$

Rot - Grundfrequenz

Blau – Die Oberwelle



Nur erste Obewelle



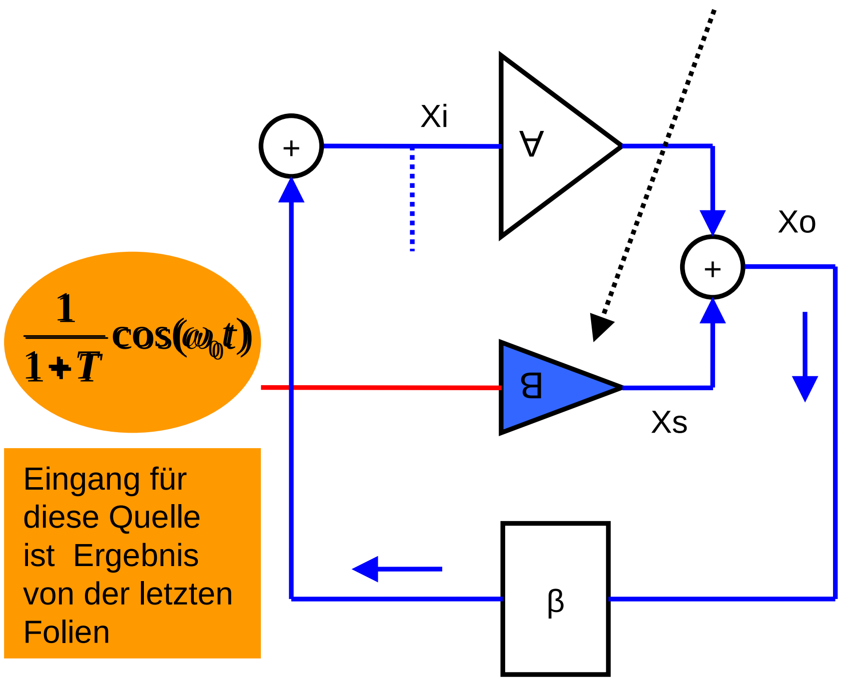
$$X_o = \frac{A}{1+T} X_s$$

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

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

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

Quelle für die 1. Oberwelle



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

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

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

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

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

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

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