

Diode

Betriebsarten:

Sperrrichtung: $v_D < 0 \rightarrow i_D = I_S \cdot [e^{\frac{v_D}{V_T}} - 1] \approx -I_S$

Nulldurchgang: $v_D = 0 \rightarrow i_D = 0$

Vorwärtsricht.: $v_D > 0 \rightarrow i_D = I_S \cdot [e^{\frac{v_D}{V_T}} - 1] \approx I_S \cdot e^{\frac{v_D}{V_T}}$

Transistor(BJT)

Stromgleichungen:

$$i_C = I_S \cdot \left(e^{\frac{v_{BE}}{V_T}} - e^{\frac{v_{BC}}{V_T}} \right) - \frac{I_S}{\beta_R} \cdot \left(e^{\frac{v_{BC}}{V_T}} - 1 \right),$$

$$v_{BE} > 0,6 V \rightarrow i_C = I_S \cdot e^{\frac{v_{BE}}{V_T}}$$

$$i_E = I_S \cdot \left(e^{\frac{v_{BE}}{V_T}} - e^{\frac{v_{BC}}{V_T}} \right) + \frac{I_S}{\beta_R} \cdot \left(e^{\frac{v_{BC}}{V_T}} - 1 \right),$$

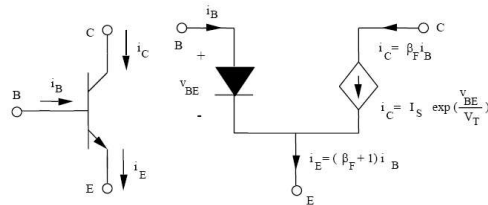
$$v_{BE} > 0,6 V \rightarrow i_E = \frac{I_S}{\alpha_F} \cdot e^{\frac{v_{BE}}{V_T}}$$

$$i_B = \frac{I_S}{\beta_F} \cdot \left(e^{\frac{v_{BE}}{V_T}} - 1 \right) + \frac{I_S}{\beta_R} \cdot \left(e^{\frac{v_{BC}}{V_T}} - 1 \right),$$

$$v_{BE} > 0,6 V \rightarrow i_C = I_S \cdot e^{\frac{v_{BE}}{V_T}}$$

Vereinfachungen gelten im Forward-Active-Bereich

$$i_C = \alpha_F \cdot i_E; \quad i_C = \beta_F \cdot i_B; \quad i_E = i_C + i_B = (\beta_F + 1) \cdot i_B$$



Arbeitsbereiche:

Base-Emitter Junction	Base-Collector Junction	
	Forward Bias	Reverse Bias
Forward Bias	Saturation Region (Closed Switch)	Forward-Active Region (Normal-Active Region) (Good Amplifier)
Reverse Bias	Reverse-Active Region (Inverse-Active Region) (Poor Amplifier)	Cutoff Region (Open Switch)

Early-Effekt:

$$i_C = I_S \cdot e^{\frac{v_{BE}}{V_T}} \cdot \left(1 + \frac{v_{CE}}{V_A} \right); \quad \beta_F = \beta_{F0} \left[1 + \frac{v_{CE}}{V_A} \right]$$

$$i_B = \frac{I_S}{\beta_{F0}} \cdot e^{\frac{v_{BE}}{V_T}}; \quad \beta_{F0} = \beta_F |_{v_{ce}=0}; \quad \alpha_F = \frac{\beta_F}{\beta_F + 1}$$

MOSFET

n-Kanal-Transistor (NMOS):

(Pfeil in B rein, oder Pfeil aus S raus)

cutoff:

$$V_{GS} > V_{TN} \quad I_D = 0$$

Nonsaturation:

$$V_{GS} > V_{TN} \text{ and } V_{DS} \leq (V_{GS} - V_{TN})$$

$$I_{D \rightarrow S} = K_n \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$$

Saturation:

$$V_{GS} > V_{TN} \text{ and } V_{DS} \geq (V_{GS} - V_{TN})$$

$$I_{D \rightarrow S} = \frac{K_n}{2} (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS})$$

p-Kanal-Transistor (PMOS):

(Pfeil aus B raus, oder Pfeil in S rein)

cutoff:

$$V_{GS} > V_{TP} \quad I_D = 0$$

Nonsaturation:

$$V_{GS} < V_{TP} \text{ and } V_{DS} \geq (V_{GS} - V_{TP})$$

$$I_{S \rightarrow D} = K_p \left(V_{GS} - V_{TP} - \frac{V_{DS}}{2} \right) V_{DS}$$

Saturation:

$$V_{GS} < V_{TP} \text{ and } V_{DS} \leq (V_{GS} - V_{TP})$$

$$I_{S \rightarrow D} = \frac{K_p}{2} (V_{GS} - V_{TP})^2 (1 - \lambda V_{DS})$$

Parameter:

$$K'_{nlp} = \mu_{nlp} \cdot C_{ox}; \quad K_{nlp} = K'_{nlp} \cdot \frac{W}{L}$$

	NMOS Device	PMOS Device
Enhancement-mode	$V_{TN} > 0$	$V_{TP} < 0$
Depletion-mode	$V_{TN} < 0$	$V_{TP} > 0$

Operationsverstärker

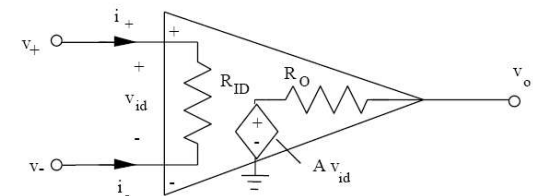
idealer Operationsverstärker:

open-loop gain: $A \rightarrow \infty \Rightarrow v_{ID} = v_+ - v_- = 0$

input resistance: $R_{ID} \rightarrow \infty \Rightarrow i_+ = i_- = 0$

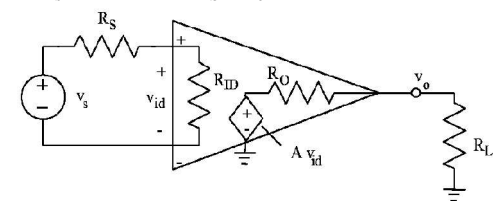
output resistance: $R_o = 0$

common-mode rej. ratio: $A_{cm} \rightarrow \infty$



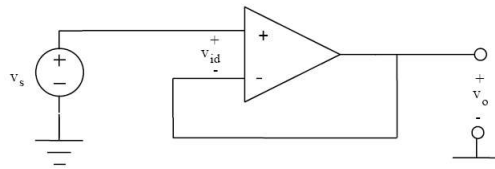
Differenzverstärker:

$$A_V = \frac{v_o}{v_s} = A \cdot \frac{R_{ID}}{R_{ID} + R_S} \cdot \frac{R_L}{R_o + R_L}$$



Spannungsfolger(Unity-Gain Buffer):

$$A_v = 1; R_{IN} = \infty; R_{OUT} = 0$$

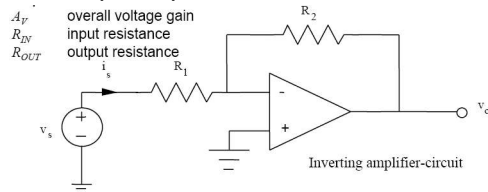


Inverting Amplifier:

$$A_v = -\frac{R_2}{R_1} \cdot \frac{A \cdot \beta}{1 + A \cdot \beta} \quad (\text{ideal}) \rightarrow -\frac{R_2}{R_1}$$

$$R_{IN} = R_1 + R_{ID} \parallel \frac{R_2}{1 + A} \approx R_1 \quad (\text{ideal}) \rightarrow R_1$$

$$R_{OUT} = \frac{R_o}{1 + A \beta} \approx \frac{R_o}{A \beta} \quad (\text{ideal}) \rightarrow 0$$



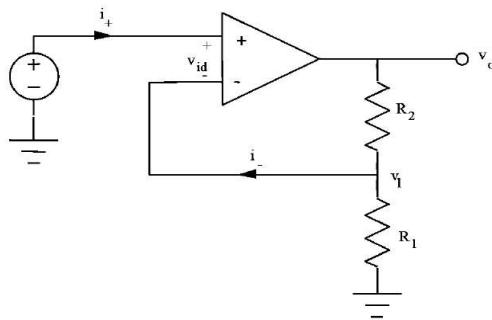
Non-Inverting Amplifier:

$$A_v = \frac{A}{1 + \frac{1}{A \cdot \beta}} \quad (\text{ideal}) \rightarrow 1 + \frac{R_2}{R_1} = \frac{1}{\beta}$$

open-loop gain

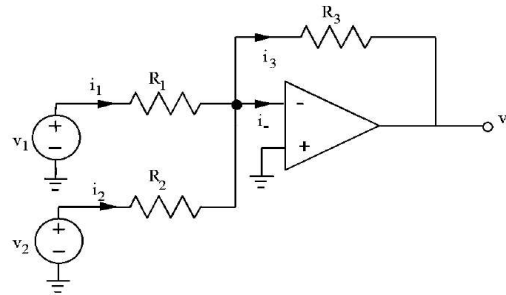
$$R_{IN} = R_{ID} (1 + A \beta) \approx R_{ID} A \beta \quad (\text{ideal}) \rightarrow \infty$$

$$R_{OUT} = \frac{R_o}{1 + A \beta} \approx \frac{R_o}{A \beta} \quad (\text{ideal}) \rightarrow 0$$



Summing Amplifier:

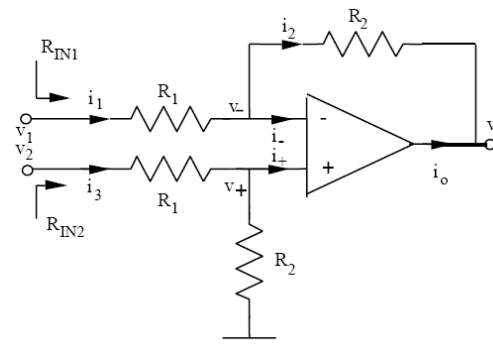
$$v_o = -\frac{R_3}{R_1} \cdot v_1 - \frac{R_3}{R_2} \cdot v_2$$



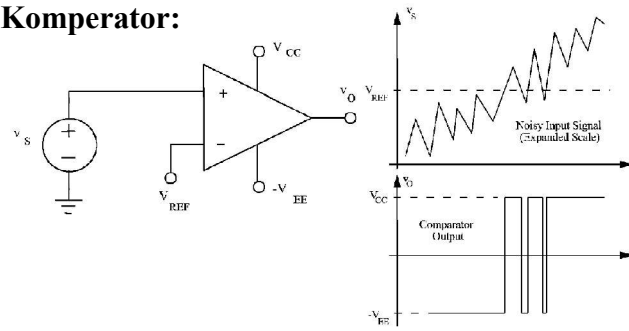
Difference Amplifier:

$$v_o = -\frac{R_2}{R_1} \cdot (v_1 - v_2)$$

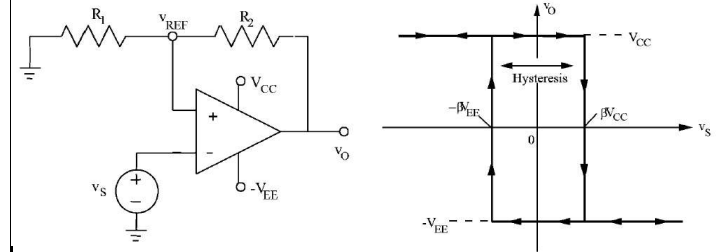
$$R_{IN1} = R_1, (v_2 = 0); R_{IN2} = R_1 + R_2; R_{OUT} = 0$$



Komparator:

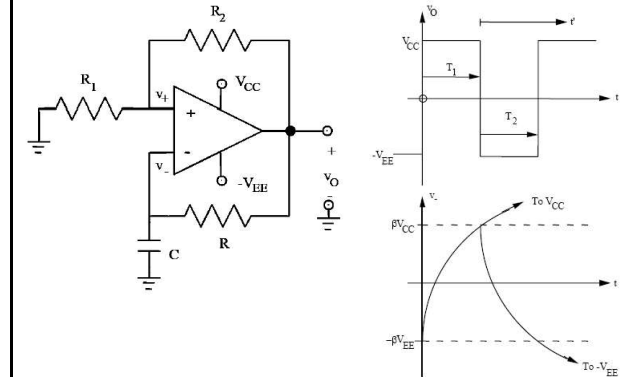


Schmidt-Trigger:



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

Astable Multivibrator:



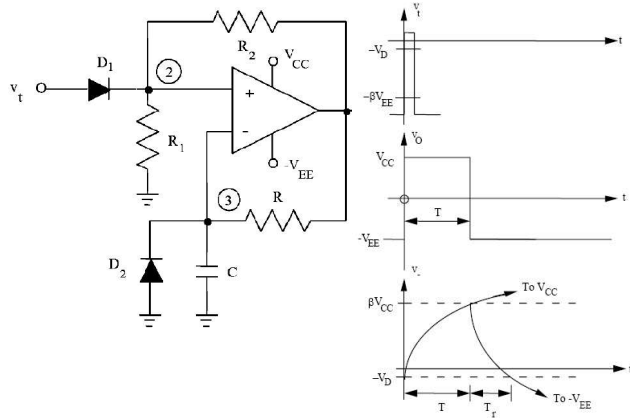
$$v_c(t) = V_{CC} - (V_{CC} + \beta V_{EE}) \cdot e^{-\frac{t}{RC}}; T_1 = RC \ln \left(\frac{1 + \beta \cdot \frac{V_{EE}}{V_{CC}}}{1 - \beta} \right)$$

$$v_c(t') = -V_{EE} + (V_{EE} + \beta V_{CC}) \cdot e^{-\frac{t'}{RC}}; T_2 = RC \ln \left(\frac{1 + \beta \cdot \frac{V_{CC}}{V_{EE}}}{1 - \beta} \right)$$

$$T = 2 RC \cdot \ln \left(\frac{1 + \beta}{1 - \beta} \right)$$

Monostable Multivibrator (One Shot):

$$v_c(t) = V_{CC} - (V_{CC} + V_D) \cdot e^{-\frac{t}{RC}}; T = RC \cdot \ln \left(\frac{1 + \frac{V_D}{V_{CC}}}{1 - \beta} \right)$$



Nonideal Amplifiers:

Finite Open-Loop Gain:

$$v_{ID} = v_+ - v_- \neq 0 \Rightarrow v_o = A \cdot v_{ID} = A \cdot (v_+ - v_-)$$

Gain Error:

$$GE = A_{V,ideal} - A_V; \quad FGE = \frac{A_{V,ideal} - A_V}{A_{V,ideal}}$$

Finite Input/Non Zero Output – Resistance:

$$R_{ID} < \infty; \quad R_o > 0$$

Finite Common-Mode Rejection Ratio:

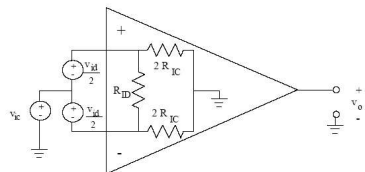
$$v_{ic} = \frac{v_1 + v_2}{2}; \quad v_o = A(v_{id}) + A_{cm}(v_{ic}); \quad CMRR = \left| \frac{A}{A_{cm}} \right|$$

Finite Power-Source Rejection Ratio:

Ein Maß wie der Verstärker Betriebsspannungsänderungen ausgleichen kann. (zwischen 60dB und 120dB)

Common Mode Input Resistance:

$$R_{IN} = R_{ID} || 4 \cdot R_{IC}$$



Input Offset Voltage

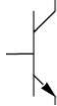
$$v_o = A \cdot \left(v_{id} + \frac{v_{ic}}{CMRR} + V_{OS} \right); \quad V_{OS} = \frac{V_o}{A}$$

Input Offset Current

$$I_{OS} = I_{B1} - I_{B2}$$

Kleinsignalmodell (lineare Verstärkung)

BJT-Verstärker:

$$V_{BE} = 0,7V; \quad |A_V| = \left| \frac{v_{ce}}{v_{be}} \right|$$


MOSFET-Verstärker:

$$V_{GS} = 3,5V; \quad |A_V| = \left| \frac{v_{ds}}{v_{gs}} \right|$$


Arbeitspunkte:

- Diode: (I_D, V_D)
- BJT: (I_C, V_{CE})
- MOSFET: (I_{DS}, V_{DS})

DC-Analyse (Großsignalanalyse):

1. ersetzen der C mit Leerläufen, der L mit Kurzschlüssen
2. Berechnung des Arbeitspunktes im Großsignalmodell:
 - Thévenin Transformation des Eingangs
 - I über Eingangsmasche berechnen
 - V über Ausgangsmasche berechnen

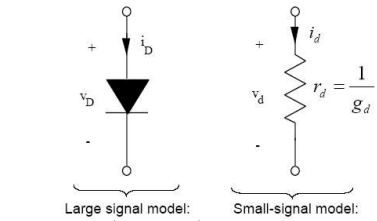
AC-Analyse (Kleinsignalanalyse):

1. - C kurzschließen
- L auftrennen
- DC-Spannungsquellen kurzschließen auf GND
- DC-Stromquellen heraustrennen
2. - Transistoren durch Kleinsignalmodell ersetzen
- Berechnen der Kleinsignalparameter
3. Analyse der Kleinsignaleigenschaften der Schaltung

Ersatzschaltbilder:

Diode:

Bedingung: $v_d \ll 2 \cdot V_{T20^\circ} = 0,05V$

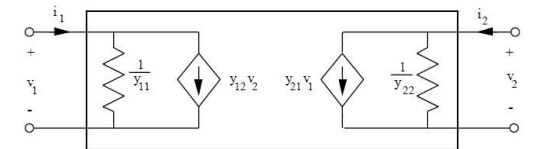


$$i_D = I_S \cdot \left(e^{\frac{v_D}{V_T}} - 1 \right); \quad i_d = g_d \cdot v_d$$

$$i_D = I_D + i_d$$

$$g_d = \frac{I_S}{V_T} \cdot e^{\frac{V_D}{V_T}} = \frac{I_D + I_S}{V_T} \approx \frac{40}{V} \cdot I_D$$

Y-Parameter Schaltbild:



$$i_1 = y_{11} \cdot v_1 + y_{12} \cdot v_2; \quad i_2 = y_{21} \cdot v_1 + y_{22} \cdot v_2$$

BJT-Transistor:

Kleinsignalvoraussetzung: $|v_{be}| \leq 0,005V$

$$g_m v_{be} = \beta_0 \cdot i_b; \quad \beta_0 = g_m \cdot r_{\pi} \quad \alpha_0 = \frac{\beta_0}{1 + \beta_0}$$

$$y_{11} = \frac{1}{r_{\pi}} = \frac{i_b}{v_{be}} |_{v_{ce}=0} = \frac{di_B}{dv_{BE}} |_{Q} = \frac{I_C}{\beta_0 \cdot V_T}$$

$$y_{12} = \frac{i_b}{v_{ce}} |_{v_{be}=0} = \frac{di_B}{dv_{CE}} |_{Q=0}$$

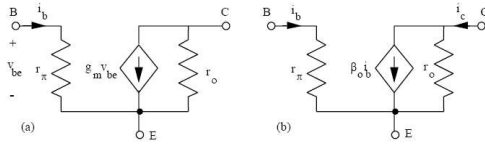
$$y_{21} = g_m = \frac{i_c}{v_{be}} |_{v_{ce}=0} = \frac{di_C}{dv_{BE}} |_{Q} = \frac{I_C}{V_T}$$

$$y_{22} = \frac{1}{r_0} = \frac{i_c}{v_{ce}} |_{v_{be}=0} = \frac{di_C}{dv_{CE}} |_{Q} = \frac{I_C}{V_A + V_{CE}}$$

$$i_c = I_S \cdot e^{\frac{v_{BE}}{V_T}} \cdot \left(1 + \frac{v_{CE}}{V_A}\right); \quad \beta_F = \beta_{F0} \cdot \left(1 + \frac{v_{CE}}{V_A}\right)$$

$$\beta_0 = \frac{\beta_F}{1 - I_C \cdot \left(d \frac{\beta_F}{\beta_F \cdot di_C}\right) | Q}$$

$$\mu_f = g_m \cdot r_0 = \frac{V_A + V_{CE}}{V_T} \approx \frac{V_A}{V_T}$$



$$g_m v_{be} = g_m r_{\pi} i_b = \beta_0 i_b$$

MOSFET-Transistor:

Kleisig.-Voraussetzung: $|v_{gs}| \leq 0.2 \cdot (V_{GS} - V_{TN})$

$$g_m = K_n \cdot (V_{GS} - V_{TN}) \cdot (1 + \lambda V_{DS})$$

$$g_m = \sqrt{2 \cdot K_n \cdot I_{DS} \cdot (1 + \lambda V_{DS})}$$

$$g_m = \frac{2 \cdot I_{DS}}{V_{GS} - V_{TN}}$$

$$y_{11} = \frac{1}{r_{\pi}} = \frac{i_g}{v_{gs}} \Big|_{v_{ds}=0} = \frac{di_G}{dv_{GS}} \Big|_{Q=0}$$

$$y_{12} = \frac{i_g}{v_{ds}} \Big|_{v_{gs}=0} = \frac{di_G}{dv_{GS}} \Big|_{Q=0}$$

$$y_{21} = g_m = \frac{i_d}{v_{gs}} \Big|_{v_{ds}=0} = \frac{di_D}{dv_{GS}} \Big|_{Q=0} = \frac{2 \cdot I_D}{V_{GS} - V_{TN}}$$

$$y_{22} = \frac{1}{r_0} = \frac{i_d}{v_{ds}} \Big|_{v_{gs}=0} = \frac{di_D}{dv_{DS}} \Big|_{Q=0} = \frac{\lambda \cdot I_D}{1 + \lambda \cdot V_{DS}}$$

$$\mu_f = g_m \cdot r_0 = \frac{\frac{1}{\lambda} + V_{DS}}{V_{GS} - V_{TN}} \approx \frac{1}{\lambda} \cdot \sqrt{\frac{2 \cdot K_n}{I_{DS}}} = \frac{2}{\lambda \cdot (V_{GS} - V_{TN})}$$

Einsufige Verstärkerschaltungen (BJT/MOSFET)

Common-Emitter/Common-Source

- integrierend
- hohe Spannungsverstärkung (C-E >> C-S)
- Eingangswiderstand (C-E << C-S)
- Ausgangswiderstand (C-E ~ C-S)

Common-Collector/Common-Drain

- Folgerschaltung
- keine Spannungsverstärkung
- hoher Eingangswiderstand
- kleiner Ausgangswiderstand
- relativ große Eingangssignale möglich

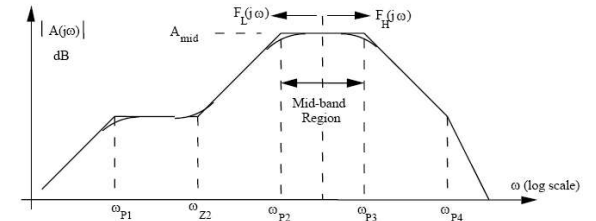
Common-Base/Common-Gate

- nichtinvertierend
- hohe Spannungsverstärkung
- kleiner Eingangswiderstand
- hoher Ausgangswiderstand

Relative Comparison of Single-Transistor Amplifiers			
	Inverting Amplifiers (C-E & C-S)	Followers (C-C & C-D)	Non-Inverting Amplifiers (C-B & C-G)
Voltage Gain	Moderate	Low (≈ 1)	Moderate
Input Resistance	Moderate to High	High	Low
Output Resistance	Moderate to High	Low	High
Input Signal Range	Low to Moderate	High	Low to Moderate
Current Gain	Moderate	Moderate	Low (≈ 1)

Frequenzverhalten von Verstärkern

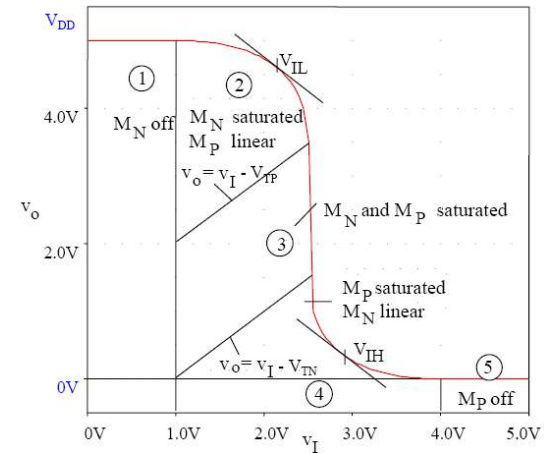
- Bei Frequenzen unterhalb des Mittelbandes dürfen die Kondensatoren nicht kurzgeschlossen werden.
- Bei Frequenzen oberhalb des Mittelbandes begrenzen die internen Kapazitäten der Bauteile die Verstärkung



$$A_V(s) = A_{mid} \cdot F_L(s) \cdot F_H(s)$$

$$|A_V(j\omega_L)| = |A_V(j\omega_H)| = \frac{A_0}{\sqrt{2}}$$

Digital Circuits



Noise Margins:

$$NM_L = V_{IL} - V_{OL}; \quad NM_H = V_{OH} - V_{IH}$$

Rise and Fall-time:

$$V_{10\%} = V_{OL} + 0.1(V_{OH} - V_{OL}); \quad V_{90\%} = V_{OL} + 0.9(V_{OH} - V_{OL})$$

Propagation Delay:

$$V_{50\%} = (V_{OH} + V_{OL})/2; \quad \tau_P = (\tau_{PLH} + \tau_{PHL})/2$$

Dynamic Power Dissipation:

$$P_D \sim C V_{DD}^2 f$$