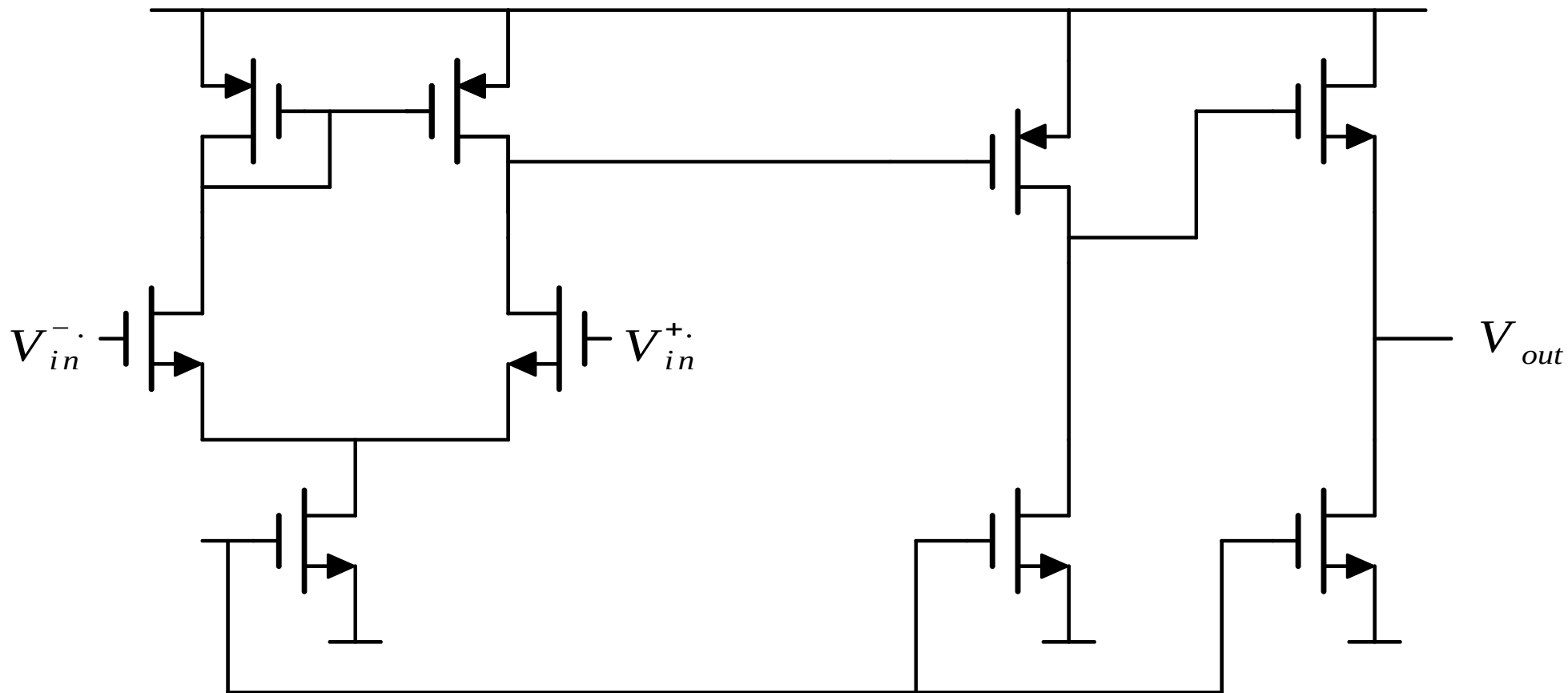
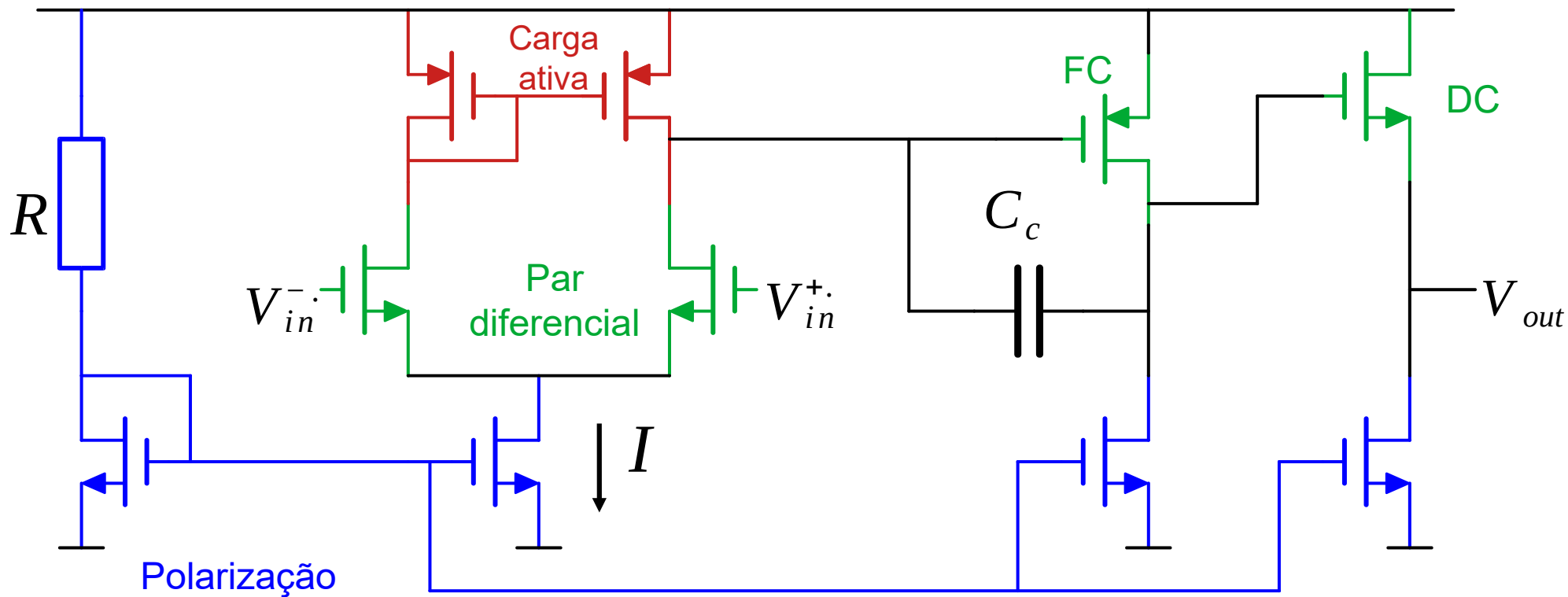


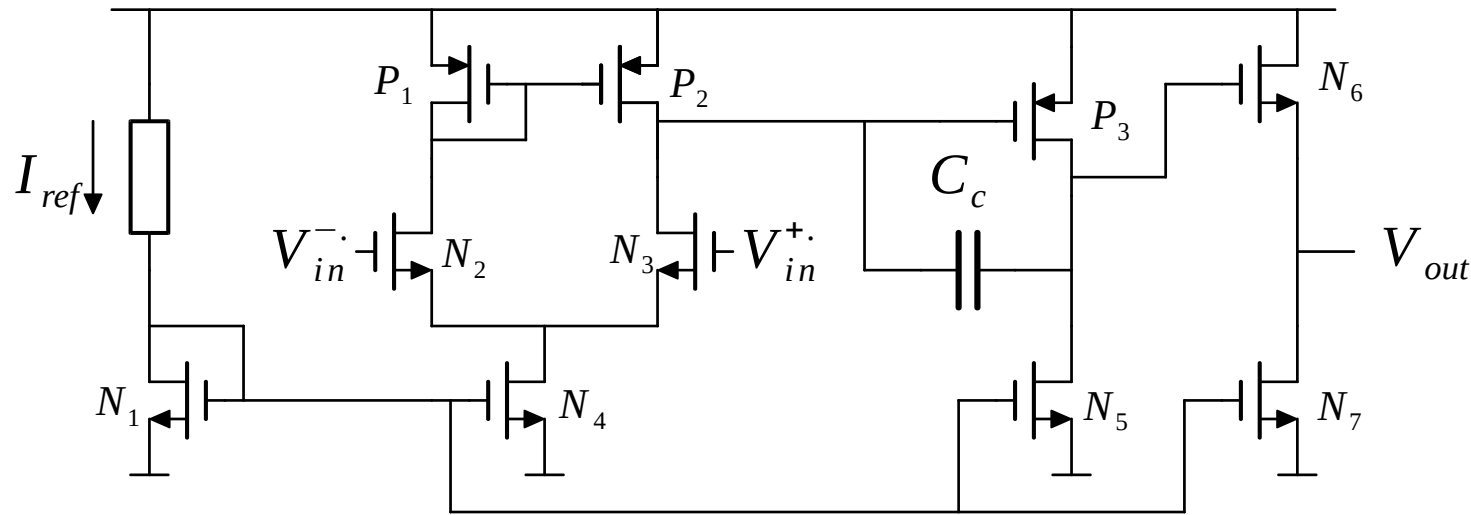


Primeiro
estágio

Segundo
estágio

Terceiro
estágio





$$I_{ref} = 1 \text{ mA}$$

$$W_1 = 1 \mu\text{m}$$

$$W_4 = 4 \mu\text{m}$$

$$W_5 = 10 \mu\text{m}$$

$$W_7 = 25 \mu\text{m}$$

$$C_c = 10 \text{ pF}$$

$$\lambda_n = 0.01 \text{ V}^{-1}$$

$$\lambda_p = 0.01 \text{ V}^{-1}$$

Obter R_{in} , R_{out} e A_{v0} do amplificador operacional
Obter o diagrama de Bode do amplificador de tensão

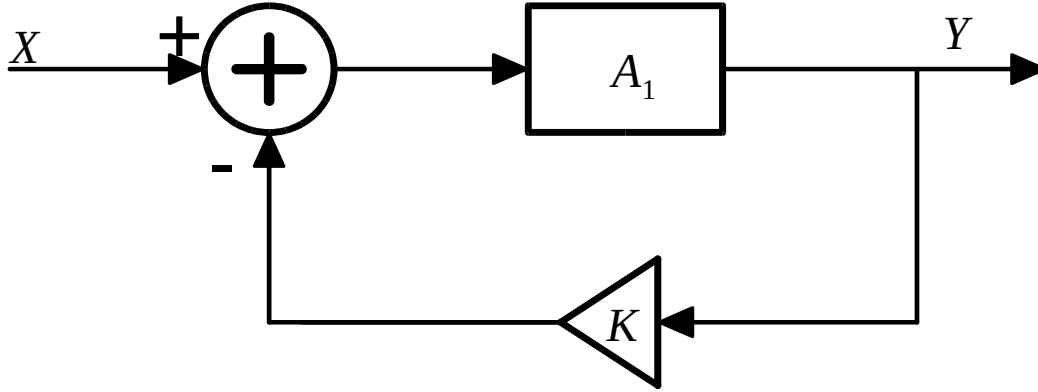
ID3 = 2.0000e-03
gm3 = 4.0000e-03
ron3 = 50000
rop2 = 50000
Av01 = -100
ID5 = 0.010000
rop3 = 10000
gmp3 = 0.016000
Av02 = -160
Av03 = 1

ID7 = 0.025000
gmn6 = 0.010000
ro1 = 25000
C1 = 1.6100e-09
C2 = 1.0063e-11
fp1 = 3954.2
fp2 =
1.5817e+06
Rin = Inf
Rout = 100
ro7 = 4000.0
Rout = 97.561
Av0 = 16000

$$\mu_n C_{ox} W_3 / L = 4 \text{ mA/V}^2$$

$$\mu_n C_{ox} W_6 / L = 2 \text{ mA/V}^2$$

$$\mu_p C_{ox} W_3 / L = 12.8 \text{ mA/V}^2$$

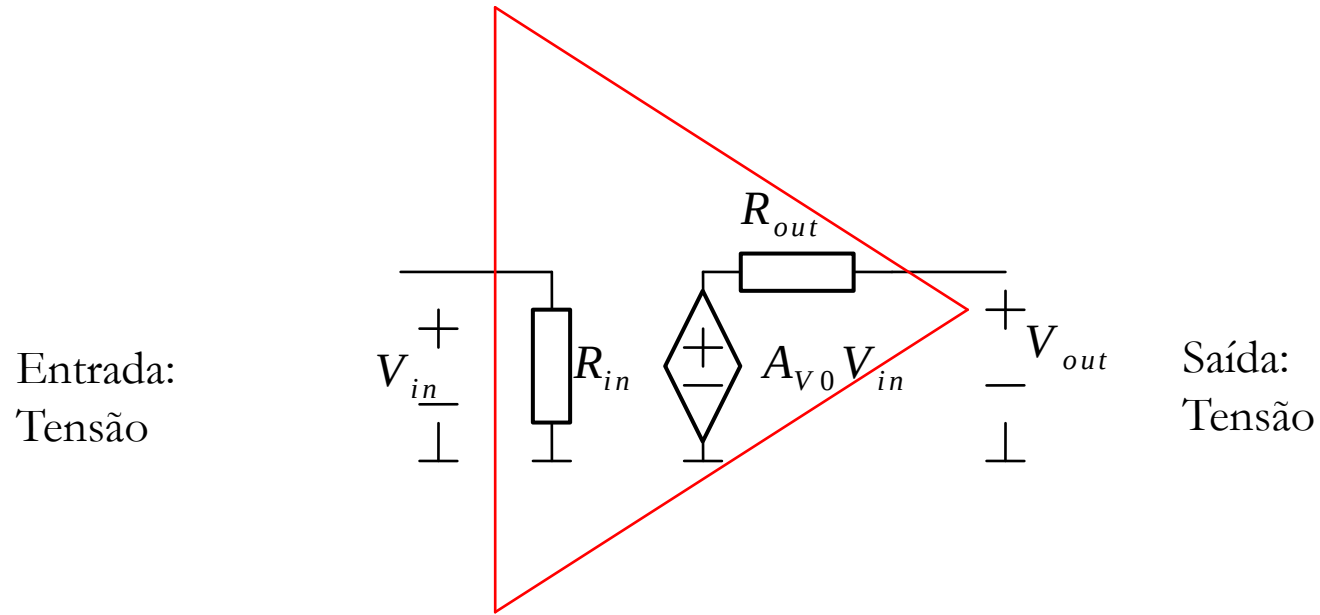


$$\frac{Y}{X} = \frac{A_1}{1 + KA_1}$$

Propriedades:

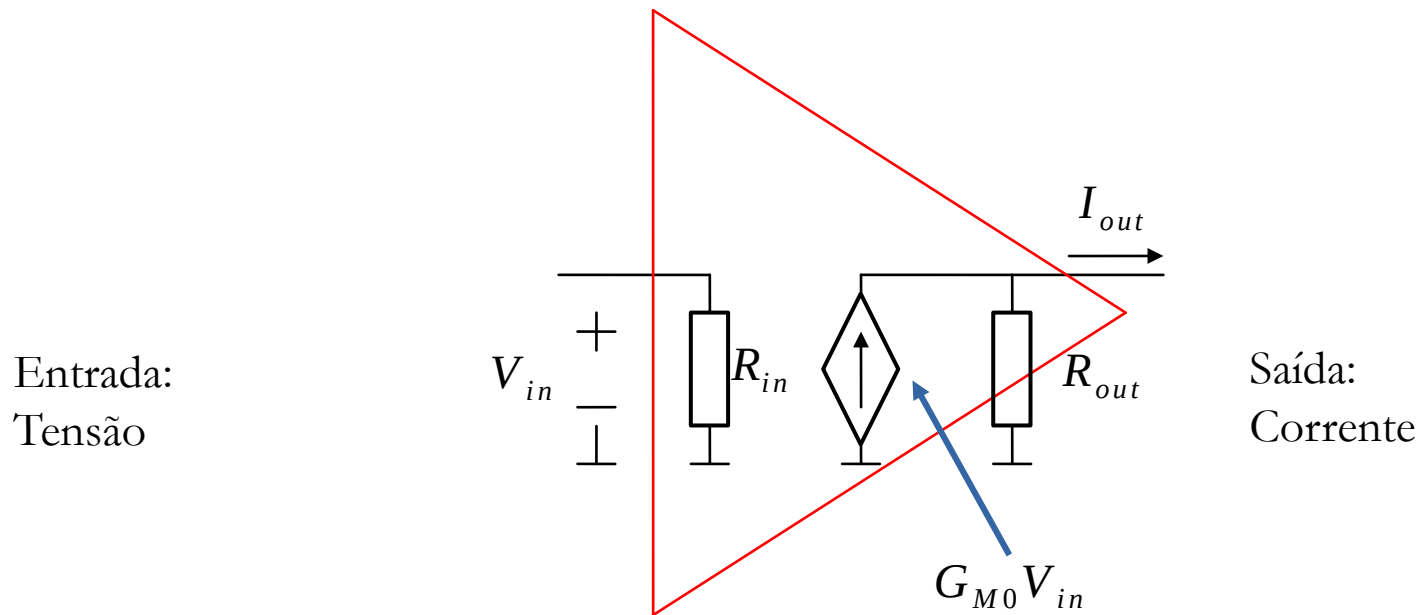
- 1) Dessensibilização do ganho
- 2) **Extensão da largura de banda**
- 3) Altera as impedâncias de entrada e de saída
- 4) Melhora a linearidade

Modelo de amplificador de tensão



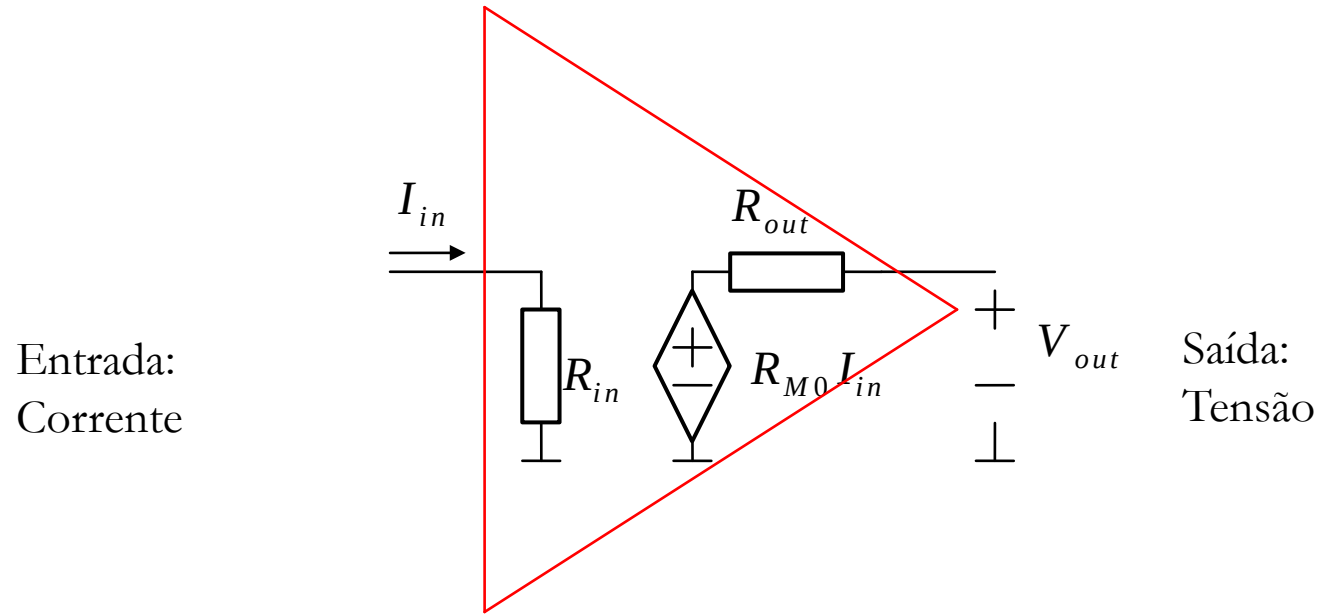
Idealmente, a resistência de entrada (R_{in}) é infinita e a resistência de saída (R_{out}) é zero

Modelo de amplificador de transcondutância



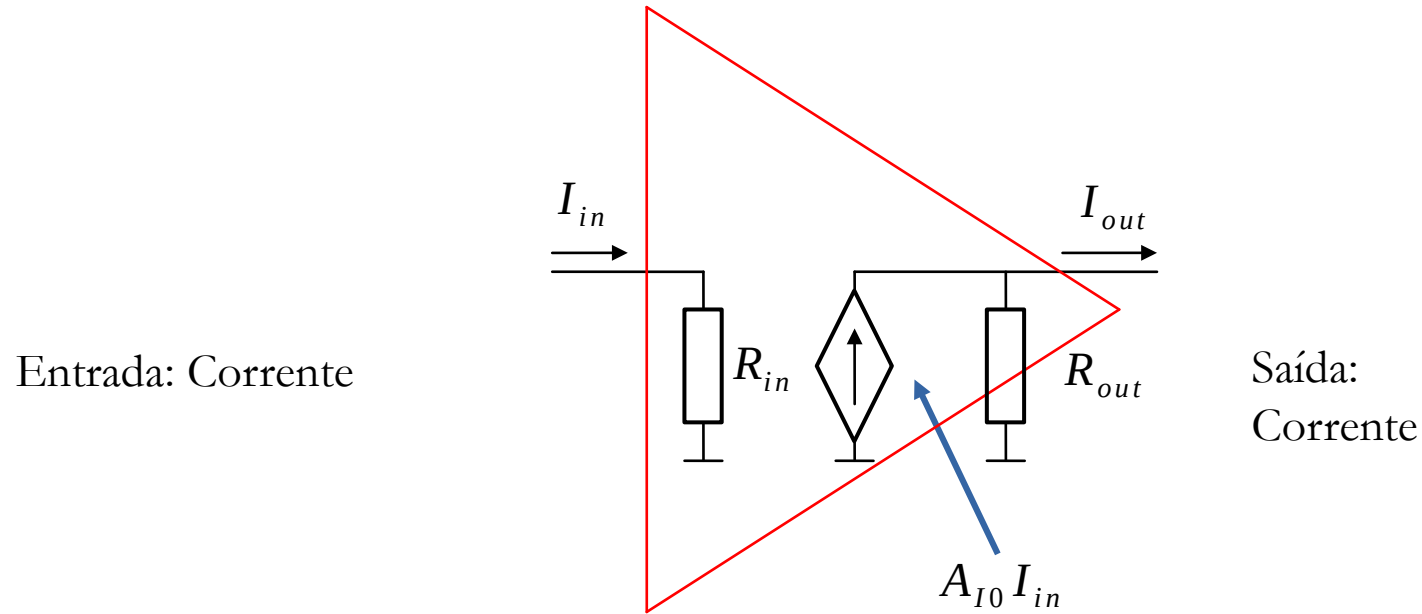
Idealmente, a resistência de entrada (R_{in}) é infinita e a resistência de saída (R_{out}) é infinita

Modelo de amplificador de transresistância



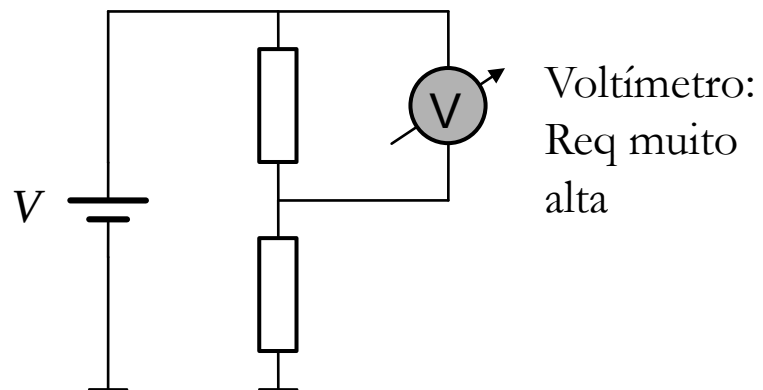
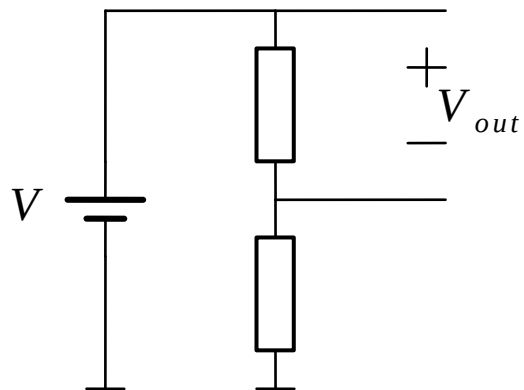
Idealmente, a resistência de entrada (R_{in}) é zero e a resistência de saída (R_{out}) é zero

Modelo de amplificador de corrente

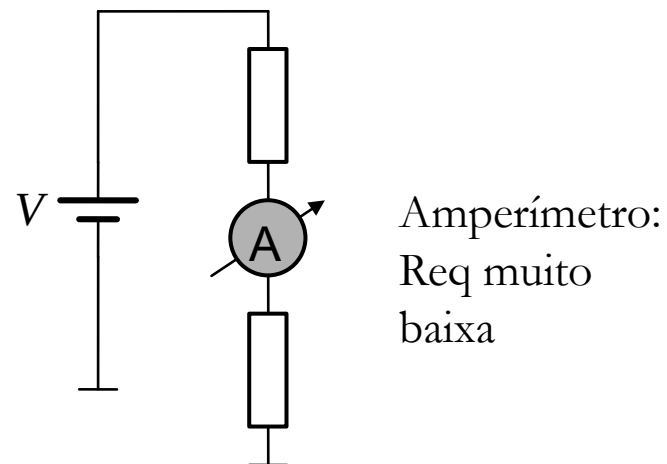
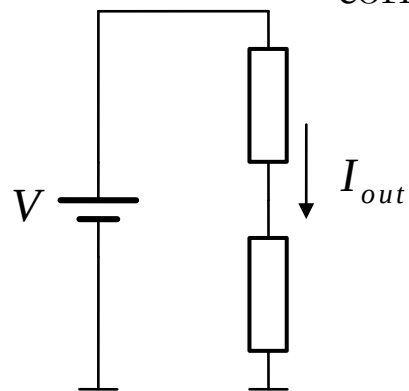


Idealmente, a resistência de entrada (R_{in}) é zero e a resistência de saída (R_{out}) é infinita

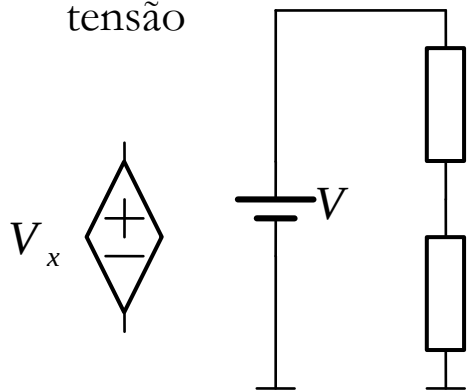
Amostragem de
tensão



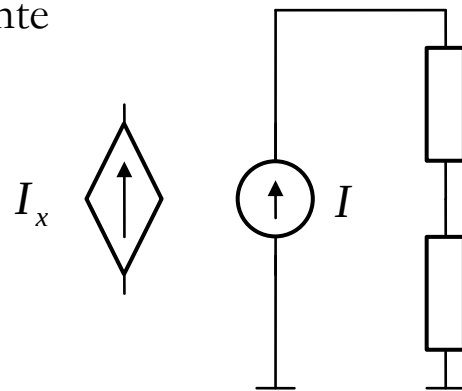
Amostragem de
corrente



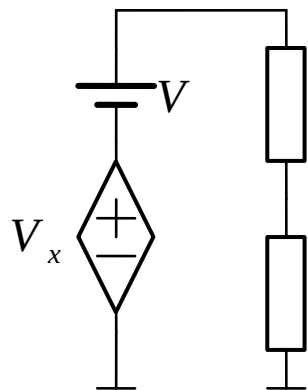
Somar/subtrair de
tensão



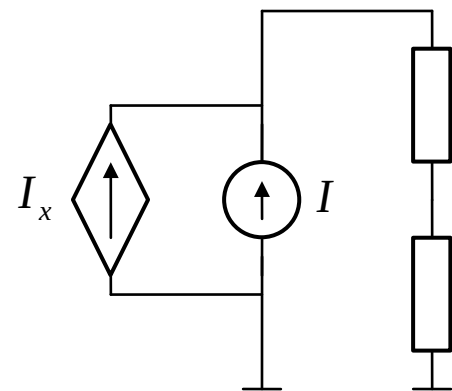
Somar/subtrair de
corrente



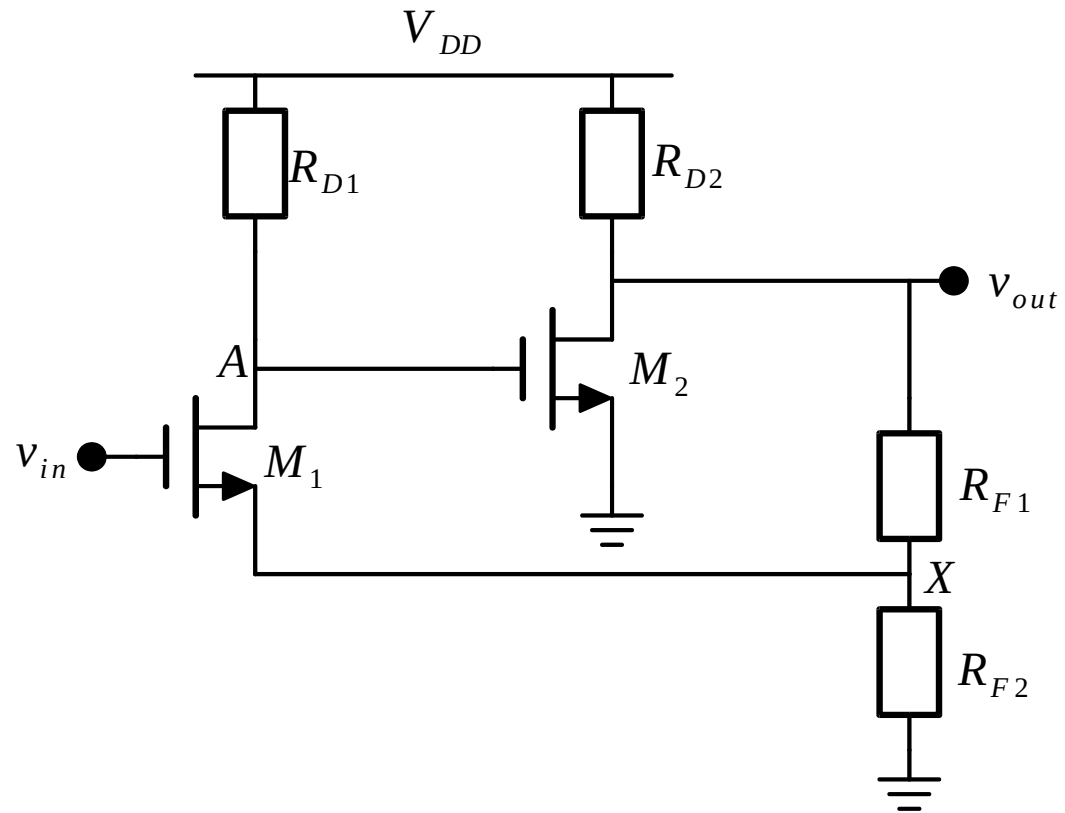
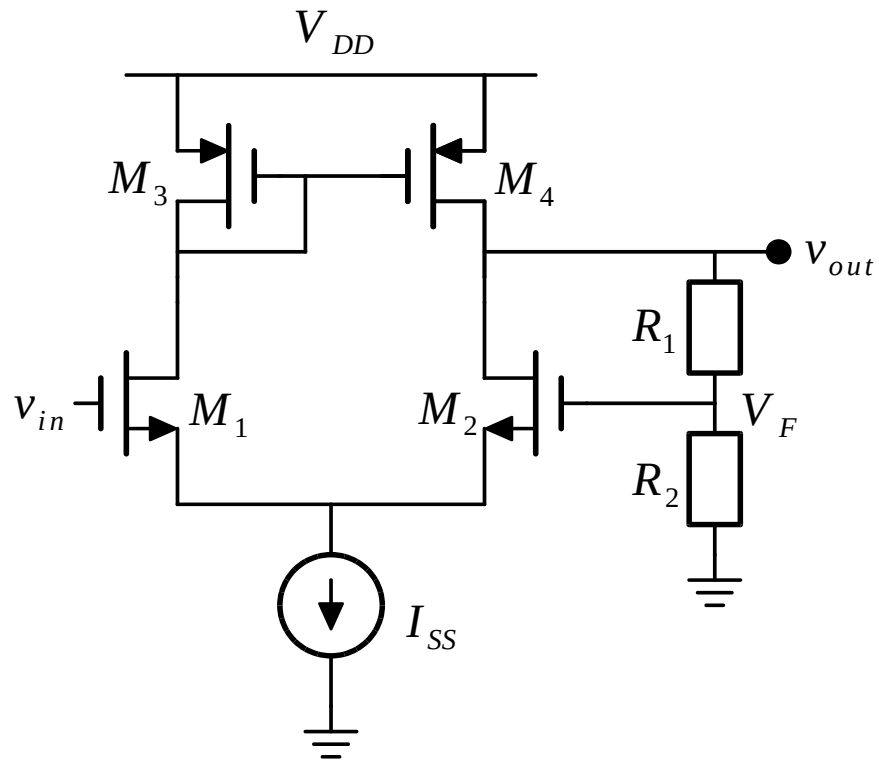
Fonte de
tensão:
Req muito baixa



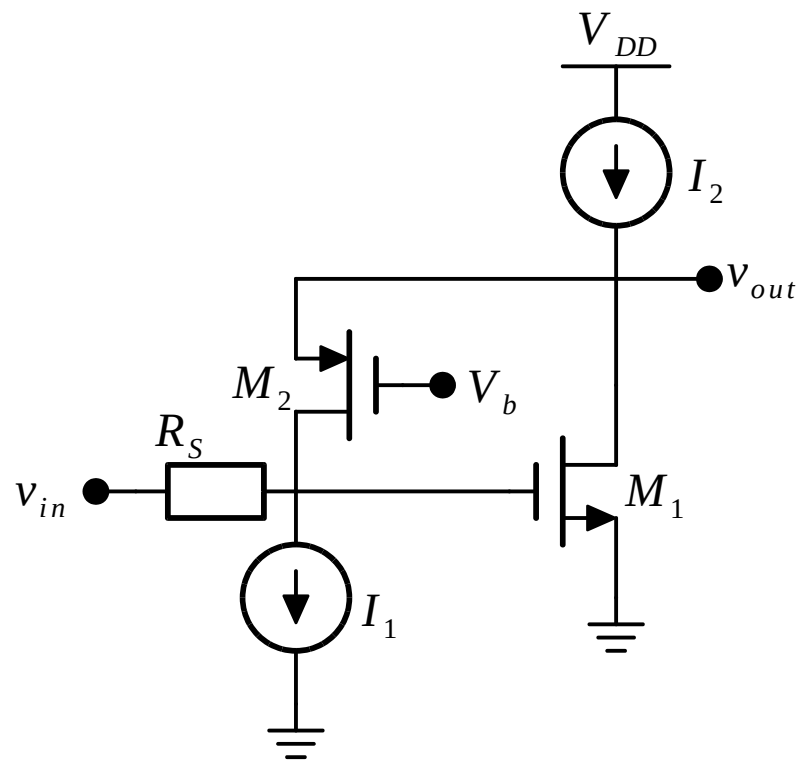
Fonte de
corrente:
Req muito alta



Verificar os circuitos e detectar a polaridade da realimentação



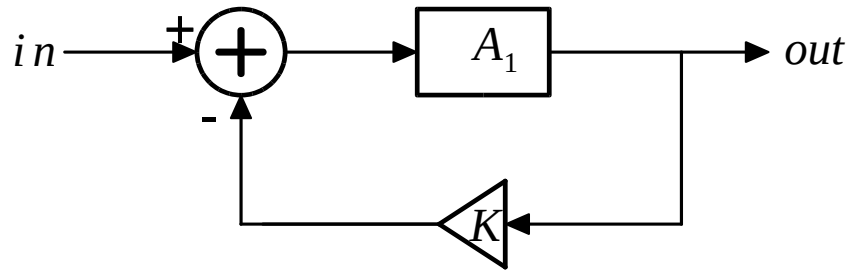
Exercício: Detectar os componentes da realimentação e determinar se é uma realimentação positiva ou negativa



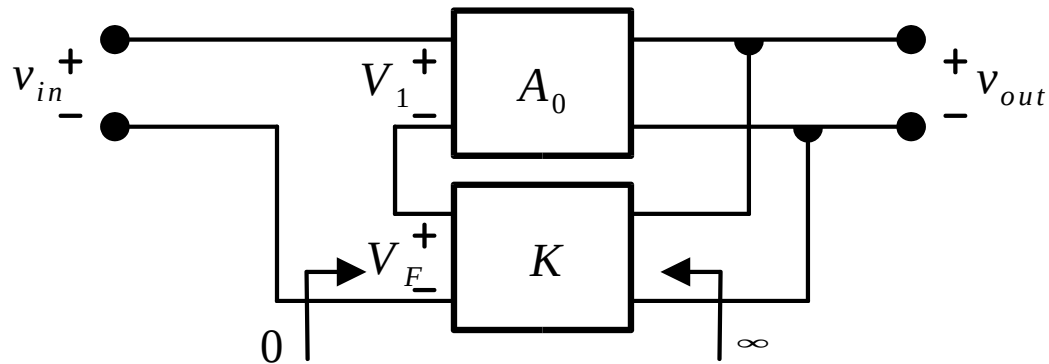
Topologias de realimentação

Entrada do bloco K | saída do bloco K

Tensão - Tensão



$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + KA_0}$$



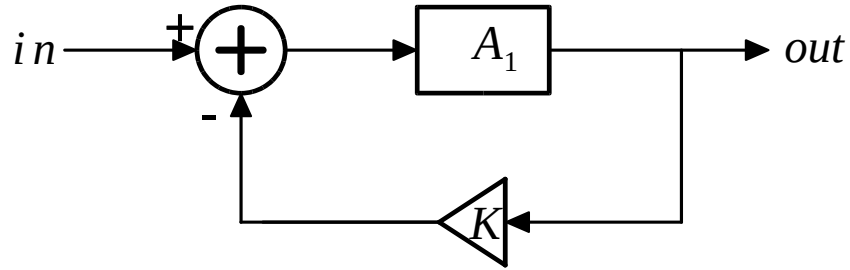
$$R_{in, fechado} = R_{in, aberta} (1 + KA_0)$$

$$R_{out, fechada} = \frac{R_{out, aberta}}{1 + KA_0}$$

Topologias de realimentação

Entrada do bloco K | saída do bloco K

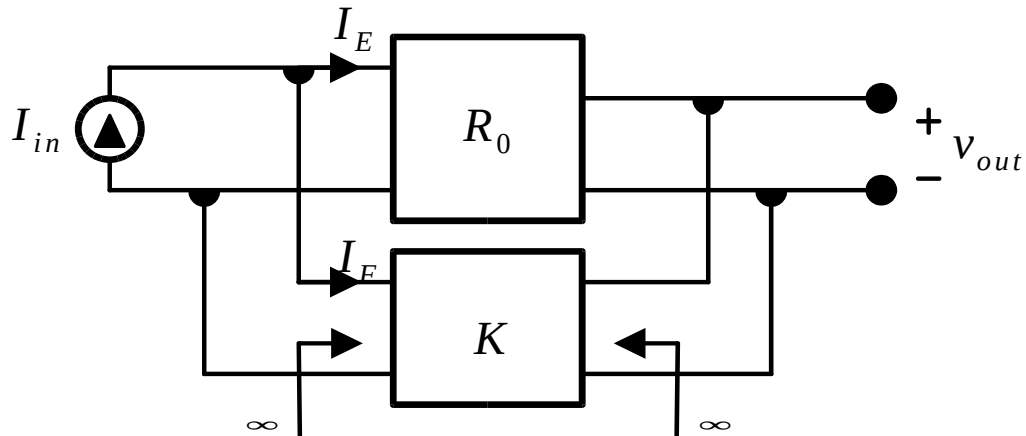
Tensão - Corrente



$$\frac{V_{out}}{I_{in}} = \frac{R_0}{1 + KR_0}$$

$$R_{in, fechado} = \frac{R_{in, aberta}}{(1 + KR_0)}$$

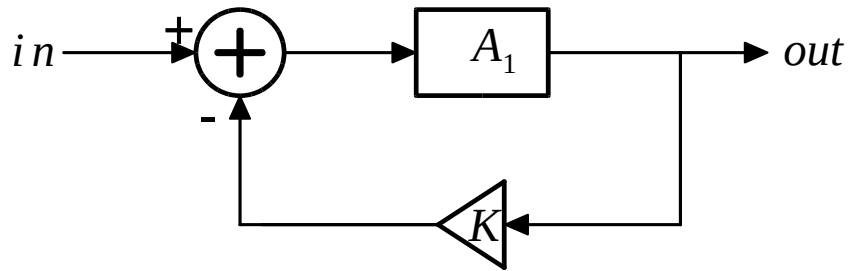
$$R_{out, fechada} = \frac{R_{out, aberta}}{1 + KR_0}$$



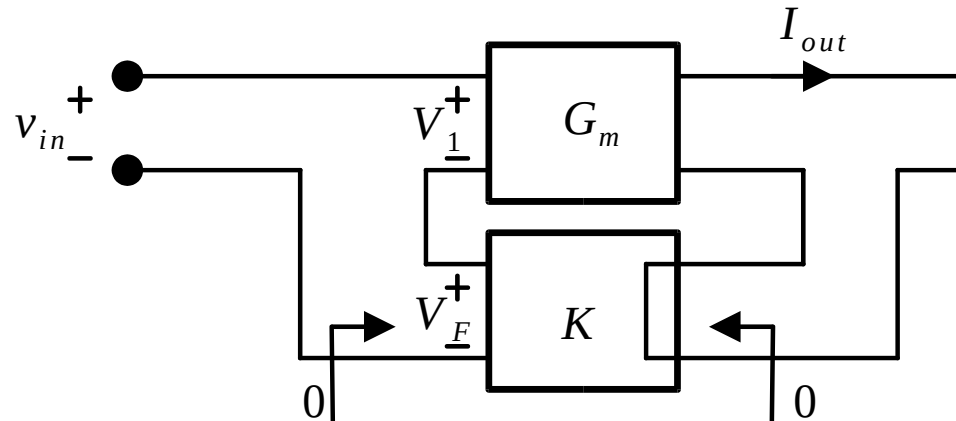
Topologias de realimentação

Entrada do bloco K | saída do bloco K

Corrente - Tensão



$$\frac{I_{out}}{V_{in}} = \frac{G_m}{1 + KG_m}$$



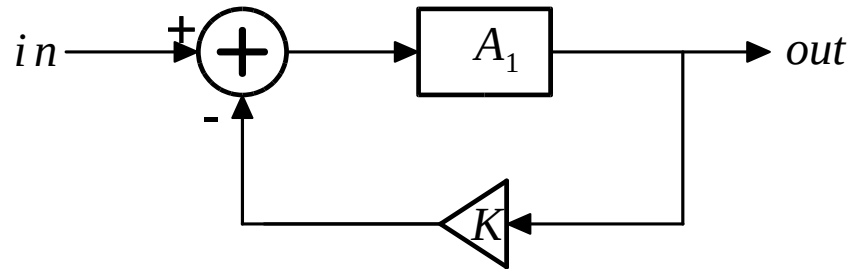
$$R_{in, fechado} = R_{in, aberta} (1 + KG_m)$$

$$R_{out, fechada} = R_{out, aberta} (1 + KG_m)$$

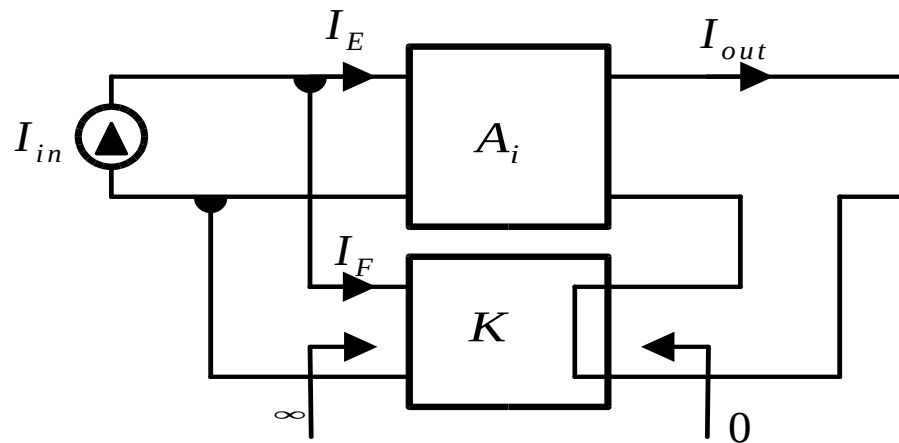
Topologias de realimentação

Entrada do bloco K | saída do bloco K

Corrente - Corrente



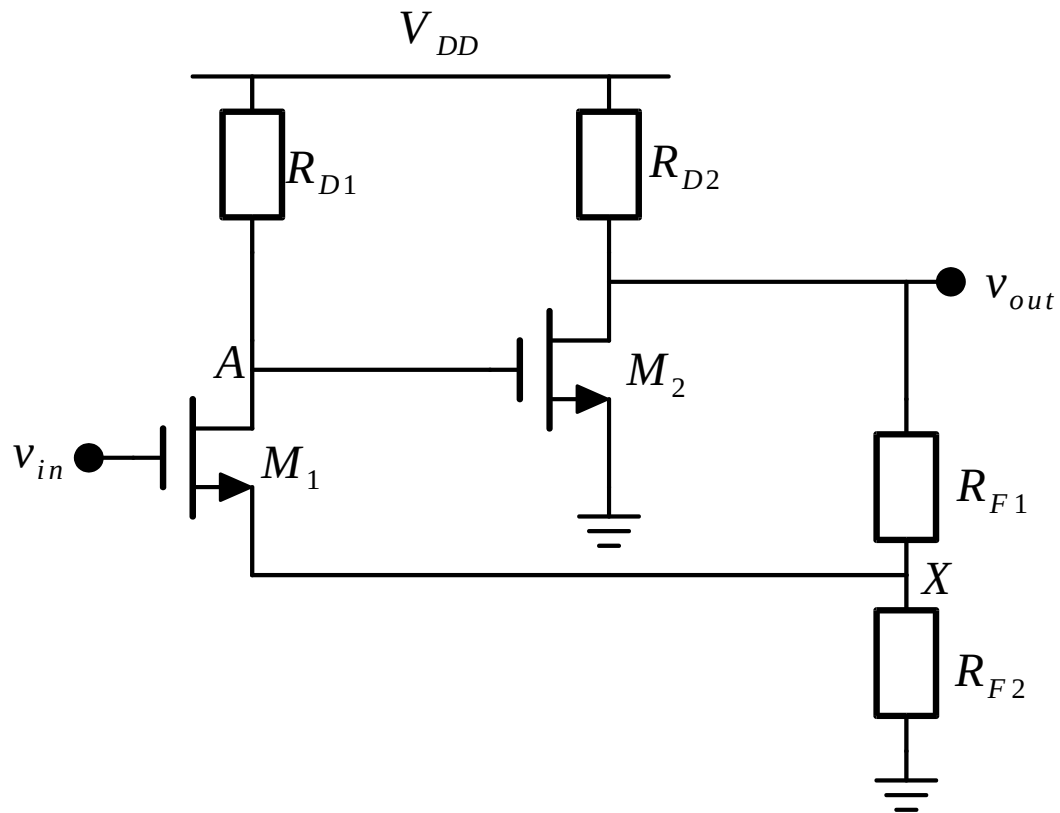
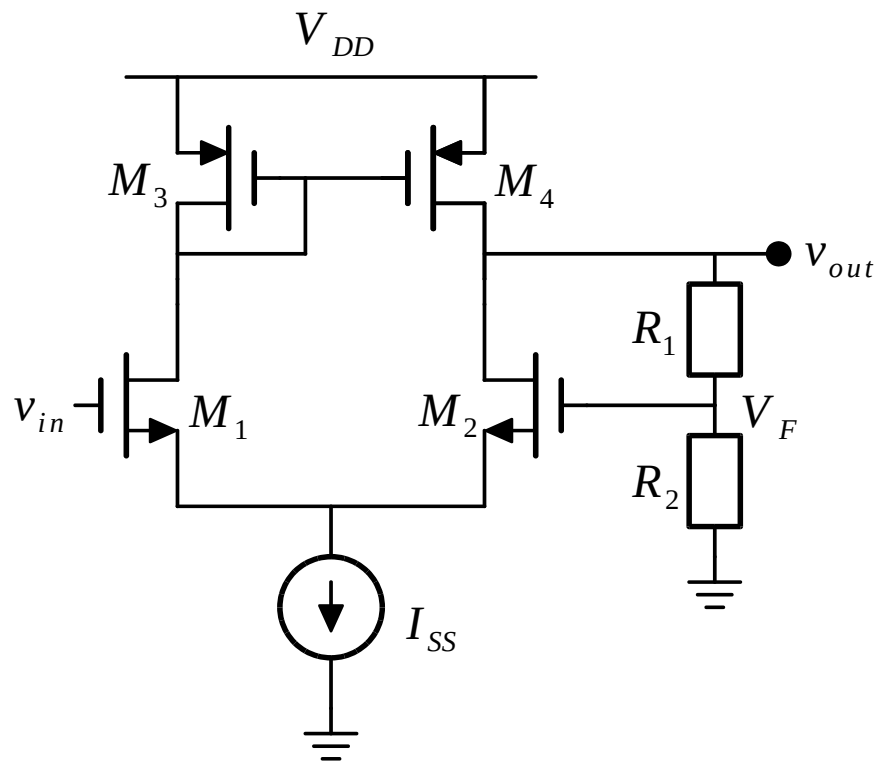
$$\frac{I_{out}}{I_{in}} = \frac{A_i}{1 + KA_i}$$



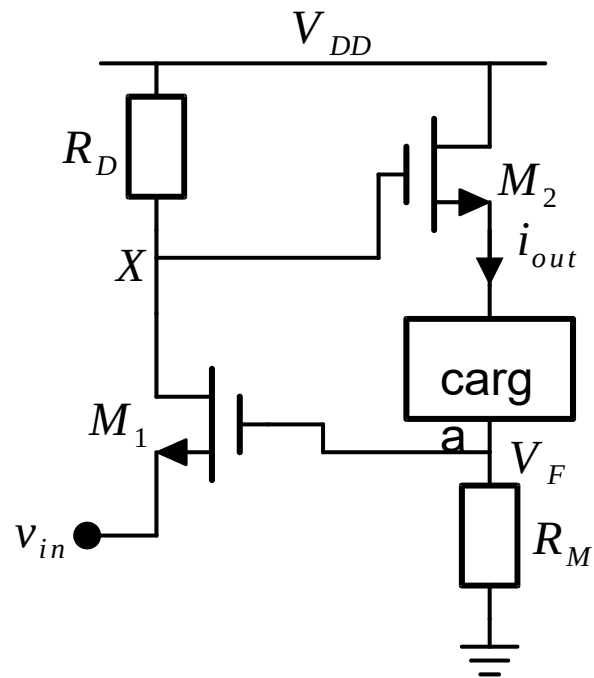
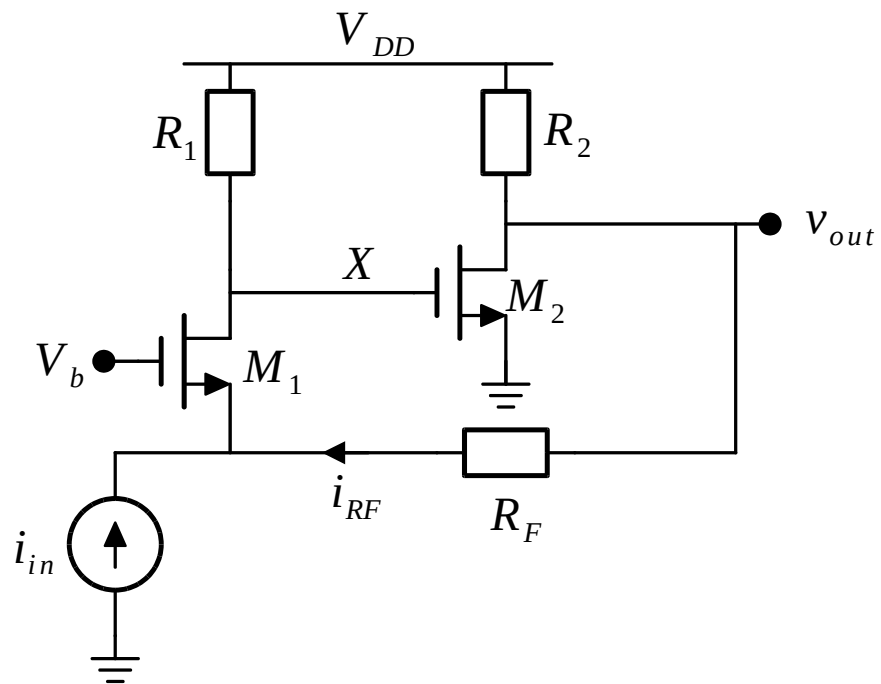
$$R_{in, fechado} = \frac{R_{in, aberta}}{(1 + KA_i)}$$

$$R_{out, fechada} = R_{out, aberta} (1 + KA_i)$$

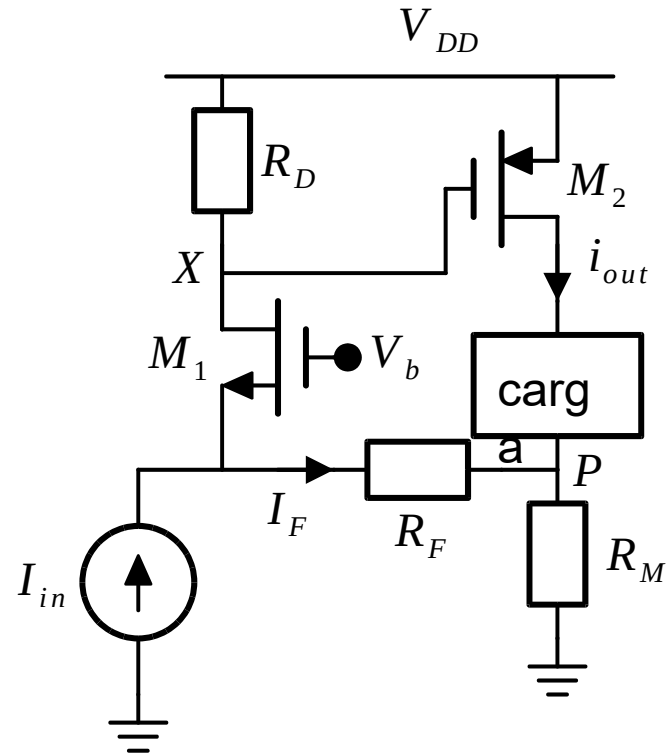
Obter ganho, R_{in} e R_{out} das configurações abaixo



Obter ganho, R_{in} e R_{out} das configurações abaixo



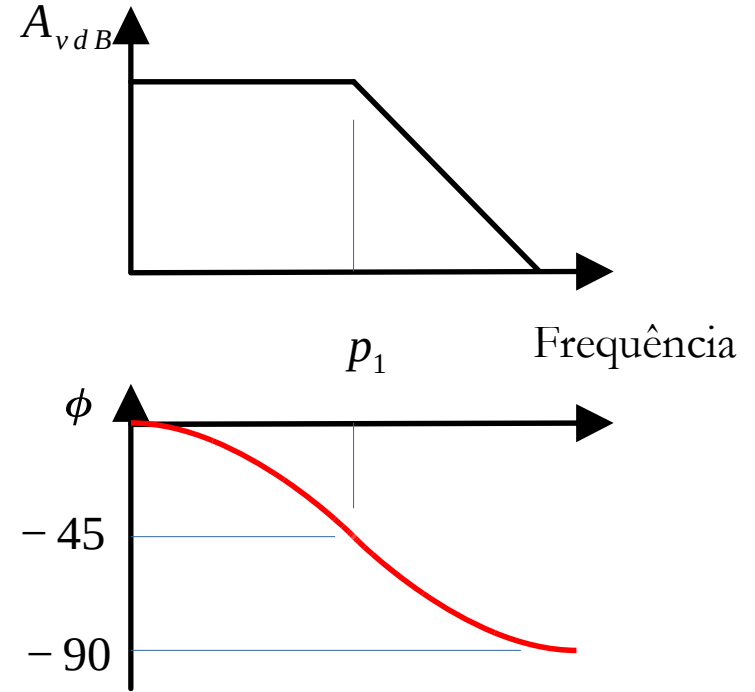
Obter ganho, R_{in} e R_{out} das configurações abaixo



Estabilidade dos sistemas de realimentação

Função de transferência com um polo

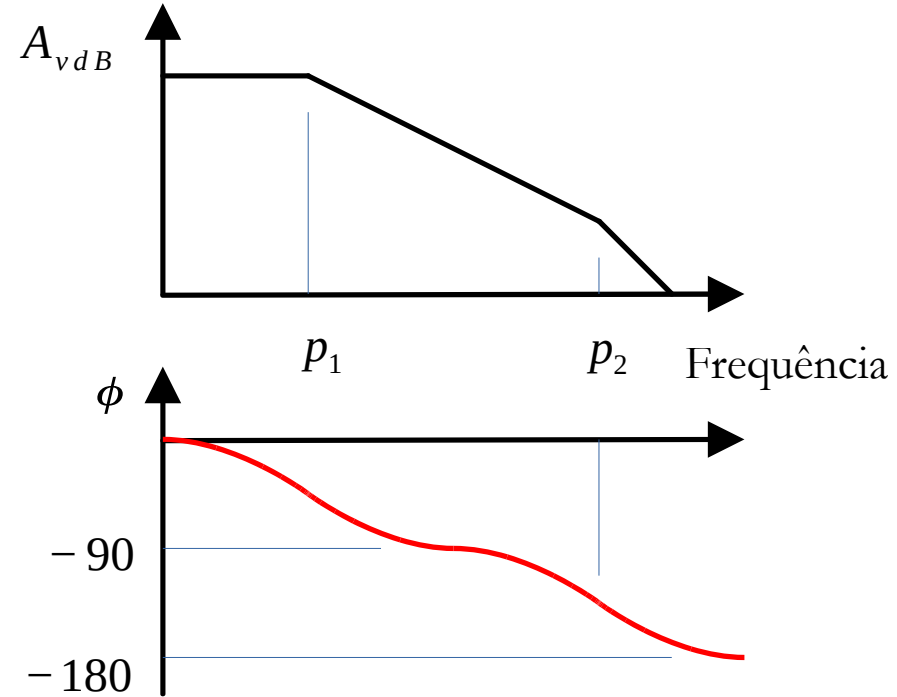
$$H(s) = \frac{A_v}{1 + s/\omega_p}$$



Estabilidade dos sistemas de realimentação

Função de transferência com 2 polos reais

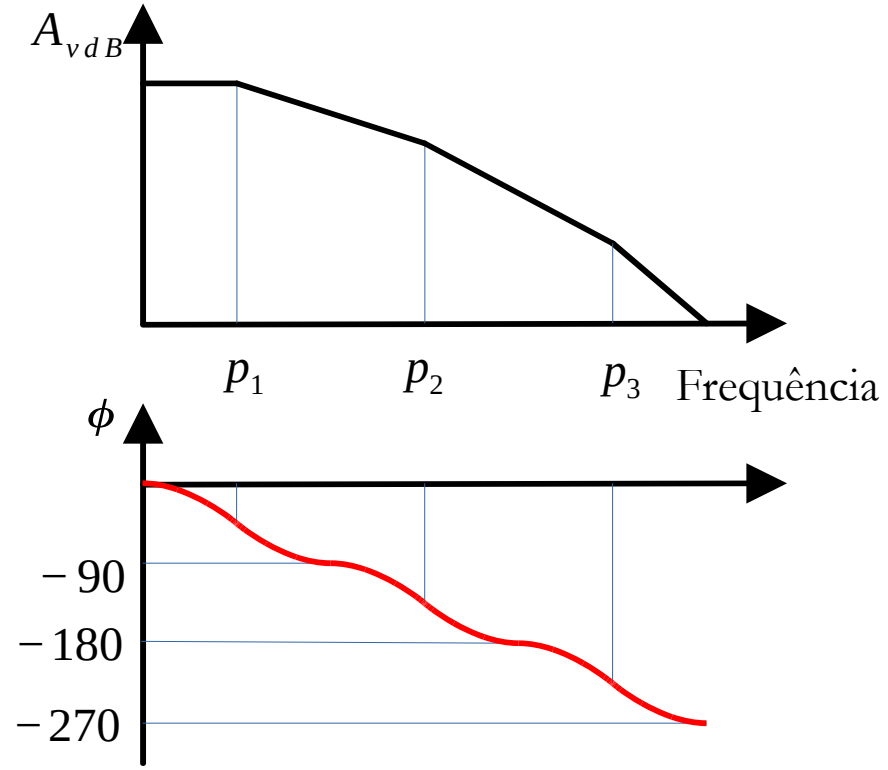
$$H(s) = \frac{A_v}{(1+s/\omega_{p1})(1+s/\omega_{p2})}$$



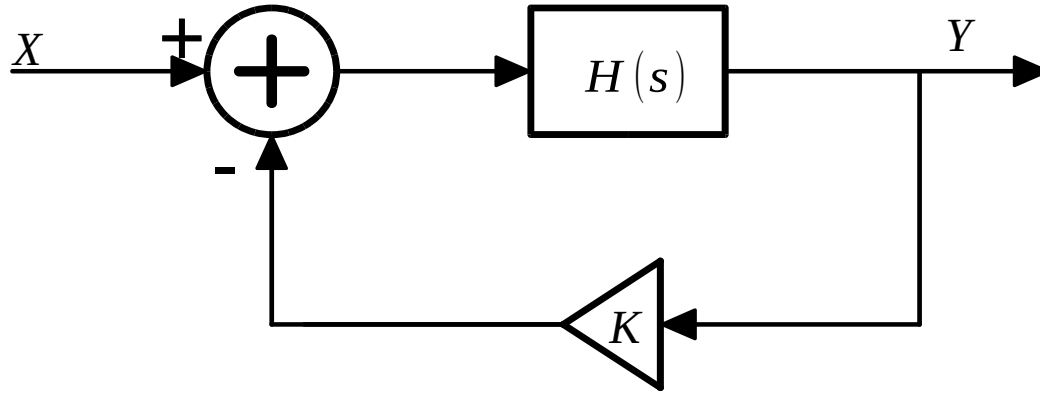
Estabilidade dos sistemas de realimentação

Função de transferência com 3 polos reais

$$H(s) = \frac{A_v}{(1+s/\omega_{p1})(1+s/\omega_{p2})(1+s/\omega_{p3})}$$



Estabilidade dos sistemas de realimentação



$$\frac{Y}{X} = \frac{H(s)}{1 + KH(s)}$$

Para garantir estabilidade:

$$1 + KH(s) \neq 0$$

O circuito é instável (mantém uma oscilação) na frequência onde:

$$|KH(j\omega_1)| = 1$$

$$\angle KH(j\omega_1) = -180^\circ$$

Critério de Barkhausen

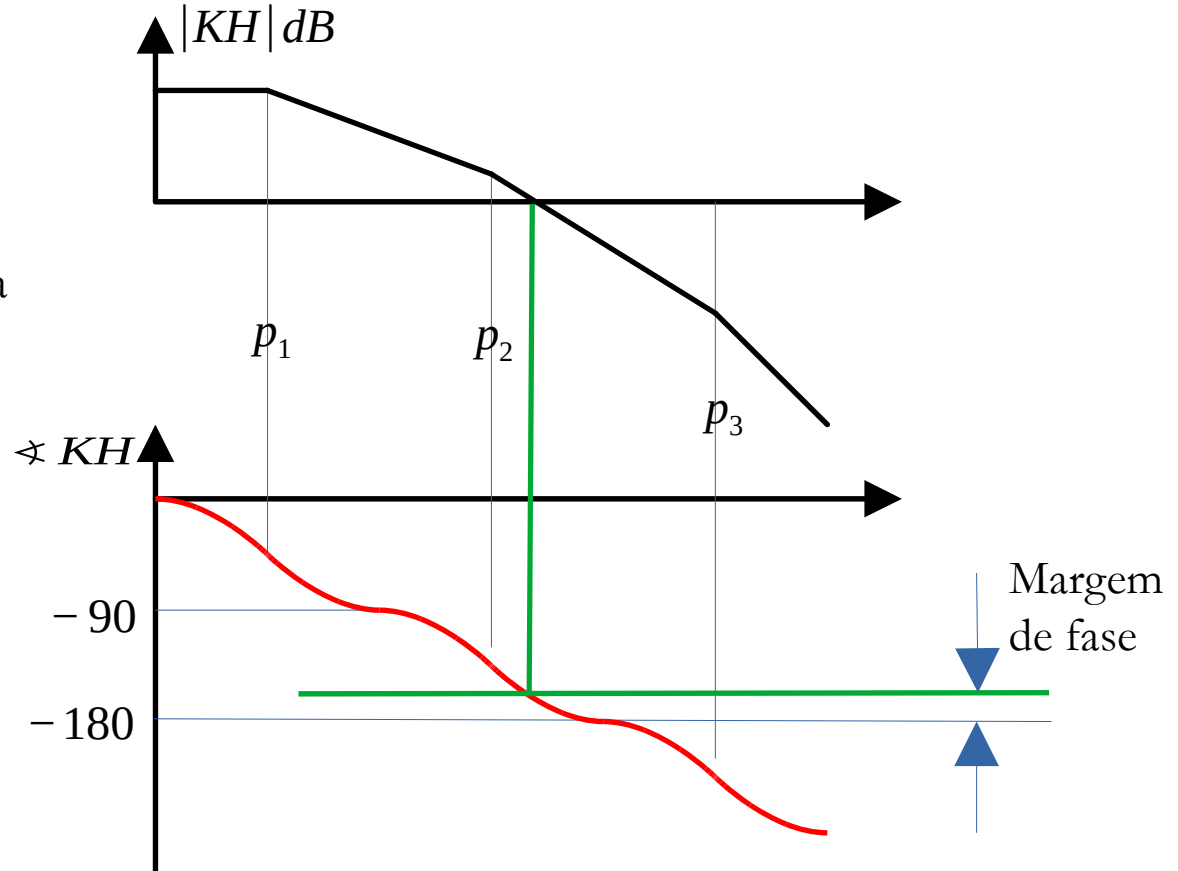
O circuito oscilará com amplitude crescente se o ganho de malha for maior que um na frequência com defasagem de -180°

Estabilidade dos sistemas de realimentação

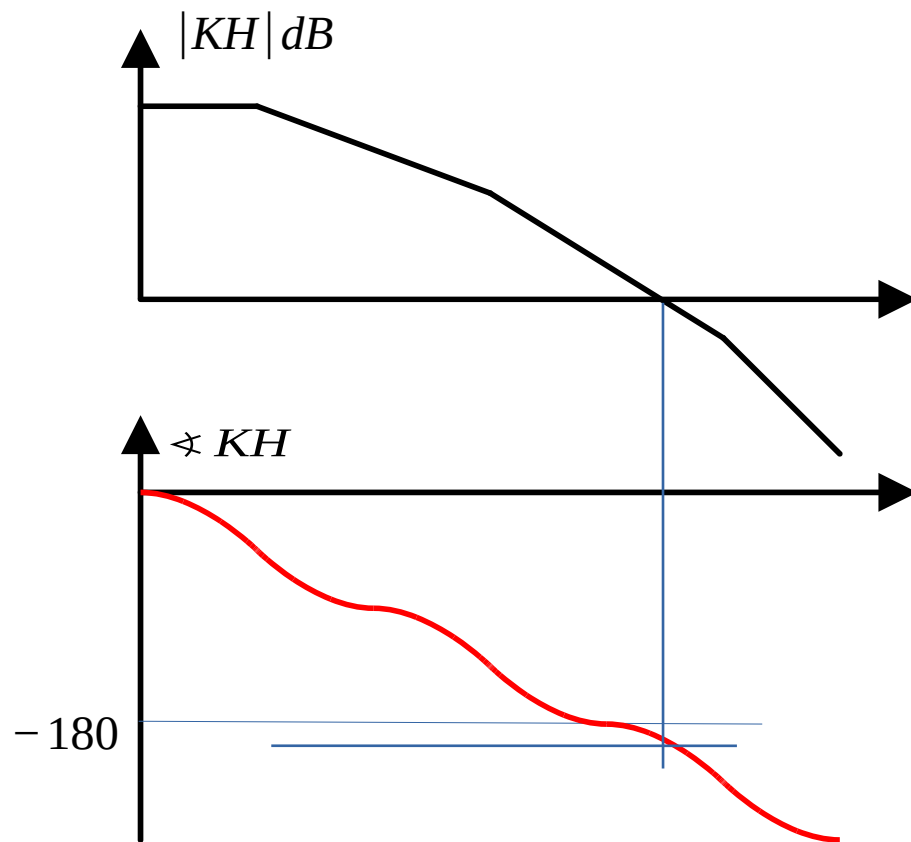
Como garantir estabilidade?

Garantir que na frequência onde o ganho é igual a 0 dB (1 V/V), exista uma margem de fase (geralmente maior que 60°).

$$|KH(j\omega_1)| = 1$$
$$\angle KH(j\omega_1) > -120$$

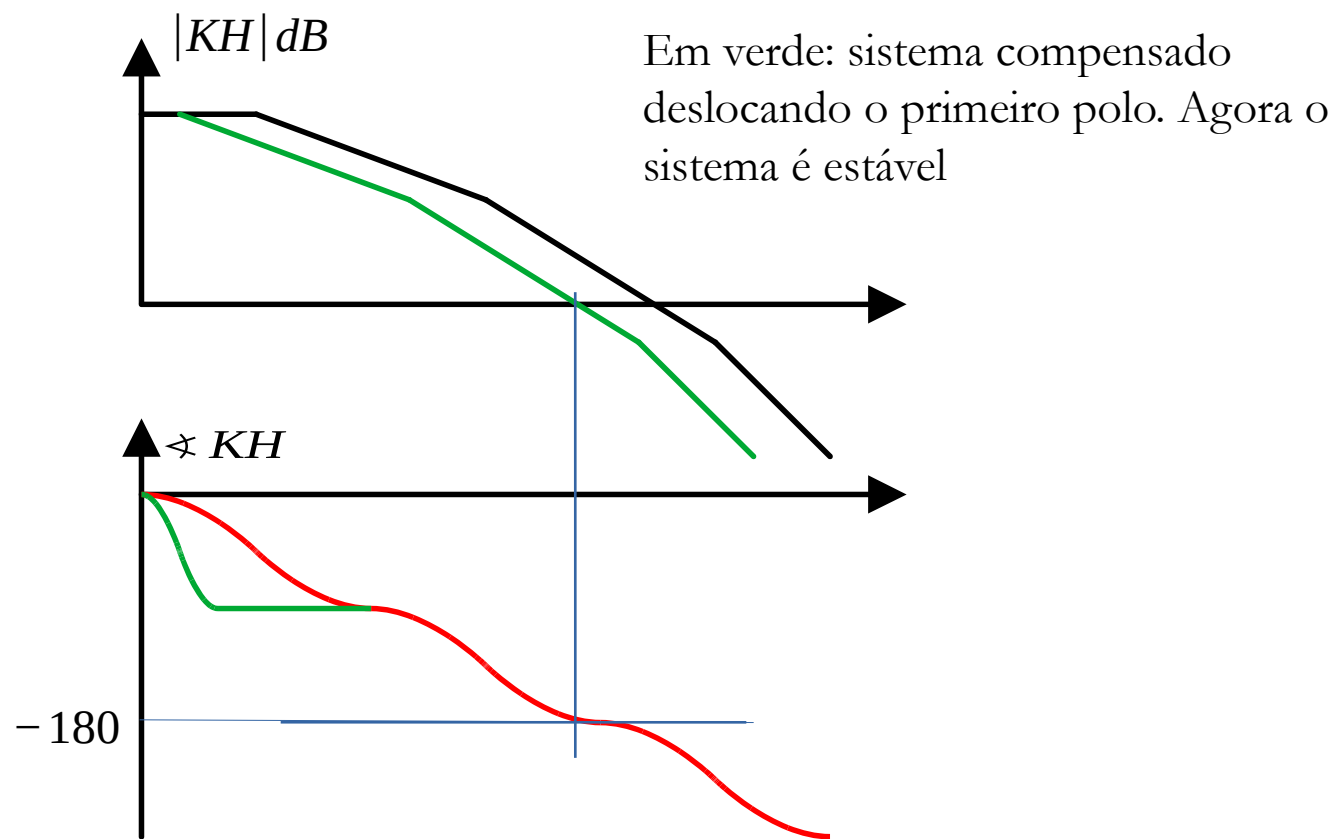


Estabilidade dos sistemas de realimentação

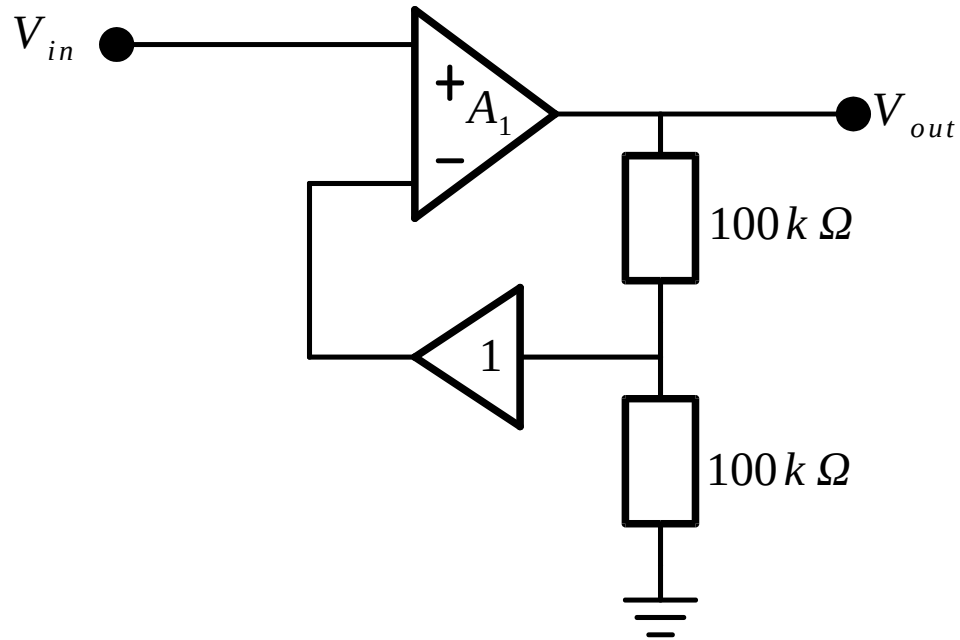


É estável? Não

Compensação de fase

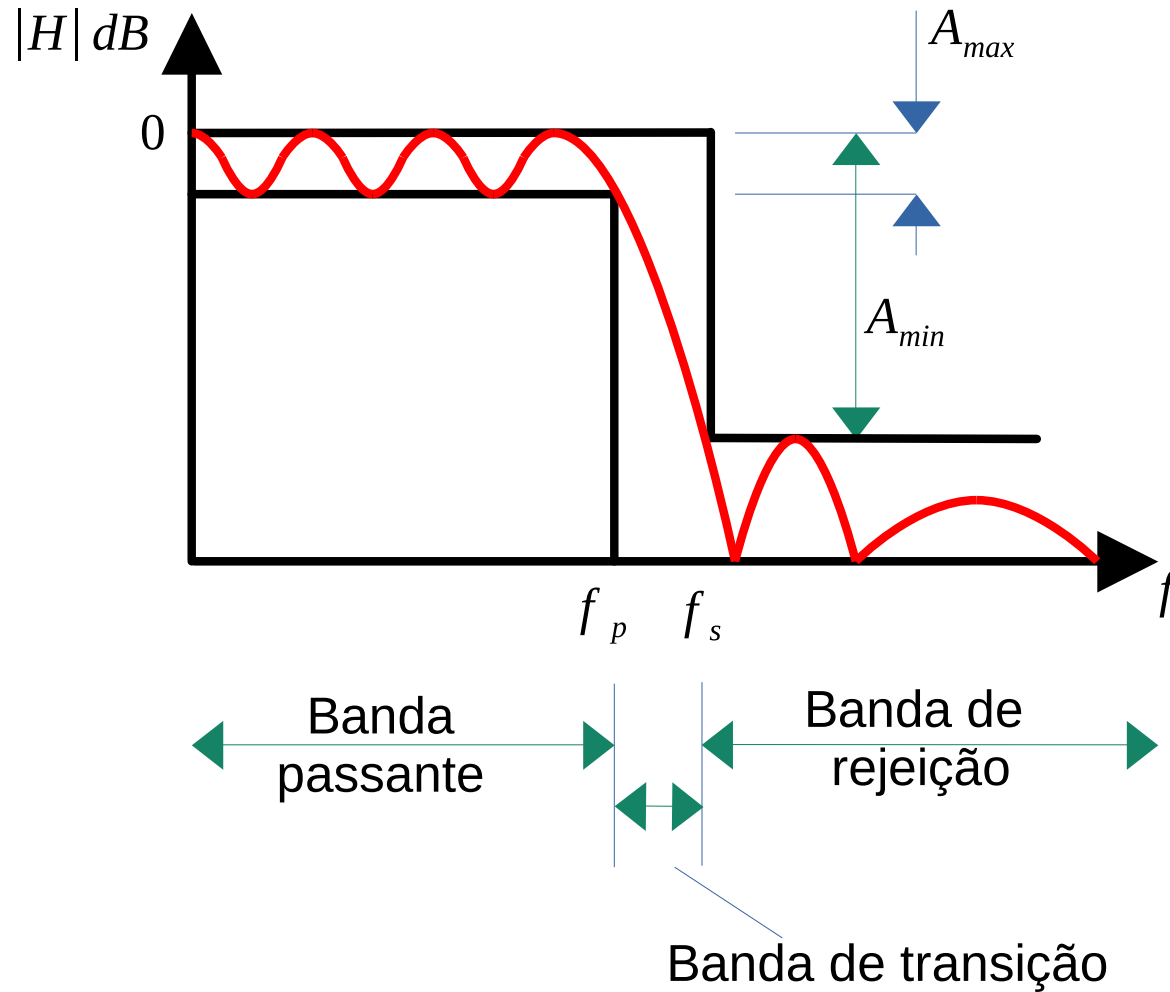


Exercício: Obter ganho, R_{in} e R_{out} da configuração abaixo e traçar o diagrama de bode de malha aberta e malha fechada



$A_1 = 100\text{ V/V}$
com $f_p = 100\text{ kHz}$
 $R_{in} = 1\text{ M}\Omega$
 $R_{out} = 1\text{ k}\Omega$

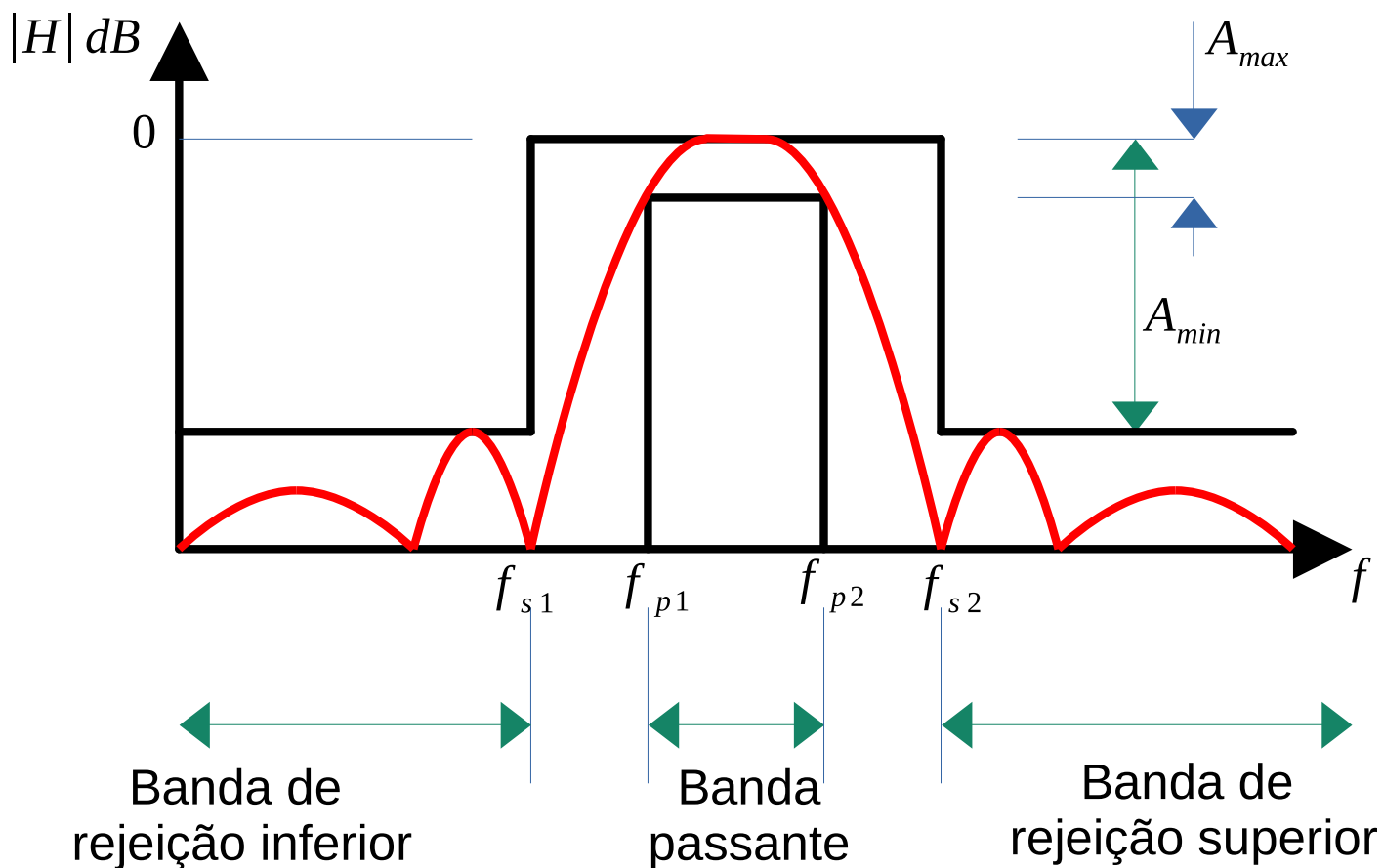
Especificação para filtro passa baixas



A_{max} : ripple máximo na banda passante;
 A_{min} : atenuação mínima da banda de rejeição;

Especificação aplicável para passa altas

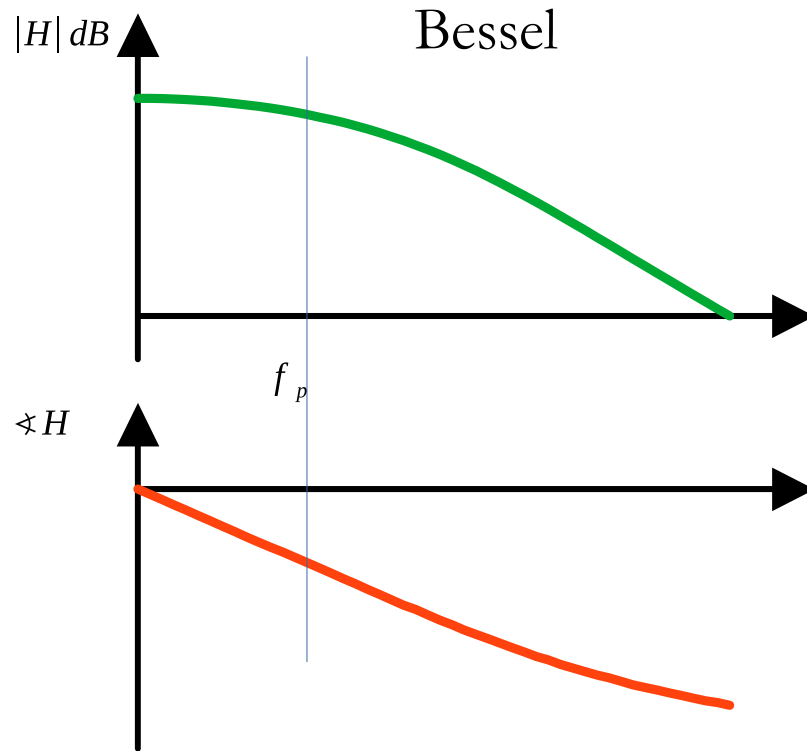
Especificação para filtro passa faixa



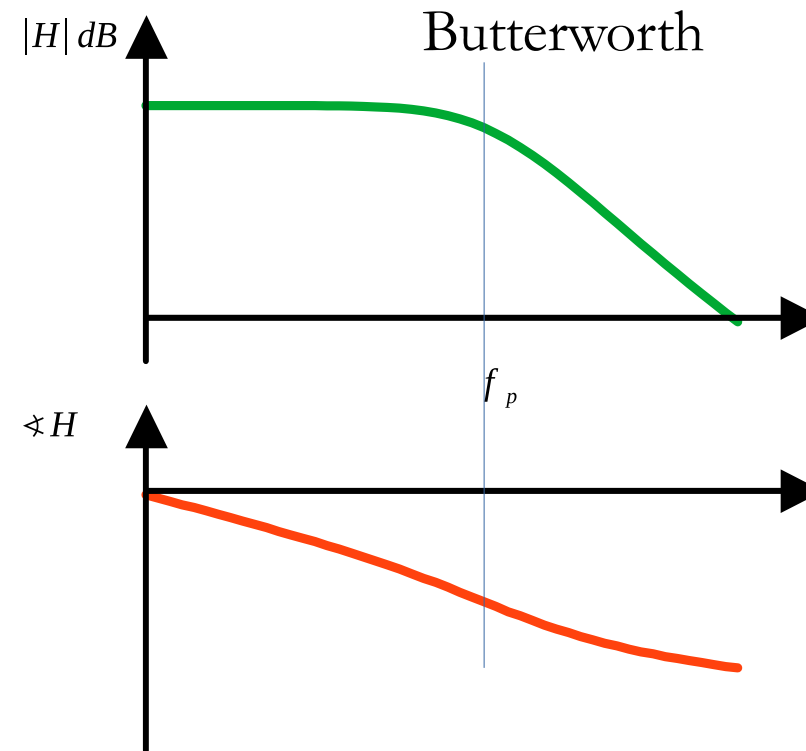
Especificação aplicável para rejeita faixa

A_{max} : ripple máximo na banda passante;
 A_{min} : atenuação mínima da banda de rejeição;

Aproximações de filtros



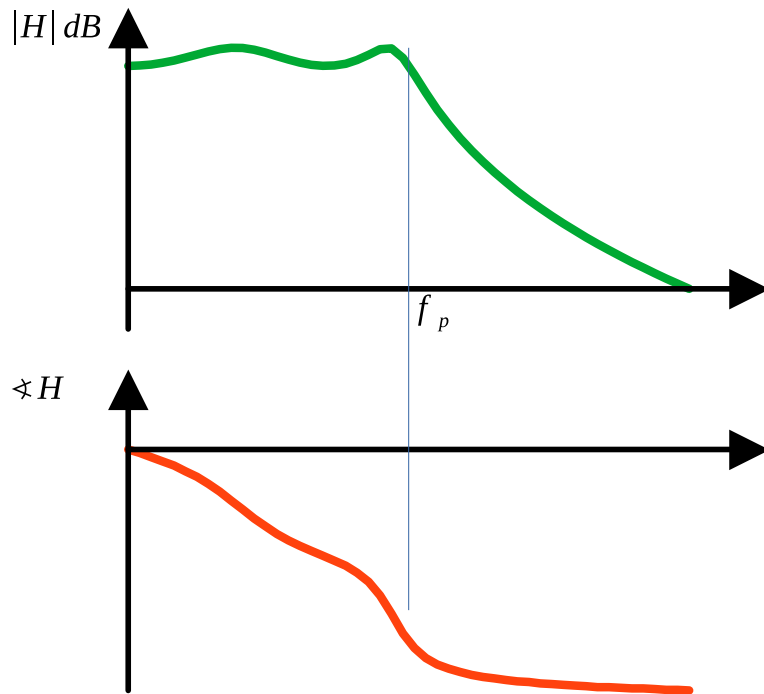
- Resposta de fase linear
- Preserva melhor o formato do sinal
- Menor atenuação fora da banda



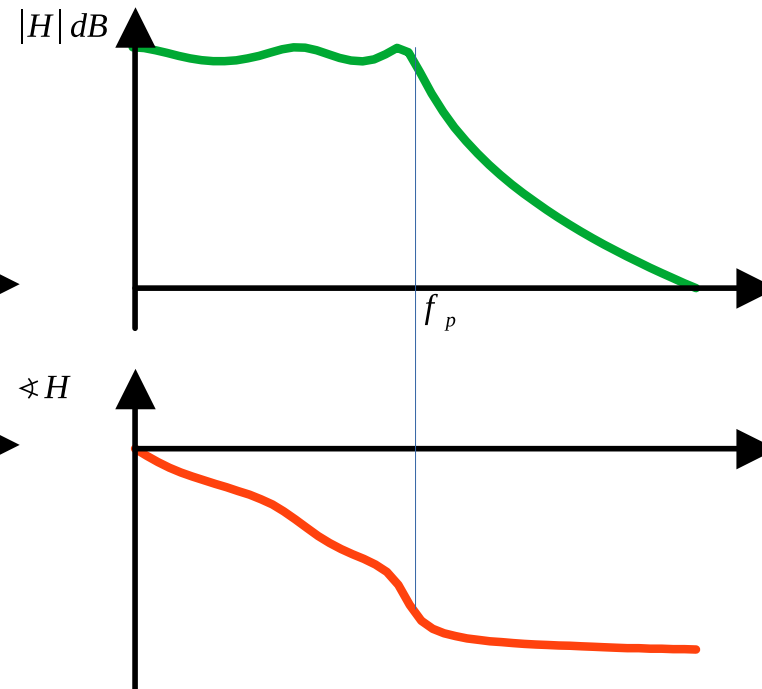
- Resposta de amplitude mais linear na banda passante
- Resposta menos linear na banda passante
- Atenuação menos eficiente fora da banda passante

Aproximações de filtros

Chebyshev tipo 1 ordem par

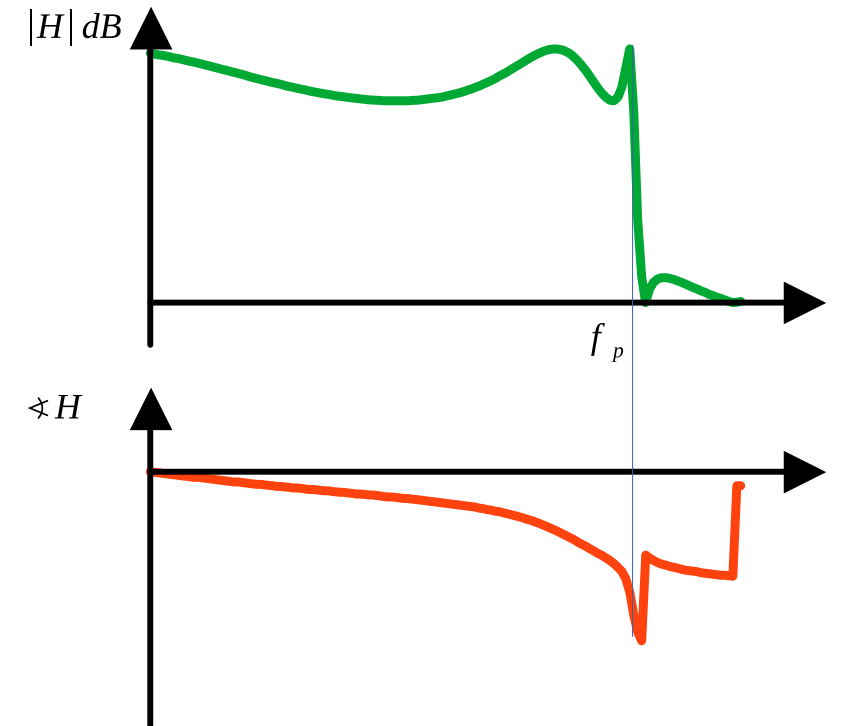


Chebyshev tipo 1 ordem ímpar



- Melhor atenuação na banda de rejeição.
- Ripple na banda passante;
- Resposta de fase não linear na banda passante.

Elíptico



- Banda de transição menor
- Ripple na banda passante
- Ripple na banda de rejeição
- Fase não linear

Aproximação de Butterworth

$$|H(j\omega)| = \frac{1}{\sqrt{1 + \epsilon^2 (\omega/\omega_p)^{2N}}}$$

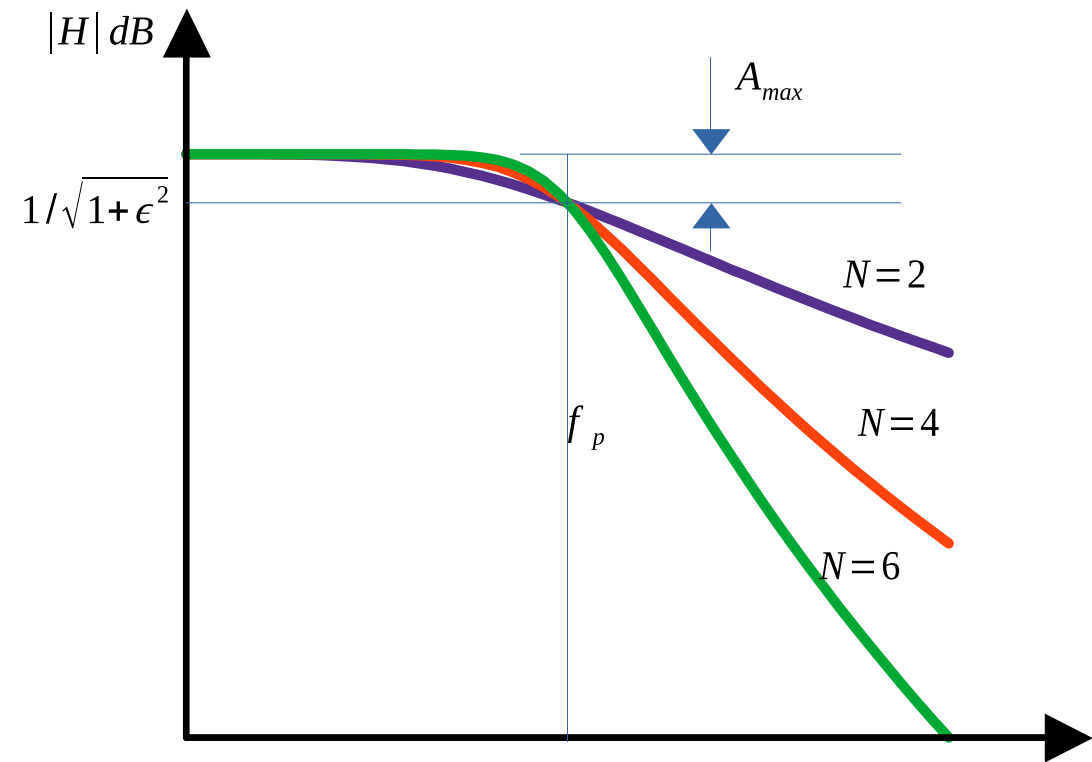
$$|H(j\omega_p)| = \frac{1}{\sqrt{1 + \epsilon^2}}$$

$$A_{max} = 20 \log_{10}(\sqrt{1 + \epsilon^2})$$

N é a ordem do filtro

$$p_k = \omega_0 \exp\left(\frac{j\pi}{2}\right) \exp\left(j\frac{2k-1}{2N}\pi\right), \quad k = 1, 2, \dots, N$$

$$\omega_0 = \omega_p \frac{1}{\epsilon^{1/N}}$$



Aproximação de Chebyshev

$$|H(j\omega)| = \frac{1}{\sqrt{1 + \epsilon^2 \cos^2[N \cos^{-1}(\omega/\omega_p)]}}, \text{ se } \omega \leq \omega_p$$

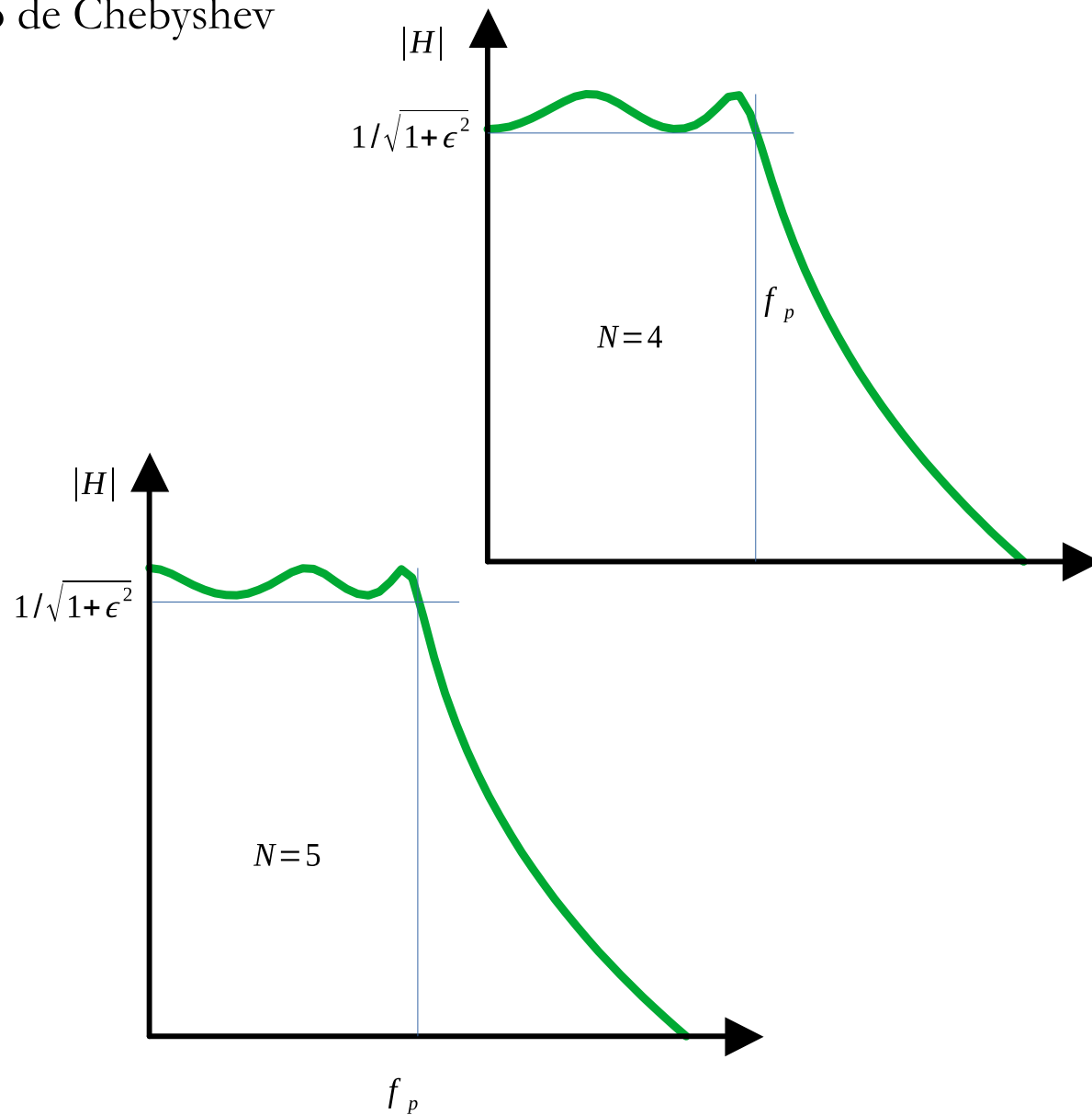
$$|H(j\omega)| = \frac{1}{\sqrt{1 + \epsilon^2 \cosh^2[N \cosh^{-1}(\omega/\omega_p)]}}, \text{ se } \omega > \omega_p$$

$$|H(j\omega_p)| = \frac{1}{\sqrt{1 + \epsilon^2}}$$

$$A_{\max} = 10 \log_{10}(1 + \epsilon^2)$$

$$\epsilon = \sqrt{10^{A_{\max}/10} - 1}$$

N é a ordem do filtro

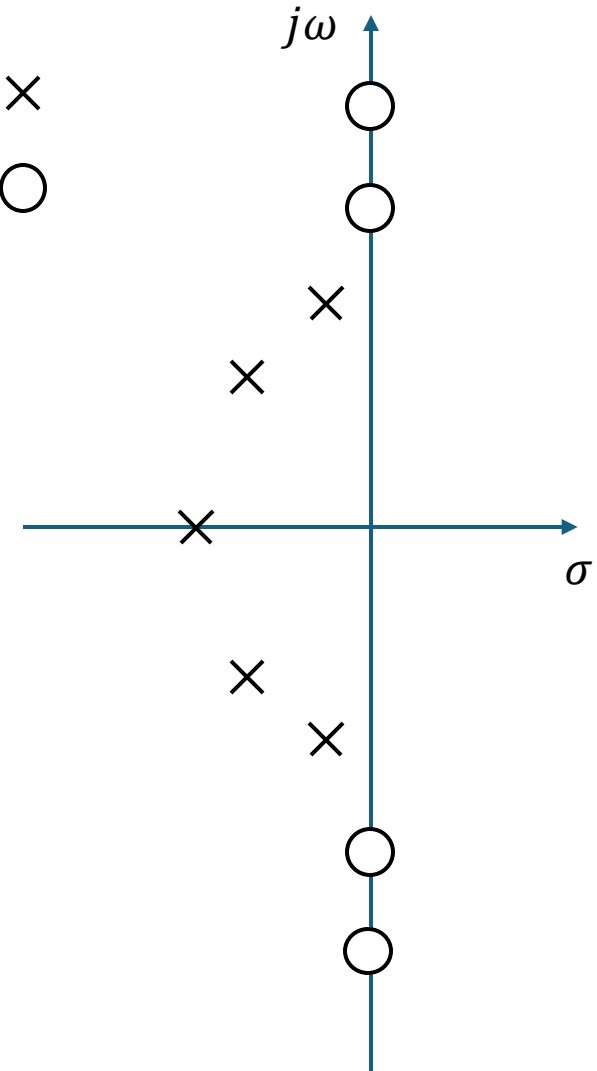


Função de transferência dos filtros

$$H(s) = a_M \frac{(s - z_1)(s - z_2) \dots (s - z_M)}{(s - p_1)(s - p_2) \dots (s - p_M)}$$

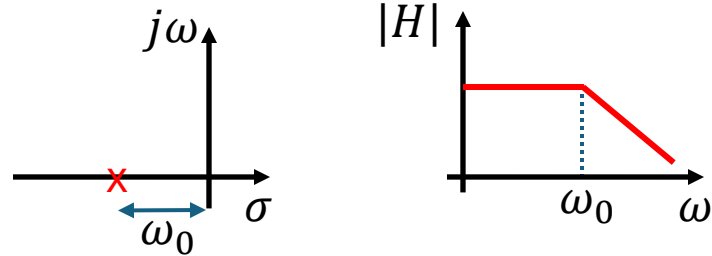
polos $\times$

zeros $\circ$



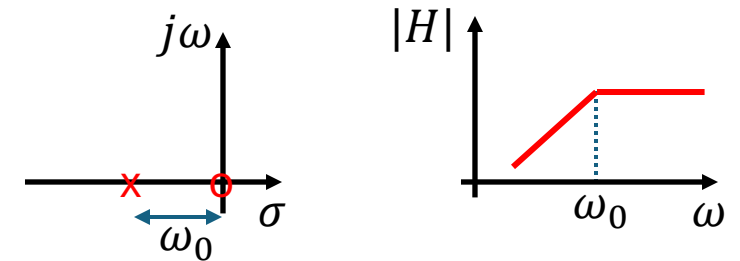
Tipos de filtros de primeira ordem

$$H(s) = \frac{a_0}{s + \omega_0}$$



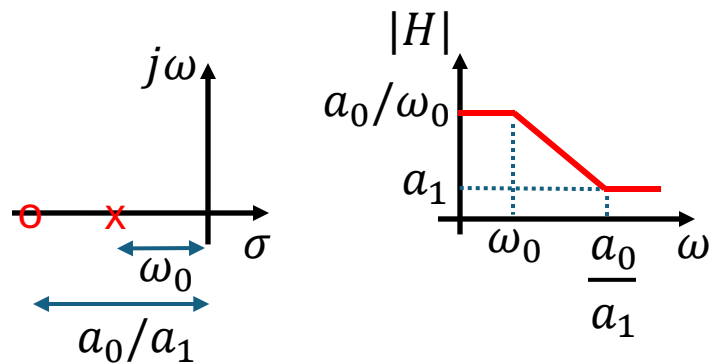
Passa baixas (LP)

$$H(s) = \frac{a_1 s}{s + \omega_0}$$



Passa altas (HP)

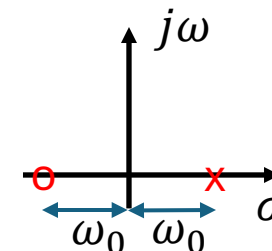
$$H(s) = \frac{a_1 s + a_0}{s + \omega_0}$$



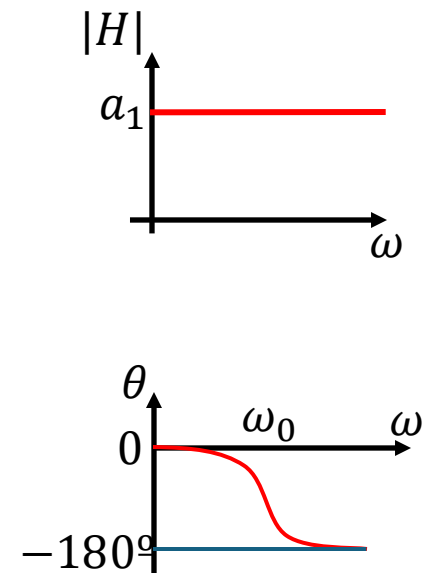
Geral

$$H(s) = -a_1 \frac{s - \omega_0}{s + \omega_0}$$

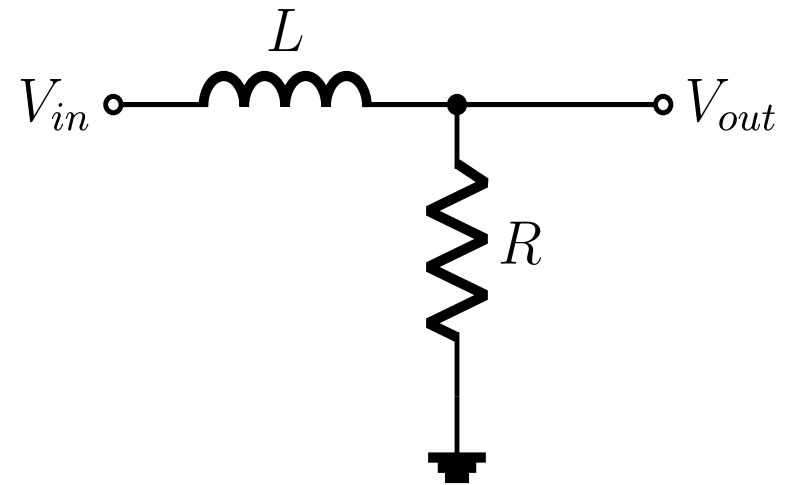
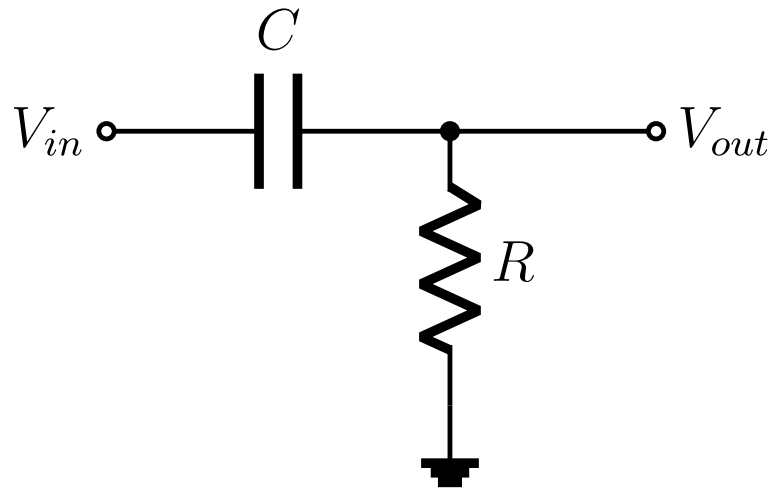
$$a_1 > 0$$



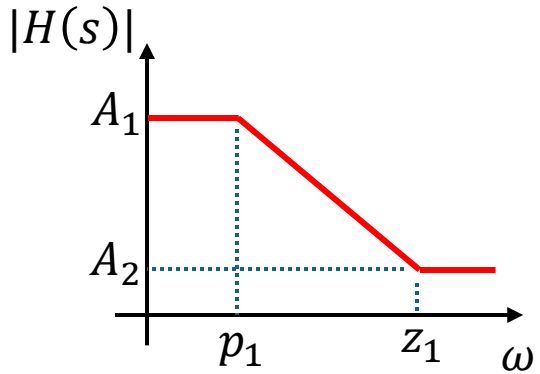
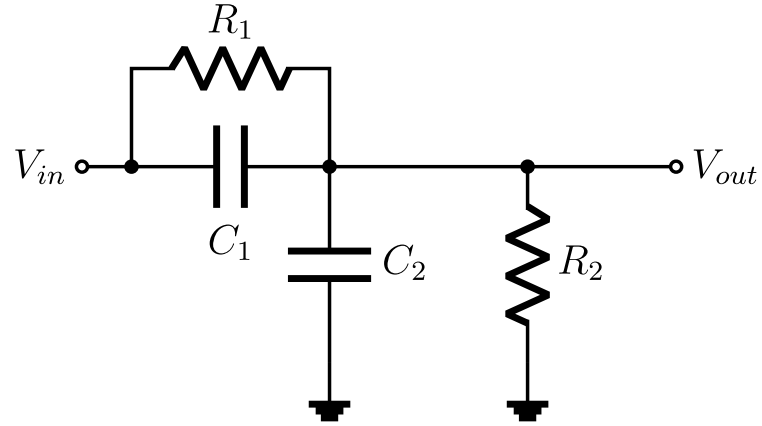
Passa tudo (AP)



Exemplos



Exemplo

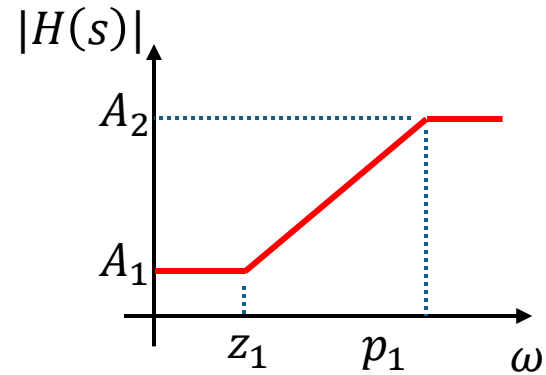


$$p_1 = \frac{1}{R_1 C_1}$$

$$A_1 = \frac{R_2}{R_1 + R_2}$$

$$A_2 = \frac{C_1}{C_1 + C_2}$$

$$z_1 = \frac{1}{(C_1 + C_2)(R_1 || R_2)}$$



$$A_2 = \frac{C_1}{C_1 + C_2}$$

$$A_1 = \frac{R_2}{R_1 + R_2}$$

$$z_1 = \frac{1}{R_1 C_1}$$

$$p_1 = \frac{1}{(C_1 + C_2)(R_1 || R_2)}$$

Filtro de segunda ordem genérico

$$H(s) = \frac{a_2 s^2 + a_1 s + a_0}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$

$$p_1, p_2 = -\frac{\omega_0}{2Q} \pm j\omega_0 \sqrt{1 - \left(\frac{1}{4Q^2}\right)}$$

Segunda ordem passa baixas

$$H(s) = \frac{a_0}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

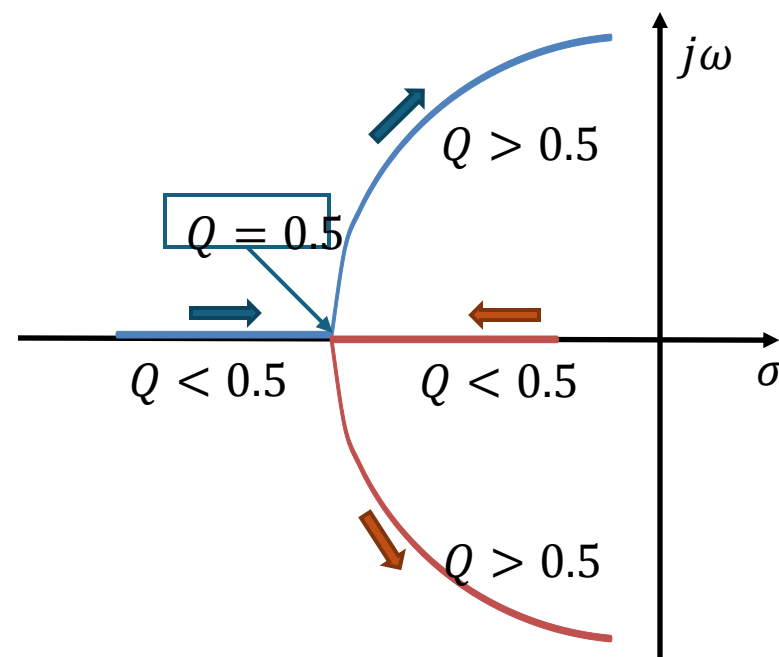
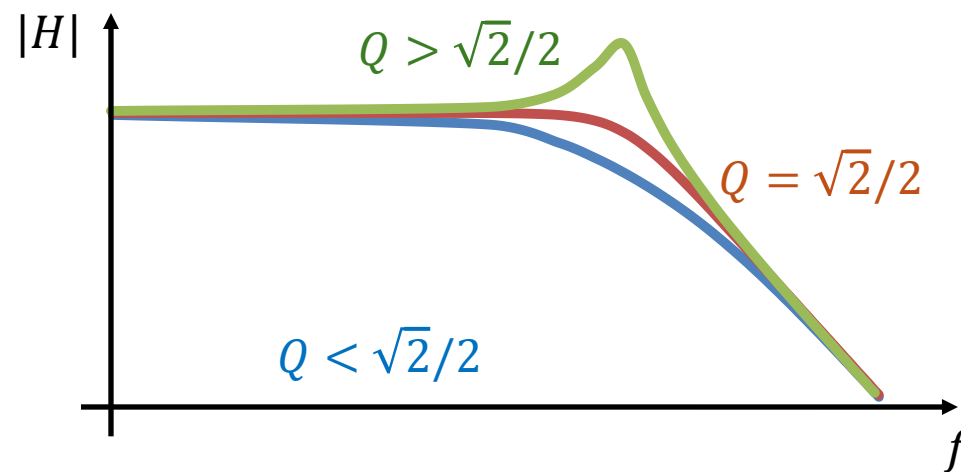
$$p_1, p_2 = -\frac{\omega_0}{2Q} \pm j\omega_0 \sqrt{1 - \left(\frac{1}{4Q^2}\right)}$$

Pico em

$$\omega_n \sqrt{1 - \frac{1}{2Q^2}}$$

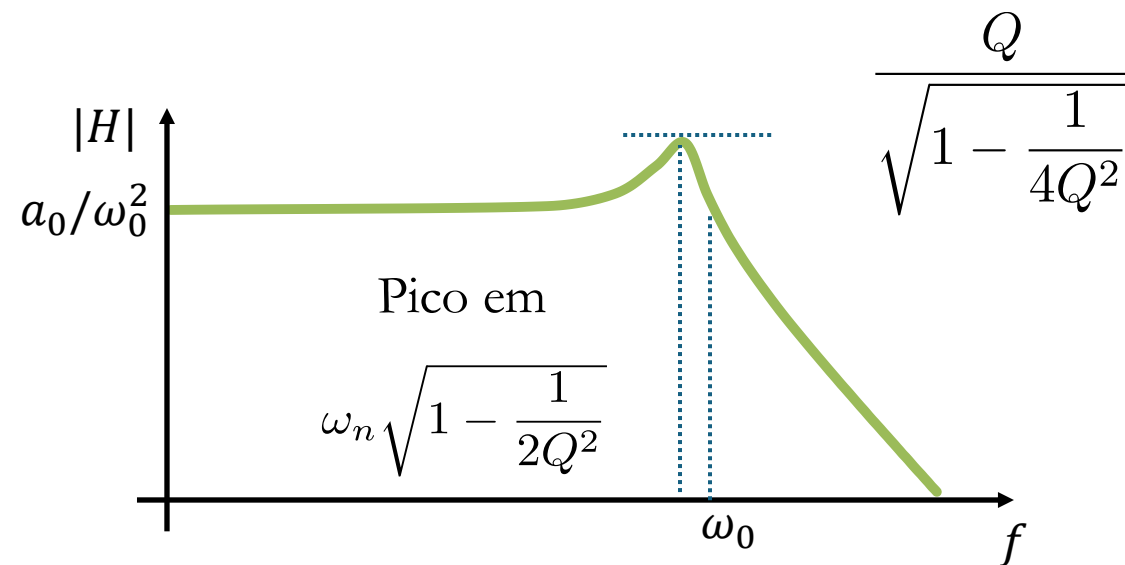
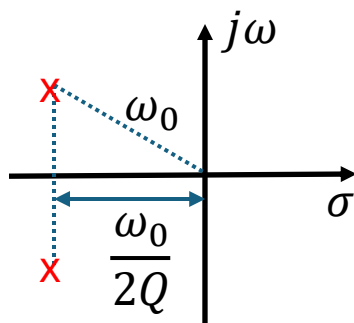
Com amplitude
normalizada de

$$\frac{Q}{\sqrt{1 - \frac{1}{4Q^2}}}$$



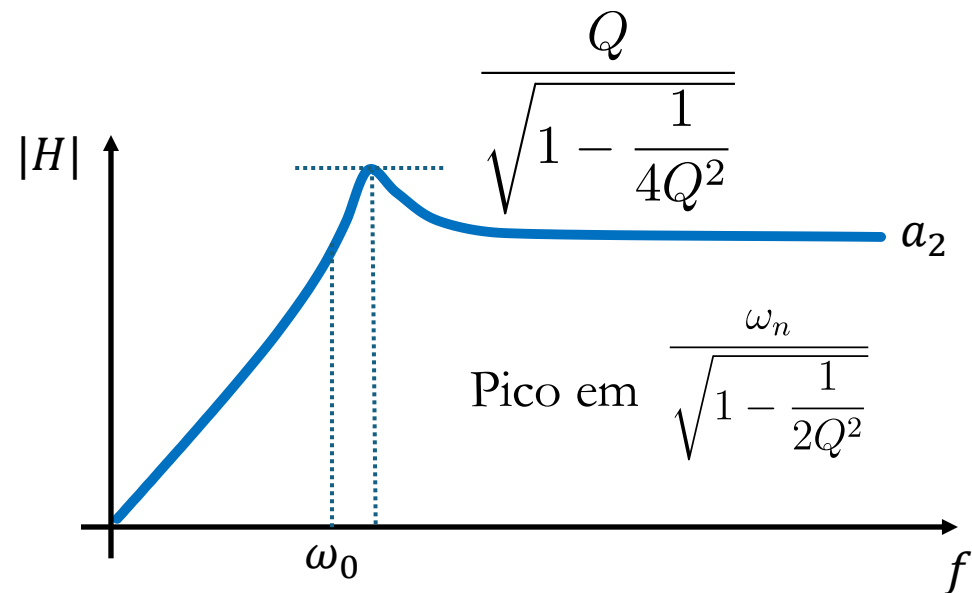
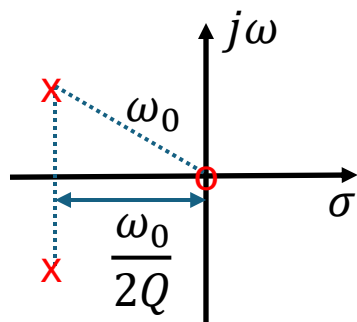
Low pass (LP)

$$H(s) = \frac{a_0}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$



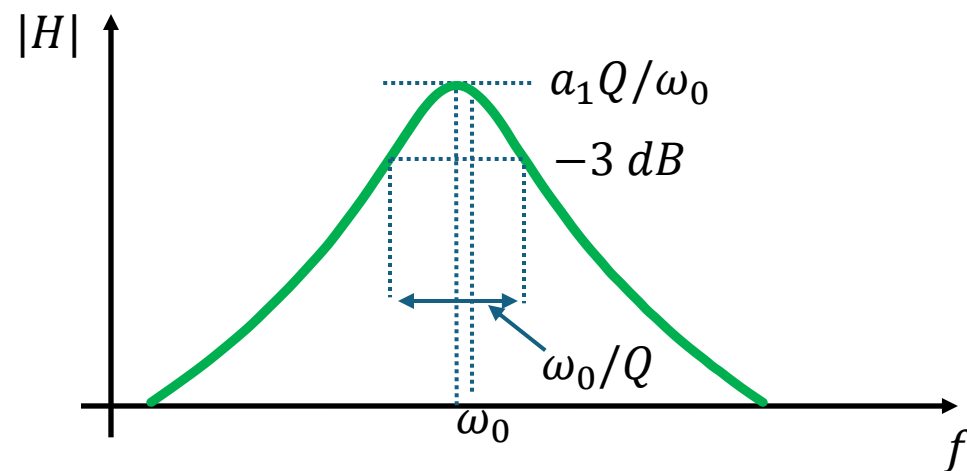
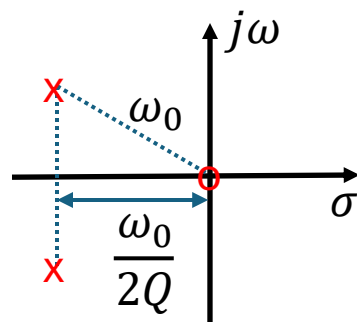
High pass (HP)

$$H(s) = \frac{a_2 s^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$



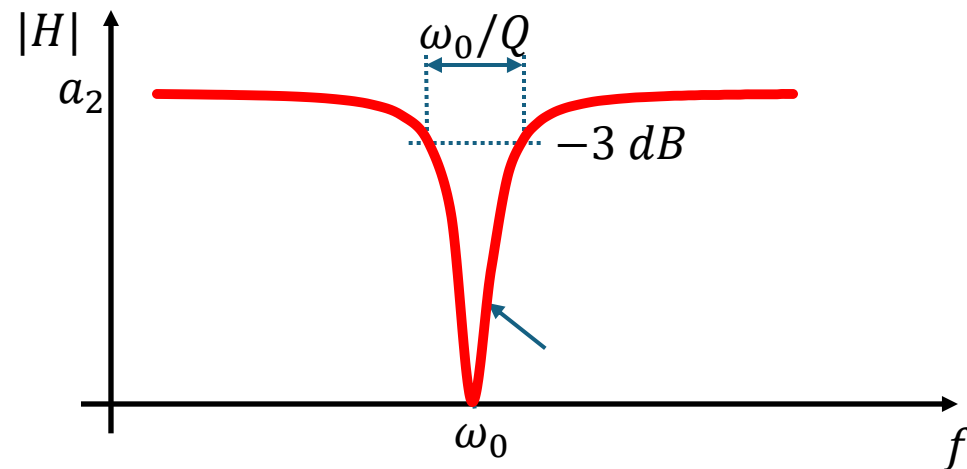
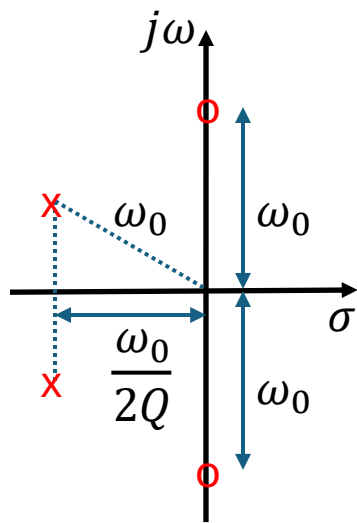
Banda passante (BP)

$$H(s) = \frac{a_1 s}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$



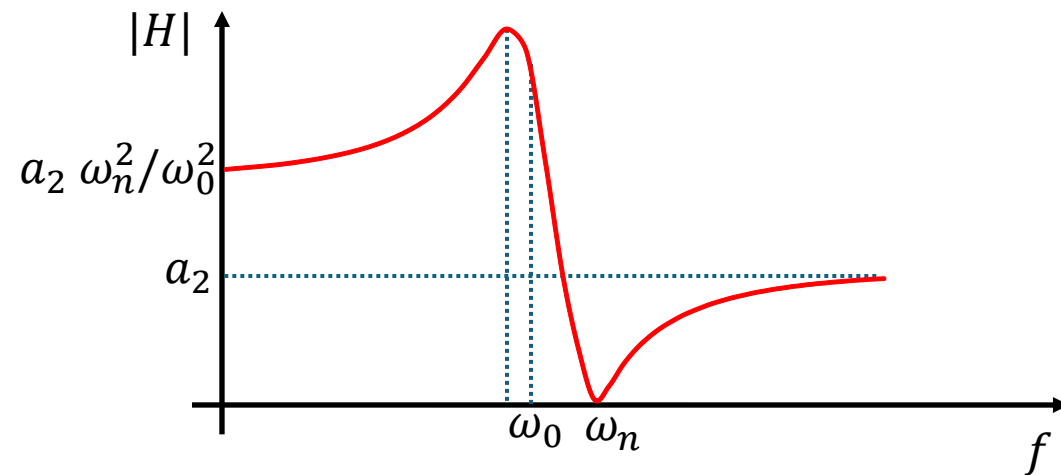
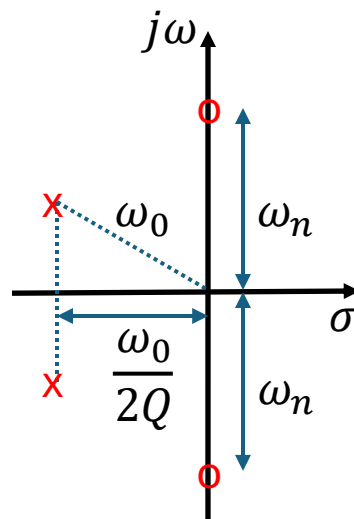
Rejeita faixa

$$H(s) = a_2 \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2}$$



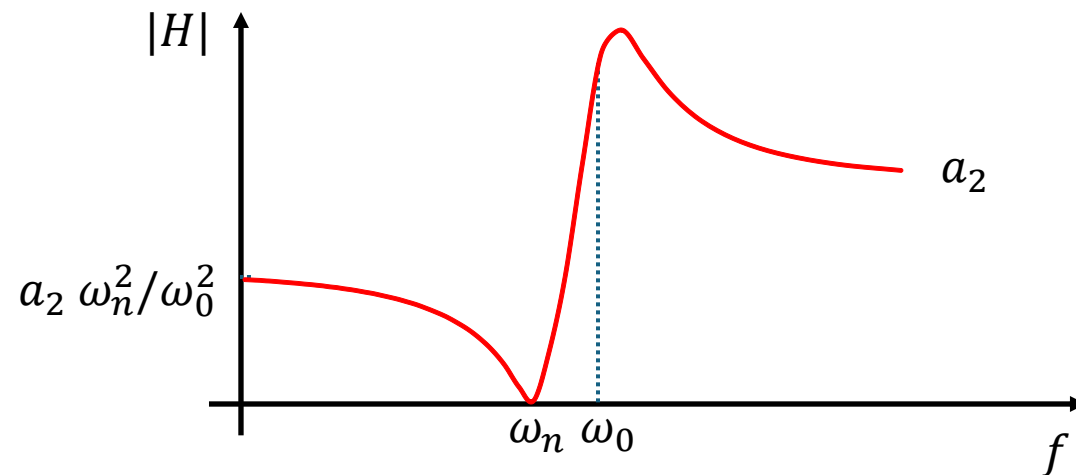
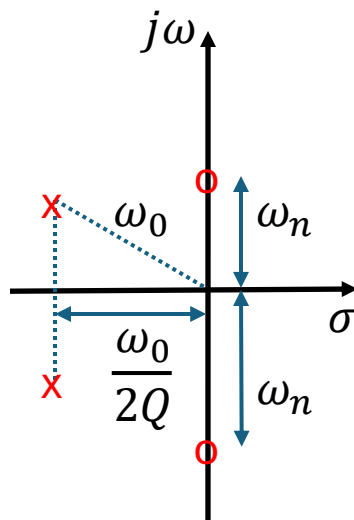
Passa baixas notch (LPN)

$$H(s) = a_2 \frac{s^2 + \omega_n^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

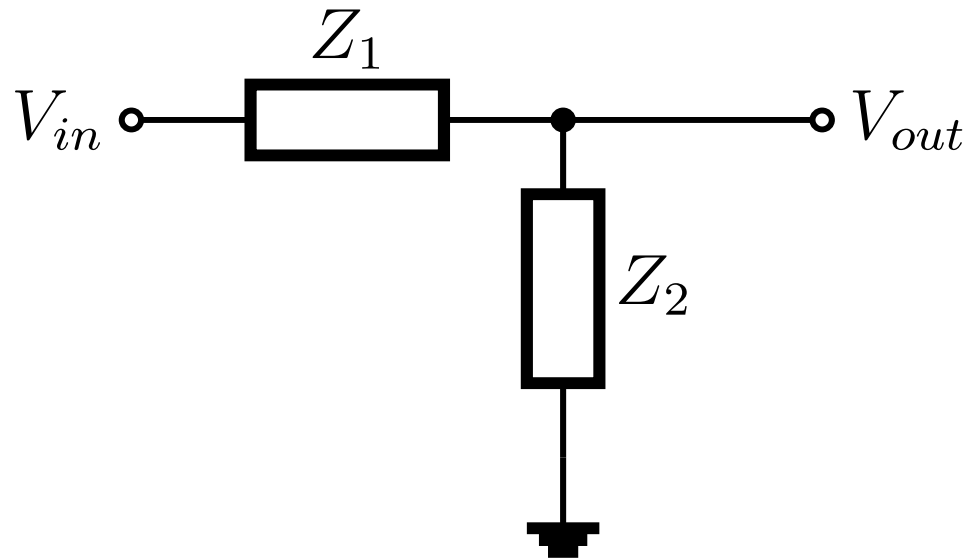


Passa altas notch (HPN)

$$H(s) = a_2 \frac{s^2 + \omega_n^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

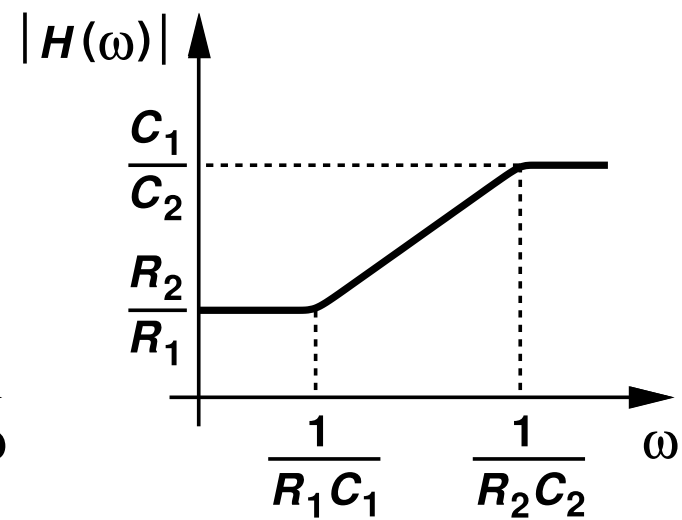
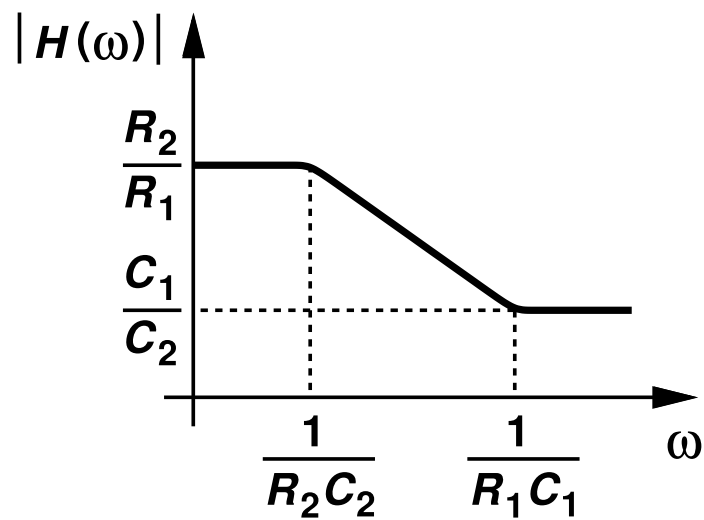
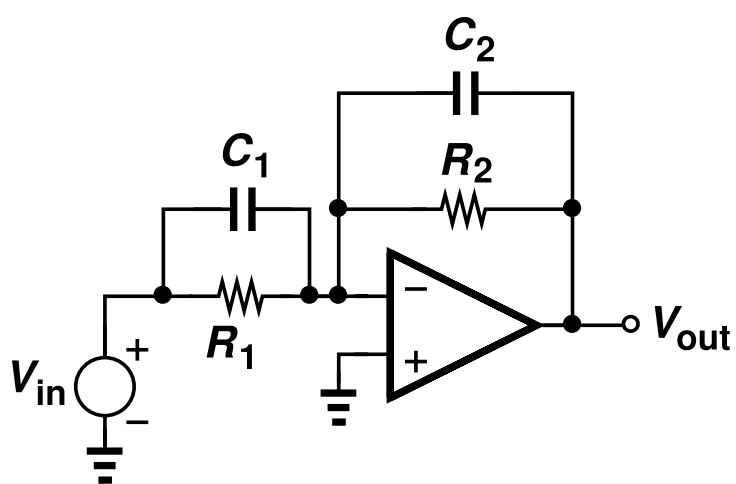


Estrutura geral de um filtro de segunda ordem



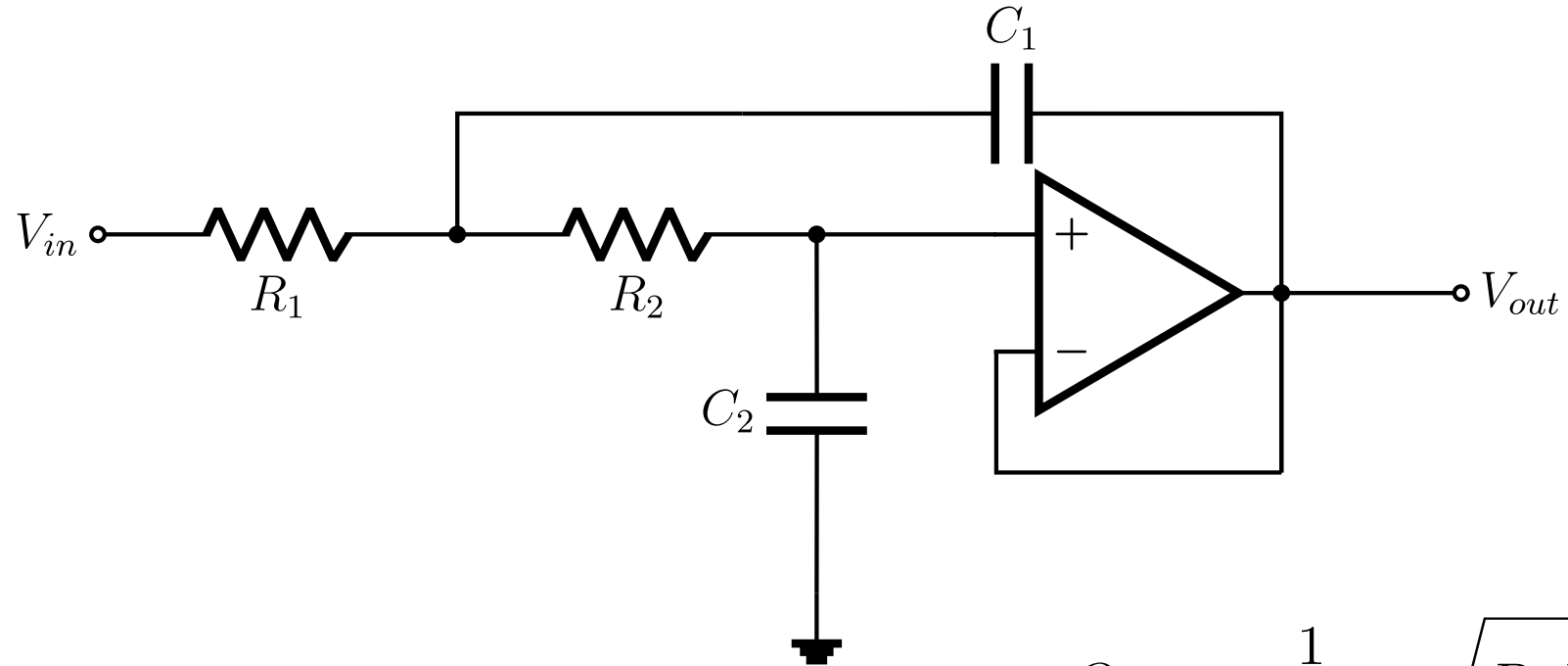
$$H(s) = \frac{V_{out}}{V_{in}} = \frac{Z_2(s)}{Z_1(s) + Z_2(s)}$$

Filtro ativo de primeira ordem



Filtro ativo de segunda ordem

Filtro de Sallen-Key



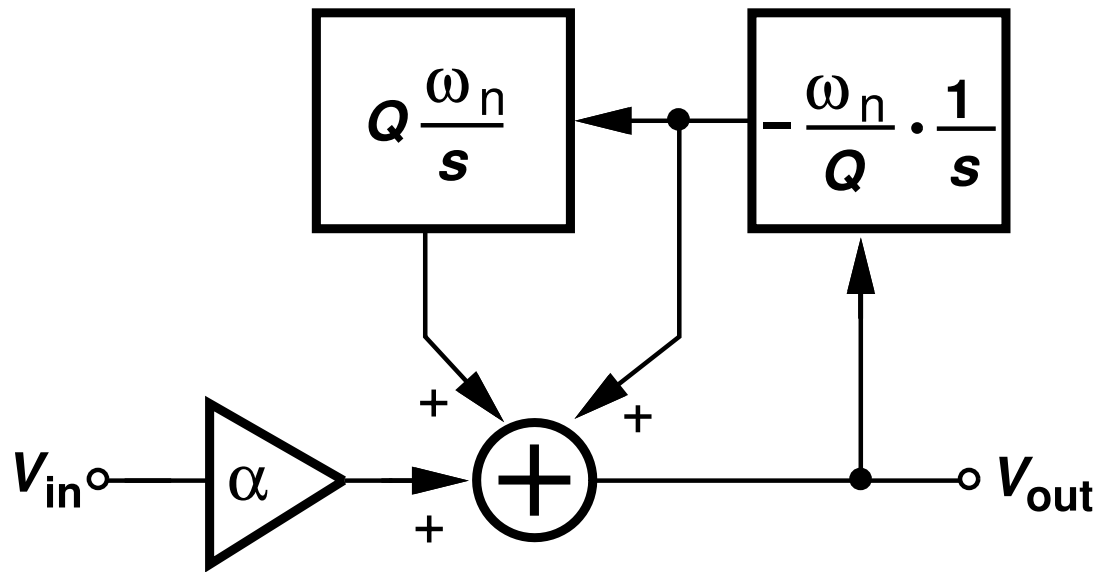
$$H(s) = \frac{1}{R_1 R_2 C_1 C_2 s^2 + (R_1 + R_2) C_2 s + 1}$$

$$Q = \frac{1}{R_1 + R_2} \sqrt{R_1 R_2 \frac{C_1}{C_2}}$$

$$\omega_n = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

Filtro ativo de segunda ordem

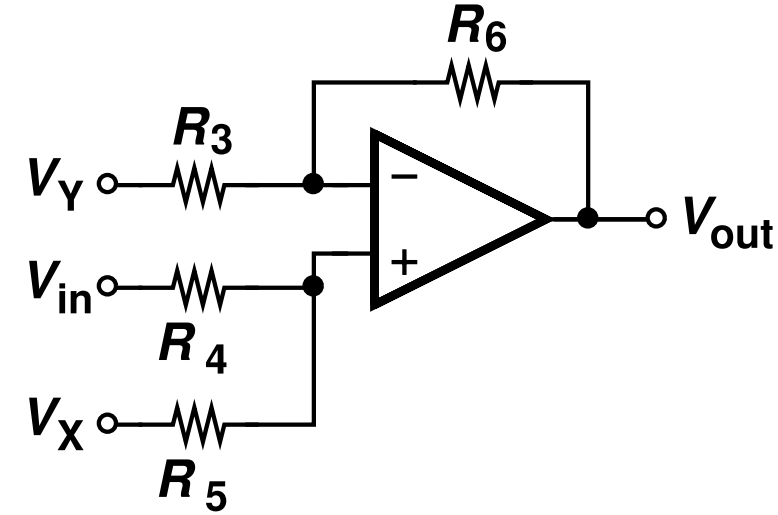
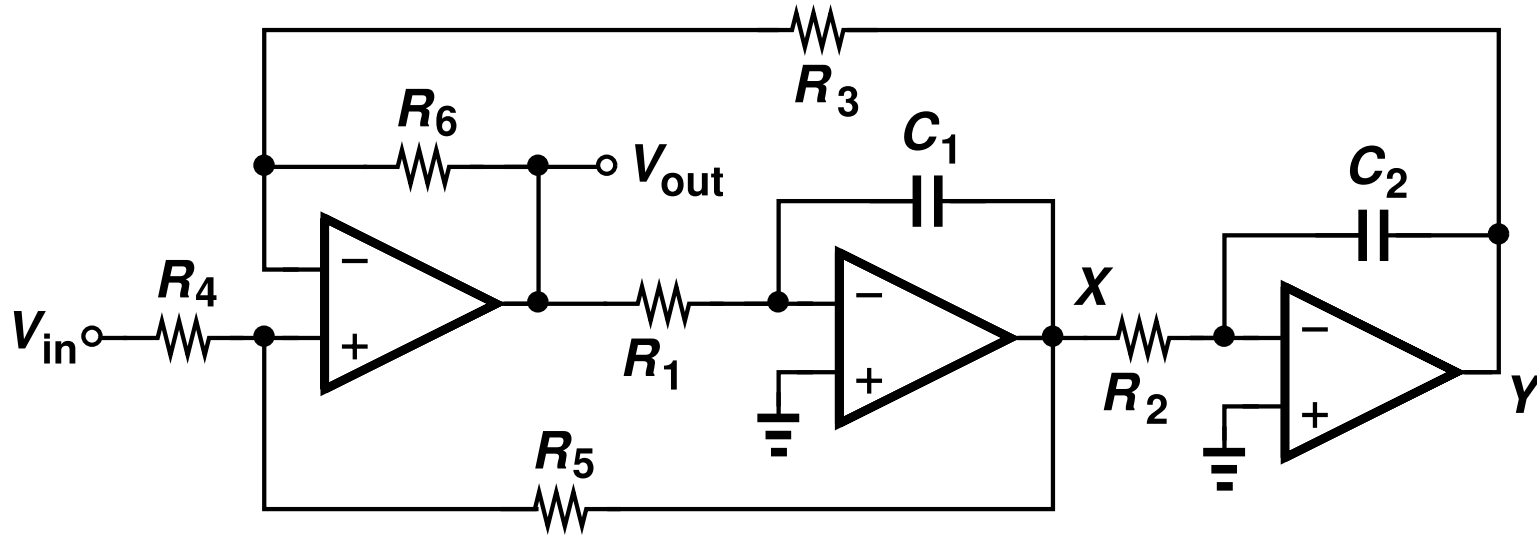
Estrutura biquadrática
baseada em integradores



$$\frac{V_{out}}{V_{in}}(s) = \frac{\alpha s^2}{s^2 + \omega_n/Q s + \omega_n^2}$$

$$V_{out}(s) = \alpha V_{in}(s) - \frac{\omega_n}{Q} \frac{1}{s} V_{out}(s) - \frac{\omega_n^2}{s^2} V_{out}(s)$$

Estrutura biquadrática baseada em integradores



$$\alpha = \frac{R_5}{R_4 + R_5} \left(1 + \frac{R_6}{R_3} \right)$$

$$\frac{V_{out}}{V_{in}} = \frac{\alpha s^2}{s^2 + (\omega_n/Q)s + \omega_n^2}$$

$$\frac{\omega_n}{Q} = \frac{R_4}{R_4 + R_5} \frac{1}{R_1 C_1}$$

$$\frac{V_X}{V_{in}} = \frac{\alpha s^2}{s^2 + \omega_n/Q s + \omega_n^2} \cdot \frac{-1}{R_1 C_1 s}$$

$$\omega_n^2 = \frac{R_6}{R_3} \frac{1}{R_1 R_2 C_1 C_2}$$

$$\frac{V_Y}{V_{in}} = \frac{\alpha s^2}{s^2 + \omega_n/Q s + \omega_n^2} \cdot \frac{1}{R_1 R_2 C_1 C_2 s^2}$$