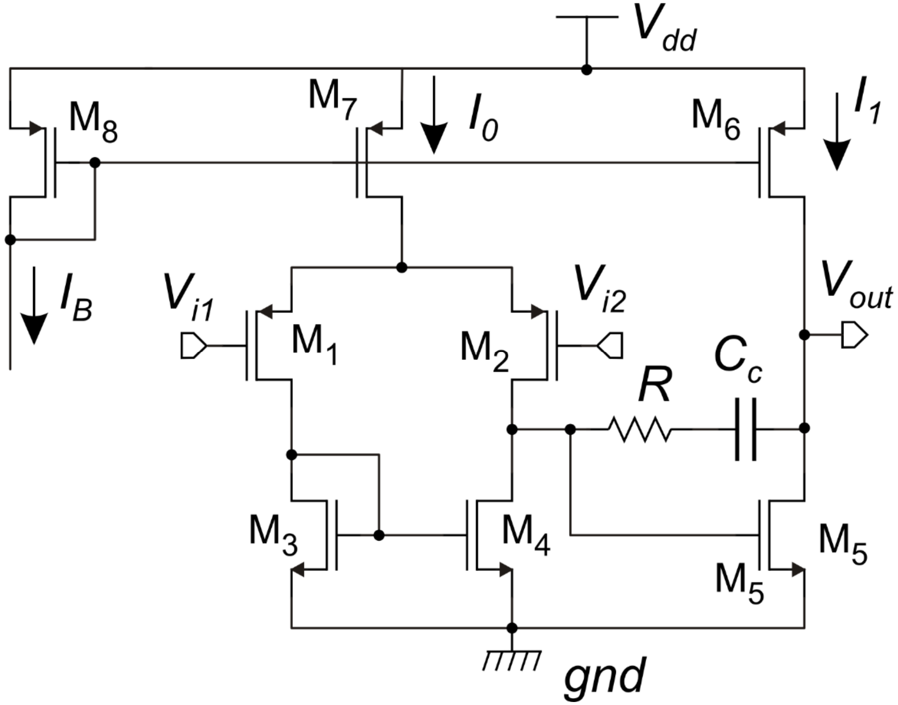
Exercise: Opamp Design



Process parameters

Parametro	n-MOS	p-MOS
μ_nCox, μ_pCox	240×10^{-6} A/V^2	50×10^{-6} A/V^2
V_{tn},V_{tp}	0.43 V	-0.56 V
γ (effetto body)	0.44 V $^{1/2}$	0.59 V $^{1/2}$
k_λ	50 V/µm	50 V/µm
α (coeff. termico della Vt)	-1 mV / ºC	1 mV / ºC
N_{fn}, N_{fp} (fattore rumore flicker)	6×10^{-10} V^{2}µm^2	2×10^{-10} V^{2}µm^2
C_{Vt} (matching Vt)	8.5 mV·µm	8.5 mV·µm
C_β (matching beta)	0.03 µm	0.03 µm
C_{OX}	6.2 fF/ µm^2	6.2 fF/ µm^2
L_C (lunghezza minima D/S)	1.2 µm	1.2 µm
C_J	1.8 fF/µm^2	1.8 fF/µm^2
Cgdo	0.6 fF/µm	0.6 fF/µm
t_{ox}	5.6 nm	5.6 nm

Specifications

- An offset voltage (absolute value) smaller than **3 mV**
- A GBW of **10 MHz** for a load capacitance (C_L) up to **10 pF**.
- A phase margin around **70°** in unity gain configuration

Offset specification

- An offset voltage (absolute value) smaller than 3 mV

$$3\sigma_{vio} = 3 \text{ mV} \Rightarrow \sigma_{vio} = 1 \text{ mV}$$

$$\sigma_{vio}^2 = \frac{A}{W_1 L_1} + \frac{B}{W_3 L_3} \qquad A = C_{Vtp}^2 + \left[\frac{(V_{GS} - V_t)_1}{2} C_{\beta p}\right]^2 \qquad B = F^2 C_{Vtn}^2 + \left[\frac{(V_{GS} - V_t)_1}{2} C_{\beta n}\right]^2$$

$$C_{Vtp} = C_{Vtn} = 8.5 \text{ mV} \cdot \mu\text{m}$$

$$C_{\beta p} = C_{\beta n} = 0.03 \ \mu\text{m}$$

In order to reduce A and B and then the total area, we choose:

$$\left|V_{GS} - V_t\right|_1 = 100 \text{ mV}$$

$$F = \frac{g_{m3}}{g_{m1}} = \frac{\left|V_{GS} - V_t\right|_1}{(V_{GS} - V_t)_3} = \frac{1}{3}$$

Offset specification

$$\left|V_{GS}-V_t\right|_1 = 100\ \text{mV}$$

$$F = \frac{g_{m3}}{g_{m1}} = \frac{\left|V_{GS}-V_t\right|_1}{\left(V_{GS}-V_t\right)_3} = \frac{1}{3}$$

$$\Rightarrow \left(V_{GS}-V_t\right)_3 = \left(V_{GS}-V_t\right)_5 = 300\ \text{mV}$$

$$A = C_{Vtp}^2 + \left[\frac{\left(V_{GS}-V_t\right)_1}{2} C_{\beta p}\right]^2 \qquad B = \left(FC_{Vtn}\right)^2 + \left[\frac{\left(V_{GS}-V_t\right)_1}{2} C_{\beta n}\right]^2$$

$$C_{Vtp} = C_{Vtn} = 8.5\ \text{mV}\cdot\mu\text{m}$$

$$FC_{Vtn} = 2.83\ \text{mV}\cdot\mu\text{m}$$

$$C_{\beta p} = C_{\beta n} = 0.03\ \mu\text{m}$$

$$\left[\frac{\left|V_{GS}-V_t\right|_1}{2} C_{\beta p}\right] = \left[\frac{\left|V_{GS}-V_t\right|_1}{2} C_{\beta n}\right] = 1.5\ \text{mV}\cdot\mu\text{m}$$

$A = 74.5\times10^{-6}\ \text{V}^2\mu\text{m}^2$

$B = 10.3\times10^{-6}\ \text{V}^2\mu\text{m}^2$

Offset specification

A=74.5×10^{-6} V^{2}μm^2

B=10.3×10^{-6} V^{2}μm^2

Optimum area distribution between differential pair and current mirror

$$a_{opt} = \left(\frac{W_3 L_3}{W_1 L_1}\right)_{opt} = \sqrt{\frac{B}{A}} = 0.37$$

$$W_1 L_1 = \frac{1}{\sigma_{vio}^2}\left(A + \frac{B}{a_{opt}}\right) \cong 102\ \mu\text{m}^2$$

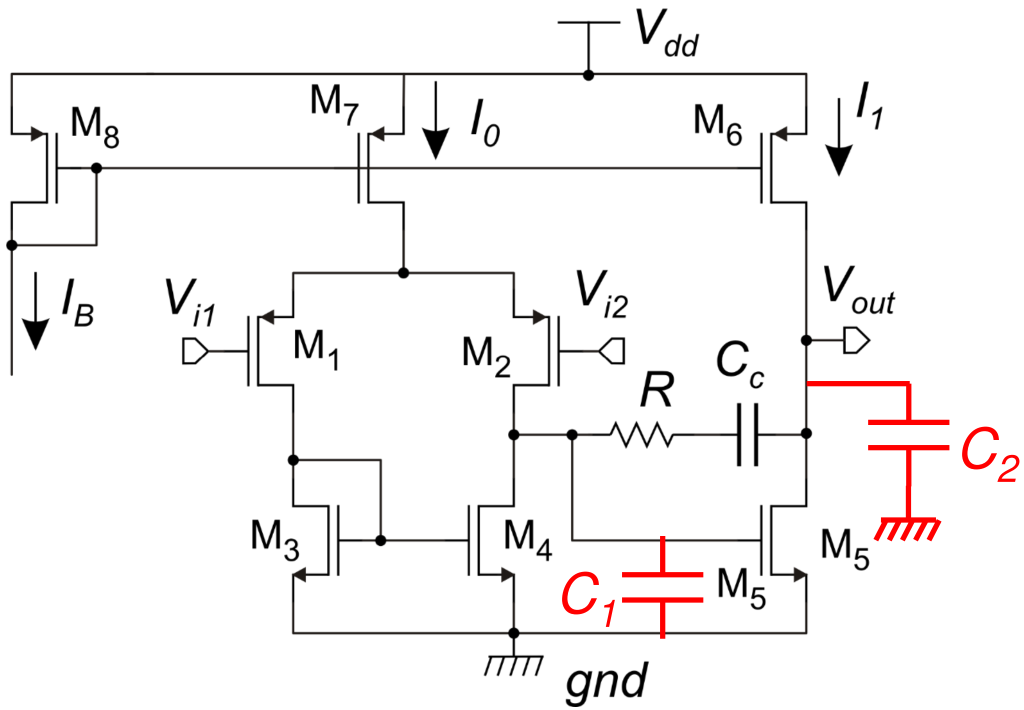
$$W_3 L_3 = a_{opt} W_1 L_1 \cong 38\ \mu\text{m}^2$$

With only the offset specification, we cannot determine other amplifier parameters.
Adding the GBW - phase margin specification we can go further into the amplifier design

GBW and phase margin

- A GBW of 10 MHz for a load capacitance (C_L) up to 10 pF.
- A phase margin around 70° in unity gain configuration

$$\sigma = \frac{\omega_2}{\omega_0} = 3$$



Hypotheses: $\begin{cases} C_1 \ll C_c, C_2 \\ C_2 = C_2' + C_L \cong C_L \end{cases}$

$$g_{m5} = 2\pi\sigma C_L \cdot GBW \cong 1.88 \text{ mS}$$

$$g_{m1} = \frac{1}{\sigma}\frac{C_C}{C_L} g_{m5}$$

Using the rule of thumb C_C=C_L:

$$g_{m1} = \frac{g_{m5}}{\sigma} \cong 0.63 \text{ mS}$$

Calculation of device aspect ratios

$$g_{m5} \cong 1.88\ \text{mS} \quad g_{m1} \cong 0.63\ \text{mS}$$

$$g_{m5} = \mu_n C_{OX} \frac{W_5}{L_5}(V_{GS} - V_t)_5 \quad \Rightarrow \quad \frac{W_5}{L_5} = \frac{g_{m5}}{\mu_n C_{OX}(V_{GS} - V_t)_5} = 26.1$$

$$\mu_n C_{ox} = 240 \times 10^{-6} \ \ \text{A/V}^2$$

300 mV

$$\frac{W_1}{L_1} = \frac{g_{m1}}{\mu_p C_{OX}(V_{GS} - V_t)_1} = 126$$

$$\mu_p C_{ox} = 50 \times 10^{-6} \ \ \text{A/V}^2$$

100 mV

$$g_{m3} = F \cdot g_{m1} = 0.21\ \mu\text{S}$$

$$\frac{W_3}{L_3} = \frac{g_{m3}}{\mu_n C_{OX}(V_{GS} - V_t)_3} = 2.92$$

300 mV

Determination of M1, M3 and M5 size

From offset specification → $W_1 L_1 = 102\ \mu\text{m}^2$

From GBW specification → $\dfrac{W_1}{L_1} = 126$

$$\left.\begin{array}{l} W_1 L_1 = 102\ \mu\text{m}^2 \\ \dfrac{W_1}{L_1} = 126 \end{array}\right\} \Rightarrow W_1 = \sqrt{W_1 L_1 \cdot \frac{W_1}{L_1}} \cong 114\,\mu\text{m} \qquad L_1 = W_1 \cdot \left(\frac{W_1}{L_1}\right)^{-1} \cong 0.9\ \mu\text{m}$$

From offset specification → $W_3 L_3 = 38\ \mu\text{m}^2$

From F=3 → $\dfrac{W_3}{L_3} = 2.92$

$$\left.\begin{array}{l} W_3 L_3 = 38\ \mu\text{m}^2 \\ \dfrac{W_3}{L_3} = 2.92 \end{array}\right\} \Rightarrow W_3 = \sqrt{W_3 L_3 \frac{W_3}{L_3}} \cong 10.5\,\mu\text{m} \qquad L_3 = W_3 \cdot \left(\frac{W_3}{L_3}\right)^{-1} \cong 3.6\ \mu\text{m}$$

From L_5=L_3 arbitrary constraint → $L_5 = 3.6\ \mu\text{m}$

From GBW specification → $\dfrac{W_5}{L_5} = 26.1$

$$\left.\begin{array}{l} L_5 = 3.6\ \mu\text{m} \\ \dfrac{W_5}{L_5} = 26.1 \end{array}\right\} \Rightarrow W_5 \cong 94\ \mu\text{m}$$

Determination of M6 and M7 size

$$I_{D6} = I_{D5}$$

$$|V_{GS} - V_t|_6 = (V_{GS} - V_t)_5 \quad \text{(Arbitrary constraint)}$$

$$I_D = \frac{\beta}{2}(V_{GS} - V_t)^2$$

$$\beta_6 = \beta_5$$

$$\mu_p C_{OX} \frac{W_6}{L_6} = \mu_n C_{OX} \frac{W_5}{L_5} \Rightarrow \frac{W_6}{L_6} = \frac{\mu_n C_{OX}}{\mu_p C_{OX}} \frac{W_5}{L_5} \cong 125$$

In order to introduce no penalization in terms of DC gain we can set:

L_6=L_5=3.6 µm

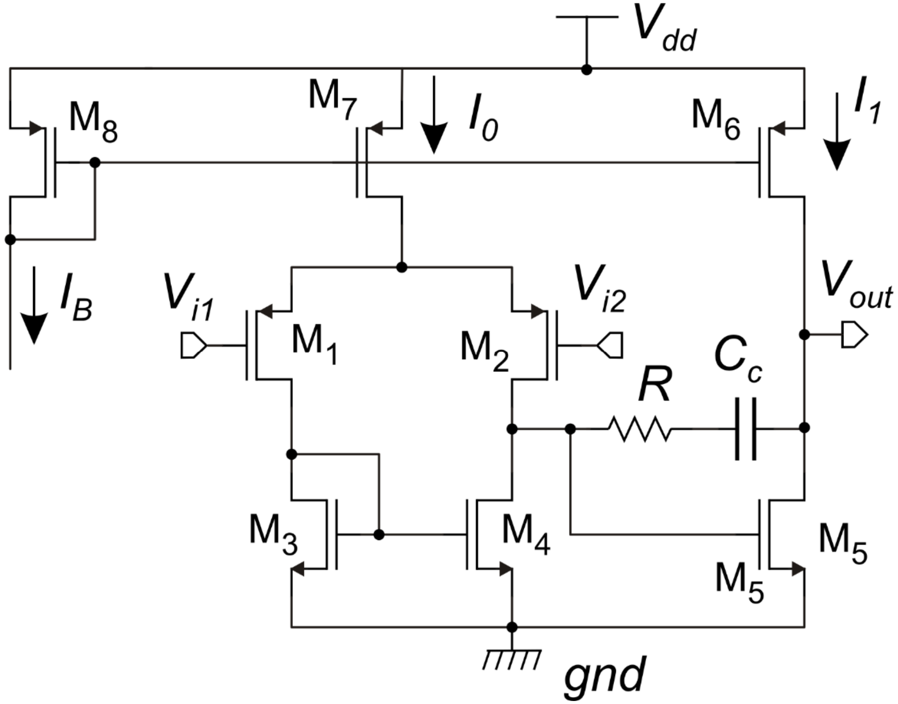
$$W_6 = L_6\left(\frac{W_6}{L_6}\right) = 450 \ \ \mu\text{m}$$

$$L_7 = L_6 = 3.6 \ \ \mu\text{m} \quad \text{(Arbitrary constraint)}$$

$$\frac{\beta_6}{\beta_7} = \frac{1}{2}\frac{\beta_5}{\beta_3} \Rightarrow \frac{\frac{W_6}{L_6}}{\frac{W_7}{L_7}} = \frac{1}{2}\frac{\frac{W_5}{L_5}}{\frac{W_3}{L_3}} \Rightarrow \frac{W_7}{L_7} = 2\frac{W_6}{L_6}\frac{\frac{W_3}{L_3}}{\frac{W_5}{L_5}} \cong 28$$

$$W_7 = L_7\left(\frac{W_7}{L_7}\right) = 101 \ \ \mu\text{m}$$

Bias and supply currents



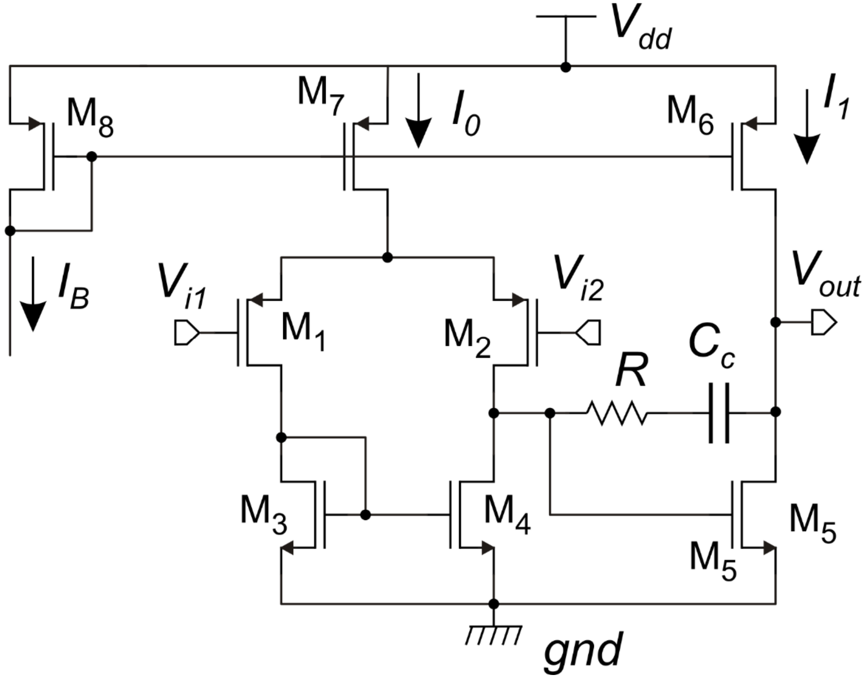
$$I_0 = 2I_{D1} \cong 2g_{m1}V_{TE1} = 2g_{m1}\frac{(V_{GS}-V_t)_1}{2} \cong 63\ \mu\text{A}$$

$$I_1 \cong g_{m5}V_{TE5} = g_{m5}\frac{(V_{GS}-V_t)_5}{2} \cong 282\ \mu\text{A}$$

In order to simplify the design:

$$I_B = I_0 = 63\ \mu\text{A}$$ ⇨ M8=M7

Total supply current (including I_B): $I_0 + I_1 + I_B \cong 408\ \mu\text{A}$



Final Design

$$V_{dd} = 2.5 \text{ V}$$

$$C_C = C_L = 10 \text{ pF}$$

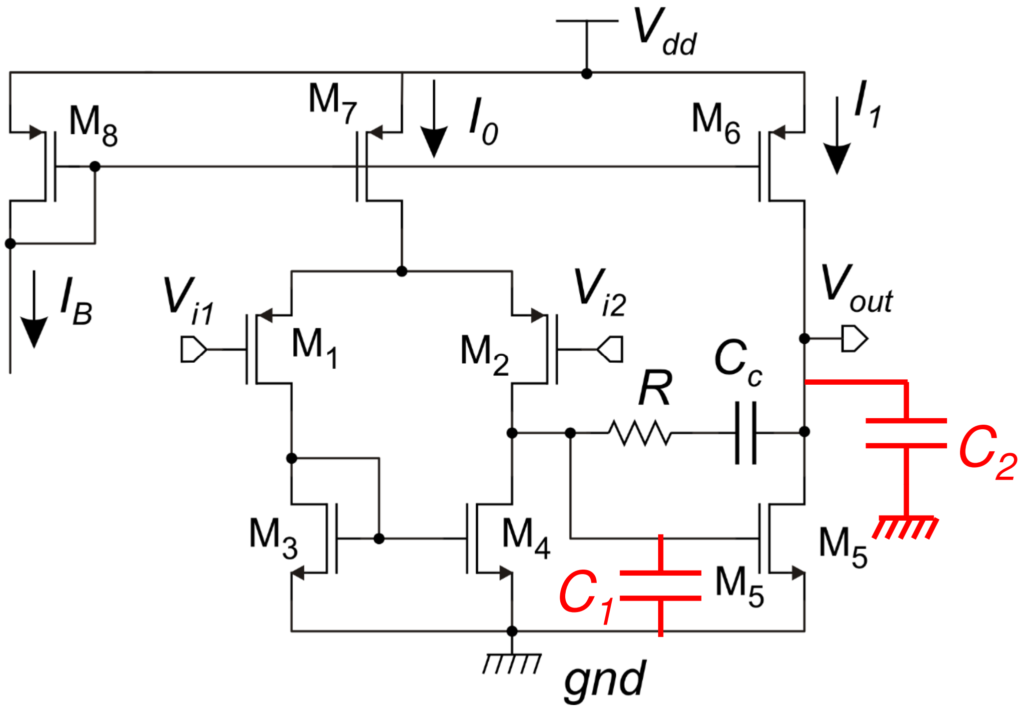
$$R_C = \frac{1}{G_{m2}} = \frac{1}{g_{m5}} = 532 \ \Omega$$

Final component table

	W (μm)	L (μm)
M_1, M_2	114	0.9
M_3, M_4	10.5	3.6
M_5	94	3.6
M_6	450	3.6

M7	101	3.6
M8	101	3.6
R	532 Ω	
C_C	10 pF	
I_B	63 μA	

Check of initial hypothesis validity



Hypotheses:

$$\begin{cases} C_1 \ll C_c, C_2 = 10 \text{ pF} \\ C_2 = C_2' + C_L \cong C_L = 10 \text{ pF} \end{cases}$$

$$C_2' \ll C_L = 10 \text{ pF}$$

$$C_1 = C_{GS5} + C_{DB2} + C_{DB4}$$

$$\left.\begin{aligned} C_{GS5} &= \frac{2}{3} C_{OX} W_5 L_5 \cong 1.4 \text{ pF} \\ C_{DB2} &= C_{Jp} L_C W_2 \cong 0.246 \text{ pF} \\ C_{DB4} &= C_{Jn} L_C W_4 \cong 0.023 \text{ pF} \end{aligned}\right\} \Rightarrow C_1 \cong 1.67 \text{ pF}$$

$$C_{OX} = 6.2 \text{ fF}/\mu\text{m}^2$$

$$C_{jn} = C_{jp} = 1.8 \text{ fF}/\mu\text{m}^2$$

$$L_C = 1.2\ \mu\text{m}$$

$$C_{jn,p} L_C = 2.16 \text{ fF}/\mu\text{m}$$

$$C'_2 = C_{DB5} + C_{DB6} = C_{jn} L_C W_5 + C_{jp} L_C W_6 \cong 1.17 \text{ pF}$$

The hypotheses are acceptable

Other performance parameters

$$S_{Vth} \cong 2\frac{8}{3}kT\frac{1}{g_{m1}}(1+F) \cong 4.5\times10^{-17}\ V^2/H_z \quad (\ 6.7\ \text{nV}/\sqrt{\text{Hz}}\ )$$

$$N_{fn} = 6\times10^{-10}\ \ \text{V}^2\mu\text{m}^2 \quad N_{fp} = 2\times10^{-10}\ \ \text{V}^2\mu\text{m}^2$$

$$k_F = 2\left(\frac{N_{fp}}{W_1L_1} + F^2\frac{N_{fn}}{W_3L_3}\right) \cong 7.42\times10^{-12}\ \ \text{V}^2$$

Flicker corner frequency

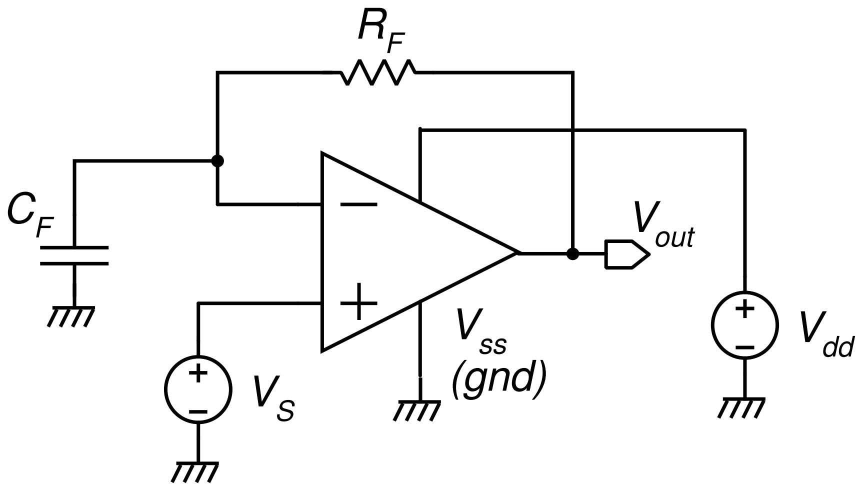
$$\text{at } f_k \Rightarrow S_{vF} = \frac{k_F}{f} = S_{VTh}$$

$$f_k = \frac{k_F}{S_{VTh}} \cong 165\ \text{kHz}$$

Slew rate:

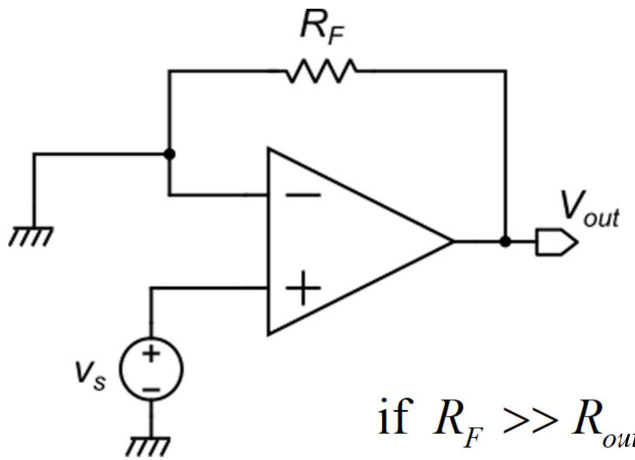
$$s_R = \frac{I_0}{C_c} = 6.3\ \text{V}/\mu\text{s}$$

Test-Bench for frequency response



if, for all frequencies of interest, $|\beta A| << 1$, then:

we can consider that the feedback is not present, thus in terms of small signal:



In DC: $V_{out}=V_S$. Setting a proper DC value for V_S we can set a correct operating point (e.g. $V_S=V_{dd}/2$)

if $R_F >> R_{out}$

and A_C *is* $<< A_D$

$$\Rightarrow \frac{v_{out}}{v_s} \cong A_d \quad (A)$$

Example:

$$R_F = 1 \text{ G}\Omega$$

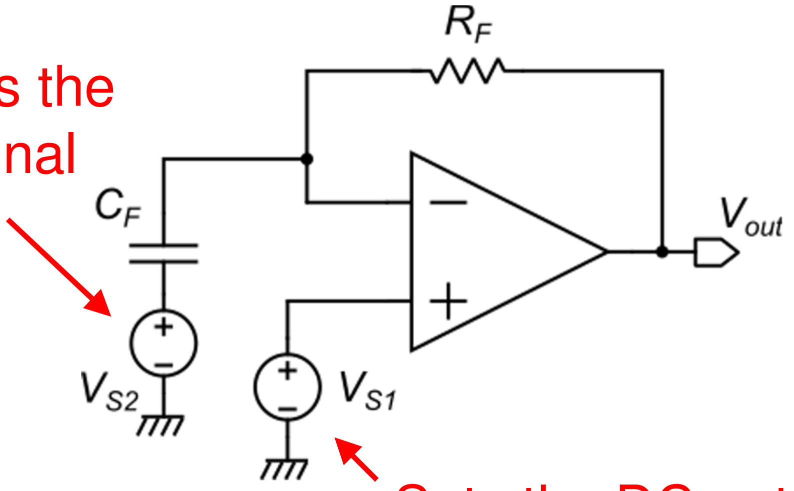
$$C_F = 1 \text{ F}$$

$$\Rightarrow f_{p\beta} = 1.59 \times 10^{-10} \text{ Hz}$$

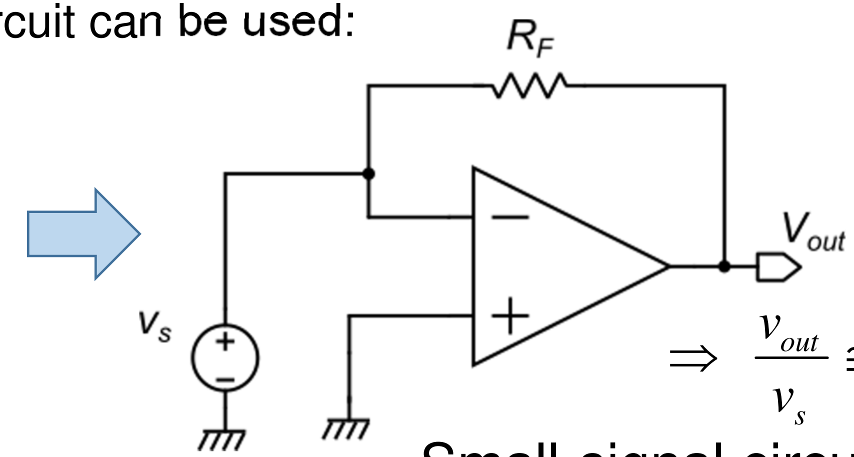
Amplification from the inverting terminal to the output

- The open-loop gain that we have found with the testbench of previous slide was not strictly the differential mode gain.
- That was the gain from the non-inverting input to the output, which is actually a combination of the differential mode and common mode gains.
- Often, the gain that matters for the stability, is the gain from the **inverting input** and the output, since in most closed-loop circuits the feedback signal stimulates only the inverting input.
- In order to simulate this gain, the following circuit can be used:

Applies the AC signal (v_s)



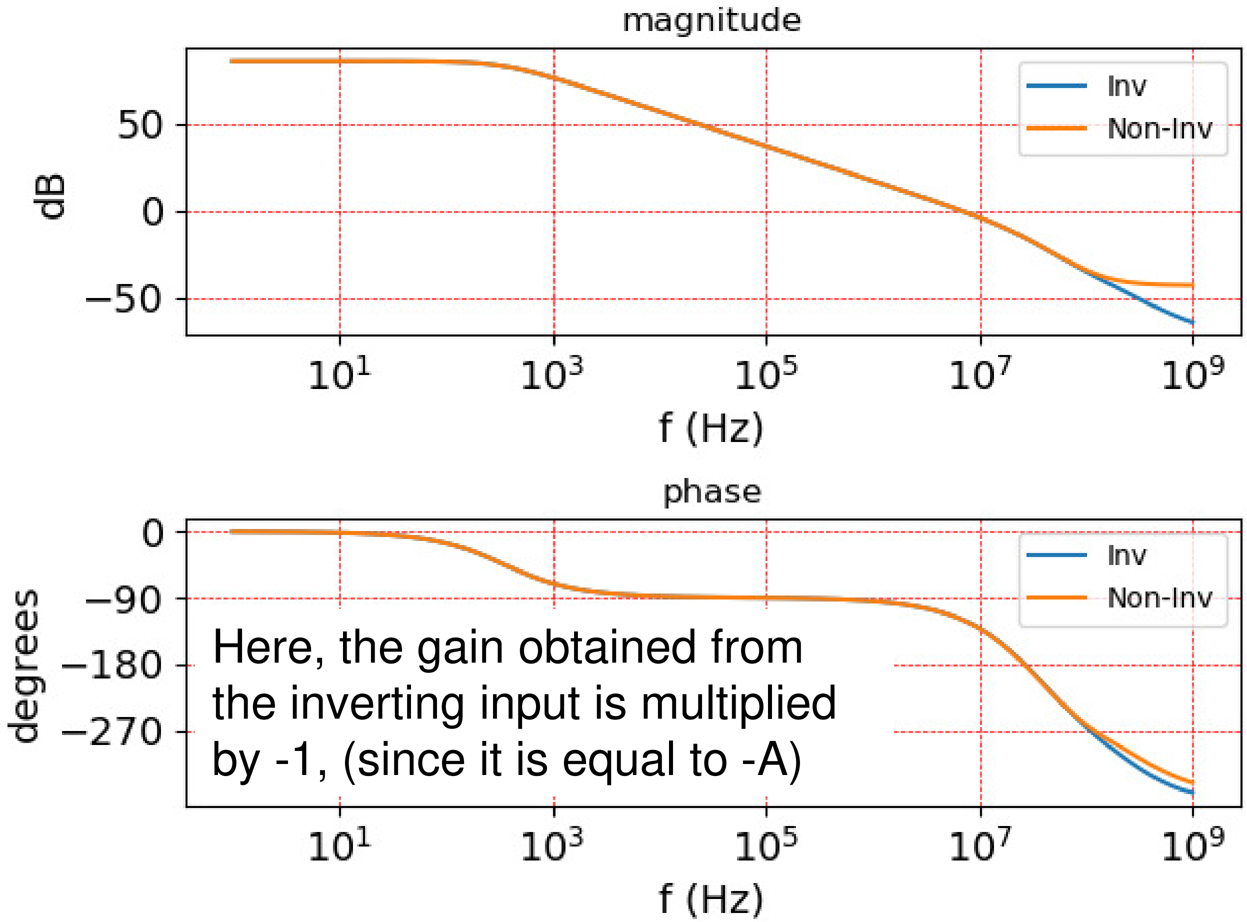
Sets the DC output voltage



$$\Rightarrow \frac{v_{out}}{v_s} \cong -A_d \quad (-A)$$

Small-signal circuit for $f \gg f_{p\beta}$

Difference between the gains measured from the inverting and non-inverting terminals for the op-amp that we have designed (from simulations)



Here, the gain obtained from the inverting input is multiplied by -1, (since it is equal to -A)

The difference occurs only at frequencies >> f_0 . Then, to study the stability, we can use one or the other gain, indifferently

The difference is due to the different impact of the first-stage singularities (mirror pole, tail pole)

For different designs (different topologies, different specifications, etc.), the differences may be more important.