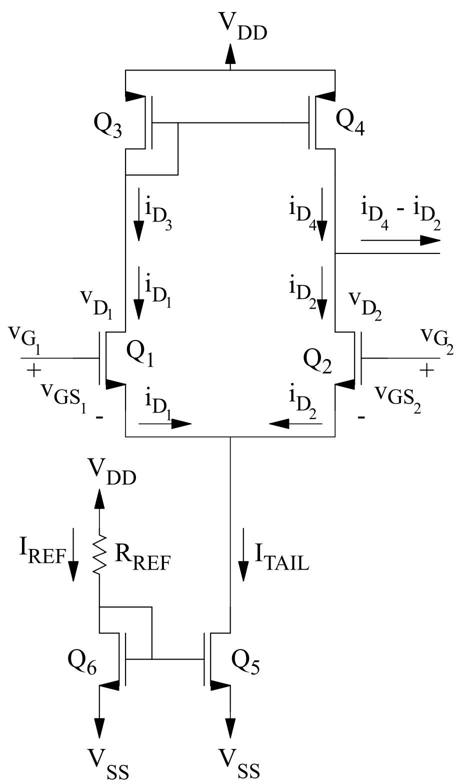
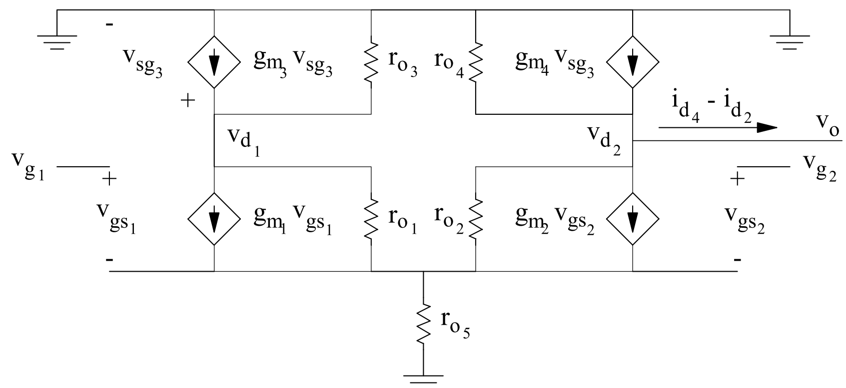
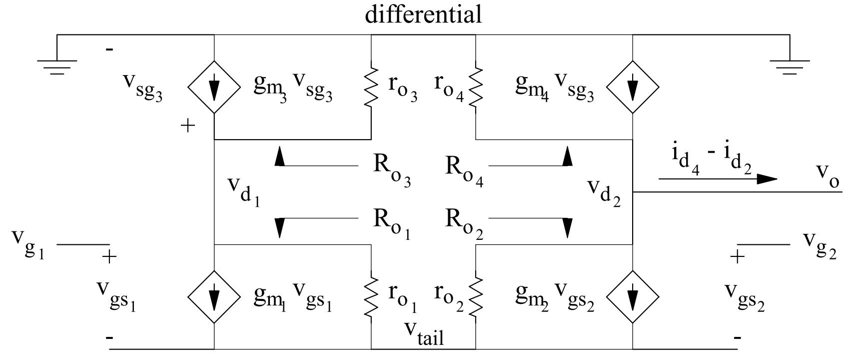
MOS transistor differential amplifiers

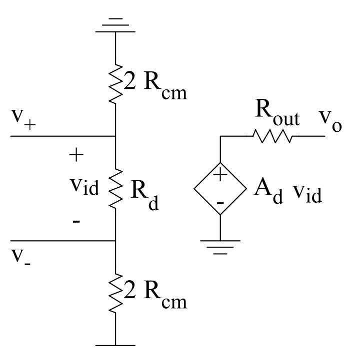
low frequency operation with active load



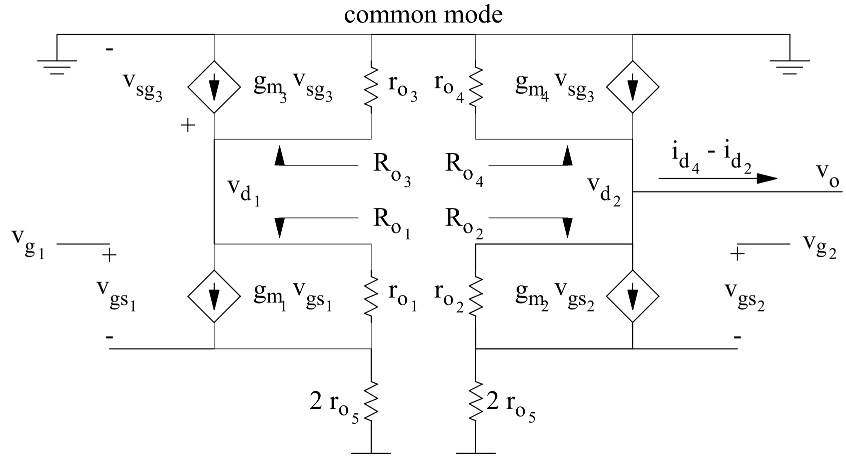


differential





common mode



for differential operation (ignoring $r_{o_1}, r_{o_2}, r_{o_3}, r_{o_4}$ on the current mirror action)

$$v_{id} = v_{g_1} - v_{g_2} \quad ; \quad v_{g_1} = +\frac{v_{id}}{2} \quad ; \quad v_{g_2} = -\frac{v_{id}}{2} \quad ; \quad i_{d_3} = i_{d_1} = g_{m_1}\left(+\frac{v_{id}}{2}\right) \quad ; \quad i_{d_2} = g_{m_2}\left(-\frac{v_{id}}{2}\right)$$

$$v_{sg_3} = \frac{i_{d_3}}{g_{m_3}} = \frac{g_{m_1}\left(\frac{v_{id}}{2}\right)}{g_{m_3}} = \frac{g_{m_1}}{g_{m_3}}\frac{v_{id}}{2} \quad ; \quad i_{d_4} = g_{m_4} v_{sg_3} = g_{m_4}\frac{g_{m_1}}{g_{m_3}}\frac{v_{id}}{2} = g_{m_1}\frac{g_{m_4}}{g_{m_3}}\frac{v_{id}}{2} = g_{m_1}\frac{v_{id}}{2}$$

$$i_o = i_{d_4} - i_{d_2} = \left(g_{m_1}\frac{v_{id}}{2}\right) - \left(g_{m_2}\left(-\frac{v_{id}}{2}\right)\right) = \left(g_{m_1}\frac{v_{id}}{2}\right) + \left(g_{m_2}\frac{v_{id}}{2}\right) = 2\,g_{m_1}\frac{v_{id}}{2} = g_{m_1} v_{id}$$

$$A_d \equiv \frac{v_o}{v_{id}} = g_{m_1}\left(r_{o_2} \parallel r_{o_4}\right)$$

for common mode operation (ignoring $r_{o_1}, r_{o_2}, r_{o_3}, r_{o_4}$ on the current mirror action)

$$v_{icm} = \frac{v_{g_1} + v_{g_2}}{2} \quad ; \quad R_{o_1} = r_{o_1} + \left(1 + g_{m_1} r_{o_1}\right)2\,r_{o_5} \quad ; \quad R_{o_2} = r_{o_2} + \left(1 + g_{m_2} r_{o_2}\right)2\,r_{o_5} \quad ; \quad R_{o_3} = \frac{1}{g_{m_3}} \quad ; \quad R_{o_4} = r_{o_4}$$

$$R_{out} = R_{o_4} \parallel R_{o_2} = \left(r_{o_4}\right) \parallel \left(r_{o_2} + \left(1 + g_{m_2} r_{o_2}\right)2\,r_{o_5}\right) \approx r_{o_4}$$

$$i_{d_3} = i_{d_1} = \frac{v_{icm}}{\frac{1}{g_{m_1}} + 2\,r_{o_5}} = \frac{g_{m_1} v_{icm}}{1 + 2\,g_{m_1} r_{o_5}} \quad ; \quad i_{d_2} = \frac{v_{icm}}{\frac{1}{g_{m_2}} + 2\,r_{o_5}} = \frac{g_{m_2} v_{icm}}{1 + 2\,g_{m_2} r_{o_5}} \quad ; \quad i_{d_4} = \frac{g_{m_4}}{g_{m_3}} i_{d_3} = \frac{g_{m_4}}{g_{m_3}}\frac{g_{m_1} v_{icm}}{1 + 2\,g_{m_1} r_{o_5}}$$

$$i_o = i_{d_4} - i_{d_2} = \left(\frac{g_{m_4}}{g_{m_3}}\frac{g_{m_1} v_{icm}}{1 + 2\,g_{m_1} r_{o_5}}\right) - \left(\frac{g_{m_2} v_{icm}}{1 + 2\,g_{m_2} r_{o_5}}\right) = \left(\left(\frac{g_{m_4}}{g_{m_3}}\frac{g_{m_1}}{1 + 2\,g_{m_1} r_{o_5}}\right) - \left(\frac{g_{m_2}}{1 + 2\,g_{m_2} r_{o_5}}\right)\right)v_{icm}$$

$$v_o = i_o R_{out} \quad ; \quad A_{cm} \equiv \frac{v_o}{v_{icm}} = \left(\left(\frac{g_{m_4}}{g_{m_3}}\frac{g_{m_1}}{1 + 2\,g_{m_1} r_{o_5}}\right) - \left(\frac{g_{m_2}}{1 + 2\,g_{m_2} r_{o_5}}\right)\right)r_{o_4}$$

$$CMRR \equiv \frac{A_d}{A_{cm}} = \frac{\left(g_{m_1}\frac{g_{m_4}}{g_{m_3}}\right)\left(r_{o_2} \parallel r_{o_4}\right)}{\left(\left(\frac{g_{m_4}}{g_{m_3}}\frac{g_{m_1}}{1 + 2\,g_{m_1} r_{o_5}}\right) - \left(\frac{g_{m_2}}{1 + 2\,g_{m_2} r_{o_5}}\right)\right)r_{o_4}} \approx \frac{g_{m_1}\left(r_{o_2} \parallel r_{o_4}\right)}{\left(\frac{1}{2\,r_{o_5}} - \frac{1}{2\,r_{o_5}}\right)r_{o_4}} = \infty$$

for differential operation (including $r_{o_1}, r_{o_2}, r_{o_3}, r_{o_4}$ in the current mirror action)

$$i_{d_1} = g_{m_1}\left(+\frac{v_{id}}{2}\right) \quad ; \quad i_{d_2} = g_{m_2}\left(-\frac{v_{id}}{2}\right)$$

$$v_{sg_3} = \frac{i_{d_1}}{g_{m_3} + \frac{1}{r_{o_1}} + \frac{1}{r_{o_3}}} = i_{d_1}\left(\frac{r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\right) = \left(g_{m_1}\frac{v_{id}}{2}\right)\left(\frac{r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\right)$$

$$i_{d_4} = g_{m_4}\, v_{sg_3} = g_{m_4}\left(\left(g_{m_1}\frac{v_{id}}{2}\right)\left(\frac{r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\right)\right) = \frac{g_{m_1}\, g_{m_4}\, r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\,\frac{v_{id}}{2}$$

$$i_o = i_{d_4} - i_{d_2} = \left(\frac{g_{m_1}\, g_{m_4}\, r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\,\frac{v_{id}}{2}\right) - \left(g_{m_2}\left(-\frac{v_{id}}{2}\right)\right) = \frac{g_{m_1}\, g_{m_4}\, r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\,\frac{v_{id}}{2} + g_{m_2}\frac{v_{id}}{2}$$

$$v_o = i_o\, R_{out} = \left(\frac{g_{m_1}\, g_{m_4}\, r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}}\,\frac{v_{id}}{2} + g_{m_2}\frac{v_{id}}{2}\right)\left(r_{o_2} \parallel r_{o_4}\right)$$

$$A_d \equiv \frac{v_o}{v_{id}} = \frac{1}{2}\left(\frac{g_{m_1}\, g_{m_4}\, r_{o_1}\, r_{o_3}}{g_{m_3}\, r_{o_1}\, r_{o_3} + r_{o_1} + r_{o_3}} + g_{m_2}\right)\left(r_{o_2} \parallel r_{o_4}\right)$$

for common mode operation (including $r_{o_1}, r_{o_2}, r_{o_3}, r_{o_4}$ in the current mirror action)

$$i_{d_1} = \frac{v_{icm}}{\frac{1}{g_{m_1}} + 2\,r_{o_5}} = \frac{g_{m_1}\,v_{icm}}{1 + 2\,g_{m_1}\,r_{o_5}} \quad ; \quad i_{d_2} = \frac{v_{icm}}{\frac{1}{g_{m_2}} + 2\,r_{o_5}} = \frac{g_{m_2}\,v_{icm}}{1 + 2\,g_{m_2}\,r_{o_5}}$$

$$v_{sg_3} = \frac{i_{d_1}}{g_{m_3} + \frac{1}{R_{o_1}} + \frac{1}{R_{o_3}}} = \frac{i_{d_1}}{g_{m_3} + \frac{1}{r_{o_1} + \left(1 + g_{m_1}\,r_{o_1}\right)2\,r_{o_5}} + \frac{1}{r_{o_3}}} \approx \frac{i_{d_1}}{g_{m_3} + \frac{1}{r_{o_3}}}$$

$$= \frac{i_{d_1}\,r_{o_3}}{1 + g_{m_3}\,r_{o_3}} = \frac{\frac{g_{m_1}\,v_{icm}}{1 + 2\,g_{m_1}\,r_{o_5}}\,r_{o_3}}{1 + g_{m_3}\,r_{o_3}} = \frac{g_{m_1}\,r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})}$$

$$i_{d_4} = g_{m_4}\,v_{sg_3} = g_{m_4}\,\frac{g_{m_1}\,r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} = \frac{g_{m_1}\,g_{m_4}\,r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})}$$

$$i_o = i_{d_4} - i_{d_2} = \left(\frac{g_{m_1}\,g_{m_4}\,r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})}\right) - \left(\frac{g_{m_2}\,v_{icm}}{1 + 2\,g_{m_2}\,r_{o_5}}\right)$$

$$= \left(\frac{g_{m_1}\,g_{m_4}\,r_{o_3}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} - \frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}}\right) v_{icm}$$

$$v_o = i_o\,R_{out} \quad ; \quad A_{cm} \equiv \frac{v_o}{v_{icm}} = \frac{g_{m_1}\,g_{m_4}\,r_{o_3}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} - \frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}}$$

$$\mathrm{CMRR} \equiv \frac{A_d}{A_{cm}} = \frac{\frac{1}{2}\left(\frac{g_{m_1}\,g_{m_4}\,r_{o_1}\,r_{o_3}}{g_{m_3}\,r_{o_1}\,r_{o_3} + r_{o_1} + r_{o_3}} + g_{m_2}\right)\left(r_{o_2} \parallel r_{o_4}\right)}{\frac{g_{m_1}\,g_{m_4}\,r_{o_3}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} - \frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}}}$$

for common mode operation (including $r_{o_1}, r_{o_2}, r_{o_3}, r_{o_4}$ in the current mirror action and g_{mb_1}, g_{mb_2})

$$i_{d_1} = \frac{v_{icm}}{\frac{1}{g_{m_1}} + 2\,r_{o_5}} + g_{mb_1}\,v_{icm} = \left(\frac{g_{m_1}}{1 + 2\,g_{m_1}\,r_{o_5}} + g_{mb_1} \right) v_{icm}$$

$$i_{d_2} = \frac{v_{icm}}{\frac{1}{g_{m_2}} + 2\,r_{o_5}} + g_{mb_2}\,v_{icm} = \left(\frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}} + g_{mb_2} \right) v_{icm}$$

$$v_{sg_3} = \frac{i_{d_1}}{g_{m_3} + \frac{1}{R_{o_1}} + \frac{1}{R_{o_3}}} = \frac{i_{d_1}}{g_{m_3} + \frac{1}{r_{o_1} + \left(1 + g_{m_1}\,r_{o_1}\right) 2\,r_{o_5}} + \frac{1}{r_{o_3}}} \approx \frac{i_{d_1}}{g_{m_3} + \frac{1}{r_{o_3}}} = \frac{i_{d_1}\,r_{o_3}}{1 + g_{m_3}\,r_{o_3}}$$

$$= \frac{\left(\left(\frac{g_{m_1}}{1 + 2\,g_{m_1}\,r_{o_5}} + g_{mb_1} \right) v_{icm} \right) r_{o_3}}{1 + g_{m_3}\,r_{o_3}} = \frac{\left(g_{m_1} + (1 + 2\,g_{m_1}\,r_{o_5})\,g_{mb_1} \right) r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})}$$

$$i_{d_4} = g_{m_4}\,v_{sg_3} = g_{m_4}\,\frac{\left(g_{m_1} + (1 + 2\,g_{m_1}\,r_{o_5})\,g_{mb_1} \right) r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})}$$

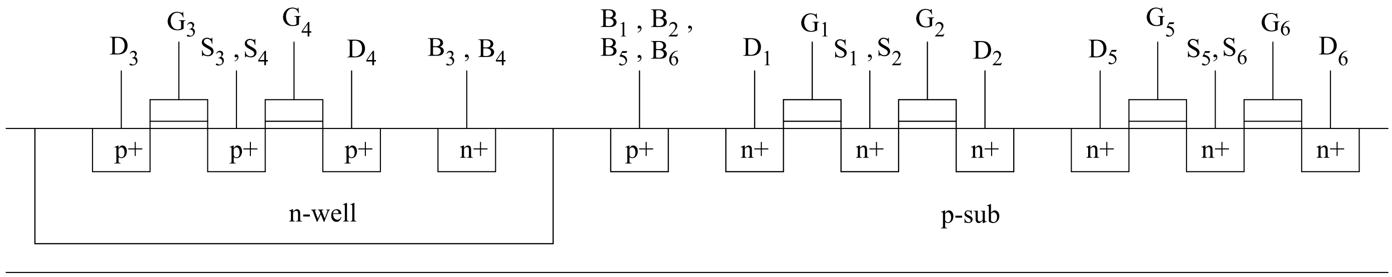
$$i_o = i_{d_4} - i_{d_2} = \left(g_{m_4}\,\frac{\left(g_{m_1} + (1 + 2\,g_{m_1}\,r_{o_5})\,g_{mb_1} \right) r_{o_3}\,v_{icm}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} \right) - \left(\left(\frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}} + g_{mb_2} \right) v_{icm} \right)$$

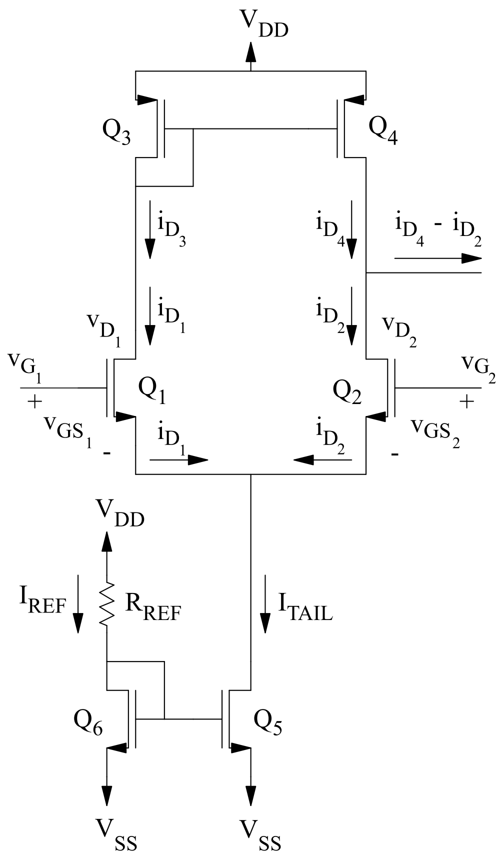
$$= \left(\frac{\left(g_{m_1} + (1 + 2\,g_{m_1}\,r_{o_5})\,g_{mb_1} \right) g_{m_4}\,r_{o_3}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} - \frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}} - g_{mb_2} \right) v_{icm}$$

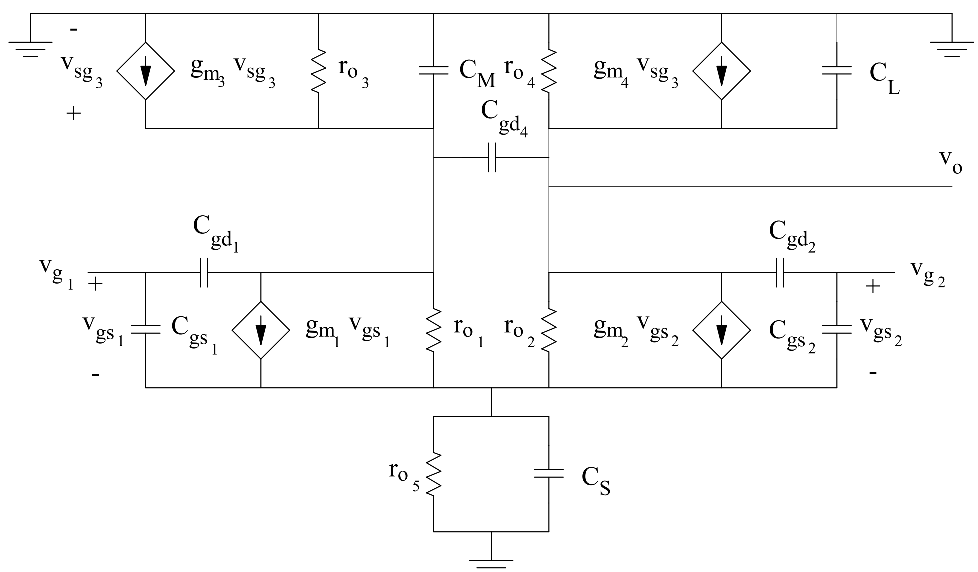
$$v_o = i_o\,R_{out} \quad ; \quad A_{cm} \equiv \frac{v_o}{v_{icm}} = \frac{\left(g_{m_1} + (1 + 2\,g_{m_1}\,r_{o_5})\,g_{mb_1} \right) g_{m_4}\,r_{o_3}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} - \frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}} - g_{mb_2}$$

$$\text{CMRR} \equiv \frac{A_d}{A_{cm}} = \frac{\frac{1}{2}\left(\frac{g_{m_1}\,g_{m_4}\,r_{o_1}\,r_{o_3}}{g_{m_3}\,r_{o_1}\,r_{o_3} + r_{o_1} + r_{o_3}} + g_{m_2} \right)\left(r_{o_2} \parallel r_{o_4} \right)}{\frac{\left(g_{m_1} + (1 + 2\,g_{m_1}\,r_{o_5})\,g_{mb_1} \right) g_{m_4}\,r_{o_3}}{(1 + 2\,g_{m_1}\,r_{o_5})(1 + g_{m_3}\,r_{o_3})} - \frac{g_{m_2}}{1 + 2\,g_{m_2}\,r_{o_5}} - g_{mb_2}}$$

high frequency operation with active load







$$C_M = C_{db_1} + C_{gs_3} + C_{db_3} + C_{gs_4}$$

$$C_L = C_{db_2} + C_{db_4} + C_x$$

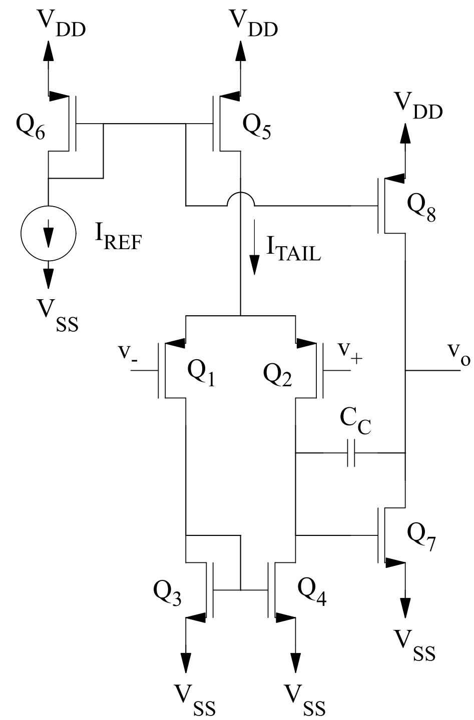
$$C_S = C_{sb_1} + C_{sb_2} + C_{db_5} + C_{gd_5}$$

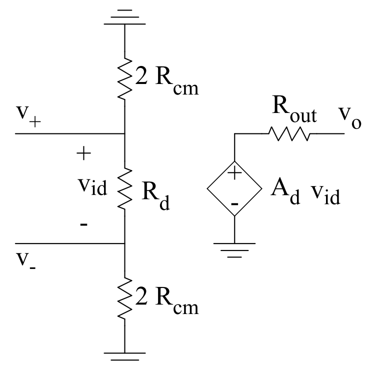
in general C_M and C_L dominate the frequency response, $f_{p_1} \approx \dfrac{1}{2\pi C_L R_{out}}$ and $f_{p_2} \approx \dfrac{1}{2\pi C_M \dfrac{1}{g_{m_3}}} = \dfrac{g_{m_3}}{2\pi C_M}$.

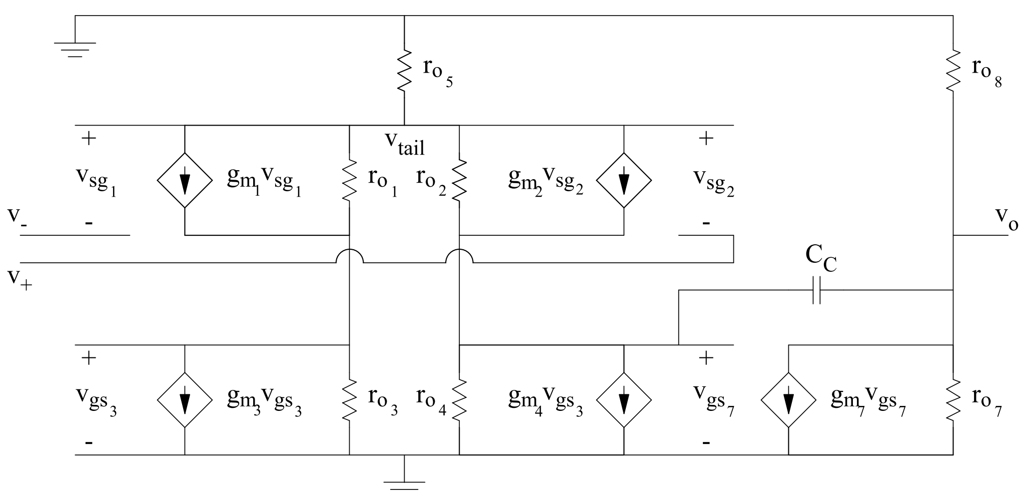
C_M also results in a pole-zero combination associated with the Q_3 and Q_4 current mirror $f_z \approx = \dfrac{2\, g_{m_3}}{2\pi C_M}$.

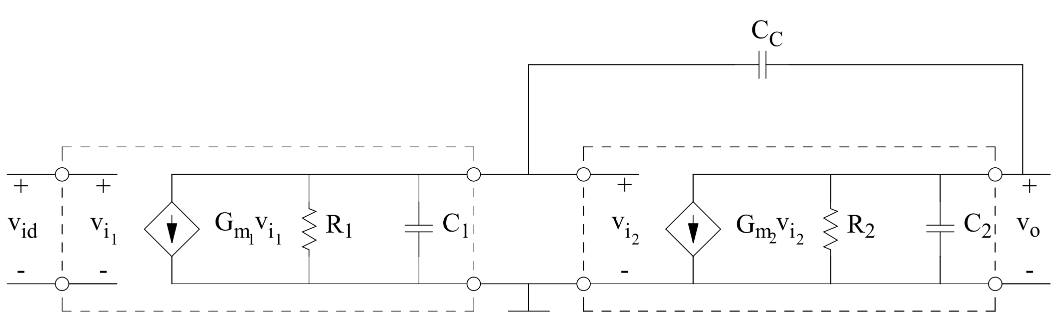
Recall that the transistors unity current gain frequency is $f_T \approx \dfrac{g_m}{2\pi(C_{gs} + C_{gd})}$ which is around f_z. This zero lift's the opamp's phase as it approachs f_T to avoid unwanted positive feedback.

multi-stage amplifiers









$$\frac{I_{D_7}}{\left(\frac{W}{L}\right)_7} = \frac{\frac{I_{TAIL}}{2}}{\left(\frac{W}{L}\right)_4} \quad ; \quad \frac{I_{D_8}}{\left(\frac{W}{L}\right)_8} = \frac{I_{TAIL}}{\left(\frac{W}{L}\right)_5} \quad ; \quad I_{D_8} = I_{D_7} \quad \rightarrow \quad \frac{\left(\frac{W}{L}\right)_7}{\left(\frac{W}{L}\right)_4} = 2\,\frac{\left(\frac{W}{L}\right)_8}{\left(\frac{W}{L}\right)_5}$$

$$V_{SS} + V_{OV_4} + V_{t_2} \le v_+ \le V_{DD} - V_{OV_5} - V_{t_2} - V_{OV_2}$$

$$V_{SS} + V_{OV_3} + V_{t_1} \le v_- \le V_{DD} - V_{OV_5} - V_{t_1} - V_{OV_1}$$

$$V_{SS} + V_{OV_7} \le v_O \le V_{DD} - V_{OV_8}$$

cascaded transconductance amplifier

$$R_d = \infty \quad ; \quad R_{cm} = \infty \quad ; \quad R_{out} = r_{o_7} \parallel r_{o_8}$$

$$A_d = A_1\,A_2 = \left(G_{m_1}\,R_1 \right)\left(G_{m_2}\,R_2 \right) = \left(g_{m_1}\,(\,r_{o_2} \parallel r_{o_4}\,) \right)\left(g_{m_7}\,(\,r_{o_7} \parallel r_{o_8}\,) \right)$$

$$C_1 \approx C_{gd_2} + C_{db_2} + C_{gd_4} + C_{db_4} + C_{gs_7} \quad ; \quad C_2 \approx C_{db_7} + C_{db_8} + C_{gd_8} + C_{load}$$

$$\omega_z \approx \frac{G_{m_2}}{C_C}$$

$$\omega_{p_1} \approx \frac{1}{R_1\left(C_1 + C_C\left(1 + G_{m_2}\,R_2 \right) \right) + R_2\,(\,C_C + C_2)} \approx \frac{1}{R_1\left(C_1 + C_C\left(1 + G_{m_2}\,R_2 \right) \right)} \approx \frac{1}{R_1\,C_C\,G_{m_2}\,R_2}$$

$$\omega_{p_2} \approx \frac{G_{m_2}\,C_C}{C_1\,C_2 + C_C\,(\,C_1 + C_2)} \approx \frac{G_{m_2}\,C_C}{C_C\,(\,C_1 + C_2)} \approx \frac{G_{m_2}}{C_1 + C_2} \approx \frac{G_{m_2}}{C_2}$$

$$\omega_t = \left(G_{m_1}\,R_1\,G_{m_2}\,R_2 \right)\omega_{p_1} = A_o\,\omega_{p_1}$$

Want $\quad \omega_t < \omega_Z \quad$ and $\quad \omega_t < \omega_{p_2}$