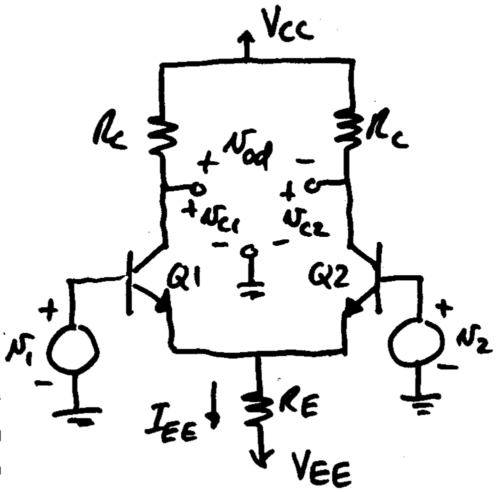
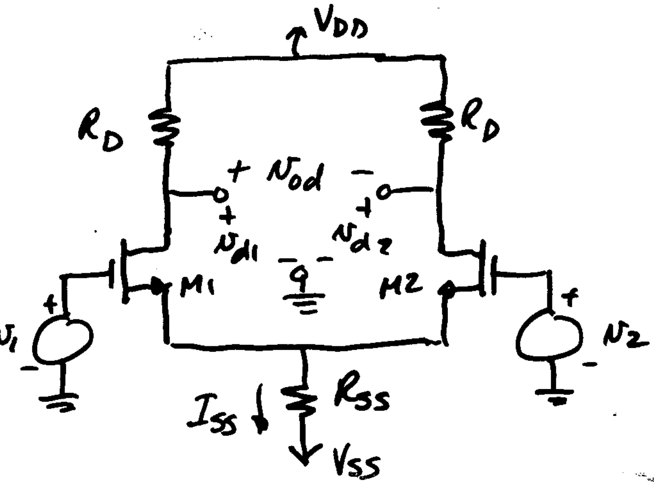
Differential Amplifiers

BJT Circuit:



MOS Circuit:



DC Analysis:

Assume that $v_1 = v_2 = 0$

$$I_{EE} = \frac{|V_{EE}| - V_{BE}}{R_E}$$

$$I_{E1} = I_{E2} = \frac{I_{EE}}{2}$$

$$I_{C1} = I_{C2} = \alpha I_E$$

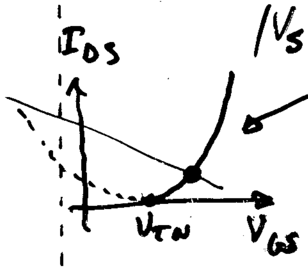
$$I_{SS} = \frac{|V_{SS}| - V_{GS}}{R_{SS}}$$

$$I_{D1} = I_{D2} = \frac{I_{SS}}{2}$$

MOS Diff. Amp Example

$V_{DD} = 5V$, $V_{SS} = -5V$, $R_S = 10k$, $R_D = 10k$, $K_n = 1mA/V^2$ & $V_{TN} = 1V$

$(v_1 = v_2 = 0)$



$$|V_{SS}| = V_{GS} + I_{SS} R_{SS} = V_{GS} + 2 I_{DS} R_{SS}$$

$$I_{DS} = \frac{K_n}{2} (V_{GS} - V_{TN})^2$$

$$|V_{SS}| = V_{GS} + R_{SS} K_n (V_{GS} - V_{TN})^2 \leftarrow V_{GS}^2 - 1.9 V_{GS} + 0.5 = 0$$

$$V_{GS} = 0.95 \pm 0.634 = 1.548 \text{ V}$$

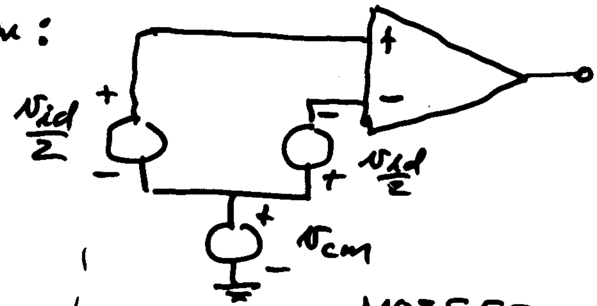
$I_{DS} = 171 \mu A$ .... $V_{DS} = 4.876V$ $\therefore$ saturated

AC Analysis of Diff. Amps

Two modes of operation:

1.) Differential (v_{id})

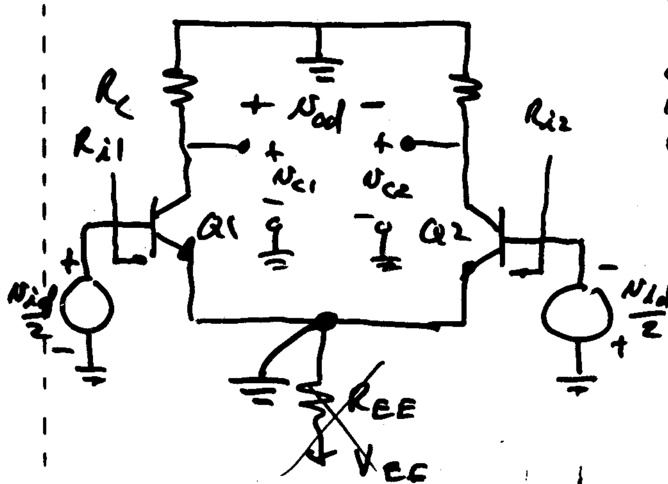
2.) Common (v_{cm})

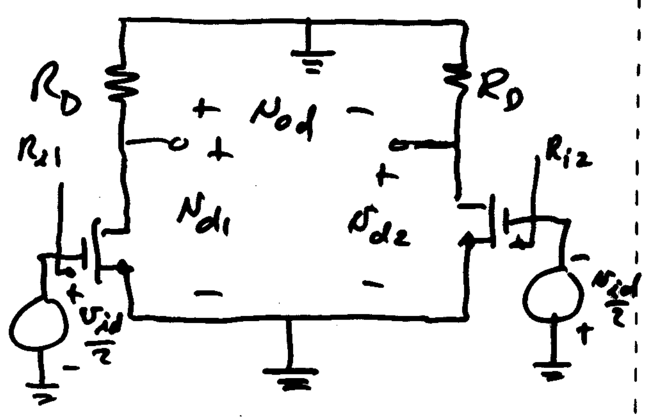


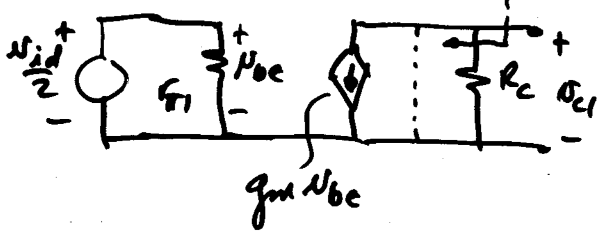
BJT | MOSFET

Differential Mode Analysis:

AC equivalent ckts:







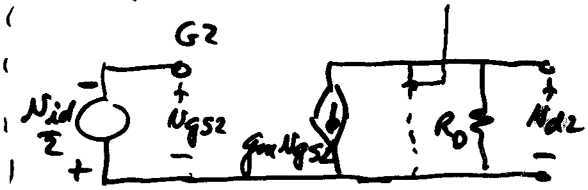
$$v_{c1} = -g_m R_C \frac{v_{id}}{2}$$

$$\frac{v_{c1}}{v_{id}} = -\frac{g_m R_C}{2}$$

$$\frac{v_{c2}}{v_{id}} = +\frac{g_m R_C}{2}$$

$$\frac{v_{od}}{v_{id}} = \frac{v_{c1}}{v_{id}} - \frac{v_{c2}}{v_{id}} = -g_m R_C$$

M2:



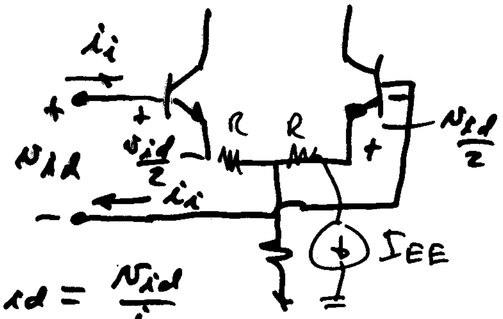
$$v_{d2} = +g_m R_D \frac{v_{id}}{2}$$

$$\frac{v_{d2}}{v_{id}} = +\frac{g_m R_D}{2}$$

$$\frac{v_{d1}}{v_{id}} = -\frac{g_m R_{D1} \| r_o}{2}$$

$$\frac{v_{od}}{v_{id}} = -g_m R_D$$

What is R_{id}?

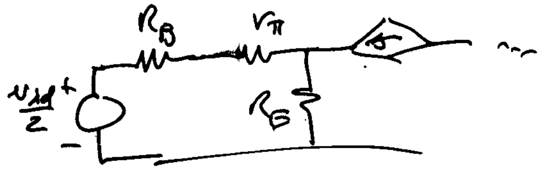


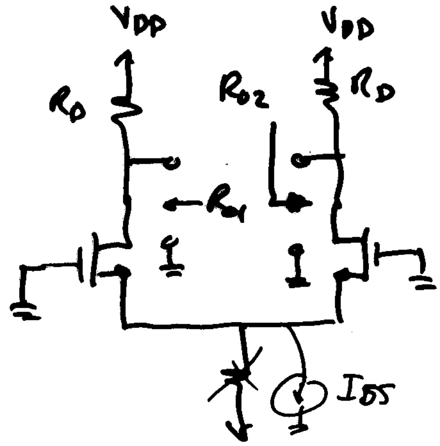
$$R_{id} = \frac{v_{id}}{i_x}$$

$$R_{id} = R_{i1} + R_{i2} = 2\,r_\pi$$

$R_{o1} \approx R_C \quad R_{o2} \approx R_C$

$$R_{od} = 2R_C$$

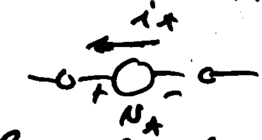




$R_{o1} = R_{D1} \| r_{o1} \cong R_{D1}$

$R_{o2} = R_{D2} \| r_{o2} \cong R_{D2}$

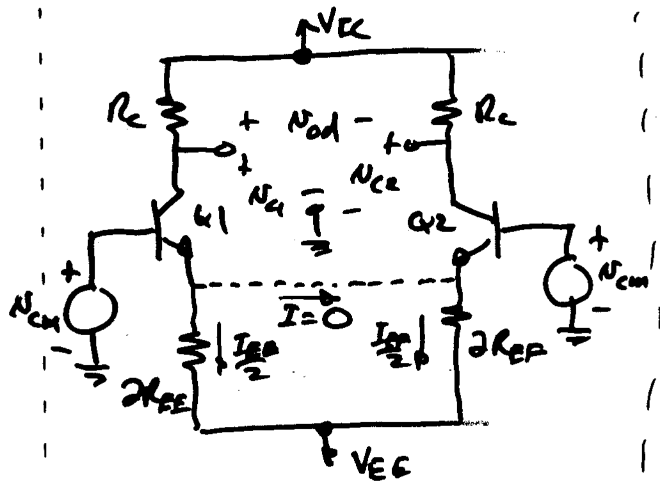
$R_{od} = ? = \frac{v_x}{i_x}$

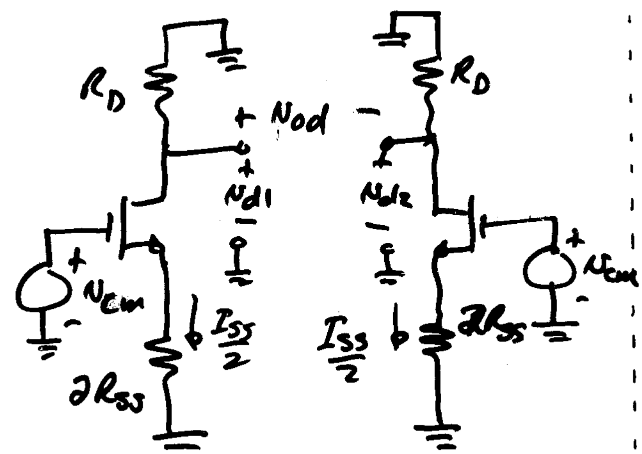


$R_{od} = R_{o1} + R_{o2}$

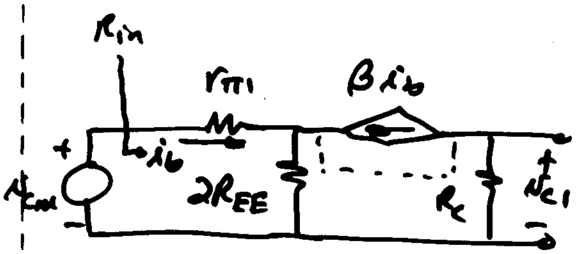
Common Mode Analysis of Diff. Amps

Common half circuit is:





Small signal analysis -



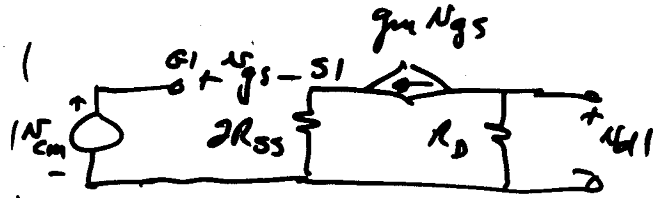
$$\frac{v_{c1}}{v_{cm}} = \left(\frac{v_{c1}}{i_b}\right)\left(\frac{i_b}{v_{cm}}\right)$$

$$= (-\beta R_c)\left(\frac{1}{r_{\pi 1} + (1+\beta)2R_{EE}}\right)$$

$$= \frac{-\beta R_c}{r_{\pi 1} + (1+\beta)2R_{EE}}$$

$$\frac{v_{c2}}{v_{cm}} = \frac{v_{c1}}{v_{cm}} \Rightarrow \frac{v_{od}}{v_{cm}} = 0$$

(Assume everything matches)



$$\frac{v_{d1}}{v_{cm}} = \left(\frac{v_{d1}}{v_{gs}}\right)\left(\frac{v_{gs}}{v_{cm}}\right)$$

$$= (-g_m R_D)(\quad)$$

$$v_{gs} = v_g - v_s = v_{cm} - 2R_{SS}\, g_m v_{gs}$$

$$v_{gs}[1 + 2R_{SS} g_m] = v_{cm}$$

$$\frac{v_{d1}}{v_{cm}} = \frac{-g_m R_D}{1 + 2R_{SS} g_m} = \frac{v_{d2}}{v_{cm}}$$

CMRR (common mode rejection ratio)

$$CMRR = \frac{\left|\frac{v_{c1}}{v_{id}}\right|}{\left|\frac{v_{c1}}{v_{cm}}\right|} = \frac{\left|\frac{v_{d1}}{v_{id}}\right|}{\left|\frac{v_{d1}}{v_{cm}}\right|}$$

$\beta = g_m r_\pi$

BJT:

$$CMRR = \frac{g_m \cancel{R_c}/2}{\frac{\beta \cancel{R_c}}{r_\pi + (1+\beta)2R_{EE}}} = \frac{r_\pi + (1+\beta)2R_{EE}}{2r_\pi} \approx \frac{(1+\beta)2R_{EE}}{2r_\pi}$$

$$\boxed{CMRR \approx g_m R_{EE}}$$

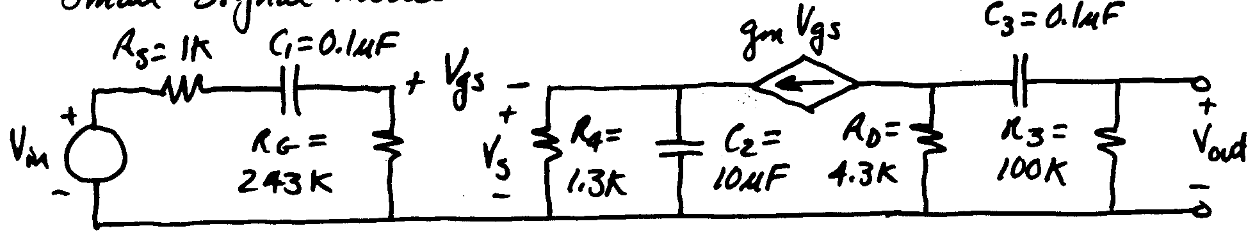
Use current sinks to improve CMRR because R_{EE} & R_{SS} become large

MOSFET:

$$CMRR = \frac{g_m R_D/2}{\frac{g_m R_D}{1+2g_m R_{SS}}} = \frac{1+2g_m R_{SS}}{2} \approx \boxed{g_m R_{SS} = CMRR}$$

MOSFET Low Frequency Example – Cont'd

Small-signal model –

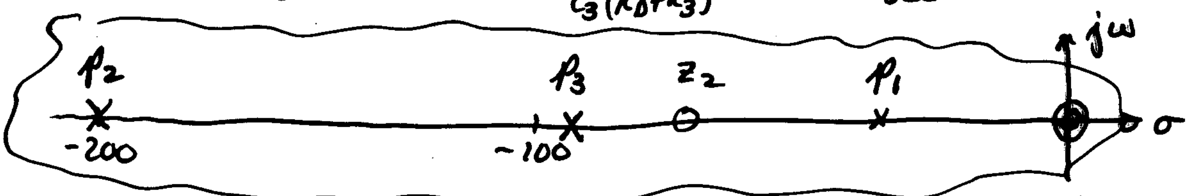


1.) Direct analysis

$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{-g_m R_D R_3 R_G}{(R_D+R_3)(R_G+R_S)}\left[\frac{s^2(s+z_2)}{(s+p_1)(s+p_2)(s+p_3)}\right]$$

$p_1 = \dfrac{-1}{C_1(R_G+R_S)} = -41\ \dfrac{\text{rads}}{\text{sec}}$, $z_2 = \dfrac{-1}{R_4 C_2} = -76.9\ \dfrac{\text{rads}}{\text{sec}}$, $p_2 = (1+g_m R_4) z_2$

$p_2 = -200\ \dfrac{\text{rads}}{\text{sec.}}$ and $p_3 = \dfrac{-1}{C_3(R_D+R_3)} = -95.9\ \dfrac{\text{rads}}{\text{sec.}}$

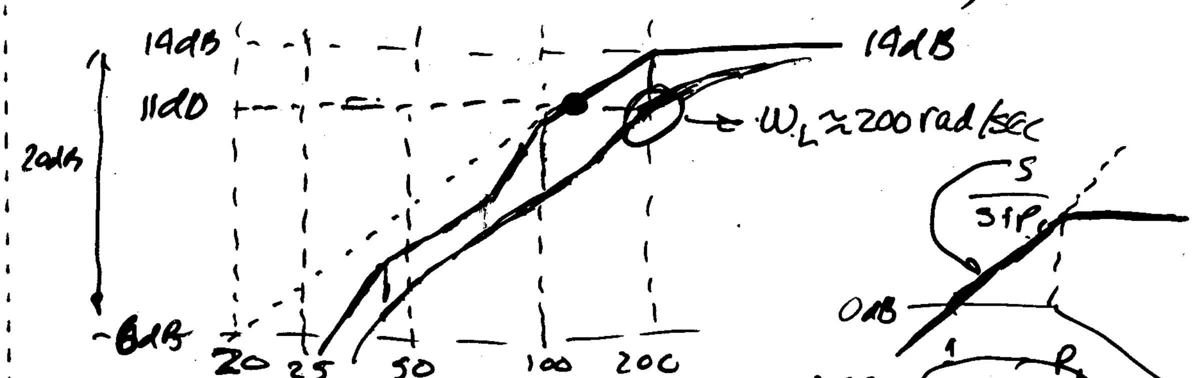


$\omega_L = ? = \omega_{-3dB}$ (lower) LF Roots

a.) $f_L = \frac{1}{2\pi}\sqrt{\sum \text{poles}^2 - 2\sum \text{zeros}^2} = \frac{1}{2\pi}\sqrt{(200)^2+(95.9)^2+(41)^2-2(76.9)^2}$

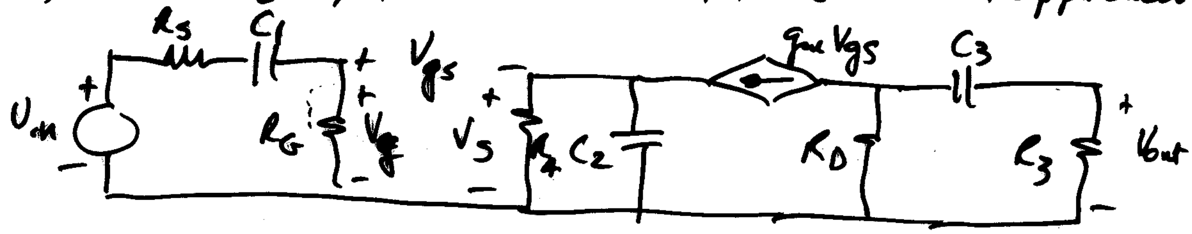
$= 31.5\ \text{Hz}$

b.) Bode Plot (Midband Gain = 14dB)



$\omega_L \cong 200 \rightarrow \frac{200}{2\pi} \cong 31.8\ \text{Hz}$

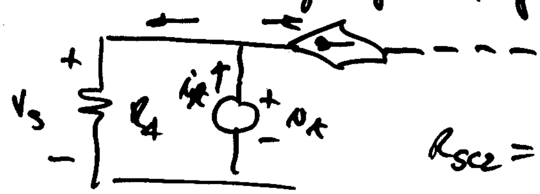
2.) Find ω_L by the short-circuit time constant approach



C_1: $R_{SC1} = R_S + R_G = 244\,K\Omega$

$$\frac{1}{C_1 R_{SC1}} = \frac{1}{(0.1\mu F)(244\,K\Omega)} = -41\text{ rad/sec} = p_1$$

C_2: R_{SC2} $\quad g_m V_{gs}$ $\quad (V_g = 0) \rightarrow g_m V_{gs} = -g_m V_s$



$$R_{SC2} = \frac{V_x}{I_x}$$

$$I_x = \frac{V_x}{R_4} + g_m V_x = V_x\left(\frac{1}{R_4} + g_m\right)$$

$$\therefore R_{SC2} = \frac{1}{g_m + \frac{1}{R_4}} = \frac{1}{g_m} \| R_4 = \frac{R_4}{1 + g_m R_4}$$

$$\frac{1}{C_2 R_{SC2}} = \frac{1 + g_m R_4}{R_4 C_2} = |p_2| = 200\text{ rad/sec}$$

C_3: $R_{SC3} = R_D + R_3 \rightarrow \frac{1}{C_3 R_{SC3}} = |p_3| = +95.9$

$$\omega_L \approx \frac{1}{R_{SC1} C_1} + \frac{1}{R_{SC2} C_2} + \frac{1}{R_{SC3} C_3} = 337\text{ rad/sec.}$$

$f_L = 53.6\text{ Hz}$???

Note: You would have been better off to use this method to find the poles and zeros (I need to show you how to do this) and use the methods used on the last page for finding ω_L.