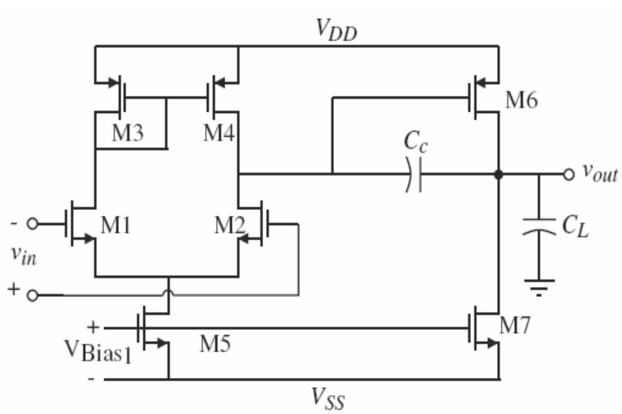
EXAMINATION NO. 2 SOLUTIONS

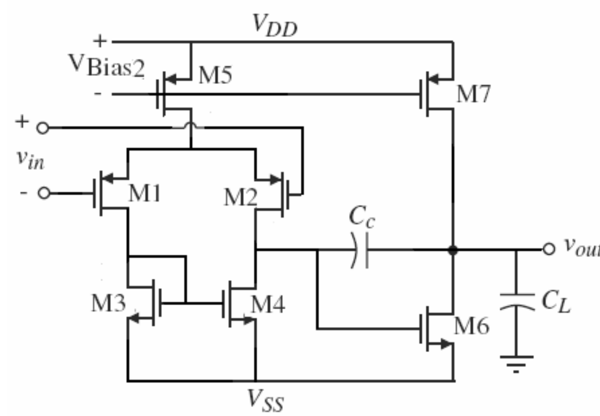
<u>Problem 1 - (35 points)</u>

The op amps below have identical DC currents and W/L values for transistors with the same number. Find parametric expressions for entries in the table in terms of bias currents I_5 and I_7, K_n', K_p', λ_N, λ_P, V_{TN}, $|V_{TP}|$, S=W/L ratios, V_{DD}, V_{SS}, C_c, C_L, and identify which is larger in magnitude for the two circuits. Assume $K'_n>K'_p$, $V_{TN}= -V_{TP}$, $\lambda_N<\lambda_P$, $(W/L)_1= (W/L)_2$, $V_{DD}=-V_{SS}$. The threshold voltage is larger than the ON (saturation) voltage. Ignore body effect.

USE THE LAST SHEET TO DO YOUR WORK AND THEN WRITE YOUR FINAL ANSWER/EXPRESSION IN THE TABLE. NO PARTIAL CREDIT.



N-channel Input Op Amp



P-channel Input Op Amp

Characteristic	N-channel Input Op Amp	<,=,>	P-channel Input Op Amp
Small-signal output resistance	$(I_7(\lambda_6+\lambda_7))^{-1}$	=	$(I_7(\lambda_6+\lambda_7))^{-1}$
Small-signal voltage gain	$\dfrac{\sqrt{8K_N'K_P'S_1S_6}}{\sqrt{I_5I_7}(\lambda_2+\lambda_4)(\lambda_6+\lambda_7)}$	=	$\dfrac{\sqrt{8K_N'K_P'S_1S_6}}{\sqrt{I_5I_7}(\lambda_2+\lambda_4)(\lambda_6+\lambda_7)}$
Gain-bandwidth	$\dfrac{\sqrt{K_N'S_1I_5}}{C_c}$	>	$\dfrac{\sqrt{K_P'S_1I_5}}{C_c}$
Upper input common mode voltage	$V_{DD}-\lvert V_{TP}\rvert+V_{TN}-\sqrt{\dfrac{I_5}{K_P'S_3}}$	>	$V_{DD}-\lvert V_{TP}\rvert-\sqrt{\dfrac{2I_5}{K_P'S_5}}-\sqrt{\dfrac{I_5}{K_P'S_1}}$
Slew rate(due to Cc)	$\dfrac{I_5}{C_c}$	=	$\dfrac{I_5}{C_c}$
Positive (V_{DD}) PSRR	no expression needed	<	no expression needed

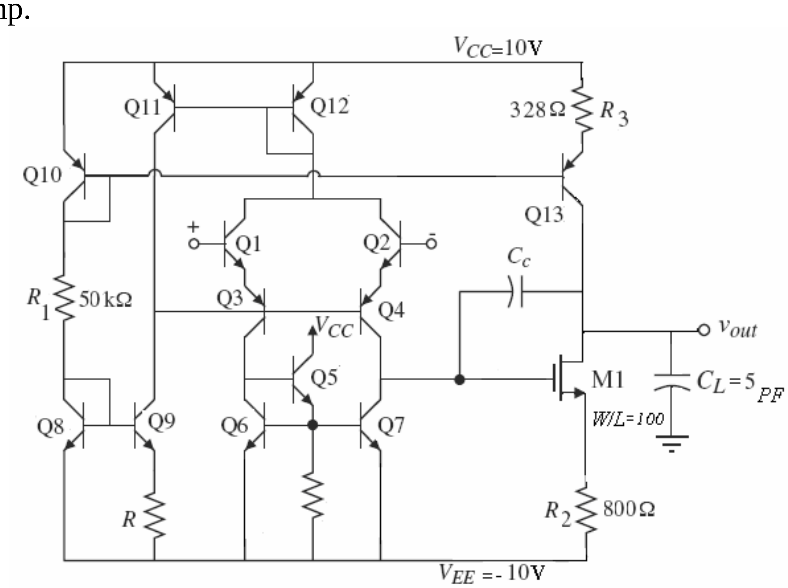
Negative (V_{SS}) PSRR	no expression needed	>	no expression needed
Phase Margin (EXTRA CREDIT)	$90^\circ - \tan^{-1}\left(\frac{\sqrt{K'_N S_1 I_5}}{\sqrt{2K'_P S_6 I_7}}\frac{C_L}{C_C}\right) - \tan^{-1}\left(\frac{\sqrt{K'_N S_1 I_5}}{\sqrt{2K'_P S_6 I_7}}\right)$	<	$90^\circ - \tan^{-1}\left(\frac{\sqrt{K'_P S_1 I_5}}{\sqrt{2K'_N S_6 I_7}}\frac{C_L}{C_C}\right) - \tan^{-1}\left(\frac{\sqrt{K'_P S_1 I_5}}{\sqrt{2K'_N S_6 I_7}}\right)$

Problem 2 - (35 points)

The device parameters for the operational amplifier shown below are given in the table. Ignore the body effect of the MOS transistor and the internal capacitances of all the transistors.

a. What resistance R in the emitter of Q9 is required to set the first stage bias currents in the emitters of Q3 and Q4 at 10μA each?
b. Calculate the overall voltage gain of the amplifier, by calculating the effective transconductances of the differential input stage and the 2nd gain stage, and their effective output resistances.
c. Calculate the value of the miller capacitance Cc required to obtain a gain-bandwidth of 2MHz for this op-amp.
d. Calculate the phase margin of this op-amp.

Parameter	NPN	PNP
Beta	200	50
Early voltage	130V	50V
VBE(on)	0.7V	0.7V
Vt	25mV	
	MOS	
lambda	$0.01V^{-1}$	
μCox	$100\mu A/V^2$	
VTO	0.7V	



a) $RI_{C9}=V_t ln(I_{C8}/I_{C9})$

$I_{C8}=(20V-1.4V)/50k\Omega=0.372mA$

$I_{C9}=20\mu A$ → $\underline{R=3.65k\Omega}$

b) $G_{mI} = \frac{g_{m1}}{1+g_{m1}r_{e3}} = \frac{g_{m1}}{2} = 200\times10^{-6}\ \frac{A}{V}$ $\quad$ *note that* : $r_{e3} = \frac{1}{g_{m3}} = \frac{1}{g_{m1}}$

$R_I = r_{07} \,||\, r_{04}(1+g_{m4}\times r_{e2}) = r_{07} \,||\, 2r_{04} = 5.65M\Omega$

because : $r_{07} = \frac{V_{Anpn}}{I_{C7}} = 13M\Omega$ *and* $r_{04} = \frac{V_{Apnp}}{I_{C4}} = 5M\Omega$

→ $A_{vI} = G_{mI}\times R_I = 1130$

$R_3 I_{C13} = V_t \ln(\frac{I_{C10}}{I_{C13}}) \quad \Rightarrow I_{C13} = 100\mu A$

$G_{mII} = \frac{g_{mm1}}{1+g_{mm1}R_2} = 0.663\times10^{-3}\ \frac{A}{V}$ $\quad$ *note that* : $g_{mm1} = \sqrt{2\mu C_{ox}(\frac{W}{L})_{mm1} I_{mm1}} = 1.414\times10^{-3}\ \frac{A}{V}$

$R_{II} = r_{dsm1}(1+g_{mm1}\times R_2) \,||\, r_{013}(1+g_{m13}\times R_3) = 2.13M\Omega \,||\, 1.16M\Omega = 0.749M\Omega$

$A_{vII} = G_{mII}R_{II} = 497$

$A_v = A_{vI}\times A_{vII} \cong 561,610$

c) $GBW = \frac{G_{mI}}{C_C} \quad \Rightarrow \quad C_C = \frac{200\times10^{-6}}{2\pi\times2\times10^{-6}} = 15.9\,pF$

d) $\Phi_M = 90^\circ - \tan^{-1}(\frac{2MHz}{p_2}) - \tan^{-1}(\frac{2MHz}{z})$

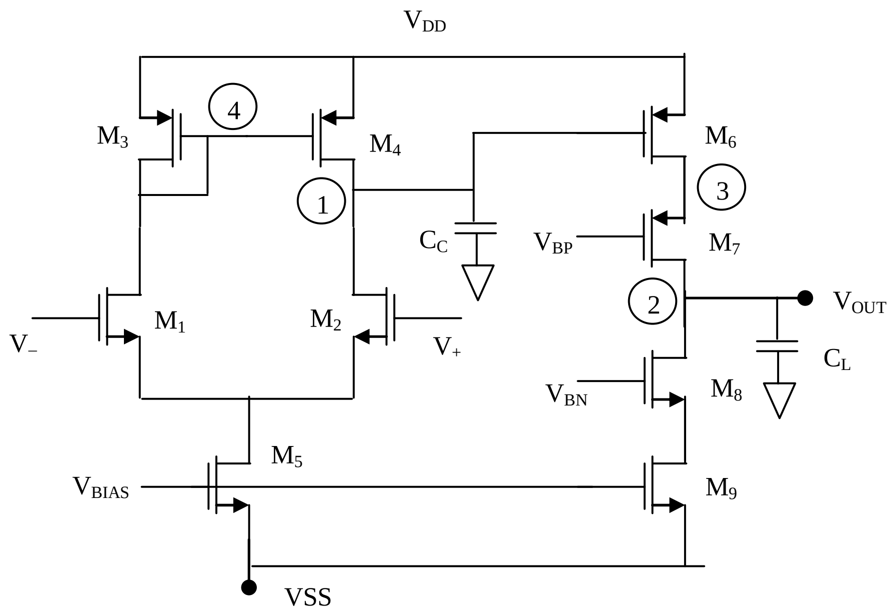
$$p_2 = \frac{G_{mII}}{C_L} = \frac{0.663\times10^{-3}}{5\times10^{-12}} = 132\times10^{6} \quad rad/\sec = 21.1 \quad MHz$$

$$z = \frac{G_{mII}}{C_C} = \frac{0.663\times10^{-3}}{15.9\times10^{-12}} = 41.69\times10^{6} \quad rad/\sec = 6.64 \quad MHz$$

$$\Rightarrow \quad \Phi_M = 90^\circ - \tan^{-1}(\frac{2}{21}) - \tan^{-1}(\frac{2}{6.64}) = 90^\circ - 5.41^\circ - 16.76^\circ = 67.82^\circ$$

Problem 3 - (30 points)

In this problem, you are not asked to provide any numerical calculations. *You are only required to provide expressions*. Make sure that your final expression for each section is clearly identified and legible. For the cascoded two-stage CMOS Op-Amp shown below:



a. Show an expression for the overall voltage gain of this amplifier as a function of transistor transconductances and output resistances.

$$A_v = g_{m1}(r_{ds4} \| r_{ds2}) \times g_{m6} \underbrace{[(g_{m7} r_{ds6} r_{ds7}) \| (g_{m8} r_{ds8} r_{ds9})]}_{R_{II}}$$

b. Show the expressions for the poles associated with the two capacitors C_C and C_L, as a function of the two capacitance values, transistor transconductances and output resistances. Assume that C_C and C_L include the transistor internal capacitances at their respective nodes.

$$p_1 = \frac{1}{(r_{ds4} \| r_{ds2})C_c} \qquad \textit{and} \qquad p_2 = \frac{1}{R_{II} C_L}$$

c. If $C_L >> C_C$, provide an expression for the unity gain frequency (GB) of the amplifier.

$$GBW = \frac{g_{m1} g_{m6} (r_{ds4} \| r_{ds2})}{C_L}$$

d. Show an expression for the pole associated with node 3, in terms of transistors internal capacitances, transconductances and output resistances. Identify all the components of the internal capacitances.

$$p_3 = \frac{1}{(r_{ds6} \parallel R_3)C_3}$$

$$C_3 = C_{gs7} + C_{sb7} + C_{gd6} + C_{db6}$$

$$R_3 = \frac{r_{ds7} + g_{m8} r_{ds8} r_{ds9}}{1 + g_{m7} r_{ds7}} \cong \frac{1}{g_{m7}} + \frac{g_{m8} r_{ds8} r_{ds9}}{g_{m7} r_{ds7}}$$

e. Is there a right half plane zero in this amplifier that would affect the phase margin? If there is, provide an expression for the position of this zero.

No, because a miller configuration is not used→ there is no RHZ that would affect the phase margin

f. **(EXTRA CREDIT)** Show expressions for any pole or zero associated with node 4. Identify all the components of the internal capacitances.

$$p_4 = \frac{-g_{m3}}{C_x}$$

$$C_x = C_{gs3} + C_{gs4} + C_{db3} + C_{db1} + C_{gd1}$$

$$z_4 = \frac{-2g_{m3}}{C_x}$$