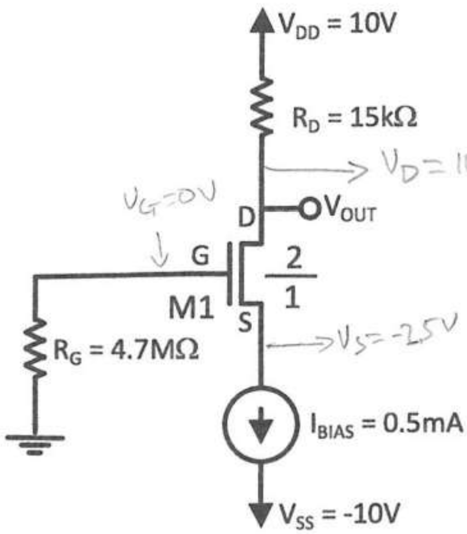
15pts

1) The circuit below is biased using a constant current source to set I_{DS} for the MOSFET. $V_T = 1.5V$ and $K_n' = 0.5mA/V^2$, and remember $K_n = (W/L)\, K_n'$.

a) Find all of the DC node voltages: V_D, V_S, V_G, and V_{GS}.
b) What is the maximum swing at the drain for which the MOSFET remains in saturation (without taking into account the signal swing at the gate)?



$V_D = 10 - 15 \times 0.5 = 2.5V$

$i_D = \frac{K}{2}(V_{GS} - V_T)^2$

$0.5m = \frac{2(0.5)m}{2}(V_{GS} - V_T)^2$

$V_{GS} = 1 + V_T = 2.5V$

$V_G = 0$ so $V_S = -2.5V$

$V_{DS} = V_{GS} - V_T$
$= 2.5 - 1.5 = 1V$

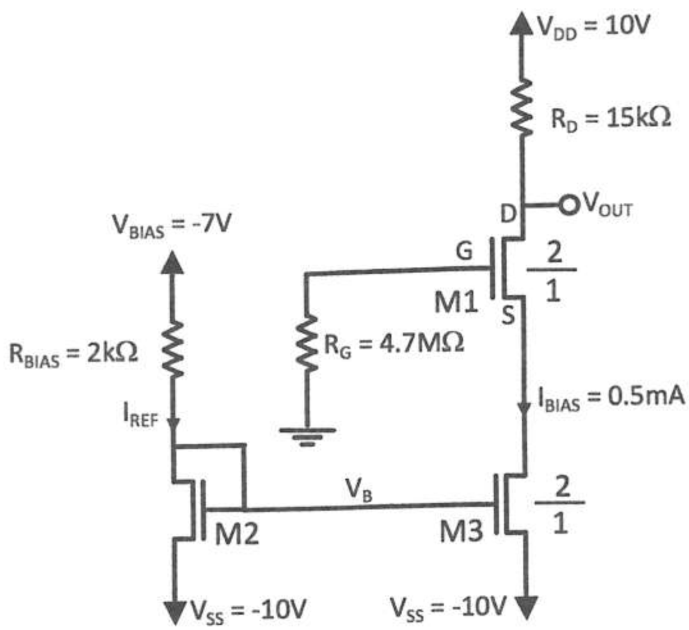
so Drain can go to $-1.5V$

and max swing $= 2.5 + 1.5 = \boxed{4V}$

2) Now complete the design of the current mirror in the circuit below to provide the bias current of 0.5mA for the circuit of problem 1.

a) What is the voltage at V_B, and what is V_{GS} for M2 and M3?

b) What is W/L for M2?



For M3

$$i_D = \frac{K}{2}(V_{GS}-V_T)^2$$

$$0.5mA = \frac{2(0.5)mA}{2}(V_{GS}-V_T)^2$$

$$V_{GS} = 1+V_T = 2.5V$$

So $\boxed{V_B = -7.5V \quad V_{GS} = 2.5V}$

$$I_{REF} = \frac{V_{BIAS}-V_B}{R_{BIAS}} = \frac{-7-(-7.5)}{2k} = \frac{0.5}{2k} = 0.25mA$$

For M2

$$i_D = \frac{K}{2}(V_{GS}-V_T)^2$$

$$0.25 = \frac{K}{2}(2.5-1.5)^2$$

$$K = 0.5 \Rightarrow \boxed{\frac{W}{L} = \frac{1}{1}}$$

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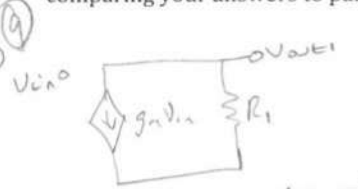
comparing your answers to part (e) and part (b).

(a)

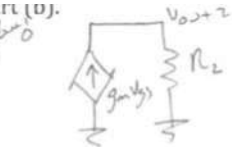
(a)



$\frac{V_{out1}}{V_{in}} = -g_m R_1 = -K(V_{IN} - V_T)R_1$
$= -4(1.6-1)1$
$\boxed{G_1 = -2.4}$

(b) $G_1 = -g_m R_1 // R_{LOAD}$
$= -4(1.6-1)\ 0.66$
$\boxed{G_1 = -1.6}$

(c)



$g_{m2} = K(V_{GS} - V_T)$
$= 8(3.3 - 1.82 - 1)$
$= 3.84$

$V_{out2} = g_{m2}(V_{out1} - V_{out2})R_2$
$V_{out2}(1 + g_{m2}R_2) = g_{m2} V_{out1} R_2$
$\frac{V_{out2}}{V_{out1}} = \frac{g_{m2}R_2}{1 + g_{m2}R_2} = \frac{1}{1 + 1/g_{m2}R_2}$
$G2 = \frac{1}{1 + 1/7.68} = 0.88$

(d) $G2 = \frac{1}{1 + 1/g_{m2}(R_2 // R_{LOAD})}$
$= \frac{1}{1 + 1/3.84} = 0.79$

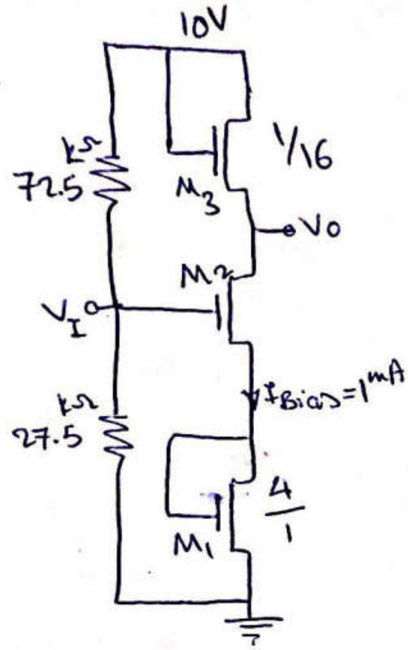
(e) $G12 = G1 \times G2$
$= -2.4 \times 0.79$
$= -1.9$

(f) The overall gain of the 2 stage amp is higher when driving R_{LOAD} (1.9x) compared to if the first common source stage directly drives R_{LOAD} (1.6x) which shows the second stage is functioning as a voltage buffer.

(g) g_{m1} and g_{m2} correspond to the operating point from problem #2.

$V_T = 1^V$

$K_n' = 2^{mA/V^2}$



a) $$V_I = \frac{27.5^{k\Omega}}{27.5^{k\Omega} + 72.5^{k\Omega}} \times 10^V = 2.75^V$$

Thevenin equivalent: $$R_{th} = \frac{27.5^{k\Omega} \times 72.5^{k\Omega}}{27.5^{k\Omega} + 72.5^{k\Omega}} \cong 20^{k\Omega}$$

For M_3:

$$i_D = \frac{k}{2}(V_{GS_3} - V_T)^2$$

$$1^{mA} = \frac{2^{mA/V^2}}{16 \times 2}(V_{GS_3} - 1)^2$$

$$\Rightarrow V_{GS_3} = 4 + 1 = 5^V \Rightarrow (10 - V_o) = 5^V$$

$$\Rightarrow \boxed{V_o = 5^V}$$

Note: For M_1 & M_3, because their Gate and Drain are Connected, they will be in saturation region because:

$V_{GD} = 0$, Saturation Conditions $\begin{cases} V_{GS} > V_T \\ V_{DS} > V_{GS} - V_T \\ \Rightarrow V_{GD} < V_T \end{cases}$

$\Rightarrow 0 < 1$ ✓

For M_1:

$$i_D = \frac{k}{2}(V_{GS_1} - V_T)^2$$

$$1^{mA} = \frac{4(2^{mA/V^2})}{2}(V_{GS_1} - 1)^2$$

$$1/4 = (V_{GS_1} - 1)^2$$

$$V_{GS_1} = 1/2 + 1 = 1.5^V$$

$$\Rightarrow (V_{G_1} - 0) = 1.5^V \Rightarrow \boxed{V_{G_1} = 1.5^V}$$

For M_2: $V_{GS_2} = V_I - V_{G_1} = 2.75 - 1.5 = 1.25 > 1$ ✓

$V_{DS} = V_o - V_{G_1} = 5 - 1.5 = 3.5 > 0.25$ ✓

M_2 is in saturation:

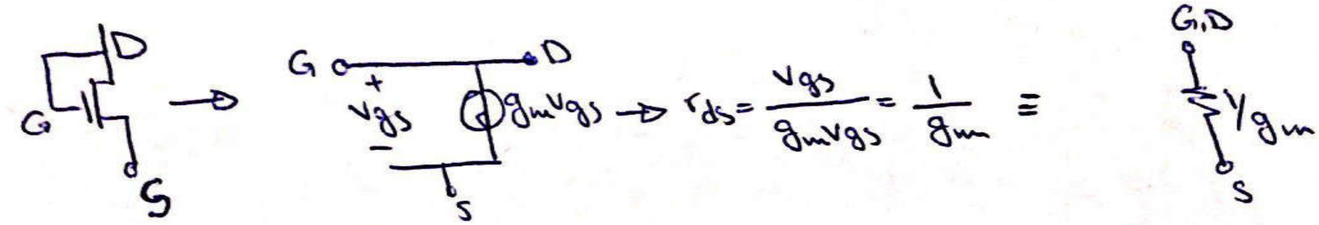
$$i_D = k/2(V_{GS} - V_T)^2$$

$$1^{mA} = k/2(1.25 - 1)^2 = k/2(1/4)^2$$

$$k = 32^m = \frac{W}{L}(2^{mA/V^2})$$

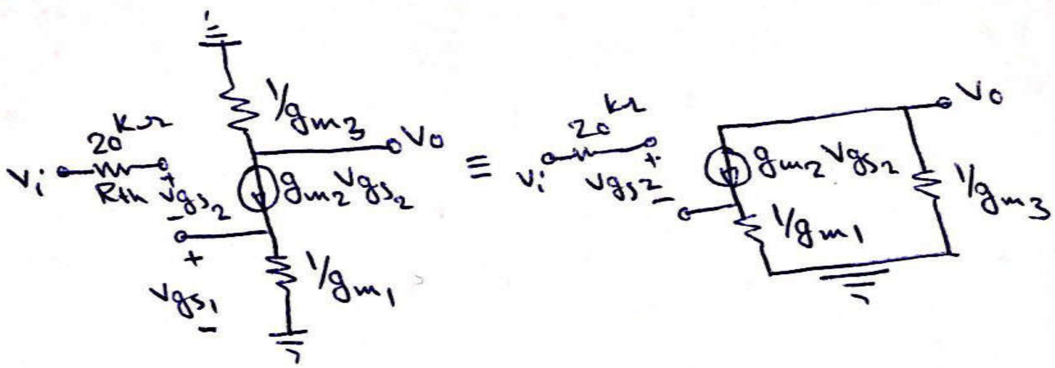
$$\Rightarrow \boxed{W/L = \frac{16}{1}}$$

b) First draw the small signal model for M_1 and M_2:



$$r_{ds} = \frac{v_{gs}}{g_m v_{gs}} = \frac{1}{g_m} \equiv$$

now use this model in the circuit's small signal model:



$v_i = v_{gs2} + v_{gs1}$, $g_{m2} v_{gs2} = g_{m1} v_{gs1} \rightarrow v_{gs1} = \frac{g_{m2}}{g_{m1}} v_{gs2}$

$\rightarrow v_i = v_{gs2} + \frac{g_{m2}}{g_{m1}} v_{gs2} = \left(1 + \frac{g_{m2}}{g_{m1}}\right) v_{gs2} = \frac{g_{m1} + g_{m2}}{g_{m1}} v_{gs2}$

$\rightarrow v_o = -g_{m2} v_{gs2} \times \frac{1}{g_{m3}} = -\frac{g_{m2}}{g_{m3}} \times \frac{g_{m1}}{g_{m1} + g_{m2}} v_i$

$$g_m = \frac{2I_D}{V_{GS} - V_T} = K(V_{GS} - V_T) \rightarrow \begin{cases} g_{m1} = K_1(V_{GS1} - V_T) = 4 \times 2^m (1.5 - 1) = 4^{mS} \\ g_{m2} = K_2(V_{GS2} - V_T) = 16 \times 2^m (1.25 - 1) = 8^{mS} \\ g_{m3} = K_3(V_{GS3} - V_T) = \frac{1}{16} \times 2^m (5 - 1) = 0.5^{mS} \end{cases}$$

$$\Rightarrow v_o = -\frac{8^m}{0.5^m} \times \frac{4^m}{4^m + 8^m} v_i \cong 5.3 v_i$$

$$\Rightarrow \boxed{\frac{v_o}{v_i} \cong -5.3} \qquad \boxed{\frac{v_o}{v_i} = -\frac{g_{m2}}{g_{m3}} \frac{g_{m1}}{g_{m1} + g_{m2}} v_i}$$

$$\boxed{\frac{v_o}{v_i} = -\frac{K_2(V_{GS2} - V_T)}{K_3(V_{GS3} - V_T)} \times \frac{K_1(V_{GS1} - V_T)}{K_2(V_{GS2} - V_T) + K_1(V_{GS1} - V_T)} v_i}$$