Name PID

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Electrical and Computer Engineering Department

ECE 65 – Spring 2022

Components and Circuits lab

Final Exam

- Closed books, four double-sided cheat sheets, and calculators are allowed
- Electronic devices are not allowed.
- Please put all answers in the provided sheets.
- You can use the back of every page as a scratch paper.
- Please submit your handwritten solutions to Gradescope by 2:40 pm.

Please do not begin until you are told to do so.

Show your work and good luck!

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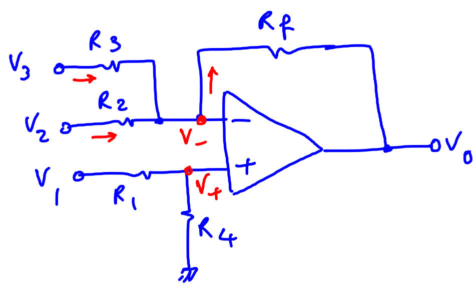
Problem 1.

Design an op-amp circuit **using only one op-amp** and assuming ideal op-amps to implement the function of

$$v_o = 2v_1 - 2v_2 - 4v_3$$

in which v_1, v_2, and v_3 are three input voltages and v_o is the output voltage.

Show your work.



ideal op-amp and negative feedback: $V_+ = V_-$

$i_+ = i_- = 0$

$$V_+ = \frac{R_4}{R_1+R_4} V_1$$

KCL @ V_- : $\frac{V_2 - V_-}{R_2} + \frac{V_3 - V_-}{R_3} = \frac{V_- - V_0}{R_f}$

$$-\frac{1}{R_2} V_2 - \frac{1}{R_3} V_3 + \left(\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_f} \right) V_- = \frac{1}{R_f} V_0$$

$$-\frac{1}{R_2} V_2 - \frac{1}{R_3} V_3 + \left(\frac{R_3 R_f + R_2 R_f + R_2 R_3}{R_2 R_3 R_f} \right) V_- = \frac{1}{R_f} V_0$$

$$V_0 = \frac{-R_f}{R_2} V_2 - \frac{R_f}{R_3} V_3 + \left(\frac{R_3 R_f + R_2 R_f + R_2 R_3}{R_2 R_3} \right) V_-$$

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$$\begin{cases} V_0 = \dfrac{-R_f}{R_2} V_2 - \dfrac{R_f}{R_3} V_3 + \left(\dfrac{R_3 R_f + R_2 R_f + R_2 R_3}{R_2 R_3} \right) V_- \\ V_+ = \dfrac{R_4}{R_1 + R_4} V_1 \quad \text{and} \quad V_- = V_+ \end{cases}$$

$$\Downarrow$$

$$\begin{cases} V_0 = \dfrac{-R_f}{R_2} V_2 - \dfrac{R_f}{R_3} V_3 + \left(\dfrac{R_3 R_f + R_2 R_f + R_2 R_3}{R_2 R_3} \right) \left(\dfrac{R_4}{R_1 + R_4} \right) V_1 \\ V_0 = 2 V_1 - 2 V_2 - 4 V_3 \end{cases}$$

$$\Downarrow$$

$$\frac{-R_f}{R_2} = -2 \quad , \quad \frac{-R_f}{R_3} = -4 \quad , \quad R_f = 4\,k\Omega \, , \quad R_2 = 2\,k\Omega \, , \quad R_3 = 1\,k\Omega$$

$$\frac{4 + 8 + 2}{2} \times \frac{R_4}{R_1 + R_4} = 2 \longrightarrow \frac{R_4}{R_1 + R_4} = \frac{4}{14}$$

$R_4 = 4\,k\Omega$, $R_1 = 10\,k\Omega$

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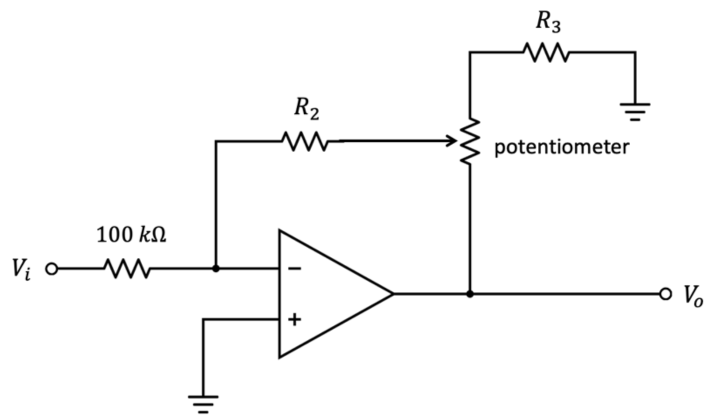
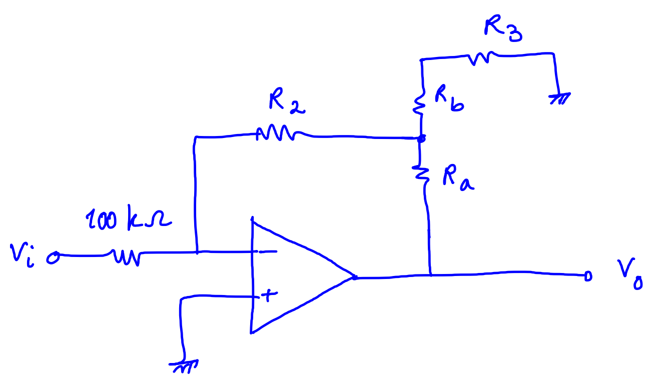
Problem 2.

Design the following circuit (find R_2 and R_3) such that the voltage gain can be varied between $-1\ V/V$ and $-100\ V/V$. Assume that the op-amp is ideal, and you have a $100\ k\Omega$ potentiometer.



Show your work.



$R_a + R_b = 100\ k\Omega$

Two cases for the $-1\ V/V$ and $-100\ V/V$ gain:

$$\begin{cases} R_a = 0, \quad R_b = 100k\Omega \\ R_a = 100\ k\Omega, \quad R_b = 0 \end{cases}$$

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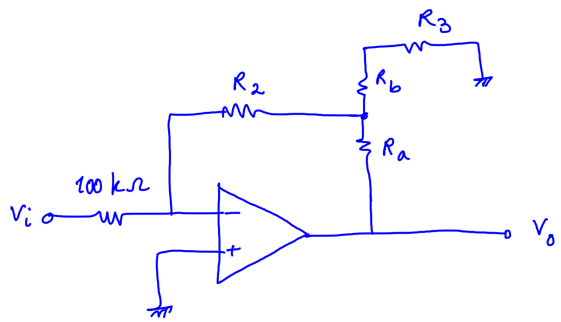
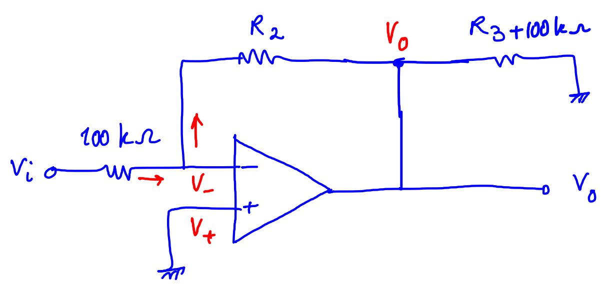
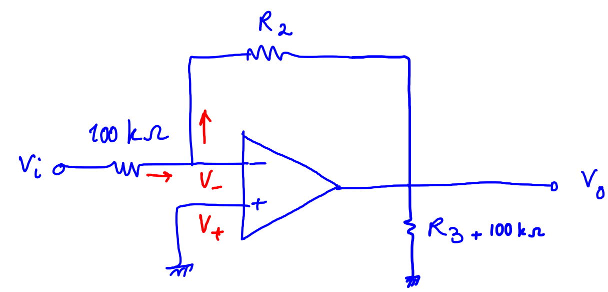
$R_a = 0, \; R_b = 100\,k\Omega$







op-amp is ideal and there is negative feedback : $i_+ = i_- = 0$

$V_+ = V_-$

$V_+ = 0 \;\longrightarrow\; V_- = 0$

KCL @ V_- :
$$\frac{V_i - V_-}{100\,k\Omega} = \frac{V_- V_0}{R_2}$$

$$\frac{V_i - 0}{100\,k\Omega} = \frac{-V_0}{R_2} \;\longrightarrow\; \frac{V_0}{V_i} = -\frac{R_2}{100\,k\Omega}$$

$$R_2 = 100\,k\Omega \;\longrightarrow\; \frac{V_0}{V_i} = -1 \; V/V$$

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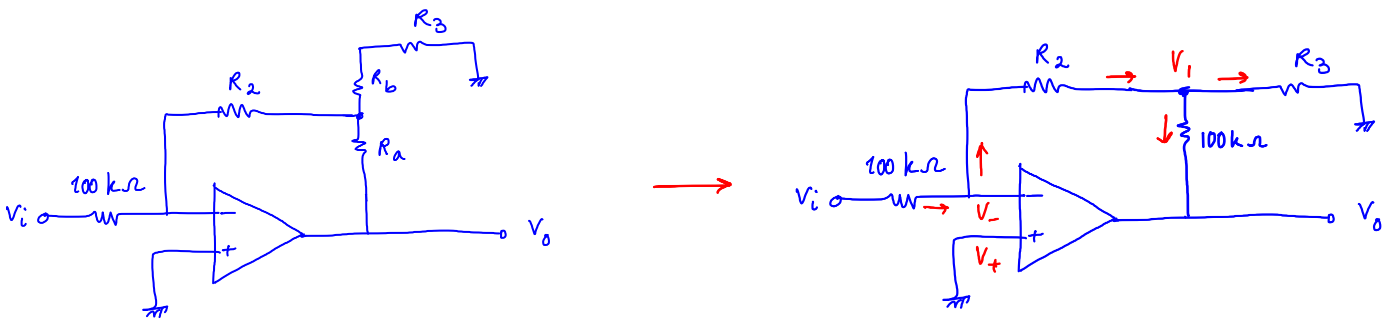
$R_a = 100\,k\Omega, \quad R_b = 0$



op-amp is ideal and there is negative feedback : $i_+ = i_- = 0$

$V_+ = V_-$

$V_+ = 0 \longrightarrow V_- = 0$

KCL @ V_- :

$$\frac{V_i - V_-}{100\,k\Omega} = \frac{V_- \; V_1}{R_2}$$

$$\frac{V_i - 0}{100\,k\Omega} = \frac{-V_1}{R_2} \longrightarrow V_i = -\frac{100\,k\Omega}{R_2} V_1$$

KCL @ V_2 :

$$\frac{V_- - V_1}{R_2} = \frac{V_1 - V_0}{100\,k\Omega} + \frac{V_1}{R_3}$$

$$\frac{0 - V_1}{R_2} = \frac{V_1 - V_0}{100\,k\Omega} + \frac{V_1}{R_3}$$

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$$\frac{0 - V_1}{R_2} = \frac{V_1 - V_0}{100\,k\Omega} + \frac{V_1}{R_3}$$

$$\frac{1}{100\,k\Omega} V_0 = \left(\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{100\,k\Omega}\right) V_1 = \left(\frac{100 R_3 + 100 R_2 + R_2 R_3}{R_2 R_3 \times 100}\right) V_1$$

$$* \; V_1 = \frac{R_2 R_3}{100 R_3 + 100 R_2 + R_2 R_3} V_0$$

from last page:

$$* \; V_i = - \frac{100\,k\Omega}{R_2} V_1$$

$$\Rightarrow \; V_i = - \frac{100\,k\Omega\, R_3}{100 R_3 + 100 R_2 + R_2 R_3} V_0$$

$$\frac{V_0}{V_i} = -\left(1 + \frac{R_2 + \frac{R_2 R_3}{100}}{R_3}\right) = -100 \; V/V$$

$$\frac{R_2 + \frac{R_2 R_3}{100}}{R_3} = 99 \quad , \; R_2 = 100\,k\Omega \longrightarrow R_3 = \frac{100}{98} k\Omega = 1.02\,k\Omega$$

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Problem 3.

a) Design a diode circuit to add $+2\,V$ DC shift to a sinusoidal input voltage with peak amplitude of $10\,V$ and frequency of $2\,kHz$. You should use regular PN junction diode(s) **and** Zener diode(s) in your design. Assume $V_{D0} = 0.7\,V$ and $V_Z = 3.3\,V$.

- Drawing the circuit is enough for this part.

b) Find the output at

i. $t = 100\,\mu s$

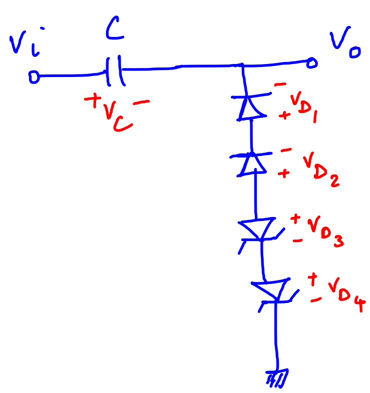
ii. $t = 450\,\mu s$

- You need to show your work on how you found the output voltage at these two time points.

c) Draw the output waveform for $0 \leq t \leq 1\,ms$.

Show your work.

a)

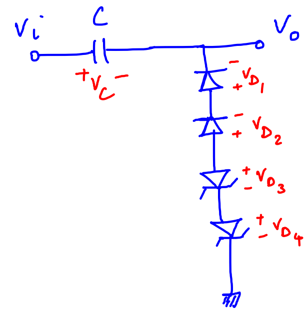


b) $V_C = V_i - (V_{D_4} + V_{D_3}) + V_{D_1} + V_{D_2}$

when $V_i = -8\,V$, D_1 and D_2 will turn ON and D_3 and D_4 will be in the Zener mode. The diodes will conduct and the capacitor will charge untill V_i reaches $-10V$. After that the diodes will turn off and V_C will not change.

when the diodes turn off: $V_C = -10 - (-3.3 - 3.3) + 0.7 + 0.7 = -2\,V$

$V_o = -V_C + V_i$



After the negative peak of V_i: $V_o = -(-2) + V_i = 2 + V_i$

+2V DC shift

$f = \frac{1}{T} = 2000\text{ Hz} \Rightarrow T = 0.5\text{ ms} = 500\,\mu s$

$t = 100\,\mu s < \frac{T}{4} \longrightarrow$ Diodes are off, $V_C = 0 \longrightarrow V_o = V_i$

$t = 450\,\mu s \longrightarrow$ after the negative peak: $V_o = 2 + V_i(t = 450\,\mu s)$

$= 2 + 10\sin(2\pi \times 2k \times 0.45m)$

$= 2 - 5.88 = -3.88\text{ V}$

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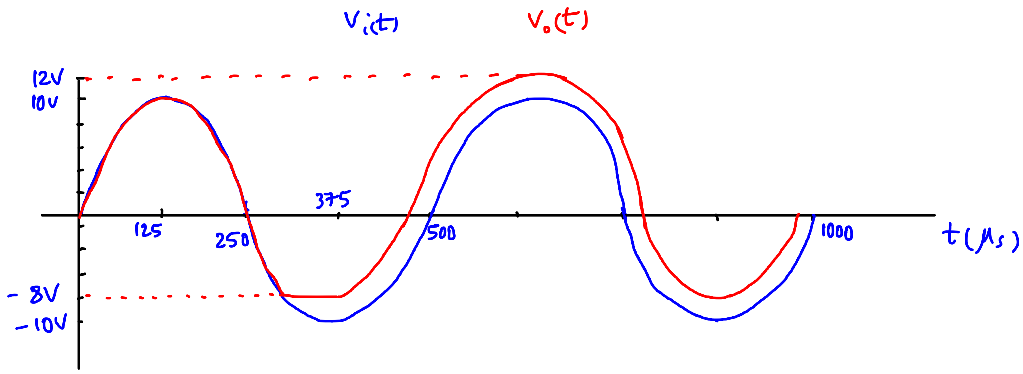
c)



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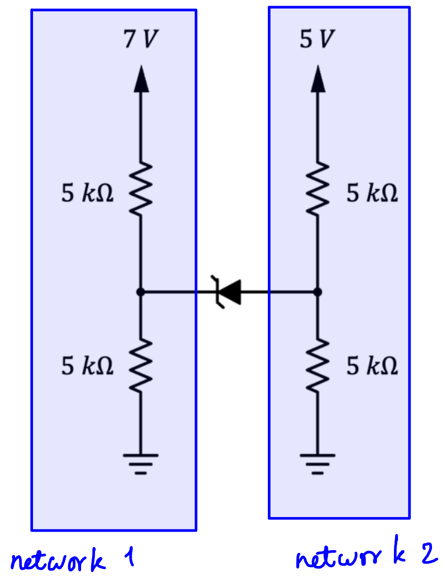
Problem 4

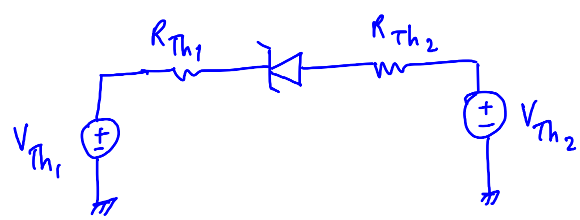
Find the current through the diode and the voltage across it in the below circuit.

Assume $V_{D0} = 0.7\ V$ and $V_Z = 2\ V$.



Show your work.

Thevenin equivalent circuit for networks 1 and 2



$$R_{Th_1} = 5\,k\Omega \parallel 5\,k\Omega = 2.5\,k\Omega$$

$$R_{Th_2} = 5\,k\Omega \parallel 5\,k\Omega = 2.5\,k\Omega$$

$$V_{Th_1} = \frac{5\,k\Omega}{5\,k\Omega + 5\,k\Omega} \times 5V = 2.5V$$

$$V_{Th_2} = \frac{5\,k\Omega}{5\,k\Omega + 5\,k\Omega} \times 7V = 3.5V$$

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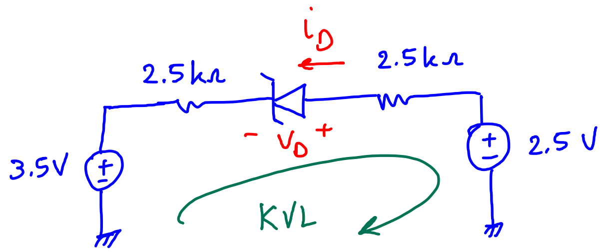

Assume the zener diode is off:

$-V_Z < V_D < V_{D_0}$ and $i_D = 0$

$-2 < V_D < 0.7$

KVL: $-3.5 - 2.5\,k\Omega \times i_D - V_D - 2.5\,k\Omega \times i_D + 2.5 = 0$

$\rightarrow V_D = -1 - 5\,k\Omega \times i_D$

$i_D = 0 \longrightarrow V_D = -1$

$-2 < V_D = -1 < 0.7 \implies$ Assumption is correct.

$i_D = 0$ and $V_D = -1\ V$

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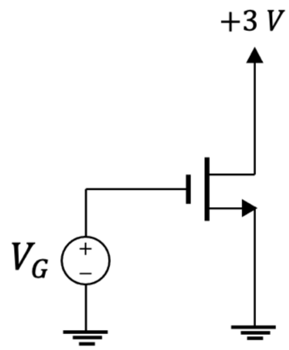
Problem 5

The MOSFET in the below circuit has $V_t = 1\ V$ and $\mu C_{ox}\frac{W}{L} = 1.5\ mA/V^2$, and $\lambda = 0$.



a) Sketch (approximately) the graph of I_D vs V_G with V_G varying in the range of 0 V to 5 V.

   Label your graph.

b) Write I_D equation(s) for the various portions of the resulting graph.

Show your work.

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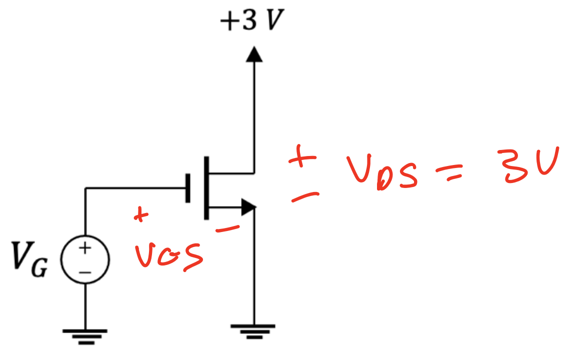
Problem 5

The MOSFET in the below circuit has $V_t = 1\ V$ and $\mu C_{ox}\frac{W}{L} = 1.5\ mA/V^2$, and $\lambda = 0$.



a) Sketch (approximately) the graph of I_D vs V_G with V_G varying in the range of 0 V to 5 V.

Label your graph.

b) Write I_D equation(s) for the various portions of the resulting graph.

Show your work.

Cut-OFF: $V_{OV} < 0 \rightarrow V_{GS} < V_t \rightarrow V_G < 1V$

$I_D = 0$

Saturation: $V_{OV} \geq 0 \rightarrow V_G \geq 1V$

$V_{DS} \geq V_{OV} \rightarrow 3 \geq V_G - V_t \rightarrow V_G \leq 4V$

$I_D = 0.5 \mu C_{ox}(W/L) V_{OV}^2$

$= 0.5(1.5mA)(V_G - 1)^2$

$I_D = 0.75mA(V_G - 1)^2$

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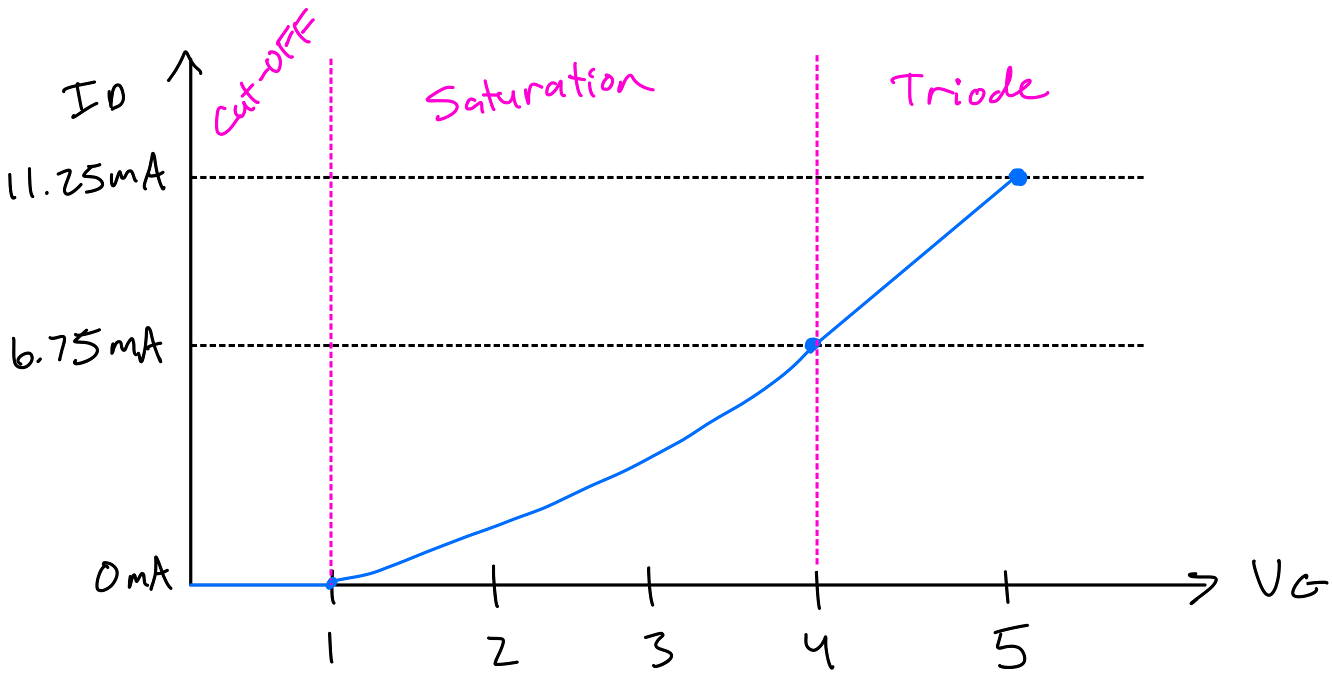
Triode : $V_{ov} \geq 0$

$V_{DS} \leq V_{ov} \rightarrow 3 \leq V_G - V_t \rightarrow V_G \geq 4$

$$I_D = 0.5\mu_n C_{ox}(W/L)(2V_{ov}V_{DS} - V_{DS}^2)$$

$$= 0.75mA\,(6(V_G - 1) - 9)$$

$$I_D = 4.5mA \cdot V_G - 11.25mA$$



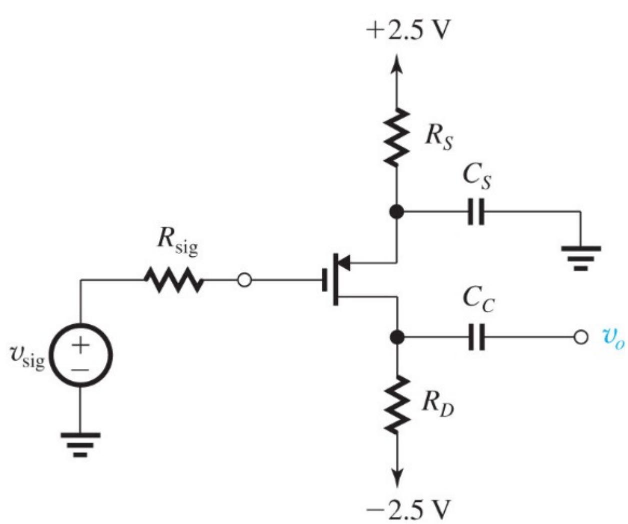
Problem 6.

The MOSFET in the following amplifier circuit has $|V_t| = 0.6\ V$. Neglect the early effect in the bias and signal circuits, and assume the capacitors are short for the signal circuit.

a) Find R_S and R_D to bias the transistor at $I_D = 0.3\ mA$ and $V_{OV} = 0.4\ V$ and achieve the voltage amplifier gain of $A_V = -12\ V/V$. (Capacitors are short for the signal circuit)

b) Find the largest $\hat{v}_{sig}$ ($\hat{v}_{sig}$ shows the peak amplitude of the sinusoid v_{sig}) that the amplifier can handle while remaining in the saturation region. Find the peak amplitude of the corresponding signal at the output?

c) If $\hat{v}_{sig}$ is limited to 10 mV, what value can R_D be increased to while maintaining saturation region operation (R_S does not change)? What is the new value of A_V?



Show your work.

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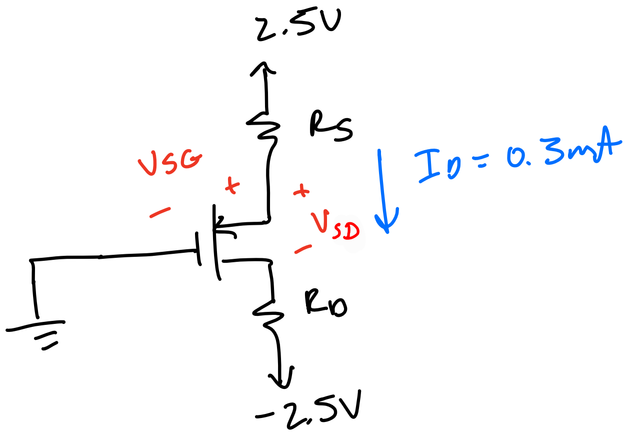
a)

Bias Circuit



$V_{ov} = 0.4V$

$V_{SG} - |V_{tp}| = 0.4$

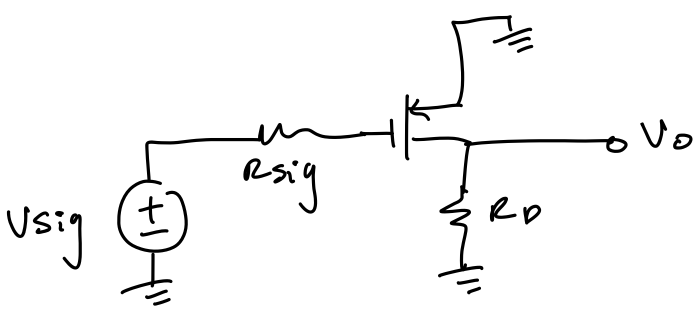
$V_{SG} = 0.4 + 0.6$

$V_{SG} = 1V$

$$R_S = \frac{2.5 - V_{SG}}{I_D} = \frac{2.5 - 1}{0.3mA}$$

$R_S = 5k\Omega$

Signal Circuit step 1:



$$g_m = \frac{2I_D}{V_{ov}} = 1.5\frac{mA}{V}$$

$$r_o = \frac{1}{\lambda \cdot I_D} = \frac{1}{0} = \infty$$

Common Source

$A_v = A_{vo} = -g_m(R_D // r_o)$

$-12 = -g_m R_D$

$$\boxed{R_D = \frac{12}{g_m} = 8k\Omega}$$

$5 = I_D(R_D + R_S) + V_{SD} \rightarrow V_{SD} = 5 - 0.3mA(13k)$

$V_{SD} = 1.1V$

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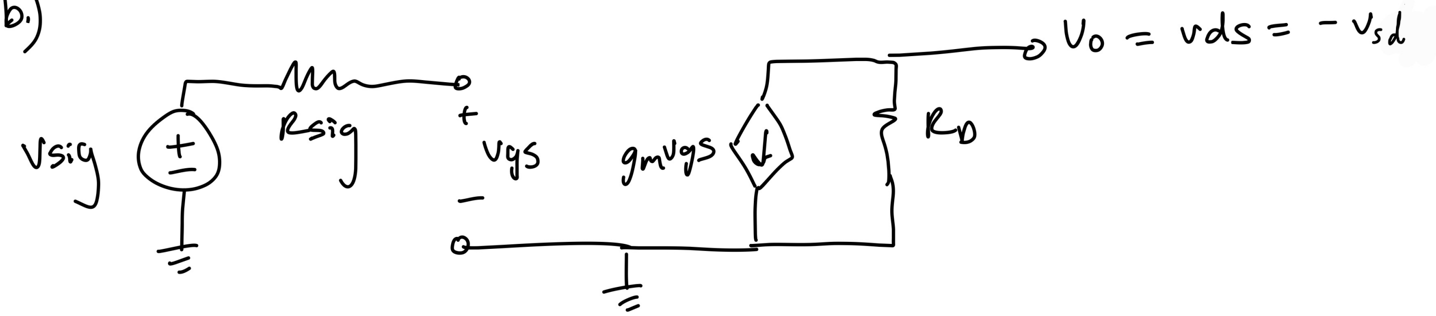
b.)



$$V_{gs} = V_{sig} = -V_{sg}$$

$$V_o = -V_{sd} = -g_m R_D V_{gs} = g_m R_D V_{sg} = -g_m R_D V_{sig}$$

$$V_{sd} = -g_m R_D V_{sg} \Rightarrow A_V = \frac{V_{sd}}{V_{sg}} = -g_m R_D$$

$\hat{V}_{sd}$ is the max amplitude of the signal V_{sd}. $\hat{V}_{sd}$ is positive. $\hat{V}_{sd} = |A_V|\,\hat{V}_{sg}$

To remain in saturation: $V_{SD} \geq V_{OV}$

$$V_{SD} - \hat{V}_{sd} \geq V_{SG} + \frac{\hat{V}_{sd}}{|A_V|} - |V_{tp}|$$

$$\left(1 + \frac{1}{|A_V|}\right)\hat{V}_{sd} \leq V_{SD} - V_{SG} + |V_{tp}|$$

$$\left(1 + \frac{1}{|A_V|}\right)\hat{V}_{sd} \leq 1.1 - 1 + 0.6$$

$$\hat{V}_{sd} \leq \frac{0.7\,V}{1 + \frac{1}{12}} \simeq 0.65\ V \longrightarrow \hat{V}_{sg} = \frac{0.65}{12} = 54.2\ mV \longrightarrow \hat{V}_{sig} = 54.2\ mV$$

max amplitude of V_{sd} max amplitude of V_{sg} max amplitude of V_{sig}

c) $\hat{v}_{sig} = 10 \text{ mV}$

From part b we know that

$$\hat{v}_{sig}(1+|A_v|) \leq V_{SD} - V_{SG} + |V_{tp}|$$

$$V_{SD} = V_S - V_D = 2.5 - R_S I_D - (R_D I_D - 2.5) = -5\,k\Omega \times 0.3\,mA + 5 - R_D \times 0.3\,mA$$

$$= 3.5 - R_D \times 0.3\,mA$$

$$V_{SG} = V_{ov} + |V_{tp}| = 1\,V$$

$$\hat{v}_{sig}(1+|A_v|) \leq 3.5 - R_D \times 0.3\,mA - 1 + 0.6$$

$$\hat{v}_{sig} = 10\,mV = 0.01\,V$$

$$0.01(1+|A_v|) \leq 3.1 - R_D \times 0.3\,mA$$

$$|A_v| = g_m R_D = 1.5\,mA/V \times R_D$$

$$0.01 + 0.01(V) \times 1.5\left(\frac{mA}{V}\right) \times R_D \leq 3.1 - R_D \times 0.3\,mA$$

$$(0.3 + 0.015) R_D \leq 3.09$$

$$R_D \leq 9.81\,k\Omega \longrightarrow R_{D_{max}} = 9.81\,k\Omega$$