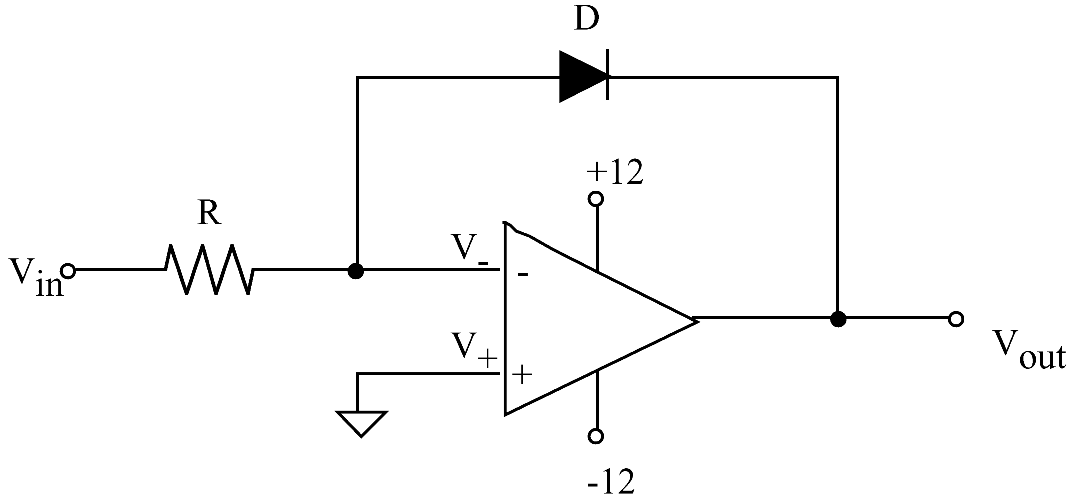
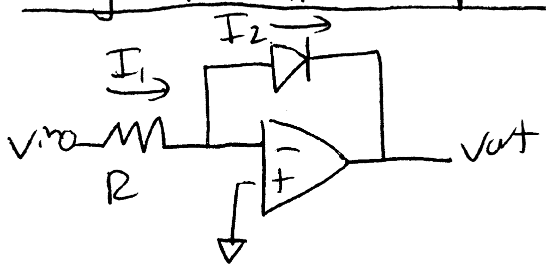
1. (50 points) The operational amplifier shown in the circuit below is ideal. The diode is at room temperature. Determine V_{out} as a function of V_{in}. Use R=1k and I_S (the saturation current in the Shockley equation, see page 172 in your text) = 1µA in your solution.



Logarithmic Amplifier



This circuit is connected just like a standard inverting amplifier, except that the feedback element is a diode, not a resistor. Since $I_n = 0$,

① $i_1 = -i_2$ $V_n = V_p = 0$; $i_1 = \frac{V_{in}}{R}$

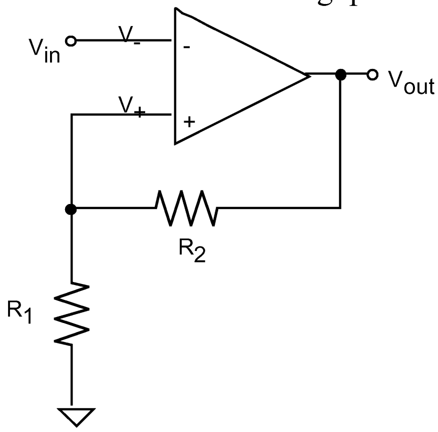
From pg. 172, $i_2 = I_s[e^{(\frac{V_D}{\eta V_T})} - 1]$ $V_D = 0 - V_{out} = -V_{out}$ $\frac{1}{\eta V_T} \approx 40$

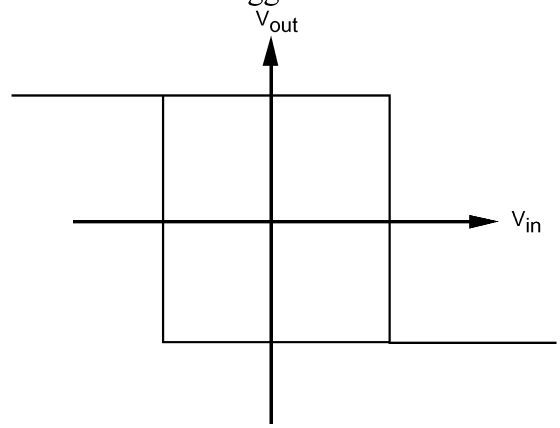
$i_2 = I_s[e^{-40V_{out}} - 1]$ substituting into ①, $\frac{V_{in}}{R} = I_s[e^{-40V_{out}} - 1]$

Assuming $e^{-40V_{out}} \gg 1$, $e^{-40V_{out}} = \frac{V_{in}}{I_s R}$ $V_{out} = -\frac{1}{40}\ln\left[\frac{V_{in}}{I_S R}\right]$ ∴

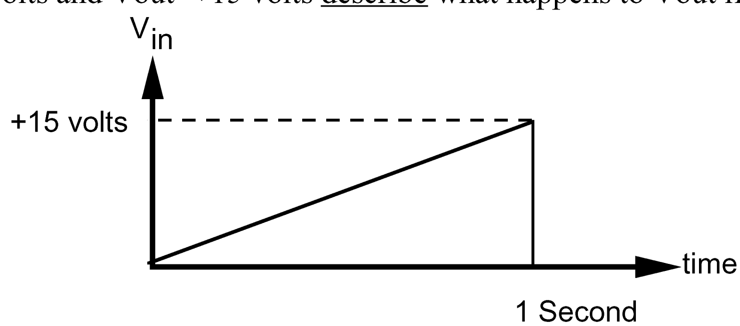
$\boxed{V_{out} = -\frac{1}{40}\ln(1{,}000 V_{in})} = -.17269 - .025\ln(V_{in})$

2. Answer the following questions about the Schmitt trigger circuit shown below.





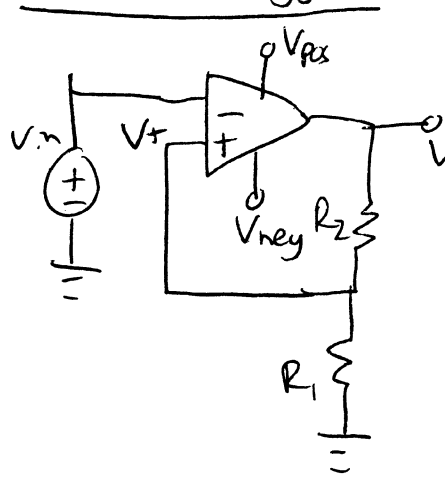
(a) If Vin=0 volts and Vout=+15 volts <u>describe</u> what happens to Vout if Vin(t) is:



(b) Using the input/output diagram at the above right, explain hysteresis, the difference between the upper and lower trip points, as it applies to a Schmitt trigger. How can you change it in the given circuit.

(c) How could you modify the above circuit so that the circuit operation is no longer centered about zero.

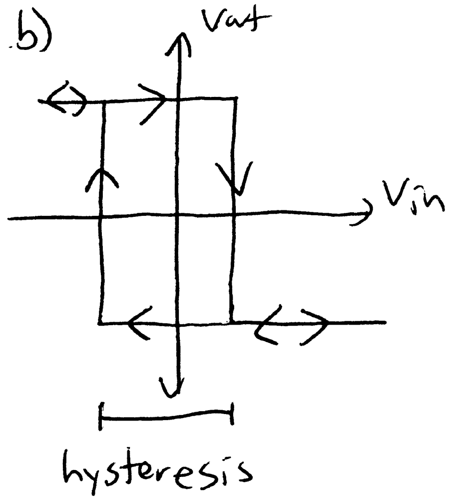
Schmitt Trigger



This Circuit is intersting because its operation is based on the present output. If $V_{out} = V_{pos}$ then $V_+ = V_{pos}\left(\frac{R_1}{R_1+R_2}\right)$ As long is Vin is less than this, Vout will remain constant. If $V_{in} > V_{pos}\left(\frac{R_1}{R_1+R_2}\right)$, then Vout is driven to V_{neg}. Then, $V_+ = V_{neg}\left(\frac{R_1}{R_1+R_2}\right)$, and will remain there until $V_{in} < V_{neg}\left(\frac{R_1}{R_1+R_2}\right)$, at which point Vout will be driven to Vpos.

(a) Vout will remain constant until Vin grows larger than the trip voltage ($15(\frac{R_1}{R_1+R_2})$), at which point the output will shift to -15 & remain there.

b)



In this circuit, the hysteresis is the difference between the upper & lower trip points. The circuit will behave differently depending on the present output & the direction of the voltage change. This change in behavior is quantified as hysteresis, the range of Vin over which the circuit operation is different. Changing the trip voltages requires altering R_1 & R_2.

(c) Either connect a voltage source through a resistance to the non-inverting terminal, or to the ground side of R_1

3. A student built the circuit shown in Figure 1 below in order to create a Schmitt trigger, but it was tested and the output voltage versus the input voltage behaved as shown in the right-hand figure.

(a) You are to examine the student's circuit and show where s/he made the error since it clearly doesn't work like it was supposed to.

(b) Explain why the circuit behaved as shown.

(c) Correct the circuit so that it will operate as a Schmitt trigger.

(d) Now that the error has been corrected, assume R_2=10k and R_3=100k and find the value of R_1 which will cause the output to switch from +10 volts to -10 volts at <u>approximately</u> V_S=3.5 volts. Show all work.

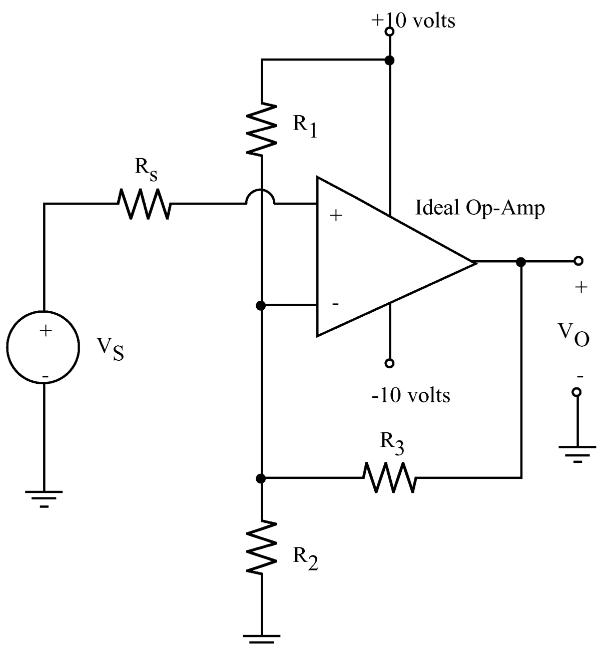


Figure 1. Circuit for problem 3.

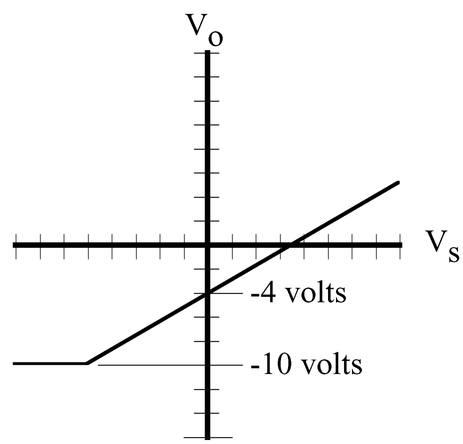
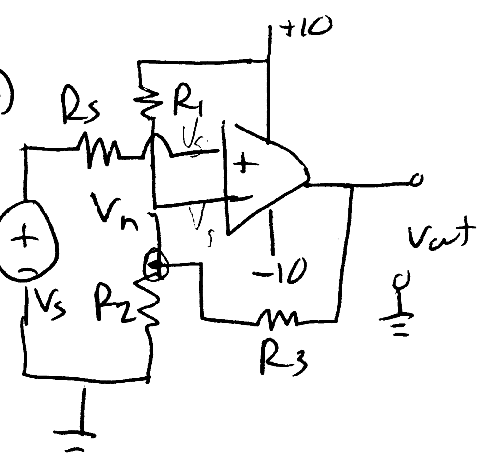


Figure 2. Graph of experimentally measured output.

3)



(a) The immediate problem is that there is no positive feedback. A Schmitt trigger is a comparator with positive feedback.

(b) KCL: $\frac{10-V_n}{R_1} + \frac{V_{out}-V_n}{R_3} = \frac{V_n-0}{R_2}$ $\quad V_n=V_p=V_s \therefore$

$$\frac{10}{R_1} + \frac{V_{out}}{R_3} = V_s\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right) \quad \boxed{V_{out} = V_s\left(\frac{R_3}{R_1}+\frac{R_3}{R_2}+1\right) - 10\left(\frac{R_3}{R_1}\right)}$$

(c) The easiest thing to do is simply reverse the inputs

(d) Again, KCL at V_n (V_{Trip})

$$\frac{10-V_{Trip}}{R_1} + \frac{10-V_{Trip}}{100K} - \frac{V_{Trip}}{10K} = 0 \qquad V_{Trip} = 3.5\,V,$$

$$\frac{10-3.5}{R_1} + 6.5\times10^{-5} - 3.5\times10^{-4} = 0 \qquad \boxed{R_1 = 22.8\,k\Omega}$$

(Incidentally, the other trip voltage, V^-, is now +0.98 Volts)

4.11. Consider the circuit shown in Figure P4.11. The transistors Q_1 and Q_2 are identical, both having $I_{ES} = 10$ fA $= 10^{-14}$ A and $\beta = 100$. Find V_{BE} and I_{C2}. Assume a temperature of 300 K for both transistors. (*Hint:* Both transistors are operating in the active region. Because the transistors are identical and have identical values of V_{BE}, their collector currents are equal.)

4.12. Repeat Problem 4.11 if Q_1 has $I_{ES1} = 10$ fA $= 10^{-14}$ A, and $\beta_1 = 100$, whereas Q_2 has $I_{ES2} = 100$ fA $= 10^{-13}$ A, and $\beta_2 = 100$.

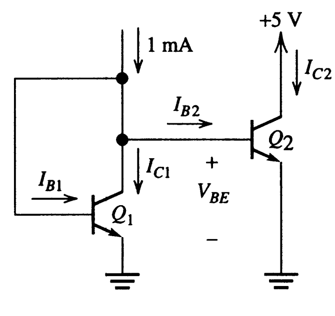
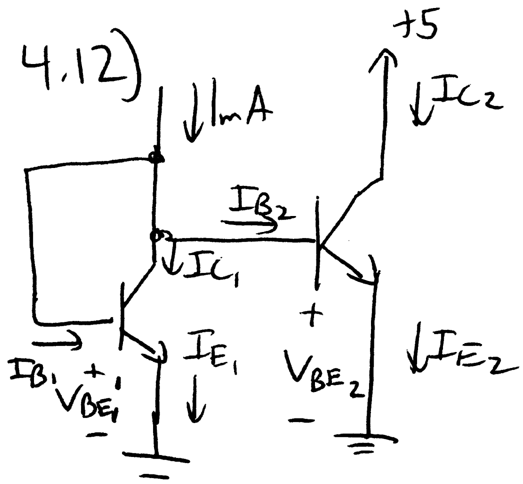


Figure P4.11

4.12)



$V_{BE1} = V_{BE2}$. $\quad \frac{I_{E1}}{I_{E2}} = \frac{I_{ES1}}{I_{ES2}} = 0.1 \therefore$

$\frac{I_{B1}}{I_{B2}} = \frac{I_{C1}}{I_{C2}} = 0.1$. By KCL,

$I_{C1} = \beta I_{B1} \therefore$

$1mA = I_{B1} + I_{C1} + I_{B2}$

$1mA = I_{B1} + 100 I_{B1} + 10 I_{B1} \therefore I_{B1} = 9.009u$

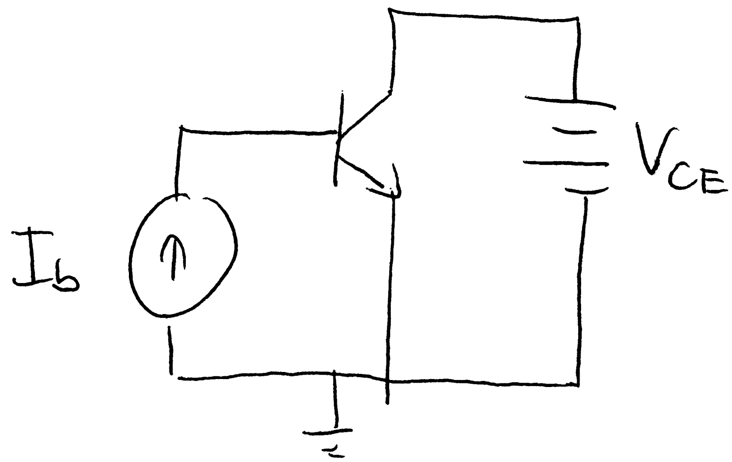
$I_{C1} = 100(I_{B1}) = .9009mA \quad I_{C2} = I_{C1} \cdot 10 \therefore \boxed{I_{C2} = 9.009mA}$

$V_{BE1} = V_T \ln\left(\frac{I_{E1}}{I_{ES1}} + 1\right)$ (from pg. 213, re-arranged)

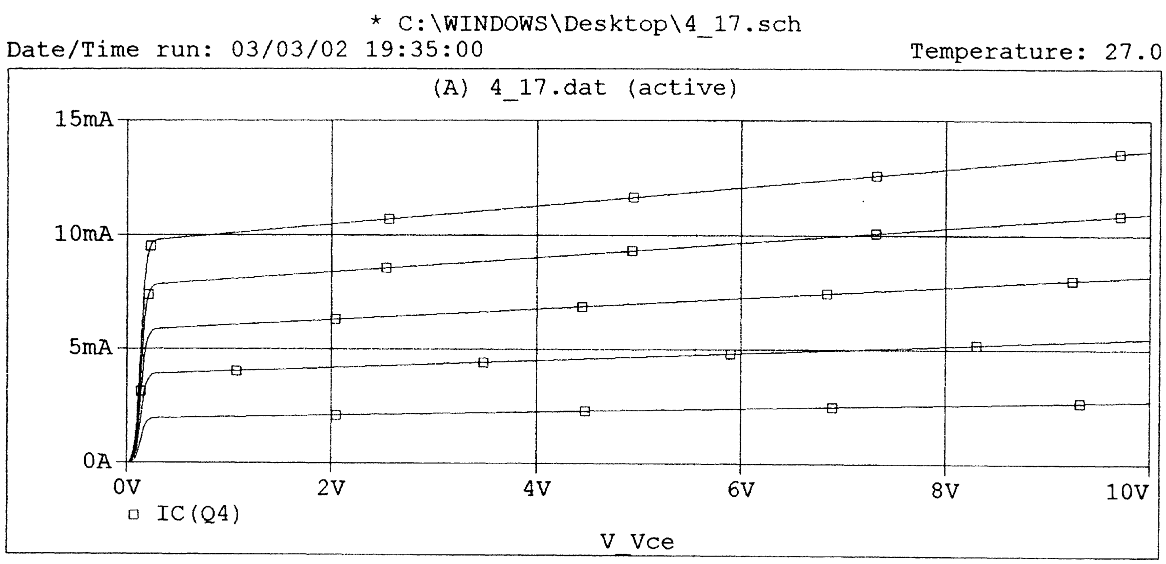
$$= .026 \ln\left(\frac{.9099\times10^{-3}}{10^{-14}} + 1\right) = \boxed{0.6561V = V_{BE2}}$$

4.17. Use SPICE to obtain output characteristics for an *npn* BJT having $I_s = 10^{-16}$ A, $\beta = 200$, and $V_A = 25$ V. Allow v_{CE} to range from 0 to 10 V, and let $i_B = 0, 10, 20, 30, 40$, and $50\,\mu$A.

Test circuit:



See pgs. 220-222 on Simulating BJT's in SPICE.



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4.20. Consider the circuit of Figure 4.10. Assume that $V_{CC} = 20\,\mathrm{V}$, $V_{BB} = 0.8\,\mathrm{V}$, $R_B = 40\,\mathrm{k\Omega}$, and $R_C = 2\,\mathrm{k\Omega}$. The input signal is a 0.2-V-peak, 1-kHz sinusoid given by $v_{in}(t) = 0.2\sin(2000\pi t)$. The common-emitter characteristics for the transistor are shown in Figure P4.20. Find the maximum, minimum, and Q-point values for v_{CE}. What is the approximate voltage gain for this circuit?

4.22. Repeat Problem 4.20 for $V_{BB} = 0.3\,\mathrm{V}$. Why is the gain so small in magnitude?

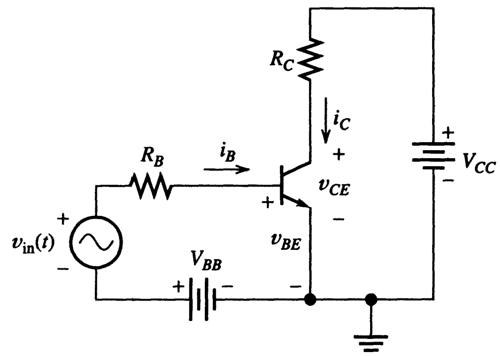
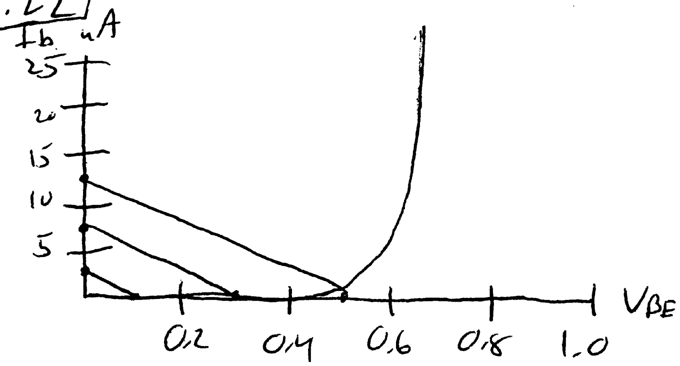


Figure 4.10
Common-emitter amplifier.

4.22



Y-intercept:

$$\frac{V_{BB}+V_{in}}{R_B}$$

X-intercept:

$$V_{BB}+V_{in}$$

As can be seen from the above load lines, $I_{b\,min} \approx I_{BQ} \approx I_{B\,max} = 0\,\mu A$ $\therefore$ $V_{CE\,min} \approx V_{CEQ} \approx V_{CE\,max} \approx 20\,V$. VBB is not sufficiently high to bias the BJT on; therefore, no signal is sent to the output. $\boxed{A_v \approx 0}$

4.33. Use the large-signal models for the transistors illustrated in Figure 4.19 to find I_C and V_{CE} for the circuits of Figure P4.33. Assume that $\beta = 100$. Repeat for $\beta = 300$ and compare the results for both values.

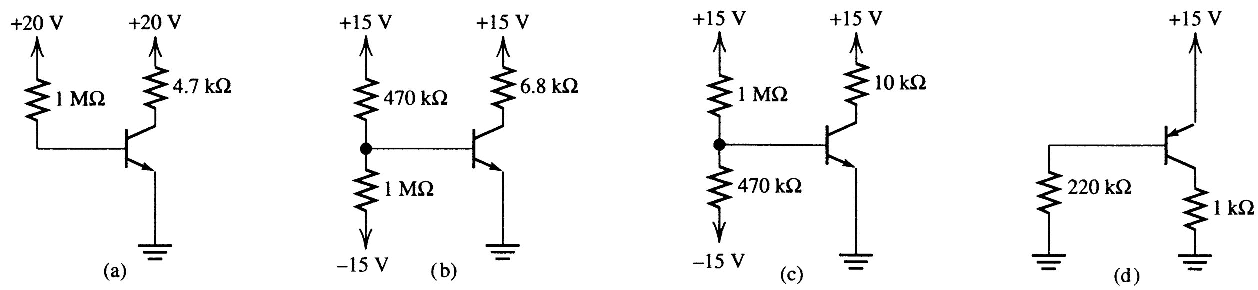


Figure P4.33

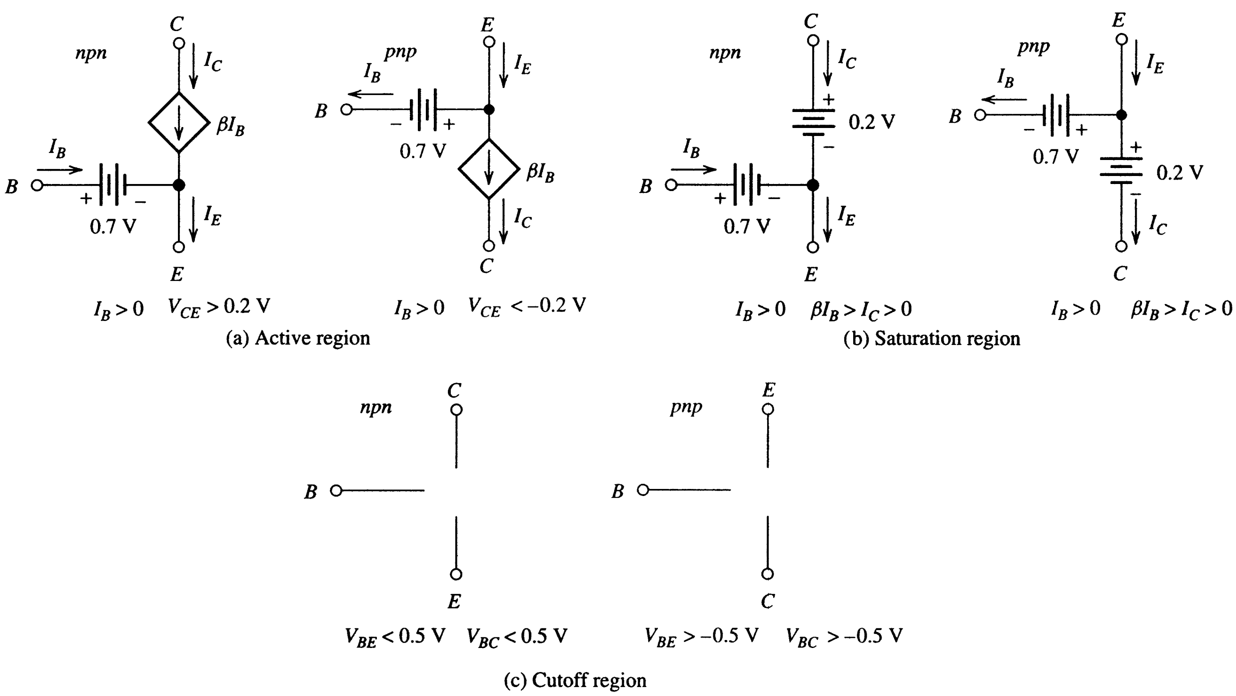
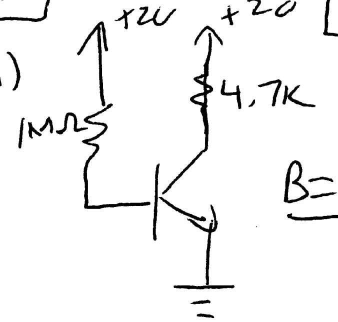


Figure 4.19 BJT large-signal models. (*Note:* Values shown are appropriate for typical small-signal silicon devices at a temperature of 300 K.)

4.33 Always assume active to start, then check. If wrong, then try saturation region.

(a)



$I_B = \frac{20-0.7}{1M\Omega} = 19.3uA$

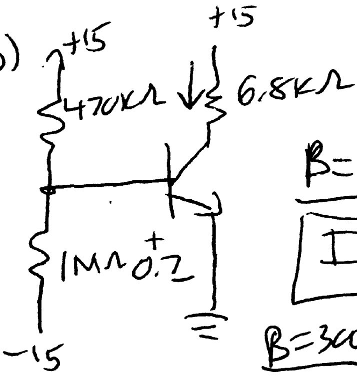
$\beta = 100$: $I_C = 1.93mA \therefore V_{CE} = 20 - (1.93mA)(4.7k\Omega)$

$V_{CE} = 10.9V > 0.2 \therefore$ $\boxed{I_C = 1.93mA \quad V_{CE} = 10.9V}$

$\beta = 300$: $I_C = 5.79mA \therefore V_{CE} = 20 - (5.79mA)(4.7k\Omega) = -7.213 < 0.2 \therefore$

BJT is in Saturation $\boxed{V_{CE} = 0.2V}$ $I_C = \frac{20-0.2}{4.7K}$ $\boxed{I_C = 4.21mA}$

(b)



$I_B = \frac{15-0.7}{470K\Omega} - \frac{0.7-(-15)}{1M\Omega} = 14.7uA$

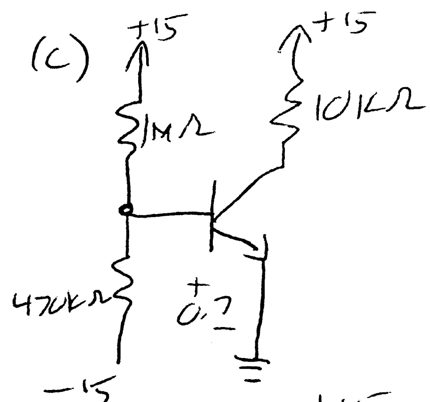
$\beta = 100$: $I_C = 1.47mA$ $V_{CE} = 15 - (1.47mA)(6.8k\Omega) = 5V >$

$\boxed{I_C = 1.47mA \quad V_{CE} = 5}$

$\beta = 300$: $I_C = 4.41mA$ $V_{CE} = 15 - (4.41mA)(6.8k\Omega) = -15 < 0.2$

Saturation: $\boxed{V_{CE} = 0.2}$ $I_C = \frac{15-0.2}{6.8k\Omega}$ $\boxed{I_C = 2.18mA}$

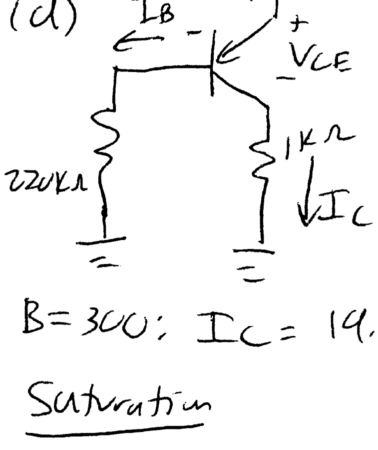
(c)



$I_B = \frac{15-0.7}{1M\Omega} - \frac{0.7-(-15)}{470K\Omega} = -19.1uA \therefore$

BJT is in cutoff: $\boxed{I_C = 0 \quad V_{CE} = 15 \text{ for } \beta = 100 \text{ or } 300}$

(d)



$I_B = \frac{(15-0.7)-0}{220K\Omega} = 65uA$

$\beta = 100$

$I_C = 6.5mA$ $V_{CE} = 15 - 6.5mA(1k\Omega) = 8.5V > 0.2$

$\boxed{I_C = 6.5mA \quad V_{CE} = 8.5V}$

$\beta = 300$: $I_C = 19.5mA$ $V_{CE} = 15 - 19.5mA(1k\Omega) = -4.5V < 0.2 \therefore$

Saturation $\boxed{V_{CE} = 0.2}$ $I_C = \frac{15-0.2-0}{1k\Omega} = \boxed{I_C = 14.8mA}$

4.34. Find I and V in the circuits shown in Figure P4.34. For all transistors, assume that $\beta = 100$ and $|V_{BE}| = 0.7$ in both the active and saturation regions. Repeat for $\beta = 300$.

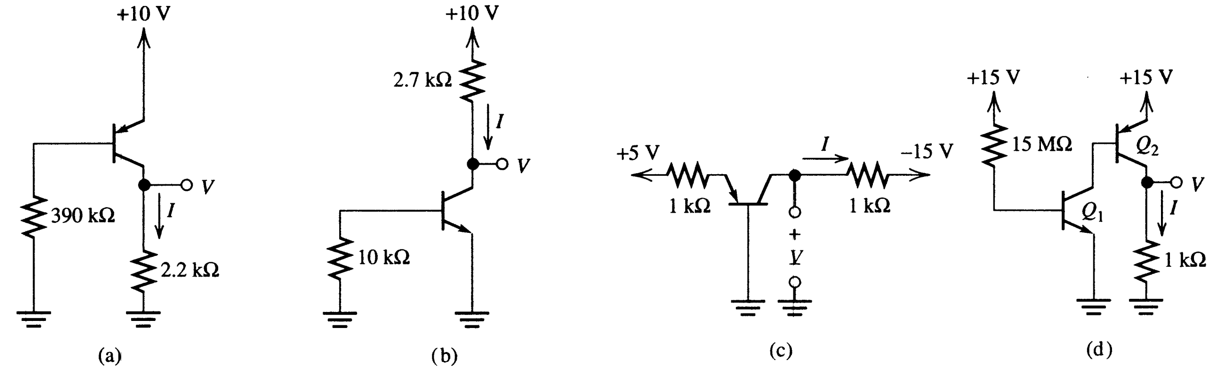
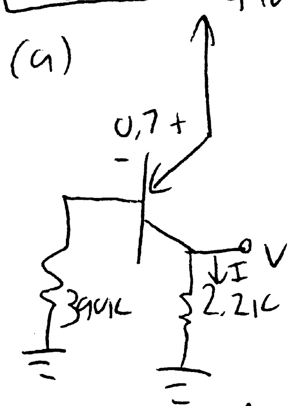


Figure P4.34

$\boxed{4.34}$

(a)



$I_B = \frac{10-0.7}{390K} = \underline{23.85uA}$

$\underline{\beta = 100}$ $I_C = 2{,}385mA$ V_{CE} $10 - 2{,}385mA(2.2K)$ $V_{CE} = 4.753V > 0{,}2$

$\boxed{I = I_C = 2{,}385mA \quad V = 10 - V_{CE} = 5{,}25V}$

$\beta = 300$ $I_C = 7{,}155mA$ $V_{CE} = 10 - 7{,}155mA(2{,}2K)$

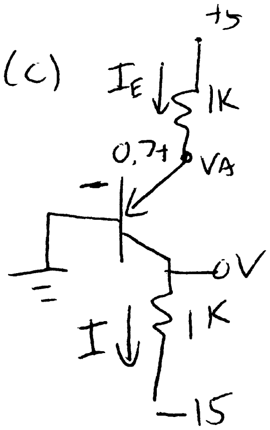
$V_{CE} = -5{,}741 < 0{,}2 \rightarrow$ saturation

$\boxed{V = 10 - 0{,}2 = 9{,}8 \quad I = \frac{9.8}{2{,}2K} = 4{,}45mA}$

(b)

There is no source to drive V_{BE}; therefore, transistor is in cutoff.

$\boxed{I = 0, V = 10}$ for $\beta = 100$ or 300

(c) 

$\beta = 100$:

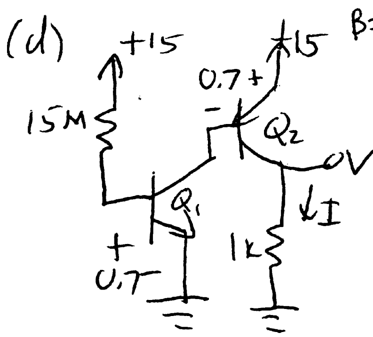
$I_E = \frac{4.3}{1K} = 4.3mA \quad I_E = I_C + I_B = I_C + \frac{I_C}{\beta}$

$I_C = \frac{I_E}{1 + 1/\beta} = \frac{4.3mA}{1 + 1/100} = \underline{4.26mA}$

$V = -15 + 4.26mA(1K) = -10.74V \quad V_{CE} = 11.44 > 0.2$

$\boxed{I = 4.26mA \quad V = -10.74V}$

$\beta = 300$: $I_C = \frac{4.3mA}{1 + 1/300} = 4.29mA \longrightarrow \boxed{I = 4.29mA \quad V = -10.71V}$

(d) 

$\beta = 100$ $I_{B_1} = \frac{15 - 0.7}{15M} = .953uA \quad I_{C_1} = I_{B2} = .953uA(100)$
$= 95.3uA$

$I_{C_2} = 100(95.3uA) = 9.53mA \quad V = (9.53mA)(1k) = 9.5$

$V_{CE} = 15 - 9.53 = 5.47 > 0.2 \therefore$ $\boxed{\begin{array}{l} I = 9.53mA \\ V = 9.53V \end{array}}$

$\beta = 300$: $I_{C_2} = 300(300)(.953uA) = 85.8mA \quad V = 85.8V \rightarrow V_{CE} < 0.2$

Saturation of Q_2: $\boxed{V = 14.8 V \quad I = 14.8mA}$

4.37. Consider the circuit shown in Figure P4.37. Find R_1 and R_C if a bias point of $V_{CE} = 5\,\text{V}$ and $I_C = 2\,\text{mA}$ is required. What are the closest 5%-tolerance nominal values for R_1 and R_C?

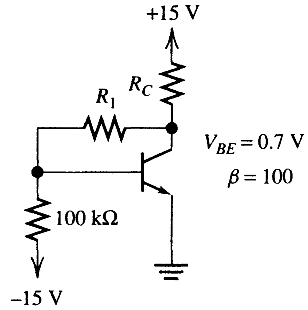
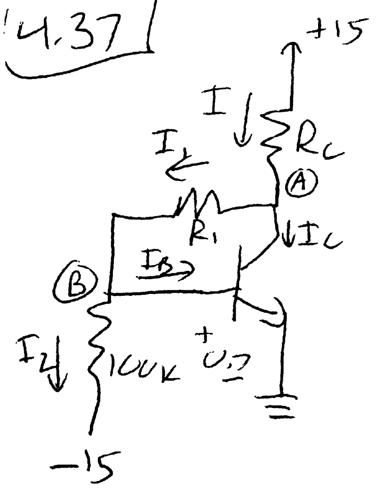


Figure P4.37

4.37



KCL at B: $I_1 = I_B + I_2$

$$\frac{V_A - 0.7}{R_1} = I_B + \frac{0.7-(-15)}{100K} \qquad V_A = 5V \therefore$$

$$\underline{I_B = \left(\frac{4.3}{R_1} - 1.57\times10^{-4}\right)}$$

$$I_C = \beta I_B = 2mA \therefore\ 2mA = 100\left(\frac{4.3}{R_1} - 1.57\times10^{-4}\right)$$

$$\underline{R_1 = 24.3K\Omega}$$

KCL at A $\quad I = I_1 + I_C = \dfrac{5-0.7}{24.3K\Omega} + 2mA = 2.177mA$

$$\frac{15 - V_A}{R_C} = 2.177mA \qquad \frac{15-5}{R_C} = 2.177mA \rightarrow \underline{R_C = 4.59K\Omega}$$

Closest values: $\boxed{R_1 = 24K\Omega \ \& \ R_C = 4.7K\Omega}$

4.42. A certain *npn* silicon transistor at room temperature has $\beta = 100$. Find the corresponding values of g_m and r_π if $I_{CQ} = 1\,\text{mA}$, $0.1\,\text{mA}$, and $1\,\mu\text{A}$. Assume that the device is operating in the active region.

$\boxed{4.42}$ From pg 250, $r_\pi = \dfrac{\beta V_T}{I_{CQ}}$ & $g_m = \dfrac{\beta}{r_\pi} = \dfrac{I_{CQ}}{V_T}$

$V_T \approx 26\,mV$, $\beta = 100$ ∴ we get the following:

I_{CQ}	r_π	g_m
$1\,\mu A$	$2.6\,M\Omega$	$38.5\,\mu S$
$0.1\,mA$	$26\,k\Omega$	$3.85\,mS$
$1\,mA$	$2.6\,k\Omega$	$38.5\,mS$

Note: unit for g_m, mS, is milli Siemens, not milliseconds. $\boxed{\text{Siemen: } S = \frac{Amp}{Volt}}$

4.45. Consider the common-emitter amplifier of Figure P4.45. Draw the dc circuit and find I_{CQ}. Find the value of r_π. Then calculate values for A_v, A_{vo}, Z_{in}, A_i, G, and Z_o. Assume that the circuit is operating in the midband region for which the coupling and bypass capacitors are short circuits.

4.46. Repeat Problem 4.45 if all resistance values, including R_s and R_L, are increased in value by a factor of 100. If you have also worked Problem 4.45, prepare a table comparing the results for the low-impedance amplifier with those for the high-impedance amplifier. (*Comment:* When we consider the high-frequency response of these circuits, we will find that the gain of the high-impedance circuit falls off at lower frequencies than the gain of the low-impedance circuit does. Thus, if we want constant gain to extend to very high frequencies, we should use the low-impedance circuit.)

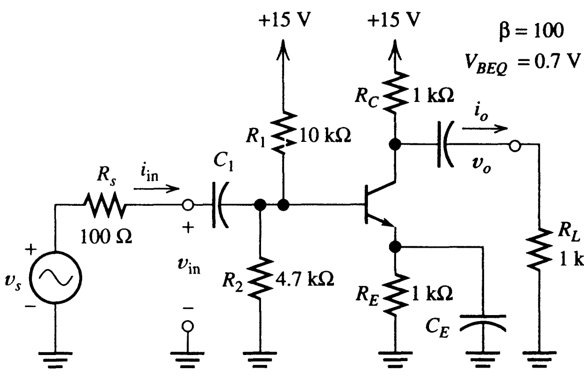
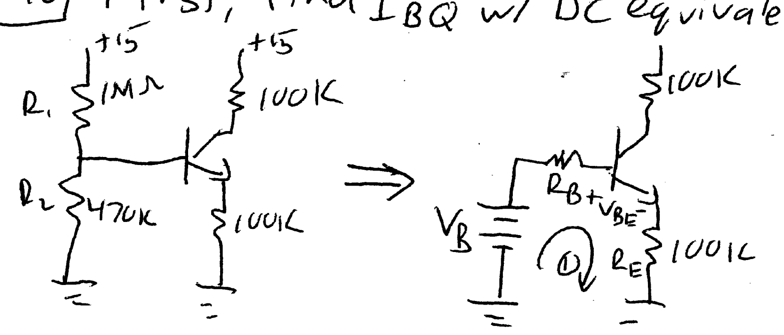


Figure P4.45

* All equations from Section 4.7 *

4.46 First, find I_{BQ} w/ DC equivalent circuit:



$V_B = \frac{15(470K)}{470K + 1M} = 4.8V = V_B$

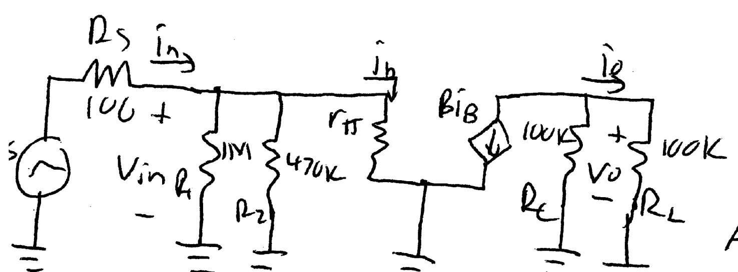
$R_B = R_1 \| R_2 = \frac{470K(1M)}{470K+1M}$

$R_B = 320\ k\Omega$

KVL around ①: $V_B = I_B R_B + V_{BE} + I_E R_E$ $\quad I_E = (\beta+1) I_B \quad V_{BE} = 0.7$

$I_B = \frac{V_B - V_{BE}}{R_B + (\beta+1) R_E}$ $\quad I_{BQ} = 0.393\mu A$ $\quad I_{CQ} = \beta I_{BQ}$ $\boxed{I_{CQ} = 39.3\mu A}$

Small signal model: (see next problem for how to draw SSm's)



$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100(26mV)}{39.3\mu A} = \boxed{66.2k\Omega}$ $\boxed{r_\pi}$

$R_L' = R_L \| R_C = 50\ k\Omega$

$A_v = \frac{-\beta R_L'}{r_\pi + (\beta+1)R_E}$ $\quad R_E = 0 \therefore A_v = \frac{-\beta R_L'}{r_\pi}$

$\boxed{A_v = -75.5}$ $\quad A_{vo} = \frac{-\beta R_C}{r_\pi} = \boxed{-151 = A_{vo}}$ $\quad Z_{in} = \frac{1}{\frac{1}{R_B} + \frac{1}{r_\pi + (\beta+1)R_E}} =$

$\frac{1}{\frac{1}{320K} + \frac{1}{66.2K}}$ $\boxed{Z_{in} = 54.8k\Omega}$ $\quad A_i = \frac{A_v Z_{in}}{R_C} = \frac{(-75.5)(54.8K)}{100K} = \boxed{-41.4 = A_i}$

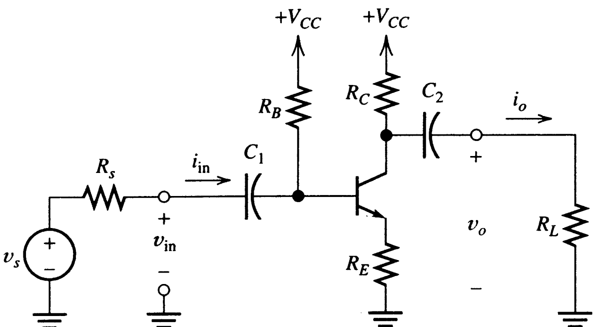
$G = A_i A_v$ $\boxed{G = 3,126}$ $\quad Z_o = R_C$ $\boxed{Z_o = 100K\Omega}$

4.49. Draw the small-signal equivalent circuits for the circuits illustrated in Figure P4.49.

4.49 In writing small signal models, remember the following rules:

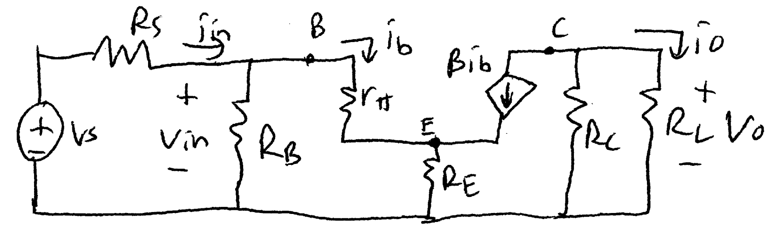
1) All DC Voltage sources become short circuits & current sources becomes open circuits

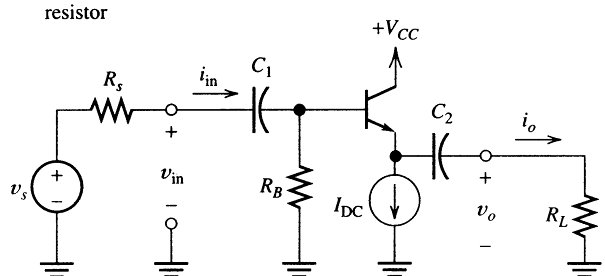
2) All capacitors become short circuits 3) BJT's are replaced w/ model on pg 251



(a) Common-emitter amplifier with unbypassed emitter resistor

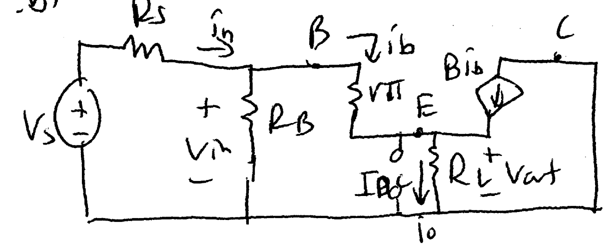
a)

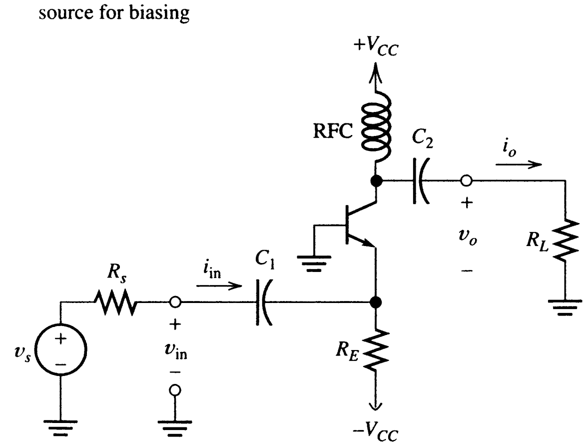




(b) Variation of the emitter follower using a dc current source for biasing

b)





(c) Variation of the common-base amplifier [assume that the *radio-frequency choke* (RFC) is an open circuit for the ac signals]

c)

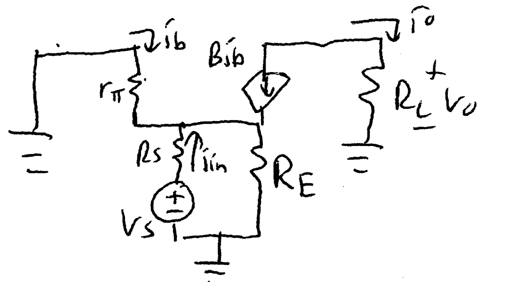


Figure P4.49 Amplifier circuits.

4.51. Consider the emitter-follower amplifier of Figure P4.51. Draw the dc circuit and find I_{CQ}. Find the value of r_π. Then calculate midband values for A_v, A_{vo}, Z_{in}, A_i, G, and Z_o.

4.52. Repeat Problem 4.51 if all resistance values, including R_s and R_L, are increased in value by a factor of 100. Prepare a table comparing the results for the low-impedance amplifier with those for the high-impedance amplifier.

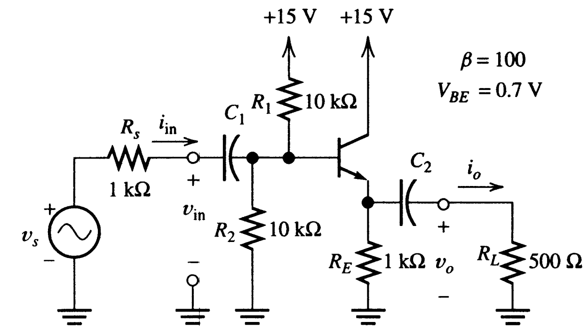
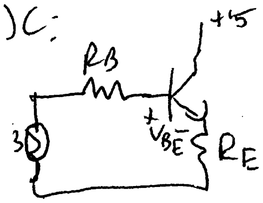


Figure P4.51

$\boxed{1.52}$ All equations come from section 4.8 directly → see circuit!

DC: $V_B = \frac{15(1M)}{1M+1M} = 7.5$ $R_B = 1M//1M = 500k$ 2



$I_{CQ} = \beta I_{BQ} = 100\left(\frac{7.5-0.7}{500k+(100+1)100k}\right)$ $\boxed{I_{CQ} = 64.1uA}$

$r_\pi = \frac{\beta V_T}{I_{CQ}}$ $\boxed{r_\pi = 40.56\,k\Omega}$ $R_L' = 100k//50k$ $R_L' = 33.3k\Omega$

$A_v = \frac{R_L'(\beta+1)}{r_\pi + R_L'(\beta+1)} = \boxed{A_v = 0.988}$ $A_{vo} = \frac{R_E(\beta+1)}{r_\pi + R_E(\beta+1)} = \boxed{A_{vo} = 0.996}$ $R_s' = R_B // R_s$ $R_s' = 83.3k\Omega$

$Z_{in} = R_B // (r_\pi + R_L'(\beta+1))$ $\boxed{Z_{in} = 436k\Omega}$ $A_i = \frac{A_v Z_{in}}{R_L}$ $\boxed{A_i = 8.61}$ 2

$G = A_v A_i$ $\boxed{G = 8.51}$ $Z_o = R_E // \left(\frac{R_s' + r_\pi}{\beta+1}\right) = \boxed{Z_o = 1.21k\Omega}$

4.56. Draw the small-signal equivalent circuit of the circuit shown in Figure P4.56, and derive expressions for the input impedance and voltage gain. Assume that the capacitors are short circuits for the signals.

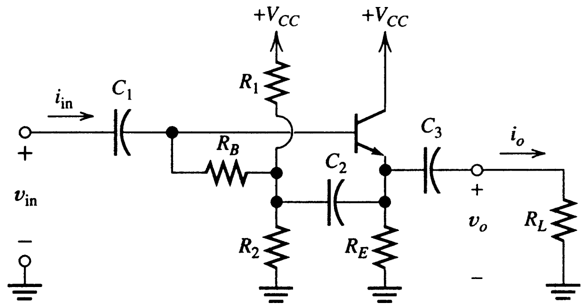
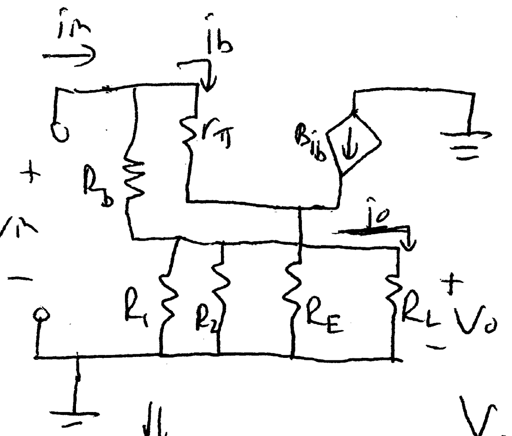
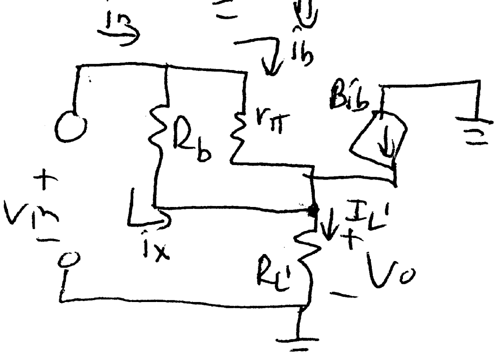


Figure P4.56

4.56 Small signal equivalent:





First, combine bottom 4 resistors:

$R_L' = R_1 // R_2 // R_E // R_L$

$V_o = i_L'(R_L')$

$i_L' = i_b + Bi_b + i_x$

$i_x = \frac{i_b r_\pi}{R_B}$ ∴

$V_o = R_L'\left(i_b + Bi_b + \frac{r_\pi i_b}{R_B}\right)$

$V_{in} = V_o + r_\pi i_b$ ∴

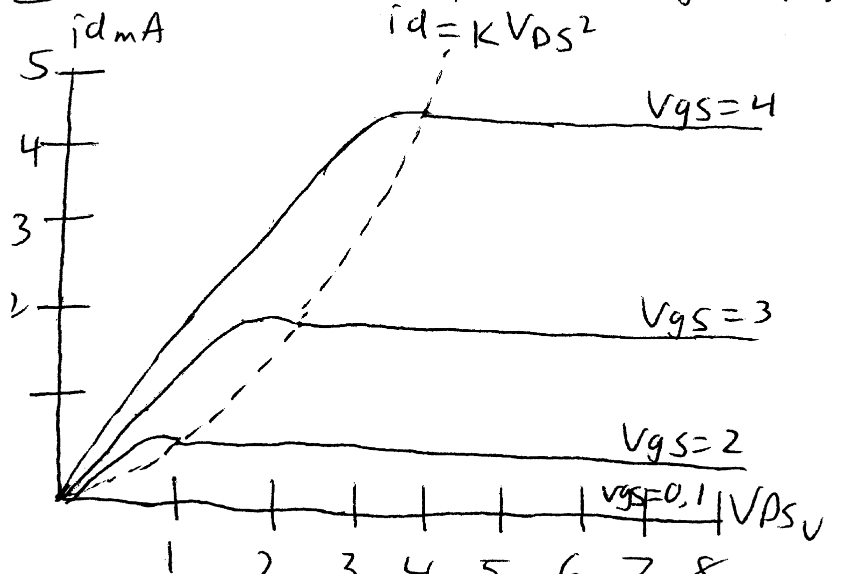
$A_v = \frac{V_o}{V_{in}} = \boxed{\frac{R_L'\left(1 + B + \frac{r_\pi}{R_B}\right)}{r_\pi + R_L'\left(1 + B + \frac{r_\pi}{R_B}\right)}} = A_v$

$i_{in} = \frac{V_{in} - V_o}{R_B // R_\pi} = \frac{V_{in} - A_v V_{in}}{R_B // R_\pi}$ $Z_{in} = \frac{V_{in}}{i_{in}} = \frac{V_{in}}{\frac{V_{in} - A_v V_{in}}{R_B // R_\pi}}$

$\boxed{Z_{in} = \frac{R_B // R_\pi}{1 - A_v}}$

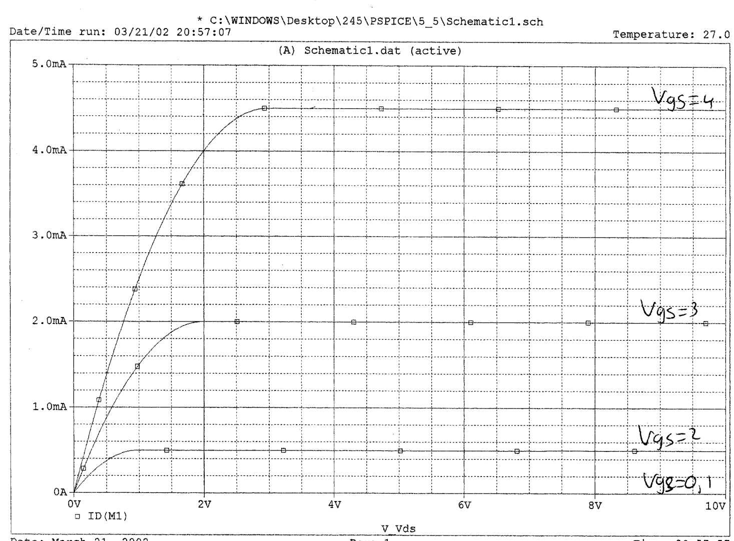
5.5. Suppose that we have an NMOS transistor with $KP = 50\,\mu A/V^2$, $V_{to} = 1\,V$, $\lambda = 0$, $L = 10\,\mu m$, and $W = 200\,\mu m$. Sketch the drain characteristics for v_{DS} ranging from 0 to 10 V and $v_{GS} = 0, 1, 2, 3,$ and 4 V. Check your hand-drawn sketches by using SPICE to plot the characteristic curves.

$\boxed{5.5}$ In saturation, $i_d = K(V_{gs} - V_{TO})^2$ $\quad K = \frac{50\times10^{-6}}{2}\left(\frac{W}{L}\right) = 5\times10^{-4}$



Vgs	idsat
2	0.5 mA
3	2 mA
4	4.5 mA

Now, for each Vgs, we start at the saturation current and $i_d = KV_{DS}^2$ intersection. To the right, a straight line; to the left, a ray to 0. For $V_{gs} < 2$, $i_d = 0$. See next page for PSPICE results. See Dr. Merat's NMOS notes for how to generate this graph.



5.13. Assume that an NMOS transistor is operating with $v_{DS} \ll v_{GS} - V_{to}$, as illustrated in Figure 5.4. Find an expression for the resistance of the channel in terms of the device parameters and voltages. Assume that $\lambda = 0$. Given that $V_{to} = 1\,\text{V}$ and $K = 0.25\,\text{mA/V}^2$, compute the resistance for $v_{GS} = 0.5, 1, 1.5$, and $2\,\text{V}$.

$\boxed{5.13}$

In the triode region, $i_d = K\left[2(V_{gs} - V_{TO})V_{DS} - V_{DS}^2\right]$

If $V_{DS} \ll V_{gs} - V_{TO}$, this reduces to $i_d \approx 2K(V_{gs} - V_{TO})V_{DS}$

$r_d = \dfrac{V_{DS}}{i_D}$ $\therefore$ $\underline{r_d = \dfrac{1}{2K(V_{gs} - V_{TO})}}$

If $V_{gs} < V_{TO}$ (cutoff), r_d is infinite because $i_d = 0$

V_{gs} (V)	r_d (kΩ)
0.5	∞
1.0	∞
1.5	4
2.0	2

5.15. Draw the load lines on the i_D–v_{DS} axes for the circuit of Figure 5.13 for

(a) $R_D = 1\,\text{k}\Omega$ and $V_{DD} = 20\,\text{V}$.
(b) $R_D = 2\,\text{k}\Omega$ and $V_{DD} = 20\,\text{V}$.
(c) $R_D = 3\,\text{k}\Omega$ and $V_{DD} = 20\,\text{V}$.

How does the position of the load line change as R_D increases in value?

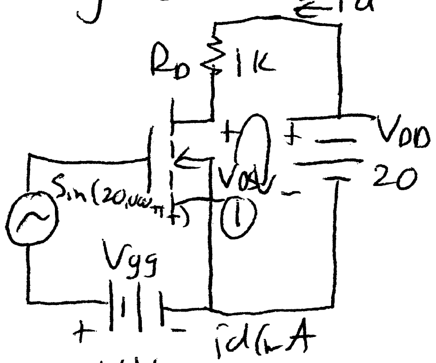
5.16. Draw the load lines on the i_D–v_{DS} axes for the circuit of Figure 5.13 for

(a) $R_D = 1\,\text{k}\Omega$ and $V_{DD} = 5\,\text{V}$.
(b) $R_D = 1\,\text{k}\Omega$ and $V_{DD} = 10\,\text{V}$.
(c) $R_D = 1\,\text{k}\Omega$ and $V_{DD} = 15\,\text{V}$.

How does the position of the load line change as V_{DD} increases in value?

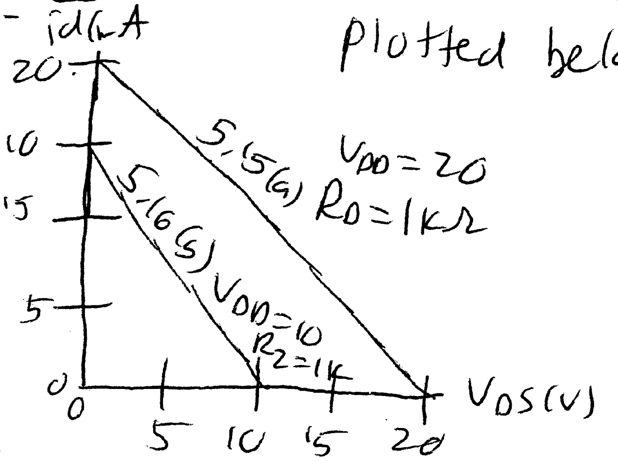
$\boxed{5.15}$ (a)

Figure 5.13:



Writing a loop equation around ① yields $-V_{DS} - i_D R_D + V_{DD} = 0$ or

$\underline{V_{DD} = i_D R_D + V_{DS}}$ This is an load line equation. Graph is plotted below for $V_{DD} = 20$, $R_D = 1\text{K}\Omega$



$\boxed{5.16\ (b)}$ Again, $V_{DD} = i_D R_D + V_{DS}$. Graph above for $V_{DD} = 10$, $R_D = 1K\Omega$

5.18. Consider the amplifier shown in Figure P5.18.

(a) Find $v_{GS}(t)$, assuming that the coupling capacitor is a short circuit for the ac signal.

(b) If the FET has $V_{to} = 1\,\text{V}$ and $K = 0.5\,\text{mA/V}^2$, sketch its drain characteristics to scale for $v_{GS} = 1, 2, 3,$ and $4\,\text{V}$.

(c) Draw the load line for the amplifier on the characteristics.

(d) Find the values of V_{DSQ}, $V_{DS\min}$, and $V_{DS\max}$.

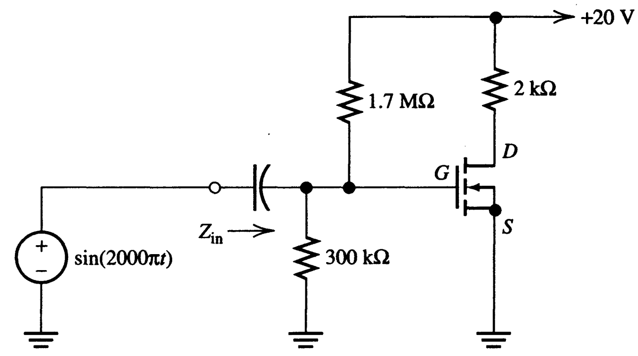
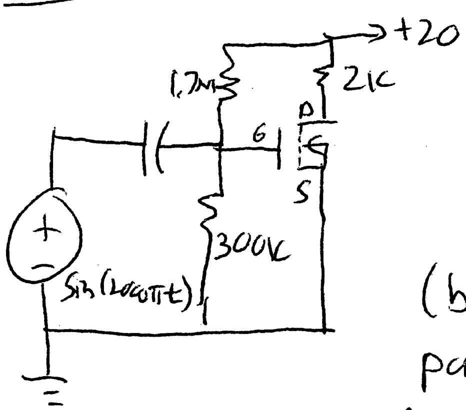


Figure P5.18

5.18



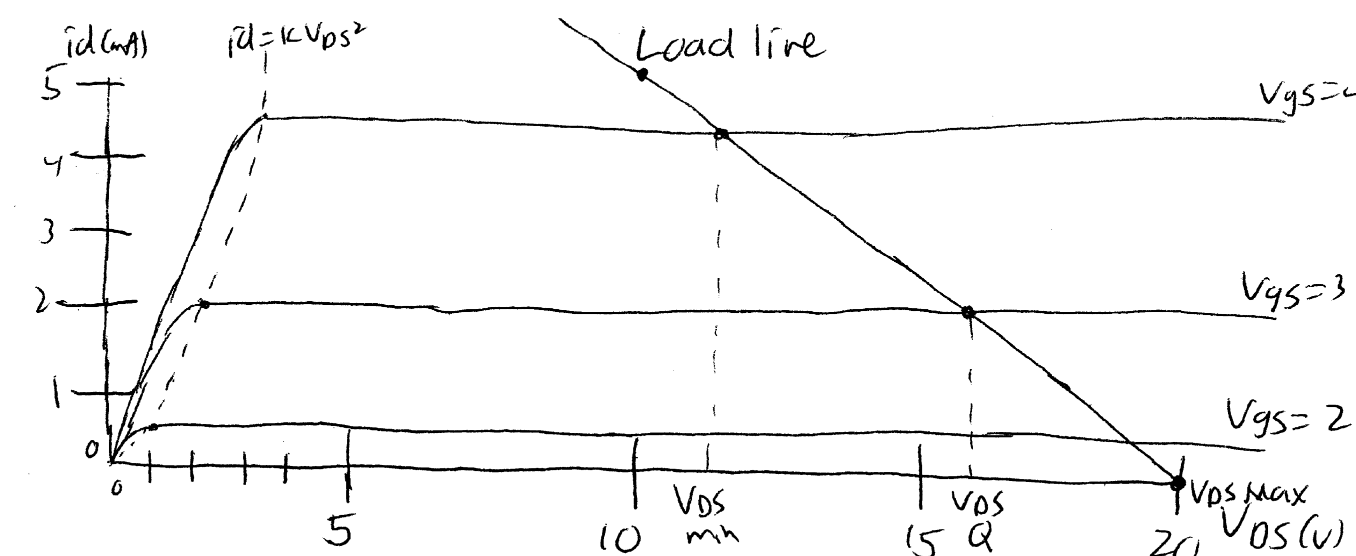
(a) $V_{gs}(t) = \sin(2000\pi t) + V_{gsQ}$

$$V_{GSQ} = 20\left(\frac{300K}{1.7M + 300K}\right) = 3V \therefore$$

$$\boxed{V_{gs}(t) = \sin(2000\pi t) + 3}$$

(b) $i_{dsat} = 0.5\times10^{-3}(V_{gs} - 1)^2$ see next page for graph, see problem 5.5 for how to draw it. Actually, it's the same as 5.5!

(c) Load line $=$ $V_{DD} = i_D R_D + V_{DS}$: $20 = i_D(2K) + V_{DS}$



(d) As can be seen from the above graph, $\boxed{V_{DS\min} \approx 11V \quad V_{DS\max} = 20V \quad V_{DSQ} \approx 16V}$

5.23. (a) Find the value of I_{DQ} for the circuit shown in Figure P5.23. Assume that $V_{to} = 4\,\text{V}$, $\lambda = 0$, and $K = 1\,\text{mA/V}^2$. (b) Repeat for $V_{to} = 2\,\text{V}$, $\lambda = 0$, and $K = 2\,\text{mA/V}^2$.

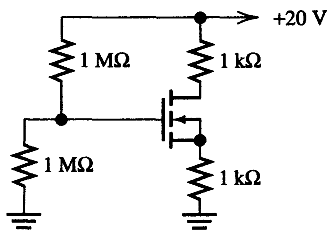
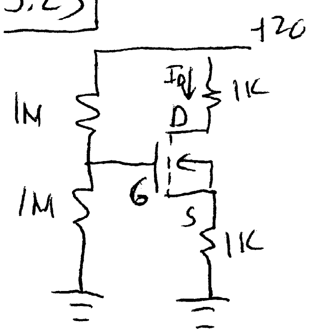


Figure P5.23

$\boxed{5.23}$



(a) $V_g = 20\left(\frac{1M}{1M+1M}\right) = 10V$

$V_S = I_S(1K)$ $I_D = I_S$ ∴ $V_S = I_D(1k\Omega)$ ∴

① $V_{gs} = 10 - I_D(1k\Omega)$

we also know that in saturation,

$I_D = K(V_{gs} - V_{TO})^2$ substituting into ①,

$V_{gs} = 10 - (1K)(1\times10^{-3})(V_{gs}-4)^2 \rightarrow V_{gs}^2 - 7V_{gs} + 6 = 0$

Solving yields $V_{gs} = 1, 6$ If $V_{gs} = 1$, transistor is l ∴ $V_{gsQ} = 6$

From ①, $I_{DQ} = 4mA$ $V_{DSQ} = 10 - (2k\Omega)(I_{DQ})$ $\boxed{V_{DSQ} = 12}$

Check: is $V_{DS} \geq V_{gs} - V_{TO}$? $12 \geq 6 - 4 \rightarrow$ correct!

As with BJT's, assume saturation, then check your assumption

$V_{DS} \geq V_{gs} - V_{TO}$ for saturation.

(b) Same equations, different numbers

$V_{gs} = 10 - (1K)(2\times10^{-3})(V_{gs}-2)^2 \rightarrow V_{gs}^2 - 3.5V_{gs} - 1 = 0$

$V_{gsQ} = 3.765, -.265 \rightarrow V_{gsQ} = 3.765V$

$I_{DQ} = \frac{3.765 - 10}{-1K} = 6.235mA$ $V_{DSQ} = 20 - (2k)(6.235mA)$

$\boxed{V_{DSQ} = 7.53V}$

$7.53 \geq 3.765 - 2 \rightarrow$ correct

5.26. Find I_{DQ} and V_{DSQ} for the circuit shown in Figure P5.26. The MOSFET has $V_{to} = 1\,\text{V}$, $\lambda = 0$, and $K = 0.25\,\text{mA/V}^2$.

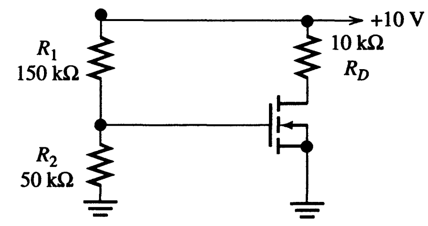
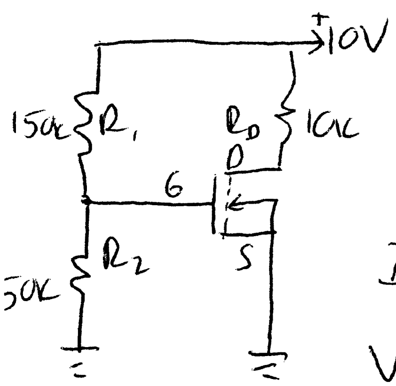


Figure P5.26

$\boxed{5.26}$



$V_S = 0 \therefore V_{gs} = V_g$

$V_g = 10\left(\frac{50K}{50K+150K}\right) = 2.5V = V_{gs}$

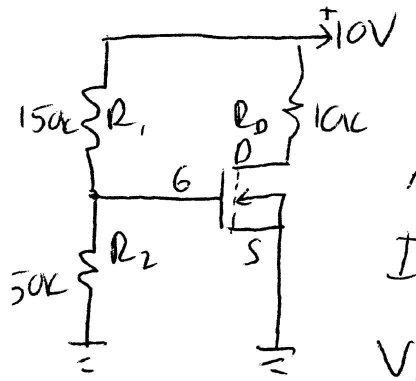
Assume saturation: $I_{DQ} = K(V_{gsQ} - V_{TO})^2$

$I_{DQ} = (.25 \times 10^{-3})(2.5 - 1)^2 = .5625\,mA$

$V_{DSQ} = V_{DD}\ R_D I_{DQ} = 10 - (10K)(.5625mA)$

$\boxed{V_{DSQ} = 4.375V}$

5.26



$V_S = 0 \therefore V_{gs} = V_g$

$V_g = 10\left(\frac{50K}{50K + 150K}\right) = 2.5V = V_{gs}$

Assume saturation: $I_{DQ} = K(V_{gsQ} - V_{TO})^2$

$I_{DQ} = (.25 \times 10^{-3})(2.5 - 1)^2 = .5625\,mA$

$V_{DSQ} = V_{DD}\ R_D I_{DQ} = 10 - (10K)(.5625mA)$

$\boxed{V_{DSQ} = 4.375V}$

5.38. Consider the amplifier illustrated in Figure P5.38.

(a) Draw the small-signal midband equivalent circuit.

(b) Assume that $r_d = \infty$, and derive expressions for the voltage gain, input resistance, and output resistance.

(c) Find I_{DQ} if $R = 100\,\text{k}\Omega$, $R_f = 100\,\text{k}\Omega$, $R_D = 3\,\text{k}\Omega$, $R_L = 10\,\text{k}\Omega$, $V_{DD} = 20\,\text{V}$, $V_{to} = 5\,\text{V}$, and $K = 1\,\text{mA/V}^2$. Determine the value of g_m at the Q-point.

(d) Evaluate the expressions found in part (b).

(e) Find $v_o(t)$ if $v(t) = 0.2\sin(2000\pi t)$.

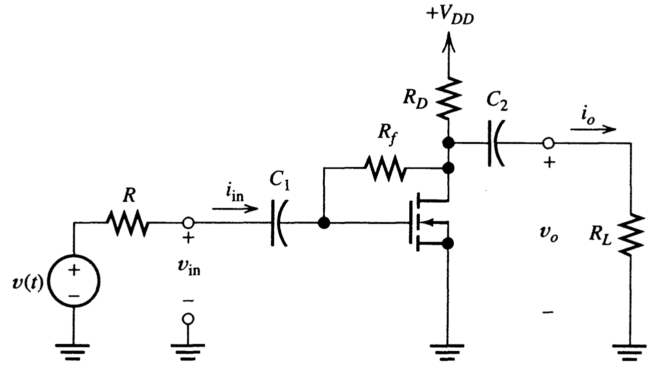
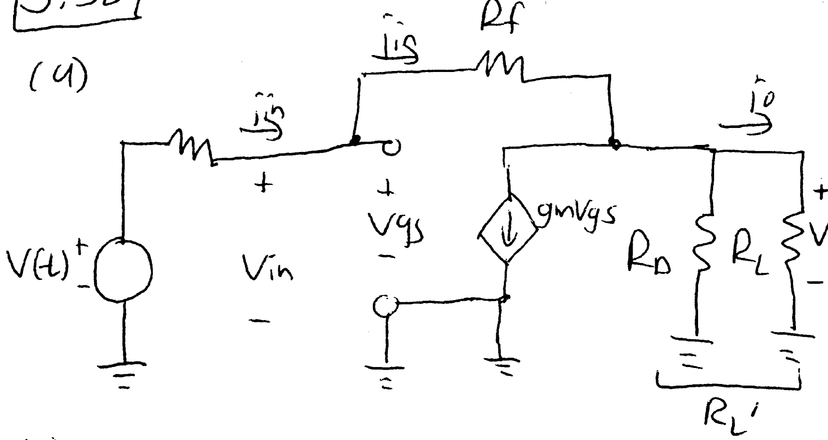


Figure P5.38

5.38

(a)



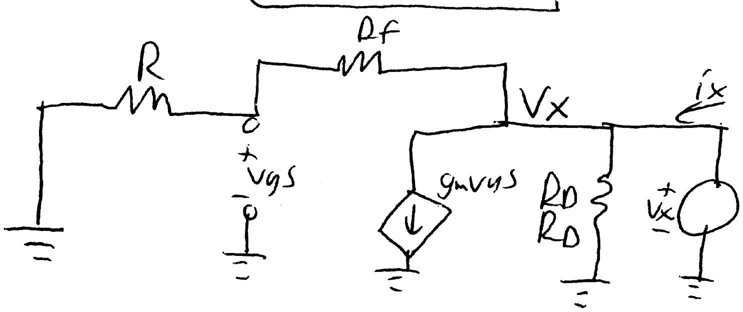
Remember, for small-signal model, C's + DC voltage sources are shorted, but the small signal, V(t) is not shorted!

(b) From above, $V_O = R_L' i_o$ $\quad i_o = i_{in} - g_m V_{gs}$ ∴ $V_o = R_L'(i_{in} - g_m V_{gs})$

$i_{in} = \dfrac{V_{in} - V_o}{R_f}$. Combining these two yields $\boxed{\dfrac{V_o}{V_{in}} = \dfrac{R_L' - g_m R_L' R_f}{R_L' + R_f} = A_v}$

$R_{in} = \dfrac{V_{in}}{i_{in}}$. $\quad i_{in} = \dfrac{(V_{in} - V_o)}{R_f} \Rightarrow \dfrac{i_{in}}{V_{in}} = \left(\dfrac{1 - \frac{V_o}{V_{in}}}{R_f}\right) \Rightarrow \dfrac{V_{in}}{i_{in}} = \dfrac{R_f}{1 - \frac{V_o}{V_{in}}}$

$\dfrac{V_o}{V_{in}} = A_v$ ∴ $\boxed{R_{in} = \dfrac{R_f}{1 - A_v}}$



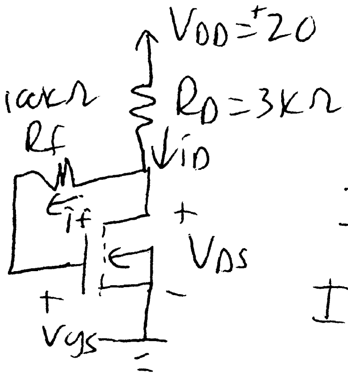
To meausre output impedance, use the following circuit. V(t) is shorted, but the dependendant source cannot be ignored.

Note that $R_D \parallel (R+R_f) = R_D'$ (R_D is in parallel with $(R+R_f)$)

$V_{gs} = V_x\left(\frac{R}{R+R_f}\right)$ (V_{gs} will divide along $R+R_f$) $\quad i_x = \frac{V_x}{R_D'} + g_m V_{gs}$

Combining, $\frac{V_x}{i_x} = \boxed{R_o = \frac{1}{\frac{1}{R_D'} + \frac{g_m R}{R_f+R}}} = \frac{R_D'(R_f+R)}{R_f + R(1+g_m R_D')}$

(c) The dc circuit is:



$i_f = 0$ since input impedance of MOSFET for DC $= \infty$ ∴

$V_{GSQ} = V_{DSQ}$ $\quad$ Assuming saturation →

$I_{DSQ} = K(V_{GSQ} - V_{TO})^2 = K(V_{DSQ} - V_{TO})^2$

$I_{DQ} = \frac{(V_{DD} - V_{DSQ})}{R_D}$ $\quad$ Combining ⟹

$3V_{DSQ}^2 - 29V_{DSQ} + 55 = 0$

Solving, $V_{DSQ} = 7.08, 2.59$

Since $V_{DS} = V_{gs}$, & $V_{TO} = 5V$, V_{DS} must $= 7.08$ for transistor to be on.

$\boxed{V_{DSQ} = 7.08}$ $\quad I_{DQ} = \frac{(20-7.08)}{3K} = \boxed{4.31mA}$ $\quad$ Check: $7.08 > 7.08 - 5$ ✓ Saturation assumption correct

$g_m = \left.\frac{\partial i_D}{\partial V_{gs}}\right|_{Q\text{-point}}$ $\quad I_{DQ} = K(V_{gsQ} - V_{TO})^2 \Rightarrow \frac{\partial I_{dQ}}{\partial V_{gsQ}} = 2K(V_{gsQ} - V_{TO})$

$\boxed{g_m = 4.16 \times 10^{-3}\,S}$

(d) $R_L' = R_D \parallel R_L = \boxed{2.31K\Omega}$ plugging into expressions in (d) yields:

$\boxed{A_v = -9.37}$ $\quad \boxed{R_{in} = 9.64K\Omega}$ $\quad \boxed{R_o = 414\,\Omega}$

(e) $V_o(t) = V(t)\left(\frac{R_{in}}{R+R_{in}}\right)A_v \quad V_o(t) = (-.164)\sin(2000\pi t)$

5.39. Find V_{DSQ} and I_{DQ} for the FET displayed in Figure P5.39, given that $V_{to} = 3\,\text{V}$ and $K = 0.5\,\text{mA/V}^2$. Find the value of g_m at the operating point. Draw the small-signal equivalent circuit, assuming that $r_d = \infty$. Derive an expression for the resistance R_o in terms of R_D and g_m. Evaluate the expression for the values given.

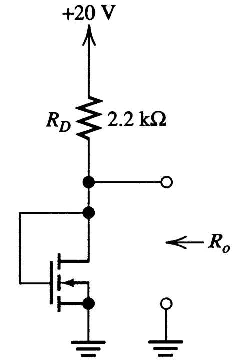
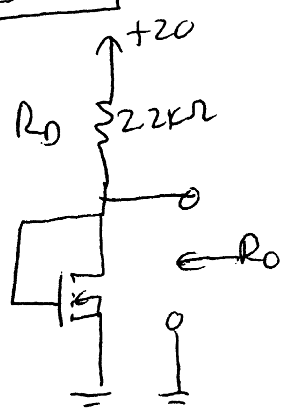


Figure P5.39

5.39

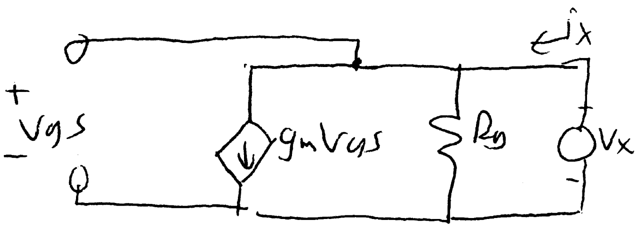


$V_{gsQ} = V_{DSQ} \therefore \underline{I_{DQ} = K(V_{DSQ} - V_{TO})^2}$

$I_{DQ} = \dfrac{(V_{DD} - V_{DSQ})}{R_D}$ Combining, $1.1V_{DSQ}^2 - 5.6V_{DSQ} - 10.1 = 0$

$V_{DSQ} = \underline{6.5}, -1.41 \therefore \boxed{V_{DSQ} = 6.5,\ I_{DQ} = 6.135\text{mA}}$

$g_m = \dfrac{\partial i_D}{\partial V_{gs}} = 2K(V_{gs} - V_{TO}) = \boxed{3.5\text{mS}}$



(Vx & ix are used to calculate Ro and are NOT part of the normal small-signal model)

$i_x = \dfrac{V_x}{R_D} + g_m V_{gs} \quad V_{gs} = V_x \therefore R_o = \dfrac{V_x}{i_x} = \dfrac{V_x}{\frac{V_x}{R_D} + g_m V_x} =$

$\dfrac{1}{1/R_D + g_m}$ $\boxed{R_o = 253\,\Omega}$

5.47. Consider the source follower shown in Figure 5.33, given that $V_{DD} = 15\,\text{V}$, $R_L = 2\,\text{k}\Omega$, $R_1 = 1\,\text{M}\Omega$, and $R_2 = 2\,\text{M}\Omega$. The NMOS transistor has $KP = 50\,\mu\text{A/V}^2$, $\lambda = 0$, $L = 10\,\mu\text{m}$, $W = 160\,\mu\text{m}$, and $V_{to} = 1\,\text{V}$. Find the value required for R_S to achieve $I_{DQ} = 2\,\text{mA}$. Then compute the voltage gain, input resistance, and output resistance of the circuit.

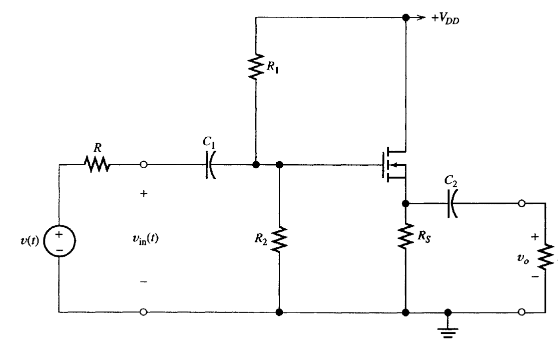
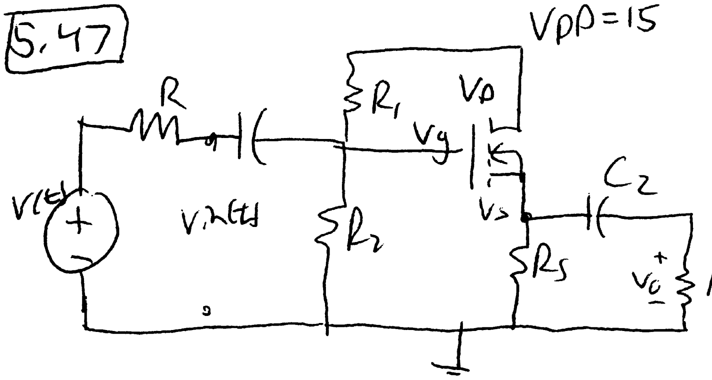


Figure 5.33 Source follower.

$\boxed{5.47}$



First, $K = \left(\frac{W}{L}\right)\left(\frac{KP}{2}\right) = \left(\frac{160}{10}\right)\left(\frac{50\times10^{-6}}{2}\right)$

$\boxed{K = 400\,\frac{uA}{V^2}}$

$I_{DQ} = K(V_{GSQ} - V_{TO})^2 \Rightarrow V_{GSQ} = V_{TO} + \sqrt{\frac{I_{DQ}}{K}}$ $\quad V_{GSQ} = 3.236$

$V_g = 15\left(\frac{2M}{1M+2M}\right) = 10V$ $\quad V_g - V_s = V_{gs}$ $\quad V_S = I_{DQ} R_S \therefore$

$V_{gs} = V_g - I_{DQ} R_s$ $\quad R_s = \frac{V_{gs} - V_g}{-I_{DQ}}$ $\quad \boxed{R_s = 3.382\,k\Omega}$

From eqn. 5.26, $g_m = 2K(V_{gsK} - V_{TO})$

$g_m = 1.79\,mS$

Looking at pg 321 in the text, $R_L' = \frac{1}{\frac{1}{r_d} + \frac{1}{R_s} + \frac{1}{R_L}}$ $\quad r_d = \infty \therefore$

$R_L' = 1.257\,k\Omega$

$R_{in} = R_1 // R_2$ $\quad \boxed{R_{in} = 666.7\,k\Omega}$

$A_v = \frac{g_m R_L'}{1 + g_m R_L'}$ $\quad \boxed{A_v = .6923}$ $\quad R_o = \frac{1}{g_m + \frac{1}{R_s} + \frac{1}{R_d}}$ $\quad \boxed{R_o = 479.5\,\Omega}$