Name: ______________________________ (please print)

Signature: ___________________________

ECE 3355 – Final Exam
December 4, 2019

Keep this exam closed and face up until you are told to begin.

1. This exam is closed book, closed notes. You may use two 8.5" x 11" crib sheets, or their equivalent.
2. Show all work on these pages. Show all work necessary to complete the problem. A solution without the appropriate work shown will receive no credit. A solution which is not given in a reasonable order will lose credit.
3. Show all units in solutions, intermediate results, and figures.
4. If the grader has difficulty following your work because it is messy or disorganized, you will lose credit.
5. Do not use red ink. Do not use red pencil.
6. You will have 160 minutes to work on this exam.

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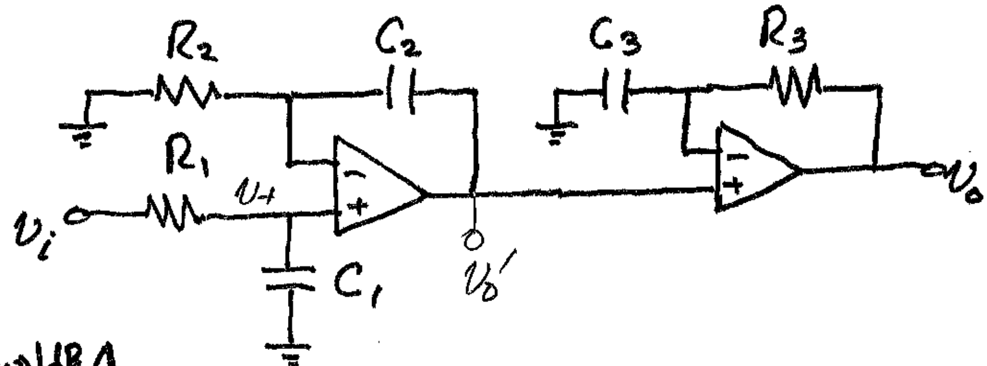
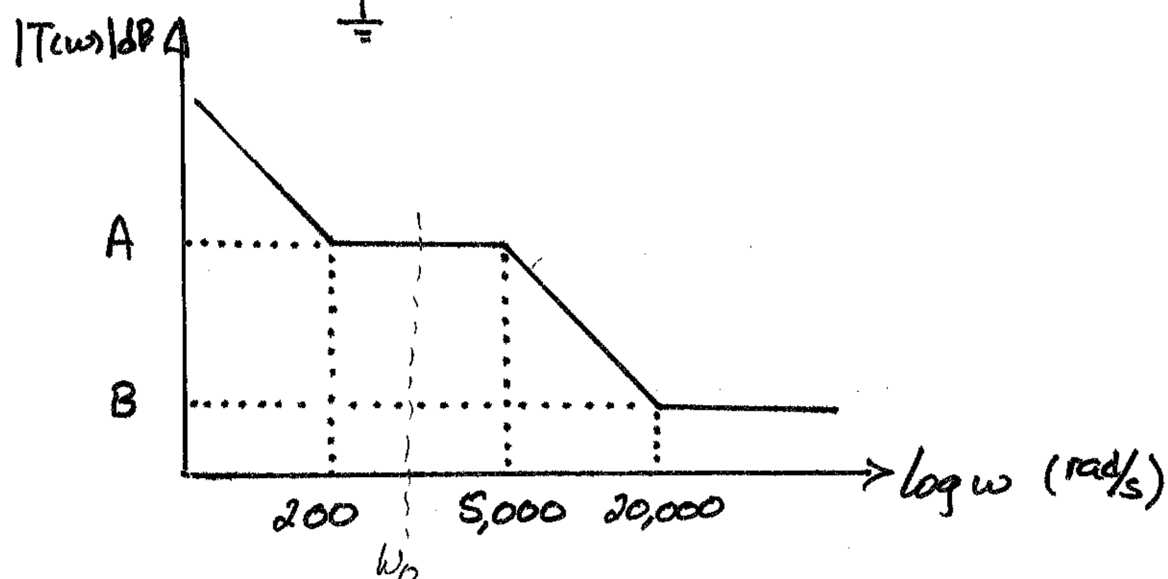
__________________/40 (extra credit)

__________________/240

1. (40 points) The op amps in the circuit below may be considered ideal. Do the following.

a. Find the transfer function T(ω) = V_o/V_i. Your expression should be in terms of the resistor and capacitor variables labeled on the diagram, that is, do not substitute numbers for those variables.
b. Choose values for the resistors and capacitors so that the transfer function has the breakpoints indicated in the Bode plot below. The magnitudes A and B indicated on the plot will depend on your choices for assigning the breakpoints. For your choices, calculate these magnitudes in dB.





a) Define v_+. Then $\bar{V}_o' = \bar{V}_+ \left(1 + \frac{1/j\omega C_2}{R_2}\right) = \bar{V}_+ \left(\frac{1 + j\omega C_2 R_2}{j\omega C_2 R_2}\right)$

$$\bar{V}_+ = \bar{V}_i \frac{1/j\omega C_1}{R_1 + 1/j\omega C_1} = \bar{V}_i \frac{1}{1 + j\omega C_1 R_1}$$

$$\bar{V}_o = \bar{V}_o' \left(1 + \frac{R_3}{1/j\omega C_3}\right) = \bar{V}_o' (1 + j\omega C_3 R_3)$$

Room for extra work

Putting these together...

$$\frac{\bar{V}_o}{\bar{V}_i} = \frac{(1+j\omega C_3 R_3)}{(1+j\omega C_1 R_1)} \cdot \frac{(1+j\omega C_2 R_2)}{(j\omega C_2 R_2)}$$ +20

b) poles & zeros: $p_1 : \omega = 0$

$p_2 : 1/C_1R_1 = 5{,}000 \text{ rad/s}$ + 2

Choose:

1. $z_1 = 1/C_2R_2 = 200$ rad/s $z_2 = 1/C_3R_3 = 20{,}000$ rad/s + 2 + 2

-or-

2. $z_1 = 1/C_2R_2 = 20{,}000$ rad/s -or- $z_1 = 1/C_3R_3 = 200$ rad/s

We can assign the zeros as in 1 or 2 - we have no information that would determine which is which. + 4

Continue with choice 1:

$$\omega \to \infty \Rightarrow T(\omega) \to \frac{C_3R_3}{C_1R_1} = \frac{1/20000}{1/5000} = 0.25 = \underline{-12\text{ dB} = B}$$

In the pass band ($200 < \omega_0 < 5000$ rad/s), we have

$$1/C_2R_2 \ll \omega_0 \ll 1/C_1R_1 \qquad \omega_0 \ll 1/C_3R_3$$

$$1 \ll \omega_0 C_2 R_2 \qquad 1 \gg \omega_0 C_1 R_1 \qquad 1 \gg \omega_0 C_3 R_3$$

+ 4

$$\Rightarrow T(\omega_0) \to 1 = \underline{0\text{ dB} = A}$$

to page 2

$C_3R_3 = \frac{1}{20000}$: $\underline{R_3 = 1\,k\Omega \Rightarrow C_3 = 50\text{ nF}}$ + 2

$C_2R_2 = \frac{1}{200}$: $\underline{R_2 = 10\,k\Omega \Rightarrow C_2 = 500\text{ nF}}$ + 2

$C_1R_1 = \frac{1}{5000}$: $\underline{R_1 = 1\,k\Omega \;\; 4 \Rightarrow C_1 = 200\text{ nF}}$ + 2

Room for extra work

If we had used choice 2, similar analysis gives

$$T(\omega \to \infty) \to \frac{C_3R_3}{C_1R_1} = \frac{1/200}{1/5000} = 25 = \underline{28\ dB = B}$$

$$T(\omega_0) \to \frac{C_3R_3}{C_2R_2} = 100 = \underline{40\ dB = A}$$

Also,

$$C_3R_3 = \frac{1}{200} : \underline{R_3 = 10\ k\Omega \Rightarrow C_3 = 500\ nF}$$

$$C_2R_2 = \frac{1}{2000} : \underline{R_2 = 1\ k\Omega \Rightarrow C_2 = 50\ nF}$$

$$C_1R_1 = \frac{1}{5000} : \underline{R_1 = 1\ k\Omega \Rightarrow C_1 = 200\ nF}$$

notation -5

$|T(\omega)|$ at bkpts -2

RC = p or z -4

algebra -5

ckt analysis -8

2. (40 points) For the transfer function given below, plot the phase Bode plot on the paper given on the next page. Your plot should include units and labels on both axes.

$$T(\omega) = 50\frac{(1 + j\omega/20{,}000)(1 + j\omega/200)}{(j\omega/200\,)(1 + j\omega/5{,}000)}$$

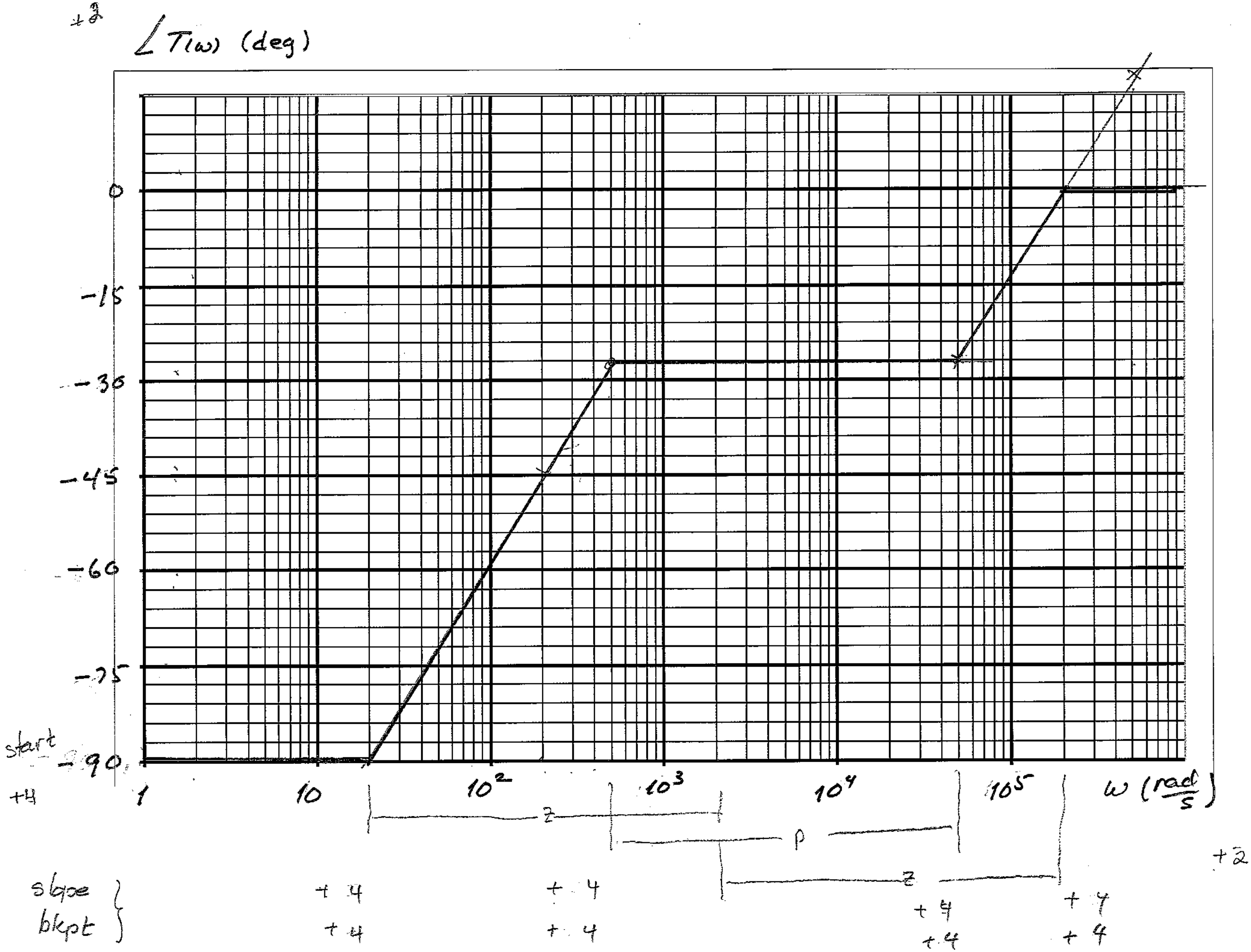
This is the transfer function from problem 1, if we had used $1/C_2R_2 = 200$ rad/s, but it is multiplied by 50 (which has no effect on phase).

poles: 0, 5,000 rad/s

zeros: 200, 20000 rad/s

The graph on the following page has guides showing where the poles and zeros start and end.

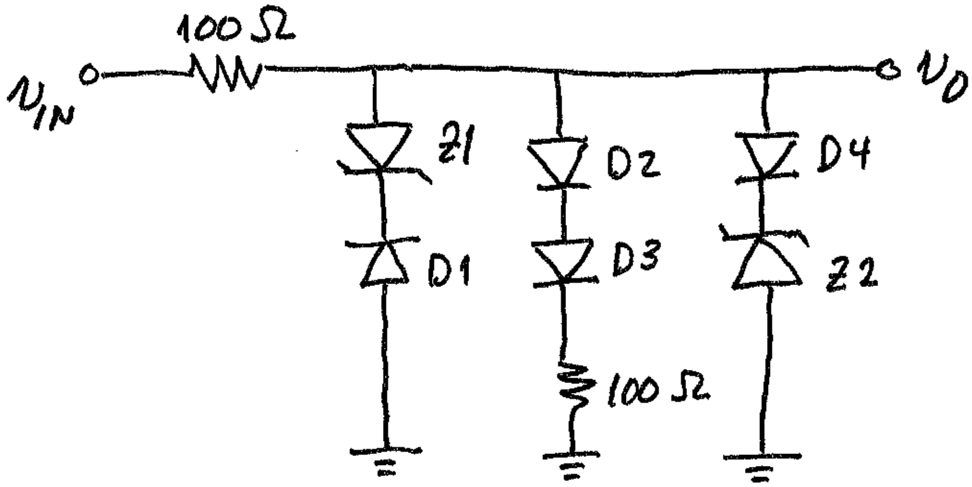
+2



∠T(ω) (deg)
0
-15
-30
-45
-60
-75
start -90
+4
1
10
10^2
10^3
10^4
10^5
ω (rad/s)
z
p
z
+2
slope
bkpt
+4
+4
+4
+4
+4
+4
+4
+4

3. (40 points) In the circuit below, the diodes D1 – D4 have a forward bias threshold voltage V_f = 1.0 V, r_d = 100 Ω, and I_S = 0. The Zener diodes Z1 and Z2 have forward bias threshold voltages V_{fZ} = 1 V, r_d = 0, I_S = 0, and Zener breakdown voltages of 6.8 V.

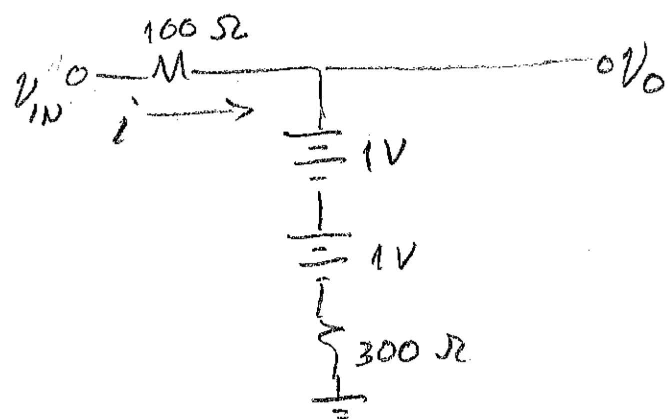
Carefully sketch the transfer characteristics v_O vs. v_{IN}, clearly showing transition points and slopes. Consider both positive and negative values for v_{IN}. Be sure your axes are clearly labeled and that the graph is easy to read.



$v_{IN} > 0$: ∘ D1 will always be negative-biased so it will not conduct.

∘ D2, D3 conduct at $v_{IN} \geq 2$ V.

+ 4 $\quad v_{IN} < 2V \Rightarrow v_O = v_{IN}$



$i = \dfrac{v_{IN} - 2}{400}$

$v_O = 2 + 300 \cdot \dfrac{v_{IN} - 2}{400}$

slope

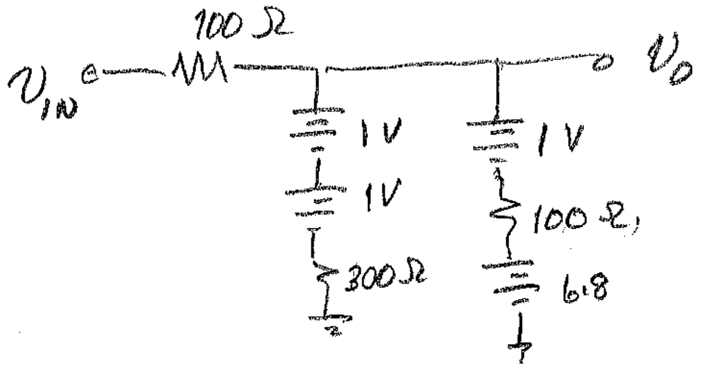
+4 $\quad v_O = 0.5 + \frac{3}{4} v_{IN}$

↗

∘ D4, Z2 conduct when $v_O = 1 + 6.8 = 7.8$ V

$v_0 = 7.8\,V$ $\quad$ + 4

Room for extra work



From previous step,

$v_0 = 0.5 + \frac{3}{4} v_{IN}$

$v_0 = 7.8\ V \Rightarrow v_{IN} = 9.73\ V$

+ 4.

$v_0 = 3.629 + \frac{3}{7} v_{IN}$

+ 4.

Slope $= 3/7 \cong 0.43$

$v_{IN} < 0$: • D_2, D_3, D_4 will be reverse-biased so will not conduct. + 3.

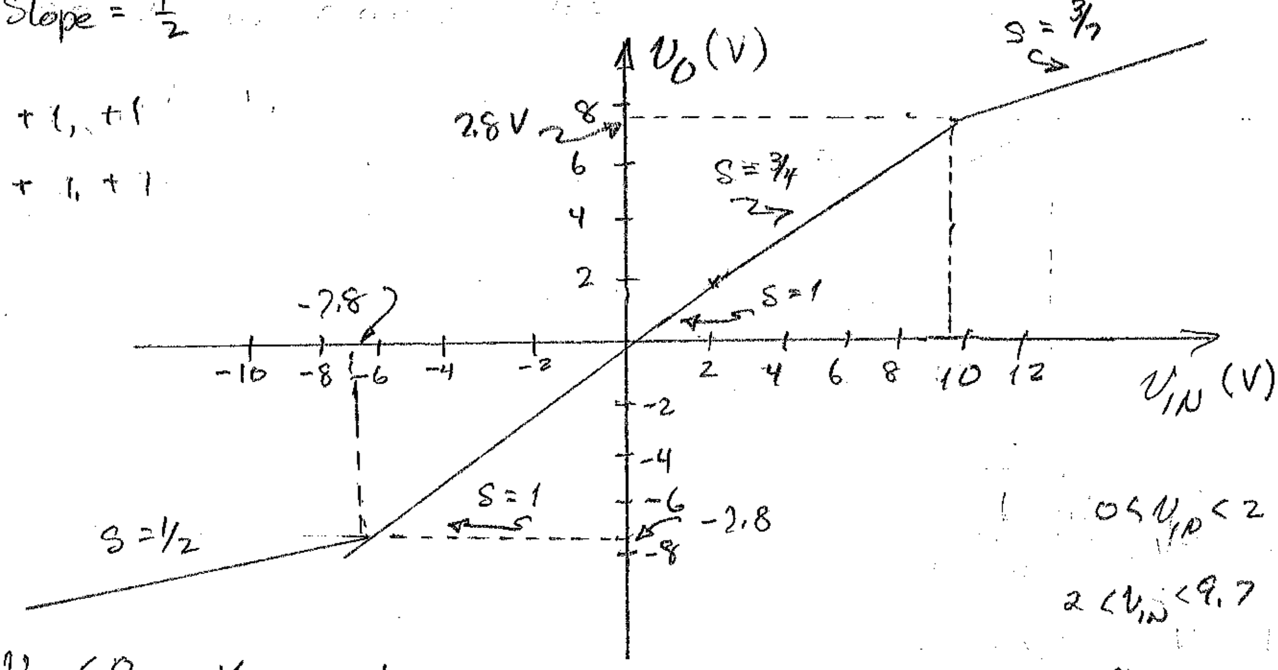
• Z1, D1 conduct when $v_{IN} = -6.8 - 1.0 = -7.8$ V. + 4.

+ 4

Slope $= \frac{1}{2}$

labels + 1, + 1

axes + 1, + 1



$0 < v_{IN} < 2$ + 1

$2 < v_{IN} < 9.7$ + 1

$9.7 < v_{IN}$ V + 1

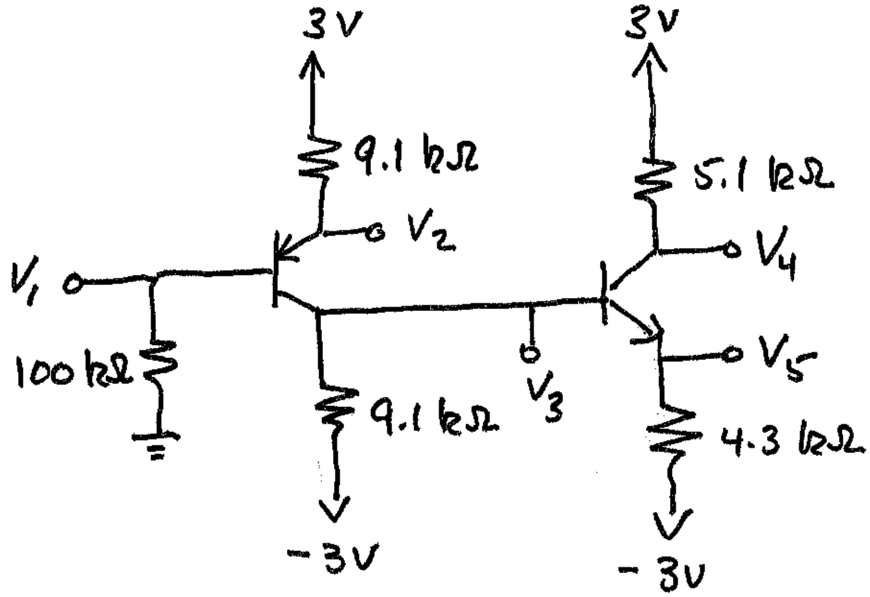
$-7.8 < v_{IN} < 0$ V + 1

$v_{IN} < -7.8$ V + 1

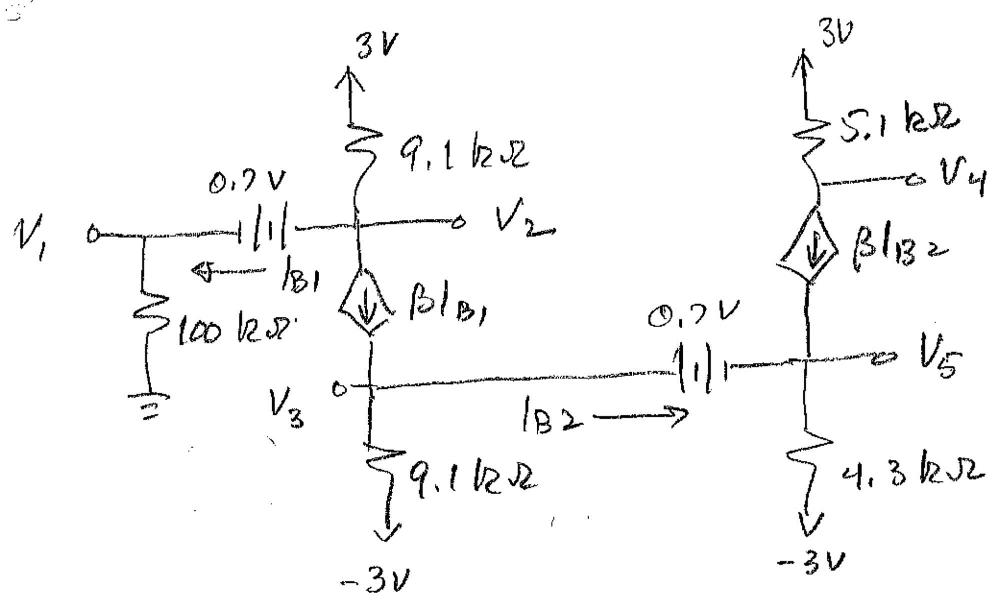
Analysis + 31

Plot + 9

4. (40 points) The BJTs in the circuit below are biased in the linear region. For both BJTs, $\beta = 100$ and $V_{CE,SAT} = 0.3$ V. Find the indicated voltages $V_1 - V_5$.



Re-draw with dc models.



model

+18

$V_3 - V_5 = 0.7$

KVL: $-100\, I_{B1} - 0.7 - (\beta+1) I_{B1} \cdot 9.1 + 3 = 0$

Room for extra work

$$\Rightarrow \quad \underline{I_{B1}} = \frac{2.3}{100 + (101)9.1} = \underline{2.257\,\mu A}$$

KVL : $\cancel{3} - (\beta I_{B1} - I_{B2})\,9.1 + 0.7 + (\beta+1) I_{B2} \cdot 4.3 - \cancel{3} = 0$

$$\Rightarrow \quad \underline{I_{B2}} = \frac{-0.7 + 9.1\,(100)\cdot 2.257\times 10^{-3}}{9.1 + (101)\cdot(4.3)} = \underline{3.053\,\mu A}$$

analysis +12

$V_1 = 10^5\, I_{B1} = 0.2257\ V$ +2

$V_2 = -(\beta+1) I_{B1} \cdot 9.1\times 10^3 + 3 = 0.9256\ V$ +2

$V_3 = \beta I_{B1} \cdot 9100 - 3 = -0.9461\ V$ +2

$V_4 = -\beta I_{B2} \cdot 5100 + 3 = 1.441\ V$ +2

$V_5 = (\beta+1) I_{B2} \cdot 4300 - 3 = -1.674\ V$ +2

calculations +10

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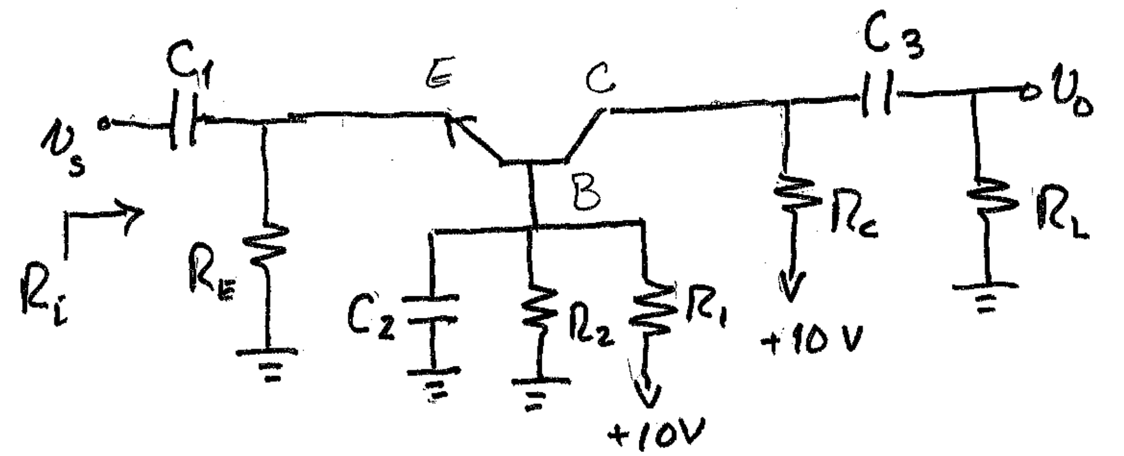
connect B2 at E1

model −6

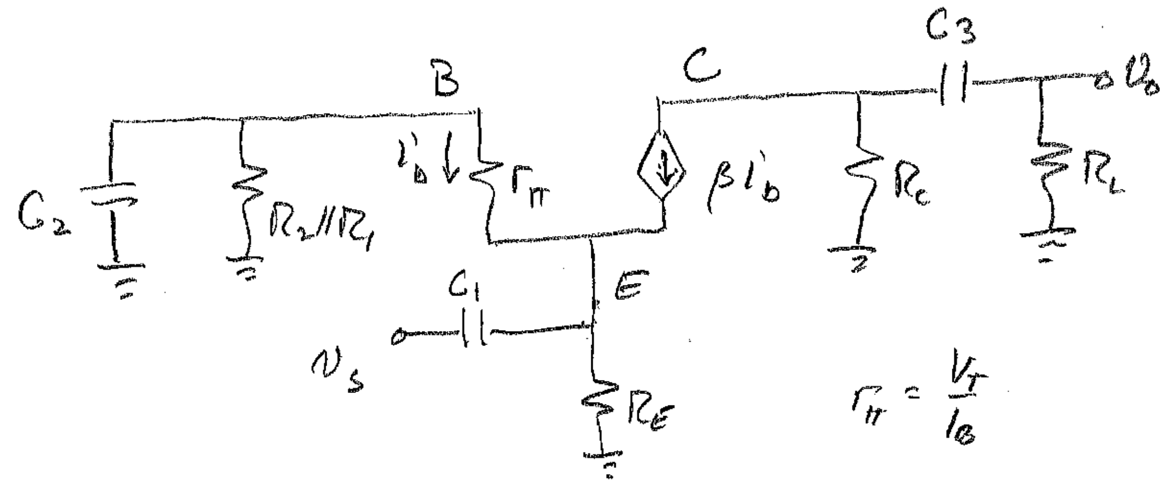
ignore $V_{\beta I_B}$ −4

5. (40 points) For the common base amplifier shown below, do the following.

a. Draw the small signal model using any of the models we discussed in class. For this part, include all three capacitors.
b. Find the gain v_o/v_s in the passband. Assume that in the passband, C2 is a short.
c. Find the input resistance R_i in the passband. Assume that in the passband, C2 is a short.



a)



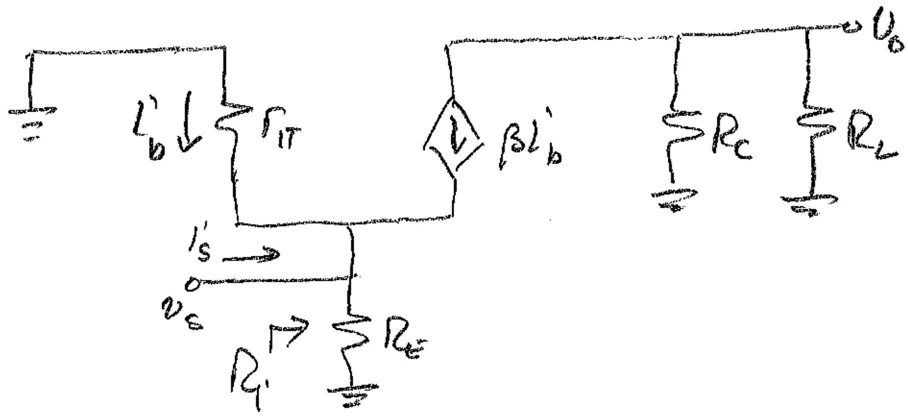
+15

b) re-draw in the pass-band, where all C's → short

10

Room for extra work

+9



+8 $\quad i_b' = -\frac{v_s}{r_\pi} \qquad v_o = -\beta i_b' \cdot R_C \| R_L$

$$v_o = -\beta\left(-\frac{v_s}{r_\pi}\right) \cdot R_C \| R_L \quad \Rightarrow \quad \frac{v_o}{v_s} = \frac{\beta}{r_\pi} R_C \| R_L$$

c) $\quad i_s' = \frac{v_s}{R_E} - (\beta+1) i_b' = \frac{v_s}{R_E} + (\beta+1)\frac{v_s}{r_\pi}$

+8 $\quad \Rightarrow \quad \frac{v_s}{i_s} = R_i = \left(\frac{1}{R_E} + \frac{\beta+1}{r_\pi}\right)^{-1}$

6. EXTRA CREDIT (40 points) Use the function generator design we discussed in class to design a square- and triangle-wave generator. The square-wave generator should be the modified Schmitt trigger shown in the figure below. The triangle wave should be an integrator built from an op amp (not shown).

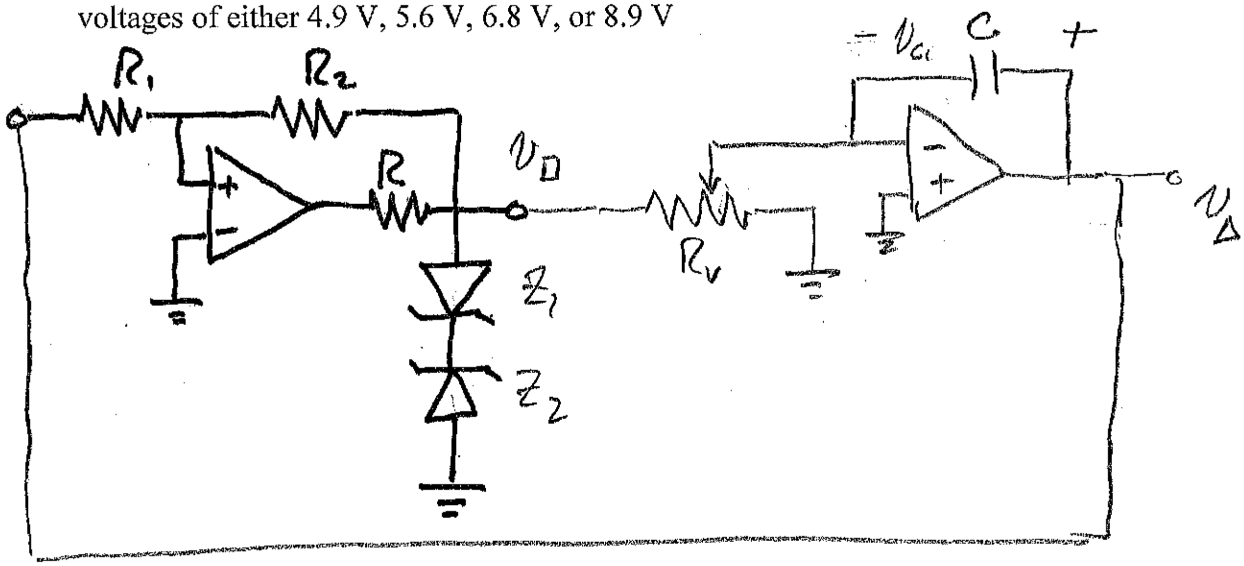
Your function generator should have the following characteristics:

- Amplitudes of square and triangle waves of approximately (within 10%) 10 V
- Frequency adjustable between 100 Hz and 10 kHz

Assume that you have any number of the following ideal circuit elements available.

- Capacitors and resistors of any value
- Potentiometers with values variable from 0 to 100 kΩ
- Op amps with power supplies +/- 15 V
- Diodes with forward voltage drop of 0.7 V, $r_d = 0$, $I_S = 0$
- Zener diodes with forward voltage drop of 0.7 V, $r_d = 0$, $I_S = 0$; and reverse breakdown voltages of either 4.9 V, 5.6 V, 6.8 V, or 8.9 V

Integrator +6
+3
feedback +3



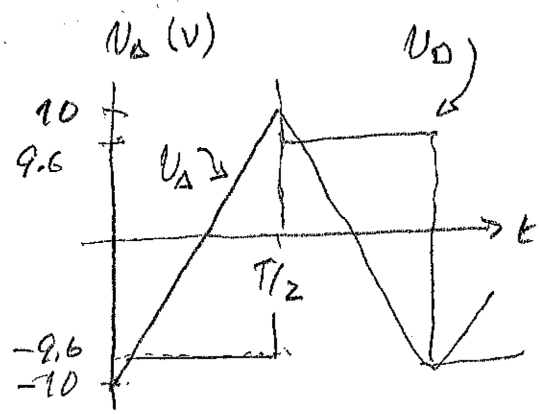
+5 If we choose Z_1 & Z_2 to have $V_Z = 8.9V$, then $v_\square$ will have a magnitude $0.7 + 8.9 = 9.6\ V$. Then

$$v_\Delta = \frac{1}{R_V C}\int_0^t (9.6)\,dt + V_c(0)$$

Room for extra work

Following the example in the notes, we can assume that v_Δ has reached -10 V $= v_c(0)$, and $v_D = 9.6$ V. We want to stop integrating when $v_\Delta \to 10$ V.

$$v_\Delta = 10 = \frac{1}{R_v C}\int_0^{T/2} 9.6\, dt - 10$$



We integrate to $T/2$ because this is the time at which $v_\Delta = 10$ V.

$$\frac{1}{R_v C}\cdot 9.6\,\frac{T}{2} = 20$$

+ 10

Choose $\underline{C = 0.1\ \mu F}$ $\Rightarrow$ $R_v = \frac{9.6\,T}{2}\,\frac{1}{20}\left(\frac{1}{0.1\times10^{-6}}\right) = 2.4\times10^{6}\,T$

So if $f = 100$ Hz $\Rightarrow$ $T = 10^{-2}$ s, $R_v = 24$ kΩ

+ 5 if $f = 10$ kHz $\Rightarrow$ $T = 10^{-4}$ s, $R_v = 240$ Ω

So we can use a 100 kΩ potentiometer for this.

We also need the Schmitt to trigger at ± 10 V, so

$$v_{TL} = -9.6\cdot\frac{R_1}{R_2} = -10 \Rightarrow \frac{R_1}{R_2} = 1.04$$

+ 6

Choose $\underline{R_1 = 5\text{ k}\Omega \Rightarrow R_2 = 5.2\text{ k}\Omega}$

+ 2 R is arbitrary : choose $\underline{R = 10\text{ k}\Omega}$