Name: ______________________________ (please print)

Signature: ___________________________

ECE 3355 – Final Exam
April 29, 2020

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

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2. Show all work necessary to complete the problem. A solution without the appropriate work shown will receive no 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 170 minutes to work on this exam.
7. **The exam will be normalized to 200 points, so there is an opportunity for extra credit.**

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1.__________________/40

2.__________________/40

3.__________________/35

4.__________________/40

5.__________________/45

6.__________________/20

__________________/220

Room for extra work

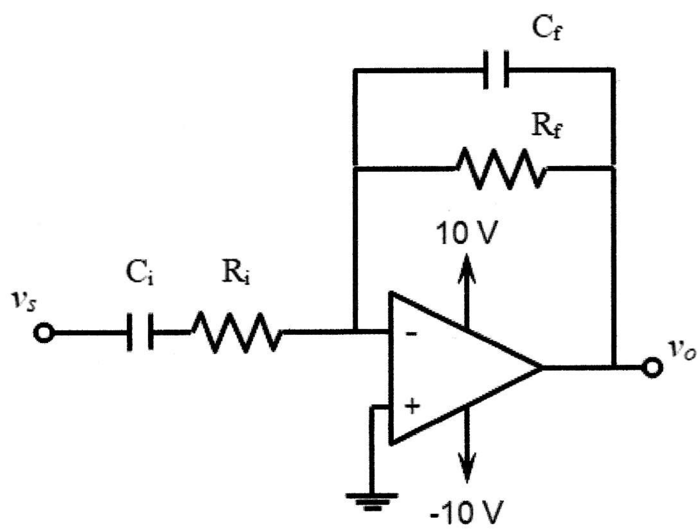
1. (40 points) In the circuit below, the op amp is ideal, and has power supply voltage of +/-10 V, as indicated.

a) Find the transfer function $T(\omega)=\frac{V_o}{V_s}$ in terms of the resistances and capacitances.

b) Choose values for the resistances and capacitances so that the following frequency response is obtained.
   a. The 3-dB bandwidth is approximately 20 krad/s.
   b. The low-frequency breakpoint is 30 rad/s.
   c. The gain in the passband is 10 dB.

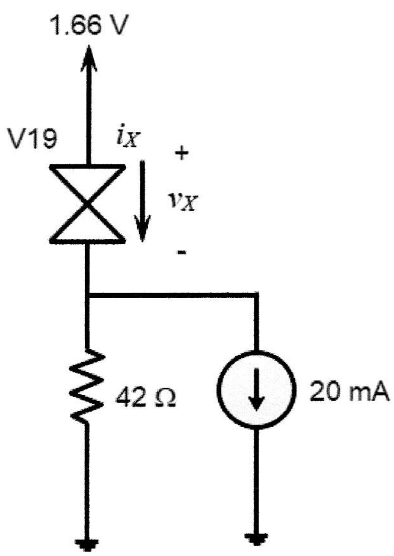
c) What is the largest signal amplitude than can be applied without saturating the op amp?

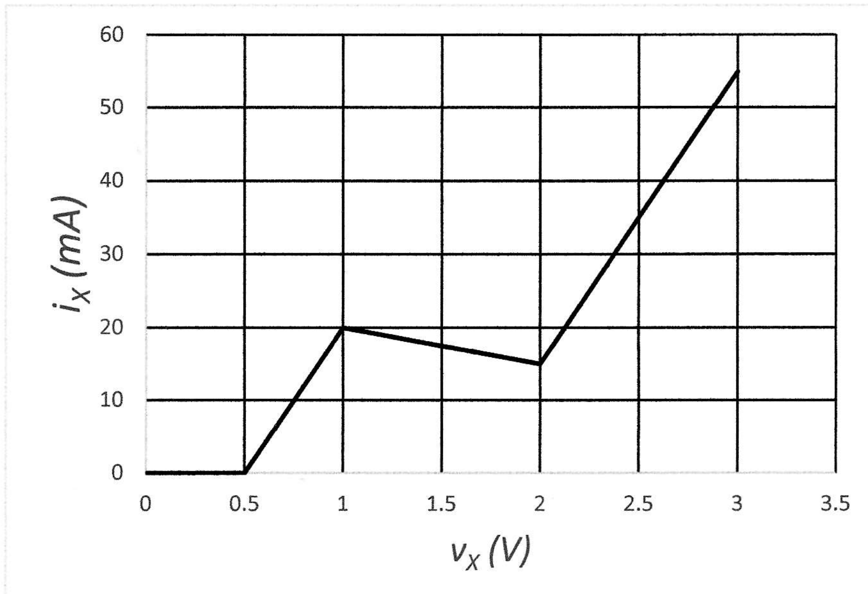
d) Plot the ***phase*** Bode plot for this transfer function using the graph paper on the next page.



2. (40 points) A new device called the Coronarator-V19 (V19 for short) is connected into the circuit shown below. The device current-voltage characteristics for $v_X > 0$ are shown in the figure.

a) For each of the piece-wise linear regions of device operation, find a circuit model that could be substituted for the device when operating in that region. Be sure to indicate polarities for i_X and v_X on your models.
b) Find the Thevenin equivalent seen by the V19. Then, draw the V19 with the Thevenin equivalent attached to it. Include values for the Thevenin voltage and resistance.
c) Find an equation for i_X in terms of v_X based on your Thevenin equivalent circuit. The equation will be that of a straight line. Plot that line on the graph provided. This is the load line for the circuit.
d) In what region is the V19 operating? How do you know?



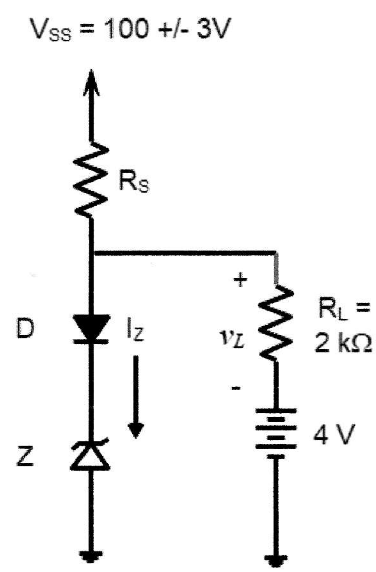


Room for extra work

3. (35 points) The circuit below uses a Zener diode and a forward-biased diode in series to keep the load voltage V_L approximately constant at 5 V. The power supply V_{SS} is 100 V but can vary by 3 V in either direction. The diode and Zener diode characteristics are as follows.

Diode D: $V_{th} = 1$ V, $r_D = 10\ \Omega$, $I_S = 0$
Zener diode Z: $V_Z = 8$ V, $r_Z = 25\ \Omega$ at $I_Z = 10$ mA.

a) For a load voltage $v_L = 5$ V, find R_S for a Zener current $I_Z = 10$ mA.
b) The Zener diode is modeled by a voltage source V_{Z0} in series with r_Z given above. Find the Zener voltage V_{Z0} for the Zener diode Z.
c) Assuming the models for D and Z given above, use the ***small signal model*** to find the variation in the output voltage v_L.

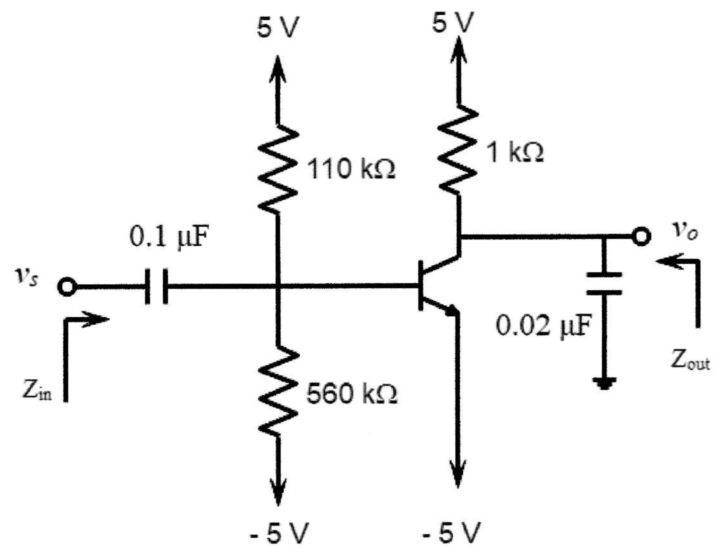


Room for extra work

4. (40 points) The BJT in the circuit below is biased in the linear region. There is no need to prove this. The BJT has $\beta = 50$ and $V_{CESAT} = 0.2$ V. The source v_s is a small signal input.

a) Draw the small signal circuit model and from that find the transfer function $T(\omega) = \frac{V_o}{V_s}$.

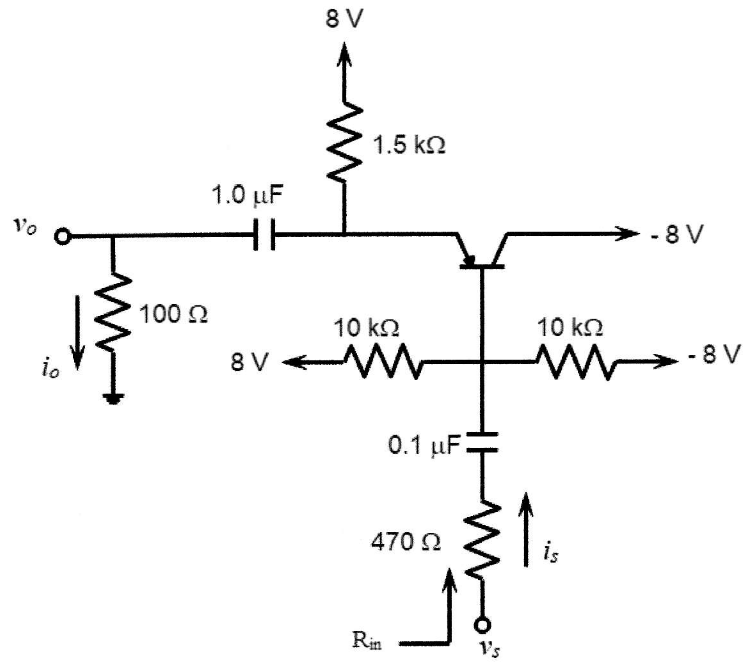
b) Find the input impedance Z_{in} seen by the source v_s.
c) Find the output impedance Z_{out} seen by the load.



Room for extra work

5. (45 points) The BJT in the circuit below has $\beta = 150$ and $V_{CESAT} = -0.3$ V.

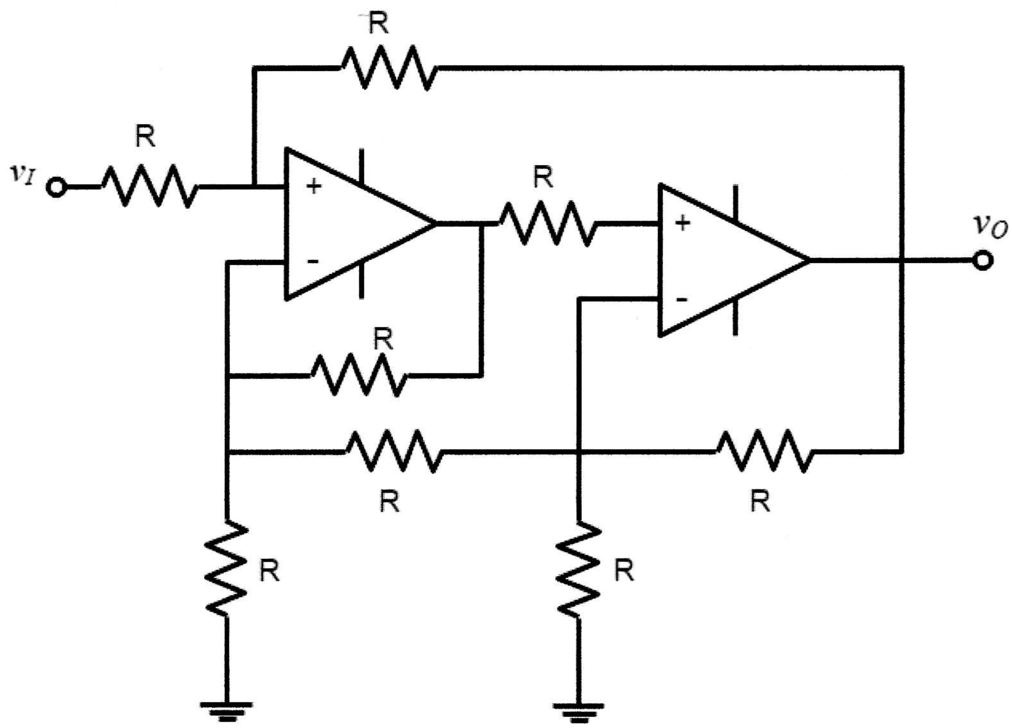
a) Draw the small signal circuit model. Include values for any small signal model parameters you use.
b) Find the input resistance R_{in} in the passband.
c) Find the current gain i_o/i_s in the passband.



Room for extra work

6 (20 points) In the circuit below, the op amps are ideal. Their power supplies are not shown, and are not important for this problem.

Find v_O in terms of v_I.



Room for extra work

Name: SOLUTIONS! (please print)

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5. ______________ /45

6. ______________ /20

______________ /220

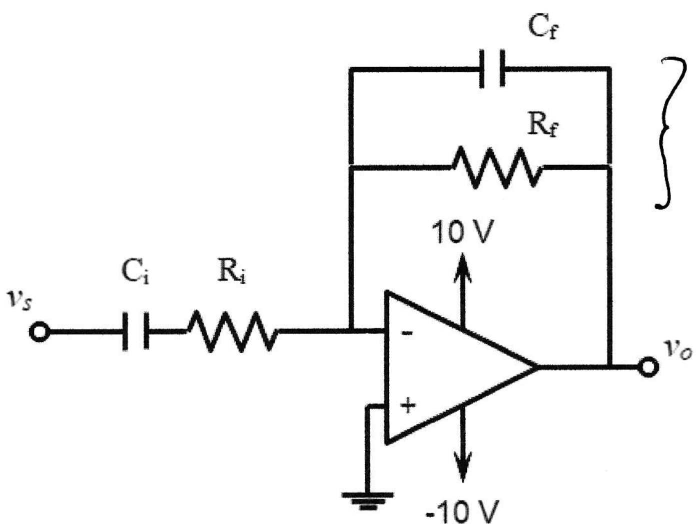
1. (40 points) In the circuit below, the op amp is ideal, and has power supply voltage of +/-10 V, as indicated.

a) Find the transfer function $T(\omega) = \frac{V_o}{V_s}$ in terms of the resistances and capacitances.

b) Choose values for the resistances and capacitances so that the following frequency response is obtained.
   a. The 3-dB bandwidth is approximately 20 krad/s.
   b. The low-frequency breakpoint is 30 rad/s.
   c. The gain in the passband is 10 dB.

c) What is the largest signal amplitude than can be applied without saturating the op amp?

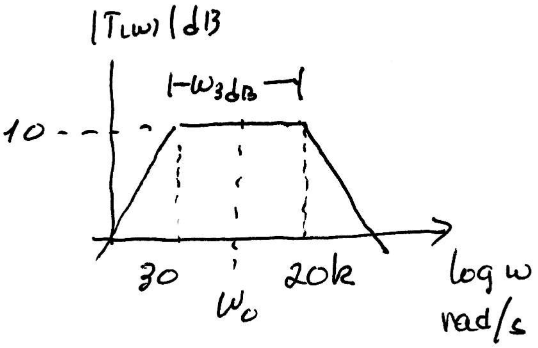
d) Plot the ***phase*** Bode plot for this transfer function using the graph paper on the next page.



$$Z_f = \frac{R_f}{1 + j\omega C_f R_f}$$

a) $$T(\omega) = \frac{-Z_f}{R_i + 1/j\omega C_i} = -\frac{j\omega C_i R_f}{(1 + j\omega C_f R_f)(1 + j\omega C_i R_i)}$$

b)



$30 \ll \omega_o \ll 20k$ rad/s

If we choose the poles to be at 30 rad/s and 20 000 rad/s,
ω_{3dB} will be $20000 - 30 \simeq 20000$ rad/s.

Room for extra work

$1/C_iR_i = 30$ rad/s $\quad R_i = 5\,k\Omega \Rightarrow C_i = 6.667\,\mu F$

$1/C_fR_f = 20000$ rad/s $\quad R_f = 15.8\,k\Omega \Rightarrow C_f = 3.16\,nF$

In the passband, $\omega_o \ll \frac{1}{C_fR_f} \Rightarrow \omega_o C_f R_f \ll 1$
$(\omega = \omega_o)$

$\omega_o \gg \frac{1}{C_iR_i} \Rightarrow \omega_o C_i R_i \gg 1$

$\Rightarrow T(\omega_o) = -\frac{R_f}{R_i} \qquad |T(\omega_o)| = \frac{R_f}{R_i} = 10\,dB = 3.16$

So $R_f = 3.16 R_i \qquad R_i = 5\,k\Omega \Rightarrow R_f = 15.8\,k\Omega$

c) Max gain is 3.16 and max output = 10V

$\Rightarrow$ max signal $v_{s,max} = \frac{10}{3.16} = 3.16\,V$

d) See Bode plot. Note $T(\omega \to 0) = -j\omega C_i R_f$

$\angle T(\omega \to 0) = -90^\circ$

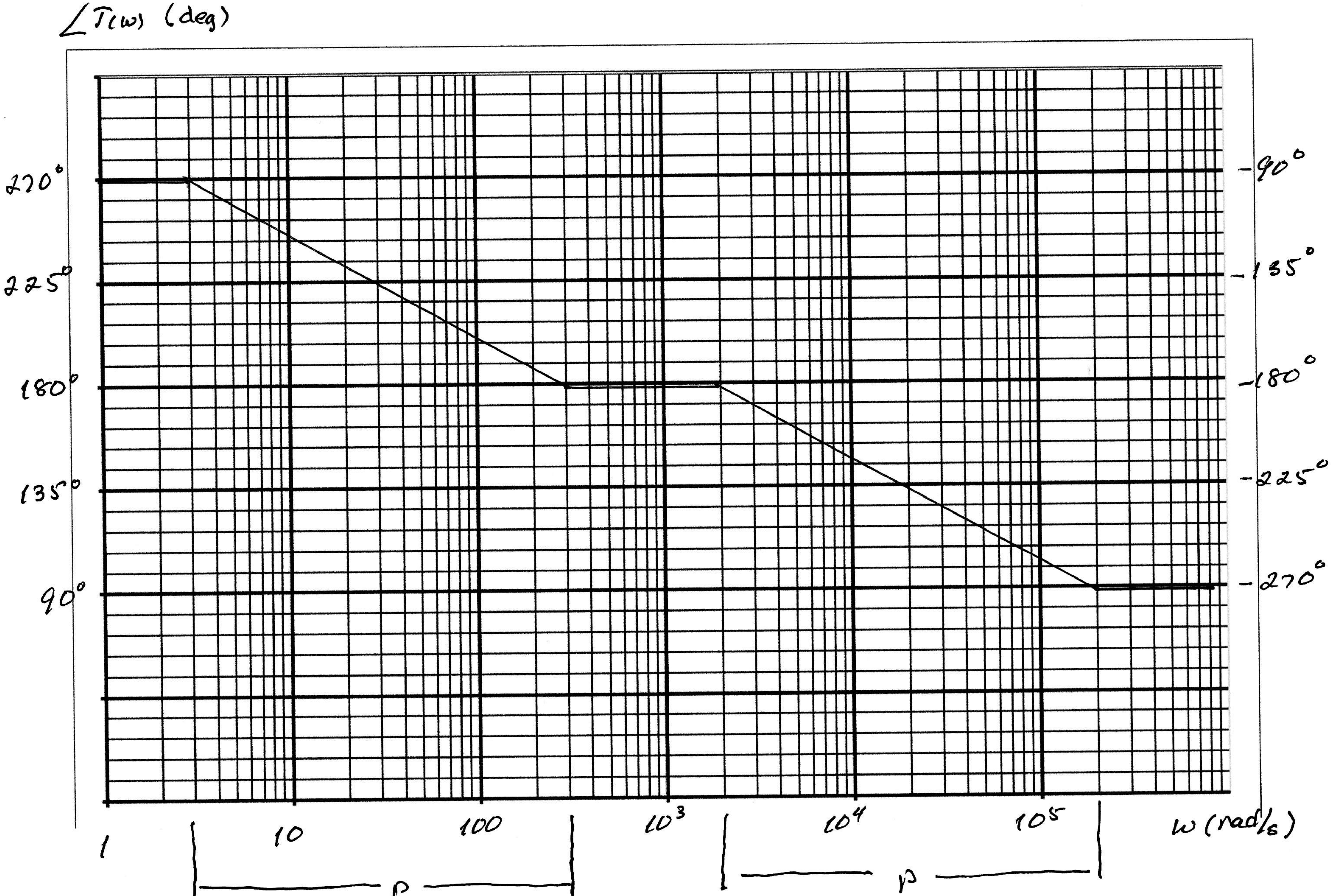
If we had reversed the poles:

$1/C_iR_i = 20000$ rad/s $\quad C_i = ~~0.1~~$ 0.316 $\mu F \Rightarrow R_i = ~~500~~$ 158.2 Ω

$1/C_fR_f = 30$ rad/s $\quad C_f = 0.1\,\mu F \Rightarrow R_f = 333.3\,k\Omega$

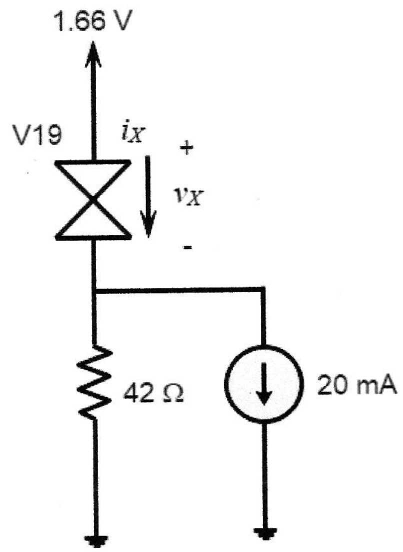
$|T(\omega_o)| \Rightarrow \frac{C_i}{C_f} = 3.16 \Rightarrow C_i = 3.16\,C_f$

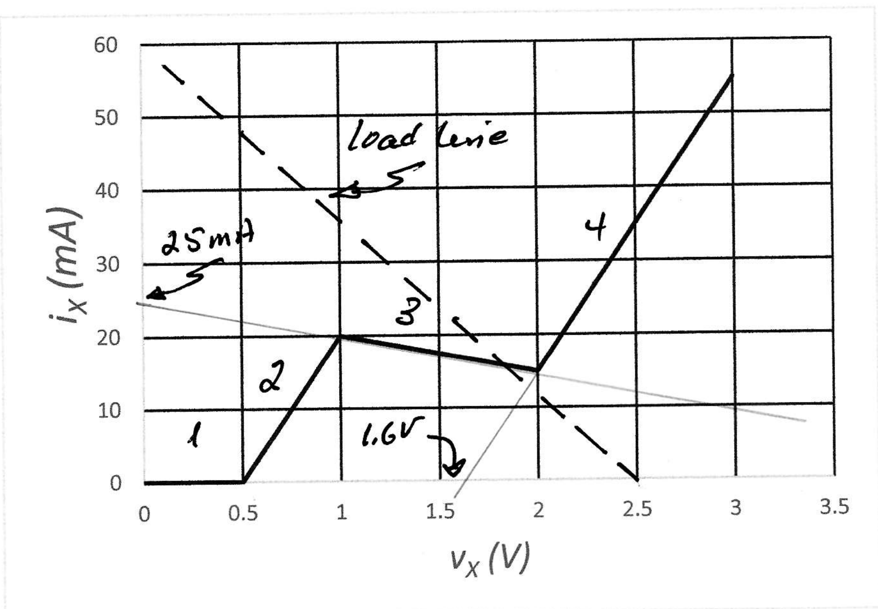
$C_f = 0.1\,\mu F \Rightarrow C_i = 0.316\,\mu F$


∠T(ω) (deg)
270°
225°
180°
135°
90°
-90°
-135°
-180°
-225°
-270°
1
10
100
10^3
10^4
10^5
ω (rad/s)
p
p

2. (40 points) A new device called the Coronarator-V19 (V19 for short) is connected into the circuit shown below. The device current-voltage characteristics for $v_X > 0$ are shown in the figure.

a) For each of the piece-wise linear regions of device operation, find a circuit model that could be substituted for the device when operating in that region. Be sure to indicate polarities for i_X and v_X on your models.
b) Find the Thevenin equivalent seen by the V19. Then, draw the V19 with the Thevenin equivalent attached to it. Include values for the Thevenin voltage and resistance.
c) Find an equation for i_X in terms of v_X based on your Thevenin equivalent circuit. The equation will be that of a straight line. Plot that line on the graph provided. This is the load line for the circuit.
d) In what region is the V19 operating? How do you know?





a) 1: no current => open circuit

+ v_x -

2: voltage source + resistor

$r_D = \frac{0.5V}{20mA} = 25\Omega$

0.5V 25Ω

i_x → + v_x -

3: voltage source + negative resistor $r_D = -\frac{1V}{5mA} = -200\Omega$

5V -200Ω

i_x → + v_x -

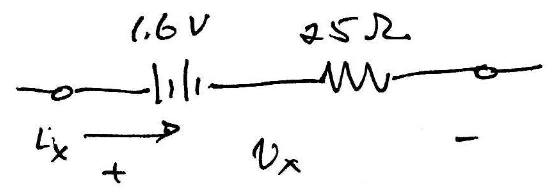
Room for extra work

The line in region 3 is $i_x = 25\,mA + \frac{1}{r_D} v_x$ $(r_D < 0)$

so $i_x = 0 \Rightarrow v_x = 5\,V$

4: voltage source + resistor

$r_D = \frac{1\,V}{40\,mA} = 25\,\Omega$



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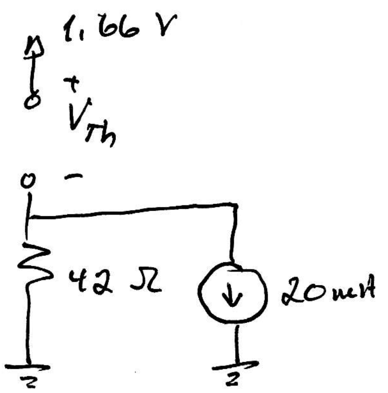
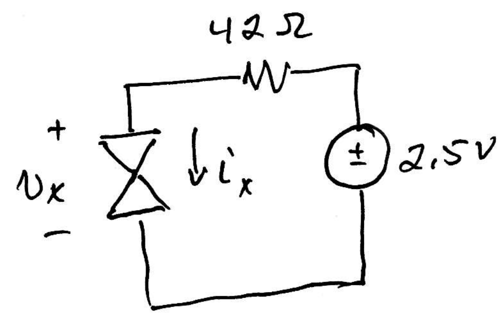
b)



$V_{Th} = 1.66 + 0.02(42) = 2.5\,V$

$R_{Th} = 42\,\Omega$



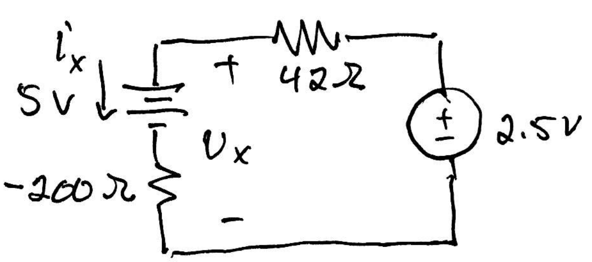
c) $v_x - 2.5 + 42 i_x = 0 \Rightarrow i_x = \frac{2.5 - v_x}{42}$

See plot: $i_x = 0 \Rightarrow v_x = 2.5\,V$

$v_x = 0 \Rightarrow i_x \cong 60\,mA$

d) The load line shows that V19 is in region 3.

We were not asked to do this but we can check region 3:



KVL: $5 - 200 i_x - 2.5 + 42 i_x = 0$

$\Rightarrow i_x = 15.83\,mA$

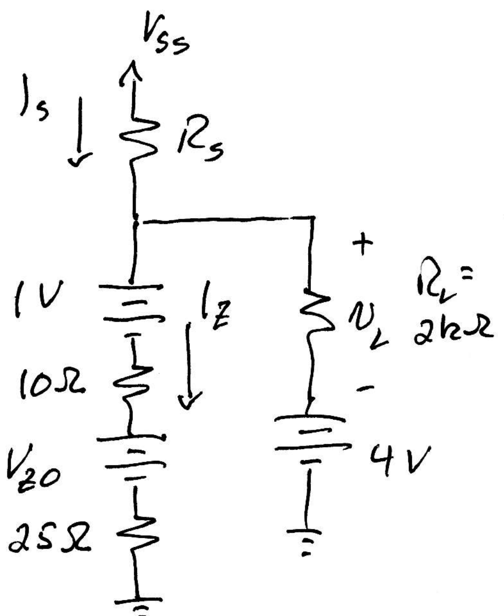
$v_x = 1.84\,V$

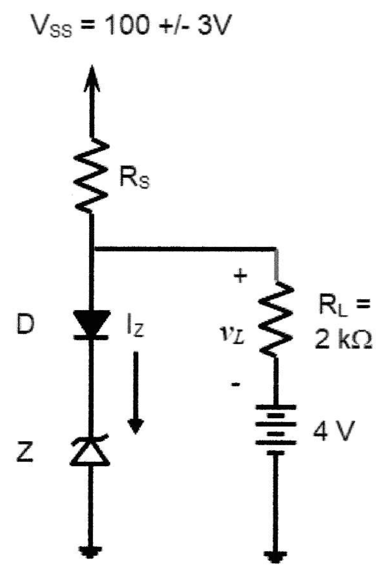
This checks out. ✓

3. (35 points) The circuit below uses a Zener diode and a forward-biased diode in series to keep the load voltage V_L approximately constant at 5 V. The power supply V_{SS} is 100 V but can vary by 3 V in either direction. The diode and Zener diode characteristics are as follows.

Diode D: $V_{th} = 1$ V, $r_D = 10\ \Omega$, $I_S = 0$
Zener diode Z: $V_Z = 8$ V, $r_Z = 25\ \Omega$ at $I_Z = 10$ mA.

a) For a load voltage $v_L = 5$ V, find R_S for a Zener current $I_Z = 10$ mA.
b) The Zener diode is modeled by a voltage source V_{Z0} in series with r_Z given above. Find the Zener voltage V_{Z0} for the Zener diode Z.
c) Assuming the models for D and Z given above, use the ***small signal model*** to find the variation in the output voltage v_L.





The diode models are inserted into the circuit in the figure above.

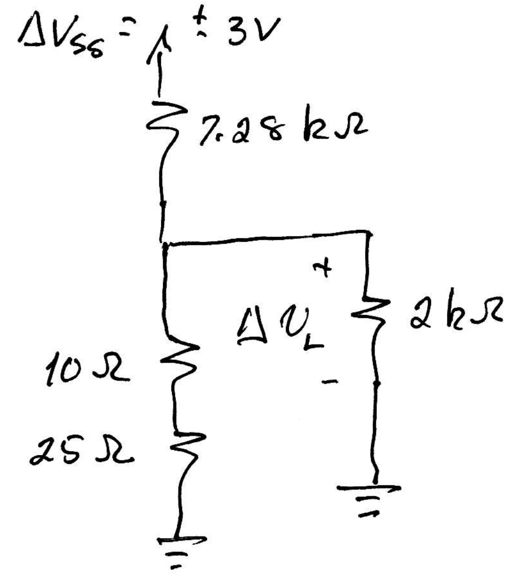
a) For $v_L = 5$ V, and $I_Z = 10$ mA,

$$I_S = \frac{100-9}{R_S} = 0.01 + \frac{5}{2000} \Rightarrow R_S = 7.28\ k\Omega$$

b) $$V_{Z0} = V_Z - I_Z r_Z = 8 - 0.01(25) = 7.75V$$

Room for extra work

c) Inserting V_{Z0} and R_s into the circuit, and de-activating DC voltage sources gives



$$\Delta v_L = \Delta V_{SS} \frac{2000||35}{2000||35 + 7280}$$

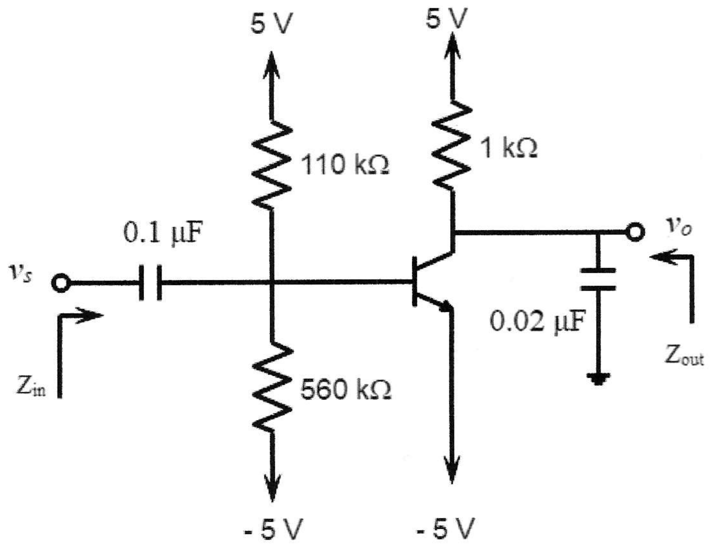
$$\boxed{\Delta v_L = \pm 14.1 \text{ mV}}$$

4. (40 points) The BJT in the circuit below is biased in the linear region. There is no need to prove this. The BJT has $\beta = 50$ and $V_{CESAT} = 0.2$ V. The source v_s is a small signal input.

a) Draw the small signal circuit model and from that find the transfer function $T(\omega) = \frac{V_o}{V_s}$.

b) Find the input impedance Z_{in} seen by the source v_s.

c) Find the output impedance Z_{out} seen by the load.

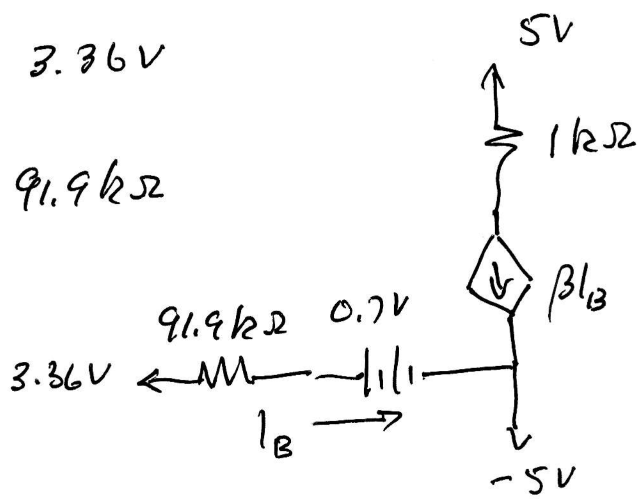


We will use the hybrid-pi model so we'll need r_π.

Thevenin equivalent at the base:

$$V_{BB} = 10 \frac{560}{560+110} - 5 = 3.36\text{V}$$

$$R_B = 560\,k\Omega \,//\, 110\,k\Omega = 91.9\,k\Omega$$



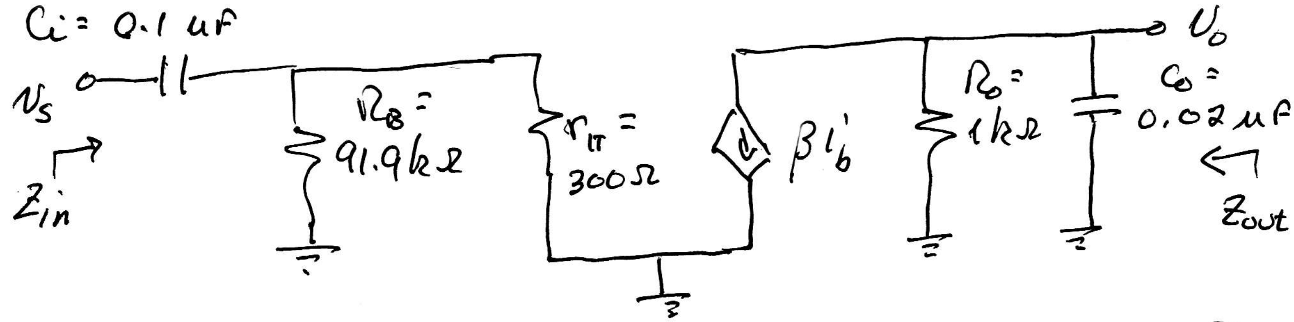
$$I_B = \frac{3.36 - 0.7 + 5}{91.9\,k\Omega}$$

$$= 83.35\,\mu A$$

$$r_\pi = \frac{V_T}{I_B} = \frac{0.025}{83.35 \times 10^{-6}} = 300\,\Omega$$

Room for extra work

Small signal model:



Note: $91.9k\Omega \,//\, 300\ \Omega \simeq 300\ \Omega$ so we will ignore R_B.

$$V_o = -\beta I_b \frac{R_o}{1+j\omega C_o R_o} \qquad I_b = \frac{V_s}{r_\pi + 1/j\omega C_i} = V_s \frac{j\omega C_i}{1+j\omega C_i r_\pi}$$

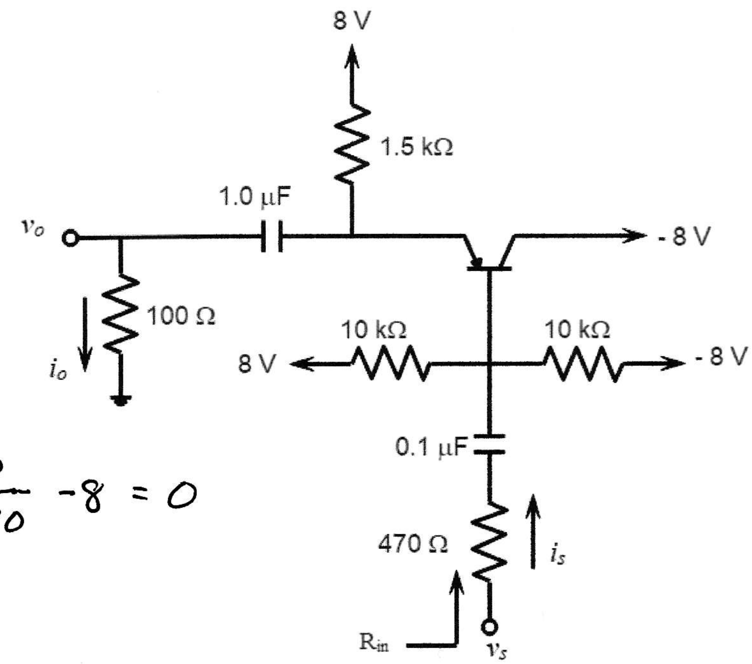
$$\Rightarrow \quad \boxed{\frac{V_o}{V_s} = -\beta \frac{R_o}{1+j\omega C_o R_o} \frac{j\omega C_i}{1+j\omega C_i r_\pi}} = \frac{-j\omega\, 0.005}{(1+j\omega(2\times10^{-5}))(1+j\omega\, 3\times10^{-5})}$$

b) $Z_{in} = 1/j\omega C_i + R_B // r_\pi \simeq 1/j\omega C_i + r_\pi$

c) $Z_{out} = R_o // 1/j\omega C_o = \dfrac{R_o}{1+j\omega C_o R_o}$

5. (45 points) The BJT in the circuit below has $\beta = 150$ and $V_{CESAT} = -0.3$ V.

a) Draw the small signal circuit model. Include values for any small signal model parameters you use.
b) Find the input resistance R_{in} in the passband.
c) Find the current gain i_o/i_s in the passband.



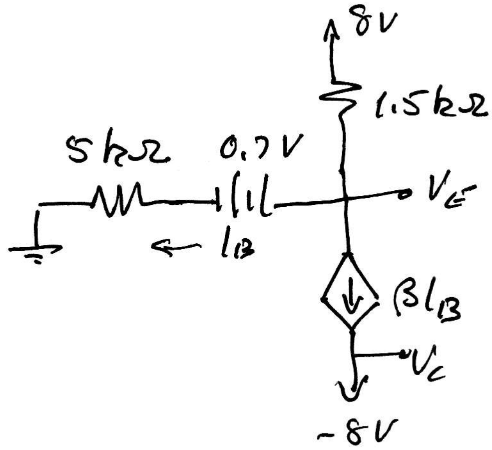
$V_{BB} = 16 \cdot \frac{10}{10+10} - 8 = 0$

$R_B = 5\,k\Omega$

We are not told the operating region, but it appears to be the linear region. Let's check.

$I_B = \frac{8-0.7}{5000 + 151(1500)}$

$= 31.53\,\mu A$ ✓



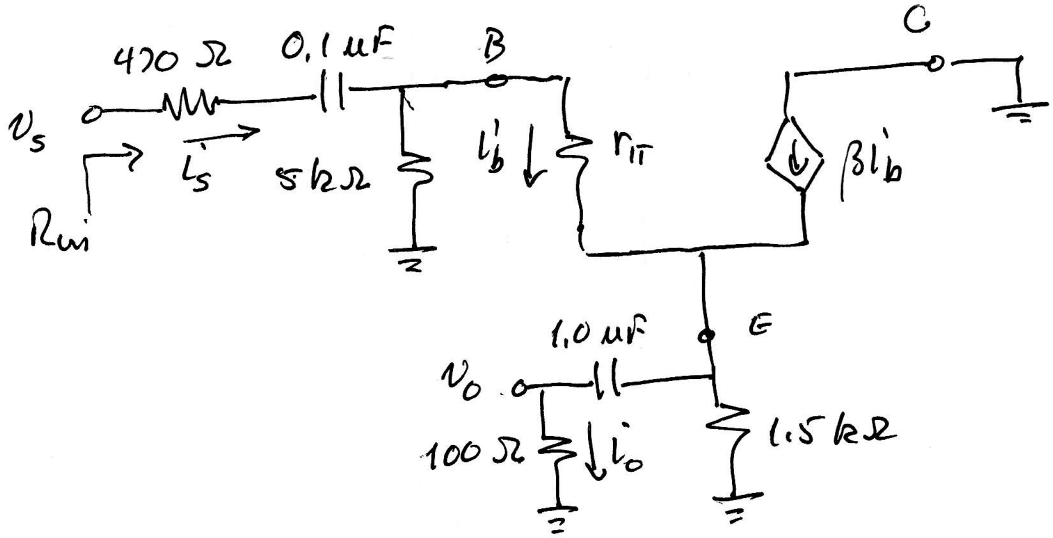
$V_{CE} = -8 - (0.7 + 5000\, I_B)$

$= -8.86\,V$ ✓

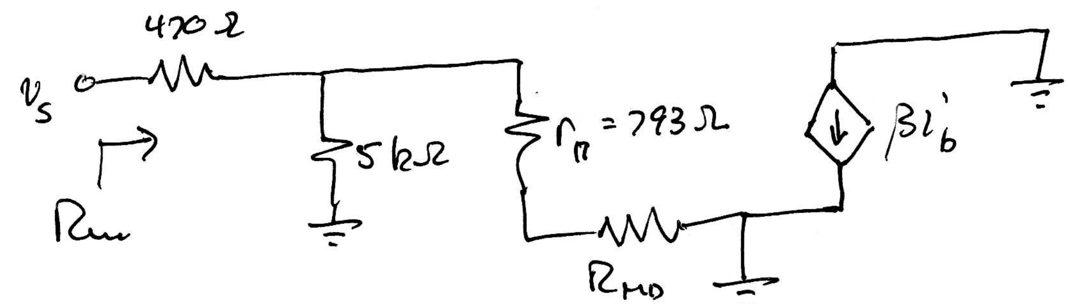
$r_\pi = \frac{V_T}{I_B} = 793\,\Omega$

Room for extra work

a) Small signal model:



b) In the passband, both capacitors are shorts. Also, we can apply Miller's Dual to 100 Ω // 1500 Ω. This gives:



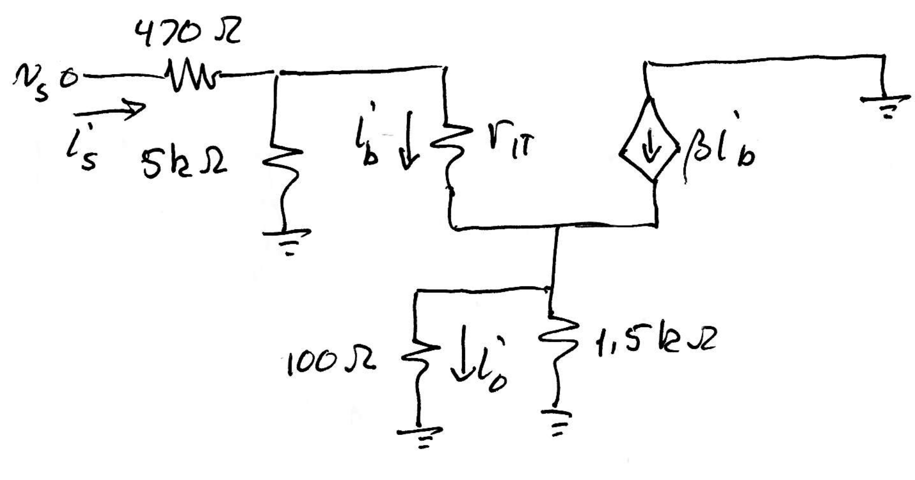
$$R_{MD} = (\beta+1)(100 // 1500)$$
$$= 14.16\ k\Omega$$

Then $R_{in} = 470 + 5k // (r_\pi + R_{MD})$

$$\boxed{R_{in} = 4.217\ k\Omega}$$

↗ p 12a

c) For current gain we will need to go back to the original circuit, with C → short.



We have

$$i_o' = (\beta+1)\, i_b' \frac{1500}{1500+100}$$

We can use the previous diagram (with Miller's Dual) to find i_b', since it has to be the same...

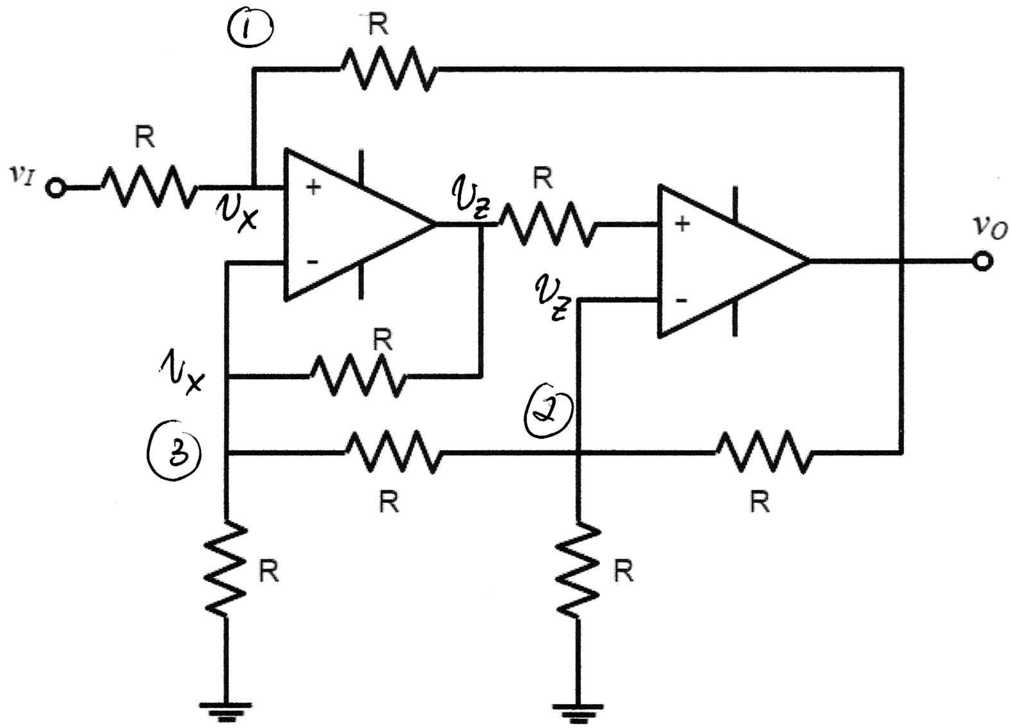
$$i_b' = i_s' \frac{5000}{5000 + r_\pi + R_{MD}}$$

$$\Rightarrow \boxed{\frac{i_o'}{i_s'} = (\beta+1) \frac{1500}{1500+100} \cdot \frac{5000}{5000+r_\pi+R_{MD}} = 35,5}$$

(A more tedious route is to do a KCL at the emitter, and a KVL through r_π, 100 Ω, and 5000 Ω, noting that the current in 5000 Ω is $i_s'-i_b'$. This gives the same result.)

6 (20 points) In the circuit below, the op amps are ideal. Their power supplies are not shown, and are not important for this problem.

Find v_O in terms of v_I.



There are several ways to do this. Here's one:

KVL at ①, ②, and ③ gives

① $\frac{v_x - v_I}{R} = \frac{v_x - v_o}{R} \Rightarrow v_x = \frac{1}{2} v_i + \frac{1}{2} v_o$

② $\frac{v_z - v_x}{R} + \frac{v_z}{R} + \frac{v_z - v_o}{R} = 0 \Rightarrow 3 v_z = v_x + v_o$

$= \frac{1}{2} v_i + \frac{3}{2} v_o$

③ $\frac{v_x - v_z}{R} + \frac{v_x - v_z}{R} + \frac{v_x}{R} = 0 \Rightarrow 3 v_x = 2 v_z$

Room for extra work

$$v_z = \frac{1}{6} v_i + \frac{1}{2} v_o \Rightarrow 2 v_z = \frac{1}{3} v_i + v_o$$

$$\therefore \quad 3 v_x = 2 v_z \Rightarrow \frac{3}{2} v_i + \frac{3}{2} v_o = \frac{1}{3} v_i + v_o$$

$$\Rightarrow \boxed{v_o = -\frac{7}{3} v_i}$$