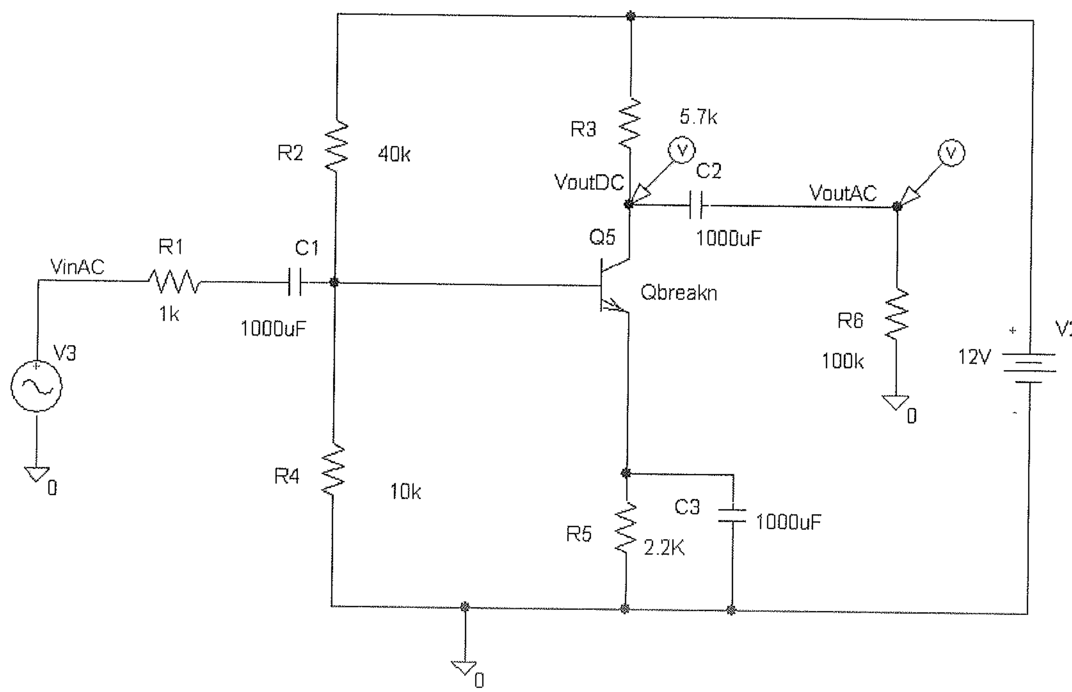
Homework 5 Solutions

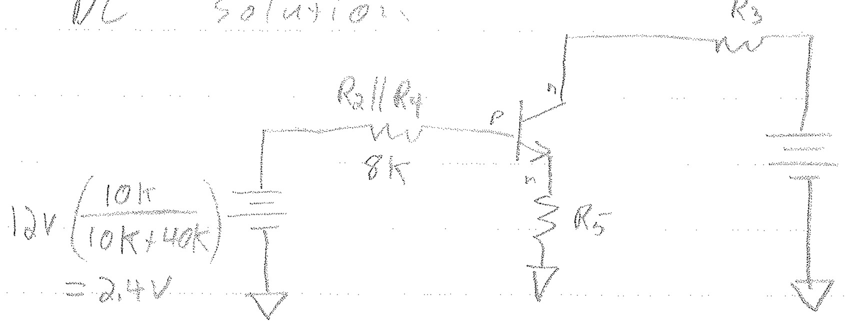
1. For the basic transistor circuit below, solve for the Q-point (all three currents and voltages on the transistor) assuming a β=100, an Early voltage, V_A=100V, a $V_{turn\ on}$=0.7 V for any forward biased Base-emitter junction and a $V_{turn\ on}$=0.3 V for any forward biased base-collector junction (different due to lower doping in CB junction):
   a. Assuming the transistor is biased in cutoff (neglect leakage currents).
   b. Assuming the transistor is biased in saturation.
   c. Assuming the transistor is biased in forward active.
   d. Which assumption is valid?



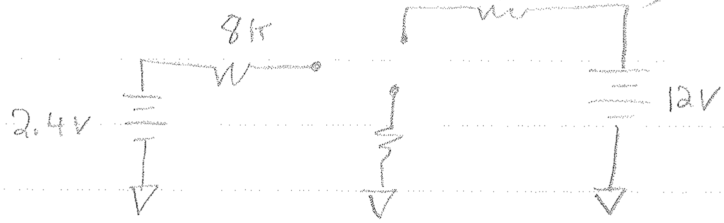
   e. What value of Is would result in 0.7 V for the base emitter voltage?
   f. Determine the voltage gain VoutAC/VinAC.
   g. Plot VoutDC and VoutAC for a 1 kHZ, 1mV VinAC signal.
   h. Note: While I am not asking for it herein, you should be able to determine, β, α, and I_S from the fundamental material parameters.

Homework 5 Solutions

1) DC Solution



a) Assume cutoff (neglecting leakage currents)

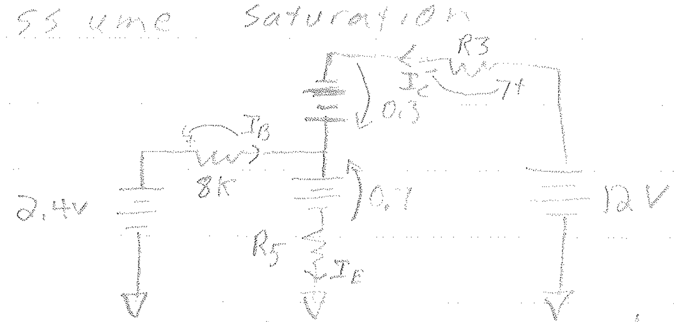


$$I_B = I_C = I_E = 0$$

Check Assumption: $V_B = 2.4V$, $V_C = 12V$, $V_E = 0V$

↳ Not true $V_B > V_E \Rightarrow$ FB V_{BE}

b) Assume saturation



<u>Note</u>: for Saturation, β <u>cannot</u> be used

1) $I_E R_5 + 0.7 - 0.3 + I_C R_3 = 12$

2) $2.4V - I_B 8K - 0.7 - I_E R_5 = 0$

or $(1+2) = (3)$ $\quad 2.4V - I_B 8K - 0.3 + I_C R_3 = 12$

$I_E = I_C + I_B$ thus,

$(1)^*$ $\quad I_C R_5 + I_B R_5 + 0.4 + I_C R_3 = 12$

$(2)^*$ $\quad +I_B 8K + I_C R_5 + I_B R_5 = +1.7V$

2 eq. 2 unknowns

$$I_B = \frac{1.7V - I_C R_5}{R_{Th} + R_5}$$

(R_{Th} = 8k)

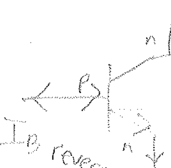
Sub into (1)*

$$I_C R_5 + \left(\frac{1.7V - I_C R_5}{R_{Th} + R_5}\right) R_5 + I_C R_3 = 11.6\ V$$

solving for $I_C = 1.62\ mA$

$I_B = -183.1\ \mu A$

$I_E = I_C + I_B = 1.44\ mA$



I_B reverse direction than expected!

Aside

$V_B = 2.4V - I_B 8k = 3.86\ V$

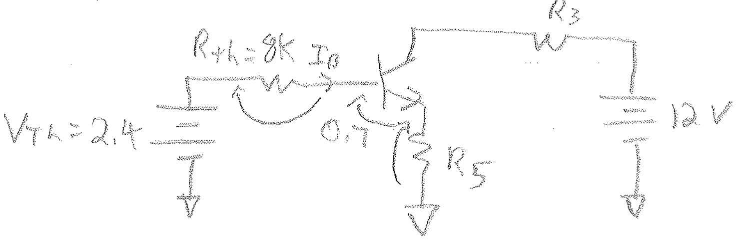
$V_C = 12V - I_C 5.7k = 2.76\ V$

$V_E = I_E 2.2k = 3.16\ V$

$V_{CE} = 0.4$, $V_{BE} = 0.7$ $V_{BC} \neq 0.3$ because I_B negative

Assumption not correct!

c) Assume forward Active



$V_{Th} = I_E R_5 + 0.7 + I_B R_{Th}$

$V_{Th} = (\beta+1) I_B R_5 + 0.7 + I_B R_{Th}$

$I_B = \dfrac{V_{Th} - 0.7}{(\beta+1) R_5 + R_{Th}} = \dfrac{1.7V}{(100+1) 2200 + 8000} = 7.38\ \mu A$

$I_c = \beta I_B = 738.5\ \mu A$

$I_E = (\beta+1) I_B$ or $\frac{1}{\alpha} I_c = 745.8\ \mu A$

$V_B = V_{Th} - I_B R_{Th} = 2.34\ V$

$V_C = 12V - I_C R_3 = 7.79\ V$

$V_E = I_E R_5 = 1.64\ V$

] side check of Math: $V_{BE} = 0.7$ ✓

<u>Check Assumption:</u> $V_B > V_E$ + $V_C > V_B$

Assumption verified.

d) Forward Active

e)

$I_c = \quad = I_s e^{V_{BE}/V_T} = I_s e^{0.7/0.0259}$

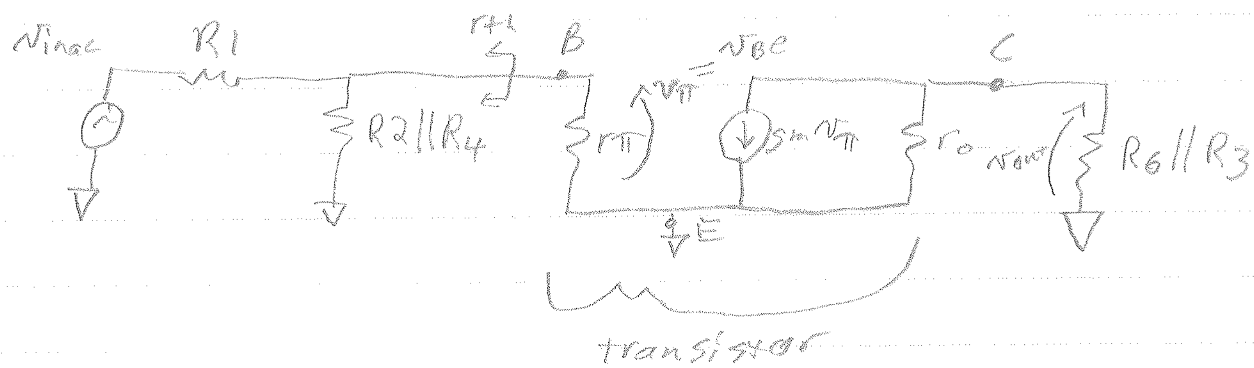
$\Rightarrow I_s =$

f) Convert to small signal model

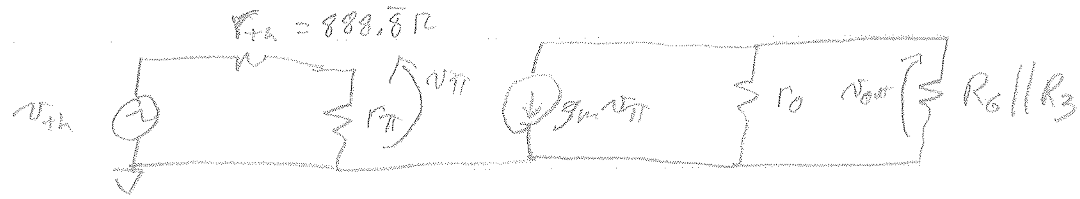
$$g_m = I_C/V_T = 738.5e{-6}/0.0255 = 0.0285\ S$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{100 + (7.79 - 1.64)}{738.5e{-6}} = 143.7\ k\Omega$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{0.0285} = 3507\ \Omega$$



Thevenize base,



(3) $\Rightarrow v_{th} = v_{inac}\left(\frac{R_2 \| R_4}{R_2 \| R_4 + R_1}\right) = v_{inac}(0.88)$ $\quad r_{th} = R_1 \| R_2 \| R_4 = 888.8\ \Omega$

$$A_v = \frac{v_{outac}}{v_{inac}} = \overset{①}{\left(\frac{v_{outac}}{v_\pi}\right)}\overset{②}{\left(\frac{v_\pi}{v_{th}}\right)}\overset{③}{\left(\frac{v_{th}}{v_{inac}}\right)}$$

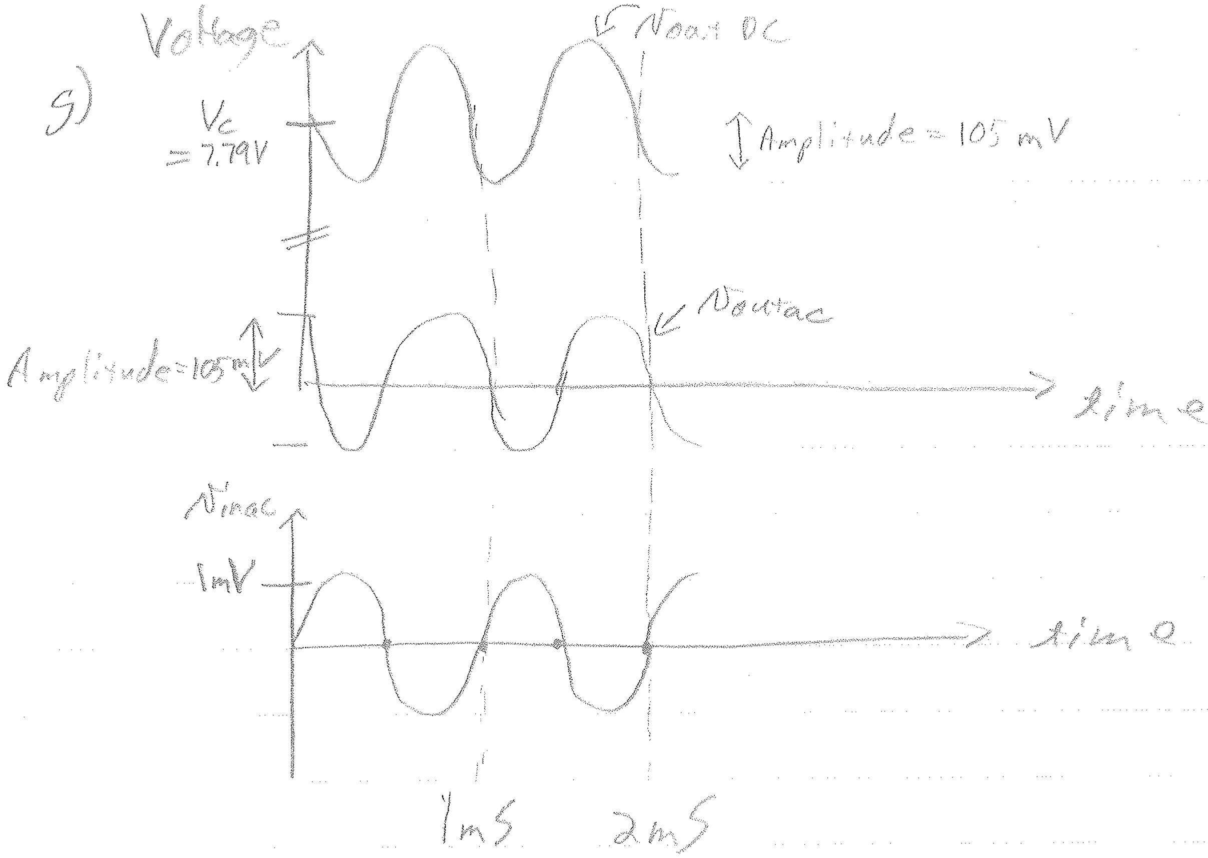
① = −148.2 v/v
② = 0.797 v/v
③ = 0.88

(1) $\Rightarrow v_{outac} = -g_m v_\pi (r_o \| R_6 \| R_3)$

(2) $\Rightarrow v_\pi = v_{th}\left(\frac{r_\pi}{r_{th} + r_\pi}\right)$

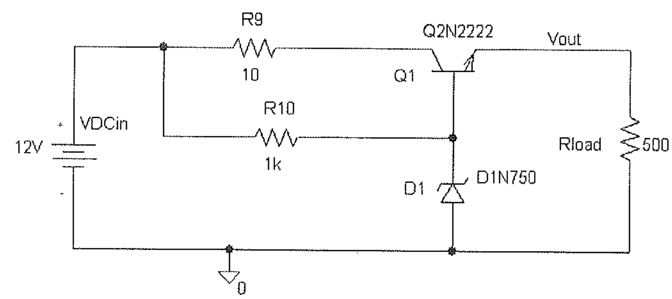
$$A_v = \frac{v_{outac}}{v_{inac}} = \overset{①}{\left(-g_m(r_o \| R_6 \| R_3)\right)}\overset{②}{\left(\frac{r_\pi}{r_{th} + r_\pi}\right)}\overset{③}{\left(\frac{R_2 \| R_4}{R_2 \| R_4 + R_1}\right)} = -105\ V/V$$

5)

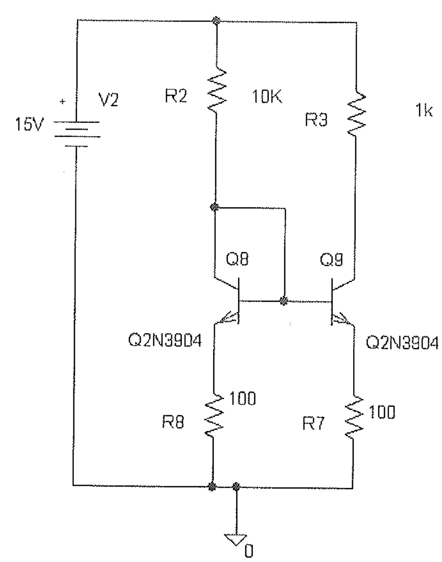


Voltage
Vc
= 7.79V
Vout DC
Amplitude = 105 mV
Voutac
Amplitude=105mV
time
Vinac
1mV
time
1mS
2mS

2. For the circuit below, assume that the transistor is biased in forward active mode and β=255.9 and I_S=14.3fA. Note that the Zener diode and R10 together operate in a similar fashion to the circuit assigned in homework 4 and you can neglect the small base current compared to all other currents. What is the voltage Vout when a) the resistance R_L=500 ohms, b) the resistance R_L=1000 ohms, c) the resistance R_L=2000 ohms. d) for a load resistance RL=500 ohms but with a power supply voltage VDCin=9V and 15 V. e) Explain the function and operation of this "voltage regulator power supply" circuit. Note: in reality , a larger "pass transistor" (as is it called in this type of application would be typically used. A 2N2222 was used only for convenience.

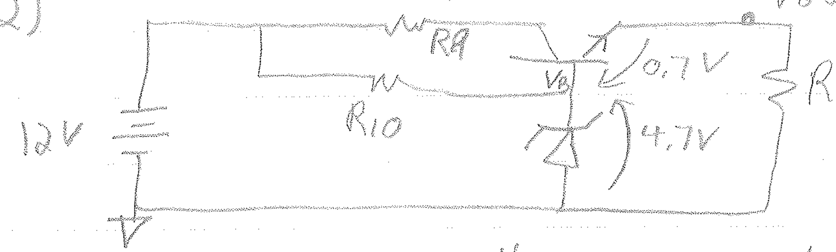


3. Assume Forward active mode bias and find the current flowing in R3 and compare it to the current flowing in R2 for this "current Mirror" circuit. What sets these currents (i.e. how can we change them)? The β=416.4 and I_S=6.734fA. Note: it may be helpful to consider the simplified Ebers Moll model only for determining the collector currents in the two transistors but otherwise use the Beta/CVD method. What happens to the currents if R3 is replaced with a 5K resistor? Why? Note this circuit is often used to implement a current source.



A Zener can have 3 possible states:
- Forward Bias ⟹ No since anode (p-side) is at lowest potential
- Reverse Off ⟹ No since V_B would be ~12 V which would break diode down (12 > 4.7V)
- Reverse Broke Down ⟹ yes!

2)



$V_{out} = 4.7 - 0.7V = 4V$

For all cases $V_{out} = 4V$ so all that needs to be checked is that the transistor remains in forward active for each case.

$V_c = V_{DC\,In} - R9\,I_c$

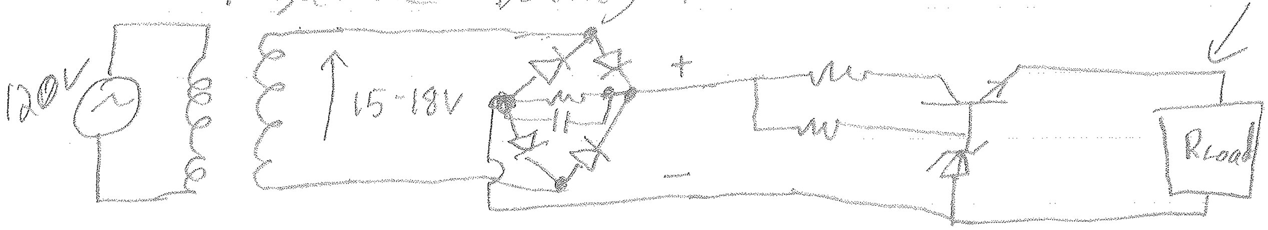
$I_c = \left(\frac{\beta}{\beta+1}\right) I_E$

Note β is large so $I_c \approx I_E$

$I_E = \frac{4V}{R_L}$

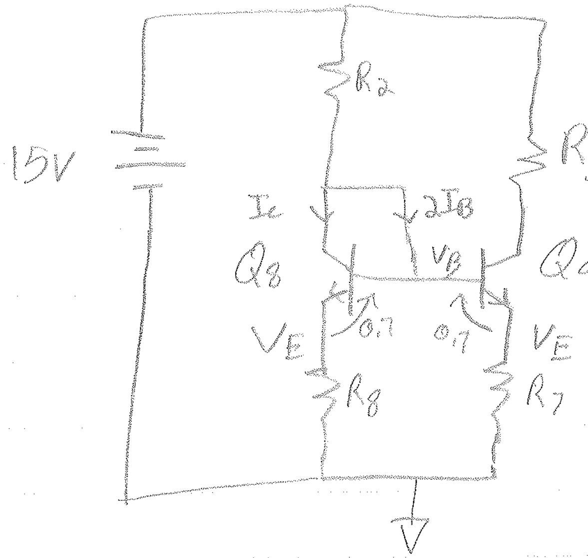
Case	V_{DC}	R_L	I_E	I_c	V_c	$V_c > V_B$? Still Forward active?
a	12V	500	8 mA	~8 mA	11.92	yes
b	12V	1000	4 mA	~4 mA	11.96	yes
c	12V	2000	2 mA	~2 mA	11.98	yes
d	15V	500	4 mA	~4 mA	14.96	yes
	9V	500	4 mA	~4 mA	8.96	yes

<u>Note:</u> This voltage regulator can be connected to our previous diode rectifiers to create a stable power supply voltage for a wide range of loads. If the load draws too much current, the transistor will saturate & not regulate voltage.



fixed voltage for most R_{Load} (except small)

3)



V_B is same for both transistors so so is V_E.
Since $V_{E8} = V_{E9}$ + $R_8 = R_7$, $I_{E8} = I_{E9}$
$V_{C8} = V_{B8}$

$I_E = \left(\frac{\beta+1}{\beta}\right) I_C$

$I_B = \frac{I_C}{\beta}$

$$15V = I_{E8} R_8 + 0.7 + R_2\left(I_{C8} + 2 I_B\right)$$

$$\frac{15V - 0.7}{R_2\left(\frac{2}{\beta}\right) + R_2 + \left(\frac{\beta+1}{\beta}\right) R_8} = I_{C8} = 1.409\,mA$$

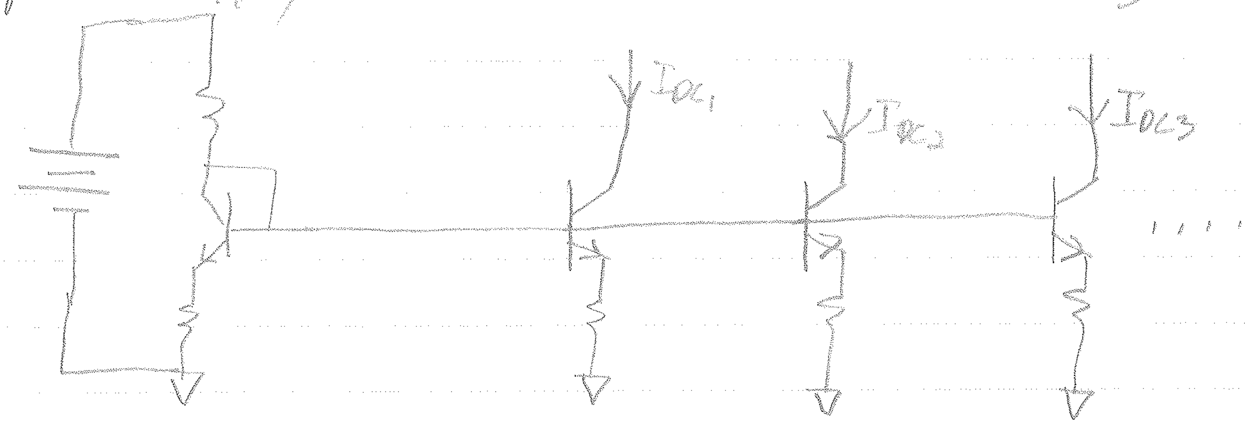
$$I_{E8} = \left(\frac{\beta+1}{\beta}\right) I_{C8} = 1.412\,mA$$

Note: Since $V_{BE8} = V_{BE9}$ and $I_C = I_S e^{V_{BE}/kT}$, $I_{C8} = I_{C9}$

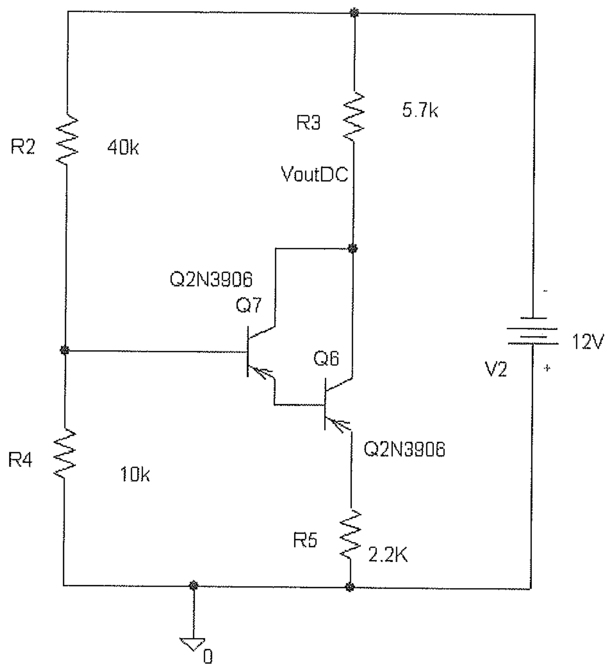
$$I_{C9} = I_{C8} = \underline{1.409\,mA}$$

Nothing changes if $R_3 = 5K$ since the current, I_{C9}, is set by Q_8. The Circuit acts as a dc current source as long as Q_8 + Q_9 remain in forward active. For this to happen, I_C must not be too high. I_C are set by R_2 (primarily) and R_8 + R_7. Also, for $I_{C8} = I_{C9}$ the choice of $R_8 = R_7$ was important.

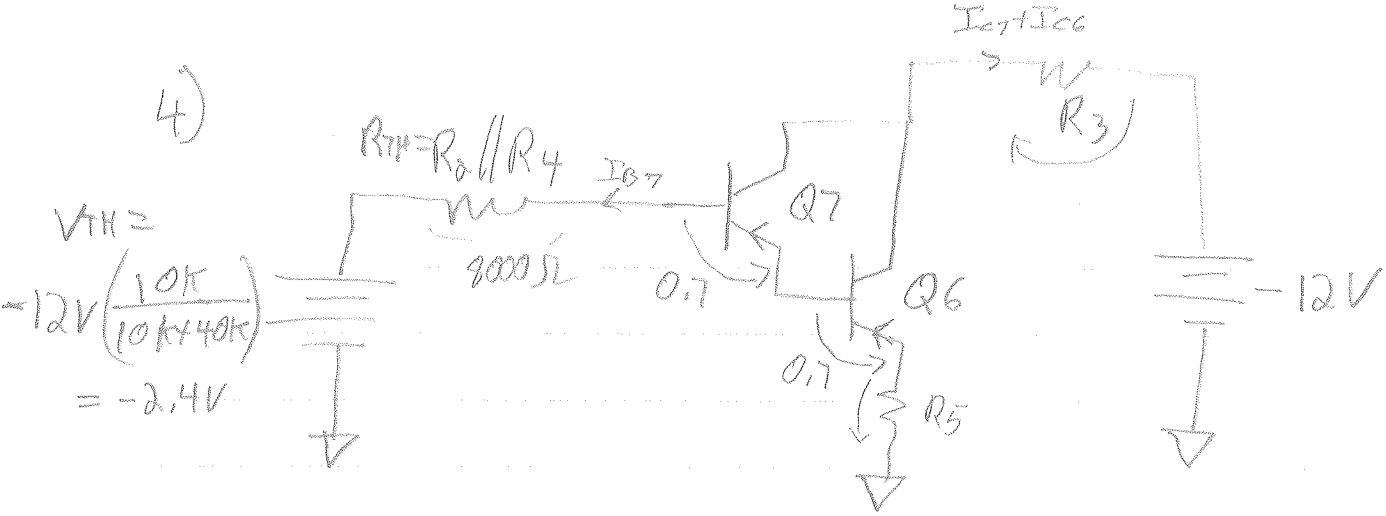
Note, multiple current sources could have been used. Also, common power supply is not needed but a common ground is.



4. Assume forward active mode and solve the Q-point for the following "Darlington configuration" and determine the total current flowing in R3 compared with the base current flowing in Q7. Τηε 2N3906 τρανσιστορ ηασ α β=180.7 and I_S=1.41fA. Sometimes this is called a "Super Beta" transistor configuration. Why is such a term applicable?



4)



$$V_{Th} + I_{B_7} R_{Th} + 0.7 + 0.7 + R_5 I_{E_6} = 0$$

$$I_{B6} = I_{E7} = (\beta+1) I_{B7}$$
$$I_{E6} = (\beta+1) I_{B6}$$
$$I_{E6} = (\beta+1)^2 I_{B7}$$

$$-\frac{(V_{Th} + 1.4)}{R_{Th} + R_5(\beta+1)^2} = I_{B7} = 1.376e\text{-}8\ A$$

$I_{C7} = \beta I_{B7} = 2.49\,\mu A$ $\quad I_{E7} = I_{B6} = (\beta+1) I_{B7} = 2.5\,\mu A$

$I_{C6} = (\beta I_{B6}) = 452\,\mu A$ $\quad I_{E6} = (\beta+1) I_{B6} = 454\,\mu A$

$$V_{C7} = V_{C6} = -12V + (I_{C7} + I_{C6}) R_3 = -9.4V$$
$$V_{E6} = 0 - I_{E6} R_5 = -1V$$
$$V_{B7} = V_{Th} + I_{B7} R_{Th} = -2.39V$$
$$V_{B6} = V_{B7} + 0.7 = -1.69V$$

Forward active verified.

Collector Currents from 2 transistors are added together but also are amplified!

$$\frac{I_{C7}+I_{C6}}{I_{B7}} = \frac{\beta I_{B7} + (\beta+1)\beta I_{B7}}{I_{B7}} = \frac{454\,\mu A}{0.0137\,\mu A} = 33013 >> \beta \; : \; \underline{33013 = \beta(\beta+2)}$$