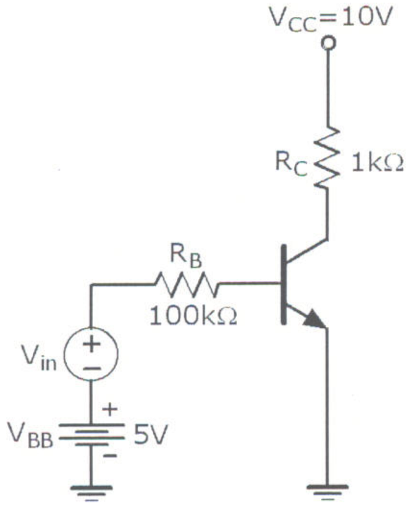
1. (18 points) For the following circuit, let $\beta = 120$, $V_{BE}(on) = 0.7V$ and $V_{CE}(sat) = 0.3V$.

8 pts **a.** Assume that $V_{in} = 0V$. Determine the Q-point (dc operating point) values, I_{CQ} and V_{CEQ}. Draw the dc load line and the Q-point.

4 pts **b.** Find the peak value of V_{in} that drives the transistor into SATURATION.

4 pts **c.** Find the peak value of V_{in} that drives the transistor into CUTOFF.

2 pts **d.** Find the maximum peak value of V_{in} for linear operation (i.e.the transistor operates in the forward-active mode).



SOLUTION:

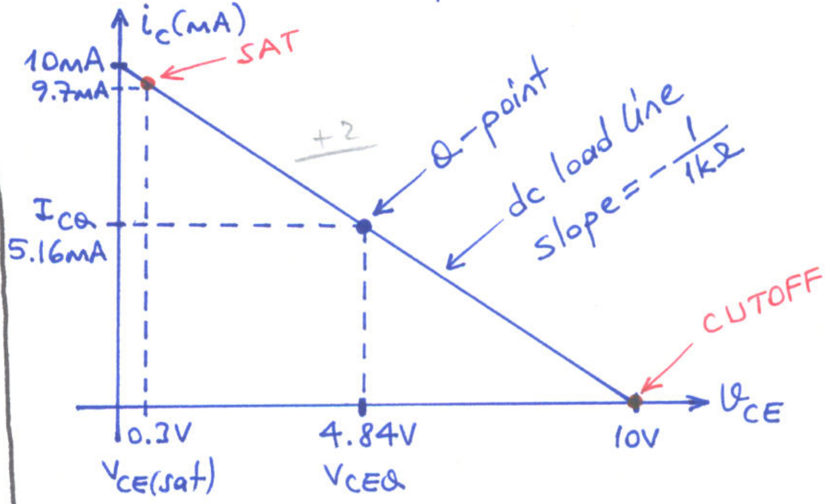
(a) Assume that the transistor is in the forward-active mode.

$$I_{BQ} = \frac{V_{BB} + V_{in} - V_{BE(on)}}{R_B} = \frac{5 - 0.7}{100k\Omega} = 43\mu A$$

$$I_{CQ} = \beta I_{BQ} = \boxed{5.16mA} \quad +3$$

$$V_{CEQ} = V_{CC} - I_{CQ} R_C = \boxed{4.84V} \quad +3$$

Our initial assumption is correct.



+4 (b) At the edge of SAT and ACT regions:

$V_{CE} = V_{CE(sat)} = 0.3V$

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = 9.7mA$$

$$I_B = \frac{I_C}{\beta} = 80.8333\mu A$$

$$V_{BB} + V_{in} - I_B R_B - V_{BE(on)} = 0$$

$$V_{in} = I_B R_B + V_{BE(on)} - V_{BB} = 8.0833 + 0.7 - 5 = \boxed{3.7833V}$$

For large ac input signal $V_p = 3.7833V$

+4 (c) In the cutoff mode: $I_B = I_C = I_E = 0A$.

Then $V_{in} = V_{BE(on)} - V_{BB} = 0.7 - 5 = \boxed{-4.3V}$

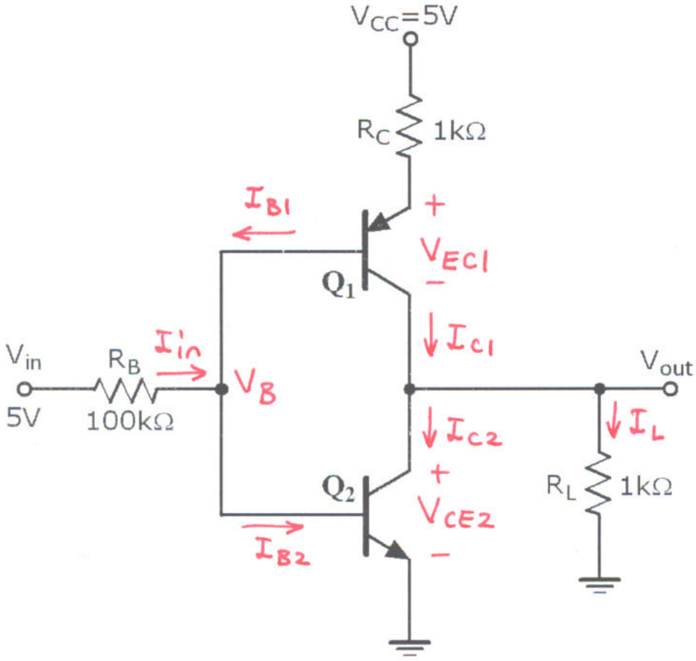
For large ac input signal $V_p = 4.3V$

+2 (d) For linear operation of the amplifier, the transistor must operate in the forward-active mode. If the transistor is drived into either SAT or CUTOFF regions, the output voltage will be distorted. Therefore, the maximum peak value of V_{in} for a linear operation is

$$\boxed{V_{in} = 3.7833V}$$ For low frequency large ac signal.

In DC mode: $-4.3 < V_{in} < 3.7833V$

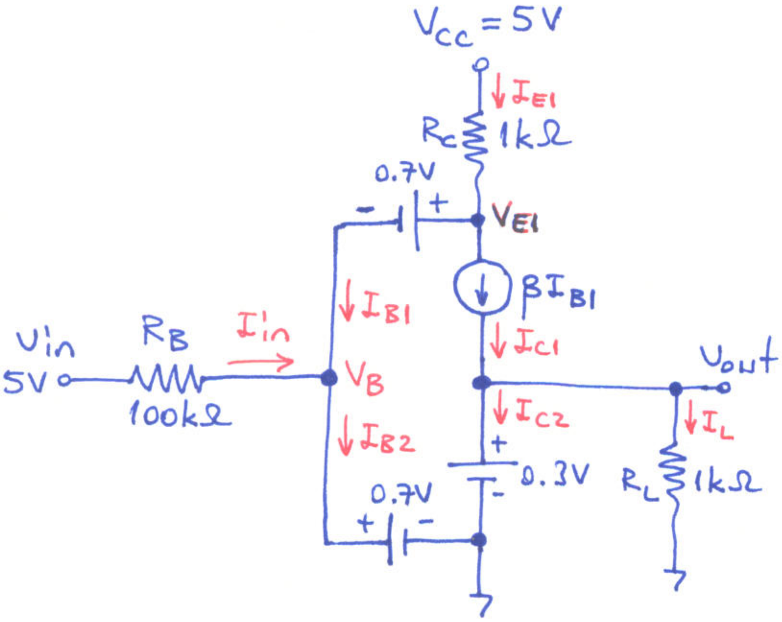
2. (20 points) For the following circuit, find the states of the transistors and the Q-point values (I_{C1}, V_{EC1}, I_{C2} and V_{CE2}). Let $\beta = 100$, $V_{BE}(on) = V_{EB}(on) = 0.7V$ and $V_{CE}(sat) = V_{EC}(sat) = 0.3V$.



SOLUTION:

If both transistors are assumed to be OFF, all currents are zero and $V_B = 5V$. This voltage forces Q_2 to be ON. If we assume that Q_2 is ON, then $V_B = 0.7V$ and this voltage forces Q_1 to be ON. Therefore, both transistors must be ON. Let's assume that both Q_1 and Q_2 are in the ACT mode. Then $I_{C2} > I_{C1}$ since $I_{B2} > I_{B1}$. This results in a negative load current ($I_L < 0$) and a negative output voltage ($V_{out} < 0$).

This means that V_{CE2} becomes negative and it is an inconsistency. Because, V_{CE} cannot be negative in the forward-active mode. So our assumption is wrong. Now, let's assume that Q_1 is in ACT mode and Q_2 is in SAT mode. Then, the equivalent circuit will be as follows.



Note that $V_B = 0.7V$, $V_{E1} = 1.4V$

$$I_{E1} = \frac{V_{CC} - V_{E1}}{R_C} = \frac{5 - 1.4}{1k\Omega} = 3.6mA$$

$$I_{B1} = \frac{I_{E1}}{\beta + 1} = 35.6436\mu A$$

$$I_{C1} = \alpha I_{E1} = \boxed{3.5644mA}$$

$$V_o = V_{C1} = V_{C2} = 0.3V$$

$$V_{EC1} = V_{E1} - V_{C1} = 1.4 - 0.3 = \boxed{1.1V}$$

$$I_{B2} = I_{in} + I_{B1} = \frac{V_{in} - V_B}{R_B} + I_{B1}$$

$$I_{B2} = \frac{5 - 0.7}{100k\Omega} + 35.6436\mu A$$

$$I_{B2} = 78.6436\mu A$$

$$I_L = \frac{V_{out}}{R_L} = \frac{0.3V}{1k\Omega} = 0.3mA$$

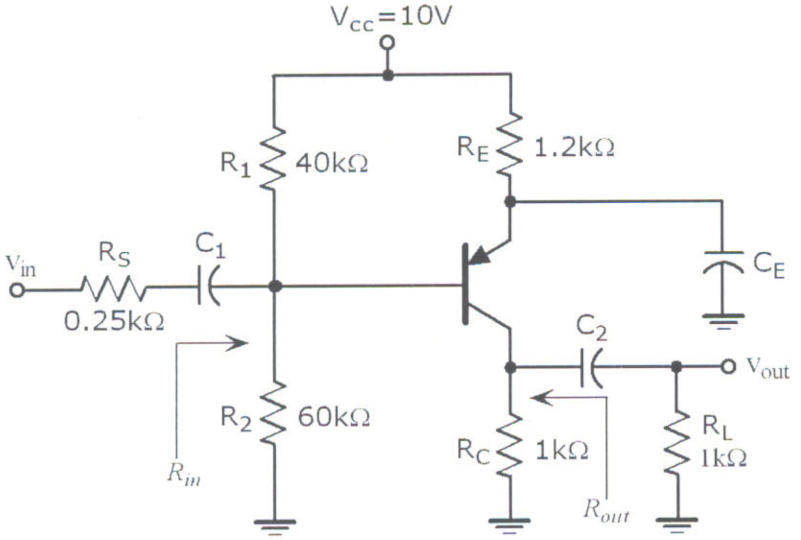
$$I_{C2} = I_{C1} - I_L = 3.5644 - 0.3 = \boxed{3.2644mA}$$

$$\beta_{forced} = \frac{I_{C2}}{I_{B2}} = 41.5 \quad \text{and} \quad \boxed{V_{CE2} = 0.3V}$$

our assumption is correct.

3. (20 points) For the following BJT amplifier circuit, let $\beta = 200$ and $V_{EB}(on) = 0.7\text{V}$, and the transistor is biased at $I_{CQ} = 2.4887$ mA. Assume that the capacitors are very large.

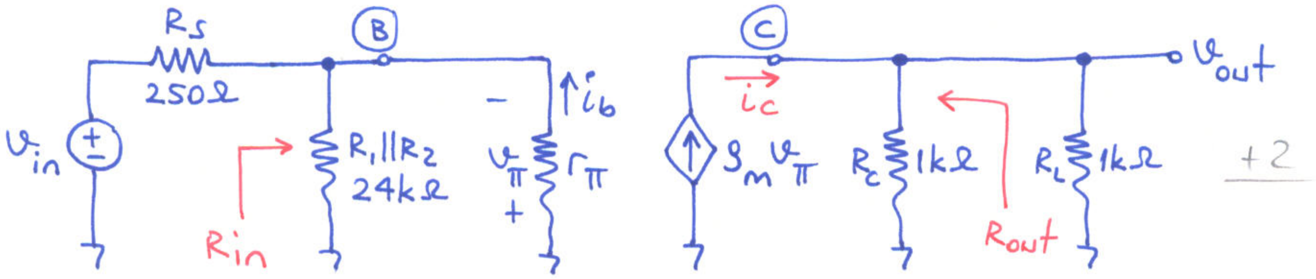
- **a.** (6 points) Draw the small-signal ac equivalent circuit and calculate the small-signal transistor parameters, r_π and g_m.
- **b.** (6 points) Determine the input resistance (R_{in}) and the output resistance (R_{out}).
- **c.** (8 points) Determine the voltage gain, $A_v = V_{out} / V_{in}$



SOLUTION:

+2 +2

(a) $r_\pi = \dfrac{\beta V_T}{I_{CQ}} = \boxed{2.0894\,k\Omega}$ and $g_m = \dfrac{I_{CQ}}{V_T} = \boxed{95.7192\ mA/V}$



(b) $R_{in} = R_1 || R_2 || r_\pi = \boxed{1.9221\,k\Omega}$ +3

To find R_{out}, we set $v_{in} = 0$. Then $V_\pi = 0$ and $i_b = i_c = 0$.

Therefore, $R_{out} = R_c = \boxed{1k\Omega}$ +3

(c) $v_{out} \overset{+2}{=} g_m v_\pi (R_c || R_L)$ and $v_\pi = \dfrac{-R_{in}}{R_s + R_{in}} v_{in}$ +2

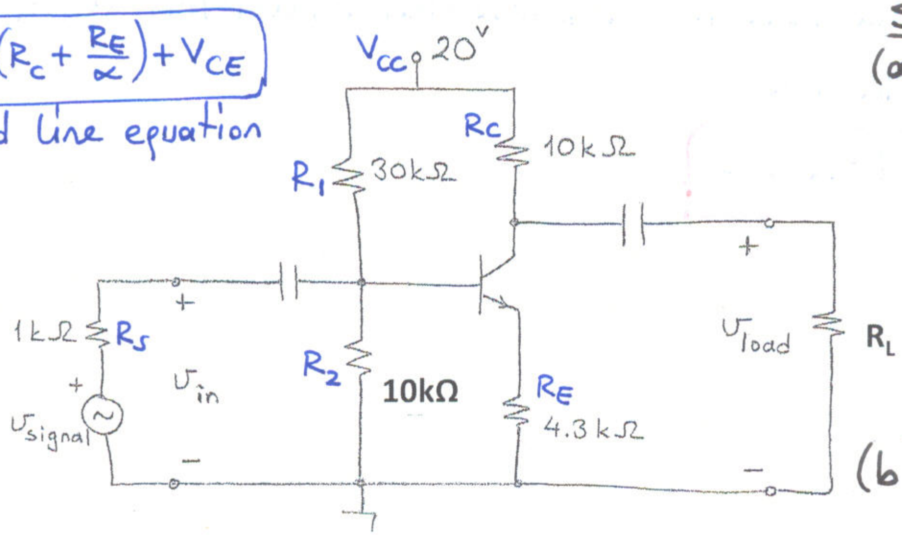
$A_v = \dfrac{V_{out}}{V_{in}} = -g_m (R_c || R_L) \left(\dfrac{R_{in}}{R_s + R_{in}} \right) = \boxed{-42.35}$ +4

4. (30 points) For the following BJT amplifier circuit, let $\beta = 100$, and $V_{BE}(on) = 1.0$V, and $V_{CE}(sat) = 0.2$V. Assume that the capacitors are very large.

- **a.** (4 points) Find the DC base current.
- **b.** (6 points) Draw the small-signal ac equivalent circuit and calculate the small-signal transistor parameters, r_π and g_m.
- **c.** (12 points) Find the value of R_L to obtain the maximum possible undistorted symmetric voltage swing across the load resistor (v_{load}). What is the value of the peak-to-peak swing?
- **d.** (8 points) Assume $R_L = 30\text{k}\Omega$. What is the value of the peak-to-peak undistorted symmetric Collector-Emitter voltage swing (v_{ce}).

$$\boxed{V_{CC} = I_C\left(R_C + \frac{R_E}{\alpha}\right) + V_{CE}}$$

dc load line equation



SOLUTION:

(a) $V_{TH} = \frac{R_2}{R_1+R_2} V_{CC} = 5V$

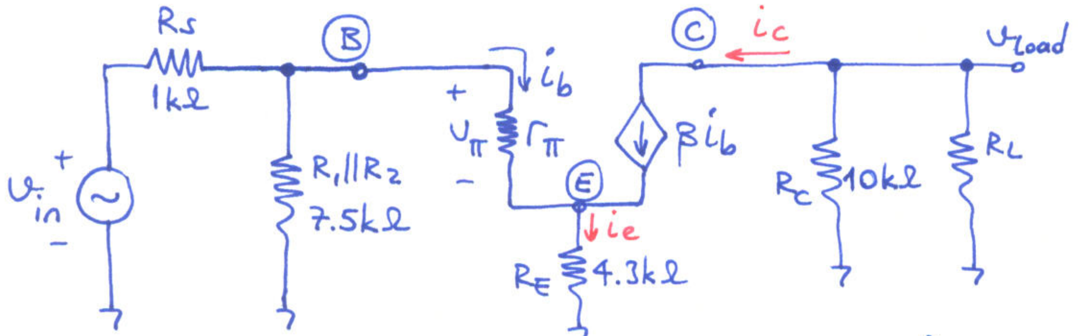
$R_{TH} = R_1 \| R_2 = 7.5k\Omega$

$I_{BQ} = \frac{V_{TH} - V_{BE(on)}}{R_{TH} + (\beta+1)R_E}$

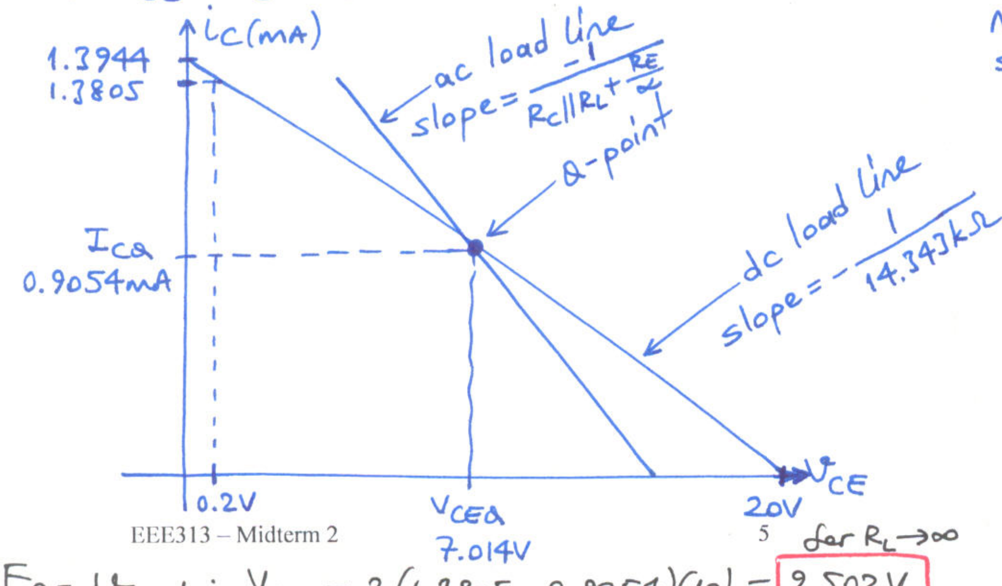
$\boxed{I_{BQ} = 9.0539\mu A}$

(b) $r_\pi = \frac{V_T}{I_{BQ}} = \boxed{2.8717k\Omega}$

$g_m = \frac{I_{CQ}}{V_T} = \boxed{34.8227\frac{mA}{V}}$



(c) $v_{ce} = v_c - v_e = -i_c(R_c \| R_L) - i_e R_E = -i_c\left[R_c \| R_L + \frac{R_E}{\alpha}\right]$: ac load line



Max. possible undistorted symmetric v_{ce} swing is

$V_{CEQ} - V_{CE(sat)} = 6.814V$

Peak value of collector current (i_c) swing is

0.9054mA

Then

$R_c \| R_L + \frac{R_E}{\alpha} = 7.526k\Omega$

Thus $\boxed{V_{pp} = 5.7638V}$

$\boxed{R_L = 4.669k\Omega}$ For v_{load}

Max. undistorted symmetric swing across the load is obtained when $R_L = \infty$

For v_{load} : $V_{pp} = 2(1.3805 - 0.9054)(10) = \boxed{9.502V}$

(d) For $R_L = 30k\Omega$, the slope of ac load line is

$$-\frac{1}{R_c \| R_L + \frac{R_E}{\alpha}} = \frac{-1}{11.843k\Omega}$$

Positive peak of ac collector-emitter voltage can be at most

$$\left(R_c \| R_L + \frac{R_E}{\alpha}\right) I_{CQ} = 10.7222V$$

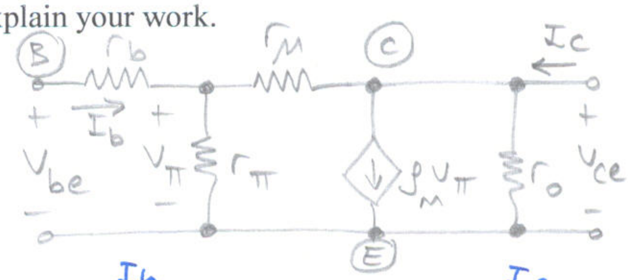
Negative peak of v_{ce} can be at most

$$V_{CEQ} - V_{CE(sat)} = 6.814V.$$

Therefore, max. possible undistorted symmetric voltage swing is $V_p = 6.814V$

$$\boxed{V_{pp} = 13.628V}$$

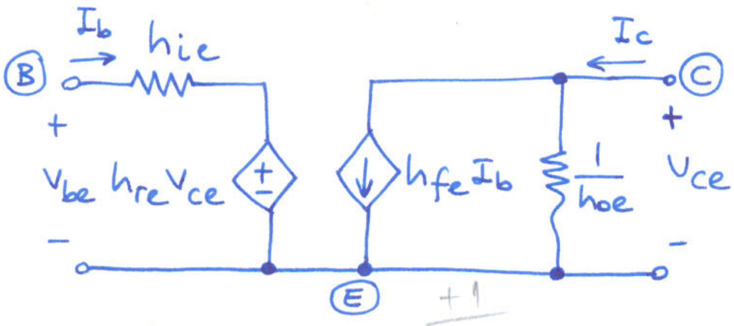
5. (12 points) For two-port network representation of a single n-p-n Bipolar Junction Transistor (BJT), express the following h-parameters in terms of the small-signal hybrid-π model parameters (include r_π, g_m and r_o only) of the transistor. Explain your work.



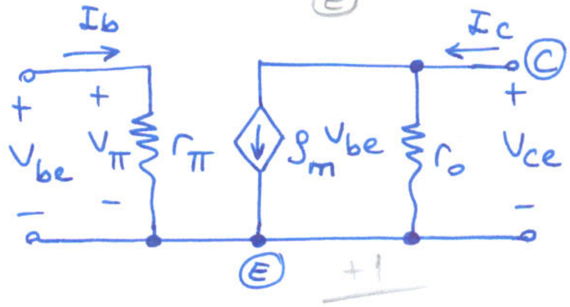
a. (6 points) h_{fe}

b. (6 points) h_{oe}

SOLUTION:



h-parameter model of BJT



Hybrid-π model of BJT

$V_{be} = h_{ie} I_b + h_{re} V_{ce}$ +2

$I_c = h_{fe} I_b + h_{oe} V_{ce}$

(a) $h_{fe} = \left.\frac{I_c}{I_b}\right|_{V_{ce}=0}$ +2

Now, set $V_{ce}=0$ in the hybrid-π model.

$I_c = g_m V_\pi$ where $V_\pi = I_b r_\pi$

Therefore, $\boxed{h_{fe} = g_m r_\pi = \beta}$ +2

$h_{fe} = \frac{\beta r_\mu - r_\pi}{r_\pi + r_\mu}$

$= \beta - (\beta+1)\frac{r_\pi}{r_\pi + r_\mu}$

(b) $h_{oe} = \left.\frac{I_c}{V_{ce}}\right|_{I_b=0}$ +2

Now, set $I_b=0$ in the hybrid-π model.

$V_\pi = 0$ and $g_m V_\pi = 0$.

Therefore, $\boxed{h_{oe} = \frac{1}{r_o}}$ +2

$h_{oe} = \frac{1}{r_o} + \frac{\beta+1}{r_\pi + r_\mu}$