Ex: 6.1 $i_C = I_S\, e^{v_{BE}/V_T}$

$v_{BE2} - v_{BE1} = V_T \ln\left[\frac{i_{C2}}{i_{C1}}\right]$

$v_{BE2} = 700 + 25 \ln\left[\frac{0.1}{1}\right]$

$= 642$ mV

$v_{BE3} = 700 + 25 \ln\left[\frac{10}{1}\right]$

$= 758$ mV

Ex: 6.2 $\therefore \alpha = \frac{\beta}{\beta + 1}$

$\frac{50}{50+1} < \alpha < \frac{150}{150+1}$

$0.980 < \alpha < 0.993$

Ex: 6.3 $I_C = I_E - I_B$

$= 1.460 \text{ mA} - 0.01446 \text{ mA}$

$= 1.446$ mA

$\alpha = \frac{I_C}{I_E} = \frac{1.446}{1.460} = 0.99$

$\beta = \frac{I_C}{I_B} = \frac{1.446}{0.01446} = 100$

$I_C = I_S e^{v_{BE}/V_T}$

$I_S = \frac{I_C}{e^{v_{BE}/V_T}} = \frac{1.446}{e^{700/25}}$

$= \frac{1.446}{e^{28}} \text{ mA} = 10^{-15}$ A

Ex: 6.4 $\beta = \frac{\alpha}{1-\alpha}$ and $I_C = 10$ mA

For $\alpha = 0.99$, $\beta = \frac{0.99}{1 - 0.99} = 99$

$I_B = \frac{I_C}{\beta} = \frac{10}{99} = 0.1$ mA

For $\alpha = 0.98$, $\beta = \frac{0.98}{1 - 0.98} = 49$

$I_B = \frac{I_C}{\beta} = \frac{10}{49} = 0.2$ mA

Ex: 6.5 Given:

$I_S = 10^{-16}$ A, $\beta = 100$, $I_C = 1$ mA

We write

$I_{SE} = I_{SC}/\alpha = I_S = \left(1 + \frac{1}{\beta}\right)$

$= 10^{-16} \times 1.01 = 1.01 \times 10^{-16}$ A

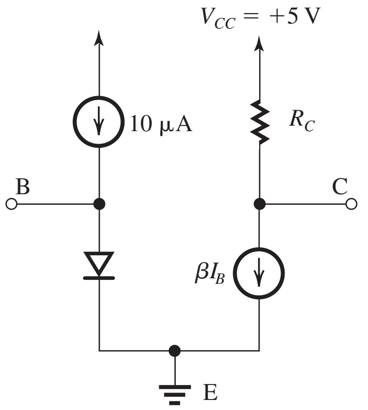
$I_{SB} = \frac{I_S}{\beta} = \frac{10^{-16}}{100} = 10^{-18}$ A

$V_{BE} = V_T \ln\left[\frac{I_C}{I_S}\right] = 25 \ln\left[\frac{1 \text{ mA}}{10^{-16}}\right]$

$= 25 \times 29.9336$

$= 748$ mV

Ex: 6.6



$v_{BE} = 690$ mV

$I_C = 1$ mA

For active range $V_C \geq V_B$,

$R_{C\max} = \frac{V_{CC} - 0.690}{I_C}$

$= \frac{5 - 0.69}{1}$

$= 4.31$ kΩ

Ex: 6.7 $I_S = 10^{-15}$ A

$\text{Area}_C = 100 \times \text{ Area}_E$

$I_{SC} = 100 \times I_S = 10^{-13}$ A

Ex: 6.8 $i_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$

for $i_C = 0$

$I_S e^{v_{BE}/V_T} = I_{SC} e^{v_{BC}/V_T}$

$\frac{I_{SC}}{I_S} = \frac{e^{v_{BE}/V_T}}{e^{v_{BC}/V_T}}$

$= e^{(v_{BE} - v_{BC})/V_T}$

$\therefore V_{CE} = V_{BE} - V_{BC} = V_T \ln\left[\frac{I_{SC}}{I_S}\right]$

For collector Area = 100 × Emitter area

$V_{CE} = 25 \ln\left[\frac{100}{1}\right] = 115$ mV

Ex: 6.9 $I_C = I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}$

$$I_B = \frac{I_S}{\beta} e^{v_{BE}/V_T} + I_{SC} e^{v_{BC}/V_T}$$

$$\beta_{\text{forced}} = \left.\frac{I_C}{I_B}\right|_{\text{sat}} < \beta$$

$$= \beta \frac{I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}}{I_S e^{v_{BE}/V_T} + \beta I_{SC} e^{v_{BC}/V_T}}$$

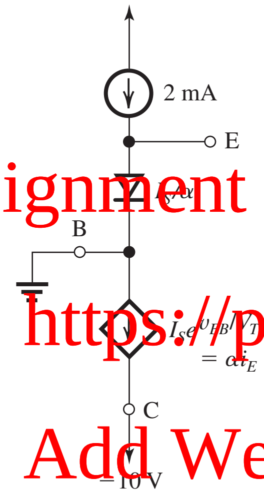
$$= \beta \frac{I_S e^{(v_{BE}-v_{BC})/V_T} - I_{SC}}{I_S e^{(v_{BE}-v_{BC})/V_T} + \beta I_{SC}}$$

$$= \beta \frac{e^{V_{CE\text{sat}}/V_T} - I_{SC}/I_S}{e^{V_{CE\text{sat}}/V_T} + \beta I_{SC}/I_S} \qquad \text{Q.E.D.}$$

$$\beta_{\text{forced}} = 100 \frac{e^{200/25} - 100}{e^{200/25} + 100 \times 100}$$

$$= 100 \times 0.2219 \approx 22.2$$

Ex: 6.10



$$I_E = \frac{I_S}{\alpha} e^{v_{BE}/V_T}$$

$$2\text{ mA} = \frac{51}{50} 10^{-14} e^{v_{BE}/V_T}$$

$$V_{BE} = 25 \ln\left[\frac{2}{10^3} \times \frac{50}{51} \times 10^{14}\right]$$

$$= 650\text{ mV}$$

$$I_C = \frac{\beta}{\beta+1} I_E = \frac{50}{51} \times 2$$

$$= 1.96\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{1.96}{50} \Rightarrow 39.2\ \mu\text{A}$$

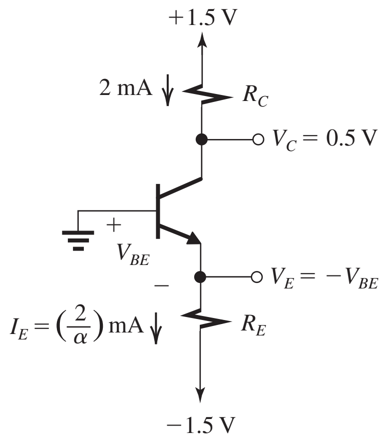
Ex: 6.11 $I_C = I_S e^{v_{BE}/V_T} = 1.5$ A

$$\therefore V_{BE} = V_T \ln\left[1.5/10^{-11}\right]$$

$$= 25 \times 25.734$$

$$= 643\text{ mV}$$

Ex: 6.12



$$R_C = \frac{1.5 - V_C}{I_C} = \frac{1.5 - 0.5}{2}$$

$$= 0.5\text{ k}\Omega = 500\ \Omega$$

Since at $I_C = 1$ mA, $V_{BE} = 0.8$ V, then at $I_C = 2$ mA,

$$V_{BE} = 0.8 + 0.025 \ln\left(\frac{2}{1}\right)$$

$$= 0.8 + 0.017$$

$$= 0.817\text{ V}$$

$$V_E = -V_{BE} = -0.817\text{ V}$$

$$I_E = \frac{2\text{ mA}}{\alpha} = \frac{2}{0.99} = 2.02\text{ mA}$$

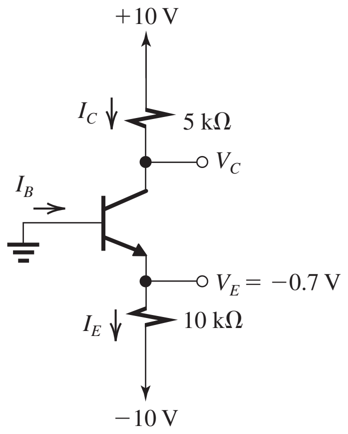
$$I_E = \frac{V_E - (-1.5)}{R_E}$$

Thus,

$$R_E = \frac{-0.817 + 1.5}{2.02} = 0.338\text{ k}\Omega$$

$$= 338\ \Omega$$

Ex: 6.13



$$I_E = \frac{V_E - (-10)}{10} = \frac{-0.7 + 10}{10}$$

$= 0.93$ mA

Assuming active-mode operation,

$$I_B = \frac{I_E}{\beta + 1} = \frac{0.93}{50 + 1} = 0.0182 \text{ mA}$$

$= 18.2\ \mu$A

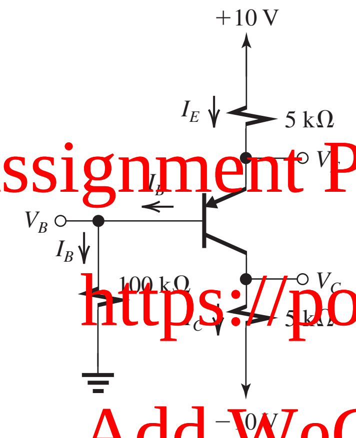
$I_C = I_E - I_B = 0.93 - 0.0182 = 0.91$ mA

$V_C = 10 - I_C \times 5$

$= 10 - 0.91 \times 5 = 5.45$ V

Since $V_C > V_B$, the transistor is operating in the active mode, as assumed.

Ex: 6.14



$V_B = 1.0$ V

Thus,

$$I_B = \frac{V_B}{100\text{ k}\Omega} = 0.01 \text{ mA}$$

$V_E = +1.7$ V

Thus,

$$I_E = \frac{10 - V_E}{5\text{ k}\Omega} = \frac{10 - 1.7}{5} = 1.66 \text{ mA}$$

and

$$\beta + 1 = \frac{I_E}{I_B} = \frac{1.66}{0.01} = 166$$

$\Rightarrow \beta = 165$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{165}{165 + 1} = 0.994$$

Assuming active-mode operation,

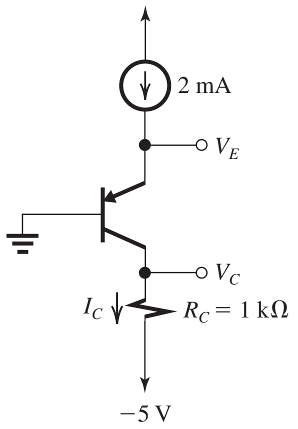
$I_C = \alpha I_E = 0.994 \times 1.66 = 1.65$ mA

and

$V_C = -10 + 1.65 \times 5 = -1.75$ V

Since $V_C < V_B$, the transistor is indeed operating in the active mode.

Ex: 6.15



The transistor is operating at a constant emitter current. Thus, a change in temperature of +30°C results in a change in V_{E} by

$\triangle V_{EB} = -2 \text{ mV} \times 30 = -60$ mV

Thus,

$\triangle V_E = +60$ mV

Since the collector current remains unchanged at αI_E, the collector voltage does not change:

$\triangle V_C = 0$ V

Ex: 6.16 Refer to Fig. 6.19(a):

$$i_C = I_S e^{v_{BE}/V_T} + \frac{v_{CE}}{r_o} \qquad (1)$$

Now using Eqs. (6.21) and (6.22), we can express r_o as

$$r_o = \frac{V_A}{I_S e^{v_{BE}/V_T}}$$

Substituting in Eq. (1), we have

$$i_C = I_S e^{v_{BE}/V_T} \left(1 + \frac{v_{CE}}{V_A}\right)$$

which is Eq. (6.18). Q.E.D.

Ex: 6.17 $r_o = \dfrac{V_A}{I_C} = \dfrac{100}{I_C}$

At $I_C = 0.1$ mA, $r_o = 1$ MΩ

At $I_C = 1$ mA, $r_o = 100$ kΩ

At $I_C = 10$ mA, $r_o = 10$ kΩ

Ex: 6.18 $\triangle I_C = \dfrac{\triangle V_{CE}}{r_o}$

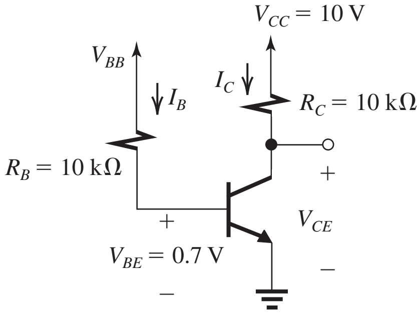
where

$$r_o = \frac{V_A}{I_C} = \frac{100}{1} = 100\ \text{k}\Omega$$

$$\triangle I_C = \frac{11-1}{100} = 0.1\ \text{mA}$$

Thus, I_C becomes 1.1 mA.

Ex: 6.19



(a) For operation in the active mode with $V_{CE} = 5$ V,

$$I_C = \frac{V_{CC} - V_C}{R_C} = \frac{10-5}{10} = 0.5\ \text{mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{0.5}{50} = 0.01\ \text{mA}$$

$$V_{BB} = V_{BE} + I_B R_B$$

$$= 0.7 + 0.01 \times 10 = 0.8\ \text{V}$$

(b) For operation at the edge of saturation,

$$V_{CE} = 0.3\ \text{V}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10-0.3}{10} = 0.97\ \text{mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{0.97}{50} = 0.0194\ \text{mA}$$

$$V_{BB} = V_B + I_B R_B$$

$$= 0.7 + 0.0194 \times 10 = 0.894\ \text{V}$$

(c) For operation deep in saturation with $\beta_{\text{forced}} = 10$, we have

$$V_{CE} \simeq 0.2\ \text{V}$$

$$I_C = \frac{10-0.2}{10} = 0.98\ \text{mA}$$

$$I_B = \frac{I_C}{\beta_{\text{forced}}} = \frac{0.98}{10} = 0.098\ \text{mA}$$

$$V_{BB} = V_B + I_B R_B$$

$$= 0.7 + 0.098 \times 10 = 1.68\ \text{V}$$

Ex: 6.20 For $V_{BB} = 0$ V, $I_B = 0$ and the transistor is cut off. Thus,

$$I_C = 0$$

and

$$V_C = V_{CC} = +10\ \text{V}$$

Ex: 6.21 Refer to the circuit in Fig. 6.22 and let $V_{BB} = 1.7$ V. The current I_B can be found from

$$I_B = \frac{V_{BB} - V_B}{R_B} = \frac{1.7 - 0.7}{10} = 0.1\ \text{mA}$$

Assuming operation in the active mode,

$$I_C = \beta\, I_B = 50 \times 0.1 = 5\ \text{mA}$$

Thus,

$$V_C = V_{CC} - R_C I_C$$

$$= 10 - 1 \times 5 = 5\ \text{V}$$

which is greater than V_B, verifying that the transistor is operating in the active mode, as assumed.

(a) To obtain operation at the edge of saturation, R_C must be increased to the value that results in $V_{CE} = 0.3$ V:

$$R_C = \frac{V_{CC} - 0.3}{I_C}$$

$$= \frac{10-0.3}{5} = 1.94\ \text{k}\Omega$$

(b) Further increasing R_C results in the transistor operating in saturation. To obtain saturation-mode operation with $V_{CE} = 0.2$ V and $\beta_{\text{forced}} = 10$, we use

$$I_C = \beta_{\text{forced}} \times I_B$$

$$= 10 \times 0.1 = 1\ \text{mA}$$

The value of R_C required can be found from

$$R_C = \frac{V_{CC} - V_{CE}}{I_C}$$

$$= \frac{10-0.2}{1} = 9.8\ \text{k}\Omega$$

Ex: 6.22 Refer to the circuit in Fig. 6.23(a) with the base voltage raised from 4 V to V_B. If at this value of V_B, the transistor is at the edge of saturation then,

$$V_C = V_B - 0.4\ \text{V}$$

Since $I_C \simeq I_E$, we can write

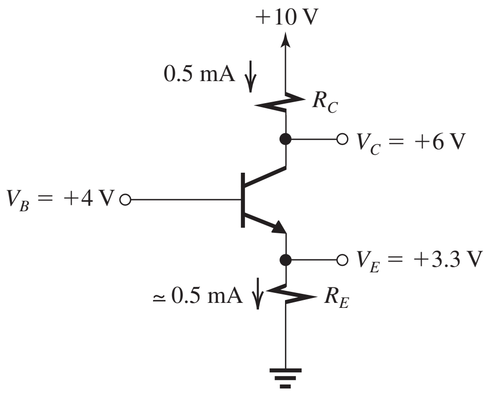
$$\frac{10 - V_C}{R_C} = \frac{V_E}{R_E} = \frac{V_B - 0.7}{R_E}$$

Thus,

$$\frac{10 - (V_B - 0.4)}{4.7} = \frac{V_B - 0.7}{3.3}$$

$\Rightarrow V_B = +4.7$ V

Ex: 6.23



To establish a reverse-bias voltage of 2 V across the CBJ,

$V_C = +6$ V

From the figure we see that

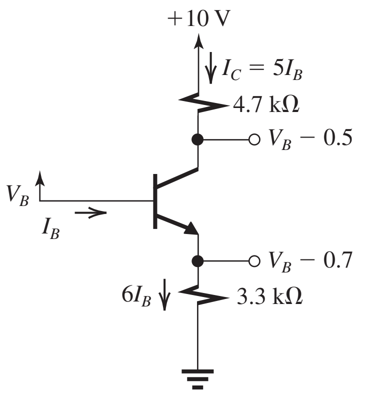
$$R_C = \frac{10 - 6}{0.5} = 8 \text{ k}\Omega$$

and

$$R_E = \frac{3.3}{0.5} = 6.6 \text{ k}\Omega$$

where we have assumed $\alpha \simeq 1$.

Ex: 6.24



The figure shows the circuit with the base voltage at V_B and the BJT operating in saturation with $V_{CE} = 0.2$ V and $\beta_{\text{forced}} = 5$.

$$I_C = 5I_B = \frac{10 - (V_B - 0.5)}{4.7} \tag{1}$$

$$I_E = 6I_B = \frac{V_B - 0.7}{3.3} \tag{2}$$

Dividing Eq. (1) by Eq. (2), we have

$$\frac{5}{6} = \frac{10.5 - V_B}{V_B - 0.7} \times \frac{3.3}{4.7}$$

$\Rightarrow V_B = +5.18$ V

Ex: 6.25 Refer to the circuit in Fig. 6.26(a). The largest value for R_C while the BJT remains in the active mode corresponds to

$V_C = +0.4$ V

Since the emitter and collector currents remain unchanged, then from Fig. 6.26(b) we obtain

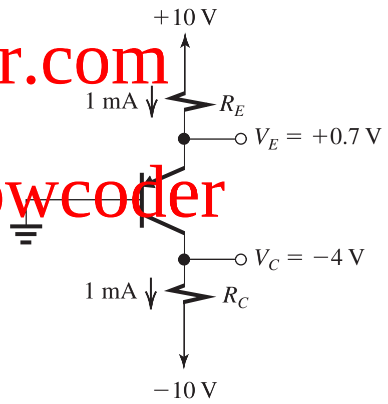
$I_C = 4.6$ mA

Thus,

$$R_C = \frac{V_C - (-10)}{I_C}$$

$$= \frac{+0.4 + 10}{4.6} = 2.26 \text{ k}\Omega$$

Ex: 6.26



For a 4-V reverse-biased voltage across the CBJ,

$V_C = -4$ V

Refer to the figure.

$$I_C = 1 \text{ mA} = \frac{V_C - (-10)}{R_C}$$

$$\Rightarrow R_C = \frac{-4 + 10}{1} = 6 \text{ k}\Omega$$

$$R_E = \frac{10 - V_E}{I_E}$$

Assuming $\alpha = 1$,

$$R_E = \frac{10 - 0.7}{1} = 9.3 \text{ k}\Omega$$

Ex: 6.27 Refer to the circuit in Fig. 6.27:

$$I_B = \frac{5 - 0.7}{100} = 0.043 \text{ mA}$$

To ensure that the transistor remains in the active mode for β in the range 50 to 150, we need to select R_C so that for the highest collector current possible, the BJT reaches the edge of saturation, that is, $V_{CE} = 0.3$ V. Thus,

$$V_{CE} = 0.3 = 10 - R_C I_{C\max}$$

where

$$I_{C\max} = \beta_{\max} I_B$$

$$= 150 \times 0.043 = 6.45 \text{ mA}$$

Thus,

$$R_C = \frac{10 - 0.3}{6.45} = 1.5 \text{ k}\Omega$$

For the lowest β,

$$I_C = \beta_{\min} I_B$$

$$= 50 \times 0.043 = 2.15 \text{ mA}$$

and the corresponding V_{CE} is

$$V_{CE} = 10 - R_C I_C = 10 - 1.5 \times 2.15$$

$$= 6.775 \text{ V}$$

Thus, V_{CE} will range from 0.3 V to 6.8 V.

Ex: 6.28 Refer to the solution of Example 6.10.

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + [R_{BB}/(\beta + 1)]}$$

$$= \frac{5 - 0.7}{3 + (33.3/51)} = 1.177 \text{ mA}$$

$$I_C = \alpha I_E = 0.98 \times 1.177 = 1.15 \text{ mA}$$

Thus the current is reduced by

$$\Delta I_C = 1.28 - 1.15 = 0.13 \text{ mA}$$

which is a -10% change.

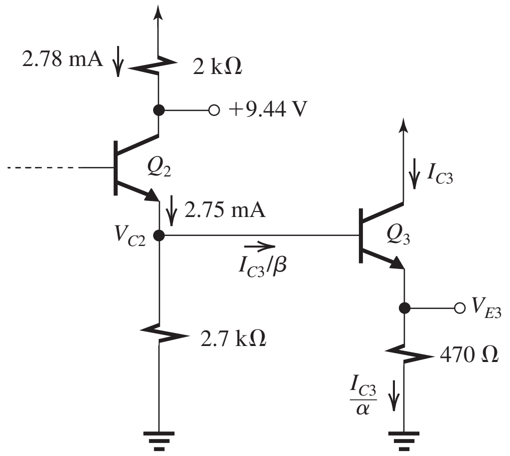
Ex: 6.29 Refer to the circuit in Fig. 6.30(b). The total current drawn from the power supply is

$$I = 0.103 + 1.252 + 2.78 = 4.135 \text{ mA}$$

Thus, the power dissipated in the circuit is

$$P = 15 \text{ V} \times 4.135 \text{ mA} = 62 \text{ mW}$$

Ex: 6.30



From the figure we see that

$$V_{E3} = \frac{I_{C3}}{\alpha} \times 0.47$$

$$V_{C2} = V_{E3} + 0.7 = \frac{I_{C3}}{\alpha} \times 0.47 + 0.7 \qquad (1)$$

A node equation at the collector of Q_2 yields

$$2.75 = \frac{V_{C2}}{2.7} + \frac{I_{C3}}{\beta}$$

Substituting for V_{C2} from Eq. (1), we obtain

$$2.75 = \frac{(0.47\, I_{C3}/\alpha) + 0.7}{2.7} + \frac{I_{C3}}{\beta}$$

Substituting $\alpha = 0.99$ and $\beta = 100$ and solving for I_{C3} results in

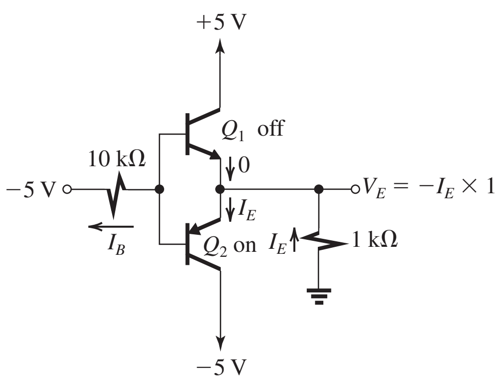
$$I_{C3} = 13.4 \text{ mA}$$

Now, V_{E3} and V_{C2} can be determined:

$$V_{E3} = \frac{I_{C3}}{\alpha} \times 0.47 = \frac{13.4}{0.99} \times 0.47 = +6.36 \text{ V}$$

$$V_{C2} = V_{E3} + 0.7 = +7.06 \text{ V}$$

Ex: 6.31



From the figure we see that Q_1 will be off and Q_2 will be on. Since the base of Q_2 will be at a voltage higher than -5 V, transistor Q_2 will be operating in the active mode. We can write a loop equation for the loop containing the 10-kΩ resistor, the EBJ of Q_2 and the 1-kΩ resistor:

$$-I_E \times 1 - 0.7 - I_B \times 10 = -5$$

Substituting $I_B = I_E/(\beta + 1) = I_E/101$ and rearranging gives

$$I_E = \frac{5 - 0.7}{\frac{10}{101} + 1} = 3.9 \text{ mA}$$

Thus,

$$V_E = -3.9 \text{ V}$$

$$V_{B2} = -4.6 \text{ V}$$

$$I_B = 0.039 \text{ mA}$$

Ex: 6.32 With the input at + 10 V, there is a strong possibility that the conducting transistor Q_1 will be saturated. Assuming this to be the case, the analysis steps will be as follows:

$$V_{CE\text{sat}}|_{Q_1} = 0.2 \text{ V}$$

$$V_E = 5 \text{ V} - V_{CE\text{sat}} = +4.8 \text{ V}$$

$$I_{E1} = \frac{4.8 \text{ V}}{1 \text{ k}\Omega} = 4.8 \text{ mA}$$

$$V_{B1} = V_E + V_{BE1} = 4.8 + 0.7 = +5.5 \text{ V}$$

$$I_{B1} = \frac{10 - 5.5}{10} = 0.45 \text{ mA}$$

$$I_{C1} = I_{E1} - I_{B1} = 4.8 - 0.45 = 4.35 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{4.35}{0.45} = 9.7$$

which is lower than $\beta_{\min}$, verifying that Q_1 is indeed saturated.

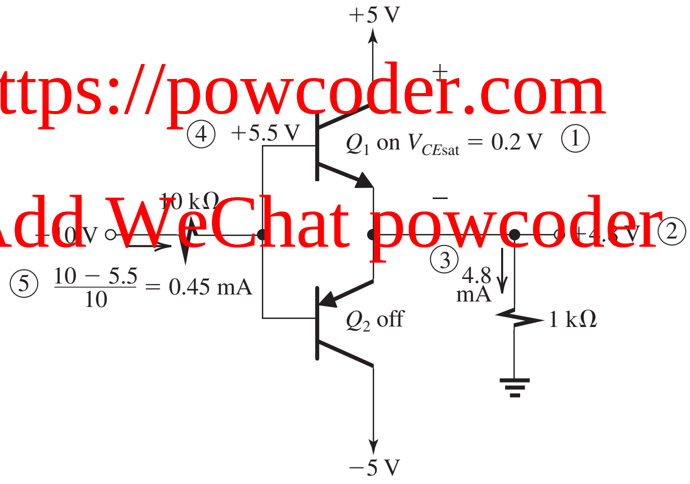
Finally, since Q_2 is off,

$$I_{C2} = 0$$

Ex: 6.33 $V_O = +10 - BV_{BCO} = 10 - 70$

$= -60$ V

This figure belongs to Exercise 6.32



6.1
1. Active
2. Saturation
3. Active
4. Saturation
5. Active
6. Cutoff

6.2 The EB junctions have a 4:1 area ratio.

$I_C = I_S e^{V_{BE}/V_T}$

$0.5 \times 10^{-3} = I_{S1} \times e^{0.75/0.025}$

$\Rightarrow I_{S1} = 4.7 \times 10^{-17}$ A

$I_{S2} = 4I_{S1} = 1.87 \times 10^{-16}$ A

6.3 $I_C = I_S e^{V_{BE}/V_T}$

$200 \times 10^{-6} = I_S e^{30}$

$\Rightarrow I_S = 1.87 \times 10^{-17}$ A

For the transistor that is 32 times larger,

$I_S = 32 \times 1.87 \times 10^{-17}$

$= 6 \times 10^{-16}$ A

At $V_{BE} = 30\ V_T$, the larger transistor conducts a current of

$I_C = 32 \times 200\ \mu\text{A} = 6.4$ mA

At $I_C = 1$ mA, the base–emitter voltage of the larger transistor can be found as

$1 \times 10^{-3} = 6 \times 10^{-16} e^{V_{BE}/V_T}$

$$V_{BE} = V_T \ln\left(\frac{1 \times 10^{-3}}{6 \times 10^{-16}}\right) = 0.704 \text{ V}$$

6.4 $$\frac{I_{S1}}{I_{S2}} = \frac{A_{E1}}{A_{E2}} = \frac{200 \times 200}{0.4 \times 0.4} = 250{,}000$$

$I_{C1} = I_{S1} e^{V_{BE1}/V_T}$

$I_{C2} = I_{S2} e^{V_{BE2}/V_T}$

For $I_{C1} = I_{C2}$ we have

$$e^{(V_{BE2} - V_{BE1})/V_T} = \frac{I_{S1}}{I_{S2}} = 250{,}000$$

$V_{BE2} - V_{BE1} = 0.025 \ln(250{,}000)$

$= 0.31$ V

6.5 $I_{C1} = 10^{-13} e^{700/25} = 0.145A = 145$ mA

$I_{C2} = 10^{-18} e^{700/25} = 1.45\ \mu$A

For the first transistor 1 to conduct a current of 1.45 μA, its V_{BE} must be

$$V_{BE1} = 0.025 \ln\left(\frac{1.45 \times 10^{-6}}{10^{-13}}\right)$$

$= 0.412$ V

6.6 Old technology:

$10^{-3} = 2 \times 10^{-15} e^{V_{BE}/V_T}$

$$V_{BE} = 0.025 \ln\left(\frac{10^{-3}}{2 \times 10^{-15}}\right) = 0.673 \text{ V}$$

New technology:

$10^{-3} = 2 \times 10^{-18} e^{V_{BE}/V_T}$

$$V_{BE} = 0.025 \ln\left(\frac{10^{-3}}{2 \times 10^{-18}}\right) = 0.846 \text{ V}$$

6.7 $5 \times 10^{-3} = I_S e^{0.76/0.025}$ (1)

$I_C = I_S e^{0.70/0.025}$ (2)

Dividing Eq. (2) by Eq. (1) yields

$I_C = 5 \times 10^{-3} e^{-0.06/0.025}$

$= 0.45$ mA

For $I_C = 5\ \mu$A,

$5 \times 10^{-6} = I_S e^{V_{BE}/0.025}$ (3)

Dividing Eq. (3) by Eq. (1) yields

$10^{-3} = e^{(V_{BE} - 0.76)/0.025}$

$V_{BE} = 0.76 + 0.025 \ln(10^{-3})$

$= 0.587$ V

6.8 $I_B = 10\ \mu$A

$I_C = 800\ \mu$A

$$\beta = \frac{I_C}{I_B} = 80$$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{80}{81} = 0.988$$

6.9

α	0.5	0.8	0.9	0.95	0.98	0.99	0.995	0.999
$\beta = \frac{\alpha}{1-\alpha}$	1	4	9	19	49	99	199	999

6.10

β	1	2	10	20	50	100	200	500	1000
$\alpha = \frac{\beta}{\beta+1}$	0.5	0.67	0.91	0.95	0.98	0.99	0.995	0.998	0.999

6.11 $$\beta = \frac{\alpha}{1 - \alpha} \quad (1)$$

$\alpha \to \alpha + \Delta\alpha$

$\beta \to \beta + \Delta\beta$

$$\beta + \Delta\beta = \frac{\alpha + \Delta\alpha}{1 - \alpha - \Delta\alpha} \quad (2)$$

Subtracting Eq. (1) from Eq. (2) gives

$$\Delta\beta = \frac{\alpha + \Delta\alpha}{1 - \alpha - \Delta\alpha} - \frac{\alpha}{1 - \alpha}$$

$$\Delta\beta = \frac{\Delta\alpha}{(1 - \alpha - \Delta\alpha)(1 - \alpha)} \qquad (3)$$

Dividing Eq. (3) by Eq. (1) gives

$$\frac{\Delta\beta}{\beta} = \left(\frac{\Delta\alpha}{\alpha}\right)\left(\frac{1}{1 - \alpha - \Delta\alpha}\right)$$

For $\Delta\alpha \ll 1$, the second factor on the right-hand side is approximately equal to β. Thus

$$\frac{\Delta\beta}{\beta} \simeq \beta\left(\frac{\Delta\alpha}{\alpha}\right) \qquad \text{Q.E.D.}$$

For $\dfrac{\Delta\beta}{\beta} = -10\%$ and $\beta = 100$,

$$\frac{\Delta\alpha}{\alpha} \simeq \frac{-10\%}{100} = -0.1\%$$

6.12 Transistor is operating in active region:

$\beta = 50 \rightarrow 300$

$I_B = 10\ \mu\text{A}$

$I_C = \beta I_B = 0.5\ \text{mA} \rightarrow 3\ \text{mA}$

$I_E = (\beta + 1)I_B = 0.51\ \text{mA} \rightarrow 3.01\ \text{mA}$

Maximum power dissipated in transistor is

$I_B \times 0.7\ \text{V} + I_C \times V_C$

$= 0.01 \times 0.7 + 3 \times 10 \simeq 30\ \text{mW}$

6.13 $i_C = I_S e^{v_{BE}/V_T}$

$= 5 \times 10^{-15} e^{0.7/0.025} = 7.2\ \text{mA}$

i_B will be in the range $\dfrac{7.2}{50}$ mA to $\dfrac{7.2}{200}$ mA, that is, 144 μA to 36 μA.

i_E will be in the range $(7.2 + 0.144)$ mA to $(7.2 + 0.036)$ mA, that is, 7.344 mA to 7.236 mA.

6.14 For $i_B = 10\ \mu\text{A}$,

$i_C = i_E - i_B = 1000 - 10 = 990\ \mu\text{A}$

$$\beta = \frac{i_C}{i_B} = \frac{990}{10} = 99$$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{99}{100} = 0.99$$

For $i_B = 20\ \mu\text{A}$,

$i_C = i_E - i_B = 1000 - 20 = 980\ \mu\text{A}$

$$\beta = \frac{i_C}{i_B} = \frac{980}{20} = 49$$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{49}{50} = 0.98$$

For $i_B = 50\ \mu\text{A}$,

$i_C = i_E - i_B = 1000 - 50 = 950\ \mu\text{A}$

$$\beta = \frac{i_C}{i_B} = \frac{950}{50} = 19$$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{19}{20} = 0.95$$

6.15 See Table below.

6.16 First we determine I_S, β, and α:

$1 \times 10^{-3} = I_S e^{700/25}$

$\Rightarrow I_S = 6.91 \times 10^{-16}\ \text{A}$

$$\beta = \frac{I_C}{I_B} = \frac{1\ \text{mA}}{10\ \mu\text{A}} = 100$$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{100}{101} = 0.99$$

Then we can determine I_{SE} and I_{SB}:

$$I_{SE} = \frac{I_S}{\alpha} = 6.98 \times 10^{-16}\ \text{A}$$

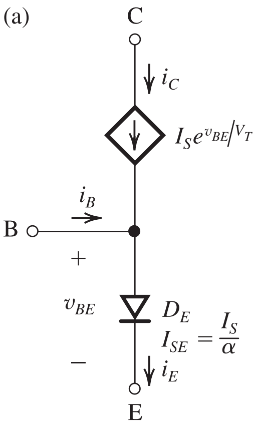
$$I_{SB} = \frac{I_S}{\beta} = 6.91 \times 10^{-18}\ \text{A}$$

The figure on next page shows the four large-signal models, corresponding to Fig. 6.5(a) to (d), together with their parameter values.

This table belongs to Problem **6.15**.

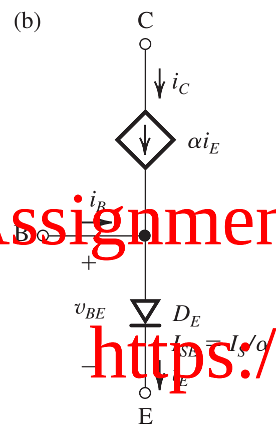
Transistor	**a**	**b**	**c**	**d**	**e**
V_{BE} (mV)	700	690	580	780	820
I_C (mA)	1.000	1.000	0.230	10.10	73.95
I_B (μA)	10	20	5	120	1050
I_E (mA)	1.010	1.020	0.235	10.22	75
α	0.99	0.98	0.979	0.988	0.986
β	100	50	46	84	70
I_S (A)	6.9×10^{-16}	1.0×10^{-15}	1.9×10^{-14}	2.8×10^{-16}	4.2×10^{-16}

(a)



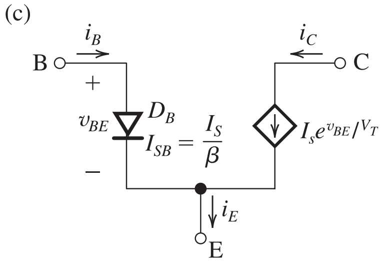
$I_S = 6.91 \times 10^{-16}$ A
$I_{SE} = 6.98 \times 10^{-16}$ A

(b)



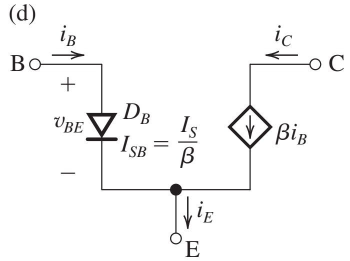
$\alpha = 0.99$
$I_{SE} = 6.98 \times 10^{-16}$ A

(c)



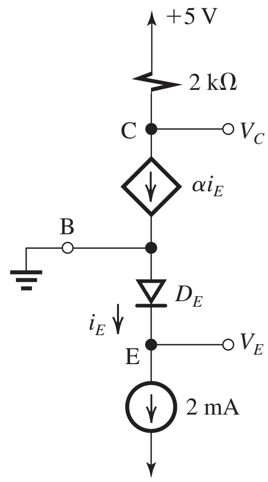
$I_S = 6.91 \times 10^{-16}$ A
$I_{SB} = 6.91 \times 10^{-18}$ A

(d)



$\beta = 100$
$I_{SB} = 6.91 \times 10^{-18}$ A

6.17



The figure shows the circuit, where

$$\alpha = \frac{\beta}{\beta + 1} = \frac{100}{101} = 0.99$$

$$I_{SE} = \frac{I_S}{\alpha} = \frac{5 \times 10^{-15}}{0.99} = 5.05 \times 100^{-15} \text{ A}$$

The voltage at the emitter V_E is

$$V_E = -V_{DE}$$

$$= -V_T \ln(I_E/I_{SE})$$

$$= -0.025 \ln\left(\frac{2 \times 10^{-3}}{5.05 \times 10^{-15}}\right)$$

$$= -0.668 \text{ V}$$

The voltage at the collector V_C is found from

$$V_C = 5 - I_C \times 2$$

$$= 5 - \alpha I_E \times 2$$

$$= 5 - 0.99 \times 2 \times 2 = 1.04 \text{ V}$$

6.18 Refer to the circuit in Fig. 6.6(b).

$$I_{SB} = \frac{I_S}{\beta} = \frac{5 \times 10^{-15}}{50} = 10^{-16} \text{ A}$$

$$I_B = \frac{I_C}{\beta} = \frac{0.5 \times 10^{-3}}{50} = 10^{-5} \text{ A}$$

$$V_B = V_{BE} = V_T \ln\left(\frac{I_B}{I_{SB}}\right)$$

$$= 0.025 \ln\left(\frac{10^{-5}}{10^{-16}}\right)$$

$$= 0.633 \text{ V}$$

We can determine R_B from

$$R_B = \frac{V_{CC} - V_B}{I_B}$$

$$= \frac{15 - 0.633}{10^{-5}} = 1.44 \text{ M}\Omega$$

To obtain $V_{CE} = 1$ V, we select R_C according to

$$R_C = \frac{V_{CC} - V_{CE}}{I_C}$$

$$= \frac{15 - 1}{0.5} = 28 \text{ k}\Omega$$

6.19 $I_S = 10^{-15}$ A

Thus, a forward-biased EBJ conducting a current of 1 mA will have a forward voltage drop V_{BE}:

$$V_{BE} = V_T \ln\left(\frac{I}{I_S}\right)$$

$$= 0.025 \ln\left(\frac{10^{-3}}{10^{-15}}\right) = 0.691 \text{ V}$$

$$I_{SC} = 100 I_S = 10^{-13} \text{ A}$$

Thus, a forward-biased CBJ conducting a 1-mA current will have a forward voltage drop V_{BC}:

$$V_{BC} = V_T \ln\left(\frac{1 \times 10^{-3}}{1 \times 10^{-13}}\right) = 0.576 \text{ V}$$

When forward-biased with 0.5 V the emitter–base junction conducts

$$I = I_S e^{0.5/0.025}$$

$$= 10^{-15} e^{0.5/0.025} = 0.49 \ \mu\text{A}$$

and the CBJ conducts

$$I = I_{SC} e^{0.5/0.025}$$

$$= 10^{-13} e^{0.5/0.025} = 48.5 \ \mu\text{A}$$

6.20 The equations utilized are

$$v_{BC} = v_{BE} - v_{CE} = 0.7 - v_{CE}$$

$$i_{BC} = I_{SC} e^{v_{BC}/V_T} = 10^{-13} e^{v_{BC}/0.025}$$

$$i_{BE} = I_{SB} e^{v_{BE}/V_T} = 10^{-17} e^{0.7/0.025}$$

$$i_B = i_{BC} + i_{BE}$$

$$i_C = I_S e^{v_{BE}/V_T} - i_{BC} = 10^{-15} e^{0.7/0.025} - i_{BC}$$

Performing these calculations for $v_{CE} = 0.4$ V, 0.3 V, and 0.2 V, we obtain the results shown in the table below.

6.21 Dividing Eq. (6.14) by Eq. (6.15) and substituting $i_C/i_B = \beta_{\text{forced}}$ gives

$$\beta_{\text{forced}} = \frac{I_S e^{v_{BE}/V_T} - I_{SC} e^{v_{BC}/V_T}}{(I_S/\beta) e^{v_{BE}/V_T} + I_{SC} e^{v_{BC}/V_T}}$$

Dividing the numerator and denominator of the right-hand side by $I_{SC} e^{v_{BC}/V_T}$ and replacing $v_{BE} - v_{BC}$ by $V_{CE\text{sat}}$ gives

$$\beta_{\text{forced}} = \frac{\left(\frac{I_S}{I_{SC}}\right) e^{V_{CE\text{sat}}/V_T} - 1}{\frac{1}{\beta}\left(\frac{I_S}{I_{SC}}\right) e^{V_{CE\text{sat}}/V_T} + 1}$$

This equation can be used to obtain $e^{V_{CE\text{sat}}/V_T}$ and hence $V_{CE\text{sat}}$ as

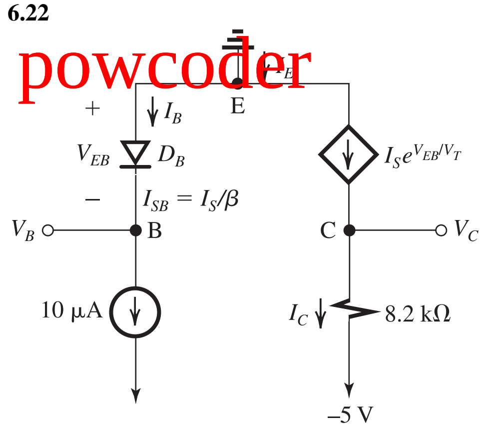
$$\left(\frac{I_S}{I_{SC}}\right) e^{V_{CE\text{sat}}/V_T} = \frac{1 + \beta_{\text{forced}}}{1 - \beta_{\text{forced}}/\beta}$$

$$\Rightarrow V_{CE\text{sat}} = V_T \ln\left[\frac{I_{SC}}{I_S} \frac{1 + \beta_{\text{forced}}}{1 - \beta_{\text{forced}}/\beta}\right] \qquad \text{Q.E.D.}$$

For $\beta = 100$ and $I_{SC}/I_S = 100$, we can use this equation to obtain $V_{CE\text{sat}}$ corresponding to the given values of β_{forced}. The results are as follows:

β_{forced}	50	10	5	1
$V_{CE\text{sat}}$ (V)	0.231	0.178	0.161	0.133

6.22



The emitter–base voltage V_{EB} is found as the voltage drop across the diode D_B, whose scale

This table belongs to Problem **6.20**.

v_{CE} (V)	v_{BC} (V)	i_{BC} (μA)	i_{BE} (μA)	i_B (μA)	i_C (mA)	i_C/i_B
0.4	0.3	0.016	14.46	14.48	1.446	100
0.3	0.4	0.89	14.46	15.35	1.445	94
0.2	0.5	48.5	14.46	62.96	1.398	29

current is $I_{SB} = I_S/\beta$, it is conducting a 10-μA current. Thus,

$$V_{EB} = V_T \ln\left(\frac{10\ \mu\text{A}}{I_{SB}}\right)$$

where

$$I_{SB} = \frac{I_S}{\beta} = \frac{10^{-14}}{50} = 2 \times 10^{-16}\ \text{A}$$

$$V_{EB} = 0.025 \ln\left(\frac{10 \times 10^{-6}}{2 \times 10^{-16}}\right)$$

$$= 0.616\ \text{V}$$

Thus,

$$V_B = -V_{EB} = -0.616\ \text{V}$$

The collector current can be found as

$$I_C = \beta I_B$$

$$= 50 \times 10 = 500\ \mu\text{A} = 0.5\ \text{mA}$$

The collector voltage can now be obtained from

$$V_C = -5 + I_C \times 8.2 = -5 + 0.5 \times 8.2 = -0.9\ \text{V}$$

The emitter current can be found as

$$I_E = I_B + I_C = 10 + 500 = 510\ \mu\text{A}$$

$$= 0.51\ \text{mA}$$

6.23 At $i_C = 1$ mA, $v_{EB} = 0.7$ V

At $i_C = 10$ mA,

$$v_{EB} = 0.7 + V_T \ln\left(\frac{10}{1}\right)$$

$$= 0.7 + 0.025 \ln(10) = 0.758\ \text{V}$$

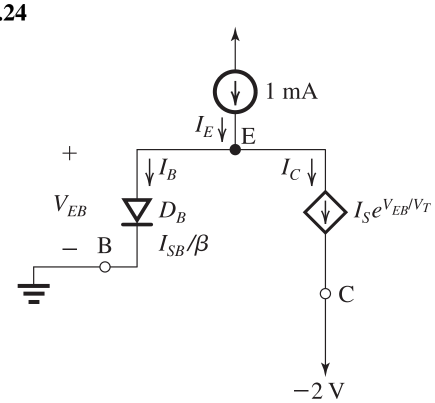
At $i_C = 100$ mA,

$$v_{EB} = 0.7 + 0.025 \ln\left(\frac{100}{1}\right)$$

$$= 0.815\ \text{V}$$

Note that v_{EB} increases by about 60 mV for every decade increase in i_C.

6.24



Referring to the figure, we see that

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

Thus,

$$I_C = \frac{I_E}{1 + \frac{1}{\beta}} = \frac{1}{1 + \frac{1}{10}} = 0.909\ \text{mA}$$

$$I_B = 0.091\ \text{mA}$$

For direction of flow, refer to the figure.

$$V_{EB} = V_T \ln\left(\frac{I_B}{I_{SB}}\right)$$

where

$$I_{SB} = \frac{I_S}{\beta} = \frac{10^{-15}}{10} = 10^{-16}\ \text{A}$$

$$V_{EB} = 0.025 \ln\left(\frac{0.091 \times 10^{-3}}{10^{-16}}\right)$$

$$= 0.688\ \text{V}$$

Thus,

$$V_E = V_B + V_{EB} = 0 + 0.688 = 0.688\ \text{V}$$

If a transistor with $\beta = 1000$ is substituted,

$$I_C = \frac{I_E}{1 + \frac{1}{\beta}} = \frac{1}{1 + \frac{1}{1000}} = 0.999\ \text{mA}$$

Thus, I_C changes by $0.999 - 0.909 = 0.09$ mA, a 9.9% increase.

6.25

$$I_B = \frac{I_E}{\beta + 1} = \frac{5}{20 + 1} = 0.238\ \text{A} = 238\ \text{mA}$$

$$I_C = I_S e^{V_{EB}/V_T}$$

$$\alpha I_E = I_S e^{V_{EB}/V_T}$$

where

$$\alpha = \frac{20}{21} = 0.95$$

$$I_S = \alpha I_E e^{-V_{EB}/V_T}$$

$$= 0.95 \times 5 e^{-(0.8/0.025)}$$

$$= 6 \times 10^{-14}\ \text{A}$$

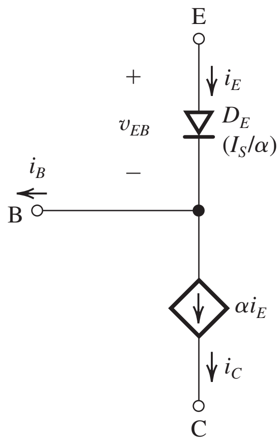
A transistor that conducts $I_C = 1$ mA with $V_{EB} = 0.70$ V has a scale current

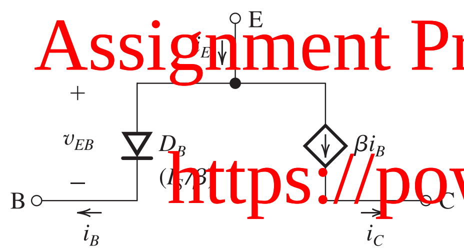
$$I_S = 1 \times 10^{-3} e^{-0.70/0.025} = 6.9 \times 10^{-16}\ \text{A}$$

The emitter–base junction areas of these two transistors will have the same ratio as that of their scale currents, thus

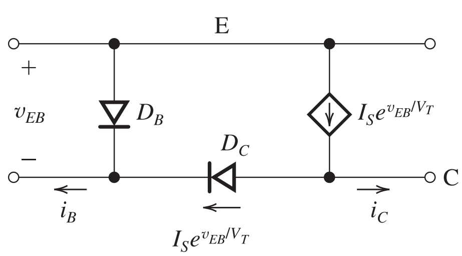
$$\frac{\text{EBJ area of first transistor}}{\text{EBJ area of second transistor}} = \frac{6 \times 10^{-14}}{6.9 \times 10^{-16}} = 87$$

6.26 The two missing large-signal equivalent circuits for the *pnp* transistor are those corresponding to the *npn* equivalent circuits in Fig. 6.5(b) and 6.5(d). They are shown in the figure.





6.27



6.28 (a) Refer to Fig. P6.28(a).

$$I_1 = \frac{10.7 - 0.7}{5\ \text{k}\Omega} = 2\ \text{mA}$$

Assuming operation in the active mode,

$$I_C = \alpha I_1 \simeq I_1 = 2\ \text{mA}$$

$$V_2 = -10.7 + I_C \times 5$$

$$= -10.7 + 2 \times 5 = -0.7\ \text{V}$$

Since V_2 is lower than V_B, which is 0 V, the transistor is operating in the active mode, as assumed.

(b) Refer to Fig. P6.28(b).

Since $V_C = -4$ V is lower than $V_B = -2.7$ V, the transistor is operating in the active mode.

$$I_C = \frac{-4 - (-10)}{2.4\ \text{k}\Omega} = 2.5\ \text{mA}$$

$$I_E = \frac{I_C}{\alpha} \simeq I_C = 2.5\ \text{mA}$$

$$V_3 = +12 - I_E \times 5.6 = 12 - 2.5 \times 5.6 = -2\ \text{V}$$

(c) Refer to Fig. P6.28(c) and use

$$I_C = \frac{0 - (-10)}{20} = 0.5\ \text{mA}$$

Assuming active-mode operation, and utilizing the fact that β is large, $I_B \simeq 0$ and

$$V_4 \simeq 2\ \text{V}$$

Since $V_C < V_B$, the transistor is indeed operating in the active region.

$$I_5 = I_E = \frac{I_C}{\alpha} \simeq I_C = 0.5\ \text{mA}$$

(d) Refer to Fig. P6.28(d). Since the collector is connected to the base with a 10-kΩ resistor and β is assumed to be very high, the voltage drop across the 10-kΩ resistor will be close to zero and the base voltage will be equal to that of the collector:

$$V_B = V_7$$

This also implies active-mode operation. Now,

$$V_E = V_B - 0.7$$

Thus,

$$V_E = V_7 - 0.7$$

$$I_6 = \frac{V_E - (-10)}{3}$$

$$= \frac{V_7 - 0.7 + 10}{3} = \frac{V_7 + 9.3}{3} \qquad (1)$$

Since $I_B = 0$, the collector current will be equal to the current through the 9.1-kΩ resistor,

$$I_C = \frac{+10 - V_7}{9.1} \qquad (2)$$

Since $\alpha 1 \simeq 1$, $I_C = I_E = I_6$ resulting in

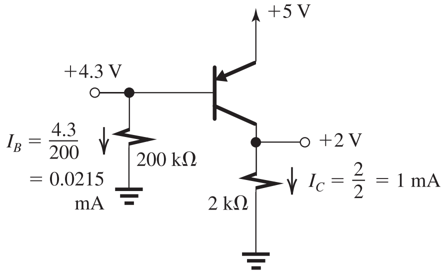
$$\frac{10 - V_7}{9.1} = \frac{V_7 + 9.3}{3}$$

$$\Rightarrow V_7 = -4.5\ \text{V}$$

and

$$I_6 = \frac{V_7 + 9.3}{3} = \frac{-4.5 + 9.3}{3} = 1.6\ \text{mA}$$

6.29 (a)



(a)

Since V_C is lower than V_B, the transistor is operating in the active region. From the figure corresponding to Fig. P6.29(a), we see that

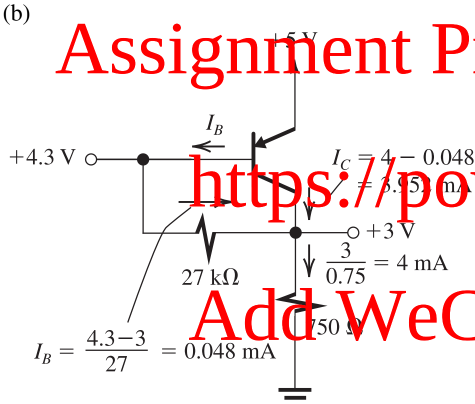
$I_C = 1$ mA

$I_B = 0.0215$ mA

Thus,

$$\beta \equiv \frac{I_C}{I_B} = \frac{1}{0.0215} = 46.5$$

(b)

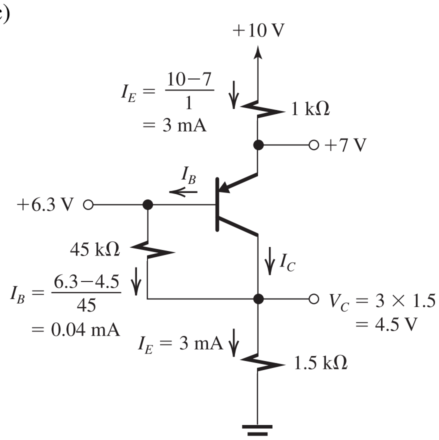


(b)

Observe that with V_C at 3 V and V_B at 4.3 V, the transistor is operating in the active region. Refer to the analysis shown in the figure, which leads to

$$\beta \equiv \frac{I_C}{I_B} = \frac{3.952}{0.048} = 82.3$$

(c)



(c)

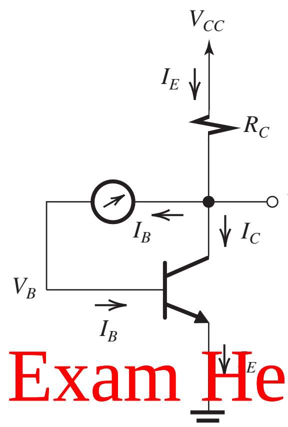
Observe that the transistor is operating in the active region and note the analysis performed on the circuit diagram. Thus,

$I_C = I_E - I_B = 3 - 0.04 = 2.96$ mA

and

$$\beta \equiv \frac{I_C}{I_B} = \frac{2.96}{0.04} = 74$$

6.30



Since the meter resistance is small, $V_C \simeq V_B$ and the transistor is operating in the active region. To obtain $I_E = 1$ mA, we arrange that $V_{BE} = 0.7$ V. Since $V_C \simeq V_B$, V_C must be set to 0.7 by selecting R_C according to

$$V_C = 0.7 = V_{CC} - I_E R_C$$

Thus,

$$0.7 = 9 - 1 \times R_C$$

$$\Rightarrow R_C = 8.3 \text{ k}\Omega$$

Since the meter reads full scale when the current flowing through it (in this case, I_B is 50 μA), a full-scale reading corresponds to

$$\beta \equiv \frac{I_C}{I_B} \simeq \frac{1 \text{ mA}}{50\ \mu\text{A}} = 20$$

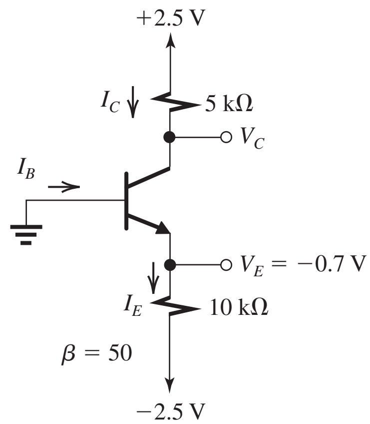
If the meter reads 1/5 of full scale, then $I_B = 10$ μA and

$$\beta = \frac{1 \text{ mA}}{10\ \mu\text{A}} = 100$$

A meter reading of 1/10 full scale indicates that

$$\beta = \frac{1 \text{ mA}}{5\ \mu\text{A}} = 200$$

6.31



$$I_E = \frac{V_E - (-2.5)}{10}$$

$$= \frac{-0.7 + 2.5}{10} = 0.18 \text{ mA}$$

Assuming the transistor is operating in the active mode, we obtain

$$I_B = \frac{I_E}{\beta + 1} = \frac{0.18}{50 + 1} = 3.5 \ \mu\text{A}$$

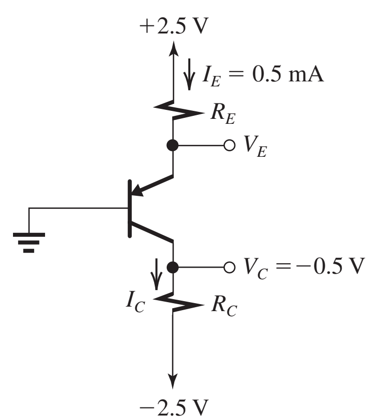
$$I_C = \left(\frac{\beta}{\beta + 1}\right) I_E = \frac{50}{51} \times 0.18 = 0.176 \text{ mA}$$

$$V_C = +2.5 - I_C R_C$$

$$= 2.5 - 0.176 \times 5 = 1.62 \text{ V}$$

Since $V_C > V_B$, active-mode operation is verified.

6.32



From the figure we see that $V_C = -0.5$ V is lower than the base voltage ($V_B = 0$ V); thus the transistor will be operating in the active mode.

$$I_C = \alpha I_E = \left(\frac{\beta}{\beta + 1}\right) I_E = \frac{100}{100 + 1} \times 0.5$$

$$= 0.495 \text{ mA}$$

$$R_C = \frac{V_C - (-2.5)}{I_C}$$

$$= \frac{-0.5 + 2.5}{0.495} = 4.04 \text{ k}\Omega \simeq 4 \text{ k}\Omega$$

The transistor V_{EB} can be found from

$$V_{EB} = 0.64 + V_T \ln\left(\frac{0.5 \text{ mA}}{0.1 \text{ mA}}\right)$$

$$= 0.68 \text{ V}$$

Thus,

$$V_E = +0.68 \text{ V}$$

and

$$R_E = \frac{2.5 - 0.68}{0.5} = 3.64 \text{ k}\Omega$$

The maximum allowable value for R_C while the transistor remains in the active mode corresponds to $V_C = +0.4$ V. Thus,

$$R_{C\max} = \frac{0.4 - (-2.5)}{0.495} = 5.86 \text{ k}\Omega$$

6.33 Refer to Fig. 6.15(a) with $R_C = 5.1$ kΩ and $R_E = 6.8$ kΩ. Assuming $V_{BE} \simeq 0.7$ V, then $V_E = -0.7$ V, and

$$I_E = \frac{-0.7 - (-15)}{6.8} = 2.1 \text{ mA}$$

$$I_C = \alpha I_E \simeq 2.1 \text{ mA}$$

$$V_C = 15 - 2.1 \times 5.1 \simeq 4.3 \text{ V}$$

6.34 Refer to the circuit in Fig. P6.34. Since $V_C = 0.5$ V is greater than V_B, the transistor will be operating in the active mode. The transistor V_{BE} can be found from

$$V_{BE} = 0.8 + 0.025 \ln\left(\frac{0.2 \text{ mA}}{1 \text{ mA}}\right)$$

$$= 0.76 \text{ V}$$

Thus,

$$V_E = -0.76 \text{ V}$$

$$I_E = \frac{I_C}{\alpha} = I_C \left(\frac{\beta + 1}{\beta}\right) = 0.2 \times \frac{101}{100}$$

$$= 0.202 \text{ mA}$$

The required value of R_E can be found from

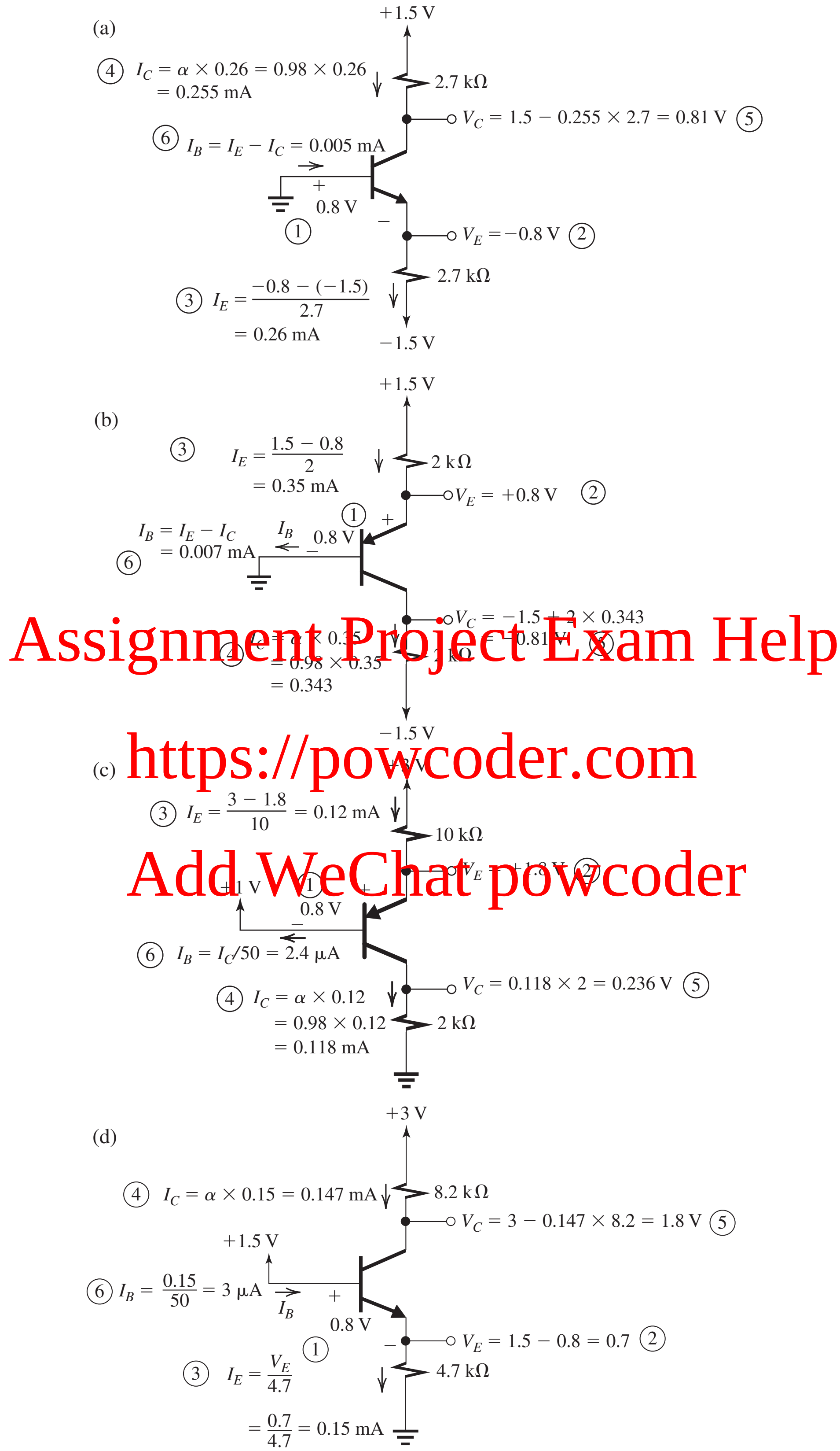
$$R_E = \frac{V_E - (-1.5)}{I_E}$$

$$R_E = \frac{-0.76 + 1.5}{0.202} = 3.66 \text{ k}\Omega$$

To establish $V_C = 0.5$ V, we select R_C according to

$$R_C = \frac{1.5 - 0.5}{0.2} = 5 \text{ k}\Omega$$

6.35

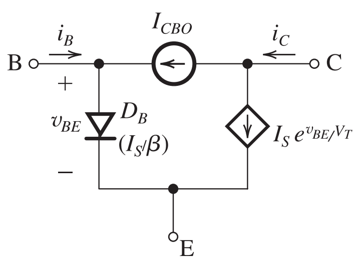


In all circuits shown in Fig. P6.35, we assume active-mode operation and verify that this is the case at the end of the solution. The solutions are indicated on the corresponding circuit diagrams; the order of the steps is shown by the circled numbers.

6.36 I_{CBO} approximately doubles for every 10°C rise in temperature. A change in temperature from 25°C to 125°C—that is, an increase of 100°C—results in 10 doublings or, equivalently, an increase by a factor of $2^{10} = 1024$. Thus I_{CBO} becomes

$$I_{CBO} = 10 \text{ nA} \times 1024 = 10.24 \ \mu\text{A}$$

6.37



From the figure we can write

$$I_B = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T} - I_{CBO} \quad (1)$$

$$I_C = I_S e^{v_{BE}/V_T} + I_{CBO} \quad (2)$$

$$I_E = I_S\left(1 + \frac{1}{\beta}\right) e^{v_{BE}/V_T} \quad (3)$$

When the base is left open-circuited, $i_B = 0$ and Eq. (1) yields

$$I_{CBO} = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

or equivalently,

$$I_S e^{v_{BE}/V_T} = \beta I_{CBO} \quad (4)$$

Substituting for $I_S e^{v_{BE}/V_T}$ in Eqs. (2) and (3) gives

$$i_C = i_E = (\beta + 1) I_{CBO}$$

6.38 Since the BJT is operating at a constant emitter current, its $|V_{BE}|$ decreases by 2 mV for every °C rise in temperature. Thus,

$|V_{BE}|$ at 0°C $= 0.7 + 0.002 \times 25 = 0.75$ V

$|V_{BE}|$ at 100°C $= 0.7 - 0.002 \times 75 = 0.55$ V

6.39 (a) If the junction temperature rises to 50°C, which is an increase of 30°C, the EB voltage decreases to

$$v_{EB} = 692 - 2 \times 30 = 632 \text{ mV}$$

(b) First, we evaluate V_T at 20°C and at 50°C:

$$V_T = \frac{kT}{q}$$

where $k = 8.62 \times 10^{-5}$ eV/K.

Thus,

At 20°C, $T = 293$ K and $V_T = 8.62 \times 10^{-5} \times 293 = 25.3$ mV

At 50°C, $T = 323$ K and $V_T = 8.62 \times 10^{-5} \times 323 = 27.8$ mV

If the transistor is operated at $v_{BE} = 700$ mV, then

(i) At 20°C, i_E becomes

$$i_E = 0.5e^{(700-692)/25.3} = 0.69 \text{ mA}$$

(ii) At 50°C, i_E becomes

$$i_E = 0.5e^{(700-632)/27.8} = 5.77 \text{ mA}$$

6.40 $v_{BE} = 0.7$ V at $i_C = 10$ mA

For $v_{BE} = 0.5$ V,

$$i_C = 10e^{(0.5-0.7)/0.025} = 3.35 \ \mu\text{A}$$

At a current I_C and a BE voltage V_{BE}, the slope of the i_C–v_{BE} curve is I_C/V_T. Thus

$$\text{Slope at } V_{BE} \text{ of 700 mV} = \frac{10 \text{ mA}}{25 \text{ mV}} = 400 \text{ mA/V}$$

$$\text{Slope at } V_{BE} \text{ of 500 mV} = \frac{3.35 \ \mu\text{A}}{25 \text{ mV}} = 0.134 \text{ mA/V}$$

$$\text{Ratio of slopes} = \frac{400}{0.134} \simeq 3000$$

6.41 Use Eq. (6.18):

$$i_C = I_S e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

with $I_S = 10^{-15}$ A and $V_A = 100$ V, to get

$$i_C = 10^{-15} e^{v_{BE}/0.025}\left(1 + \frac{v_{CE}}{100}\right)$$

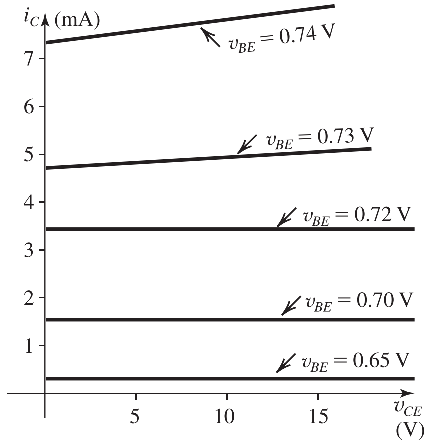
v_{BE}	0.65 V	0.70 V	0.72 V	0.73 V	0.74 V
v_{CE} (V)	i_C (mA)	i_C (mA)	i_C (mA)	i_C (mA)	i_C (mA)
0	0.196	1.45	3.21	4.81	7.16
15	0.225	1.67	3.70	5.52	8.24

To find the intercept of the straight-line characteristics on the i_c axis, we substitute $v_{CE} = 0$ and evaluate

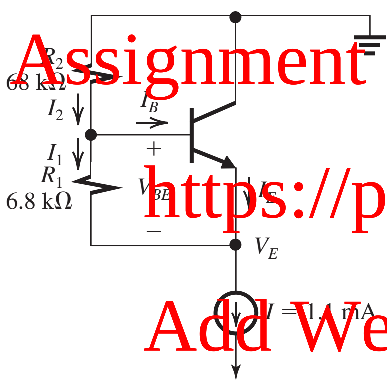
$$i_C = 10^{-15} e^{v_{BE}/V_T} \text{ A}$$

for the given value of v_{BE}. The slope of each straight line is equal to this value divided by 100 V (V_A). Thus we obtain

v_{BE} (V)	0.65	0.70	0.72	0.73	0.74
Intercept (mA)	0.2	1.45	3.22	4.80	7.16
Slope (mA/V)	0.002	0.015	0.032	0.048	0.072



6.42



At 25°C, assume $I_E = 1$ mA. Thus,

$$V_{BE} = 0.68 \text{ V}$$

$$I_1 = \frac{V_{BE}}{R_1} = \frac{0.68 \text{ V}}{6.8 \text{ k}\Omega} = 0.1 \text{ mA}$$

$$I_E = I - I_1 = 1.1 - 0.1 = 1 \text{ mA}$$

which is the value assumed.

$$I_2 = I_1 + I_B = I_1 + \frac{I_E}{\beta + 1}$$

$$= 0.1 + \frac{1}{101} = 0.11 \text{ mA}$$

Note that the currents in R_1 and R_2 differ only by the small base current, 0.01 mA. Had I_1 and I_2 been equal, then we would have had

$$I_1 R_1 = V_{BE}$$

$$I_2 R_2 \simeq I_1 R_2 = V_{BE} \frac{R_2}{R_1}$$

$$V_E = -(I_1 R_1 + I_2 R_2)$$

$$= -V_{BE}\left(1 + \frac{R_2}{R_1}\right) \qquad (1)$$

$$= -V_{BE}\left(1 + \frac{6.8}{0.68}\right) = -11\ V_{BE} = -7.48 \text{ V}$$

which gives this circuit the name "V_{BE} multiplier." A more accurate value of V_E can be obtained by taking I_B into account:

$$V_E = -(I_1 R_1 + I_2 R_2)$$

$$= -\left(V_{BE} + \frac{R_2}{R_1} V_{BE} + I_B R_2\right)$$

$$= -\left(1 + \frac{R_2}{R_1}\right) V_{BE} - I_B R_2 \qquad (2)$$

$$= -7.48 - 0.01 \times 68 = -8.16 \text{ V}$$

As temperature increases, an approximate estimate for the temperature coefficient of V_E can be obtained by assuming that I_E remains constant and ignoring the temperature variation of β. Thus, we would be neglecting the temperature change of the $(I_B R_2)$ terms in Eq. (2). From Eq. (2) we can obtain the temperature coefficient of V_E by utilizing the fact the V_{BE} changes by – 2.2 mV/°C. Thus,

Temperature coefficient of V_E

$$= -\left(1 + \frac{R_2}{R_1}\right) \times -2.2$$

$$= -11 \times -2.2 = +24.2 \text{ mV/°C}$$

At 75°C, which is a temperature increase of 50°C,

$$V_E = -8.16 + 24.2 \times 50 = -6.95 \text{ V}$$

As a check on our assumption of constant I_E, let us find the value of I_E at 75°C:

$$I_1(75°\text{C}) = \frac{V_{BE}(75°\text{C})}{R_1}$$

$$= \frac{0.68 - 2.2 \times 10^{-3} \times 50}{6.8}$$

$$= 0.084 \text{ mA}$$

$$I_E(75°\text{C}) = I - I_1(75°\text{C})$$

$$= 1.1 - 0.084 = 1.016 \text{ mA}$$

which is reasonably close to the assumed value of 1 mA.

6.43 $r_o = 1/\text{slope}$

$$= 1/(0.8 \times 10^{-5})$$

$$= 125 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_C}$$

$$125 \text{ k}\Omega = \frac{V_A}{1 \text{ mA}} \Rightarrow V_A = 125 \text{ V}$$

At $I_C = 10$ mA,

$$r_o = \frac{V_A}{I_C} = \frac{125 \text{ V}}{10 \text{ mA}} = 12.5 \text{ k}\Omega$$

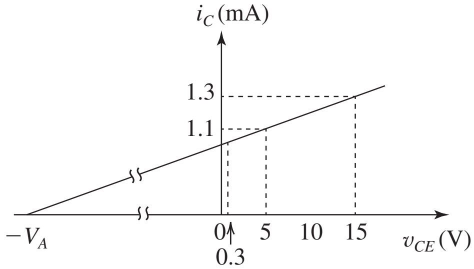
6.44 $r_o = \dfrac{V_A}{I_C} = \dfrac{50\text{ V}}{I_C}$

Thus,

At $I_C = 1$ mA, $\quad r_o = \dfrac{50\text{ V}}{1\text{ mA}} = 50\text{ k}\Omega$

At $I_C = 100\ \mu\text{A}$, $\quad r_o = \dfrac{50\text{ V}}{0.1\text{ mA}} = 500\text{ k}\Omega$

6.45



Slope of i_C–v_{CE} line corresponding to $v_{BE} = 710$ mV is

$$\text{Slope} = \frac{1.3 - 1.1}{15 - 5} = \frac{0.2\text{ mA}}{10\text{ V}} = 0.02\text{ mA/V}$$

Near saturation, $V_{CE} = 0.3$ V, thus

$$i_C = 1.1 - 0.02 \times (5 - 0.3)$$

$$= 1.006 \simeq 1\text{ mA}$$

i_C will be 1.2 mA at

$$v_{CE} = 5 + \frac{1.2 - 1.1}{0.02} = 10\text{ V}$$

The intercept of the i_C–v_{CE} straight line on the i_C axis will be at

$$i_C = 1.1 - 5 \times 0.02 = 1\text{ mA}$$

Thus, the Early voltage is obtained as

$$\text{Slope} = \frac{i_C(\text{at } v_{CE} = 0)}{V_A}$$

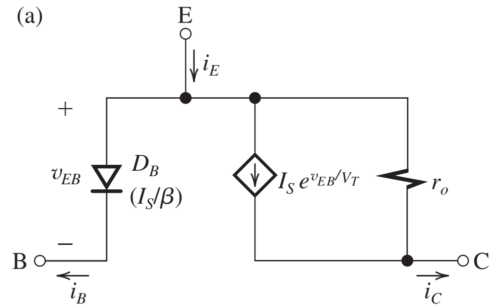
$$\Rightarrow V_A = \frac{1}{0.02} = 50\text{ V}$$

$$r_o = \frac{V_A}{I_C} = \frac{50\text{ V}}{1\text{ mA}} = 50\text{ k}\Omega$$

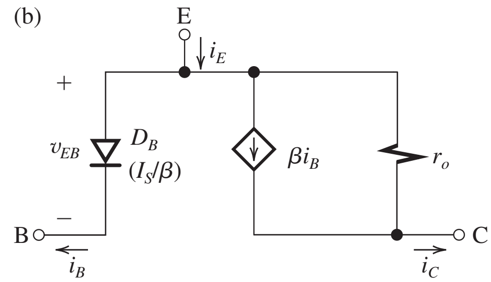
which is the inverse of the slope of the i_C–v_{CE} line.

6.46 The equivalent circuits shown in the figure correspond to the circuits in Fig. 6.19.

(a)



(b)



6.47 $\beta = \dfrac{i_C}{i_B} = \dfrac{1\text{ mA}}{10\ \mu\text{A}} = 100$

$$\beta_{ac} = \left.\frac{\Delta i_C}{\Delta i_B}\right|_{v_{\text{CE}}\text{ constant}} = \frac{0.08\text{ mA}}{1.0\ \mu\text{A}} = 80$$

$$\Delta i_C = \Delta i_B \times \beta_{ac} + \frac{\Delta v_{CE}}{r_o}$$

where

$$r_o = \frac{V_A}{I_C} = \frac{100}{1} = 100\text{ k}\Omega$$

Thus,

$$\Delta i_C = 2 \times 80 + \frac{2}{100} \times 10^3 = 180\ \mu\text{A}$$

$$= 0.18\text{ mA}$$

6.48 Refer to the circuit in Fig. P6.48.

(a) For active-mode operation with $V_C = 2$ V:

$$I_C = \frac{V_{CC} - V_C}{R_C} = \frac{10 - 2}{1} = 8\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{8}{50} = 0.16\text{ mA}$$

$$V_{BB} = I_B R_B + V_{BE}$$

$$= 0.16 \times 10 + 0.7 = 2.3\text{ V}$$

(b) For operation at the edge of saturation:

$$V_{CE} = 0.3\text{ V}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10 - 0.3}{1} = 9.7\text{ mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{9.7}{50} = 0.194 \text{ mA}$$

$$V_{BB} = I_B R_B + V_{BE}$$

$$= 0.194 \times 10 + 0.7 = 2.64 \text{ V}$$

(c) For operation deep in saturation with $\beta_{\text{forced}} = 10$:

$$V_{CE} = 0.2 \text{ V}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10 - 0.2}{1} = 9.8 \text{ mA}$$

$$I_B = \frac{I_C}{\beta_{\text{forced}}} = \frac{9.8}{10} = 0.98 \text{ mA}$$

$$V_{BB} = I_B R_B + V_{BE}$$

$$= 0.98 \times 10 + 0.7 = 10.5 \text{ V}$$

6.49 Refer to the circuit in Fig. P6.48 (with $V_{BB} = V_{CC}$) and to the BJT equivalent circuit of Fig. 6.21.

$$I_C = \frac{V_{CC} - 0.2}{R_C}$$

$$I_B = \frac{V_{CC} - 0.7}{R_B}$$

$$\beta_{\text{forced}} \equiv \frac{I_C}{I_B}$$

Thus,

$$\beta_{\text{forced}} = \left(\frac{V_{CC} - 0.2}{V_{CC} - 0.7}\right)\left(\frac{R_B}{R_C}\right) \qquad (1)$$

$$P_{\text{dissipated}} = V_{CC}(I_C + I_B)$$

$$= V_{CC}(\beta_{\text{forced}} I_B + I_B)$$

$$= (\beta_{\text{forced}} + 1)V_{CC} I_B \qquad (2)$$

For $V_{CC} = 5$ V and $\beta_{\text{forced}} = 10$ and $P_{\text{dissipated}} \leq 20$ mW, we can proceed as follows.

Using Eq. (1) we can determine (R_B/R_C):

$$10 = \left(\frac{5 - 0.2}{5 - 0.7}\right)\left(\frac{R_B}{R_C}\right)$$

$$\Rightarrow \frac{R_B}{R_C} = 8.96 \qquad (3)$$

Using Eq. (2), we can find I_B:

$$(10 + 1) \times 5 \times I_B \leq 20 \text{ mW}$$

$$\Rightarrow I_B \leq 0.36 \text{ mA}$$

Thus,

$$\frac{V_{CC} - 0.7}{R_B} \leq 0.36 \text{ mA}$$

$$\Rightarrow R_B \geq 11.9 \text{ k}\Omega$$

From the table of 1% resistors in Appendix J we select

$$R_B = 12.1 \text{ k}\Omega$$

Substituting in Eq. (3), we have

$$R_C = 1.35 \text{ k}\Omega$$

From the table of 1% resistors in Appendix J we select

$$R_C = 1.37 \text{ k}\Omega$$

For these values:

$$I_C = \frac{5 - 0.2}{1.37} = 3.5 \text{ mA}$$

$$I_B = \frac{5 - 0.7}{12.1} = 0.36 \text{ mA}$$

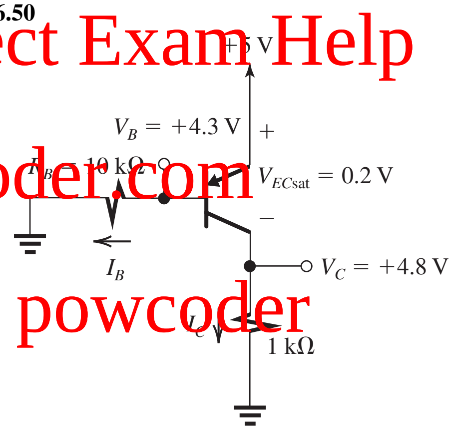
Thus,

$$\beta_{\text{forced}} = \frac{3.5}{0.36} = 9.7$$

$$P_{\text{dissipated}} = V_{CC}(I_C + I_B)$$

$$= 5 \times 3.86 = 19.2 \text{ mW}$$

6.50



Assume saturation-mode operation. From the figure we see that

$$I_C = \frac{V_C}{1 \text{ k}\Omega} = \frac{4.8}{1} = 4.8 \text{ mA}$$

$$I_B = \frac{V_B}{R_B} = \frac{4.3}{10} = 0.43 \text{ mA}$$

Thus,

$$\beta_{\text{forced}} \equiv \frac{I_C}{I_B} = \frac{4.8}{0.43} = 11.2$$

Since 11.2 is lower than the transistor β of 50, we have verified that the transistor is operating in saturation, as assumed.

$$V_C = V_{CC} - V_{EC\text{sat}} = 5 - 0.2 = 4.8 \text{ V}$$

To operate at the edge of saturation,

$$V_{EC} = 0.3 \text{ V} \qquad \text{and} \qquad I_C/I_B = \beta = 50$$

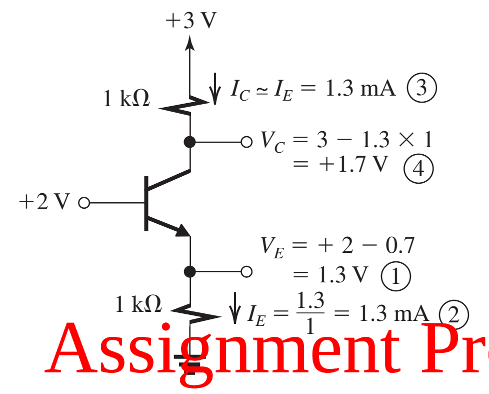
Thus,

$$I_C = \frac{5 - 0.3}{1} = 4.7 \text{ mA}$$

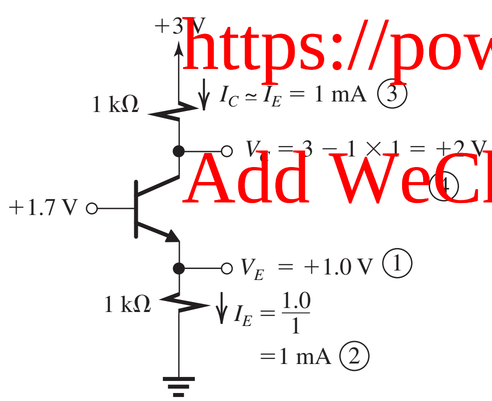
$$I_B = \frac{I_C}{\beta} = \frac{4.7}{50} = 0.094 \text{ mA}$$

$$R_B = \frac{4.3}{I_B} = \frac{4.3}{0.094} = 45.7 \text{ k}\Omega$$

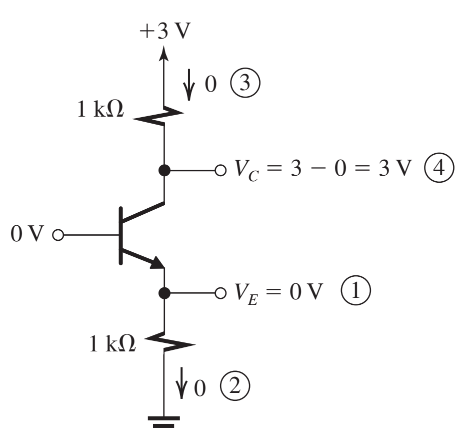
6.51



(a)



(b)



(c)

The analysis and the results are given on the circuit diagrams of Figs. 1 through 3. The circled numbers indicate the order of the analysis steps.

6.52

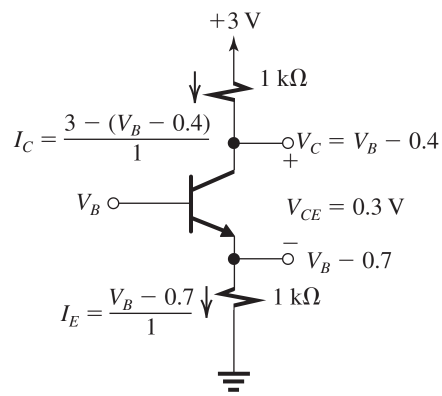


Figure 1

Figure 1 shows the circuit with the value of V_B that results in operation at the edge of saturation. Since β is very high,

$$I_C \simeq I_E$$

$$\frac{3 - (V_B - 0.4)}{1} = \frac{V_B - 0.7}{1}$$

$$\Rightarrow V_B = 2.05 \text{ V}$$

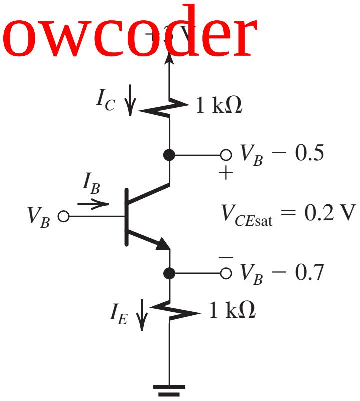


Figure 2

Figure 2 shows the circuit with the value of V_B that results in the transistor operating in saturation, with

$$I_E = \frac{V_B - 0.7}{1} = V_B - 0.7$$

$$I_C = \frac{3 - (V_B - 0.5)}{1} = 3.5 - V_B$$

$$I_B = I_E - I_C = 2V_B - 4.2$$

For $\beta_{\text{forced}} = 2$,

$$\frac{I_C}{I_B} = 2$$

$$\frac{3.5 - V_B}{2V_B - 4.2} = 2$$

$$\Rightarrow V_B = 2.38 \text{ V}$$

6.53 Refer to the circuit in Fig. P6.53.

(a) For $V_B = -1$ V,

$$V_E = V_B - V_{BE} = -1 - 0.7 = -1.7 \text{ V}$$

$$I_E = \frac{V_E - (-3)}{1} = \frac{-1.7 + 3}{1} = 1.3 \text{ mA}$$

Assuming active-mode operation, we have

$$I_C = \alpha I_E \simeq I_E = 1.3 \text{ mA}$$

$$V_C = +3 - I_C \times 1 = 3 - 1.3 = +1.7 \text{ V}$$

Since $V_C > V_B - 0.4$, the transistor is operating in the active mode as assumed.

(b) For $V_B = 0$ V,

$$V_E = 0 - V_{BE} = -0.7 \text{ V}$$

$$I_E = \frac{-0.7 - (-3)}{1} = 2.3 \text{ mA}$$

Assuming operation in the active mode, we have

$$I_C = \alpha I_E \simeq I_E = 2.3 \text{ mA}$$

$$V_C = +3 - I_C \times 1 = 3 - 2.3 = +0.7 \text{ V}$$

Since $V_C > V_B - 0.4$, the BJT is operating in the active mode, as assumed.

(c) For $V_B = +1$ V,

$$V_E = 1 - 0.7 = +0.3 \text{ V}$$

$$I_E = \frac{0.3 - (-3)}{1} = 3.3 \text{ mA}$$

Assuming operation in the active mode, we have

$$I_C = \alpha I_E \simeq I_E = 3.3 \text{ mA}$$

$$V_C = 3 - 3.3 \times 1 = -0.3 \text{ V}$$

Now $V_C < V_B - 0.4$, indicating that the transistor is operating in saturation, and our original assumption is incorrect. It follows that

$$V_C = V_E + V_{CE\text{sat}}$$

$$= 0.3 + 0.2 = 0.5 \text{ V}$$

$$I_C = \frac{3 - V_C}{1} = \frac{3 - 0.5}{1} = 2.5 \text{ mA}$$

$$I_B = I_E - I_C = 3.3 - 2.5 = 0.8 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{2.5}{0.8} = 3.1$$

(d) When $V_B = 0$ V, $I_E = 2.3$ mA. The emitter current becomes 0.23 mA at

$$V_B = -3 + 0.23 \times 1 + 0.7 = -2.07 \text{ V}$$

(e) The transistor will be at the edge of conduction when $I_E \simeq 0$ and $V_{BE} = 0.5$ V, that is,

$$V_B = -3 + 0.5 = -2.5 \text{ V}$$

In this case,

$$V_E = -3 \text{ V}$$

$$V_C = +3 \text{ V}$$

(f) The transistor reaches the edge of saturation when $V_{CE} = 0.3$ V but $I_C = \alpha I_E \simeq I_E$:

$$V_E = V_B - 0.7$$

$$I_E = \frac{V_B - 0.7 - (-3)}{1} = V_B + 2.3$$

$$V_C = V_E + 0.3 = V_B - 0.4$$

$$I_C = \frac{3 - V_C}{1} = \frac{3 - V_B + 0.4}{1} = 3.4 - V_B$$

Since

$$I_C \simeq I_E$$

$$3.4 - V_B = V_B + 2.3$$

$$V_B = 0.55 \text{ V}$$

For this value,

$$V_E = 0.55 - 0.7 = -0.15 \text{ V}$$

$$V_C = -0.15 + 0.3 = +0.15 \text{ V}$$

(g) For the transistor to operate in saturation with $\beta_{\text{forced}} = 2$,

$$V_E = V_B - 0.7$$

$$I_E = \frac{V_B - 0.7 - (-3)}{1} = V_B + 2.3$$

$$V_C = V_E + V_{CE\text{sat}} = V_B - 0.7 + 0.2 = V_B - 0.5$$

$$I_C = \frac{3 - (V_B - 0.5)}{1} = 3.5 - V_B$$

$$I_B = I_E - I_C = 2\,V_B - 1.2$$

$$\frac{I_C}{I_B} = \frac{3.5 - V_B}{2\,V_B - 1.2} = 2$$

$$\Rightarrow V_B = +1.18 \text{ V}$$

6.54 (a) $V_B = 0$ V

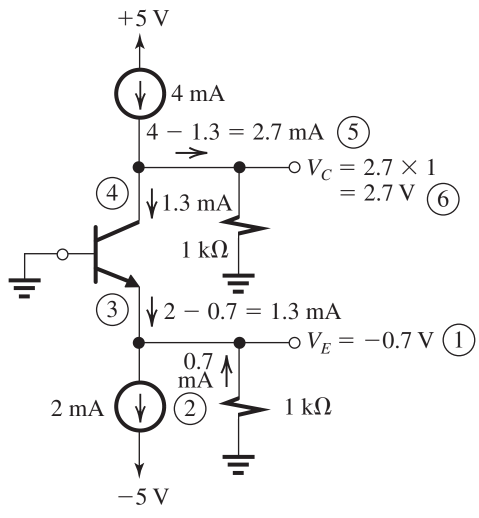


Figure 1

The analysis is shown on the circuit diagram in Fig. 1. The circled numbers indicate the order of the analysis steps.

(b) The transistor cuts off at the value of V_B that causes the 2-mA current of the current source feeding the emitter to flow through the 1-kΩ resistor connected between the emitter and ground. The circuit under these conditions is shown in Fig. 2.

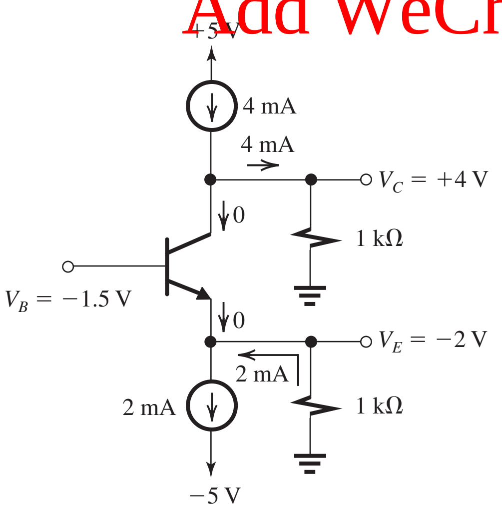


Figure 2

Observe that $V_E = -2$ mA $\times 1$ kΩ $= -2$ V, $I_E = 0$, and $V_B = V_E + 0.5 = -1.5$ V. Since $I_C = 0$, all the 4 mA supplied by the current source feeding the collector flows through the collector 1-kΩ resistor, resulting in $V_C = +4$ V.

(c)

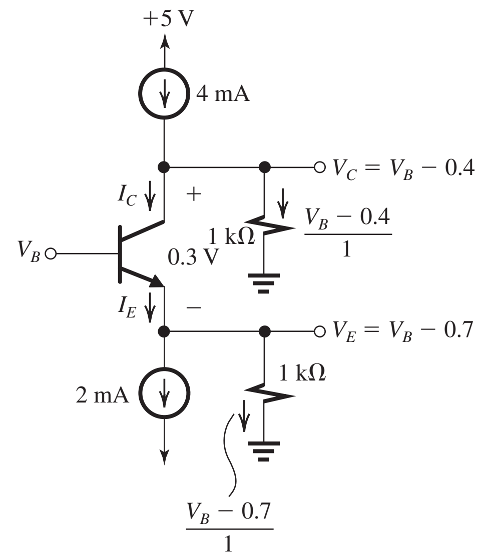


Figure 3

Figure 3 shows the transistor at the edge of saturation. Here $V_{CE} = 0.3$ V and $I_C = \alpha I_E \simeq I_E$. A node equation at the emitter gives

$I_E = 2 + V_B - 0.7 = V_B + 1.3$ mA

A node equation at the collector gives

$I_C = 4 - (V_B - 0.4) = 4.4 - V_B$ mA

Imposing the condition $I_C \simeq I_E$ gives

$4.4 - V_B = V_B + 1.3$

$\Rightarrow V_B = +1.55$ V

Correspondingly,

$V_E = +0.85$ V

$V_C = +1.15$ V

6.55

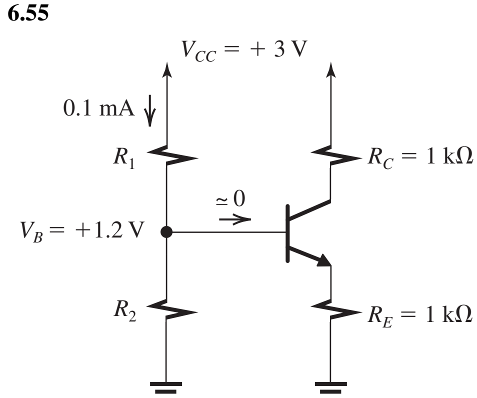


Figure 1

From Fig. 1 we see that

$$R_1 + R_2 = \frac{V_{CC}}{0.1\text{ mA}} = \frac{3}{0.1} = 30\text{ k}\Omega$$

$$V_{CC}\frac{R_2}{R_1 + R_2} = 1.2$$

$$3 \times \frac{R_2}{30} = 1.2$$

$$\Rightarrow R_2 = 12\text{ k}\Omega$$

$$R_1 = 30 - 12 = 18\text{ k}\Omega$$

For $\beta = 100$, to obtain the collector current, we replace the voltage divider with its Thévenin equivalent, consisting of

$$V_{BB} = 3 \times \frac{R_2}{R_1 + R_2} = 3 \times \frac{12}{18 + 12} = 1.2\text{ V}$$

$$R_B = R_1 \parallel R_2 = 12 \parallel 18 = 7.2\text{ k}\Omega$$

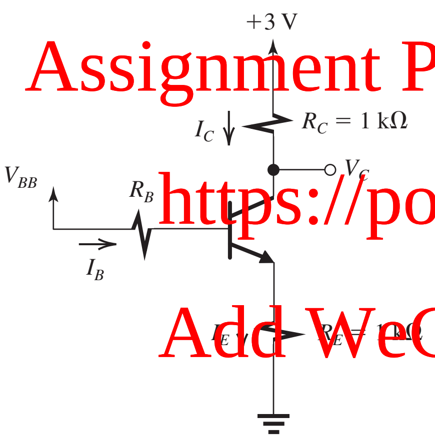


Figure 2

Refer to Fig. 2. Assuming active-mode operation, we can write a loop equation for the base–emitter loop:

$$V_{BB} = I_B R_B + V_{BE} + I_E R_E$$

$$1.2 = \frac{I_E}{\beta + 1} \times 7.2 + 0.7 + I_E \times 1$$

$$\Rightarrow I_E = \frac{1.2 - 0.7}{1 + \dfrac{7.2}{101}} = 0.47\text{ mA}$$

$$I_C = \alpha I_E = 0.99 \times 0.47 = 0.46\text{ mA}$$

$$V_C = +3 - 0.46 \times 1 = +2.54\text{ V}$$

Since $V_B = I_E R_E + V_{BE} = 0.47 + 0.7 = 1.17$ V, we see that $V_C > V_B - 0.4$, and thus the transistor is operating in the active region, as assumed.

6.56 Refer to the circuit in Fig. P6.56.

$$V_E = 1\text{ V}$$

$$I_E = \frac{3 - 1}{5} = 0.4\text{ mA}$$

$$V_B = V_E - 0.7 = 0.3\text{ V}$$

$$I_B = \frac{V_B}{50\text{ k}\Omega} = \frac{0.3}{50} = 0.006\text{ mA}$$

$$I_C = I_E - I_B = 0.4 - 0.006 = 0.394\text{ mA}$$

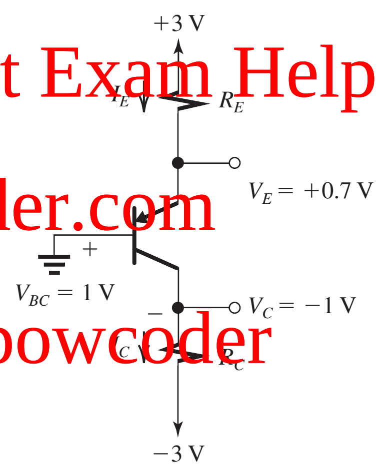
$$V_C = -3 + 5 \times 0.394 = -1.03\text{ V}$$

Observe that $V_C < V_B$, confirming our implicit assumption that the transistor is operating in the active region.

$$\beta = \frac{I_C}{I_B} = \frac{0.394}{0.006} = 66$$

$$\alpha = \frac{I_C}{I_E} = \frac{0.394}{0.4} = 0.985$$

6.57



Refer to the figure. To obtain $I_E = 0.5$ mA we select R_E according to

$$R_E = \frac{3 - 0.7}{0.5} = 4.6\text{ k}\Omega$$

To obtain $V_C = -1$ V, we select R_C according to

$$R_C = \frac{-1 - (-3)}{0.5} = 4\text{ k}\Omega$$

where we have utilized the fact that $\alpha \simeq 1$ and thus $I_C \simeq I_E = 0.5$ mA. From the table of 5% resistors in Appendix J we select

$$R_E = 4.7\text{ k}\Omega \quad \text{and} \quad R_C = 3.9\text{ k}\Omega$$

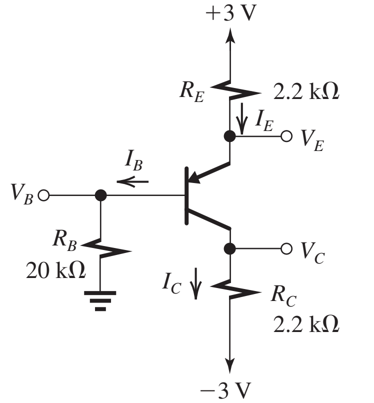
For these values,

$$I_E = \frac{3 - 0.7}{4.7} = 0.49\text{ mA}$$

$$I_C \simeq I_E = 0.49\text{ mA}$$

$$V_{BC} = 0 - V_C = -(-3 + 0.49 \times 3.9) = -1.1\text{ V}$$

6.58



Writing a loop equation for the EBJ loop, we have

$$3 = I_E R_E + V_{EB} + I_B R_B \qquad (1)$$

$$= I_E \times 2.2 + 0.7 + \frac{I_E}{\beta + 1} \times 20$$

$$\Rightarrow I_E = \frac{3 - 0.7}{2.2 + \frac{20}{41}} = 0.86 \text{ mA}$$

$$V_E = 3 - 0.86 \times 2.2 = +1.11 \text{ V}$$

$$V_B = V_E - 0.7 = +0.41 \text{ V}$$

Assuming active-mode operation, we obtain

$$I_C = \alpha I_E = \frac{40}{41} \times 0.86 = 0.84 \text{ mA}$$

$$V_C = -3 + 0.84 \times 2.2 = -1.15 \text{ V}$$

Since $V_C < V_B + 0.4$, the transistor is operating in the active mode, as assumed. Now, if R_B is increased to 100 kΩ, the loop equation [Eq. (1)] yields

$$I_E = \frac{3 - 0.7}{2.2 + \frac{100}{41}} = 0.5 \text{ mA}$$

$$V_E = 3 - 0.5 \times 2.2 = +1.9 \text{ V}$$

$$V_B = V_E - V_{EB} = 1.9 - 0.7 = +1.2 \text{ V}$$

Assuming active-mode operation, we obtain

$$I_C = \alpha I_E = \frac{40}{41} \times 0.5 = 0.48 \text{ mA}$$

$$V_C = -3 + 0.48 \times 2.2 = -1.9 \text{ V}$$

Since $V_C < V_B + 0.4$, the transistor is operating in the active mode, as assumed.

If with $R_B = 100$ kΩ, we need the voltages to remain at the values obtained with $R_B = 20$ kΩ, the transistor must have a β value determined as follows. For I_E to remain unchanged,

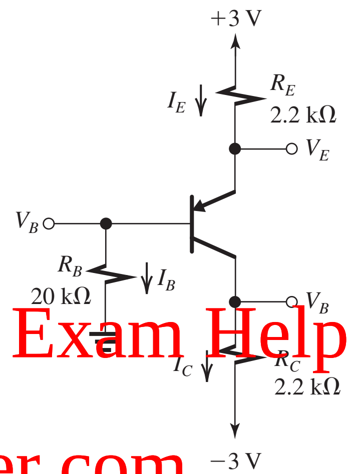
$$\frac{3 - 0.7}{2.2 + \frac{20}{41}} = \frac{3 - 0.7}{2.2 + \frac{100}{\beta + 1}}$$

$$\Rightarrow \frac{20}{41} = \frac{100}{\beta + 1}$$

$$\beta + 1 = \frac{410}{2} = 205$$

$$\beta = 204$$

6.59



Assume active-mode operation:

$$I_E = \frac{3 - V_{EB}}{R_E + \frac{R_B}{\beta + 1}}$$

$$I_E = \frac{3 - 0.7}{2.2 + \frac{20}{51}} = 0.887 \text{ mA}$$

$$I_B = \frac{I_E}{\beta + 1} = \frac{0.887}{51} = 0.017 \text{ mA}$$

$$I_C = I_E - I_B = 0.887 - 0.017 = 0.870 \text{ mA}$$

$$V_B = I_B R_B = 0.017 \times 20 = 0.34 \text{ V}$$

$$V_E = V_B + V_{EB} = 0.34 + 0.7 = 1.04 \text{ V}$$

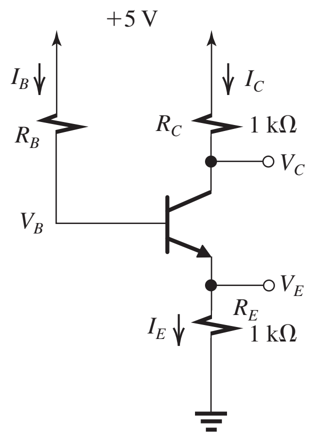
$$V_C = -3 + I_C R_C = -3 + 0.87 \times 2.2 = -1.09 \text{ V}$$

Thus, $V_C < V_B + 0.4$, which means active-mode operation, as assumed. The maximum value of R_C that still guarantees active-mode operation is that which causes V_C to be 0.4 V above V_B: that is, $V_C = 0.34 + 0.4 = 0.74$ V.

Correspondingly,

$$R_{C\max} = \frac{0.74 - (-3)}{0.87} = 4.3 \text{ kΩ}$$

6.60



A loop equation for the EB loop yields

$$5 = I_B R_B + V_{BE} + I_E R_E$$

$$\Rightarrow I_E = \frac{5 - 0.7}{R_E + \dfrac{R_B}{\beta + 1}}$$

$$I_E = \frac{4.3}{1 + \dfrac{R_B}{101}}$$

(a) For $R_B = 100$ kΩ,

$$I_E = \frac{4.3}{1 + \dfrac{100}{101}} = 2.16 \text{ mA}$$

$$V_E = I_E R_E = 2.16 \times 1 = 2.16 \text{ V}$$

$$V_B = V_E + 0.7 = 2.86 \text{ V}$$

Assuming active-mode operation, we obtain

$$I_C = \alpha I_E = 0.99 \times 2.16 = 2.14 \text{ mA}$$

$$V_C = 5 - 2.14 \times 1 = +2.86 \text{ V}$$

Since $V_C > V_B - 0.4$, the transistor is operating in the active region, as assumed.

(b) For $R_B = 10$ kΩ,

$$I_E = \frac{4.3}{1 + \dfrac{10}{101}} = 3.91 \text{ mA}$$

$$V_E = 3.91 \times 1 = 3.91 \text{ V}$$

$$V_B = 3.91 + 0.7 = 4.61 \text{ V}$$

Assuming active-mode operation, we obtain

$$I_C = \alpha I_E = 0.99 \times 3.91 = 3.87 \text{ mA}$$

$$V_C = 5 - 3.87 = +1.13 \text{ V}$$

Since $V_C < V_B - 0.4$, the transistor is operating in saturation, contrary to our original assumption. Therefore, we need to redo the analysis assuming saturation-mode operation, as follows:

$$V_B = V_E + 0.7$$

$$V_C = V_E + V_{CEsat} = V_E + 0.2$$

$$I_B = \frac{5 - V_B}{R_B}$$

$$= \frac{5 - V_E - 0.7}{10} = \frac{4.3 - V_E}{10} \qquad (1)$$

$$I_C = \frac{5 - V_C}{R_C} = \frac{5 - V_E - 0.2}{1}$$

$$= 4.8 - V_E \qquad (2)$$

$$I_E = \frac{V_E}{R_E} = \frac{V_E}{1} = V_E \qquad (3)$$

Substituting from Eqs. (1), (2), and (3) into

$$I_E = I_B + I_C$$

gives

$$V_E = 0.43 - 0.1\, V_E + 4.8 - V_E$$

$$\Rightarrow V_E = 2.5 \text{ V}$$

$$V_C = 2.7 \text{ V}$$

$$V_B = 3.2 \text{ V}$$

$$I_B = \frac{5 - 3.2}{10} = 0.18 \text{ mA}$$

$$I_C = \frac{5 - 2.7}{1} = 2.3 \text{ mA}$$

Thus,

$$\frac{I_C}{I_B} = \frac{2.3}{0.18} = 12.8$$

which is lower than the value of β, verifying saturation-mode operation.

(c) For $R_B = 1$ kΩ, we assume saturation-mode operation:

$$V_B = V_E + 0.7$$

$$V_C = V_E + 0.2$$

$$I_B = \frac{5 - (V_E + 0.7)}{1} = 4.3 - V_E$$

$$I_C = \frac{5 - (V_E + 0.2)}{1} = 4.8 - V_E$$

$$I_E = \frac{V_E}{1} = V_E$$

These values can be substituted into

$$I_E = I_B + I_C$$

to obtain

$$V_E = 4.3 - V_E + 4.8 - V_E$$

$$\Rightarrow V_E = 3 \text{ V}$$

$$V_B = 3.7 \text{ V}$$

$$V_C = 3.2 \text{ V}$$

Now checking the currents,

$$I_B = \frac{5 - 3.7}{1} = 1.3 \text{ mA}$$

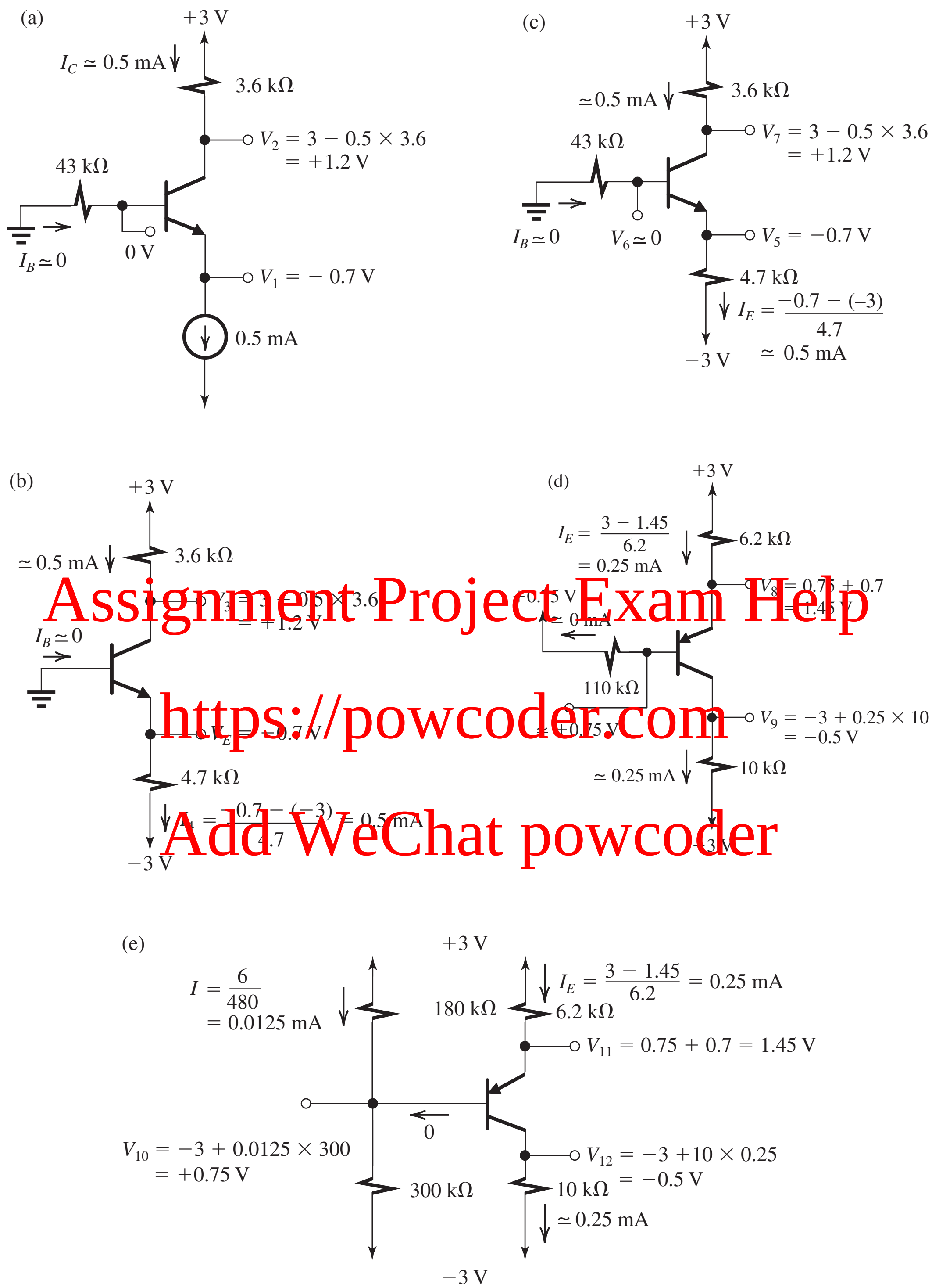
$$I_C = \frac{5 - 3.2}{1} = 1.8 \text{ mA}$$

Thus, the transistor is operating at a forced β of

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{1.8}{1.3} = 1.4$$

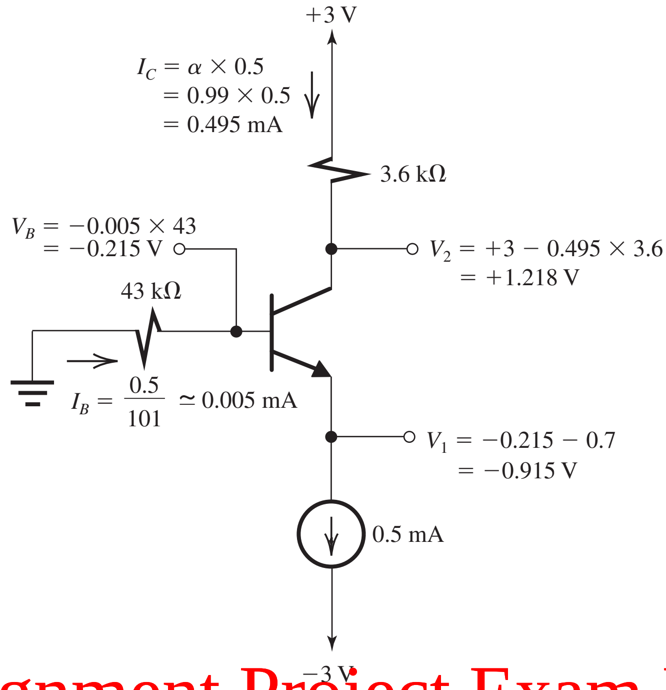
which is much lower than the value of β, confirming operation in saturation.

6.61



For the solutions and answers to parts (a) through (e), see the corresponding circuit diagrams.

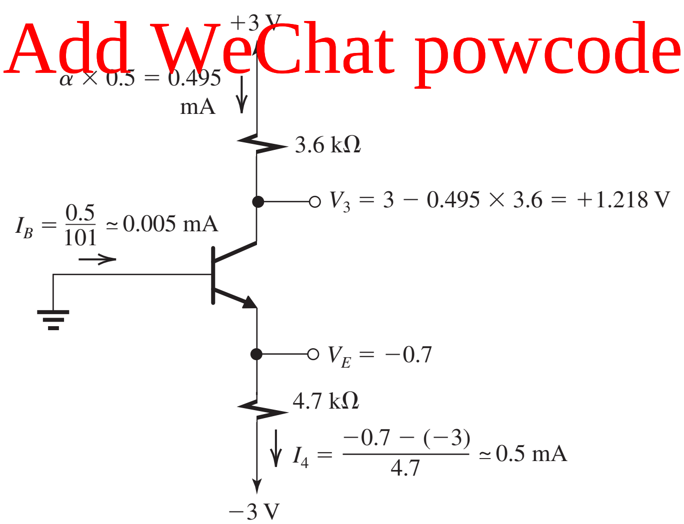
6.62 (a)



(a)

See solution and answer on the figure, which corresponds to Fig. P6.61(a).

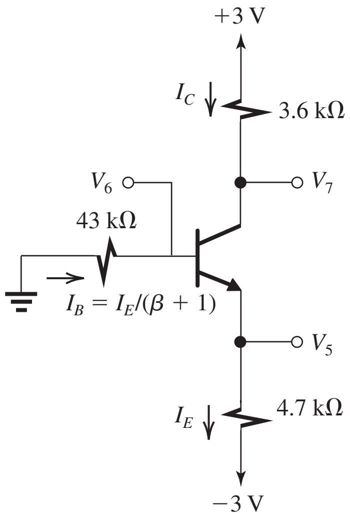
(b)



(b)

See solution and answer on the figure, which corresponds to Fig. P6.61(b).

(c)



(c)

Writing an equation for the loop containing the BEJ of the transistor leads to

$$I_E = \frac{3 - 0.7}{4.7 + \frac{43}{101}} = 0.449 \text{ mA}$$

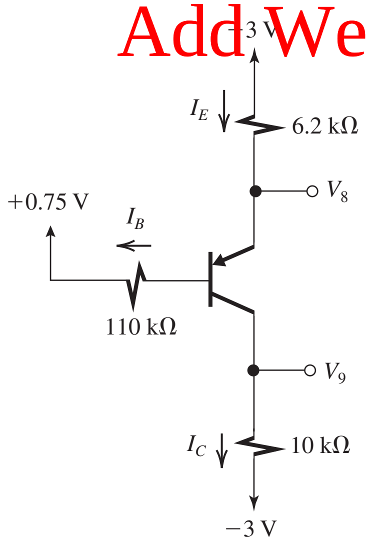
$V_5 = -3 + 0.449 \times 4.7 = -0.9$ V

$V_6 = -0.9 + 0.7 = -0.2$ V

$I_C = \alpha I_E = 0.99 \times 0.449 = 0.444$ mA

$V_7 = 3 - 0.444 \times 3.6 = +1.4$ V

(d)



(d)

An equation for the loop containing the EBJ of the transistor yields

$$I_E = \frac{3 - 0.75 - 0.7}{6.2 + \frac{110}{101}} = 0.213 \text{ mA}$$

$V_8 = +3 - 0.213 \times 6.2 = +1.7$ V

$I_C = \alpha I_E = 0.99 \times 0.213 = 0.21$ mA

$V_9 = -3 + 0.21 \times 10 = -0.9$ V

(e) See figure on next page.

First, we use Thévenin's theorem to replace the voltage divider feeding the base with V_{BB} and R_B:

$$V_{BB} = -3 + \frac{6}{480} \times 300 = +0.75 \text{ V}$$

$R_B = 180 \parallel 300 = 112.5$ kΩ

Next we write an equation for the loop containing the EBJ to obtain

$$I_E = \frac{3 - 0.75 - 0.7}{6.2 + \frac{112.5}{101}} = 0.212 \text{ mA}$$

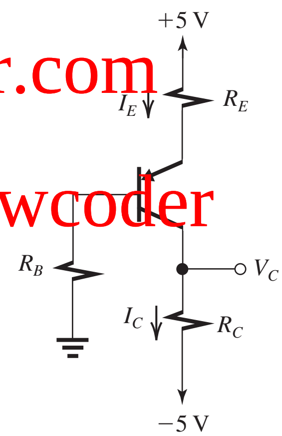
$V_{11} = +3 - 0.212 \times 6.2 = +1.7$ V

$V_{10} = 1.7 - 0.7 = +1$ V

$I_C = \alpha I_E = 0.99 \times 0.212 = 0.21$ mA

$V_{12} = -3 + 0.21 \times 10 = -0.9$ V

6.63



We required I_E to be nominally 1 mA (i.e., at $\beta = 100$) and to remain within ±10% as β varies from 50 to 150. Writing an equation for the loop containing the EBJ results in

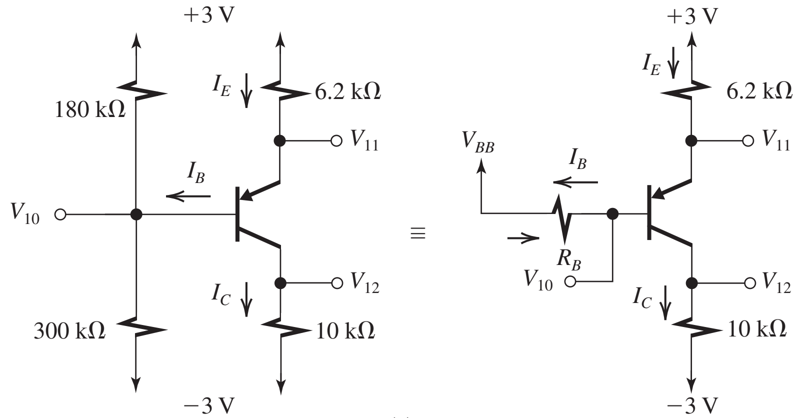
$$I_E = \frac{5 - 0.7}{R_E + \frac{R_B}{\beta + 1}}$$

Thus,

$$\frac{4.3}{R_E + \frac{R_B}{101}} = 1 \quad (1)$$

$$\frac{4.3}{R_E + \frac{R_B}{51}} = I_{E\min} \quad (2)$$

This figure belongs to Problem 6.62, part (e).



(e)

$$\frac{4.3}{R_E + \dfrac{R_B}{151}} = I_{E\max} \tag{3}$$

If we set $I_{E\min} = 0.9$ mA and solve Eqs. (1) and (2) simultaneously, we obtain

$R_E = 3.81$ kΩ

$R_B = 49.2$ kΩ

Substituting theses values in Eqs. (2) and (3) gives

$I_{E\min} = 0.9$ mA

$I_{E\max} = 1.04$ mA

Obviously, this is an acceptable design. Alternatively, if we set $I_{E\max}$ in Eq. (3) to 1.1 mA and solve Eqs. (1) and (3) simultaneously, we obtain

$R_E = 3.1$ kΩ

$R_B = 119.2$ kΩ

Substituting these values in Eqs. (2) and (3) gives

$I_{E\min} = 0.8$ mA

$I_{E\max} = 1.1$ mA

Obviously this is not an acceptable design ($I_{E\min}$ is 20% lower than nominal).

Therefore, we shall use the first design. Specifying the resistor values to the nearest kilohm results in

$R_E = 4$ kΩ

$R_B = 50$ kΩ

To obtain the value of R_C, we note that at the nominal emitter current value of 1 mA, $V_C = -1$ V,

$I_C = \alpha I_E = 0.99$ mA

$$R_C = \frac{-1-(-5)}{0.99} = 4.04 \text{ k}\Omega$$

Specified to the nearest kilohm,

$R_C = 4$ kΩ

Finally, for our design we need to determine the range obtained for collector current and collector voltage for β ranging from 50 to 150 with a nominal value of 100. We compute the nominal value of I_E from

$$I_{E\text{nominal}} = \frac{4.3}{4 + \dfrac{50}{101}} = 0.96 \text{ mA}$$

We utilize Eqs. (2) and (3) to compute $I_{E\min}$ and $I_{E\max}$,

$$I_{E\min} = \frac{4.3}{4 + \dfrac{50}{51}} = 0.86 \text{ mA}$$

$$I_{E\max} = \frac{4.3}{4 + \dfrac{50}{151}} = 0.99 \text{ mA}$$

Thus,

$$\frac{I_{E\max}}{I_{E\text{nominal}}} = \frac{0.99}{0.96} = 1.03$$

$$\frac{I_{E\min}}{I_{E\text{nominal}}} = \frac{0.86}{0.96} = 0.9$$

which meet our specifications. The collector currents are

$I_{C\text{nominal}} = 0.99 \times 0.96 = 0.95$ mA

$I_{C\min} = 0.99 \times 0.86 = 0.85$ mA

$I_{C\max} = 0.99 \times 0.99 = 0.98$ mA

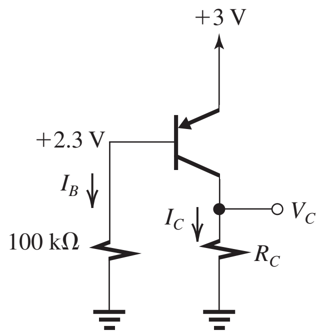
and the collector voltages are

$V_{C\text{nominal}} = -5 + 0.95 \times 4 = -1.2$ V

$V_{C\min} = -5 + 0.85 \times 4 = -1.6$ V

$V_{C\max} = -5 + 0.98 \times 4 = -1.1$ V

6.64



$$I_B = \frac{2.3 \text{ V}}{100 \text{ k}\Omega} = 0.023 \text{ mA}$$

Since $V_C = 2$ V is lower than V_B, which is +2.3 V, the transistor will be operating in the active mode. Thus,

$$I_C = \beta I_B = 50 \times 0.023 = 1.15 \text{ mA}$$

To obtain $V_C = 2$ V, we select R_C according to

$$R_C = \frac{V_C}{I_C} = \frac{2 \text{ V}}{1.15 \text{ mA}} = 1.74 \text{ k}\Omega$$

Now, if the transistor is replaced with another having $\beta = 100$, then

$$I_C = 100 \times 0.023 = 2.3 \text{ mA}$$

which would imply

$$V_C = 2.3 \times 1.74 = 4 \text{ V}$$

which is impossible because the base is at 2.3 V. Thus the transistor must be in the saturation mode and

$$V_C = V_E - V_{EC\text{sat}}$$

$$= 3 - 0.2 = 2.8 \text{ V}$$

open circuited. The circuit is shown in Fig. 1, where $\beta = \infty$ and R is open circuited. Since $V_{D1} = V_{BE1}$, we have

$$V_1 = V_{E1}$$

Thus,

$$I_{D1} \times 40 = I_{E1} \times 2$$

$$\Rightarrow I_{D1} = 0.05 I_{E1}$$

But

$$I_{D1} = \frac{9 - 0.7}{80 + 40} = 0.069 \text{ mA} \simeq 0.07 \text{ mA}$$

Thus,

$$I_{E1} = \frac{0.069}{0.05} = 1.38 \text{ mA} \simeq 1.4 \text{ mA}$$

$$V_{E1} = I_{E1} \times 2 = 2.77 \text{ V} \simeq 2.8 \text{ V}$$

$$V_{B1} = V_{E1} + 0.7 = 3.5 \text{ V}$$

$$I_{C1} = I_E = 1.38 \text{ mA} \simeq 1.4 \text{ mA}$$

$$V_2 = 9 - I_{C1} \times 2 = 9 - 1.38 \times 2 \simeq 6.2 \text{ V}$$

$$V_{C1} = V_2 - V_{D2} = 6.2 - 0.7 = 5.5 \text{ V}$$

$$V_{E2} = V_2 = 6.2 \text{ V}$$

$$I_{E2} = \frac{9 - 6.2}{100 \ \Omega} = 28 \text{ mA}$$

$$I_{C2} = I_E = 28 \text{ mA}$$

$$V_{C2} = 28 \times 0.1 = 2.8 \text{ V}$$

6.65

(a) Consider first the case $\beta = \infty$ and R

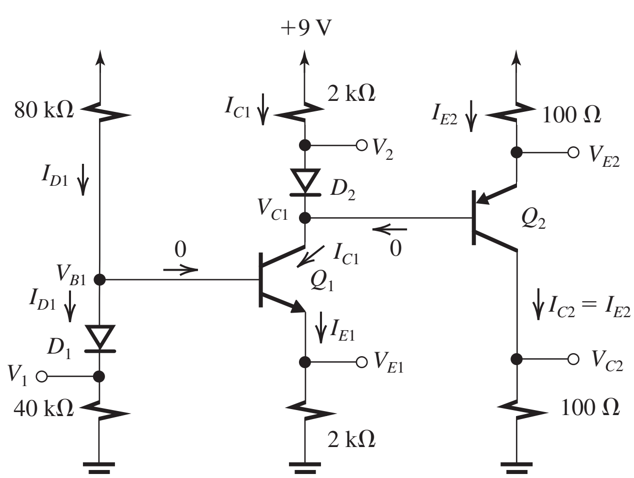


Figure 1 $\beta = \infty$, and R is open circuited

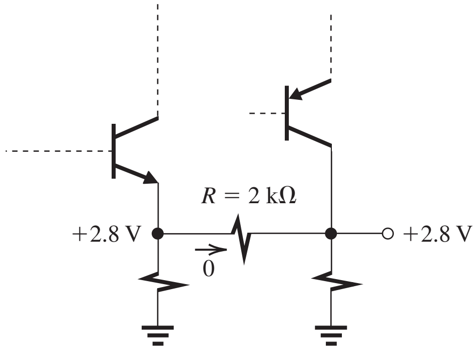


Figure 2

Now connecting the resistance $R = 2\ \text{k}\Omega$ between C_1 and E_2 (see Fig. 2) both of which at 2.8 V, will result in zero current through R; thus all voltages and currents remain unchanged.

(b) We next consider the situation with $\beta = 100$, first with R disconnected. The circuit is shown in Fig. 3.

Once again we observe that $V_{E1} = V_1$, thus

$I_{E1} \times 2 = I_{D1} \times 40$

$\Rightarrow I_{D1} = 0.05 I_{E1}$

The base current of Q_1 is $I_{E1}/101 \simeq 0.01 I_{E1}$. Thus, the current through the 80-kΩ resistor is $0.05 I_{E1} + 0.01 I_{E1} = 0.06 I_{E1}$, and

$V_{B1} = V_{E1} + 0.7 = 2I_{E1} + 0.7$

$$0.06 I_{E1} = \frac{9 - V_{B1}}{80} = \frac{9 - (2I_{E1} + 0.7)}{80}$$

$\Rightarrow I_{E1} = 1.22$ mA

$V_{E1} = 1.22 \times 2 = 2.44$ V

$V_{B1} = 2.44 + 0.7 = 3.14$ V

$I_{C1} = \alpha I_{E1} = 0.99 \times 1.22 = 1.21$ mA

Observing that $V_{E2} = V_2$, we see that the voltage drops across the 2-kΩ resistor and the 100-Ω resistor are equal, thus

$I_{D2} \times 2 = I_{E2} \times 0.1$

$\Rightarrow I_{D2} = 0.05 I_{E2}$

As the base current of Q_2 is approximately $0.01 I_{E2}$, a node equation at C_1 yields

$I_{D2} = I_{C1} - 0.01 I_{E2}$

Thus,

$0.05 I_{E2} = I_{C1} - 0.01 I_{E2}$

$\Rightarrow 0.06 I_{E2} = I_{C1}$

$$I_{E2} = \frac{I_{C1}}{0.06} = \frac{1.21}{0.06} = 20.13 \text{ mA}$$

$I_{D2} = 0.05 \times 20.13 = 1$ mA

$V_{C1} = 9 - 1 \times 2 - 0.7 = 6.3$ V

$V_{E2} = 6.3 + 0.7 = 7$ V

$I_{C2} = \alpha I_{E2} = 0.99 \times 20.13 = 20$ mA

$V_{C2} = 20 \times 0.1 = 2$ V

Finally, with the resistance R connected between E_1 and C_2, it will conduct a current that we can initially estimate as

$$I = \frac{V_{E1} - V_{C2}}{R} = \frac{2.44 - 2}{2} = 0.22 \text{ mA}$$

This is a substantial amount compared to $I_{E1} = 1.22$ mA, requiring that we redo the analysis with R in place. The resulting circuit is shown in Fig. 4.

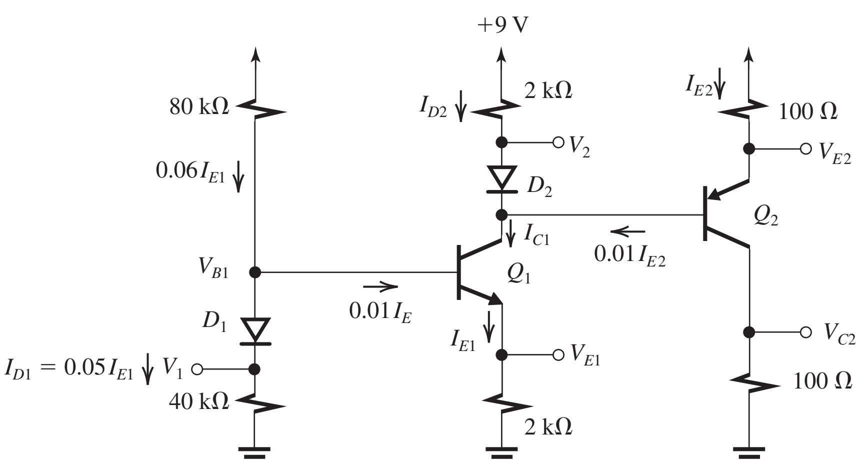


Figure 3

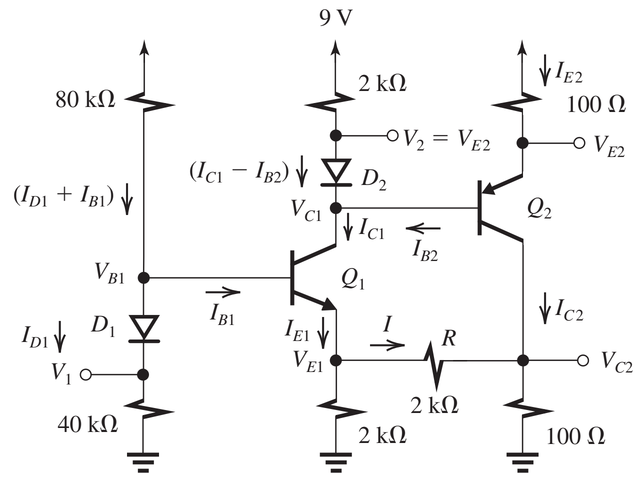


Figure 4

Denoting the emitter voltage of Q_1, V_{E1}, and the current through R as I, the analysis proceeds as follows:

$V_1 = V_{E1}$

$I_{D1} = \dfrac{V_1}{40} = \dfrac{V_{E1}}{40} = 0.025V_{E1}$

$I_{E1} = \dfrac{V_{E1}}{2} + I = 0.5V_{E1} + I$

$I_{B1} = \dfrac{I_{E1}}{101} = 0.005V_{E1} + 0.01I$

$I_{80\,\mathrm{k\Omega}} = I_{D1} + I_{B1} = 0.03V_{E1} + 0.01I$

$V_{C2} = V_{E1} - I \times 2 = V_{E1} - 2I$

$I_{C2} = -I + \dfrac{V_{C2}}{0.1} = 10V_{E1} - 21I$

$I_{B2} = \dfrac{I_{C2}}{101} = 0.1V_{E1} - 0.21I$

$I_{C1} = \alpha I_{E1} = 0.495V_{E1} + 0.99I$

$I_{D2} = I_{C1} - I_{B2} = 0.395V_{E1} + 1.2I$

$I_{E2} = \dfrac{I_{C2}}{\alpha} = 10.1V_{E1} - 21.2I$

$I_{D2} \times 2 = I_{E2} \times 0.1$

$2(0.395V_{E1} + 1.2I) = 0.1(10.1V_{E1} - 21.2I)$

$\Rightarrow I = 0.05V_{E2}$

Voltage drop across 80-kΩ resistor = $(0.03\ V_{E1} + 0.01I) \times 80 = 9 - V_{E1} - 0.7$

Substituting $I = 0.05\ V_{E2}$ gives

$V_{E1} = 2.41$ V

$I = 0.12$ mA

Substituting these quantities in the equations above gives

$V_{B1} = 2.41 + 0.7 = 3.11$ V

$I_{E1} = 1.325$ mA

$I_{C1} = 1.31$ mA

$I_{D1} = 1.09$ mA

$V_{C1} = 9 - 1.09 \times 2 - 0.7 = 6.12$ V

$V_{E2} = 6.82$ V

$I_{E2} = \dfrac{9 - 6.82}{0.1} = 21.8$ mA

$I_{C2} = 0.99 \times 21.8 = 21.6$ mA

$V_{C2} = 2.17$ V

6.66 (a) $\beta = \infty$

The analysis and results are given in the circuit diagram in Fig. 1 on page 27. The circled numbers indicate the order of the analysis steps.

(b) $\beta = 100$

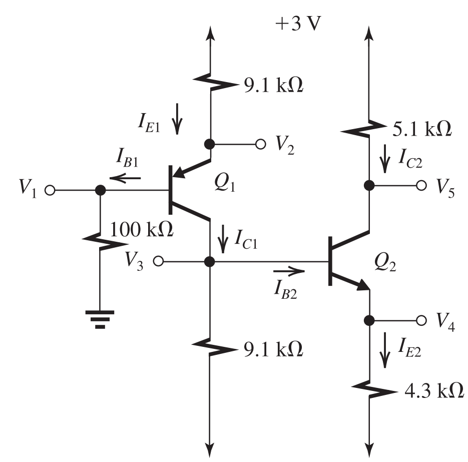


Figure 2 ($\beta = 100$)

This figure belongs to Problem 6.66, part (a).

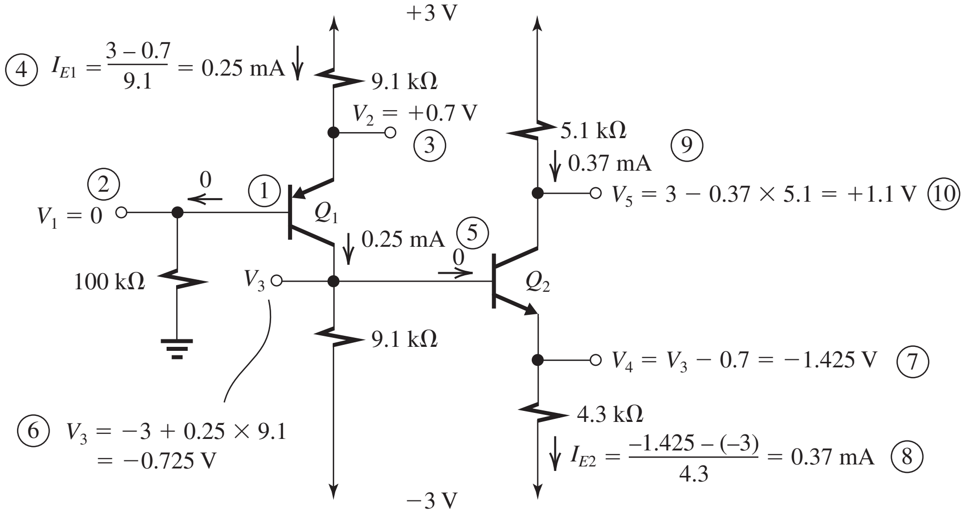


Figure 1 $(\beta = \infty)$

By reference to Fig. 2 on page 26, we can write an equation for the loop containing the EBJ of Q_1 as follows:

$3 = I_{E1} \times 9.1 + 0.7 + I_{B1} \times 100$

Substituting $I_{B1} = I_E/(\beta + 1) = I_E/101$ and rearranging, we obtain

$$I_{E1} = \frac{3 - 0.7}{9.1 + \frac{100}{101}} = 0.228 \text{ mA}$$

Thus,

$$I_{B1} = \frac{I_{E1}}{101} = 0.0023 \text{ mA}$$

$V_2 = V_1 + 0.7 = 0.93$ V

$I_{C1} = \alpha I_{E1} = 0.99 \times 0.228 = 0.226$ mA

Then we write a node equation at C_1:

$$I_{C1} = I_{B2} + \frac{V_3 - (-3)}{9.1}$$

Substituting for $I_{C1} = 0.226$ mA, $I_{B2} = I_{E2}/101$, and $V_3 = V_4 + 0.7 = -3 + I_{E2} \times 4.3 + 0.7$ gives

$$0.226 = \frac{I_{E2}}{101} + \frac{-3 + 4.3I_{E2} + 0.7 + 3}{9.1}$$

$$= \frac{I_{E2}}{101} + \frac{4.3I_{E2}}{9.1} + \frac{0.7}{9.1}$$

$\Rightarrow I_{E2} = 0.31$ mA

$I_{B2} = 0.0031$

$I_{C1} - I_{B2} = 0.226 - 0.0031 = 0.223$ mA

$V_3 = -3 + 0.223 \times 9.1 = -0.97 \text{ V} \simeq -1$ V

$V_4 = V_3 - 0.7 = -1.7$ V

$I_{C2} = \alpha I_{E2} = 0.99 \times 0.31 = 0.3$ mA

$V_{C2} = +3 - 0.3 \times 5.1 = +1.47$ V

6.67 Figure 1 on page 28 shows the circuit with $\beta = \infty$; the required voltage values are indicated. The resistor values are obtained as follows:

$V_2 = -0.7$ V

$$R_1 = \frac{V_2 - (-5)}{0.5 \text{ mA}}$$

$\Rightarrow R_1 = 8.6$ kΩ

$$R_2 = \frac{5 - V_3}{0.5} = \frac{5 - 0}{0.5} = 10 \text{ k}\Omega$$

$V_4 = 0 + 0.7 = 0.7$ V

$$R_3 = \frac{5 - V_4}{0.5} = \frac{5 - 0.7}{0.5} = 8.6 \text{ k}\Omega$$

$$R_4 = \frac{V_5 - (-5)}{0.5} = \frac{-2 + 5}{0.5} = 6 \text{ k}\Omega$$

$V_6 = V_5 - 0.7 = -2 - 0.7 = -2.7$ V

$$R_6 = \frac{V_6 - (-5)}{1} = \frac{-2.7 + 5}{1} = 2.3 \text{ k}\Omega$$

$$R_5 = \frac{5 - V_7}{1} = \frac{5 - 1}{1} = 4 \text{ k}\Omega$$

Consulting the table of 5% resistors in Appendix J, we select the following resistor values:

$R_1 = 8.2$ kΩ $\quad R_2 = 10$ kΩ $\quad R_3 = 10$ kΩ

$R_4 = 6.2$ kΩ $\quad R_5 = 3.9$ kΩ $\quad R_6 = 2.4$ kΩ

The circuit with the selected resistor values is shown in Fig. 2. Analysis of the circuit proceeds as follows:

$V_2 = -0.7$ V

This figure belongs to Problem 6.67.

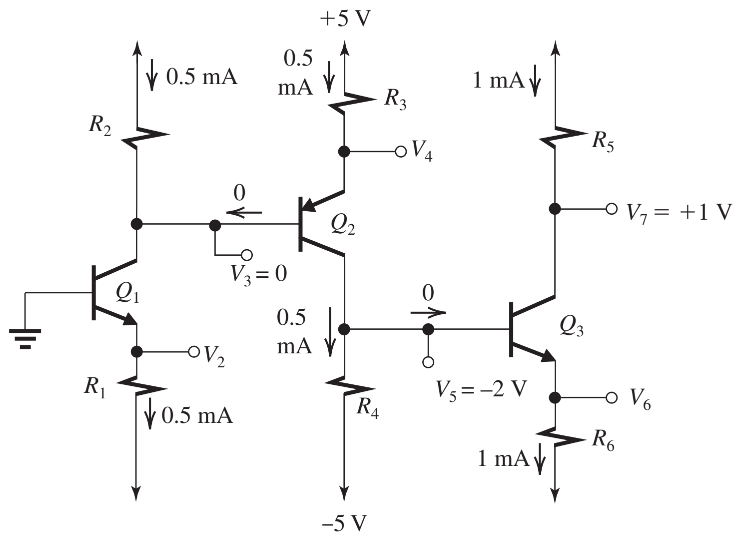


Figure 1

This figure belongs to Problem 6.67.

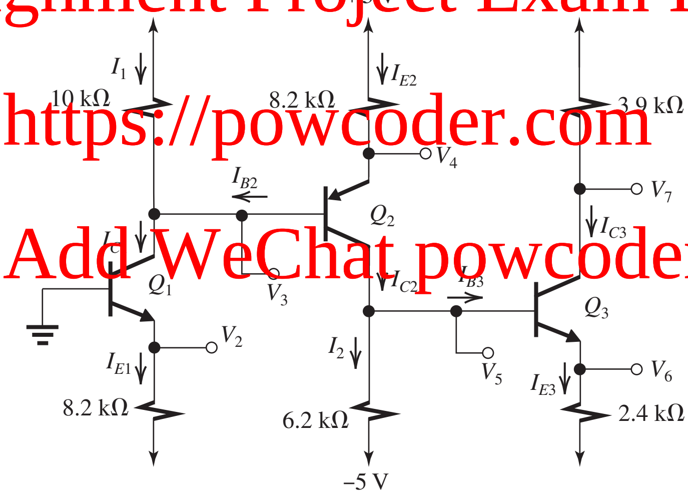


Figure 2

$$I_{E1} = \frac{V_2 - (-5)}{8.2} = \frac{-0.7 + 5}{8.2} = 0.524 \text{ mA}$$

$$I_{C1} = \alpha I_{E1} = 0.99 \times 0.524 = 0.52 \text{ mA}$$

The current I_1 through the 10-kΩ resistor is given by

$$I_1 = I_{C1} - I_{B2} = I_{C1} - \frac{I_{E2}}{101}$$

Noting that the voltage drop across the 10 kΩ resistor is equal to $(I_{E2} \times 8.2 + 0.7)$, we can write

$$I_1 \times 10 = 8.2 I_{E2} + 0.7$$

Thus,

$$10\left(0.52 - \frac{I_{E2}}{101}\right) = 8.2 I_{E2} + 0.7$$

$$\Rightarrow I_{E2} = 0.542 \text{ mA}$$

$$V_4 = 5 - 0.542 \times 8.2 = 0.56 \text{ V}$$

$$V_3 = 0.56 - 0.7 = -0.14 \text{ V}$$

$$I_{C2} = \alpha I_{E2} = 0.99 \times 0.542 = 0.537 \text{ mA}$$

$$I_2 = I_{C2} - I_{B3} = 0.537 - \frac{I_{E3}}{101}$$

Since the voltage drop across the 6.2-kΩ resistor is equal to $(0.7 + I_{E3} \times 2.4)$,

$$I_2 \times 6.2 = 0.7 + 2.4 I_{E3}$$

$$6.2\left(0.537 - \frac{I_{E3}}{101}\right) = 0.7 + 2.4 I_{E3}$$

$$\Rightarrow I_{E3} = 1.07 \text{ mA}$$

$V_6 = -5 + 1.07 \times 2.4 = -2.43$ V

$V_5 = V_6 + 0.7 = -1.73$

$I_{C3} = \alpha \times I_{E3} = 0.99 \times 1.07 = 1.06$ mA

$V_7 = -3.9 \times 1.06 = 0.87$ V

6.68 Refer to the circuit in Fig. P6.68.

(a) For $v_I = 0$, both transistors are cut off and all currents are zero. Thus

$V_B = 0$ V and $V_E = 0$ V

(b) For $v_I = +2$ V, Q_1 will be conducting and Q_2 will be cut off, and the circuit reduces to that in Fig. 1.

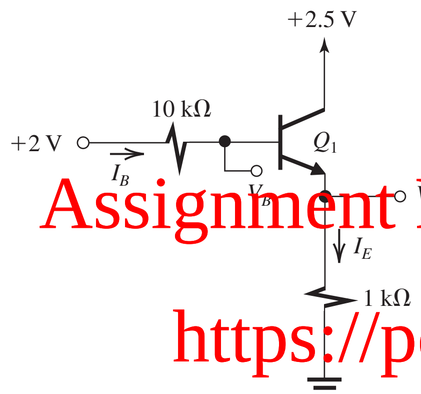


Figure 1

Since V_B will be lower than +2 V, V_C will be higher than V_B and the transistor will be operating in the active mode. Thus,

$$I_E = \frac{2 - 0.7}{1 + \frac{10}{51}} = 1.1 \text{ mA}$$

$V_E = +1.1$ V

$V_B = 1.8$ V

(c) For $v_I = -2.5$, Q_1 will be off and Q_2 will be on, and the circuit reduces to that in Fig. 2.

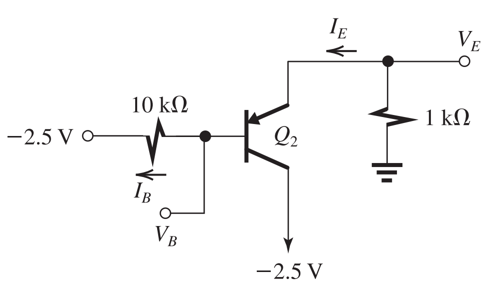


Figure 2

Since $V_B > -2.5$, V_C will be lower than V_B and Q_2 will be operating in the active region. Thus

$$I_E = \frac{2.5 - 0.7}{1 + \frac{10}{51}} = 1.5 \text{ mA}$$

$V_E = -I_E \times 1 = -1.5$ V

$V_B = -1.5 - 0.7 = -2.2$ V

(d) For $v_I = -5$ V, Q_1 will be off and Q_2 will be on, and the circuit reduces to that in Fig. 3.

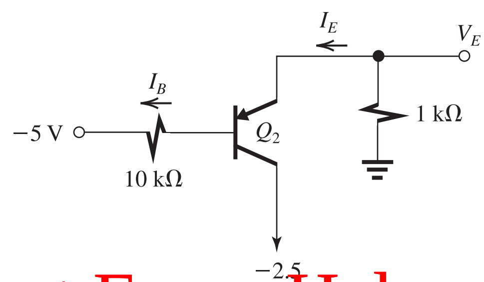


Figure 3

Here we do not know whether Q_2 is operating in the active mode or in saturation. Assuming active-mode operation, we obtain

$$I_E = \frac{5 - 0.7}{1 + \frac{10}{51}} = 3.6 \text{ mA}$$

$V_E = -3.6$ V

$V_B = -4.3$ V

which is impossible, indicating that our original assumption is incorrect and that Q_2 is saturated. Assuming saturation-mode operation, we obtain

$V_E = V_C + V_{ECsat} = -2.5 + 0.2 = -2.3$ V

$$I_E = \frac{-V_E}{1 \text{ k}\Omega} = 2.3 \text{ mA}$$

$V_B = V_E - 0.7 = -3$ V

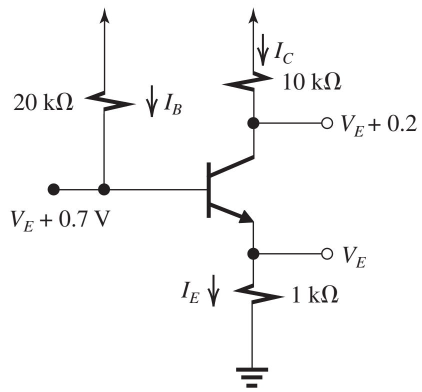
$$I_B = \frac{-3 - (-5)}{10} = 0.2 \text{ mA}$$

$I_C = I_E - I_B = 2.3 - 0.2 = 2.1$ mA

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{2.1}{0.2} = 10.5$$

which is lower than β, verifying that Q_2 is operating in saturation.

6.69 (a)



(a)

Assuming saturation-mode operation, the terminal voltages are interrelated as shown in the figure, which corresponds to Fig. P6.69(a). Thus we can write

$$I_E = \frac{V_E}{1} = V_E$$

$$I_C = \frac{5 - (V_E + 0.2)}{10} = 0.5 - 0.1(V_E + 0.2)$$

$$I_B = \frac{5 - (V_E + 0.7)}{20} = 0.25 - 0.05(V_E + 0.7)$$

Now, imposing the constraint

$$I_E = I_C + I_B$$

results in

$$V_E = 0.5 - 0.1(V_E + 0.2) + 0.25 - 0.05(V_E + 0.7)$$

$$\Rightarrow V_E = 0.6 \text{ V}$$

$$V_C = 0.8 \text{ V}$$

$$V_B = 1.3 \text{ V}$$

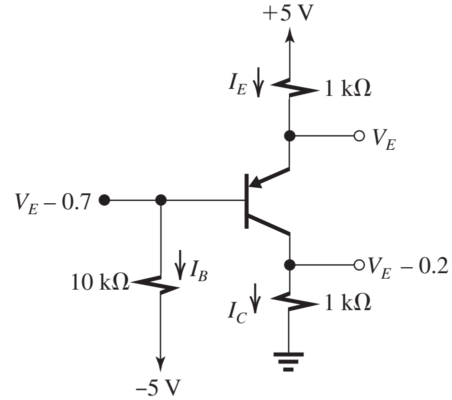
$$I_C = \frac{5 - 0.8}{10} = 0.42 \text{ mA}$$

$$I_B = \frac{5 - 1.3}{20} = 0.185 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{0.42}{0.185} = 2.3$$

which is less than the value of β_1 verifying saturation-mode operation.

(b)



(b)

Assuming saturation-mode operation, the terminal voltages are interrelated as shown in the figure, which corresponds to Fig. P6.69(b). We can obtain the currents as follows:

$$I_E = \frac{5 - V_E}{1} = 5 - V_E$$

$$I_C = \frac{V_E - 0.2}{1} = V_E - 0.2$$

$$I_B = \frac{V_E - 0.7 - (-5)}{10} = 0.1\ V_E + 0.43$$

Imposing the constraint

$$I_E = I_B + I_C$$

results in

$$5 - V_E = V_E - 0.2 + 0.1\ V_E + 0.43$$

$$\Rightarrow V_E = +2.27 \text{ V}$$

$$V_C = +2.07 \text{ V}$$

$$V_B = 1.57 \text{ V}$$

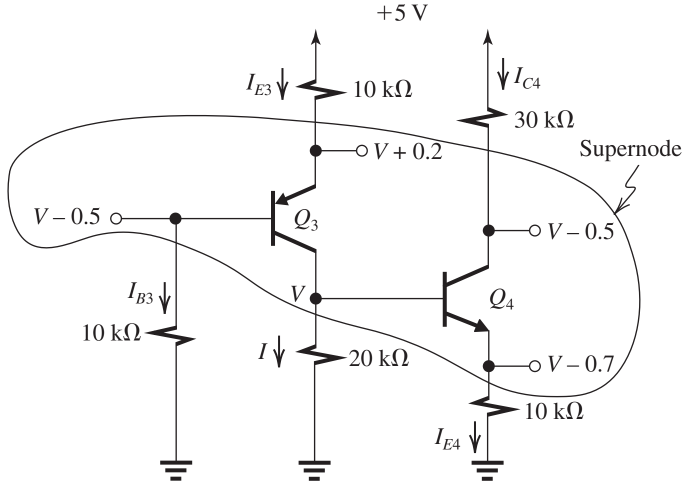
$$I_C = \frac{2.07}{1} = 2.07 \text{ mA}$$

$$I_B = \frac{1.57 - (-5)}{10} = 0.657 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{2.07}{0.657} = 3.2$$

which is lower than the value of β, verifying saturation-mode operation.

This figure belongs to Problem 6.69, part (c).



(c)

(c) We shall assume that both Q_3 and Q_4 are operating in saturation. To begin the analysis shown in the figure, which corresponds to Fig. P6.69(c), we denote the voltage at the emitter of Q_3 as V and then obtain the voltages at all other nodes in terms of V, utilizing the fact that a saturated transistor has $|V_{CE}| = 0.2$ V and of course $|V_{BE}| = 0.7$ V. Note that the choice of the collector node to begin the analysis is arbitrary; we could have selected any other node and denoted its voltage as V. We next draw a circle around the two transistors to define a "supernode." A node equation for the supernode will be

$$I_{E3} + I_{C4} = I_{B3} + I + I_{E4} \qquad (1)$$

where

$$I_{E3} = \frac{5 - (V + 0.2)}{10} = 0.48 - 0.1V \qquad (2)$$

$$I_{C4} = \frac{5 - (V - 0.5)}{30} = 0.183 - 0.033V \qquad (3)$$

$$I_{B3} = \frac{5 - (V - 0.5)}{10} = 0.1V - 0.05 \qquad (4)$$

$$I = \frac{V}{20} = 0.05V \qquad (5)$$

$$I_{E4} = \frac{V - 0.7}{10} = 0.1V - 0.07 \qquad (6)$$

Substituting from Eqs. (2)–(6) into Eq. (1) gives

$$0.48 - 0.1V + 0.183 - 0.033V$$
$$= 0.1V - 0.05 + 0.05V + 0.1V - 0.07$$

$$\Rightarrow V = 2.044 \text{ V}$$

Thus

$$V_{E3} = V = 2.044 \text{ V}$$

$$V_{C4} = V - 0.5 = 1.54 \text{ V}$$

Next we determine all currents utilizing Eqs. (2)–(6):

$$I_{E3} = 0.276 \text{ mA}\ I_{C4} = 0.116 \text{ mA}$$

$$I_{B3} = 0.154 \text{ mA}\ I = 0.102 \text{ mA}$$

$$I_{E4} = 0.134$$

The base current of Q_4 can be obtained from

$$I_{B4} = I_{E4} - I_{C4} = 0.134 - 0.116 = 0.018 \text{ mA}$$

Finally, the collector current of Q_3 can be found as

$$I_{C3} = I + I_{B4} = 0.102 + 0.018 = 0.120$$

The forced β values can now be found as

$$\beta_{\text{forced3}} = \frac{I_{C3}}{I_{B3}} = \frac{0.120}{0.154} = 0.8$$

$$\beta_{\text{forced4}} = \frac{I_{C4}}{I_{B4}} = \frac{0.116}{0.018} = 6.4$$

Both β_{forced} values are well below the β value of 50, verifying that Q_3 and Q_4 are in deep saturation.