

CHAPTER 5

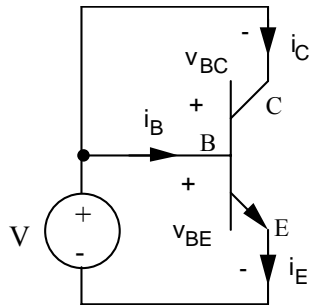
5.1

Base Contact = B
n-type Emitter = D

Collector Contact = A
n-type Collector = F

Emitter Contact = C
Active Region = E

5.2

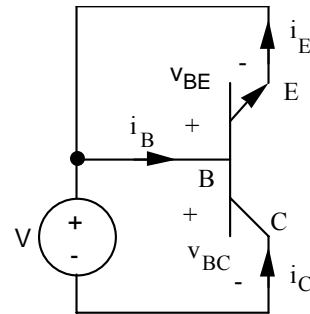


For $V_{BE} > 0$ and $V_{BC} = 0$, $I_C = \beta_F I_B$ or $\beta_F = \frac{I_C}{I_B} = \frac{275\mu A}{4\mu A} = 68.8$

$$\beta_R = \frac{\alpha_R}{1 - \alpha_R} = \frac{0.5}{1 - 0.5} = 1$$

$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \text{ or } I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{275\mu A}{\exp\left(\frac{0.64}{0.025}\right)} = 2.10 \text{ fA}$$

5.3



For $V_{BC} > 0$ and $V_{BE} = 0$, $I_E = -\beta_R I_B$ or $\beta_R = -\frac{I_E}{I_B} = -\left(\frac{-275\mu A}{125\mu A}\right) = 2.20$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F} = \frac{0.975}{1 - 0.975} = 39$$

$$I_E = -I_S \exp\left(\frac{V_{BC}}{V_T}\right) \text{ or } I_S = \frac{I_C}{\exp\left(\frac{V_{BE}}{V_T}\right)} = \frac{275\mu A}{\exp\left(\frac{0.63}{0.025}\right)} = 3.13 \text{ fA}$$

5.4

Using $\beta = \frac{\alpha}{1-\alpha}$ and $\alpha = \frac{\beta}{\beta+1}$:

Table 5.P1	
□	□
0.167	0.200
0.400	0.667
0.750	3.00
0.909	10.0
0.980	49.0
0.995	200
0.999	1000
0.9998	5000

5.5

(a) For this circuit, $V_{BE} = 0$ V, $V_{BC} = -5$ V and $I = I_C$. Substituting these values into the collector current expression in Eq. (5.13):

$$I_C = I_S \left[\exp\left(\frac{0}{V_T}\right) - \exp\left(\frac{-5}{0.025}\right) \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right]$$

$$I = I_C = I_S \left(1 + \frac{1}{\beta_R} \right) = 10^{-15} \text{ A} \left(1 + \frac{1}{1} \right) = 2 \text{ fA.}$$

(b) For this circuit, the constraints are $V_{BC} = -5$ V and $I_E = 0$. Substituting these values into the emitter current expression in Eq. (5.13):

$$I_E = I_S \left[\exp\left(\frac{V_{BE}}{V_T}\right) - \exp\left(\frac{V_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] = 0 \quad \text{which gives}$$

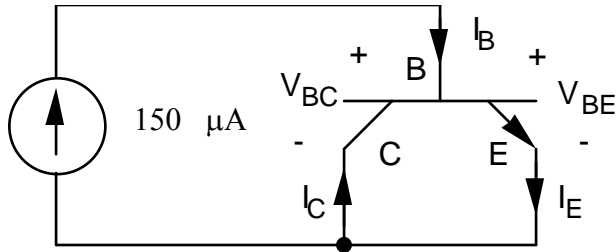
$$\exp\left(\frac{V_{BE}}{V_T}\right) = \frac{1}{1 + \beta_F} + \frac{\beta_F}{1 + \beta_F} \exp\left(\frac{V_{BC}}{V_T}\right). \quad \text{Substituting this result into } I_C :$$

$$I_{CBO} = \frac{I_S}{1 + \beta_F} \left[1 - \exp\left(\frac{V_{BC}}{V_T}\right) \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1 \right].$$

$$\text{For } V_{BC} = -5\text{V}, I_{CBO} = I_S \left[\frac{1}{1 + \beta_F} + \frac{1}{\beta_R} \right] = 10^{-15} \text{ A} \left[\frac{1}{101} + \frac{1}{1} \right] = 1.01 \text{ fA, and}$$

$$V_{BE} = V_T \ln\left(\frac{1}{1 + \beta_F}\right) = 0.025\text{V} \ln\left(\frac{1}{101}\right) = -0.115 \text{ V} \neq 0!$$

5.6



(a) - (c)

(b) npn transistor (d) $V_{BE} = V_{BC}$

$$(e) \quad I_C = -\frac{I_S}{\beta_R} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

$$I_E = +\frac{I_S}{\beta_F} \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

$$I_B = I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

$$\frac{I_E}{I_B} = \frac{1}{1 + \frac{\beta_F}{\beta_R}} \quad \text{and} \quad \frac{I_E}{I_C} = -\frac{\beta_R}{\beta_F}$$

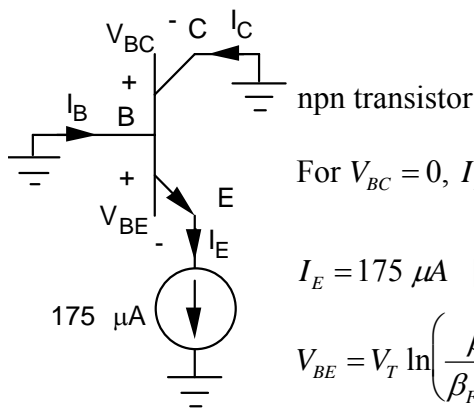
(f) Using $I_C = -\frac{\beta_F}{\beta_R} I_E = -400 I_E$ and $I_B = I_E - I_C = 401 I_E$

For the circuit $I_B = 150 \mu A$

Therefore $I_E = \frac{150 \mu A}{401} = 0.374 \mu A$, and $I_C = -149.6 \mu A$.

$$V_{BC} = V_{BE} = V_T \ln \left(\frac{I_B}{I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right)} \right) = (0.025 V) \ln \left(\frac{150 \mu A}{2 fA \left(\frac{1}{100} + \frac{1}{0.25} \right)} \right) = 0.591 V$$

5.7

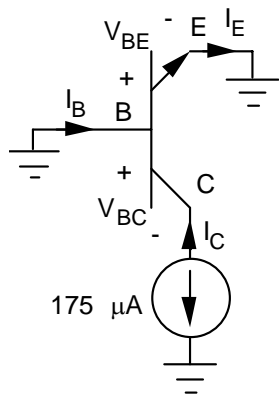


For $V_{BC} = 0$, $I_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$ | $I_B = \frac{I_E}{\beta_F + 1}$ | $I_C = \beta_F I_B$

$$I_E = 175 \mu A \quad | \quad I_B = \frac{175 \mu A}{101} = 1.73 \mu A \quad | \quad I_C = \frac{100}{101} 175 \mu A = 173 \mu A$$

$$V_{BE} = V_T \ln \left(\frac{\beta_F}{\beta_F + 1} \frac{I_E}{I_S} + 1 \right) = 0.025 V \ln \left(\frac{100}{101} \frac{175 \mu A}{2 fA} + 1 \right) = 0.630 V$$

5.8



nnp transistor

For $V_{BE} = 0$, $I_C = -I_S \left(1 + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1 \right]$ | $I_B = -\frac{I_C}{\beta_R + 1}$ | $I_E = -\beta_R I_B$

$I_C = -175 \mu\text{A}$ | $I_B = -\left(\frac{-175 \mu\text{A}}{1.25}\right) = 140 \mu\text{A}$ | $I_E = -\frac{0.25}{1.25} 175 \mu\text{A} = -35 \mu\text{A}$

$V_{BC} = V_T \ln\left(-\frac{\beta_R}{\beta_R + 1} \frac{I_C}{I_S} + 1\right) = 0.025\text{V} \ln\left(\frac{0.25}{1.25} \frac{175 \mu\text{A}}{2 \text{fA}} + 1\right) = 0.590 \text{V}$

5.9

Using $v_{BC} = 0$ in Eq. 5.13 and recognizing that $i = i_C + i_B = i_E$:

$$i = i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right], \text{ and the reverse saturation current}$$

of the diode connected transistor is $I'_S = I_S \left(1 + \frac{1}{\beta_F} \right) = (2 \text{fA}) \left(1 + \frac{1}{100} \right) = 2.02 \text{fA}$

5.10

Using $v_{BE} = 0$ in Eq. 5.13 and recognizing that $i = -i_C$:

$$i = -i_C = -I_S \left(1 + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right], \text{ and the reverse saturation current}$$

of the diode connected transistor is $I'_S = I_S \left(1 + \frac{1}{\beta_R} \right) = (5 \text{fA}) \left(1 + \frac{1}{3} \right) = 6.67 \text{fA}$

5.11

$$(a) i_T = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] = 5 \times 10^{-16} \text{A} \left[\exp\left(\frac{0.75}{0.025}\right) - \exp\left(\frac{-3}{0.025}\right) \right] = 5.34 \text{mA}$$

(b) The current is symmetric: For $V_{BC} = 0.75 \text{V}$ and $V_{BE} = -3 \text{V}$, $i_T = -5.34 \text{mA}$.

5.12

$$(a) i_T = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] = 10^{-15} \text{A} \left[\exp\left(\frac{0.70}{0.025}\right) - \exp\left(\frac{-3}{0.025}\right) \right] = 1.45 \text{mA}$$

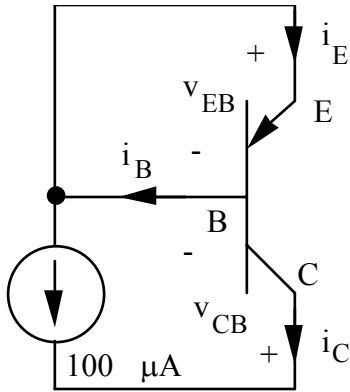
(b) The current is symmetric: For $V_{BC} = 0.70 \text{V}$ and $V_{BE} = -3 \text{V}$, $i_T = -1.45 \text{mA}$.

5.13

Base Contact = F	Collector Contact = G	Emitter Contact = E
p-type Emitter = D	p-type Collector = A	Active Region = C

5.14

(a) pnp transistor



(b)-(c)

(d) Using Eq. (5.17) with $v_{EB} = 0$ and dropping the "-1" terms:

$$i_C = -I_S \left(1 + \frac{1}{\beta_R} \right) \exp\left(\frac{v_{CB}}{V_T}\right) \quad i_E = -I_S \exp\left(\frac{v_{CB}}{V_T}\right) \quad i_B = \frac{I_S}{\beta_R} \exp\left(\frac{v_{CB}}{V_T}\right)$$

$$\frac{I_E}{I_C} = \frac{1}{1 + \frac{1}{\beta_R}} = \frac{\beta_R}{\beta_R + 1} = \alpha_R \quad \frac{I_E}{I_B} = -\beta_R$$

$$I_C = -100 \mu\text{A}, \quad I_E = \alpha_R I_C = 0.25 I_C = -25.0 \mu\text{A}$$

$$I_B = -\frac{I_E}{\beta_R} \quad \beta_R = \frac{\alpha_R}{1 - \alpha_R} = \frac{0.25}{1 - 0.25} = \frac{1}{3} \quad I_B = +75 \mu\text{A}$$

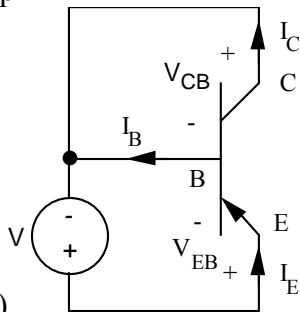
$$\beta_F = \frac{\alpha_F}{1 - \alpha_F} = \frac{0.985}{1 - 0.985} = 65.7$$

$$V_{EB} = 0 \quad \text{and} \quad I_E = -I_S \exp\left(\frac{V_{CB}}{V_T}\right) \quad V_{CB} = V_T \ln\left(-\frac{I_E}{I_S}\right)$$

$$V_{CB} = 0.025 \text{V} \ln\left(-\frac{-25 \times 10^{-6} \text{A}}{10^{-15} \text{A}}\right) = 0.599 \text{V}$$

5.15

(a) pnp



(b)-(c)

(d) Using Eq. (5.17) with $v_{CB} = 0$ and dropping the "-1" terms:

$$i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \exp\left(\frac{v_{EB}}{V_T}\right) \quad i_C = -I_S \exp\left(\frac{v_{EB}}{V_T}\right) \quad i_B = \frac{I_S}{\beta_F} \exp\left(\frac{v_{EB}}{V_T}\right)$$

$$I_S = \frac{I_C}{\exp\left(\frac{V_{EB}}{V_T}\right)} = \frac{300 \mu\text{A}}{\exp\left(\frac{0.640}{0.025\text{V}}\right)} = 2.29 \text{ fA}$$

$$\beta_F = \frac{I_C}{I_B} = \frac{300 \mu\text{A}}{4 \mu\text{A}} = 75 \quad | \quad \beta_R = \frac{\alpha_R}{1 - \alpha_R} = \frac{0.2}{1 - 0.2} = 0.25$$

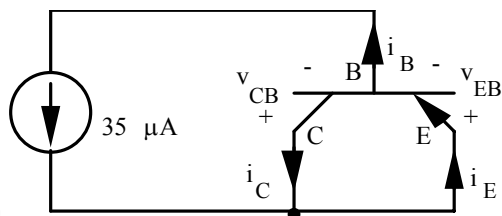
5.16

Using $V_{CB} = 0$ in Eq. 5.17 and recognizing that $i = i_E$:

$$i = i_E = I_S \left[1 + \frac{1}{\beta_F} \right] \exp\left(\frac{v_{EB}}{V_T}\right) - 1$$
, and the reverse saturation current

$$\text{of the diode connected transistor is } I'_S = I_S \left(1 + \frac{1}{\beta_F} \right) = (2 \text{ fA}) \left(1 + \frac{1}{100} \right) = 2.02 \text{ fA}$$

5.17



(a)-(c)

(b) pnp transistor(d)

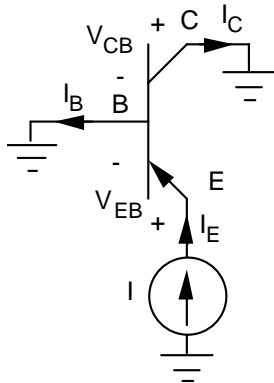
$$v_{EB} = v_{CB} \quad i_C = -\frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] \quad i_E = +\frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] \quad i_B = +I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right]$$

$$\frac{I_E}{I_B} = \frac{\frac{1}{\beta_F}}{\frac{1}{\beta_F} + \frac{1}{\beta_R}} = \frac{\beta_R}{\beta_F + \beta_R} = \frac{4}{79} = 0.0506 \quad \frac{I_E}{I_B} = -\frac{\beta_R}{\beta_F} = -\frac{4}{75} = -0.0533$$

$$I_B = 35 \mu\text{A} \quad I_E = \frac{4}{79} I_B = 1.77 \mu\text{A} \quad I_C = -\frac{75}{4} I_E = -33.2 \mu\text{A}$$

$$V_{EB} = V_T \ln \left(1 - \frac{\beta_R I_C}{I_S} \right) \quad V_{CB} = V_{EB} = 0.025\text{V} \ln \left(1 - \frac{4(-33.2 \times 10^{-6} \text{A})}{2 \times 10^{-15} \text{A}} \right) = 0.623 \text{V}$$

5.18



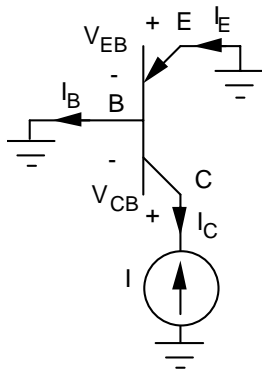
pnp transistor

$$\text{For } V_{CB} = 0, I_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp \left(\frac{V_{EB}}{V_T} \right) - 1 \right] \quad | \quad I_B = \frac{I_E}{\beta_F + 1} \quad | \quad I_C = \beta_F I_B$$

$$I_E = 300 \mu\text{A} \quad | \quad I_B = \frac{300 \mu\text{A}}{101} = 2.97 \mu\text{A} \quad | \quad I_C = 100(2.97 \mu\text{A}) = 297 \mu\text{A}$$

$$V_{EB} = V_T \ln \left[\left(\frac{\beta_F}{\beta_F + 1} \right) \frac{I_E}{I_S} + 1 \right] = 0.025\text{V} \ln \left[\left(\frac{100}{101} \right) \frac{300 \mu\text{A}}{4 \text{fA}} + 1 \right] = 0.626 \text{V}$$

5.19



pnp transistor

$$\text{For } V_{EC} = 0, I_C = -I_S \left(1 + \frac{1}{\beta_R} \right) \left[\exp \left(\frac{V_{CB}}{V_T} \right) - 1 \right] \quad | \quad I_B = -\frac{I_C}{\beta_R + 1} \quad | \quad I_E = -\beta_R I_B$$

$$I_C = -300 \mu\text{A} \quad | \quad I_B = -\left(\frac{-300 \mu\text{A}}{2} \right) = 150 \mu\text{A} \quad | \quad I_E = -1(150 \mu\text{A}) = -150 \mu\text{A}$$

$$V_{CB} = V_T \ln \left[-\left(\frac{\beta_R}{\beta_R + 1} \right) \frac{I_C}{I_S} + 1 \right] = 0.025\text{V} \ln \left[-\frac{1}{2} \left(\frac{-300 \mu\text{A}}{5 \text{fA}} \right) + 1 \right] = 0.603 \text{V}$$

5.20

$$(a) i_T = I_S \left[\exp \left(\frac{v_{EB}}{V_T} \right) - \exp \left(\frac{v_{CB}}{V_T} \right) \right] = 5 \times 10^{-16} \text{A} \left[\exp \left(\frac{0.70}{0.025} \right) - \exp \left(\frac{-3}{0.025} \right) \right] = 723 \mu\text{A}$$

(b) The current is symmetric: For $V_{CB} = 0.75 \text{V}$ and $V_{EB} = -3 \text{V}$, $i_T = -723 \mu\text{A}$.

5.21

$$(a) i_F = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} \text{ A} \left[\exp\left(\frac{0.73\text{V}}{0.025\text{V}}\right) - 1 \right] = 19.2 \text{ mA}$$

$$i_R = I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} \text{ A} \left[\exp\left(\frac{-3\text{V}}{0.025\text{V}}\right) - 1 \right] = -4.00 \text{ fA}$$

$$i_T = i_F - i_R = 19.2 \text{ mA} \quad \left| \quad \frac{i_F}{\beta_F} = \frac{19.2\text{mA}}{80} = 240 \text{ } \mu\text{A} \quad \left| \quad \frac{i_R}{\beta_R} = \frac{-4.00\text{fA}}{2} = -2.00 \text{ } \mu\text{A} \right.$$

$$(b) i_F = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} \text{ A} \left[\exp\left(\frac{-3\text{V}}{0.025\text{V}}\right) - 1 \right] = -4.00 \text{ fA}$$

$$i_R = I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = 4 \times 10^{-15} \text{ A} \left[\exp\left(\frac{0.73\text{V}}{0.025\text{V}}\right) - 1 \right] = 19.2 \text{ mA}$$

$$i_T = i_F - i_R = -19.2 \text{ mA} \quad \left| \quad \frac{i_F}{\beta_F} = \frac{-4.00\text{fA}}{80} = -0.05 \text{ } \mu\text{A} \quad \left| \quad \frac{i_R}{\beta_R} = \frac{19.2\text{mA}}{2} = 9.60 \text{ mA} \right.$$

5.22

$$(a) i_F = I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} \text{ A} \left[\exp\left(\frac{0.68\text{V}}{0.025\text{V}}\right) - 1 \right] = 3.90 \text{ mA}$$

$$i_R = I_S \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} \text{ A} \left[\exp\left(\frac{-3\text{V}}{0.025\text{V}}\right) - 1 \right] = -6.00 \text{ fA}$$

$$i_T = i_F - i_R = 3.90 \text{ mA} \quad \left| \quad \frac{i_F}{\beta_F} = \frac{3.90\text{mA}}{60} = 65.0 \text{ } \mu\text{A} \quad \left| \quad \frac{i_R}{\beta_R} = \frac{-6.00\text{fA}}{3} = -2.00 \text{ } \mu\text{A} \right.$$

$$(b) i_F = I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} \text{ A} \left[\exp\left(\frac{-3\text{V}}{0.025\text{V}}\right) - 1 \right] = -6.00 \text{ fA}$$

$$i_R = I_S \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] = 6 \times 10^{-15} \text{ A} \left[\exp\left(\frac{0.68\text{V}}{0.025\text{V}}\right) - 1 \right] = 3.90 \text{ mA}$$

$$i_T = i_F - i_R = -3.90 \text{ mA} \quad \left| \quad \frac{i_F}{\beta_F} = \frac{-6.00\text{fA}}{60} = -0.100 \text{ fA} \quad \left| \quad \frac{i_R}{\beta_R} = \frac{3.90\text{mA}}{3} = 1.30 \text{ mA} \right.$$

5.23

$$i_E = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 - \exp\left(\frac{v_{BC}}{V_T}\right) + 1 \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right]$$

$$i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 - \exp\left(\frac{v_{BC}}{V_T}\right) + 1 \right] - I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = \frac{I_S}{\alpha_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

$$i_C = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 - \exp\left(\frac{v_{BC}}{V_T}\right) + 1 \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

$$i_C = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - I_S \left(1 + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - \frac{I_S}{\alpha_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

Defining $I_{ES} = \frac{I_S}{\alpha_F}$ and $I_{CS} = \frac{I_S}{\alpha_R}$, then we see $I_S = \alpha_F I_{ES} = \alpha_R I_{CS}$ and

$$i_E = I_{ES} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - \alpha_R I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

$$i_C = \alpha_F I_{ES} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] - I_{CS} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

$$i_B = i_E - i_C = (1 - \alpha_F) I_{ES} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right] + (1 - \alpha_R) I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

5.24

$$\alpha_F = \frac{\beta_F}{\beta_F + 1} = \frac{100}{101} = 0.990 \quad | \quad \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.5}{1.5} = 0.333 \quad | \quad I_{ES} = \frac{I_S}{\alpha_F} = \frac{2 \text{ fA}}{0.990} = 2.02 \text{ fA}$$

$$I_{CS} = \frac{I_S}{\alpha_R} = \frac{2 \text{ fA}}{0.333} = 6.00 \text{ fA} \quad | \quad \alpha_F I_{ES} = \alpha_R I_{CS} = I_S$$

5.25

$$i_E = I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 - \exp\left(\frac{v_{CB}}{V_T}\right) + 1 \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - I_S \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right]$$

$$i_C = I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 - \exp\left(\frac{v_{CB}}{V_T}\right) + 1 \right] - \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right] = I_S \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - I_S \left(1 + \frac{1}{\beta_R} \right) \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right]$$

$$i_E = I_{ES} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - \alpha_R I_{CS} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right]$$

$$i_C = \alpha_F I_{ES} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] - I_{CS} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right]$$

$$i_B = i_E - i_C = (1 - \alpha_F) I_{ES} \left[\exp\left(\frac{v_{EB}}{V_T}\right) - 1 \right] + (1 - \alpha_R) I_{CS} \left[\exp\left(\frac{v_{CB}}{V_T}\right) - 1 \right]$$

5.26

At $I_C = 5 \text{ mA}$ and $V_{CE} = 5 \text{ V}$, $I_B = 60 \mu\text{A}$: $\beta_F = \frac{I_C}{I_B} = \frac{5 \text{ mA}}{60 \mu\text{A}} = 83.3$

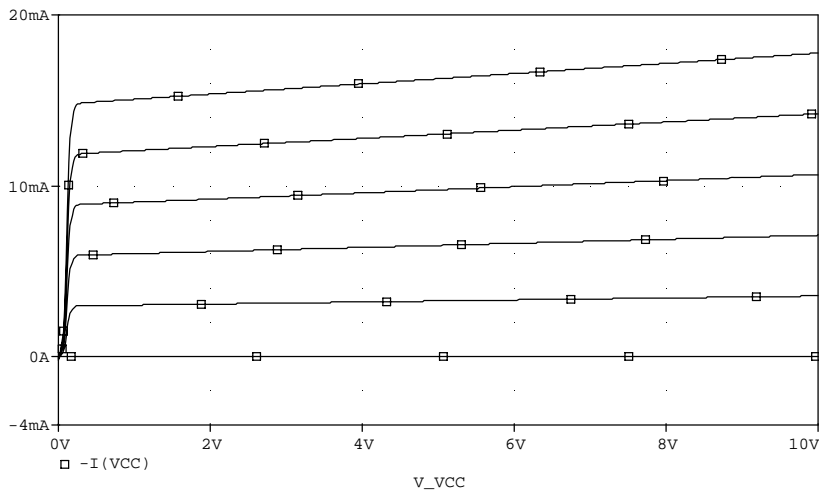
At $I_C = 7 \text{ mA}$ and $V_{CE} = 7.5 \text{ V}$, $I_B = 80 \mu\text{A}$: $\beta_F = \frac{I_C}{I_B} = \frac{7 \text{ mA}}{80 \mu\text{A}} = 87.5$

At $I_C = 10 \text{ mA}$ and $V_{CE} = 14 \text{ V}$, $I_B = 100 \mu\text{A}$: $\beta_F = \frac{I_C}{I_B} = \frac{10 \text{ mA}}{100 \mu\text{A}} = 100$

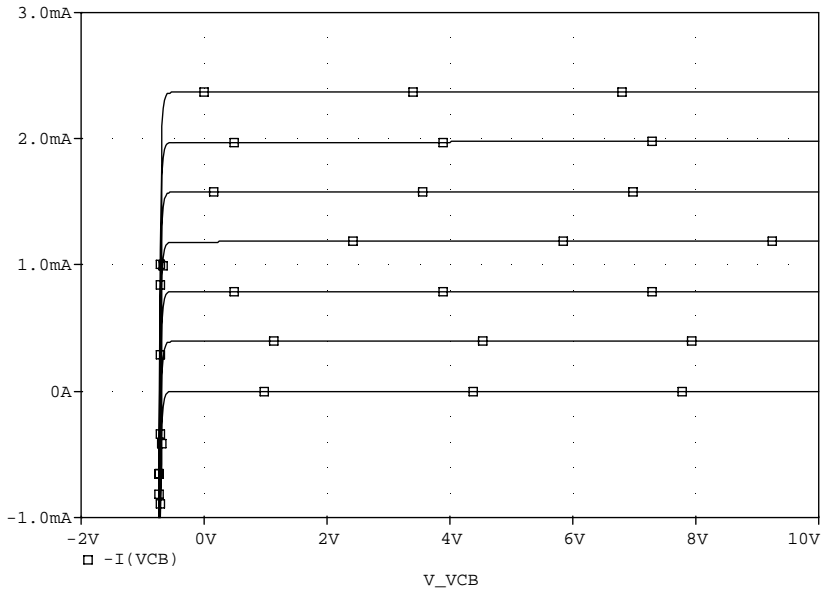
5.27

See Problem 5.28

5.28



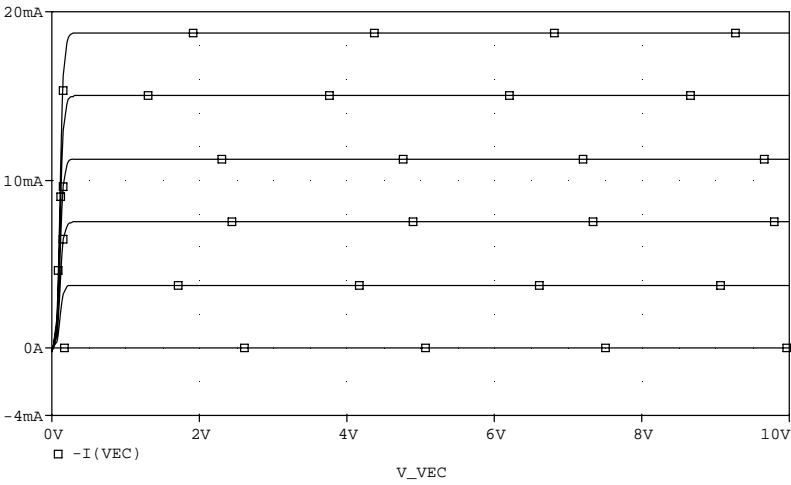
5.29



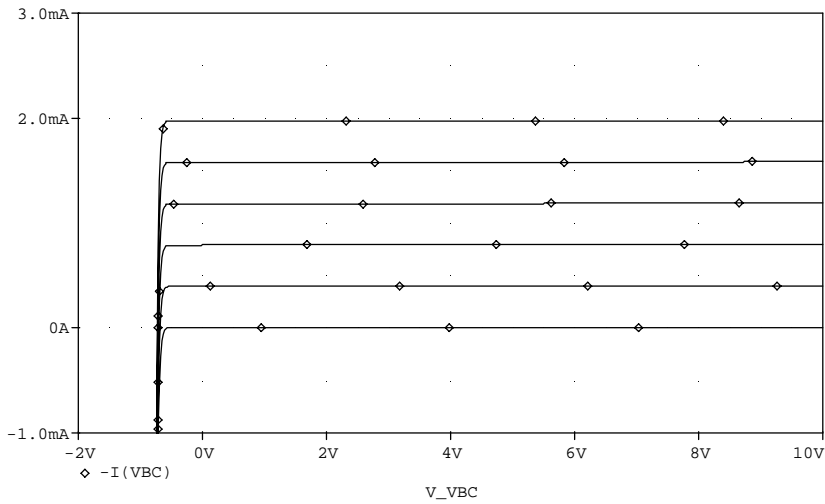
5.30

See Problem 5.31

5.31



5.32



5.33

The change in v_{BE} for a decade change in i_C is $\Delta V_{BE} = V_T \ln(10) = 2.30V_T$.

The reciprocal of the slope is $2.30V_T = 2.30 \frac{kT}{q} = 2.30 \left(\frac{1.38 \times 10^{-23}}{1.60 \times 10^{-19}} \right) T$ (V/dec)

(a) 39.6 mV/dec (b) 49.5 mV/dec (c) 59.4 mV/dec (d) 69.3 mV/dec

5.34

(a) The break down voltage is equal to that of the emitter-base junction: $V_Z = 6$ V. (b) The break down voltage is determined by the base-collector junction: $V_Z = 50$ V. (c) The break down voltage is set by the emitter-base junction: $V_Z = 6$ V.

5.35

(a) The base-emitter junction breaks down with $V_{EB} = 6.3$ V.

$$I_R = \frac{5 - 6.3 - (-5)V}{1600 \Omega} = 2.31 \text{ mA}$$

(b) The base-emitter junction is forward biased; $V_{BE} = 0.7$ V

$$I_R = \frac{5 - 0.7 - (-5)V}{24000 \Omega} = 388 \mu\text{A}$$

(c) $V_{BE} = 0$, and the collector-base junction is reversed biased with $V_{BC} \approx -10$ V which is less than the breakdown voltage of 75 V. The transistor is operating in cutoff.

$$\text{Using Eq. (5.13), } I_R = I_C = I_S(1-0) - \frac{I_S}{\beta_R}(0-1) = I_S \left(1 + \frac{1}{\beta_R} \right) \approx 0$$

5.36

$$V_{CE} = V_{CB} + V_{BE} = V_{CB} + 0.7 \leq 65.7 \text{ V}$$

5.37

(a) I_B is forced to be negative by the current source, and the largest negative base current according to the Transport model is

$$I_B = -I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) = -10^{-15} \text{ A} \left(\frac{1}{50} + \frac{1}{0.5} \right) = -2.02 \text{ fA}$$

(b) I_B is forced to be -1 mA by the current source. One or both of the junctions must enter the breakdown region in order to supply this current. For the case of a normal BJT, the base-emitter junction will break down and supply the current since it has the lower reverse breakdown voltage.

5.38

Base-Emitter Voltage	Base-Collector Voltage	
	0.7 V	-5.0 V
-5.0 V	Reverse Active	Cutoff
0.7 V	Saturation	Forward Active

5.39

(a) $v_{BE} > 0$, $v_{BC} = 0$, forward-active region; $v_{BE} = 0$, $v_{BC} > 0$, reverse-active region; $v_{BE} > 0$, $v_{BC} = 0$, forward-active region

(b) $v_{EB} < 0$, $v_{CB} < 0$, cutoff region

(c) $v_{EB} > 0$, $v_{CB} < 0$, forward-active region

(d) $v_{BE} > 0$, $v_{BC} < 0$, forward-active region; $v_{BE} > 0$, $v_{BC} > 0$, saturation region

5.40

(a) $v_{BE} = 0$, $v_{BC} < 0$ cutoff region

(b) $v_{BC} < 0$, $I_E = 0$, cutoff region

5.41

(a) $v_{BE} > 0$, $v_{BC} > 0$ saturation region

(b) $v_{BE} > 0$, $v_{BC} = 0$, forward-active region

(c) $v_{BE} = 0$, $v_{BC} > 0$, reverse-active region

5.42

Emitter-Base Voltage	Collector-Base Voltage	
	0.7 V	-0.65 V
0.7 V	Saturation	Forward Active
-0.65 V	Reverse Active	Cutoff

5.43

- (a) $v_{BE} > 0$, $v_{BC} = 0$, forward-active region
 (b) $v_{BE} = 0$, $v_{BC} > 0$, reverse-active region

5.44

- (a) $v_{EB} = 0$, $v_{CB} > 0$, reverse-active region
 (b) $v_{EB} > 0$, $v_{CB} = 0$, forward-active region

5.45

- (a) $v_{EB} > 0$, $v_{CB} > 0$, saturation region
 (b) $v_{EB} > 0$, $v_{CB} = 0$, forward-active region
 (c) $v_{EB} = 0$, $v_{CB} > 0$, reverse-active region

5.46

(a) pnp transistor with $V_{EB} = -3V$ and $V_{CB} = -3V \rightarrow Cutoff$ | Using Eq. (5.17):

$$I_C = +\frac{I_S}{\beta_R} = \frac{10^{-15} A}{2} = 0.5 \times 10^{-15} = 0.5 \text{ fA} \quad | \quad I_E = -\frac{I_S}{\beta_F} = \frac{10^{-15} A}{75} = 13.3 \times 10^{-18} = 13.3 \text{ aA}$$

$$I_B = -I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right) = 10^{-15} A \left(\frac{1}{75} + \frac{1}{4} \right) = 0.263 \times 10^{-15} = 0.263 \text{ fA}$$

(b) npn transistor with $V_{BE} = -5V$ and $V_{BC} = -5V \rightarrow Cutoff$ | The currents are the same as in part (a).

5.47

$$i_C = 10^{-16} \left[\exp\left(\frac{0.3}{0.025}\right) - \exp\left(\frac{-5}{0.025}\right) \right] - \frac{10^{-16}}{1} \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right] = 16.3 \text{ pA}$$

$$i_E = 10^{-16} \left[\exp\left(\frac{0.3}{0.025}\right) - \exp\left(\frac{-5}{0.025}\right) \right] + \frac{10^{-16}}{19} \left[\exp\left(\frac{0.3}{0.025}\right) - 1 \right] = 17.1 \text{ pA}$$

$$i_B = \frac{10^{-16}}{19} \left[\exp\left(\frac{0.3}{0.025}\right) - 1 \right] + \frac{10^{-16}}{1} \left[\exp\left(\frac{-5}{0.025}\right) - 1 \right] = 0.857 \text{ pA}$$

These currents are all very small - for most practical purposes it still appears to be cutoff. Since $V_{BE} > 0$ and $V_{BC} < 0$, the transistor is actually operating in the forward-active region. Note that $I_C = \beta_F I_B$.

5.48

An npn transistor with $V_{BE} = 0.7V$ and $V_{BC} = -0.7V \rightarrow$ Forward - active region

$$\text{Using Eq. (5.45): } I_E = (\beta_F + 1)I_B \quad | \quad \beta_F = \frac{I_E}{I_B} - 1 = \frac{10mA}{0.15mA} - 1 = 65.7$$

$$I_E = I_S \left(1 + \frac{1}{\beta_F} \right) \exp\left(\frac{V_{BE}}{V_T}\right) \quad | \quad I_S = \frac{0.01A}{\left(1 + \frac{1}{65.7} \right) \exp\left(\frac{0.7}{0.025}\right)} = 6.81 \times 10^{-15} A = 6.81 fA$$

5.49

A pnp transistor with $V_{EB} = 0.7V$ and $V_{CB} = -0.7V \Rightarrow$ Forward - active region

$$\text{Using Eq. (5.44): } \beta_F = \frac{I_C}{I_B} = \frac{2.5mA}{0.04mA} = 62.5 \quad | \quad I_C = I_S \exp\left(\frac{V_{EB}}{V_T}\right) \quad | \quad I_S = \frac{2.5mA}{\exp\left(\frac{0.7V}{0.025V}\right)} = 1.73 fA$$

5.50

$$I_E = \frac{-0.7V - (-3.3V)}{47k\Omega} = 55.3\mu A \quad | \quad I_B = \frac{I_E}{\beta_F + 1} = \frac{55.3\mu A}{81} = 0.683\mu A$$

$$I_C = \beta_F I_B = 80(0.683\mu A) = 54.6\mu A \quad | \quad \text{Check: } I_B + I_C = I_E \text{ is ok}$$

5.51

$$(a) f_\beta = \frac{f_T}{\beta_F} = \frac{500MHz}{759} = 6.67 MHz$$

$$(b) \text{ The graph represents the Bode magnitude plot. Thus } \beta(s) = \frac{\beta_F}{1 + \frac{s}{\omega_\beta}} = \frac{\beta_F \omega_\beta}{s + \omega_\beta} = \frac{\omega_T}{s + \omega_\beta}$$

$$\alpha(s) = \frac{\beta(s)}{\beta(s) + 1} = \frac{\frac{\omega_T}{s + \omega_\beta}}{\frac{\omega_T}{s + \omega_\beta} + 1} = \frac{\omega_T}{s + \omega_T + \omega_\beta} = \frac{\beta_F \omega_\beta}{s + (\beta_F + 1)\omega_\beta} = \frac{\frac{\beta_F}{\beta_F + 1}}{1 + \frac{s}{(\beta_F + 1)\omega_\beta}} \approx \frac{\alpha_F}{1 + \frac{s}{\omega_T}}$$

$$|\alpha(j\omega)| = \frac{\alpha_F}{\sqrt{1 + \left(\frac{\omega}{\omega_T}\right)^2}}$$

5.52

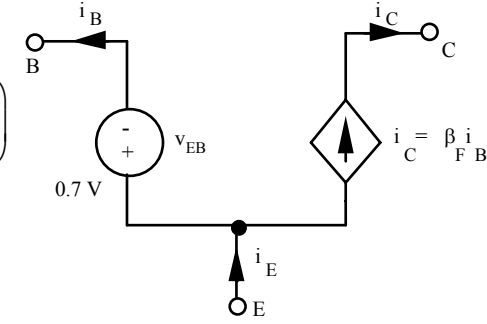
$$v_{EB} > 0 \quad v_{CB} < -4V_T$$

$$i_C = I_S \exp\left(\frac{V_{EB}}{V_T}\right) + \frac{I_S}{\beta_R} \approx I_S \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$i_E = I_S \exp\left(\frac{V_{EB}}{V_T}\right) + \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right) = \frac{I_S}{\alpha_F} \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$i_B = \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right) - \frac{I_S}{\beta_R} \approx \frac{I_S}{\beta_F} \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$i_C = \beta_F i_B \quad | \quad i_C = \alpha_F i_E$$



5.53

An npn transistor with $V_{BE} = -0.7V$ and $V_{BC} = +0.7V \rightarrow$ Reverse - active region

$$\text{Using Eq. (5.51): } I_C = -(\beta_R + 1)I_B \quad | \quad \beta_R = -\frac{I_C}{I_B} - 1 = -\frac{-75\mu A}{40\mu A} - 1 = 0.875$$

$$I_E = -I_S \exp\left(\frac{V_{BC}}{V_T}\right) \quad | \quad I_E = -35\mu A \quad | \quad I_S = -\frac{-35\mu A}{\exp\left(\frac{0.7}{0.025}\right)} = 2.42 \times 10^{-17} A = 0.0242 fA = 24.2 aA$$

5.54

A pnp transistor with $V_{EB} = -0.7 V$ and $V_{CB} = +0.7 V \rightarrow$ Reverse - active region

$$i_C = -I_S \exp\left(\frac{V_{CB}}{V_T}\right) - \frac{I_S}{\beta_R} \exp\left(\frac{V_{CB}}{V_T}\right) = -\frac{I_S}{\alpha_R} \exp\left(\frac{V_{CB}}{V_T}\right)$$

$$i_E = -I_S \exp\left(\frac{V_{CB}}{V_T}\right) - \frac{I_S}{\beta_F} \approx -I_S \exp\left(\frac{V_{CB}}{V_T}\right)$$

$$i_B = -\frac{I_S}{\beta_F} + \frac{I_S}{\beta_R} \exp\left(\frac{V_{CB}}{V_T}\right) \approx \frac{I_S}{\beta_R} \exp\left(\frac{V_{CB}}{V_T}\right)$$

$$\beta_R = -\frac{i_E}{i_B} = -\frac{(-0.1mA)}{0.15mA} = 0.667 \quad | \quad I_S = -\frac{i_E}{\exp\left(\frac{V_{CB}}{V_T}\right)} = -\frac{-10^{-4} A}{\exp\left(\frac{0.7}{0.025}\right)} = 6.91 \times 10^{-17} A$$

5.55

$$I_C = -\frac{-0.7V - (-3.3V)}{56k\Omega} = -46.4 \mu A \quad | \quad I_B = -\frac{I_C}{\beta_R + 1} = -\frac{-46.4\mu A}{1.75} = 26.5 \mu A$$

$$I_E = I_C + I_B = -46.4\mu A + 26.5\mu A = -19.9 \mu A$$

5.56

$$\beta_{FOR} = \frac{I_C}{I_B} = \frac{1mA}{1mA} = 1 \quad | \quad V_{CESAT} = V_T \ln \left[\frac{\left(\frac{1}{\alpha_R}\right)^{1 + \frac{\beta_{FOR}}{\beta_R + 1}}}{1 - \frac{\beta_{FOR}}{\beta_F}} \right] \quad | \quad \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{2}{3}$$

$$V_{CESAT} = 0.025 \ln \left[\frac{\left(\frac{3}{2}\right)^{1 + \frac{1}{2+1}}}{1 - \frac{1}{50}} \right] = 17.8 \text{ mV}$$

$$V_{BE} = V_T \ln \left[\frac{I_B + (1 - \alpha_R) I_C}{I_S \left(\frac{1}{\beta_F} + 1 - \alpha_R \right)} \right] = (0.025V) \ln \left[\frac{1mA + (1 - 0.667) 1mA}{10^{-15} A (0.02 + 1 - 0.667)} \right] = 0.724 \text{ V}$$

5.57

$$i_C = I_S \exp\left(\frac{v_{EB}}{V_T}\right) - \frac{I_S}{\alpha_R} \exp\left(\frac{v_{CB}}{V_T}\right) \quad | \quad i_B = \frac{I_S}{\beta_F} \exp\left(\frac{v_{EB}}{V_T}\right) + \frac{I_S}{\beta_R} \exp\left(\frac{v_{CB}}{V_T}\right) \quad | \quad \text{Simultaneous}$$

solution yields: $v_{EB} = V_T \ln \frac{i_B + (1 - \alpha_R) i_C}{I_S \left[\frac{1}{\beta_F} + (1 - \alpha_R) \right]}$ $|$ $v_{CB} = V_T \ln \frac{i_B - \frac{i_C}{\beta_F}}{I_S \left[\frac{1}{\alpha_R} \left[\frac{1}{\beta_F} + (1 - \alpha_R) \right] \right]}$

$$v_{ECSAT} = v_{EB} - v_{CB} = V_T \ln \left[\frac{\left(\frac{1}{\alpha_R}\right)^{1 + \frac{i_C}{(\beta_R + 1) i_B}}}{1 - \frac{i_C}{\beta_F i_B}} \right] \quad \text{for } i_B > \frac{i_C}{\beta_F}$$

5.58

(a) Substituting $i_C = 0$ in Eq. 5.30 gives

$$V_{CESAT} = V_T \ln \left(\frac{1}{\alpha_R} \right) = (0.025V) \ln \left(\frac{1}{0.5} \right) = 0.0173 \text{ V} = 17.3 \text{ mV}$$

(b) By symmetry

$$V_{ECSAT} = V_T \ln \left(\frac{1}{\alpha_F} \right)$$

or by using $i_E = 0$ and $i_C = -i_B$,

$$V_{CESAT} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{1 - \frac{1}{\beta_R + 1}}{1 + \frac{1}{\beta_F}} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{\frac{\beta_R}{\beta_R + 1}}{\frac{\beta_F}{\beta_F + 1}} = V_T \ln\left(\frac{1}{\alpha_R}\right) \frac{\alpha_R}{\frac{1}{\alpha_F}}$$

$$V_{CESAT} = V_T \ln(\alpha_F) \text{ and } V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right)$$

$$V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right) = (0.025V) \ln\left(\frac{1}{0.99}\right) = 0.000251 V = 0.251 mV$$

5.59

(a) Substituting $i_C = 0$ in Eq. 5.30 gives

$$V_{CESAT} = V_T \ln\left(\frac{1}{\alpha_R}\right) = (0.025V) \ln\left(\frac{1}{0.33}\right) = 27.7 mV$$

(b) By symmetry

$$V_{ECSAT} = V_T \ln\left(\frac{1}{\alpha_F}\right) = (0.025V) \ln\left(\frac{1}{0.95}\right) = 1.28 mV$$

5.60

$$(a) V_{CESAT} = V_T \ln\left[\frac{\left(\frac{1}{\alpha_R}\right)^{1 + \frac{\beta_{FOR}}{\beta_R + 1}}}{1 - \left(\frac{\beta_{FOR}}{\beta_F}\right)}\right] \mid \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{0.9}{0.9 + 1} = 0.4737$$

$$0.1 = 0.025 \ln\left[\frac{\left(\frac{1}{0.4737}\right)^{1 + \frac{\beta_{FOR}}{(0.9 + 1)}}}{1 - \left(\frac{\beta_{FOR}}{15}\right)}\right] \rightarrow \beta_{FOR} = 11.05$$

$$0.4737 \exp(4) = \frac{1 + \frac{\beta_{FOR}}{(0.9 + 1)}}{1 - \left(\frac{\beta_{FOR}}{15}\right)} \rightarrow \beta_{FOR} = 11.05 \mid I_B = \frac{I_C}{\beta_{FOR}} = \frac{20A}{11.05} = 1.81A$$

$$(b) 0.04 = 0.025 \ln\left[\frac{\left(\frac{1}{0.4737}\right)^{1 + \frac{\beta_{FOR}}{(0.9 + 1)}}}{1 - \left(\frac{\beta_{FOR}}{15}\right)}\right] \rightarrow \beta_{FOR} = 1.97 \mid I_B = \frac{I_C}{\beta_{FOR}} = \frac{20A}{1.97} = 10.1A$$

5.61

With $V_{BE} = 0.7$ and $V_{BC} = 0.5$, the transistor is technically in the saturation region, but calculating the currents using the transport model in Eq. (5.13) yields

$$i_C = 10^{-16} \left[\exp\left(\frac{0.7}{0.025}\right) - \exp\left(\frac{0.5}{0.025}\right) \right] - \frac{10^{-16}}{1} \left[\exp\left(\frac{0.5}{0.025}\right) - 1 \right] = 144.5 \mu A$$

$$i_E = 10^{-16} \left[\exp\left(\frac{0.7}{0.025}\right) - \exp\left(\frac{0.5}{0.025}\right) \right] + \frac{10^{-16}}{39} \left[\exp\left(\frac{0.7}{0.025}\right) - 1 \right] = 148.3 \mu A$$

$$i_B = \frac{10^{-16}}{39} \left[\exp\left(\frac{0.7}{0.025}\right) - 1 \right] + \frac{10^{-16}}{1} \left[\exp\left(\frac{0.5}{0.025}\right) - 1 \right] = 3.757 \mu A$$

At 0.5 V, the collector-base junction is not heavily forward biased compared to the base-emitter junction, and $I_C = 38.5I_B \cong \beta_F I_B$. The transistor still acts as if it is operating in the forward-active region.

5.62

(a) The current source will forward bias the base - emitter junction ($V_{BE} \cong 0.7V$) and the collector - base junction will then be reverse biased ($V_{BC} \cong -2.3V$). Therefore, the npn transistor is in the forward - active region.

$$I_C = \beta_F I_B = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \quad | \quad V_{BE} = 0.025 \ln\left(\frac{50(175 \times 10^{-6} A)}{10^{-16} A}\right) = 0.803 V$$

(b) Since $I_B = 175 \mu A$ and $I_C = 0$, $I_C < \beta_F I_B$, and the transistor is saturated.

$$\text{Using Eq. (5.53): } V_{BE} = 0.025 \ln \frac{175 \times 10^{-6} + 0}{10^{-16} \left[\frac{1}{50} + \left(1 - \frac{.5}{1.5}\right) \right]} = 0.714 V \quad | \quad \text{Using Eq. (5.54) with } i_C = 0,$$

$$V_{CESAT} = 0.025 \ln\left(\frac{1}{\alpha_R}\right) = 0.025 \ln\left(\frac{\beta_R + 1}{\beta_R}\right) = 0.025 \ln\left(\frac{1.5}{0.5}\right) = 27.5 mV$$

5.63

$$i_C = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$$

$$i_E = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right) \right] + \frac{I_S}{\beta_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1 \right]$$

$$v_{BE} > 4V_T \text{ and } v_{BC} < -4V_T$$

$$i_C \cong I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) \right] \text{ and } i_E = I_S \left(1 + \frac{1}{\beta_F} \right) \left[\exp\left(\frac{v_{BE}}{V_T}\right) \right] = \frac{I_S}{\alpha_F} \left[\exp\left(\frac{v_{BE}}{V_T}\right) \right] \rightarrow i_C \cong \alpha_F i_E$$

$$v_{BE} \cong V_T \ln\left(\frac{i_C}{I_S}\right) = V_T \ln\left(\frac{\alpha_F i_E}{I_S}\right)$$

5.64

$$I_{SD} = \frac{I_S}{\alpha_F} = \frac{1 \text{ fA}}{0.98} = 1.02 \text{ fA}$$

5.65

Both transistors are in the forward - active region. For simplicity, assume $V_A = \infty$.

$I = I_{C1} + I_{B1} + I_{B2}$ | Since the transistors are identical and have the same V_{BE} ,

$$I_{C2} = I_{C1} \text{ and } I_{B1} = I_{B2} \text{ | } I = I_{C1} + 2I_{B1} = (\beta_F + 2)I_{B1} \text{ | } I_{C2} = \beta_F I_{B2} = \beta_F I_{B1}$$

$$I_{C2} = \frac{\beta_F}{\beta_F + 2} I = \frac{25}{25 + 2} 25 \mu\text{A} \text{ | } I_{C2} = 23.2 \mu\text{A} \text{ | See the Current Mirror in Chapter 15.}$$

5.66

$$C_D = \frac{I_C}{V_T} \tau_F = \frac{50 \times 10^{-12}}{0.025} I_C = 2 \times 10^{-9} I_C \text{ (F)} \text{ (a) } 4 \text{ fF} \text{ (b) } 0.4 \text{ pF} \text{ (c) } 40 \text{ pF}$$

5.67

Using Fig. 2.8 with $N = \frac{10^{18}}{\text{cm}^3}$, $\mu_n = 260 \frac{\text{cm}^2}{\text{v-s}}$ and $\mu_p = 100 \frac{\text{cm}^2}{\text{v-s}}$

$$(a) \text{ npn : } \tau_F = \frac{W_B^2}{2D_n} = \frac{W_B^2}{2V_T \mu_n} = \frac{(1 \times 10^{-4} \text{ cm})^2}{2(0.025 \text{ V}) \left(260 \frac{\text{cm}^2}{\text{v-s}} \right)} = 0.769 \text{ ns}$$

$$(b) \text{ pnp : } \tau_F = \frac{W_B^2}{2D_p} = \frac{W_B^2}{2V_T \mu_p} = \frac{(1 \times 10^{-4} \text{ cm})^2}{2(0.025 \text{ V}) \left(100 \frac{\text{cm}^2}{\text{v-s}} \right)} = 2.00 \text{ ns}$$

5.68

For $f \gg f_\beta$, $f_T = \beta \cdot f = 10(75\text{MHz}) = 750\text{ MHz}$ | $f_\beta = \frac{f_T}{\beta_F} = \frac{750\text{MHz}}{200} = 3.75\text{ MHz}$

5.69

$\beta_F = \frac{f_T}{f_\beta} = \frac{900\text{MHz}}{5\text{MHz}} = 180$ | For $f \gg 5\text{ MHz}$, $\beta(f) = \frac{f_T}{f} = \frac{900\text{MHz}}{50\text{MHz}} = 18$

5.70

$N_A = \frac{6 \times 10^{18}}{\text{cm}^3} \rightarrow \mu_n = 130 \frac{\text{cm}^2}{\text{v-s}}$ using Fig. 2.8. $D_n = \mu_n V_T = 130 \frac{\text{cm}^2}{\text{v-s}} (0.025\text{V}) = 3.25 \frac{\text{cm}^2}{\text{s}}$

$I_S = \frac{qAD_n n_i^2}{N_A W_B} = \frac{1.60 \times 10^{-19} \text{C} (25 \times 10^{-8} \text{cm}^2) \left(3.25 \frac{\text{cm}^2}{\text{s}} \right) \left(\frac{10^{20}}{\text{cm}^6} \right)}{\frac{6 \times 10^{18}}{\text{cm}^3} (0.4 \times 10^{-4} \text{cm})} = 5.42 \times 10^{-20} \text{A}$

5.71

$W_B = \sqrt{2D_n \tau_F}$ | $\tau_F \leq \frac{1}{2\pi f} = \frac{1}{2\pi(5 \times 10^9)} = 31.8\text{ ps}$

$N_A = \frac{5 \times 10^{18}}{\text{cm}^3} \rightarrow \mu_n = 135 \frac{\text{cm}^2}{\text{v-s}}$ using Fig. 2.8.

$D_n = \mu_n V_T = 135 \frac{\text{cm}^2}{\text{v-s}} (0.025\text{V}) = 3.38 \frac{\text{cm}^2}{\text{s}}$

$W_B \leq \sqrt{2 \left(3.38 \frac{\text{cm}^2}{\text{s}} \right) 31.8 \times 10^{-12} \text{s}} = 0.147 \mu\text{m}$

5.72

$I_C = \beta_F I_B = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) I_B$ | $\beta_{FO} \left(1 + \frac{5}{V_A} \right) = \frac{240 \mu\text{A}}{3 \mu\text{A}}$ and $\beta_{FO} \left(1 + \frac{10}{V_A} \right) = \frac{265 \mu\text{A}}{3 \mu\text{A}}$

$\frac{\left(1 + \frac{10}{V_A} \right)}{\left(1 + \frac{5}{V_A} \right)} = \frac{265 \mu\text{A}}{240 \mu\text{A}} \Rightarrow V_A = 43.1 \text{ V}$ | $\beta_{FO} = \frac{80}{\left(1 + \frac{5}{43.1} \right)} = 71.7$

5.73

$$(a) I_C = I_S \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] \left(1 + \frac{V_{CE}}{V_A} \right) = 10^{-16} A \left[\exp\left(\frac{0.72V}{0.025V}\right) - 1 \right] \left(1 + \frac{10V}{65V} \right) = 371 \mu A$$

$$(b) I_C = I_S \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right] = 10^{-16} A \left[\exp\left(\frac{0.72V}{0.025V}\right) - 1 \right] = 322 \mu A$$

(c) 1.15:1 (a) is 15% larger than (b) due to the Early effect.

5.74

$$I_C = \beta_F I_B = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) I_B \quad | \quad \text{We need two Q - points from the output characteristics.}$$

For example : (10 mA, 14 V) and (5 mA, 5 V)

$$10mA = \beta_{FO} \left(1 + \frac{14}{V_A} \right) 0.1mA \quad \text{and} \quad 5mA = \beta_{FO} \left(1 + \frac{5}{V_A} \right) 0.06mA \quad \text{yields}$$

$$100 = \beta_{FO} \left(1 + \frac{14}{V_A} \right) \quad \text{and} \quad 83.3 = \beta_{FO} \left(1 + \frac{5}{V_A} \right). \quad \text{Solving these two equations yields}$$

$$\beta_{FO} = 72.9 \quad \text{and} \quad V_A = 37.6 V.$$

5.75

$$\text{Fig. 5.16(a): } I_E = I_C + I_B = \left[\beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) + 1 \right] I_B \cong \left[\beta_{FO} \left(1 + \frac{V_{CB} + V_{BE}}{V_A} \right) + 1 \right] \frac{I_S}{\beta_{FO}} \exp\left(\frac{V_{BE}}{V_T}\right)$$

$$\left[1 + \frac{5 + V_{BE}}{50} + \frac{1}{19} \right] (5 \times 10^{-15}) \exp\left(\frac{V_{BE}}{0.025}\right) = 100 \mu A \rightarrow V_{BE} = 0.589V \text{ by iteration}$$

$$I_B = \frac{100 \mu A}{\left[19 \left(1 + \frac{5.589}{50} \right) + 1 \right]} = 4.52 \mu A \quad | \quad I_C = 19 \left(1 + \frac{5.589}{50} \right) I_B = 95.48 \mu A$$

$$\text{For } V_A = \infty, I_E = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \quad | \quad V_{BE} = 0.025 \ln \frac{100 \mu A}{5 fA} = 0.593 V$$

$$\text{Fig. 5.16(b): } I_B = \frac{I_S}{\beta_{FO}} \exp\left(\frac{V_{BE}}{V_T}\right) \rightarrow V_{BE} = 0.025 \ln \frac{19(100 \mu A)}{5 fA} = 0.667 V$$

$$I_C = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A} \right) I_B = 19 \left(1 + \frac{5}{50} \right) 100 \mu A = 2.09 mA \quad | \quad I_E = I_C + I_B = 2.19 mA$$

V_{BE} is independent of V_A in the equation above.

5.76

$$I_C = \beta_F I_B \mid I_E = (\beta_F + 1)I_B \mid \beta_F = \beta_{FO} \left(1 + \frac{V_{CE}}{V_A}\right) = 50 \left(1 + \frac{9 + 0.7}{50}\right) = 59.7$$

$$I_E = \frac{(9 - 0.7)V}{8200\Omega} = 1.01 \text{ mA} \mid I_B = \frac{I_E}{\beta_F + 1} = \frac{1.01 \text{ mA}}{60.7} = 16.7 \mu\text{A} \mid I_C = 59.7 I_B = 0.996 \text{ mA}$$

5.77

$$g_m = \frac{I_C}{V_T} \mid V_T = \frac{kT}{q} = \frac{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})}{1.60 \times 10^{-19} \text{ C}} = 25.9 \text{ mV}$$

$$(a) g_m = \frac{10^{-5} \text{ A}}{V_T} = 0.387 \text{ mS} \quad (b) g_m = \frac{10^{-4} \text{ A}}{V_T} = 3.87 \text{ mS}$$

$$(c) g_m = \frac{10^{-3} \text{ A}}{V_T} = 38.7 \text{ mS} \quad (d) g_m = \frac{10^{-2} \text{ A}}{V_T} = 0.387 \text{ S}$$

(e) The values of g_m are the same for the pnp.

5.78

$$C_D = \frac{I_C}{V_T} \tau_F = \frac{10 \times 10^{-12}}{0.0258} I_C = 3.88 \times 10^{-10} I_C \text{ (F)} \quad (a) 0.388 \text{ fF} \quad (b) 0.388 \text{ pF} \quad (c) 3.88 \text{ pF}$$

5.79

The following are from the Cadence website and the file psrefman.pdf:

IS = 10fA, BF = 100, BR = 1, VAF = ∞ , VAR = ∞ , TF = 0, TR = 0,

NF = 1, NE = 1.5, RB = 0, RC = 0, RE = 0, ISE = 0, ISC = 0, ISS = 0,

IKF = ∞ , IKR = ∞ , CJE = 0, CJC = 0.

These default values apply to both npn and pnp transistors.

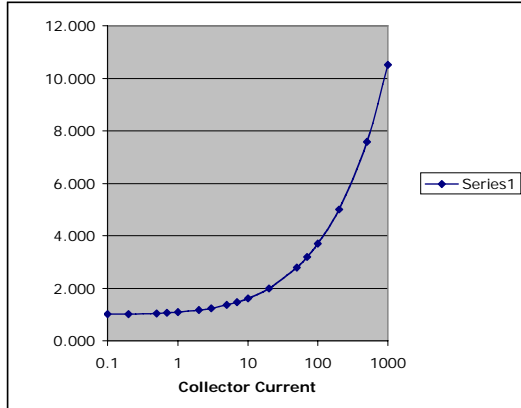
5.80

$$(a) KBQ = \frac{1 + \left[1 + 4 \left(\frac{i_F}{IKF}\right)\right]^{NK}}{2} = \frac{1 + \sqrt{1 + 4 \left(\frac{1 \text{ mA}}{10 \text{ mA}}\right)}}{2} = 1.09 \rightarrow 8.3\% \text{ reduction}$$

$$(a) KBQ = \frac{1 + \sqrt{1 + 4 \left(\frac{10 \text{ mA}}{10 \text{ mA}}\right)}}{2} = 1.62 \mid i_C = \frac{i_F}{1.62} = 0.62 i_F \rightarrow 38\% \text{ reduction}$$

$$(a) KBQ = \frac{1 + \sqrt{1 + 4 \left(\frac{50 \text{ mA}}{10 \text{ mA}}\right)}}{2} = 2.79 \mid i_C = \frac{i_F}{2.79} = 0.36 i_F \rightarrow 64\% \text{ reduction}$$

5.81



5.82

$$(a) V_{EQ} = \frac{36k\Omega}{36k\Omega + 68k\Omega} 10V = 3.462V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{3.462 - 0.7}{23.54 + (50+1)33k\Omega} V = 1.618\mu A \quad | \quad I_C = 50I_B = 80.9 \mu A \quad | \quad I_E = 51I_B = 82.5 \mu A$$

$$V_{CE} = 10 - 43000I_C - 33000I_E = 3.797V \quad | \quad \text{Q-point : } (80.9 \mu A, 3.80 V)$$

$$(b) V_{EQ} = \frac{7.2k\Omega}{7.2k\Omega + 13.6k\Omega} 10V = 3.462V \quad | \quad R_{EQ} = 7.2k\Omega \parallel 13.6k\Omega = 4.708k\Omega$$

$$I_B = \frac{3.462 - 0.7}{4.708 + (50+1)6.6k\Omega} V = 8.092\mu A \quad | \quad I_C = 50I_B = 404.6\mu A \quad | \quad I_E = 51I_B = 412.7 \mu A$$

$$V_{CE} = 10 - 8600I_C - 6600I_E = 3.7976V \quad | \quad \text{Q-point : } (405 \mu A, 3.80 V)$$

$$(c) V_{EQ} = \frac{68k\Omega}{36k\Omega + 68k\Omega} 10V = 6.538V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{10 - 0.7 - 6.538}{23.54 + (50+1)33k\Omega} V = 1.618\mu A \quad | \quad I_C = 50I_B = 80.9 \mu A \quad | \quad I_E = 51I_B = 82.5 \mu A$$

$$V_{EC} = 10 - 33000I_C - 43000I_E = 3.797V \quad | \quad \text{Q-point : } (80.9 \mu A, 3.80 V)$$

$$(b) V_{EQ} = \frac{13.6k\Omega}{7.2k\Omega + 13.6k\Omega} 10V = 6.538V \quad | \quad R_{EQ} = 7.2k\Omega \parallel 13.6k\Omega = 4.708k\Omega$$

$$I_B = \frac{10 - 0.7 - 6.538}{4.708 + (50+1)6.6k\Omega} V = 8.092\mu A \quad | \quad I_C = 50I_B = 404.6\mu A \quad | \quad I_E = 51I_B = 412.7 \mu A$$

$$V_{EC} = 10 - 6600I_C - 8600I_E = 3.7976V \quad | \quad \text{Q-point : } (405 \mu A, 3.80 V)$$

5.83

$$(a) V_{EQ} = \frac{36k\Omega}{36k\Omega + 68k\Omega} 10V = 3.462V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{3.462 - 0.7}{23.54 + (75+1)22k\Omega} V = 1.629\mu A \quad | \quad I_C = 75I_B = 122.2\mu A \quad | \quad I_E = 76I_B = 123.8\mu A$$

$$V_{CE} = 10 - 43000I_C - 22000I_E = 2.022V \quad | \quad \text{Q - point : } (122\mu A, 2.02V)$$

$$(b) V_{EQ} = \frac{68k\Omega}{36k\Omega + 68k\Omega} 10V = 6.538V \quad | \quad R_{EQ} = 36k\Omega \parallel 68k\Omega = 23.54k\Omega$$

$$I_B = \frac{10 - 0.7 - 6.538}{23.54 + (75+1)22k\Omega} V = 1.629\mu A \quad | \quad I_C = 75I_B = 122.2\mu A \quad | \quad I_E = 76I_B = 123.8\mu A$$

$$V_{EC} = 10 - 22000I_C - 43000I_E = 2.022V \quad | \quad \text{Q - point : } (122\mu A, 2.02V)$$

5.84

*Problem 5.83(a)

VCC 1 0 10

R1 3 0 36K

R2 1 3 68K

RC 1 2 43K

RE 4 0 33K

Q1 2 3 4 NPN

.MODEL NPN NPN IS=1E-16 BF=50 BR=0.25

.OP

.END

*Problem 5.83(b)

VCC 1 0 10

R1 3 0 36K

R2 1 3 68K

RC 1 2 43K

RE 4 0 33K

Q1 2 3 4 NPN

.MODEL NPN NPN IS=1E-16 BF=50 BR=0.25 VAF=60

.OP

.END

*Problem 5.83(c)

VCC 1 0 10

R1 1 3 36K

R2 3 0 68K

RC 4 0 43K

RE 1 2 33K

Q1 4 3 2 PNP

.MODEL PNP PNP IS=1E-16 BF=50 BR=0.25

.OP

.END

*Problem 5.83(d)

VCC 1 0 10

R1 1 3 36K
R2 3 0 68K
RC 4 0 43K
RE 1 2 33K
Q1 4 3 2 PNP
.MODEL PNP PNP IS=1E-16 BF=50 BR=0.25 VAF=60
.OP
.END

5.85

$$V_{EQ} = 10 \frac{6.2k\Omega}{6.2k\Omega + 12k\Omega} = 3.41V \text{ and } R_{EQ} = 6.2k\Omega \parallel 12k\Omega = 4.09k\Omega$$

$$I_C = \beta_F I_B = 100 \frac{3.41 - 0.7}{4090 + 101(7500)} = 0.356mA$$

$$V_{CE} = 10 - 0.356mA(5.1k\Omega) - \frac{101}{100} 0.356mA(7.5k\Omega) = 5.49V$$

Q - point : (0.356 mA, 5.49 V)

5.86

$$V_{EQ} = 15 \frac{120k\Omega}{120k\Omega + 240k\Omega} = 5.00V \text{ and } R_{EQ} = 120k\Omega \parallel 240k\Omega = 80k\Omega$$

$$I_C = \beta_F I_B = 100 \frac{5.00 - 0.700}{80000 + 101(100000)} = 42.2\mu A$$

$$V_{CE} = 15 - 42.2 \times 10^{-6} A(10^5 \Omega) - \frac{101}{100} 42.2 \times 10^{-6} A(1.5 \times 10^5 \Omega) = 4.39V$$

Q - point : (42.2 μ A, 4.39 V)

5.87

$$(a) I_E = \frac{I_C}{\alpha_F} = \left(\frac{101}{100} \right) 1mA = 1.01mA \quad | \quad R_E = \frac{2V}{1.01mA} = 1.98k\Omega \rightarrow 2.0k\Omega$$

$$R_C = \frac{(12 - 5 - 2)V}{1.00mA} = 5k\Omega \rightarrow 5.1k\Omega \quad | \quad V_B = 2 + 0.7 = 2.7V$$

$$\text{Set } R_1 = \frac{V_B}{10I_B} = \frac{2.7V}{10(0.01mA)} = 27k\Omega \rightarrow 27k\Omega$$

$$R_2 = \frac{(12 - 2.7)V}{11I_B} = \frac{9.3V}{11(0.01mA)} = 84.55k\Omega \rightarrow 82k\Omega$$

$$(b) V_{EQ} = \frac{27k\Omega}{27k\Omega + 82k\Omega} 12V = 2.972V \quad | \quad R_{EQ} = 27k\Omega \parallel 82k\Omega = 20.31k\Omega$$

$$I_B = \frac{2.972 - 0.7}{20.31 + (100 + 1)k\Omega} V = 10.22\mu A \quad | \quad I_C = 100I_B = 1.022mA \quad | \quad I_E = 101I_B = 1.033mA$$

$$V_{CE} = 12 - 5100I_C - 2000I_E = 4.723V \quad | \quad Q - \text{point} : (1.02mA, 4.72V)$$

5.88

$$(a) I_E = \frac{I_C}{\alpha_F} = \left(\frac{76}{75}\right) 10\mu A = 10.13\mu A \quad | \quad \text{Let } V_{R_C} = V_{R_E} = V_{CE} = 6V$$

$$R_E = \frac{6V}{10.13\mu A} = 592k\Omega \rightarrow 620k\Omega$$

$$R_C = \frac{6V}{10\mu A} = 600k\Omega \rightarrow 620k\Omega \quad | \quad V_B = 6 + 0.7 = 6.7V$$

$$\text{Set } R_1 = \frac{V_B}{10I_B} = \frac{6.7V}{10\left(\frac{10\mu A}{75}\right)} = 5.03M\Omega \rightarrow 5.1M\Omega$$

$$R_2 = \frac{(18 - 6.7)V}{11I_B} = \frac{11.3V}{11\left(\frac{10\mu A}{75}\right)} = 7.71M\Omega \rightarrow 7.5M\Omega$$

$$(b) V_{EQ} = \frac{5.1M\Omega}{5.1M\Omega + 7.5M\Omega} 18V = 7.286V \quad | \quad R_{EQ} = 5.1M\Omega \parallel 7.5M\Omega = 3.036M\Omega$$

$$I_B = \frac{7.286 - 0.7}{3036 + (75 + 1)620k\Omega} V = 0.1313\mu A \quad | \quad I_C = 75I_B = 9.848\mu A \quad | \quad I_E = 76I_B = 9.980\mu A$$

$$V_{CE} = 18 - 620000I_C - 620000I_E = 5.707V \quad | \quad Q - \text{point} : (9.85\mu A, 5.71V)$$

5.89

$$(a) I_E = \frac{I_C}{\alpha_F} = \left(\frac{61}{60}\right) 850\mu A = 864.2\mu A \quad | \quad R_E = \frac{1V}{864.2\mu A} = 1.16k\Omega \rightarrow 1.2k\Omega$$

$$R_C = \frac{(5 - 2 - 1)V}{850\mu A} = 2.35k\Omega \rightarrow 2.4k\Omega \quad | \quad V_B = 5 - 1 - 0.7 = 3.3V$$

$$\text{Set } R_1 = \frac{V_{R_1}}{10I_B} = \frac{5 - 3.3V}{10\left(\frac{850\mu A}{60}\right)} = 12.0k\Omega \rightarrow 12k\Omega$$

$$R_2 = \frac{V_{R_2}}{11I_B} = \frac{3.3V}{11\left(\frac{850\mu A}{60}\right)} = 21.2k\Omega \rightarrow 22k\Omega$$

$$(b) V_{EQ} = \frac{22k\Omega}{12k\Omega + 22k\Omega} 5V = 3.24V \quad | \quad R_{EQ} = 12k\Omega \parallel 22k\Omega = 7.77k\Omega$$

$$I_B = \frac{5 - 0.7 - 3.24}{7.77 + (60 + 1) \cdot 1.2 k\Omega} V = 13.1\mu A \quad | \quad I_C = 60I_B = 786\mu A \quad | \quad I_E = 61I_B = 799\mu A$$

$$V_{CE} = 5 - 1200I_E - 2400I_C = 2.14V \quad | \quad \text{Q-point} : (786 \mu A, 2.14 V)$$

5.90

$$(a) V_{R_E} = 1 V, V_{R_C} = 9 V \quad | \quad I_B = \frac{11mA}{50} = 0.220mA$$

$$I_E = \frac{I_C}{\alpha_F} = \left(\frac{51}{50}\right) 11mA = 11.22mA \quad | \quad R_E = \frac{1V}{11.22mA} = 89.1\Omega \rightarrow 91 \Omega$$

$$R_C = \frac{9V}{11.0mA} = 818\Omega \rightarrow 820 \Omega \quad | \quad V_B = -15 + 1 + 0.7 = -13.3V$$

$$\text{Set } R_1 = \frac{V_{R_1}}{10I_B} = \frac{-13.3V - (-15V)}{10(0.220mA)} = 772\Omega \rightarrow 750 \Omega$$

$$R_2 = \frac{0 - (13.3V)}{11I_B} = \frac{13.3V}{11(0.220mA)} = 5.50k\Omega \rightarrow 5.6 k\Omega$$

$$(b) V_{EQ} = \frac{5.6k\Omega}{0.75k\Omega + 5.6k\Omega} (-15V) = -13.2V \quad | \quad R_{EQ} = 0.75k\Omega \parallel 5.6k\Omega = 0.661k\Omega$$

$$I_B = \frac{-13.2 - 0.7 - (-15)V}{661 + (50 + 1)(91) \Omega} = 0.207mA \quad | \quad I_C = 50I_B = 10.3mA \quad | \quad I_E = 51I_B = 10.6mA$$

$$V_{EC} = 0 - 820I_C - 91I_E - (-15V) = 5.59V \quad | \quad \text{Q-point} : (10.2 mA, 5.59 V)$$

5.91 Problem numbers on graph

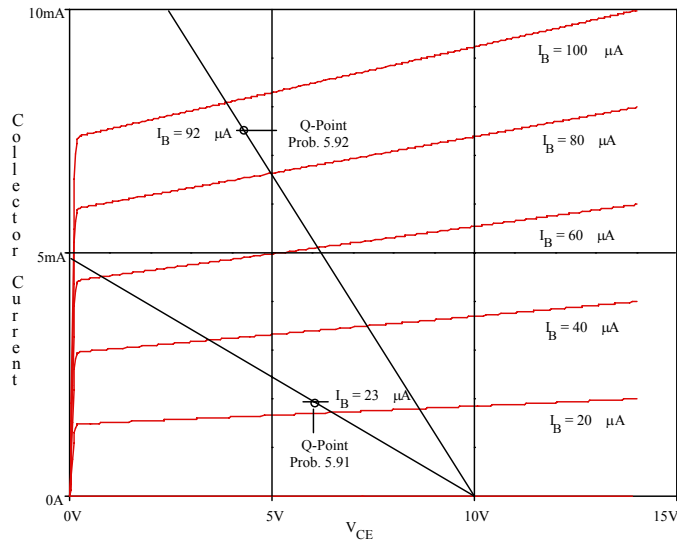
$$V_{EQ} = \frac{3.3k\Omega}{3.3k\Omega + 7.5k\Omega} 10V = 3.056V \quad | \quad R_{EQ} = 7.5k\Omega \parallel 3.3k\Omega = 2.292k\Omega$$

$$V_{CE} = 10 - 820I_C - 1200I_E \quad | \quad \text{From characteristics at } V_{CE} = 5V : \beta_F \cong \frac{5mA}{60\mu A} = 83$$

$$V_{CE} = 10 - 820I_C - 1200 \frac{84}{83} I_C = 10 - 2034I_C$$

$$\text{Load line points} : I_C = 0, V_{CE} = 10V \text{ and } V_{CE} = 0, I_C = 4.9mA$$

$$I_B = \frac{3.056 - 0.7}{2292 + (83 + 1)1200} = 23\mu A \quad | \quad \text{From Graph} : \text{Q-point} : (1.9 mA, 6.0 V)$$



5.92

$$V_{EQ} = \frac{6.8k\Omega}{6.8k\Omega + 3.6k\Omega} (10) = 6.538V \quad | \quad R_{EQ} = 6.8k\Omega || 3.6k\Omega = 2.354k\Omega$$

$$V_{EC} = 10 - 420I_C - 330I_E \quad | \quad \text{From characteristics at } V_{EC} = 5V : \beta_F \cong \frac{5mA}{60\mu A} = 83$$

$$V_{EC} = 10 - 420I_C - 3300 \frac{84}{83} I_C = 10 - 754I_C$$

Load line points: $I_C = 0, V_{EC} = 10V$ and $V_{EC} = 0, I_C = 13.3mA$ – off the graph

$$V_{EC} = 5V, I_C = 6.63mA \quad | \quad I_B = \frac{10 - 0.7 - 6.538}{2354 + (83 + 1)330} = 92\mu A$$

From Graph : Q - point : (7.5 mA, 4.3 V)

5.93

Writing a loop equation starting at the 9 V supply gives: $9 = 1500(I_C + I_B) + 10000I_B + V_{BE}$
 Assuming forward-active region operation, $V_{BE} = 0.7$ V and $I_C = \beta_F I_B$.

$$9 = 1500(\beta_F I_B + I_B) + 10000I_B + 0.7$$

$$I_B = \frac{9 - 0.7}{1500(\beta_F + 1) + 10000} \quad \text{and} \quad I_C = \beta_F I_B = \frac{\beta_F(9 - 0.7)}{1500(\beta_F + 1) + 10000}$$

$$(a) I_C = \frac{30(9 - 0.7)V}{1.5k\Omega(30 + 1) + 10k\Omega} = 4.41 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 2.17V \quad | \quad \text{Q-pt : (4.41mA, 2.17V)}$$

$$(b) I_C = \frac{100(9 - 0.7)V}{1.5k\Omega(100 + 1) + 10k\Omega} = 5.14 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 1.21V \quad | \quad \text{Q-pt : (5.14mA, 1.21V)}$$

$$(c) I_C = \frac{250(9 - 0.7)V}{1.5k\Omega(250 + 1) + 10k\Omega} = 5.37 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 0.913V \quad | \quad \text{Q-pt : (5.37mA, 0.913V)}$$

$$(d) I_C = \frac{(9 - 0.7)V}{1500\Omega} = 5.53 \text{ mA} \quad | \quad V_{CE} = 9 - 1500I_E = 0.705V \quad | \quad \text{Q-pt : (5.53mA, 0.705V)}$$

5.94

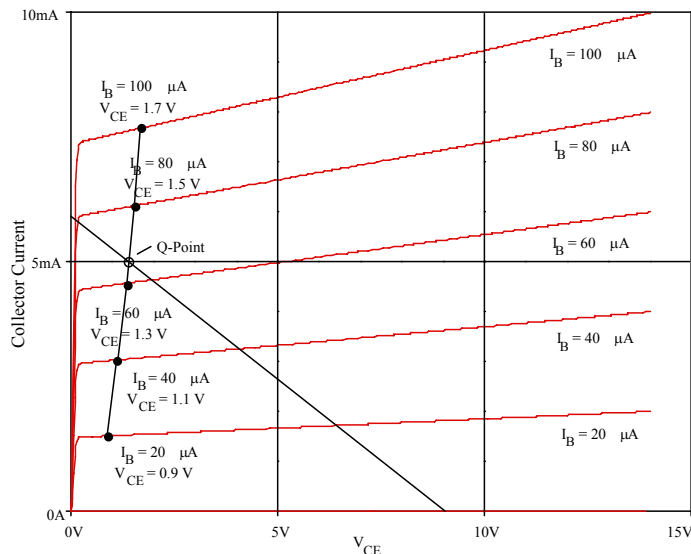
$$V_{CE} = 9 - (I_C + I_B)1500 \quad | \quad V_{CE} = 9 - \left(I_C + \frac{I_C}{\beta_F}\right)1500 \quad | \quad I_B = \frac{V_{CE} - 0.7}{10^4}$$

$$\text{From Fig. P5.26 at 5V: } \beta_F = \frac{5\text{mA}}{60\mu\text{A}} = 83.3 \quad | \quad V_{CE} = 9 - 1518I_C$$

$$I_C = 0, V_{CE} = 9V \quad | \quad V_{CE} = 0, I_C = 5.93\text{mA}$$

$$V_{CE} = 0.9V, I_B = 20\mu\text{A} \quad | \quad V_{CE} = 1.3V, I_B = 60\mu\text{A} \quad | \quad V_{CE} = 1.7V, I_B = 100\mu\text{A}$$

From graph: Q-point = (5.0 mA, 1.3 V)



5.95

$$(a) V_{EC} = 10 - (I_C + I_B)R_C = 10 - I_E R_C \quad | \quad I_E = \frac{I_C}{\alpha_F} = \frac{\beta_F + 1}{\beta_F} I_C = \frac{61}{60} 10 \text{mA} = 10.17 \text{mA}$$

$$R_C = \frac{(10 - 3) \text{V}}{10.17 \text{mA}} = 689 \Omega \rightarrow 680 \Omega \quad | \quad R_B = \frac{V_{EC} - V_{EB}}{I_B} = \frac{(3 - 0.7) \text{V}}{0.1667 \text{mA}} = 13.8 \text{k}\Omega \rightarrow 14 \text{k}\Omega$$

$$(b) 5 - 0.7 - 14000 I_B - 680(I_C + I_B) - (-5) = 0$$

$$I_B = \frac{10 - 0.7}{14000 + 41(680)} \text{V} = 222.1 \mu\text{A} \quad | \quad I_C = \beta_F I_B = 8.88 \text{mA}$$

$$V_{EC} = 10 \text{V} - (8.88 \text{mA}) 680 \Omega = 3.96 \text{V} \quad | \quad Q\text{-point} : (8.88 \text{mA}, 3.96 \text{V})$$

5.96

$$V_{CE} = 1.5 - (I_C + I_B)R_C \rightarrow R_C = \frac{1.5 - 0.9}{20 \mu\text{A} + \frac{20 \mu\text{A}}{50}} = 29.4 \text{k}\Omega \rightarrow 30 \text{k}\Omega$$

$$R_B = \frac{V_{CE} - V_{BE}}{I_B} = \frac{0.9 - 0.65}{\frac{20 \mu\text{A}}{50}} = 625 \text{k}\Omega \rightarrow 620 \text{k}\Omega$$

$$\text{For } R_C = 30 \text{k}\Omega: V_{CE} = 1.5 - 30 \text{k}\Omega(I_C + I_B)R_C = 1.5 - 30 \text{k}\Omega(126)I_B \quad | \quad I_B = \frac{V_{CE} - 0.65}{620 \text{k}\Omega}$$

$$V_{CE} = 1.5 - 30 \text{k}\Omega(126) \frac{V_{CE} - 0.65}{620 \text{k}\Omega} \rightarrow V_{CE} = 0.770 \text{V}$$

$$I_C = 125 I_B = 125 \frac{0.770 - 0.65}{620 \text{k}\Omega} = 24.2 \mu\text{A} \quad | \quad Q\text{-point} : (24.2 \mu\text{A}, 0.770 \text{V})$$

5.97

$$12 = R_C(I_C + I_B) + V_Z + V_{BE} = 500(I_E) + 7.7 \quad | \quad I_E = \frac{12 - 7.7}{500} = 8.60 \text{mA}$$

$$I_B = \frac{I_E}{\beta_F + 1} = \frac{8.60 \text{mA}}{101} = 85.2 \mu\text{A} \quad | \quad I_C = \beta_F I_B = 8.52 \text{mA} \quad | \quad V_{CE} = 7.70 \text{V}$$

$$Q\text{-point} = (8.52 \text{mA}, 7.70 \text{V})$$

5.95

$$V_{EQ} = 6 + 100 \frac{15 - 6}{7800 + 100} = 6.114 \text{V} \quad | \quad R_{EQ} = 100 \Omega || 7800 \Omega = 98.73 \Omega$$

$$I_B = \frac{20 \text{mA}}{51} + \frac{V_O}{51(4700 \Omega)} = \frac{20 \text{mA}}{51} + \frac{6.14 - 98.7 I_B - V_{BE}}{51(4700 \Omega)} \rightarrow I_C = 50 I_B = 50 \frac{101.1 - V_{BE}}{2.398 \times 10^5}$$

$$V_{BE} = 0.025 \ln \frac{I_C}{10^{-16}}$$

Using MATLAB: fzero('IC107',.02) ---> ans =0.0207

```
function f=IC107(ic)
vbe=0.025*log(ic/1e-16);
f=ic-50*(101.1-vbe)/2.398e5;
```

$$V_o = 6.14 - 98.7 \frac{20.7 \text{mA}}{51} - .025 \ln \frac{20.7 \text{mA}}{10^{-16}} = 5.276 \text{ V}$$

5.99

*Problem 5.98

VCC 1 0 DC 15

R1 1 2 7.8K

RZ 2 4 100

VZ 4 0 DC 6

Q1 1 2 3 NPN

RE 3 0 4.7K

IL 3 0 20MA

.MODEL NPN NPN IS=1E-16 BF=50 BR=0.25

.OP

.END

Output voltages will differ slightly due to different value of V_T .

5.100

$$v_o = 7 - 100i_B - v_{BE} = 7 - 100i_B - V_T \ln \frac{i_C}{I_S} = 7 - 100i_B - V_T \ln \frac{\alpha_F i_L}{I_S}$$

$$v_o = 7 - 100i_B - V_T \ln i_L - V_T \ln \frac{\alpha_F}{I_S}$$

$$R_o = -\frac{dv_o}{di_L} = -\left(-100\Omega \frac{di_B}{di_L} - \frac{V_T}{i_L}\right) = \frac{100\Omega}{51} + \frac{0.025V}{0.02A} = 3.21\Omega$$

5.101

Since the voltage across the op - amp input must be zero, $v_o = V_Z = 10 \text{ V}$.

Since the input current to the op amp is zero, $I_E = \frac{V_o}{100} = 100 \text{ mA}$

$$I_{+15} = I_Z + I_C = I_Z + \alpha_F I_E = \frac{15V - 10V}{47k\Omega} + \frac{60}{61} 100 \text{mA} = 98.5 \text{ mA}$$

5.102

Since the voltage across the op - amp input must be zero, $v_o \frac{47\Omega}{47\Omega + 47\Omega} = V_Z$

and $v_o = 10 V$. Since the input current to the op amp is zero,

$$I_E = \frac{I_C}{\alpha_F} = \frac{10V}{94\Omega} \left(\frac{41}{40} \right) = 109 \text{ mA} \quad I_{+15} = I_Z + I_E = \frac{15V - 5V}{82k\Omega} + 109 \text{ mA} = 109 \text{ mA}$$

5.103

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} \quad | \quad \text{For } I_C^{\min} : V_{CC} = 0.95(15) = 14.25 V$$

$$R_1 = 0.95(82k\Omega) = 77.9k\Omega \quad | \quad R_2 = 1.05(120k\Omega) = 126k\Omega \quad | \quad R_E = 1.05(6.8k\Omega) = 7.14k\Omega$$

$$V_{EQ} = \frac{77.9}{77.9 + 126} 14.25V = 5.44V \quad | \quad R_{EQ} = 77.9k\Omega \parallel 126k\Omega = 48.1k\Omega$$

$$I_C^{\min} = 100 \frac{5.44V - 0.7V}{48.1k\Omega + (101)7.14k\Omega} = 616 \mu A$$

$$V_{CE}^{\max} = 14.25 - I_C^{\min} [0.95(6.8k\Omega)] - I_E^{\min} 7.14k\Omega$$

$$V_{CE}^{\max} = 14.25 - 3.98 - 4.44 = 5.83V \quad | \quad Q - \text{point} : (616 \mu A, 5.83 V)$$

$$\text{For } I_C^{\max} : V_{CC} = 1.05(15) = 15.75 V$$

$$R_1 = 1.05(82k\Omega) = 86.1k\Omega \quad | \quad R_2 = 0.95(120k\Omega) = 114k\Omega \quad | \quad R_E = 0.95(6.8k\Omega) = 6.46k\Omega$$

$$V_{EQ} = \frac{86.1}{86.1 + 114} 15.75V = 6.78V \quad | \quad R_{EQ} = 86.1k\Omega \parallel 114k\Omega = 49.0k\Omega$$

$$I_C^{\max} = 100 \frac{6.78V - 0.7V}{49.0k\Omega + (101)6.46k\Omega} = 867 \mu A$$

$$V_{CE}^{\min} = 15.75 - I_C^{\max} [1.05(6.8k\Omega)] - I_E^{\max} 6.46k\Omega$$

$$V_{CE}^{\min} = 15.75 - 6.19 - 5.66V = 3.90V \quad | \quad Q - \text{point} : (867 \mu A, 3.90 V)$$

5.104

Using the Spreadsheet approach in Fig. 5.40, Eq. set (5.66) becomes:

1. $V_{CC} = 15 (1 + 0.1 (RAND() - 0.5))$ | 2. $R_1 = 82000 (1 + 0.1 (RAND() - 0.5))$
3. $R_2 = 120000 (1 + 0.1 (RAND() - 0.5))$ | 4. $R_E = 6800 (1 + 0.1 (RAND() - 0.5))$
5. $R_C = 6800 (1 + 0.1 (RAND() - 0.5))$ | 6. $\beta_F = 100$

500 Cases	I_C (A)	V_{CE} (V)
Average	7.69E-04	4.51
Std. Dev.	4.02E-05	0.40
Min	6.62E-04	3.31
Max	8.93E-04	5.55

5.105

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} \quad | \quad \text{For } I_C^{\min}: V_{CC} = 0.95(12) = 11.4 \text{ V}$$

$$R_1 = 0.95(18k\Omega) = 17.1k\Omega \quad | \quad R_2 = 1.05(36k\Omega) = 37.8k\Omega \quad | \quad R_E = 1.05(16k\Omega) = 16.8k\Omega$$

$$V_{EQ} = \frac{17.1}{17.1 + 37.8} 11.4V = 3.55V \quad | \quad R_{EQ} = 17.1k\Omega || 37.8k\Omega = 11.8k\Omega$$

$$I_C^{\min} = 50 \frac{3.55V - 0.7V}{11.8k\Omega + (51)16.8k\Omega} = 164 \mu A$$

$$V_{CE}^{\max} = 11.4 - I_C^{\min} [0.95(22k\Omega)] - I_E^{\min} 16.8k\Omega$$

$$V_{CE}^{\max} = 11.4 - 3.43 - 2.81 = 5.16V \quad | \quad Q - \text{point}: (164 \mu A, 5.16 V)$$

$$\text{For } I_C^{\max}: V_{CC} = 1.05(12) = 12.6 \text{ V}$$

$$R_1 = 1.05(18k\Omega) = 18.9k\Omega \quad | \quad R_2 = 0.95(36k\Omega) = 34.2k\Omega \quad | \quad R_E = 0.95(16k\Omega) = 15.2k\Omega$$

$$V_{EQ} = \frac{18.9}{18.9 + 34.2} 12.6V = 4.49V \quad | \quad R_{EQ} = 18.9k\Omega || 34.2k\Omega = 12.2k\Omega$$

$$I_C^{\max} = 150 \frac{4.49V - 0.7V}{12.2k\Omega + (151)15.2k\Omega} = 246 \mu A$$

$$V_{CE}^{\min} = 12.6 - I_C^{\max} [1.05(22k\Omega)] - I_E^{\max} 15.2k\Omega$$

$$V_{CE}^{\min} = 12.6 - 5.68 - 3.77V = 3.15V \quad | \quad Q - \text{point}: (246 \mu A, 3.15 V)$$

500 Cases	I_C (A)	V_{CE} (V)
Average	2.02E-04	4.26
Std. Dev.	1.14E-05	0.32
Min	1.71E-04	3.43
Max	2.35E-04	5.21

The averages are close to the hand calculations that go with Fig. 5.35. The minimum and maximum values fall within the worst-case analysis as we expect.

5.106

Using the Spreadsheet approach with zero tolerance on the current gain, Eq. set (5.66) becomes:

$$\begin{aligned}
 1. \quad V_{CC} &= 12 \left(1 + 0.0 \left(\text{RAND}() - 0.5\right)\right) & | & \quad 2. \quad R_1 = 18000 \left(1 + 0.1 \left(\text{RAND}() - 0.5\right)\right) \\
 3. \quad R_2 &= 36000 \left(1 + 0.1 \left(\text{RAND}() - 0.5\right)\right) & | & \quad 4. \quad R_E = 16000 \left(1 + 0.1 \left(\text{RAND}() - 0.5\right)\right) \\
 5. \quad R_C &= 22000 \left(1 + 0.1 \left(\text{RAND}() - 0.5\right)\right) & | & \quad 6. \quad \beta_F = 100 \left(1 + 0.0 \left(\text{RAND}() - 0.5\right)\right)
 \end{aligned}$$

500 Cases	IC (A)	VCE (V)
Average	2.03E-04	4.29
Std. Dev.	1.10E-05	0.32
Min	1.74E-04	3.46
Max	2.36E-04	5.27

Note that the current gain tolerance has little effect on the results.

5.107

(a) Approximately 22 cases fall outside the interval $[170\mu\text{A}, 250\mu\text{A}]$: $100\% \frac{22}{500} = 4.4\%$ fail

(b) Approximately 125 cases fall inside the interval $[3.2\text{V}, 4.8\text{V}]$: $100\% \frac{125}{500} = 25\%$ fail

5.108

Using the Spreadsheet approach with 50% tolerance on the current gain, a tolerance TP on V_{CC} , and a tolerance TR on resistor values, Eq. set (5.66) becomes:

$$\begin{aligned}
 1. \quad V_{CC} &= 12 * \left(1 + 2 * TP * \left(\text{RAND}() - 0.5\right)\right) & | & \quad 2. \quad R_1 = 18000 * \left(1 + 2 * TR * \left(\text{RAND}() - 0.5\right)\right) \\
 3. \quad R_2 &= 36000 * \left(1 + 2 * TR * \left(\text{RAND}() - 0.5\right)\right) & | & \quad 4. \quad R_E = 16000 * \left(1 + 2 * TR * \left(\text{RAND}() - 0.5\right)\right) \\
 5. \quad R_C &= 22000 * \left(1 + 2 * TR * \left(\text{RAND}() - 0.5\right)\right) & | & \quad 6. \quad \beta_F = 100 * \left(1 + 1 * \left(\text{RAND}() - 0.5\right)\right)
 \end{aligned}$$

10,000 case Monte Carlo runs indicate that the specifications cannot be achieved even with ideal resistors. For TP = 5% and TR = 0%, 18 % of the circuits fail. With TP = 2% and TR = 0%, 1.5% percent fail. The specifications can be met with TP = 1% and TR = 1%.

5.109

$$I_C = \beta_F I_B = \beta_F \frac{V_{EQ} - V_{BE}}{R_{EQ} + (\beta_F + 1)R_E} \quad | \quad \text{For } I_C^{\min} : V_{CC} = 0.95(12) = 11.4 \text{ V}$$

$$R_1 = 0.8(18k\Omega) = 14.4k\Omega \quad | \quad R_2 = 1.2(36k\Omega) = 43.2k\Omega \quad | \quad R_E = 1.2(16k\Omega) = 19.2k\Omega$$

$$V_{EQ} = \frac{14.4}{14.4 + 43.2} 11.4 \text{ V} = 2.85 \text{ V} \quad | \quad R_{EQ} = 14.4k\Omega \parallel 43.2k\Omega = 10.8k\Omega$$

$$I_C^{\min} = 50 \frac{2.85 \text{ V} - 0.7 \text{ V}}{10.8k\Omega + (51)19.2k\Omega} = 109 \mu\text{A}$$

$$V_{CE}^{\max} = 11.4 - I_C^{\min} [0.8(22k\Omega)] - I_E^{\min} 19.2k\Omega$$

$$V_{CE}^{\max} = 11.4 - 1.91 - 2.13 = 7.36 \text{ V} \quad | \quad \text{Q - point : (109 mA, 7.36 V)}$$

$$\text{For } I_C^{\max} : V_{CC} = 1.05(12) = 12.6 \text{ V}$$

$$R_1 = 1.2(18k\Omega) = 21.6k\Omega \quad | \quad R_2 = 0.80(36k\Omega) = 28.8k\Omega \quad | \quad R_E = 0.80(16k\Omega) = 12.8k\Omega$$

$$V_{EQ} = \frac{21.6}{21.6 + 28.8} 12.6 \text{ V} = 5.40 \text{ V} \quad | \quad R_{EQ} = 21.6k\Omega \parallel 28.8k\Omega = 12.3k\Omega$$

$$I_C^{\max} = 150 \frac{5.4 \text{ V} - 0.7 \text{ V}}{12.3k\Omega + (151)12.8k\Omega} = 362 \mu\text{A}$$

$$V_{CE}^{\min} = 12.6 - I_C^{\max} [1.2(22k\Omega)] - I_E^{\max} 12.8k\Omega$$

$$V_{CE}^{\min} = 12.6 - 9.57 - 4.67 \text{ V} = -1.64 \text{ V! Saturated!}$$

The forward - active region assumption is violated. See the next problem.

Based upon a Monte Carlo analysis, only about 1% of the circuits actually have this problem, although V_{CE} will be relatively small in many circuits.

5.110

Using the Spreadsheet approach:

1. $V_{CC} = 12 * (1 + .1 * (RAND() - 0.5))$ | 2. $R_1 = 18000 * (1 + 0.4 * (RAND() - 0.5))$
3. $R_2 = 36000 * (1 + 0.4 * (RAND() - 0.5))$ | 4. $R_E = 16000 * (1 + 0.4 * (RAND() - 0.5))$
5. $R_C = 22000 * (1 + 0.4 * (RAND() - 0.5))$ | 6. $\beta_F = 100 * (1 + 1 * (RAND() - 0.5))$
7. $V_A = 75 * (1 + 0.66 * (RAND() - 0.5))$

In order to avoid an iterative solution at each step, assume that V_{CE} does not influence the base current. Then,

$$I_B = \frac{V_{EQ} - 0.7}{R_{EQ} + (\beta_{FO} + 1)R_E} \quad \text{and} \quad V_{CE} = \frac{V_{CC} - \beta_{FO} I_B \left(R_C + \frac{R_E}{\alpha_F} \right)}{1 + \frac{\beta_{FO}}{V_A} I_B \left(R_C + \frac{R_E}{\alpha_F} \right)} \quad | \quad I_C = \beta_{FO} I_B \left(1 + \frac{V_{CE}}{V_A} \right)$$

500 Cases	V_{CE} (V)	I_C (A)
Average	3.81E+00	2.049E-04
Std. Dev.	1.26E+00	3.785E-05
Min**	-2.07E-01	1.264E-04
Max	6.94E+00	3.229E-04

**Note: In this particular simulation, there were 4 cases in which the transistor was saturated.