Chapter 10: Bipolar Junction Transistors: Operation, Circuit Models, and Applications – Instructor Notes

Chapter 10 introduces bipolar junction transistors. The material on transistors is divided into two independent chapters, one on bipolar devices, and one on field-effect devices. The two chapters are functionally independent, except for the fact that **Section 10.1, introducing the concept of transistors as amplifiers and switches, can be covered prior to starting Chapter 11 if the instructor decides to only teach field-effect devices, or to cover them before bipolar devices.**

Section 10.2 introduces the fundamental ideas behind the operation of bipolar transistors, and illustrates the calculation of the state and operating point of basic transistor circuits. The discussion of the properties of the BJT in Section 10.2 is centered around a description of the base and collector characteristics, and purposely avoids a detailed description of the physics of the device, with the intent of providing an intuitive understanding of the transistor as an amplifier and electronic switch.

The second part of the chapter has been reorganized for clarity. Section 10.3 introduces large-signal models of the BJT, and also includes the box *Focus on Methodology: Using device data sheets* (pp. 559-561). Example 10.4 (LED Driver) and the box *Focus on Measurements: Large Signal Amplifier for Diode Thermometer* (pp. 566-568) provide two application examples. New to the 5th Edition are examples 10.5 and 10.6, that present simple but practically useful battery charger and DC motor drive BJT circuits. These examples are accompanied by related homework problems (10.25-10.27). Section 10.4 defines the concept of operating point and illustrates the selection of a bias point, introducing the idea of a small-signal amplifier in the most basic way.

Finally, Section 10.5 introduces the analysis of BJT switches and presents TTL gates.

The end-of-chapter problems are straightforward applications of the concepts illustrated in the chapter. The 5th Edition of this book includes 17 new problems; some of the 4th Edition problems were removed, increasing the end-of-chapter problem count from 40 to 51.

Learning Objectives

1. Understand the basic principles of amplification and switching. *Section 10.1.*
2. Understand the physical operation of bipolar transistors, and identify their state. *Section 10.2*
3. Understand the large-signal model of the bipolar transistor, and apply it to simple amplifier circuits. *Section 10.3.*
4. Determine and select the operating point of a bipolar transistor circuit; understand the principle of small signal amplifiers. *Section 10.4.*
5. Understand the operation of bipolar transistor as a switch and analyze basic analog and digital gate circuits. *Section 10.5.*

Section 10.2: Operation of the Bipolar Junction Transistor

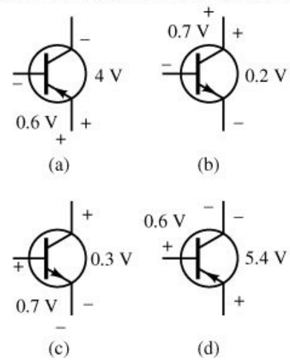
Problem 10.1

Solution:

Known quantities:

Transistor diagrams, as shown in Figure P10.1:

(a) *pnp*, $V_{EB} = 0.6$ V and $V_{EC} = 4.0$ V
(b) *npn*, $V_{CB} = 0.7$ V and $V_{CE} = 0.2$ V
(c) *npn*, $V_{BE} = 0.7$ V and $V_{CE} = 0.3$ V
(d) *pnp*, $V_{BC} = 0.6$ V and $V_{EC} = 5.4$ V



Find:

For each transistor shown in Figure P10.1, determine whether the BE and BC junctions are forward or reverse biased, and determine the operating region.

Analysis:

(a) $V_{BE} = -\ 0.6$ V for a *pnp* transistor implies that the BE junction is forward-biased.

$V_{BC} = V_{EC} - V_{EB} = 3.4$ V. The CB junction is reverse-biased. Therefore, the transistor is in the active region.

(b) $V_{BC} = -\ 0.7$ V for a *npn* transistor implies that the CB junction is reverse-biased.

$V_{BE} = V_{BC} - V_{EC} = -0.5$ V. The BE junction is reverse-biased. Therefore, the transistor is in the cutoff region.

(c) $V_{BE} = 0.7$ V for a *npn* transistor implies that the BE junction is forward-biased.

$V_{BC} = V_{EC} - V_{EB} = 0.4$ V. The CB junction is forward-biased. Therefore, the transistor is in the saturation region.

(d) $V_{BC} = 0.6$ V for a *pnp* transistor implies that the CB junction is reverse-biased.

$V_{BE} = V_{BC} – V_{EC} = -\ 4.8$ V. The BE junction is forward-biased. Therefore, the transistor is in the active region.

Problem 10.2

Solution:

Known quantities:

Transistor type and operating characteristics:

a) *npn*, $V_{BE} = 0.8$ V and $V_{CE} = 0.4$ V
b) *npn*, $V_{CB} = 1.4$ V and $V_{CE} = 2.1$ V
c) *pnp*, $V_{CB} = 0.9$ V and $V_{CE} = 0.4$ V
d) *npn*, $V_{BE} = -\ 1.2$ V and $V_{CB} = 0.6$ V

Find:

The region of operation for each transistor.

Analysis:

a) Since $V_{BE} = 0.8$ V, the BE junction is forward-biased. $V_{CB} = V_{CE} + V_{EB} = -\ 0.4$ V. Thus, the CB junction is forward-biased. Therefore, the transistor is in the saturation region.

b) $V_{BE} = V_{BC} + V_{CE} = 0.7$ V. The BE junction is forward-biased.

$V_{CB} = 1.4$ V. The CB junction is reverse-biased. Therefore, the transistor is in the active region.

c) $V_{CB} = 0.9$ V for a *pnp* transistor implies that the CB junction is forward-biased.

$V_{BE} = V_{BC} – V_{CE} = - 1.3$ V. The BE junction is forward-biased. Therefore, the transistor is in the saturation region.

d) With $V_{BE} = - 1.2$ V, the BE junction is reverse-biased.

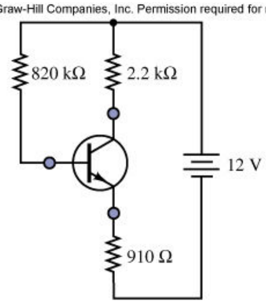
$V_{CB} = - 0.6$ V. The CB junction is reverse-biased. Therefore, the transistor is in the cutoff region.

Problem 10.3

Solution:

Known quantities:

The circuit of Figure P10.3: $\beta = \frac{I_C}{I_B} = 100$.



Find:

The operating point and the state of the transistor.

Analysis:

$V_{BE} = 0.6$ V and the BE junction is forward biased.

$$I_B = \frac{V_{CC} - V_{BE}}{R_1} = \frac{12 - 0.6}{820} = 13.9\ \mu\text{A}$$

$$I_C = \beta \cdot I_B = 1.39\text{mA}$$

Writing KVL around the right-hand side of the circuit:

$$-V_{CC} + I_C R_C + V_{CE} + I_E R_E = 0$$

$$V_{CE} = V_{CC} - I_C R_C - (I_C + I_B) R_E = 12 - (1.39)(2.2) - (1.39 + 0.0139)(0.910) = 7.664\ \text{V}$$

$$V_{BC} = V_{BE} + V_{CE} = 0.6\_7.664 = 8.264\ \text{V}$$

$$V_{CE} > V_{BE} \Rightarrow$$

The transistor is in the active region.

Problem 10.4

Solution:

Known quantities:

The magnitude of a *pnp* transistor's emitter and base current, and the magnitudes of the voltages across the emitter-base and collector-base junctions:
I_E = 6 mA, I_B = 0.1 mA and V_{EB} = 0.65 V, V_{CB} = 7.3 V.

Find:

a) V_{CE}.
b) I_C.
c) The total power dissipated in the transistor, defined as $P = V_{CE} I_C + V_{BE} I_B$.

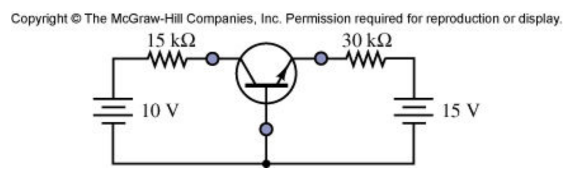
Analysis:

a) $V_{CE} = V_{CB} - V_{EB}$ = 7.3 - 0.65 = 6.65 V.
b) $I_C = I_E - I_B$ = 6 - 0.1 = 5.9 mA.
c) The total power dissipated in the transistor can be found to be: $P \approx V_{CE} I_C = 6.65 \times 5.9 \times 10^{-3} = 39 \text{ mW}$

Problem 10.5

Solution:

Known quantities:



The circuit of Figure P10.5, assuming the BJT has V_γ = 0.6 V.

Find:

The emitter current and the collector-base voltage.

Analysis:

Applying KVL to the right-hand side of the circuit, $I_E = -\left(\frac{V_{BE} + 15}{30000}\right) = -\left(\frac{0.6 + 15}{30000}\right) = -520\ \mu\text{A}$

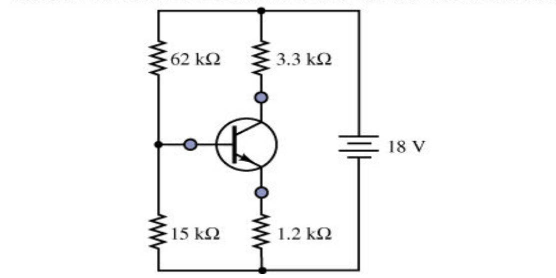
Then, on the left-hand side, assuming $\beta >> 1$:
$-10 + I_C R_C + V_{CB} = 0 \Rightarrow$
$V_{CB} = 10 - I_C R_C = 10 - \left(-520 \times 10^{-6}\right) \times 10 \times 10^3 = 17.8 \text{ V}$

Problem 10.6

Solution:

Known quantities:

The circuit of Figure P10.6, assuming the BJT has $V_{BE} = 0.6\text{ V}$ and $\beta = 150$.



Find:

The operating point and the region in which the transistor operates.

Analysis:

Define $R_C = 3.3\text{ k}\Omega,\ R_E = 1.2\text{ k}\Omega,\ R_1 = 62\text{ k}\Omega,\ R_2 = 15\text{ k}\Omega,\ V_{CC} = 18\text{ V}$

By applying Thevenin's theorem from base and mass, we have

$R_B = R_1 \| R_2 = 12.078\text{ k}\Omega$

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC} \cong 3.5\text{ V}$$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B + R_E(1+\beta)} \cong 15\ \mu\text{A}$$

$$I_C = \beta I_B = 2.25\text{ mA}$$

$$V_{CE} = V_{CC} - R_C I_C - R_E I_E = 18 - 3300 \cdot 2.25 \cdot 10^{-3} - 1200 \cdot 151 \cdot 15 \cdot 10^{-6} = 7.857\text{ V}$$

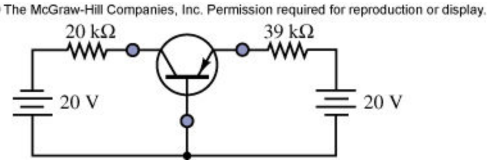
From the value of V_{CE} it is clear that the BJT is in the active region.

Problem 10.7

Solution:

Known quantities:

The circuit of Figure P10.7, assuming the BJT has $V_\gamma = 0.6\text{ V}$.



Find:

The emitter current and the collector-base voltage.

Analysis:

Applying KVL to the right-hand side of the circuit,

$$-V_{CC} + I_E R_E + V_{EB} = 0$$

$$I_E = \frac{V_{CC} - V_{EB}}{R_E} = \frac{20 - 0.6}{39 \cdot 10^3} = 497.4\mu\text{A}.\ \text{Since } \beta >> 1,\ \ I_C \approx I_E = 497.4\mu\text{A}$$

Applying KVL to the left-hand side: $V_{CB} + I_C R_C - V_{DD} = 0$

$$V_{CB} = V_{DD} - I_C R_C = 20 - 497.4 \cdot 20 \cdot 10^{-3} = 10.05\text{ V}$$

Problem 10.8

Solution:

Known quantities:

The circuit of Figure P10.7, assuming the emitter resistor is changed to $22\ \text{k}\Omega$ and the BJT has $V_\gamma = 0.6\,\text{V}$.

Find:

The operating point of the transistor.

Analysis:

$$I_E = \frac{V_{CC} - V_{EB}}{R_E} = \frac{20 - 0.6}{22 \cdot 10^3} = 881.8\,\mu\text{A}\,, \quad I_C \approx I_E = 881.8\,\mu\text{A}$$

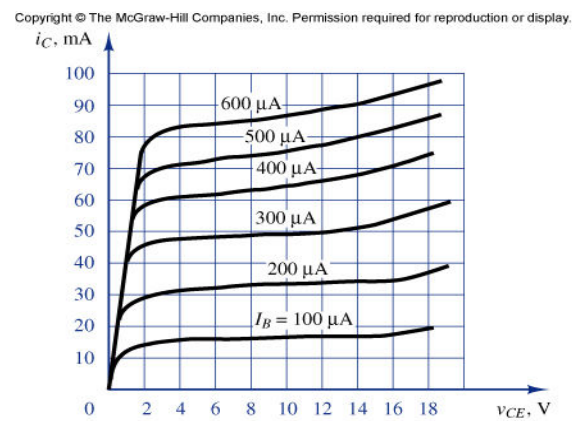
$$V_{CB} = V_{DD} - I_C R_C = 20 - 881.8 \cdot 20 \cdot 10^{-3} = 2.364\,\text{V}$$

Problem 10.9

Solution:

Known quantities:

The collector characteristics for a certain transistor, as shown in Figure P10.9.



Find:

a) The ratio I_C/I_B for V_{CE} = 10 V and $I_B = 100\ \mu\text{A},\ 200\,\mu\text{A},\ \text{and}\ 600\ \mu\text{A}$

b) V_{CE}, assuming the maximum allowable collector power dissipation is 0.5 W for $I_B = 500\ \mu\text{A}$.

Analysis:

a) For I_B = 100 µA and V_{CE} = 10 V, from the characteristics, we have I_C = 17 mA. The ratio I_C/I_B is 170.

For I_B = 200 µA and V_{CE} = 10 V, from the characteristics, we have I_C = 33 mA. The ratio I_C/I_B is 165.

For I_B = 600 µA and V_{CE} = 10 V, from the characteristics, we have I_C = 86 mA. The ratio I_C/I_B is 143.

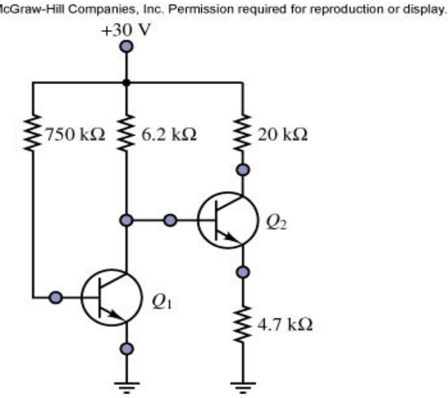
b) For I_B = 500 µA, and if we consider an average β from a., we have I_C = 159·500 10^{-3}= 79.5 mA. The power dissipated by the transistor is $P = V_{CE} I_C + V_{BE} I_B \approx V_{CE} I_C$, therefore: $V_{CE} \approx \dfrac{P}{I_C} = \dfrac{0.5}{79.5 \cdot 10^{-3}} = 6.29\,\text{V}$.

Problem 10.10

Solution:

Known quantities:

Figure P10.10, assuming both transistors are silicon-based with $\beta = 100$.



Find:

a) I_{C1}, V_{C1}, V_{CE1}.
b) I_{C2}, V_{C2}, V_{CE2}.

Analysis:

a) From KVL: $-30 + I_{B1}R_{B1} + V_{BE1} = 0 \quad \Rightarrow$

$$I_{B1} = \frac{30-0.7}{750 \cdot 10^3} = 39.07\,\mu\text{A}$$

$$I_{C1} = \beta \cdot I_{B1} = 3.907\,\text{mA} \quad \Rightarrow$$

$$V_{C1} = 30 - R_{C1}I_{C1} = 30 - 3.907 \cdot 6.2 = 5.779\,\text{V}$$

$$V_{CE1} = V_{C1} = 5.779\,\text{V}.$$

b) Again, from KVL: $-5.779 + V_{BE2} + I_{E2}R_{E2} = 0 \quad \Rightarrow \quad I_{E2} = \dfrac{5.779-0.7}{4.7 \cdot 10^3} = 1.081\,\text{mA}$

and $I_{C2} = I_{E2}\left(\dfrac{\beta}{\beta+1}\right) = 1.081 \cdot \left(\dfrac{100}{101}\right) = 1.07\,\text{mA}$.

Also, $-30 + I_{C2}(R_{C2} + R_{E2}) + V_{CE2} = 0 \quad \Rightarrow \quad V_{CE2} = 30 - (1.07) \cdot (20 + 4.7) = 3.574\,\text{V}$.

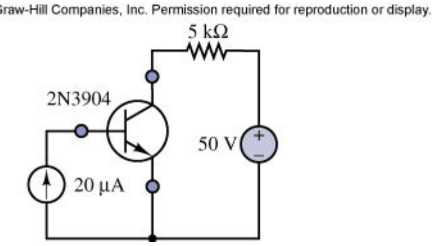
Finally, $I_{C2} = \dfrac{30 - V_{C2}}{R_{C2}} \quad \Rightarrow \quad V_{C2} = 30 - (1.07) \cdot (20) = 8.603\,\text{V}$.

Problem 10.11

Solution:

Known quantities:

Collector characteristics of the 2N3904 *npn* transistor, see data sheet pg. 560.



Find:

The operating point of the transistor in Figure P10.11, and the value of β at this point.

Analysis:

Construct a load line. Writing KVL, we have: $-50 + 5000 \cdot I_C + V_{CE} = 0$.

Then, if $I_C = 0$, $V_{CE} = 50\,\text{V}$; and if $V_{CE} = 0$, $I_C = 10\,\text{mA}$. The load line is shown superimposed on the collector characteristic below:

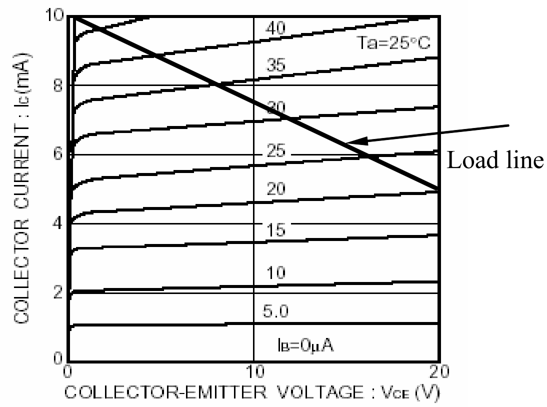
The operating point is at the intersection of the load line and the $I_B = 20\ \mu\text{A}$ line of the characteristic. Therefore, $I_{CQ} \approx 5$ mA and $V_{CEQ} \approx 20$ V .

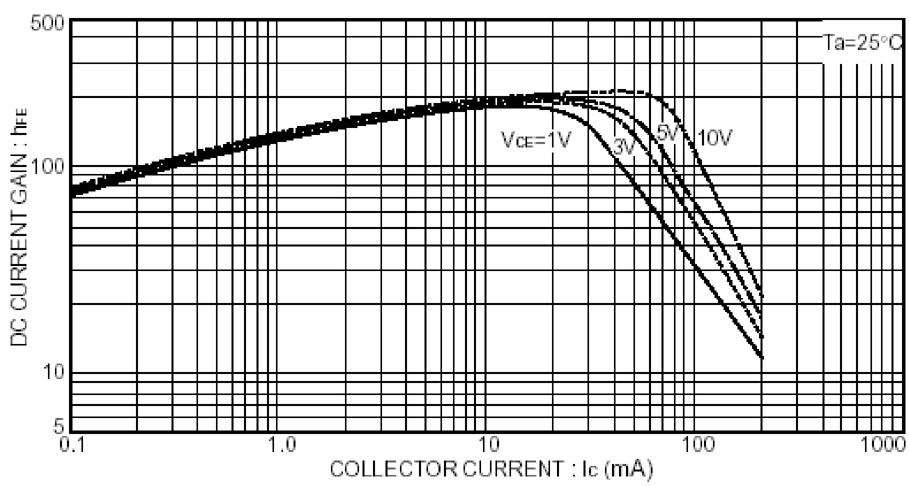
Under these conditions, an $5\ \mu\text{A}$ increase in I_B yields an increase in I_C of approximately $6-5=1$ mA .

Therefore,

$$\beta \approx \frac{\Delta I_C}{\Delta I_B} = \frac{1 \cdot 10^{-3}}{5 \cdot 10^{-6}} = 200$$

The same result can be obtained by checking the h_{FE} gain from the data-sheets corresponding to 5 mA.





Problem 10.12

Solution:

Known quantities:

The circuit shown in Figure P10.12. With reference to Figure 10.20, assume $V_\gamma = 0.6\,\text{V}$, $V_{sat} = 0.2\,\text{V}$.

Find:

The operating point of the transistor, by computing the ratio of collector current to base current.

Analysis:

$V_{CE} = V_{sat} = 0.2\,\text{V}$, therefore $I_C = \dfrac{10-0.2}{R_C} = 9.8\,\text{mA}$ $V_{BE} = V_\gamma = 0.6\,\text{V}$, therefore $I_B = \dfrac{5.7-0.6}{R_B} = 102\,\mu\text{A}$

$$\frac{I_C}{I_B} = \frac{9.8 \cdot 10^{-3}}{102 \cdot 10^{-6}} = 96.08 << \beta$$

Problem 10.13

Solution:

Known quantities:

The circuit in Figure 10.28 in the text. V_{CC}=20 V, R_C=5kΩ, R_E=1kΩ.

Find:

The region of operation of the transistor.

Analysis:

(a) $I_E = I_C + I_B = 1 \text{ mA} + 20\mu\text{A} = 1.02 \text{ mA}$

$V_E = 1000\ I_E = 1.02 \text{ V}$

$V_{RC} = 5000\ I_C = 5 \text{ V}$

$V_{CB} = 20 - V_{RC} - V_{BE} - V_E$

$= 20 - 5 - 0.7 - 1.02 = 13.28 \text{ V}$

The CB junction is reverse-biased. Therefore, the transistor is operating in the active region.

(b) $I_E = 3.2 \text{ mA} + 0.3 \text{ mA} = 3.5 \text{ mA}$

$V_E = 3.5 \text{ V}$

$V_{RC} = 16 \text{ V}$

$V_{CB} = 20 - 16 - 0.8 - 3.5 = -30 \text{ mV}$

The CB junction is forward-biased. Therefore, the transistor is operating in the saturation region.

(c) $I_E = 3 \text{ mA} + 1.5 \text{ mA} = 4.5 \text{ mA}$

$V_E = 4.5 \text{ V}$

$V_{RC} = 15 \text{ V}$

$V_{CB} = 20 - 15 - 0.85 - 4.5 = -0.35 \text{ V}$

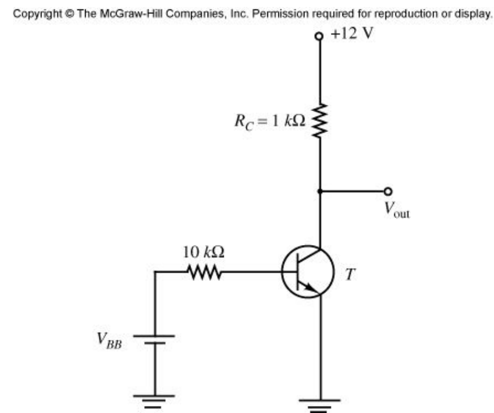
The CB junction is forward-biased. Therefore, the transistor is operating in the saturation region.

Problem 10.14

Solution:

Known quantities:

The circuit of Figure P10.14, V_{CEsat}=0.1V, V_{BEsat}=0.6V, and □=50.



Find:

The base voltage required to saturate the transistor.

Analysis:

The collector current is

$$I_C = \frac{12-0.1}{1} = 11.9 \text{ mA}$$

The base current is

$$I_B = \frac{I_C}{\beta} = \frac{11.9}{50} = 0.238 \text{ mA} = 238\mu\text{A}$$

And since

$$I_B = \frac{V_{BB} - V_{BEsat}}{10} \text{ mA}$$

Therefore,

V $V_{BB} = 0.238\text{ mA} \cdot 10\text{k}\Omega + 0.6 = 2.98 \text{ V}$

Problem 10.15

Solution:

Known quantities:

β=60; V_{BE}=0.6V; V_{CB}=7.2V; $|I_E|$=4mA.

Find:

a) I_B;
b) V_{CE};

Analysis:

(a) Since

$$I_E = I_B + I_C = (\beta+1)I_B$$

we can compute

$$I_B = \frac{I_E}{\beta+1} = \frac{4}{61} = 65.6 \text{ mA}$$

(b) $V_{CE} = V_{CB} - V_{BE}$

$= 7.2 - 0.6 = 6.6$ V

Problem 10.16

Solution:

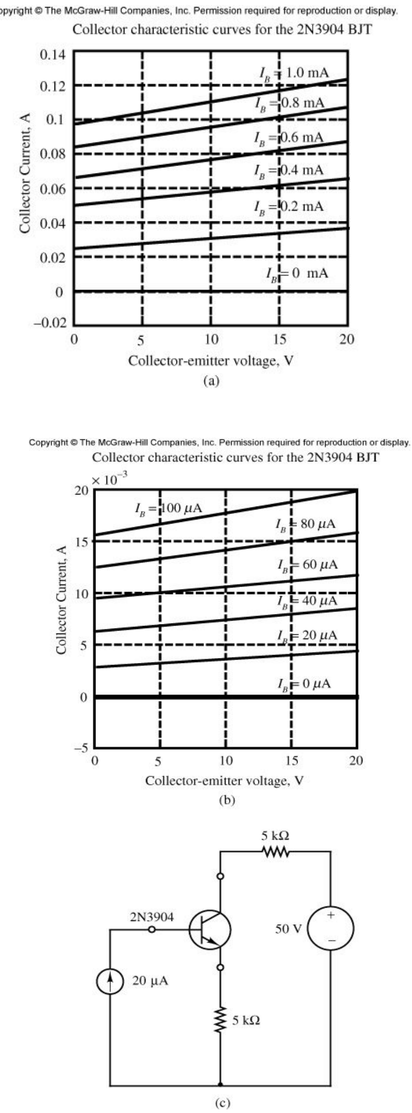
Known quantities:

Collector characteristics of 2N3904 npn transistor; Transistor circuits;

Find:

The operating point;

Analysis:



From KVL,

$$-50 + 5kI_C + V_{CE} + 5k(I_C + 20\mu A) = 0$$

or

$$V_{CE} + 10kI_C = 50 - 0.1 = 49.9$$

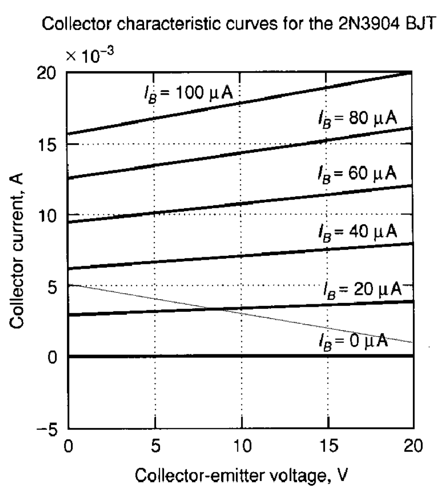
If $V_{CE} = 0$, $I_C = \dfrac{49.9}{10k} = 4.99mA$, and if $I_C = 0$, $V_{CE} = 49.9V$. The load line is shown superimposed on the collector characteristic below:

The operating point is at the intersection of the load line and the $I_B = 20\mu A$ line of the characteristic. Therefore, $I_{CQ} \approx 3mA$ and $V_{CEQ} \approx 8V$.

Under these conditions, a $10\mu A$ increase in I_B yields an increase in I_C of approximately $5mA - 3mA = 2mA$. Therefore,

$$\beta \approx \frac{\Delta I_C}{\Delta I_B} = \frac{2mA}{10\mu A} = 200$$

Addition of the emitter resistor effectively increased the current gain by decreasing the magnitude of the slope of the load line.



Section 10.3: BJT Large-Signal Model

Problem 10.17

Solution:

Known quantities:

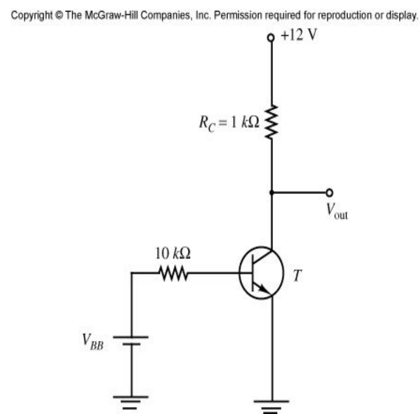
For the circuit shown in Figure 10.14 in the text:

$V_{off} = 0\,\text{V}, V_{on} = 5\,\text{V}, I_B = 5\,\text{mA}, R_B = 1\,\text{k}\Omega, V_{CC} = 5\,\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 0.2\,\text{V}, \beta = 95,$

$V_{\gamma\ LED} = 1.4\,\text{V}, I_{LED} \geq 10\,\text{mA}, P_{\max} = 100\,\text{mW}$

Find:

Range of R_C.



Analysis:

$$R_C = \frac{V_{CC} - V_{\gamma\ LED} - V_{CEsat}}{I_{LED}} \leq \frac{5 - 1.4 - 0.2}{0.01} = 340\ \Omega$$

From the maximum power

$$I_{LED\max} = \frac{P_{\max}}{V_{\gamma\ LED}} = \frac{0.1}{1.4} = 71\ \text{mA}$$

$$R_C > \frac{V_{CC} - V_{\gamma\ LED} - V_{CEsat}}{I_{LED\max}} = 47\ \Omega$$

Therefore, $R_C \in [47,\ 340]\ \Omega$

Problem 10.18

Solution:

Known quantities:

For the circuit shown in Figure 10.18 in the text:

$V_D = 1.1\,\text{V}, R_B = 33\,\text{k}\Omega, V_{CC} = 12\,\text{V}, V_{BE} = 0.75\,\text{V}, V_{CEQ} = 6\,\text{V}, \beta = 188.5, R_S = 500\,\Omega$

Find:

The resistance R_C.

Analysis:

The current through the resistance R_B is given by

$$I_B = \frac{V_D - V_{BEQ}}{R_B} = \frac{1.1 - 0.75}{33000} = 10.6\,\mu\text{A}$$

The current through R_S is: $I_S = \dfrac{V_{CEQ} - V_D}{R_S} = \dfrac{6 - 1.1}{500} = 9.8\,\text{mA}$

It follows that the current through the resistance R_C is

$$I_{CQ} = \beta I_B + I_S = 11.8\,\text{mA}$$

Finally, $R_C = \dfrac{V_{CC} - V_{CEQ}}{I_{CQ}} = \dfrac{12 - 6}{0.0118} = 508.5\,\Omega$

Problem 10.19

Solution:

Known quantities:

For the circuit shown in Figure 10.14 in the text:
$V_{off} = 0\,\text{V}, V_{on} = 5\,\text{V}, I_{B\max} = 5\,\text{mA}, R_C = 340\,\Omega, V_{CC} = 5\,\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 0.2\,\text{V}, \beta = 95,$

$V_{\gamma\, LED} = 1.4\,\text{V}, I_{LED} \geq 10\,\text{mA}, P_{\max} = 100\,\text{mW}$

Find:

Range of R_B.

Analysis:

If the BJT is in saturation

$$I_C = \frac{V_{CC} - V_{\gamma\, LED} - V_{CEsat}}{R_C} = 10\,\text{mA}$$

In order to guarantee that the BJT is in saturation

$$R_B \leq \frac{V_{on} - V_\gamma}{I_C / \beta} = \frac{5 - 0.7}{\frac{0.01}{95}} = 40.85\,\text{k}\Omega$$

$$R_B \geq \frac{V_{on} - V_\gamma}{I_{B\max}} = 860\,\Omega$$

Problem 10.20

Solution:

Known quantities:

For the circuit shown in Figure 10.14 in the text:
$V_{off} = 0\text{V}, V_{on} = 5\text{V}, I_{B\max} = 5\text{mA}, R_B = 10\text{k}\Omega, R_C = 340\Omega, V_{CC} = 5\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 0.2\text{V},$

$V_{\gamma\, LED} = 1.4\text{V}, I_{LED} \geq 10\text{mA}, P_{\max} = 100\text{mW}$

Find:

Minimum value of β that will ensure the correct operation of the LED.

Analysis:

$$I_B = \frac{V_{on} - V_\gamma}{R_B} = \frac{4.3}{10000} = 0.43\,\text{mA}$$

$$\beta_{\min} = \frac{I_{LED\min}}{I_B} = \frac{0.01}{0.43 \cdot 10^{-3}} = 23.25$$

Problem 10.21

Solution:

Known quantities:

For the circuit shown in Figure 10.14 in the text:

$V_{off} = 0\text{V}, V_{on} = 3.3\text{V}, I_{B\max} = 5\text{mA}, R_B = 10\text{k}\Omega, R_C = 340\Omega, V_{CC} = 5\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 0.2\text{V},$

$V_{\gamma\,LED} = 1.4\text{V}, I_{LED} \geq 10\text{mA}, P_{\max} = 100\text{mW}$

Find:

Minimum value of β that will ensure the correct operation of the LED.

Analysis:

$$I_B = \frac{V_{on} - V_\gamma}{R_B} = \frac{3.3 - 0.7}{10000} = 0.26\,\text{mA}$$

$$\beta_{\min} = \frac{I_{LED\min}}{I_B} = \frac{0.01}{0.26 \cdot 10^{-3}} = 38.5$$

Problem 10.22

Solution:

Known quantities:

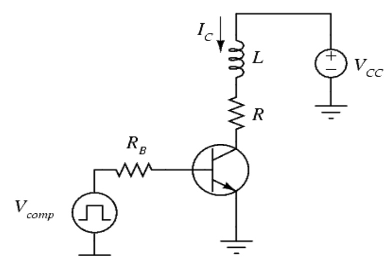
For the circuit shown in Figure 10.14 in the text:

$V_{off} = 0\,\text{V}, V_{on} = 5\,\text{V}, I_{B\max} = 1\,\text{mA}, R_B = 1\,\text{k}\Omega, R = 12\,\Omega, V_{CC} = 13\,\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 1\,\text{V},$

$I_C \geq 1\,\text{A}$

Find:

Minimum value of β that will ensure the correct operation of the fuel injector.



Analysis:

$$I_C = \frac{V_{CC} - V_{CEsat}}{R} = \frac{13 - 1}{12} = 1\,\text{A}$$

$$\beta_{\min} = \frac{I_C}{I_{B\max}} = \frac{1}{1 \cdot 10^{-3}} = 1000$$

Problem 10.23

Solution:

Known quantities:

For the circuit shown in Figure 10.14 in the text:

$V_{off} = 0\,\text{V}, V_{on} = 5\,\text{V}, I_{B\max} = 1\,\text{mA}, \beta = 2000, R = 12\,\Omega, V_{CC} = 13\,\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 1\,\text{V},$

$I_C \geq 1\,\text{A}$

Find:

The range of R_B that will ensure the correct operation of the fuel injector.

Analysis:

If the BJT is in saturation

$$I_C = \frac{V_{CC} - V_{CEsat}}{R} = 1\,\text{A}$$

Because this is the minimum value allowed for the current to drive the fuel injector, it is necessary to guarantee that the BJT is in saturation.

In order to guarantee that the BJT is in saturation

$$R_B \leq \frac{V_{on} - V_\gamma}{I_C / \beta} = \frac{5 - 0.7}{\frac{1}{2000}} = 8.6\,\text{k}\Omega$$

$$R_B \geq \frac{V_{on} - V_\gamma}{I_{B\max}} = 4.3\,\text{k}\Omega$$

Problem 10.24

Solution:

Known quantities:

For the circuit shown in Figure 10.14 in the text:

$V_{off} = 0\,\text{V}, V_{on} = 3.3\,\text{V}, I_{B\max} = 1\,\text{mA}, \beta = 2000, R = 12\,\Omega, V_{CC} = 13\,\text{V}, V_\gamma = 0.7\text{V}, V_{CEsat} = 1\,\text{V},$

$I_C \geq 1\,\text{A}$

Find:

The range of R_B that will ensure the correct operation of the fuel injector.

Analysis:

If the BJT is in saturation

$$I_C = \frac{V_{CC} - V_{CEsat}}{R} = 1\,\text{A}$$

Because this is the minimum value allowed for the current to drive the fuel injector, it is necessary to guarantee that the BJT is in saturation.

In order to guarantee that the BJT is in saturation

$$R_B \leq \frac{V_{on} - V_\gamma}{I_C / \beta} = \frac{3.3 - 0.7}{\frac{1}{2000}} = 5.2\,\text{k}\Omega$$

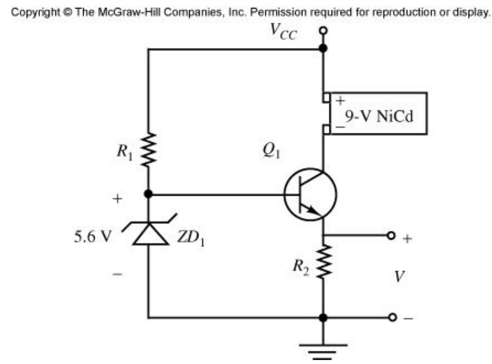
$$R_B \geq \frac{V_{on} - V_\gamma}{I_{B\max}} = 2.6\,\text{k}\Omega$$

Problem 10.25

Solution:

Known quantities:

The circuit of Figure P10.25: $I_C = 40$ mA; Transistor large signal parameters.



Find:

Design a constant-current battery charging circuit, that is, find the values of V_{CC}, R_1, R_2 that will cause the transistor Q_1 to act as a 40-mA constant current source.

Assumptions:

Assume that the transistor is forward biased. Use the large-signal model with $\beta = 100$.

Analysis:

The battery charging current is 40 mA, $I_C = 40$ mA.

Thus, the emitter current must be $I_E = \frac{\beta + 1}{\beta} I_E = 40.4\text{mA}$.

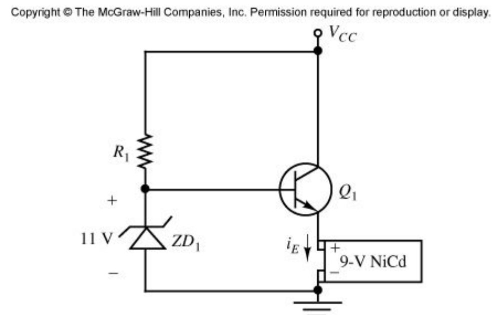
Since the base-emitter junction voltage is assumed to be 0.6 V, then resistor R_2 has a voltage:
$V_2 = V_z - V_\gamma = 5.6 - 0.6 = 5\text{ V}$, so the required value of R_2 to be:

$$R_2 = \frac{V}{I_E} = \frac{5}{0.0404} = 123.8\Omega$$

Since the only purpose of R_1 is to bias the Zener diode, we can select a value that will supply enough current fro the Zener to operate, for example $R_1 > 100\ \Omega$, so that there will be as little current flow through this resistance as possible.
Finally, we need to select an appropriate supply voltage. V_{CC} must be greater than or equal to the sum of the battery voltage, the CE junction voltage and the voltage across R_2. That is, $V_{CC} \geq 9 + V_{CE} + 5$. A collector supply of 24 V will be more than adequate for this task.

Problem 10.26

Solution:



Known quantities:

The circuit of Figure of P10.26.

Find:

Analyze the operation of the circuit and explain how I_E is decreasing until the battery is full.
Find the values of V_{CC}, R_1 that will result in a practical design.

Assumptions:

Assume that the transistor is forward biased.

Analysis:

When the Zener Diode works in its reverse breakdown area, it provides a constant voltage:
$V_z = 11\text{ V}$. That means:
$V_B = V_Z = 11\text{ V}$.
When the transistor is forward biased, according to KVL,
$V_Z = I_{BE} \cdot R_{BE} + V_\gamma + V_{battery}$, where R_{BE} is the base resistance.

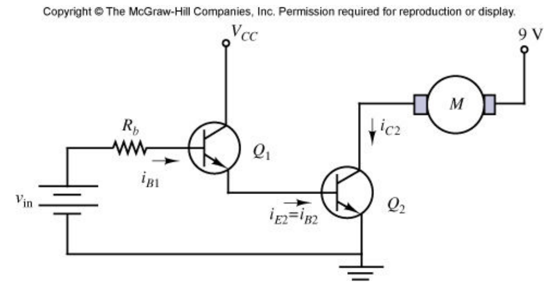
As the battery gets charged, the actual battery charging voltage $V_{battery}$ will increase from 9.6 V to 10.4 V.
As $V_{battery}$ increases gradually, V_Z and V_γ stay unchanged, then we can see that I_{BE} will decrease gradually.
So $I_E = (\beta + 1)I_{BE}$ will also decrease at the same time.

Since the only purpose of R_1 is to bias the Zener diode, we can select a value that will supply enough current fro the Zener to operate, for example $R_1 > 100\ \Omega$, so that there will be as little current flow through this resistance as possible.

Finally, we need to select an appropriate supply voltage. V_{CC} must be greater than or equal to the sum of the battery voltage, the CE junction voltage. That is, $V_{CC} \geq 11 + V_{CE}$. A collector supply of 12 V should be adequate for this task.

Problem 10.27

Solution:



Known quantities:

The circuit of Figure P10.27: V_{in}= 5 V

Find:

Values of R_b.

Assumptions:

Assume that the transistors are in the active region. Use the large-signal model with $\beta = 40$ for each transistor.

Analysis:

The emitter current from Q_1, $i_{E1} = (\beta+1)\, i_{B1}$ becomes the base current for Q_2, and therefore, $i_{C2} = \beta\, i_{E1} = \beta\, (\beta+1)\, i_{B1}$.

The Q_1 base current is given by the expression

$$i_{B1} = \frac{V_{in} - V_\gamma - V_\gamma}{R_b}$$

Therefore the motor current will reach maximum when V_{in}= 5 V:

$$i_{C\max} = \beta(\beta+1)\left(\frac{V_{in} - V_\gamma - V_\gamma}{R_b}\right) = 0.34 \text{ A}$$

So, $R_b = \dfrac{\beta(\beta+1)}{0.34}\left(V_{in} - 2V_\gamma\right) = \dfrac{40 \cdot 41}{0.34}(5 - 1.2) = 18{,}329\Omega$

Since 18.33 kΩ is a standard resistor value, we should select R_b = 18.33 kΩ, which will result in a slightly lower maximum current.

Section 10.4: Selecting an Operating Point for a BJT

Problem 10.28

Solution:

Known quantities:

The circuit of Figure of 10.22 in the text, $R_C = 1\text{K}\Omega$, $V_{BB} = 5\text{V}$, $\beta_{\min} = 50$, $V_{CC} = 10\text{V}$.

Find:

The range of R_B to make the transistor in the saturation state.

Analysis:

Assuming $V_{CEsat} = 0.2\ \text{V}$, the current I_C is:

$$I_C = \frac{V_{CC} - V_{CEsat}}{R_C} = 9.8\ \text{mA}$$

Therefore, $I_B = \dfrac{I_C}{b} = 0.196\ \text{mA}$

Assuming $V_\gamma = V_{BEsat} = 0.6\ \text{V}$, we have

$$R_B = \frac{V_{BB} - V_{BE}}{I_B} = 22.45\ \text{k}\Omega$$

That is $0 < R_B < 22.45\ \text{k}\Omega$

Problem 10.29

Solution:

Known quantities:

The circuit of Figure of 10.22 in the text, $R_C = 1\text{K}\Omega$, $R_B = 10\text{K}\Omega$, $\beta_{\min} = 50$, $V_{CC} = 5\text{V}$.

Find:

The range of V_{BB} to make the transistor in the saturation state.

Analysis:

Assume $V_{CEsat} = 0.2\ \text{V}$, the current I_C can be found as

$$I_C = \frac{V_{CC} - V_{CEsat}}{R_C} = 4.8\ \text{mA}$$

Therefore, $I_B = \dfrac{I_C}{b} = 0.096\ \text{mA} = 96\ \mu\text{A}$

Assuming $V_\gamma = V_{BEsat} = 0.6\ \text{V}$, we have

$$V_{BB} = I_B R_B + V_{BEsat} = 1.56\ \text{V}$$

That is $V_{BB} > 1.56\ \text{V}$

Problem 10.30

Solution:

Known quantities:

The circuit of Figure 10.20 in the text, $R_C = 2\text{k}\Omega$, $I_{BB} = 20\mu\text{A}$, $\beta = 100$, $V_{CC} = 10\text{V}$.

Find:

I_C, I_E, V_{CE}, V_{CB}.

Analysis:

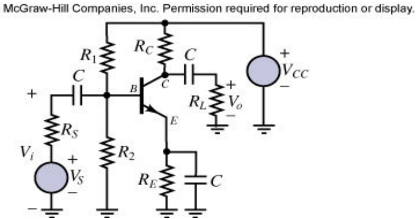
$$I_C = \beta I_B = 100 \times 20 \times 10^{-6} = 2 \text{ mA}$$
$$I_E = I_B + I_C = (\beta + 1) I_B$$
$$= 101 \times 20 \times 10^{-6} = 2.02 \text{ mA}$$
$$V_{CE} = V_{CC} - I_C R_C = 10 - 2 \times 2 = 6 \text{ V}$$

Assume $V_{BE} = 0.6 \text{ V}$

Then $V_{CB} = V_{CE} - V_{BE} = 6 - 0.6 = 5.4 \text{ V}$

Problem 10.31

Solution:



Known quantities:

For the circuit shown in Figure P10.31:

$V_{CC} = 20 \text{ V}$ $\beta = 130$ $R_1 = 1.8 \text{ M}\Omega$ $R_2 = 300 \text{ k}\Omega$

$R_C = 3 \text{k}\Omega$ $R_E = 1 \text{k}\Omega$

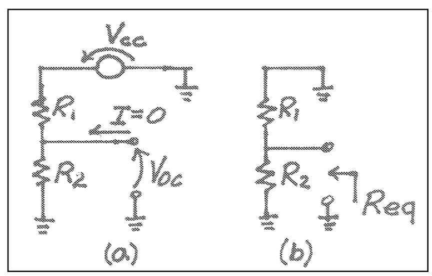
$R_L = 1 \text{k}\Omega$ $R_S = 0.6 \text{k}\Omega$ $v_S = 1 \cos(6.28 \times 10^3 t) \text{ mV}$.

Find:

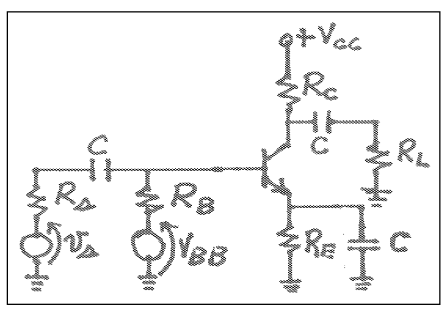
The Thèvenin equivalent of the part of the circuit containing R_1, R_2, and V_{CC} with respect to the terminals of R_2. Redraw the schematic using the Thèvenin equivalent.

Analysis:

Extracting the part of the circuit specified, the Thèvenin equivalent voltage is the open circuit voltage. The equivalent resistance is obtained by suppressing the ideal independent voltage source:



Note that V_{CC} must remain in the circuit because it supplies current to other parts of the circuit:



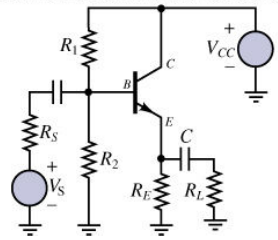
Problem 10.32

Solution:

Known quantities:

For the circuit shown in Figure P10.32:

$V_{CC} = 12\,\text{V} \quad \beta = 130 \quad R_1 = 82\,\text{k}\Omega \quad R_2 = 22\,\text{k}\Omega \quad R_E = 0.5\,\text{k}\Omega \quad R_L = 16\,\Omega$.



Find:

V_{CEQ} at the DC operating point.

Analysis:

Simplify the circuit by obtaining the Thèvenin equivalent of the biasing network (R_1, R_2, V_{CC}) in the base circuit:

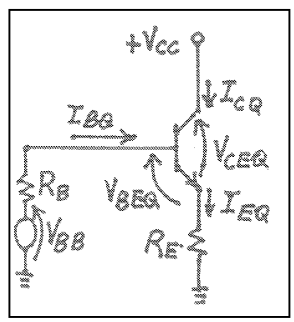
$$\text{VD}: \; V_{BB} = V_{TH} = V_{OC} = \frac{V_{CC} R_2}{R_1 + R_2} = \frac{12 \cdot 22}{82 + 22} = 2.538\,\text{V}$$

$$\text{Suppress } V_{CC}: \quad R_B = R_{eq} = \frac{R_1 R_2}{R_1 + R_2} = \frac{82 \cdot 22}{82 + 22} = 17.35\,\text{k}\Omega$$

Redraw the circuit using the Thèvenin equivalent. The "DC blocking" or "AC coupling" capacitors act as open circuits for DC; therefore, the signal source and load can be neglected since this is a DC problem. Specify directions of current and polarities of voltages.

Assume the transistor is operating in its active region. Then, the base-emitter junction is forward biased.

$$V_{BEQ} \approx 700\,\text{mV} \quad [Si] \qquad I_{EQ} = [\,\beta + 1\,]\, I_{BQ}$$



$$\text{KVL}: \; -V_{BB} + I_{BQ} R_B + V_{BEQ} + I_{EQ} R_E = 0$$

$$-V_{BB} + I_{BQ} R_B + V_{BEQ} + [\,\beta + 1\,]\, I_{BQ} R_E = 0$$

$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_B + (\beta + 1) \cdot R_E} = \frac{2.538 - 0.7}{17350 + (130 + 1) \cdot 500} = 22.18\,\mu\text{A}$$

$$I_{EQ} = (\beta + 1)\, I_{BQ} = (130 + 1) \cdot 22.18 \cdot 10^{-6} = 2.906\,\text{mA}$$

$$\text{KVL}: \; -I_{EQ} R_E - V_{CEQ} + V_{CC} = 0$$

$$V_{CEQ} = V_{CC} - I_{EQ} R_E = 12 - 2.906 \cdot 0.5 = 10.55\,\text{V}$$

The collector-emitter voltage is greater than its saturation value (0.3 V for Silicon). Therefore the initial assumption (operation in the active region) was correct and the solution is valid.

Problem 10.33

Solution:

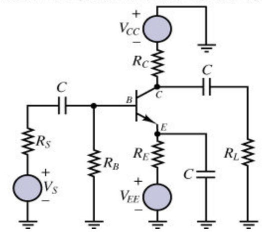
Known quantities:

For the circuit shown in Figure P10.33:

$V_{CC} = 12\,\text{V}$ $\beta = 100$ $V_{EE} = 4\,\text{V}$ $R_B = 100\,\text{k}\Omega$

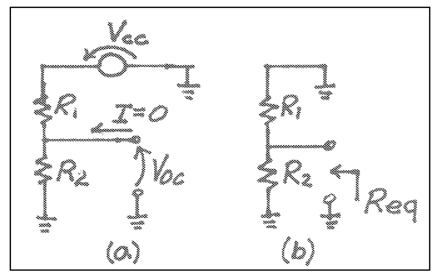
$R_C = 3\,\text{k}\Omega$ $R_E = 3\,\text{k}\Omega$

$R_L = 6\,\text{k}\Omega$ $R_S = 0.6\,\text{k}\Omega$ $v_S = 1\cos(6.28 \times 10^3 t)\,\text{mV}$.



Find:

V_{CEQ} and the region of operation.



Analysis:

The "DC blocking" or "AC coupling" capacitors act as open circuits for DC; therefore, the signal source and load can be neglected since this is a DC problem. Specify directions of current and polarities of voltages. Assume the transistor is operating in its active region; then, the base-emitter junction is forward biased and:

$$V_{BEQ} \approx 700\,\text{mV} \quad [Si]$$

$$I_{CQ} = \beta \cdot I_{BQ} \qquad I_{EQ} = (\beta + 1) I_{BQ}$$

$$\text{KVL}: \; -V_{EE} + I_{BQ} R_B + V_{BEQ} + I_{EQ} R_E = 0 \quad \Rightarrow$$

$$I_{BQ} = \frac{V_{EE} - V_{BEQ}}{R_B + [\beta + 1] R_E} = \frac{4 - 0.7}{100000 + (100+1)(3000)} = 8.189\,\mu\text{A}$$

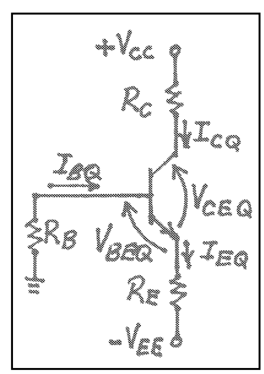
$$I_{CQ} = \beta \cdot I_{BQ} = (100) \cdot 8.189 \cdot 10^{-6} = 818.9\,\mu\text{A}$$

$$I_{EQ} = (\beta + 1) \cdot I_{BQ} = (100 + 1) \cdot 8.189 \cdot 10^{-6} = 827.0\,\mu\text{A}$$

$$\text{KVL}: \; +V_{EE} - I_{EQ} R_E - V_{CEQ} - I_{CQ} R_C + V_{CC} = 0 \quad \Rightarrow$$

$$V_{CEQ} = V_{EE} + V_{CC} - I_{CQ} R_C - I_{EQ} R_E = 4 + 12 - 818.9 \cdot 10^{-6} \cdot 3000 - 827.0 \cdot 10 \cdot 10^{-6} \cdot 3000$$

$$= 11.06\,\text{V}$$



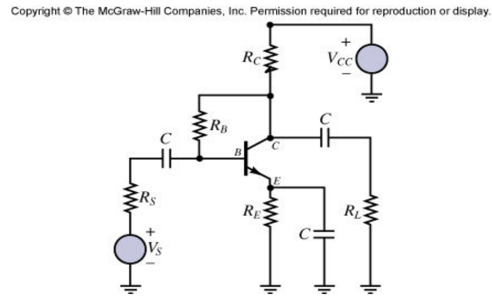
The collector-emitter voltage is greater (more positive) than its saturation value (+ 0.3 V for Silicon). Therefore the initial assumption (operation in the active region) was correct and the solution is valid.

Notes:

1. DC power may be supplied to an *npn* BJT circuit by connecting the positive terminal of a DC source to the collector circuit, or, by connecting the negative terminal of a DC source to the emitter circuit, or, as was done here, both.
2. In a *pnp* BJT circuit the polarities of the sources must be reversed. Negative to collector and positive to emitter.

Problem 10.34

Solution:



Known quantities:

For the circuit shown in Figure P10.34:

$V_{CC} = 12\,\text{V}$ $\beta = 130$ $R_B = 325\,\text{k}\Omega$ $R_C = 1.9\,\text{k}\Omega$ $R_E = 2.3\,\text{k}\Omega$

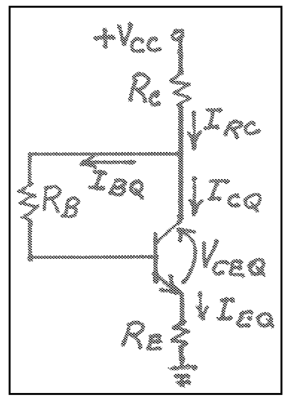
$R_L = 10\,\text{k}\Omega$ $R_S = 0.5\,\text{k}\Omega$ $v_S = 1\cos(6.28\times10^3 t)\,\text{mV}$.

Find:

V_{CEQ} and the region of operation.

Analysis:

The "DC blocking" or "AC coupling" capacitors act as open circuits for DC; therefore, the signal source and load can be neglected since this is a DC problem. Specify directions of current and polarities of voltages. Assume the transistor is operating in its active region; then, the base-emitter junction is forward biased. The base and collector currents both flow through the collector resistor in this circuit.



$$V_{BEQ} \approx 700\,\text{mV} \quad [Si]$$

$$I_{CQ} = \beta \cdot I_{BQ} \qquad I_{EQ} = (\beta+1)I_{BQ}$$

$$\text{KCL}: \; I_{BQ} + I_{CQ} - I_{RC} = 0 \quad \Rightarrow$$

$$I_{RC} = I_{CQ} + I_{BQ} = (\beta+1)I_{BQ}$$

$$I_{BQ} = \frac{V_{CC} - V_{BEQ}}{R_B + (\beta+1)(R_E + R_C)} = \frac{12 - 0.7}{(325 + (130+1)\cdot(2.3+1.9))\cdot 10^3} = 12.91\mu\text{A}$$

$$I_{RC} = I_{EQ} = (\beta+1)\cdot I_{BQ} = (130+1)\cdot 12.96\cdot 10^{-6} = 1.691\,\text{mA}$$

$$\text{KVL}: \; -I_{EQ}R_E - V_{CEQ} - I_{RC}R_C + V_{CC} = 0 \quad \Rightarrow$$

$$V_{CEQ} = V_{CC} - I_{RC}R_C - I_{EQ}R_E = 12 - 1.691\cdot 1.9 - 1.691\cdot 2.3$$

$$= 4.896\,\text{V}$$

$$\text{KVL}: \; -I_{EQ}R_E - V_{BEQ} - I_{BQ}R_B - I_{RC}R_C + V_{CC} = 0 \quad \Rightarrow$$

$$-(\beta+1)I_{BQ}(R_E + R_C) - V_{BEQ} - I_{BQ}R_B + V_{CC} = 0$$

The collector-emitter voltage is greater than its saturation value (0.3 V for Silicon). Therefore the initial assumption (operation in the active region) was correct and the solution is valid.

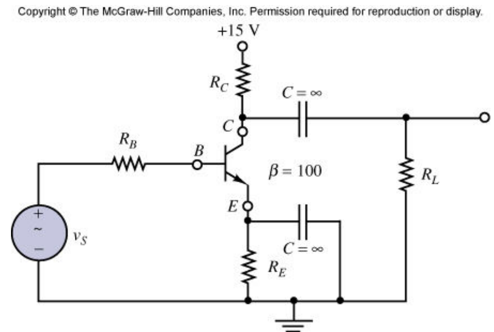
Problem 10.35

Solution:

Known quantities:

For the circuit shown in Figure P10.35:

$v_S = 3\,\text{V}$ $\qquad \beta = 100$ $\qquad R_B = 60\,\text{k}\Omega$



Find:

a) The value of R_E so that I_E is 1 mA.

b) R_C so that V_C is 5 V.

c) The small-signal equivalent circuit of the amplifier for $R_L = 5\text{k}\Omega$

d) The voltage gain.

Analysis:

(a) With $R_B = 60\,\text{k}\Omega$ and $V_B = 3\ \text{V}$, applying KVL, we have

$$3 = I_B R_B + 0.6 + (1+\beta) I_B R_E$$

$$I_B = \frac{2.4}{60\text{k}\Omega + 101 R_E}$$

$$I_E = 101 \frac{2.4}{60k\Omega + 101 R_E} = 1mA$$

Therefore,

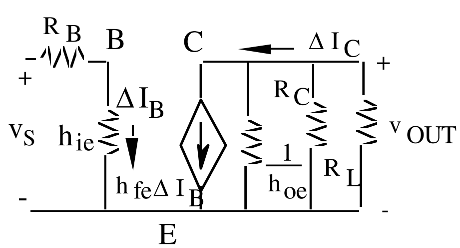
$$R_E = \frac{101 \cdot 2.4 - 60}{101} = 1.81\,\text{k}\Omega$$

(b) $V_{CE} = 15 - I_C R_C - I_E R_E$

From (a), we have $I_C = I_E \dfrac{\beta}{\beta + 1} = 0.99\ \text{mA}$

Therefore, $R_C = \dfrac{15 - 5 - 1.81}{0.99} = 8.27\ \text{k}\Omega$

(c) The small signal equivalent circuit is shown below



(d) $\qquad \Delta I_B = \dfrac{V_S}{R_B + h_{iw}}$

$$v_{out} = -\Delta I_C \left(R_L \middle\| \frac{1}{h_{oe}} \right) \qquad \Delta I_C = \frac{V_{out}}{1/h_{oe}} + h_{fe} \Delta I_B$$

$$h_{ie} = \frac{\partial V_{BE}}{\partial I_B}\bigg|_{I_{BQ}} = \frac{0.6}{0.0099 \times 10^{-3}} = 60.6k\Omega$$

Since h_{oe} is not given, we can reasonably assume that $1/h_{oe}$ is very large. Therefore,

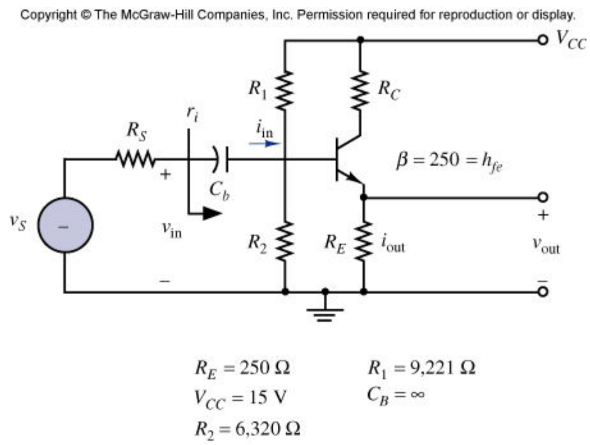
$$A_V = \frac{v_{out}}{v_s} = -\frac{100 \cdot R_L}{R_B + h_{ie}} = -4.15$$

Problem 10.36

Solution:

Known quantities:

For the circuit shown in Figure P10.36:
$R_C = 200\,\text{k}\Omega$



Find:

e) The operating point of the transistor.
f) Voltage gain v_{out}/v_{in} ; current gain i_{out}/i_{in}
g) Input resistance r_i
h) Output resistance r_o

Analysis:

(a) $V_B = V_{CC}\dfrac{R_2}{R_1 + R_2} = 6.1\ \text{V}$

$$R_B = R_1 \,||\, R_2 = 3749.87\ \Omega$$

Assuming $V_{BE} = 0.6\ \text{V}$, we have

$$V_{EV} = V_B - V_{BE} = 5.5\ \text{V}$$

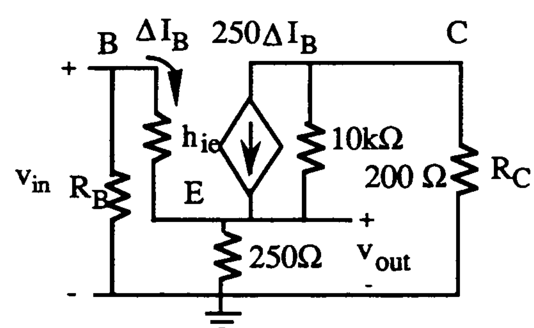
$$I_E = \frac{V_E}{R_E} = 22\ \text{mA}$$

$$I_B = \frac{I_E}{b+1} = 0.088\ \text{mA}$$

and

$$V_{CE} = V_C - V_E = (V_{CC} - R_C I_C) - 5.5$$
$$= 15 - 200 \cdot 21.912 \cdot 10^{-3} - 5.5 = 5.12\ \text{V}$$

(b) The AC equivalent circuit is shown on the right:



$$h_{ie} = \frac{\partial V_{BE}}{\partial I_B}\bigg|_{I_{BQ}} \approx \frac{0.6}{0.088 \times 10^{-3}} = 6.82k\Omega$$

$$v_{out} = R_E(I_B + I_C) = 250(250+1)I_B$$

$$v_{in} = I_B h_{ie} + v_{out} = I_B h_{ie} + 250 \cdot 251 \cdot I_B$$

Therefore, the voltage gain is

$$A_V = \frac{v_{out}}{v_{in}} = 0.902 \qquad \text{and}$$

$$i_{out} = I_B + I_C + (\beta+1) \cdot I_B$$

$$i_{in} = I_B + \frac{v_{in}}{R_B} = I_B + (I_B h_{ie} + 250 \cdot 251 \cdot I_B)/R_B$$

and the current gain is

$$\frac{i_{out}}{i_{in}} = \frac{(\beta+1)I_B}{I_B + (I_B h_{ie} + 250 \cdot 251 \cdot I_B)/R_B} = 12.84$$

(c) To find the input resistance we compute:

$$v_{in} = I_B h_{ie} + 250 \cdot 251 \cdot I_B$$

$$i_{in} = I_B + (I_B h_{ie} + 250 \cdot 251 \cdot I_B)/R_B$$

Therefore. the input resistance is

$$r_i = \frac{v_{in}}{i_{in}} = 3558\Omega$$

(d) To find the output resistance we compute

$$v_{out} = R_E(I_B + I_C) = 250(250+1)I_B$$

$$i_{out} = I_B + I_C + (\beta + 1) \cdot I_B$$

Therefore, the output resistance is

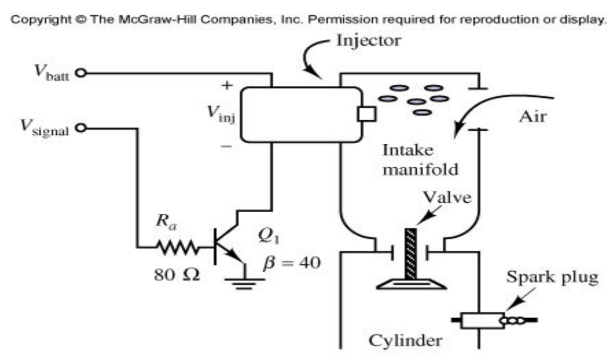
$$r_o = \frac{v_{out}}{i_{out}} = 250\Omega$$

Problem 10.37

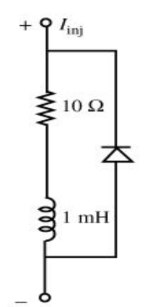
Solution:

Known quantities:

The circuit shown in Figure P10.37(a), P10.37(b):



(a)



(b)

Find:

The duration of the fuel injector pulse.

Analysis:

(a) With $V_{CE} = 0.3$ V, $V_{BE} = 0.9$ V and $V_{BATT} = 13$ V, $T_C = 100°$, from Figure P9.6(d), we have $K_C = 0$, VCIT = 16/13= 1.23 ms. The signal duration is:

$\tau = 1\times10^{-3}\times0 + 1.23\times10^{-3} = 1.23$ ms

When V_{signal} is applied, the base current is

$I_B = V_{BATT}/80 = 0.1625$ A

Thus, the transistor will be in the saturation region.

Therefore,

$V_{inj} = V_{BATT} - V_{CE} = 13 - 0.3 = 12.7$ V

The time constant of the injector circuit is:

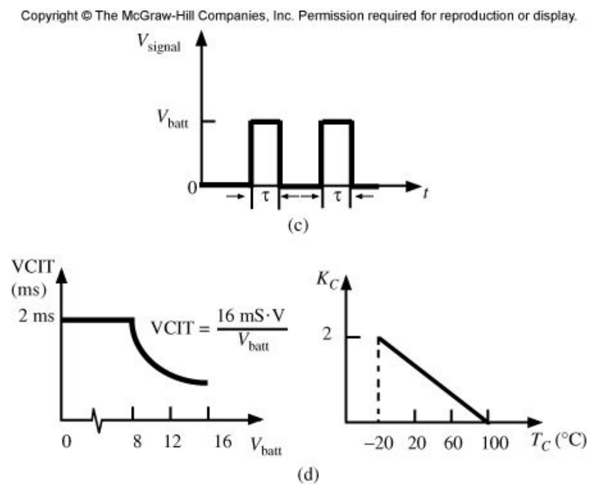
$\tau' = L/R = 0.1$ ms $<< \tau = 1.23$ ms

As $V_{signal} = 0$, the transistor is in the cut-off region. The differential equation governing the injector current is:

$1\times10^{-3}\, dI_{inj}/dt + 10 I_{inj} = V_{inj}$,

and $I_{inj}(0) = 0$. Thus,

I_{inj} = Vinj/10- Vinj/10·$e^{-10000t}$



(c)

(d)

The time when $I_{inj} \geq 0.1$ is then found to be

t_{inj} = -(ln(1.17/1.27))/10^4= 8.2 μs

That is, 8.2 ms after the V_{signal} is applied, the fuel will be injected into the intake manifold.

(b) From Figure P10.37(d), we have

$K_C = - 1/60 \cdot T_C + 5/3$; at $T_C = 20$, $K_C = 4/3$. Also, VCIT = 16/8.6= 1.86 ms

The signal duration therefore is

$\tau = 1\times10^{-3}\times4/3+ 1.86\times10^{-3} = 3.19$ ms

When V_{signal} is applied, the base current is

$I_B = V_{BATT}/80= 0.1075$ A

Thus, the transistor will be in the saturation region. Therefore,

$V_{inj} = V_{BATT} - V_{CE} = 8.6 - 0.3 = 8.3$ V

The time constant of the injection circuit is:

τ' = L/R= 0.1 ms << τ = 3.19 ms

When V_{signal} is 0, the transistor is in the cut-off region. Using the same differential equation and initial condition as in part (a),

I_{inj} = Vinj/10- Vinj/10·$e^{-10000t}$

The time when $I_{inj} \geq 0.1$ can be found as

t = 12.84 μs

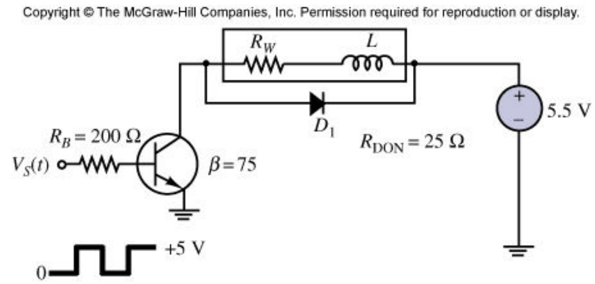
That is, 12.84 μs after the V_{signal} is applied, the fuel will be injected into the intake manifold.

Problem 10.38

Solution:

Known quantities:

For the circuit shown in Figure P10.38: $V_\gamma = 0.8$ V



Find:

The maximum of frequency with which the light can be switched.

Analysis:

From the power dissipation of the relay,

$$P = 0.5 = \frac{V^2}{R_W} \text{ W},$$

we can compute

$R_W = 50\ \Omega$

When v_S is 5 V, the transistor is in the saturation region and the relay current at steady state is:

$$I_R = \frac{55 - 0.2}{50} = 106 \text{ mA}$$

When v_S is 0 V, the transistor will be in cut off, and we have the following equation

$$0.005\frac{dI_R}{dt} + 50 I_R = 0$$

That is

$$\frac{dI_R}{dt} + 10 \cdot 10^3 I_R = 0$$

Solving the above equation with

$I_R(0) = 0.106$ A,

$I_R(t) = 0.106e^{-10000t}$

$v_R(t) = -25\ I_R = -2.65e^{-10000t}$

The relay will be cut-off as soon as v_S is 0.

Therefore, the switching frequency will be the frequency of the input signal v_S.

Problem 10.39

Solution:

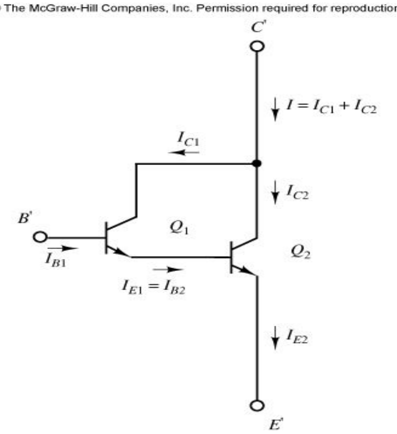
Known quantities:

For the circuit shown in Figure P10.39:
$Q_1 : \beta = 130; Q_2 : \beta = 70$.

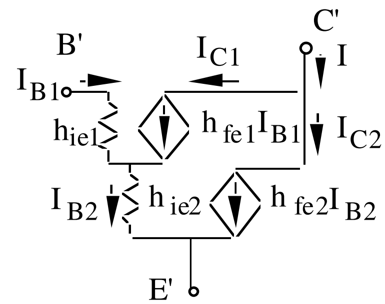
Find:

The overall current gain.

Analysis:



The AC circuit is shown on the right:



The current gain is

$$A_i = \frac{I}{I_{B1}} = \frac{I_{C1} + I_{C2}}{I_{B1}}$$
$$= \frac{I_{C1}}{I_{B1}} + \frac{I_{C2}}{I_{B2}}$$
$$= \mathrm{h_{fe1}} + \frac{h_{fe2} I_{B2}}{I_{B1}}$$
$$= \mathrm{h_{fe1}} + \frac{h_{fe2} I_{E1}}{I_{B1}} = \mathrm{h_{fe1}} + h_{fe2}(h_{fe1} + 1)\frac{I_{B1}}{I_{B1}} = 9300$$

Problem 10.40

Solution:

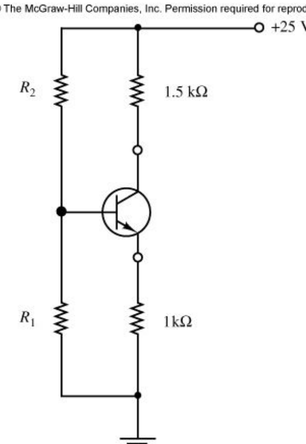
Known quantities:

For the circuit shown in Figure P10.40: $V_\gamma = 0.6$ V .

Find:

R_1 and R_2 .

Analysis:



a) It's given by the problem.

b)
For $V_{CEQ} = 5$, $V_{R_C} + V_{R_E} = 20V$.

Assume $I_C \approx I_E$.

$$I_C = \frac{20}{2.5k} = 8mA \Rightarrow V_E = 8V$$
$$V_B = 8 + 0.7 = 8.7V$$

For $\beta = 20$, $I_B = \frac{8}{20} = 0.4mA$.

For $\beta = 50$, and $I_C \le 8.8mA$,

$I_B \le \frac{8.8}{50} = 0.176mA$

$V_B = 8.8 + 0.7 = 9.5V$

$V_B - 0.4\times10^{-3} R_B = 8.7$

$V_B - 0.176\times10^{-3} R_B = 9.5$

Solving, $R_B = 5.35k\Omega$.

$V_B = 9.84V$

Since $V_B = \frac{R_1}{R_1 + R_2} V_{CC} = \frac{R_1}{R_1 + R_2}(25)$

and $R_B = \frac{R_1 R_2}{R_1 + R_2}$, we can solve for

$R_1 = 8.82k\Omega$ and $R_2 = 13.59k\Omega$.

c)

Assume $V_{CE_{\max}} \approx 23V$ and $V_{CE_{\min}} \approx 3V$.

Then V_{CEQ} should be set to the middle of this range, or $V_{CEQ} = \frac{23+3}{2} = 13V$.

From KVL,

$1000 I_{EQ} + V_{CEQ} + 1500 I_{CQ} = 25$

or,

$1000(\beta+1) I_{BQ} + V_{CEQ} + 1500(\beta) I_{BQ} = 25$

Solving,

$251000 I_{BQ} = 25 - 13 = 12$

$\therefore I_{BQ} = 47.81\mu A$

$V_{EQ} = 1000(\beta+1) I_{BQ} = 4.829V$

$V_{BQ} = V_{EQ} + V_{BE} = 5.529V$

Again from KVL,

$R_1\left(I_{R_2} - I_{BQ}\right) = V_{BQ} \Rightarrow R_1(I_{R_2} - 47.81\mu A) = 5.529$

And $R_2 I_{R_2} + V_{BQ} = 25 \Rightarrow R_2 I_{R_2} = 25 - 5.529 = 19.471$

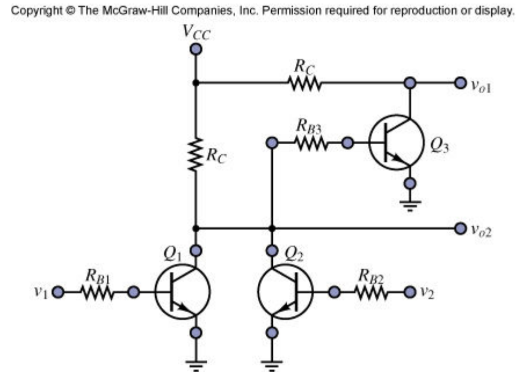
Choose a typical value for R_2, say $R_2 = 10k\Omega$. Then,

$I_{R_2} = \frac{19.471}{R_2} = 1.947mA$

And $R_1 = \frac{5.529}{1.947mA - 47.81\mu A} = 2911\Omega$

Section 10.4: BJT Switches and Gates

Problem 10.41



Solution:

Known quantities:

The circuit given in Figure P10.41.

Find:

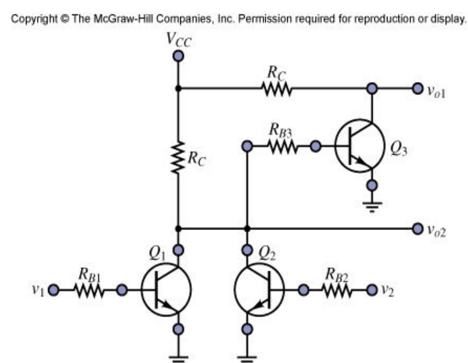
Show that the given circuit functions as an OR gate if the output is taken at v_{01}.

Analysis:

Construct a state table. This table clearly describes an AND gate when the output is taken at v_{o1}.

v_1	v_2	Q_1	Q_2	Q_3	v_{o1}	v_{o2}
0	0	off	off	on	0	5V
0	5V	off	on	off	5V	0
5V	0	on	off	off	5V	0
5V	5V	on	on	off	5V	0

Problem 10.42



Solution:

Known quantities:

The circuit given in Figure P10.41.

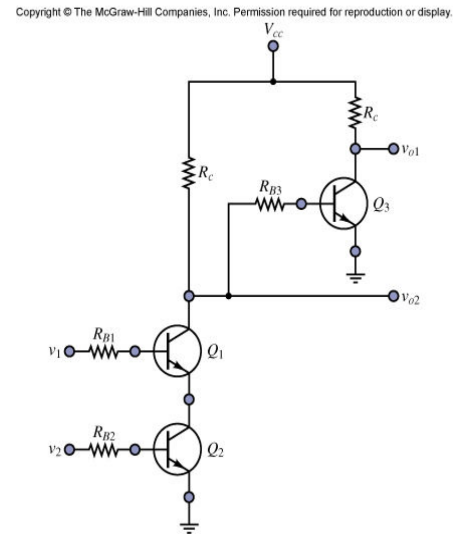
Find:

Show that the given circuit functions as a NOR gate if the output is taken at v_{02}.

Analysis:

See the state table constructed for Problem 10.41. This table clearly describes a NOR gate when the output is taken at v_{o2}.

Problem 10.43



Solution:

Known quantities:

The circuit given in Figure P10.43.

Find:

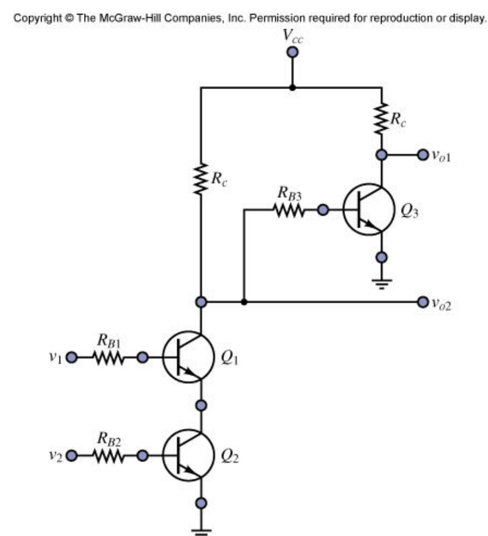
Show that the given circuit functions as an AND gate if the output is taken at v_{01}.

Analysis:

Construct a state table. This table clearly describes an AND gate when the output is taken at v_{o1}.

v_1	v_2	Q_1	Q_2	Q_3	v_{o1}	v_{o2}
0	0	off	off	on	0	5V
0	5V	off	on	on	0	5V
5V	0	on	off	on	0	5V
5V	5V	on	on	off	5V	0

Problem 10.44



Solution:

Known quantities:

The circuit given in Figure P10.43.

Find:

Show that the given circuit functions as a NAND gate if the output is taken at v_{02}.

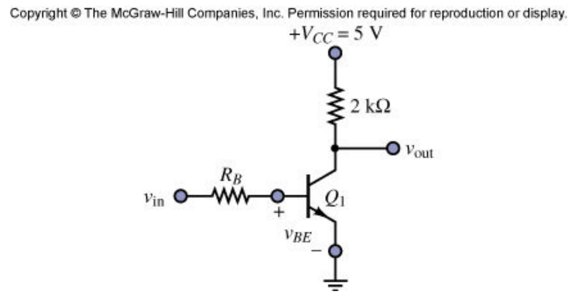
Analysis:

See the state table constructed for Problem 10.32. This table clearly describes a NAND gate when the output is taken at v_{o2}.

Problem 10.45

Solution:

Known quantities:



In the circuit given in Figure P10.45 the minimum value of v_{in} for a high input is 2.0 V. Assume that the transistor Q_1 has a β of at least 10.

Find:

The range for resistor R_B that can guarantee that the transistor is on.

Analysis:

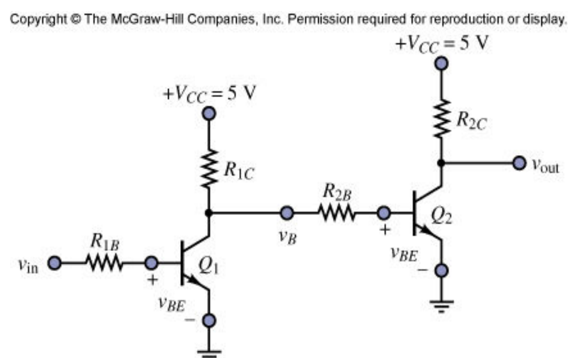
$i_c = \frac{5-0.2}{2000} = 2.4\,\text{mA}$, therefore, $i_B = i_C/\beta = 0.24$ mA.

$(v_{in})\text{min} = 2.0$ V and $(v_{in})\text{max} = 5.0$ V, therefore, applying KVL: $-v_{in} + R_B\, i_B + 0.6 = 0$

or $R_B = \frac{v_{in} - 0.6}{i_B}$. Substituting for $(v_{in})\text{min}$ and $(v_{in})\text{max}$, we find the following range for R_B:

$5.833\,k\Omega \le R_B \le 18.333\,k\Omega$

Problem 10.46



Solution:

Known quantities:

For the circuit given in Figure P10.46:

$$R_{1C} = R_{2C} = 10\,\text{k}\Omega \quad , \quad R_{1B} = R_{2B} = 27\,\text{k}\Omega\ .$$

Find:

a) v_B, v_{out}, and the state of the transistor Q_1 when v_{in} is low.
b) v_B, v_{out}, and the state of the transistor Q_1 when v_{in} is high.

Analysis:

a) v_{in} is low $\Rightarrow Q_1$ is cutoff $\Rightarrow v_B = 5$ V $\Rightarrow Q_2$ is in saturation $\Rightarrow v_{out} = low = 0.2$ V.

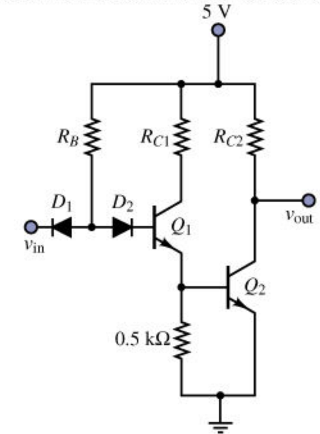
b) v_{in} is high $\Rightarrow Q_1$ is in saturation $\Rightarrow v_B = 0.2$ V $\Rightarrow Q_2$ is cutoff $\Rightarrow v_{out} = high = 5$ V.

Problem 10.47

Solution:

Known quantities:

For the inverter given in Figure P10.47:
$R_{C1} = R_{C2} = 2\,\text{k}\Omega \quad , \quad R_B = 5\,\text{k}\Omega$.



Find:

The minimum values of β_1 and β_2 to ensure that Q_1 and Q_2 saturate when v_{in} is high.

Analysis:

$i_c = \frac{5-0.2}{2000} = 2.4\,\text{mA}$, therefore, $i_c = \frac{2.5}{\beta}\,\text{mA}$. Applying

KVL: $-5 + R_B i_{B1} + 0.6 + 0.6 + 0.6 = 0$

Therefore, i_{B1}= 0.64 mA. $i_{E1} = \beta_1 \cdot i_{B1} = {}^{600}\!/_{500} + i_{B2}$ or

$0.64 \cdot \beta_1 = 1.2 + {}^{2.5}\!/_{\beta_2}$

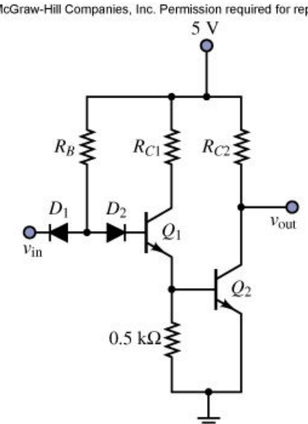
Choose $\beta_2 = 10 \;\Rightarrow\; \beta_1 = 2.27$.

Problem 10.48

Solution:

Known quantities:

For the inverter given in Figure P10.47:
$R_{C1} = 2.5\,\text{k}\Omega \quad , \quad R_{C2} = 2\,\text{k}\Omega \quad , \quad \beta_1 = \beta_2 = 4$.



Find:

Show that Q_1 saturates when v_{in} is high. Find a condition for R_{C2} to ensure that Q_2 also saturates.

Analysis:

$i_{B1} = \frac{3.2}{4000} = 0.8\,\text{mA} \quad \Rightarrow \quad i_{C1} = 3.2\,\text{mA}$

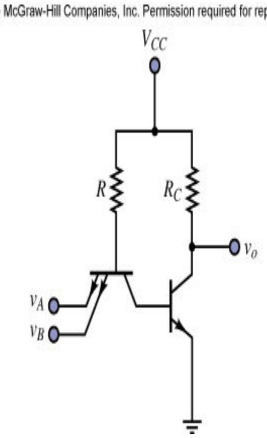
Applying KCL:

$\frac{600}{500} + i_{B2} = 3.2 \quad \Rightarrow \quad i_{B2} = 2\,\text{mA} \quad ; \quad i_{C2} = \beta \cdot i_{B2} = 8\,\text{mA}$

Applying KVL: $5 - 0.2 = 0.008 \cdot R_{C2} \quad \Rightarrow \quad R_{C2} = 600\,\Omega$

Problem 10.49

Solution:

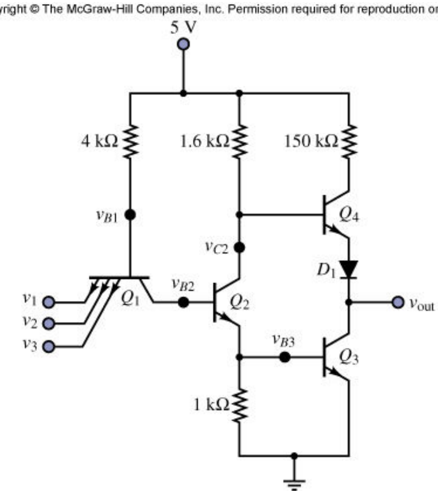


Known quantities:
The basic circuit of a TTL gate, shown in Figure P10.49.

Find:
The logic function performed by this circuit.

Analysis:
The circuit performs the function of a 2-input NAND gate. The analysis is similar to Example 10.10.

Problem 10.50



Solution:

Known quantities:
The circuit diagram of a three-input TTL NAND gate, given in Figure P10.50.

Find:
v_{B1}, v_{B2}, v_{B3}, v_{C2}, and v_{out}, assuming that all the input voltages are high.

Analysis:
Q_2 and Q_3 conduct, while Q_4 is cutoff. v_{B1} = 1.8 V, v_{B2} = 1.2 V, v_{B3} = 0.6 V, and $v_{C2} = v_{out}$ = 0.2 V.

Problem 10.51

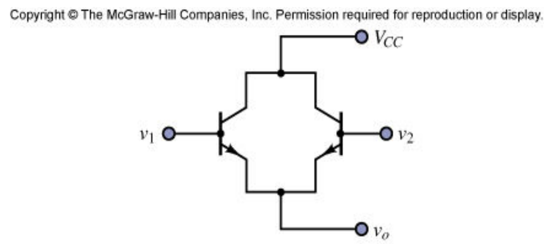
Solution:

Known quantities:

Figure P10.51.

Find:

Show that when two or more emitter-follower outputs are connected to a common load, as shown in Figure P10.51, the OR operation results; that is, $v_0 = v_1$ OR v_2.



Analysis:

v_2	v_1	Q_1	Q_2	v_0
L	L	L	L	L
L	H	H	L	H
H	L	L	H	H
H	H	H	H	H

L : Low; H : High.