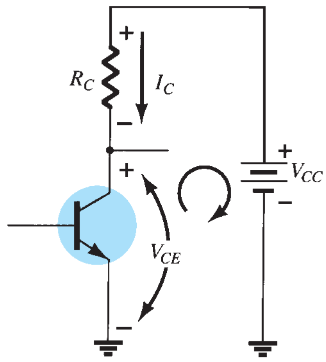

FIG. 4.5
Collector–emitter loop.

Collector–Emitter Loop

The collector–emitter section of the network appears in Fig. 4.5 with the indicated direction of current I_C and the resulting polarity across R_C. The magnitude of the collector current is related directly to I_B through

$$\boxed{I_C = \beta I_B} \qquad \textbf{(4.5)}$$

It is interesting to note that because the base current is controlled by the level of R_B and I_C is related to I_B by a constant β, the magnitude of I_C is not a function of the resistance R_C. Changing R_C to any level will not affect the level of I_B or I_C as long as we remain in the active region of the device. However, as we shall see, the level of R_C will determine the magnitude of V_{CE}, which is an important parameter.

Applying Kirchhoff's voltage law in the clockwise direction around the indicated closed loop of Fig. 4.5 results in the following:

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

and

$$\boxed{V_{CE} = V_{CC} - I_C R_C} \qquad \textbf{(4.6)}$$

which states that the voltage across the collector–emitter region of a transistor in the fixed-bias configuration is the supply voltage less the drop across R_C.

As a brief review of single- and double-subscript notation recall that

$$\boxed{V_{CE} = V_C - V_E} \qquad \textbf{(4.7)}$$

where V_{CE} is the voltage from collector to emitter and V_C and V_E are the voltages from collector and emitter to ground, respectively. *In this case,* since $V_E = 0$ V, we have

$$\boxed{V_{CE} = V_C} \qquad \textbf{(4.8)}$$

In addition, because

$$\boxed{V_{BE} = V_B - V_E} \qquad \textbf{(4.9)}$$

and $V_E = 0$ V, then

$$\boxed{V_{BE} = V_B} \qquad \textbf{(4.10)}$$

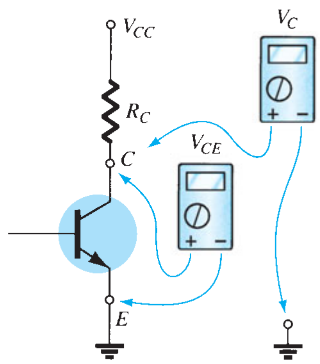

FIG. 4.6
Measuring V_{CE} and V_C.

Keep in mind that voltage levels such as V_{CE} are determined by placing the positive lead (normally red) of the voltmeter at the collector terminal with the negative lead (normally black) at the emitter terminal as shown in Fig. 4.6. V_C is the voltage from collector to ground and is measured as shown in the same figure. In this case the two readings are identical, but in the networks to follow the two can be quite different. Clearly understanding the difference between the two measurements can prove to be quite important in the troubleshooting of transistor networks.

EXAMPLE 4.1 Determine the following for the fixed-bias configuration of Fig. 4.7.

a. I_{B_Q} and I_{C_Q}.
b. V_{CE_Q}.
c. V_B and V_C.
d. V_{BC}.

Solution:

a. Eq. (4.4): $$I_{B_Q} = \frac{V_{CC} - V_{BE}}{R_B} = \frac{12\text{ V} - 0.7\text{ V}}{240\text{ k}\Omega} = \mathbf{47.08\ \mu A}$$

Eq. (4.5): $$I_{C_Q} = \beta I_{BQ} = (50)(47.08\ \mu\text{A}) = \mathbf{2.35\ mA}$$

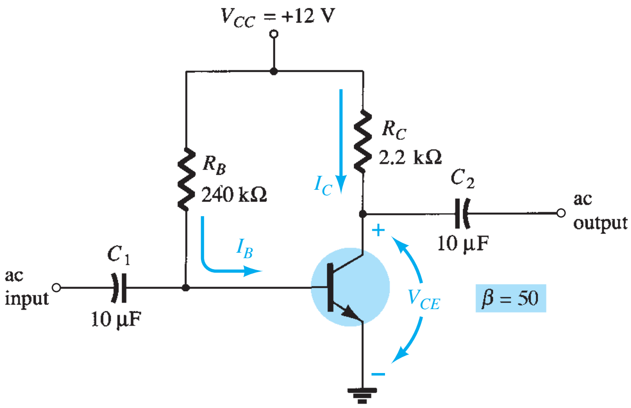

FIG. 4.7
DC fixed-bias circuit for Example 4.1.

b. Eq. (4.6):

$$\begin{aligned} V_{CE_Q} &= V_{CC} - I_C R_C \\ &= 12\text{ V} - (2.35\text{ mA})(2.2\text{ k}\Omega) \\ &= \mathbf{6.83\text{ V}} \end{aligned}$$

c. $V_B = V_{BE} = \mathbf{0.7\text{ V}}$
$V_C = V_{CE} = \mathbf{6.83\text{ V}}$

d. Using double-subscript notation yields

$$\begin{aligned} V_{BC} &= V_B - V_C = 0.7\text{ V} - 6.83\text{ V} \\ &= \mathbf{-6.13\text{ V}} \end{aligned}$$

with the negative sign revealing that the junction is reversed-biased, as it should be for linear amplification.

Transistor Saturation

The term *saturation* is applied to any system where levels have reached their maximum values. A saturated sponge is one that cannot hold another drop of water. For a transistor operating in the saturation region, the current is a maximum value *for the particular design.* Change the design and the corresponding saturation level may rise or drop. Of course, the highest saturation level is defined by the maximum collector current as provided by the specification sheet.

Saturation conditions are normally avoided because the base–collector junction is no longer reverse-biased and the output amplified signal will be distorted. An operating point in the saturation region is depicted in Fig. 4.8a. Note that it is in a region where the characteristic curves join and the collector-to-emitter voltage is at or below $V_{CE_{sat}}$. In addition, the collector current is relatively high on the characteristics.

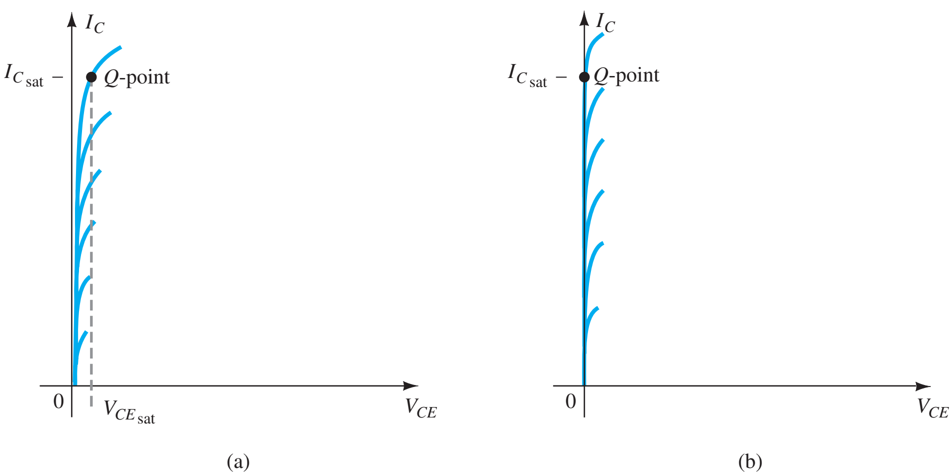

FIG. 4.8
Saturation regions: (a) actual; (b) approximate.

EXAMPLE 4.3 Given the load line of Fig. 4.16 and the defined Q-point, determine the required values of V_{CC}, R_C, and R_B for a fixed-bias configuration.

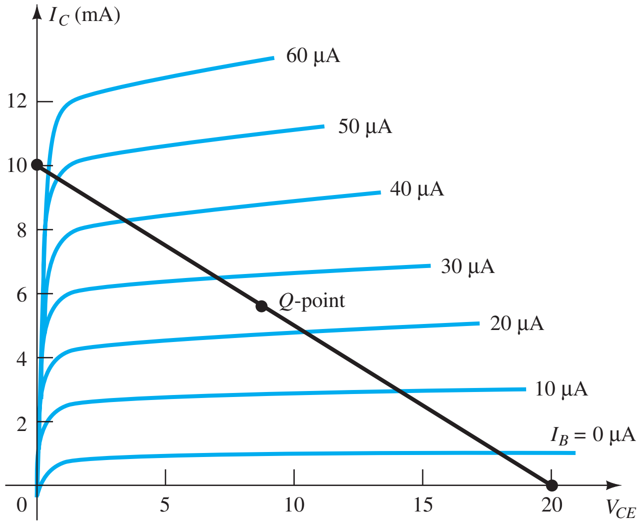

FIG. 4.16
Example 4.3.

Solution: From Fig. 4.16,

$$V_{CE} = V_{CC} = \mathbf{20\ V} \text{ at } I_C = 0\text{ mA}$$

$$I_C = \frac{V_{CC}}{R_C} \text{ at } V_{CE} = 0\text{ V}$$

and
$$R_C = \frac{V_{CC}}{I_C} = \frac{20\text{ V}}{10\text{ mA}} = \mathbf{2\ k\Omega}$$

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

and
$$R_B = \frac{V_{CC} - V_{BE}}{I_B} = \frac{20\text{ V} - 0.7\text{ V}}{25\ \mu\text{A}} = \mathbf{772\ k\Omega}$$

4.4 EMITTER-BIAS CONFIGURATION

The dc bias network of Fig. 4.17 contains an emitter resistor to improve the stability level over that of the fixed-bias configuration. The more stable a configuration, the less its response will change due to undesireable changes in temperature and parameter

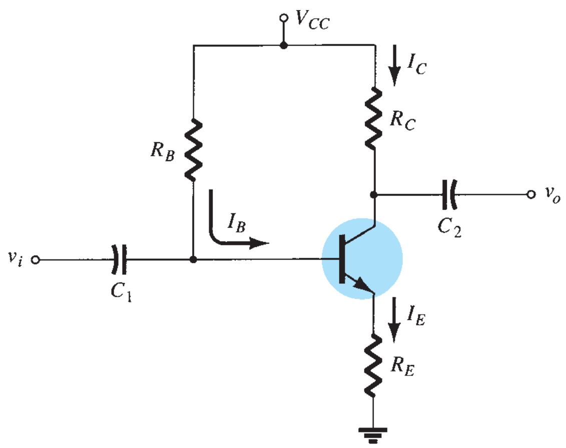

FIG. 4.17
BJT bias circuit with emitter resistor.

The single-subscript voltage V_E is the voltage from emitter to ground and is determined by

$$\boxed{V_E = I_E R_E} \tag{4.20}$$

whereas the voltage from collector to ground can be determined from

$$V_{CE} = V_C - V_E$$

and

$$\boxed{V_C = V_{CE} + V_E} \tag{4.21}$$

or

$$\boxed{V_C = V_{CC} - I_C R_C} \tag{4.22}$$

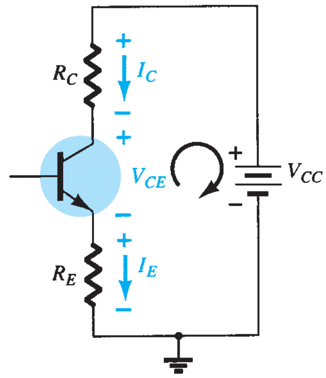

FIG. 4.22
Collector–emitter loop.

The voltage at the base with respect to ground can be determined using Fig. 4.18

$$\boxed{V_B = V_{CC} - I_B R_B} \tag{4.23}$$

or

$$\boxed{V_B = V_{BE} + V_E} \tag{4.24}$$

EXAMPLE 4.4 For the emitter-bias network of Fig. 4.23, determine:

a. I_B.
b. I_C.
c. V_{CE}.
d. V_C.
e. V_E.
f. V_B.
g. V_{BC}.

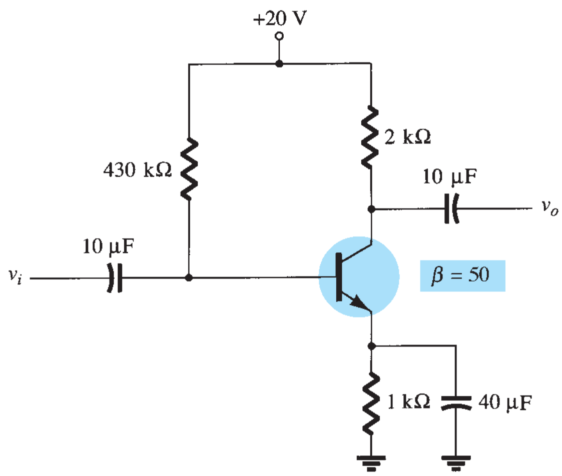

FIG. 4.23
Emitter-stabilized bias circuit for Example 4.4.

Solution:

a. Eq. (4.17): $$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{20\text{ V} - 0.7\text{ V}}{430\text{ k}\Omega + (51)(1\text{ k}\Omega)}$$

$$= \frac{19.3\text{ V}}{481\text{ k}\Omega} = \mathbf{40.1\ \boldsymbol{\mu}A}$$

b. $I_C = \beta I_B$

$= (50)(40.1\ \mu\text{A})$

$\cong$ **2.01 mA**

c. Eq. (4.19): $V_{CE} = V_{CC} - I_C(R_C + R_E)$
$= 20\text{ V} - (2.01\text{ mA})(2\text{ k}\Omega + 1\text{ k}\Omega) = 20\text{ V} - 6.03\text{ V}$
$= \mathbf{13.97\ V}$

d. $V_C = V_{CC} - I_C R_C$
$= 20\text{ V} - (2.01\text{ mA})(2\text{ k}\Omega) = 20\text{ V} - 4.02\text{ V}$
$= \mathbf{15.98\ V}$

e. $V_E = V_C - V_{CE}$
$= 15.98\text{ V} - 13.97\text{ V}$
$= \mathbf{2.01\ V}$

or $V_E = I_E R_E \cong I_C R_E$
$= (2.01\text{ mA})(1\text{ k}\Omega)$
$= \mathbf{2.01\ V}$

f. $V_B = V_{BE} + V_E$
$= 0.7\text{ V} + 2.01\text{ V}$
$= \mathbf{2.71\ V}$

g. $V_{BC} = V_B - V_C$
$= 2.71\text{ V} - 15.98\text{ V}$
$= \mathbf{-13.27\ V}$ (reverse-biased as required)

Improved Bias Stability

The addition of the emitter resistor to the dc bias of the BJT provides improved stability, that is, the dc bias currents and voltages remain closer to where they were set by the circuit when outside conditions, such as temperature and transistor beta, change. Although a mathematical analysis is provided in Section 4.12, some comparison of the improvement can be obtained as demonstrated by Example 4.5.

EXAMPLE 4.5 Prepare a table and compare the bias voltage and currents of the circuits of Fig. 4.7 and Fig. 4.23 for the given value of $\beta = 50$ and for a new value of $\beta = 100$. Compare the changes in I_C and V_{CE} for the same increase in β.

Solution: Using the results calculated in Example 4.1 and then repeating for a value of $\beta = 100$ yields the following:

Effect of β variation on the response of the fixed-bias configuration of Fig. 4.7.

β	I_B (μA)	I_C (mA)	V_{CE} (V)
50	47.08	2.35	6.83
100	47.08	4.71	1.64

The BJT collector current is seen to change by 100% due to the 100% change in the value of β. The value of I_B is the same, and V_{CE} decreased by 76%.

Using the results calculated in Example 4.4 and then repeating for a value of $\beta = 100$, we have the following:

Effect of β variation on the response of the emitter-bias configuration of Fig. 4.23.

β	I_B (μA)	I_C (mA)	V_{CE} (V)
50	40.1	2.01	13.97
100	36.3	3.63	9.11

Choosing $I_C = 0$ mA gives

$$\boxed{V_{CE} = V_{CC}\big|_{I_C = 0\,\text{mA}}} \tag{4.26}$$

as obtained for the fixed-bias configuration. Choosing $V_{CE} = 0$ V gives

$$\boxed{I_C = \frac{V_{CC}}{R_C + R_E}\bigg|_{V_{CE} = 0\,\text{V}}} \tag{4.27}$$

as shown in Fig. 4.25. Different levels of I_{B_Q} will, of course, move the Q-point up or down the load line.

EXAMPLE 4.7

a. Draw the load line for the network of Fig. 4.26a on the characteristics for the transistor appearing in Fig. 4.26b.
b. For a Q-point at the intersection of the load line with a base current of 15 μA, find the values of I_{C_Q} and V_{CE_Q}.
c. Determine the dc beta at the Q-point.
d. Using the beta for the network determined in part c, calculate the required value of R_B and suggest a possible standard value.

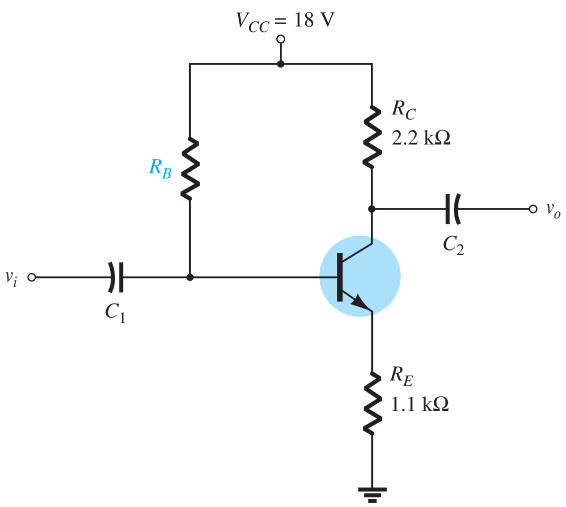

FIG. 4.26a
Network for Example 4.7.

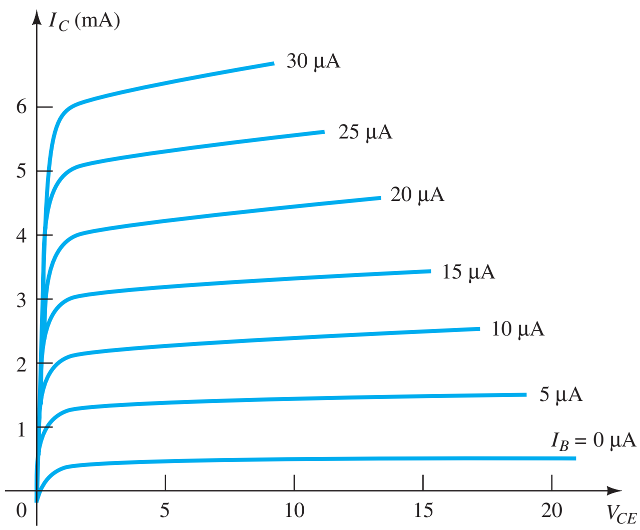

FIG. 4.26b
Example 4.7.

Solution:

a. Two points on the characteristics are required to draw the load line.

At $V_{CE} = 0$ V: $\quad I_C = \dfrac{V_{CC}}{R_C + R_E} = \dfrac{18\text{ V}}{2.2\text{ k}\Omega + 1.1\text{ k}\Omega} = \dfrac{18\text{ V}}{3.3\text{ k}\Omega} = 5.45\text{ mA}$

At $I_C = 0$ mA: $V_{CE} = V_{CC} = 18$ V

The resulting load line appears in Fig. 4.27.

b. From the characteristics of Fig. 4.27 we find

$V_{CE_Q} \cong$ **7.5 V**, $I_{C_Q} \cong$ **3.3 mA**

c. The resulting dc beta is:

$$\beta = \frac{I_{C_Q}}{I_{B_Q}} = \frac{3.3\text{ mA}}{15\ \mu\text{A}} = \mathbf{220}$$

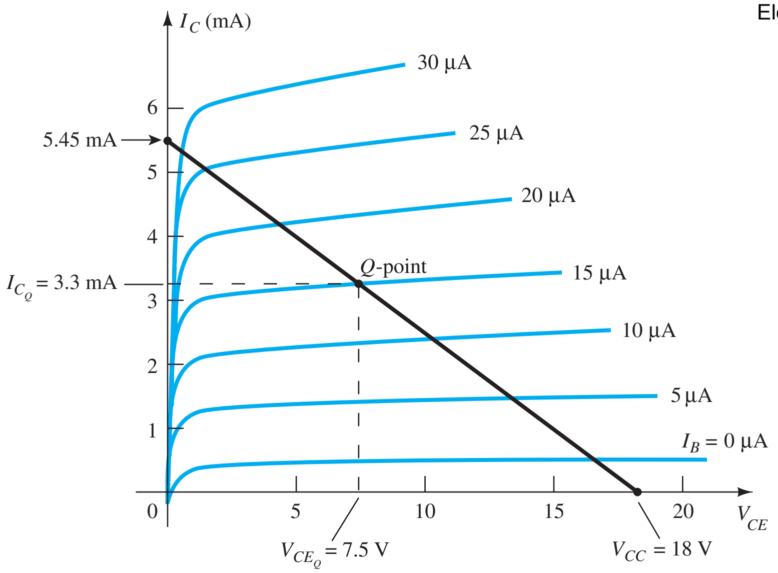

FIG. 4.27
Example 4.7.

d. Applying Eq. 4.17:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta + 1)R_E} = \frac{18\text{ V} - 0.7\text{ V}}{R_B + (220 + 1)(1.1\text{ k}\Omega)}$$

and $15\ \mu\text{A} = \dfrac{17.3\text{ V}}{R_B + (221)(1.1\text{ k}\Omega)} = \dfrac{17.3\text{ V}}{R_B + 243.1\text{ k}\Omega}$

so that $(15\ \mu\text{A})(R_B) + (15\ \mu\text{A})(243.1\text{ k}\Omega) = 17.3\text{ V}$

and $(15\ \mu\text{A})(R_B) = 17.3\text{ V} - 3.65\text{ V} = 13.65\text{ V}$

resulting in $R_B + \dfrac{13.65\text{ V}}{15\ \mu\text{A}} = \mathbf{910\ k\Omega}$

4.5 VOLTAGE-DIVIDER BIAS CONFIGURATION

In the previous bias configurations the bias current I_{C_Q} and voltage V_{CE_Q} were a function of the current gain β of the transistor. However, because β is temperature sensitive, especially for silicon transistors, and the actual value of beta is usually not well defined, it would be desirable to develop a bias circuit that is less dependent on, or in fact is independent of, the transistor beta. The voltage-divider bias configuration of Fig. 4.28 is such a network. If analyzed on an exact basis, the sensitivity to changes in beta is quite small. If the circuit parameters are properly chosen, the resulting levels of I_{C_Q} and V_{CE_Q} can be almost totally independent of beta. Recall from previous discussions that a Q-point is defined by a fixed level of I_{C_Q} and V_{CE_Q} as shown in Fig. 4.29. The level of I_{B_Q} will change with the change in beta, but the operating point on the characteristics defined by I_{C_Q} and V_{CE_Q} can remain fixed if the proper circuit parameters are employed.

As noted earlier, there are two methods that can be applied to analyze the voltage-divider configuration. The reason for the choice of names for this configuration will become obvious in the analysis to follow. The first to be demonstrated is the *exact method*, which can be applied to *any* voltage-divider configuration. The second is referred to as the *approximate method* and can be applied only if specific conditions are satisfied. The approximate approach permits a more direct analysis with a savings in time and energy. It is also particularly helpful in the design mode to be described in a later section. All in all, the approximate approach can be applied to the majority of situations and therefore should be examined with the same interest as the exact method.

EXAMPLE 4.8 Determine the dc bias voltage V_{CE} and the current I_C for the voltage-divider configuration of Fig. 4.35.

Solution: Eq. (4.28):
$$R_{Th} = R_1 \| R_2 = \frac{(39\text{ k}\Omega)(3.9\text{ k}\Omega)}{39\text{ k}\Omega + 3.9\text{ k}\Omega} = 3.55\text{ k}\Omega$$

Eq. (4.29):
$$E_{Th} = \frac{R_2 V_{CC}}{R_1 + R_2} = \frac{(3.9\text{ k}\Omega)(22\text{ V})}{39\text{ k}\Omega + 3.9\text{ k}\Omega} = 2\text{ V}$$

Eq. (4.30):
$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E} = \frac{2\text{ V} - 0.7\text{ V}}{3.55\text{ k}\Omega + (101)(1.5\text{ k}\Omega)} = \frac{1.3\text{ V}}{3.55\text{ k}\Omega + 151.5\text{ k}\Omega} = 8.38\ \mu\text{A}$$

$$I_C = \beta I_B = (100)(8.38\ \mu\text{A}) = \mathbf{0.84\ mA}$$

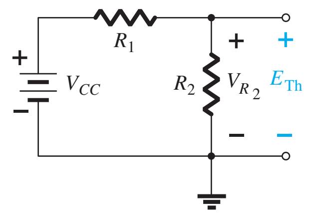

FIG. 4.33
Determining E_{Th}.

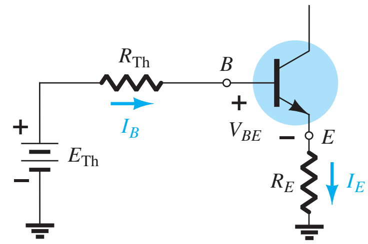

FIG. 4.34
Inserting the Thévenin equivalent circuit.

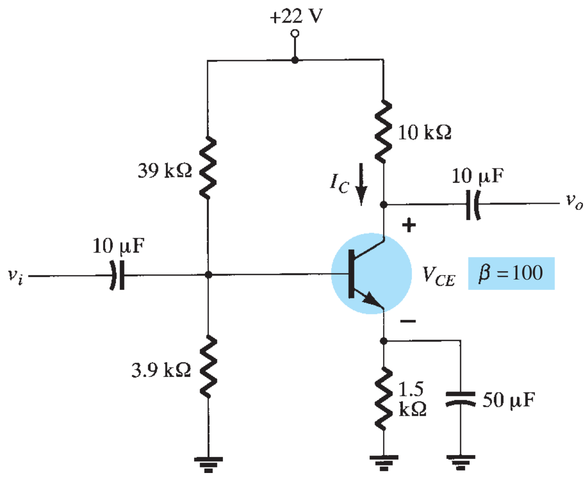

FIG. 4.35
Beta-stabilized circuit for Example 4.8.

Eq. (4.31):
$$V_{CE} = V_{CC} - I_C(R_C + R_E) = 22\text{ V} - (0.84\text{ mA})(10\text{ k}\Omega + 1.5\text{ k}\Omega) = 22\text{ V} - 9.66\text{ V} = \mathbf{12.34\ V}$$

Approximate Analysis

The input section of the voltage-divider configuration can be represented by the network of Fig. 4.36. The resistance R_i is the equivalent resistance between base and ground for the transistor with an emitter resistor R_E. Recall from Section 4.4 [Eq. (4.18)] that the reflected resistance between base and emitter is defined by $R_i = (\beta + 1)R_E$. If R_i is much larger than the resistance R_2, the current I_B will be much smaller than I_2 (current always seeks the path of least resistance) and I_2 will be approximately equal to I_1. If we accept the approximation that I_B is essentially 0 A compared to I_1 or I_2, then $I_1 = I_2$, and R_1 and R_2 can be considered series elements. The voltage across R_2, which is actually the base voltage, can be

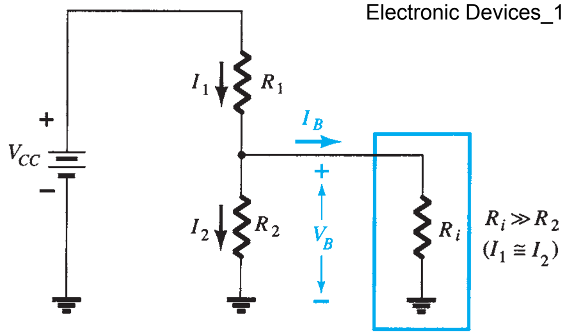

FIG. 4.36
Partial-bias circuit for calculating the approximate base voltage V_B.

determined using the voltage-divider rule (hence the name for the configuration). That is,

$$\boxed{V_B = \frac{R_2 V_{CC}}{R_1 + R_2}} \tag{4.32}$$

Because $R_i = (\beta + 1)R_E \cong \beta R_E$ the condition that will define whether the approximate approach can be applied is

$$\boxed{\beta R_E \geq 10R_2} \tag{4.33}$$

In other words, if β times the value of R_E is at least 10 times the value of R_2, the approximate approach can be applied with a high degree of accuracy.

Once V_B is determined, the level of V_E can be calculated from

$$\boxed{V_E = V_B - V_{BE}} \tag{4.34}$$

and the emitter current can be determined from

$$\boxed{I_E = \frac{V_E}{R_E}} \tag{4.35}$$

and

$$\boxed{I_{C_Q} \cong I_E} \tag{4.36}$$

The collector-to-emitter voltage is determined by

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

but because $I_E \cong I_C$,

$$\boxed{V_{CE_Q} = V_{CC} - I_C(R_C + R_E)} \tag{4.37}$$

Note in the sequence of calculations from Eq. (4.33) through Eq. (4.37) that β does not appear and I_B was not calculated. The Q-point (as determined by I_{C_Q} and V_{CE_Q}) is therefore independent of the value of β.

EXAMPLE 4.9 Repeat the analysis of Fig. 4.35 using the approximate technique, and compare solutions for I_{C_Q} and V_{CE_Q}.

Solution: Testing:

$$\beta R_E \geq 10R_2$$
$$(100)(1.5\text{ k}\Omega) \geq 10(3.9\text{ k}\Omega)$$
$$150\text{ k}\Omega \geq 39\text{ k}\Omega\ (\textit{satisfied})$$

$$\text{Eq. (4.32):} \quad V_B = \frac{R_2 V_{CC}}{R_1 + R_2}$$
$$= \frac{(3.9\ \text{k}\Omega)(22\ \text{V})}{39\ \text{k}\Omega + 3.9\ \text{k}\Omega}$$
$$= 2\ \text{V}$$

Note that the level of V_B is the same as E_{Th} determined in Example 4.7. Essentially, therefore, the primary difference between the exact and approximate techniques is the effect of R_{Th} in the exact analysis that separates E_{Th} and V_B.

$$\text{Eq. (4.34):} \quad V_E = V_B - V_{BE}$$
$$= 2\ \text{V} - 0.7\ \text{V}$$
$$= 1.3\ \text{V}$$
$$I_{CQ} \cong I_E = \frac{V_E}{R_E} = \frac{1.3\ \text{V}}{1.5\ \text{k}\Omega} = \mathbf{0.867\ mA}$$

compared to 0.84 mA with the exact analysis. Finally,

$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$
$$= 22\ \text{V} - (0.867\ \text{mA})(10\ \text{kV} + 1.5\ \text{k}\Omega)$$
$$= 22\ \text{V} - 9.97\ \text{V}$$
$$= \mathbf{12.03\ V}$$

versus 12.34 V obtained in Example 4.8.

The results for I_{C_Q} and V_{CE_Q} are certainly close, and considering the actual variation in parameter values, one can certainly be considered as accurate as the other. The larger the level of R_i compared to R_2, the closer is the approximate to the exact solution. Example 4.11 will compare solutions at a level well below the condition established by Eq. (4.33).

EXAMPLE 4.10 Repeat the exact analysis of Example 4.8 if β is reduced to 50, and compare solutions for I_{C_Q} and V_{CE_Q}.

Solution: This example is not a comparison of exact versus approximate methods, but a testing of how much the Q-point will move if the level of β is cut in half. R_{Th} and E_{Th} are the same:

$$R_{Th} = 3.55\ \text{k}\Omega, \qquad E_{Th} = 2\ \text{V}$$
$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E}$$
$$= \frac{2\ \text{V} - 0.7\ \text{V}}{3.55\ \text{k}\Omega + (51)(1.5\ \text{k}\Omega)} = \frac{1.3\ \text{V}}{3.55\ \text{k}\Omega + 76.5\ \text{k}\Omega}$$
$$= 16.24\ \mu\text{A}$$
$$I_{C_Q} = \beta I_B$$
$$= (50)(16.24\ \mu\text{A})$$
$$= \mathbf{0.81\ mA}$$
$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$
$$= 22\ \text{V} - (0.81\ \text{mA})(10\ \text{k}\Omega + 1.5\ \text{k}\Omega)$$
$$= \mathbf{12.69\ V}$$

Tabulating the results, we have:

Effect of β variation on the response of the voltage-divider configuration of Fig. 4.35.

β	I_{C_Q} (mA)	V_{CE_Q} (V)
100	0.84 mA	12.34 V
50	0.81 mA	12.69 V

The results clearly show the relative insensitivity of the circuit to the change in β. Even though β is drastically cut in half, from 100 to 50, the levels of I_{C_Q} and V_{CE_Q} are essentially the same.

Important Note: Looking back on the results for the fixed-bias configuration, we find the current decreased from 4.71 mA to 2.35 mA when beta dropped from 100 to 50. For the voltage-divider configuration, the same change in beta only resulted in a change in current from 0.84 mA to 0.81 mA. Even more noticeable is the change in V_{CE_Q} for the fixed-bias configuration. Dropping beta from 100 to 50 resulted in an increase in voltage from 1.64 to 6.83 V (a change of over 300%). For the voltage-divider configuration, the increase in voltage was only from 12.34 V to 12.69 V, which is a change of less than 3%. In summary, therefore, changing beta by 50% resulted in a change in an important network parameter of over 300% for the fixed-bias configuration and less than 3% for the voltage-divider configuration—a significant difference.

EXAMPLE 4.11 Determine the levels of I_{C_Q} and V_{CE_Q} for the voltage-divider configuration of Fig. 4.37 using the exact and approximate techniques and compare solutions. In this case, the conditions of Eq. (4.33) *will not be satisfied* and the results will reveal the difference in solution if the criterion of Eq. (4.33) is ignored.

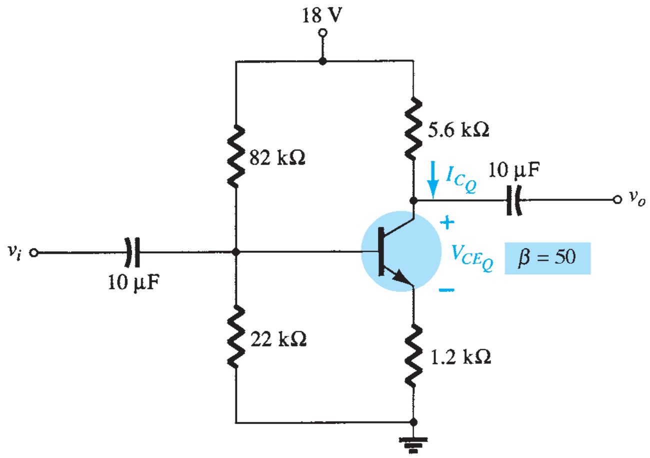

FIG. 4.37
Voltage-divider configuration for Example 4.11.

Solution: Exact analysis:

Eq. (4.33):

$$\beta R_E \geq 10R_2$$
$$(50)(1.2\text{ k}\Omega) \geq 10(22\text{ k}\Omega)$$
$$60\text{ k}\Omega \ngeq 220\text{ k}\Omega\ (\textit{not satisfied})$$
$$R_{Th} = R_1\|R_2 = 82\text{ k}\Omega\|22\text{ k}\Omega = 17.35\text{ k}\Omega$$
$$E_{Th} = \frac{R_2V_{CC}}{R_1 + R_2} = \frac{22\text{ k}\Omega(18\text{ V})}{82\text{ k}\Omega + 22\text{ k}\Omega} = 3.81\text{ V}$$
$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E} = \frac{3.81\text{ V} - 0.7\text{ V}}{17.35\text{ k}\Omega + (51)(1.2\text{ k}\Omega)} = \frac{3.11\text{ V}}{78.55\text{ k}\Omega} = 39.6\ \mu\text{A}$$
$$I_{C_Q} = \beta I_B = (50)(39.6\ \mu\text{A}) = \mathbf{1.98\ mA}$$
$$\begin{aligned} V_{CE_Q} &= V_{CC} - I_C(R_C + R_E) \\ &= 18\text{ V} - (1.98\text{ mA})(5.6\text{ k}\Omega + 1.2\text{ k}\Omega) \\ &= \mathbf{4.54\ V} \end{aligned}$$

Approximate analysis:

$$V_B = E_{Th} = 3.81\text{ V}$$
$$V_E = V_B - V_{BE} = 3.81\text{ V} - 0.7\text{ V} = 3.11\text{ V}$$
$$I_{C_Q} \cong I_E = \frac{V_E}{R_E} = \frac{3.11\text{ V}}{1.2\text{ k}\Omega} = \mathbf{2.59\ mA}$$
$$\begin{aligned} V_{CE_Q} &= V_{CC} - I_C(R_C + R_E) \\ &= 18\text{ V} - (2.59\text{ mA})(5.6\text{ k}\Omega + 1.2\text{ k}\Omega) \\ &= \mathbf{3.88\ V} \end{aligned}$$

Tabulating the results, we have:

Comparing the exact and approximate approaches.

	I_{C_Q} (mA)	V_{CE_Q} (V)
Exact	1.98	4.54
Approximate	2.59	3.88

The results reveal the difference between exact and approximate solutions. I_{C_Q} is about 30% greater with the approximate solution, whereas V_{CE_Q} is about 10% less. The results are notably different in magnitude, but even though βR_E is only about three times larger than R_2, the results are still relatively close to each other. For the future, however, our analysis will be dictated by Eq. (4.33) to ensure a close similarity between exact and approximate solutions.

Transistor Saturation

The output collector–emitter circuit for the voltage-divider configuration has the same appearance as the emitter-biased circuit analyzed in Section 4.4. The resulting equation for the saturation current (when V_{CE} is set to 0 V on the schematic) is therefore the same as obtained for the emitter-biased configuration. That is,

$$\boxed{I_{C_{\text{sat}}} = I_{C_{\text{max}}} = \frac{V_{CC}}{R_C + R_E}} \qquad \textbf{(4.38)}$$

Load-Line Analysis

The similarities with the output circuit of the emitter-biased configuration result in the same intersections for the load line of the voltage-divider configuration. The load line will therefore have the same appearance as that of Fig. 4.25, with

$$\boxed{I_C = \left.\frac{V_{CC}}{R_C + R_E}\right|_{V_{CE}=0\text{ V}}} \qquad \textbf{(4.39)}$$

and

$$\boxed{V_{CE} = V_{CC}\big|_{I_C=0\text{ mA}}} \qquad \textbf{(4.40)}$$

The level of I_B is of course determined by a different equation for the voltage-divider bias and the emitter-bias configurations.

4.6 COLLECTOR FEEDBACK CONFIGURATION

An improved level of stability can also be obtained by introducing a feedback path from collector to base as shown in Fig. 4.38. Although the Q-point is not totally independent of beta (even under approximate conditions), the sensitivity to changes in beta or temperature variations is normally less than encountered for the fixed-bias or emitter-biased configurations. The analysis will again be performed by first analyzing the base–emitter loop, with the results then applied to the collector–emitter loop.

Base–Emitter Loop

Figure 4.39 shows the base–emitter loop for the voltage feedback configuration. Writing Kirchhoff's voltage law around the indicated loop in the clockwise direction will result in

$$V_{CC} - I'_C R_C - I_B R_F - V_{BE} - I_E R_E = 0$$

It is important to note that the current through R_C is not I_C, but I'_C (where $I'_C = I_C + I_B$). However, the level of I_C and I'_C far exceeds the usual level of I_B, and the approximation $I'_C \cong I_C$ is normally employed. Substituting $I'_C \cong I_C = \beta I_B$ and $I_E \cong I_C$ results in

$$V_{CC} - \beta I_B R_C - I_B R_F - V_{BE} - \beta I_B R_E = 0$$

Because $I'_C \cong I_C$ and $I_E \cong I_C$, we have

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

and

$$\boxed{V_{CE} = V_{CC} - I_C(R_C + R_E)} \tag{4.42}$$

which is exactly as obtained for the emitter-bias and voltage-divider bias configurations.

EXAMPLE 4.12 Determine the quiescent levels of I_{C_Q} and V_{CE_Q} for the network of Fig. 4.41.

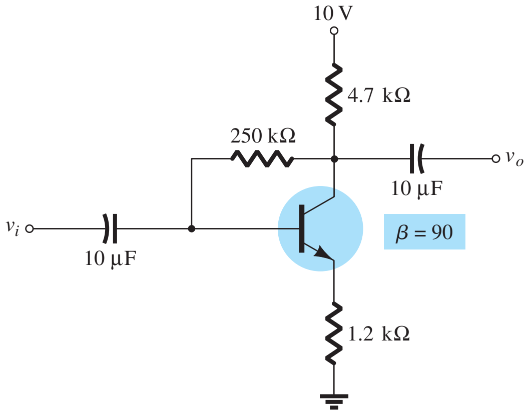

FIG. 4.41
Network for Example 4.12.

Solution: Eq. (4.41):

$$\begin{aligned}
I_B &= \frac{V_{CC} - V_{BE}}{R_F + \beta(R_C + R_E)} \\
&= \frac{10\text{ V} - 0.7\text{ V}}{250\text{ k}\Omega + (90)(4.7\text{ k}\Omega + 1.2\text{ k}\Omega)} \\
&= \frac{9.3\text{ V}}{250\text{ k}\Omega + 531\text{ k}\Omega} = \frac{9.3\text{ V}}{781\text{ k}\Omega} \\
&= 11.91\ \mu\text{A} \\
I_{C_Q} &= \beta I_B = (90)(11.91\ \mu\text{A}) \\
&= \mathbf{1.07\ mA} \\
V_{CE_Q} &= V_{CC} - I_C(R_C + R_E) \\
&= 10\text{ V} - (1.07\text{ mA})(4.7\text{ k}\Omega + 1.2\text{ k}\Omega) \\
&= 10\text{ V} - 6.31\text{ V} \\
&= \mathbf{3.69\ V}
\end{aligned}$$

EXAMPLE 4.13 Repeat Example 4.12 using a beta of 135 (50% greater than in Example 4.12).

Solution: It is important to note in the solution for I_B in Example 4.12 that the second term in the denominator of the equation is much larger than the first. Recall in a recent discussion that the larger this second term is compared to the first, the less is the sensitivity to changes in beta. In this example, the level of beta is increased by 50%, which will increase the magnitude of this second term even more compared to the first. It is more important to note in these examples, however, that once the second term is relatively large compared to the first, the sensitivity to changes in beta is significantly less.

Solving for I_B gives

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta(R_C + R_E)}$$
$$= \frac{10\text{ V} - 0.7\text{ V}}{250\text{ k}\Omega + (135)(4.7\text{ k}\Omega + 1.2\text{ k}\Omega)}$$
$$= \frac{9.3\text{ V}}{250\text{ k}\Omega + 796.5\text{ k}\Omega} = \frac{9.3\text{ V}}{1046.5\text{ k}\Omega}$$
$$= 8.89\ \mu\text{A}$$

and

$$I_{C_Q} = \beta I_B$$
$$= (135)(8.89\ \mu\text{A})$$
$$= \mathbf{1.2\ mA}$$

and

$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$
$$= 10\text{ V} - (1.2\text{ mA})(4.7\text{ k}\Omega + 1.2\text{ k}\Omega)$$
$$= 10\text{ V} - 7.08\text{ V}$$
$$= \mathbf{2.92\ V}$$

Even though the level of β increased 50%, the level of I_{C_Q} only increased 12.1%, whereas the level of V_{CE_Q} decreased about 20.9%. If the network were a fixed-bias design, a 50% increase in β would have resulted in a 50% increase in I_{C_Q} and a dramatic change in the location of the Q-point.

EXAMPLE 4.14 Determine the dc level of I_B and V_C for the network of Fig. 4.42.

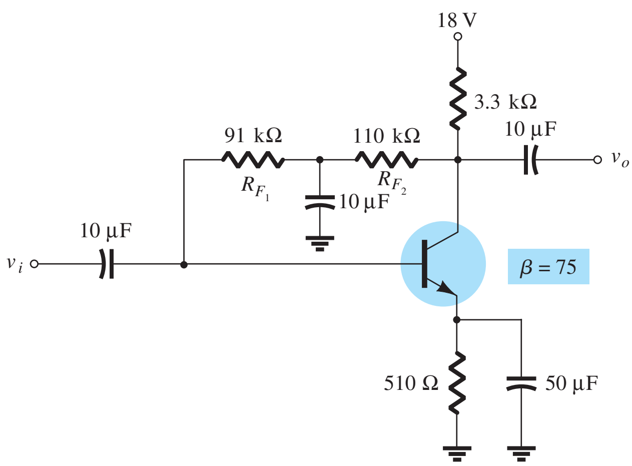

FIG. 4.42
Network for Example 4.14.

Solution: In this case, the base resistance for the dc analysis is composed of two resistors with a capacitor connected from their junction to ground. For the dc mode, the capacitor assumes the open-circuit equivalence, and $R_B = R_{F_1} + R_{F_2}$.

Solving for I_B gives

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta(R_C + R_E)}$$
$$= \frac{18\text{ V} - 0.7\text{ V}}{(91\text{ k}\Omega + 110\text{ k}\Omega) + (75)(3.3\text{ k}\Omega + 0.51\text{ k}\Omega)}$$
$$= \frac{17.3\text{ V}}{201\text{ k}\Omega + 285.75\text{ k}\Omega} = \frac{17.3\text{ V}}{486.75\text{ k}\Omega}$$
$$= \mathbf{35.5\ \mu A}$$

$$
\begin{aligned}
I_C &= \beta I_B \\
&= (75)(35.5\ \mu\text{A}) \\
&= 2.66\ \text{mA} \\
V_C &= V_{CC} - I'_C R_C \cong V_{CC} - I_C R_C \\
&= 18\ \text{V} - (2.66\ \text{mA})(3.3\ \text{k}\Omega) \\
&= 18\ \text{V} - 8.78\ \text{V} \\
&= \mathbf{9.22\ V}
\end{aligned}
$$

Saturation Conditions

Using the approximation $I'_C = I_C$, we find that the equation for the saturation current is the same as obtained for the voltage-divider and emitter-bias configurations. That is,

$$\boxed{I_{C_{\text{sat}}} = I_{C_{\max}} = \frac{V_{CC}}{R_C + R_E}} \qquad \textbf{(4.43)}$$

Load-Line Analysis

Continuing with the approximation $I'_C = I_C$ results in the same load line defined for the voltage-divider and emitter-biased configurations. The level of I_{B_Q} is defined by the chosen bias configuration.

EXAMPLE 4.15 Given the network of Fig. 4.43 and the BJT characteristics of Fig. 4.44.

a. Draw the load line for the network on the characteristics.
b. Determine the dc beta in the center region of the characteristics. Define the chosen point as the Q-point.
c. Using the dc beta calculated in part b, find the dc value of I_B.
d. Find I_{C_Q} and I_{CE_Q}.

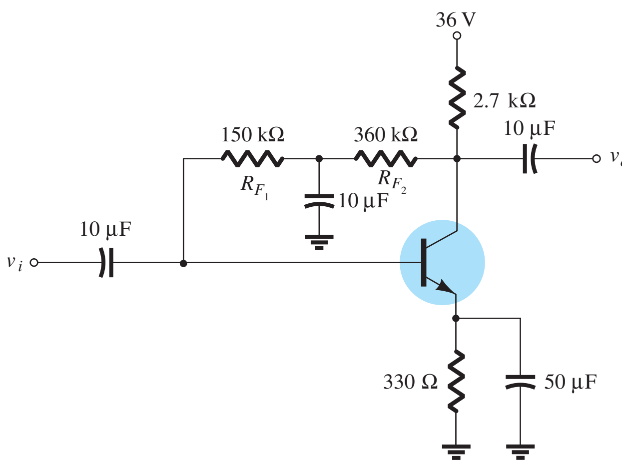

FIG. 4.43
Network for Example 4.15.

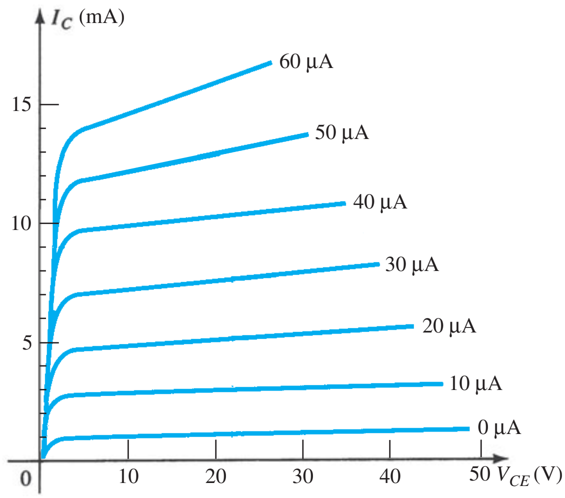

FIG. 4.44
BJT characteristics.

Solution:

a. The load line is drawn on Fig. 4.45 as determined by the following intersections:

$$V_{CE} = 0\ \text{V}: I_C = \frac{V_{CC}}{R_C + R_E} = \frac{36\ \text{V}}{2.7\ \text{k}\Omega + 330\ \Omega} = \mathbf{11.88\ mA}$$

$$I_C = 0\ \text{mA}: V_{CE} = V_{CC} = \mathbf{36\ V}$$

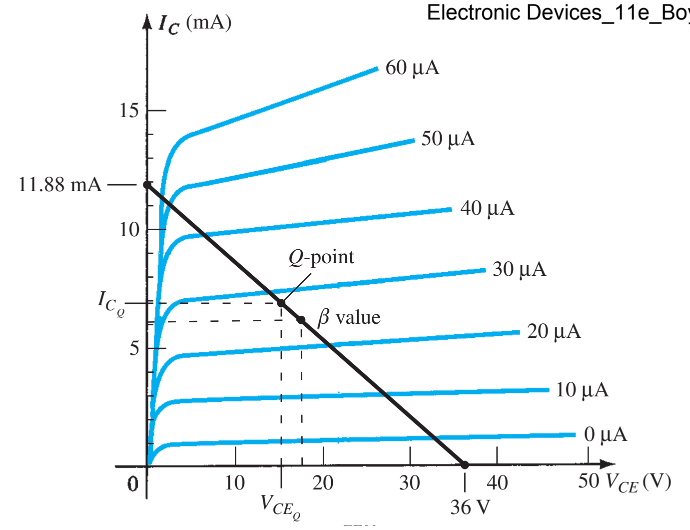

FIG. 4.45
Defining the Q-point for the voltage-divider bias configuration of Fig. 4.43.

b. The dc beta was determined using $I_B = 25\ \mu A$ and V_{CE} about 17 V.

$$\beta \cong \frac{I_{C_Q}}{I_{B_Q}} = \frac{6.2\text{ mA}}{25\ \mu\text{A}} = \mathbf{248}$$

c. Using Eq. 4.41:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta(R_C + R_E)} = \frac{36\text{ V} - 0.7\text{ V}}{510\text{ k}\Omega + 248(2.7\text{ k}\Omega + 330\ \Omega)}$$

$$= \frac{35.3\text{ V}}{510\text{ k}\Omega + 751.44\text{ k}\Omega}$$

and $I_B = \dfrac{35.3\text{ V}}{1.261\text{ M}\Omega} = \mathbf{28\ \mu A}$

d. From Fig. 4.45 the quiescent values are

$I_{C_Q} \cong$ **6.9 mA** and $V_{CE_Q} \cong$ **15 V**

4.7 EMITTER-FOLLOWER CONFIGURATION

The previous sections introduced configurations in which the output voltage is typically taken off the collector terminal of the BJT. This section will examine a configuration where the output is taken off the emitter terminal as shown in Fig. 4.46. The configuration of Fig. 4.46 is not the only one where the output can be taken off the emitter terminal. In fact, any of the configurations just described can be used so long as there is a resistor in the emitter leg.

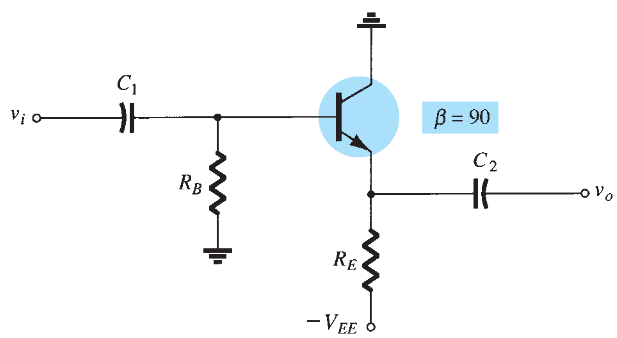

FIG. 4.46
Common-collecter (emitter-follower) configuration.

The dc equivalent of the network of Fig. 4.46 appears in Fig. 4.47

Applying Kirchhoff's voltage rule to the input circuit will result in

$$-I_B R_B - V_{BE} - I_E R_E + V_{EE} = 0$$

and using $I_E = (\beta + 1)I_B$

$$I_B R_B + (\beta + 1)I_B R_E = V_{EE} - V_{BE}$$

so that

$$\boxed{I_B = \frac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}} \qquad \textbf{(4.44)}$$

For the output network, an application of Kirchhoff's voltage law will result in

$$-V_{CE} - I_E R_E + V_{EE} = 0$$

and

$$\boxed{V_{CE} = V_{EE} - I_E R_E} \qquad \textbf{(4.45)}$$

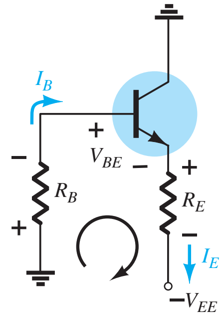

FIG. 4.47
dc equivalent of Fig. 4.46.

EXAMPLE 4.16 Determine V_{CE_Q} and I_{E_Q} for the network of Fig. 4.48.

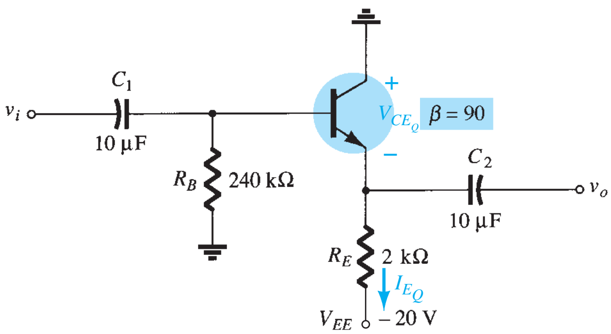

FIG. 4.48
Example 4.16.

Solution:

Eq. 4.44:
$$I_B = \frac{V_{EE} - V_{BE}}{R_B + (\beta + 1)R_E}$$
$$= \frac{20\text{ V} - 0.7\text{ V}}{240\text{ k}\Omega + (90 + 1)2\text{ k}\Omega} = \frac{19.3\text{ V}}{240\text{ k}\Omega + 182\text{ k}\Omega}$$
$$= \frac{19.3\text{ V}}{422\text{ k}\Omega} = 45.73\ \mu\text{A}$$

and Eq. 4.45:
$$V_{CE_Q} = V_{EE} - I_E R_E$$
$$= V_{EE} - (\beta + 1)I_B R_E$$
$$= 20\text{ V} - (90 + 1)(45.73\ \mu\text{A})(2\text{ k}\Omega)$$
$$= 20\text{ V} - 8.32\text{ V}$$
$$= \mathbf{11.68\ V}$$
$$I_{E_Q} = (\beta + 1)I_B = (91)(45.73\ \mu\text{A})$$
$$= 4.16\text{ mA}$$

4.8 COMMON-BASE CONFIGURATION

The common-base configuration is unique in that the applied signal is connected to the emitter terminal and the base is at, or just above, ground potential. It is a fairly popular configuration because in the ac domain it has a very low input impedance, high output impedance, and good gain.

A typical common-base configuration appears in Fig. 4.49. Note that two supplies are used in this configuration and the base is the common terminal between the input emitter terminal and output collector terminal.

The dc equivalent of the input side of Fig. 4.49 appears in Fig. 4.50.

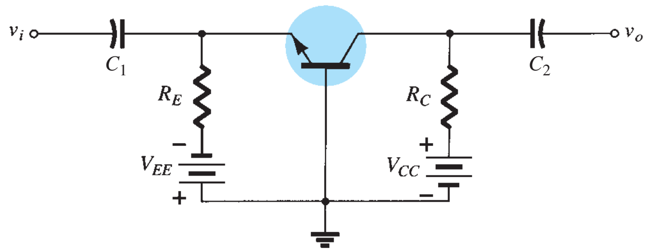

FIG. 4.49
Common-base configuration.

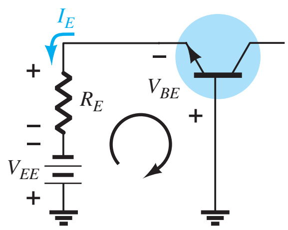

FIG. 4.50
Input dc equivalent of Fig. 4.49.

Applying Kirchhoff's voltage law will result in

$$-V_{EE} + I_E R_E + V_{BE} = 0$$

$$\boxed{I_E = \frac{V_{EE} - V_{BE}}{R_E}} \tag{4.46}$$

Applying Kirchhoff's voltage law to the entire outside perimeter of the network of Fig. 4.51 will result in

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

and solving for V_{CE}: $$V_{CE} = V_{EE} + V_{CC} - I_E R_E - I_C R_C$$

Because $$I_E \cong I_C$$

$$\boxed{V_{CE} = V_{EE} + V_{CC} - I_E(R_C + R_E)} \tag{4.47}$$

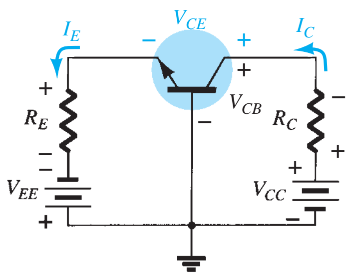

FIG. 4.51
Determining V_{CE} and V_{CB}.

The voltage V_{CB} of Fig. 4.51 can be found by applying Kirchhoff's voltage law to the output loop of Fig 4.51 to obtain:

$$V_{CB} + I_C R_C - V_{CC} = 0$$

or $$V_{CB} = V_{CC} - I_C R_C$$

Using $$I_C \cong I_E$$

we have $$\boxed{V_{CB} = V_{CC} - I_C R_C} \tag{4.48}$$

EXAMPLE 4.17 Determine the currents I_E and I_B and the voltages V_{CE} and V_{CB} for the common-base configuration of Fig. 4.52.

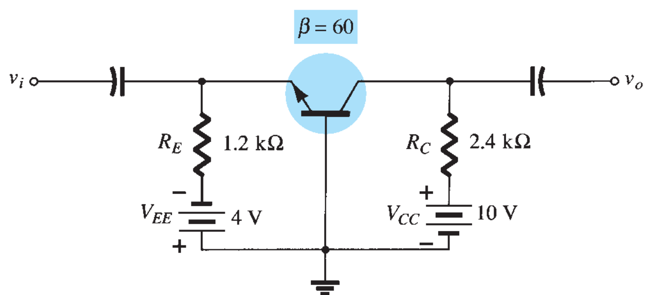

FIG. 4.52
Example 4.17.

Solution: Eq. 4.46:
$$I_E = \frac{V_{EE} - V_{BE}}{R_E}$$
$$= \frac{4\text{ V} - 0.7\text{ V}}{1.2\text{ k}\Omega} = \mathbf{2.75\text{ mA}}$$
$$I_B = \frac{I_E}{\beta + 1} = \frac{2.75\text{ mA}}{60 + 1} = \frac{2.75\text{ mA}}{61}$$
$$= \mathbf{45.08\ \mu A}$$

Eq. 4.47:
$$\begin{aligned} V_{CE} &= V_{EE} + V_{CC} - I_E(R_C + R_E) \\ &= 4\text{ V} + 10\text{ V} - (2.75\text{ mA})(2.4\text{ k}\Omega + 1.2\text{ k}\Omega) \\ &= 14\text{ V} - (2.75\text{ mA})(3.6\text{ k}\Omega) \\ &= 14\text{ V} - 9.9\text{ V} \\ &= \mathbf{4.1\text{ V}} \end{aligned}$$

Eq. 4.48:
$$\begin{aligned} V_{CB} &= V_{CC} - I_C R_C = V_{CC} - \beta I_B R_C \\ &= 10\text{ V} - (60)(45.08\ \mu\text{A})(24\text{ k}\Omega) \\ &= 10\text{ V} - 6.49\text{ V} \\ &= \mathbf{3.51\text{ V}} \end{aligned}$$

4.9 MISCELLANEOUS BIAS CONFIGURATIONS

There are a number of BJT bias configurations that do not match the basic mold of those analyzed in the previous sections. In fact, there are variations in design that would require many more pages than is possible in a single publication. However, the primary purpose here is to emphasize those characteristics of the device that permit a dc analysis of the configuration and to establish a general procedure toward the desired solution. For each configuration discussed thus far, the first step has been the derivation of an expression for the base current. Once the base current is known, the collector current and voltage levels of the output circuit can be determined quite directly. This is not to imply that all solutions will take this path, but it does suggest a possible route to follow if a new configuration is encountered.

The first example is simply one where the emitter resistor has been dropped from the voltage-feedback configuration of Fig. 4.38. The analysis is quite similar, but does require dropping R_E from the applied equation.

EXAMPLE 4.18 For the network of Fig. 4.53:

a. Determine I_{C_Q} and V_{CE_Q}.
b. Find V_B, V_C, V_E, and V_{BC}.

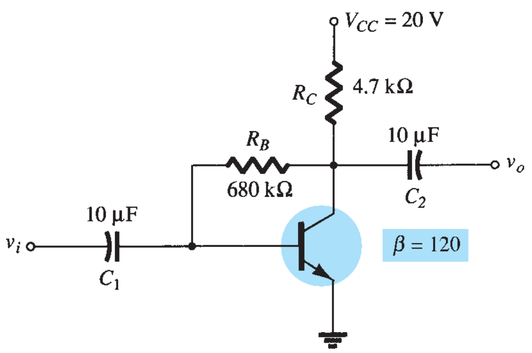

FIG. 4.53
Collector feedback with $R_E = 0\ \Omega$.

Solution:

a. The absence of R_E reduces the reflection of resistive levels to simply that of R_C, and the equation for I_B reduces to

$$I_B = \frac{V_{CC} - V_{BE}}{R_B + \beta R_C}$$
$$= \frac{20\text{ V} - 0.7\text{ V}}{680\text{ k}\Omega + (120)(4.7\text{ k}\Omega)} = \frac{19.3\text{ V}}{1.244\text{ M}\Omega}$$
$$= \mathbf{15.51\ \mu A}$$
$$I_{C_Q} = \beta I_B = (120)(15.51\ \mu\text{A})$$
$$= \mathbf{1.86\ mA}$$
$$V_{CE_Q} = V_{CC} - I_C R_C$$
$$= 20\text{ V} - (1.86\text{ mA})(4.7\text{ k}\Omega)$$
$$= \mathbf{11.26\ V}$$

b.
$$V_B = V_{BE} = \mathbf{0.7\ V}$$
$$V_C = V_{CE} = \mathbf{11.26\ V}$$
$$V_E = \mathbf{0\ V}$$
$$V_{BC} = V_B - V_C = 0.7\text{ V} - 11.26\text{ V}$$
$$= \mathbf{-10.56\ V}$$

In the next example, the applied voltage is connected to the emitter leg and R_C is connected directly to ground. Initially, it appears somewhat unorthodox and quite different from those encountered thus far, but one application of Kirchhoff's voltage law to the base circuit will result in the desired base current.

EXAMPLE 4.19 Determine V_C and V_B for the network of Fig. 4.54.

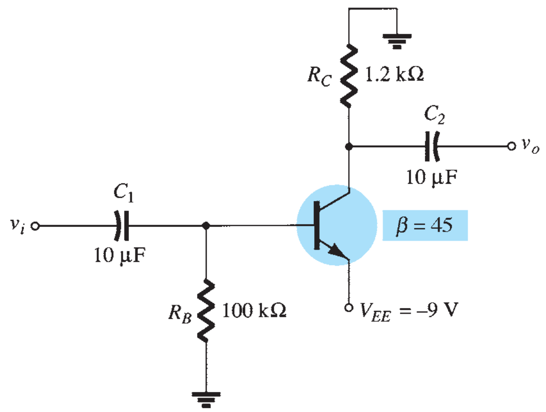

FIG. 4.54
Example 4.19.

Solution: Applying Kirchhoff's voltage law in the clockwise direction for the base–emitter loop results in

$$-I_B R_B - V_{BE} + V_{EE} = 0$$

and
$$I_B = \frac{V_{EE} - V_{BE}}{R_B}$$

Substitution yields

$$I_B = \frac{9\text{ V} - 0.7\text{ V}}{100\text{ k}\Omega}$$
$$= \frac{8.3\text{ V}}{100\text{ k}\Omega}$$
$$= 83\ \mu\text{A}$$

$$
\begin{aligned}
I_C &= \beta I_B \\
&= (45)(83\ \mu\text{A}) \\
&= 3.735\ \text{mA} \\
V_C &= -I_C R_C \\
&= -(3.735\ \text{mA})(1.2\ \text{k}\Omega) \\
&= \mathbf{-4.48\ V} \\
V_B &= -I_B R_B \\
&= -(83\ \mu\text{A})(100\ \text{k}\Omega) \\
&= \mathbf{-8.3\ V}
\end{aligned}
$$

Example 4.20 employs a split supply and will require the application of Thévenin's theorem to determine the desired unknowns.

EXAMPLE 4.20 Determine V_C and V_B for the network of Fig. 4.55.

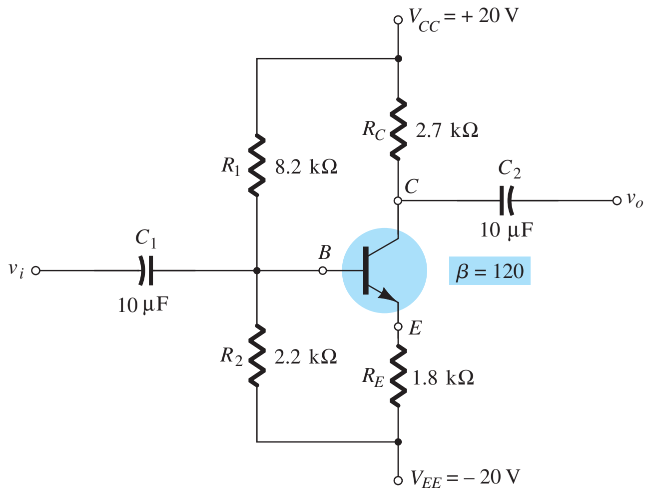

FIG. 4.55
Example 4.20.

Solution: The Thévenin resistance and voltage are determined for the network to the left of the base terminal as shown in Figs. 4.56 and 4.57.

R_{Th}

$$R_{Th} = 8.2\ \text{k}\Omega \| 2.2\ \text{k}\Omega = 1.73\ \text{k}\Omega$$

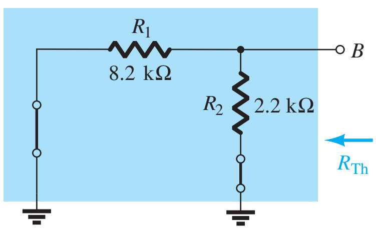

FIG. 4.56
Determining R_{Th}.

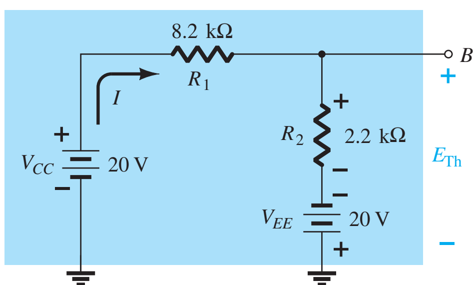

FIG. 4.57
Determining E_{Th}.

E_{Th}

$$I = \frac{V_{CC} + V_{EE}}{R_1 + R_2} = \frac{20\text{ V} + 20\text{ V}}{8.2\text{ k}\Omega + 2.2\text{ k}\Omega} = \frac{40\text{ V}}{10.4\text{ k}\Omega}$$
$$= 3.85\text{ mA}$$
$$E_{Th} = IR_2 - V_{EE}$$
$$= (3.85\text{ mA})(2.2\text{ k}\Omega) - 20\text{ V}$$
$$= -11.53\text{ V}$$

The network can then be redrawn as shown in Fig. 4.58, where the application of Kirchhoff's voltage law results in

$$-E_{Th} - I_B R_{Th} - V_{BE} - I_E R_E + V_{EE} = 0$$

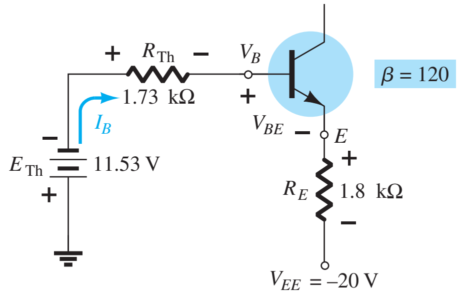

FIG. 4.58
Substituting the Thévenin equivalent circuit.

Substituting $I_E = (\beta + 1)I_B$ gives

$$V_{EE} - E_{Th} - V_{BE} - (\beta + 1)I_B R_E - I_B R_{Th} = 0$$

and
$$I_B = \frac{V_{EE} - E_{Th} - V_{BE}}{R_{Th} + (\beta + 1)R_E}$$
$$= \frac{20\text{ V} - 11.53\ V - 0.7\text{ V}}{1.73\text{ k}\Omega + (121)(1.8\text{ k}\Omega)}$$
$$= \frac{7.77\text{ V}}{219.53\text{ k}\Omega}$$
$$= 35.39\ \mu\text{A}$$
$$I_C = \beta I_B$$
$$= (120)(35.39\ \mu\text{A})$$
$$= 4.25\text{ mA}$$
$$V_C = V_{CC} - I_C R_C$$
$$= 20\text{ V} - (4.25\text{ mA})(2.7\text{ k}\Omega)$$
$$= \mathbf{8.53\ V}$$
$$V_B = -E_{Th} - I_B R_{Th}$$
$$= -(11.53\text{ V}) - (35.39\ \mu\text{A})(1.73\text{ k}\Omega)$$
$$= \mathbf{-11.59\ V}$$

4.10 SUMMARY TABLE

Table 4.1 is a review of the most common single-stage BJT configurations with their respective equations. Note the similarities that exist between the equations for the various configurations.