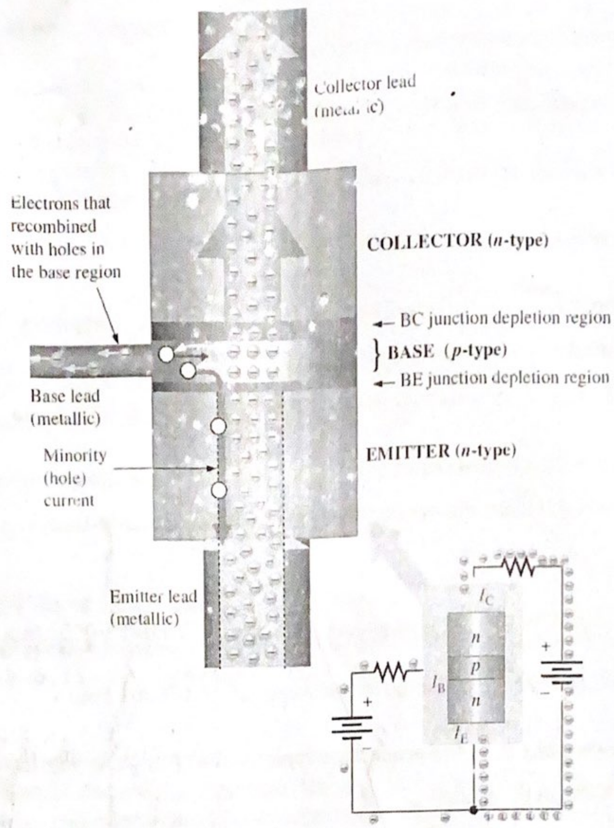


▲ FIGURE 4–4

BJT operation showing electron flow.

When the electrons that have recombined with holes as valence electrons leave the crystalline structure of the base, they become free electrons in the metallic base lead and produce the external base current. Most of the free electrons that have entered the base do not recombine with holes because the base is very thin. As the free electrons move toward the reverse-biased BC junction, they are swept across into the collector region by the attraction of the positive collector supply voltage. The free electrons move through the collector region, into the external circuit, and then return into the emitter region along with the base current, as indicated. The emitter current is slightly greater than the collector current because of the small base current that splits off from the total current injected into the base region from the emitter.

Transistor Currents

The directions of the currents in an *npn* transistor and its schematic symbol are as shown in Figure 4–5(a); those for a *pnp* transistor are shown in Figure 4–5(b). Notice that the arrow on the emitter inside the transistor symbols points in the direction of conventional current. These diagrams show that the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows:

Equation 4–1

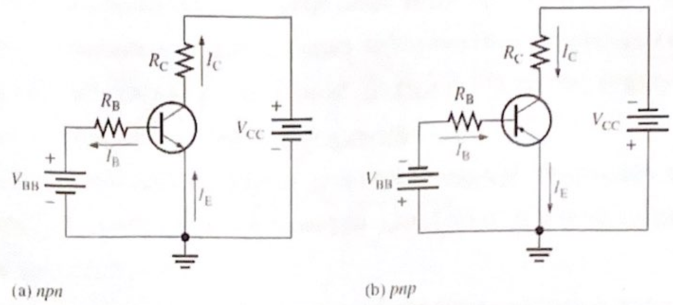
$$I_E = I_C + I_B$$

As mentioned before, I_B is very small compared to I_E or I_C. The capital-letter subscripts indicate dc values.

When a transistor is connected to dc bias voltages, as shown in Figure 4–6 for both *npn* and *pnp* types, V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction. Although in this chapter we are using separate battery symbols to represent the bias voltages, in practice the voltages are often derived from a single dc power supply. For example, V_{CC} is normally taken directly from the power supply output and V_{BB} (which is smaller) can be produced with a voltage divider. Bias circuits are examined thoroughly in Chapter 5.

FIGURE 4–6

Transistor dc bias circuits.



DC Beta (β_{DC}) and DC Alpha (α_{DC})

The dc current **gain** of a transistor is the ratio of the dc collector current (I_C) to the dc base current (I_B) and is designated dc **beta** (β_{DC}).

Equation 4–2

$$\beta_{DC} = \frac{I_C}{I_B}$$

Typical values of β_{DC} range from less than 20 to 200 or higher. β_{DC} is usually designated as an equivalent hybrid (h) parameter, h_{FE}, on transistor datasheets. h-parameters are covered in Chapter 6. All you need to know now is that

$$h_{FE} = \beta_{DC}$$

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc **alpha** (α_{DC}). The alpha is a less-used parameter than beta in transistor circuits.

$$\alpha_{DC} = \frac{I_C}{I_E}$$

Typically, values of α_{DC} range from 0.95 to 0.99 or greater, but α_{DC} is always less than 1. The reason is that I_C is always slightly less than I_E by the amount of I_B. For example, if $I_E = 100$ mA and $I_B = 1$ mA, then $I_C = 99$ mA and $\alpha_{DC} = 0.99$.

EXAMPLE 4–1

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = \mathbf{3.70\text{ mA}}$$

*Related Problem** A certain transistor has a β_{DC} of 200. When the base current is 50 μA, determine the collector current.

*Answers can be found at www.pearsonhighered.com/floyd

Transistor DC Model

You can view the unsaturated BJT as a device with a current input and a dependent current source in the output circuit, as shown in Figure 4–7 for an *npn*. The input circuit is a forward-biased diode through which there is base current. The output circuit is a dependent current source (diamond-shaped element) with a value that is dependent on the base current, I_B, and equal to $\beta_{DC}I_B$. Recall that independent current source symbols have a circular shape.

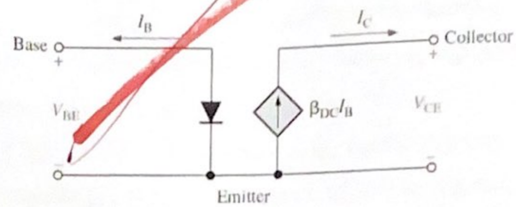


FIGURE 4–7
Ideal dc model of an *npn* transistor.

BJT Circuit Analysis

Consider the basic transistor bias circuit configuration in Figure 4–8. Three transistor dc currents and three dc voltages can be identified.

I_B: dc base current

I_E: dc emitter current

I_C: dc collector current

V_{BE}: dc voltage at base with respect to emitter

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter

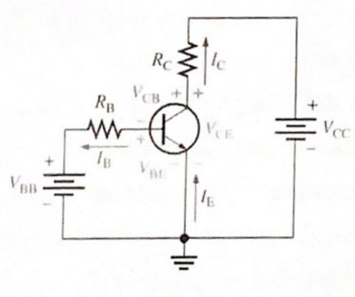


FIGURE 4–8
Transistor currents and voltages.

The base-bias voltage source, V_{BB}, forward-biases the base-emitter junction, and the collector-bias voltage source, V_{CC}, reverse-biases the base-collector junction. When the base-emitter junction is forward-biased, it is like a forward-biased diode and has a nominal forward voltage drop of

$$V_{BE} \cong 0.7\text{ V}$$ Equation 4–3

Although in an actual transistor V_{BE} can be as high as 0.9 V and is dependent on current, we will use 0.7 V throughout this text in order to simplify the analysis of the basic concepts. Keep in mind that the characteristic of the base-emitter junction is the same as a normal diode curve like the one in Figure 2-12.

Since the emitter is at ground (0 V), by Kirchhoff's voltage law, the voltage across R_B is

$$V_{R_B} = V_{BB} - V_{BE}$$

Also, by Ohm's law,

$$V_{R_B} = I_B R_B$$

Substituting for V_{R_B} yields

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

Solving for I_B,

Equation 4–4

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

The voltage at the collector with respect to the grounded emitter is

$$V_{CE} = V_{CC} - V_{R_C}$$

Since the drop across R_C is

$$V_{R_C} = I_C R_C$$

the voltage at the collector with respect to the emitter can be written as

Equation 4–5

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

where $I_C = \beta_{DC} I_B$.

The voltage across the reverse-biased collector-base junction is

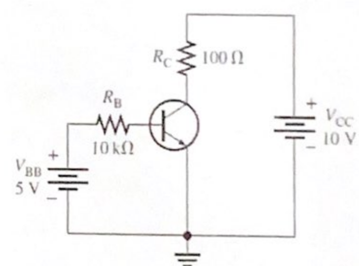
Equation 4–6

$$V_{CB} = V_{CE} - V_{BE}$$

EXAMPLE 4–2

Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of Figure 4–9. The transistor has a $\beta_{DC} = 150$.

FIGURE 4–9



Solution From Equation 4–3, $V_{BE} \cong$ **0.7 V**. Calculate the base, collector, and emitter currents as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \mathbf{430\ \mu A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = \mathbf{64.5\ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = \mathbf{64.9\ mA}$$

Solve for V_{CE} and V_{CB}.

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega) = 10\text{ V} - 6.45\text{ V} = \mathbf{3.55\ V}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = \mathbf{2.85\ V}$$

Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

SECTION 5–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. What are the upper and lower limits on a dc load line in terms of V_{CE} and I_C?
2. Define *Q-point*.
3. At what point on the load line does saturation occur? At what point does cutoff occur?
4. For maximum V_{ce}, where should the Q-point be placed?

5–2 VOLTAGE-DIVIDER BIAS

You will now study a method of biasing a transistor for linear operation using a single-source resistive voltage divider. This is the most widely used biasing method. Four other methods are covered in Section 5–3.

After completing this section, you should be able to

- **Analyze a voltage-divider biased circuit**
  - Define the term *stiff voltage-divider* • Calculate currents and voltages in a voltage-divider biased circuit
- Explain the loading effects in voltage-divider bias
  - Describe how dc input resistance at the transistor base affects the bias
- Apply Thevenin's theorem to the analysis of voltage-divider bias
  - Analyze both *npn* and *pnp* circuits

Up to this point a separate dc source, V_{BB}, was used to bias the base-emitter junction because it could be varied independently of V_{CC} and it helped to illustrate transistor operation. A more practical bias method is to use V_{CC} as the single bias source, as shown in Figure 5–9. To simplify the schematic, the battery symbol is omitted and replaced by a line termination circle with a voltage indicator (V_{CC}) as shown.

A dc bias voltage at the base of the transistor can be developed by a resistive voltage-divider that consists of R_1 and R_2, as shown in Figure 5–9. V_{CC} is the dc collector supply voltage. Two current paths are between point *A* and ground: one through R_2 and the other through the base-emitter junction of the transistor and R_E.

Generally, voltage-divider bias circuits are designed so that the base current is much smaller than the current (I_2) through R_2 in Figure 5–9. In this case, the voltage-divider circuit is very straightforward to analyze because the loading effect of the base current can be ignored. A voltage divider in which the base current is small compared to the current in R_2 is said to be a **stiff voltage divider** because the base voltage is relatively independent of different transistors and temperature effects.

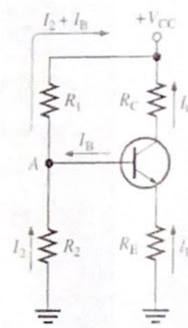


FIGURE 5–9
Voltage-divider bias.

To analyze a voltage-divider circuit in which I_B is small compared to I_2, first calculate the voltage on the base using the unloaded voltage-divider rule:

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} \qquad \text{Equation 5–1}$$

Once you know the base voltage, you can find the voltages and currents in the circuit, as follows:

$$V_E = V_B - V_{BE} \qquad \text{Equation 5–2}$$

and

$$I_C \cong I_E = \frac{V_E}{R_E} \qquad \text{Equation 5–3}$$

Then,

$$V_C = V_{CC} - I_C R_C \qquad \text{Equation 5–4}$$

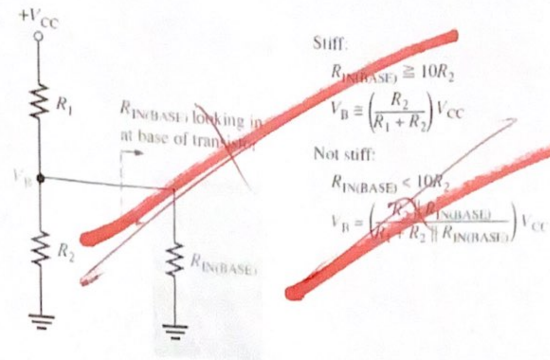


FIGURE 5–11

Voltage divider with load.

Loading Effects of Voltage-Divider Bias

DC Input Resistance at the Transistor Base The dc input resistance of the transistor is proportional to β_{DC}, so it will change for different transistors. When a transistor is operating in its linear region, the emitter current (I_E) is $\beta_{DC}I_B$. When the emitter resistor is viewed from the base circuit, the resistor appears to be larger than its actual value because of the dc current gain in the transistor. That is, $R_{IN(BASE)} = V_B/I_B = V_B/(I_E/\beta_{DC})$.

$$R_{IN(BASE)} = \frac{\beta_{DC}V_B}{I_E} \qquad \text{Equation 5–5}$$

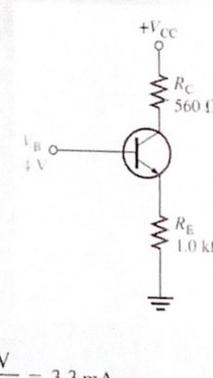
This is the effective load on the voltage divider illustrated in Figure 5–11.

You can quickly estimate the loading effect by comparing $R_{IN(BASE)}$ to the resistor R_2 in the voltage divider. As long as $R_{IN(BASE)}$ is at least ten times larger than R_2, the loading effect will be 10% or less and the voltage divider is stiff. If $R_{IN(BASE)}$ is less than ten times R_2, it should be combined in parallel with R_2.

EXAMPLE 5–3

Determine the dc input resistance looking in at the base of the transistor in Figure 5–12. $\beta_{DC} = 125$ and $V_B = 4$ V.

FIGURE 5–12



Solution

$$I_E = \frac{V_B - 0.7\text{ V}}{R_E} = \frac{3.3\text{ V}}{1.0\text{ k}\Omega} = 3.3\text{ mA}$$

$$R_{IN(BASE)} = \frac{\beta_{DC}V_B}{I_E} = \frac{125(4\text{ V})}{3.3\text{ mA}} = \mathbf{152\text{ k}\Omega}$$

Related Problem What is $R_{IN(BASE)}$ in Figure 5–12 if $\beta_{DC} = 60$ and $V_B = 2$ V?

Emitter Bias

in Figure 5–17, the small base current causes the base voltage to be slightly below ground. The emitter voltage is one diode drop less than this. The combination of this small drop across R_B and V_{BE} forces the emitter to be at approximately −1 V. Using this approximation, you can obtain the emitter current as

$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E}$$

V_{EE} is entered as a negative value in this equation.

You can apply the approximation that $I_C \cong I_E$ to calculate the collector voltage.

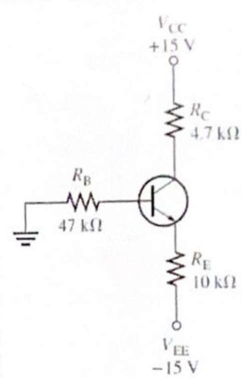
$$V_C = V_{CC} - I_C R_C$$

The approximation that $V_E \cong -1$ V is useful for troubleshooting because you won't need to perform any detailed calculations. As in the case of voltage-divider bias, there is a more rigorous calculation for cases where you need a more exact result.

EXAMPLE 5–6

Calculate I_E and V_{CE} for the circuit in Figure 5–16 using the approximations $V_E \cong -1$ V and $I_C \cong I_E$.

FIGURE 5–16



Solution

$$V_E \cong -1\text{ V}$$

$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E} = \frac{-(-15\text{ V}) - 1\text{ V}}{10\text{ k}\Omega} = \frac{14\text{ V}}{10\text{ k}\Omega} = \mathbf{1.4\text{ mA}}$$

$$V_C = V_{CC} - I_C R_C = +15\text{ V} - (1.4\text{ mA})(4.7\text{ k}\Omega) = 8.4\text{ V}$$

$$V_{CE} = 8.4\text{ V} - (-1) = \mathbf{9.4\text{ V}}$$

Related Problem If V_{EE} is changed to −12 V, what is the new value of V_{CE}?

Emitter Bias:

The approximation that $V_E \cong -1$ V and the neglect of β_{DC} may not be accurate enough for design work or detailed analysis. In this case, Kirchhoff's voltage law can be applied as follows to develop a more detailed formula for I_E. Kirchhoff's voltage law applied around the base-emitter circuit in Figure 5–17(a), which has been redrawn in part (b) for analysis, gives the following equation:

$$V_{EE} + V_{R_B} + V_{BE} + V_{R_E} = 0 \quad ✓$$

Substituting, using Ohm's law,

$$V_{EE} + I_B R_B + V_{BE} + I_E R_E = 0 \quad ✓$$

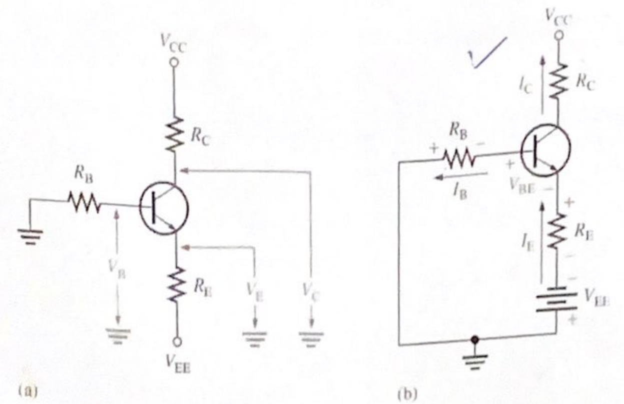


FIGURE 5–17

An *npn* transistor with emitter bias. Polarities are reversed for a *pnp* transistor. Single subscripts indicate voltages with respect to ground.

Substituting for $I_B \cong I_E/\beta_{DC}$ and transposing V_{EE},

$V_B + V_E + V_{BE} + V_{EE} = 0$ close loop.

$$\left(\frac{I_E}{\beta_{DC}}\right)R_B + I_E R_E + V_{BE} = -V_{EE}$$

Factoring out I_E and solving for I_E,

$$I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}}$$

Equation 5–9

Voltages with respect to ground are indicated by a single subscript. The emitter voltage with respect to ground is

$$V_E = V_{EE} + I_E R_E$$

The base voltage with respect to ground is

$$V_B = V_E + V_{BE}$$

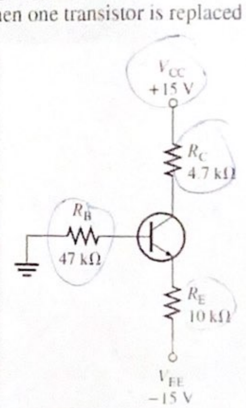
The collector voltage with respect to ground is

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

EXAMPLE 5–7

Determine how much the Q-point (I_C, V_{CE}) for the circuit in Figure 5–18 will change if β_{DC} increases from 100 to 200 when one transistor is replaced by another.

FIGURE 5–18



Solution For $\beta_{DC} = 100$,

$$I_{C(1)} \cong I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-15\text{ V}) - 0.7\text{ V}}{10\text{ k}\Omega + 47\text{ k}\Omega/100} = 1.37\text{ mA}$$

$$V_C = V_{CC} - I_{C(1)}R_C = 15\text{ V} - (1.37\text{ mA})(4.7\text{ k}\Omega) = 8.56\text{ V}$$

$$V_E = V_{EE} + I_E R_E = -15\text{ V} + (1.37\text{ mA})(10\text{ k}\Omega) = -1.3\text{ V}$$

Therefore,

$$V_{CE(1)} = V_C - V_E = 8.56\text{ V} - (-1.3\text{ V}) = 9.83\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} \cong I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{-(-15\text{ V}) - 0.7\text{ V}}{10\text{ k}\Omega + 47\text{ k}\Omega/200} = 1.38\text{ mA}$$

$$V_C = V_{CC} - I_{C(2)}R_C = 15\text{ V} - (1.38\text{ mA})(4.7\text{ k}\Omega) = 8.51\text{ V}$$

$$V_E = V_{EE} + I_E R_E = -15\text{ V} + (1.38\text{ mA})(10\text{ k}\Omega) = -1.2\text{ V}$$

Therefore,

$$V_{CE(2)} = V_C - V_E = 8.51\text{ V} - (-1.2\text{ V}) = 9.71\text{ V}$$

The percent change in I_C as β_{DC} changes from 100 to 200 is

$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\% = \left(\frac{1.38\text{ mA} - 1.37\text{ mA}}{1.37\text{ mA}}\right)100\% = 0.730\%$$

The percent change in V_{CE} is

$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\% = \left(\frac{9.71\text{ V} - 9.83\text{ V}}{9.83\text{ V}}\right)100\% = \mathbf{-1.22\%}$$

Related Problem Determine the Q-point in Figure 5–18 if β_{DC} increases to 300.

Base Bias

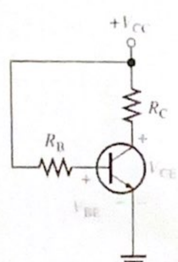


FIGURE 5–19

Base bias.

This method of biasing is common in switching circuits. Figure 5–19 shows a base-biased transistor. The analysis of this circuit for the linear region shows that it is directly dependent on β_{DC}. Starting with Kirchhoff's voltage law around the base circuit,

$$V_{CC} - V_{R_B} - V_{BE} = 0$$

Substituting $I_B R_B$ for V_{R_B}, you get

$$V_{CC} - I_B R_B - V_{BE} = 0$$

Then solving for I_B,

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

Kirchhoff's voltage law applied around the collector circuit in Figure 5–19 gives the following equation:

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

Solving for V_{CE},

Equation 5–10

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

Substituting the expression for I_B into the formula $I_C = \beta_{DC} I_B$ yields

Equation 5–11

$$I_C = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right)$$

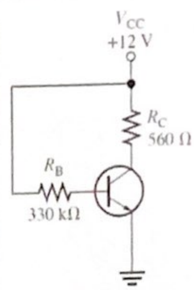
Q-Point Stability of Base Bias Notice that Equation 5–11 shows that I_C is dependent on β_{DC}. The disadvantage of this is that a variation in β_{DC} causes I_C and, as a result, V_{CE} to change, thus changing the Q-point of the transistor. This makes the base bias circuit extremely beta-dependent and unpredictable.

Recall that β_{DC} varies with temperature and collector current. In addition, there is a large spread of β_{DC} values from one transistor to another of the same type due to manufacturing variations. For these reasons, base bias is rarely used in linear circuits but is discussed here so you will be familiar with it.

EXAMPLE 5–8

Determine how much the Q-point (I_C, V_{CE}) for the circuit in Figure 5–20 will change over a temperature range where β_{DC} increases from 100 to 200.

FIGURE 5–20



Solution For $\beta_{DC} = 100$,

$$I_{C(1)} = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right) = 100\left(\frac{12\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega}\right) = 3.42\text{ mA}$$

$$V_{CE(1)} = V_{CC} - I_{C(1)}R_C = 12\text{ V} - (3.42\text{ mA})(560\ \Omega) = 10.1\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} = \beta_{DC}\left(\frac{V_{CC} - V_{BE}}{R_B}\right) = 200\left(\frac{12\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega}\right) = 6.84\text{ mA}$$

$$V_{CE(2)} = V_{CC} - I_{C(2)}R_C = 12\text{ V} - (6.84\text{ mA})(560\ \Omega) = 8.17\text{ V}$$

The percent change in I_C as β_{DC} changes from 100 to 200 is

$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\%$$

$$= \left(\frac{6.84\text{ mA} - 3.42\text{ mA}}{3.42\text{ mA}}\right)100\% = \mathbf{100\%}\text{ (an increase)}$$

The percent change in V_{CE} is

$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\%$$

$$= \left(\frac{8.17\text{ V} - 10.1\text{ V}}{10.1\text{ V}}\right)100\% = \mathbf{-19.1\%}\text{ (a decrease)}$$

As you can see, the Q-point is very dependent on β_{DC} in this circuit and therefore makes the base bias arrangement very unreliable. Consequently, base bias is not normally used if linear operation is required. However, it can be used in switching applications.

Related Problem Determine I_C if β_{DC} increases to 300.