$$R_{TH} = \frac{R_1R_2}{R_1 + R_2} = \frac{(68\,k\Omega)(47\,k\Omega)}{(68\,k\Omega + 47\,k\Omega)} = 27.8\,k\Omega$$

Use Equation 5–7 to determine I_E.

$$I_E = \frac{-V_{TH} + V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{2.45\,V + 0.7\,V}{2.2\,k\Omega + 371\,\Omega}$$

$$= \frac{3.15\,V}{2.57\,k\Omega} = 1.23\,mA$$

From I_E, you can determine I_C and V_{CE} as follows:

$$I_C \cong I_E = \mathbf{1.23\,mA}$$
$$V_C = -V_{CC} + I_CR_C = -6\,V + (1.23\,mA)(1.8\,k\Omega) = -3.79\,V$$
$$V_E = -I_ER_E = -(1.23\,mA)(2.2\,k\Omega) = -2.71\,V$$
$$V_{CE} = V_C - V_E = -3.79\,V + 2.71\,V = \mathbf{-1.08\,V}$$

Related Problem What value of β_{DC} is required in this example in order to neglect $R_{IN(BASE)}$ in keeping with the basic ten-times rule for a stiff voltage divider?

SECTION 5–2 CHECKUP

1. If the voltage at the base of a transistor is 5 V and the base current is 5 μA, what is the dc input resistance at the base?
2. If a transistor has a dc beta of 190, $V_B = 2$ V, and $I_E = 2$ mA, what is the dc input resistance at the base?
3. What bias voltage is developed at the base of a transistor if both resistors in a stiff voltage divider are equal and $V_{CC} = +10$ V?
4. What are two advantages of voltage-divider bias?

5–3 OTHER BIAS METHODS

In this section, four additional methods for dc biasing a transistor circuit are discussed. Although these methods are not as common as voltage-divider bias, you should be able to recognize them when you see them and understand the basic differences.

After completing this section, you should be able to

- **Analyze four more types of bias circuits**
- Discuss emitter bias
  - Analyze an emitter-biased circuit
- Discuss base bias
  - Analyze a base-biased circuit
  - Explain Q-point stability of base bias
- Discuss emitter-feedback bias
  - Define negative feedback
  - Analyze an emitter-feedback biased circuit
- Discuss collector-feedback bias
  - Analyze a collector-feedback biased circuit
  - Discuss Q-point stability over temperature

Emitter Bias

Emitter bias provides excellent bias stability in spite of changes in β or temperature. It uses both a positive and a negative supply voltage. To obtain a reasonable estimate of the key dc values in an emitter-biased circuit, analysis is quite easy. In an *npn* circuit, such as shown 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.

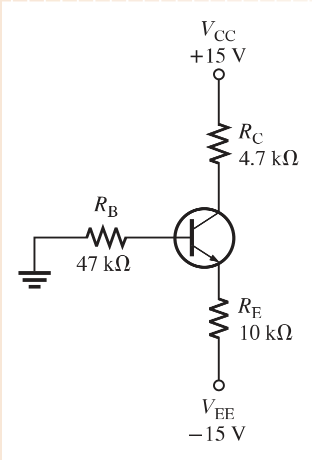
$$V_C = V_{CC} - I_C R_C$$

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

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

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

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

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

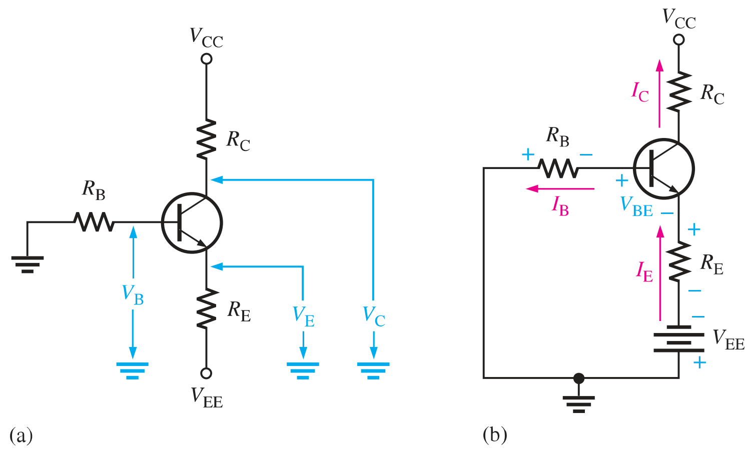
Related Problem If V_{EE} is changed to -12 V, what is the new value of V_{CE}?

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:

$$V_{EE} + V_{R_B} + V_{BE} + V_{R_E} = 0$$

Substituting, using Ohm's law,

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



◀ **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},

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

Factoring out I_E and solving for I_E,

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

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

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

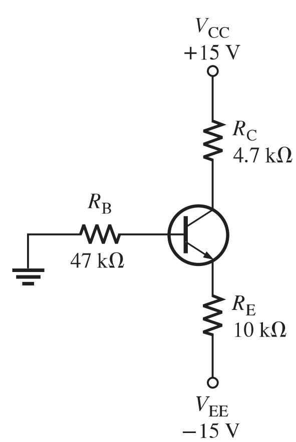
The collector voltage with respect to ground is

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

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

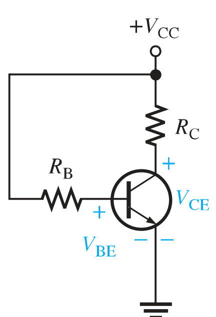
$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\% = \left(\frac{1.38\text{ mA} - 1.37\text{ mA}}{1.37\text{ mA}}\right)100\% = 0.730\%$$

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

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

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

Equation 5–11

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

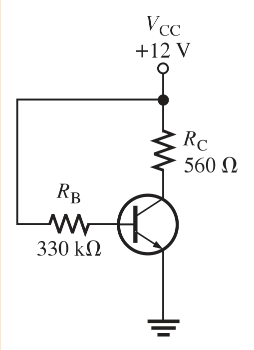
Q-Point Stability of Base Bias Notice that Equation 5–11 shows that I_C is dependent on β_{DC}. The disadvantage of this is that a variation in β_{DC} causes I_C and, as a result, V_{CE} to change, thus changing the Q-point of the transistor. This makes the base bias circuit extremely beta-dependent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

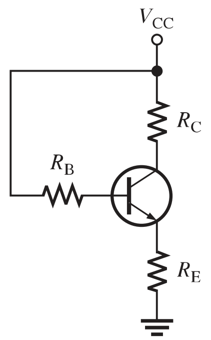
$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\%$$

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

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.

Open the Multisim file E05-08 in the Examples folder on the companion website. Set $\beta_{DC} = 100$ and measure I_C and V_{CE}. Next, set $\beta_{DC} = 200$ and measure I_C and V_{CE}. Compare results with the calculated values.



▲ FIGURE 5–21

Emitter-feedback bias.

Emitter-Feedback Bias

If an emitter resistor is added to the base-bias circuit in Figure 5–20, the result is emitter-feedback bias, as shown in Figure 5–21. The idea is to help make base bias more predictable with negative **feedback**, which negates any attempted change in collector current with an opposing change in base voltage. If the collector current tries to increase, the emitter voltage increases, causing an increase in base voltage because $V_B = V_E + V_{BE}$. This increase in base voltage reduces the voltage across R_B, thus reducing the base current and keeping the collector current from increasing. A similar action occurs if the collector current tries to decrease. While this is better for linear circuits than base bias, it is still dependent on β_{DC} and is not as predictable as voltage-divider bias. To calculate I_E, you can write Kirchhoff's voltage law (KVL) around the base circuit.

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

Substituting I_E/β_{DC} for I_B, you can see that I_E is still dependent on β_{DC}.

Equation 5–12

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

EXAMPLE 5–9

The base-bias circuit from Example 5–8 is converted to emitter-feedback bias by the addition of a 1 kΩ emitter resistor. All other values are the same, and a transistor with a $\beta_{DC} = 100$ is used. Determine how much the Q-point will change if the first transistor is replaced with one having a $\beta_{DC} = 200$. Compare the results to those of the base-bias circuit.

Solution

For $\beta_{DC} = 100$,

$$I_{C(1)} = I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{12\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega + 330\text{ k}\Omega/100} = 2.63\text{ mA}$$

$$V_{CE(1)} = V_{CC} - I_{C(1)}(R_C + R_E) = 12\text{ V} - (2.63\text{ mA})(560\ \Omega + 1\text{ k}\Omega) = 7.90\text{ V}$$

For $\beta_{DC} = 200$,

$$I_{C(2)} = I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}} = \frac{12\text{ V} - 0.7\text{ V}}{1\text{ k}\Omega + 330\text{ k}\Omega/200} = 4.26\text{ mA}$$

$$V_{CE(2)} = V_{CC} - I_{C(2)}(R_C + R_E) = 12\text{ V} - (4.26\text{ mA})(560\ \Omega + 1\text{ k}\Omega) = 5.35\text{ V}$$

The percent change in I_C is

$$\%\Delta I_C = \left(\frac{I_{C(2)} - I_{C(1)}}{I_{C(1)}}\right)100\% = \left(\frac{4.26\text{ mA} - 2.63\text{ mA}}{2.63\text{ mA}}\right)100\% = \mathbf{62.0\%}$$

$$\%\Delta V_{CE} = \left(\frac{V_{CE(2)} - V_{CE(1)}}{V_{CE(1)}}\right)100\% = \left(\frac{7.90\text{ V} - 5.35\text{ V}}{7.90\text{ V}}\right)100\% = \mathbf{-32.3\%}$$

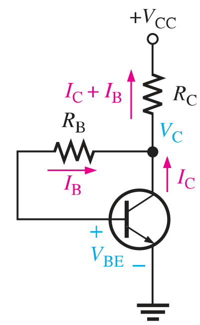
Although the emitter-feedback bias significantly improved the stability of the bias for a change in β_{DC} compared to base bias, it still does not provide a reliable Q-point.

Related Problem

Determine I_C if a transistor with $\beta_{DC} = 300$ is used in the circuit.

Collector-Feedback Bias

In Figure 5–22, the base resistor R_B is connected to the collector rather than to V_{CC}, as it was in the base bias arrangement discussed earlier. The collector voltage provides the bias for the base-emitter junction. The negative feedback creates an "offsetting" effect that tends to keep the Q-point stable. If I_C tries to increase, it drops more voltage across R_C, thereby causing V_C to decrease. When V_C decreases, there is a decrease in voltage across R_B, which decreases I_B. The decrease in I_B produces less I_C which, in turn, drops less voltage across R_C and thus offsets the decrease in V_C.



▲ FIGURE 5–22

Collector-feedback bias.

Analysis of a Collector-Feedback Bias Circuit By Ohm's law, the base current can be expressed as

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

Let's assume that $I_C \gg I_B$. The collector voltage is

$$V_C \cong V_{CC} - I_C R_C$$

Also,

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

Substituting for V_C in the equation $I_B = (V_C - V_{BE})/R_B$,

$$\frac{I_C}{\beta_{DC}} = \frac{V_{CC} - I_C R_C - V_{BE}}{R_B}$$

The terms can be arranged so that

$$\frac{I_C R_B}{\beta_{DC}} + I_C R_C = V_{CC} - V_{BE}$$

Then you can solve for I_C as follows:

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

$$\mathbf{I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}}} \qquad \text{Equation 5–13}$$

Since the emitter is ground, $V_{CE} = V_C$.

$$\mathbf{V_{CE} = V_{CC} - I_C R_C} \qquad \text{Equation 5–14}$$

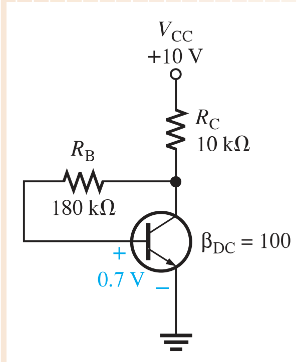
Q-Point Stability Over Temperature Equation 5–13 shows that the collector current is dependent to some extent on β_{DC} and V_{BE}. This dependency, of course, can be minimized by making $R_C \gg R_B/\beta_{DC}$ and $V_{CC} \gg V_{BE}$. An important feature of collector-feedback bias is that it essentially eliminates the β_{DC} and V_{BE} dependency even if the stated conditions are met.

As you have learned, β_{DC} varies directly with temperature, and V_{BE} varies inversely with temperature. As the temperature goes up in a collector-feedback circuit, β_{DC} goes up and V_{BE} goes down. The increase in β_{DC} acts to increase I_C. The decrease in V_{BE} acts to increase I_B which, in turn also acts to increase I_C. As I_C tries to increase, the voltage drop across R_C also tries to increase. This tends to reduce the collector voltage and therefore the voltage across R_B, thus reducing I_B and offsetting the attempted increase in I_C and the attempted decrease in V_C. The result is that the collector-feedback circuit maintains a relatively stable Q-point. The reverse action occurs when the temperature decreases.

EXAMPLE 5–10

Calculate the Q-point values (I_C and V_{CE}) for the circuit in Figure 5–23.

▶ FIGURE 5–23



Solution Using Equation 5–13, the collector current is

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} = \frac{10\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega + 180\text{ k}\Omega/100} = \mathbf{788\ \mu A}$$

Using Equation 5–14, the collector-to-emitter voltage is

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (788\ \mu\text{A})(10\text{ k}\Omega) = \mathbf{2.12\ V}$$

Related Problem Calculate the Q-point values in Figure 5–23 for $\beta_{DC} = 200$ and determine the percent change in the Q-point from $\beta_{DC} = 100$ to $\beta_{DC} = 200$.

Open the Multisim file E05-10 in the Examples folder on the companion website. Measure I_C and V_{CE}. Compare with the calculated values.

SECTION 5–3 CHECKUP

1. Why is emitter bias more stable than base bias?
2. What is the main disadvantage of emitter bias?
3. Explain how an increase in β_{DC} causes a reduction in base current in a collector-feedback circuit.
4. What is the main disadvantage of the base bias method?
5. Explain why the base bias Q-point changes with temperature.
6. How does emitter-feedback bias improve on base bias?

5–4 TROUBLESHOOTING

In a biased transistor circuit, the transistor can fail or a resistor in the bias circuit can fail. We will examine several possibilities in this section using the voltage-divider bias arrangement. Many circuit failures result from open resistors, internally open transistor leads and junctions, or shorted junctions. Often, these failures can produce an apparent cutoff or saturation condition when voltage is measured at the collector.

After completing this section, you should be able to

- **Troubleshoot faults in transistor bias circuits**
- Troubleshoot a voltage-divider biased transistor circuit
  - ◆ Troubleshoot the circuit for several common faults ◆ Use voltage measurement to isolate a fault