Substituting values gives

$$V_{CE} = -18 \text{ V} + (2.24 \text{ mA})(2.4 \text{ k}\Omega + 1.1 \text{ k}\Omega)$$
$$= -18 \text{ V} + 7.84 \text{ V}$$
$$= \mathbf{-10.16 \text{ V}}$$

4.12 BIAS STABILIZATION

The stability of a system is a measure of the sensitivity of a network to variations in its parameters. In any amplifier employing a transistor the collector current I_C is sensitive to each of the following parameters:

β: increases with increase in temperature

$|V_{BE}|$: decreases about 7.5 mV per degree Celsius (°C) increase in temperature

I_{CO} (reverse saturation current): doubles in value for every 10°C increase in temperature

Any or all of these factors can cause the bias point to drift from the designed point of operation. Table 4.1 reveals how the level of I_{CO} and V_{BE} changed with increase in temperature for a particular transistor. At room temperature (about 25°C) $I_{CO} =$ 0.1 nA, while at 100°C (boiling point of water) I_{CO} is about 200 times larger at 20 nA. For the same temperature variation, β increased from 50 to 80 and V_{BE} dropped from 0.65 to 0.48 V. Recall that I_B is quite sensitive to the level of V_{BE}, especially for levels beyond the threshold value.

TABLE 4.1 Variation of Silicon Transistor Parameters with Temperature

T (°C)	I_{CO} (nA)	β	V_{BE}(V)
−65	0.2×10^{-3}	20	0.85
25	0.1	50	0.65
100	20	80	0.48
175	3.3×10^{3}	120	0.3

The effect of changes in leakage current (I_{CO}) and current gain (β) on the dc bias point is demonstrated by the common-emitter collector characteristics of Fig. 4.65a and b. Figure 4.65 shows how the transistor collector characteristics change from a temperature of 25°C to a temperature of 100°C. Note that the significant increase in leakage current not only causes the curves to rise but also an increase in beta, as revealed by the larger spacing between curves.

An operating point may be specified by drawing the circuit dc load line on the graph of the collector characteristic and noting the intersection of the load line and the dc base current set by the input circuit. An arbitrary point is marked in Fig. 4.65a at $I_B = 30\ \mu$A. Since the fixed-bias circuit provides a base current whose value depends approximately on the supply voltage and base resistor, neither of which is affected by temperature or the change in leakage current or beta, the same base current magnitude will exist at high temperatures as indicated on the graph of Fig. 4.65b. As the figure shows, this will result in the dc bias point's shifting to a higher collector current and a lower collector–emitter voltage operating point. In the extreme, the transistor could be driven into saturation. In any case, the new operating point may not

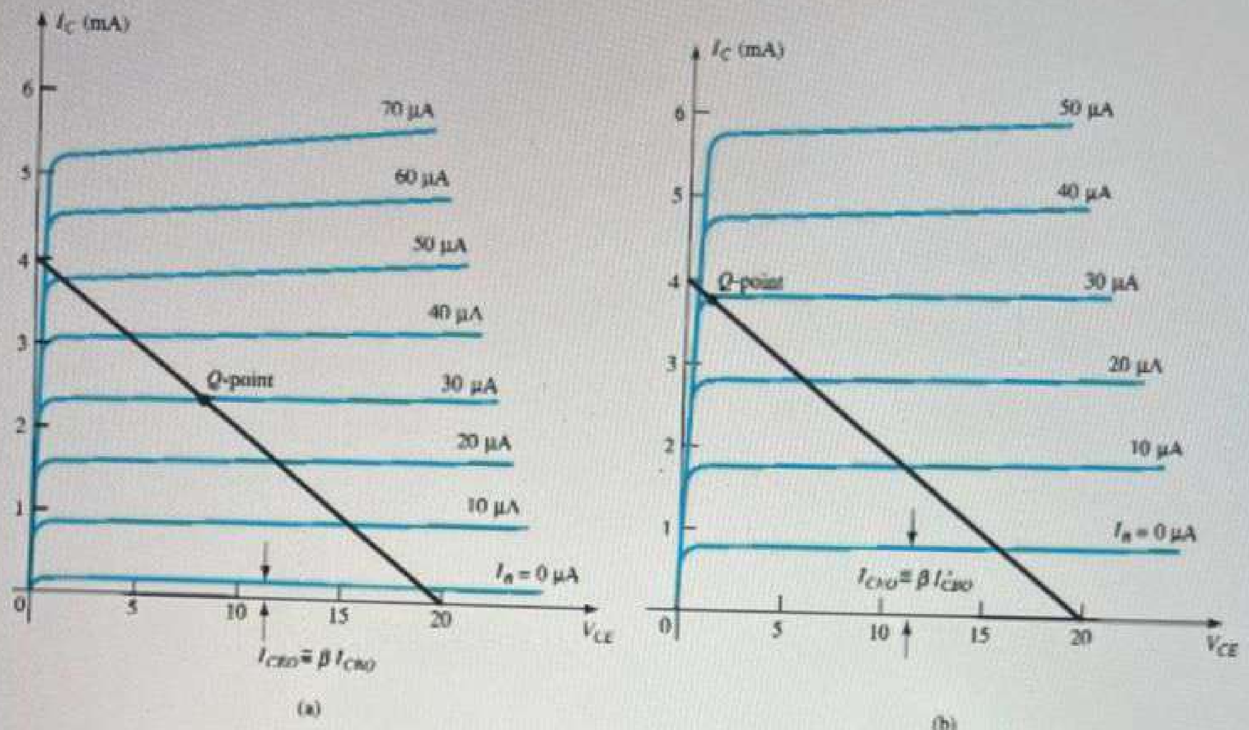

Figure 4.65 Shift in dc bias point (*Q*-point) due to change in temperature: (a) 25°C; (b) 100°C.

be at all satisfactory, and considerable distortion may result because of the bias-point shift. A better bias circuit is one that will stabilize or maintain the dc bias initially set, so that the amplifier can be used in a changing-temperature environment.

Stability Factors, $S(I_{CO})$, $S(V_{BE})$, and $S(\beta)$

A stability factor, S, is defined for each of the parameters affecting bias stability as listed below:

$$S(I_{CO}) = \frac{\Delta I_C}{\Delta I_{CO}} \tag{4.51}$$

$$S(V_{BE}) = \frac{\Delta I_C}{\Delta V_{BE}} \tag{4.52}$$

$$S(\beta) = \frac{\Delta I_C}{\Delta \beta} \tag{4.53}$$

In each case, the delta symbol (Δ) signifies change in that quantity. The numerator of each equation is the change in collector current as established by the change in the quantity in the denominator. For a particular configuration, if a change in I_{CO} fails to produce a significant change in I_C, the stability factor defined by $S(I_{CO}) = \Delta I_C/\Delta I_{CO}$ will be quite small. In other words:

Networks that are quite stable and relatively insensitive to temperature variations have low stability factors.

In some ways it would seem more appropriate to consider the quantities defined by Eqs. (4.51–4.53) to be sensitivity factors because:

The higher the stability factor, the more sensitive the network to variations in that parameter.

The study of stability factors requires the knowledge of differential calculus. Our purpose here, however, is to review the results of the mathematical analysis and to form an overall assessment of the stability factors for a few of the most popular bias configurations. A great deal of literature is available on this subject, and if time permits, you are encouraged to read more on the subject.

$S(I_{CO})$: EMITTER-BIAS CONFIGURATION

For the emitter-bias configuration, an analysis of the network will result in

$$S(I_{CO}) = (\beta + 1)\frac{1 + R_B/R_E}{(\beta + 1) + R_B/R_E} \qquad (4.54)$$

For $R_B/R_E \gg (\beta + 1)$, Eq. (4.54) will reduce to the following:

$$S(I_{CO}) = \beta + 1 \qquad (4.55)$$

as shown on the graph of $S(I_{CO})$ versus R_B/R_E in Fig. 4.66.

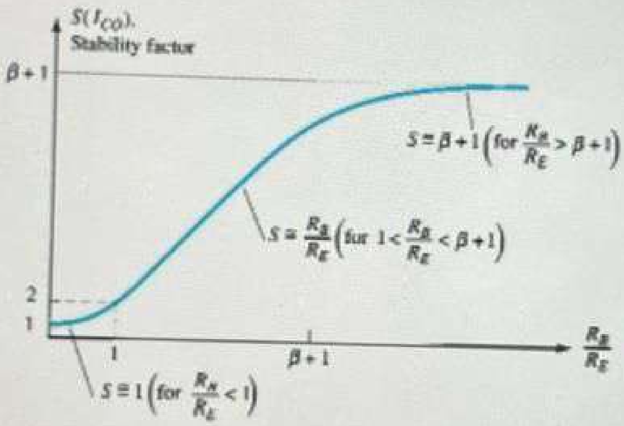

Figure 4.66 Variation of stability factor $S(I_{CO})$ with the resistor ratio R_B/R_E for the emitter-bias configuration.

For $R_B/R_E \ll 1$, Eq. (4.54) will approach the following level (as shown in Fig. 4.66):

$$S(I_{CO}) = (\beta + 1)\frac{1}{(\beta + 1)} = \rightarrow 1 \qquad (4.56)$$

revealing that the stability factor will approach its lowest level as R_E becomes sufficiently large. Keep in mind, however, that good bias control normally requires that R_B be greater than R_E. The result therefore is a situation where the best stability levels are associated with poor design criteria. Obviously, a trade-off must occur that will satisfy both the stability and bias specifications. It is interesting to note in Fig. 4.66 that the lowest value of $S(I_{CO})$ is 1, revealing that I_C will always increase at a rate equal to or greater than I_{CO}.

For the range where R_B/R_E ranges between 1 and $(\beta + 1)$, the stability factor will be determined by

$$S(I_{CO}) \cong \frac{R_B}{R_E} \qquad (4.57)$$

as shown in Fig. 4.66. The results reveal that the emitter-bias configuration is quite stable when the ratio R_B/R_E is as small as possible and the least stable when the same ratio approaches $(\beta + 1)$.

EXAMPLE 4.28

Calculate the stability factor and the change in I_C from 25°C to 100°C for the transistor defined by Table 4.1 for the following emitter-bias arrangements.

(a) $R_B/R_E = 250$ $(R_B = 250R_E)$

(b) $R_B/R_E = 10$ $(R_B = 10R_E)$.

(c) $R_B/R_E = 0.01$ $(R_E = 100R_B)$.

Solution

(a)
$$S(I_{CO}) = (\beta + 1)\ 1 + \frac{R_B/R_E}{1 + \beta + R_B/R_E}$$
$$= 51\left(\frac{1 + 250}{51 + 250}\right) = 51\left(\frac{251}{301}\right)$$
$$\cong \mathbf{42.53}$$

which begins to approach the level defined by $\beta + 1 = 51$.

$$\Delta I_C = [S(I_{CO})](\Delta I_{CO}) = (42.53)(19.9\text{ nA})$$
$$\cong \mathbf{0.85\ \mu A}$$

(b)
$$S(I_{CO}) = (\beta + 1)\frac{1 + R_B/R_E}{1 + \beta + R_B/R_E}$$
$$= 51\left(\frac{1 + 10}{51 + 10}\right) = 51\left(\frac{11}{61}\right)$$
$$\cong \mathbf{9.2}$$
$$\Delta I_C = [S(I_{CO})](\Delta\ I_{CO}) = (9.2)(19.9\text{ nA})$$
$$\cong \mathbf{0.18\ \mu A}$$

(c)
$$S(I_{CO}) = (\beta + 1)\frac{1 + R_B/R_E}{1 + \beta + R_B/R_E}$$
$$= 51\left(\frac{1 + 0.01}{51 + 0.01}\right) = 51\left(\frac{1.01}{51.01}\right)$$
$$\cong \mathbf{1.01}$$

which is certainly very close to the level of 1 forecast if $R_B/R_E \ll 1$.

$$\Delta I_C = [S(I_{CO})](\Delta\ I_{CO}) = 1.01(19.9\text{ nA})$$
$$= \mathbf{20.1\ nA}$$

Example 4.28 reveals how lower and lower levels of I_{CO} for the modern-day BJT transistor have improved the stability level of the basic bias configurations. Even though the change in I_C is considerably different in a circuit having ideal stability $(S = 1)$ from one having a stability factor of 42.53, the change in I_C is not that significant. For example, the amount of change in I_C from a dc bias current set at, say, 2 mA, would be from 2 to 2.085 mA in the worst case, which is obviously small enough to be ignored for most applications. Some power transistors exhibit larger leakage currents, but for most amplifier circuits the lower levels of I_{CO} have had a very positive impact on the stability question.

FIXED-BIAS CONFIGURATION

For the fixed-bias configuration, if we multiply the top and bottom of Eq. (4.54) by R_E and then plug in $R_E = 0\ \Omega$, the following equation will result:

$$\boxed{S(I_{CO}) = \beta + 1} \qquad (4.58)$$

Note that the resulting equation matches the maximum value for the emitter-bias configuration. The result is a configuration with a poor stability factor and a high sensitivity to variations in I_{CO}.

Voltage-Divider Bias Configuration

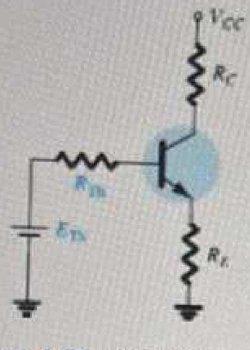

Figure 4.67 Equivalent circuit for the voltage-divider configuration.

Recall from Section 4.5 the development of the Thévenin equivalent network appearing in Fig. 4.67, for the voltage-divider bias configuration. For the network of Fig. 4.67, the equation for $S(I_{CO})$ is the following:

$$S(I_{CO}) = (\beta + 1)\frac{1 + R_{Th}/R_E}{(\beta + 1) + R_{Th}/R_E} \tag{4.59}$$

Note the similarities with Eq. (4.54), where it was determined that $S(I_{CO})$ had its lowest level and the network had its greatest stability when $R_E > R_B$. For Eq. (4.59), the corresponding condition is $R_E > R_{Th}$ or R_{Th}/R_E should be as small as possible. For the voltage-divider bias configuration, R_{Th} can be much less than the corresponding R_B of the emitter-bias configuration and still have an effective design.

Feedback-Bias Configuration (R_E 5 0 Ω)

In this case,

$$S(I_{CO}) = (\beta + 1)\frac{1 + R_B/R_C}{(\beta + 1) + R_B/R_C} \tag{4.60}$$

Since the equation is similar in format to that obtained for the emitter-bias and voltage-divider bias configurations, the same conclusions regarding the ratio R_B/R_C can be applied here also.

Physical Impact

Equations of the type developed above often fail to provide a physical sense for why the networks perform as they do. We are now aware of the relative levels of stability and how the choice of parameters can affect the sensitivity of the network, but without the equations it may be difficult for us to explain in words why one network is more stable than another. The next few paragraphs attempt to fill this void through the use of some of the very basic relationships associated with each configuration.

For the fixed-bias configuration of Fig. 4.68a, the equation for the base current is the following:

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

with the collector current determined by

$$I_C = \beta I_B + (\beta + 1)I_{CO} \tag{4.61}$$

If I_C as defined by Eq. (4.61) should increase due to an increase in I_{CO}, there is nothing in the equation for I_B that would attempt to offset this undesirable increase in current level (assuming V_{BE} remains constant). In other words, the level of I_C would continue to rise with temperature, with I_B maintaining a fairly constant value—a very unstable situation.

For the emitter-bias configuration of Fig. 4.68b, however, an increase in I_C due to an increase in I_{CO} will cause the voltage $V_E = I_E R_E \cong I_C R_E$ to increase. The result is a drop in the level of I_B as determined by the following equation:

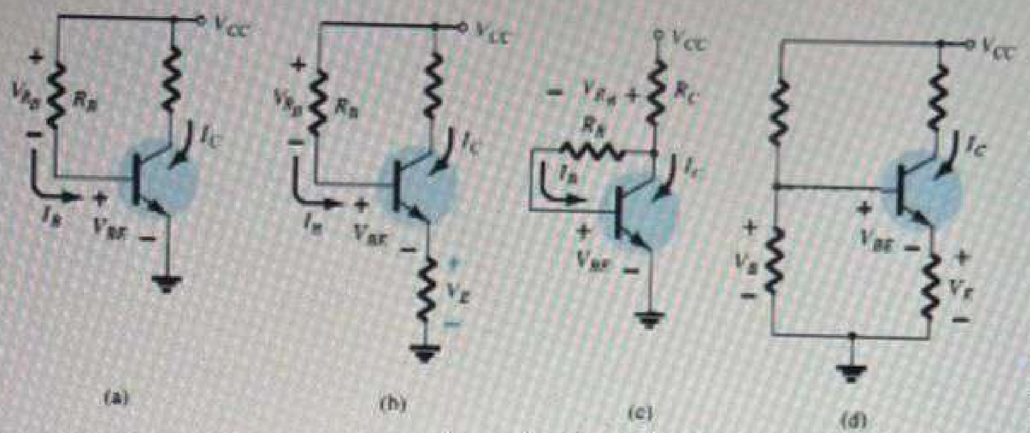

Figure 4.68 Review of biasing managements and the stability factor $S(I_{CO})$.

$$I_B \downarrow = \frac{V_{CC} - V_{BE} - V_E \uparrow}{R_B} \tag{4.62}$$

A drop in I_B will have the effect of reducing the level of I_C through transistor action and thereby offset the tendency of I_C to increase due to an increase in temperature. In total, therefore, the configuration is such that there is a reaction to an increase in I_C that will tend to oppose the change in bias conditions.

The feedback configuration of Fig. 4.68c operates in much the same way as the emitter-bias configuration when it comes to levels of stability. If I_C should increase due to an increase in temperature, the level of V_{R_C} will increase in the following equation:

$$I_B \downarrow = \frac{V_{CC} - V_{BE} - V_{R_C} \uparrow}{R_B} \tag{4.63}$$

and the level of I_B will decrease. The result is a stabilizing effect as described for the emitter-bias configuration. One must be aware that the action described above does not happen in a step-by-step sequence. Rather, it is a simultaneous action to maintain the established bias conditions. In other words, the very instant I_C begins to rise the network will sense the change and the balancing effect described above will take place.

The most stable of the configurations is the voltage-divider bias network of Fig. 4.68d. If the condition $\beta R_E \gg 10R_2$ is satisfied, the voltage V_B will remain fairly constant for changing levels of I_C. The base-to-emitter voltage of the configuration is determined by $V_{BE} = V_B - V_E$. If I_C should increase, V_E will increase as described above, and for a constant V_B the voltage V_{BE} will drop. A drop in V_{BE} will establish a lower level of I_B, which will try to offset the increased level of I_C.

$S(V_{BE})$

The stability factor defined by

$$S(V_{BE}) = \frac{\Delta I_C}{\Delta V_{BE}}$$

will result in the following equation for the emitter-bias configuration:

$$S(V_{BE}) = \frac{-\beta}{R_B + (\beta + 1)R_E} \tag{4.64}$$

Substituting $R_E = 0\ \Omega$ as occurs for the fixed-bias configuration will result in

$$S(V_{BE}) = -\frac{\beta}{R_B} \tag{4.65}$$

Equation (4.64) can be written in the following form:

$$S(V_{BE}) = \frac{-\beta/R_E}{R_B/R_E + (\beta + 1)} \tag{4.66}$$

Substituting the condition $(\beta + 1) \gg R_B/R_E$ will result in the following equation for $S(V_{BE})$:

$$S(V_{BE}) \cong \frac{-\beta/R_E}{\beta + 1} \cong \frac{-\beta/R_E}{\beta} = -\frac{1}{R_E} \tag{4.67}$$

revealing that the larger the resistance R_E, the lower the stability factor and the more stable the system.

EXAMPLE 4.29

Determine the stability factor $S(V_{BE})$ and the change in I_C from 25°C to 100°C for the transistor defined by Table 4.1 for the following bias arrangements.
(a) Fixed-bias with $R_B = 240\ \text{k}\Omega$ and $\beta = 100$.
(b) Emitter-bias with $R_B = 240\ \text{k}\Omega$, $R_E = 1\ \text{k}\Omega$, and $\beta = 100$.
(c) Emitter-bias with $R_B = 47\ \text{k}\Omega$, $R_E = 4.7\ \text{k}\Omega$, and $\beta = 100$.

Solution

(a) Eq. (4.65):

$$\begin{aligned} S(V_{BE}) &= -\frac{\beta}{R_B} \\ &= -\frac{100}{240\ \text{k}\Omega} \\ &= \mathbf{-0.417 \times 10^{-3}} \end{aligned}$$

and

$$\begin{aligned} \Delta I_C &= [S(V_{BE})](\Delta V_{BE}) \\ &= (-0.417 \times 10^{-3})(0.48\ \text{V} - 0.65\ \text{V}) \\ &= (-0.417 \times 10^{-3})(-0.17\ \text{V}) \\ &= \mathbf{70.9\ \mu A} \end{aligned}$$

(b) In this case, $(\beta + 1) = 101$ and $R_B/R_E = 240$. The condition $(\beta + 1) \gg R_B/R_E$ is not satisfied, negating the use of Eq. (4.67) and requiring the use of Eq. (4.64).

Eq. (4.64):

$$\begin{aligned} S(V_{BE}) &= \frac{-\beta}{R_B + (\beta + 1)R_E} \\ &= \frac{-100}{240\ \text{k}\Omega + (101)1\ \text{k}\Omega} = -\frac{100}{341\ \text{k}\Omega} \\ &= \mathbf{-0.293 \times 10^{-3}} \end{aligned}$$

which is about 30% less than the fixed-bias value due to the additional $(\beta + 1)R_E$ term in the denominator of the $S(V_{BE})$ equation.

$$\begin{aligned} \Delta I_C &= [S(V_{BE})](\Delta V_{BE}) \\ &= (-0.293 \times 10^{-3})(-0.17\ V) \\ &\cong \mathbf{50\ \mu A} \end{aligned}$$

(c) In this case,

$$(\beta + 1) = 101 \gg \frac{R_B}{R_E} = \frac{47\ \text{k}\Omega}{4.7\ \text{k}\Omega} = 10\ (\textit{satisfied})$$