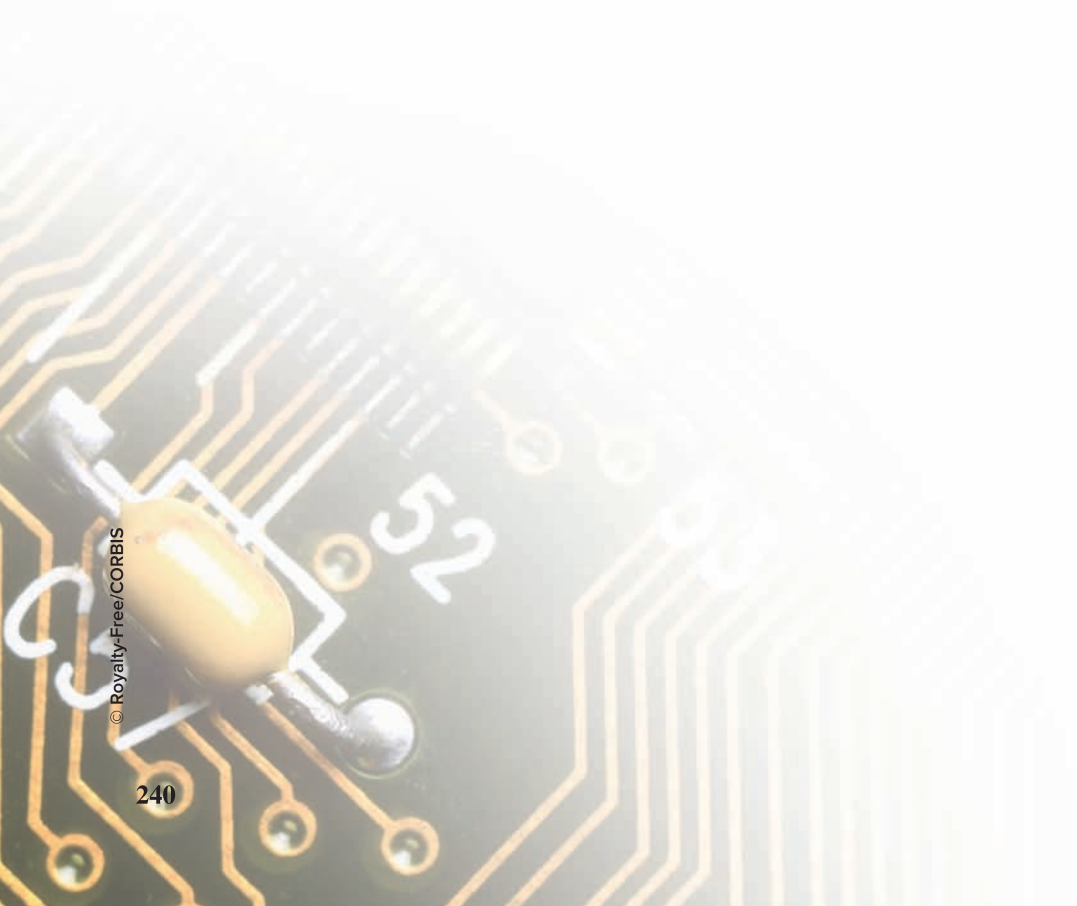
chapter 7

BJT Biasing

A **prototype** is a basic circuit design that can be modified to get more advanced circuits. Base bias is a prototype used in the design of switching circuits. Emitter bias is a prototype used in the design of amplifying circuits. In this chapter, we emphasize emitter bias and the practical circuits that can be derived from it.



Chapter Outline

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7-2 LED Drivers

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7-4 More Optoelectronic Devices

7-5 Voltage-Divider Bias

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7-11 *PNP* Transistors

Objectives

After studying this chapter, you should be able to:

- Draw an emitter bias circuit and explain why it works well in amplifying circuits.
- Draw a diagram of a voltage-divider bias circuit.
- Calculate the divider current, base voltage, emitter voltage, emitter current, collector voltage, and collector-emitter voltage for an *npn* VDB circuit.
- Determine how to draw the load line and calculate the *Q* point for a given VDB circuit.
- Design a VDB circuit using design guidelines.
- Draw a two-supply emitter bias circuit and calculate V_{RE}, I_E, V_C, and V_{CE}.
- Compare several different types of bias and describe how well each works.
- Calculate the *Q* point of *pnp* VDB circuits.
- Troubleshoot transistor-biasing circuits.

Vocabulary

collector-feedback bias
correction factor
emitter bias
emitter-feedback bias
firm voltage divider
phototransistor
prototype
self-bias
stage
stiff voltage divider
swamp out
two-supply emitter bias (TSEB)
voltage-divider bias (VDB)

7-1 Emitter Bias

Digital circuits are the type of circuits used in computers. In this area, base bias and circuits derived from base bias are useful. But when it comes to amplifiers, we need circuits whose *Q* points are immune to changes in current gain.

Figure 7-1 shows **emitter bias.** As you can see, the resistor has been moved from the base circuit to the emitter circuit. That one change makes all the difference in the world. The *Q* point of this new circuit is now rock-solid. When the current gain changes from 50 to 150, the *Q* point shows almost no movement along the load line.

Basic Idea

The base supply voltage is now applied directly to the base. Therefore, a troubleshooter will read V_{BB} between the base and ground. The emitter is no longer grounded. Now the emitter is above the ground and has a voltage given by:

$$V_E = V_{BB} - V_{BE} \tag{7-1}$$

If V_{BB} is more than 20 times V_{BE}, the ideal approximation will be accurate. If V_{BB} is less than 20 times V_{BE}, you may want to use the second approximation. Otherwise, your error will be more than 5 percent.

Finding the Q Point

Let us analyze the emitter-biased circuit of Fig. 7-2. The base supply voltage is only 5 V, so we use the second approximation. The voltage between the base and ground is 5 V. From now on, we refer to this base-to-ground voltage as the *base voltage,* or V_B. The voltage across the base-emitter terminals is 0.7 V. We refer to this voltage as the *base-emitter voltage,* or V_{BE}.

Figure 7-1 Emitter bias.

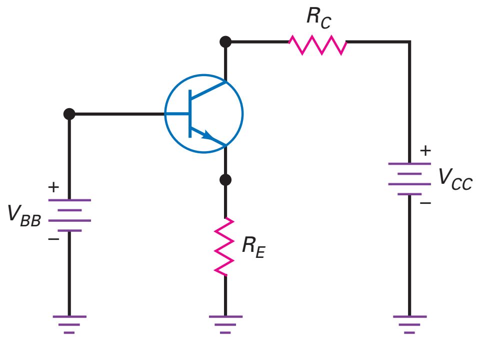
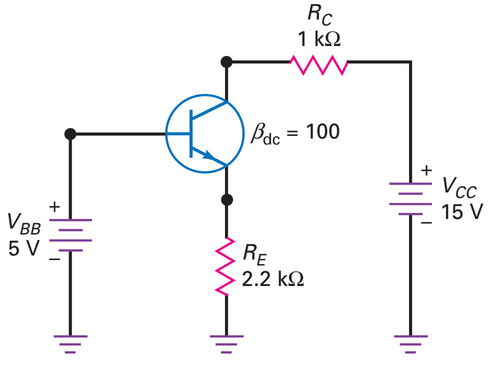


Figure 7-2 Finding the *Q* point.



The voltage between the emitter and ground is called the *emitter voltage.* It equals:

$$V_E = 5 \text{ V} - 0.7 \text{ V} = 4.3 \text{ V}$$

This voltage is across the emitter resistance, so we can use Ohm's law to find the emitter current:

$$I_E = \frac{4.3 \text{ V}}{2.2 \text{ k}\Omega} = 1.95 \text{ mA}$$

This means that the collector current is 1.95 mA to a close approximation. When this collector current flows through the collector resistor, it produces a voltage drop of 1.95 V. Subtracting this from the collector supply voltage gives the voltage between the collector and ground:

$$V_C = 15 \text{ V} - (1.95 \text{ mA})(1 \text{ k}\Omega) = 13.1 \text{ V}$$

From now on, we will refer to this collector-to-ground voltage as the *collector voltage.*

This is the voltage a troubleshooter would measure when testing a transistor circuit. One lead of the voltmeter would be connected to the collector, and the other lead would be connected to ground. If you want the collector-emitter voltage, you have to subtract the emitter voltage from the collector voltage as follows:

$$V_{CE} = 13.1 \text{ V} - 4.3 \text{ V} = 8.8 \text{ V}$$

So, the emitter-biased circuit of Fig. 7-2 has a Q point with these coordinates: $I_C = 1.95$ mA and $V_{CE} = 8.8$ V.

The collector-emitter voltage is the voltage used for drawing load lines and for reading transistor data sheets. As a formula:

$$\boldsymbol{V_{CE} = V_C - V_E} \qquad \textbf{(7-2)}$$

Circuit Is Immune to Changes in Current Gain

GOOD TO KNOW

Because the values of I_C and V_{CE} are not affected by the value of beta in an emitter-biased circuit, this type of circuit is said to be *beta-independent*.

Here is why emitter bias excels. The Q point of an emitter-biased circuit is immune to changes in current gain. The proof lies in the process used to analyze the circuit. Here are the steps we used earlier:

1. Get the emitter voltage.
2. Calculate the emitter current.
3. Find the collector voltage.
4. Subtract the emitter from the collector voltage to get V_{CE}.

At no time do we need to use the current gain in the foregoing process. Since we don't use it to find the emitter current, collector current, and so on, the exact value of current gain no longer matters.

By moving the resistor from the base to the emitter circuit, we force the base-to-ground voltage to equal the base supply voltage. Before, almost all this supply voltage was across the base resistor, setting up a *fixed base current.* Now, all this supply voltage minus 0.7 V is across the emitter resistor, setting up a *fixed emitter current.*

Minor Effect of Current Gain

The current gain has a minor effect on the collector current. Under all operating conditions, the three currents are related by:

$$I_E = I_C + I_B$$

which can be rearranged as:

$$I_E = I_C + \frac{I_C}{\beta_{dc}}$$

Solve this for the collector current, and you get:

$$I_C = \frac{\beta_{dc}}{\beta_{dc} + 1} I_E \tag{7-3}$$

The quantity that multiplies I_E is called a **correction factor.** It tells you how I_C differs from I_E. When the current gain is 100, the correction factor is:

$$\frac{\beta_{dc}}{\beta_{dc} + 1} = \frac{100}{100 + 1} = 0.99$$

This means that the collector current is equal to 99 percent of the emitter current. Therefore, we get only a 1 percent error when we ignore the correction factor and say that the collector current equals the emitter current.

Example 7-1

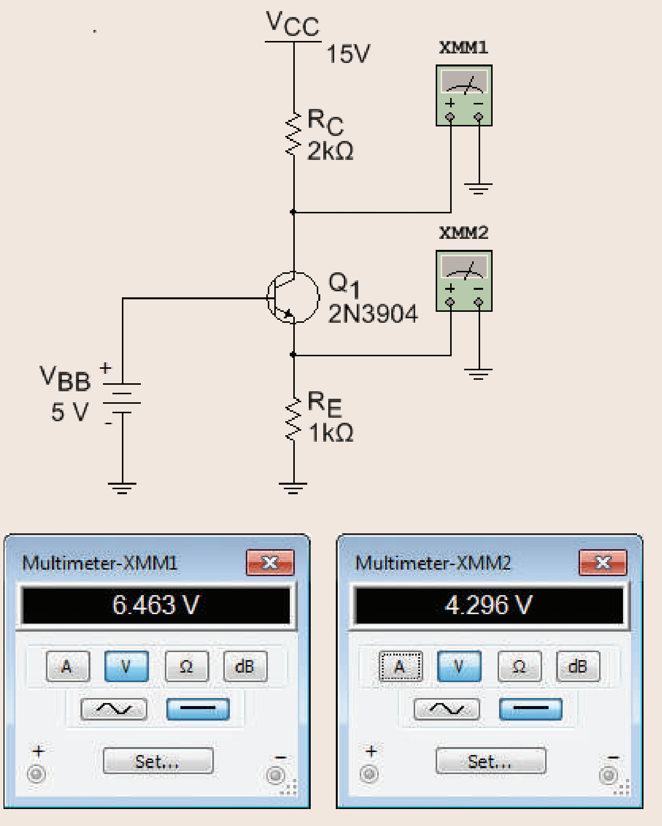
Multisim

What is the voltage between the collector and ground in the Multisim Fig. 7-3? Between the collector and the emitter?

SOLUTION The base voltage is 5 V. The emitter voltage is 0.7 V less than this, or:

$$V_E = 5 \text{ V} - 0.7 \text{ V} = 4.3 \text{ V}$$

Multisim **Figure 7-3** Meter Values.



This voltage is across the emitter resistance, which is now 1 kΩ. Therefore, the emitter current is 4.3 V divided by 1 kΩ, or:

$$I_E = \frac{4.3\text{ V}}{1\text{ k}\Omega} = 4.3\text{ mA}$$

The collector current is approximately equal to 4.3 mA. When this current flows through the collector resistance (now 2 kΩ), it produces a voltage of:

$$I_C R_C = (4.3\text{ mA})(2\text{ k}\Omega) = 8.6\text{ V}$$

When you subtract this voltage from the collector supply voltage, you get:

$$V_C = 15\text{ V} - 8.6\text{ V} = 6.4\text{ V}$$

This voltage value is very close to the value measured by the Multisim meter. Remember, this is the voltage between the collector and ground. This is what you would measure when troubleshooting.

Unless you have a voltmeter with a high input resistance and a floating ground lead, you should not attempt to connect a voltmeter directly between the collector and the emitter because this may short the emitter to ground. If you want to know the value of V_{CE}, you should measure the collector-to-ground voltage, then measure the emitter-to-ground voltage, and subtract the two. In this case:

$$V_{CE} = 6.4\text{ V} - 4.3\text{ V} = 2.1\text{ V}$$

PRACTICE PROBLEM 7-1 **Multisim** Decrease the base supply voltage of Fig. 7-3 to 3 V. Predict and measure the new value of V_{CE}.

7-2 LED Drivers

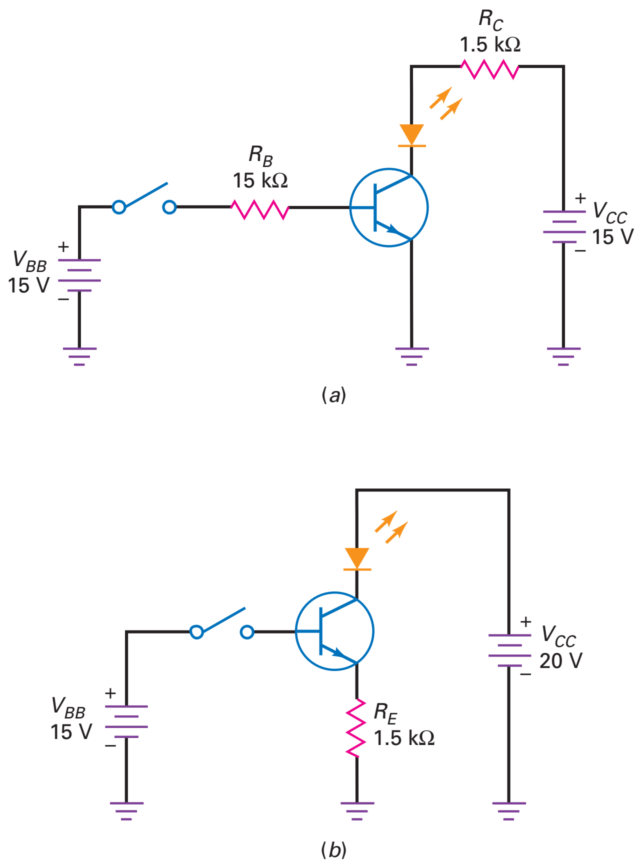
You have learned that base-biased circuits set up a fixed value of base current, and emitter-biased circuits set up a fixed value of emitter current. Because of the problem with current gain, base-biased circuits are normally designed to switch between saturation and cutoff, whereas emitter-biased circuits are usually designed to operate in the active region.

In this section, we discuss two circuits that can be used as LED drivers. The first circuit uses base bias, and the second circuit uses emitter bias. This will give you a chance to see how each circuit performs in the same application.

Base-Biased LED Driver

The base current is zero in Fig. 7-4*a*, which means that the transistor is at cutoff. When the switch of Fig. 7-4*a* closes, the transistor goes into hard saturation. Visualize a short between the collector-emitter terminals. Then the collector supply voltage (15 V) appears across the series connection of the 1.5 kΩ and the LED. If we ignore the voltage drop across the LED, the collector current is ideally 10 mA. But if we allow 2 V across the LED, then there is 13 V across the 1.5 kΩ, and the collector current is 13 V divided by 1.5 kΩ, or 8.67 mA.

Figure 7-4 (*a*) Base-biased; (*b*) emitter-biased.



There is nothing wrong with this circuit. It makes a fine LED driver because it is designed for hard saturation, where the current gain doesn't matter. If you want to change the LED current in this circuit, you can change either the collector resistance or the collector supply voltage. The base resistance is made 10 times larger than the collector resistance because we want hard saturation when the switch is closed.

Emitter-Biased LED Driver

The emitter current is zero in Fig. 7-4*b*, which means that the transistor is at cutoff. When the switch of Fig. 7-4*b* closes, the transistor goes into the active region. Ideally, the emitter voltage is 15 V. This means that we get an emitter current of 10 mA. This time, the LED voltage drop has no effect. It doesn't matter whether the exact LED voltage is 1.8, 2, or 2.5 V. This is an advantage of the emitter-biased design over the base-biased design. The LED current is independent of the LED voltage. Another advantage is that the circuit doesn't require a collector resistor.

The emitter-biased circuit of Fig. 7-4*b* operates in the active region when the switch is closed. To change the LED current, you can change the base supply voltage or the emitter resistance. For instance, if you vary the base supply voltage, the LED current varies in direct proportion.

Application Example 7-2

We want 25 mA of LED current when the switch is closed in Fig. 7-4*b*. How can we do it?

SOLUTION One solution is to increase the base supply. We want 25 mA to flow through the emitter resistance of 1.5 kΩ. Ohm's law tells us that the emitter voltage has to be:

$$V_E = (25 \text{ mA})(1.5 \text{ k}\Omega) = 37.5 \text{ V}$$

Ideally, V_{BB} = 37.5 V. To a second approximation, V_{BB} = 38.2 V. This is a bit high for typical power supplies. But the solution is workable if the particular application allows this high a supply voltage.

A supply voltage of 15 V is common in electronics. Therefore, a better solution in most applications is to decrease the emitter resistance. Ideally, the emitter voltage will be 15 V, and we want 25 mA through the emitter resistor. Ohm's law gives:

$$R_E = \frac{15 \text{ V}}{25 \text{ mA}} = 600 \ \Omega$$

The nearest standard value with a tolerance of 5 percent is 620 Ω. If we use the second approximation, the resistance is:

$$R_E = \frac{14.3 \text{ V}}{25 \text{ mA}} = 572 \ \Omega$$

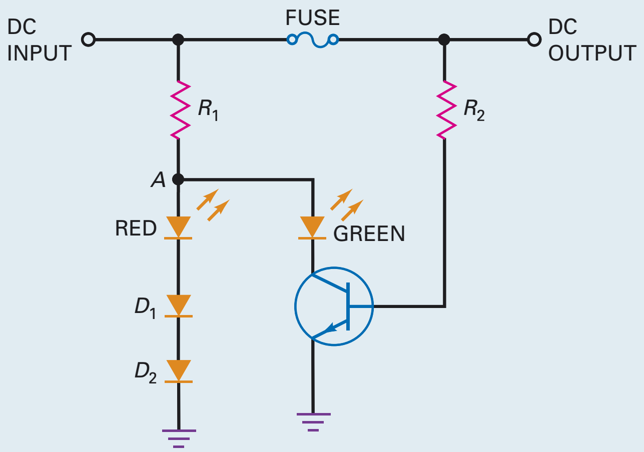
The nearest standard value is 560 Ω.

PRACTICE PROBLEM 7-2 In Fig. 7-4*b*, what value of R_E is needed to produce an LED current of 21 mA?

Application Example 7-3

What does the circuit in Fig. 7-5 do?

Figure 7-5 Base-biased LED driver.

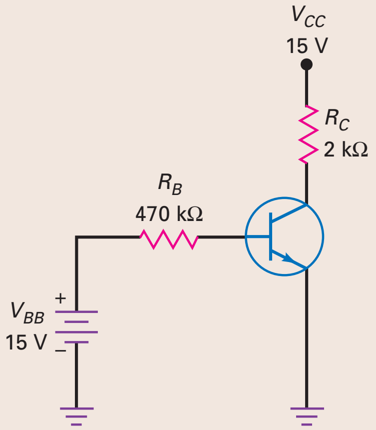


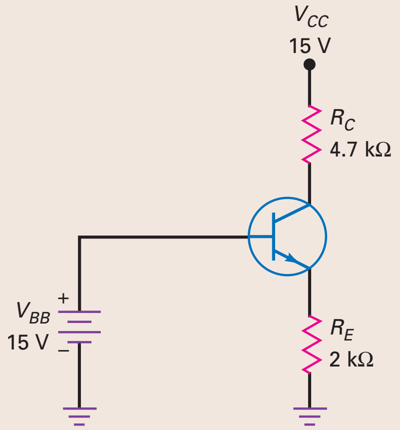
SOLUTION This is a blown-fuse indicator for a dc power supply. When the fuse is intact, the transistor is base-biased into saturation. This turns on the green LED to indicate that all is OK. The voltage between point A and ground is approximately 2 V. This voltage is not enough to turn on the red LED. The two series diodes (D_1 and D_2) prevent the red LED from turning on because they require a drop of 1.4 V to conduct.

When the fuse blows, the transistor goes into cutoff, turning off the green LED. Then, the voltage of point *A* is pulled up toward the supply voltage. Now there is enough voltage to turn on the two series diodes and the red LED to indicate a blown fuse. Summary Table 7-1 illustrates the differences between base bias and emitter bias.

Summary Table 7-1 Base Bias versus Emitter Bias

Circuit





Characteristic	Fixed base current	Fixed emitter current
$\beta_{dc} = 100$	$I_B = 9.15\ \mu A$ $I_C = 915\ \mu A$	$I_B = 21.5\ \mu A$ $I_E = 2.15$ mA
$\beta_{dc} = 300$	$I_B = 9.15\ \mu A$ $I_C = 2.74$ mA	$I_B = 7.17\ \mu A$ $I_E = 2.15$ mA
Modes used	Cutoff and saturation	Active or linear
Applications	Switching/digital circuits	Controlled I_C drivers and amplifiers

7-3 Troubleshooting Emitter Bias Circuits

When a transistor is disconnected from the circuit, you can use a DMM or ohmmeter to test the transistor. When the transistor is in the circuit with power on, you can measure its voltages, which are clues to possible troubles.

In-Circuit Tests

The simplest in-circuit tests measure transistor voltages with respect to ground. For instance, measuring the collector voltage V_C and the emitter voltage V_E is a good start. The difference $V_C - V_E$ should be more than 1 V but less than V_{CC}. If the reading is less than 1 V in an amplifier circuit, the transistor may be shorted. If the reading equals V_{CC}, the transistor may be open.

The foregoing test usually pins down a dc trouble if one exists. Many people include a test of V_{BE}, done as follows: Measure the base voltage V_B and the emitter voltage V_E. The difference of these readings is V_{BE}, which should be 0.6 to 0.7 V for small-signal transistors operating in the active region. For power transistors, V_{BE} may be 1 V or more because of the bulk resistance of the emitter diode. If the V_{BE} reading is less than approximately 0.6 V, the emitter diode is not being forward biased. The trouble could be in the transistor or in the biasing components.

Some people include a cutoff test, performed as follows: Short the base-emitter terminals with a jumper wire. This removes the forward bias on the emitter diode and should force the transistor into cutoff. The collector-to-ground voltage should equal the collector supply voltage. If it does not, something is wrong with the transistor or the circuitry.

Care should be taken when doing this test. If another device or circuit is directly connected to the collector terminal, be sure that the increase in collector-to-ground voltage will not cause any damage.

A Table of Troubles

As discussed in basic electronics, a shorted component is equivalent to a resistance of zero, and an open component is equivalent to a resistance of infinity. For instance, the emitter resistor may be shorted or open. Let us designate these troubles by R_{ES} and R_{EO}, respectively. Similarly, the collector resistor may be shorted or open, symbolized by R_{CS} and R_{CO}, respectively.

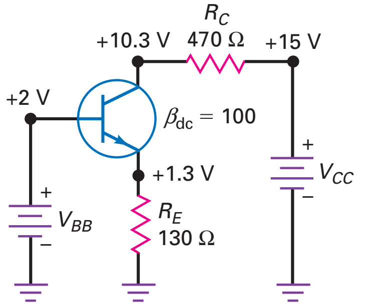
When a transistor is defective, anything can happen. For instance, one or both diodes may be internally shorted or open. We are going to limit the number of possibilities to the most likely defects as follows: a collector-emitter short (*CES*) will represent all three terminals shorted together (base, collector, and emitter), and a collector-emitter open (*CEO*) stands for all three terminals open. A base-emitter open (*BEO*) means that the base-emitter diode is open, and a collector-base open (*CBO*) means that the collector-base diode is open.

Summary Table 7-2 shows a few of the troubles that could occur in a circuit like Fig. 7-6. The voltages were calculated by using the second approximation. When the circuit is operating normally, you should measure a base voltage of 2 V, an emitter voltage of 1.3 V, and a collector voltage of approximately 10.3 V. If the emitter resistor were shorted, +2 V would appear across the emitter diode. This large voltage would destroy the transistor, possibly producing a collector-emitter open. This trouble R_{ES} and its voltages are shown in Summary Table 7-2.

If the emitter resistor were open, there would be no emitter current. Furthermore, the collector current would be zero, and the collector voltage would increase to 15 V. This trouble R_{EO} and its voltages are shown in Summary Table 7-2. Continuing like this, we can get the remaining entries of the table.

Notice the entry for no V_{CC}. This is worth commenting on. Your initial instinct might be that the collector voltage is zero, because there is no collector supply voltage. But that is not what you will measure with a voltmeter. When you connect a voltmeter between the collector and ground, the base supply will set up a small forward current through the collector diode in series with the voltmeter. Since the base voltage is fixed at 2 V, the collector voltage is 0.7 V less than this. Therefore, the voltmeter will read 1.3 V between the collector and ground. In other words, the voltmeter completes the circuit to ground because the voltmeter looks like a very large resistance in series with the collector diode.

Figure 7-6 In-circuit tests.

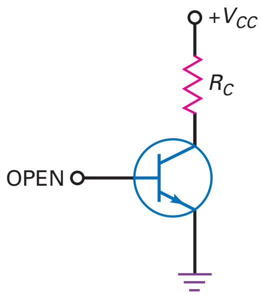


Summary Table 7-2	Troubles and Symptoms			
Trouble	**V_B, V**	**V_E, V**	**V_C, V**	**Comments**
None	2	1.3	10.3	No trouble
R_{ES}	2	0	15	Transistor destroyed (CEO)
R_{EO}	2	1.3	15	No base or collector current
R_{CS}	2	1.3	15	
R_{CO}	2	1.3	1.3	
No V_{BB}	0	0	15	Check supply and lead
No V_{CC}	2	1.3	1.3	Check supply and lead
CES	2	2	2	All transistor terminals shorted
CEO	2	0	15	All transistor terminals open
BEO	2	0	15	Base-emitter diode open
CBO	2	1.3	15	Collector-base diode open

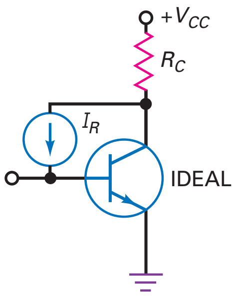
7-4 More Optoelectronic Devices

As mentioned earlier, a transistor with an open base has a small collector current consisting of thermally produced minority carriers and surface leakage. By exposing the collector junction to light, a manufacturer can produce a **phototransistor,** a device that has more sensitivity to light than a photodiode.

Figure 7-7 (*a*) Transistor with open base; (*b*) equivalent circuit.



(*a*)



(*b*)

Basic Idea of Phototransistors

Figure 7-7*a* shows a transistor with an open base. As mentioned earlier, a small collector current exists in this circuit. Ignore the surface-leakage component, and concentrate on the thermally produced carriers in the collector diode. Visualize the reverse current produced by these carriers as an ideal current source in parallel with the collector-base junction of an ideal transistor (Fig. 7-7*b*).

Because the base lead is open, all the reverse current is forced into the base of the transistor. The resulting collector current is:

$$I_{CEO} = \beta_{dc} I_R$$

where I_R is the reverse minority carrier current. This says that the collector current is higher than the original reverse current by a factor of β_{dc}.

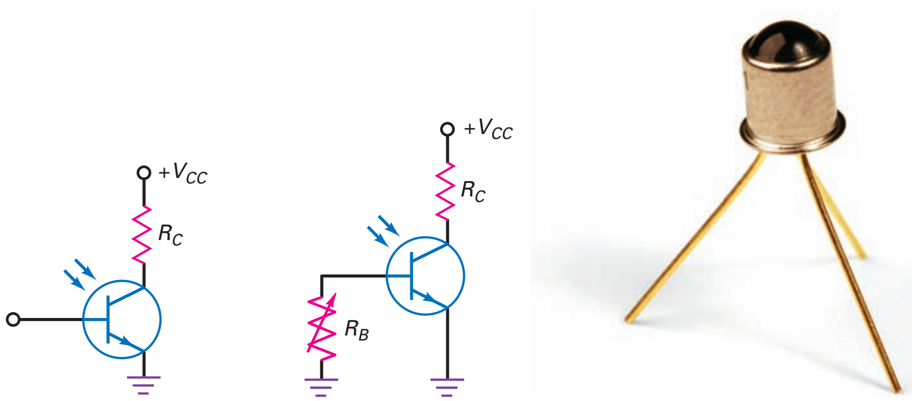
The collector diode is sensitive to light as well as heat. In a phototransistor, light passes through a window and strikes the collector-base junction. As the light increases, I_R increases, and so does I_{CEO}.

Phototransistor versus Photodiode

The main difference between a phototransistor and a photodiode is the current gain β_{dc}. The same amount of light striking both devices produces β_{dc} times more current in a phototransistor than in a photodiode. The increased sensitivity of a phototransistor is a big advantage over that of a photodiode.

Figure 7-8*a* shows the schematic symbol of a phototransistor. Notice the open base. This is the usual way to operate a phototransistor. You can control the

Figure 7-8 Phototransistor. (*a*) Open base gives maximum sensitivity; (*b*) variable base resistor changes sensitivity; (*c*) typical phototransistor.



(*a*) (*b*) (*c*)

GOOD TO KNOW

The optocoupler was actually designed as a solid-state replacement for a mechanical relay. Functionally, the optocoupler is similar to its older mechanical counterpart because it offers a high degree of isolation between its input and its output terminals. Some of the advantages of using an optocoupler versus a mechanical relay are faster operating speeds, no bouncing of contacts, smaller size, no moving parts to stick, and compatibility with digital microprocessor circuits.

sensitivity with a variable base return resistor (Fig. 7-8*b*), but the base is usually left open to get maximum sensitivity to light.

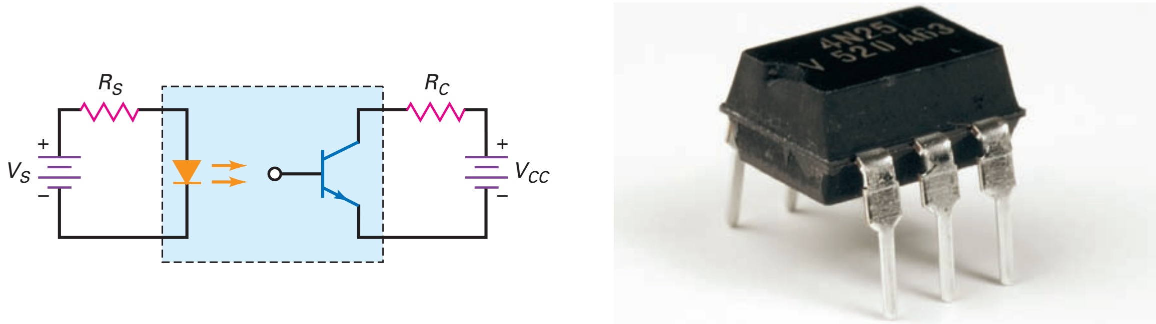
The price paid for increased sensitivity is reduced speed. A phototransistor is more sensitive than a photodiode, but it cannot turn on and off as fast. A photodiode has typical output currents in microamperes and can switch on and off in nanoseconds. The phototransistor has typical output currents in milliamperes but switches on and off in microseconds. A typical phototransistor is shown in Fig. 7-8*c*.

Optocoupler

Figure 7-9*a* shows an LED driving a phototransistor. This is a much more sensitive optocoupler than the LED-photodiode discussed earlier. The idea is straightforward. Any changes in V_S produce changes in the LED current, which changes the current through the phototransistor. In turn, this produces a changing voltage across the collector-emitter terminals. Therefore, a signal voltage is coupled from the input circuit to the output circuit.

Again, the big advantage of an optocoupler is the electrical isolation between the input and output circuits. Stated another way, the common for the input circuit is different from the common for the output circuit. Because of this, no conductive path exists between the two circuits. This means that you can ground one of the circuits and float the other. For instance, the input circuit can be grounded to the chassis of the equipment, while the common of the output side is ungrounded. Figure 7-9*b* shows a typical optocoupler *IC*.

Figure 7-9 (*a*) Optocoupler with LED and phototransistor; (*b*) optocoupler *IC*.



(*a*) (*b*)

Application Example 7-4

What does the circuit in Fig. 7-10 do?

The 4N24 optocoupler in Fig. 7-10*a* provides isolation from the power line and detects zero crossings of line voltage. The graph in Fig. 7-10*b* shows how the collector current is related to the LED current. Here is how you can calculate the peak output voltage from the optocoupler:

The bridge rectifier produces a full-wave current through the LED. Ignoring diode drops, the peak current through the LED is:

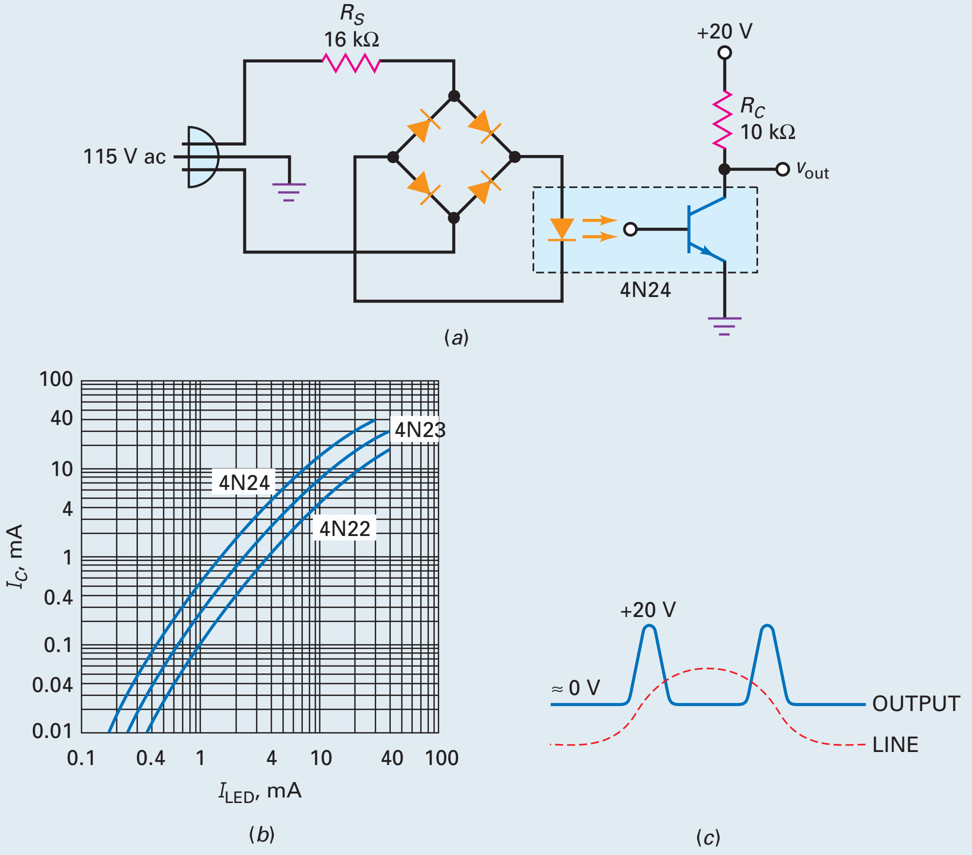
$$I_{LED} = \frac{1.414(115\text{ V})}{16\text{ k}\Omega} = 10.2\text{ mA}$$

The saturated value of the phototransistor current is:

$$I_{C(sat)} = \frac{20\text{ V}}{10\text{ k}\Omega} = 2\text{ mA}$$

Figure 7-10*b* shows the static curves of phototransistor current versus LED current for three different optocouplers. With a 4N24 (top curve), an LED current of 10.2 mA produces a collector current of approximately 15 mA when the load resistance is zero. In Fig. 7-10*a*, the phototransistor current never reaches 15 mA because the phototransistor saturates at 2 mA. In other words, there is more than enough LED current to produce saturation. Since the peak LED current is 10.2 mA, the transistor is saturated during most of the cycle. At this time, the output voltage is approximately zero, as shown in Fig. 7-10*c*.

Figure 7-10 (*a*) Zero-crossing detector; (*b*) optocoupler curves; (*c*) output of detector.



The zero crossings occur when the line voltage is changing polarity, from positive to negative, or vice versa. At a zero crossing, the LED current drops to zero. At this instant, the phototransistor becomes an open circuit, and the output voltage increases to approximately 20 V, as indicated in Fig. 7-10*c*. As you can see, the output voltage is near zero most of the cycle. At the zero crossings, it increases rapidly to 20 V and then decreases to the baseline.

A circuit like Fig. 7-10*a* is useful because it does not require a transformer to provide isolation from the line. The photocoupler takes care of this. Furthermore, the circuit detects zero crossings, desirable in applications where you want to synchronize some other circuit to the frequency of the line voltage.

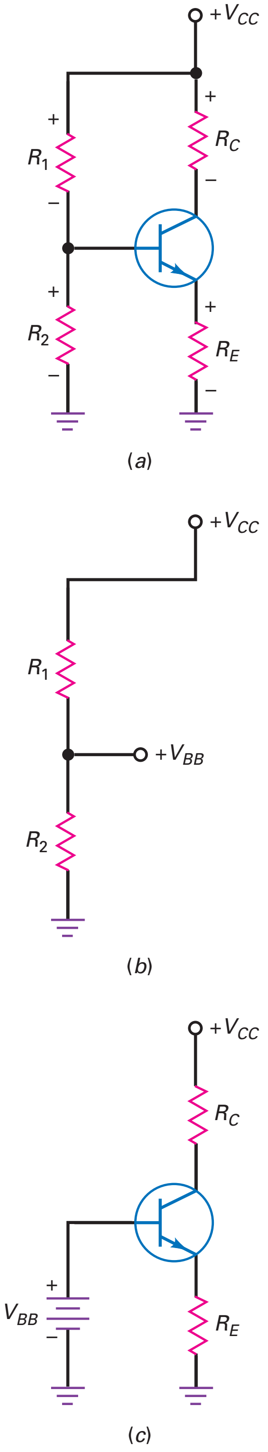


Figure 7-11 Voltage-divider bias. (*a*) Circuit; (*b*) voltage divider; (*c*) simplified circuit.

7-5 Voltage-Divider Bias

Figure 7-11*a* shows the most widely used biasing circuit. Notice that the base circuit contains a voltage divider (R_1 and R_2). Because of this, the circuit is called **voltage-divider bias (VDB).**

Simplified Analysis

For troubleshooting and preliminary analysis, use the following method. In any well-designed VDB circuit, the base current is much smaller than the current through the voltage divider. Since the base current has a negligible effect on the voltage divider, we can mentally open the connection between the voltage divider and the base to get the equivalent circuit in Fig. 7-11*b*. In this circuit, the output of the voltage divider is:

$$V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC}$$

Ideally, this is the base-supply voltage as shown in Fig. 7-11*c*.

As you can see, voltage-divider bias is really emitter bias in disguise. In other words, Fig. 7-11*c* is an equivalent circuit for Fig. 7-11*a*. This is why VDB sets up a fixed value of emitter current, resulting in a solid *Q* point that is independent of the current gain.

There is an error in this simplified approach, however, and we will discuss it in the next section. The crucial point is this: In any well-designed circuit, the error in using Fig. 7-11*c* is very small. In other words, a designer deliberately chooses circuit values so that Fig. 7-11*a* acts like Fig. 7-11*c*.

Conclusion

After you calculate V_{BB}, the rest of the analysis is the same as discussed earlier for emitter bias. Here is a summary of the equations you can use to analyze VDB:

$$\boldsymbol{V_{BB} = \frac{R_2}{R_1 + R_2} V_{CC}} \qquad \textbf{(7-4)}$$

$$\boldsymbol{V_E = V_{BB} - V_{BE}} \qquad \textbf{(7-5)}$$

$$\boldsymbol{I_E = \frac{V_E}{R_E}} \qquad \textbf{(7-6)}$$

$$\boldsymbol{I_C \approx I_E} \qquad \textbf{(7-7)}$$

$$\boldsymbol{V_C = V_{CC} - I_C R_C} \qquad \textbf{(7-8)}$$

$$\boldsymbol{V_{CE} = V_C - V_E} \qquad \textbf{(7-9)}$$

These equations are based on Ohm's and Kirchhoff's laws. Here are the steps in the analysis:

1. Calculate the base voltage V_{BB} out of the voltage divider.
2. Subtract 0.7 V to get the emitter voltage (use 0.3 V for germanium).
3. Divide by the emitter resistance to get the emitter current.
4. Assume that the collector current is approximately equal to the emitter current.

5. Calculate the collector-to-ground voltage by subtracting the voltage across the collector resistor from the collector supply voltage.
6. Calculate the collector-emitter voltage by subtracting the emitter voltage from the collector voltage.

Since these six steps are logical, they should be easy to remember. After you analyze a few VDB circuits, the process becomes automatic.

GOOD TO KNOW

Since $V_E \cong I_C R_E$, Eq. (7-9) can also be shown as

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

or

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

Example 7-5

Multisim

What is the collector-emitter voltage in Fig. 7-12?

SOLUTION The voltage divider produces an unloaded output voltage of:

$$V_{BB} = \frac{2.2\ \text{k}\Omega}{10\ \text{k}\Omega + 2.2\ \text{k}\Omega} 10\ \text{V} = 1.8\ \text{V}$$

Subtract 0.7 V from this to get:

$$V_E = 1.8\ \text{V} - 0.7\ \text{V} = 1.1\ \text{V}$$

The emitter current is:

$$I_E = \frac{1.1\ \text{V}}{1\ \text{k}\Omega} = 1.1\ \text{mA}$$

Since the collector current almost equals the emitter current, we can calculate the collector-to-ground voltage like this:

$$V_C = 10\ \text{V} - (1.1\ \text{mA})(3.6\ \text{k}\Omega) = 6.04\ \text{V}$$

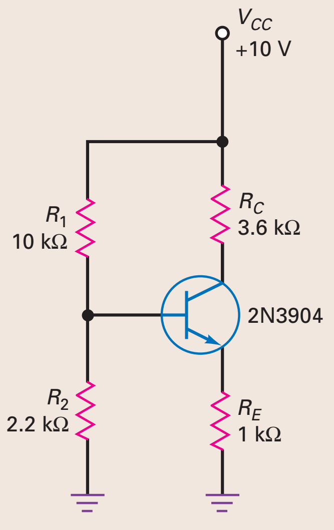
The collector-emitter voltage is:

$$V_{CE} = 6.04 - 1.1\ \text{V} = 4.94\ \text{V}$$

Here is an important point: The calculations in this preliminary analysis do not depend on changes in the transistor, the collector current, or the temperature. This is why the Q point of this circuit is stable, almost rock-solid.

PRACTICE PROBLEM 7-5 Change the power supply voltage in Fig. 7-12 from 10 V to 15 V and solve for V_{CE}.

Figure 7-12 Example.



Example 7-6

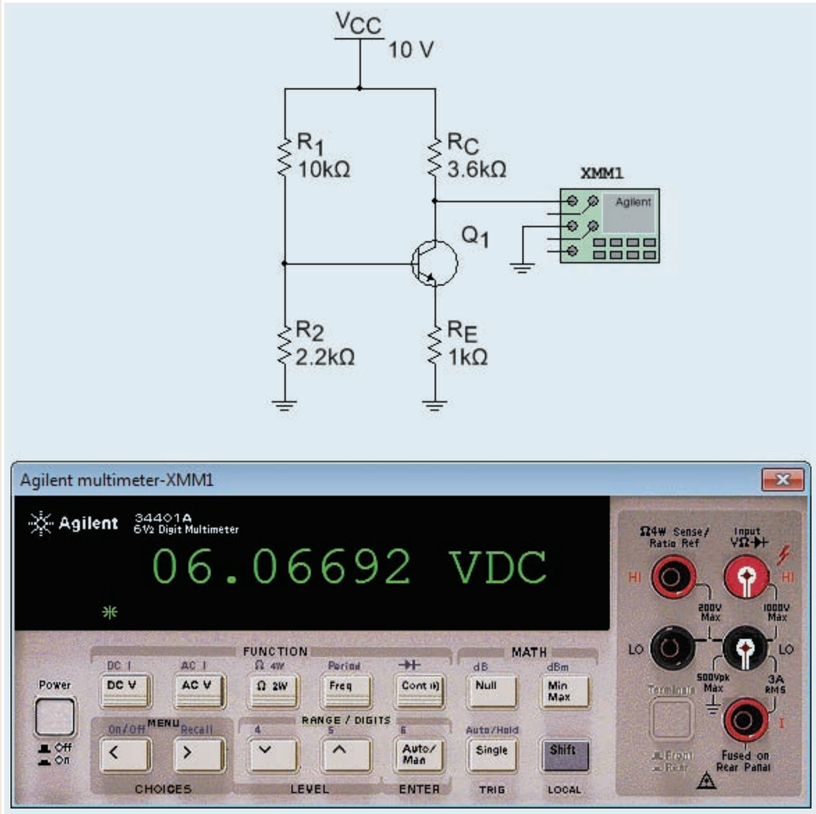
Multisim

Discuss the significance of Fig. 7-13, which shows a Multisim analysis of the same circuit analyzed in the preceding example.

SOLUTION This really drives the point home. Here we have an almost identical answer using a computer to analyze the circuit. As you can see, the voltmeter reads 6.07 V (rounded to two places). Compare this to 6.04 V in the preceding example, and you can see the point. A simplified analysis has produced essentially the same result as a computer analysis.

You can expect this kind of close agreement whenever a VDB circuit has been well designed. After all, the whole point of VDB is to act like emitter bias to virtually eliminate the effects of changing the transistor, collector current, or temperature.

Multisim **Figure 7-13** Multisim example.



PRACTICE PROBLEM 7-6 Using Multisim, change the supply voltage in Fig. 7-13 to 15 V and measure V_{CE}. Compare your measured value to the answer of Practice Problem 7-5.

7-6 Accurate VDB Analysis

What is a well-designed VDB circuit? It is one in which *the voltage divider appears stiff to the input resistance of the base.* The meaning of the last sentence needs to be discussed.

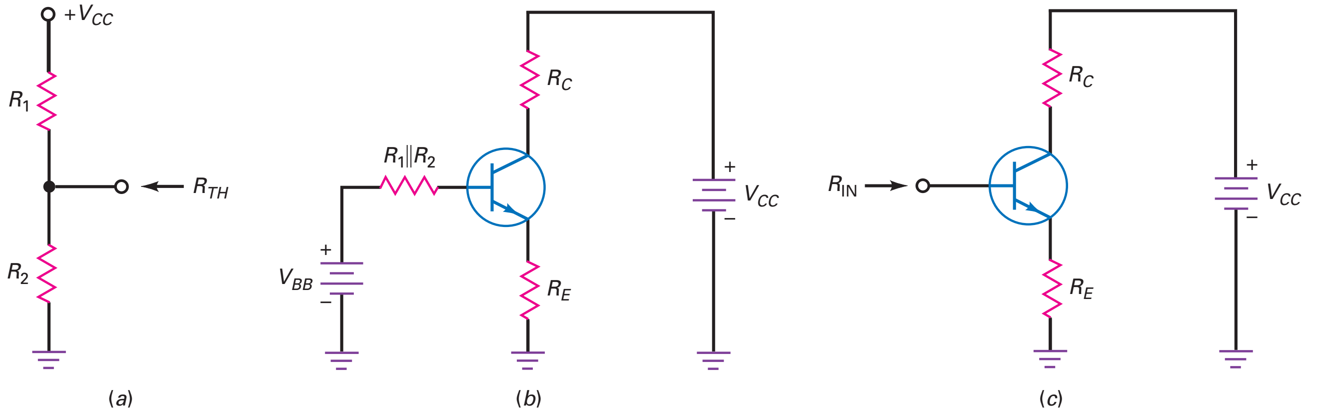
Source Resistance

In a stiff voltage source, we can ignore the source resistance when it is at least 100 times smaller than the load resistance:

$$\text{Stiff voltage source: } R_S < 0.01R_L$$

When this condition is satisfied, the load voltage is within 1 percent of the ideal voltage. Now, let us extend this idea to the voltage divider.

Figure 7-14 (*a*) Thevenin resistance; (*b*) equivalent circuit; (*c*) input resistance of base.



What is the Thevenin resistance of the voltage divider in Fig. 7-14*a*? Looking back into the voltage divider with V_{CC} grounded, we see R_1 in parallel with R_2. As an equation:

$$R_{TH} = R_1 \| R_2$$

Because of this resistance, the output voltage of the voltage divider is not ideal. A more accurate analysis includes the Thevenin resistance, as shown in Fig. 7-14*b*. The current through this Thevenin resistance reduces the base voltage from the ideal value of V_{BB}.

Load Resistance

How much less than ideal is the base voltage? The voltage divider has to supply the base current in Fig. 7-14*b*. Put another way, the voltage divider sees a load resistance of R_{IN}, as shown in Fig. 7-14*c*. For the voltage divider to appear stiff to the base, the 100 : 1 rule:

$$R_S < 0.01R_L$$

translates to:

$$\boldsymbol{R_1 \| R_2 < 0.01R_{IN}} \quad \textbf{(7-10)}$$

A well-designed VDB circuit will satisfy this condition.

Stiff Voltage Divider

If the transistor in Fig. 7-14*c* has a current gain of 100, its collector current is 100 times greater than the base current. This implies that the emitter current is also 100 times greater than the base current. When seen from the base side of the transistor, the emitter resistance R_E appears to be 100 times larger. As a derivation:

$$\boldsymbol{R_{IN} = \beta_{dc}R_E} \quad \textbf{(7-11)}$$

Therefore, Eq. (7-10) may be written as:

$$\textbf{Stiff voltage divider: } \boldsymbol{R_1 \| R_2 < 0.01\beta_{dc}R_E} \quad \textbf{(7-12)}$$

Whenever possible, a designer selects circuit values to satisfy this 100 : 1 rule because it will produce an ultrastable Q point.

Firm Voltage Divider

Sometimes, a stiff design results in such small values of R_1 and R_2 that other problems arise (discussed later). In this case, many designers compromise by using this rule:

$$\textbf{Firm voltage divider: } R_1 \| R_2 < 0.1\beta_{dc} R_E \tag{7-13}$$

We call any voltage divider that satisfies this 10 : 1 rule a **firm voltage divider.** In the worst case, using a firm voltage divider means that the collector current will be approximately 10 percent lower than the stiff value. This is acceptable in many applications because the VDB circuit still has a reasonably stable Q point.

A Closer Approximation

If you want a more accurate value for the emitter current, you can use the following derivation:

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + (R_1 \| R_2)/\beta_{dc}} \tag{7-14}$$

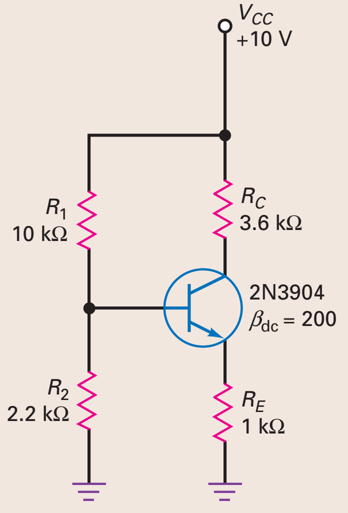
This differs from the stiff value because $(R_1 \| R_2)/\beta_{dc}$ is in the denominator. As this term approaches zero, the equation simplifies to the stiff value.

Equation (7-14) will improve the analysis, but it is a fairly complicated formula. If you have a computer and need a more accurate analysis obtained with the stiff analysis, you should use Multisim or an equivalent circuit simulator.

Example 7-7

Multisim

Figure 7-15 Example.



Is the voltage divider in Fig. 7-15 stiff? Calculate the more accurate value of emitter current using Eq. (7-14).

SOLUTION Check to see whether the 100 : 1 rule has been used:

$$\text{Stiff voltage divider: } R_1 \| R_2 < 0.01\beta_{dc} R_E$$

The Thevenin resistance of the voltage divider is:

$$R_1 \| R_2 = 10 \text{ k}\Omega \,\|\, 2.2 \text{ k}\Omega = \frac{(10 \text{ k}\Omega)(2.2 \text{ k}\Omega)}{10 \text{ k}\Omega + 2.2 \text{ k}\Omega} = 1.8 \text{ k}\Omega$$

The input resistance of the base is:

$$\beta_{dc} R_E = (200)(1 \text{ k}\Omega) = 200 \text{ k}\Omega$$

and one-hundredth of this is:

$$0.01\beta_{dc} R_E = 2 \text{ k}\Omega$$

Since 1.8 kΩ is less than 2 kΩ, the voltage divider is stiff.

With Eq. (7-14), the emitter current is:

$$I_E = \frac{1.8 \text{ V} - 0.7 \text{ V}}{1 \text{ k}\Omega + (1.8 \text{ k}\Omega)/200} = \frac{1.1 \text{ V}}{1 \text{ k}\Omega + 9 \text{ }\Omega} = 1.09 \text{ mA}$$

This is extremely close to 1.1 mA, the value we get with the simplified analysis.

The point is this: You don't have to use Eq. (7-14) to calculate emitter current when the voltage divider is stiff. Even when the voltage divider is firm, the use of Eq. (7-14) will improve the calculation for emitter current only by at most 10 percent. Unless otherwise indicated, from now on, all analysis of VDB circuits will use the simplified method.

7-7 VDB Load Line and Q Point

Because of the stiff voltage divider in Fig. 7-16, the emitter voltage is held constant at 1.1 V in the following discussion.

The Q Point

The Q point was calculated in Sec. 7-5. It has a collector current of 1.1 mA and a collector-emitter voltage of 4.94 V. These values are plotted to get the Q point shown in Fig. 7-16. Since voltage-divider bias is derived from emitter bias, the Q point is virtually immune to changes in current gain. One way to move the Q point in Fig. 7-16 is by varying the emitter resistor.

For instance, if the emitter resistance is changed to 2.2 kΩ, the collector current decreases to:

$$I_E = \frac{1.1 \text{ V}}{2.2 \text{ k}\Omega} = 0.5 \text{ mA}$$

The voltages change as follows:

$$V_C = 10 \text{ V} - (0.5 \text{ mA})(3.6 \text{ k}\Omega) = 8.2 \text{ V}$$

and

$$V_{CE} = 8.2 \text{ V} - 1.1 \text{ V} = 7.1 \text{ V}$$

Therefore, the new Q point will be Q_L and will have coordinates of 0.5 mA and 7.1 V.

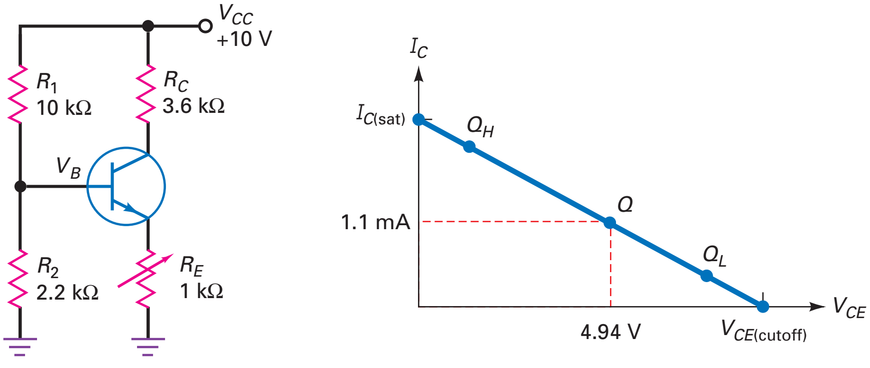
On the other hand, if we decrease the emitter resistance to 510 Ω, the emitter current increases to:

$$I_E = \frac{1.1 \text{ V}}{510 \ \Omega} = 2.15 \text{ mA}$$

and the voltages change to:

$$V_C = 10 \text{ V} - (2.15 \text{ mA})(3.6 \text{ k}\Omega) = 2.26 \text{ V}$$

Figure 7-16 Calculating the Q point.



and

$$V_{CE} = 2.26\text{ V} - 1.1\text{ V} = 1.16\text{ V}$$

In this case, the Q point shifts to a new position at Q_H with coordinates of 2.15 mA and 1.16 V.

Q Point in Middle of Load Line

V_{CC}, R_1, R_2, and R_C control the saturation current and the cutoff voltage. A change in any of these quantities will change $I_{C(sat)}$ and/or $V_{CE(cutoff)}$. Once the designer has established the values of the foregoing variables, the *emitter resistance* is varied to set the Q point at any position along the load line. If R_E is too large, the Q point moves into the cutoff point. If R_E is too small, the Q point moves into saturation. Some designers set the Q point at the middle of the load line. When we examine transistor amplifiers, the dc load line Q point will be adjusted from the middle of the dc load line to achieve maximum output signal.

GOOD TO KNOW

Centering the Q point on a transistor load line is important because it allows for the maximum ac output voltage from the amplifier. Centering the Q point on the dc load line is sometimes referred to as *midpoint bias*.

VDB Design Guideline

Figure 7-17 shows a VDB circuit. This circuit will be used to demonstrate a simplified design guideline to establish a stable Q point. This design technique is suitable for most circuits, but it is only a guideline. Other design techniques can be used.

Before starting the design, it is important to determine the circuit requirements or specifications. The circuit is normally biased for V_{CE} to be at a midpoint value with a specified collector current. You also need to know the value of V_{CC} and the range of β_{dc} for the transistor being used. Also, be sure the circuit will not cause the transistor to exceed its power dissipation limits.

Start by making the emitter voltage approximately one-tenth of the supply voltage:

$$V_E = 0.1\ V_{CC}$$

Next, calculate the value of R_E to set up the specified collector current:

$$R_E = \frac{V_E}{I_E}$$

Since the Q point needs to be at approximately the middle of the dc load line, about 0.5 V_{CC} appears across the collector-emitter terminals. The remaining 0.4 V_{CC} appears across the collector resistor; therefore:

$$R_C = 4\ R_E$$

Next, design for a stiff voltage divider using the 100:1 rule:

$$R_{TH} \le 0.01\ \beta_{dc}\ R_E$$

Usually, R_2 is smaller than R_1. Therefore, the stiff voltage divider equation can be simplified to:

$$R_2 \le 0.01\ \beta_{dc}\ R_E$$

You may also choose to design for a firm voltage divider by using the 10:1 rule:

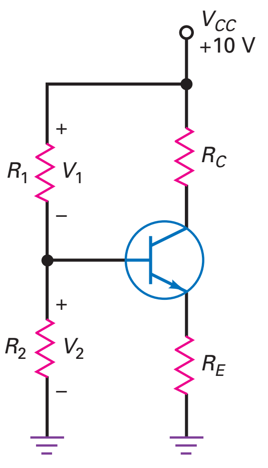
$$R_2 \le 0.1\ \beta_{dc}\ R_E$$

In either case, use the minimum-rated β_{dc} value at the specified collector current.

Finally, calculate R_1 by using proportion:

$$R_1 = \frac{V_1}{V_2} R_2$$

Figure 7-17 VDB design.



Application Example 7-8

For the circuit shown in Fig. 7-17, design the resistor values to meet these specifications:

$V_{CC} = 10\text{V}$ $\quad V_{CE}$ @ midpoint

$I_C = 10 \text{ mA}$ $\quad$ 2N3904's $\beta_{dc} = 100\text{–}300$

SOLUTION First, establish the emitter voltage by:

$$V_E = 0.1\, V_{CC}$$

$$V_E = (0.1)\,(10 \text{ V}) = 1 \text{ V}$$

The emitter resistor is found by:

$$R_E = \frac{V_E}{I_E}$$

$$R_E = \frac{1 \text{ V}}{10 \text{ mA}} = 100\ \Omega$$

The collector resistor is:

$$R_C = 4\, R_E$$

$$R_C = (4)\,(100\ \Omega) = 400\ \Omega \text{ (use } 390\ \Omega)$$

Next, choose either a stiff or firm voltage divider. A stiff value of R_2 is found by:

$$R_2 \leq 0.01\, \beta_{dc}\, R_E$$

$$R_2 \leq (0.01)\,(100)\,(100\ \Omega) = 100\ \Omega$$

Now, the value of R_1 is:

$$R_1 = \frac{V_1}{V_2} R_2$$

$$V_2 = V_E + 0.7 \text{ V} = 1 \text{ V} + 0.7 \text{ V} = 1.7 \text{ V}$$

$$V_1 = V_{CC} - V_2 = 10 \text{ V} - 1.7 \text{ V} = 8.3 \text{ V}$$

$$R_1 = \left(\frac{8.3 \text{ V}}{1.7 \text{ V}}\right)(100\ \Omega) = 488\ \Omega \text{ (use } 490\ \Omega)$$

PRACTICE PROBLEM 7-8 Using the given VDB design guidelines, design the VDB circuit of Fig. 7-17 to meet these specifications:

$V_{CC} = 10\text{V}$ $\quad V_{CE}$ @ midpoint $\quad$ stiff voltage divider

$I_C = 1 \text{ mA}$ $\quad \beta_{dc} = 70\text{–}200$

7-8 Two-Supply Emitter Bias

Some electronics equipment have a power supply that produces both positive and negative supply voltages. For instance, Fig. 7-18 shows a transistor circuit with two power supplies: +10 and −2 V. The negative supply forward-biases the emitter diode. The positive supply reverse-biases the collector diode. This circuit

Figure 7-18 Two-supply emitter bias.

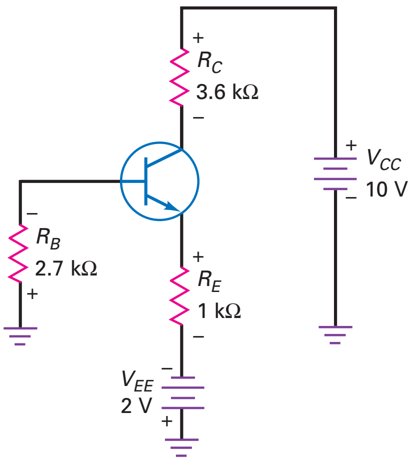
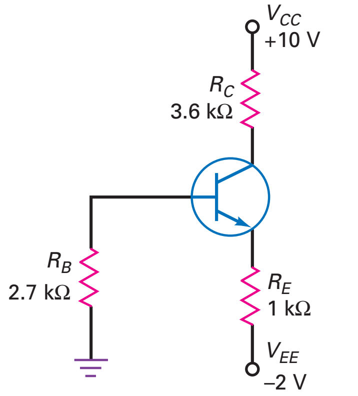


Figure 7-19 Redrawn TSEB circuit.



is derived from emitter bias. For this reason, we refer to it as **two-supply emitter bias (TSEB).**

Analysis

The first thing to do is redraw the circuit as it usually appears on schematic diagrams. This means deleting the battery symbols, as shown in Fig. 7-19. This is necessary on schematic diagrams because there usually is no room for battery symbols on complicated diagrams. All the information is still on the diagram, except that it is in condensed form. That is, a negative supply voltage of −2 V is applied to the bottom of the 1 kΩ, and a positive supply voltage of +10 V is applied to the top of the 3.6-kΩ resistor.

When this type of circuit is correctly designed, the base current will be small enough to ignore. This is equivalent to saying that the base voltage is approximately 0 V, as shown in Fig. 7-20.

The voltage across the emitter diode is 0.7 V, which is why −0.7 V is shown on the emitter node. If this is not clear, stop and think about it. There is a plus-to-minus drop of 0.7 V going from the base to the emitter. If the base voltage is 0 V, the emitter voltage must be −0.7 V.

In Fig. 7-20, the emitter resistor again plays the key role in setting up the emitter current. To find this current, apply Ohm's law to the emitter resistor as follows: The top of the emitter resistor has a voltage of −0.7 V, and the bottom has a voltage of −2 V. Therefore, the voltage across the emitter resistor equals the difference between the two voltages. To get the right answer, subtract the more negative value from the more positive value. In this case, the more negative value is −2 V, so:

$$V_{RE} = -0.7\text{ V} - (-2\text{ V}) = 1.3\text{ V}$$

Once you have found the voltage across the emitter resistor, calculate the emitter current with Ohm's law:

$$I_E = \frac{1.3\text{ V}}{1\text{ k}\Omega} = 1.3\text{ mA}$$

This current flows through the 3.6 kΩ and produces a voltage drop that we subtract from +10 V as follows:

$$V_C = 10\text{ V} - (1.3\text{ mA})(3.6\text{ k}\Omega) = 5.32\text{ V}$$

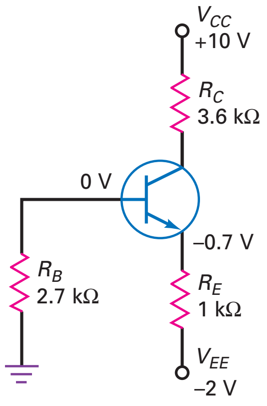
The collector-emitter voltage is the difference between the collector voltage and the emitter voltage:

$$V_{CE} = 5.32\text{ V} - (-0.7\text{ V}) = 6.02\text{ V}$$

GOOD TO KNOW

When transistors are biased using well-designed voltage-divider or emitter-bias configurations, they are classified as beta-independent circuits because the values of I_C and V_{CE} are unaffected by changes in the transistor's beta.

Figure 7-20 Base voltage is ideally zero.



When two-supply emitter bias is well designed, it is similar to voltage-divider bias and satisfies this 100 : 1 rule:

$$R_B < 0.01\beta_{dc}R_E \tag{7-15}$$

In this case, the simplified equations for analysis are:

$$V_B \approx 0 \tag{7-16}$$

$$I_E = \frac{V_{EE} - 0.7\text{ V}}{R_E} \tag{7-17}$$

$$V_C = V_{CC} - I_C R_C \tag{7-18}$$

$$V_{CE} = V_C + 0.7\text{ V} \tag{7-19}$$

Base Voltage

One source of error in the simplified method is the small voltage across the base resistor of Fig. 7-20. Since a small base current flows through this resistance, a negative voltage exists between the base and ground. In a well-designed circuit, this base voltage is less than −0.1 V. If a designer has to compromise by using a larger base resistance, the voltage may be more negative than −0.1 V. If you are troubleshooting a circuit like this, the voltage between the base and ground should produce a low reading; otherwise, something is wrong with the circuit.

Example 7-9

Multisim

What is the collector voltage in Fig. 7-20 if the emitter resistor is increased to 1.8 kΩ?

SOLUTION The voltage across the emitter resistor is still 1.3 V. The emitter current is:

$$I_E = \frac{1.3\text{ V}}{1.8\text{ k}\Omega} = 0.722\text{ mA}$$

The collector voltage is:

$$V_C = 10\text{ V} - (0.722\text{ mA})(3.6\text{ k}\Omega) = 7.4\text{ V}$$

PRACTICE PROBLEM 7-9 Change the emitter resistor in Fig. 7-20 to 2 kΩ and solve for V_{CE}.

Example 7-10

A **stage** is a transistor and the passive components connected to it. Figure 7-21 shows a three-stage circuit using two-supply emitter bias. What are the collector-to-ground voltages for each stage in Fig. 7-21?

SOLUTION To begin with, ignore the capacitors because they appear as open circuits to dc voltage and currents. Then, we are left with three isolated transistors, each using two-supply emitter bias.

The first stage has an emitter current of:

$$I_E = \frac{15\text{ V} - 0.7\text{ V}}{20\text{ k}\Omega} = \frac{14.3\text{ V}}{20\text{ k}\Omega} = 0.715\text{ mA}$$

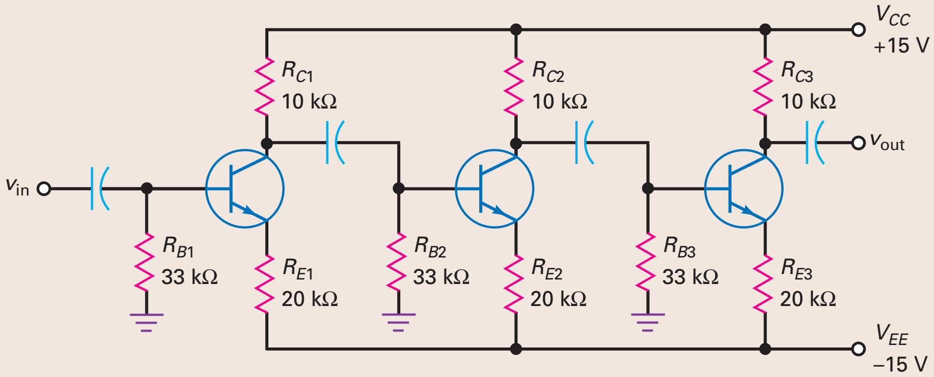
and a collector voltage of:

$$V_C = 15\text{ V} - (0.715\text{ mA})(10\text{ k}\Omega) = 7.85\text{ V}$$

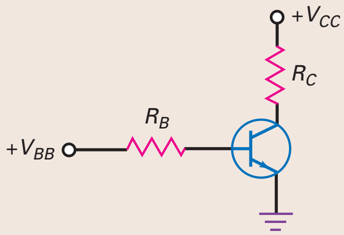
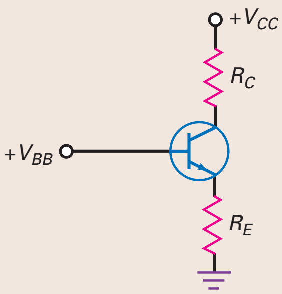
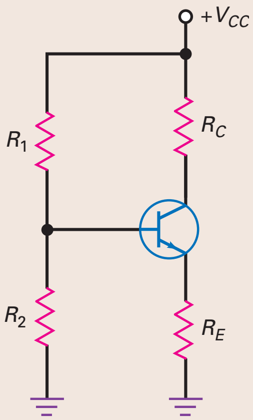
Since the other stages have the same circuit values, each has a collector-to-ground voltage of approximately 7.85 V. Summary Table 7-3 illustrates the four main types of bias circuits.

PRACTICE PROBLEM 7-10 Change the supply voltages in Fig. 7-21 to +12 V and −12 V. Then, calculate V_{CE} for each transistor.

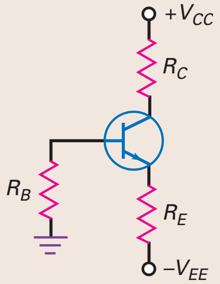
Figure 7-21 Three-stage circuit.



Summary Table 7-3 Main Bias Circuits

Type	Circuit	Calculations	Characteristics	Where used
Base bias		$I_B = \frac{V_{BB} - 0.7\text{ V}}{R_B}$ $I_C = \beta I_B$ $V_{CE} = V_{CC} - I_C R_C$	Few parts; β dependent; fixed base current	Switch; digital
Emitter bias		$V_E = V_{BB} - 0.7\text{ V}$ $I_E = \frac{V_E}{R_E}$ $V_C = V_C - I_C R_C$ $V_{CE} = V_C - V_E$	Fixed emitter current; β independent	I_C driver; amplifier
Voltage divider bias		$V_B = \frac{R_2}{R_1 + R_2} V_{CC}$ $V_E = V_B - 0.7\text{ V}$ $I_E = \frac{V_E}{R_E}$ $V_C = V_{CC} - I_C R_C$ $V_{CE} = V_C - V_E$	Needs more resistors; β independent; needs only one power supply	Amplifier

Summary Table 7-3 (continued)

Type	Circuit	Calculations	Characteristics	Where used
Two-supply emitter bias		$V_B \approx 0$ V $V_E = V_B - 0.7$ V $V_{RE} = V_{EE} - 0.7$ V $I_E = \frac{V_{RE}}{R_E}$ $V_C = V_{CC} - I_C R_C$ $V_{CE} = V_C - V_E$	Needs positive and negative power supplies; β independent	Amplifier

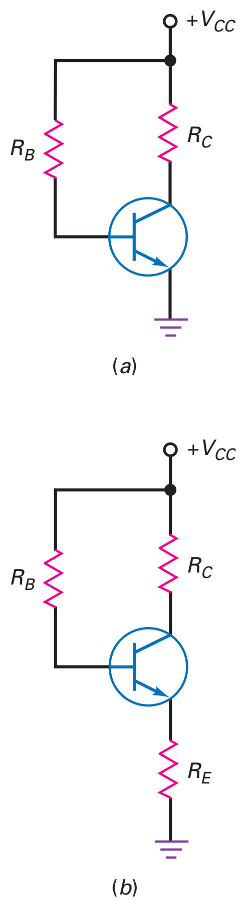


Figure 7-22 (*a*) Base bias; (*b*) emitter-feedback bias.

7-9 Other Types of Bias

In this section, we will discuss some other types of bias. A detailed analysis of these types of bias is not necessary because they are rarely used in new designs. But you should at least be aware of their existence in case you see them on a schematic diagram.

Emitter-Feedback Bias

Recall our discussion of base bias (Fig. 7-22*a*). This circuit is the worst when it comes to setting up a fixed *Q* point. Why? Since the base current is fixed, the collector current varies when the current gain varies. In a circuit like this, the *Q* point moves all over the load line with transistor replacement and temperature change.

Historically, the first attempt at stabilizing the *Q* point was **emitter-feedback bias,** shown in Fig. 7-22*b*. Notice that an emitter resistor has been added to the circuit. The basic idea is this: If I_C increases, V_E increases, causing V_B to increase. More V_B means less voltage across R_B. This results in less I_B, which opposes the original increase in I_C. It's called *feedback* because the change in emitter voltage is being fed back to the base circuit. Also, the feedback is called *negative* because it opposes the original change in collector current.

Emitter-feedback bias never became popular. The movement of the *Q* point is still too large for most applications that have to be mass-produced. Here are the equations for analyzing the emitter-feedback bias:

$$I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{dc}} \tag{7-20}$$

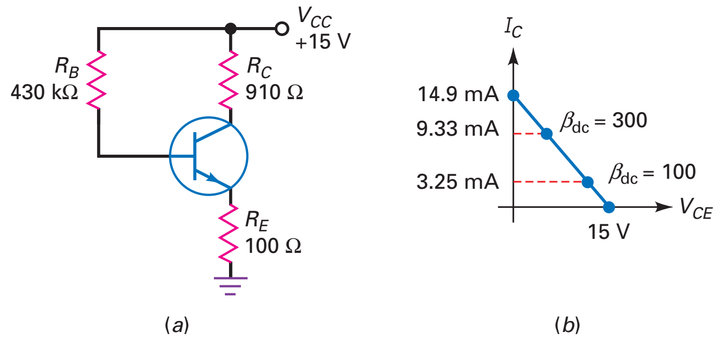
$$V_E = I_E R_E \tag{7-21}$$

$$V_B = V_E + 0.7 \text{ V} \tag{7-22}$$

$$V_C = V_{CC} - I_C R_C \tag{7-23}$$

The intent of emitter-feedback bias is to **swamp out** the variations in β_{dc}; that is, R_E should be much greater than R_B/β_{dc}. If this condition is satisfied,

Figure 7-23 (*a*) Example of emitter-feedback bias; (*b*) *Q* point is sensitive to changes in current gain.



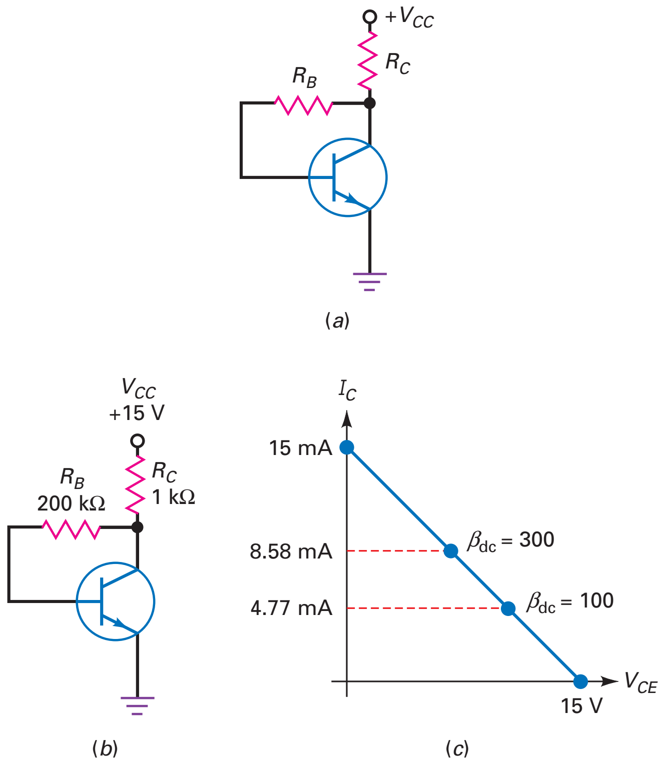
Eq. (7-20) will be insensitive to changes in β_{dc}. In practical circuits, however, a designer cannot select R_E large enough to swamp out the effects of β_{dc} without cutting off the transistor.

Figure 7-23*a* shows an example of an emitter-feedback bias circuit. Figure 7-23*b* shows the load line and the *Q* points for two different current gains. As you can see, a 3 : 1 variation in current gain produces a large variation in collector current. The circuit is not much better than base bias.

Collector-Feedback Bias

Figure 7-24*a* shows **collector-feedback bias** (also called **self-bias**). Historically, this was another attempt at stabilizing the *Q* point. Again, the basic idea is to feed back a voltage to the base in an attempt to neutralize any change in collector

Figure 7-24 (*a*) Collector-feedback bias; (*b*) example; (*c*) *Q* point is less sensitive to changes in current gain.



current. For instance, suppose the collector current increases. This decreases the collector voltage, which decreases the voltage across the base resistor. In turn, this decreases the base current, which opposes the original increase in collector current.

Like emitter-feedback bias, collector-feedback bias uses negative feedback in an attempt to reduce the original change in collector current. Here are the equations for analyzing collector-feedback bias:

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{dc}} \qquad (7\text{-}24)$$

$$V_B = 0.7 \text{ V} \qquad (7\text{-}25)$$

$$V_C = V_{CC} - I_C R_C \qquad (7\text{-}26)$$

The Q point is usually set near the middle of the load line by using a base resistance of:

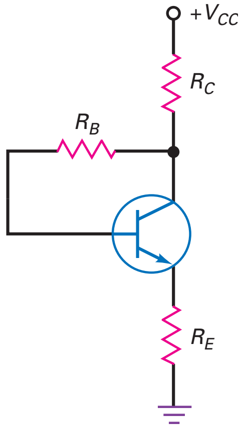
$$R_B = \beta_{dc} R_C \qquad (7\text{-}27)$$

Figure 7-24*b* shows an example of collector-feedback bias. Figure 7-24*c* shows the load line and the Q points for two different current gains. As you can see, a 3:1 variation in current gain produces less variation in collector current than emitter-feedback (see Fig. 7-23*b*).

Collector-feedback bias is more effective than emitter-feedback bias in stabilizing the Q point. Although the circuit is still sensitive to changes in current gain, it is used in practice because of its simplicity.

Collector- and Emitter-Feedback Bias

Figure 7-25 Collector-emitter feedback bias.



Emitter-feedback bias and collector-feedback bias were the first steps toward a more stable bias for transistor circuits. Even though the idea of negative feedback is sound, these circuits fall short because there is not enough negative feedback to do the job. This is why the next step in biasing was the circuit shown in Fig. 7-25. The basic idea is to use both emitter and collector feedback to try to improve the operation.

As it turns out, more is not always better. Combining both types of feedback in one circuit helps, but still falls short of the performance needed for mass production. If you come across this circuit, here are the equations for analyzingit:

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + R_E + R_B/\beta_{dc}} \qquad (7\text{-}28)$$

$$V_E = I_E R_E \qquad (7\text{-}29)$$

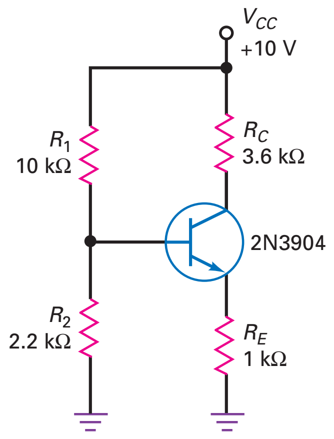
$$V_B = V_E + 0.7 \text{ V} \qquad (7\text{-}30)$$

$$V_C = V_{CC} - I_C R_C \qquad (7\text{-}31)$$

7-10 Troubleshooting VDB Circuits

Let us discuss troubleshooting voltage-divider bias because this biasing method is the most widely used. Figure 7-26 shows the VDB circuit analyzed earlier. Summary Table 7-4 lists the voltages for the circuit when it is simulated with Multisim. The voltmeter used to make the measurements has an input impedance of 10 MΩ.

Figure 7-26 VDB Troubleshooting.



Summary Table 7-4 Troubles and Symptoms

Trouble	V_B	V_E	V_C	Comment
None	1.79	1.12	6	No trouble
R_{1S}	10	9.17	9.2	Transistor saturated
R_{1O}	0	0	10	Transistor cutoff
R_{2S}	0	0	10	Transistor cutoff
R_{2O}	3.38	2.68	2.73	Reduces to emitter-feedback bias
R_{ES}	0.71	0	0.06	Transistor saturated
R_{EO}	1.8	1.37	10	10-MΩ voltmeter reduces V_E
R_{CS}	1.79	1.12	10	Collector resistor shorted
R_{CO}	1.07	0.4	0.43	Large base current
CES	2.06	2.06	2.06	All transistor terminals shorted
CEO	1.8	0	10	All transistor terminals open
No V_{CC}	0	0	0	Check supply and leads

Unique Troubles

Often, an open or shorted component produces unique voltages. For instance, the only way to get 10 V at the base of the transistor in Fig. 7-26 is with a shorted R_1. No other shorted or open component can produce the same result. Most of the entries in Summary Table 7-4 produce a unique set of voltages, so you can identify them without breaking into the circuit to make further tests.

Ambiguous Troubles

Two troubles in Summary Table 7-4 do not produce unique voltages: R_{1O} and R_{2S}. They both have measured voltages of 0, 0, and 10 V. With ambiguous troubles like this, the troubleshooter has to disconnect one of the suspected components and use an ohmmeter or other instrument to test it. For instance, we could disconnect R_1 and measure its resistance with an ohmmeter. If it's open, we have found the trouble. If it's OK, then R_2 is shorted.

Voltmeter Loading

Whenever you use a voltmeter, you are connecting a new resistance to a circuit. This resistance will draw current from the circuit. If the circuit has a large resistance, the voltage being measured will be lower than normal.

For instance, suppose the emitter resistor is open in Fig. 7-26. The base voltage is 1.8 V. Since there can be no emitter current with an open emitter resistor, the unmeasured voltage between the emitter and ground must also be 1.8 V. When you measure V_E with a 10-MΩ voltmeter, you are connecting 10 MΩ between the emitter and ground. This allows a small emitter current to flow, which produces a voltage across the emitter diode. This is why $V_E = 1.37$ V instead of 1.8 V for R_{EO} in Summary Table 7-4.

Figure 7-27 *PNP* transistor.

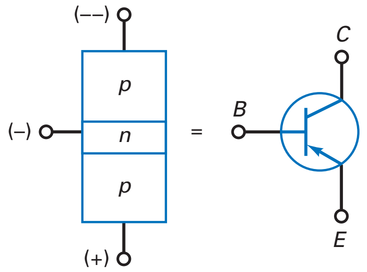


Figure 7-28 *PNP* currents.

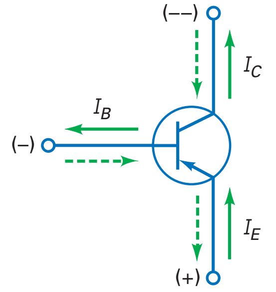
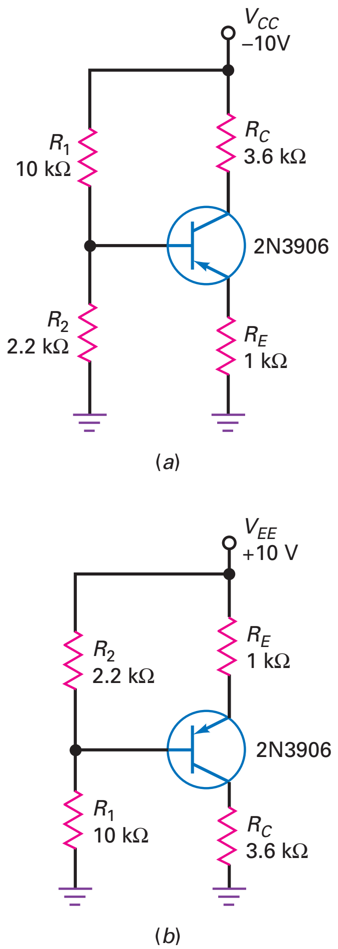


Figure 7-29 *PNP* circuit. (*a*) Negative supply; (*b*) positive supply.



7-11 *PNP* Transistors

Up to this point, we have concentrated on bias circuits using *npn* transistors. Many circuits also use *pnp* transistors. This type of transistor is often used when the electronics equipment has a negative power supply. Also, *pnp* transistors are used as complements to *npn* transistors when dual (positive and negative) power supplies are available.

Figure 7-27 shows the structure of a *pnp* transistor along with its schematic symbol. Because the doped regions are of the opposite type, we have to turn our thinking around. Specifically, holes are the majority carriers in the emitter instead of free electrons. Just as with an *npn* transistor, to properly bias a *pnp* transistor, the base-emitter diode must be forward biased and the base-collector diode must be reverse biased. This is shown in Fig. 7-27.

Basic Ideas

Briefly, here is what happens at the atomic level: The emitter injects holes into the base. The majority of these holes flow on to the collector. For this reason, the collector current is almost equal to the emitter current.

Figure 7-28 shows the three transistor currents. Solid arrows represent conventional current, and dashed arrows represent electron flow.

Negative Supply

Figure 7-29*a* shows voltage-divider bias with a *pnp* transistor and a negative supply voltage of −10 V. The 2N3906 is the complement of the 2N3904; that is, its characteristics have the same absolute values as those of the 2N3904, but all currents and voltage polarities are reversed. Compare this *pnp* circuit with the *npn* circuit in Fig. 7-26. The only differences are the supply voltages and the transistors.

The point is this: Whenever you have a circuit with *npn* transistors, you can often use the same circuit with a negative power supply and *pnp* transistors.

Because the negative supply voltage produces negative circuit values, care needs to be taken when doing circuit calculations. The steps in determining the Q point of Fig. 7-29*a* would be as follows:

$$V_B = \frac{R_2}{R_1 + R_2} V_{CC} = \frac{2.2\ \text{k}\Omega}{10\ \text{k}\Omega + 2.2\ \text{k}\Omega}(-10\ \text{V}) = -1.8\ \text{V}$$

With a *pnp* transistor, the base-emitter junction will be forward biased when V_E is 0.7 V above V_B. Therefore,

$$V_E = V_B + 0.7\ \text{V}$$

$$V_E = -1.8\ \text{V} + 0.7\ \text{V}$$

$$V_E = -1.1\ \text{V}$$

Next, determine the emitter and collector currents:

$$I_E = \frac{V_E}{R_E} = \frac{-1.1\ \text{V}}{1\ \text{k}\Omega} = 1.1\ \text{mA}$$

$$I_C \approx I_E = 1.1\ \text{mA}$$

Now, solve for the collector and collector-emitter voltage values:

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

$$V_C = -10\ \text{V} + (1.1\ \text{mA})(3.6\ \text{k}\Omega)$$

$$V_C = -6.04\ \text{V}$$

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

$$V_{CE} = -6.04\ \text{V} - (-1.1\ \text{V}) = -4.94\ \text{V}$$

Positive Power Supply

Positive power supplies are used more often in transistor circuits than are negative power supplies. Because of this, you often see *pnp* transistors drawn upside down, as shown in Fig. 7-29*b*. Here is how the circuit works: The voltage across R_2 is applied to the emitter diode in series with the emitter resistor. This sets up the emitter current. The collector current flows through R_C, producing a collector-to-ground voltage. For troubleshooting, you can calculate V_C, V_B, and V_E as follows:

1. Get the voltage across R_2.
2. Subtract 0.7 V to get the voltage across the emitter resistor.
3. Get the emitter current.
4. Calculate the collector-to-ground voltage.
5. Calculate the base-to-ground voltage.
6. Calculate the emitter-to-ground voltage.

Example 7-11

Multisim

Calculate the three transistor voltages for the *pnp* circuit in Fig. 7-29*b*.

SOLUTION Start with the voltage across R_2. We can calculate this voltage using the voltage-divider equation:

$$V_2 = \frac{R_2}{R_1 + R_2} V_{EE}$$

Alternatively, we can calculate the voltage in a different way: Get the current through the voltage divider and then multiply by R_2. The calculation looks like this:

$$I = \frac{10 \text{ V}}{12.2 \text{ k}\Omega} = 0.82 \text{ mA}$$

and

$$V_2 = (0.82 \text{ mA})(2.2 \text{ k}\Omega) = 1.8 \text{ V}$$

Next, subtract 0.7 V from the foregoing voltage to get the voltage across the emitter resistor:

$$1.8 \text{ V} - 0.7 \text{ V} = 1.1 \text{ V}$$

Then, calculate the emitter current:

$$I_E = \frac{1.1 \text{ V}}{1 \text{ k}\Omega} = 1.1 \text{ mA}$$

When the collector current flows through the collector resistor, it produces a collector-to-ground voltage of:

$$V_C = (1.1 \text{ mA})(3.6 \text{ k}\Omega) = 3.96 \text{ V}$$

The voltage between the base and ground is:

$$V_B = 10 \text{ V} - 1.8 \text{ V} = 8.2 \text{ V}$$

The voltage between the emitter and ground is:

$$V_E = 10 \text{ V} - 1.1 \text{ V} = 8.9 \text{ V}$$

PRACTICE PROBLEM 7-11 For both circuits, Fig. 7-29*a* and 7-29*b*, change the power supply voltage from 10 V to 12 V and calculate V_B, V_E, V_C, and V_{CE}.