chapter 6

BJT Fundamentals

In 1951, William Schockley invented the first **junction transistor,** a semiconductor device that can amplify (enlarge) electronic signals such as radio and television signals. The transistor has led to many other semiconductor inventions, including the **integrated circuit (IC),** a small device that contains thousands of miniaturized transistors. Because of the IC, modern computers and other electronic miracles are possible.

This chapter introduces the fundamental operation of a **bipolar junction transistor (BJT),** the kind that uses both free electrons and holes. The word *bipolar* is an abbreviation for "two polarities." This chapter will also explore how this BJT can be properly biased to act as a switch.

Chapter Outline

Objectives

After studying this chapter, you should be able to:

- Describe the relationships among the base, emitter, and collector currents of a bipolar junction transistor.
- Draw a diagram of the CE circuit and label each terminal, voltage, and resistance.
- Draw a hypothetical base curve and a set of collector curves, labeling both axes.
- Label the three regions of operation on a bipolar junction transistor collector curve.
- Calculate the respective CE transistor current and voltage values using the ideal transistor and the second transistor approximation.
- List several bipolar junction transistor ratings that might be used by a technician.
- State why base bias does not work well in amplifying circuits.
- Identify the saturation point and the cutoff point for a given base-biased circuit.
- Calculate the Q point for a given base-biased circuit.

Vocabulary

active region
amplifying circuit
base
base bias
bipolar junction transistor
breakdown region
collector
collector diode
common emitter
current gain
cutoff point
cutoff region
dc alpha
dc beta
emitter
emitter diode
h parameters
heat sink
integrated circuit
junction transistor
load line
power transistors
quiescent point
saturation point
saturation region
small-signal transistors
soft saturation
surface-mount transistors
switching circuit
thermal resistance
two-state circuit

6-1 The Unbiased Transistor

A transistor has three doped regions, as shown in Fig. 6-1. The bottom region is called the **emitter,** the middle region is the **base,** and the top region is the **collector.** In an actual transistor, the base region is much thinner as compared to the collector and emitter regions. The transistor of Fig. 6-1 is an *npn device* because there is a *p* region between two *n* regions. Recall that the majority carriers are free electrons in *n*-type material and holes in *p*-type material.

Transistors are also manufactured as *pnp* devices. A *pnp* transistor has an *n* region between two *p* regions. To avoid confusion between the *npn* and the *pnp* transistors, our early discussions will focus on the *npn* transistor.

GOOD TO KNOW

During the afternoon of December 23, 1947, Walter H. Brattain and John Bardeen demonstrated the amplifying action of the *first* transistor at the Bell Telephone Laboratories. The first transistor was called a *point-contact transistor*, which was the predecessor to the junction transistor invented by Schockley.

Doping Levels

In Fig. 6-1, the emitter is heavily doped. On the other hand, the base is lightly doped. The doping level of the collector is intermediate, between the heavy doping of the emitter and the light doping of the base. The collector is physically the largest of the three regions.

Emitter and Collector Diodes

The transistor of Fig. 6-1 has two junctions: one between the emitter and the base, and another between the collector and the base. Because of this, a transistor is like two back-to-back diodes. The lower diode is called the *emitter-base diode,* or simply the **emitter diode.** The upper diode is called the *collector-base diode,* or the **collector diode.**

GOOD TO KNOW

The transistor in Fig. 6-1 is sometimes referred to as a *bipolar junction transistor*, or *BJT*. However, most people in the electronics industry still use the word *transistor*, with the understanding that a bipolar junction transistor is meant.

Before and After Diffusion

Figure 6-1 shows the transistor regions before diffusion has occurred. Because of their repulsion for each other, the free electrons in the *n* regions will spread in all directions. Some of the free electrons in the *n* region will diffuse across the junction and recombine with the holes in the *p* region. Visualize the free electrons in each *n* region crossing the junction and recombining with holes.

The result is two depletion layers, as shown in Fig. 6-2*a*. For each of these depletion layers, the barrier potential is approximately 0.7 V at 25°C for a silicon

Figure 6-1 Structure of a transistor.

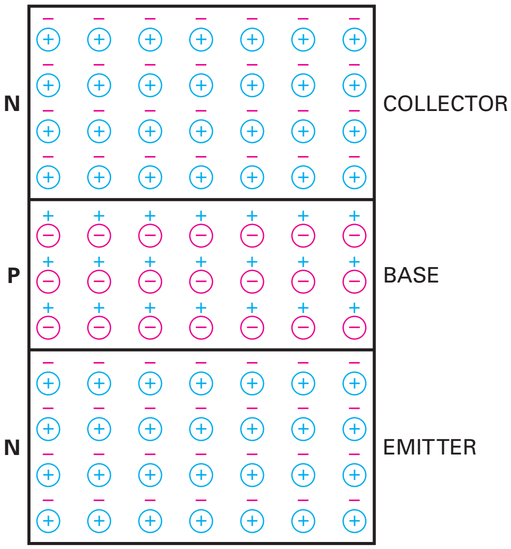
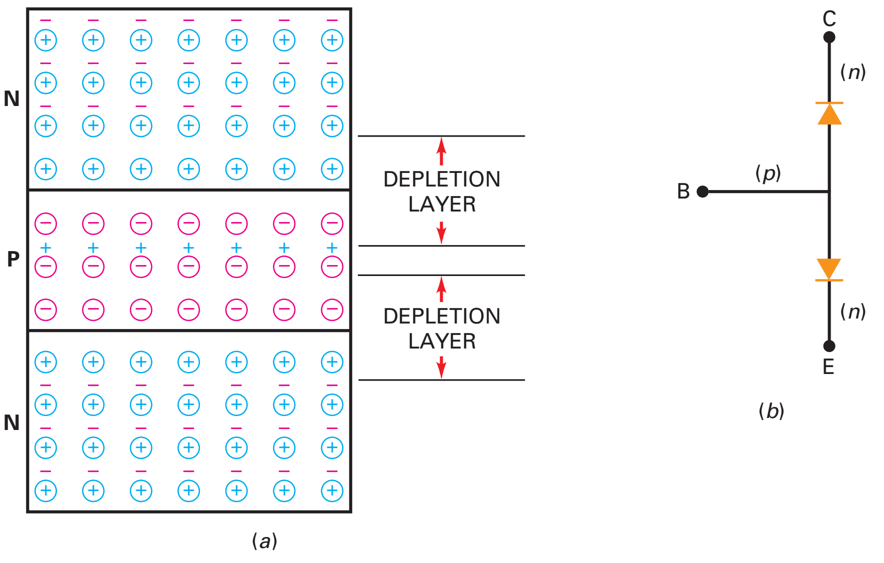


Figure 6-2 Unbiased transistor. (*a*) Depletion layers; (*b*) diode equivalent.



transistor (0.3 V at 25°C for a germanium transistor). As before, we emphasize silicon devices because they are now more widely used than germanium devices.

6-2 The Biased Transistor

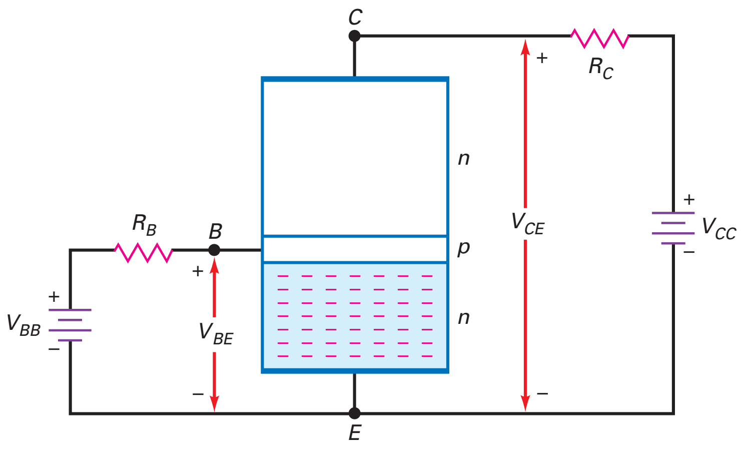
An unbiased transistor is like two back-to-back diodes, as shown in Fig. 6-2*b*. Each diode has a barrier potential of approximately 0.7 V. Keep this diode equivalent in mind when testing an *npn* transistor with a DMM. When you connect external voltage sources to the transistor, you will get currents through the different parts of the transistor.

Emitter Electrons

Figure 6-3 shows a biased transistor. The minus signs represent free electrons. The heavily doped emitter has the following job: to emit or inject its free electrons into the base. The lightly doped base also has a well-defined purpose: to pass emitter-injected electrons on to the collector. The collector is so named because it collects or gathers most of the electrons from the base.

Figure 6-3 is the usual way to bias a transistor. The left source V_{BB} of Fig. 6-3 forward-biases the emitter diode, and the right source V_{CC} reverse-biases the collector

Figure 6-3 Biased transistor.



diode. Although other biasing methods are possible, forward-biasing the emitter diode and reverse-biasing the collector diode produce the most useful results.

GOOD TO KNOW

In a transistor, the emitter-base depletion layer is narrower than the collector-base depletion layer. The reason can be attributed to the different doping levels of the emitter and collector regions. With much heavier doping in the emitter region, the penetration into the *n* material is minimal because of the availability of many more free electrons. However, on the collector side, fewer free electrons are available and the depletion layer must penetrate more deeply in order to set up the barrier potential.

Base Electrons

At the instant that forward bias is applied to the emitter diode of Fig. 6-3, the electrons in the emitter have not yet entered the base region. If V_{BB} is greater than the emitter-base barrier potential in Fig. 6-3, emitter electrons will enter the base region, as shown in Fig. 6-4. Theoretically, these free electrons can flow in either of two directions. First, they can flow to the left and out of the base, passing through R_B on the way to the positive source terminal. Second, the free electrons can flow into the collector.

Which way will the free electrons go? Most will continue on to the collector. Why? Two reasons: The base is *lightly doped* and *very thin.* The light doping means that the free electrons have a long lifetime in the base region. The very thin base means that the free electrons have only a short distance to go to reach the collector. For these two reasons, almost all the emitter-injected electrons pass through the base to the collector.

Only a few free electrons will recombine with holes in the lightly doped base of Fig. 6-4. Then, as valence electrons, they will flow through the base resistor to the positive side of the V_{BB} supply.

Collector Electrons

Almost all the free electrons go into the collector, as shown in Fig. 6-5. Once they are in the collector, they feel the attraction of the V_{CC} source voltage. Because of

Figure 6-4 Emitter injects free electrons into base.

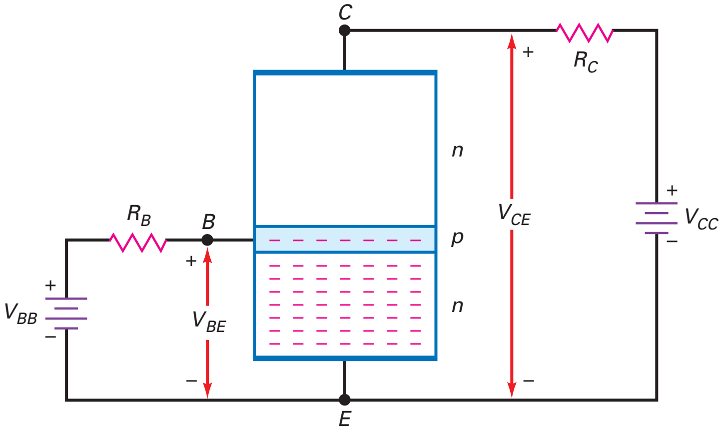


Figure 6-5 Free electrons from base flow into collector.

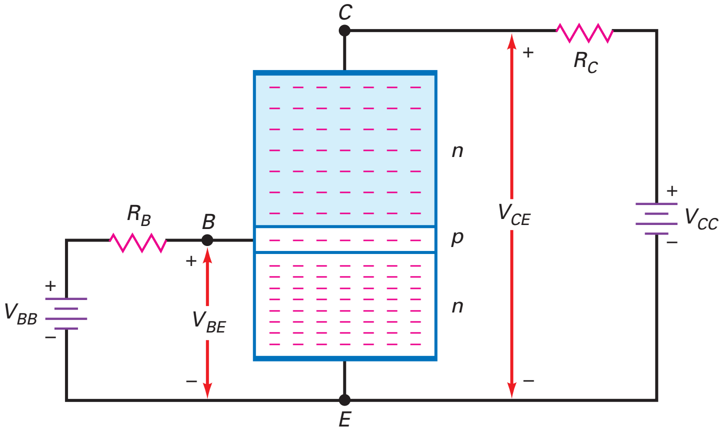
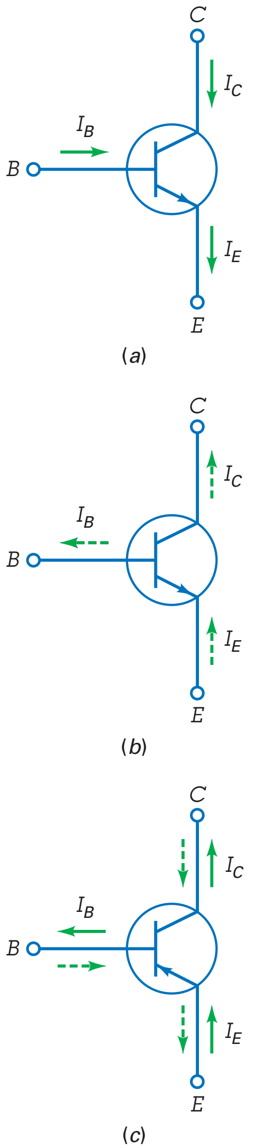


Figure 6-6 Three transistor currents. (*a*) Conventional flow; (*b*) electron flow; (*c*) *pnp* currents.



this, the free electrons flow through the collector and through R_C until they reach the positive terminal of the collector supply voltage.

Here's a summary of what's going on: In Fig. 6-5, V_{BB} forward-biases the emitter diode, forcing the free electrons in the emitter to enter the base. The thin and lightly doped base gives almost all these electrons enough time to diffuse into the collector. These electrons flow through the collector, through R_C, and into the positive terminal of the V_{CC} voltage source.

6-3 Transistor Currents

Figures 6-6*a* and 6-6*b* show the schematic symbol for an *npn* transistor. If you prefer conventional flow, use Fig. 6-6*a*. If you prefer electron flow, use Fig. 6-6*b*. In Fig. 6-6, there are three different currents in a transistor: emitter current I_E, base current I_B, and collector current I_C.

How the Currents Compare

Because the emitter is the source of the electrons, it has the largest current. Since most of the emitter electrons flow to the collector, the collector current is almost as large as the emitter current. The base current is very small by comparison, *often less than 1 percent of the collector current.*

Relation of Currents

Recall Kirchhoff's current law. It says that the sum of all currents into a point or junction equals the sum of all currents out of the point or junction. When applied to a transistor, Kirchhoff's current law gives us this important relationship:

$$\boldsymbol{I_E = I_C + I_B} \qquad \textbf{(6-1)}$$

This says that the emitter current is the sum of the collector current and the base current. Since the base current is so small, the collector current approximately equals the emitter current:

$$I_C \approx I_E$$

and the base current is much smaller than the collector current:

$$I_B << I_C$$

(*Note:* << means *much smaller than*.)

Figure 6-6*c* shows the schematic symbol for a *pnp* transistor and its currents. Notice that the current directions are opposite that of the *npn*. Again notice that Eq. (6-1) holds true for the *pnp* transistor currents.

Alpha

The **dc alpha** (symbolized α_{dc}) is defined as the dc collector current divided by the dc emitter current:

$$\boldsymbol{\alpha_{dc} = \frac{I_C}{I_E}} \qquad \textbf{(6-2)}$$

Since the collector current almost equals the emitter current, the dc alpha is slightly less than 1. For instance, in a low-power transistor, the dc alpha is typically greater than 0.99. Even in a high-power transistor, the dc alpha is typically greater than 0.95.

Beta

The **dc beta** (symbolized β_{dc}) of a transistor is defined as the ratio of the dc collector current to the dc base current:

$$\beta_{dc} = \frac{I_C}{I_B} \tag{6-3}$$

The dc beta is also known as the **current gain** because a small base current controls a much larger collector current.

The current gain is a major advantage of a transistor and has led to all kinds of applications. For low-power transistors (under 1 W), the current gain is typically 100 to 300. High-power transistors (over 1 W) usually have current gains of 20 to 100.

Two Derivations

Equation (6-3) may be rearranged into two equivalent forms. First, when you know the value of β_{dc} and I_B, you can calculate the collector current with this derivation:

$$I_C = \beta_{dc} I_B \tag{6-4}$$

Second, when you have the value of β_{dc} and I_C, you can calculate the base current with this derivation:

$$I_B = \frac{I_C}{\beta_{dc}} \tag{6-5}$$

Example 6-1

A transistor has a collector current of 10 mA and a base current of 40 μA. What is the current gain of the transistor?

SOLUTION Divide the collector current by the base current to get:

$$\beta_{dc} = \frac{10 \text{ mA}}{40\ \mu\text{A}} = 250$$

PRACTICE PROBLEM 6-1 What is the current gain of the transistor in Example 6-1 if its base current is 50 μA?

Example 6-2

A transistor has a current gain of 175. If the base current is 0.1 mA, what is the collector current?

SOLUTION Multiply the current gain by the base current to get:

$$I_C = 175(0.1 \text{ mA}) = 17.5 \text{ mA}$$

PRACTICE PROBLEM 6-2 Find I_C in Example 6-2 if $\beta_{dc} = 100$.

Example 6-3

A transistor has a collector current of 2 mA. If the current gain is 135, what is the base current?

SOLUTION Divide the collector current by the current gain to get:

$$I_B = \frac{2 \text{ mA}}{135} = 14.8\ \mu\text{A}$$

PRACTICE PROBLEM 6-3 If $I_C = 10$ mA in Example 6-3, find the transistor's base current.

GOOD TO KNOW

The base loop is sometimes referred to as the input loop and the collector loop the output loop. In a CE connection, the input loop controls the output loop.

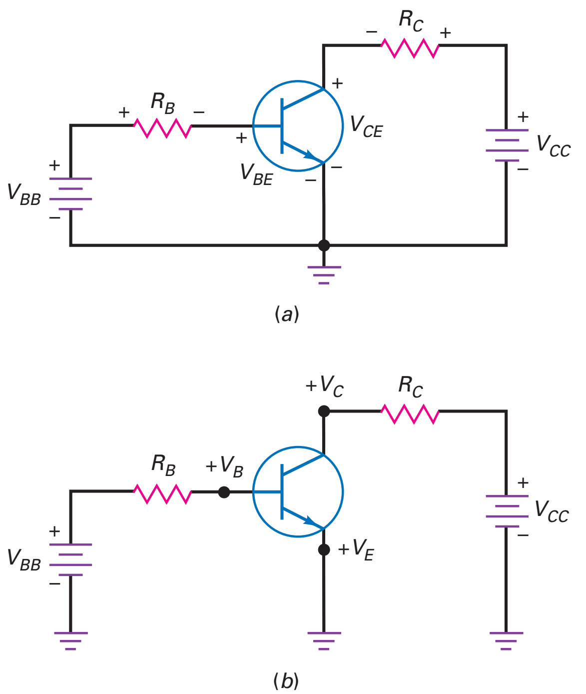
6-4 The CE Connection

There are three useful ways to connect a transistor: with a CE (common emitter), a CC (common collector), or a CB (common base). The CC and CB connections are discussed in later chapters. In this chapter, we will focus on the CE connection because it is the most widely used.

Common Emitter

In Fig. 6-7*a*, the common or ground side of each voltage source is connected to the emitter. Because of this, the circuit is called a **common emitter (CE)** connection. The circuit has two loops. The left loop is the base loop, and the right loop is the collector loop.

Figure 6-7 CE connection. (*a*) Basic circuit; (*b*) circuit with grounds.



GOOD TO KNOW

The "transistor" was first named by John Pierce while working at Bell Labs. This new device was to be a dual of the vacuum tube. The vacuum tube had "transconductance", while the new device had "transresistance" characteristics.

In the base loop, the V_{BB} source forward-biases the emitter diode with R_B as a current-limiting resistance. By changing V_{BB} or R_B, we can change the base current. Changing the base current will change the collector current. In other words, *the base current controls the collector current.* This is important. It means that a small current (base) controls a large current (collector).

In the collector loop, a source voltage V_{CC} reverse-biases the collector diode through R_C. The supply voltage V_{CC} must reverse-bias the collector diode as shown, or else the transistor won't work properly. Stated another way, the collector must be positive in Fig. 6-7*a* to collect most of the free electrons injected into the base.

In Fig. 6-7*a*, the flow of base current in the left loop produces a voltage across the base resistor R_B with the polarity shown. Similarly, the flow of collector current in the right loop produces a voltage across the collector resistor R_C with the polarity shown.

Double Subscripts

Double-subscript notation is used with transistor circuits. When the subscripts are the same, the voltage represents a source (V_{BB} and V_{CC}). When the subscripts are different, the voltage is between the two points (V_{BE} and V_{CE}).

For instance, the subscripts of V_{BB} are the same, which means that V_{BB} is the base voltage source. Similarly, V_{CC} is the collector voltage source. On the other hand, V_{BE} is the voltage between points B and E, between the base and the emitter. Likewise, V_{CE} is the voltage between points C and E, between the collector and the emitter. When measuring double-subscripted voltages, the main or positive meter probe is placed on the first subscript point and the common probe is connected to the second subscript point of the circuit.

Single Subscripts

Single subscripts are used for node voltages, that is, voltages between the subscripted point and ground. For instance, if we redraw Fig. 6-7*a* with grounds, we get Fig. 6-7*b*. Voltage V_B is the voltage between the base and ground, voltage V_C is the voltage between the collector and ground, and voltage V_E is the voltage between the emitter and ground. (In this circuit, V_E is zero.)

You can calculate a double-subscript voltage of different subscripts by subtracting its single-subscript voltages. Here are three examples:

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

$$V_{CB} = V_C - V_B$$

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

This is how you could calculate the double-subscript voltages for any transistor circuit: Since V_E is zero in this CE connection (Fig. 6-7*b*), the voltages simplify to:

$$V_{CE} = V_C$$

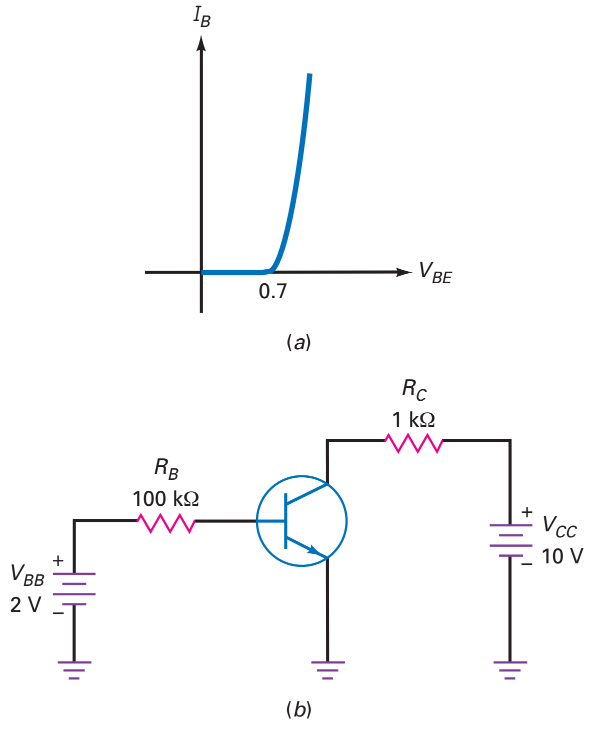
$$V_{CB} = V_C - V_B$$

$$V_{BE} = V_B$$

6-5 The Base Curve

What do you think the graph of I_B versus V_{BE} looks like? It looks like the graph of an ordinary diode as shown in Fig. 6-8*a*. And why not? This is a forward-biased emitter diode, so we would expect to see the usual diode graph of current versus voltage. What this means is that we can use any of the diode approximations discussed earlier.

Figure 6-8 (*a*) Diode curve; (*b*) example.



Applying Ohm's law to the base resistor of Fig. 6-8*b* gives this derivation:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \tag{6-6}$$

If you use an ideal diode, $V_{BE} = 0$. With the second approximation, $V_{BE} = 0.7$ V.

Most of the time, you will find the second approximation to be the best compromise between the speed of using the ideal diode and the accuracy of higher approximations. All you need to remember for the second approximation is that V_{BE} is 0.7 V, as shown in Fig. 6-8*a*.

Example 6-4

Multisim

Use the second approximation to calculate the base current in Fig. 6-8*b*. What is the voltage across the base resistor? The collector current if $\beta_{dc} = 200$?

SOLUTION The base source voltage of 2 V forward-biases the emitter diode through a current-limiting resistance of 100 kΩ. Since the emitter diode has 0.7 V across it, the voltage across the base resistor is:

$$V_{BB} - V_{BE} = 2\text{ V} - 0.7\text{ V} = 1.3\text{ V}$$

The current through the base resistor is:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{1.3\text{V}}{100\text{ k}\Omega} = 13\ \mu\text{A}$$

With a current gain of 200, the collector current is:

$$I_C = \beta_{dc} I_B = (200)(13\ \mu A) = 2.6\text{ mA}$$

PRACTICE PROBLEM 6-4 Repeat Example 6-4 using a base source voltage $V_{BB} = 4$ V.

6-6 Collector Curves

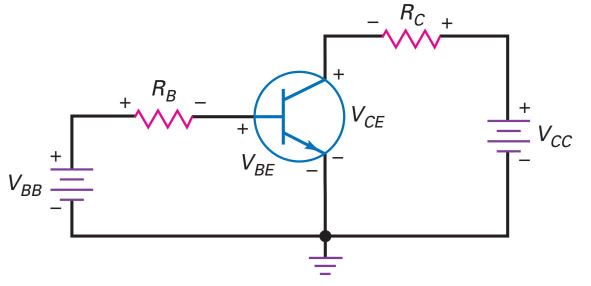
In Fig. 6-9*a*, we already know how to calculate the base current. Since V_{BB} forward-biases the emitter diode, all we need to do is calculate the current through the base resistor R_B. Now, let us turn our attention to the collector loop.

We can vary V_{BB} and V_{CC} in Fig. 6-9*a* to produce different transistor voltages and currents. By measuring I_C and V_{CE}, we can get data for a graph of I_C versus V_{CE}.

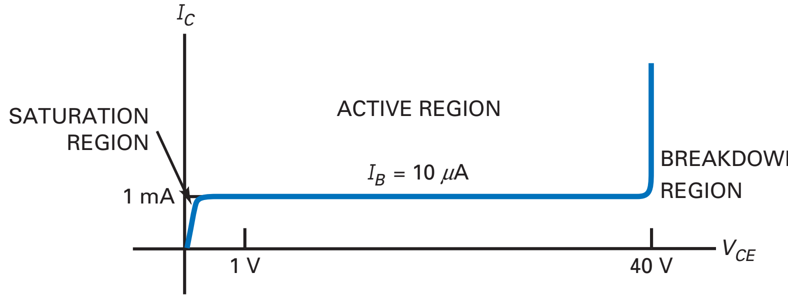
For instance, suppose we change V_{BB} as needed to get $I_B = 10\ \mu A$. With this fixed value of base current, we can now vary V_{CC} and measure I_C and V_{CE}. Plotting the data gives the graph shown in Fig. 6-9*b*. (*Note:* This graph is for a 2N3904, a widely used low-power transistor. With other transistors, the numbers may vary but the shape of the curve will be similar.)

When V_{CE} is zero, the collector diode is not reverse biased. This is why the graph shows a collector current of zero when V_{CE} is zero. When V_{CE} increases from zero, the collector current rises sharply in Fig. 6-9*b*. When V_{CE} is a few tenths of a volt, the collector current becomes *almost constant* and equal to 1 mA.

Figure 6-9 (*a*) Basic transistor circuit; (*b*) collector curve.



(*a*)



(*b*)

The constant-current region in Fig. 6-9*b* is related to our earlier discussions of transistor action. After the collector diode becomes reverse biased, it is gathering all the electrons that reach its depletion layer. Further increases in V_{CE} cannot increase the collector current. Why? Because the collector can collect only those free electrons that the emitter injects into the base. The number of these injected electrons depends only on the base circuit, not on the collector circuit. This is why Fig. 6-9*b* shows a constant collector current between a V_{CE} of less than 1 V to a V_{CE} of more than 40 V.

If V_{CE} is greater than 40 V, the collector diode breaks down and normal transistor action is lost. The transistor is not intended to operate in the breakdown region. For this reason, one of the maximum ratings to look for on a transistor data sheet is the collector-emitter breakdown voltage $V_{CE(\max)}$. If the transistor breaks down, it will be destroyed.

Collector Voltage and Power

Kirchhoff's voltage law says that the sum of voltages around a loop or closed path is equal to zero. When applied to the collector circuit of Fig. 6-9*a*, Kirchhoff's voltage law gives us this derivation:

$$V_{CE} = V_{CC} - I_C R_C \tag{6-7}$$

This says that the collector-emitter voltage equals the collector supply voltage minus the voltage across the collector resistor.

In Fig. 6-9*a*, the transistor has a power dissipation of approximately:

$$P_D = V_{CE} I_C \tag{6-8}$$

This says that the transistor power equals the collector-emitter voltage times the collector current. This power dissipation causes the junction temperature of the collector diode to increase. The higher the power, the higher the junction temperature.

Transistors will burn out when the junction temperature is between 150 and 200°C. One of the most important pieces of information on a data sheet is the maximum power rating $P_{D(\max)}$. The power dissipation given by Eq. (6-8) must be less than $P_{D(\max)}$. Otherwise, the transistor will be destroyed.

Regions of Operation

The curve of Fig. 6-9*b* has different regions where the action of a transistor changes. First, there is the region in the middle where V_{CE} is between 1 and 40 V. This represents the normal operation of a transistor. In this region, the emitter diode is forward biased, and the collector diode is reverse biased. Furthermore, the collector is gathering almost all the electrons that the emitter has sent into the base. This is why changes in collector voltage have no effect on the collector current. This region is called the **active region.** Graphically, the active region is the horizontal part of the curve. In other words, the collector current is *constant* in this region.

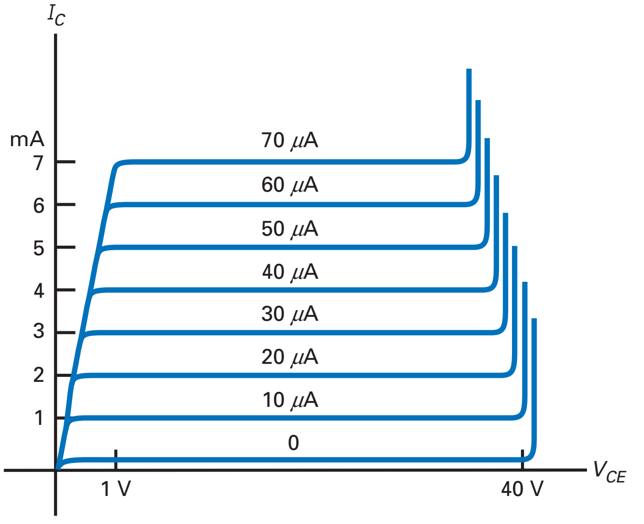
Another region of operation is the **breakdown region.** The transistor should never operate in this region because it will be destroyed. Unlike the zener diode, which is optimized for breakdown operation, a transistor is not intended for operation in the breakdown region.

Third, there is the early rising part of the curve, where V_{CE} is between 0 V and a few tenths of a volt. This sloping part of the curve is called the **saturation region.** In this region, the collector diode has insufficient positive voltage to collect all the free electrons injected into the base. In this region, the base current I_B is larger than normal and the current gain β_{dc} is smaller than normal.

GOOD TO KNOW

When displayed on a curve tracer, the collector curves in Fig. 6-10 actually have a slight upward slope as V_{CE} increases. This rise is the result of the base region becoming slightly smaller as V_{CE} increases. (As V_{CE} increases, the CB depletion layer widens, thus narrowing the base.) With a smaller base region, there are fewer holes available for recombination. Since each curve represents a constant base current, the effect looks like an increase in collector current.

Figure 6-10 Set of collector curves.



More Curves

If we measure I_C and V_{CE} for $I_B = 20\ \mu$A, we can plot the second curve of Fig. 6-10. The curve is similar to the first curve, except that the collector current is 2 mA in the active region. Again, the collector current is constant in the active region.

When we plot several curves for different base currents, we get a set of collector curves like those in Fig. 6-10. Another way to get this set of curves is with a *curve tracer* (a test instrument that can display I_C versus V_{CE} for a transistor). In the active region of Fig. 6-10, each collector current is 100 times greater than the corresponding base current. For instance, the top curve has a collector current of 7 mA and a base current of 70 μA. This gives a current gain of:

$$\beta_{\text{dc}} = \frac{I_C}{I_B} = \frac{7\text{ mA}}{70\ \mu\text{A}} = 100$$

If you check any other curve, you get the same result: a current gain of 100.

With other transistors, the current gain may be different from 100, but the shape of the curves will be similar. All transistors have an active region, a saturation region, and a breakdown region. The active region is the most important because amplification (enlargement) of signals is possible in the active region.

Cutoff Region

Figure 6-10 has an unexpected curve, the one on the bottom. This represents a fourth possible region of operation. Notice that the base current is zero, but there still is a small collector current. On a curve tracer, this current is usually so small that you cannot see it. We have exaggerated the bottom curve by drawing it larger than usual. This bottom curve is called the **cutoff region** of the transistor, and the small collector current is called the *collector cutoff current.*

Why does the collector cutoff current exist? Because the collector diode has reverse minority-carrier current and surface-leakage current. In a well-designed circuit, the collector cutoff current is small enough to ignore. For instance, a 2N3904 has a collector cutoff current of 50 nA. If the actual collector current is 1 mA, ignoring a collector cutoff current of 50 nA produces a calculation error of less than 5 percent.

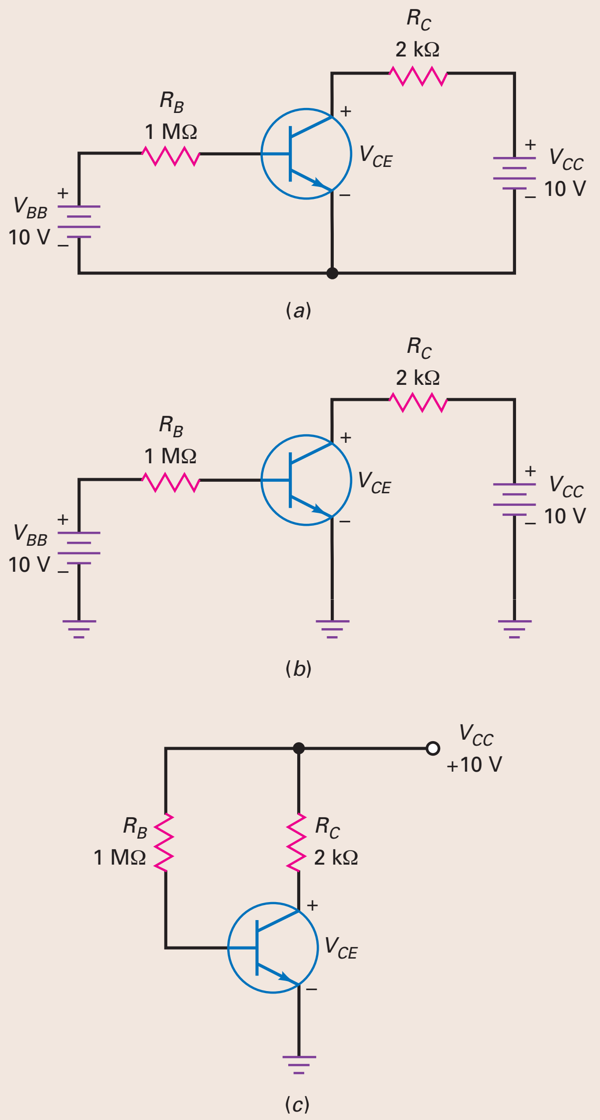
Recap

A transistor has four distinct operating regions: *active, cutoff, saturation,* and *breakdown.* Transistors operate in the active region when they are used to amplify weak signals. Sometimes, the active region is called the *linear region* because changes in the input signal produce proportional changes in the output signal. The saturation and cutoff regions are useful in digital and computer circuits, referred to as **switching circuits.**

Example 6-5

The transistor of Fig. 6-11*a* has $\beta_{dc} = 300$. Calculate I_B, I_C, V_{CE}, and P_D.

Figure 6-11 Transistor circuit. (*a*) Basic schematic diagram; (*b*) circuit with grounds; (*c*) simplified schematic diagram.



SOLUTION Figure 6-11*b* shows the same circuit with grounds. The base currente quals:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{10\text{ V} - 0.7\text{ V}}{1\text{ M}\Omega} = 9.3\ \mu\text{A}$$

The collector current is:

$$I_C = \beta_{dc} I_B = (300)(9.3\ \mu\text{A}) = 2.79\text{ mA}$$

and the collector-emitter voltage is:

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (2.79\text{ mA})(2\text{ k}\Omega) = 4.42\text{ V}$$

The collector power dissipation is:

$$P_D = V_{CE} I_C = (4.42\text{ V})(2.79\text{ mA}) = 12.3\text{ mW}$$

Incidentally, when both the base and the collector supply voltages are equal, as in Fig. 6-11*b*, you usually see the circuit drawn in the simpler form of Fig. 6-11*c*.

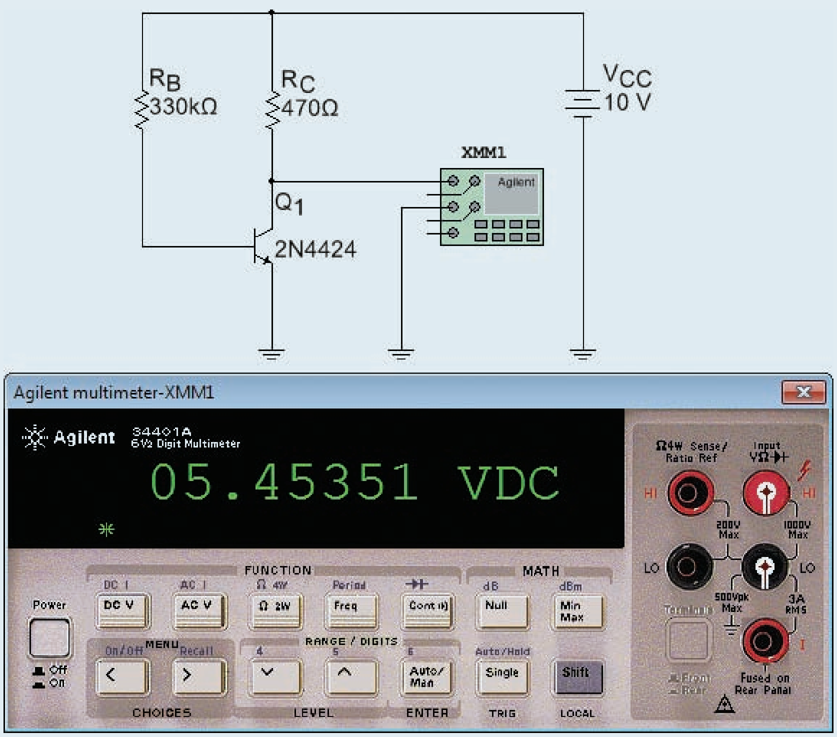
PRACTICE PROBLEM 6-5 Change R_B to 680 kΩ and repeat Example 6-5.

Application Example 6-6

Multisim

Figure 6-12 shows a transistor circuit built on a computer screen with Multisim. Calculate the current gain of the 2N4424.

Figure 6-12 Multisim circuit for calculating current gain of 2N4424.



SOLUTION First, get the base current as follows:

$$I_B = \frac{10\text{ V} - 0.7\text{ V}}{330\text{ k}\Omega} = 28.2\ \mu\text{A}$$

Next, we need the collector current. Since the multimeter indicates a collector-emitter voltage of 5.45 V (rounded to three places), the voltage across the collector resistor is:

$$V = 10\text{ V} - 5.45\text{ V} = 4.55\text{ V}$$

Since the collector current flows through the collector resistor, we can use Ohm's law to get the collector current:

$$I_C = \frac{4.55\text{ V}}{470\ \Omega} = 9.68\text{ mA}$$

Now, we can calculate the current gain:

$$\beta_{\text{dc}} = \frac{9.68\text{ mA}}{28.2\ \mu\text{A}} = 343$$

The 2N4424 is an example of a transistor with a high current gain. The typical range of β_{dc} for small-signal transistors is 100 to 300.

PRACTICE PROBLEM 6-6 Using Multisim, change the base resistor of Fig. 6-12 to 560 kΩ and calculate the current gain of the 2N4424.

6-7 Transistor Approximations

Figure 6-13*a* shows a transistor. A voltage V_{BE} appears across the emitter diode, and a voltage V_{CE} appears across the collector-emitter terminals. What is the equivalent circuit for this transistor?

Ideal Approximation

Figure 6-13*b* shows the ideal approximation of a transistor. We visualize the emitter diode as an ideal diode. In this case, $V_{BE} = 0$. This allows us to calculate base current quickly and easily. This equivalent circuit is often useful for troubleshooting when all we need is a rough approximation of base current.

As shown in Fig. 6-13*b*, the collector side of the transistor acts like a current source that pumps a collector current of $\beta_{\text{dc}}I_B$ through the collector resistor. Therefore, after you calculate the base current, you can multiply by the current gain to get the collector current.

GOOD TO KNOW

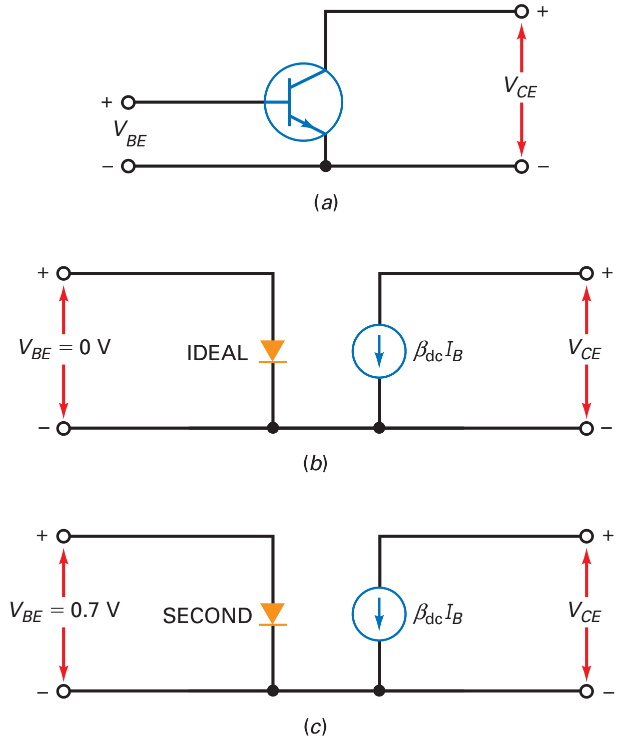
A bipolar transistor is frequently used as a constant current source.

The Second Approximation

Figure 6-13*c* shows the second approximation of a transistor. This is more commonly used because it may improve the analysis significantly when the base-supply voltage is small.

This time, we use the second approximation of a diode when calculating base current. For silicon transistors, this means that $V_{BE} = 0.7$ V. (For germanium transistors, $V_{BE} = 0.3$ V.) With the second approximation, the base and collector currents will be slightly less than their ideal values.

Figure 6-13 Transistor approximations. (*a*) Original device; (*b*) ideal approximation; (*c*) second approximation.



Higher Approximations

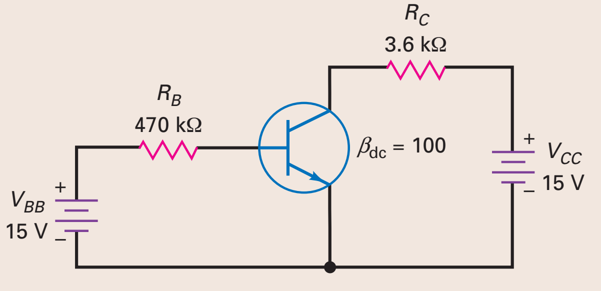
The bulk resistance of the emitter diode becomes important only in high-power applications in which the currents are large. The effect of bulk resistance in the emitter diode is to increase V_{BE} to more than 0.7 V. For instance, in some high-power circuits, the V_{BE} across the base-emitter diode may be more than 1 V.

Likewise, the bulk resistance of the collector diode may have a noticeable effect in some designs. Besides emitter and collector bulk resistances, a transistor has many other higher-order effects that make hand calculations tedious and time-consuming. For this reason, calculations beyond the second approximation should use a computer solution.

Example 6-7

What is the collector-emitter voltage in Fig. 6-14? Use the ideal transistor.

Figure 6-14 Example.



SOLUTION An ideal emitter diode means that:

$$V_{BE} = 0$$

Therefore, the total voltage across R_B is 15 V. Ohm's law tells us that:

$$I_B = \frac{15\text{ V}}{470\text{ k}\Omega} = 31.9\ \mu\text{A}$$

The collector current equals the current gain times the base current:

$$I_C = 100(31.9\ \mu\text{A}) = 3.19\text{ mA}$$

Next, we calculate the collector-emitter voltage. It equals the collector supply voltage minus the voltage drop across the collector resistor:

$$V_{CE} = 15\text{ V} - (3.19\text{ mA})(3.6\text{ k}\Omega) = 3.52\text{ V}$$

In a circuit like Fig. 6-14, knowing the value of the emitter current is not important, so most people would not calculate this quantity. But since this is an example, we will calculate the emitter current. It equals the sum of the collector current and the base current:

$$I_E = 3.19\text{ mA} + 31.9\ \mu\text{A} = 3.22\text{ mA}$$

This value is extremely close to the value of the collector current, which is another reason for not bothering to calculate it. Most people would say that the emitter current is approximately 3.19 mA, the value of the collector current.

Example 6-8

Multisim

What is the collector-emitter voltage in Fig. 6-14 if you use the second approximation?

SOLUTION In Fig. 6-14, here is how you would calculate the currents and voltages, using the second approximation. The voltage across the emitter diode is:

$$V_{BE} = 0.7\text{ V}$$

Therefore, the total voltage across R_B is 14.3 V, the difference between 15 and 0.7 V. The base current is:

$$I_B = \frac{14.3\text{ V}}{470\text{ k}\Omega} = 30.4\ \mu\text{A}$$

The collector current equals the current gain times the base current:

$$I_C = 100(30.4\ \mu\text{A}) = 3.04\text{ mA}$$

The collector-emitter voltage equals:

$$V_{CE} = 15\text{ V} - (3.04\text{ mA})(3.6\text{ k}\Omega) = 4.06\text{ V}$$

The improvement in this answer over the ideal answer is about half a volt: 4.06 versus 3.52 V. Is this half a volt important? It depends on whether you are troubleshooting, designing, and so on.

Example 6-9

Suppose you measure a V_{BE} of 1 V. What is the collector-emitter voltage in Fig. 6-14?

SOLUTION The total voltage across R_B is 14 V, the difference between 15 and 1 V. Ohm's law tells us that the base current is:

$$I_B = \frac{14\text{ V}}{470\text{ k}\Omega} = 29.8\ \mu\text{A}$$

The collector current equals the current gain times the base current:

$$I_C = 100(29.8\ \mu\text{A}) = 2.98\text{ mA}$$

The collector-emitter voltage equals:

$$V_{CE} = 15\text{ V} - (2.98\text{ mA})(3.6\text{ k}\Omega) = 4.27\text{ V}$$

Example 6-10

What is the collector-emitter voltage in the three preceding examples if the base supply voltage is 5 V?

SOLUTION With the ideal diode:

$$I_B = \frac{5\text{ V}}{470\text{ k}\Omega} = 10.6\ \mu\text{A}$$

$$I_C = 100(10.6\ \mu\text{A}) = 1.06\text{ mA}$$

$$V_{CE} = 15\text{ V} - (1.06\text{ mA})(3.6\text{ k}\Omega) = 11.2\text{ V}$$

With the second approximation:

$$I_B = \frac{4.3\text{ V}}{470\text{ k}\Omega} = 9.15\ \mu\text{A}$$

$$I_C = 100(9.15\ \mu\text{A}) = 0.915\text{ mA}$$

$$V_{CE} = 15\text{ V} - (0.915\text{ mA})(3.6\text{ k}\Omega) = 11.7\text{ V}$$

With the measured V_{BE}:

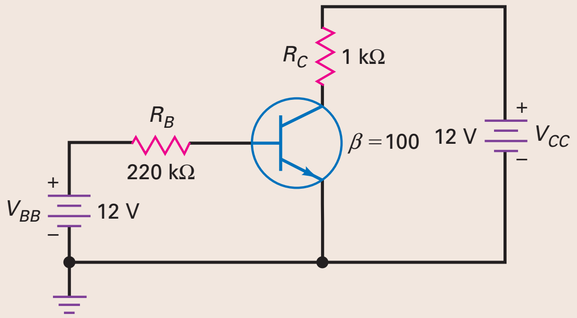
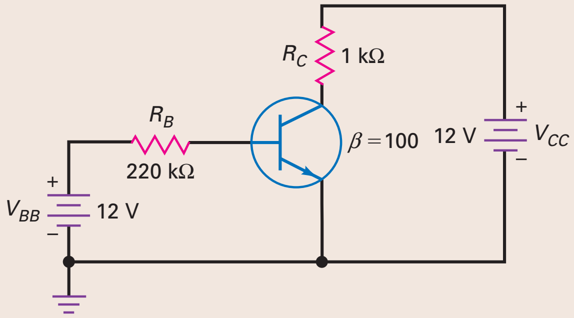
$$I_B = \frac{4\text{ V}}{470\text{ k}\Omega} = 8.51\ \mu\text{A}$$

$$I_C = 100(8.51\ \mu\text{A}) = 0.851\text{ mA}$$

$$V_{CE} = 15\text{ V} - (0.851\text{ mA})(3.6\text{ k}\Omega) = 11.9\text{ V}$$

This example allows you to compare the three approximations for the case of low base supply voltage. As you can see, all answers are within a volt of each other. This is the first clue as to which approximation to use. If you are troubleshooting this circuit, the ideal analysis will probably be adequate. But if you are designing the circuit, you might want to use a computer solution because of its accuracy. Summary Table 6-1 illustrates the difference between the ideal and second transistor approximations.

PRACTICE PROBLEM 6-10 Repeat Example 6-10 using a base supply voltage of 7 V.

Summary Table 6–1	Transistor Circuit Approximations	
	Ideal	**Second**
Circuit		
When used	Troubleshooting or rough estimates	When more accurate calculations are needed. Especially when V_{BB} is small.
$V_{BE} =$	0 V	0.7 V
$I_B =$	$\frac{V_{BB}}{R_B} = \frac{12\text{ V}}{220\text{ k}\Omega} = 54.5\ \mu\text{A}$	$\frac{V_{BB} - 0.7\text{ V}}{R_B} = \frac{12\text{ V} - 0.7\text{ V}}{220\text{ k}\Omega} = 51.4\ \mu\text{A}$
$I_C =$	$(I_B)(\beta_{dc}) = (54.5\ \mu\text{A})(100) = 5.45$ mA	$(I_B)(\beta_{dc}) = (51.4\ \mu\text{A})(100) = 5.14$ mA
$V_{CE} =$	$V_{CC} - I_C R_C$ $= 12\text{ V} - (5.45\text{ mA})(1\text{ k}\Omega) = 6.55$ V	$V_{CC} - I_C R_C$ $= 12\text{ V} - (5.14\text{ mA})(1\text{ k}\Omega) = 6.86$ V

6-8 Reading Data Sheets

Small-signal transistors can dissipate less than a watt; **power transistors** can dissipate more than a watt. When you look at a data sheet for either type of transistor, you should start with the maximum ratings because these are the limits on the transistor currents, voltages, and other quantities.

Breakdown Ratings

In the data sheet shown in Fig. 6-15, the following maximum ratings of a 2N3904 are given:

V_{CEO}	40 V
V_{CBO}	60 V
V_{EBO}	6 V

These voltage ratings are reverse breakdown voltages, and V_{CEO} is the voltage between the collector and the emitter with the base open. The second rating is V_{CBO}, which stands for the voltage from collector to base with the emitter open. Likewise, V_{EBO} is the maximum reverse voltage from emitter to base with the collector open. As usual, a conservative design never allows voltages to get even close to the foregoing maximum ratings. If you recall, even getting close to maximum ratings can shorten the lifetime of some devices.

Figure 6-15(*a*) 2N3904 data sheet. (© Fairchild Semiconductor. Used by permission.)

FAIRCHILD
SEMICONDUCTOR®

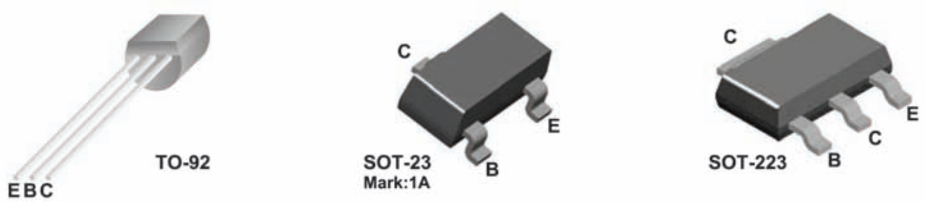
October 2011

2N3904 / MMBT3904 / PZT3904
NPN General Purpose Amplifier

Features

- This device is designed as a general purpose amplifier and switch.
- The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

2N3904 **MMBT3904** **PZT3904**



Absolute Maximum Ratings* T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:

1) These ratings are based on a maximum junction temperature of 150 degrees C.

2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Thermal Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Max.			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

* Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06".

** Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

2N3904 / MMBT3904 / PZT3904 Rev. B0
www.fairchildsemi.com

Figure 6-15(*b*) (continued)

Electrical Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1.0mA, I_B = 0	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10∝A, I_E = 0	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10∝A, I_C = 0	6.0		V
I_{BL}	Base Cutoff Current	V_{CE} = 30V, V_{EB} = 3V		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30V, V_{EB} = 3V		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 1.0V I_C = 1.0mA, V_{CE} = 1.0V I_C = 10mA, V_{CE} = 1.0V I_C = 50mA, V_{CE} = 1.0V I_C = 100mA, V_{CE} = 1.0V	40 70 100 60 30	 300	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10mA, I_B = 1.0mA I_C = 50mA, I_B = 5.0mA	0.65	0.85 0.95	V V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 10mA, V_{CE} = 20V, f = 100MHz	300		MHz
C_{obo}	Output Capacitance	V_{CB} = 5.0V, I_E = 0, f = 1.0MHz		4.0	pF
C_{ibo}	Input Capacitance	V_{EB} = 0.5V, I_C = 0, f = 1.0MHz		8.0	pF
NF	Noise Figure	I_C = 100∝A, V_{CE} = 5.0V, R_S = 1.0kΩ, f = 10Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	V_{CC} = 3.0V, V_{BE} = 0.5V I_C = 10mA, I_{B1} = 1.0mA		35	ns
t_r	Rise Time			35	ns
t_s	Storage Time	V_{CC} = 3.0V, I_C = 10mA, I_{B1} = I_{B2} = 1.0mA		200	ns
t_f	Fall Time			50	ns

* Pulse Test: Pulse Width ≤ 300∝s, Duty Cycle ≤ 2.0%

Ordering Information

Part Number	Marking	Package	Packing Method	Pack Qty
2N3904BU	2N3904	TO-92	BULK	10000
2N3904TA	2N3904	TO-92	AMMO	2000
2N3904TAR	2N3904	TO-92	AMMO	2000
2N3904TF	2N3904	TO-92	TAPE REEL	2000
2N3904TFR	2N3904	TO-92	TAPE REEL	2000
MMBT3904	1A	SOT-23	TAPE REEL	3000
MMBT3904_D87Z	1A	SOT-23	TAPE REEL	10000
PZT3904	3904	SOT-223	TAPE REEL	2500

Maximum Current and Power

Also shown in the data sheet are these values:

I_C 200 mA
P_D 625 mW

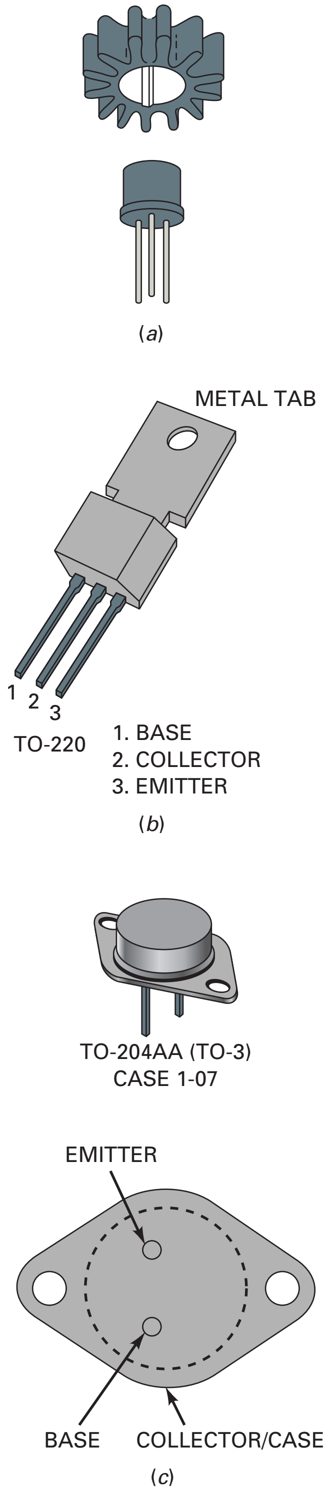
Here, I_C is the maximum dc collector current rating. This means that a 2N3904 can handle up to 200 mA of direct current, provided the power rating is not exceeded. The next rating, P_D, is the maximum power rating of the device. This power rating depends on whether any attempt is being made to keep the transistor cool. If the transistor is not being fan-cooled and does not have a heat sink (discussed next), its case temperature T_C will be much higher than the ambient temperature T_A.

In most applications, a small-signal transistor like the 2N3904 is not fan-cooled and it does not have a heat sink. In this case, the 2N3904 has a power rating of 625 mW when the ambient temperature T_A is 25°C.

The case temperature T_C is the temperature of the transistor package or housing. In most applications, the case temperature will be higher than 25°C because the internal heat of the transistor increases the case temperature.

The only way to keep the case temperature at 25°C when the ambient temperature is 25°C is by fan-cooling or by using a large heat sink. If fan cooling or a large heat sink is used, it is possible to reduce the temperature of the transistor case to 25°C. For this condition, the power rating can be increased to 1.5 W.

Figure 6-16 (*a*) Push-on heat sink; (*b*) power-tab transistor; (*c*) power transistor with collector connected to case.



Derating Factors

What is the importance of a derating factor? The derating factor tells you how much you have to reduce the power rating of a device. The derating factor of the 2N3904 is given as 5 mW/°C. This means that you have to reduce the power rating of 625 mW by 5 mW for each degree above 25°C.

Heat Sinks

One way to increase the power rating of a transistor is to get rid of the internal heat faster. This is the purpose of a **heat sink** (a mass of metal). If we increase the surface area of the transistor case, we allow the heat to escape more easily into the surrounding air. For instance, Fig. 6-16*a* shows one type of heat sink. When this is pushed onto the transistor case, heat radiates more quickly because of the increased surface area of the fins.

Figure 6-16*b* shows another approach. This is the outline of a power-tab transistor. A metal tab provides a path out of the transistor for heat. This metal tab can be fastened to the chassis of electronic equipment. Because the chassis is a massive heat sink, heat can easily escape from the transistor to the chassis.

Large power transistors like Fig. 6-16*c* have the collector connected to the case to let heat escape as easily as possible. The transistor case is then fastened to the chassis. To prevent the collector from shorting to chassis ground, a thin insulating washer and heat-conducting compound is used between the transistor case and the chassis. The important idea here is that heat can leave the transistor more rapidly, which means that the transistor has a higher power rating at the same ambient temperature. Sometimes, the transistor is fastened to a large heat sink with fins; this is even more efficient in removing heat from the transistor. In Fig. 6-16*c*, the case outline displays the base and emitter leads, as viewed from the bottom of the transistor (leads pointing at you). Notice that the base and emitter leads are offset from the center of the case.

No matter what kind of heat sink is used, the purpose is to lower the case temperature because this will lower the internal or junction temperature of the transistor. The data sheet includes other quantities called **thermal resistances.** These allow a designer to work out the case temperature for different heat sinks.

Current Gain

In another system of analysis called **h parameters,** h_{FE} rather than β_{dc} is defined as the symbol for current gain. The two quantities are equal:

$$\beta_{dc} = h_{FE} \tag{6-9}$$

Remember this relation because data sheets use the symbol h_{FE} for the current gain.

In the section labeled "On Characteristics," the data sheet of a 2N3904 lists the values of h_{FE} as follows:

I_C, mA	Min. h_{FE}	Max. h_{FE}
0.1	40	—
1	70	—
10	100	300
50	60	—
100	30	—

The 2N3904 works best when the collector current is in the vicinity of 10 mA. At this level of current, the minimum current gain is 100 and the maximum current gain is 300. What does this mean? It means that if you mass-produce a circuit using 2N3904s and a collector current of 10 mA, some of the transistors will have a current gain as low as 100, and some will have a current gain as high as 300. Most of the transistors will have a current gain in the middle of this range.

Notice how the minimum current gain decreases for collector currents that are less than or greater than 10 mA. At 0.1 mA, the minimum current gain is 40. At 100 mA, the minimum current gain is 30. The data sheet shows only the minimum current gain for currents different from 10 mA because the minimum values represent the worst case. Designers usually do worst-case design; that is, they figure out how the circuit will work when the transistor characteristics such as current gain are at their worst case.

Example 6-11

A 2N3904 has $V_{CE} = 10$ V and $I_C = 20$ mA. What is the power dissipation? How safe is this level of power dissipation if the ambient temperature is 25°C?

SOLUTION Multiply V_{CE} by I_C to get:

$$P_D = (10 \text{ V})(20 \text{ mA}) = 200 \text{ mW}$$

Is this safe? If the ambient temperature is 25°C, the transistor has a power rating of 625 mW. This means that the transistor is well within its power rating.

As you know, a good design includes a safety factor to ensure a longer operating life for the transistor. Safety factors of 2 or more are common. A safety factor of 2 means that the designer would allow up to half of 625 mW, or 312 mW. Therefore, a power of only 200 mW is very conservative, provided the ambient temperature stays at 25°C.

Example 6-12

How safe is the level of power dissipation if the ambient temperature is 100°C in Example 6-11?

SOLUTION First, work out the number of degrees that the new ambient temperature is above the reference temperature of 25°C. Do this as follows:

$$100°C - 25°C = 75°C$$

Sometimes, you will see this written as:

$$\Delta T = 75°C$$

where Δ stands for "difference in." Read the equation as the difference in temperature equals 75°C.

Now, multiply the derating factor by the difference in temperature to get:

$$(5\ \text{mW/°C})(75°C) = 375\ \text{mW}$$

You often see this written as:

$$\Delta P = 375\ \text{mW}$$

where ΔP stands for the difference in power. Finally, you subtract the difference in power from the power rating at 25°C:

$$P_{D(\max)} = 625\ \text{mW} - 375\ \text{mW} = 250\ \text{mW}$$

This is the power rating of the transistor when the ambient temperature is 100°C.

How safe is this design? The transistor is still all right because its power is 200 mW compared with the maximum rating of 250 mW. But we no longer have a safety factor of 2. If the ambient temperature were to increase further, or if the power dissipation were to increase, the transistor could get dangerously close to the burnout point. Because of this, a designer might redesign the circuit to restore the safety factor of 2. This means changing circuit values to get a power dissipation of half of 250 mW, or 125 mW.

PRACTICE PROBLEM 6-12 Using a safety factor of 2, could you safely use the 2N3904 transistor of Example 6-12 if the ambient temperature were 75°C?

6-9 Surface-Mount Transistors

Surface-mount transistors are usually found in a simple three-terminal, gull-wing package. The SOT-23 package is the smaller of the two and is used for transistors rated in the milliwatt range. The SOT-223 is the larger package and is used when the power rating is about 1 W.

Figure 6-17 shows a typical SOT-23 package. Viewed from the top, the terminals are numbered in a counterclockwise direction, with terminal 3 the lone terminal on one side. The terminal assignments are fairly well standardized for bipolar transistors: 1 is the base, 2 is the emitter, and 3 is the collector.

Figure 6-17 The SOT-23 package is suitable for SM transistors with power ratings less than 1 W.

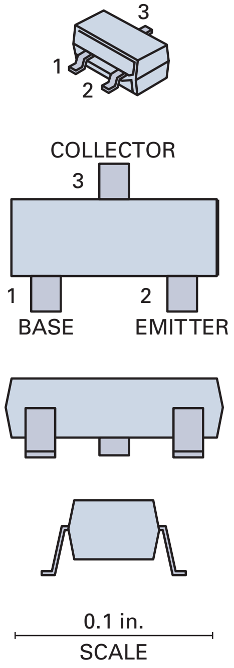
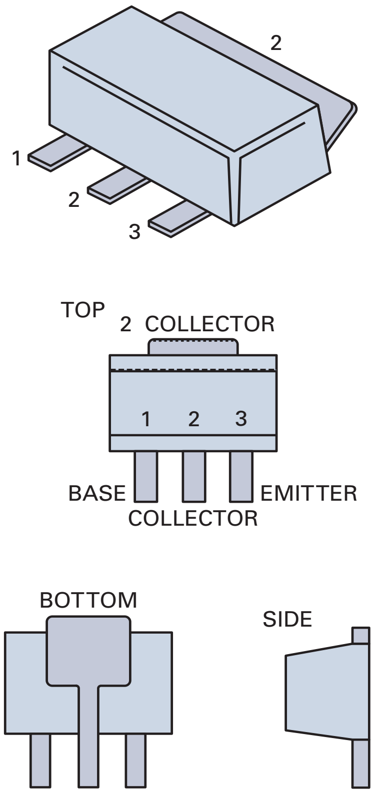


Figure 6-18 The SOT-223 package is designed to dissipate the heat generated by transistors operating in the 1-W range.



The SOT-223 package is designed to dissipate the heat generated by transistors operating in the 1-W range. This package has a larger surface area than the SOT-23; this increases its ability to dissipate heat. Some of the heat is dissipated from the top surface, and much is carried away by the contact between the device and the circuit board below. The special feature of the SOT-223 case, however, is the extra collector tab that extends from the side opposite the main terminals. The bottom view in Fig. 6-18 shows that the two collector terminals are electrically identical.

The standard terminal assignments are different for the SOT-23 and SOT-223 packages. The three terminals located on one edge are numbered in sequence, from left to right as viewed from the top. Terminal 1 is the base, 2 is the collector (electrically identical to the large tab at the opposite edge), and 3 is the emitter. Looking back at Fig. 6-15, note that the 2N3904 comes in two surface-mount packages. The MMBT3904 is an SOT-23 package with a maximum power dissipation of 350 mW, while the PZT3904 is an SOT-223 package with a power dissipation rating of 1000 mW.

The SOT-23 packages are too small to have any standard part identification codes printed on them. Usually, the only way to determine the standard identifier is by noting the part number printed on the circuit board and then consulting the parts list for the circuit. SOT-223 packages are large enough to have identification codes printed on them, but these codes are rarely standard transistor identification codes. The typical procedure for learning more about a transistor in an SOT-223 package is the same as for the smaller SOT-23 configurations.

Occasionally, a circuit uses SOIC packages that house multiple transistors. The SOIC package resembles the tiny dual-inline package commonly used for ICs and the older feed-through circuit board technology. The terminals on the SOIC, however, have the gull-wing shape required for SM technology.

GOOD TO KNOW

The symbol h_{FE} represents the forward current transfer ratio in the common-emitter configuration. The symbol h_{FE} is a hybrid (h)-parameter symbol. The h-parameter system is the most common system in use today for specifying transistor parameters.

6-10 Variations in Current Gain

The current gain β_{dc} of a transistor depends on three factors: the transistor, the collector current, and the temperature. For instance, when you replace a transistor with another of the same type, the current gain usually changes. Likewise, if the collector current or temperature changes, the current gain will change.

Worst and Best Case

As a concrete example, the data sheet of a 2N3904 lists a minimum h_{FE} of 100 and a maximum of 300 when the temperature is 25°C and the collector current is 10 mA. If we build thousands of circuits with 2N3904s, some of the transistors will have a current gain as low as 100 (worst case), and others will have a current gain as high as 300 (best case).

Figure 6-19 shows the graphs of a 2N3904 for the worst case (minimum h_{FE}). Look at the middle curve, the current gain for an ambient temperature of 25°C. When the collector current is 10 mA, the current gain is 100, the worst case for a 2N3904. (In the best case, a few 2N3904s have a current gain of 300 at 10 mA and 25°C.)

Effect of Current and Temperature

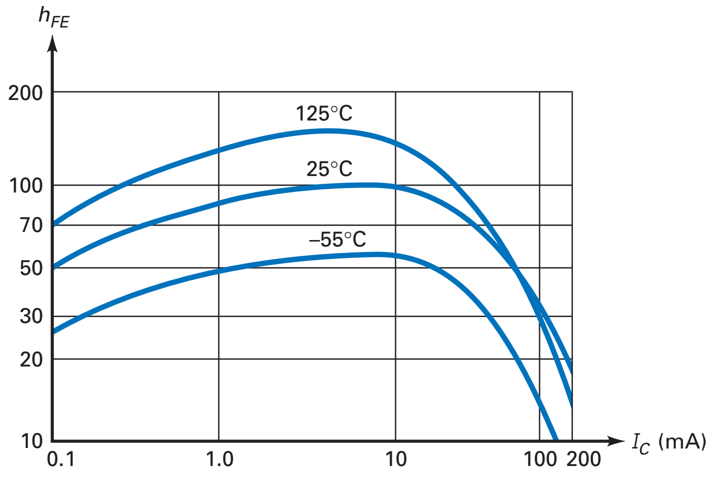
When the temperature is 25°C (the middle curve), the current gain is 50 at 0.1 mA. As the current increases from 0.1 mA to 10 mA, h_{FE} increases to a maximum of 100. Then, it decreases to less than 20 at 200 mA.

Also notice the effect of temperature. When the temperature decreases, the current gain is less (the bottom curve). On the other hand, when the temperature increases, h_{FE} increases over most of the current range (the top curve).

Main Idea

As you can see, transistor replacement, collector-current changes, or temperature changes can produce large changes in h_{FE} or β_{dc}. At a given temperature, a 3:1 change is possible when a transistor is replaced. When the temperature varies, an additional 3:1 variation is possible. And when the current varies, more than a 3:1 variation is possible. In summary, the 2N3904 may have a current gain of less than 10 to more than 300. Because of this, any design that depends on a precise value of current gain will fail in mass production.

Figure 6-19 Variation of current gain.



6-11 The Load Line

In order for a transistor to function as an amplifier or a switch, it must first have its dc circuit conditions set properly. This is referred to as properly biasing the transistor. Various biasing methods are possible, with each having advantages and disadvantages. In this chapter, we will begin with base bias.

Base Bias

The circuit of Fig. 6-20*a* is an example of **base bias,** which means setting up a *fixed value of base current.* For instance, if $R_B = 1\ \text{M}\Omega$, the base current is 14.3 μA (second approximation). Even with transistor replacements and temperature changes, the base current remains fixed at approximately 14.3 μA under all operating conditions.

If $\beta_{dc} = 100$ in Fig. 6-20*a*, the collector current is approximately 1.43 mA and the collector-emitter voltage is:

$$V_{CE} = V_{CC} - I_C R_C = 15\ \text{V} - (1.43\ \text{mA})(3\ \text{k}\Omega) = 10.7\ \text{V}$$

Therefore, the quiescent, or *Q*, point in Fig. 6-20*a* is:

$$I_C = 1.43\ \text{mA} \qquad \text{and} \qquad V_{CE} = 10.7\ \text{V}$$

Graphical Solution

We can also find the *Q* point using a graphical solution based on the transistor **load line,** a graph of I_C versus V_{CE}. In Fig. 6-20*a*, the collector-emitter voltage is given by:

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

Solving for I_C gives:

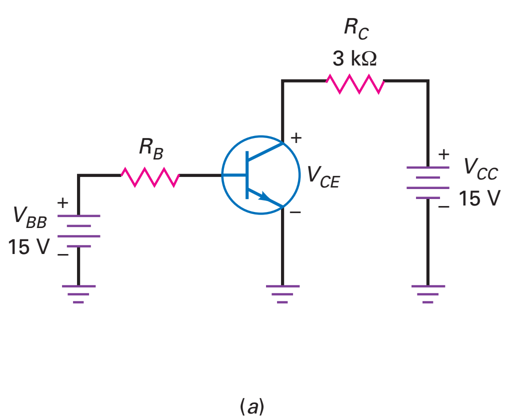
$$\boldsymbol{I_C = \frac{V_{CC} - V_{CE}}{R_C}} \qquad \textbf{(6-10)}$$

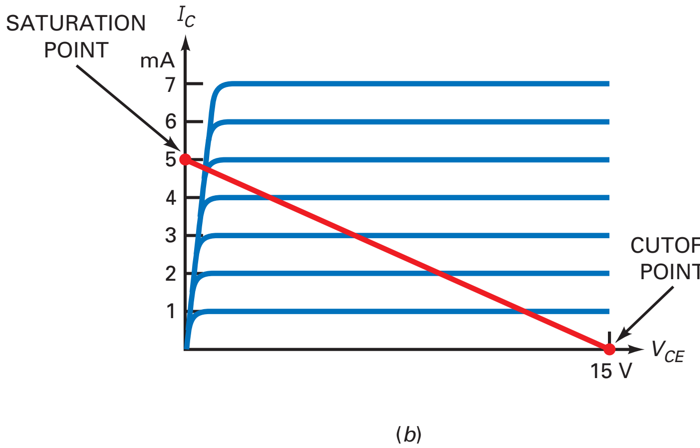
If we graph this equation (I_C versus V_{CE}), we will get a straight line. This line is called the *load line* because it represents the effect of the load on I_C and V_{CE}.

For instance, substituting the values of Fig. 6-20*a* into Eq. (6-10) gives:

$$I_C = \frac{15\ \text{V} - V_{CE}}{3\ \text{k}\Omega}$$

Figure 6-20 Base bias. (*a*) Circuit; (*b*) load line.





This equation is a linear equation; that is, its graph is a straight line. (*Note:* A *linear equation* is any equation that can be reduced to the standard form of $y = mx + b$.) If we graph the foregoing equation on top of the collector curves, we get Fig. 6-20*b*.

The ends of the load line are the easiest to find. When $V_{CE} = 0$ in the load-line equation (the foregoing equation):

$$I_C = \frac{15\text{ V}}{3\text{ k}\Omega} = 5\text{ mA}$$

The values, $I_C = 5$ mA and $V_{CE} = 0$, plot as the upper end of the load line in Fig. 6-20*b*.

When $I_C = 0$, the load-line equation gives:

$$0 = \frac{15\text{ V} - V_{CE}}{3\text{ k}\Omega}$$

or

$$V_{CE} = 15\text{ V}$$

The coordinates, $I_C = 0$ and $V_{CE} = 15$ V, plot as the lower end of the load line in Fig. 6-20*b*.

Visual Summary of All Operating Points

Why is the load line useful? Because it contains every possible operating point for the circuit. Stated another way, when the base resistance varies from zero to infinity, it causes I_B to vary, which makes I_C and V_{CE} vary over their entire ranges. If you plot the I_C and V_{CE} values for every possible I_B value, you will get the load line. Therefore, the load line is a visual summary of *all possible transistor operatingpoints* .

The Saturation Point

When the base resistance is too small, there is too much collector current, and the collector-emitter voltage drops to approximately zero. In this case, the transistor goes into *saturation*. This means that the collector current has increased to its maximum possible value.

The **saturation point** is the point in Fig. 6-20*b* where the load line intersects the saturation region of the collector curves. Because the collector-emitter voltage V_{CE} at saturation is very small, the saturation point is almost touching the upper end of the load line. From now on, we will approximate the saturation point as the upper end of the load line, bearing in mind that there is a slight error.

The saturation point tells you the maximum possible collector current for the circuit. For instance, the transistor of Fig. 6-21*a* goes into saturation when the collector current is approximately 5 mA. At this current, V_{CE} has decreased to approximatelyz ero.

There is an easy way to find the current at the saturation point. Visualize a short between the collector and emitter to get Fig. 6-21*b*. Then V_{CE} drops to zero. All the 15 V from the collector supply will be across the 3 kΩ. Therefore, the current is:

$$I_C = \frac{15\text{ V}}{3\text{ k}\Omega} = 5\text{ mA}$$

You can apply this "mental short" method to any base-biased circuit.

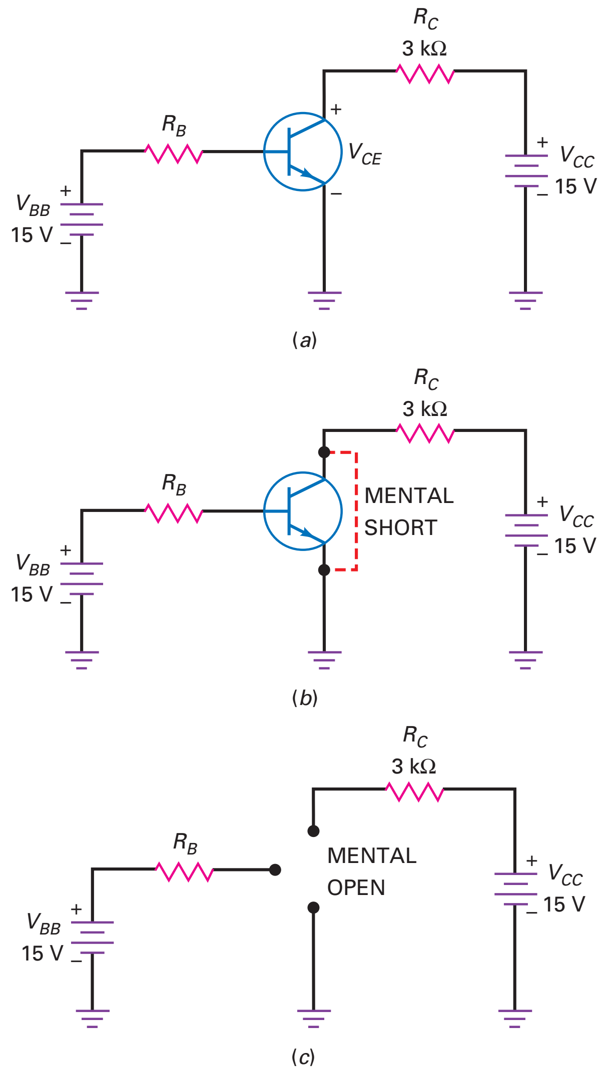
Here is the formula for the saturation current in base-biased circuits:

$$\boldsymbol{I_{C(\text{sat})} = \frac{V_{CC}}{R_C}} \qquad \textbf{(6-11)}$$

GOOD TO KNOW

When a transistor is saturated, further increases in base current produce no further increases in collector current.

Figure 6-21 Finding the ends of the load line. (*a*) Circuit; (*b*) calculating collector saturation current; (*c*) calculating collector-emitter cutoff voltage.



This says that the maximum value of the collector current equals the collector supply voltage divided by the collector resistance. It is nothing more than Ohm's law applied to the collector resistor. Figure 6-21*b* is a visual reminder of this equation.

GOOD TO KNOW

A transistor is cut off when its collector current is zero.

The Cutoff Point

The **cutoff point** is the point at which the load line intersects the cutoff region of the collector curves in Fig. 6-20*b*. Because the collector current at cutoff is very small, the cutoff point almost touches the lower end of the load line. From now on, we will approximate the cutoff point as the lower end of the load line.

The cutoff point tells you the maximum possible collector-emitter voltage for the circuit. In Fig. 6-21*a*, the maximum possible V_{CE} is approximately 15 V, the collector supply voltage.

There is a simple process for finding the cutoff voltage. Visualize the transistor of Fig. 6-21*a* as an open between the collector and the emitter (see Fig. 6-21*c*). Since there is no current through the collector resistor for this open condition, all the 15 V from the collector supply will appear between the collector-emitter terminals. Therefore, the voltage between the collector and the emitter will equal 15 V:

$$V_{CE(\text{cutoff})} = V_{CC} \tag{6-12}$$

Example 6-13

Multisim

What are the saturation current and the cutoff voltage in Fig. 6-22*a*?

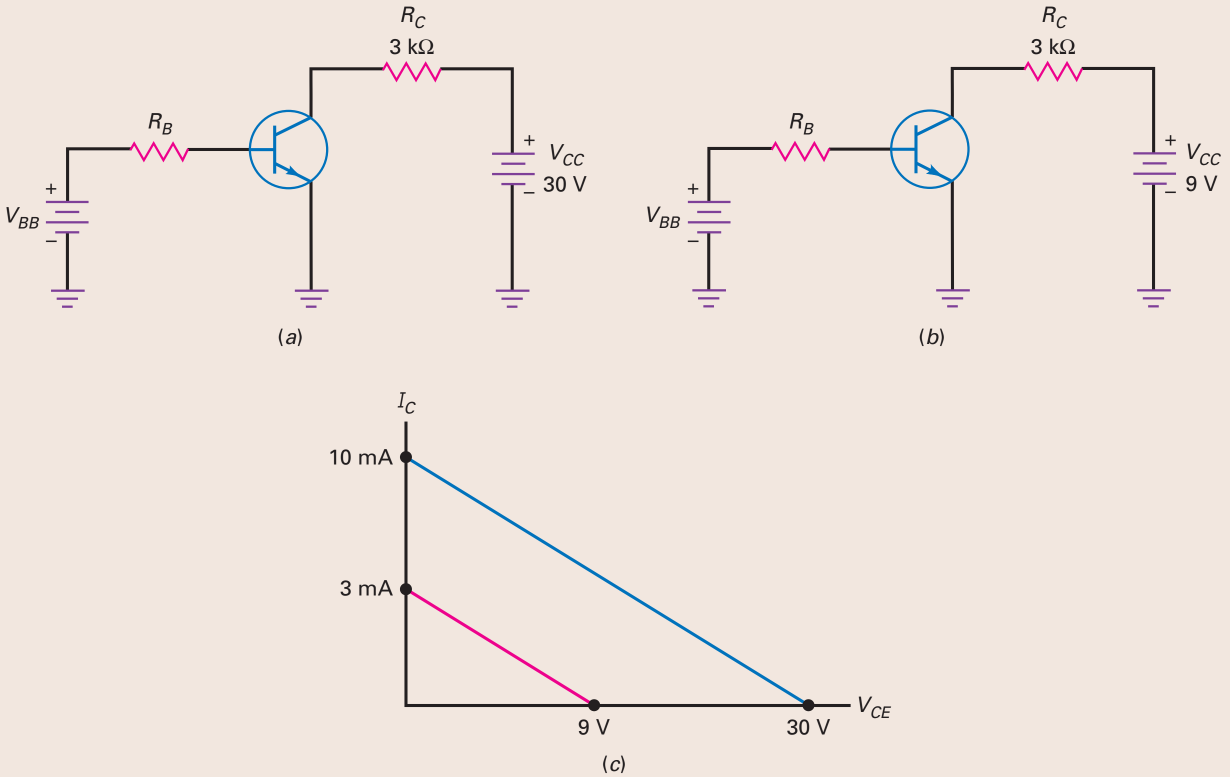
SOLUTION Visualize a short between the collector and emitter. Then:

$$I_{C(\text{sat})} = \frac{30 \text{ V}}{3 \text{ k}\Omega} = 10 \text{ mA}$$

Next, visualize the collector-emitter terminals open. In this case:

$$V_{CE(\text{cutoff})} = 30 \text{ V}$$

Figure 6-22 Load lines when collector resistance is the same. (*a*) With a collector supply of 30 V; (*b*) with a collector supply of 9 V; (*c*) load lines have same slope.



Example 6-14

Calculate the saturation and cutoff values for Fig. 6-22*b*. Draw the load lines for this and the preceding example.

SOLUTION With a mental short between the collector and emitter:

$$I_{C(\text{sat})} = \frac{9 \text{ V}}{3 \text{ k}\Omega} = 3 \text{ mA}$$

A mental open between the collector and emitter gives:

$$V_{CE(\text{cutoff})} = 9 \text{ V}$$

Figure 6-22*c* shows the two load lines. Changing the collector supply voltage while keeping the same collector resistance produces two load lines of the same slope but with different saturation and cutoff values.

PRACTICE PROBLEM 6-14 Find the saturation current and cutoff voltage of Fig. 6-22*b* if the collector resistor is 2 kΩ and V_{CC} is 12 V.

Example 6-15

Multisim

What are the saturation current and the cutoff voltage in Fig. 6-23*a*?

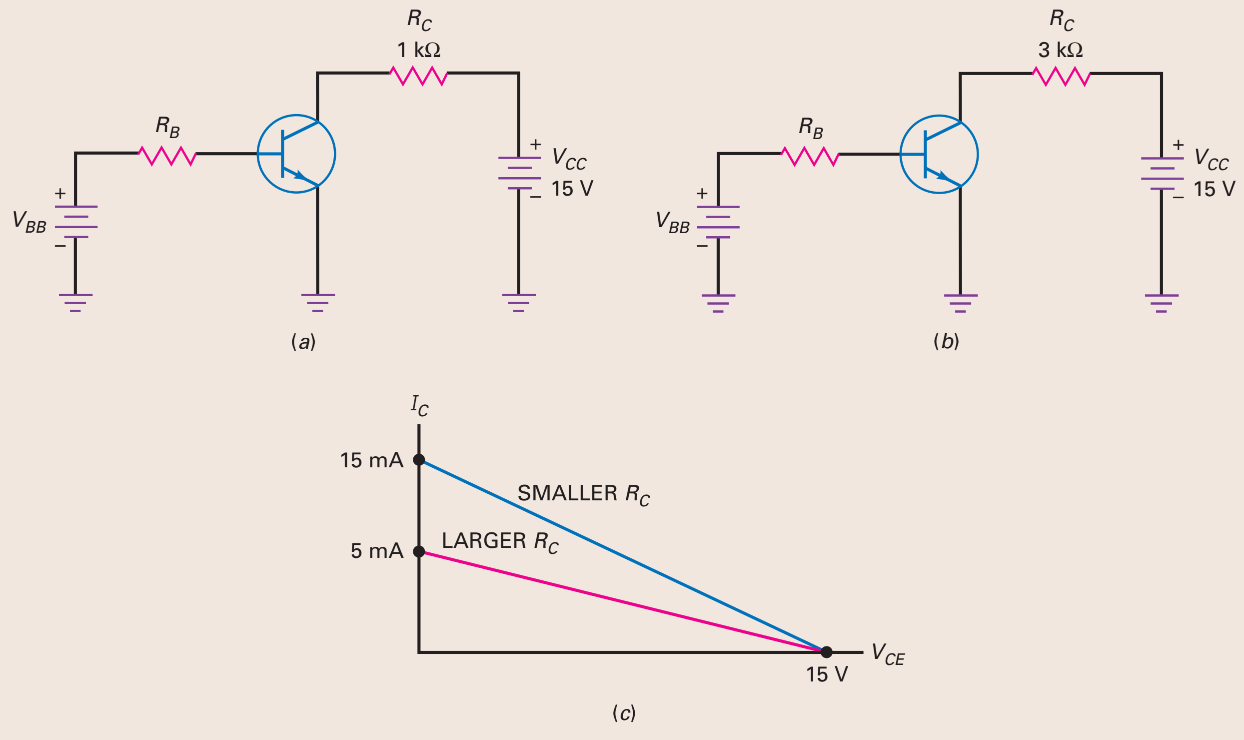
SOLUTION The saturation current is:

$$I_{C(\mathrm{sat})} = \frac{15\ \mathrm{V}}{1\ \mathrm{k\Omega}} = 15\ \mathrm{mA}$$

The cutoff voltage is:

$$V_{CE(\mathrm{cutoff})} = 15\ \mathrm{V}$$

Figure 6-23 Load lines when collector voltage is the same. (*a*) With a collector resistance of 1 kΩ; (*b*) with a collector resistance of 3 kΩ; (*c*) smaller R_C produces steeper slope.



Example 6-16

Calculate the saturation and cutoff values for Fig. 6-23*b*. Then, compare the load lines for this and the preceding example.

SOLUTION The calculations are as follows:

$$I_{C(\mathrm{sat})} = \frac{15\ \mathrm{V}}{3\ \mathrm{k\Omega}} = 5\ \mathrm{mA}$$

and

$$V_{CE(\text{cutoff})} = 15\text{ V}$$

Figure 6-23c shows the two load lines. Changing the collector resistor with the same collector supply voltage produces load lines of different slopes but the same cutoff values. Also, notice that a smaller collector resistance produces a larger slope (steeper or closer to vertical). This happens because the slope of the load line is equal to the reciprocal of the collector resistance:

$$\text{Slope} = \frac{1}{R_C}$$

PRACTICE PROBLEM 6-16 Using Fig. 6-23b, what happens to the circuit's load line if the collector resistor is changed to 5 kΩ?

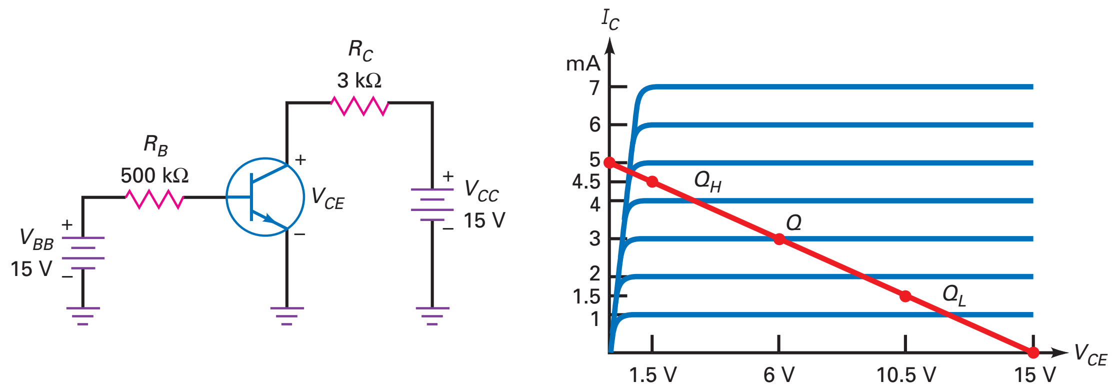
6-12 The Operating Point

Every transistor circuit has a load line. Given any circuit, work out the saturation current and the cutoff voltage. These values are plotted on the vertical and horizontal axes. Then draw a line through these two points to get the load line.

Plotting the Q Point

Figure 6-24a shows a base-biased circuit with a base resistance of 500 kΩ. We get the saturation current and cutoff voltage by the process given earlier. First, visualize a short across the collector-emitter terminals. Then all the collector supply voltage appears across the collector resistor, which means that the saturation current is 5 mA. Second, visualize the collector-emitter terminals open. Then there is no current, and all the supply voltage appears across the collector-emitter terminals, which means that the cutoff voltage is 15 V. If we plot the saturation current and cutoff voltage, we can draw the load line shown in Fig. 6-24b.

Figure 6-24 Calculating the *Q* point. (*a*) Circuit; (*b*) change in current gain changes *Q* point.



(*a*) (*b*)

Let us keep the discussion simple for now by assuming an ideal transistor. This means that all the base supply voltage will appear across the base resistor. Therefore, the base current is:

$$I_B = \frac{15\text{ V}}{500\text{ k}\Omega} = 30\ \mu\text{A}$$

We cannot proceed until we have a value for the current gain. Suppose the current gain of the transistor is 100. Then the collector current is:

$$I_C = 100(30\ \mu\text{A}) = 3\text{ mA}$$

This current flowing through 3 kΩ produces a voltage of 9 V across the collector resistor. When we subtract this from the collector supply voltage, we get the voltage across the transistor. Here are the calculations:

$$V_{CE} = 15\text{ V} - (3\text{ mA})(3\text{ k}\Omega) = 6\text{ V}$$

By plotting 3 mA and 6 V (the collector current and voltage), we get the operating point shown on the load line of Fig. 6-24*b*. The operating point is labeled Q because this point is often called the **quiescent point.** (*Quiescent* means quiet, still, or resting.)

Why the Q Point Varies

We assumed a current gain of 100. What happens if the current gain is 50? If it is 150? To begin, the base current remains the same because the current gain has no effect on the base current. Ideally, the base current is fixed at 30 μA. When the current gain is 50:

$$I_C = 50(30\ \mu\text{A}) = 1.5\text{ mA}$$

and the collector-emitter voltage is:

$$V_{CE} = 15\text{ V} - (1.5\text{ mA})(3\text{ k}\Omega) = 10.5\text{ V}$$

plotting the values gives the low point Q_L shown in Fig. 6-24*b*.

If the current gain is 150, then:

$$I_C = 150(30\ \mu\text{A}) = 4.5\text{ mA}$$

and the collector-emitter voltage is:

$$V_{CE} = 15\text{ V} - (4.5\text{ mA})(3\text{ k}\Omega) = 1.5\text{ V}$$

plotting these values gives the high point Q_H point shown in Fig. 6-24*b*.

The three Q points of Fig. 6-24*b* illustrate how sensitive the operating point of a base-biased transistor is to changes in β_{dc}. When the current gain varies from 50 to 150, the collector current changes from 1.5 to 4.5 mA. If the changes in current gain were much greater, the operating point could be driven easily into saturation or cutoff. In this case, an amplifying circuit would become useless because of the loss of current gain outside the active region.

GOOD TO KNOW

Because the values of I_C and V_{CE} are dependent on the values of beta in a base-biased circuit, the circuit is said to be *beta-dependent.*

The Formulas

The formulas for calculating the Q point are as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} \tag{6-13}$$

$$I_C = \beta_{dc} I_B \tag{6-14}$$

$$V_{CE} = V_{CC} - I_C R_C \tag{6-15}$$

Example 6-17

Multisim

Suppose the base resistance of Fig. 6-24*a* is increased to 1 MΩ. What happens to the collector-emitter voltage if β_{dc} is 100?

SOLUTION Ideally, the base current would decrease to 15 μA, the collector current would decrease to 1.5 mA, and the collector-emitter voltage would increaseto:

$$V_{CE} = 15 - (1.5 \text{ mA})(3 \text{ k}\Omega) = 10.5 \text{ V}$$

To a second approximation, the base current would decrease to 14.3 μA, and the collector current would decrease to 1.43 mA. The collector-emitter voltage would increase to:

$$V_{CE} = 15 - (1.43 \text{ mA})(3 \text{ k}\Omega) = 10.7 \text{ V}$$

PRACTICE PROBLEM 6-17 If the β_{dc} value of Example 6-17 changed to 150 due to a temperature change, find the new value of V_{CE}.

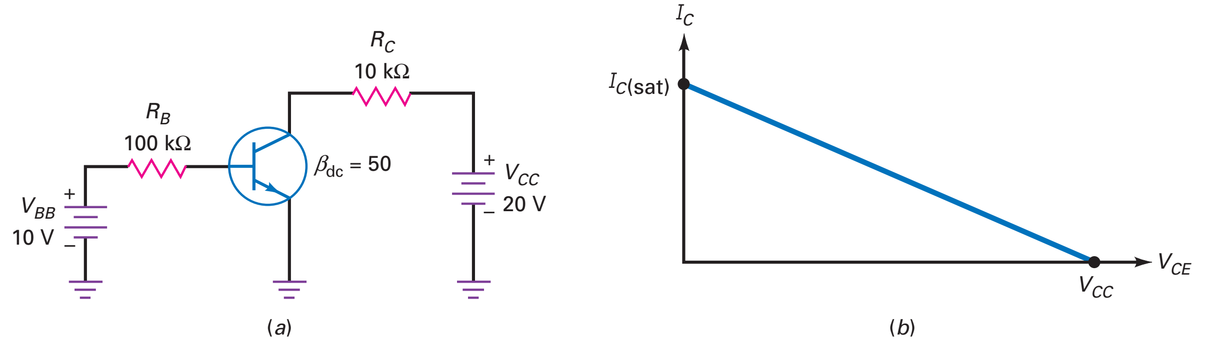
6-13 Recognizing Saturation

There are two basic kinds of transistor circuits: **amplifying** and **switching.** With amplifying circuits, the Q point must remain in the active region under all operating conditions. If it does not, the output signal will be distorted on the peak where saturation or cutoff occurs. With switching circuits, the Q point usually switches between saturation and cutoff. How switching circuits work, what they do, and why they are used will be discussed later.

Impossible Answers

Assume that the transistor of Fig. 6-25*a* has a breakdown voltage greater than 20 V. Then, we know that it is not operating in the breakdown region. Furthermore, we can tell at a glance that the transistor is not operating in the cutoff region because of the biasing voltages. What is not immediately clear, however, is whether the transistor is operating in the active region or the saturation region. It must be operating in one of these regions. But which?

Figure 6-25 (*a*) Base-biased circuit; (*b*) load line.



Troubleshooters and designers often use the following method to determine whether a transistor is operating in the active region or the saturation region. Here are the steps:

1. Assume that the transistor is operating in the active region.
2. Carry out the calculations for currents and voltages.
3. If an impossible result occurs in any calculation, the assumption is false.

An impossible answer means that the transistor is saturated. Otherwise, the transistor is operating in the active region.

Saturation-Current Method

For instance, Fig. 6-25*a* shows a base-biased circuit. Start by calculating the saturation current:

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

The base current is ideally 0.1 mA. Assuming a current gain of 50 as shown, the collector current is:

$$I_C = 50(0.1\text{ mA}) = 5\text{ mA}$$

The answer is impossible because the collector current cannot be greater than the saturation current. Therefore, the transistor cannot be operating in the active region; it must be operating in the saturation region.

Collector-Voltage Method

Suppose you want to calculate V_{CE} in Fig. 6-25*a*. Then you can proceed like this: The base current is ideally 0.1 mA. Assuming a current gain of 50 as shown, the collector current is:

$$I_C = 50(0.1\text{ mA}) = 5\text{ mA}$$

and the collector-emitter voltage is:

$$V_{CE} = 20\text{ V} - (5\text{ mA})(10\text{ k}\Omega) = -30\text{ V}$$

This result is impossible because the collector-emitter voltage cannot be negative. So the transistor cannot be operating in the active region; it must be operating in the saturation region.

Current Gain Is Less in Saturation Region

When you are given the current gain, it is usually for the active region. For instance, the current gain of Fig. 6-25*a* is shown as 50. This means that the collector current will be 50 times the base current, provided the transistor is operating in the active region.

When a transistor is saturated, the current gain is less than the current gain in the active region. You can calculate the saturated current gain as follows:

$$\beta_{\text{dc(sat)}} = \frac{I_{C(\text{sat})}}{I_B}$$

In Fig. 6-25*a*, the saturated current gain is

$$\beta_{\text{dc(sat)}} = \frac{2\text{ mA}}{0.1\text{ mA}} = 20$$

Hard Saturation

A designer who wants a transistor to operate in the saturation region under all conditions often selects a base resistance that produces a current gain of 10. This is called **hard saturation,** because there is more than enough base current to saturate the transistor. For example, a base resistance of 50 kΩ in Fig. 6-25*a* will produce a current gain of:

$$\beta_{dc} = \frac{2\text{ mA}}{0.2\text{ mA}} = 10$$

For the transistor in Fig. 6-25*a*, it takes only

$$I_B = \frac{2\text{ mA}}{50} = 0.04\text{ mA}$$

to saturate the transistor. Therefore, a base current of 0.2 mA will drive the transistor deep into saturation.

Why does a designer use hard saturation? Recall that the current gain changes with collector current, temperature variation, and transistor replacement. To make sure that the transistor does not slip out of saturation at low collector currents, low temperatures, and so on, the designer uses hard saturation to ensure transistor saturation under all operating conditions.

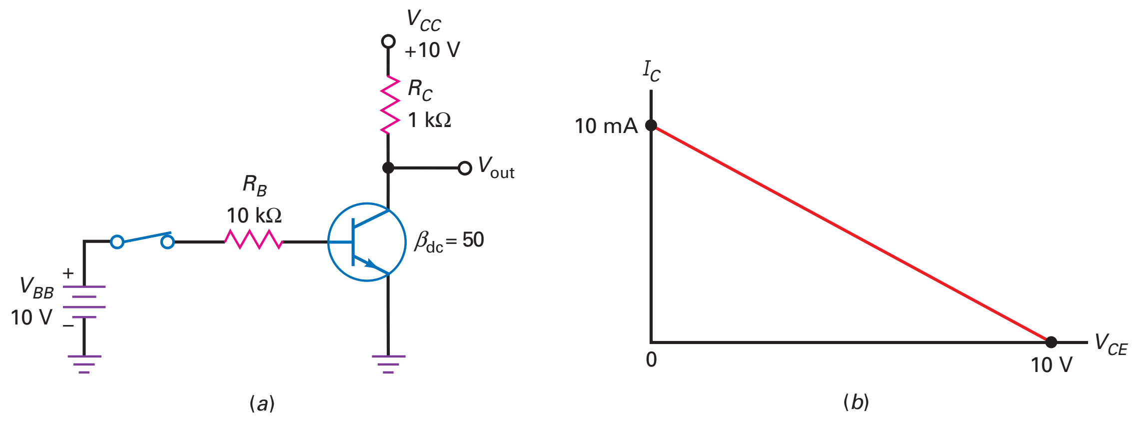
From now on, *hard saturation* will refer to any design that makes the saturated current gain approximately 10. **Soft saturation** will refer to any design in which the transistor is barely saturated, that is, in which the saturated current gain is only a little less than the active current gain.

Recognizing Hard Saturation at a Glance

Here is how you can quickly tell whether a transistor is in hard saturation. Often, the base supply voltage and the collector supply voltage are equal: $V_{BB} = V_{CC}$. When this is the case, a designer will use the 10 : 1 rule, which says to make the base resistance approximately 10 times as large as the collector resistance.

Figure 6-26*a* was designed by using the 10 : 1 rule. Therefore, whenever you see a circuit with a 10 : 1 ratio (R_B to R_C), you can expect it to be saturated.

Figure 6-26 (*a*) Hard saturation; (*b*) load line.



Example 6-18

Suppose the base resistance of Fig. 6-25*a* is increased to 1 MΩ. Is the transistor still saturated?

SOLUTION Assume the transistor is operating in the active region, and see whether a contradiction arises. Ideally, the base current is 10 V divided by 1 MΩ, or 10 μA. The collector current is 50 times 10 μA, or 0.5 mA. This current produces 5 V across the collector resistor. Subtract 5 from 20 V to get:

$$V_{CE} = 15 \text{ V}$$

There is no contradiction here. If the transistor were saturated, we would have calculated a negative number or, at most, 0 V. Because we got 15 V, we know that the transistor is operating in the active region.

Example 6-19

Suppose the collector resistance of Fig. 6-25*a* is decreased to 5 kΩ. Does the transistor remain in the saturation region?

SOLUTION Assume the transistor is operating in the active region, and see whether a contradiction arises. We can use the same approach as in Example 6-18, but for variety, let us try the second method.

Start by calculating the saturation value of the collector current. Visualize a short between the collector and the emitter. Then you can see that 20 V will be across 5 kΩ. This gives a saturated collector current of:

$$I_{C(\text{sat})} = 4 \text{ mA}$$

The base current is ideally 10 V divided by 100 kΩ, or 0.1 mA. The collector current is 50 times 0.1 mA, or 5 mA.

There is a contradiction. The collector current cannot be greater than 4 mA because the transistor saturates when $I_C = 4$ mA. The only thing that can change at this point is the current gain. The base current is still 0.1 mA, but the current gain decreases to:

$$\beta_{\text{dc(sat)}} = \frac{4 \text{ mA}}{0.1 \text{ mA}} = 40$$

This reinforces the idea discussed earlier. A transistor has two current gains, one in the active region and another in the saturation region. The second is equal to or smaller than the first.

PRACTICE PROBLEM 6-19 If the collector resistance of Fig. 6-25*a* is 4.7 kΩ, what value of base resistor would produce hard saturation using the 10:1 design rule?

6-14 The Transistor Switch

Base bias is useful in *digital circuits* because these circuits are usually designed to operate at saturation and cutoff. Because of this, they have either low output voltage or high output voltage. In other words, none of the *Q* points between saturation and cutoff are used. For this reason, variations in the Q point don't matter because the transistor remains in saturation or cutoff when the current gain changes.

Here is an example of using a base-biased circuit to switch between saturation and cutoff. Figure 6-26*a* shows an example of a transistor in hard saturation. Therefore, the output voltage is approximately 0 V. This means the Q point is at the upper end of the load line (Fig. 6-26*b*).

When the switch opens, the base current drops to zero. Because of this, the collector current drops to zero. With no current through the 1 kΩ, all the collector supply voltage will appear across the collector-emitter terminals. Therefore, the output voltage rises to +10 V. Now, the Q point is at the lower end of load line (see Fig. 6-26*b*).

The circuit can have only two output voltages: 0 or +10 V. This is how you can recognize a digital circuit. It has only two output levels: low or high. The exact values of the two output voltages are not important. All that matters is that you can distinguish the voltages as low or high.

Digital circuits are often called *switching circuits* because their Q point switches between two points on the load line. In most designs, the two points are saturation and cutoff. Another name often used is **two-state circuits,** referring to the low and high outputs.

Example 6-20

The collector supply voltage of Fig. 6-26*a* is decreased to 5 V. What are the two values of the output voltage? If the saturation voltage $V_{CE(\text{sat})}$ is 0.15 V and the collector leakage current I_{CEO} is 50 nA, what are the two values of the output voltage?

SOLUTION The transistor switches between saturation and cutoff. Ideally, the two values of output voltage are 0 and 5 V. The first voltage is the voltage across the saturated transistor, and the second voltage is the voltage across the cutoff transistor.

If you include the effects of saturation voltage and collector leakage current, the output voltages are 0.15 and 5 V. The first voltage is the voltage across the saturated transistor, which is given as 0.15 V. The second voltage is the collector-emitter voltage with 50 nA flowing through 1 kΩ:

$$V_{CE} = 5\text{ V} - (50\text{ nA})(1\text{ k}\Omega) = 4.99995\text{ V}$$

which rounds to 5 V.

Unless you are a designer, it is a waste of time to include the saturation voltage and the leakage current in your calculations of switching circuits. With switching circuits, all you need is two distinct voltages: one low and the other high. It doesn't matter whether the low voltage is 0, 0.1, 0.15 V, and so on. Likewise, it doesn't matter whether the high voltage is 5, 4.9, or 4.5 V. All that usually matters in the analysis of switching circuits is that you can distinguish the low voltage from the high voltage.

PRACTICE PROBLEM 6-20 If the circuit in Fig. 6-26*a* used 12 V for its collector and base supply voltage, what are the two values of switched output voltage? ($V_{CE(\text{sat})} = 0.15$ V and $I_{CEO} = 50$ nA)

6-15 Troubleshooting

Figure 6-27 shows a common-emitter circuit with grounds. A base supply of 15 V forward-biases the emitter diode through a resistance of 470 kΩ. A collector supply of 15 V reverse-biases the collector diode through a resistance of 1 kΩ. Let us use the ideal approximation to find the collector-emitter voltage. The calculations are as follows:

$$I_B = \frac{15\text{ V}}{470\text{ k}\Omega} = 31.9\ \mu\text{A}$$

$$I_C = 100(31.9\ \mu\text{A}) = 3.19\text{ mA}$$

$$V_{CE} = 15\text{ V} - (3.19\text{ mA})(1\text{ k}\Omega) = 11.8\text{ V}$$

Common Troubles

If you are troubleshooting a circuit like Fig. 6-27, one of the first things to measure is the collector-emitter voltage. It should have a value in the vicinity of 11.8 V. Why don't we use the second or third approximation to get a more accurate answer? Because resistors usually have a tolerance of at least ±5 percent, which causes the collector-emitter voltage to differ from your calculations, no matter what approximation you use.

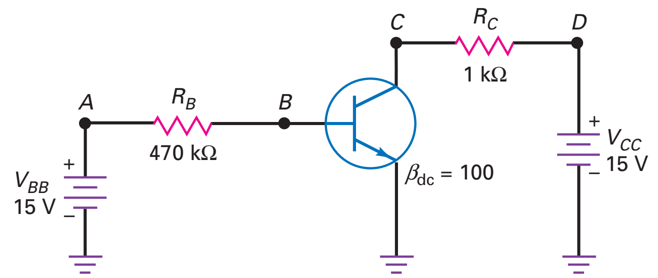
In fact, when troubles come, they are usually big troubles like shorts or opens. Shorts may occur because of damaged devices or solder splashes across resistors. Opens may occur when components burn out. Troubles like these produce big changes in currents and voltages. For instance, one of the most common troubles occurs when no supply voltage reaches the collector. This could happen in a number of ways, such as a trouble in the power supply itself, an open lead between the power supply and the collector resistor, an open collector resistor, and so on. In any of these cases, the collector voltage of Fig. 6-27 will be approximately zero because there is no collector supply voltage.

Another possible trouble is an open base resistor, which drops the base current to zero. This forces the collector current to drop to zero and the collector-emitter voltage to rise to 15 V, the value of the collector supply voltage. An open transistor has the same effect.

How Troubleshooters Think

The point is this: Typical troubles cause big deviations in transistor currents and voltages. Troubleshooters are seldom looking for differences in tenths of a volt. They are looking for voltages that are radically different from the ideal values.

Figure 6-27 Troubleshooting a circuit.



Summary Table 6-2	Troubles and Symptoms		
Trouble	**V_B, V**	**V_C, V**	**Comments**
None	0.7	12	No trouble
R_{BS}	15	15	Transistor blown
R_{BO}	0	15	No base or collector current
R_{CS}	0.7	15	
R_{CO}	0.7	0	
No V_{BB}	0	15	Check supply and lead
No V_{CC}	0.7	0	Check supply and lead

This is why the ideal transistor is useful as a starting point in troubleshooting. Furthermore, it explains why many troubleshooters don't even use calculators to find the collector-emitter voltage.

If they don't use calculators, what do they do? They mentally estimate the value of the collector-emitter voltage. Here is the thinking of an experienced troubleshooter while estimating the collector-emitter voltage in Fig. 6-27.

> ***The voltage across the base resistor is about 15 V. A base resistance of 1 MΩ would produce a base current of about 15 μA. Since 470 kΩ is half of 1 MΩ, the base current is twice as much, approximately 30 μA. A current gain of 100 gives a collector current of about 3 mA. When this flows through 1 kΩ, it produces a voltage drop of 3 V. Subtracting 3 V from 15 V leaves 12 V across the collector-emitter terminals. So, V_{CE} should measure in the vicinity of 12 V, or else there is something wrong in this circuit.***

A Table of Troubles

A shorted component is equivalent to a resistance of zero, whereas an open component is equivalent to a resistance of infinity. For instance, the base resistor R_B may be shorted or open. Let us designate these troubles by R_{BS} and R_{BO}. Similarly, the collector resistor may be shorted or open, symbolized by R_{CS} and R_{CO}.

Summary Table 6-2 shows a few of the troubles that could occur in a circuit like Fig. 6-27. The voltages were calculated using the second approximation. When the circuit is operating normally, you should measure a collector voltage of approximately 12 V. If the base resistor were shorted, +15 V would appear at the base. This large voltage would destroy the emitter diode. The collector diode would probably open as a result, forcing the collector voltage to go to 15 V. The trouble R_{BS} and its voltages are shown in Summary Table 6-2.

If the base resistor were open, there would be no base voltage or current. Furthermore, the collector current would be zero, and the collector voltage would increase to 15 V. The trouble R_{BO} and its voltages are shown in Summary Table 6-2. Continuing like this, we can get the remaining entries of the table.

Figure 6-28 *NPN* transistor.

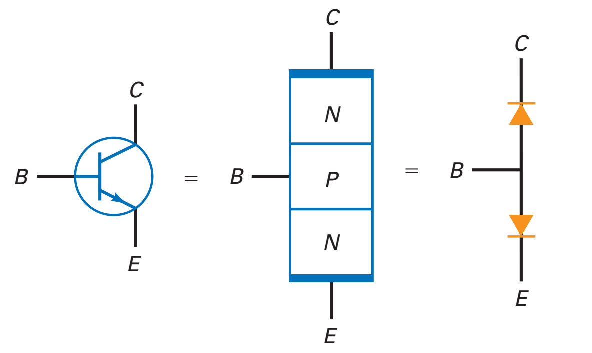
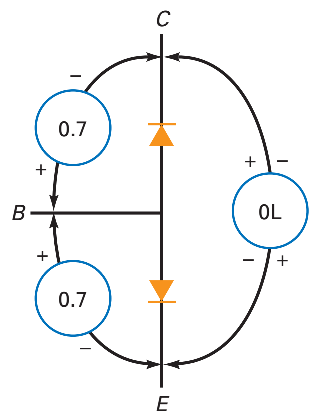


Figure 6-29 *NPN* DMM readings (*a*) Polarity connections; (*b*) *pn* junction readings.

+	−	Reading
B	*E*	0.7
E	*B*	0L
B	*C*	0.7
C	*B*	0L
C	*E*	0L
E	*C*	0L

(*a*)



(*b*)

Many things can go wrong with a transistor. Since it contains two diodes, exceeding any of the breakdown voltages, maximum currents, or power ratings can damage either or both diodes. The troubles may include shorts, opens, high leakage currents, and reduced β_{dc}.

Out-of-Circuit Tests

A transistor is commonly tested using a DMM set to the diode test range. Figure 6-28 shows how an *npn* transistor resembles two back-to-back diodes. Each *pn* junction can be tested for normal forward- and reverse-biased readings. The collector to emitter can also be tested and should result in an overrange indication with either DMM polarity connection. Since a transistor has three leads, there are six DMM polarity connections possible. These are shown in Fig. 6-29*a*. Notice that only two polarity connections result in approximately a 0.7 V reading. Also important to note here is that the base lead is the only connection common to both 0.7 V readings and it requires a (+) polarity connection. This is also shown in Fig. 6-29*b*.

A *pnp* transistor can be tested using the same technique. As shown in Fig. 6-30, the *pnp* transistor also resembles two back-to-back diodes. Again, using the DMM in the diode test range, Fig. 6-31*a* and 6-31*b* show the results for a normaltra nsistor.

Figure 6-30 *PNP* transistor.

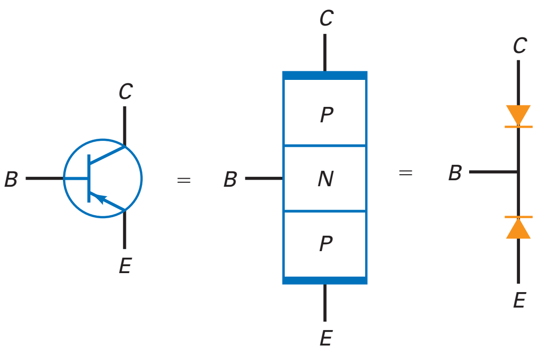
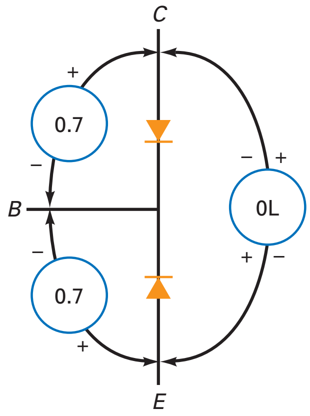


Figure 6-31 *PNP* DMM readings (*a*) polarity connections; (*b*) *pn* junction readings.

+	−	Readings
B	*E*	0L
E	*B*	0.7
B	*C*	0L
C	*B*	0.7
C	*E*	0L
E	*C*	0L

(*a*)



(*b*)

Many DMMs have a special β_{dc} or h_{FE} test function. By placing the transistor's leads into the proper slots, the forward current gain is displayed. This current gain is for a specified base current or collector current and V_{CE}. You can check the DMM's manual for the specific test condition.

Another way to test transistors is with an ohmmeter. You can begin by measuring the resistance between the collector and the emitter. This should be very high in both directions because the collector and emitter diodes are back to back in series. One of the most common troubles is a collector-emitter short, produced by exceeding the power rating. If you read zero to a few thousand ohms in either direction, the transistor is shorted and should be replaced.

Assuming that the collector-emitter resistance is very high in both directions (in megohms), you can read the reverse and forward resistances of the collector diode (collector-base terminals) and the emitter diode (base-emitter terminals). You should get a high reverse/forward ratio for both diodes, typically more than 1000 : 1 (silicon). If you do not, the transistor is defective.

Even if the transistor passes the ohmmeter tests, it still may have some faults. After all, the ohmmeter tests each transistor junction only under dc conditions. You can use a curve tracer to look for more subtle faults, such as too much leakage current, low β_{dc}, or insufficient breakdown voltage. A transistor being tested with a curve tracer is shown in Fig. 6-32. Commercial transistor testers are also available; these check the leakage current, current gain β_{dc}, and other quantities.

Figure 6-32 Transistor curve tracer test.