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

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

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

6-6 Collector Curves

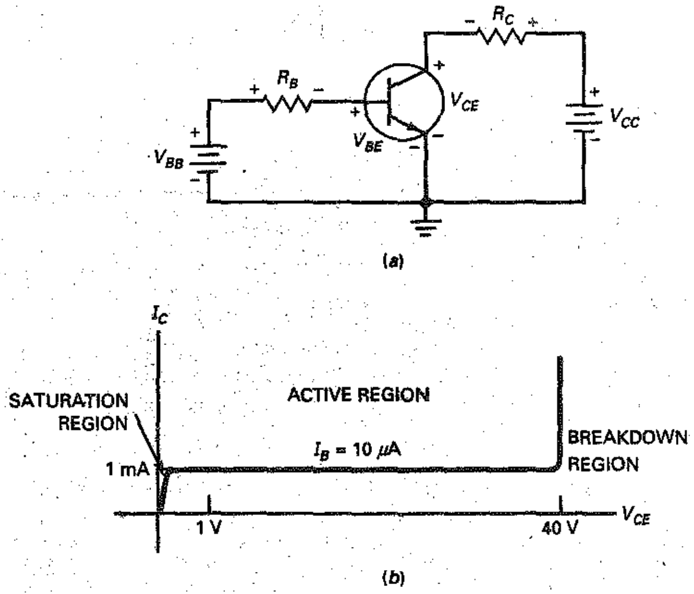
In Fig. 6-9*a*, we already know how to calculate the base current. Since V_{BB} forward biases the emitter diode, all we need to do is calculate the current through the base resistor R_B. Now, let us turn our attention to the collector loop.

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.



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.

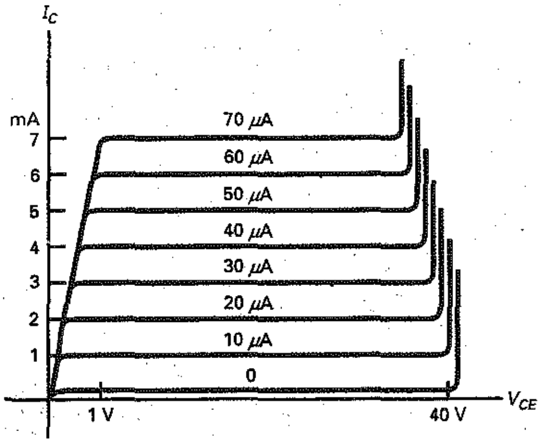
Another region of operation is the **breakdown region.** The transistor should never operate in this region because it will be destroyed. Unlike the zener diode, which is optimized for breakdown operation, a transistor is not intended for operation in the breakdown region.

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_B 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:

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

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.

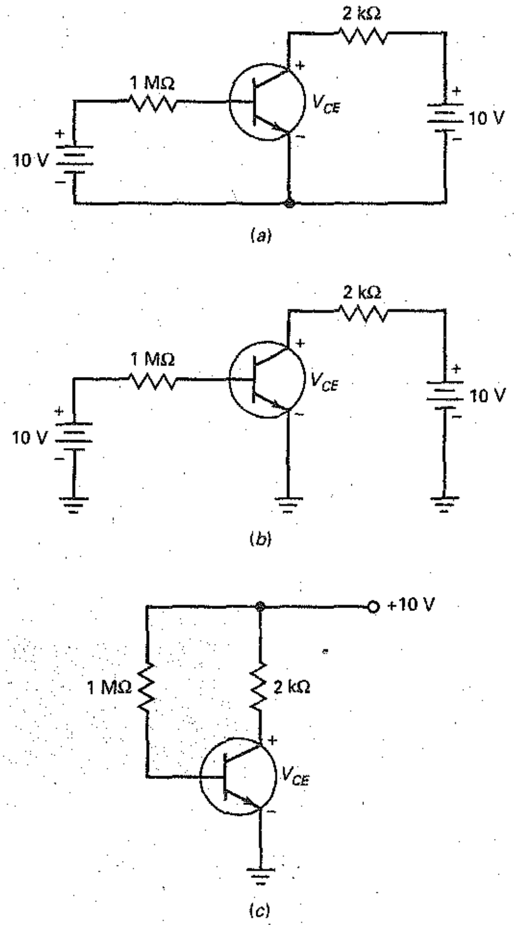
Recap

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 current equals:

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

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*.

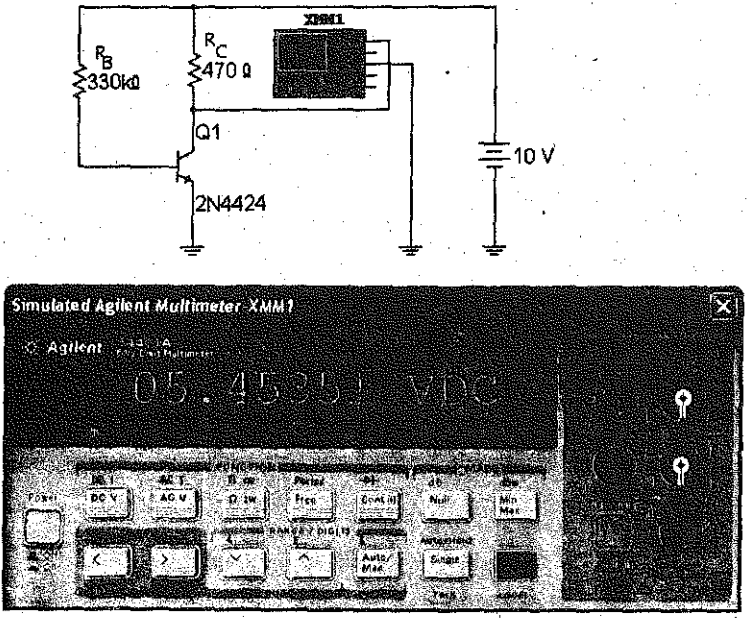
PRACTICE PROBLEM 6-5 Change R_B to 680 kΩ and repeat Example 6-5.

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 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.