SECTION 4–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. Name the two types of BJTs according to their structure.
2. The BJT is a three-terminal device. Name the three terminals.
3. What separates the three regions in a BJT?

4–2 BASIC BJT OPERATION

In order for a BJT to operate properly as an amplifier, the two *pn* junctions must be correctly biased with external dc voltages. In this section, we mainly use the *npn* transistor for illustration. The operation of the *pnp* is the same as for the *npn* except that the roles of the electrons and holes, the bias voltage polarities, and the current directions are all reversed.

After completing this section, you should be able to

- **Discuss basic BJT operation**
- Describe forward-reverse bias
  - Show how to bias *pnp* and *npn* BJTs with dc sources
- Explain the internal operation of a BJT
  - Discuss the hole and electron movement
- Discuss transistor currents
  - Calculate any of the transistor currents if the other two are known

Biasing

Figure 4–3 shows a bias arrangement for both *npn* and *pnp* BJTs for operation as an **amplifier.** Notice that in both cases the base-emitter (BE) junction is forward-biased and the base-collector (BC) junction is reverse-biased. This condition is called *forward-reverse bias.*

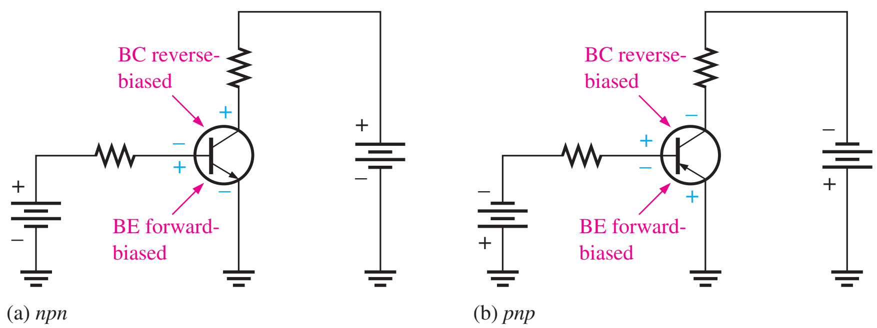
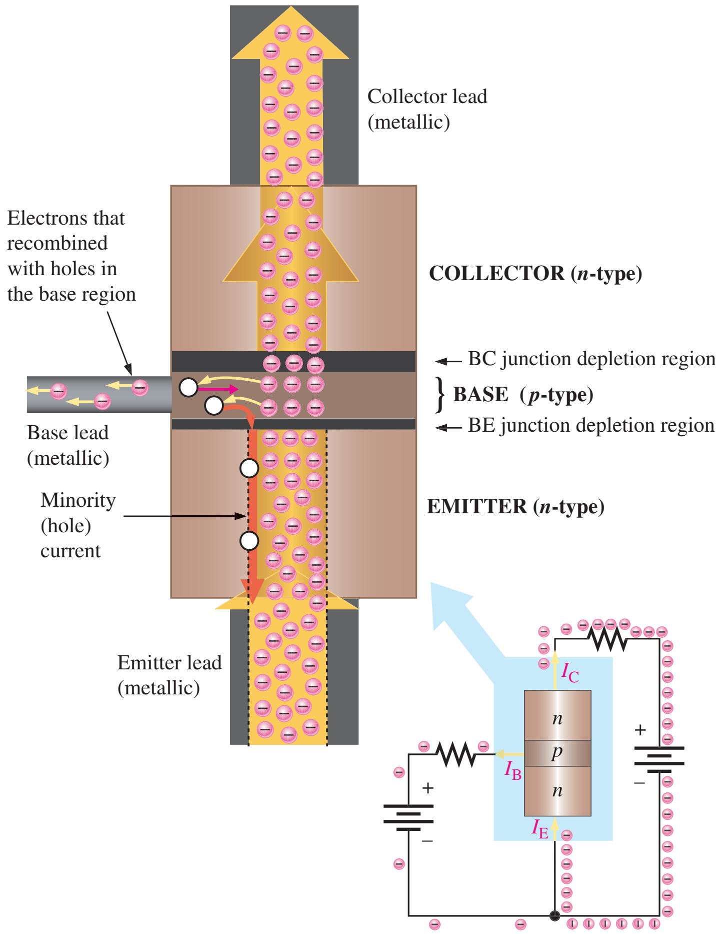


FIGURE 4–3
Forward-reverse bias of a BJT.

Operation

To understand how a transistor operates, let's examine what happens inside the *npn* structure. The heavily doped *n*-type emitter region has a very high density of conduction-band (free) electrons, as indicated in Figure 4–4. These free electrons easily diffuse through the forward-based BE junction into the lightly doped and very thin *p*-type base region, as indicated by the wide arrow. The base has a low density of holes, which are the majority carriers, as represented by the white circles. A small percentage of the total number of free electrons injected into the base region recombine with holes and move as valence electrons through the base region and into the emitter region as hole current, indicated by the red arrows.



▲ FIGURE 4–4

BJT operation showing electron flow.

When the electrons that have recombined with holes as valence electrons leave the crystalline structure of the base, they become free electrons in the metallic base lead and produce the external base current. Most of the free electrons that have entered the base do not recombine with holes because the base is very thin. As the free electrons move toward the reverse-biased BC junction, they are swept across into the collector region by the attraction of the positive collector supply voltage. The free electrons move through the collector region, into the external circuit, and then return into the emitter region along with the base current, as indicated. The emitter current is slightly greater than the collector current because of the small base current that splits off from the total current injected into the base region from the emitter.

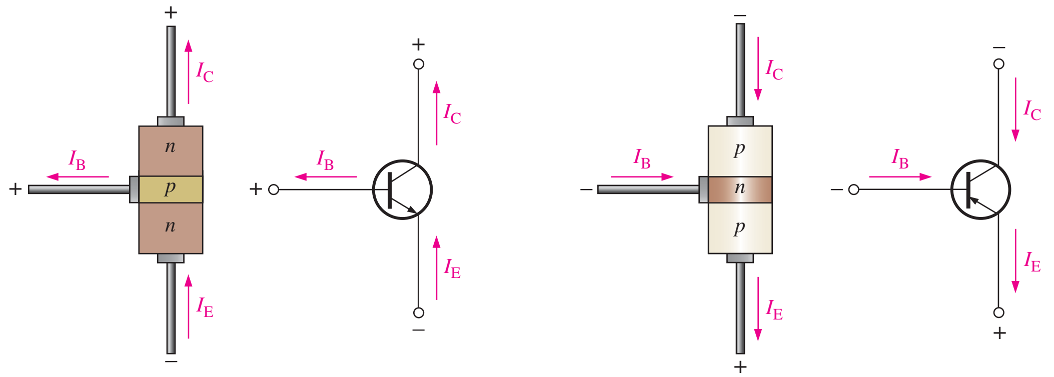
Transistor Currents

The directions of the currents in an *npn* transistor and its schematic symbol are as shown in Figure 4–5(a); those for a *pnp* transistor are shown in Figure 4–5(b). Notice that the arrow on the emitter inside the transistor symbols points in the direction of conventional current. These diagrams show that the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B), expressed as follows:

Equation 4–1

$$I_E = I_C + I_B$$

As mentioned before, I_B is very small compared to I_E or I_C. The capital-letter subscripts indicate dc values.



(a) *npn* (b) *pnp*

▲ **FIGURE 4–5**

Transistor currents.

SECTION 4–2 CHECKUP

1. What are the bias conditions of the base-emitter and base-collector junctions for a transistor to operate as an amplifier?
2. Which is the largest of the three transistor currents?
3. Is the base current smaller or larger than the emitter current?
4. Is the base region much thinner or much wider than the collector and emitter regions?
5. If the collector current is 1 mA and the base current is 10 μA, what is the emitter current?

4–3 BJT CHARACTERISTICS AND PARAMETERS

Two important parameters, β_{DC} (dc current gain) and α_{DC} are introduced and used to analyze a BJT circuit. Also, transistor characteristic curves are covered, and you will learn how a BJT's operation can be determined from these curves. Finally, maximum ratings of a BJT are discussed.

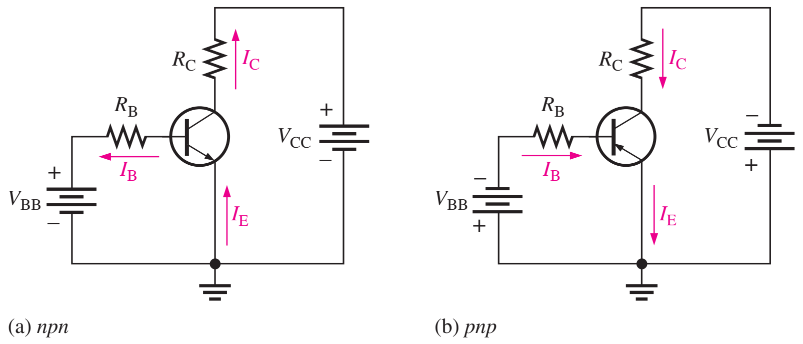
After completing this section, you should be able to

- **Discuss basic BJT parameters and characteristics and analyze transistor circuits**
- Define *dc beta* (β_{DC}) and *dc alpha* (α_{DC})
  - Calculate (β_{DC}) and (α_{DC}) based on transistor current
- Describe a basic dc model of a BJT
- Analyze BJT circuits
  - Identify transistor currents and voltages ◆ Calculate each transistor current
  - Calculate each transistor voltage
- Interpret collector characteristic curves
  - Discuss the linear region ◆ Explain saturation and cutoff in relation to the curves
- Describe the cutoff condition in a BJT circuit
- Describe the saturation condition in a BJT circuit
- Discuss the dc load line and apply it to circuit analysis
- Discuss how β_{DC} changes with temperature
- Explain and apply maximum transistor ratings
- Derate a transistor for power dissipation
- Interpret a BJT datasheet

When a transistor is connected to dc bias voltages, as shown in Figure 4–6 for both *npn* and *pnp* types, V_{BB} forward-biases the base-emitter junction, and V_{CC} reverse-biases the base-collector junction. Although in this chapter we are using separate battery symbols to represent the bias voltages, in practice the voltages are often derived from a single dc power supply. For example, V_{CC} is normally taken directly from the power supply output and V_{BB} (which is smaller) can be produced with a voltage divider. Bias circuits are examined thoroughly in Chapter 5.

▶ FIGURE 4–6

Transistor dc bias circuits.



DC Beta (β_{DC}) and DC Alpha (α_{DC})

The dc current **gain** of a transistor is the ratio of the dc collector current (I_C) to the dc base current (I_B) and is designated dc **beta** (β_{DC}).

Equation 4–2

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

Typical values of β_{DC} range from less than 20 to 200 or higher. β_{DC} is usually designated as an equivalent hybrid (*h*) parameter, h_{FE}, on transistor datasheets. *h*-parameters are covered in Chapter 6. All you need to know now is that

$$h_{FE} = \beta_{DC}$$

The ratio of the dc collector current (I_C) to the dc emitter current (I_E) is the dc **alpha** (α_{DC}). The alpha is a less-used parameter than beta in transistor circuits.

$$\alpha_{DC} = \frac{I_C}{I_E}$$

Typically, values of α_{DC} range from 0.95 to 0.99 or greater, but α_{DC} is always less than 1. The reason is that I_C is always slightly less than I_E by the amount of I_B. For example, if $I_E = 100$ mA and $I_B = 1$ mA, then $I_C = 99$ mA and $\alpha_{DC} = 0.99$.

EXAMPLE 4–1

Determine the dc current gain β_{DC} and the emitter current I_E for a transistor where $I_B = 50\ \mu A$ and $I_C = 3.65$ mA.

Solution

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{3.65\text{ mA}}{50\ \mu\text{A}} = \mathbf{73}$$

$$I_E = I_C + I_B = 3.65\text{ mA} + 50\ \mu\text{A} = \mathbf{3.70\ mA}$$

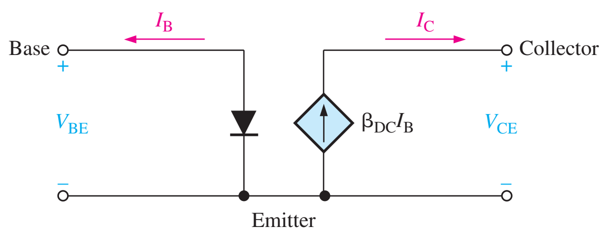
*Related Problem**

A certain transistor has a β_{DC} of 200. When the base current is 50 μA, determine the collector current.

***Answers can be found at www.pearsonhighered.com/floyd**

Transistor DC Model

You can view the unsaturated BJT as a device with a current input and a dependent current source in the output circuit, as shown in Figure 4–7 for an *npn*.The input circuit is a forward-biased diode through which there is base current. The output circuit is a dependent current source (diamond-shaped element) with a value that is dependent on the base current, I_B, and equal to $\beta_{DC}I_B$. Recall that independent current source symbols have a circular shape.



◀ **FIGURE 4–7**

Ideal dc model of an *npn* transistor.

BJT Circuit Analysis

Consider the basic transistor bias circuit configuration in Figure 4–8. Three transistor dc currents and three dc voltages can be identified.

I_B: dc base current

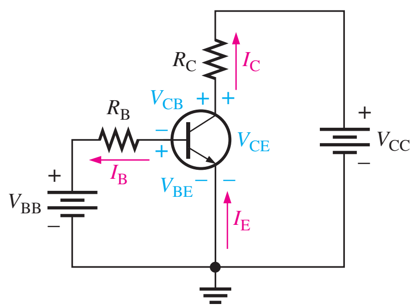
I_E: dc emitter current

I_C: dc collector current

V_{BE}: dc voltage at base with respect to emitter

V_{CB}: dc voltage at collector with respect to base

V_{CE}: dc voltage at collector with respect to emitter



◀ **FIGURE 4–8**

Transistor currents and voltages.

The base-bias voltage source, V_{BB}, forward-biases the base-emitter junction, and the collector-bias voltage source, V_{CC}, reverse-biases the base-collector junction. When the base-emitter junction is forward-biased, it is like a forward-biased diode and has a nominal forward voltage drop of

$$\mathbf{V_{BE} \cong 0.7\ V}$$ **Equation 4–3**

Although in an actual transistor V_{BE} can be as high as 0.9 V and is dependent on current, we will use 0.7 V throughout this text in order to simplify the analysis of the basic concepts. Keep in mind that the characteristic of the base-emitter junction is the same as a normal diode curve like the one in Figure 2-12.

Since the emitter is at ground (0 V), by Kirchhoff's voltage law, the voltage across R_B is

$$V_{R_B} = V_{BB} - V_{BE}$$

Also, by Ohm's law,

$$V_{R_B} = I_B R_B$$

Substituting for V_{R_B} yields

$$I_B R_B = V_{BB} - V_{BE}$$

Solving for I_B,

Equation 4–4

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

The voltage at the collector with respect to the grounded emitter is

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

Since the drop across R_C is

$$V_{R_C} = I_C R_C$$

the voltage at the collector with respect to the emitter can be written as

Equation 4–5

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

where $I_C = \beta_{DC} I_B$.

The voltage across the reverse-biased collector-base junction is

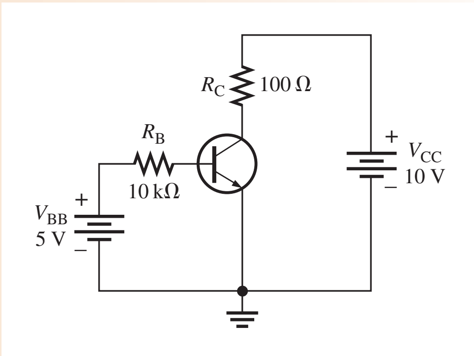
Equation 4–6

$$\mathbf{V_{CB} = V_{CE} - V_{BE}}$$

EXAMPLE 4–2

Determine I_B, I_C, I_E, V_{BE}, V_{CE}, and V_{CB} in the circuit of Figure 4–9. The transistor has a $\beta_{DC} = 150$.

▶ FIGURE 4–9



Solution From Equation 4–3, $V_{BE} \cong$ **0.7 V.** Calculate the base, collector, and emitter currents as follows:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \mathbf{430\ \mu A}$$

$$I_C = \beta_{DC} I_B = (150)(430\ \mu\text{A}) = \mathbf{64.5\ mA}$$

$$I_E = I_C + I_B = 64.5\text{ mA} + 430\ \mu\text{A} = \mathbf{64.9\ mA}$$

Solve for V_{CE} and V_{CB}.

$$V_{CE} = V_{CC} - I_C R_C = 10\text{ V} - (64.5\text{ mA})(100\ \Omega) = 10\text{ V} - 6.45\text{ V} = \mathbf{3.55\ V}$$

$$V_{CB} = V_{CE} - V_{BE} = 3.55\text{ V} - 0.7\text{ V} = \mathbf{2.85\ V}$$

Since the collector is at a higher voltage than the base, the collector-base junction is reverse-biased.

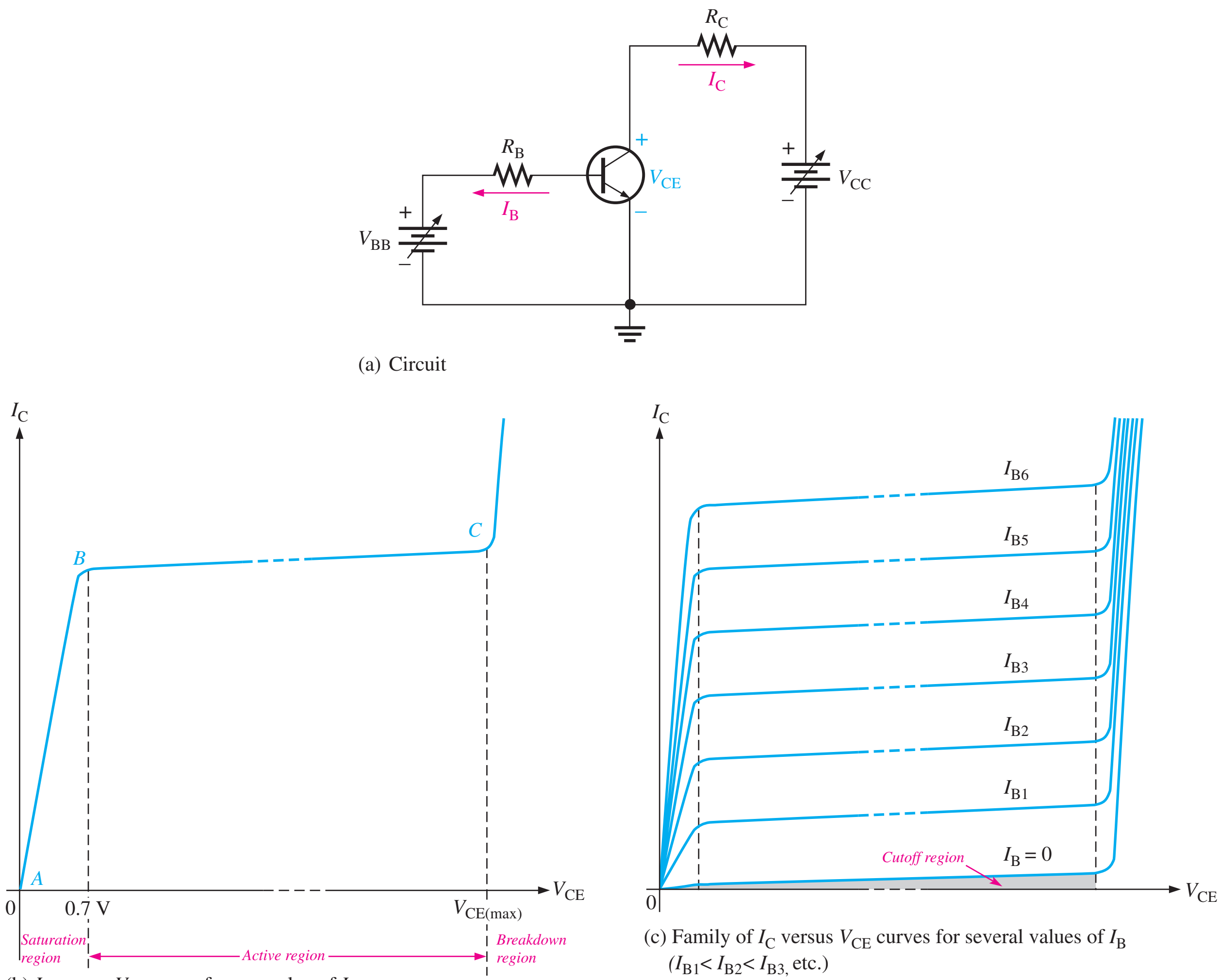
Related Problem Determine I_B, I_C, I_E, V_{CE}, and V_{CB} in Figure 4–9 for the following values: $R_B = 22\ k\Omega$, $R_C = 220\ \Omega$, $V_{BB} = 6$ V, $V_{CC} = 9$ V, and $\beta_{DC} = 90$.

Open the Multisim file E04-02 in the Examples folder on the companion website. Measure each current and voltage and compare with the calculated values.

Collector Characteristic Curves

Using a circuit like that shown in Figure 4–10(a), a set of *collector characteristic curves* can be generated that show how the collector current, I_C, varies with the collector-to-emitter voltage, V_{CE}, for specified values of base current, I_B. Notice in the circuit diagram that both V_{BB} and V_{CC} are variable sources of voltage.

Assume that V_{BB} is set to produce a certain value of I_B and V_{CC} is zero. For this condition, both the base-emitter junction and the base-collector junction are forward-biased because the base is at approximately 0.7 V while the emitter and the collector are at 0 V. The base current is through the base-emitter junction because of the low impedance path to



(a) Circuit

(b) I_C versus V_{CE} curve for one value of I_B

(c) Family of I_C versus V_{CE} curves for several values of I_B ($I_{B1} < I_{B2} < I_{B3}$, etc.)

▲ **FIGURE 4–10**

Collector characteristic curves.

ground and, therefore, I_C is zero. When both junctions are forward-biased, the transistor is in the saturation region of its operation. **Saturation** is the state of a BJT in which the collector current has reached a maximum and is independent of the base current.

As V_{CC} is increased, V_{CE} increases as the collector current increases. This is indicated by the portion of the characteristic curve between points *A* and *B* in Figure 4–10(b). I_C increases as V_{CC} is increased because V_{CE} remains less than 0.7 V due to the forward-biased base-collector junction.

Ideally, when V_{CE} exceeds 0.7 V, the base-collector junction becomes reverse-biased and the transistor goes into the *active,* or **linear**, *region* of its operation. Once the base-collector junction is reverse-biased, I_C levels off and remains essentially constant for a given value of I_B as V_{CE} continues to increase. Actually, I_C increases very slightly as V_{CE} increases due to widening of the base-collector depletion region. This results in fewer holes for recombination in the base region which effectively causes a slight increase in β_{DC}. This is shown by the portion of the characteristic curve between points *B* and *C* in Figure 4–10(b). For this portion of the characteristic curve, the value of I_C is determined only by the relationship expressed as $I_C = \beta_{DC} I_B$.

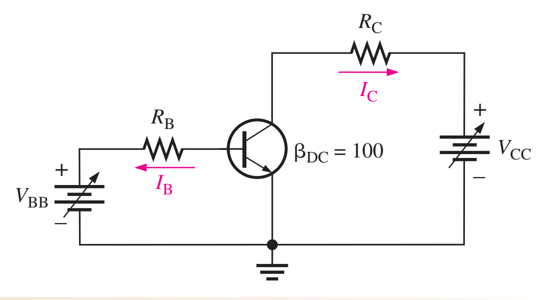
When V_{CE} reaches a sufficiently high voltage, the reverse-biased base-collector junction goes into breakdown; and the collector current increases rapidly as indicated by the part of the curve to the right of point *C* in Figure 4–10(b). A transistor should never be operated in this breakdown region.

A family of collector characteristic curves is produced when I_C versus V_{CE} is plotted for several values of I_B, as illustrated in Figure 4–10(c). When $I_B = 0$, the transistor is in the cutoff region although there is a very small collector leakage current as indicated. **Cutoff** is the nonconducting state of a transistor. The amount of collector leakage current for $I_B = 0$ is exaggerated on the graph for illustration.

EXAMPLE 4–3

Sketch an ideal family of collector curves for the circuit in Figure 4–11 for $I_B = 5\ \mu A$ to $25\ \mu A$ in $5\ \mu A$ increments. Assume $\beta_{DC} = 100$ and that V_{CE} does not exceed breakdown.

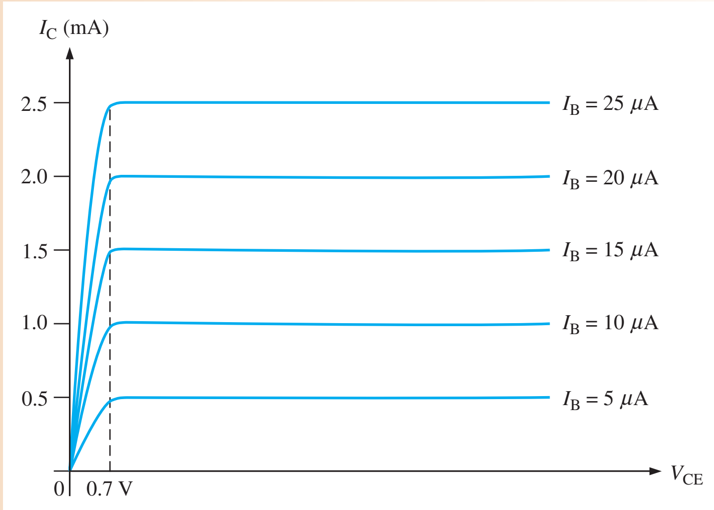
▶ FIGURE 4–11



Solution Using the relationship $I_C = \beta_{DC} I_B$, values of I_C are calculated and tabulated in Table 4–1. The resulting curves are plotted in Figure 4–12.

▶ TABLE 4–1

I_B	I_C
5 μA	0.5 mA
10 μA	1.0 mA
15 μA	1.5 mA
20 μA	2.0 mA
25 μA	2.5 mA

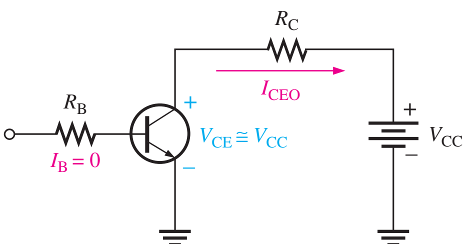


▲ FIGURE 4–12

Related Problem Where would the curve for $I_B = 0$ appear on the graph in Figure 4–12, neglecting collector leakage current?

Cutoff

As previously mentioned, when $I_B = 0$, the transistor is in the cutoff region of its operation. This is shown in Figure 4–13 with the base lead open, resulting in a base current of zero. Under this condition, there is a very small amount of collector leakage current, I_{CEO}, due mainly to thermally produced carriers. Because I_{CEO} is extremely small, it will usually be neglected in circuit analysis so that $V_{CE} = V_{CC}$. In cutoff, neither the base-emitter nor the base-collector junctions are forward-biased. The subscript CEO represents collector-to-emitter with the base open.



◀ FIGURE 4–13

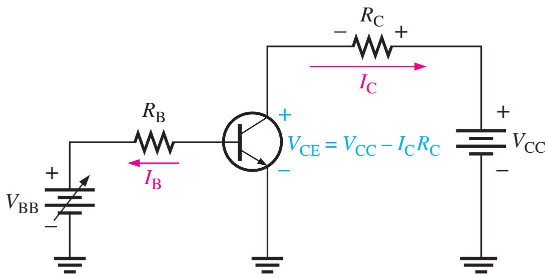
Cutoff: Collector leakage current (I_{CEO}) is extremely small and is usually neglected. Base-emitter and base-collector junctions are reverse-biased.

Saturation

When the base-emitter junction becomes forward-biased and the base current is increased, the collector current also increases ($I_C = \beta_{DC} I_B$) and V_{CE} decreases as a result of more drop across the collector resistor ($V_{CE} = V_{CC} - I_C R_C$). This is illustrated in Figure 4–14. When V_{CE} reaches its saturation value, $V_{CE(sat)}$, the base-collector junction becomes forward-biased and I_C can increase no further even with a continued increase in I_B. At the point of saturation, the relation $I_C = \beta_{DC} I_B$ is no longer valid. $V_{CE(sat)}$ for a transistor occurs somewhere below the knee of the collector curves, and it is usually only a few tenths of a volt.

▶ FIGURE 4–14

Saturation: As I_B increases due to increasing V_{BB}, I_C also increases and V_{CE} decreases due to the increased voltage drop across R_C. When the transistor reaches saturation, I_C can increase no further regardless of further increase in I_B. Base-emitter and base-collector junctions are forward-biased.

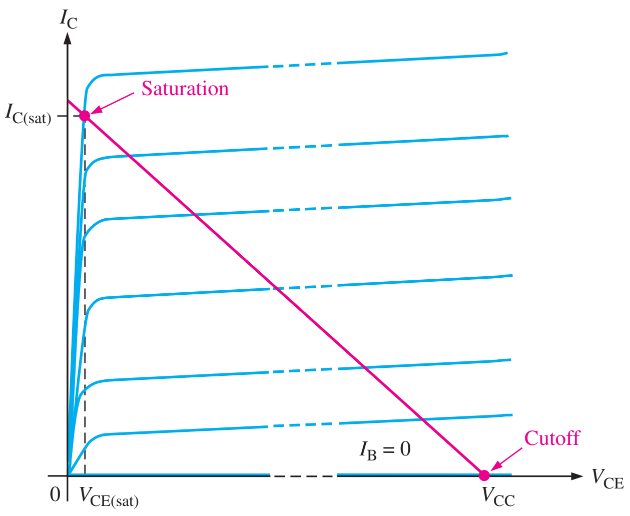


DC Load Line

Cutoff and saturation can be illustrated in relation to the collector characteristic curves by the use of a load line. Figure 4–15 shows a dc load line drawn on a family of curves connecting the cutoff point and the saturation point. The bottom of the load line is at ideal cutoff where $I_C = 0$ and $V_{CE} = V_{CC}$. The top of the load line is at saturation where $I_C = I_{C(sat)}$ and $V_{CE} = V_{CE(sat)}$. In between cutoff and saturation along the load line is the *active region* of the transistor's operation. Load line operation is discussed more in Chapter 5.

▶ FIGURE 4–15

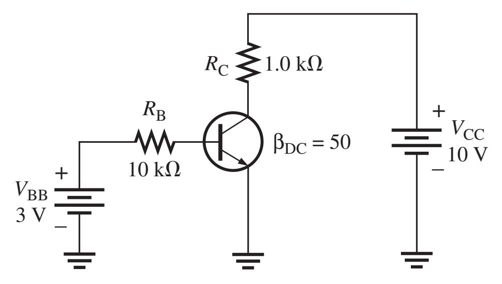
DC load line on a family of collector characteristic curves illustrating the cutoff and saturation conditions.



EXAMPLE 4–4

Determine whether or not the transistor in Figure 4–16 is in saturation. Assume $V_{CE(sat)} = 0.2$ V.

▶ FIGURE 4–16



Solution First, determine $I_{C(sat)}$.

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{10\text{ V} - 0.2\text{ V}}{1.0\text{ k}\Omega} = \frac{9.8\text{ V}}{1.0\text{ k}\Omega} = 9.8\text{ mA}$$

Now, see if I_B is large enough to produce $I_{C(sat)}$.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{3\text{ V} - 0.7\text{ V}}{10\text{ k}\Omega} = \frac{2.3\text{ V}}{10\text{ k}\Omega} = 0.23\text{ mA}$$

$$I_C = \beta_{DC} I_B = (50)(0.23\text{ mA}) = 11.5\text{ mA}$$

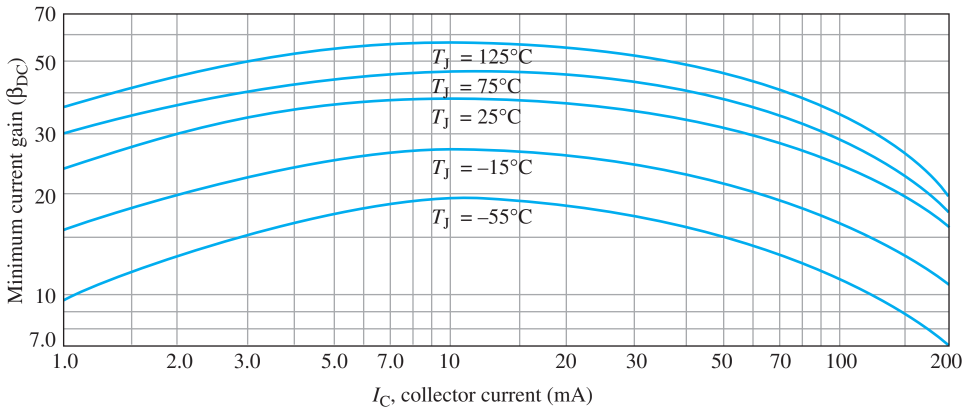
This shows that with the specified β_{DC}, this base current is capable of producing an I_C greater than $I_{C(sat)}$. Therefore, the **transistor is saturated,** and the collector current value of 11.5 mA is never reached. If you further increase I_B, the collector current remains at its saturation value of 9.8 mA.

Related Problem Determine whether or not the transistor in Figure 4–16 is saturated for the following values: $\beta_{DC} = 125$, $V_{BB} = 1.5$ V, $R_B = 6.8$ kΩ, $R_C = 180$ Ω, and $V_{CC} = 12$ V.

Open the Multisim file E04-04 in the Examples folder on the companion website. Determine if the transistor is in saturation and explain how you did this.

More About β_{DC}

The β_{DC} or h_{FE} is an important BJT parameter that we need to examine further. β_{DC} is not truly constant but varies with both collector current and with temperature. Keeping the junction temperature constant and increasing I_C causes β_{DC} to increase to a maximum. A further increase in I_C beyond this maximum point causes β_{DC} to decrease. If I_C is held constant and the temperature is varied, β_{DC} changes directly with the temperature. If the temperature goes up, β_{DC} goes up and vice versa. Figure 4–17 shows the variation of β_{DC} with I_C and junction temperature (T_J) for a typical BJT.



▲ **FIGURE 4–17**

Variation of β_{DC} with I_C for several temperatures.

A transistor datasheet usually specifies β_{DC} (h_{FE}) at specific I_C values. Even at fixed values of I_C and temperature, β_{DC} varies from one device to another for a given type of transistor due to inconsistencies in the manufacturing process that are unavoidable. The β_{DC} specified at a certain value of I_C is usually the minimum value, $\beta_{DC(min)}$, although the maximum and typical values are also sometimes specified.

Maximum Transistor Ratings

A BJT, like any other electronic device, has limitations on its operation. These limitations are stated in the form of maximum ratings and are normally specified on the manufacturer's datasheet. Typically, maximum ratings are given for collector-to-base voltage, collector-to-emitter voltage, emitter-to-base voltage, collector current, and power dissipation.

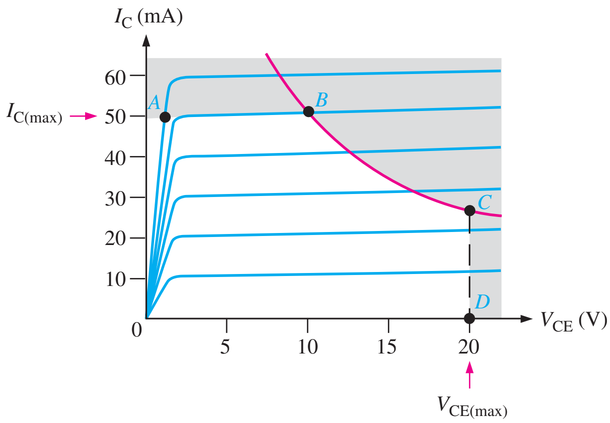
The product of V_{CE} and I_C must not exceed the maximum power dissipation. Both V_{CE} and I_C cannot be maximum at the same time. If V_{CE} is maximum, I_C can be calculated as

$$I_C = \frac{P_{D(max)}}{V_{CE}}$$

If I_C is maximum, V_{CE} can be calculated by rearranging the previous equation as follows:

$$V_{CE} = \frac{P_{D(max)}}{I_C}$$

For any given transistor, a maximum power dissipation curve can be plotted on the collector characteristic curves, as shown in Figure 4–18(a). These values are tabulated in Figure 4–18(b). Assume $P_{D(max)}$ is 500 mW, $V_{CE(max)}$ is 20 V, and $I_{C(max)}$ is 50 mA. The curve shows that this particular transistor cannot be operated in the shaded portion of the graph. $I_{C(max)}$ is the limiting rating between points *A* and *B*, $P_{D(max)}$ is the limiting rating between points *B* and *C*, and $V_{CE(max)}$ is the limiting rating between points *C* and *D*.



(a)

$P_{D(max)}$	V_{CE}	I_C
500 mW	5 V	100 mA
500 mW	10 V	50 mA
500 mW	15 V	33 mA
500 mW	20 V	25 mA

(b)

▲ **FIGURE 4–18**

Maximum power dissipation curve and tabulated values.

EXAMPLE 4–5

A certain transistor is to be operated with $V_{CE} = 6$ V. If its maximum power rating is 250 mW, what is the most collector current that it can handle?

Solution

$$I_C = \frac{P_{D(max)}}{V_{CE}} = \frac{250 \text{ mW}}{6 \text{ V}} = \mathbf{41.7\ mA}$$

This is the maximum current for this particular value of V_{CE}. The transistor can handle more collector current if V_{CE} is reduced, as long as $P_{D(max)}$ and $I_{C(max)}$ are not exceeded.

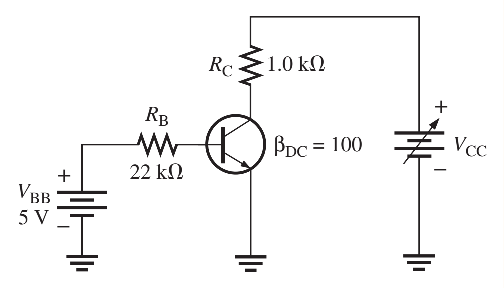
Related Problem

If $P_{D(max)} = 1$ W, how much voltage is allowed from collector to emitter if the transistor is operating with $I_C = 100$ mA?

EXAMPLE 4–6

The transistor in Figure 4–19 has the following maximum ratings: $P_{D(max)} = 800$ mW, $V_{CE(max)} = 15$ V, and $I_{C(max)} = 100$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first?

▶ FIGURE 4–19



Solution First, find I_B so that you can determine I_C.

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = 195\ \mu\text{A}$$

$$I_C = \beta_{DC} I_B = (100)(195\ \mu\text{A}) = 19.5\text{ mA}$$

I_C is much less than $I_{C(max)}$ and ideally will not change with V_{CC}. It is determined only by I_B and β_{DC}.

The voltage drop across R_C is

$$V_{R_C} = I_C R_C = (19.5\text{ mA})(1.0\text{ k}\Omega) = 19.5\text{ V}$$

Now you can determine the value of V_{CC} when $V_{CE} = V_{CE(max)} = 15$ V.

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

So,

$$V_{CC(max)} = V_{CE(max)} + (V_{R_C} = 15\text{ V} + 19.5\text{ V} = \mathbf{34.5\text{ V}}$$

V_{CC} can be increased to 34.5 V, under the existing conditions, before $V_{CE(max)}$ is exceeded. However, at this point it is not known whether or not $P_{D(max)}$ has been exceeded.

$$P_D = V_{CE(max)} I_C = (15\text{ V})(19.5\text{ mA}) = 293\text{ mW}$$

Since $P_{D(max)}$ is 800 mW, it is *not* exceeded when $V_{CC} = 34.5$ V. So, $V_{CE(max)} = 15$ V is the limiting rating in this case. If the base current is removed causing the transistor to turn off, **$V_{CE(max)}$ will be exceeded first** because the entire supply voltage, V_{CC}, will be dropped across the transistor.

Related Problem The transistor in Figure 4–19 has the following maximum ratings: $P_{D(max)} = 500$ mW, $V_{CE(max)} = 25$ V, and $I_{C(max)} = 200$ mA. Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first?

Derating $P_{D(max)}$

$P_{D(max)}$ is usually specified at 25°C. For higher temperatures, $P_{D(max)}$ is less. Datasheets often give derating factors for determining $P_{D(max)}$ at any temperature above 25°C. For example, a derating factor of 2 mW/°C indicates that the maximum power dissipation is reduced 2 mW for each degree Celsius increase in temperature.

EXAMPLE 4–7 A certain transistor has a $P_{D(max)}$ of 1 W at 25°C. The derating factor is 5 mW/°C. What is the $P_{D(max)}$ at a temperature of 70°C?

Solution The change (reduction) in $P_{D(max)}$ is

$$\Delta P_{D(max)} = (5\text{ mW/°C})(70\text{°C} - 25\text{°C}) = (5\text{ mW/°C})(45\text{°C}) = 225\text{ mW}$$

Therefore, the $P_{D(max)}$ at 70°C is

$$1\text{ W} - 225\text{ mW} = \mathbf{775\text{ mW}}$$

Related Problem A transistor has a $P_{D(max)} = 5$ W at 25°C. The derating factor is 10 mW/°C. What is the $P_{D(max)}$ at 70°C?

BJT Datasheet

A partial datasheet for the 2N3904 *npn* transistor is shown in Figure 4–20. Notice that the maximum collector-emitter voltage (V_{CEO}) is 40 V. The CEO subscript indicates that the voltage is measured from collector (C) to emitter (E) with the base open (O). In the text, we use $V_{CE(max)}$ for this parameter. Also notice that the maximum collector current is 200 mA.

The β_{DC} (h_{FE}) is specified for several values of I_C. As you can see, h_{FE} varies with I_C as we previously discussed.

The collector-emitter saturation voltage, $V_{CE(sat)}$ is 0.2 V maximum for $I_{C(sat)} = 10$ mA and increases with the current.

EXAMPLE 4–8 A 2N3904 transistor is used in the circuit of Figure 4–19 (Example 4–6). Determine the maximum value to which V_{CC} can be adjusted without exceeding a rating. Which rating would be exceeded first? Refer to the datasheet in Figure 4–20.

Solution From the datasheet,

$$P_{D(max)} = P_D = 625\text{ mW}$$
$$V_{CE(max)} = V_{CEO} = 40\text{ V}$$
$$I_{C(max)} = I_C = 200\text{ mA}$$

Assume $\beta_{DC} = 100$. This is a reasonably valid assumption based on the datasheet $h_{FE} =$ 100 minimum for specified conditions (β_{DC} and h_{FE} are the same parameter). As you have learned, the β_{DC} has considerable variations for a given transistor, depending on circuit conditions. Under this assumption, $I_C = 19.5$ mA and $V_{R_C} = 19.5$ V from Example 4–6.

Since I_C is much less than $I_{C(max)}$ and, ideally, will not change with V_{CC}, the maximum value to which V_{CC} can be increased before $V_{CE(max)}$ is exceeded is

$$V_{CC(max)} = V_{CE(max)} + V_{R_C} = 40\text{ V} + 19.5\text{ V} = 59.5\text{ V}$$

However, at the maximum value of V_{CE}, the power dissipation is

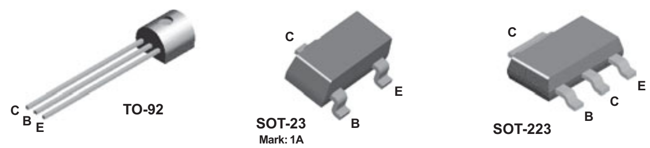
$$P_D = V_{CE(max)}I_C = (40\text{ V})(19.5\text{ mA}) = 780\text{ mW}$$

Power dissipation exceeds the maximum of 625 mW specified on the datasheet.

Related Problem Use the datasheet in Figure 4–20 to find the maximum P_D at 50°C.

FAIRCHILD
SEMICONDUCTOR™

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



NPN General Purpose Amplifier

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.

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	Characteristic	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 cm².

Electrical Characteristics T_A = 25°C unless otherwise noted

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

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

◄ **FIGURE 4–20**

Partial datasheet. For a complete 2N3904 datasheet, go to *http://www.fairchildsemi.com/ds/2N%2F2N3904.pdf*. Copyright Fairchild Semiconductor Corporation. Used by permission.

SECTION 4–3 CHECKUP

1. Define β_{DC} and α_{DC}. What is h_{FE}?
2. If the dc current gain of a transistor is 100, determine β_{DC} and α_{DC}.
3. What two variables are plotted on a collector characteristic curve?
4. What bias conditions must exist for a transistor to operate as an amplifier?
5. Does β_{DC} increase or decrease with temperature?
6. For a given type of transistor, can β_{DC} be considered to be a constant?

4–4 THE BJT AS AN AMPLIFIER

Amplification is the process of linearly increasing the amplitude of an electrical signal and is one of the major properties of a transistor. As you learned, a BJT exhibits current gain (called β). When a BJT is biased in the active (or linear) region, as previously described, the BE junction has a low resistance due to forward bias and the BC junction has a high resistance due to reverse bias.

After completing this section, you should be able to

- **Discuss how a BJT is used as a voltage amplifier**
- List the dc and ac quantities in an amplifier
  - Describe how the dc and ac quantities are identified
- Describe voltage amplification
  - Draw the schematic for a basic BJT amplifier ◆ Define *current gain* and *voltage gain* ◆ Calculate voltage gain ◆ Calculate amplifier output voltage

DC and AC Quantities

Before discussing the concept of transistor amplification, the designations that we will use for the circuit quantities of current, voltage, and resistance must be explained because amplifier circuits have both dc and ac quantities.

In this text, italic capital letters are used for both dc and ac currents (I) and voltages (V). This rule applies to rms, average, peak, and peak-to-peak ac values. AC current and voltage values are always rms unless stated otherwise. Although some texts use lowercase i and v for ac current and voltage, we reserve the use of lowercase i and v only for instantaneous values. In this text, the distinction between a dc current or voltage and an ac current or voltage is in the subscript.

DC quantities always carry an uppercase roman (nonitalic) subscript. For example, I_{B}, I_{C}, and I_{E} are the dc transistor currents. V_{BE}, V_{CB}, and V_{CE} are the dc voltages from one transistor terminal to another. Single subscripted voltages such as V_{B}, V_{C}, and V_{E} are dc voltages from the transistor terminals to ground.

AC and all time-varying quantities always carry a lowercase italic subscript. For example, I_b, I_c, and I_e are the ac transistor currents. V_{be}, V_{cb}, and V_{ce} are the ac voltages from one transistor terminal to another. Single subscripted voltages such as V_b, V_c, and V_e are ac voltages from the transistor terminals to ground.

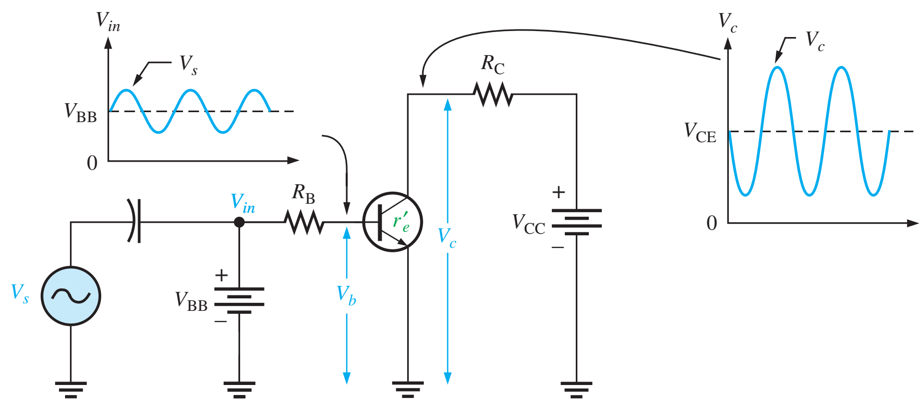
The rule is different for *internal* transistor resistances. As you will see later, transistors have internal ac resistances that are designated by lowercase r' with an appropriate subscript. For example, the internal ac emitter resistance is designated as r'_e.

Circuit resistances external to the transistor itself use the standard italic capital R with a subscript that identifies the resistance as dc or ac (when applicable), just as for current and voltage. For example R_{E} is an external dc emitter resistance and R_e is an external ac emitter resistance.

Voltage Amplification

As you have learned, a transistor amplifies current because the collector current is equal to the base current multiplied by the current gain, β. The base current in a transistor is very small compared to the collector and emitter currents. Because of this, the collector current is approximately equal to the emitter current.

With this in mind, let's look at the circuit in Figure 4–21. An ac voltage, V_s, is superimposed on the dc bias voltage V_{BB} by capacitive coupling as shown. The dc bias voltage V_{CC} is connected to the collector through the collector resistor, R_C.



◀ FIGURE 4–21

Basic transistor amplifier circuit with ac source voltage V_s and dc bias voltage V_{BB} superimposed.

The ac input voltage produces an ac base current, which results in a much larger ac collector current. The ac collector current produces an ac voltage across R_C, thus producing an amplified, but inverted, reproduction of the ac input voltage in the active region of operation, as illustrated in Figure 4–21.

The forward-biased base-emitter junction presents a very low resistance to the ac signal. This internal ac emitter resistance is designated r'_e in Figure 4–21 and appears in series with R_B. The ac base voltage is

$$V_b = I_e r'_e$$

The ac collector voltage, V_c, equals the ac voltage drop across R_C.

$$V_c = I_c R_C$$

Since $I_c \cong I_e$, the ac collector voltage is

$$V_c \cong I_e R_C$$

V_b can be considered the transistor ac input voltage where $V_b = V_s - I_b R_B$. V_c can be considered the transistor ac output voltage. Since *voltage gain* is defined as the ratio of the output voltage to the input voltage, the ratio of V_c to V_b is the ac voltage gain, A_v, of the transistor.

$$A_v = \frac{V_c}{V_b}$$

Substituting $I_e R_C$ for V_c and $I_e r'_e$ for V_b yields

$$A_v = \frac{V_c}{V_b} \cong \frac{I_e R_C}{I_e r'_e}$$

The I_e terms cancel; therefore,

$$\boldsymbol{A_v \cong \frac{R_C}{r'_e}} \qquad \text{Equation 4–7}$$

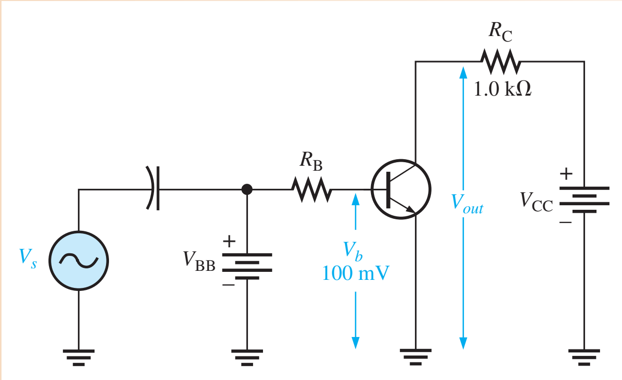
Equation 4–7 shows that the transistor in Figure 4–21 provides amplification in the form of voltage gain, which is dependent on the values of R_C and r'_e.

Since R_C is always considerably larger in value than r'_e, the output voltage for this configuration is greater than the input voltage. Various types of amplifiers are covered in detail in later chapters.

EXAMPLE 4–9

Determine the voltage gain and the ac output voltage in Figure 4–22 if $r'_e = 50\ \Omega$.

▶ FIGURE 4–22



Solution The voltage gain is

$$A_v \cong \frac{R_C}{r'_e} = \frac{1.0\ \text{k}\Omega}{50\ \Omega} = \mathbf{20}$$

Therefore, the ac output voltage is

$$V_{out} = A_v V_b = (20)(100\ \text{mV}) = \mathbf{2\ V\ rms}$$

Related Problem What value of R_C in Figure 4–22 will it take to have a voltage gain of 50?

SECTION 4–4 CHECKUP

1. What is amplification?
2. How is voltage gain defined?
3. Name two factors that determine the voltage gain of an amplifier.
4. What is the voltage gain of a transistor amplifier that has an output of 5 V rms and an input of 250 mV rms?
5. A transistor connected as in Figure 4–22 has an $r'_e = 20\ \Omega$. If R_C is 1200 Ω, what is the voltage gain?

4–5 THE BJT AS A SWITCH

In the previous section, you saw how a BJT can be used as a linear amplifier. The second major application area is switching applications. When used as an electronic switch, a BJT is normally operated alternately in cutoff and saturation. Many digital circuits use the BJT as a switch.

After completing this section, you should be able to

- **Discuss how a BJT is used as a switch**
- Describe BJT switching operation
- Explain the conditions in cutoff
  - Determine the cutoff voltage in terms of the dc supply voltage