6

BJT Amplifiers

CHAPTER OBJECTIVES

◆ Describe amplifier operation
◆ Discuss transistor models
◆ Describe and analyze the operation of common-emitter amplifiers
◆ Describe and analyze the operation of common-collector amplifiers
◆ Describe and analyze the operation of common-base amplifiers
◆ Describe and analyze the operation of multistage amplifiers
◆ Discuss the differential amplifier and its operation
◆ Troubleshoot amplifier circuits

KEY TERMS

◆ *r* parameter
◆ Common-emitter
◆ ac ground
◆ Input resistance
◆ Output resistance
◆ Attenuation
◆ Bypass capacitor
◆ Common-collector
◆ Emitter-follower
◆ Common-base
◆ Decibel
◆ Differential amplifier
◆ Common mode
◆ CMRR (Common-mode rejection ratio)

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INTRODUCTION

The things you learned about biasing a transistor in Chapter 5 are now applied in this chapter where bipolar junction transistor (BJT) circuits are used as small-signal amplifiers. The term *small-signal* refers to the use of signals that take up a relatively small percentage of an amplifier's operational range. Additionally, you will learn how to reduce an amplifier to an equivalent dc and ac circuit for easier analysis, and you will learn about multistage amplifiers. The differential amplifier is also covered.

DEVICE APPLICATION PREVIEW

The Device Application in this chapter involves a preamplifier circuit for a public address system. The complete system includes the preamplifier, a power amplifier, and a dc power supply. You will focus on the preamplifier in this chapter and then on the power amplifier in Chapter 7.

6–1   Amplifier Operation

The biasing of a transistor is purely a dc operation. The purpose of biasing is to establish a Q-point about which variations in current and voltage can occur in response to an ac input signal. In applications where small signal voltages must be amplified—such as from an antenna or a microphone—variations about the Q-point are relatively small. Amplifiers designed to handle these small ac signals are often referred to as *small-signal amplifiers.*

After completing this section, you should be able to

❑   **Describe amplifier operation**
❑   Identify ac quantities
◆   Distinguish ac quantities from dc quantities
❑   Discuss the operation of a linear amplifier
◆   Define *phase inversion*   ◆   Graphically illustrate amplifier operation
◆   Analyze ac load line operation

AC Quantities

In the previous chapters, dc quantities were identified by nonitalic uppercase (capital) subscripts such as I_C, I_E, V_C, and V_{CE}. Lowercase italic subscripts are used to indicate ac quantities of rms, peak, and peak-to-peak currents and voltages: for example, I_c, I_e, I_b, V_c, and V_{ce} (rms values are assumed unless otherwise stated). Instantaneous quantities are represented by both lowercase letters and subscripts such as i_c, i_e, i_b, and v_{ce}. Figure 6–1 illustrates these quantities for a specific voltage waveform.

V_{ce} can represent rms, average, peak, or peak-to-peak, but rms will be assumed unless stated otherwise. v_{ce} can be any instantaneous value on the curve.
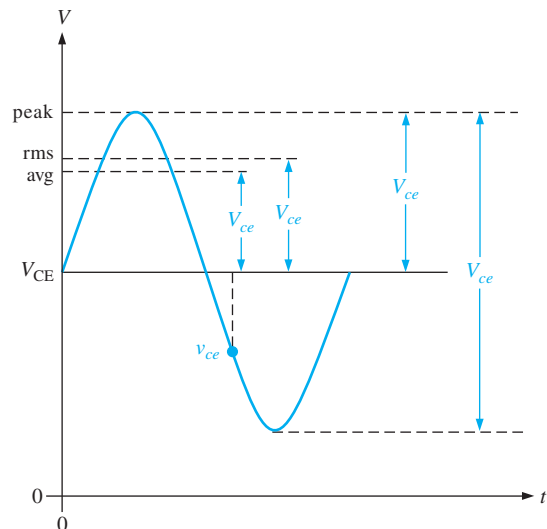
In addition to currents and voltages, resistances often have different values when a circuit is analyzed from an ac viewpoint as opposed to a dc viewpoint. Lowercase subscripts are used to identify ac resistance values. For example, R_c is the ac collector resistance, and R_C is the dc collector resistance. You will see the need for this distinction later. Resistance values *internal* to the transistor use a lowercase r' to show it is an ac resistance. An example is the internal ac emitter resistance, r'_e.

The Linear Amplifier

A linear amplifier provides amplification of a signal without any distortion so that the output signal is an exact amplified replica of the input signal. A voltage-divider biased transistor with a sinusoidal ac source capacitively coupled to the base through C_1 and a load capacitively coupled to the collector through C_2 is shown in Figure 6–2. The coupling capacitors block dc and thus prevent the internal source resistance, R_s, and the load resistance, R_L, from changing the dc bias voltages at the base and collector. The capacitors ideally appear as shorts to the signal voltage. The sinusoidal source voltage causes the base voltage to vary sinusoidally above and below its dc bias level, V_{BQ}. The resulting variation in base current produces a larger variation in collector current because of the current gain of the transistor.
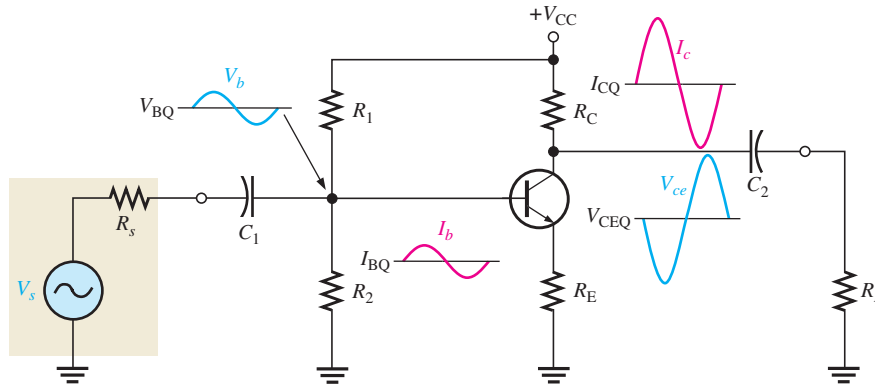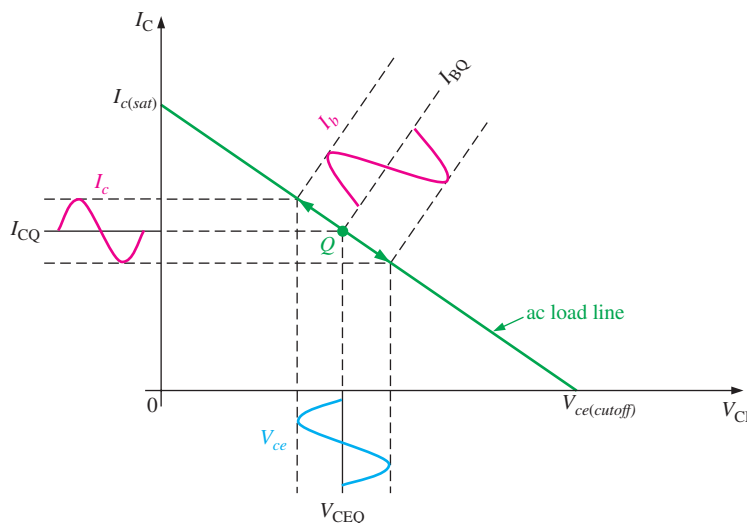

◀ FIGURE 6–2

An amplifier with voltage-divider bias driven by an ac voltage source with an internal resistance, R_s.

As the sinusoidal collector current increases, the collector voltage decreases. The collector current varies above and below its Q-point value, I_{CQ}, in phase with the base current. The sinusoidal collector-to-emitter voltage varies above and below its Q-point value, V_{CEQ}, 180° out of phase with the base voltage, as illustrated in Figure 6–2. A transistor always produces a **phase inversion** between the base voltage and the collector voltage.

A Graphical Picture   The operation just described can be illustrated graphically on the ac load line, as shown in Figure 6–3. The ac signal varies along the ac load line, which is different from the dc load line because the capacitors are seen ideally as a short to the ac signal but an open to the dc bias. The sinusoidal voltage at the base produces a base current that varies above and below the Q-point on the ac load line, as shown by the arrows.

Determination of the Q-point was discussed in Chapter 5, Section 5–1. The ac load line intersects the vertical axis (I_C) at the ac value of the collector saturation current $I_{c(sat)}$ and

◀ FIGURE 6–3

Graphical ac load line operation of the amplifier showing the variation of the base current, collector current, and collector-to-emitter voltage about their dc Q-point values. I_b and I_c are on different scales.

intersects the horizontal axis (V_{CE}) at the ac value of the collector-to-emitter cutoff voltage $V_{ce(cutoff)}$. These values are determined as follows:

$$I_{c(sat)} = V_{CEQ}/R_c + I_{CQ}$$
$$V_{ce(cutoff)} = V_{CEQ} + I_{CQ}R_c$$

Where R_c is the parallel combination of R_C and R_L.

Lines projected from the peaks of the base current, across to the I_C axis, and down to the V_{CE} axis, indicate the peak-to-peak variations of the collector current and collector-to-emitter voltage, as shown. The ac load line differs from the dc load line because the capacitors C_1 and C_2 effectively change the resistance seen by the ac signal. In the circuit in Figure 6–2, notice that the ac collector resistance is R_L in parallel with R_C, which is less than the dc collector resistance R_C alone. This difference between the dc and the ac load lines is covered further in Chapter 7 in relation to power amplifiers.

EXAMPLE 6–1

Given the Q-point value of $I_{CQ} = 4$ mA, $V_{CEQ} = 2$ V, $R_C = 1$ kΩ, and $R_L = 10$ kΩ for a certain amplifier, determine the ac load line values of $I_{c(sat)}$ and $V_{ce(cutoff)}$.

Solution The ac load line values of $I_{c(sat)}$ and $V_{ce(cutoff)}$ are

$$R_c = R_C \| R_L = 1 \text{ kΩ} \| 10 \text{ kΩ} = 909 \text{ Ω}$$
$$I_{c(sat)} = V_{CEQ}/R_c + I_{CQ} = 2 \text{ V}/909Ω + 4 \text{ mA} = 6.2 \text{ mA}$$
$$V_{ce(cutoff)} = V_{CEQ} + I_{CQ} R_c = 2 \text{ V} + 4 \text{ mA} (909 \text{ Ω}) = 5.64 \text{ V}$$

*Related Problem** If the Q-point is changed to 3 V and 6 mA, what is the intersection values of the ac load line on the two axes?

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

EXAMPLE 6–2

The ac load line operation of a certain amplifier extends 10 μA above and below the Q-point base current value of 50 μA, as shown in Figure 6–4. Determine the resulting peak-to-peak values of collector current and collector-to-emitter voltage from the graph.

▶ FIGURE 6–4
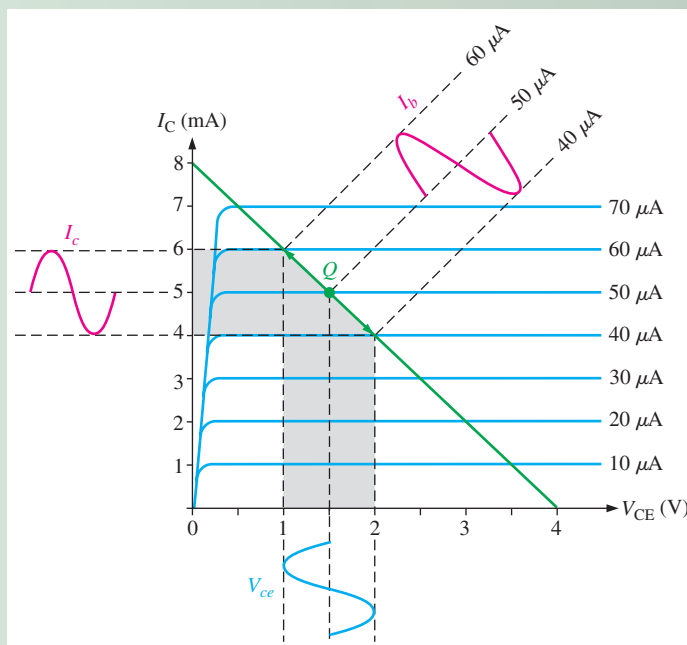
Solution	Projections on the graph of Figure 6–4 show the collector current varying from 6 mA to 4 mA for a peak-to-peak value of **2 mA** and the collector-to-emitter voltage varying from 1 V to 2 V for a peak-to-peak value of **1 V**.
Related Problem	What are the Q-point values of I_C and V_{CE} in Figure 6–4?

SECTION 6–1 CHECKUP
Answers can be found at www .pearsonhighered.com/floyd.

1. When I_b is at its positive peak, I_c is at its _____ peak, and V_{ce} is at its _____ peak.
2. What is the difference between V_{CE} and V_{ce}?
3. What is the difference between R_e and r'_e?
4. Why is the ac resistance seen by the collector different from the dc resistance?

6–2 TRANSISTOR AC MODELS

To visualize the operation of a transistor in an amplifier circuit, it is often useful to represent the device by a model circuit. A transistor model circuit uses various internal transistor parameters to represent its operation. Transistor models are described in this section based on resistance or *r* parameters. Another system of parameters, called hybrid or *h* parameters, is briefly described.

After completing this section, you should be able to

❑ **Discuss transistor models**
❑ List and define the *r* parameters
❑ Describe the *r*-parameter transistor model
❑ Determine r'_e using a formula
❑ Compare ac beta and dc beta
❑ List and define the *h* parameters

r Parameters

The *r* parameters that are commonly used for BJTs are given in Table 6–1. Strictly speaking, α_{ac} and β_{ac} are current ratios, not *r* parameters, but they are used with the resistance parameters to model basic transistor circuits. The italic lowercase letter *r* with a prime denotes resistances internal to the transistor.

◀ **TABLE 6–1**

r parameters.

r PARAMETERS	DESCRIPTION
r'_e	ac emitter resistance
r'_b	ac base resistance
r'_c	ac collector resistance
α_{ac}	ac alpha (I_c/I_e)
β_{ac}	ac beta (I_c/I_b)

r-Parameter Transistor Model

An **_r_-parameter** model for a BJT is shown in Figure 6–5(a). For most general analysis work, it can be simplified as follows: The effect of the ac base resistance (r'_b) is usually

(a) Generalized *r*-parameter model for a BJT   (b) Simplified *r*-parameter model for a BJT
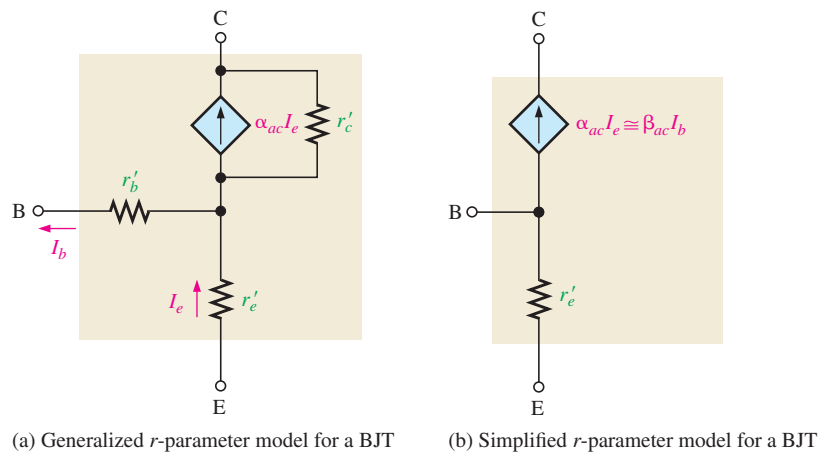
▲ FIGURE 6–5

r-parameter transistor model.

small enough to neglect, so it can generally be replaced by a short. The ac collector resistance (r_c') is usually several hundred kilohms and can approximately be replaced by an open. The resulting simplified *r*-parameter equivalent circuit is shown in Figure 6–5(b).

The interpretation of this model circuit in terms of a transistor's ac operation is as follows: A resistance (r_e') appears between the emitter and base terminals. This is the resistance "seen" looking into the emitter of a forward-biased transistor. The collector effectively acts as a dependent current source of $\alpha_{ac}I_e$ or, equivalently, $\beta_{ac}I_b$, represented by the diamond-shaped symbol. These factors are shown with a transistor symbol in Figure 6–6.

► FIGURE 6–6

Relation of transistor symbol to *r*-parameter model.
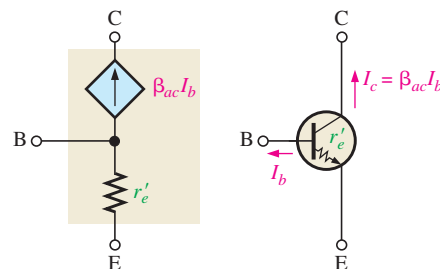
Determining r_e' by a Formula

For amplifier analysis, the ac emitter resistance, r_e', is the most important of the *r* parameters. To calculate the approximate value of r_e', you can use Equation 6–1, which is derived assuming an abrupt junction between the *n* and *p* regions. It is also temperature dependent and is based on an ambient temperature of 20°C.

**Equation 6–1**

$$r_e' \cong \frac{25 \text{ mV}}{I_E}$$

The numerator will be slightly larger for higher temperatures or transistors with a gradual (instead of an abrupt) junction. Although these cases will yield slightly different results, most designs are not critically dependent on the value of r_e', and you will generally obtain excellent agreement with actual circuits using the equation as given. The derivation for Equation 6–1 can be found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd.

EXAMPLE 6–3

Determine the r'_e of a transistor that is operating with a dc emitter current of 2 mA.

Solution

$$r'_e \cong \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{2 \text{ mA}} = \mathbf{12.5 \ \Omega}$$

Related Problem   What is I_E if $r'_e = 8 \ \Omega$?

Comparison of the AC Beta (β_{ac}) to the DC Beta (β_{DC})

For a typical transistor, a graph of I_C versus I_B is nonlinear, as shown in Figure 6–7(a). If you pick a Q-point on the curve and cause the base current to vary an amount ΔI_B, then the collector current will vary an amount ΔI_C as shown in part (b). At different points on the nonlinear curve, the ratio $\Delta I_C/\Delta I_B$ will be different, and it may also differ from the I_C/I_B ratio at the Q-point. Since $\beta_{DC} = I_C/I_B$ and $\beta_{ac} = \Delta I_C/\Delta I_B$, the values of these two quantities can differ slightly.

(a) $\beta_{DC} = I_C/I_B$ at Q-point
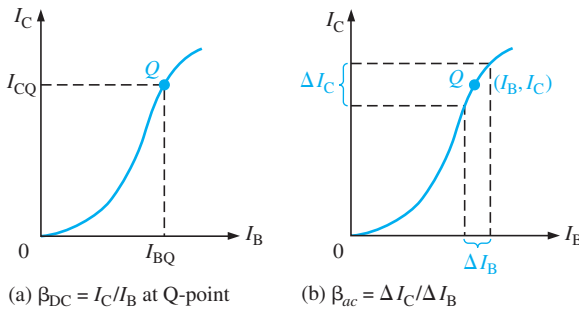
(b) $\beta_{ac} = \Delta I_C/\Delta I_B$

◀ **FIGURE 6–7**

I_C-versus-I_B curve illustrates the difference between $\beta_{DC} = I_C/I_B$ and $\beta_{ac} = \Delta I_C/\Delta I_B$.

h Parameters

A manufacturer's datasheet typically specifies h (hybrid) parameters (h_i, h_r, h_f, and h_o) because they are relatively easy to measure.

The four basic ac h parameters and their descriptions are given in Table 6–2. Each of the four h parameters carries a second subscript letter to designate the common-emitter (e), common-base (b), or common-collector (c) amplifier configuration, as listed in Table 6–3. The term *common* refers to one of the three terminals (E, B, or C) that is referenced to ac ground for both input and output signals. The characteristics of each of these three BJT amplifier configurations are covered later in this chapter.

h PARAMETER	DESCRIPTION	CONDITION
h_i	Input impedance (resistance)	Output shorted
h_r	Voltage feedback ratio	Input open
h_f	Forward current gain	Output shorted
h_o	Output admittance (conductance)	Input open

◀ **TABLE 6–2**

Basic ac *h* parameters.

CONFIGURATION	*h* PARAMETERS
Common-Emitter	$h_{ie}, h_{re}, h_{fe}, h_{oe}$
Common-Base	$h_{ib}, h_{rb}, h_{fb}, h_{ob}$
Common-Collector	$h_{ic}, h_{rc}, h_{fc}, h_{oc}$

◀ **TABLE 6–3**

Subscripts of *h* parameters for each of the three amplifier configurations.

Relationships of *h* Parameters and *r* Parameters

The ac current ratios, α_{ac} and β_{ac}, convert directly from *h* parameters as follows:

$$\alpha_{ac} = h_{fb}$$
$$\beta_{ac} = h_{fe}$$

Because datasheets often provide only common-emitter *h* parameters, the following formulas show how to convert them to *r* parameters. We will use *r* parameters throughout the text because they are easier to apply and more practical.

$$r_e' = \frac{h_{re}}{h_{oe}}$$

$$r_c' = \frac{h_{re} + 1}{h_{oe}}$$

$$r_b' = h_{ie} - \frac{h_{re}}{h_{oe}}(1 + h_{fe})$$


**SECTION 6–2
CHECKUP**

1. Define each of the parameters: α_{ac}, β_{ac}, r_e', r_b', r_c'.
2. Which *h* parameter is equivalent to β_{ac}?
3. If $I_E = 15$ mA, what is the approximate value of r_e'.
4. What is the difference between β_{ac} and β_{DC}?

6–3 THE COMMON-EMITTER AMPLIFIER

As you have learned, a BJT can be represented in an ac model circuit. Three amplifier configurations are the common-emitter, the common-base, and the common-collector. The common-emitter (CE) configuration has the emitter as the common terminal, or ground, to an ac signal. CE amplifiers exhibit high voltage gain and high current gain. The common-collector and common-base configurations are covered in the Sections 6–4 and 6–5.

After completing this section, you should be able to

❑ **Describe and analyze the operation of common-emitter amplifiers**
❑ Discuss a common-emitter amplifier with voltage-divider bias
  ◆ Show input and output signals ◆ Discuss phase inversion
❑ Perform a dc analysis
  ◆ Represent the amplifier by its dc equivalent circuit
❑ Perform an ac analysis
  ◆ Represent the amplifier by its ac equivalent circuit ◆ Define *ac ground*
  ◆ Discuss the voltage at the base ◆ Discuss the input resistance at the base and the output resistance
❑ Analyze the amplifier for voltage gain
  ◆ Define *attenuation* ◆ Define *bypass capacitor* ◆ Describe the effect of an emitter bypass capacitor on voltage gain ◆ Discuss voltage gain without a bypass capacitor ◆ Explain the effect of a load on voltage gain
❑ Discuss the stability of the voltage gain
  ◆ Define *stability* ◆ Explain the purpose of swamping r_e' and the effect on input resistance
❑ Determine current gain and power gain
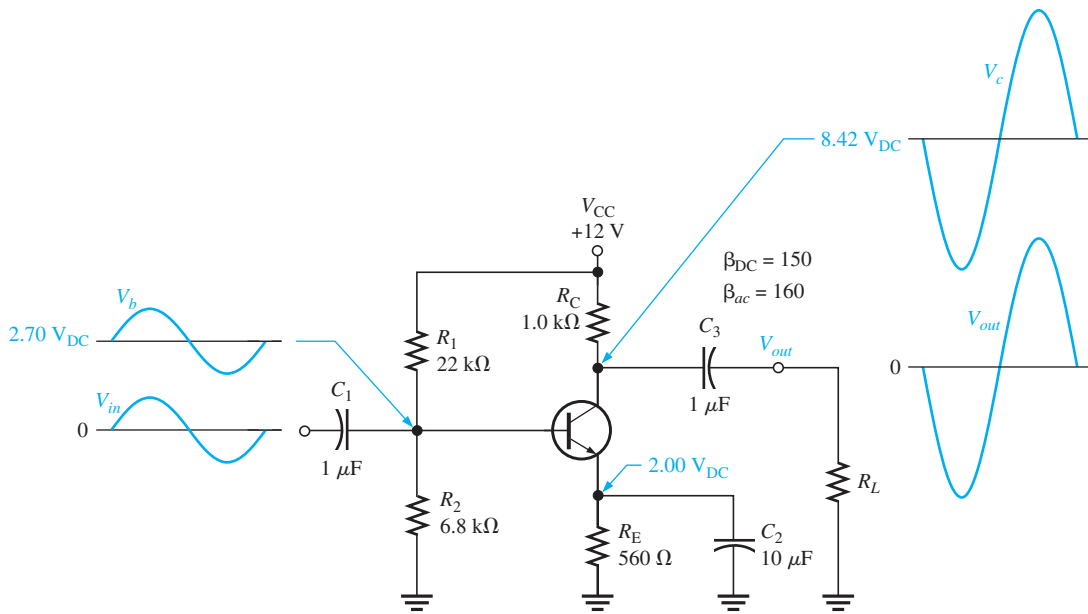
▲ FIGURE 6–8

A common-emitter amplifier.

Figure 6–8 shows a **common-emitter** amplifier with voltage-divider bias and coupling capacitors C_1 and C_3 on the input and output and a bypass capacitor, C_2, from emitter to ground. The input signal, V_{in}, is capacitively coupled to the base terminal, the output signal, V_{out}, is capacitively coupled from the collector to the load. The amplified output is 180° out of phase with the input. Because the ac signal is applied to the base terminal as the input and taken from the collector terminal as the output, the emitter is common to both the input and output signals. There is no signal at the emitter because the bypass capacitor effectively shorts the emitter to ground at the signal frequency. All amplifiers have a combination of both ac and dc operation, which must be considered, but keep in mind that the common-emitter designation refers to the ac operation.

Phase Inversion   The output signal is 180° out of phase with the input signal. As the input signal voltage changes, it causes the ac base current to change, resulting in a change in the collector current from its Q-point value. If the base current increases, the collector current increases above its Q-point value, causing an increase in the voltage drop across R_C. This increase in the voltage across R_C means that the voltage at the collector decreases from its Q-point. So, any change in input signal voltage results in an opposite change in collector signal voltage, which is a phase inversion.
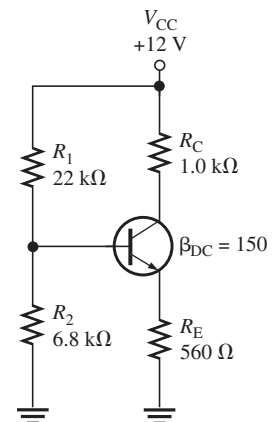
DC Analysis

To analyze the amplifier in Figure 6–8, the dc bias values must first be determined. To do this, a dc equivalent circuit is developed by removing the coupling and bypass capacitors because they appear open as far as the dc bias is concerned. This also removes the load resistor and signal source. The dc equivalent circuit is shown in Figure 6–9.

Theveninizing the bias circuit and applying Kirchhoff's voltage law to the base-emitter circuit,

▲ FIGURE 6–9

DC equivalent circuit for the amplifier in Figure 6–8.

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(6.8\ \text{k}\Omega)(22\ \text{k}\Omega)}{6.8\ \text{k}\Omega + 22\ \text{k}\Omega} = 5.19\ \text{k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{6.8\ \text{k}\Omega}{6.8\ \text{k}\Omega + 22\ \text{k}\Omega}\right)12\ \text{V} = 2.83\ \text{V}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{2.83\ V - 0.7\ V}{560\ \Omega + 34.6\ \Omega} = 3.58\ mA$$

$$I_C \cong I_E = 3.58\ mA$$

$$V_E = I_E R_E = (3.58\ mA)(560\ \Omega) = 2.00\ V$$

$$V_B = V_E + 0.7\ V = 2.70\ V$$

$$V_C = V_{CC} - I_C R_C = 12\ V - (3.58\ mA)(1.0\ k\Omega) = 8.42\ V$$

$$V_{CE} = V_C - V_E = 8.42\ V - 2.00\ V = 6.42\ V$$

AC Analysis

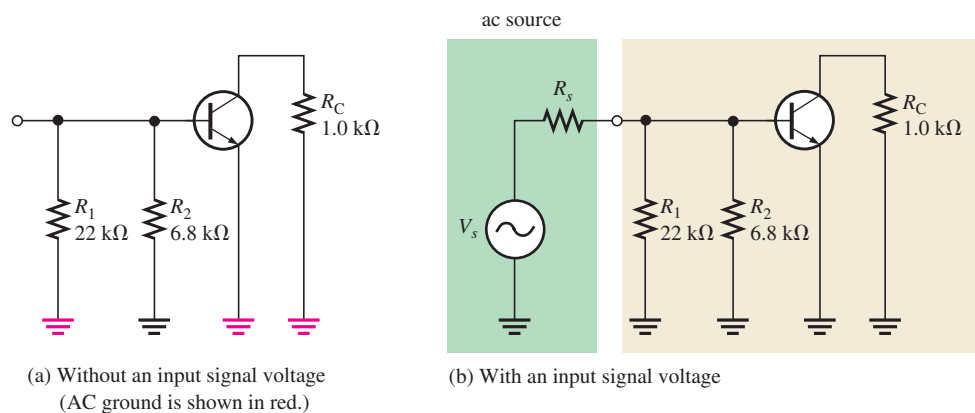To analyze the ac signal operation of an amplifier, an ac equivalent circuit is developed as follows:

1. The capacitors C_1, C_2, and C_3 are replaced by effective shorts because their values are selected so that X_C is negligible at the signal frequency and can be considered to be 0 Ω.

2. The dc source is replaced by ground.

A dc voltage source has an internal resistance of near 0 Ω because it holds a constant voltage independent of the load (within limits); no ac voltage can be developed across it so it appears as an ac short. This is why a dc source is called an **ac ground**.

The ac equivalent circuit for the common-emitter amplifier in Figure 6–8 is shown in Figure 6–10(a). Notice that both R_C and R_1 have one end connected to ac ground (red) because, in the actual circuit, they are connected to V_{CC} which is, in effect, ac ground.

AC equivalent circuit for the amplifier in Figure 6–8.

(a) Without an input signal voltage (AC ground is shown in red.)

(b) With an input signal voltage

In ac analysis, the ac ground and the actual ground are treated as the same point electrically. The amplifier in Figure 6–8 is called a common-emitter amplifier because the bypass capacitor C_2 keeps the emitter at ac ground. Ground is the common point in the circuit.

Signal (AC) Voltage at the Base   An ac voltage source, V_s, is shown connected to the input in Figure 6–10(b). If the internal resistance of the ac source is 0 Ω, then all of the source voltage appears at the base terminal. If, however, the ac source has a nonzero internal resistance, then three factors must be taken into account in determining the actual signal voltage at the base. These are the *source resistance* (R_s), the *bias resistance* ($R_1 \| R_2$), and the *ac input resistance* at the base of the transistor ($R_{in(base)}$). This is illustrated in Figure 6–11(a) and is simplified by combining R_1, R_2, and $R_{in(base)}$ in parallel to get the total **input resistance**, $R_{in(tot)}$, which is the resistance "seen" by an ac source connected to the input, as shown in Figure 6–11(b). A high value of input resistance is desirable so that the amplifier will not excessively load the signal source. This is opposite to the requirement for a stable
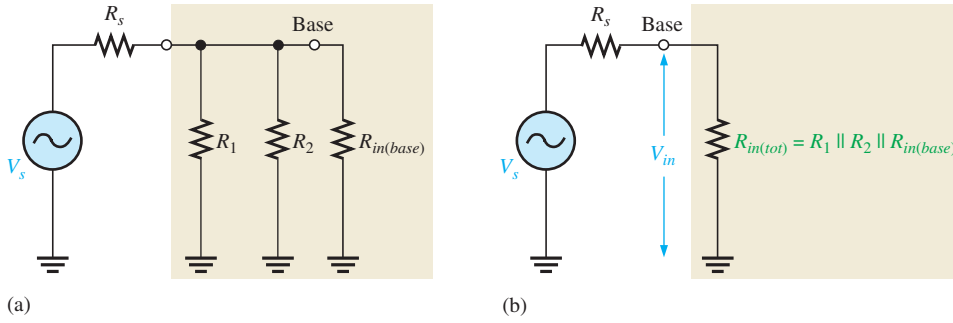
AC equivalent of the base circuit.

(a)   (b)

Q-point, which requires smaller resistors. The conflicting requirement for high input resistance and stable biasing is but one of the many trade-offs that must be considered when choosing components for a circuit. The total input resistance is expressed by the following formula:

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)}$$

Equation 6–2

As you can see in the figure, the source voltage, V_s, is divided down by R_s (source resistance) and $R_{in(tot)}$ so that the signal voltage at the base of the transistor is found by the voltage-divider formula as follows:

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}} \right) V_s$$

If $R_s \ll R_{in(tot)}$, then $V_b \cong V_s$ where V_b is the input voltage, V_{in}, to the amplifier.

Input Resistance at the Base   To develop an expression for the ac input resistance looking in at the base, use the simplified *r*-parameter model of the transistor. Figure 6–12 shows the transistor model connected to the external collector resistor, R_C. The input resistance looking in at the base is

$$R_{in(base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b}$$

The base voltage is

$$V_b = I_e r'_e$$

and since $I_e \cong I_c$,

$$I_b \cong \frac{I_e}{\beta_{ac}}$$

Substituting for V_b and I_b,

$$R_{in(base)} = \frac{V_b}{I_b} = \frac{I_e r'_e}{I_e / \beta_{ac}}$$

Cancelling I_e,

$$R_{in(base)} = \beta_{ac} r'_e$$

Equation 6–3

r-parameter transistor model (inside shaded block) connected to external circuit.

Output Resistance   The **output resistance** of the common-emitter amplifier is the resistance looking in at the collector and is approximately equal to the collector resistor.

$$R_{out} \cong R_C$$

Equation 6–4

Actually, $R_{out} = R_C \parallel r'_c$, but since the internal ac collector resistance of the transistor, r'_c, is typically much larger than R_C, the approximation is usually valid.
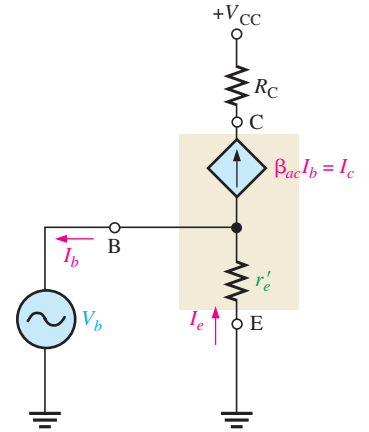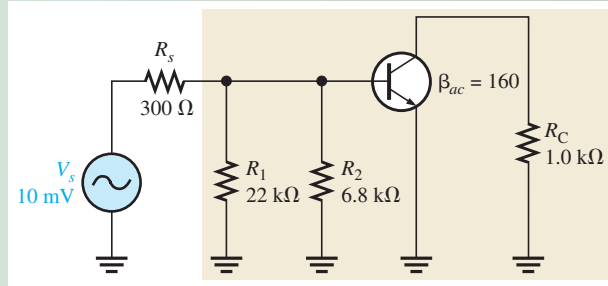
EXAMPLE 6–4

Determine the signal voltage at the base of the transistor in Figure 6–13. This circuit is the ac equivalent of the amplifier in Figure 6–8 with a 10 mV rms, 300 Ω signal source. I_E was previously found to be 3.58 mA.

▶ FIGURE 6–13

Solution First, determine the ac emitter resistance.

$$r'_e \cong \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{3.58 \text{ mA}} = 6.98 \text{ }\Omega$$

Then,

$$R_{in(base)} = \beta_{ac}r'_e = 160(6.98 \text{ }\Omega) = 1.12 \text{ k}\Omega$$

Next, determine the total input resistance viewed from the source.

$$R_{in(tot)} = R_1 \| R_2 \| R_{in(base)} = \frac{1}{\frac{1}{22 \text{ k}\Omega} + \frac{1}{6.8 \text{ k}\Omega} + \frac{1}{1.12 \text{ k}\Omega}} = 920 \text{ }\Omega$$

The source voltage is divided down by R_s and $R_{in(tot)}$, so the signal voltage at the base is the voltage across $R_{in(tot)}$.

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}}\right)V_s = \left(\frac{920 \text{ }\Omega}{1221 \text{ }\Omega}\right)10 \text{ mV} = \textbf{7.53 mV}$$

As you can see, there is significant attenuation (reduction) of the source voltage due to the source resistance and amplifier's input resistance combining to act as a voltage divider.

Related Problem Determine the signal voltage at the base of Figure 6–13 if the source resistance is 75 Ω and another transistor with an ac beta of 200 is used.
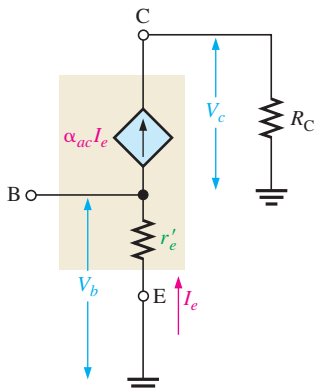
▲ FIGURE 6–14

Model circuit for obtaining ac voltage gain.

Voltage Gain

The ac voltage gain expression for the common-emitter amplifier is developed using the model circuit in Figure 6–14. The gain is the ratio of ac output voltage at the collector (V_c) to ac input voltage at the base (V_b).

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_b}$$

Notice in the figure that $V_c = \alpha_{ac}I_eR_C \cong I_eR_C$ and $V_b = I_er'_e$. Therefore,

$$A_v = \frac{I_eR_C}{I_er'_e}$$

The I_e terms cancel, so

$$A_v = \frac{R_C}{r'_e}$$

Equation 6–5 is the voltage gain from base to collector. To get the overall gain of the amplifier from the source voltage to collector, the attenuation of the input circuit must be included.

Attenuation is the reduction in signal voltage as it passes through a circuit and corresponds to a gain of less than 1. For example, if the signal amplitude is reduced by half, the attenuation is 2, which can be expressed as a gain of 0.5 because gain is the reciprocal of attenuation. Suppose a source produces a 10 mV input signal and the source resistance combined with the load resistance results in a 2 mV output signal. In this case, the attenuation is 10 mV/2 mV = 5. That is, the input signal is reduced by a factor of 5. This can be expressed in terms of gain as 1/5 = 0.2.

Assume that the amplifier in Figure 6–15 has a voltage gain from base to collector of A_v and the attenuation from the source to the base is V_s/V_b. This attenuation is produced by the source resistance and total input resistance of the amplifier acting as a voltage divider and can be expressed as

$$\text{Attenuation} = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}}$$

The overall voltage gain of the amplifier, A'_v, is the voltage gain from base to collector, V_c/V_b, times the reciprocal of the attenuation, V_b/V_s.

$$A'_v = \left(\frac{V_c}{V_b}\right)\left(\frac{V_b}{V_s}\right) = \frac{V_c}{V_s}$$
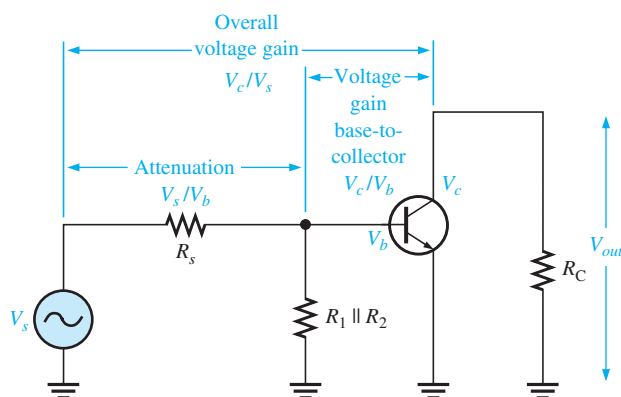
▲ **FIGURE 6–15**

Base circuit attenuation and overall voltage gain.

Effect of the Emitter Bypass Capacitor on Voltage Gain   The emitter **bypass capacitor**, which is C_2 in Figure 6–8, provides an effective short to the ac signal around the emitter resistor, thus keeping the emitter at ac ground, as you have seen. With the bypass capacitor, the gain of a given amplifier is maximum and equal to R_C/r'_e.

The value of the bypass capacitor must be large enough so that its reactance over the frequency range of the amplifier is very small (ideally 0 Ω) compared to R_E. A good rule of thumb is that the capacitive reactance, X_C, of the bypass capacitor should be at least 10 times smaller than R_E at the minimum frequency for which the amplifier must operate.

$$10X_C \leq R_E$$

EXAMPLE 6–5

Select a minimum value for the emitter bypass capacitor, C_2, in Figure 6–16 if the amplifier must operate over a frequency range from 200 Hz to 10 kHz.

▶ **FIGURE 6–16**
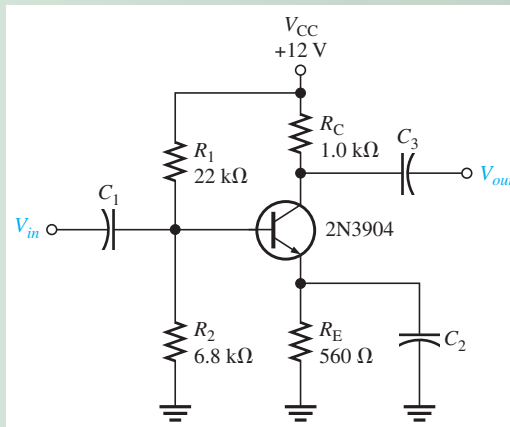
Solution The X_C of the bypass capacitor, C_2, should be at least ten times less than R_E.

$$X_{C2} = \frac{R_E}{10} = \frac{560 \ \Omega}{10} = 56 \ \Omega$$

Determine the capacitance value at the minimum frequency of 200 Hz as follows:

$$C_2 = \frac{1}{2\pi f X_{C2}} = \frac{1}{2\pi(200 \ \text{Hz})(56 \ \Omega)} = \textbf{14.2} \ \boldsymbol{\mu}\textbf{F}$$

This is the minimum value for the bypass capacitor for this circuit. You can always use a larger value, although cost and physical size may impose limitations.

Related Problem If the minimum frequency is reduced to 100 Hz, what value of bypass capacitor must you use?

Voltage Gain Without the Bypass Capacitor   To see how the bypass capacitor affects ac voltage gain, let's remove it from the circuit in Figure 6–16 and compare voltage gains.

Without the bypass capacitor, the emitter is no longer at ac ground. Instead, R_E is seen by the ac signal between the emitter and ground and effectively adds to r'_e in the voltage gain formula.

Equation 6–6

$$A_v = \frac{R_C}{r'_e + R_E}$$

The effect of R_E is to decrease the ac voltage gain.

EXAMPLE 6–6

Calculate the base-to-collector voltage gain of the amplifier in Figure 6–16 both without and with an emitter bypass capacitor if there is no load resistor.

Solution From Example 6–4, $r'_e = 6.98 \ \Omega$ for this same amplifier. Without C_2, the gain is

$$A_v = \frac{R_C}{r'_e + R_E} = \frac{1.0 \ \text{k}\Omega}{567 \ \Omega} = \textbf{1.76}$$

With C_2, the gain is

$$A_v = \frac{R_C}{r'_e} = \frac{1.0 \text{ k}\Omega}{6.98 \text{ }\Omega} = 143$$

As you can see, the bypass capacitor makes quite a difference.

Related Problem   Determine the base-to-collector voltage gain in Figure 6–16 with R_E bypassed, for the following circuit values: $R_C = 1.8 \text{ k}\Omega$, $R_E = 1.0 \text{ k}\Omega$, $R_1 = 33 \text{ k}\Omega$, and $R_2 = 6.8 \text{ k}\Omega$.

Effect of a Load on the Voltage Gain   A **load** is the amount of current drawn from the output of an amplifier or other circuit through a load resistance. When a resistor, R_L, is connected to the output through the coupling capacitor C_3, as shown in Figure 6–17(a), it creates a load on the circuit. The collector resistance at the signal frequency is effectively R_C in parallel with R_L. Remember, the upper end of R_C is effectively at ac ground. The ac equivalent circuit is shown in Figure 6–17(b). The total ac collector resistance is
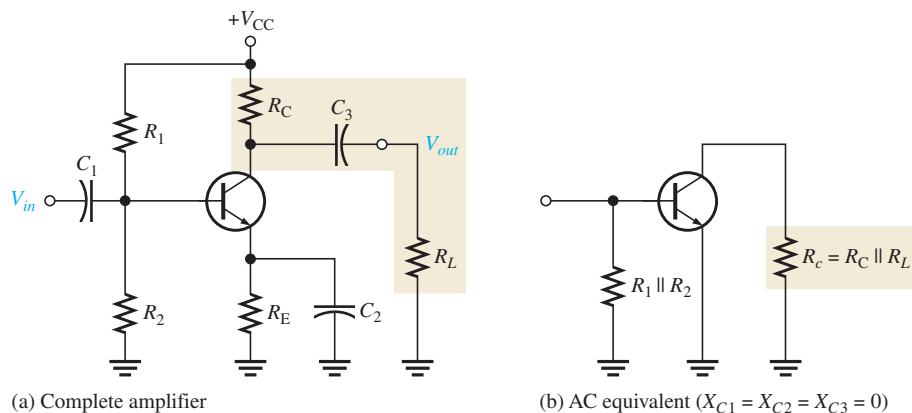
$$R_c = \frac{R_C R_L}{R_C + R_L}$$

Replacing R_C with R_c in the voltage gain expression gives

$$A_v = \frac{R_c}{r'_e}$$

Equation 6–7

When $R_c < R_C$ because of R_L, the voltage gain is reduced. However, if $R_L \gg R_C$, then $R_c \cong R_C$ and the load has very little effect on the gain.

(a) Complete amplifier

(b) AC equivalent ($X_{C1} = X_{C2} = X_{C3} = 0$)

▲ FIGURE 6–17

A common-emitter amplifier with an ac (capacitively) coupled load.

EXAMPLE 6–7   Calculate the base-to-collector voltage gain of the amplifier in Figure 6–16 when a load resistance of 5 kΩ is connected to the output. The emitter is effectively bypassed and $r'_e = 6.98 \text{ }\Omega$.

Solution   The ac collector resistance is

$$R_c = \frac{R_C R_L}{R_C + R_L} = \frac{(1.0 \text{ k}\Omega)(5 \text{ k}\Omega)}{6 \text{ k}\Omega} = 833 \text{ }\Omega$$

Therefore,

$$A_v = \frac{R_c}{r'_e} = \frac{833 \ \Omega}{6.98 \ \Omega} = \mathbf{119}$$

The unloaded gain was found to be 143 in Example 6–6.

Related Problem   Determine the base-to-collector voltage gain in Figure 6–16 when a 10 kΩ load resist-
ance is connected from collector to ground. Change the resistance values as follows:
$R_C = 1.8$ kΩ, $R_E = 1.0$ kΩ, $R_1 = 33$ kΩ, and $R_2 = 6.8$ kΩ. The emitter resistor is
effectively bypassed and $r'_e = 18.5 \ \Omega$.

Stability of the Voltage Gain

Stability is a measure of how well an amplifier maintains its design values over changes in
temperature or for a transistor with a different β. Although bypassing R_E does produce the
maximum voltage gain, there is a stability problem because the ac voltage gain is depend-
ent on r'_e since $A_v = R_C/r'_e$. Also, r'_e depends on I_E and on temperature. This causes the gain
to be unstable over changes in temperature because when r'_e increases, the gain decreases
and vice versa.

    With no bypass capacitor, the gain is decreased because R_E is now in the ac circuit
$(A_v = R_C/(r'_e + R_E))$. However, with R_E unbypassed, the gain is much less dependent on r'_e.
If $R_E \gg r'_e$, the gain is essentially independent of r'_e because

$$A_v \cong \frac{R_C}{R_E}$$

Swamping r'_e to Stabilize the Voltage Gain   *Swamping* is a method used to minimize the
effect of r'_e without reducing the voltage gain to its minimum value. This method "swamps"
out the effect of r'_e on the voltage gain. Swamping is, in effect, a compromise between hav-
ing a bypass capacitor across R_E and having no bypass capacitor at all. Whenever a bypass
capacitor is used, its reactance should be small compared to the ac emitter resistance at the
lowest frequency at which the amplifier will be used.

    In a swamped amplifier, R_E is partially bypassed so that a reasonable gain can be
achieved, and the effect of r'_e on the gain is greatly reduced or eliminated. The total ex-
ternal emitter resistance, R_E, is formed with two separate emitter resistors, R_{E1} and R_{E2}, as
indicated in Figure 6–18. One of the resistors, R_{E2}, is bypassed and the other is not.

    Both resistors $(R_{E1} + R_{E2})$ affect the dc bias while only R_{E1} affects the ac voltage gain.

$$A_v = \frac{R_C}{r'_e + R_{E1}}$$

▶ **FIGURE 6–18**

A swamped amplifier uses a partially
bypassed emitter resistance to mini-
mize the effect of r'_e on the gain in
order to achieve gain stability.
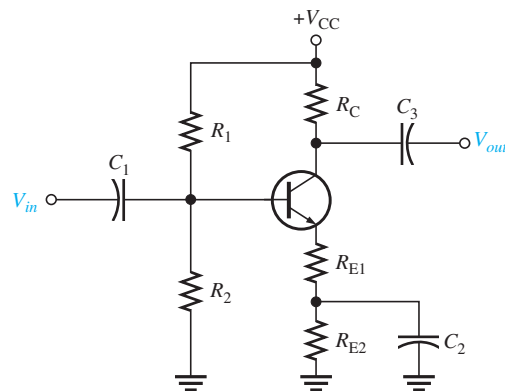
If R_{E1} is at least ten times larger than r'_e, then the effect of r'_e is minimized and the approximate voltage gain for the swamped amplifier is
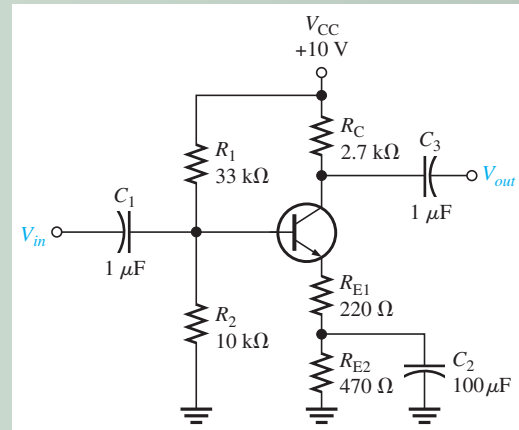
$$A_v \cong \frac{R_C}{R_{E1}}$$

EXAMPLE 6–8

Determine the voltage gain of the swamped amplifier in Figure 6–19. Assume that the bypass capacitor has a negligible reactance for the frequency at which the amplifier is operated. Assume $r'_e = 15\ \Omega$.

▶ **FIGURE 6–19**

Solution R_{E2} is bypassed by C_2. R_{E1} is more than ten times r'_e so the approximate voltage gain is

$$A_v \cong \frac{R_C}{R_{E1}} = \frac{2.7\ \text{k}\Omega}{220\ \Omega} = 12$$

Related Problem   What would be the voltage gain without C_2? What would be the approximate voltage gain if R_{E1} and R_{E2} were exchanged?

The Effect of Swamping on the Amplifier's Input Resistance   The ac input resistance, looking in at the base of a common-emitter amplifier with R_E completely bypassed, is $R_{in} = \beta_{ac}r'_e$. When the emitter resistance is partially bypassed, the portion of the resistance that is unbypassed is seen by the ac signal and results in an increase in the ac input resistance by appearing in series with r'_e. The formula is
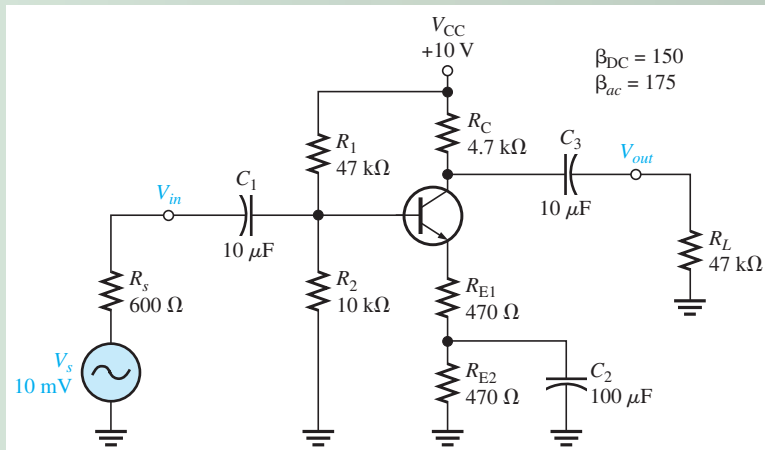
$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1})$$

EXAMPLE 6–9

For the amplifier in Figure 6–20,

(a) Determine the dc collector voltage.

(b) Determine the ac collector voltage.

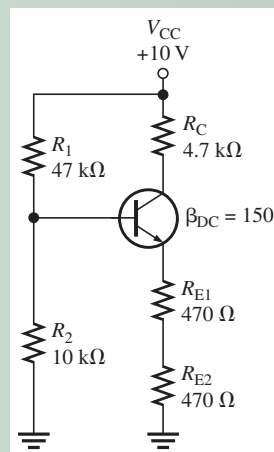**(c)** Draw the total collector voltage waveform and the total output voltage waveform.

Solution (a) Determine the dc bias values using the dc equivalent circuit in Figure 6–21.

▶ FIGURE 6–21

DC equivalent for the circuit in
Figure 6–20.

Apply Thevenin's theorem and Kirchhoff's voltage law to the base-emitter circuit in
Figure 6–21.

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(47 \text{ k}\Omega)(10 \text{ k}\Omega)}{47 \text{ k}\Omega + 10 \text{ k}\Omega} = 8.25 \text{ k}\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{10 \text{ k}\Omega}{47 \text{ k}\Omega + 10 \text{ k}\Omega}\right)10 \text{ V} = 1.75 \text{ V}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{1.75 \text{ V} - 0.7 \text{ V}}{940 \text{ }\Omega + 55 \text{ }\Omega} = 1.06 \text{ mA}$$

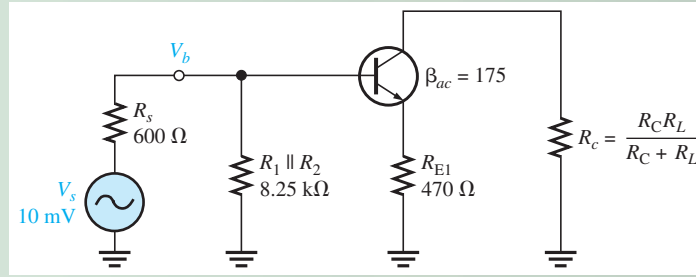$$I_C \cong I_E = 1.06 \text{ mA}$$

$$V_E = I_E(R_{E1} + R_{E2}) = (1.06 \text{ mA})(940 \text{ }\Omega) = 1 \text{ V}$$

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

$$V_C = V_{CC} - I_C R_C = 10 \text{ V} - (1.06 \text{ mA})(4.7 \text{ k}\Omega) = \textbf{5.02 V}$$

(a) The ac analysis is based on the ac equivalent circuit in Figure 6–22.

AC equivalent for the circuit in Figure 6–20.

The first thing to do in the ac analysis is calculate r'_e.

$$r'_e \cong \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{1.06 \text{ mA}} = 23.6 \text{ } \Omega$$

Next, determine the attenuation in the base circuit. Looking from the 600 Ω source, the total R_{in} is

$$R_{in(tot)} = R_1 \| R_2 \| R_{in(base)}$$
$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1}) = 175(494 \text{ } \Omega) = 86.5 \text{ k}\Omega$$

Therefore,

$$R_{in(tot)} = 47 \text{ k}\Omega \| 10 \text{ k}\Omega \| 86.5 \text{ k}\Omega = 7.53 \text{ k}\Omega$$

The attenuation from source to base is

$$\text{Attenuation } = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}} = \frac{600 \text{ } \Omega + 7.53 \text{ k}\Omega}{7.53 \text{ k}\Omega} = 1.08$$

Before A_v can be determined, you must know the ac collector resistance R_c.

$$R_c = \frac{R_C R_L}{R_C + R_L} = \frac{(4.7 \text{ k}\Omega)(47 \text{ k}\Omega)}{4.7 \text{ k}\Omega + 47 \text{ k}\Omega} = 4.27 \text{ k}\Omega$$

The voltage gain from base to collector is

$$A_v \cong \frac{R_c}{R_{E1}} = \frac{4.27 \text{ k}\Omega}{470 \text{ } \Omega} = 9.09$$

The overall voltage gain is the reciprocal of the attenuation times the amplifier voltage gain.

$$A'_v = \left(\frac{V_b}{V_s}\right) A_v = (0.93)(9.09) = 8.45$$

The source produces 10 mV rms, so the rms voltage at the collector is

$$V_c = A'_v V_s = (8.45)(10 \text{ mV}) = \textbf{84.5 mV}$$

(b) The total collector voltage is the signal voltage of 84.5 mV rms riding on a dc level of 4.74 V, as shown in Figure 6–23(a), where approximate peak values are determined as follows:
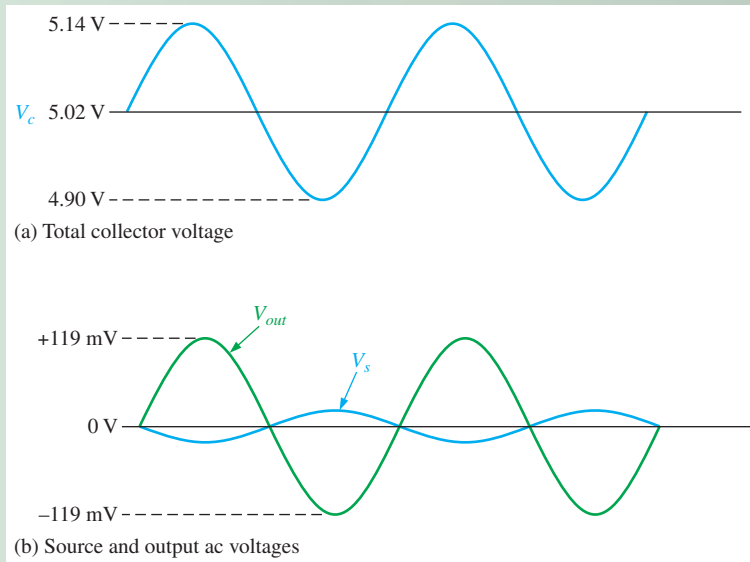
$$\text{Max } V_{c(p)} = V_C + 1.414 \, V_c = 5.02 \text{ V} + (84.5 \text{ mV})(1.414) = 5.14 \text{ V}$$
$$\text{Min } V_{c(p)} = V_C - 1.414 \, V_c = 5.02 \text{ V} - (84.5 \text{ mV})(1.414) = 4.90 \text{ V}$$

The coupling capacitor, C_3, keeps the dc level from getting to the output. So, V_{out} is equal to the ac component of the collector voltage ($V_{out(p)} = (84.5 \text{ mV})(1.414) = 119 \text{ mV}$),

Voltages for Figure 6–20.

(a) Total collector voltage

(b) Source and output ac voltages

as indicated in Figure 6–23(b). The source voltage, V_s, is shown to emphasize the phase inversion.

Related Problem   What is A_v in Figure 6–20 with R_L removed?

Open the Multisim file EXM06-09 or the LT Spice file EXS06-09 in the Examples folder on the website. Measure the dc and the ac values of the collector voltage and compare with the calculated values.

Current Gain

The focus in this section has been on voltage gain because that is the principal use for a CE amplifier. However, for completeness, we end this section with a discussion of current and power gain. The current gain from base to collector is I_c/I_b or β_{ac}. However, the overall current gain of the common-emitter amplifier is

Equation 6–10

$$A_i = \frac{I_c}{I_s}$$

I_s is the total signal input current produced by the source, part of which (I_b) is base current and part of which (I_{bias}) goes through the bias circuit ($R_1 \parallel R_2$), as shown in Figure 6–24. The source "sees" a total resistance of $R_s + R_{in(tot)}$. The total current produced by the source is

$$I_s = \frac{V_s}{R_s + R_{in(tot)}}$$

Signal currents (directions shown are for the positive half-cycle of V_s).
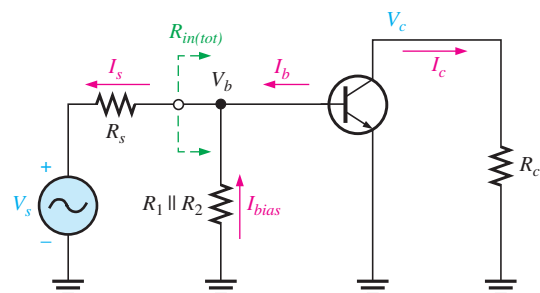
The ac current in the collector circuit is composed of current in the collector resistor, R_C and current in the load resistor R_L. If you are interested in current gain to the load, you need to apply the current divider rule to these resistors to determine ac load current.

Power Gain

As mentioned, CE amplifiers are rarely used to provide power gain. However, for completeness, the overall power gain is the product of the overall voltage gain (A'_v) and the overall current gain (A_i).

$$A_p = A'_v A_i$$

where $A'_v = V_c/V_s$. If you are interested in power gain to just the load, then the formula uses voltage gain times the current gain to the load rather than the overall current gain.

SECTION 6–3 CHECKUP	1. In the dc equivalent circuit of an amplifier, how are the capacitors treated? 2. When the emitter resistor is bypassed with a capacitor, how is the gain of the amplifier affected? 3. Explain swamping. 4. List the elements included in the total input resistance of a common-emitter amplifier. 5. What elements determine the overall voltage gain of a common-emitter amplifier? 6. When a load resistor is capacitively coupled to the collector of a CE amplifier, is the voltage gain increased or decreased? 7. What is the phase relationship of the input and output voltages of a CE amplifier?

6–4 THE COMMON-COLLECTOR AMPLIFIER

The **common-collector** (CC) amplifier is usually referred to as an emitter-follower (EF). The input is applied to the base through a coupling capacitor, and the output is at the emitter. The voltage gain of a CC amplifier is approximately 1, and its main advantages are its high input resistance and current gain.

After completing this section, you should be able to

❑ **Describe and analyze the operation of common-collector amplifiers**
❑ Discuss the emitter-follower amplifier with voltage-divider bias
❑ Analyze the amplifier for voltage gain
  ◆ Explain the term *emitter-follower*
❑ Discuss and calculate input resistance
❑ Determine output resistance
❑ Determine current gain to the load
❑ Determine power gain to the load
❑ Describe the Darlington pair
  ◆ Discuss an application
❑ Discuss the Sziklai pair

An **emitter-follower** circuit with voltage-divider bias is shown in Figure 6–25. Notice that the input signal is capacitively coupled to the base, the output signal is capacitively coupled from the emitter, and the collector is at ac ground. There is no phase inversion, and the output is approximately the same amplitude as the input.

Emitter-follower with voltage-divider bias.
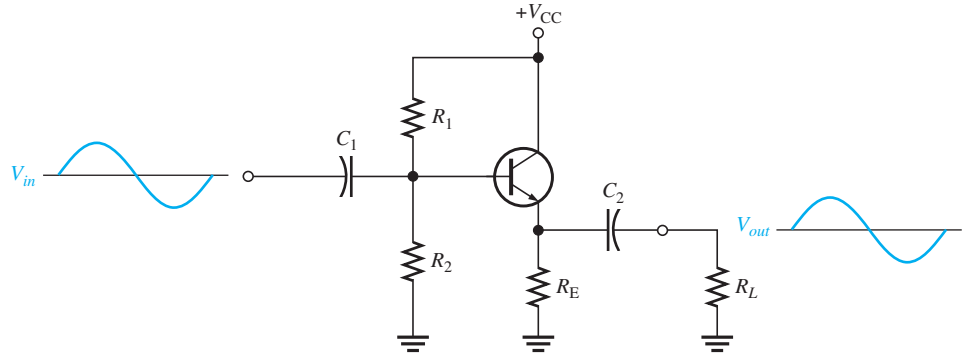
Voltage Gain

As in all amplifiers, the voltage gain is $A_v = V_{out}/V_{in}$. The capacitive reactances are assumed to be negligible at the frequency of operation. For the emitter-follower, as shown in the ac model in Figure 6–26,

$$V_{out} = I_e R_e$$

and

$$V_{in} = I_e(r'_e + R_e)$$

Therefore, the voltage gain is

$$A_v = \frac{I_e R_e}{I_e(r'_e + R_e)}$$

The I_e current terms cancel, and the base-to-emitter voltage gain expression simplifies to

$$A_v = \frac{R_e}{r'_e + R_e}$$

where R_e is the parallel combination of R_E and RL. If there is no load, then $R_e = R_E$. Notice that the voltage gain is always less than 1. If $R_e \gg r'_e$, then a good approximation is

Equation 6–12

$$A_v \cong 1$$

Since the output voltage is at the emitter, it is in phase with the base voltage, so there is no inversion from input to output. Because there is no inversion and because the voltage gain is approximately 1, the output voltage closely follows the input voltage in both phase and amplitude; thus the term *emitter-follower*.

Emitter-follower model for voltage gain derivation.
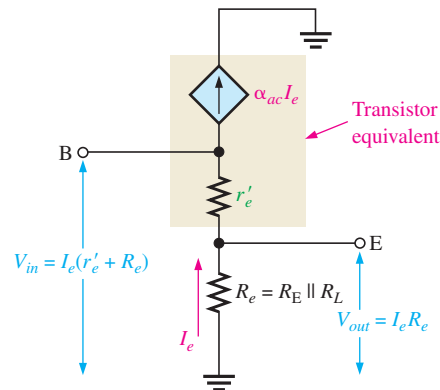
Input Resistance

The emitter-follower is characterized by a high input resistance and low output resistance; this is what makes it a useful circuit. Because of the high input resistance, it can be used as a buffer to minimize loading effects when a circuit is driving a low-resistance load. The

derivation of the input resistance, looking in at the base of the common-collector amplifier, is similar to that for the common-emitter amplifier. In a common-collector circuit, however, the emitter resistor is *never* bypassed because the output is taken across R_e, which is R_E in parallel with R_L.

$$R_{in(base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b} = \frac{I_e(r'_e + R_e)}{I_b}$$

Since $I_e \cong I_c = \beta_{ac}I_b$,

$$R_{in(base)} \cong \frac{\beta_{ac}I_b(r'_e + R_e)}{I_b}$$

The I_b terms cancel; therefore,

$$R_{in(base)} \cong \beta_{ac}(r'_e + R_e)$$

If $R_e \gg r'_e$, then the input resistance at the base is simplified to

$$R_{in(base)} \cong \beta_{ac}R_e$$

Equation 6–13

The bias resistors in Figure 6–25 appear in parallel with $R_{in(base)}$, looking from the input source; and just as in the common-emitter circuit, the total input resistance is

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)}$$

Output Resistance

With the load removed, the output resistance, looking into the emitter of the emitter-follower, is approximated as follows:

$$R_{out} \cong \left(\frac{R_s}{\beta_{ac}}\right) \parallel R_E$$

Equation 6–14

R_s is the resistance of the input source. The derivation of Equation 6–14, found in "Derivations of Selected Equations" at www.pearsonhighered.com/floyd, is relatively involved and several assumptions have been made. The output resistance is very low, making the emitter-follower useful for driving low-resistance loads.

Current Gain

Although the voltage gain is less than 1, the current gain is not. The current gain for the emitter-follower in Figure 6–25 is

$$A_i = \frac{I_e}{I_{in}}$$

Equation 6–15

where $I_{in} = V_{in}/R_{in(tot)}$.

Notice that I_e in Equation 6–15 includes both emitter and load currents. If you want only the current gain to the load, you can apply the current divider rule.

Power Gain

The common-collector power gain is the product of the voltage gain and the current gain. For the emitter-follower, the power gain is approximately equal to the current gain because the voltage gain is approximately 1.

$$A_p = A_v A_i$$

Since $A_v \cong 1$, the total power gain is

$$A_p \cong A_i$$

Equation 6–16

The power gain to the load is approximately equal to the current gain to the load; use the current divider rule to determine the load current.

EXAMPLE 6–10

Determine the total input resistance of the emitter-follower in Figure 6–27. Also find the voltage gain, current gain, and power gain in terms of power delivered to the load, R_L. Assume $\beta_{ac} = 175$ and that the capacitive reactances are negligible at the frequency of operation.

▶ **FIGURE 6–27**
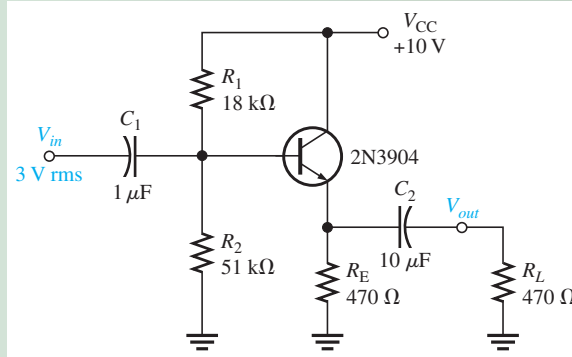
Solution   The ac emitter resistance external to the transistor is

$$R_e = R_E \| R_L = 470 \ \Omega \| 470 \ \Omega = 235 \ \Omega$$

The approximate resistance, looking in at the base, is

$$R_{in(base)} \cong \beta_{ac}R_e = (175)(235 \ \Omega) = 41.1 \ \text{k}\Omega$$

The total input resistance is

$$R_{in(tot)} = R_1 \| R_2 \| R_{in(base)} = 18 \ \text{k}\Omega \| 51 \ \text{k}\Omega \| 41.1 \ \text{k}\Omega = \mathbf{10.1 \ k\Omega}$$

The voltage gain is $A_v \cong 1$. By using r'_e, you can determine a more precise value of A_v if necessary.

$$V_E = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} - V_{BE} = \left(\frac{51 \ \text{k}\Omega}{18 \ \text{k}\Omega + 51 \ \text{k}\Omega}\right)10 \ \text{V} - 0.7 \ \text{V}$$
$$= (0.739)(10 \ \text{V}) - 0.7 \ \text{V} = 6.69 \ \text{V}$$

Therefore,

$$I_E = \frac{V_E}{R_E} = \frac{6.69 \ \text{V}}{470 \ \Omega} = 14.2 \ \text{mA}$$

and

$$r'_e \cong \frac{25 \ \text{mV}}{I_E} = \frac{25 \ \text{mV}}{14.2 \ \text{mA}} = 1.76 \ \Omega$$

So,

$$A_v = \frac{R_e}{r'_e + R_e} = \frac{235 \ \Omega}{237 \ \Omega} = \mathbf{0.992}$$

The small difference in A_v as a result of considering r'_e is insignificant in most cases.

The total current gain is $A_i = I_e/I_{in}$. The calculations are as follows:

$$I_e = \frac{V_e}{R_e} = \frac{A_v V_b}{R_e} \cong \frac{(0.992)(3 \ \text{V})}{235 \ \Omega} = \frac{2.98 \ \text{V}}{235 \ \Omega} = 12.7 \ \text{mA}$$

$$I_{in} = \frac{V_{in}}{R_{in(tot)}} = \frac{3 \ \text{V}}{10.1 \ \text{k}\Omega} = 297 \ \mu\text{A}$$

$$A_i = \frac{I_e}{I_{in}} = \frac{12.7 \ \text{mA}}{297 \ \mu\text{A}} = \mathbf{42.8}$$

The total power gain is

$$A_p \cong A_i = 42.8$$

Since $R_L = R_E$, one-half of the power is dissipated in R_E and one-half in R_L. Therefore, in terms of power to the load, the power gain is

$$A_{p(load)} = \frac{A_p}{2} = \frac{42.8}{2} = \textbf{21.4}$$

If R_E is not equal to R_L, apply the current divider rule to find the current in the load resistor.

Related Problem   If R_L in Figure 6–27 is decreased in value, does power gain to the load increase or decrease?

MultiSim   Open the Multisim file EXM06-10 or the LT Spice file EXS06-10 in the Examples
LT Spice   folder on the website. Measure the voltage gain and compare with the calculated value.

The Darlington Pair

As you have seen, β_{ac} is a major factor in determining the input resistance of an amplifier. The β_{ac} of the transistor limits the maximum achievable input resistance you can get from a given emitter-follower circuit.

One way to boost input resistance is to use a **Darlington pair,** as shown in Figure 6–28. The collectors of two transistors are connected, and the emitter of the first drives the base of the second. This configuration achieves β_{ac} multiplication as shown in the following steps. The emitter current of the first transistor is

$$I_{e1} \cong \beta_{ac1}I_{b1}$$

This emitter current becomes the base current for the second transistor, producing a second emitter current of

$$I_{e2} \cong \beta_{ac2}I_{e1} = \beta_{ac1}\beta_{ac2}I_{b1}$$

Therefore, the effective current gain of the Darlington pair is

$$\beta_{ac} = \beta_{ac1}\beta_{ac2}$$

Neglecting r'_e by assuming that it is much smaller than R_E, the input resistance is

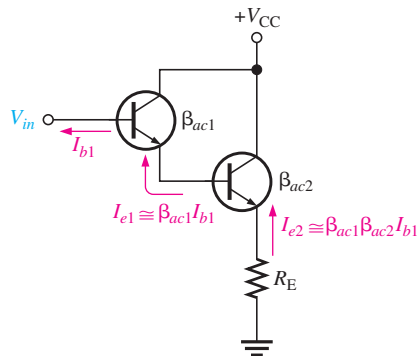$$R_{in} = \beta_{ac1}\beta_{ac2}R_E$$ Equation 6–17

◄ **FIGURE 6–28**

A Darlington pair multiplies β_{ac}, thus increasing the input resistance.

An Application   The emitter-follower is often used as an interface between a circuit with a high output resistance and a low-resistance load. In such an application, the emitter-follower is called a *buffer*.

Suppose a common-emitter amplifier with a 1.0 kΩ collector resistance must drive a low-resistance load such as an 8 Ω low-power speaker. If the speaker is capacitively coupled to the output of the amplifier, the 8 Ω load appears—to the ac signal—in parallel with the 1.0 kΩ collector resistor. This results in an ac collector resistance of

$$R_c = R_C \| R_L = 1.0 \text{ k}\Omega \| 8 \text{ }\Omega = 7.94 \text{ }\Omega$$

Obviously, this is not acceptable because most of the voltage gain is lost ($A_v = R_c/r'_e$). For example, if $r'_e = 5 \text{ }\Omega$, the voltage gain is reduced from

$$A_v = \frac{R_C}{r'_e} = \frac{1.0 \text{ k}\Omega}{5 \text{ }\Omega} = 200$$

with no load to

$$A_v = \frac{R_c}{r'_e} = \frac{7.94 \text{ }\Omega}{5 \text{ }\Omega} = 1.59$$

with an 8 Ω speaker load.

An emitter-follower using a Darlington pair can be used to interface the amplifier and the speaker, as shown in Figure 6–29. This circuit is discussed further in Section 7–1 with power amplifiers, but it serves as a good example of the application of a CC amplifier.

▶ **FIGURE 6–29**

A Darlington emitter-follower used as a buffer between a common emitter amplifier and a low resistance load such as a speaker.

Partial diagram of common-emitter amplifier

Darlington emitter-follower

Load
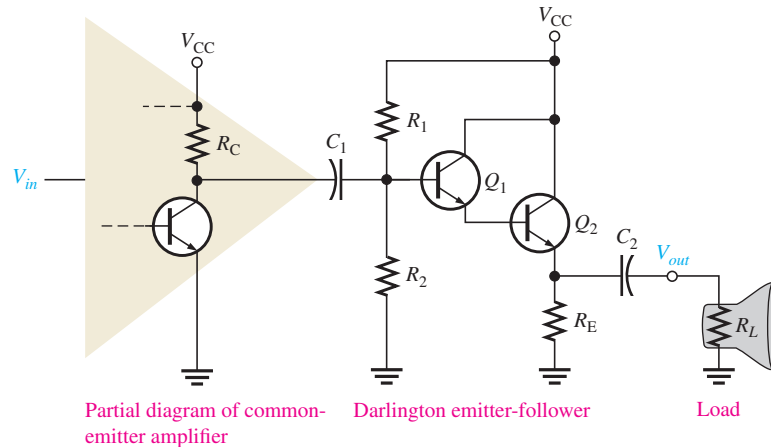
EXAMPLE 6–11

In Figure 6–29 for the common-emitter amplifier, $V_{CC} = 10$ V, $R_C = 1.0$ kΩ and $r'_e = 5 \text{ }\Omega$. For the Darlington emitter-follower, $R_1 = 10$ kΩ, $R_2 = 22$ kΩ, $R_E = 22 \text{ }\Omega$, $R_L = 8 \text{ }\Omega$, $V_{CC} = 10$ V, and $\beta_{DC} = \beta_{ac} = 100$ for each transistor. Neglect $R_{IN(BASE)}$ of the Darlington.

(a) Determine the voltage gain of the common-emitter amplifier.

(b) Determine the voltage gain of the Darlington emitter-follower.

(c) Determine the overall voltage gain and compare to the gain of the common-emitter amplifier driving the speaker directly without the Darlington emitter-follower.

Solution **(a)** To determine A_v for the common-emitter amplifier, first find r'_e for the Darlington emitter-follower.

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{22 \text{ k}\Omega}{32 \text{ k}\Omega}\right)10 \text{ V} = 6.88 \text{ V}$$

$$I_E = \frac{V_E}{R_E} = \frac{V_B - 2V_{BE}}{R_E} = \frac{6.88 \text{ V} - 1.4 \text{ V}}{22 \text{ }\Omega} = \frac{5.48 \text{ V}}{22 \text{ }\Omega} = 250 \text{ mA}$$

$$r'_e = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{250 \text{ mA}} = 100 \text{ m}\Omega$$

Note that R_E must dissipate a power of

$$P_{R_E} = I_E^2 R_E = (250 \text{ mA})^2(22 \text{ } \Omega) = 1.38 \text{ W}$$

and transistor Q_2 must dissipate

$$P_{Q2} = (V_{CC} - V_E)I_E = (4.52 \text{ V})(250 \text{ mA}) = 1.13 \text{ W}$$

Next, the ac emitter resistance of the Darlington emitter-follower is

$$R_e = R_E \| R_L = 22 \text{ } \Omega \| 8 \text{ } \Omega = 5.87 \text{ } \Omega$$

The total input resistance of the Darlington emitter-follower is

$$R_{in(tot)} = R_1 \| R_2 \| \beta_{ac}^2(r_e' + R_e)$$
$$= 10 \text{ k}\Omega \| 22 \text{ k}\Omega \| 100^2(100 \text{ m}\Omega + 5.87 \text{ } \Omega) = 6.16 \text{ k}\Omega$$

The effective ac collector resistance of the common-emitter amplifier is

$$R_c = R_C \| R_{in(tot)} = 1.0 \text{ k}\Omega \| 6.16 \text{ k}\Omega = 860 \text{ } \Omega$$

The voltage gain of the common-emitter amplifier is

$$A_v = \frac{R_c}{r_e'} = \frac{860 \text{ } \Omega}{5 \text{ } \Omega} = \textbf{172}$$

(b) The effective ac emitter resistance was found in part (a) to be 5.87 Ω. The voltage gain for the Darlington emitter-follower is

$$A_v = \frac{R_e}{r_e' + R_e} = \frac{5.87 \text{ } \Omega}{100 \text{ m}\Omega + 5.87 \text{ } \Omega} = \textbf{0.99}$$

(c) The overall voltage gain is

$$A_v' = A_{v(EF)}A_{v(CE)} = (0.99)(172) = \textbf{170}$$

If the common-emitter amplifier drives the speaker directly, the gain is 1.59 as we previously calculated.

Related Problem   Using the same circuit values, determine the voltage gain of the common-emitter amplifier in Figure 6–29 if a single transistor is used in the emitter-follower in place of the Darlington pair. Assume $\beta_{DC} = \beta_{ac} = 100$. Explain the difference in the voltage gain without the Darlington pair.

The Sziklai Pair

The **Sziklai pair,** shown in Figure 6–30, is similar to the Darlington pair except that it consists of two types of transistors, an *npn* and a *pnp*. This configuration is sometimes known as a *complementary Darlington* or a *compound transistor*. The current gain is about the same as in the Darlington pair, as illustrated. The difference is that the Q_2 base current is the Q_1 collector current instead of emitter current, as in the Darlington arrangement.

An advantage of the Sziklai pair, compared to the Darlington, is that it takes less voltage to turn it on because only one barrier potential has to be overcome. A Sziklai pair is sometimes used in conjunction with a Darlington pair as the output stage of power amplifiers. This makes it easier to obtain exact matches of the output transistors, resulting in improved thermal stability and better sound quality in audio applications.
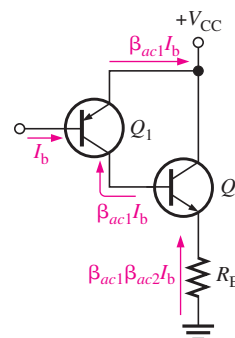
▲ **FIGURE 6–30**

The Sziklai pair.

6–5 THE COMMON-BASE AMPLIFIER

The common-base (CB) amplifier provides high voltage gain with a maximum current gain of 1. Since it has a low input resistance, the CB amplifier is the most appropriate type for certain applications where sources tend to have very low-resistance outputs.

After completing this section, you should be able to

❑ **Describe and analyze the operation of common-base amplifiers**
❑ Determine the voltage gain
   ◆ Explain why there is no phase inversion
❑ Discuss and calculate input resistance
❑ Determine output resistance
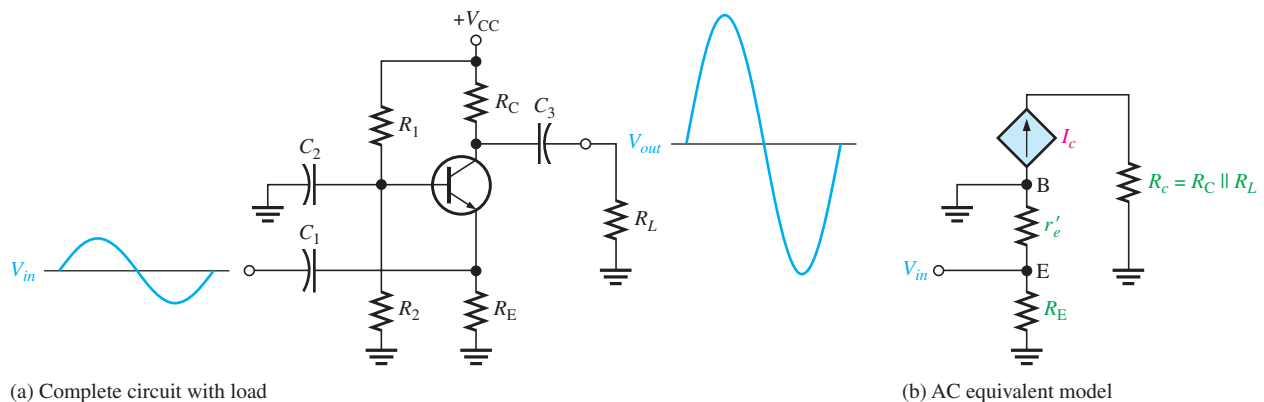❑ Determine current gain
❑ Determine power gain

FYI

The CB amplifier is useful at high frequencies when impedance matching is required because input impedance can be controlled and because noninverting amps have better frequency response than inverting amps.

A typical **common-base** amplifier is shown in Figure 6–31. The base is the common terminal and is at ac ground because of capacitor C_2. The input signal is capacitively coupled to the emitter. The output is capacitively coupled from the collector to a load resistor.

Voltage Gain

The voltage gain from emitter to collector is developed as follows ($V_{in} = V_e$, $V_{out} = V_c$).

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_e} = \frac{I_c R_c}{I_e(r'_e \parallel R_E)} \cong \frac{I_e R_c}{I_e(r'_e \parallel R_E)}$$

(a) Complete circuit with load

(b) AC equivalent model

▲ FIGURE 6–31

Common-base amplifier with voltage-divider bias.

If $R_E \gg r'_e$, then

$$A_v \cong \frac{R_c}{r'_e}$$

Equation 6–18

where $R_c = R_C \| R_L$. Notice that the gain expression is the same as for the common-emitter amplifier. However, there is no phase inversion from emitter to collector.

Input Resistance

The resistance, looking in at the emitter, is

$$R_{in(emitter)} = \frac{V_{in}}{I_{in}} = \frac{V_e}{I_e} = \frac{I_e(r'_e \| R_E)}{I_e}$$

If $R_E \gg r'_e$, then

$$R_{in(emitter)} \cong r'_e$$

Equation 6–19

R_E is typically much greater than r'_e, so the assumption that $r'_e \| R_E \cong r'_e$ is usually valid. The input resistance can be set to a desired value within limits by using a swamping resistor. This is useful in communication systems and other applications where you need to match a source impedance to prevent a reflected signal.

Output Resistance

Looking into the collector, the ac collector resistance, r'_c, appears in parallel with R_C. As you have previously seen in connection with the CE amplifier, r'_c is typically much larger than R_C, so a good approximation for the output resistance is

$$R_{out} \cong R_C$$

Equation 6–20

Current Gain

The current gain is the output current divided by the input current. I_c is the ac output current, and I_e is the ac input current. Since $I_c \cong I_e$, the current gain is approximately 1.

$$A_i \cong 1$$

Equation 6–21

Power Gain

The CB amplifier is primarily a voltage amplifier, so power gain is not too important. Since the current gain is approximately 1 for the common-base amplifier and $A_p = A_v A_i$, the total power gain is approximately equal to the voltage gain.

$$A_P \cong A_v$$

Equation 6–22

This power gain includes power to the collector resistor and to the load resistor. If you want the power gain only to the load, then divide V_{out}^2/R_L by the input power.

EXAMPLE 6–12

Find the input resistance, voltage gain, current gain, and power gain for the amplifier in Figure 6–32. $\beta_{DC} = 250$.
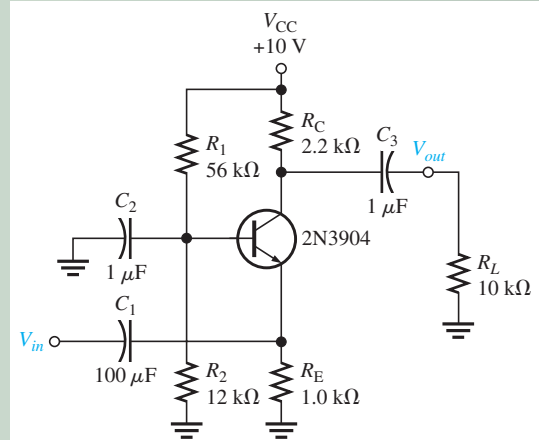
Solution First, find I_E so that you can determine r'_e. Then $R_{in} \cong r'_e$.

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2} = \frac{(56\ k\Omega)(12\ k\Omega)}{56\ k\Omega + 12\ k\Omega} = 9.88\ k\Omega$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{12\ k\Omega}{56\ k\Omega + 12\ k\Omega}\right)10\ V = 1.76\ V$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{1.76\ V - 0.7\ V}{1.0\ k\Omega + 39.5\ \Omega} = 1.02\ mA$$

Therefore,

$$R_{in} \cong r'_e = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{1.02 \text{ mA}} = \textbf{24.5 } \boldsymbol{\Omega}$$

Calculate the voltage gain as follows:

$$R_c = R_C \parallel R_L = 2.2 \text{ k}\Omega \parallel 10 \text{ k}\Omega = 1.8 \text{ k}\Omega$$

$$A_v = \frac{R_c}{r'_e} = \frac{1.8 \text{ k}\Omega}{24.5 \text{ }\Omega} = \textbf{73.5}$$

Also, $A_i \cong \textbf{1}$ and $A_p \cong A_v = \textbf{73.5.}$

Related Problem Find A_v in Figure 6–32 if $\beta_{DC} = 50$.

> Open the Multisim file EXM06-12 or the LT Spice file EXS06-12 in the Examples folder on the website. Measure the voltage gain and compare with the calculated value.

**SECTION 6–5
CHECKUP**

1. Can the same voltage gain be achieved with a common-base as with a common-emitter amplifier?
2. Does the common-base amplifier have a low or a high input resistance?
3. What is the maximum current gain in a common-base amplifier?
4. Does a common-base amplifier invert the input signal?

6–6 MULTISTAGE AMPLIFIERS

Two or more amplifiers can be connected in a **cascaded** arrangement with the output of one amplifier driving the input of the next. Each amplifier in a cascaded arrangement is known as a **stage.** The basic purpose of a multistage arrangement is to increase the overall voltage gain. Although discrete multistage amplifiers are not as common as they once were, a familiarization with this area provides insight into how circuits affect each other when they are connected together.

After completing this section, you should be able to

❏ **Describe and analyze the operation of multistage amplifiers**
❏ Determine the overall voltage gain of multistage amplifiers
  ◆ Express the voltage gain in decibels (dB)
❏ Discuss and analyze capacitively-coupled multistage amplifiers
  ◆ Describe loading effects   ◆ Determine the voltage gain of each stage in a two-stage amplifier   ◆ Determine the overall voltage gain   ◆ Determine the dc voltages
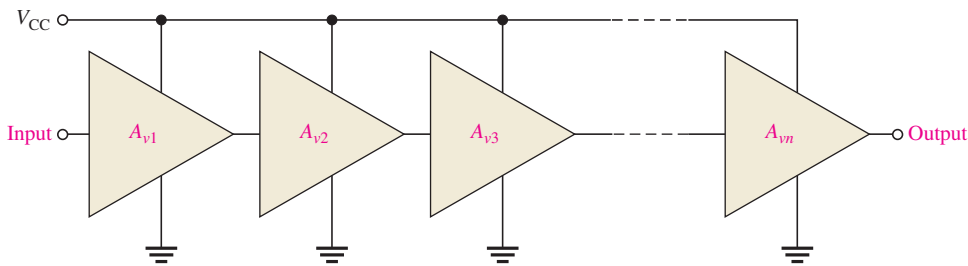❏ Describe direct-coupled multistage amplifiers

Multistage Voltage Gain

The overall voltage gain, A_v', of cascaded amplifiers, as shown in Figure 6–33, is the product of the individual voltage gains.

$$A_v' = A_{v1}A_{v2}A_{v3} \ldots A_{vn}$$

<div align="right">**Equation 6–23**</div>

where n is the number of stages.

▲ FIGURE 6–33

Cascaded amplifiers. Each triangular symbol represents a separate amplifier.

Amplifier voltage gain is often expressed in **decibels** (dB) as follows:

$$A_{v(\text{dB})} = 20 \log A_v$$

<div align="right">**Equation 6–24**</div>

This is particularly useful in **multistage** systems because the overall voltage gain in dB is the *sum* of the individual voltage gains in dB.

$$A_{v(\text{dB})}' = A_{v1(\text{dB})} + A_{v2(\text{dB})} + \cdots + A_{vn(\text{dB})}$$

EXAMPLE 6–13

A certain cascaded amplifier arrangement has the following voltage gains: $A_{v1} = 10$, $A_{v2} = 15$, and $A_{v3} = 20$. What is the overall voltage gain? Also express each gain in decibels (dB) and determine the total voltage gain in dB.

Solution

$$A_v' = A_{v1}A_{v2}A_{v3} = (10)(15)(20) = \textbf{3000}$$

$$A_{v1(\text{dB})} = 20 \log 10 = \textbf{20.0 dB}$$

$$A_{v2(\text{dB})} = 20 \log 15 = \textbf{23.5 dB}$$

$$A_{v3(\text{dB})} = 20 \log 20 = \textbf{26.0 dB}$$

$$A_{v(\text{dB})}' = 20.0 \text{ dB} + 23.5 \text{ dB} + 26.0 \text{ dB} = \textbf{69.5 dB}$$

Related Problem In a certain multistage amplifier, the individual stages have the following voltage gains: $A_{v1} = 25$, $A_{v2} = 5$, and $A_{v3} = 12$. What is the overall gain? Express each gain in dB and determine the total voltage gain in dB.

Capacitively Coupled Multistage Amplifier

For purposes of illustration, we will use the two-stage capacitively coupled amplifier in Figure 6–34. Notice that both stages are identical common-emitter amplifiers with the output of the first stage capacitively coupled to the input of the second stage. Capacitive coupling prevents the dc bias of one stage from affecting that of the other but allows the ac signal to pass without attenuation because $X_C \cong 0\ \Omega$ at the frequency of operation. Notice, also, that the transistors are labeled Q_1 and Q_2.
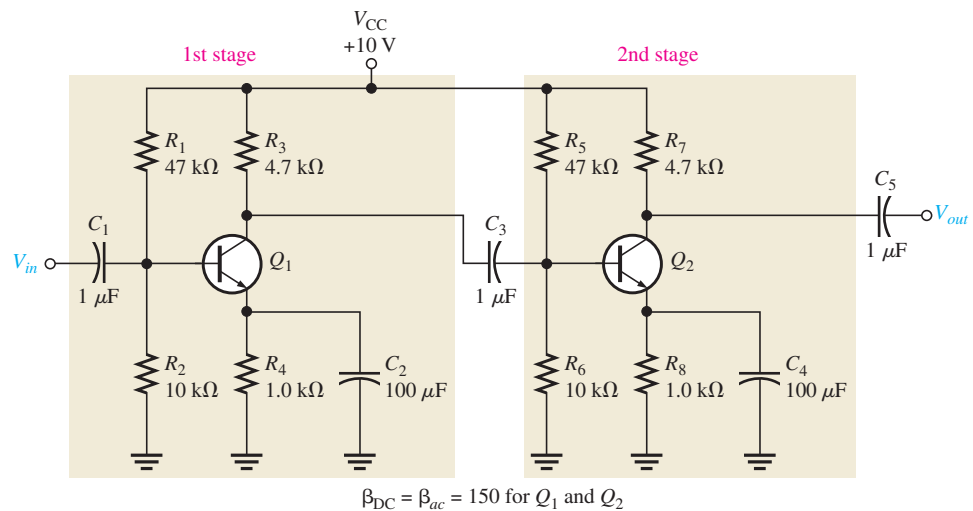
▲ **FIGURE 6–34**

A two-stage common-emitter amplifier.

Loading Effects In determining the voltage gain of the first stage, you must consider the loading effect of the second stage. Because the coupling capacitor C_3 effectively appears as a short at the signal frequency, the total input resistance of the second stage presents an ac load to the first stage.

Looking from the collector of Q_1, the two biasing resistors in the second stage, R_5 and R_6, appear in parallel with the input resistance at the base of Q_2. In other words, the signal at the collector of Q_1 "sees" R_3, R_5, R_6, and $R_{in(base2)}$ of the second stage all in parallel to ac ground. Thus, the effective ac collector resistance of Q_1 is the total of all these resistances in parallel, as Figure 6–35 illustrates. The voltage gain of the first stage is reduced by the loading of the second stage because the effective ac collector resistance of the first stage is less than the actual value of its collector resistor, R_3. Remember that $A_v = R_c/r'_e$.

Voltage Gain of the First Stage The ac collector resistance of the first stage is

$$R_{c1} = R_3 \parallel R_5 \parallel R_6 \parallel R_{in(base2)}$$

Remember that lowercase italic subscripts denote ac quantities such as for R_c.

You can verify that $I_E = 1.05$ mA, $r'_e = 23.8\ \Omega$, and $R_{in(base2)} = 3.57$ kΩ. The effective ac collector resistance of the first stage is as follows:

$$R_{c1} = 4.7\ \text{k}\Omega \parallel 47\ \text{k}\Omega \parallel 10\ \text{k}\Omega \parallel 3.57\ \text{k}\Omega = 1.63\ \text{k}\Omega$$
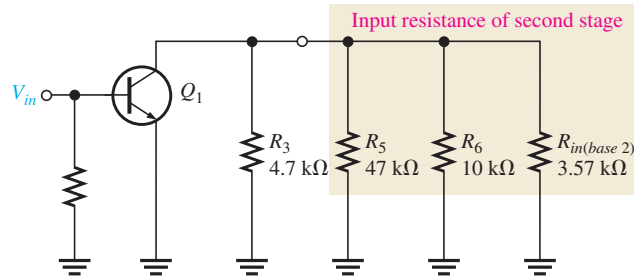
AC equivalent of first stage in Figure 6–34, showing loading from second stage input resistance.

Therefore, the base-to-collector voltage gain of the first stage is

$$A_{v1} = \frac{R_{c1}}{r'_e} = \frac{1.63 \text{ k}\Omega}{23.8 \text{ }\Omega} = 68.5$$

This can also be expressed as $A_{v1} = 36.7$ dB

Voltage Gain of the Second Stage The second stage has no load resistor, so the ac collector resistance is R_7, and the gain is

$$A_{v2} = \frac{R_7}{r'_e} = \frac{4.7 \text{ k}\Omega}{23.8 \text{ }\Omega} = 197$$

In dB, this is expressed as $A_{v2} = 45.9$ dB.

Compare this to the gain of the first stage, and notice how much the loading from the second stage reduced the gain.

Overall Voltage Gain The overall amplifier gain with no load on the output is

$$A'_v = A_{v1}A_{v2} = (68.5)(197) \cong 13,495$$

If an input signal of 100 μV, for example, is applied to the first stage and if there is no attenuation in the input base circuit due to the source resistance, an output from the second stage of $(100 \text{ }\mu\text{V})(13,495) \cong 1.35$ V will result. The overall voltage gain can be expressed in dB as follows:

$$A'_{v(\text{dB})} = 20 \log (13,495) = 82.6 \text{ dB}$$

Notice that the overall gain is also the sum of the two stages: 36.7 dB + 45.9 dB = 82.6 dB.

You can also view the amplifier as two identical gain stages separated by an attenuation network composed of a resistive divider. The unloaded gain of each stage (197) is used for the amplifiers and loading effects between stages are treated separately; these resistances form a voltage divider. The divider resistances are the source resistance of Q_1 which is the collector resistor (R_3) and the input resistance of Q_2, which is composed of $R_5 \parallel R_6 \parallel R_{in(base)}$. A simplified view of the amplifier is drawn in Figure 6–36.

Applying the voltage divider rule to the attenuation network:

$$Gain = \frac{2.49 \text{ k}\Omega}{2.49 \text{ k}\Omega + 4.7 \text{ k}\Omega} = 0.346$$

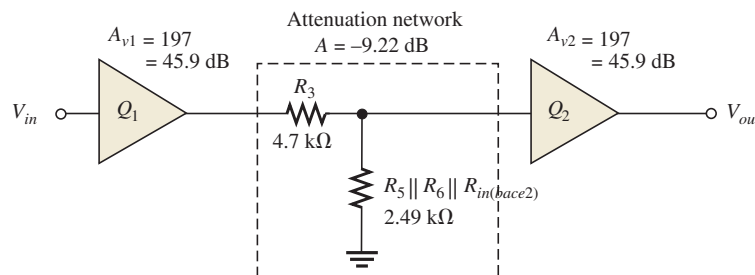Expressed in dB, the attenuation network has a gain of –9.22 dB.

Simplifying the two-stage amplifier shown in Figure 6–34.

Thus the overall gain is $(197)(0.346)(197) = 13,428$ (difference is due to round off).

Expressed in dB, the overall gain is the sum of the three parts: $45.9 \text{ dB} - 9.22 \text{ dB} + 45.9 \text{ dB} = 82.6 \text{ dB}$.

DC Voltages in the Capacitively Coupled Multistage Amplifier

Since both stages in Figure 6–34 are identical, the dc voltages for Q_1 and Q_2 are the same. Since $\beta_{DC}R_4 \gg R_2$ and $\beta_{DC}R_8 \gg R_6$, the dc base voltage for Q_1 and Q_2 is

$$V_B \cong \left(\frac{R_2}{R_1 + R_2} \right) V_{CC} = \left(\frac{10 \text{ k}\Omega}{57 \text{ k}\Omega} \right) 10 \text{ V} = 1.75 \text{ V}$$

The dc emitter and collector voltages are as follows:

$$V_E = V_B - 0.7 \text{ V} = 1.05 \text{ V}$$

$$I_E = \frac{V_E}{R_4} = \frac{1.05 \text{ V}}{1.0 \text{ k}\Omega} = 1.05 \text{ mA}$$

$$I_C \cong I_E = 1.05 \text{ mA}$$

$$V_C = V_{CC} - I_C R_3 = 10 \text{ V} - (1.05 \text{ mA})(4.7 \text{ k}\Omega) = 5.07 \text{ V}$$
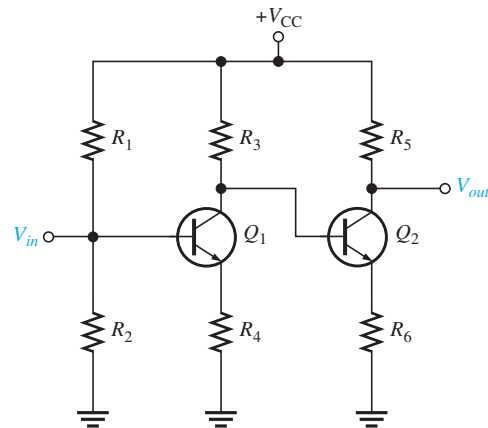
Direct-Coupled Multistage Amplifiers

A basic two-stage, direct-coupled amplifier is shown in Figure 6–37. Notice that there are no coupling or bypass capacitors in this circuit. The dc collector voltage of the first stage provides the base-bias voltage for the second stage. Because of the direct coupling, this type of amplifier has a better low-frequency response than the capacitively coupled type in which the reactance of coupling and bypass capacitors at very low frequencies may become excessive. The increased reactance of capacitors at lower frequencies produces gain reduction in capacitively coupled amplifiers.

Direct-coupled amplifiers can be used to amplify low frequencies all the way down to dc (0 Hz) without loss of voltage gain because there are no capacitive reactances in the circuit. The disadvantage of direct-coupled amplifiers, on the other hand, is that small changes in the dc bias voltages from temperature effects or power-supply variation are amplified by the succeeding stages, which can result in a significant drift in the dc levels throughout the circuit.

▶ **FIGURE 6–37**

A basic two-stage direct-coupled amplifier.

SECTION 6–6 CHECKUP

1. What does the term *stage* mean?
2. How is the overall voltage gain of a multistage amplifier determined?
3. Express a voltage gain of 500 in dB.
4. Discuss a disadvantage of a capacitively coupled amplifier.

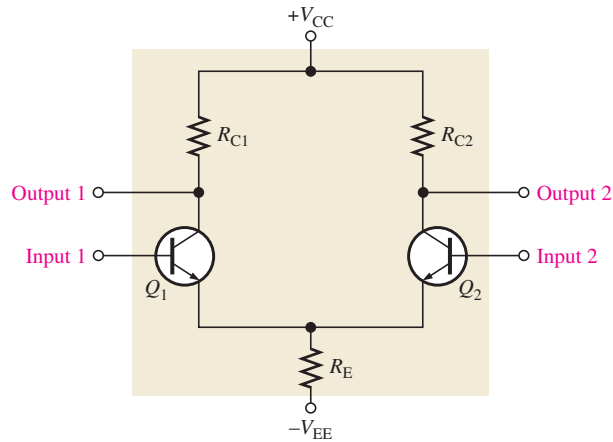## 6–7   THE DIFFERENTIAL AMPLIFIER

A **differential amplifier** is an amplifier that produces outputs that are a function of the difference between two input voltages. The differential amplifier has two basic modes of operation: differential (in which the two inputs are different) and common mode (in which the two inputs are the same). The differential amplifier is important in operational amplifiers, which are covered beginning in Chapter 12.

After completing this section, you should be able to

- ❏ **Describe the differential amplifier and its operation**
- ❏ Discuss the basic operation
    - ◆ Calculate dc currents and voltages
- ❏ Discuss the modes of signal operation
    - ◆ Describe single-ended differential input operation   ◆ Describe double-ended differential input operation   ◆ Determine common-mode operation
- ❏ Define and determine the common-mode rejection ratio (CMRR)

Basic Operation

A basic differential amplifier (diff-amp) circuit is shown in Figure 6–38. Notice that the differential amplifier has two inputs and two outputs.

◀ **FIGURE 6–38**

Basic differential amplifier.

The following discussion is in relation to Figure 6–39 and consists of a basic dc analysis of the diff-amp's operation. First, when both inputs are grounded (0 V), the emitters are at −0.7 V, as indicated in Figure 6–39(a). It is assumed that the transistors are identically matched by careful process control during manufacturing so that their dc emitter currents are the same when there is no input signal. Thus,

$$I_{E1} = I_{E2}$$

Since both emitter currents combine through R_E,

$$I_{E1} = I_{E2} = \frac{I_{R_E}}{2}$$

where

$$I_{R_E} = \frac{V_E - V_{EE}}{R_E}$$

Based on the approximation that $I_C \cong I_E$,

$$I_{C1} = I_{C2} \cong \frac{I_{R_E}}{2}$$

Since both collector currents and both collector resistors are equal (when the input voltage is zero),

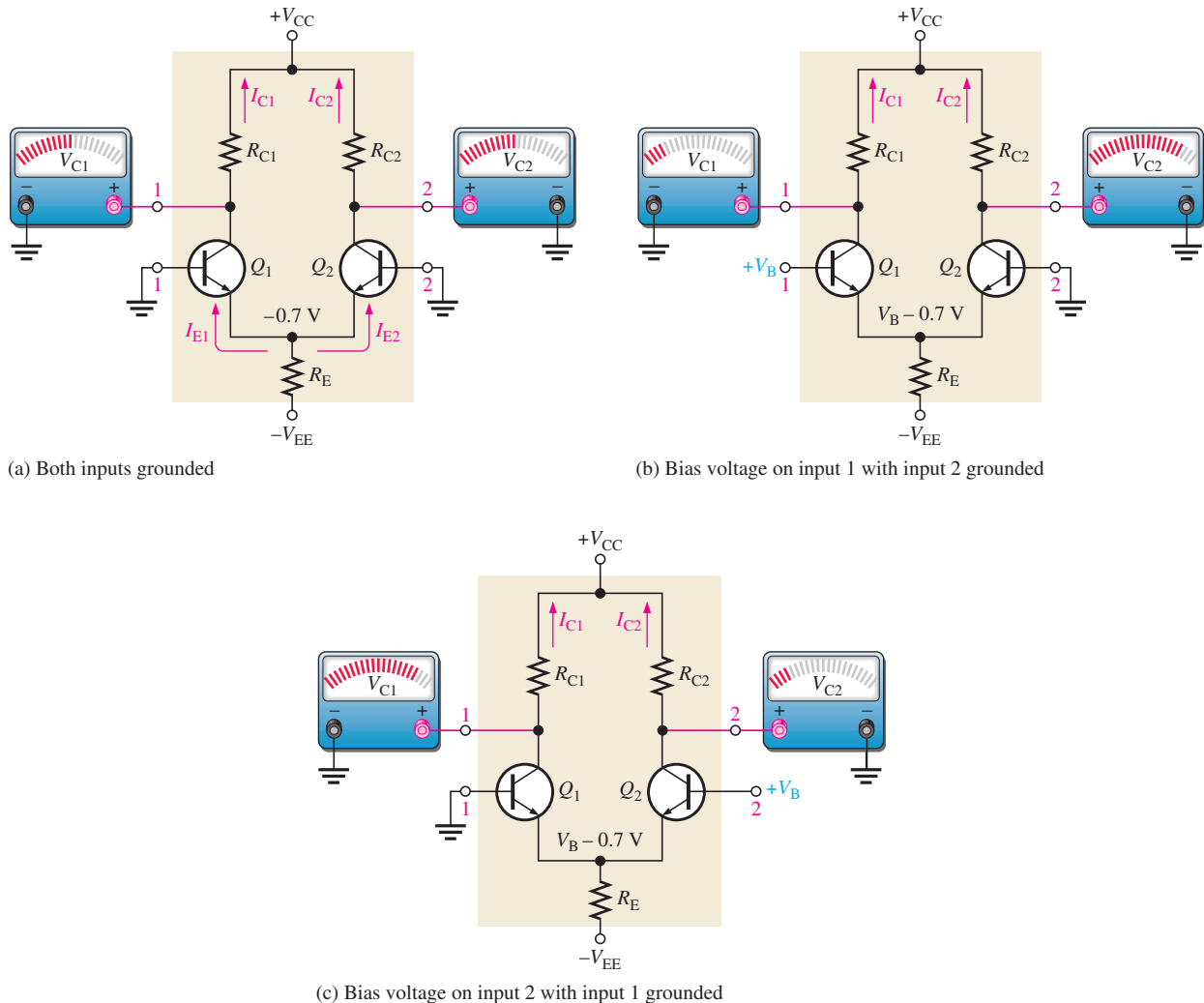$$V_{C1} = V_{C2} = V_{CC} - I_{C1}R_{C1}$$

This condition is illustrated in Figure 6–39(a).

Next, input 2 is left grounded, and a positive bias voltage is applied to input 1, as shown in Figure 6–39(b). The positive voltage on the base of Q_1 increases I_{C1} and raises the emitter voltage to

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

This action reduces the forward bias (V_{BE}) of Q_2 because its base is held at 0 V (ground), thus causing I_{C2} to decrease. The net result is that the increase in I_{C1} causes a decrease in V_{C1}, and the decrease in I_{C2} causes an increase in V_{C2}, as shown.

Finally, input 1 is grounded and a positive bias voltage is applied to input 2, as shown in Figure 6–39(c). The positive bias voltage causes Q_2 to conduct more, thus increasing I_{C2}.

(a) Both inputs grounded

(b) Bias voltage on input 1 with input 2 grounded

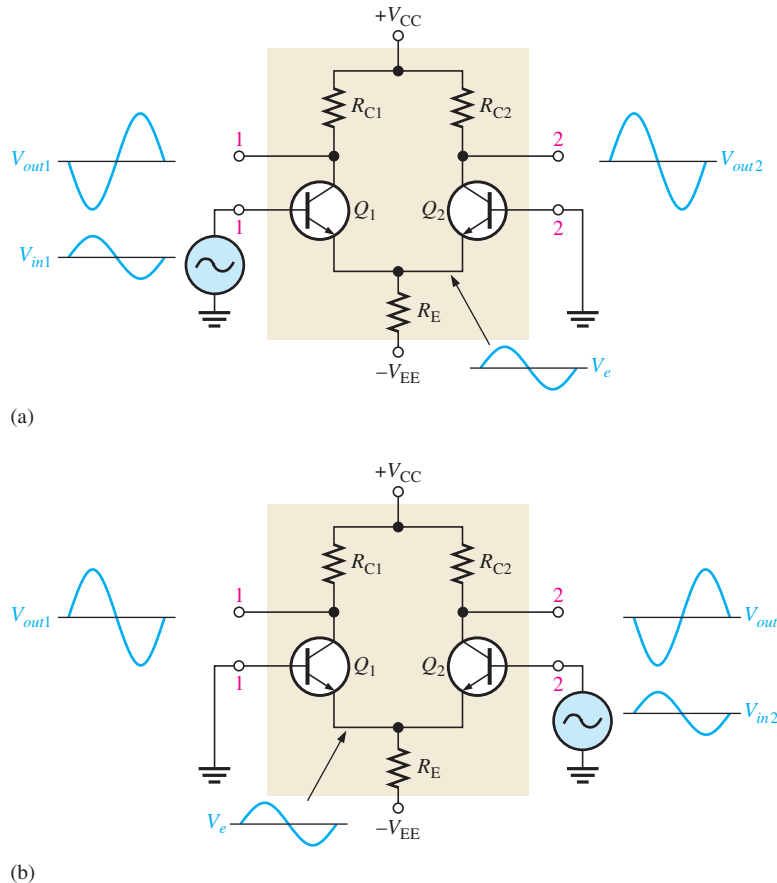(c) Bias voltage on input 2 with input 1 grounded

▲ FIGURE 6–39

Basic operation of a differential amplifier (ground is zero volts) showing relative changes in voltages.

Also, the emitter voltage is raised. This reduces the forward bias of Q_1, since its base is held at ground, and causes I_{C1} to decrease. The result is that the increase in I_{C2} produces a decrease in V_{C2}, and the decrease in I_{C1} causes V_{C1} to increase, as shown.

Modes of Signal Operation

Single-Ended Differential Input   When a diff-amp is operated with this input configuration, one input is grounded and the signal voltage is applied only to the other input, as shown in Figure 6–40. In the case where the signal voltage is applied to input 1 as in part (a), an inverted, amplified signal voltage appears at output 1 as shown. Also, a signal voltage appears in phase at the emitter of Q_1. Since the emitters of Q_1 and Q_2 are common, the emitter signal becomes an input to Q_2, which functions as a common-base amplifier. The signal is amplified by Q_2 and appears, noninverted, at output 2. This action is illustrated in part (a).
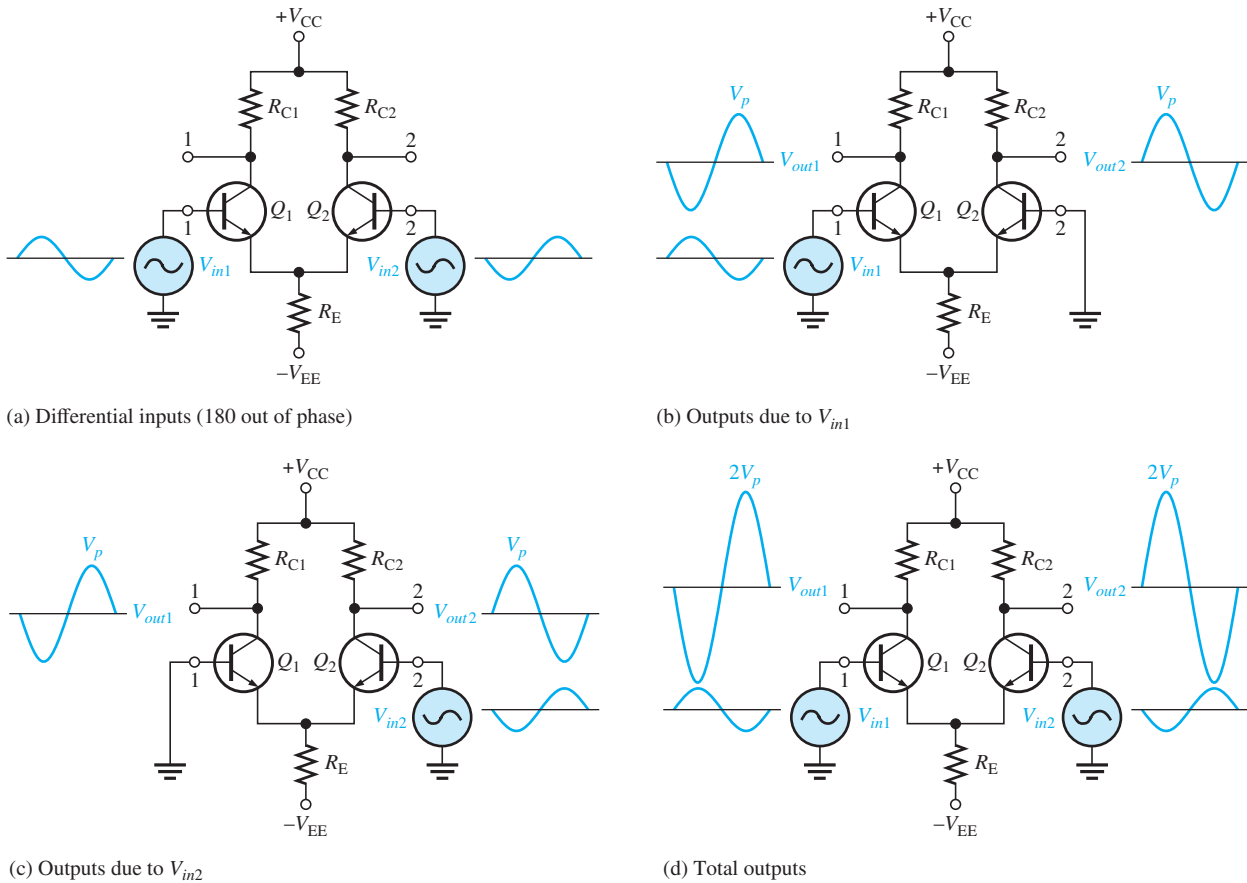

(a)

(b)

◀ **FIGURE 6–40**

Single-ended differential input operation.

In the case where the signal is applied to input 2 with input 1 grounded, as in Figure 6–40(b), an inverted, amplified signal voltage appears at output 2. In this situation, Q_1 acts as a common-base amplifier, and a noninverted, amplified signal appears at output 1.

Double-Ended Differential Inputs   In this input configuration, two opposite-polarity (out-of-phase) signals are applied to the inputs, as shown in Figure 6–41(a). Each input affects the outputs, as you will see in the following discussion.

Figure 6–41(b) shows the output signals due to the signal on input 1 acting alone as a single-ended input. Figure 6–41(c) on page 292 shows the output signals due to the signal on input 2 acting alone as a single-ended input. Notice in parts (b) and (c) that the signals on output 1 are of the same polarity. The same is also true for output 2. By applying the superposition theorem and summing both output 1 signals and both output 2 signals, you get the total output signals, as shown in Figure 6–41(d).

(a) Differential inputs (180 out of phase)

(b) Outputs due to V_{in1}

(c) Outputs due to V_{in2}

(d) Total outputs

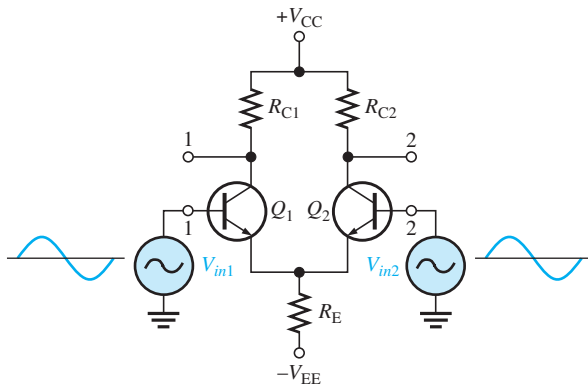▲ **FIGURE 6–41**

Double-ended differential operation.

Common-Mode Inputs   One of the most important aspects of the operation of a diff-amp can be seen by considering the **common-mode** condition where two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in Figure 6–42(a). Again, by considering each input signal as acting alone, you can understand the basic operation.

Figure 6–42(b) shows the output signals due to the signal on only input 1, and Figure 6–42(c) shows the output signals due to the signal on only input 2. Notice that the corresponding signals on output 1 are of the opposite polarity, and so are the ones on output 2. When the input signals are applied to both inputs, the outputs are superimposed and they cancel, resulting in a zero output voltage, as shown in Figure 6–42(d).

This action is called *common-mode rejection*. Its importance lies in the situation where an unwanted signal appears commonly on both diff-amp inputs. Common-mode rejection means that this unwanted signal will not appear on the outputs and distort the desired signal. Common-mode signals (noise) generally are the result of the pick-up of radiated energy on the input lines from adjacent lines, the 60 Hz power line, or other sources.

Common-Mode Rejection Ratio

Desired signals appear on only one input or with opposite polarities on both input lines. These desired signals are amplified and appear on the outputs as previously discussed. Unwanted signals (noise) appearing with the same polarity on both input lines are essentially cancelled by the diff-amp and do not appear on the outputs. The measure of an amplifier's ability to reject common-mode signals is a parameter called the **CMRR (common-mode rejection ratio)**.

(a) Common-mode inputs (in phase)
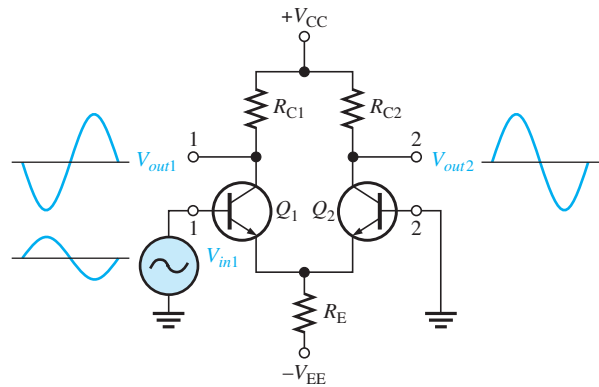
(b) Outputs due to V_{in1}
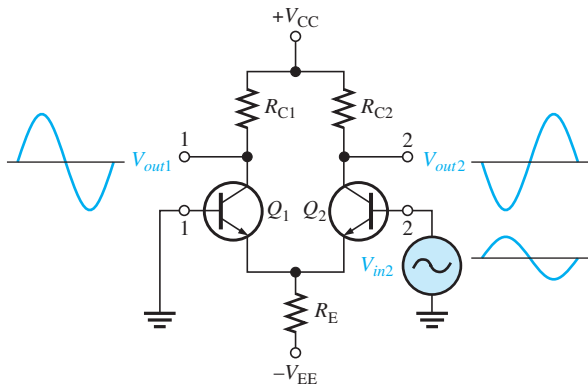
(c) Outputs due to V_{in2}
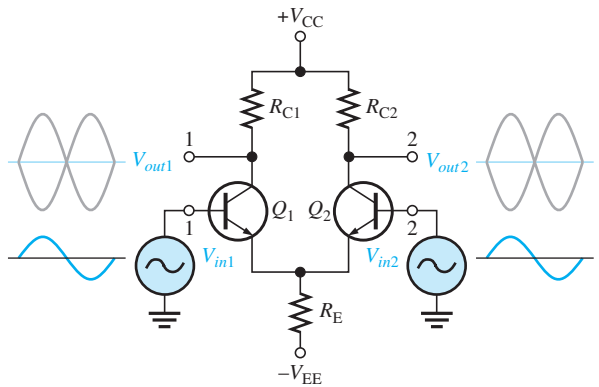
(d) Outputs due to V_{in1} and V_{in2} cancel because they are equal in amplitude but opposite in phase. The resulting outputs are 0 V ac.

▲ **FIGURE 6–42**

Common-mode operation of a differential amplifier.

Ideally, a diff-amp provides a very high gain for desired signals (single-ended or differential) and zero gain for common-mode signals. Practical diff-amps, however, do exhibit a very small common-mode gain (usually much less than 1), while providing a high differential voltage gain (usually several thousand). The higher the differential gain with respect to the common-mode gain, the better the performance of the diff-amp in terms of rejection of common-mode signals. This suggests that a good measure of the diff-amp's performance in rejecting unwanted common-mode signals is the ratio of the differential voltage gain $A_{v(d)}$ to the common-mode gain, A_{cm}. This ratio is the common-mode rejection ratio, CMRR.

$$\text{CMRR} = \frac{A_{v(d)}}{A_{cm}}$$

<div align="right">Equation 6–25</div>

The higher the CMRR, the better. A very high value of CMRR means that the differential gain $A_{v(d)}$ is high and the common-mode gain A_{cm} is low.

The CMRR is often expressed in decibels (dB) as

$$\text{CMRR} = 20 \log\left(\frac{A_{v(d)}}{A_{cm}}\right)$$

<div align="right">Equation 6–26</div>

EXAMPLE 6–14

A certain diff-amp has a differential voltage gain of 2000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibels.

Solution $A_{v(d)} = 2000$, and $A_{cm} = 0.2$. Therefore,

$$\text{CMRR} = \frac{A_{v(d)}}{A_{cm}} = \frac{2000}{0.2} = \textbf{10,000}$$

Expressed in decibels,

$$\text{CMRR} = 20 \log (10,000) = \textbf{80 dB}$$

Related Problem Determine the CMRR and express it in decibels for an amplifier with a differential voltage gain of 8500 and a common-mode gain of 0.25.

A CMRR of 10,000 means that the desired input signal (differential) is amplified 10,000 times more than the unwanted noise (common-mode). For example, if the amplitudes of the differential input signal and the common-mode noise are equal, the desired signal will appear on the output 10,000 times greater in amplitude than the noise. Thus, the noise or interference has been essentially eliminated.

SECTION 6–7 CHECKUP

1. Distinguish between double-ended and single-ended differential inputs.
2. Define *common-mode rejection*.
3. For a given value of differential gain, does a higher CMRR result in a higher or lower common-mode gain?
4. What is the difference between a common-mode signal and a differential signal?

6–8 TROUBLESHOOTING
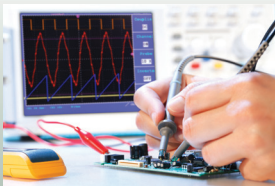
In working with any circuit, you must first know how it is supposed to work before you can troubleshoot it for a failure. The two-stage capacitively coupled amplifier discussed in Section 6–6 is used to illustrate a typical troubleshooting procedure.
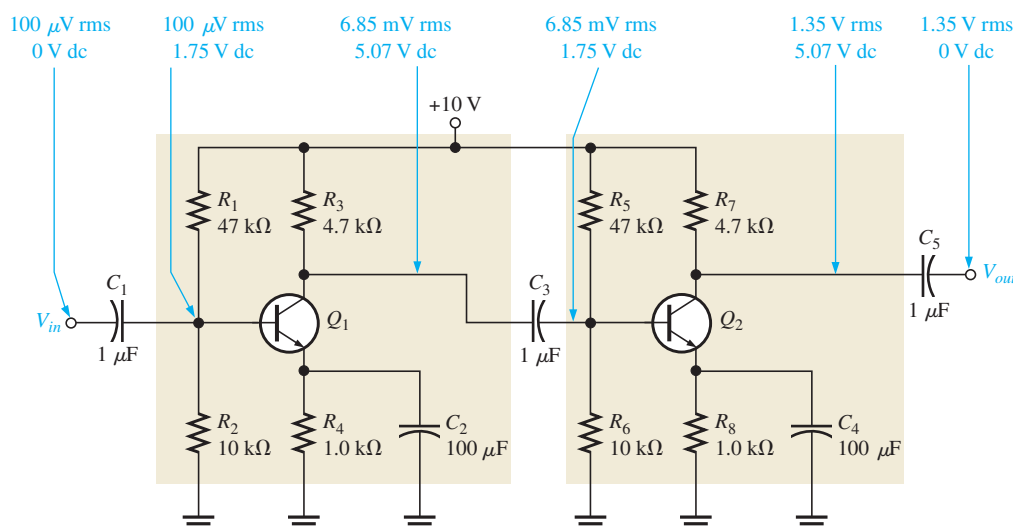
After completing this section, you should be able to

❏ **Troubleshoot amplifier circuits**
❏ Discuss a troubleshooting procedure
   ◆ Describe the analysis phase   ◆ Describe the planning phase   ◆ Describe the measurement phase

When you are faced with having to troubleshoot a circuit, the first thing you need is a schematic with the proper dc and signal voltages labeled. You must know what the correct voltages in the circuit should be before you can identify an incorrect voltage. Schematics of some circuits are available with voltages indicated at certain points. If this is not the case, you must use your knowledge of the circuit operation to determine the correct voltages. Figure 6–43 is the schematic for the two-stage amplifier that was analyzed in Section 6–6. The correct voltages are indicated at each point.

Troubleshooting Procedure

The analysis, planning, and measurement approach to troubleshooting, discussed in Chapter 2, will be used.

100 μV rms
0 V dc

100 μV rms
1.75 V dc

6.85 mV rms
5.07 V dc

6.85 mV rms
1.75 V dc

1.35 V rms
5.07 V dc

1.35 V rms
0 V dc

+10 V

▲ FIGURE 6–43

A two-stage common-emitter amplifier with correct voltages indicated. Both transistors have dc and ac betas of 150. Different values of β will produce slightly different results.

Analysis It has been found that there is no output voltage, V_{out}. You have also determined that the circuit did work properly and then failed. A visual check of the circuit board or assembly for obvious problems such as broken or poor connections, solder splashes, wire clippings, or burned components turns up nothing. You conclude that the problem is most likely a faulty component in the amplifier circuit or an open connection. Also, the dc supply voltage may not be correct or may be missing.

Planning You decide to use a DMM to check the dc levels and an oscilloscope to check the ac signals at certain test points. A function generator with the signal attenuated by a voltage divider to 100 μV will be used to apply a test signal to the input. Also, you decide to apply the half-splitting method to trace the voltages in the circuit and use an in-circuit transistor tester if a transistor is suspected of being faulty.

Measurement To determine the faulty component in a multistage amplifier, use the general five-step troubleshooting procedure which is illustrated as follows.

   Step 1: *Perform a power check*. Assume the dc supply voltage is correct as indicated in Figure 6–44.

   Step 2: *Check the input and output voltages*. Assume the measurements indicate that the input signal voltage is correct. However, there is no output signal voltage or the output signal voltage is much less than it should be, as shown by the diagram in Figure 6–44.
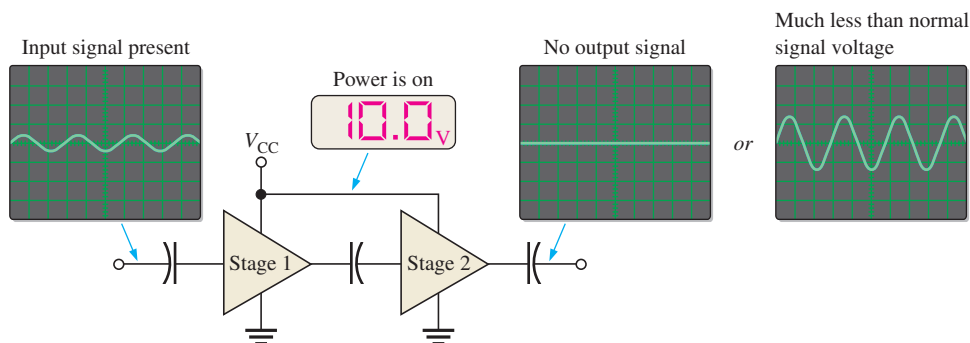
◄ FIGURE 6–44

Initial check of a faulty two-stage amplifier.

Step 3: *Apply the half-splitting method of signal tracing*. Check the voltages at the output of the first stage. No signal voltage or a much less than normal signal voltage indicates that the problem is probably in the first stage (an incorrect load could be the problem). An incorrect dc voltage also indicates a first-stage problem. If the signal voltage and the dc voltage are correct at the output of the first stage, the problem is in the second stage. After this check, you have narrowed the problem to one of the two stages. This step is illustrated in Figure 6–45.
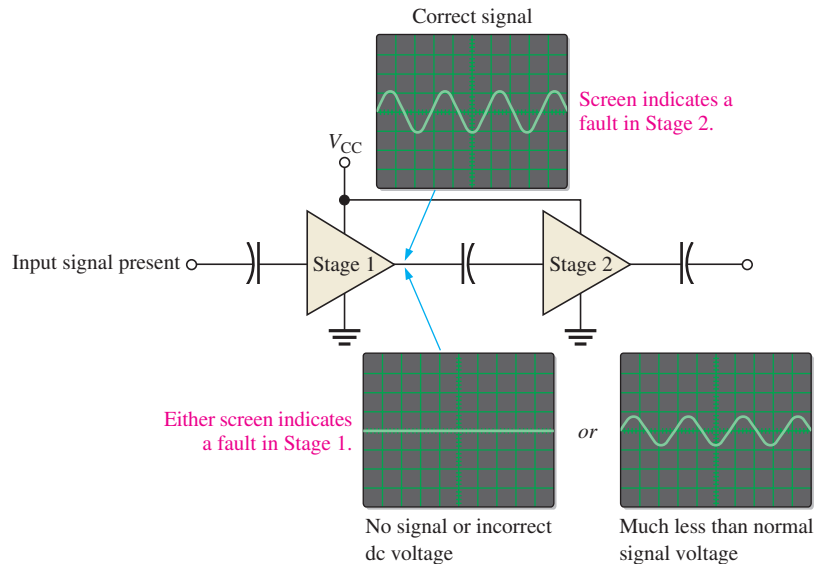
▲ **FIGURE 6–45**

Half-splitting signal tracing isolates the faulty stage.

Step 4: *Apply fault analysis*. Focus on the faulty stage and determine the component failure that can produce the incorrect output.
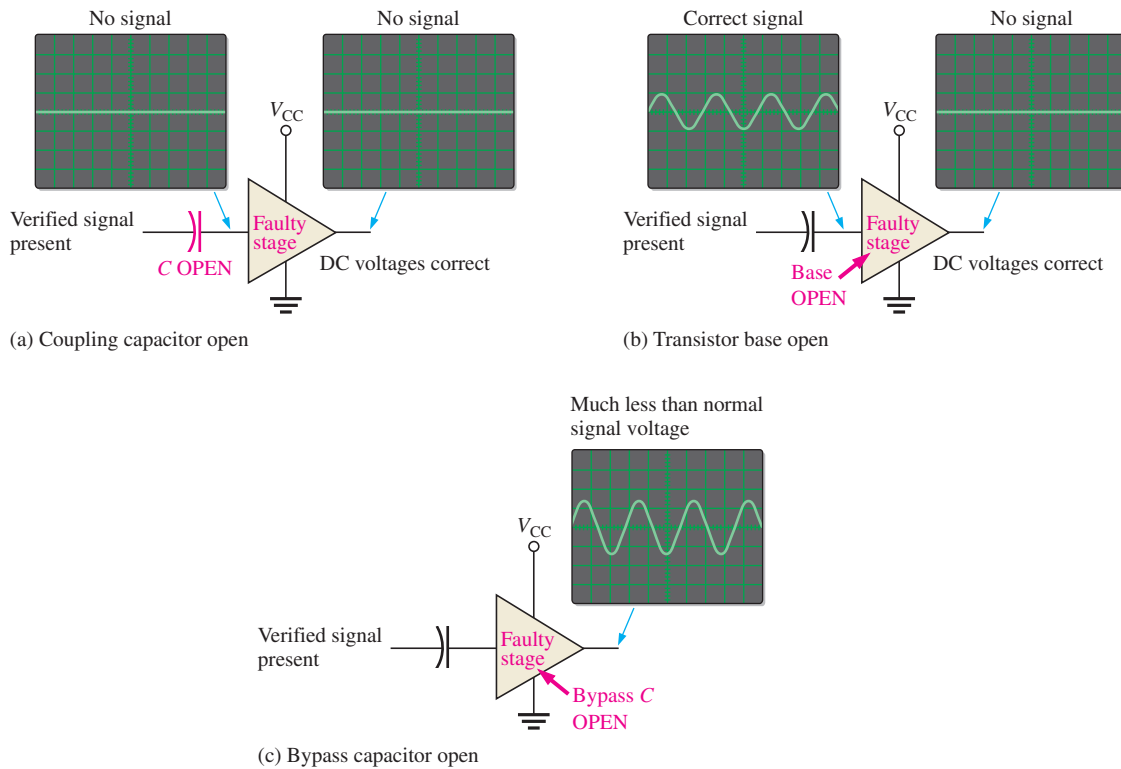
Symptom: DC voltages incorrect.

Likely faults: A failure of any resistor or the transistor will produce an incorrect dc bias voltage. A leaky bypass or coupling capacitor will also affect the dc bias voltages. Further measurements in the stage are necessary to isolate the faulty component.

Incorrect ac voltages and the most likely fault(s) are illustrated in Figure 6–46 as follows:

(a) *Symptom 1:* Signal voltage at output missing; dc voltage correct.
Symptom 2: Signal voltage at base missing; dc voltage correct.
Likely fault: Input coupling capacitor open. This prevents the signal from getting to the base.

(b) *Symptom:* Correct signal at base but no output signal.
Likely fault: Transistor base open.

(c) *Symptom:* Signal voltage at output much less than normal; dc voltage correct.
Likely fault: Bypass capacitor open.

Step 5: *Replace or repair*. With the power turned off, replace the defective component or repair the defective connection. Turn on the power, and check for proper operation.

No signal

No signal

Correct signal

No signal

V_{CC}

Verified signal present

Faulty stage

DC voltages correct

C OPEN

(a) Coupling capacitor open

V_{CC}

Verified signal present

Faulty stage

DC voltages correct

Base OPEN

(b) Transistor base open

Much less than normal signal voltage

V_{CC}

Verified signal present

Faulty stage

Bypass C OPEN

(c) Bypass capacitor open

▲ FIGURE 6–46

Troubleshooting a faulty stage.

EXAMPLE 6–15

The two-stage amplifier in Figure 6–43 has malfunctioned such that there is no output signal with a verified input. Specify the step-by-step troubleshooting procedure for an assumed fault.

Solution Assume there are no visual or other indications of a problem such as a charred resistor, solder splash, wire clipping, broken connection, or extremely hot component. The troubleshooting procedure for a certain fault scenario is as follows:

Step 1: There is power to the circuit as indicated by a correct V_{CC} measurement.

Step 2: There is a verified input signal voltage, but no output signal voltage is measured.

Step 3: The signal voltage and the dc voltage at the collector of Q_1 are correct. This means that the problem is in the second stage or the coupling capacitor C_3 between the stages.

Step 4: The correct signal voltage and dc bias voltage are measured at the base of Q_2. This eliminates the possibility of a fault in C_3 or the second stage bias circuit.

The collector of Q_2 is at 10 V and there is no signal voltage. This measurement, made directly on the transistor collector, indicates that either the collector is shorted to V_{CC} or the transistor is internally open. It is unlikely that the collector resistor R_7 is shorted but to verify, turn off the power and use an ohmmeter to check.

The possibility of a short is eliminated by the ohmmeter check. The other possible faults are (a) transistor Q_2 internally open or (b) emitter resistor or

connection open. Use a transistor tester and/or ohmmeter to check each of these possible faults with power off.

Step 5: Replace the faulty component or repair open connection and retest the circuit for proper operation.

Related Problem   Determine the possible fault(s) if, in Step 4, you find no signal voltage at the base of Q_2 but the dc voltage is correct.

Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSM06-01

2. Multisim file TSM06-02

3. Multisim file TSM06-03

4. Multisim file TSM06-04

5. Multisim file TSM06-05

SECTION 6–8 CHECKUP

1. If C_4 in Figure 6–43 were open, how would the output signal be affected? How would the dc level at the collector of Q_2 be affected?
2. If R_5 in Figure 6–43 were open, how would the output signal be affected?
3. If the coupling capacitor C_3 in Figure 6–43 shorted out, would any of the dc voltages in the amplifier be changed? If so, which ones?
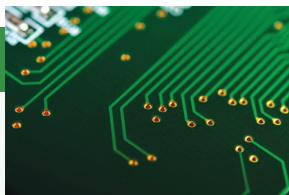
Device Application: *Audio Preamplifier for PA System*

An audio preamplifier is to be developed for use in a small portable public address (PA) system. The preamplifier will have a microphone input, and its output will drive a power amplifier to be developed in Chapter 7. A block diagram of the complete PA system is shown in Figure 6–47(a), and its physical configuration is shown in part (b). The dc supply voltages are provided by a battery pack or by an electronic power supply.

The Circuit

A two-stage audio voltage preamplifier is shown in Figure 6–48. The first stage is a common-emitter *pnp* with voltage-divider bias, and the second stage is a common-emitter *npn* with voltage-divider bias. It has been decided that the amplifier should operate from 30 V dc to get a large enough signal voltage swing to provide a maximum of 6 W to the speaker. Because small IC regulators such as the 78xx and 79xx series are not available

(a) PA system block diagram   (b) Physical configuration
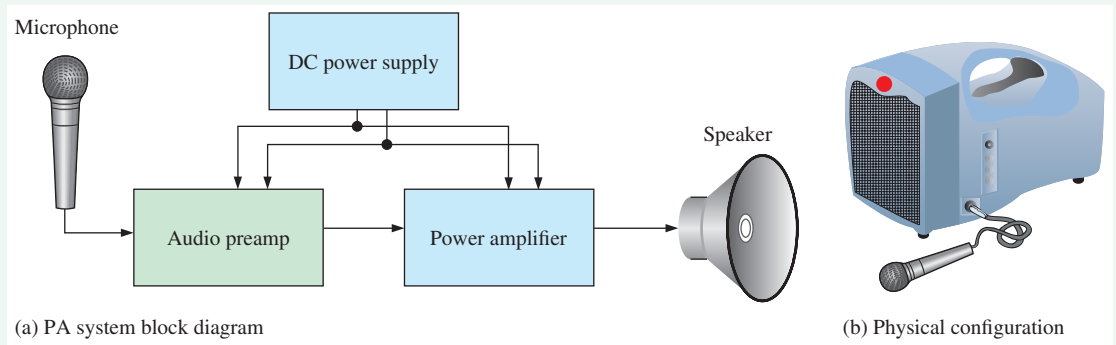
▲ **FIGURE 6–47**

The public address system.
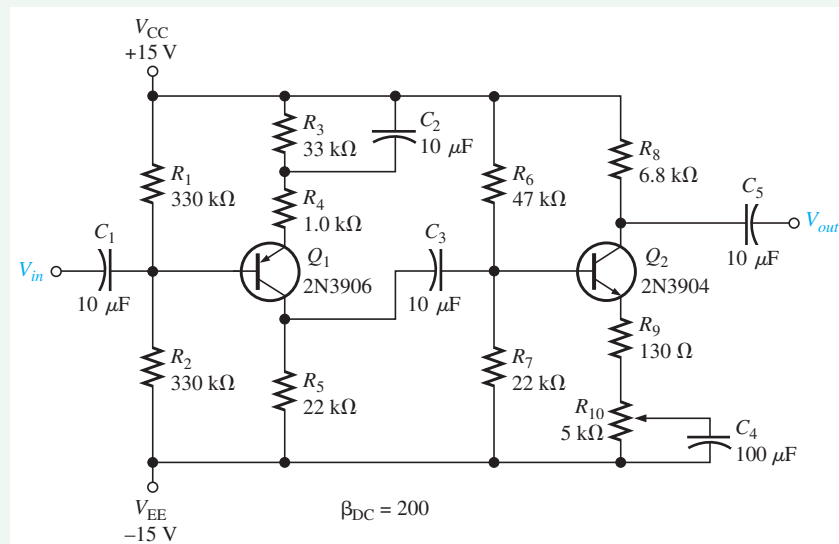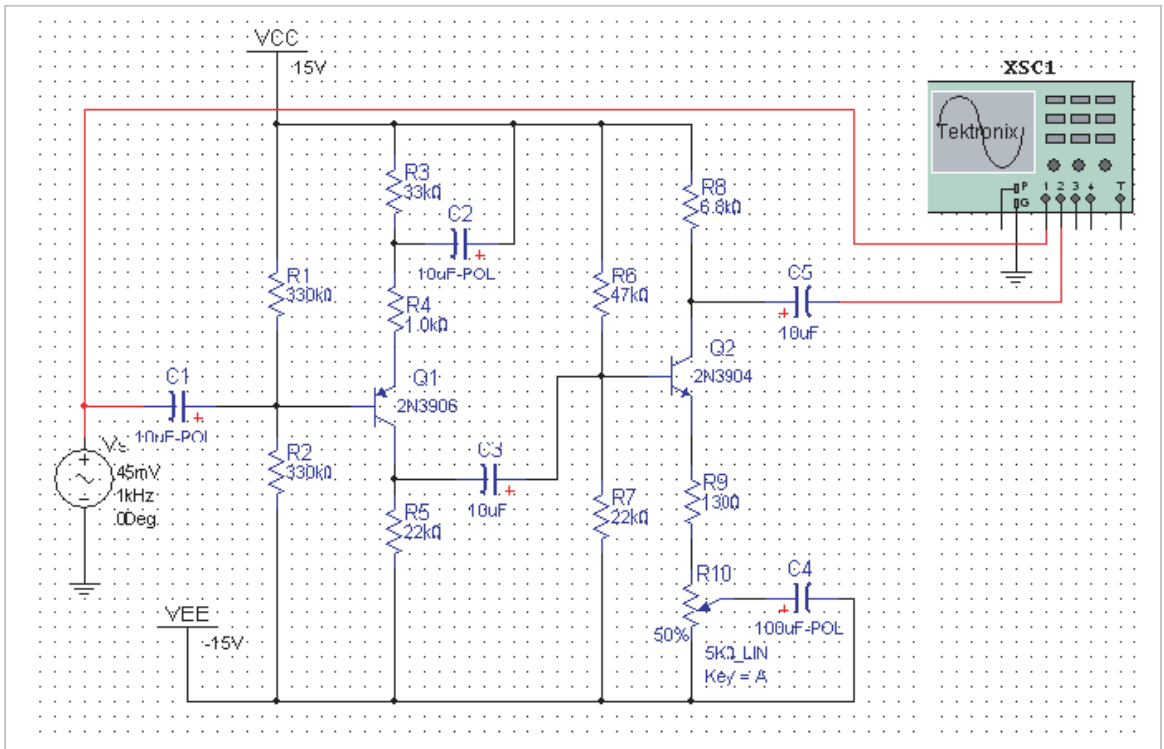

▲ **FIGURE 6–48**

Two-stage voltage preamplifier.

above 24 V, dual ± 15 V dc supplies are used in this particular system instead of a single supply. The operation is essentially the same as if a single $+30$ V dc source had been used. The potentiometer at the output provides gain adjustment for volume control. The input to the first stage is from the microphone, and the output of the second stage will drive a power amplifier to be developed in Chapter 7. The power amplifier will drive the speaker. The preamp is to operate with a peak input signal range of from 25 mV to 50 mV. The minimum range of voltage gain adjustment is from 90 to 170.

1. Calculate the theoretical voltage gain of the first stage when the second stage is set for maximum gain.
2. Calculate the theoretical maximum voltage gain of the second stage.
3. Determine the overall theoretical voltage gain.
4. Calculate the circuit power dissipation with no signal (quiescent).

Simulation

The preamp is simulated with a peak input signal of 45 mV using Multisim. The results are shown in Figure 6–49.

5. Determine the voltage gain of the simulated circuit based on the voltage measurements.
6. Compare the measured voltage gain with the calculated voltage gain.

(a) Circuit screen
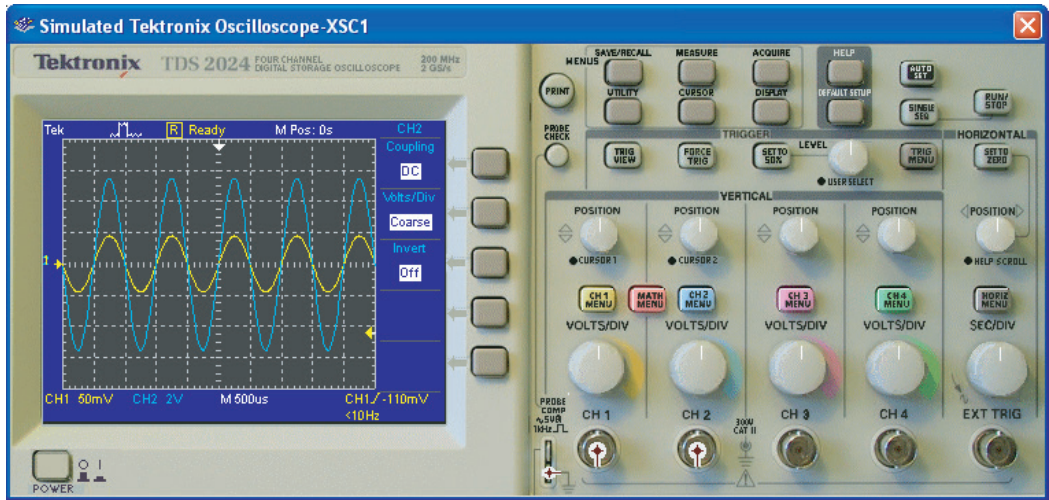
(b) Input signal (yellow) and output signal (blue)

▲ **FIGURE 6–49**

Preamp input and output signals.

Simulate the preamp circuit using your Multisim or LT Spice software. Observe the operation with the virtual oscilloscope.

Prototyping and Testing*

Now that the circuit has been simulated, the prototype circuit is constructed and tested. After the circuit is successfully tested on a protoboard, it is ready to be finalized on a printed circuit board.

Lab Experiment
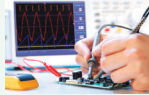
To build and test a similar circuit, go to Experiment 6 in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).

Circuit Board

The preamp is implemented on a printed circuit board as shown in Figure 6–50.

7. Check the printed circuit board and verify that it agrees with the schematic in Figure 6–48. The volume control potentiometer is mounted off the PC board for easy access.
8. Label each input and output pin according to function.
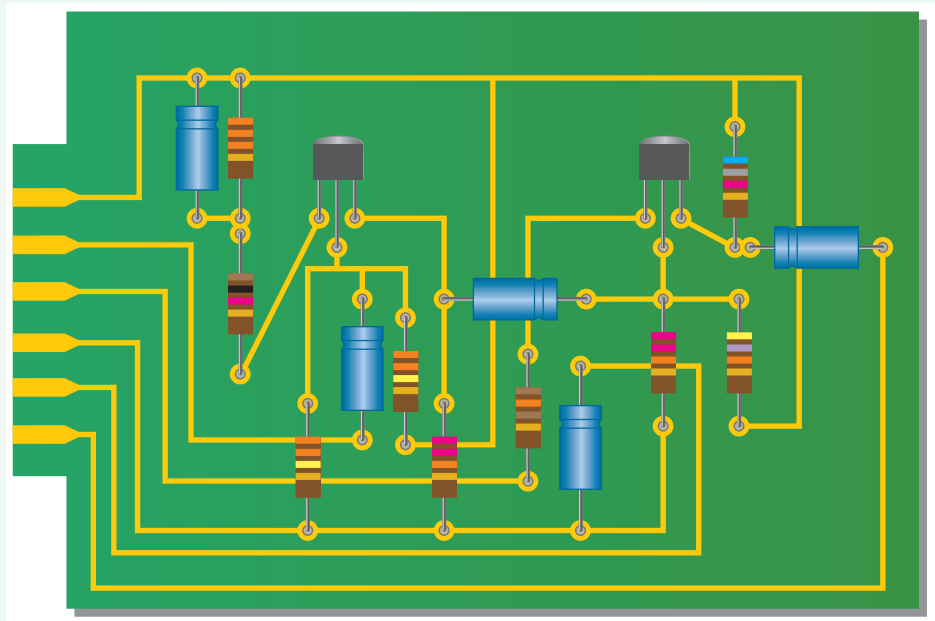
▲ **FIGURE 6–50**
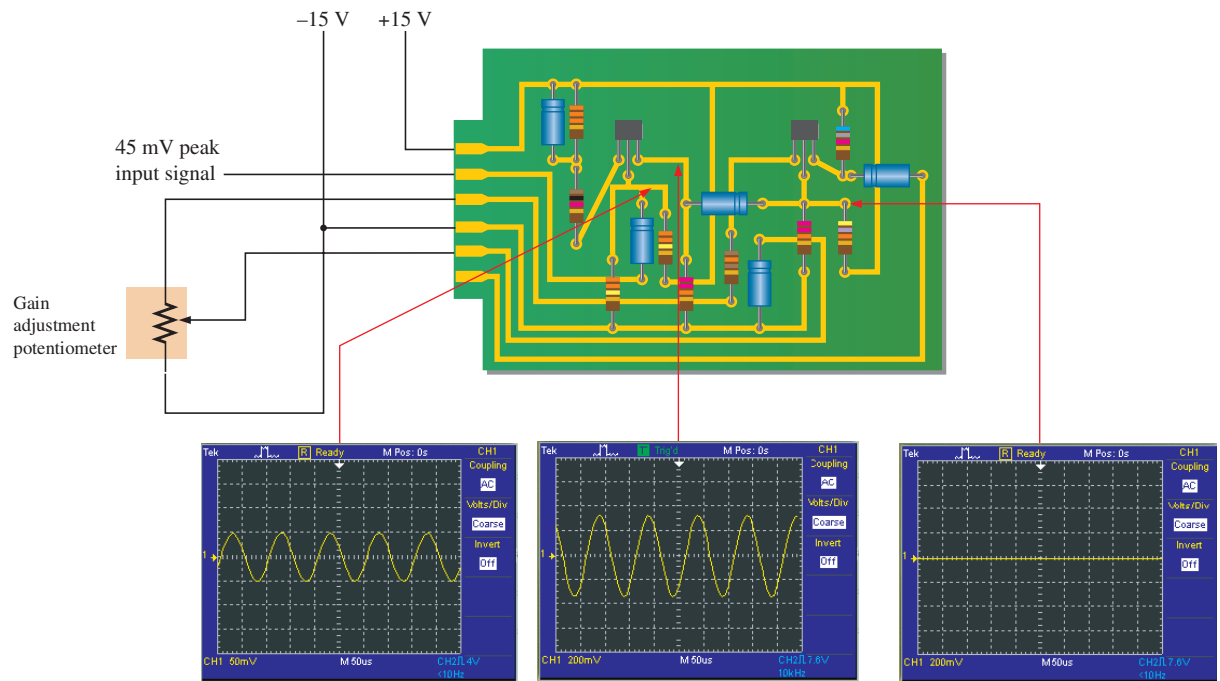
Preamp circuit board.

Troubleshooting

Two preamp circuit boards have failed the production test. You will troubleshoot the boards based on the scope measurements shown in Figure 6–51.

9. List possible faults for board 1.
10. List possible faults for board 2.

* An example of a combined software/hardware approach to simulating and prototyping a circuit is NI ELVIS (National Instrument Educational Laboratory Virtual Instrumentation Suite), which combines Multisim software with actual prototyping hardware.
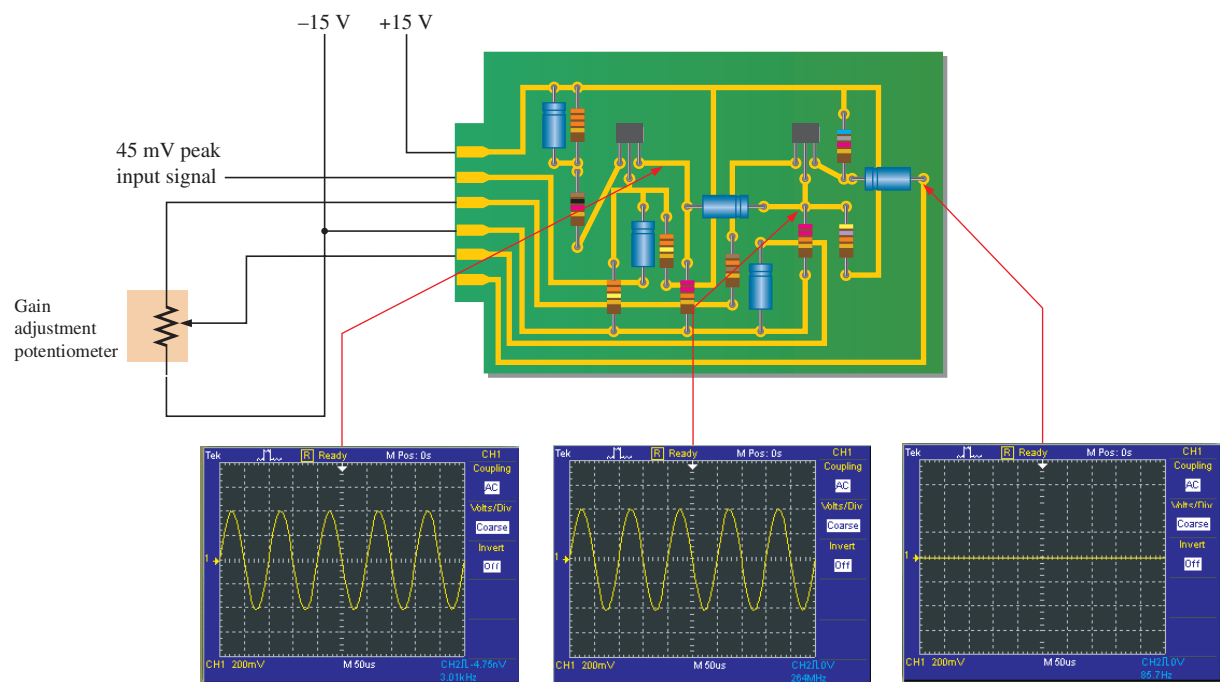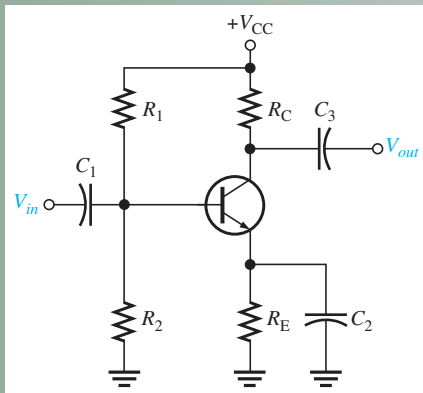
(a) Test result for board 1

(b) Test result for board 2

▲ **FIGURE 6–51**

Test of two faulty preamp boards.

SUMMARY OF THE COMMON-EMITTER AMPLIFIER

CIRCUIT WITH VOLTAGE-DIVIDER BIAS

- Input is at the base. Output is at the collector.
- There is a phase inversion from input to output.
- C_1 and C_3 are coupling capacitors for the input and output signals.
- C_2 is the emitter-bypass capacitor.
- All capacitors must have a negligible reactance at the frequency of operation, so they appear as shorts.
- Emitter is at ac ground due to the bypass capacitor.

EQUIVALENT CIRCUITS AND FORMULAS
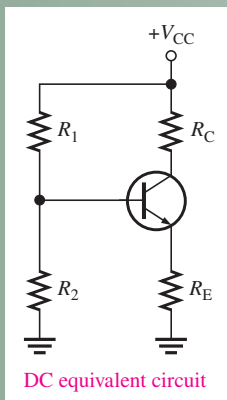
DC equivalent circuit
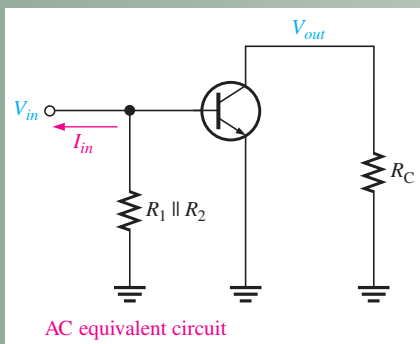
- DC formulas:

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}}$$

$$V_E = I_E R_E$$
$$V_B = V_E + V_{BE}$$
$$V_C = V_{CC} - I_C R_C$$

AC equivalent circuit

- AC formulas:

$$r'_e = \frac{25 \text{ mV}}{I_E}$$

$$R_{in(base)} = \beta_{ac} r'_e$$
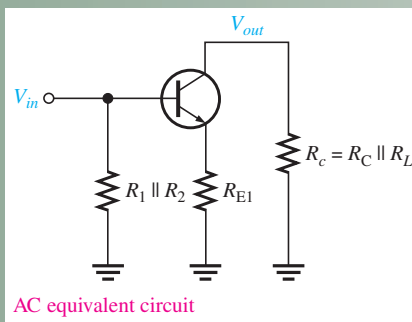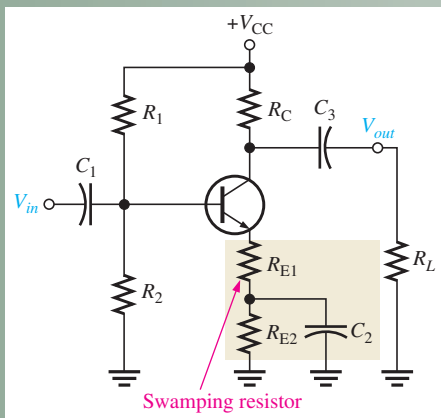
$$R_{out} \cong R_C$$

$$A_v = \frac{R_C}{r'_e}$$

$$A_i = \frac{I_c}{I_{in}}$$

$$A_p = A'_v A_i$$

SWAMPED AMPLIFIER WITH RESISTIVE LOAD

Swamping resistor

AC equivalent circuit

- AC formulas:

$$A_v \cong \frac{R_c}{R_{E1}}$$
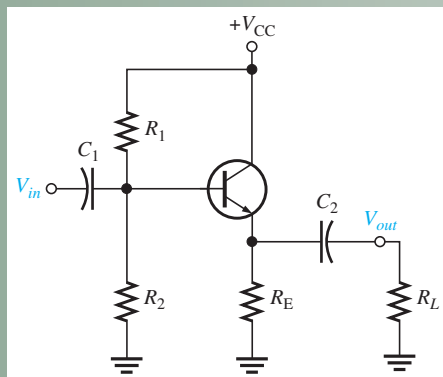
where $R_c = R_C \parallel R_L$

$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1})$$

- Swamping stabilizes gain by minimizing the effect of r'_e.

- Swamping reduces the voltage gain from its unswamped value.

- Swamping increases input resistance.

- The load resistance reduces the voltage gain. The smaller the load resistance, the less the gain.

SUMMARY OF THE COMMON-COLLECTOR AMPLIFIER

CIRCUIT WITH VOLTAGE-DIVIDER BIAS

- Input is at the base. Output is at the emitter.

- There is no phase inversion from input to output.

- Input resistance is high. Output resistance is low.

- Maximum theoretical voltage gain is 1. Actual voltage gain is nearly 1.

- Collector is at ac ground.

- Coupling capacitors must have a negligible reactance at the frequency of operation.

- $A_p \approx A_i$

EQUIVALENT CIRCUITS AND FORMULAS

DC equivalent circuit

■ DC formulas:

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}}$$

$$V_E = I_E R_E$$

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

$$V_C = V_{CC}$$

AC equivalent circuit

■ AC formulas:

$$r'_e = \frac{25 \text{ mV}}{I_E}$$

$$R_{in(base)} = \beta_{ac}(r'_e + R_e) \cong \beta_{ac} R_e$$

$$R_{out} = \left(\frac{R_s}{\beta_{ac}}\right) \| R_E$$

$$A_v = \frac{R_e}{r'_e + R_e} \cong 1$$

$$A_i = \frac{I_e}{I_{in}}$$
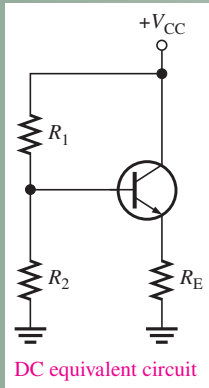
$$A_p \cong A_i$$

SUMMARY OF COMMON-BASE AMPLIFIER

CIRCUIT WITH VOLTAGE-DIVIDER BIAS
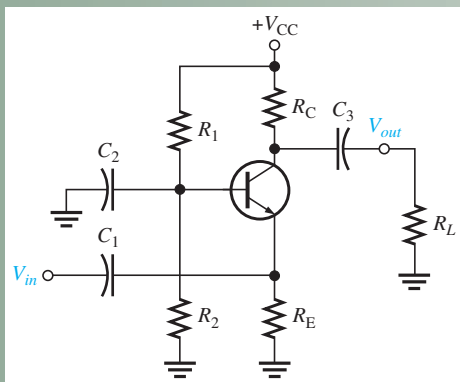
■ Input is at the emitter. Output is at the collector.

■ There is no phase inversion from input to output.

■ Input resistance is low. Output resistance is high.

■ Maximum theoretical current gain is 1. Actual current gain is nearly 1.

■ Base is at ac ground.

■ Capacitors must have a negligible reactance at the frequency of operation.

EQUIVALENT CIRCUITS AND FORMULAS
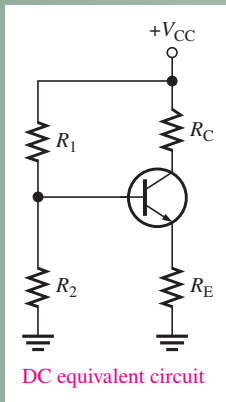
DC equivalent circuit
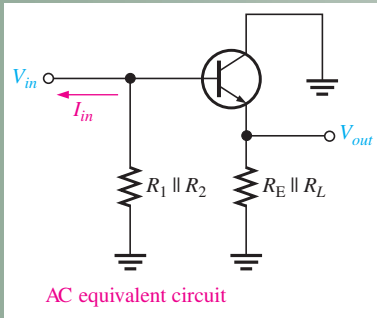
- DC formulas:

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}}$$

$$V_E = I_E R_E$$

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

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

AC equivalent circuit
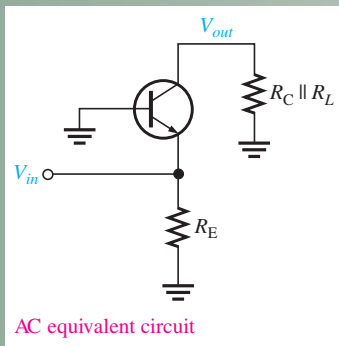
- AC formulas:

$$r_e' = \frac{25 \text{ mV}}{I_E}$$

$$R_{in(emitter)} \cong r_e'$$

$$R_{out} \cong R_C$$

$$A_v \cong \frac{R_c}{r_e'}$$

$$A_i \cong 1$$

$$A_p \cong A_v$$

SUMMARY OF DIFFERENTIAL AMPLIFIER

CIRCUIT WITH DIFFERENTIAL INPUTS
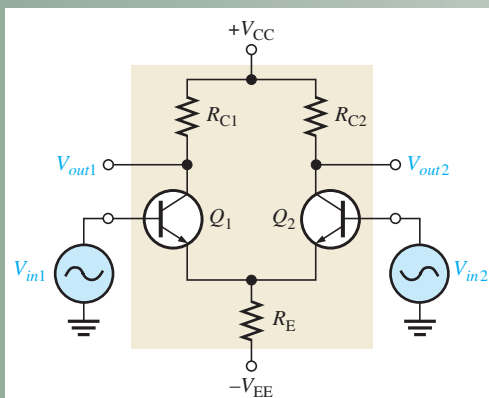
- Double-ended differential inputs (shown)

  Signal on both inputs

  Input signals are out of phase

- Single-ended differential inputs (not shown)

  Signal on one input only

  One input connected to ground

CIRCUIT WITH COMMON-MODE INPUTS

■ Both input signals are the same phase, frequency, and amplitude.

■ Common-mode rejection ratio:

$$\text{CMRR} = \frac{A_{v(d)}}{A_{cm}}$$

$$\text{CMRR} = 20 \log \left(\frac{A_{v(d)}}{A_{cm}} \right)$$

SUMMARY

Section 6–1 ◆ A small-signal amplifier uses only a small portion of its load line under signal conditions.

◆ The ac load line differs from the dc load line because the effective ac output resistance is less than the dc output resistance.

Section 6–2 ◆ r parameters are easily identifiable and applicable with a transistor's circuit operation.

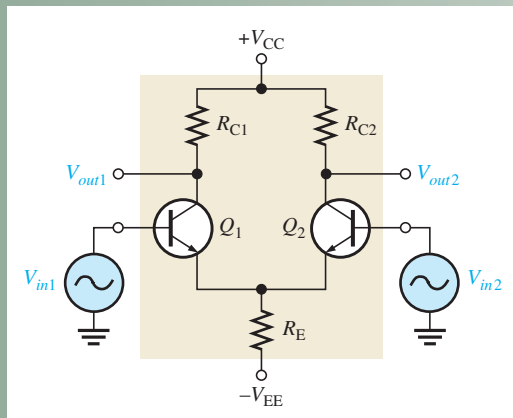◆ h parameters are important because manufacturers' datasheets specify transistors using h parameters.

Section 6–3 ◆ A common-emitter amplifier has high voltage, current, and power gains, but a relatively low input resistance.

◆ Swamping is a method of stabilizing the voltage gain.

Section 6–4 ◆ A common-collector amplifier has high input resistance and high current gain, but its voltage gain is approximately 1.

◆ A Darlington pair provides beta multiplication for increased input resistance.

◆ A common-collector amplifier is known as an emitter-follower.

Section 6–5 ◆ The common-base amplifier has a high voltage gain, but it has a very low input resistance and its current gain is approximately 1.

◆ Equations for basic configurations of common-emitter, common-collector, and common-base amplifiers are given in the Key Formula list.

Section 6–6 ◆ The total gain of a multistage amplifier is the product of the individual gains (sum of the individual dB gains).

◆ Single-stage amplifiers can be connected in sequence with capacitively-coupling and direct coupling methods to form multistage amplifiers.

Section 6–7 ◆ A differential input voltage appears between the inverting and noninverting inputs of a differential amplifier.

◆ In the differential mode, a diff-amp can be operated with single-ended or double-ended inputs.

◆ In single-ended operation, there is a signal on one input and the other input is grounded.

◆ In double-ended operation, two signals that are 180° out of phase are on the inputs.

◆ Common-mode occurs when equal in-phase voltages are applied to both input terminals.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

ac ground   A point in a circuit that appears as ground to ac signals only.

Attenuation   The reduction in the level of power, current, or voltage.

Bypass capacitor   A capacitor placed across the emitter resistor of an amplifier.

CMRR (common-mode rejection ratio)   A measure of a differential amplifier's ability to reject common-mode signals.

Common-base (CB)   A BJT amplifier configuration in which the base is the common terminal to an ac signal or ground.

Common-collector (CC)   A BJT amplifier configuration in which the collector is the common terminal to an ac signal or ground.

Common-emitter (CE)   A BJT amplifier configuration in which the emitter is the common terminal to an ac signal or ground.

Common mode   A condition where two signals applied to differential inputs are of the same phase, frequency, and amplitude.

Decibel   A logarithmic measure of the ratio of one voltage to another or one power to another.

Differential amplifier   An amplifier in which the output is a function of the difference between two input voltages.

Emitter-follower   A popular term for a common-collector amplifier.

Input resistance   The resistance seen by an ac source connected to the input of an amplifier.

Output resistance   The ac resistance looking in at the output of an amplifier.

r parameter   One of a set of BJT characteristic parameters that include α_{ac}, β_{ac}, r'_e, r'_b, and r'_c.

KEY FORMULAS

6–1 $\quad r'_e \cong \dfrac{25\ \text{mV}}{I_E}$ $\qquad\qquad$ Internal ac emitter resistance

Common-Emitter

6–2 $\quad R_{in(tot)} = R_1 \| R_2 \| R_{in(base)}$ $\qquad$ Total amplifier input resistance, voltage-divider bias

6–3 $\quad R_{in(base)} = \beta_{ac} r'_e$ $\qquad\qquad$ Input resistance at base

6–4 $\quad R_{out} \cong R_C$ $\qquad\qquad\qquad$ Output resistance

6–5 $\quad A_v = \dfrac{R_C}{r'_e}$ $\qquad\qquad\qquad$ Voltage gain, base-to-collector, unloaded

6–6 $\quad A_v = \dfrac{R_C}{r'_e + R_E}$ $\qquad\qquad$ Voltage gain without bypass capacitor

6–7 $\quad A_v = \dfrac{R_c}{r'_e}$ $\qquad\qquad\qquad$ Voltage gain, base-to-collector, loaded, bypassed R_E

6–8 $\quad A_v \cong \dfrac{R_C}{R_{E1}}$ $\qquad\qquad\qquad$ Voltage gain, swamped amplifier

6–9 $\quad R_{in(base)} = \beta_{ac}(r'_e + R_{E1})$ $\qquad$ Input resistance at base, swamped amplifier

6–10 $\quad A_i = \dfrac{I_c}{I_s}$ $\qquad\qquad\qquad$ Current gain, input source to collector

6–11 $\quad A_p = A'_v A_i$ $\qquad\qquad\qquad$ Power gain

Common-Collector (Emitter-Follower)

6–12 $\quad A_v \cong 1$ $\qquad\qquad\qquad$ Voltage gain, base-to-emitter

6–13 $\quad R_{in(base)} \cong \beta_{ac} R_e$ $\qquad\qquad$ Input resistance at base, loaded

6–14 $\quad R_{out} \cong \left(\dfrac{R_s}{\beta_{ac}} \right) \| R_E$ $\qquad\qquad$ Output resistance

6–15 $A_i = \dfrac{I_e}{I_{in}}$ Current gain

6–16 $A_p \cong A_i$ Power gain

6–17 $R_{in} = \beta_{ac1}\beta_{ac2}R_E$ Input resistance, Darlington pair

Common-Base

6–18 $A_v \cong \dfrac{R_c}{r'_e}$ Voltage gain, emitter-to-collector

6–19 $R_{in(emitter)} \cong r'_e$ Input resistance at emitter

6–20 $R_{out} \cong R_C$ Output resistance

6–21 $A_i \cong 1$ Current gain

6–22 $A_p \cong A_v$ Power gain

Multistage Amplifier

6–23 $A'_v = A_{v1}A_{v2}A_{v3}\dots A_{vn}$ Overall voltage gain

6–24 $A_{v(dB)} = 20 \log A_v$ Voltage gain expressed in dB

Differential Amplifier

6–25 $CMRR = \dfrac{A_{v(d)}}{A_{cm}}$ Common-mode rejection ratio

6–26 $CMRR = 20 \log\left(\dfrac{A_{v(d)}}{A_{cm}}\right)$ Common mode rejection ratio in dB

TRUE/FALSE QUIZ

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

1. In an amplifier, a coupling capacitor should appear ideally as a short to the signal.
2. r parameters include β_{ac} and r'_e.
3. h parameters are never specified on a datasheet.
4. The r parameter β_{ac} is the same as the h parameter h_{fe}.
5. A bypass capacitor in a CE amplifier decreases the voltage gain.
6. If R_C in a CE amplifier is increased, the voltage gain is reduced.
7. The load is the amount of current between a load and the output of an amplifier.
8. In a CE amplifier, the gain can be stabilized by using a swamping resistor.
9. An emitter-follower is a CC amplifier.
10. A CC amplifier has high voltage gain.
11. A Darlington pair consists essentially of two CC amplifiers.
12. A CB amplifier has high current gain.
13. The overall voltage gain of a multistage amplifier is the product of the gains of each stage.
14. A differential amplifier amplifies the difference of two input signals.
15. CMRR is the common-mode resistance ratio.

CIRCUIT-ACTION QUIZ

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

1. If the transistor in Figure 6–8 is exchanged for one with higher betas, V_{out} will
      (a) increase   (b) decrease   (c) not change
2. If C_2 is removed from the circuit in Figure 6–8, V_{out} will
      (a) increase   (b) decrease   (c) not change

3. If the value of R_C in Figure 6–8 is increased, V_{out} will

    (a) increase   **(b)** decrease   **(c)** not change

4. If the amplitude of V_{in} in Figure 6–8 is decreased, V_{out} will

    (a) increase   **(b)** decrease   **(c)** not change

5. If C_2 in Figure 6–27 is shorted, the average value of the output voltage will

    (a) increase   **(b)** decrease   **(c)** not change

6. If the value of R_E in Figure 6–27 is increased, the voltage gain will

    (a) increase   **(b)** decrease   **(c)** not change

7. If the value of C_1 in Figure 6–27 is increased, V_{out} will

    (a) increase   **(b)** decrease   **(c)** not change

8. If the value of R_C in Figure 6–32 is increased, the current gain will

    (a) increase   **(b)** decrease   **(c)** not change

9. If C_2 and C_4 in Figure 6–34 are increased in value, V_{out} will

    (a) increase   **(b)** decrease   **(c)** not change

10. If the value of R_4 in Figure 6–34 is reduced, the overall voltage gain will

    (a) increase   **(b)** decrease   **(c)** not change

SELF-TEST

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

Section 6–1

1. A small-signal amplifier

    (a) uses only a small portion of its load line

    (b) always has an output signal in the mV range

    (c) goes into saturation once on each input cycle

    (d) is always a common-emitter amplifier

Section 6–2

2. The parameter h_{fe} corresponds to

    (a) β_{DC} **(b)** β_{ac} **(c)** r'_e **(d)** r'_c

3. If the dc emitter current in a certain transistor amplifier is 3 mA, the approximate value of r'_e is

    (a) 3 kΩ   **(b)** 3 Ω   **(c)** 8.33 Ω   **(d)** 0.33 kΩ

Section 6–3

4. A certain common-emitter amplifier has a voltage gain of 100. If the emitter bypass capacitor is removed,

    (a) the circuit will become unstable   **(b)** the voltage gain will decrease

    (c) the voltage gain will increase   **(d)** the Q-point will shift

5. For a common-emitter amplifier, $R_C = 1.0$ kΩ, $R_E = 390$ Ω, $r'_e = 15$ Ω, and $\beta_{ac} = 75$. Assuming that R_E is completely bypassed at the operating frequency, the voltage gain is

    (a) 66.7   **(b)** 2.56   **(c)** 2.47   **(d)** 75

6. In the circuit of Question 5, if the frequency is reduced to the point where $X_{C(bypass)} = R_E$, the voltage gain

    (a) remains the same   **(b)** is less   **(c)** is greater

7. In a common-emitter amplifier with voltage-divider bias, $R_{in(base)} = 68$ kΩ, $R_1 = 33$ kΩ, and $R_2 = 15$ kΩ. The total ac input resistance is

    (a) 68 kΩ   **(b)** 8.95 kΩ   **(c)** 22.2 kΩ   **(d)** 12.3 kΩ

8. A CE amplifier is driving a 10 kΩ load. If $R_C = 2.2$ kΩ and $r'_e = 10$ Ω, the voltage gain is approximately

    (a) 220   **(b)** 1000   **(c)** 10   **(d)** 180

Section 6–4

9. For a common-collector amplifier, $R_E = 100$ Ω, $r'_e = 10$ Ω, and $\beta_{ac} = 150$. The ac input resistance at the base is

    (a) 1500 Ω   **(b)** 15 kΩ   **(c)** 110 Ω   **(d)** 16.5 kΩ

10. If a 10 mV signal is applied to the base of the emitter-follower circuit in Question 9, the output signal is approximately

(a) 100 mV   (b) 150 mV   (c) 1.5 V   (d) 10 mV

11. In a certain emitter-follower circuit, the current gain is 50. The power gain is approximately

(a) $50A_v$ (b) 50   (c) 1   (d) answers (a) and (b)

12. In a Darlington pair configuration, each transistor has an ac beta of 125. If R_E is 560 Ω, the input resistance is

(a) 560 Ω (b) 70 kΩ (c) 8.75 MΩ (d) 140 kΩ

Section 6–5   13. The input resistance of a common-base amplifier is

(a) very low   (b) very high

(c) the same as a CE   (d) the same as a CC

Section 6–6   14. Each stage of a four-stage amplifier has a voltage gain of 15. The overall voltage gain is

(a) 60   (b) 15   (c) 50,625   (d) 3078

15. The overall gain found in Question 14 can be expressed in decibels as

(a) 94.1 dB   (b) 47.0 dB   (c) 35.6 dB   (d) 69.8 dB

Section 6–7   16. A differential amplifier

(a) is used in op-amps   (b) has one input and one output

(c) has two outputs   (d) answers (a) and (c)

17. When a differential amplifier is operated single-ended,

(a) the output is grounded

(b) one input is grounded and a signal is applied to the other

(c) both inputs are connected together

(d) the output is not inverted

18. In the double-ended differential mode,

(a) opposite polarity signals are applied to the inputs

(b) the gain is 1

(c) the outputs are different amplitudes

(d) only one supply voltage is used

19. In the common mode,

(a) both inputs are grounded

(b) the outputs are connected together

(c) an identical signal appears on both inputs

(d) the output signals are in-phase

PROBLEMS

Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 6–1   **Amplifier Operation**

1. What is the lowest value of dc collector current to which a transistor having the characteristic curves in Figure 6–4 can be biased and still retain linear operation with a peak-to-peak base current swing of 20 μA?

2. What is the highest value of I_C under the conditions described in Problem 1?

3. Describe the end points on an ac load line.

Section 6–2   **Transistor AC Models**

4. Define all of the r parameters and all of the h parameters.

5. If the dc emitter current in a transistor is 3 mA, what is the value of r'_e?

6. If the h_{fe} of a transistor is specified as 200, determine β_{ac}.

7. A certain transistor has a dc beta (h_{FE}) of 130. If the dc base current is 10 μA, determine r_e'. $\alpha_{DC} = 0.99$.

8. At the dc bias point of a certain transistor circuit, $I_B = 15$ μA and $I_C = 2$ mA. Also, a variation in I_B of 3 μA about the Q-point produces a variation in I_C of 0.35 mA about the Q-point. Determine β_{DC} and β_{ac}.

Section 6–3 The Common-Emitter Amplifier

9. Draw the dc equivalent circuit and the ac equivalent circuit for the unloaded amplifier in Figure 6–52.

10. Determine the following dc values for the amplifier in Figure 6–52.

   (a) V_B (b) V_E (c) I_E (d) I_C (e) V_C

11. Calculate the quiescent power dissipation in Figure 6–52.

12. Determine the following values for the amplifier in Figure 6–52.

   (a) $R_{in(base)}$ (b) $R_{in(tot)}$ (c) A_v

13. Connect a bypass capacitor across R_E in Figure 6–52, and repeat Problem 12.

14. Connect a 10 kΩ load resistor to the output in Figure 6–52, and repeat Problem 13.

15. Determine the following dc values for the amplifier in Figure 6–53.

   (a) I_E (b) V_E (c) V_B (d) I_C (e) V_C (f) V_{CE}
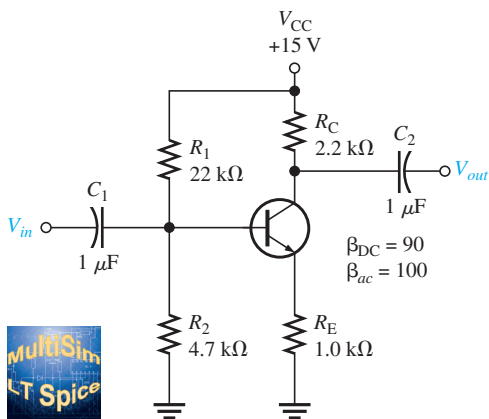
▲ FIGURE 6–52

Multisim file circuits and LT Spice file circuits are identified with a logo and are in the Problems folder on the website. Filenames correspond to figure numbers (e.g., FGM06-52 or FGS06-52).
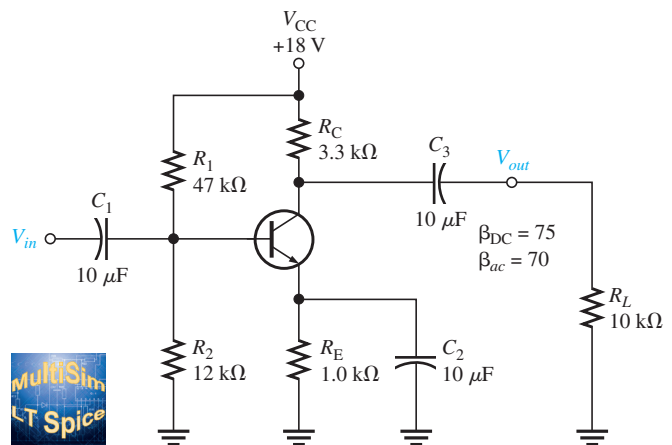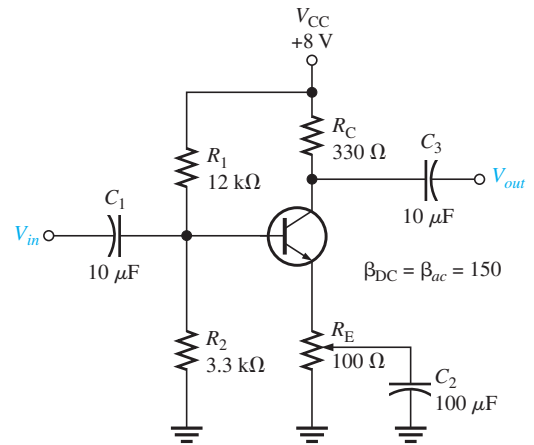

▲ FIGURE 6–53

16. Determine the following ac values for the amplifier in Figure 6–53.

   (a) $R_{in(base)}$ (b) R_{in} (c) A_v (d) A_i (e) A_p

17. Assume that a 600 Ω, 12 μV rms voltage source is driving the amplifier in Figure 6–53. Determine the overall voltage gain by taking into account the attenuation in the base circuit, and find the *total* output voltage (ac and dc). What is the phase relationship of the collector signal voltage to the base signal voltage?

18. The amplifier in Figure 6–54 has a variable gain control, using a 100 Ω potentiometer for R_E with the wiper ac-grounded. As the potentiometer is adjusted, more or less of R_E is bypassed to ground, thus varying the gain. The total R_E remains constant to dc, keeping the bias fixed. Determine the maximum and minimum gains for this unloaded amplifier.

19. If a load resistance of 600 Ω is placed on the output of the amplifier in Figure 6–54, what are the maximum and minimum gains?
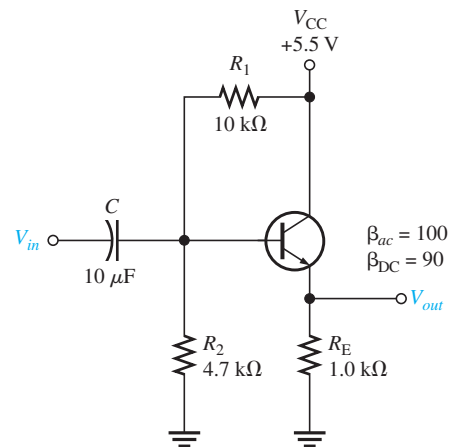
▶ FIGURE 6–54

20. Find the overall maximum voltage gain for the amplifier in Figure 6–54 with a 1.0 kΩ load if it is being driven by a 300 kΩ source.

21. Modify the schematic to show how you would "swamp out" the temperature effects of r'_e in Figure 6–53 by making R_e at least ten times larger than r'_e. Keep the same total R_E. How does this affect the voltage gain?

Section 6–4   **The Common-Collector Amplifier**

22. Determine the *exact* voltage gain for the unloaded emitter-follower in Figure 6–55.

23. What is the total input resistance in Figure 6–55? What is the dc output voltage?

24. A load resistance is capacitively coupled to the emitter in Figure 6–55. In terms of signal operation, the load appears in parallel with R_E and reduces the effective emitter resistance. How does this affect the voltage gain?
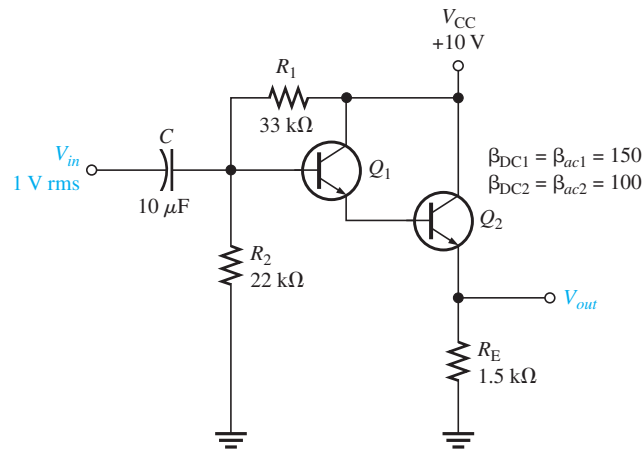
▶ FIGURE 6–55

25. In Problem 24, what value of R_L will cause the voltage gain to drop to 0.9?

26. For the circuit in Figure 6–56, determine the following:

    (a) Q_1 and Q_2 dc terminal voltages

    (b) overall β_{ac}

    (c) r'_e for each transistor

    (d) total input resistance

27. Find the overall current gain A_i in Figure 6–56.

### Section 6–5 The Common-Base Amplifier

28. What is the main disadvantage of the common-base amplifier compared to the common-emitter and the emitter-follower amplifiers?

29. Find $R_{in(emitter)}$, A_v, A_i, and A_p for the unloaded amplifier in Figure 6–57.

30. Match the following generalized characteristics with the appropriate amplifier configuration.

(a) Unity current gain, high voltage gain, very low input resistance

(b) High current gain, high voltage gain, low input resistance

(c) High current gain, unity voltage gain, high input resistance
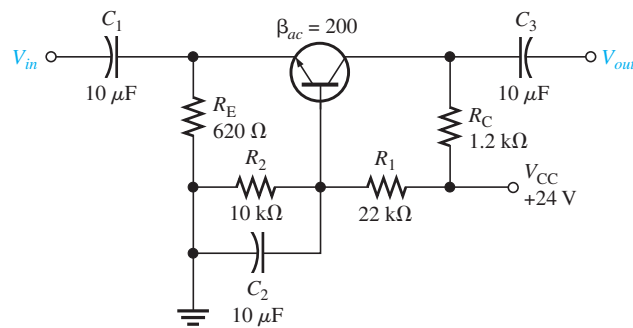
Section 6–6 Multistage Amplifiers

31. Each of two cascaded amplifier stages has an $A_v = 20$. What is the overall gain?

32. Each of three cascaded amplifier stages has a dB voltage gain of 10 dB. What is the overall voltage gain in dB? What is the actual overall voltage gain?

33. For the two-stage, capacitively coupled amplifier in Figure 6–58, find the following values:

(a) voltage gain of each stage

(b) overall voltage gain

(c) Express the gains found in (a) and (b) in dB.

34. If the multistage amplifier in Figure 6–58 is driven by a 75 Ω, 50 μV source and the second stage is loaded with an $R_L = 18$ kΩ, determine

(a) voltage gain of each stage

(b) overall voltage gain

(c) Express the gains found in (a) and (b) in dB.
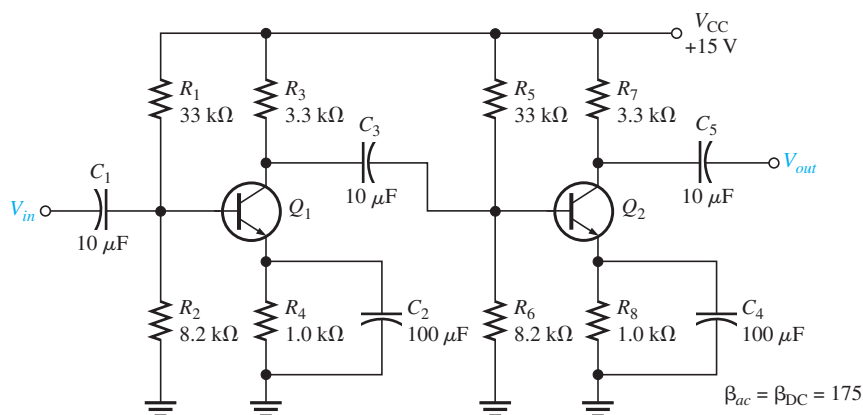
▲ FIGURE 6–58

35. Figure 6–59 shows a direct-coupled (i.e., with no coupling capacitors between stages) two-stage amplifier. The dc bias of the first stage sets the dc bias of the second. Determine all dc voltages for both stages and the overall ac voltage gain.
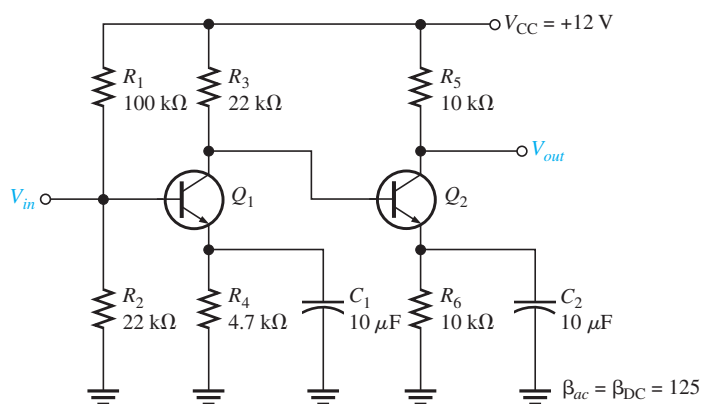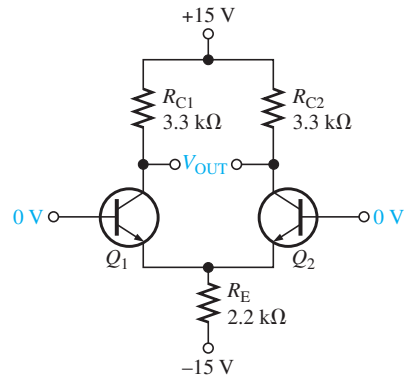

▲ FIGURE 6–59

36. Express the following voltage gains in dB:

(a) 12   (b) 50   (c) 100   (d) 2500

37. Express the following voltage gains in dB as standard voltage gains:

(a) 3 dB   (b) 6 dB   (c) 10 dB   (d) 20 dB   (e) 40 dB
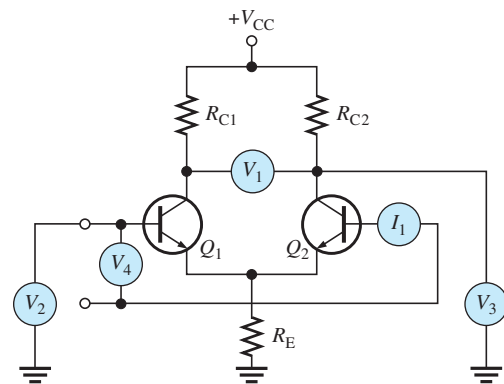
Section 6–7   The Differential Amplifier

38. The dc base voltages in Figure 6–60 are zero. Using your knowledge of transistor analysis, determine the dc differential output voltage. Assume that Q_1 has an $\alpha = 0.980$ and Q_2 has an $\alpha = 0.975$.
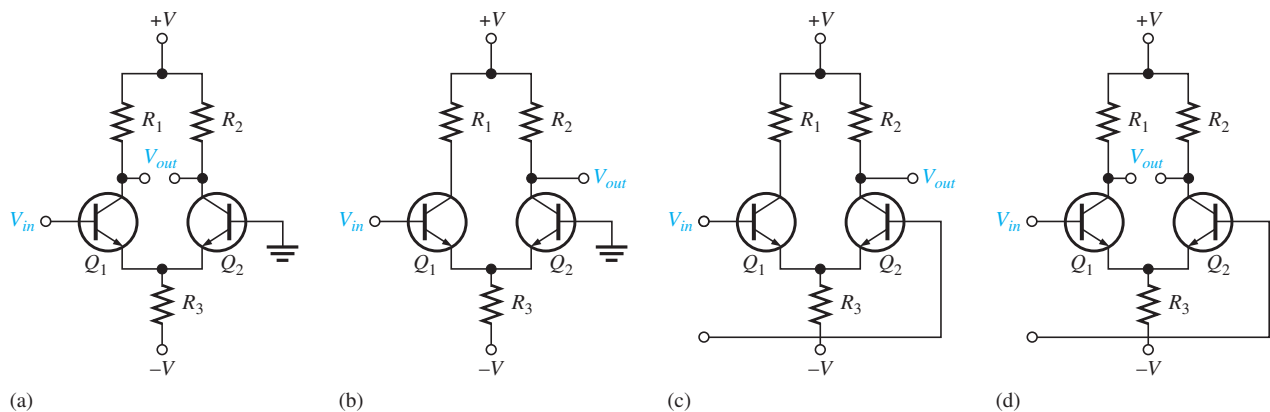
39. Identify the quantity being measured by each meter in Figure 6–61.

40. A differential amplifier stage has collector resistors of 5.1 kΩ each. If $I_{C1} = 1.35$ mA and $I_{C2} = 1.29$ mA, what is the differential output voltage?

41. Identify the type of input and output configuration for each basic differential amplifier in Figure 6–62.

(a)   (b)   (c)   (d)

Section 6–8   Troubleshooting

42. Assume that the coupling capacitor C_3 is shorted in Figure 6–34. What dc voltage will appear at the collector of Q_1?

43. Assume that R_5 opens in Figure 6–34. Will Q_2 be in cutoff or in conduction? What dc voltage will you observe at the Q_2 collector?

44. Refer to Figure 6–58 and determine the general effect of each of the following failures:

   (a) C_2 open

   (b) C_3 open

   (c) C_4 open

   (d) C_2 shorted

   (e) base-collector junction of Q_1 open

   (f) base-emitter junction of Q_2 open

45. Assume that you must troubleshoot the amplifier in Figure 6–58. Set up a table of test point values, input, output, and all transistor terminals that include both dc and rms values that you expect to observe when a 300 Ω test signal source with a 25 μV rms output is used.

APPLICATION ACTIVITY PROBLEMS

46. Refer to the public address system block diagram in Figure 6–47. You are asked to repair a system that is not working. After a preliminary check, you find that there is no output signal from the power amplifier or from the preamplifier. Based on this check and assuming that only one of the blocks is faulty, which block can you eliminate as the faulty one? What would you check next?

47. What effect would each of the following faults in the amplifier of Figure 6–63 have on the output signal?

   (a) Open C_1 (b) Open C_2 (c) Open C_3 (d) Open C_4

   (e) Q_1 collector internally open   (f) Q_2 emitter shorted to ground

▶ FIGURE 6–63
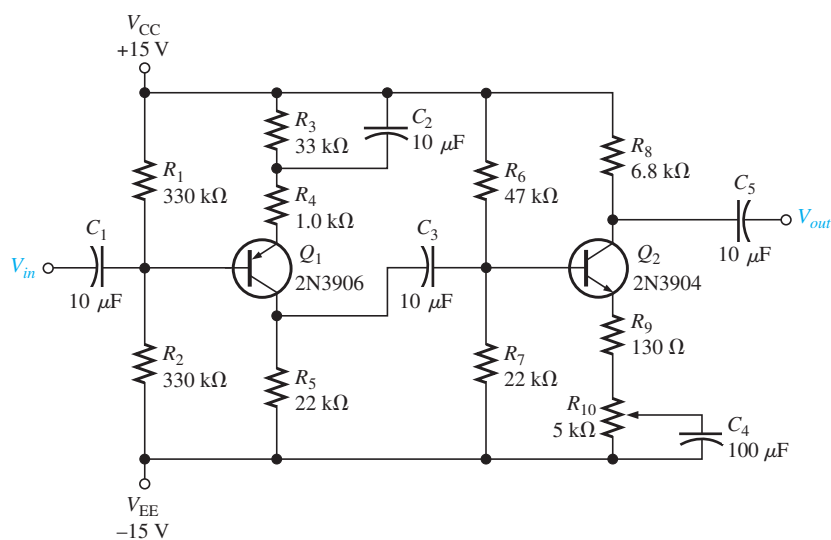
48. Suppose a 220 Ω resistor is incorrectly installed in the R_7 position of the amplifier in Figure 6–63. What effect does this have on the circuit?

49. The connection from R_1 to the supply voltage V_1 in Figure 6–63 has opened.

   (a) What happens to Q_1?

   (b) What is the dc voltage at the Q_1 collector?

   (c) What is the dc voltage at the Q_2 collector?

DATASHEET PROBLEMS

50. Refer to the 2N3946/2N3947 partial datasheet in Figure 6–64 on page 318. Determine the minimum value for each of the following r parameters:

   (a) β_{ac} (b) r_e' (c) r_c'

51. Repeat Problem 50 for maximum values.

52. Should you use a 2N3946 or a 2N3947 transistor in a certain application if the criterion is maximum current gain?

Electrical Characteristics (T_A = 25°C unless otherwise noted.)

Characteristic		Symbol	Min	Max	Unit
Input capacitance (V_{EB} = 1.0 V dc, I_C = 0, f = 1.0 MHz)		C_{ibo}	–	8.0	pF
Input impedance (I_C = 1.0 mA, V_{CE} = 10 V, f = 1.0 kHz)	2N3946 2N3947	h_{ie}	0.5 2.0	6.0 12	kohms
Voltage feedback ratio (I_C = 1.0 mA, V_{CE} = 10 V, f = 1.0 kHz)	2N3946 2N3947	h_{re}	– –	10 20	$\times 10^{-4}$
Small-signal current gain (I_C = 1.0 mA, V_{CE} = 10 V, f = 1.0 kHz)	2N3946 2N3947	h_{fe}	50 100	250 700	–
Output admittance (I_C = 1.0 mA, V_{CE} = 10 V, f = 1.0 kHz)	2N3946 2N3947	h_{oe}	1.0 5.0	30 50	μmhos
Collector base time constant (I_C = 10 mA, V_{CE} = 20 V, f = 31.8 MHz)		$rb'C_c$	–	200	ps
Noise figure (I_C = 100 μA, V_{CE} = 5.0 V, R_G = 1.0 kΩ, f = 1.0 kHz)		NF	–	5.0	dB

Switching Characteristics

Delay time	V_{CC} = 3.0 V dc, V_{OB} = 0.5 V dc,		t_d	–	35	ns
Rise time	I_C = 10 mA dc, I_{B1} = 1.0 mA		t_r	–	35	ns
Storage time	V_{CC} = 3.0 V, I_C = 10 mA,	2N3946 2N3947	t_s	– –	300 375	ns
Fall time	I_{B1} = I_{B2} = 1.0 mA dc		t_f	–	75	ns

(1) Pulse test: $PW \leq 300$ μs, Duty Cycle $\leq 2\%$.

▲ **FIGURE 6–64**

Partial datasheet for the 2N3946/2N3947.

ADVANCED PROBLEMS

53. In an amplifier such as the one in Figure 6–63, explain the general effect that a leaky coupling capacitor would have on circuit performance.

54. Draw the dc and ac equivalent circuits for the amplifier in Figure 6–63.

55. Modify the two-stage amplifier in Figure 6–63 to drive a load of 10 kΩ and maintain the same voltage gain.

56. Design a single-stage common-emitter amplifier with a voltage gain of 40 dB that operates from a dc supply voltage of +12 V. Use a 2N2222 transistor, voltage-divider bias, and a 330 Ω swamping resistor. The maximum input signal is 25 mV rms.

57. Design an emitter-follower with a minimum input resistance of 50 kΩ using a 2N3904 *npn* transistor with a β_{ac} = 100.

58. Repeat Problem 57 using a 2N3906 with a β_{ac} = 100.

59. Design a single-stage common-base amplifier for a voltage gain of 75. Use a 2N3904 with emitter bias. The dc supply voltages are to be ± 6 V.

60. Refer to the amplifier in Figure 6–63 and determine the minimum value of coupling capacitors necessary for the amplifier to produce the same output voltage at 100 Hz that it does at 5000 Hz.

61. Prove that for any unloaded common-emitter amplifier with a collector resistor R_C and R_E bypassed, the voltage gain is $A_v \cong 40 V_{R_C}$.

MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on the website.

62. Open file TPM06-62 and determine the fault.

63. Open file TPM06-63 and determine the fault.

64. Open file TPM06-64 and determine the fault.

65. Open file TPM06-65 and determine the fault.

66. Open file TPM06-66 and determine the fault.

67. Open file TPM06-67 and determine the fault.