# UNIT 6

# SMALL-SIGNAL BIPOLAR AMPLIFIERS

## 6–1 ■ SMALL-SIGNAL 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, a microphone, etc., variations about the Q-point are relatively small. Amplifiers designed to handle these small ac signals are called small-signal amplifiers.***

***After completing this section, you should be able to***

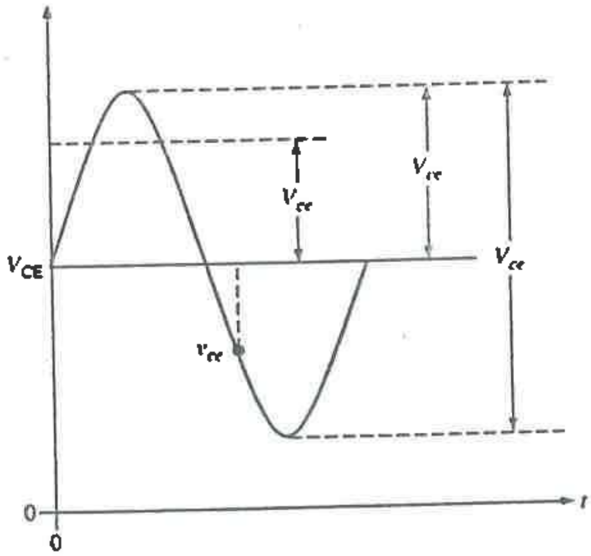
- **Understand the concept of small-signal amplifiers**
  - ☐ Interpret labels used for dc and ac voltages and currents
  - ☐ Discuss the general operation of a small-signal amplifier
  - ☐ Analyze ac load line operation
  - ☐ Describe phase inversion

### 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.

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.

FIGURE 6–1
*$V_{ce}$ can represent rms, average, peak, or peak-to-peak, but rms is always assumed unless stated otherwise. $v_{ce}$ can be any instantaneous value on the curve.*



Resistance values *internal* to the transistor use a lowercase $r'$. An example is the internal ac emitter resistance, $r'_e$.

## The Small-Signal Amplifier

A voltage-divider biased transistor with a sinusoidal ac source capacitively coupled to the base and a load capacitively coupled to the collector is shown in Figure 6–2. The coupling capacitors block dc and thus prevent the source resistance, $R_s$, and the load resistance $R_L$ from changing the dc bias voltages at the base and collector. The sinusoidal source voltage causes the base voltage to vary sinusoidally above and below its dc bias level. The resulting variation in base current produces a larger variation in collector current because of the current gain of the transistor.

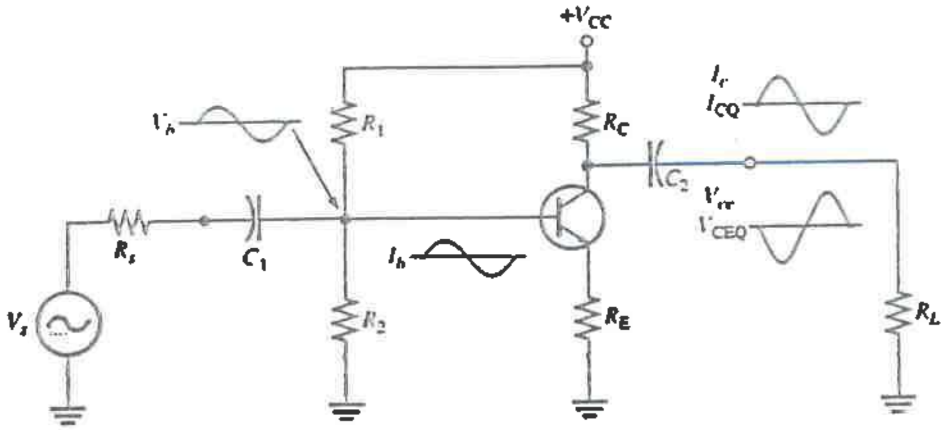



**FIGURE 6–2**
*An amplifier with voltage-divider bias driven by an ac voltage source with an internal resistance, $R_s$.*

As the sinusoidal collector current increases, the collector voltage decreases. The collector current varies above and below its Q-point value in phase with the base current. The sinusoidal collector-to-emitter voltage varies above and below its Q-point value 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 collector-characteristic curves, as shown in Figure 6–3. 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. 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 effective ac collector resistance is $R_L$ in parallel with $R_C$ and is less than the dc collector resistance $R_C$ alone without $R_L$ in parallel. This difference between the dc and the ac load lines is covered in Chapter 7 in relation to power amplifiers.

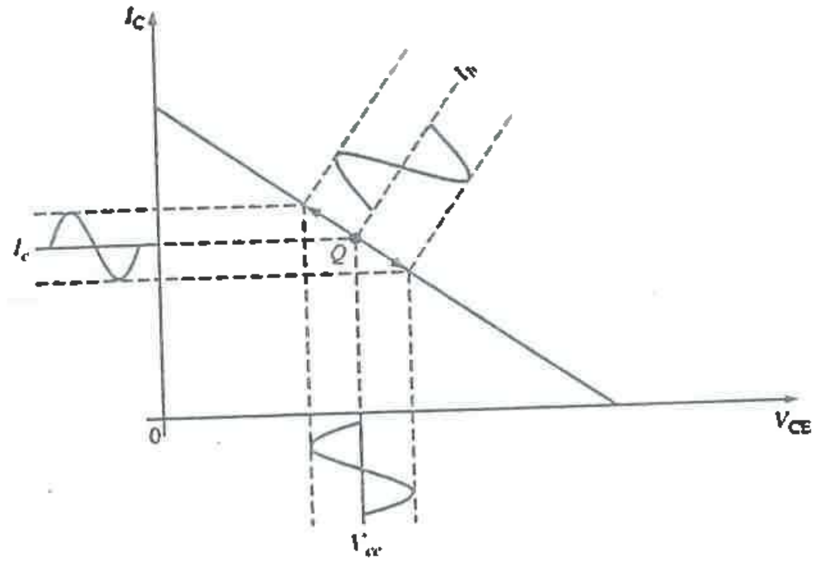
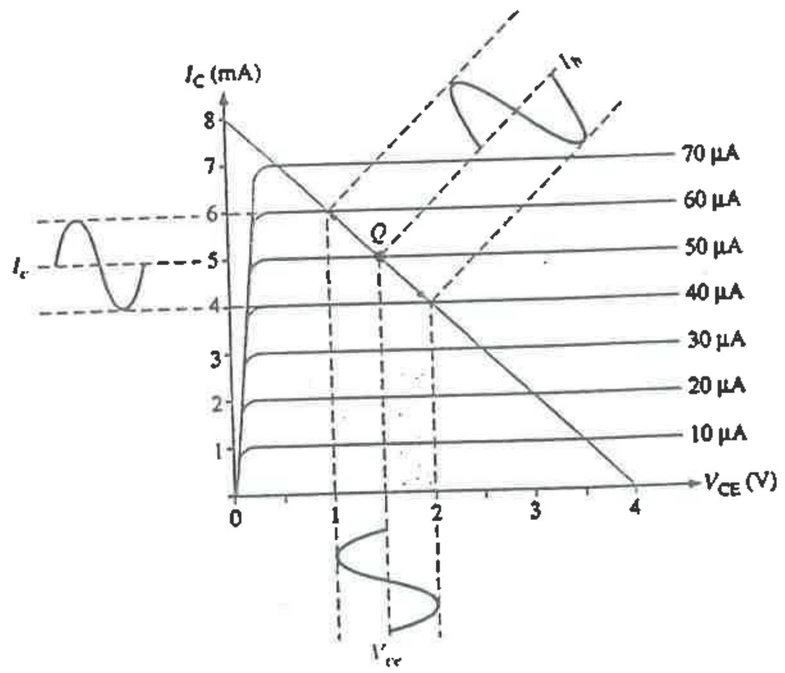



FIGURE 6–3
*Graphical operation of the amplifier showing the base current, collector current, and collector-to-emitter voltage. $I_b$ and $I_c$ are on different scales.*

**EXAMPLE 6–1**

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 Exercise* What are the Q-point values of $I_C$ and $V_{CE}$ in Figure 6–4?

**SECTION 6–1 REVIEW**

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 $r'_e$?

## 6–2 ■ TRANSISTOR AC EQUIVALENT CIRCUITS

*To visualize the operation of a transistor in an amplifier circuit, it is often useful to represent the device by an equivalent circuit. An equivalent circuit uses various internal transistor parameters to represent the transistor's operation. Two types of equivalent circuit representations are described in this section. One is based on hybrid or h parameters and the other is based on resistance or r parameters.*

### *r* Parameters

The resistance, *r*, parameters are perhaps easier to work with than the *h* parameters. The five *r* parameters are given in Table 6–4. As previously mentioned, the italic lowercase letter *r* with a prime denotes resistance values internal to the transistor.

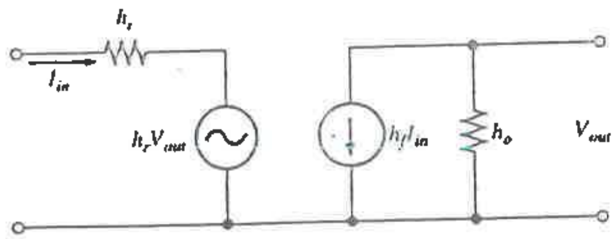



FIGURE 6–7
*Generalized h parameter equivalent circuit for a bipolar junction transistor.*

TABLE 6–4
*r parameters*

| *r* Parameter | Description |
|---|---|
| $\alpha_{ac}$ | ac alpha ($I_c/I_e$) |
| $\beta_{ac}$ | ac beta ($I_c/I_b$) |
| $r'_e$ | ac emitter resistance |
| $r'_b$ | ac base resistance |
| $r'_c$ | ac collector resistance |

Because data sheets often provide only common-emitter $h$ parameters, the following formulas show how to convert them to $r$ parameters.

$$r'_e = \frac{h_{re}}{h_{oe}} \tag{6–7}$$

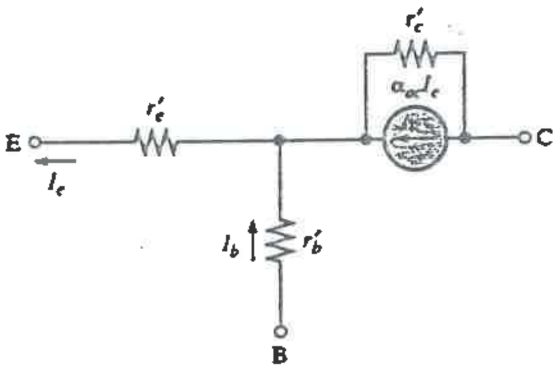
$$r'_c = \frac{h_{re} + 1}{h_{oe}} \tag{6–8}$$

$$r'_b = h_{ie} - \frac{h_{re}}{h_{oe}}(1 + h_{fe}) \tag{6–9}$$

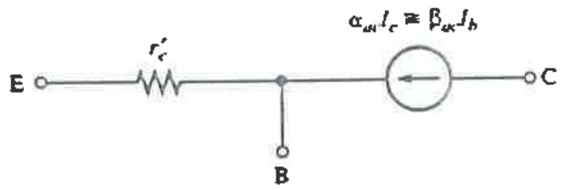
We will use $r$ parameters throughout the text.

## $r$-Parameter Equivalent Circuits

An $r$-parameter equivalent circuit is shown in Figure 6–9(a). For most general analysis work, Figure 6–9(a) can be simplified as follows: The effect of the ac base resistance $r'_b$ is usually small enough to neglect, so that it can be replaced by a short. The ac collector resistance is usually several hundred kilohms and can be replaced by an open. The resulting simplified $r$-parameter equivalent circuit is shown in Figure 6–9(b).




(a) Generalized $r$-parameter equivalent circuit for a bipolar junction transistor




(b) Simplified $r$-parameter equivalent circuit for a bipolar junction transistor

**FIGURE 6–9**
***r*-parameter equivalent circuits.**

The interpretation of this equivalent 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 current source of $\alpha_{ac}I_e$ or, equivalently, $\beta_{ac}I_b$. These factors are shown with a transistor symbol in Figure 6–10.

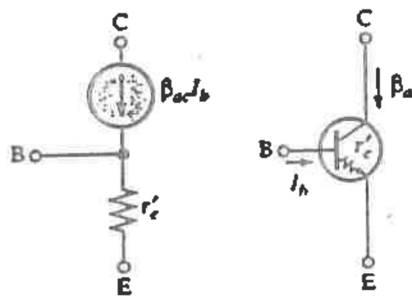



FIGURE 6–10
*Relation of transistor symbol to r-parameter equivalent.*

## Determining $r_e'$ by a Formula

For amplifier analysis, $r_e'$ is the most important of the $r$ parameters. Instead of using $h$ parameters to get $r_e'$, you can use the simple formula of Equation (6–10) to calculate an approximate value.

$$r_e' \cong \frac{25\text{ mV}}{I_E} \quad (6\text{–}10)$$

Although the formula is simple, its derivation is not and is therefore reserved for Appendix B.

**EXAMPLE 6–2**

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

***Solution***

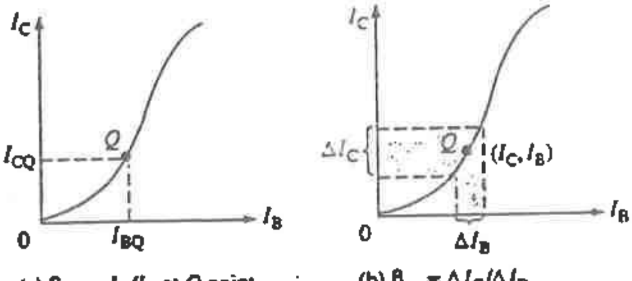
$$r_e' \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{2\text{ mA}} = 12.5\ \Omega$$

***Related Exercise*** What is $I_E$ if $r_e' = 8\ \Omega$?

## Comparison of the AC Beta ($\beta_{ac}$) to the DC Beta ($\beta_{DC}$)

For a typical transistor, a graph of $I_C$ versus $I_B$ is nonlinear, as shown in Figure 6–11(a). If you pick a Q-point on the curve and cause the base current to vary an amount $\Delta I_B$, then the collector current will vary an amount $\Delta I_C$ 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. Remember that $\beta_{DC} = h_{FE}$ and $\beta_{ac} = h_{fe}$.

FIGURE 6–11
*$I_C$-versus-$I_B$ curve illustrates the difference between $\beta_{DC} = I_C/I_B$ and $\beta_{ac} = \Delta I_C/\Delta I_B$.*




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

**SECTION 6–2 REVIEW**

1. Define each of the parameters: $h_{ie}$, $h_{re}$, $h_{fe}$, and $h_{oe}$.
2. Which $h$ parameter is equivalent to $\beta_{ac}$?
3. If $I_E = 15$ mA, what is the approximate value of $r_e'$?

## 6–3 ■ COMMON-EMITTER AMPLIFIERS

***Now that you have an idea of how a transistor can be modeled in an ac circuit, a complete amplifier circuit will be examined. The common-emitter (CE) configuration is covered in this section. CE amplifiers exhibit high voltage and current gains. The common-collector and common-base configurations are covered in the following sections.***

***After completing this section, you should be able to***

- Understand and analyze the operation of common-emitter amplifiers
  - ☐ Represent a CE amplifier by its dc equivalent circuit
  - ☐ Analyze the dc operation of a CE amplifier
  - ☐ Represent a CE amplifier by its ac equivalent circuit
  - ☐ Analyze the ac operation of a CE amplifier
  - ☐ Determine the input resistance
  - ☐ Determine the output resistance
  - ☐ Determine the voltage gain
  - ☐ Explain the effects of an emitter-bypass capacitor
  - ☐ Describe swamping and discuss its purpose and effects
  - ☐ Describe the effect of a load resistor on the voltage gain
  - ☐ Discuss phase inversion in a CE amplifier
  - ☐ Determine current gain
  - ☐ Determine power gain

Figure 6–12 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 circuit has a combination of dc and ac operation, both of which must be considered.

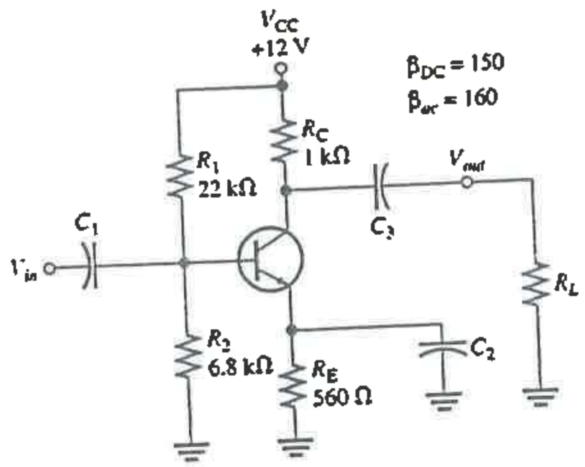



**FIGURE 6–12**
*A common-emitter amplifier.*

## DC Analysis

To analyze the amplifier in Figure 6–12, the dc bias values must first be determined. To do this, a dc equivalent circuit is developed by replacing the coupling and bypass capacitors with opens (remember, a capacitor appears open to dc), as shown in Figure 6–13. Recall from Chapter 5 that the dc input resistance at the base is determined as follows:

$$R_{IN(base)} = \beta_{DC}R_E = (150)(560\ \Omega) = 84\ k\Omega$$

Since $R_{IN(base)}$ is more than ten times $R_2$, it will be neglected when calculating the dc base voltage.

$$V_B \cong \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{6.8\ k\Omega}{28.8\ k\Omega}\right)12\ V = 2.83\ V$$

and

$$V_E = V_B - V_{BE} = 2.83\ V - 0.7\ V = 2.13\ V$$

Therefore,

$$I_E = \frac{V_E}{R_E} = \frac{2.13\ V}{560\ \Omega} = 3.80\ mA$$

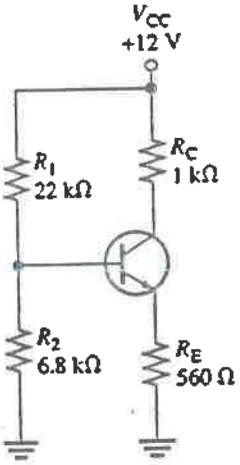
Since $I_C \cong I_E$, then

$$V_C = V_{CC} - I_C R_C = 12\ V - 3.80\ V = 8.20\ V$$

Finally,

$$V_{CE} = V_C - V_E = 8.20\ V - 2.13\ V = 6.07\ V$$

FIGURE 6–13
*DC equivalent circuit for the amplifier in Figure 6–12.*




## The AC Equivalent Circuit

To analyze the ac signal operation of an amplifier, an ac equivalent circuit is developed as follows: The capacitors $C_1$, $C_2$, and $C_3$ are replaced by effective shorts because we assume that $X_C \cong 0\ \Omega$ at the signal frequency.

*AC Ground* The dc source is replaced by a ground. We assume that the voltage source has an internal resistance of approximately 0 Ω, so that no ac voltage is developed across the source terminals. Therefore, the $V_{CC}$ terminal is at a zero-volt ac potential and is called *ac ground.*

The ac equivalent circuit for the common-emitter amplifier in Figure 6–12 is shown in Figure 6–14(a). Notice that both $R_C$ and $R_1$ have one end connected to ac ground because, in the actual circuit, they are connected to $V_{CC}$ which is, in effect, ac ground.

In ac analysis, the ac ground and the actual ground are treated as the same point electrically. The amplifier in Figure 6–12 is a common-emitter type because the bypass capacitor $C_2$ keeps the emitter at ac ground (ground is the common point in the circuit).

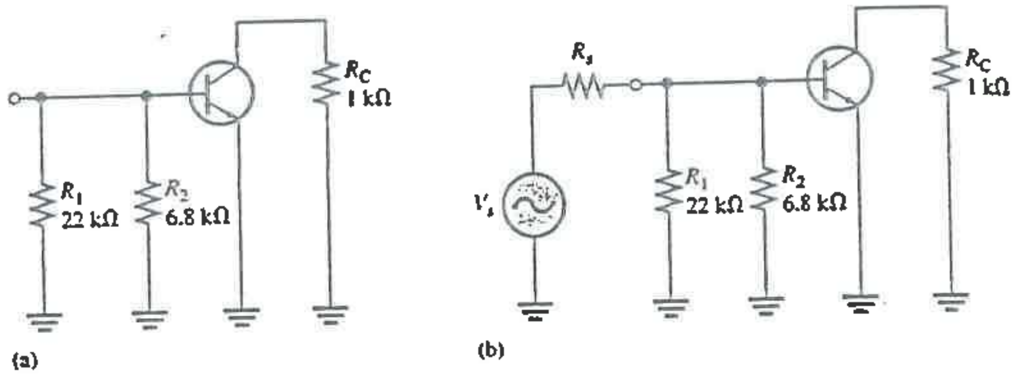



FIGURE 6–14
*AC equivalent circuit for the amplifier in Figure 6–12.*

*Signal (AC) Voltage at the Base* An ac voltage source is shown connected to the input in Figure 6–14(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, the bias resistance, and the input resistance at the base. This is illustrated in Figure 6–15(a) and is simplified by combining

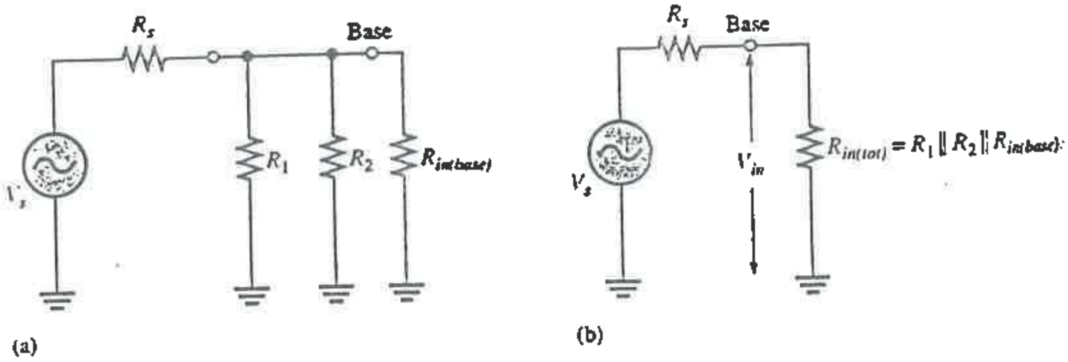



FIGURE 6–15
*AC equivalent base circuit.*

$R_1$, $R_2$, and $R_{in(base)}$ in parallel to get the total input resistance, $R_{in(tot)}$, as shown in Figure 6–15(b). As you can see, the source voltage $V_s$ is divided down by $R_s$ (source resistance) and $R_{in}$, so that the signal voltage at the base of the transistor is found by the voltage-divider formula as follows:

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

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

***Input Resistance*** To develop an expression for the input resistance as seen by an ac source looking in at the base, we will use the simplified *r*-parameter model of the transistor. Figure 6–16 shows the transistor connected with the external 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 $I_e \cong I_c$,

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

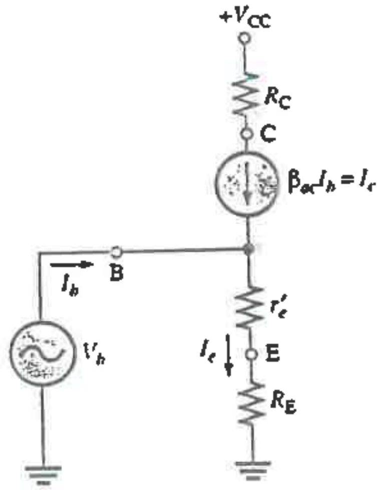
Substituting for $V_b$ and $I_b$, we get

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

Cancelling $I_e$, we get

$$R_{in(base)} = \beta_{ac} r'_e \tag{6–11}$$

**FIGURE 6–16**
***r-parameter transistor model (inside shaded block) connected to external circuit.***



The total input resistance seen by the source is the parallel combination of $R_1$, $R_2$, and $R_{in(base)}$.

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)} \tag{6–12}$$

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

$$R_{out} \cong R_C \tag{6–13}$$

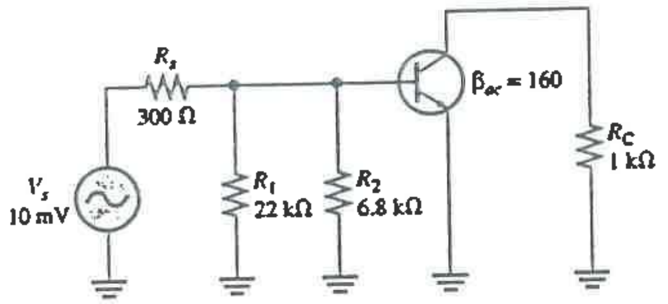
Actually, $R_{out} = R_C \parallel r'_c$, but since the internal ac collector resistance of the transistor, $r'_c$, is typically much larger than $R_C$, the approximation is usually valid. For example, the partial data sheet in Figure 6–5 gives minimum values for the 2N3904 of $h_{re} = 0.5 \times 10^{-4}$ and $h_{oe} = 1.0\ \mu S$. (Siemens and mhos are the same unit; mhos is the older designation but Siemens is the current standard.) From these values, $r'_c$ can be calculated using Equation (6–8).

$$r'_c = \frac{h_{re} + 1}{h_{oe}} = \frac{0.5 \times 10^{-4} + 1}{1.0\ \mu S} \cong 1\ M\Omega$$

**EXAMPLE 6–3**

Determine the signal voltage at the base in Figure 6–17. This circuit is the ac equivalent of the amplifier in Figure 6–12 with a 10 mV rms, 300 Ω signal source. $I_E$ was previously found to be 3.80 mA.

FIGURE 6–17




***Solution*** First, determine the ac emitter resistance:

$$r'_e = \frac{25\ mV}{I_E} = \frac{25\ mV}{3.80\ mA} = 6.58\ \Omega$$

Then,

$$R_{in(base)} = \beta_{ac} r'_e = 160(6.58\ \Omega) = 1.05\ k\Omega$$

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

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)} = \frac{1}{\dfrac{1}{22\ k\Omega} + \dfrac{1}{6.8\ k\Omega} + \dfrac{1}{1.05\ k\Omega}} = 873\ \Omega$$

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

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}}\right)V_s = \left(\frac{873\ \Omega}{1173\ \Omega}\right)10\ \text{mV} = 7.44\ \text{mV}$$

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

***Related Exercise*** Determine the signal voltage at the base of Figure 6–17 if the source resistance is 75 Ω and another transistor with an ac beta of 200 is used.

## Voltage Gain of the CE Amplifier

The ac voltage gain expression is developed using the equivalent circuit in Figure 6–18. The gain is the ratio of ac output voltage ($V_c$) 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 $V_c = \alpha_{ac} I_e R_C \cong I_e R_C$ and $V_b = I_e r'_e$. Therefore,

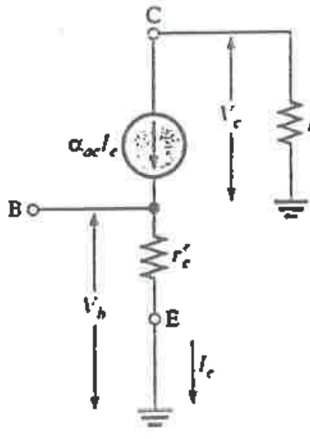
$$A_v = \frac{I_e R_C}{I_e r'_e}$$

The $I_e$ terms cancel, so

$$A_v = \frac{R_C}{r'_e} \qquad (6\text{–}14)$$

Equation (6–14) 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 defined as a gain of less than 1 and results in a reduction of the signal voltage. The attenuation from source to base multiplied by the gain from base to collector is the overall amplifier gain. Suppose the source produces 10 mV and the

FIGURE 6–18
*Equivalent circuit for obtaining ac voltage gain.*



source resistance and input resistance is such that the base voltage is 5 mV. The attenuation is therefore 5 mV/10 mV = 0.5. Now assume the amplifier has a voltage gain from base to collector of 20. The output voltage is 5 mV × 20 = 100 mV. Therefore, the overall gain is 100 mV/10 mV = 10 and is equal to the attenuation times the gain (0.5 × 20 = 10). Overall gain is illustrated in Figure 6–19.

The expression for the attenuation in the base circuit where $R_s$ and $R_{in(tot)}$ act as a voltage divider is

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

The overall gain, $A'_v$, is the product of the attenuation and the gain from base to collector $A_v$.

$$A'_v = \left(\frac{V_b}{V_s}\right) A_v \qquad (6\text{–}15)$$

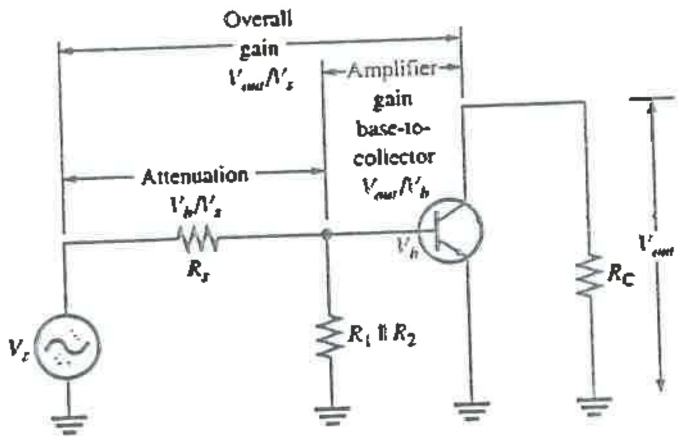



FIGURE 6–19
*Base circuit attenuation and overall gain.*

***Effect of the Emitter-Bypass Capacitor on Voltage Gain*** The emitter-bypass capacitor 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 $R_C/r'_e$.

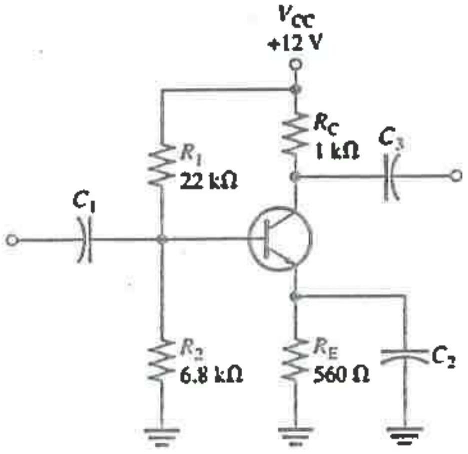
The value of the bypass capacitor must be large enough so that its reactance over the frequency range of the amplifier is very small (ideally 0 Ω) compared to $R_E$. A good rule-of-thumb is that $X_C$ of the bypass capacitor should be at least 10 times smaller than $R_E$ at the minimum frequency for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

$$10X_C \leq R_E$$

**EXAMPLE 6–4**

Select a minimum value for the emitter-bypass capacitor in Figure 6–20 if the amplifier must operate over a frequency range from 2 kHz to 10 kHz.

FIGURE 6–20




***Solution*** Since $R_E = 560\ \Omega$, $X_C$ of the bypass capacitor should be no greater than

$$10X_C = R_E$$

$$X_C = \frac{R_E}{10} = \frac{560\ \Omega}{10} = 56\ \Omega$$

The capacitance value is determined at the minimum frequency of 2 kHz as follows:

$$C_2 = \frac{1}{2\pi f X_C} = \frac{1}{2\pi(2\text{ kHz})(56\ \Omega)} = 1.42\ \mu\text{F}$$

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

***Related Exercise*** If the minimum frequency is reduced to 1 kHz, 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 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.

$$A_v = \frac{R_C}{r'_e + R_E} \qquad (6\text{–}16)$$

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

**EXAMPLE 6–5** Calculate the base-to-collector voltage gain of the amplifier in Figure 6–12 without and with an emitter bypass capacitor if there is no load resistor.

***Solution*** From Example 6–3, $r'_e = 6.58\ \Omega$ for this particular amplifier. Without $C_2$, the gain is

$$A_v = \frac{R_C}{r'_e + R_E} = \frac{1\ \text{k}\Omega}{566.58\ \Omega} = 1.76$$

With $C_2$, the gain is

$$A_v = \frac{R_C}{r'_e} = \frac{1\ \text{k}\Omega}{6.58\ \Omega} = 152$$

What a difference the bypass capacitor makes!

***Related Exercise*** Determine the base-to-collector voltage gain in Figure 6–12 with $R_E$ bypassed, for the following circuit values: $R_C = 1.8\ \text{k}\Omega$, $R_E = 1\ \text{k}\Omega$, $R_1 = 33\ \text{k}\Omega$, and $R_2 = 6.8\ \text{k}\Omega$.

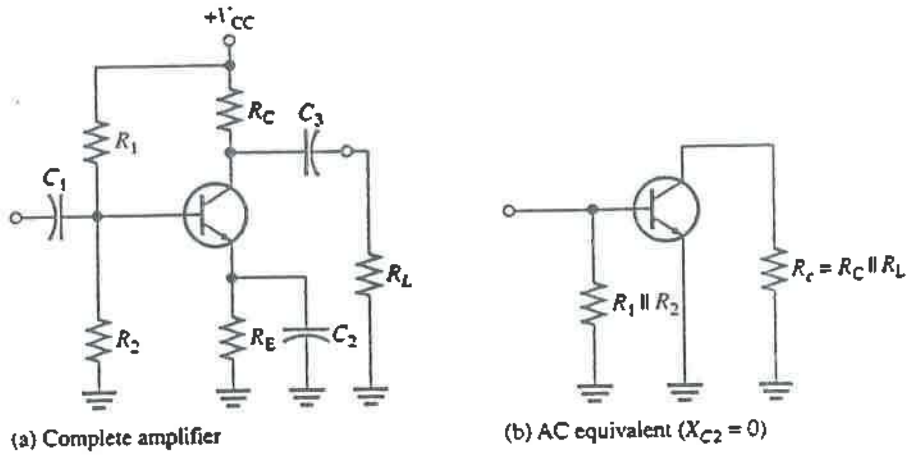
***Effect of a Load on Voltage Gain*** When a **load**, $R_L$, is connected to the output through the coupling capacitor $C_3$, as shown in Figure 6–21(a), the collector resistance at the signal frequency is effectively $R_C$ in parallel with $R_L$. Remember, the upper end of $R_C$ is effectively at ac ground. The ac equivalent circuit is shown in Figure 6–21(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

$$A_v = \frac{R_c}{r'_e} \qquad (6\text{–}17)$$

**FIGURE 6–21**
***A common-emitter amplifier with an ac (capacitively) coupled load.***



When $R_c < R_C$, the voltage gain is reduced. If $R_L >> R_C$, then $R_c \cong R_C$ and the load has very little effect on the gain.

**EXAMPLE 6–6**

Calculate the base-to-collector voltage gain of the amplifier in Figure 6–12 when a load resistance of 5 kΩ is connected to the output. The emitter is effectively bypassed and $r_e' = 6.58\ \Omega$.

***Solution*** The ac collector resistance is

$$R_c = \frac{R_C R_L}{R_C + R_L} = \frac{(1\text{ k}\Omega)(5\text{ k}\Omega)}{6\text{ k}\Omega} = 833\ \Omega$$

Therefore,

$$A_v = \frac{R_c}{r_e'} = \frac{833\ \Omega}{6.58\ \Omega} \doteq 127$$

The unloaded gain was found to be 152 in Example 6–5.

***Related Exercise*** Determine the base-to-collector voltage gain in Figure 6–12 when a 10 kΩ load resistance is connected from collector to ground. Change the resistance values as follows: $R_C = 1.8$ kΩ, $R_E = 1$ kΩ, $R_1 = 33$ kΩ, and $R_2 = 6.8$ kΩ. The emitter resistor is effectively bypassed and $r_e' = 10\ \Omega$.

## Stability of the Voltage Gain

Although bypassing $R_E$ does produce the maximum voltage gain, there is a stability problem because the ac voltage gain is dependent on $r_e'$ ($A_v = R_C/r_e'$) and $r_e'$ depends on $I_E$ and varies considerably with temperature. This causes the gain to be unstable over 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 $R_E$, the gain is much less dependent on $r_e'$; if $R_E >> r_e'$, 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 having a bypass capacitor across $R_E$ and having no bypass capacitor at all.

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 external emitter resistance, $R_E$, is formed with two separate emitter resistors, $R_{E1}$ and $R_{E2}$, as indicated in Figure 6–22. One of the resistors, $R_{E2}$, is bypassed and the other is not.

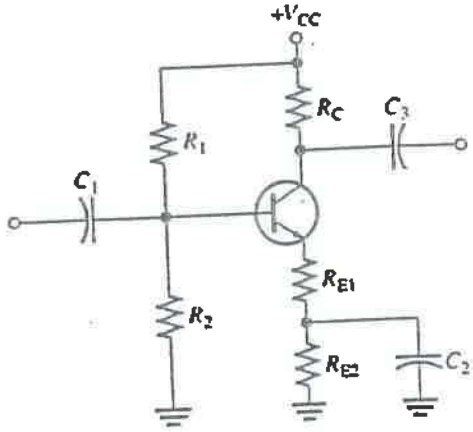
Both resistors ($R_{E1} + R_{E2}$) affect the dc bias while only $R_{E1}$ affects the ac voltage gain.

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

If $R_{E1}$ is several times larger than $r'_e$, then the effect of $r'_e$ is minimized and the approximate voltage gain is

$$A_v \cong \frac{R_C}{R_{E1}} \quad (6\text{–}18)$$

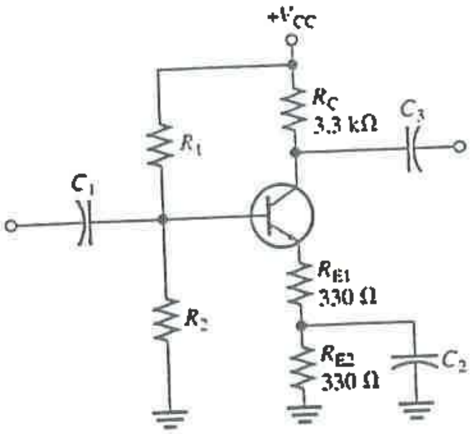
FIGURE 6–22
*A swamped amplifier uses a partially bypassed emitter resistance to achieve gain stability.*




**EXAMPLE 6–7**

Determine the voltage gain of the swamped amplifier in Figure 6–23. Assume that the bypass capacitor has a negligible reactance for the frequency at which the amplifier is operated. Assume $r'_e = 20\ \Omega$.

FIGURE 6–23




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

$$A_v = \frac{R_C}{R_{E1}} = \frac{3.3\ \text{k}\Omega}{330\ \Omega} = 10$$

***Related Exercise*** What would be the voltage gain without $C_2$? What would be the voltage gain with $C_2$ bypassing both $R_{E1}$ and $R_{E2}$?

***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 contributes to the input resistance by appearing in series with $r'_e$. The formula is

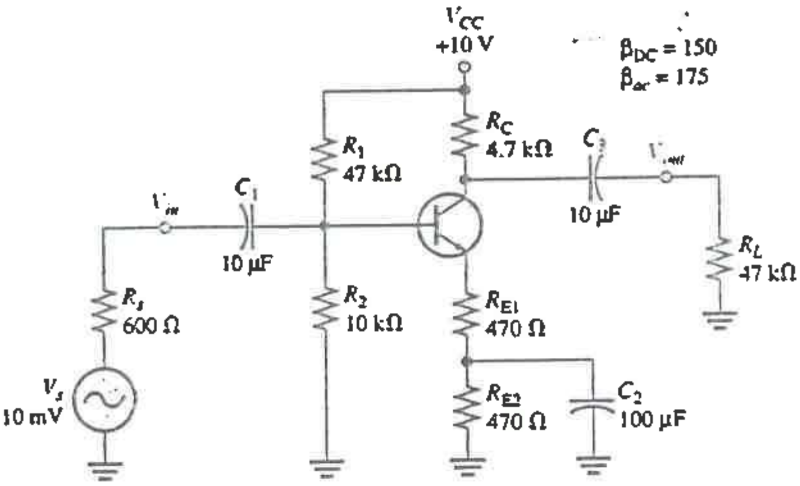
$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1}) \qquad (6\text{–}19)$$

## Phase Inversion in a Common-Emitter Amplifier

The output voltage at the collector of a common-emitter amplifier is 180° out of phase with the input voltage at the base. The phase inversion is sometimes indicated by a negative sign in front of voltage gain, $-A_v$. The next example pulls together the concepts covered so far as they relate to the common-emitter amplifier.

**EXAMPLE 6–8** For the amplifier in Figure 6–24, determine the total collector voltage (dc and ac).

FIGURE 6–24




*Solution* Two sets of calculations are necessary to determine the total collector voltage.

**Step 1:** Determine the dc bias values. Refer to the dc equivalent circuit in Figure 6–25.

$$R_{IN(base)} = \beta_{DC}(R_{E1} + R_{E2}) = 150(940\ \Omega) = 141\ \text{k}\Omega$$

Since $R_{IN(base)}$ is more than ten times larger than $R_2$, it can be neglected in the dc base voltage calculation.

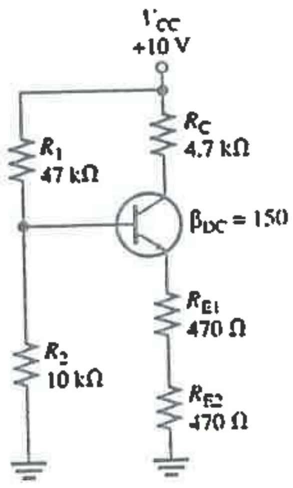
$$V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{10\ \text{k}\Omega}{47\ \text{k}\Omega + 10\ \text{k}\Omega}\right)10\ \text{V} = 1.75\ \text{V}$$

$$V_E = V_B - 0.7\ \text{V} = 1.75\ \text{V} - 0.7\ \text{V} = 1.05\ \text{V}$$

$$I_E = \frac{V_E}{R_{E1} + R_{E2}} = \frac{1.05}{940\ \Omega} = 1.12\ \text{mA}$$

$$V_C = V_{CC} - I_C R_C = 10\ \text{V} - (1.12\ \text{mA})(4.7\ \text{k}\Omega) = 4.74\ \text{V}$$

FIGURE 6–25
*DC equivalent for the circuit in Figure 6–24.*




**Step 2:** The ac analysis is based on the ac equivalent circuit in Figure 6–26. The first thing to do in the ac analysis is calculate $r'_e$.

$$r'_e \cong \frac{25\text{ mV}}{I_E} = \frac{25\text{ mV}}{1.12\text{ mA}} = 22\ \Omega$$

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

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(base)}$$
$$R_{in(base)} = \beta_{ac}(r'_e + R_{E1}) = 175(492\ \Omega) = 86.1\text{ k}\Omega$$

Therefore,

$$R_{in(tot)} = 47\text{ k}\Omega \parallel 10\text{ k}\Omega \parallel 86.1\text{ k}\Omega = 7.53\text{ k}\Omega$$

The attenuation from source to base is

$$\text{Attenuation} = \frac{V_b}{V_s} = \frac{R_{in(tot)}}{R_s + R_{in(tot)}} = \frac{7.53\text{ k}\Omega}{600\ \Omega + 7.53\text{ k}\Omega} = 0.93$$

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

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

The overall voltage gain is 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

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

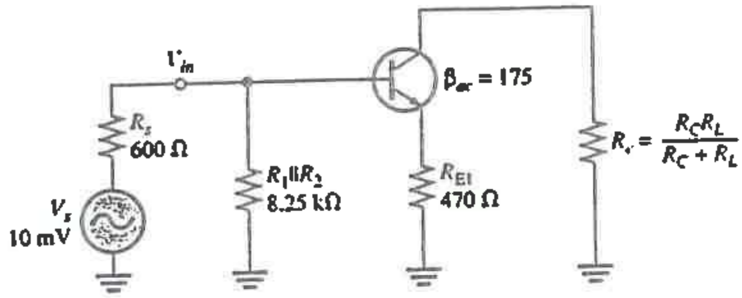



**FIGURE 6–26**
*AC equivalent for the circuit in Figure 6–24.*

The total collector voltage is the signal of 84.5 mV rms riding on a dc level of 4.74 V, as shown in Figure 6–27(a), where approximate peak values are shown. The coupling capacitor $C_3$ keeps the dc level from getting to the output. So, $V_{out}$ is equal to the ac portion of the collector voltage, as indicated in Figure 6–27(b). The source voltage is shown to emphasize the phase inversion.

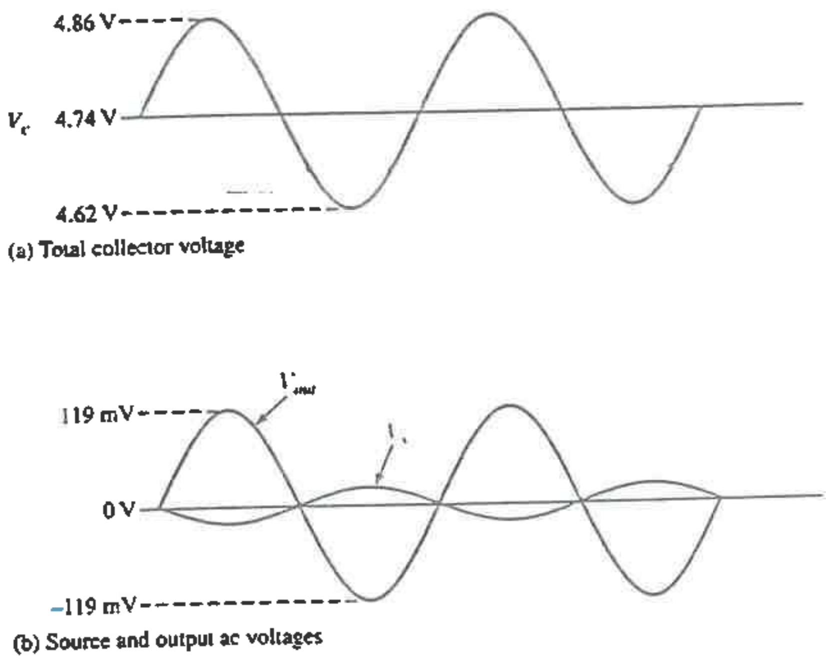



**FIGURE 6–27**
*Voltages for Figure 6–24.*

***Related Exercise*** What is $A_v$ in Figure 6–24 with $R_L$ removed?

## Current Gain

The current gain from base to collector is $I_c/I_b$ or $\beta_{ac}$. However, the overall current gain of the amplifier is

$$A_i = \frac{I_c}{I_s} \tag{6–20}$$

$I_s$ is the total signal current from the source, part of which is base current and part of which is the signal current in the bias network ($R_1 \parallel R_2$), as shown in Figure 6–28. The total current signal from the source is

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

## Power Gain

The power gain is the product of the overall voltage gain and the current gain.

$$A_p = A_v' A_i \tag{6–21}$$

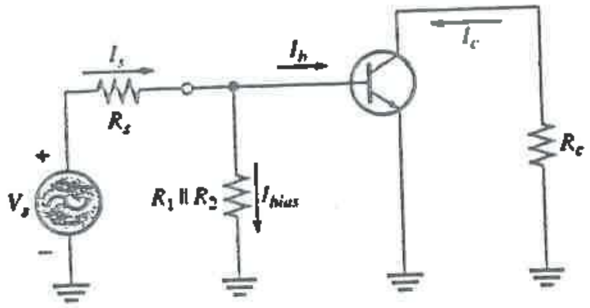
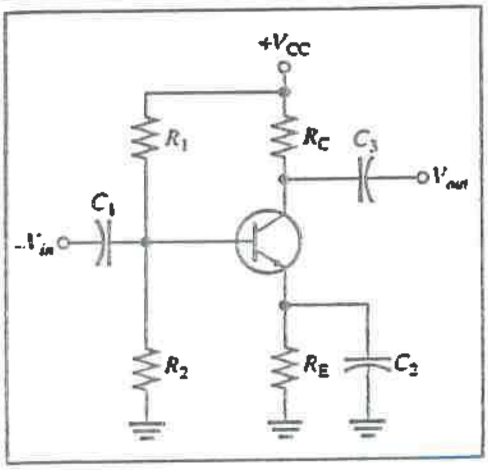



FIGURE 6–28
*Total input signal current (directions shown are for the positive half-cycle of $V_s$).*

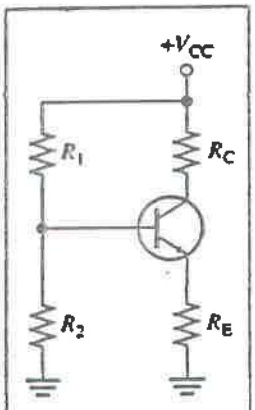
## SUMMARY OF THE COMMON-EMITTER AMPLIFIER

### 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.
- Emitter is at ac ground due to the bypass capacitor.

### EQUIVALENT CIRCUITS AND FORMULAS




DC equivalent

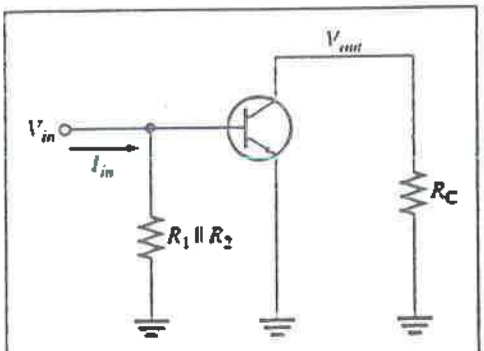
- DC formulas:

$$V_B = \left(\frac{R_2 \parallel \beta_{DC} R_E}{R_1 + R_2 \parallel \beta_{DC} R_E}\right) V_{CC}$$

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

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

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




AC equivalent

- AC formulas:

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

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

$$R_{out} \cong R_C$$

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

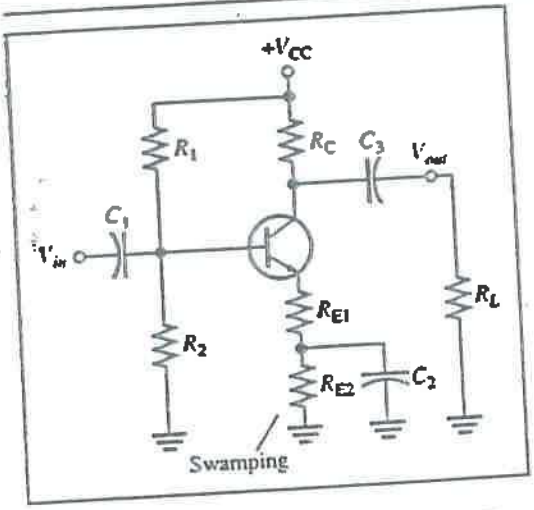
$$A'_v = \left(\frac{V_b}{V_s}\right) A_v$$

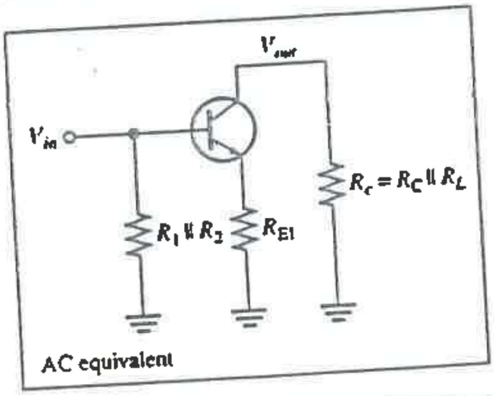
$$A_i = \frac{I_C}{I_{in}}$$

$$A_p = A'_v A_i$$

## SUMMARY OF THE COMMON-EMITTER AMPLIFIER, *continued*

### SWAMPED AMPLIFIER WITH RESISTIVE LOAD




- AC formulas:

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

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

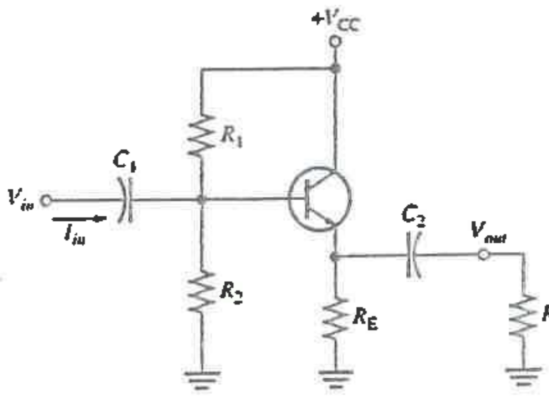
- Swamping stabilizes gain by minimizing the effect of $r'_e$.
- Swamping reduces voltage gain from its unswamped value.
- Swamping increases input resistance.
- Load resistance reduces voltage gain.

### SECTION 6–3 REVIEW

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 COMMON-COLLECTOR AMPLIFIERS

FIGURE 6–29
*Emitter-follower with voltage-divider bias.*




# 6-5 COMMON-BASE AMPLIFIERS

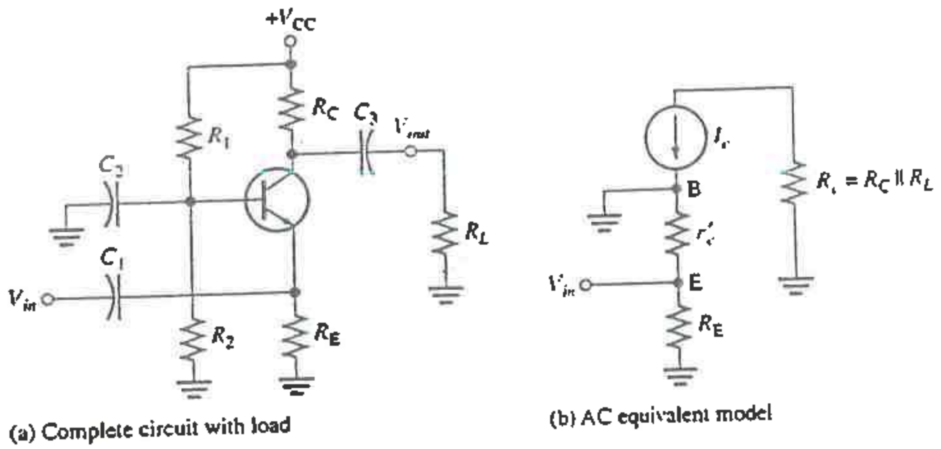



FIGURE 6–34
*Common-base amplifier with voltage-divider bias.*

***Several amplifiers can be connected in a cascaded arrangement with the output of one amplifier driving the input of the next. Each amplifier in the cascaded arrangement is known as a stage. The basic purpose of a multistage arrangement is to increase the overall voltage gain.***

***After completing this section, you should be able to***

- **Discuss multistage amplifiers and analyze their operation**
  - Determine multistage voltage gain
  - Express the voltage gain in decibels (dB)
  - Determine the loading effects in a multistage amplifier
  - Analyze each stage to determine the overall voltage gain
  - Discuss capacitive coupling in multistage amplifiers
  - Describe a basic direct-coupled multistage amplifier
  - Describe a basic transformer-coupled multistage amplifier

## Multistage Voltage Gain

The overall voltage gain, $A'_v$, of cascaded amplifiers, as shown in Figure 6–36, is the product of the individual gains.

$$A'_v = A_{v1}A_{v2}A_{v3} \cdots A_{vn} \qquad (6\text{–}34)$$

where $n$ is the number of stages.

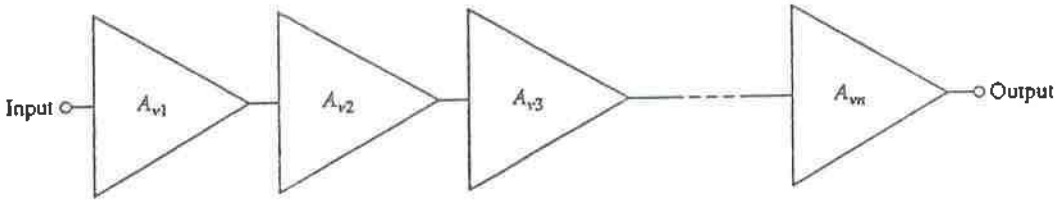



FIGURE 6–36
*Cascaded amplifiers. Each triangular symbol represents a separate amplifier.*

## Voltage Gain Expressed in Decibels

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

$$A_{v(dB)} = 20 \log A_v \qquad (6\text{–}35)$$

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

$$A'_{v(dB)} = A_{v1(dB)} + A_{v2(dB)} + \cdots + A_{vn(dB)} \qquad (6\text{–}36)$$

**EXAMPLE 6–12** 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*

$$A'_v = A_{v1}A_{v2}A_{v3} = (10)(15)(20) = 3000$$

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

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

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

$$A'_{v(dB)} = 20 \text{ dB} + 23.5 \text{ dB} + 26.0 \text{ dB} = 69.5 \text{ dB}$$

***Related Exercise*** 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.