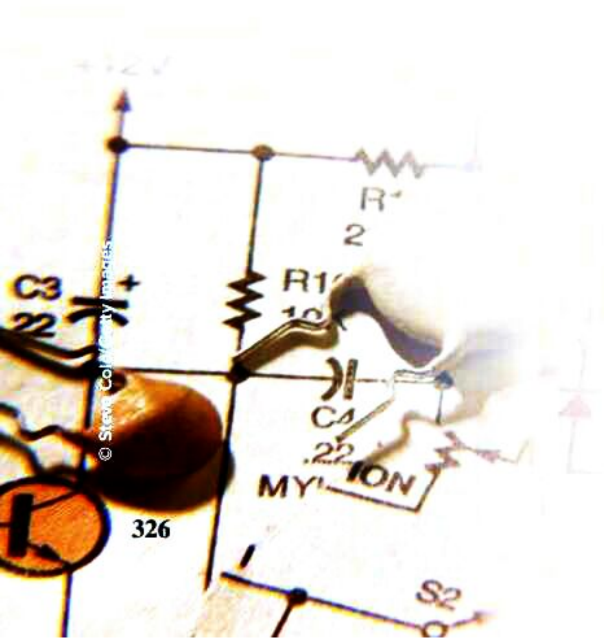
chapter 9

Multistage, CC, and CB Amplifiers

When the load resistance is small compared to the collector resistance, the voltage gain of a CE stage becomes small and the amplifier may become overloaded. One way to prevent overloading is to use a common-collector (CC) amplifier or emitter follower. This type of amplifier has a large input impedance and can drive small load resistances. In addition to emitter followers, this chapter discusses multistage amplifiers, Darlington amplifiers, improved voltage regulation, and common-base (CB) amplifiers.



Objectives

After studying this chapter, you should be able to:

- Draw a diagram of a two-stage CE amplifier.
- Draw a diagram of an emitter follower and describe its advantages.
- Analyze an emitter follower for dc and ac operation.
- Describe the purpose of cascading CE and CC amplifiers.
- State the advantages of a Darlington transistor.
- Draw a schematic for a zener follower and discuss how it increases the load current out of a zener regulator.
- Analyze a common-base amplifier for dc and ac operation.
- Compare the characteristics of CE, CC, and CB amplifiers.
- Troubleshoot Multistage Amplifiers.

Chapter Outline

Vocabulary

buffer
cascading
common-base (CB) amplifier
common-collector (CC) amplifier
complementary Darlington
Darlington connection
Darlington pair
Darlington transistor
direct coupled
emitter follower
multistage amplifier
total voltage gain
two-stage feedback
zener follower

9-1 Multistage Amplifiers

To get more voltage gain, we can create a **multistage amplifier** by **cascading** two or more amplifier stages. This means using the output of the first stage as the input to a second stage. In turn, the output of the second stage can be used as the input to the third stage, and so on.

Figure 9-1*a* shows a two-stage amplifier. The amplified and inverted signal out of the first stage is coupled to the base of the second stage. The amplified and inverted output of the second stage is then coupled to the load resistance. The signal across the load resistance is in phase with the generator signal. The reason is that each stage inverts the signal by 180°. Therefore, two stages invert the signal by 360°, equivalent to 0° (in phase).

Voltage Gain of First Stage

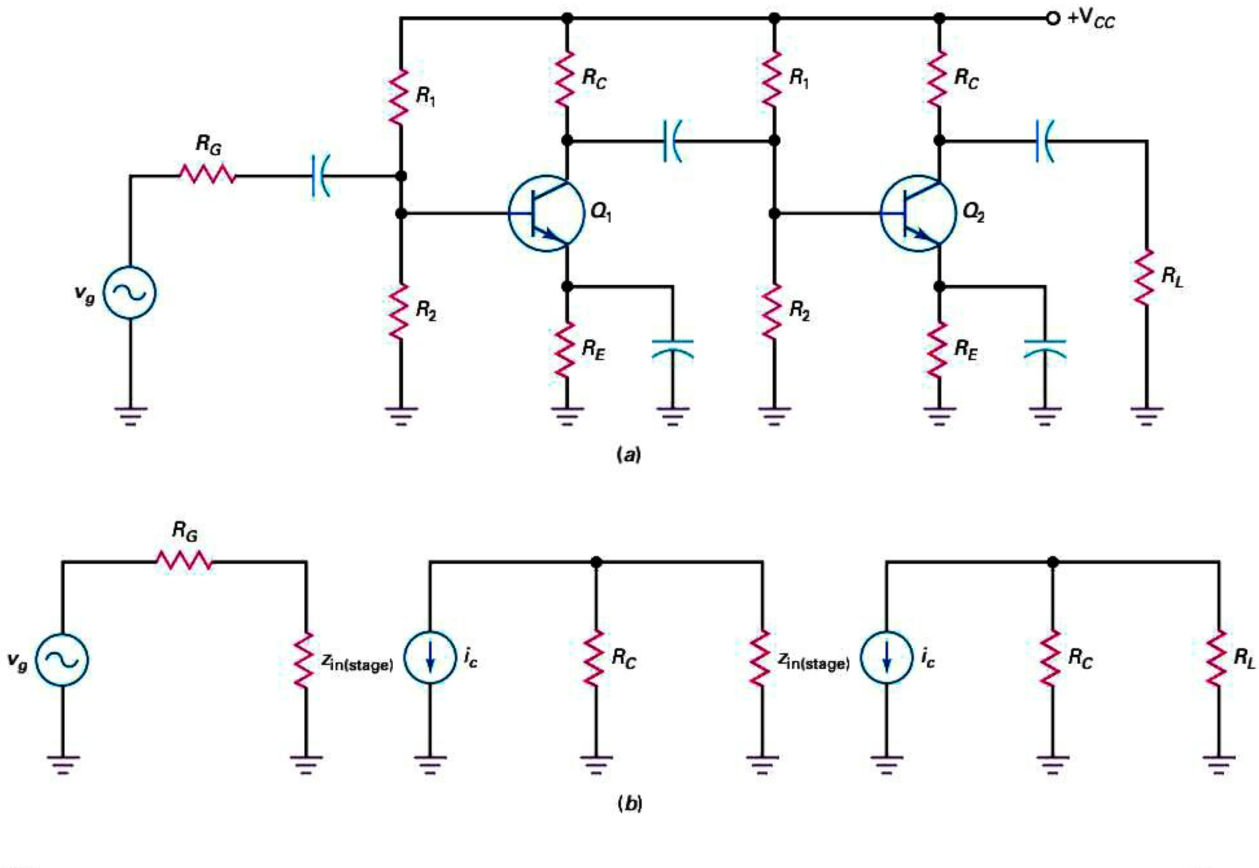
Figure 9-1*b* shows the ac-equivalent circuit. Note that the input impedance of the second stage loads down the first stage. In other words, the z_{in} of the second stage is in parallel with the R_C of the first stage. The ac collector resistance of the first stage is:

$$r_c = R_C \parallel z_{in(stage)}$$

The voltage gain of the first stage is:

$$A_{V_1} = \frac{R_C \parallel z_{in(stage)}}{r'_e}$$

Figure 9-1 (*a*) Two-stage amplifier; (*b*) ac-equivalent circuit.



Voltage Gain of Second Stage

The ac collector resistance of the second stage is:

$$r_c = R_C \| R_L$$

and the voltage gain is:

$$A_{V_2} = \frac{R_C \| R_L}{r'_e}$$

Total Voltage Gain

The **total voltage gain** of the amplifier is given by the product of the individual gains:

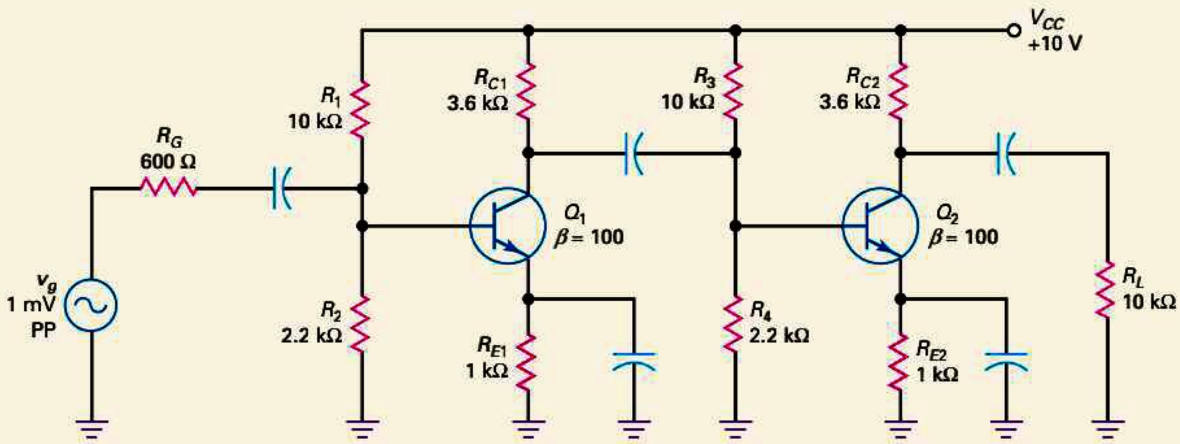
$$A_V = (A_{V_1})(A_{V_2}) \tag{9-1}$$

For instance, if each stage has a voltage gain of 50, the overall voltage gain is 2500.

Example 9-1

What is the ac collector voltage in the first stage of Fig. 9-2? The ac output voltage across the load resistor?

Figure 9-2 Example.



SOLUTION From earlier dc calculations:

$$V_B = 1.8 \text{ V}$$
$$V_E = 1.1 \text{ V}$$
$$V_{CE} = 4.94 \text{ V}$$
$$I_E = 1.1 \text{ mA}$$
$$r'_e = 22.7 \text{ ohms}$$

The input impedance of the first base is:

$$z_{in(base)} = (100)(22.7\ \Omega) = 2.27\ \text{k}\Omega$$

The input impedance of the first stage is:

$$z_{in(stage)} = 10\ \text{k}\Omega \| 2.2\ \text{k}\Omega \| 2.27\ \text{k}\Omega = 1\ \text{k}\Omega$$

The input signal to the first base is:

$$v_{in} = \frac{1\ k\Omega}{600\ \Omega + 1\ k\Omega}\ 1\ mV = 0.625\ mV$$

The input impedance of the second base is the same as the first stage:

$$z_{in(stage)} = 10\ k\Omega \parallel 2.2\ k\Omega \parallel 2.27\ k\Omega = 1\ k\Omega$$

This input impedance is the load resistance of the first stage. In other words, the ac collector resistance of the first stage is:

$$r_c = 3.6\ k\Omega \parallel 1\ k\Omega = 783\ \Omega$$

The voltage gain of the first stage is:

$$A_{V_1} = \frac{783\ \Omega}{22.7\ \Omega} = 34.5$$

Therefore, the ac collector voltage of the first stage is:

$$v_c = A_{V_1} v_{in} = (34.5)(0.625\ mV) = 21.6\ mV$$

The ac collector resistance of the second stage is:

$$r_c = 3.6\ k\Omega \parallel 10\ k\Omega = 2.65\ k\Omega$$

and the voltage gain is:

$$A_{V_2} = \frac{2.65\ k\Omega}{22.7\ \Omega} = 117$$

Therefore, the ac output voltage across the load resistor is:

$$v_{out} = A_{V_2} v_{b_2} = (117)(21.6\ mV) = 2.52\ V$$

Another way to calculate the final output voltage is by using the overall voltage gain:

$$A_V = (34.5)(117) = 4037$$

The ac output voltage across the load resistor is:

$$v_{out} = A_V v_{in} = (4037)(0.625\ mV) = 2.52\ V$$

PRACTICE PROBLEM 9-1 In Fig. 9-2, change the load resistance of stage two from 10 kΩ to 6.8 kΩ and calculate the final output voltage.

Example 9-2

What is the output voltage in Fig. 9-3 if $\beta = 200$? Ignore r_e' in the calculations.

SOLUTION The first stage has these values:

$$z_{in(base)} = \beta_{re} = (200)(180\ \Omega) = 36\ k\Omega$$

The input impedance of the stage is:

$$z_{in(stage)} = 10\ k\Omega \parallel 2.2\ k\Omega \parallel 36\ k\Omega = 1.71\ k\Omega$$

The ac input voltage to the first base is:

$$v_{in} = \frac{1.71\ k\Omega}{600\ \Omega + 1.71\ k\Omega}\ 1\ mV = 0.74\ mV$$

The input impedance of the second stage is the same as the first stage: $z_{in(stage)} = 1.71\ k\Omega$. Therefore, the ac collector resistance of the first stage is:

$$r_c = 3.6\ k\Omega \parallel 1.71\ k\Omega = 1.16\ k\Omega$$

and the voltage gain of the first stage is:

$$A_{V_1} = \frac{1.16\ \text{k}\Omega}{180\ \Omega} = 6.44$$

The amplified and inverted ac voltage at the first collector and the second base is:

$$v_c = (6.44)(0.74\ \text{mV}) = 4.77\ \text{mV}$$

The ac collector resistance of the second stage is:

$$r_c = R_C \parallel R_L = 3.6\ \text{k}\Omega \parallel 10\ \text{k}\Omega = 2.65\ \text{k}\Omega$$

Therefore, it has a voltage gain of:

$$A_{V_2} = \frac{2.65\ \text{k}\Omega}{180\ \Omega} = 14.7$$

The final output voltage equals:

$$v_{out} = (14.7)(4.77\ \text{mV}) = 70\ \text{mV}$$

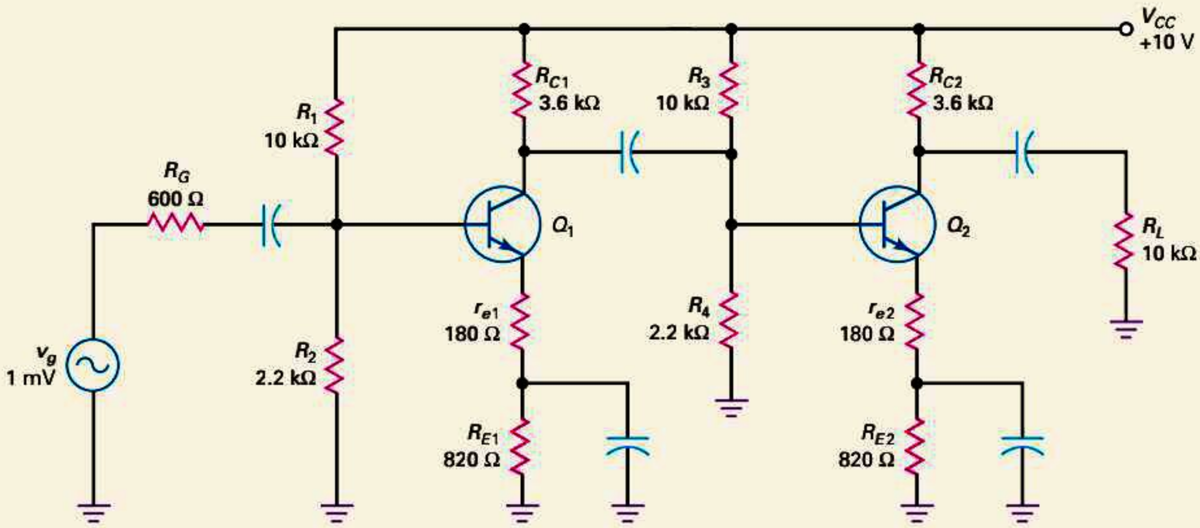
Another way to calculate the output voltage is to use the overall voltage gain:

$$A_V = (A_{V_1})(A_{V_2}) = (6.44)(14.7) = 95$$

Then:

$$v_{out} = A_V v_{in} = (95)(0.74\ \text{mV}) = 70\ \text{mV}$$

Figure 9-3 Two-stage swamped amplifier example.



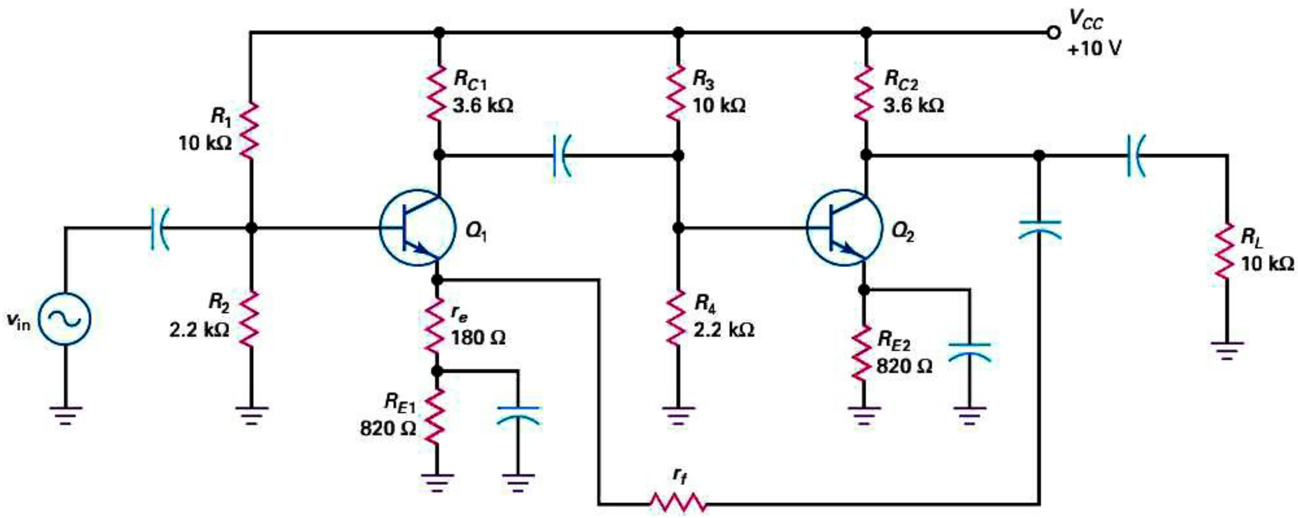
9-2 Two-Stage Feedback

A swamped amplifier is an example of single-stage feedback. It works reasonably well to stabilize the voltage gain, increase the input impedance, and reduce distortion. **Two-stage feedback** works even better.

Basic Idea

Figure 9-4 shows a two-stage feedback amplifier. The first stage has an unbypassed emitter resistance of r_e. This first stage is often referred to as a preamplfier.

Figure 9-4 Two-stage feedback amplifier.



It is used to pick up the input signal from the source, without loading down the source, and to pass on the signal to the second stage for further amplification. The second stage is a CE stage, with the emitter at ac ground to produce maximum gain in this stage. The output signal is coupled back through a feedback resistance r_f to the first emitter. Because of the voltage divider, the ac voltage between the first emitter and ground is:

$$v_e = \frac{r_e}{r_f + r_e} v_{out}$$

Here is the basic idea of how the two-stage feedback works: Assume that an increase in temperature causes the output voltage to increase. Since part of the output voltage is fed back to the first emitter, v_e increases. This decreases v_{be} in the first stage, decreases v_c in the first stage, and decreases v_{out}. On the other hand, if the output voltage tries to decrease, v_{be} increases and v_{out} increases.

In either case, any attempted change in the output voltage is fed back, and the amplified change opposes the original change. The overall effect is that the output voltage will change by a much smaller amount than it would without the negative feedback.

Voltage Gain

In a well-designed two-stage feedback amplifier, the voltage gain is given by this derivation:

$$A_V = \frac{r_f}{r_e} + 1 \tag{9-2}$$

In most designs, the first term in this equation is much greater than 1, so the equation simplifies to:

$$A_V = \frac{r_f}{r_e}$$

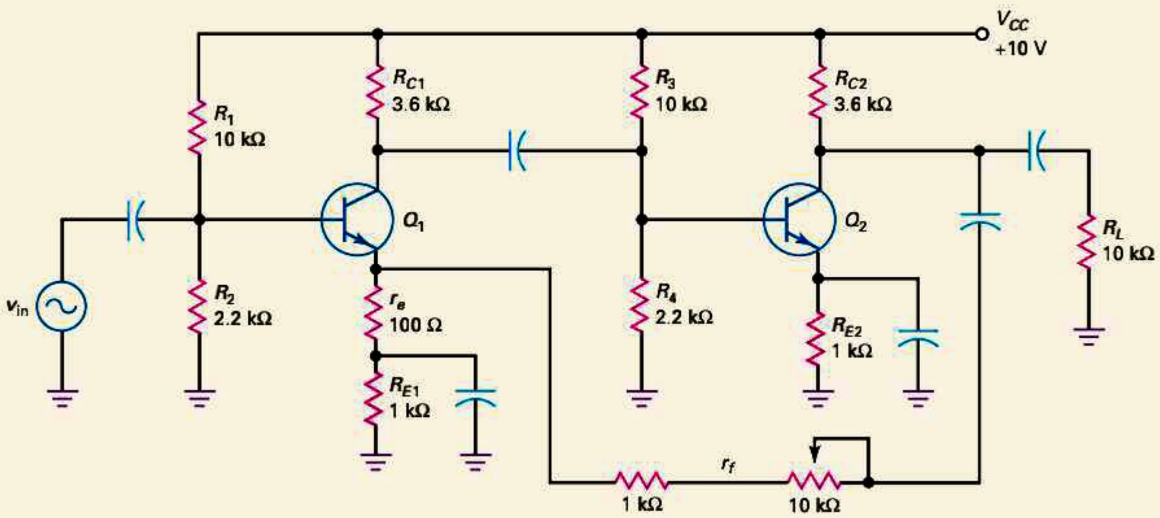
When we discuss op amps, we will analyze negative feedback in detail. At that time, you will see what is meant by a *well-designed feedback amplifier.*

What's important about Eq. (9-2) is this: *The voltage gain depends only on external resistances r_f and r_e.* Since these resistances are fixed in value, the voltage gain is fixed.

Example 9-3

A variable resistor is used in Fig. 9-5. It can vary from 0 to 10 kΩ. What is the minimum voltage gain of the two-stage amplifier? The maximum?

Figure 9-5 Example of two-stage feedback.



SOLUTION The feedback resistance r_f is the sum of 1 kΩ and the adjustable resistance. The minimum voltage gain occurs when the variable resistor is zeroed:

$$A_V = \frac{r_f}{r_e} = \frac{1\text{ k}\Omega}{100\ \Omega} = 10$$

The maximum voltage gain when the variable resistance is 10 kΩ is:

$$A_V = \frac{r_f}{r_e} = \frac{11\text{ k}\Omega}{100\ \Omega} = 110$$

PRACTICE PROBLEM 9-3 In Fig. 9-5, what value of resistance would the variable resistor need to be for a voltage gain of 50?

Application Example 9-4

How could the circuit in Fig. 9-5 be modified for use as a portable microphone preamplifier?

SOLUTION The 10-V dc power supply could be replaced with a 9-V battery and on/off switch. Connect a properly sized microphone jack to the preamplifier's input coupling capacitor and ground. The microphone should ideally be a low-impedance dynamic style. If an electret microphone is used, it will be necessary to power it from the 9-V battery through a series resistor. For good low-frequency response, the coupling and bypass capacitors need to have low capacitive reactance. A value of 47 μF for each coupling capacitor and 100 μF for each bypass capacitor can be used. The 10-kΩ output load can be changed to a 10-kΩ potentiometer to vary the output level. If more voltage gain is needed, change the 10-kΩ feedback potentiometer to a higher value. The output should be able to drive the line/CD/aux/tape inputs of a home stereo amplifier. Check your system's specifications for the proper input needed. Placing all components in a small metal box and using shielded cables will reduce external noise and interference.

9-3 CC Amplifier

The **emitter follower** is also called a **common-collector (CC) amplifier**. The input signal is coupled to the base, and the output signal is taken from the emitter.

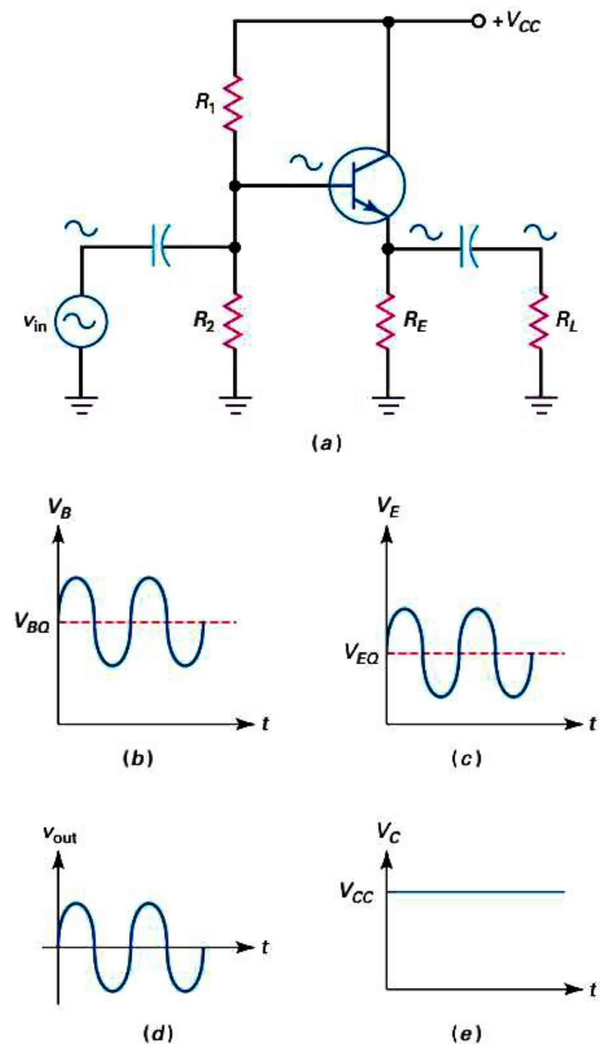
Basic Idea

Figure 9-6*a* shows an emitter follower. Because the collector is at ac ground, the circuit is a CC amplifier. The input voltage is coupled to the base. This sets up an ac emitter current and produces an ac voltage across the emitter resistor. This ac voltage is then coupled to the load resistor.

Figure 9-6*b* shows the total voltage between the base and ground. It has a dc component and an ac component. As you can see, the ac input voltage rides on the quiescent base voltage V_{BQ}. Similarly, Fig. 9-6*c* shows the total voltage between the emitter and ground. This time, the ac input voltage is centered on a quiescent emitter voltage V_{EQ}.

The ac emitter voltage is coupled to the load resistor. This output voltage is shown in Fig. 9-6*d*, a pure ac voltage. This output voltage is in phase and

Figure 9-6 Emitter follower and waveforms.



GOOD TO KNOW

In some emitter-follower circuits, a small collector resistance is used to limit the dc collector current in the transistor in case a short occurs between the emitter and ground. If a small R_C is used, the collector will have a bypass capacitor going to ground. The small value of R_C will have only a slight bearing on the dc operation of the circuit and no bearing at all on the circuit's ac operation.

is approximately equal to the input voltage. The reason the circuit is called an *emitter follower* is because the output voltage follows the input voltage.

Since there is no collector resistor, the total voltage between the collector and ground equals the supply voltage. If you look at the collector voltage with an oscilloscope, you will see a constant dc voltage like Fig. 9-6*e*. There is no ac signal on the collector because it is an ac ground point.

Negative Feedback

Like a swamped amplifier, the emitter follower uses negative feedback. But with the emitter follower, the negative feedback is massive because the feedback resistance equals all of the emitter resistance. As a result, the voltage gain is ultrastable, the distortion is almost nonexistent, and the input impedance of the base is very high. Because of these characteristics, the emitter follower is often used as a preamplifier. The trade-off is the voltage gain, which has a maximum value of 1.

AC Emitter Resistance

In Fig. 9-6*a*, the ac signal coming out of the emitter sees R_E in parallel with R_L. Let us define the ac emitter resistance as follows:

$$r_e = R_E \parallel R_L \tag{9-3}$$

This is the external ac emitter resistance, which is different from the internal ac emitter resistance r_e'.

Voltage Gain

Figure 9-7*a* shows the ac-equivalent with the T model. Using Ohm's law, we can write these two equations:

$$v_{out} = i_e r_e$$

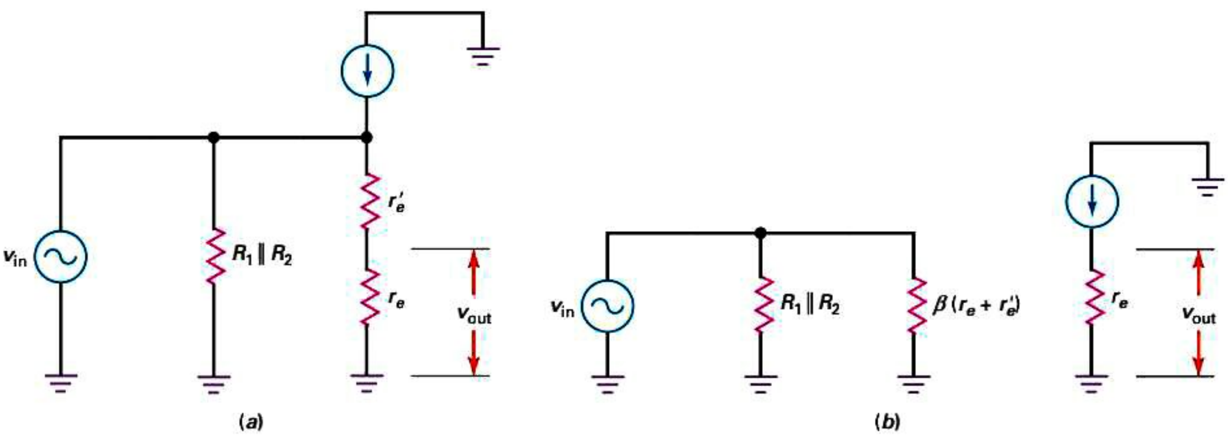
$$v_{in} = i_e(r_e + r_e')$$

Divide the first equation by the second, and you get the voltage gain of the emitter follower:

$$A_V = \frac{r_e}{r_e + r_e'} \tag{9-4}$$

Usually, a designer makes r_e much greater than r_e' so that the voltage gain equals 1 (approximately). This is the value to use for all preliminary analysis and troubleshooting.

Figure 9-7 AC-equivalent circuits for emitter follower.



Why is an emitter follower called an *amplifier* if its voltage gain is only 1? Because it has a current gain of β. The stages near the end of a system need to produce more current because the final load is usually a low impedance. The emitter follower can produce the large output currents needed by low-impedance loads. In short, although it is not a voltage amplifier, the emitter follower is a current or power amplifier.

Input Impedance of the Base

Figure 9-7*b* shows the ac-equivalent circuit with the π model of the transistor. As far as the input impedance of the base is concerned, the action is the same as that of a swamped amplifier. The current gain transforms the total emitter resistance up by a factor of β. The derivation is therefore identical to that of a swamped amplifier:

$$z_{in(base)} = \beta(r_e + r'_e) \tag{9-5}$$

For troubleshooting, you can assume that r_e is much greater than r'_e, which means that the input impedance is approximately βr_e.

The step-up in impedance is the major advantage of an emitter follower. Small load resistances that would overload a CE amplifier can be used with an emitter follower because it steps up the impedance and prevents overloading.

GOOD TO KNOW

In Fig. 9-8, the biasing resistors R_1 and R_2 lower z_{in} to a value that is not much different from that of a swamped CE amplifier. This disadvantage is overcome in most emitter-follower designs by simply not using the biasing resistors R_1 and R_2. Instead, the emitter-follower is dc biased by the stage driving the emitter follower.

Input Impedance of the Stage

When the ac source is not stiff, some of the ac signal will be lost across the internal resistance. If you want to calculate the effect of the internal resistance, you will need to use the input impedance of the stage, given by:

$$z_{in(stage)} = R_1 \parallel R_2 \parallel \beta(r_e + r'_e) \tag{9-6}$$

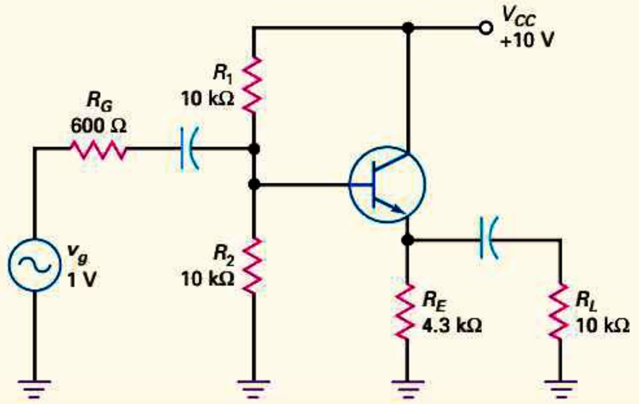
With the input impedance and the source resistance, you can use the voltage divider to calculate the input voltage reaching the base. The calculations are the same as shown in earlier chapters.

Example 9-5

Multisim

What is the input impedance of the base in Fig. 9-8 if $\beta = 200$? What is the input impedance of the stage?

Figure 9-8 Example.



SOLUTION Because each resistance in the voltage divider is 10 kΩ, the dc base voltage is half the supply voltage, or 5 V. The dc emitter voltage is 0.7 V less, or 4.3 V. The dc emitter voltage is 4.3 V divided by 4.3 kΩ, or 1 mA. Therefore, the ac resistance of the emitter diode is:

$$r_e' = \frac{25\text{ mV}}{1\text{ mA}} = 25\ \Omega$$

The external ac emitter resistance is the parallel equivalent of R_E and R_L, which is:

$$r_e = 4.3\text{ k}\Omega \parallel 10\text{ k}\Omega = 3\text{ k}\Omega$$

Since the transistor has an ac current gain of 200, the input impedance of the base is:

$$z_{in(base)} = 200(3\text{ k}\Omega + 25\ \Omega) = 605\text{ k}\Omega$$

The input impedance of the base appears in parallel with the two biasing resistors. The input impedance of the stage is:

$$z_{in(stage)} = 10\text{ k}\Omega \parallel 10\text{ k}\Omega \parallel 605\text{ k}\Omega = 4.96\text{ k}\Omega$$

Because the 605 kΩ is much larger than 5 kΩ, troubleshooters usually approximate the input impedance of the stage as the parallel of the biasing resistors only:

$$z_{in(stage)} = 10\text{ k}\Omega \parallel 10\text{ k}\Omega = 5\text{ k}\Omega$$

PRACTICE PROBLEM 9-5 Find the input impedance of the base and the stage, using Fig. 9-8, if β changes to 100.

Example 9-6

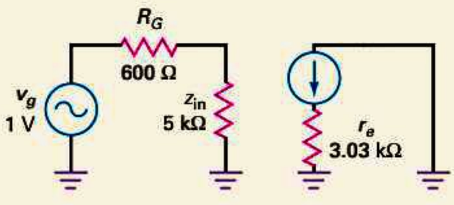
Multisim

Assuming a β of 200, what is the ac input voltage to the emitter follower of Fig. 9-8?

SOLUTION Figure 9-9 shows the ac-equivalent circuit. The ac base voltage appears across z_{in}. Because the input impedance of the stage is large compared to the generator resistance, most of the generator voltage appears at the base. With the voltage-divider theorem:

$$v_{in} = \frac{5\text{ k}\Omega}{5\text{ k}\Omega + 600\ \Omega} 1\text{ V} = 0.893\text{ V}$$

Figure 9-9 Example.



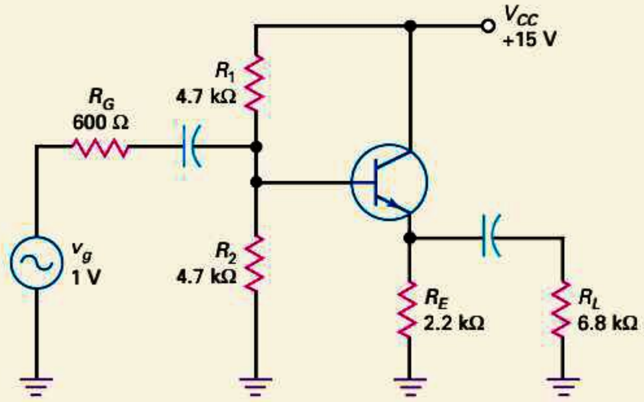
PRACTICE PROBLEM 9-6 If the β value is 100, find the ac input voltage of Fig. 9-8.

Example 9-7

Multisim

What is the voltage gain of the emitter follower in Fig. 9-10? If $\beta = 150$, what is the ac load voltage?

Figure 9-10 Example.



SOLUTION The dc base voltage is half the supply voltage:

$$V_B = 7.5\text{ V}$$

The dc emitter current is:

$$I_E = \frac{6.8\text{ V}}{2.2\text{ k}\Omega} = 3.09\text{ mA}$$

and the ac resistance of the emitter diode is:

$$r'_e = \frac{25\text{ mV}}{3.09\text{ mA}} = 8.09\ \Omega$$

The external ac emitter resistance is:

$$r_e = 2.2\text{ k}\Omega \parallel 6.8\text{ k}\Omega = 1.66\text{ k}\Omega$$

The voltage gain equals:

$$A_V = \frac{1.66\text{ k}\Omega}{1.66\text{ k}\Omega + 8.09\ \Omega} = 0.995$$

The input impedance of the base is:

$$z_{in(base)} = 150(1.66\text{ k}\Omega + 8.09\ \Omega) = 250\text{ k}\Omega$$

This is much larger than the biasing resistors. Therefore, to a close approximation, the input impedance of the emitter follower is:

$$z_{in(stage)} = 4.7\text{ k}\Omega \parallel 4.7\text{ k}\Omega = 2.35\text{ k}\Omega$$

The ac input voltage is:

$$v_{in} = \frac{2.35\text{ k}\Omega}{600\ \Omega + 2.35\text{ k}\Omega}1\text{ V} = 0.797\text{ V}$$

The ac output voltage is:

$$v_{out} = 0.995(0.797\text{ V}) = 0.793\text{ V}$$

PRACTICE PROBLEM 9-7 Repeat Example 9-7 using an R_G value of 50 Ω.

9-4 Output Impedance

The output impedance of an amplifier is the same as its Thevenin impedance. One of the advantages of an emitter follower is its low output impedance.

As discussed in earlier electronics courses, maximum power transfer occurs when the load impedance is *matched* (made equal) to the source (Thevenin) impedance. Sometimes, when maximum load power is wanted, a designer can match the load impedance to the output impedance of an emitter follower. For instance, the low impedance of a speaker can be matched to the output impedance of an emitter follower to deliver maximum power to the speaker.

Basic Idea

Figure 9-11*a* shows an ac generator driving an amplifier. If the source is not stiff, some of the ac voltage is dropped across the internal resistance R_G. In this case, we need to analyze the voltage divider shown in Fig. 9-11*b* to get the input voltage v_{in}.

A similar idea can be used with the output side of the amplifier. In Fig. 9-11*c*, we can apply the Thevenin theorem at the load terminals. Looking back into the amplifier, we see an output impedance z_{out}. In the Thevenin-equivalent circuit, this output impedance forms a voltage divider with the load resistance, as shown in Fig. 9-11*d*. If z_{out} is much smaller than R_L, the output source is stiff and v_{out} equals v_{th}.

CE Amplifiers

Figure 9-12*a* shows the ac-equivalent circuit for the output side of a CE amplifier. When we apply Thevenin's theorem, we get Fig. 9-12*b*. In other words, the output

Figure 9-11 Input and output impedances.

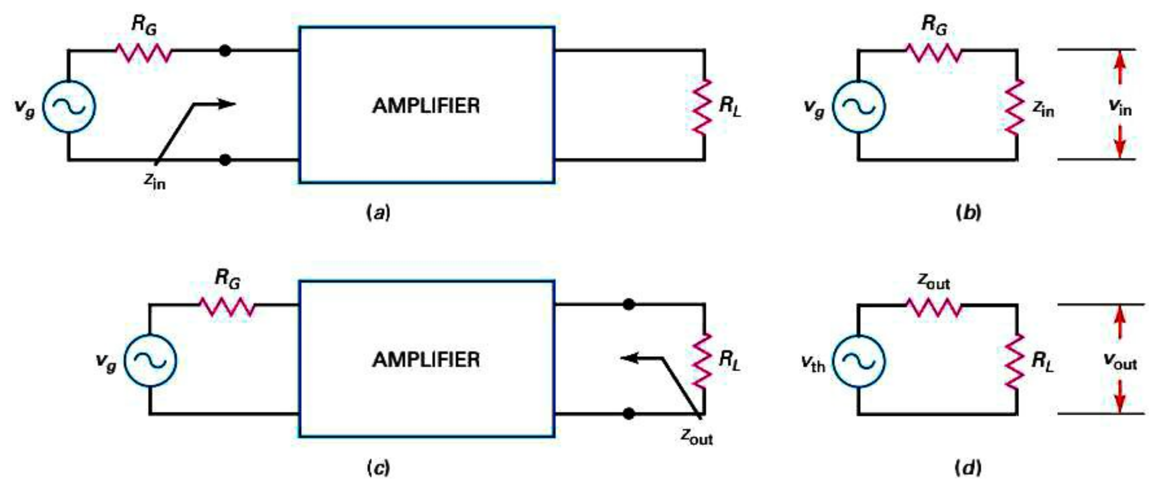
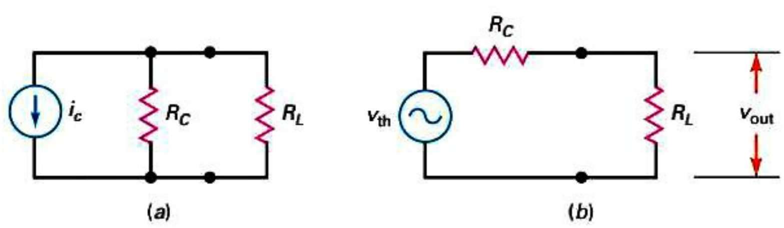


Figure 9-12 Output impedance of CE stage.



impedance facing the load resistance is R_C. Since the voltage gain of a CE amplifier depends on R_C, a designer cannot make R_C too small without losing voltage gain. Stated another way, it is difficult to get a small output impedance with a CE amplifier. Because of this, CE amplifiers are not suited to driving small load resistances.

Emitter Follower

Figure 9-13*a* shows the ac-equivalent circuit for an emitter follower. When we apply Thevenin's theorem to point *A*, we get Fig. 9-13*b*. The output impedance z_{out} is much smaller than you can get with a CE amplifier. It equals:

$$z_{out} = R_E \parallel \left(r'_e + \frac{R_G \parallel R_1 \parallel R_2}{\beta} \right) \tag{9-7}$$

The impedance of the base circuit is $R_G \parallel R_1 \parallel R_2$. The current gain of the transistor steps this impedance down by a factor of β. The effect is similar to what we get with a swamped amplifier, except that we are moving from the base back to the emitter. Therefore, we get a reduction of impedance rather than an increase. The stepped-down impedance of $(R_G \parallel R_1 \parallel R_2)/\beta$ is in series with r'_e as indicated by Eq. (9-7).

GOOD TO KNOW

Transformers can also be used to match impedances between source and load. Looking into the transformer, z_{in} can be found by:

$$z_{in} = \left(\frac{N_p}{N_s}\right)^2 R_L$$

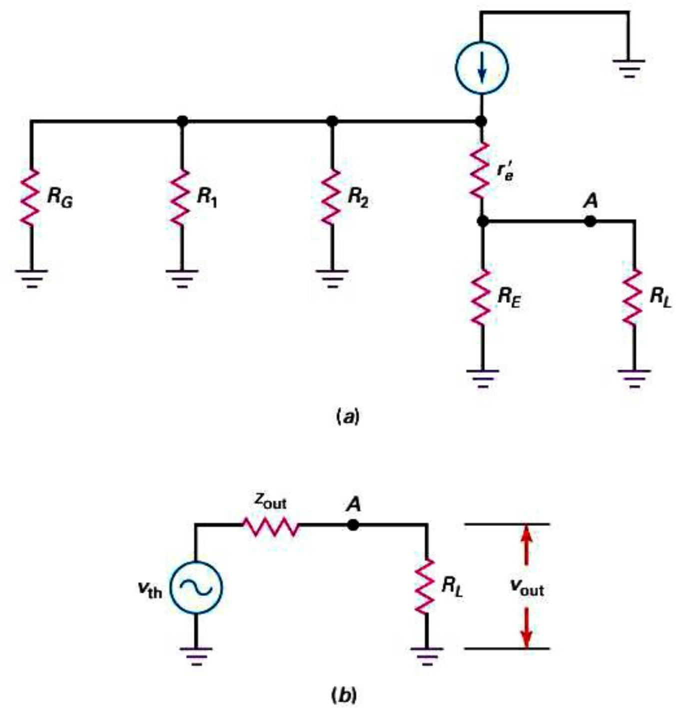
Ideal Action

In some designs, the biasing resistances and the ac resistance of the emitter diode become negligible. In this case, the output impedance of an emitter follower can be approximated by:

$$z_{out} = \frac{R_G}{\beta} \tag{9-8}$$

This brings out the key idea of an emitter follower: It steps the impedance of the ac source down by a factor of β. As a result, the emitter follower allows us to build

Figure 9-13 Output impedance of emitter follower.



stiff ac sources. Instead of using a stiff ac source that maximizes the load voltage, a designer may prefer to maximize the load power. In this case, instead of designing for:

$$z_{out} << R_L \qquad \text{(Stiff voltage source)}$$

the designer will select values to get:

$$z_{out} = R_L \qquad \text{(Maximum power transfer)}$$

In this way, the emitter follower can deliver maximum power to a low-impedance load such as a stereo speaker. By basically removing the effect of R_L on the output voltage, the circuit is acting as a buffer between the input and output.

Equation (9-8) is an ideal formula. You can use it to get an approximate value for the output impedance of an emitter follower. With discrete circuits, the equation usually gives only an estimate of the output impedance. Nevertheless, it is adequate for troubleshooting and preliminary analysis. When necessary, you can use Eq. (9-7) to get an accurate value for the output impedance.

Example 9-8

Estimate the output impedance of the emitter follower in Fig. 9-14*a*.

SOLUTION Ideally, the output impedance equals the generator resistance divided by the current gain of the transistor:

$$z_{out} = \frac{600\Omega}{300} = 2\ \Omega$$

Figure 9-14*b* shows the equivalent output circuit. The output impedance is much smaller than the load resistance, so most of the signal appears across the load resistor. As you can see, the output source of Fig. 9-14*b* is almost stiff because the ratio of load to source resistance is 50.

PRACTICE PROBLEM 9-8 Using Fig. 9-14, change the source resistance to 1 kΩ and solve for the approximate z_{out} value.

Example 9-9

Calculate the output impedance in Fig. 9-14*a* using Eq. (9-7).

SOLUTION The quiescent base voltage is approximately:

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

Ignoring V_{BE}, the quiescent emitter current is approximately:

$$I_{EQ} = \frac{15\text{V}}{100\ \Omega} = 150\text{ mA}$$

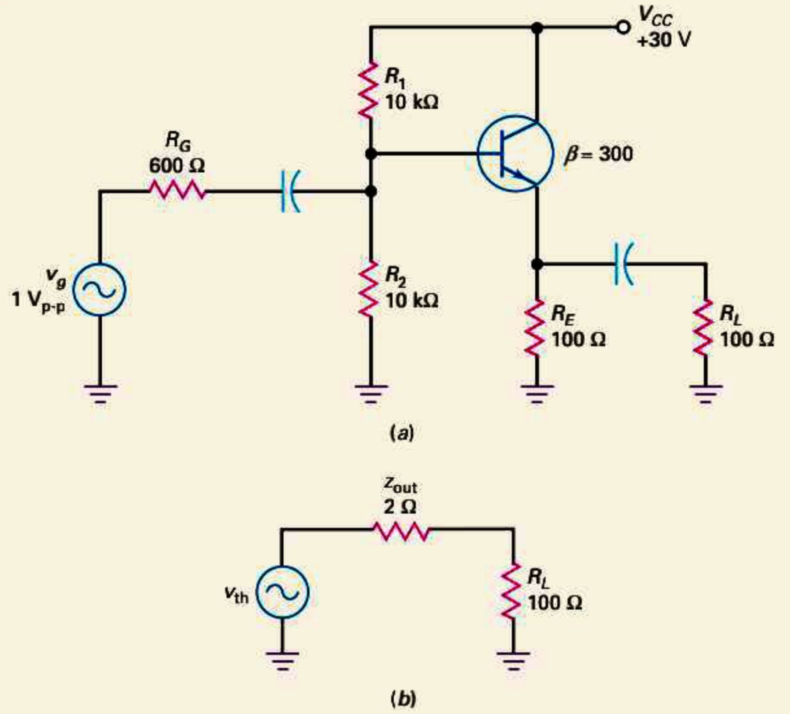
The ac resistance of the emitter diode is:

$$r_e' = \frac{25\text{ mV}}{150\text{ mA}} = 0.167\ \Omega$$

The impedance seen looking back from the base is:

$$R_G \parallel R_1 \parallel R_2 = 600\ \Omega \parallel 10\text{ k}\Omega \parallel 10\text{ k}\Omega = 536\ \Omega$$

Figure 9-14 Example.



The current gain steps this down to:

$$\frac{R_G \| R_1 \| R_2}{\beta} = \frac{536\ \Omega}{300} = 1.78\ \Omega$$

This is in series with r'_e, so the impedance looking back into the emitter is:

$$r'_e + \frac{R_G \| R_1 \| R_2}{\beta} = 0.167\ \Omega + 1.78\ \Omega = 1.95\ \Omega$$

This is in parallel with the dc emitter resistance, so the output impedance is:

$$z_{out} = R_E \left\| \left(r'_e + \frac{R_G \| R_1 \| R_2}{\beta} \right) \right. = 100\ \Omega \| 1.95\ \Omega = 1.91\ \Omega$$

This accurate answer is extremely close to the ideal answer of 2 Ω. This result is typical of many designs. For all troubleshooting and preliminary analysis, you can use the ideal method to estimate the output impedance.

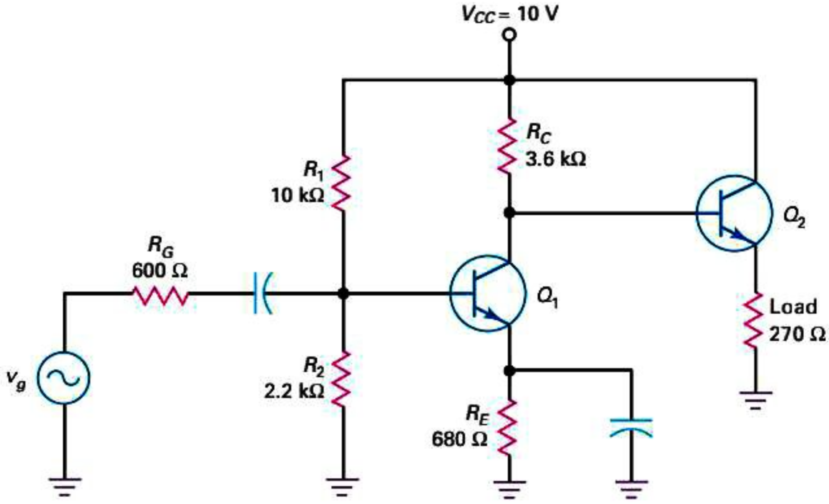
PRACTICE PROBLEM 9-9 Repeat Example 9-9 using an R_G value of 1 kΩ.

9-5 Cascading CE and CC

To illustrate the buffering action of a CC amplifier, suppose we have a load resistance of 270 Ω. If we try to couple the output of a CE amplifier directly into this load resistance, we may overload the amplifier. One way to avoid this overload is by using an emitter follower between the CE amplifier and the load resistance. The signal can be coupled capacitively (this means through coupling capacitors), or it may be **direct coupled** as shown in Fig. 9-15.

As you can see, the base of the second transistor is connected directly to the collector of the first transistor. Because of this, the dc collector voltage

Figure 9-15 Direct coupled output stage.



of the first transistor is used to bias the second transistor. If the dc current gain of the second transistor is 100, the dc resistance looking into the base of the second transistor is $R_{in} = 100\ (270\ \Omega) = 27\ k\Omega$.

Because 27 kΩ is large compared to 3.6 kΩ, the dc collector voltage of the first stage is only slightly disturbed.

In Fig. 9-15, the amplified voltage out of the first stage drives the emitter follower and appears across the final load resistance of 270 Ω. Without the emitter follower, the 270 Ω would overload the first stage. But with the emitter follower, its impedance effect is increased by a factor of β. Instead of appearing like 270 Ω, it now looks like 27 kΩ in both the dc- and the ac-equivalent circuits.

This demonstrates how an emitter follower can act as a **buffer** between a high-output impedance and a low-resistance load.

This example shows you the effects of overloading a CE amplifier. The load resistance should be much greater than the dc collector resistance to get maximum voltage gain. We have just the opposite; the load resistance (270 Ω) is much smaller than the dc collector resistance (3.6 kΩ).

Application Example 9-10

Multisim

What is the voltage gain of the CE stage in Fig. 9-15 for a β of 100?

SOLUTION The dc base voltage of the CE stage is 1.8 V and the dc emitter voltage is 1.1 V. The dc emitter current is $I_E = \dfrac{1.1\ V}{680\ \Omega} = 1.61$ mA and the ac resistance of the emitter diode is $r'_e = \dfrac{25\ mV}{1.61\ mA} = 15.5\ \Omega$. Next, we need to calculate the input impedance of the emitter follower. Since there are no biasing resistors, the input impedance equals the input impedance looking into the base: $z_{in} = (100)(270\ \Omega) = 27\ k\Omega$. The ac collector resistance of the CE amplifier is $r_c = 3.6\ k\Omega \parallel 27\ k\Omega = 3.18\ k\Omega$ and the voltage gain of this stage is:

$$A_v = \frac{3.18\ k\Omega}{15.5\ \Omega} = 205$$

PRACTICE PROBLEM 9-10 Using Fig. 9-15, find the voltage gain of the CE stage for a β of 300.

Application Example 9-11

Suppose the emitter follower is removed in Fig. 9-15 and a capacitor is used to couple the ac signal to the 270-Ω load resistor. What happens to the voltage gain of the CE amplifier?

SOLUTION The value of r'_e remains the same for the CE stage: 15.5 Ω. But the ac collector resistance is much lower. To begin with, the ac collector resistance is the parallel resistance of 3.6 kΩ and 270 Ω: $r_c = 3.6\ \text{k}\Omega \parallel 270\ \Omega = 251\ \Omega$.

Because this is much lower, the voltage gain decreases to:

$$A_v = \frac{251\ \Omega}{15.5\ \Omega} = 16.2.$$

PRACTICE PROBLEM 9-11 Repeat Application Example 9-11 using a load resistance of 100 Ω.

9-6 Darlington Connections

A **Darlington connection** is a connection of two transistors whose overall current gain equals the product of the individual current gains. Since its current gain is much higher, a Darlington connection can have a very high input impedance and can produce very large output currents. Darlington connections are often used with voltage regulators, power amplifiers, and high current switching applications.

Darlington Pair

Figure 9-16*a* shows a **Darlington pair**. Since the emitter current of Q_1 is the base current for Q_2, the Darlington pair has an overall current gain of:

$$\beta = \beta_1\beta_2 \quad \textbf{(9-9)}$$

For instance, if each transistor has a current gain of 200, the overall current gain is:

$$\beta = (200)(200) = 40{,}000$$

Semiconductor manufacturers can put a Darlington pair inside a single case like that shown in Fig. 9-16*b*. This device, known as a **Darlington transistor,** acts like a single transistor with a very high current gain. For instance, the 2N6725 is a Darlington transistor with a current gain of 25,000 at 200 mA. As another example, the TIP102 is a power Darlington with a current gain of 1000 at 3 A.

This is shown in the data sheet in Fig. 9-17. Notice that this device uses a TO-220 case style and has built-in base-emitter shunt resistors, along with an

Figure 9-16 (*a*) Darlington pair; (*b*) Darlington transistor; (*c*) complementary Darlington.

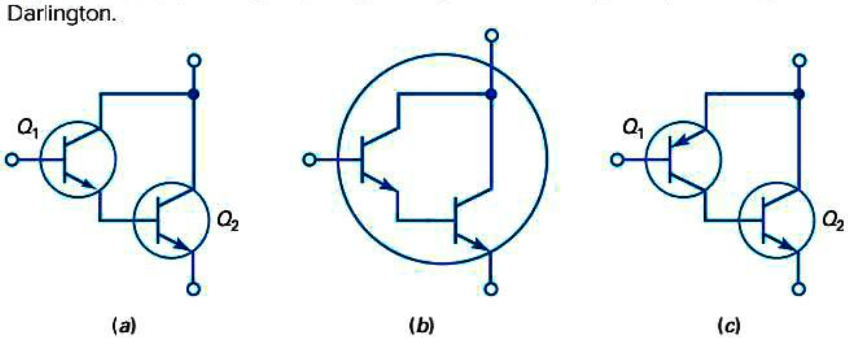


Figure 9-17 Darlington transistor. (Courtesy Fairchild Semiconductor Corporation)

FAIRCHILD SEMICONDUCTOR®

October 2008

TIP100/TIP101/TIP102

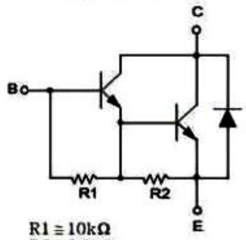
NPN Epitaxial Silicon Darlington Transistor

- Monolithic Construction With Built In Base-Emitter Shunt Resistors
- High DC Current Gain : h_{FE}=1000 @ V_{CE}=4V, I_C=3A (Min.)
- Collector-Emitter Sustaining Voltage
- Low Collector-Emitter Saturation Voltage
- Industrial Use
- Complementary to TIP105/106/107

TO-220

1.Base 2.Collector 3.Emitter

Equivalent Circuit



R1 ≅ 10kΩ
R2 ≅ 0.6kΩ

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

Symbol	Parameter	Ratings	Units
V_{CBO}	Collector-Base Voltage : TIP100	60	V
	: TIP101	80	V
	: TIP102	100	V
V_{CEO}	Collector-Emitter Voltage : TIP100	60	V
	: TIP101	80	V
	: TIP102	100	V
V_{EBO}	Emitter-Base Voltage	5	V
I_C	Collector Current (DC)	8	A
I_{CP}	Collector Current (Pulse)	15	A
I_B	Base Current (DC)	1	A
P_C	Collector Dissipation (T_a=25°C)	2	W
	Collector Dissipation (T_C=25°C)	80	W
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	- 65 ~ 150	°C

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

Electrical Characteristics* T_a=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Typ.	Max.	Units
V_{CEO}(sus)	Collector-Emitter Sustaining Voltage					
	: TIP100	I_C = 30mA, I_B = 0	60			V
	: TIP101		80			V
	: TIP102		100			V
I_{CEO}	Collector Cut-off Current					
	: TIP100	V_{CE} = 30V, I_B = 0			50	μA
	: TIP101	V_{CE} = 40V, I_B = 0			50	μA
	: TIP102	V_{CE} = 50V, I_B = 0			50	μA
I_{CBO}	Collector Cut-off Current					
	: TIP100	V_{CE} = 60V, I_E = 0			50	μA
	: TIP101	V_{CE} = 80V, I_E = 0			50	μA
	: TIP102	V_{CE} = 100V, I_E = 0			50	μA
I_{EBO}	Emitter Cut-off Current	V_{EB} = 5V, I_C = 0			2	mA
h_{FE}	DC Current Gain	V_{CE} = 4V, I_C = 3A	1000		20000	
		V_{CE} = 4V, I_C = 8A	200			
V_{CE}(sat)	Collector-Emitter Saturation Voltage	I_C = 3A, I_B = 6mA			2	V
		I_C = 8A, I_B = 80mA			2.5	V
V_{BE}(on)	Base-Emitter On Voltage	V_{CE} = 4V, I_C = 8A			2.8	V
C_{ob}	Output Capacitance	V_{CB} = 10V, I_E = 0, f = 0.1MHz			200	pF

* Pulse Test: Pulse Width≤300μs, Duty Cycle≤2%

TIP100/TIP101/TIP102 Rev. 1.0.0

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internal diode. These internal components must be taken into consideration when testing this device with an ohmmeter.

The analysis of a circuit using a Darlington transistor is almost identical to the emitter-follower analysis. With the Darlington transistor, since there are two transistors, there are two V_{BE} drops. The base current of Q_2 is the same as the emitter current of Q_1. Also, using Eq. 9-9, the input impedance at the base of Q_1 can be found by $z_{in(base)} \cong \beta_1\beta_2 r_e$ or stated as:

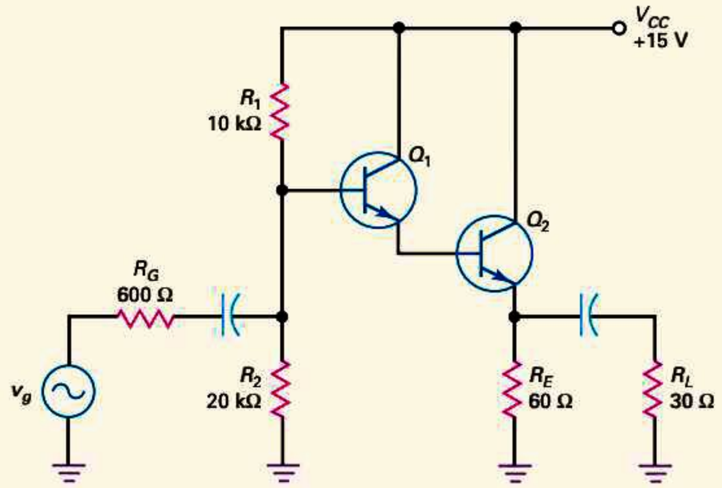
$$z_{in(base)} \cong \beta r_e \tag{9-10}$$

Example 9-12

Multisim

If each transistor in Fig. 9-18 has a beta value of 100, what is the overall current gain, base current of Q_1, and input impedance at the base of Q_1?

Figure 9-18 Example.



SOLUTION The overall current gain is found by:

$$\beta = \beta_1\beta_2 = (100)(100) = 10{,}000$$

The dc emitter current of Q_2 is:

$$I_{E2} = \frac{10\text{ V} - 1.4\text{ V}}{60\ \Omega} = 143\text{ mA}$$

The emitter current of Q_1 is equal to the base current of Q_2. This is found by:

$$I_{E1} = I_{B2} \cong \frac{I_{E2}}{\beta_2} = \frac{143\text{ mA}}{100} = 1.43\text{ mA}$$

The base current of Q_1 is:

$$I_{B1} = \frac{I_{E1}}{\beta_1} = \frac{1.43\text{ mA}}{100} = 14.3\ \mu\text{A}$$

To find the input impedance at the base of Q_1, first solve for r_e. The ac emitter resistance is:

$$r_e = 60\ \Omega \parallel 30\ \Omega = 20\ \Omega$$

The input impedance of the Q_1 base is:

$$z_{in(base)} = (10{,}000)(20\ \Omega) = 200\ k\Omega$$

PRACTICE PROBLEM 9-12 Repeat Example 9-12 using a Darlington pair with each transistor having a current gain of 75.

GOOD TO KNOW

The complementary Darlington transistor in Fig. 9-16*c* was originally developed because complementary high-power transistors were not readily available. The complementary transistor is often used in a special stage known as a *quasi-complementary output stage.*

Complementary Darlington

Figure 9-16*c* shows another Darlington connection called a **complementary Darlington,** a connection of *npn* and *pnp* transistors. The collector current of Q_1 is the base current of Q_2. If the *pnp* transistor has a current gain of β_1 and the *npn* output transistor has a current gain of β_2 the complementary Darlington acts like a single *pnp* transistor with a current gain of $\beta_1\beta_2$.

Npn and *pnp* Darlington transistors can be manufactured to be complements to each other. As an example, the TIP105/106/107 *pnp* Darlington series is complementary to the TIP/101/102 *npn* series.

9-7 Voltage Regulation

Besides being used in buffer circuits and impedance matching amplifiers, the emitter follower is widely used in voltage regulators. In conjunction with a zener diode, the emitter follower can produce regulated output voltages with much larger output currents.

Zener Follower

Figure 9-19*a* shows a **zener follower,** a circuit that combines a zener regulator and an emitter follower. Here is how it works: The zener voltage is the input to the base of the emitter follower. The dc output voltage of the emitter follower is:

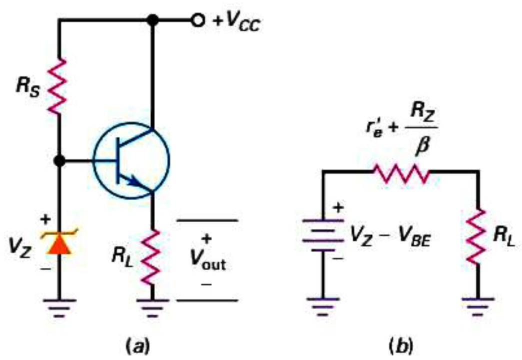
$$V_{out} = V_Z - V_{BE} \qquad (9\text{-}11)$$

This output voltage is fixed so that it is equal to the zener voltage minus the V_{BE} drop of the transistor. If the supply voltage changes, the zener voltage

GOOD TO KNOW

In Fig. 9-19, the emitter-follower circuit reduces the zener current variations by a factor of β if you compare the zener current variations that would exist if the transistor were not there.

Figure 9-19 (*a*) Zener follower; (*b*) ac-equivalent circuit.



remains approximately constant, and so does the output voltage. In other words, the circuit acts like a voltage regulator because the output voltage is always one V_{BE} drop less than the zener voltage.

The zener follower has two advantages over an ordinary zener regulator: First, the zener diode in Fig. 9-19*a* has to produce a load current of only:

$$I_B = \frac{I_{out}}{\beta_{dc}} \tag{9-12}$$

Since this base current is much smaller than the output current, we can use a much smaller zener diode.

For instance, if you are trying to supply several amperes to a load resistor, an ordinary zener regulator requires a zener diode capable of handling several amperes. On the other hand, with the improved regulator in Fig. 9-19*a*, the zener diode needs to handle only tens of milliamperes.

The second advantage of a zener follower is its low output impedance. In an ordinary zener regulator, the load resistor sees an output impedance of approximately R_Z, the zener impedance. But in the zener follower, the output impedance is:

$$z_{out} = r'_e + \frac{R_Z}{\beta_{dc}} \tag{9-13}$$

Figure 9-19*b* shows the equivalent output circuit. Because z_{out} is usually very small compared to R_L, an emitter follower can hold the dc output voltage almost constant because the source looks stiff.

In summary, the zener follower provides the regulation of a zener diode with the increased current-handling capability of an emitter follower.

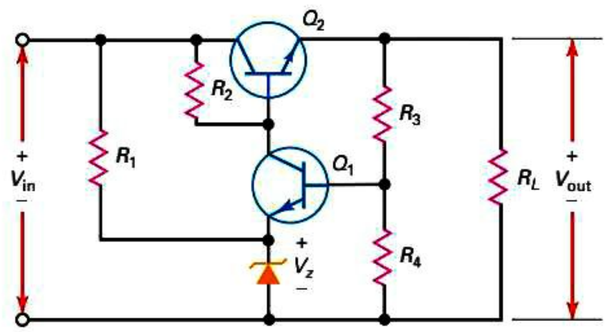
Two-Transistor Regulator

Figure 9-20 shows another voltage regulator. The dc input voltage V_{in} comes from an unregulated power supply, such as a bridge rectifier with a capacitor-input filter. Typically, V_{in} has a peak-to-peak ripple of about 10 percent of the dc voltage. The final output voltage V_{out} has almost no ripple and is almost constant in value, even though the input voltage and load current may vary over a large range.

How does it work? Any attempted change in output voltage produces an amplified feedback voltage that opposes the original change. For instance, suppose the output voltage increases. Then, the voltage appearing at the base of Q_1 will increase. Since Q_1 and R_2 form a CE amplifier, the collector voltage of Q_1 will decrease because of the voltage gain.

Since the collector voltage of Q_1 has decreased, the base voltage of Q_2 decreases. Because Q_2 is an emitter follower, the output voltage will decrease. In

Figure 9-20 Transistor voltage regulator.



other words, we have negative feedback. The original increase in output voltage produces an opposing decrease in output voltage. The overall effect is that the output voltage will increase only slightly, much less than it would without the negative feedback.

Conversely, if the output voltage tries to decrease, less voltage appears at the Q_1 base, more voltage appears at the Q_1 collector, and more voltage appears at the Q_2 emitter. Again, we have a returning voltage that opposes the original change in output voltage. Therefore, the output voltage will decrease only a little, far less than without the negative feedback.

Because of the zener diode, the Q_1 emitter voltage equals V_Z. The Q_1 base voltage is one V_{BE} drop higher. Therefore, the voltage across R_4 is:

$$V_4 = V_Z + V_{BE}$$

With Ohm's law, the current through R_4 is:

$$I_4 = \frac{V_Z + V_{BE}}{R_4}$$

Since this current flows through R_3 in series with R_4, the output voltage is:

$$V_{out} = I_4(R_3 + R_4)$$

After expanding:

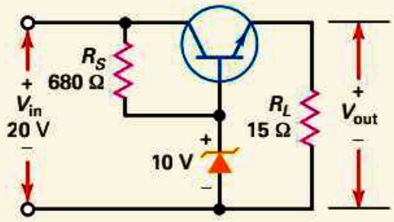
$$V_{out} = \frac{R_3 + R_4}{R_4}(V_Z + V_{BE}) \tag{9-14}$$

Example 9-13

Multisim

Figure 9-21 shows a zener follower as it is usually drawn on a schematic diagram. What is the output voltage? What is the zener current if $\beta_{dc} = 100$?

Figure 9-21 Example.



SOLUTION The output voltage is approximately:

$$V_{out} = 10\text{ V} - 0.7\text{ V} = 9.3\text{ V}$$

With a load resistance of 15 Ω, the load current is:

$$I_{out} = \frac{9.3\text{ V}}{15\ \Omega} = 0.62\text{ A}$$

The base current is:

$$I_B = \frac{0.62\text{ A}}{100} = 6.2\text{ mA}$$

The current through the series resistor is:

$$I_S = \frac{20\text{ V} - 10\text{ V}}{680\ \Omega} = 14.7\text{ mA}$$

The zener current is:

$$I_Z = 14.7\text{ mA} - 6.2\text{ mA} = 8.5\text{ mA}$$

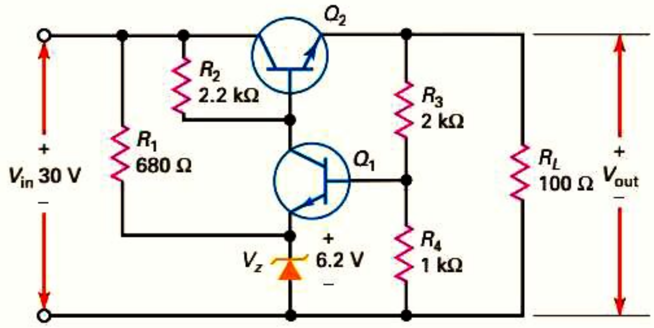
PRACTICE PROBLEM 9-13 Repeat Example 9-13 using an 8.2-V zener diode and an input voltage of 15 V.

Example 9-14

Multisim

What is the output voltage in Fig. 9-22?

Figure 9-22 Example.



SOLUTION Using Eq. (9-14):

$$V_{out} = \frac{2\text{ k}\Omega + 1\text{ k}\Omega}{1\text{ k}\Omega}(6.2\text{ V} + 0.7\text{ V}) = 20.7\text{ V}$$

You can also solve the problem as follows: The current through the 1-kΩ resistor is:

$$I_4 = \frac{6.2\text{ V} + 0.7\text{ V}}{1\text{ k}\Omega} = 6.9\text{ mA}$$

This current flows through a total resistance of 3 kΩ, which means that the output voltage is:

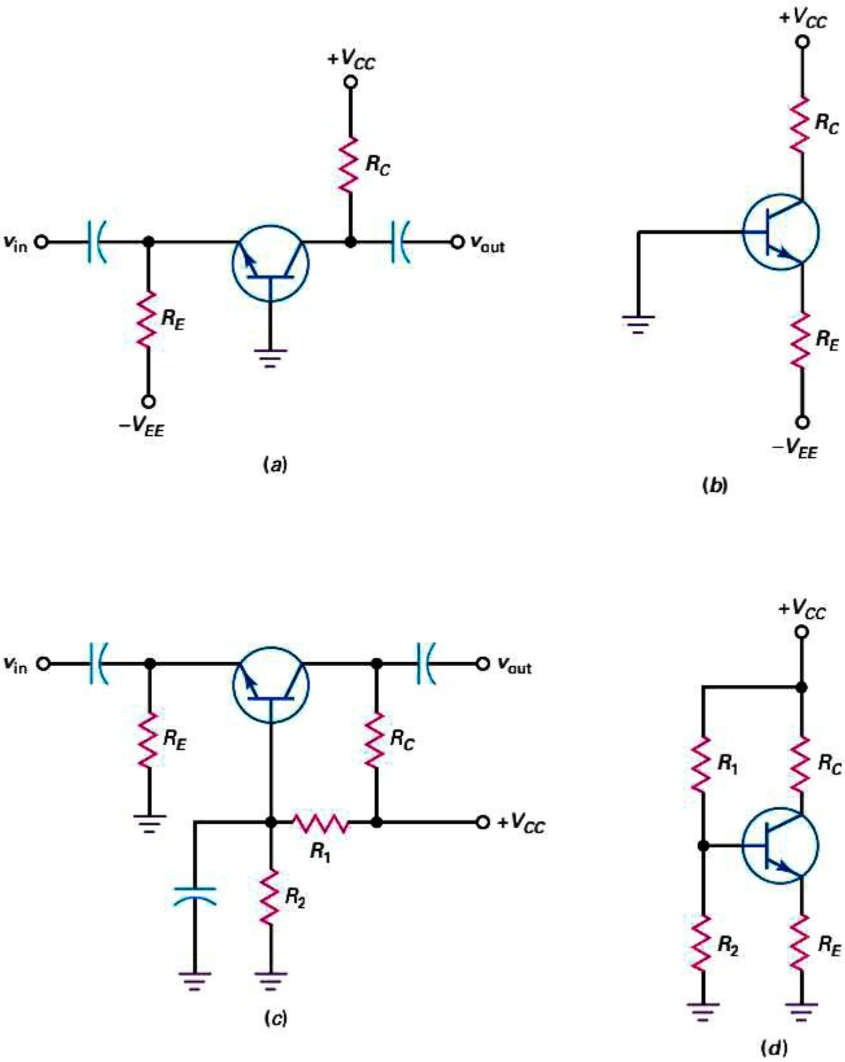
$$V_{out} = (6.9\text{ mA})(3\text{ k}\Omega) = 20.7\text{ V}$$

PRACTICE PROBLEM 9-14 Using Fig. 9-22, change the zener value to 5.6 V and find the new V_{out} value.

9-8 The Common-Base Amplifier

Figure 9-23*a* shows a **common-base (CB) amplifier** using a dual polarity or split power supply. Since the base is grounded, this circuit is also called a grounded-based amplifier. The Q point is set by emitter bias, as shown by the

Figure 9-23 CB amplifier. (*a*) Split supply; (*b*) emitter-biased dc-equivalent circuit; (*c*) single supply; (*d*) voltage-divider-biased dc-equivalent circuit.



dc-equivalent circuit shown in Fig. 9-23*b*. Therefore, the dc emitter current is found by:

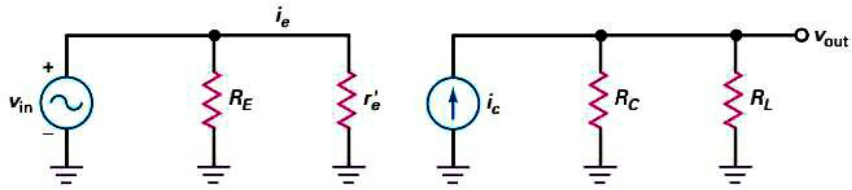
$$I_E = \frac{V_{EE} - V_{BE}}{R_E} \quad \text{(9-15)}$$

Figure 9-23*c* shows a voltage-divider bias CB amplifier using a single power supply source. Notice the bypass capacitor across R_2. This places the base at ac ground. By drawing the dc-equivalent circuit, as shown in Fig. 9-23*d*, you should recognize the voltage-divider bias configuration.

In either amplifier, the base is at ac ground. The input signal drives the emitter, and the output signal is taken from the collector. Figure 9-24*a* shows the ac-equivalent circuit of a CB amplifier during the positive half-cycle of input voltage. In this circuit, the ac collector voltage, or v_{out}, equals:

$$v_{out} \cong i_c r_c$$

Figure 9-24 Ac-equivalent circuit.



This is in phase with the ac input voltage v_e. Since the input voltage equals:

$$v_{in} = i_e r'_e$$

The voltage gain is:

$$A_v = \frac{v_{out}}{v_{in}} = \frac{i_c\, r_c}{i_e\, r'_e}$$

because $i_c \cong i_e$, the equation simplifies to:

$$A_v = \frac{r_c}{r'_e} \tag{9-16}$$

Notice that the voltage gain has the same magnitude as it would in an unswamped CE amplifier. The only difference is the phase of the output voltage. Whereas the output signal of a CE amplifier is 180° out of phase with the input signal, the output voltage of the CB amplifier is in phase with the input signal.

Ideally, the collector current source in Fig. 9-24 has an infinite internal impedance. Therefore, the output impedance of a CB amplifier is:

$$z_{out} \cong R_C \tag{9-17}$$

One of the major differences between the CB amplifier and other amplifier configurations is its low input impedance. Looking into the emitter of Fig. 9-24, we have an input impedance of:

$$z_{in(emitter)} = \frac{v_e}{i_e} = \frac{i_e r'_e}{i_e} \quad \text{or} \quad z_{in(emitter)} = r'_e$$

The input impedance of the circuit is:

$$z_{in} = R_E \parallel r'_e$$

Since R_E is normally much larger than r'_e, the circuit input impedance is approximately:

$$z_{in} \cong r'_e \tag{9-18}$$

As an example, if $I_E = 1$ mA, the input impedance of a CB amplifier is only 25 Ω. Unless the input ac source is very small, most of the signal will be lost across the source resistance.

The input impedance of a CB amplifier is normally so low that it overloads most signal sources. Because of this, a discrete CB amplifier is not used too often at low frequencies. It is mainly used in high-frequency applications (above 10 MHz) where low source impedances are common. Also, at high frequencies, the base separates the input and output, resulting in fewer oscillations at these frequencies.

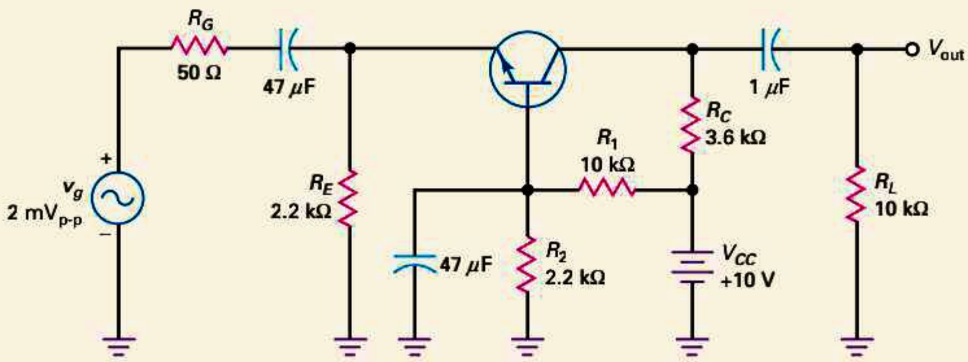
An emitter-follower circuit was used in applications where a high impedance source needed to drive a low impedance load. Just the opposite, a common-base circuit can be used to couple a low impedance source to a high impedanceloa d.

Example 9-15

Multisim

What is the output voltage in Fig. 9-25?

Figure 9-25 Example.



SOLUTION The circuit needs to have its Q point determined.

$$V_B = \frac{2.2\text{ k}\Omega}{10\text{ k}\Omega + 2.2\text{ k}\Omega}(+10\text{ V}) = 1.8\text{ V}$$

$$V_E = V_B - 0.7\text{ V} = 1.8\text{ V} - 0.7\text{ V} = 1.1\text{ V}$$

$$I_E = \frac{V_E}{R_E} = \frac{1.1\text{ V}}{2.2\text{ k}\Omega} = 500\ \mu\text{A}$$

Therefore, $r'_e = \dfrac{25\text{ mV}}{500\ \mu\text{A}} = 50\ \Omega$

Now, solving for the ac circuit values:

$$z_{in} = R_E \parallel r'_e = 2.2\text{ k}\Omega \parallel 50\ \Omega \cong 50\ \Omega$$

$$z_{out} = R_C = 3.6\text{ k}\Omega$$

$$A_V = \frac{r_c}{r'_e} = \frac{3.6\text{ k}\Omega \parallel 10\text{ k}\Omega}{50\ \Omega} = \frac{2.65\text{ k}\Omega}{50\ \Omega} = 53$$

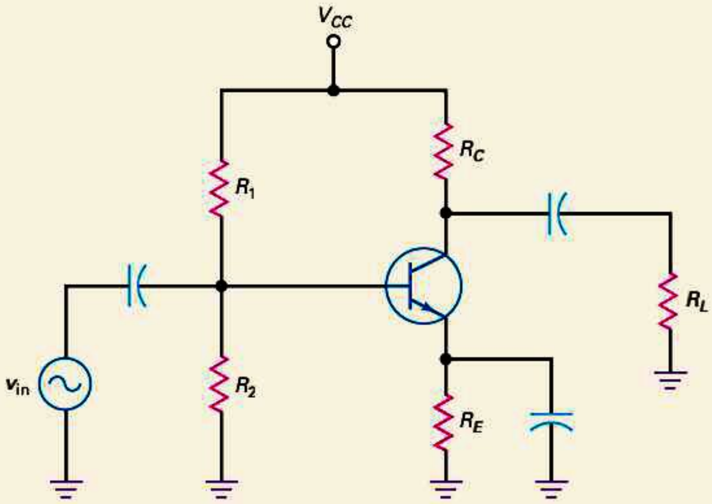
$$v_{in(base)} = \frac{r'_e}{R_G}(v_g) = \frac{50\ \Omega}{50\ \Omega + 50\ \Omega}(2\text{ mV}_{p\text{-}p}) = 1\text{ mV}_{p\text{-}p}$$

$$v_{out} = (A_v)(v_{in(base)}) = (53)(1\text{ mV}_{p\text{-}p}) = 53\text{ mV}_{p\text{-}p}$$

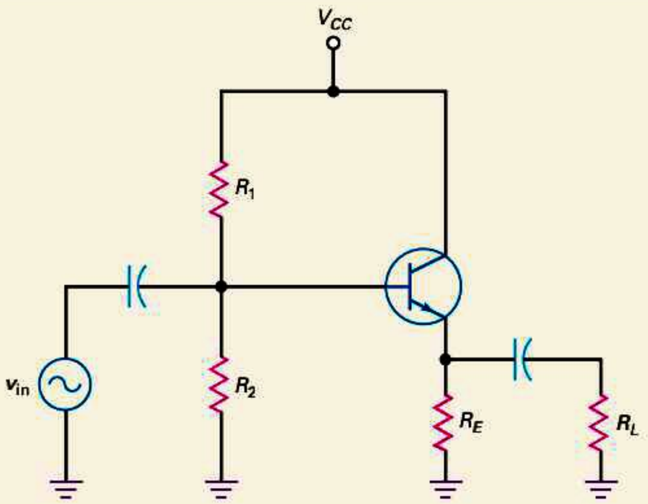
PRACTICE PROBLEM 9-15 In Fig. 9-25, change V_{CC} to 20 V and find v_{out}.

A summary of the four common transistor amplifier configurations is shown in Summary Table 9-1. It is important to be able to recognize the amplifier configuration, know its basic characteristics, and understand its common applications.

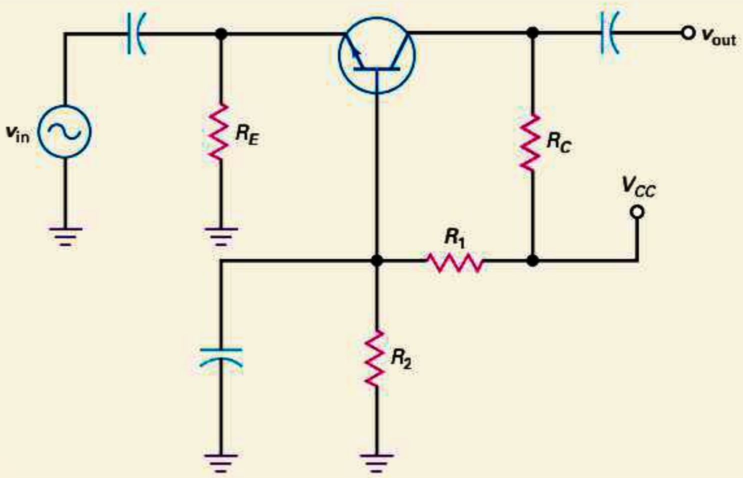
Summary Table 9-1 Common Amplifier Configurations



Type: CE	θ: 180°
A_v: Medium-High	z_{in}: Medium
A_i: β	z_{out}: Medium
A_p: High	Applications: General-purpose amplifier, with voltage and current gain

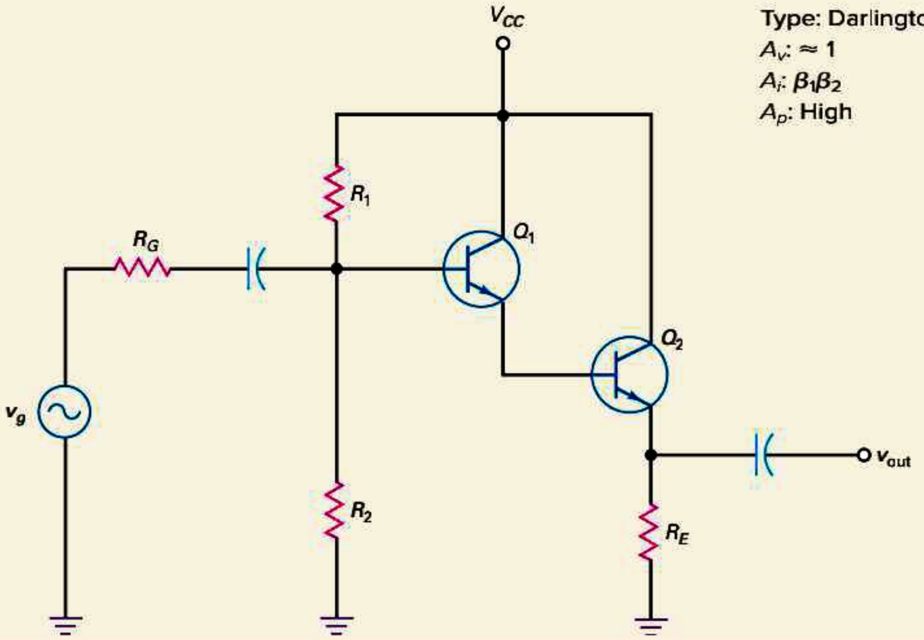


Type: CC	θ: 0°
A_v: ≈ 1	z_{in}: High
A_i: β	z_{out}: Low
A_p: Medium	Applications: Buffer, impedance matching, high current driver



Type: CB	θ: 0°
A_v: Medium-high	z_{in}: Low
A_i: ≈ 1	z_{out}: High
A_p: Medium	Applications: High-frequency amplifier, low to high impedance matching

Summary Table 9-1 (continued)



Type: Darlington
A_v: ≈ 1
A_i: $\beta_1\beta_2$
A_p: High
θ: 0°
z_{in}: Very high
z_{out}: Low
Applications: Buffer, high current driver, and amplifier

9-9 Troubleshooting Multistage Amplifiers

When an amplifier consists of two or more stages, what techniques can be followed to efficiently troubleshoot the problem? In a single-stage amplifier, you can start by measuring the dc voltages, including the power supply voltages. When an amplifier consists of two or more stages, measuring all of the dc voltages, as a starting point, is not very efficient.

In a multistage amplifier, it is best to isolate the defective stage first by using signal tracing or signal injection techniques. As an example, if the amplifier consists of four stages, split the amplifier in half by either measuring or injecting a signal at the output of the second stage. By doing so, you should be able to determine if the trouble is either before or after this circuit point. If the measured signal at the output of the second stage is proper, this verifies that the first two stages are working correct and that the problem must be in one of the next two stages. Now, move your next troubleshooting point to the midpoint of the remaining stages. This split-half method of troubleshooting can quickly isolate a defective stage.

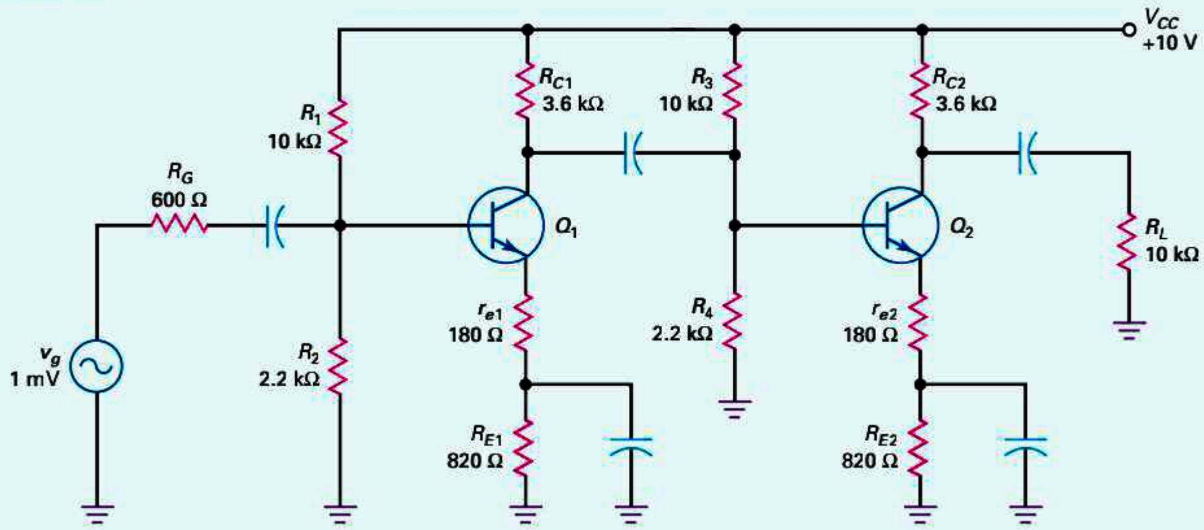
Once the defective stage is identified, now you can measure the dc voltages to see if they are approximately correct. If these dc voltages are found to be correct, then further troubleshooting is continued by determining what has gone wrong with the ac-equivalent circuit. This type of failure is often an open coupling or bypass capacitor.

As a final point, in multistage amplifiers the output of a stage will be loaded by the input of the next stage. A failure in the input side of stage two can have a negative effect at the output of stage one. Sometimes, it will be necessary to physically create an open between two stages to verify if there is a loading problem.

Application Example 9-16

What is the problem with the two-stage amplifier in Fig. 9-26?

Figure 9-26 Troubleshooting multistage amplifiers.



SOLUTION Examining Fig. 9-26, the first stage circuit is a CE preamplifier which takes an input signal from the signal source, amplifies it and passes it on to the second stage. The second stage, also a CE, amplifies the output of Q_1 and couples the output of Q_2 to the load resistor. In Example 9-2, we calculated the ac voltages to be:

$v_{in} = 0.74$ mV
$v_c = 4.74$ mV (output of the first stage)
$v_{out} = 70$ mV

These are the approximate ac voltages that you should measure when the amplifier is working correctly. (Sometimes, ac and dc voltages values are given on schematic diagrams used for troubleshooting.)

Now, when connecting and measuring the circuit's output voltage, the output signal across the 10 kΩ load is only 13 mV. The measured input voltage is normal at approximately 0.74 mV. What measurements should you take next?

Using the split-half signal tracing method, measure the ac voltage at the amplifier's midpoint. When doing so, the output voltage at the collector of Q_1 and the input voltage at the base of Q_2 measures 4.90 mV, slightly higher than normal. This measurement verifies that the first stage is working properly. Therefore, the problem must be with stage two.

Measurements of the dc voltages at the base, emitter and collector of Q_2 all measure normal. This indicates that the stage is operating correctly dc wise and must have an ac circuit problem. What could cause this to happen? Further ac measurements show that a signal level of approximately 4 mV across the 820 Ω resistor R_{E2}. Removal and testing of the bypass capacitor across R_{E2} verifies that it has opened. This failed capacitor caused the gain of stage two to significantly drop. Also, the open capacitor caused the input impedance of stage two to increase. This increase was the reason that the output signal of the first stage was slightly higher than normal.

Whether the amplifier is made up of two stages or many more, the split-half signal tracing or signal injection technique is an efficient troubleshooting method.

Summary

SEC. 9-1 MULTISTAGE AMPLIFIERS

The overall voltage gain equals the product of the individual voltage gains. The input impedance of the second stage is the load resistance on the first stage. Two CE stages produce an amplified in-phase signal.

SEC. 9-2 TWO-STAGE FEEDBACK

We can feed back the output voltage of the second collector to the first emitter through a voltage divider. This produces negative feedback, which stabilizes the voltage gain of the two-stage amplifier.

SEC. 9-3 CC AMPLIFIER

A CC amplifier, better known as an emitter follower, has its collector at ac ground. The input signal drives the base, and the output signal comes from the emitter. Because it is heavily swamped, an emitter follower has stable voltage gain, high input impedance, and low distortion.

SEC. 9-4 OUTPUT IMPEDANCE

The output impedance of an amplifier is the same as its Thevenin impedance. An emitter follower has a low output impedance. The current gain of a transistor transforms the source impedance driving the base to a much lower value when seen from the emitter.

SEC. 9-5 CASCADING CE AND CC

When a low resistance load is connected to the output of a CE amplifier, it may become overloaded, resulting in a very small voltage gain. A CC amplifier placed between the CE output and load will significantly reduce this effect. In this way, the CC amplifier is acting as a buffer.

SEC. 9-6 DARLINGTON CONNECTIONS

Two transistors can be connected as a Darlington pair. The emitter of the first is connected to the base of the second. This produces an overall current gain equal to the product of the individual current gains.

SEC. 9-7 VOLTAGE REGULATION

By combining a zener diode and an emitter follower, we get a zener follower. This circuit produces regulated output voltage with large load currents. The advantage is that the zener current is much smaller than the load current. By adding a stage of voltage gain, a larger regulated output voltage can be produced.

SEC. 9-8 COMMON-BASE AMPLIFIER

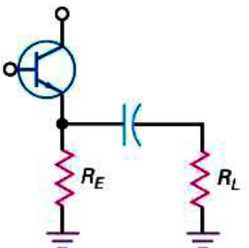
The CB amplifier configuration has its base at ac ground. The input signal drives the emitter, and the output signal comes from the collector. Even though this circuit has no current gain, it can produce a significant voltage gain. The CB amplifier has a low input impedance and high output impedance, and is used in high-frequency applications.

SEC. 9-9 TROUBLESHOOTING MULTISTAGE AMPLIFIERS

Multistage amplifier troubleshooting uses signal tracing or signal injection techniques. The split-half method quickly determines the defective stage. DC voltage measurements, including the power supply voltages, isolates the problem.

Definitions

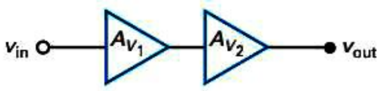
(9-3) AC emitter resistance:



$$r_e = R_E \| R_L$$

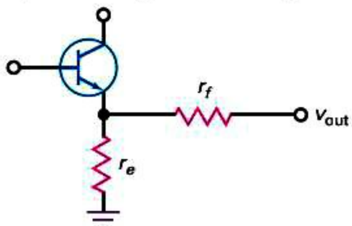
Derivations

(9-1) Two-stage voltage gain:



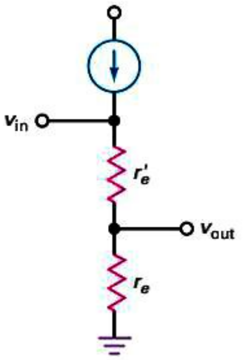
$$A_V = (A_{V_1})(A_{V_2})$$

(9-2) Two-stage feedback gain:



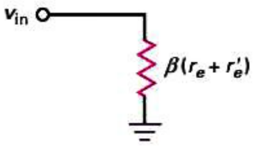
$$A_V = \frac{r_f}{r_e} + 1$$

(9-4) Emitter-follower voltage gain:



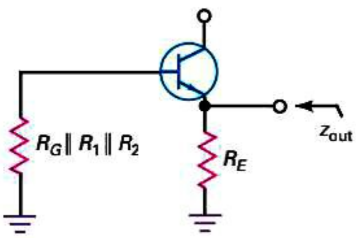
$$A_V = \frac{r_e}{r_e + r'_e}$$

(9-5) Emitter-follower input impedance of base:



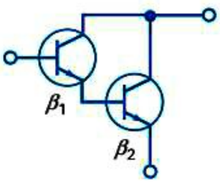
$$z_{in(base)} = \beta(r_e + r'_e)$$

(9-7) Emitter-follower output impedance:



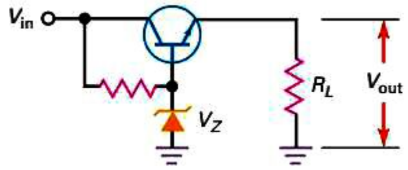
$$z_{out} = R_E \| \left(r'_e + \frac{R_G \| R_1 \| R_2}{\beta} \right)$$

(9-9) Darlington current gain:



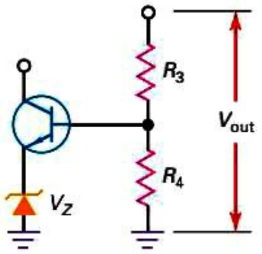
$$\beta = \beta_1 \beta_2$$

(9-11) Zener follower:



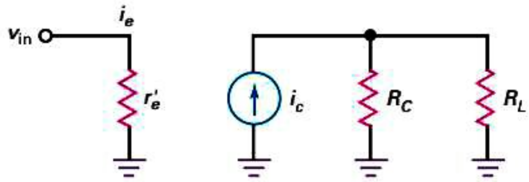
$$V_{out} = V_Z - V_{BE}$$

(9-14) Voltage regulator:



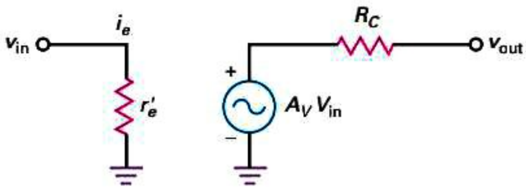
$$V_{out} = \frac{R_3 + R_4}{R_4}(V_Z + V_{BE})$$

(9-16) Common-base voltage gain:



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

(9-18) Common-base input impedance:



$$z_{in} \cong r'_e$$

Self-Test

1. If the input impedance of the second stage decreases, the voltage gain of the first stage will

a. Decrease
b. Increase
c. Remain the same
d. Equal zero

2. If the BE diode of the second stage opens, the voltage gain of the first stage will

a. Decrease
b. Increase
c. Remain the same
d. Equal zero

3. If the load resistance of the second stage opens, the voltage gain of the first stage will

a. Decrease
b. Increase
c. Remain the same
d. Equal zero

4. An emitter follower has a voltage gain that is

a. Much less than one
b. Approximately equal to one
c. Greater than one
d. Zero

5. The total ac emitter resistance of an emitter follower equals

a. r'_e
b. r_e
c. $r_e + r'_e$
d. R_E

6. **The input impedance of the base of an emitter follower is usually**
   a. Low
   b. High
   c. Shorted to ground
   d. Open

7. **The dc current gain of an emitter follower is**
   a. 0
   b. ≈ 1
   c. β_{dc}
   d. Dependant on r'_e

8. **The ac base voltage of an emitter follower is across the**
   a. Emitter diode
   b. DC emitter resistor
   c. Load resistor
   d. Emitter diode and external ac emitter resistance

9. **The output voltage of an emitter follower is across the**
   a. Emitter diode
   b. DC collector resistor
   c. Load resistor
   d. Emitter diode and external ac emitter resistance

10. **If $\beta = 200$ and $r_e = 150\ \Omega$, the input impedance of the base is**
   a. 30 kΩ
   b. 600 Ω
   c. 3 kΩ
   d. 5 kΩ

11. **The input voltage to an emitter follower is usually**
   a. Less than the generator voltage
   b. Equal to the generator voltage
   c. Greater than the generator voltage
   d. Equal to the supply voltage

12. **The ac emitter current is closest to**
   a. V_G divided by r_e
   b. v_{in} divided by r'_e
   c. V_G divided by r'_e
   d. v_{in} divided by r_e

13. **The output voltage of an emitter follower is approximately**
   a. 0
   b. V_G
   c. v_{in}
   d. V_{CC}

14. **The output voltage of an emitter follower is**
   a. In phase with v_{in}
   b. Much greater than v_{in}
   c. 180° out of phase
   d. Generally much less than v_{in}

15. **An emitter-follower buffer is generally used when**
   a. $R_G << R_L$
   b. $R_G = R_L$
   c. $R_L << R_G$
   d. R_L is very large

16. **For maximum power transfer, a CC amplifier is designed so**
   a. $R_G << z_{in}$
   b. $z_{out} >> R_L$
   c. $z_{out} << R_L$
   d. $z_{out} = R_L$

17. **If a CE stage is directly coupled to an emitter follower**
   a. Low and high frequencies will be passed
   b. Only high frequencies will be passed
   c. High-frequency signals will be blocked
   d. Low-frequency signals will be blocked

18. **If the load resistance of an emitter follower is very large, the external ac emitter resistance equals**
   a. Generator resistance
   b. Impedance of the base
   c. DC emitter resistance
   d. DC collector resistance

19. **If an emitter follower has $r'_e = 10\ \Omega$ and $r_e = 90\ \Omega$, the voltage gain is approximately**
   a. 0
   b. 0.5
   c. 0.9
   d. 1

20. **An emitter-follower circuit always makes the source resistance**
   a. β times smaller
   b. β times larger
   c. Equal to the load
   d. Zero

21. **A Darlington transistor has**
   a. A very low input impedance
   b. Three transistors
   c. A very high current gain
   d. One V_{BE} drop

22. **The amplifier configuration that produces a 180° phase shift is the**
   a. CB
   b. CC
   c. CE
   d. All of the above

23. **If the generator voltage is 5 mV in an emitter follower, the output voltage across the load is closest to**
   a. 5 mV
   b. 150 mV
   c. 0.25 V
   d. 0.5 V

24. **If the load resistor in Fig. 9-6*a* is shorted, which of the following are different from their normal values:**
   a. Only ac voltages
   b. Only dc voltages
   c. Both dc and ac voltages
   d. Neither dc nor ac voltages

25. **If R_1 is open in an emitter follower, which of these is true?**
   a. DC base voltage is V_{CC}
   b. DC collector voltage is zero
   c. Output voltage is normal
   d. DC base voltage is zero

26. **Usually, the distortion in an emitter follower is**
   a. Very low
   b. Very high
   c. Large
   d. Not acceptable

27. The distortion in an emitter follower is

a. Seldom low

b. Often high

c. Always low

d. High when clipping occurs

28. If a CE stage is direct coupled to an emitter follower, how many coupling capacitors are there between the two stages?

a. 0 c. 2

b. 1 d. 3

29. A Darlington transistor has a β of 8000. If R_E = 1 kΩ and R_L = 100 Ω, the input impedance of the base is closest to

a. 8 kΩ c. 800 kΩ

b. 80 kΩ d. 8 MΩ

30. The ac emitter resistance of an emitter follower

a. Equals the dc emitter resistance

b. Is larger than the load resistance

c. Is β times smaller than the load resistance

d. Is usually less than the load resistance

31. A common-base amplifier has a voltage gain that is

a. Much less than one

b. Approximately equal to one

c. Greater than one

d. Zero

32. An application of a common-base amplifier is when

a. $R_{source} >> R_L$

b. $R_{source} << R_L$

c. A high current gain is required

d. High frequencies need to be blocked

33. A common-base amplifier can be used when

a. Matching low to high impedances

b. A voltage gain without a current gain is required

c. A high-frequency amplifier is needed

d. All of the above

34. The zener current in a zener follower is

a. Equal to the output current

b. Smaller than the output current

c. Larger than the output current

d. Prone to thermal runaway

35. In the two-transistor voltage regulator, the output voltage

a. Is regulated

b. Has much smaller ripple than the input voltage

c. Is larger than the zener voltage

d. All of the above

36. When troubleshooting multistage amplifiers, begin by

a. Measuring all dc voltages

b. Signal tracing or signal injection

c. Taking resistance measurements

d. Replacing components

Problems

SEC. 9-1 MULTISTAGE AMPLIFIERS

9-1 In Fig. 9-27, what is the ac voltage at the first base? At the second base? Across the load resistor?

9-2 If the supply voltage is increased to +12 V in Fig. 9-27, what is the output voltage?

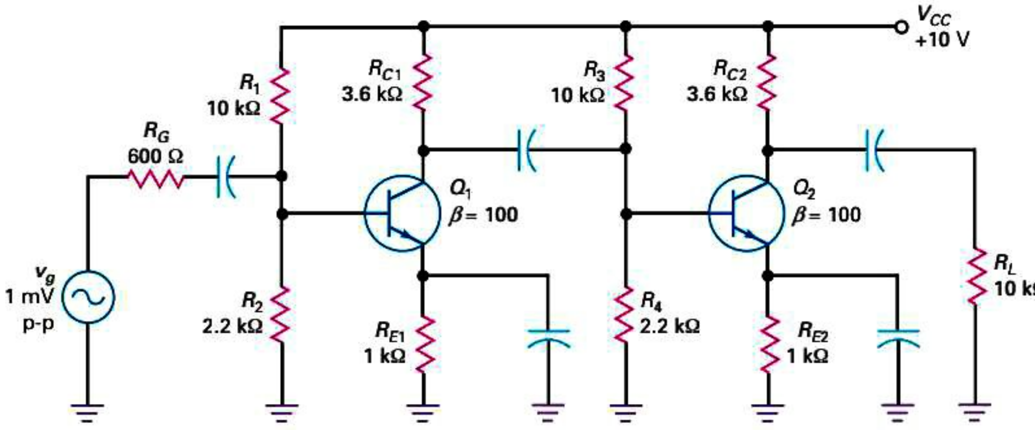
9-3 If β = 300 in Fig. 9-27, what is the output voltage?

SEC. 9-2 TWO-STAGE FEEDBACK

9-4 A feedback amplifier like Fig. 9-4 has r_f = 5 kΩ and r_e = 50 Ω. What is the voltage gain?

9-5 In a feedback amplifier like Fig. 9-5, r_e = 125 Ω. If you want a voltage gain of 100, what value should r_f be?

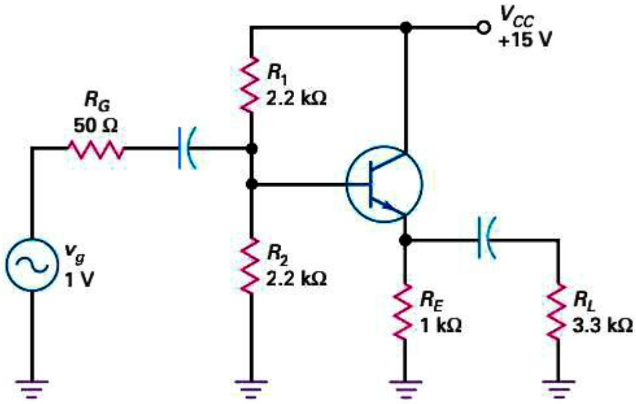
Figure 9-27



SEC. 9-3 CC AMPLIFIER

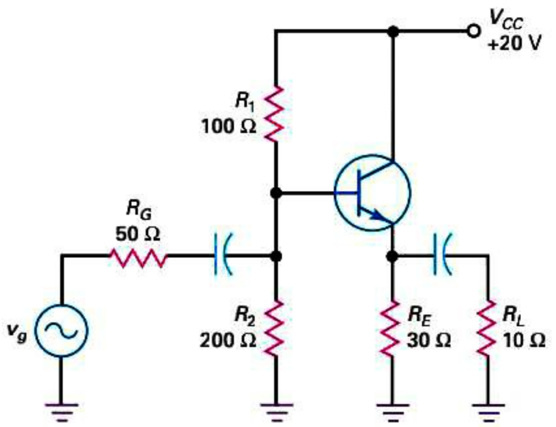
9-6 In Fig. 9-28, what is the input impedance of the base if $\beta = 200$? The input impedance of the stage?

Figure 9-28



9-7 If $\beta = 150$ in Fig. 9-28, what is the ac input voltage to the emitter follower?

Figure 9-29



9-8 What is the voltage gain in Fig. 9-28? If $\beta = 175$, what is the ac load voltage?

9-9 What is the input voltage in Fig. 9-28 if β varies over a range of 50 to 300?

9-10 All resistors are doubled in Fig. 9-28. What happens to the input impedance of the stage if $\beta = 150$? To the input voltage?

9-11 What is the input impedance of the base if $\beta = 200$ in Fig. 9-29? The input impedance of the stage?

9-12 In Fig. 9-29, what is the ac input voltage to the emitter follower if $\beta = 150$ and $v_g = 1$ V?

9-13 What is the voltage gain in Fig. 9-29? If $\beta = 175$, what is the ac load voltage?

SEC. 9-4 OUTPUT IMPEDANCE

9-14 What is the output impedance in Fig. 9-28 if $\beta = 200$?

9-15 What is the output impedance in Fig. 9-29 if $\beta = 100$?

SEC. 9-5 CASCADING CE AND CC

9-16 What is the voltage gain of the CE stage in Fig. 9-30 if the second transistor has a dc and ac current gain of 200?

9-17 If both transistors in Fig. 9-30 have a dc and ac current gain of 150, what is the output voltage when $v_g = 10$ mV?

9-18 If both transistors have a dc and ac current gain of 200 in Fig. 9-30, what is the voltage gain of the CE stage if the load resistance drops to 125 Ω?

9-19 In Fig. 9-30, what would happen to the voltage gain of the CE amplifier if the emitter follower stage were removed and a capacitor were used to couple the ac signal to the 150 Ω load?

Figure 9-30

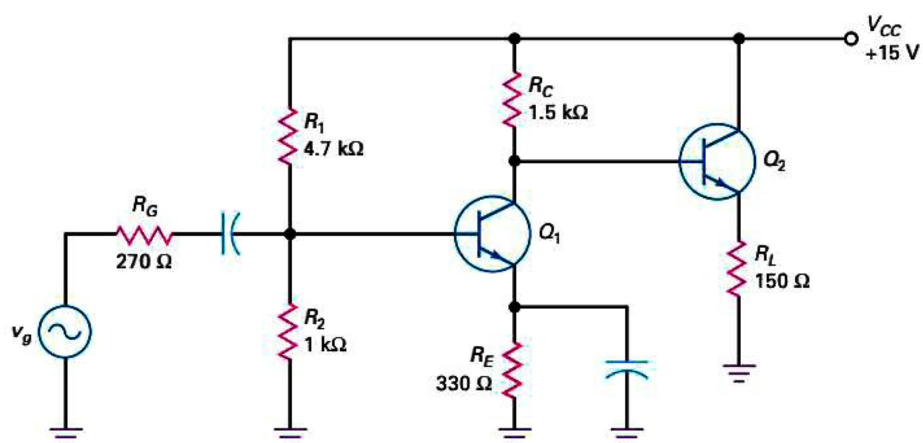


Figure 9-31

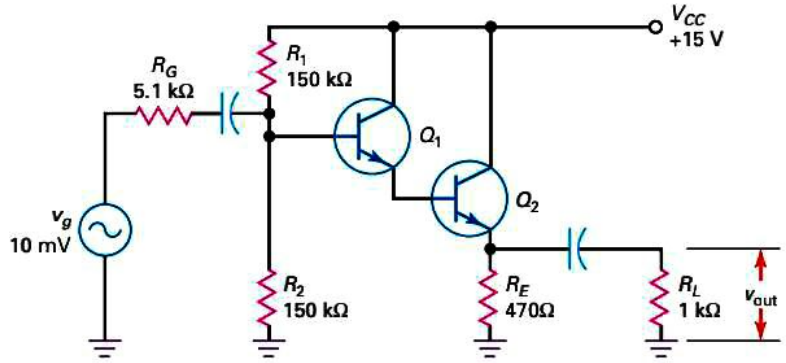
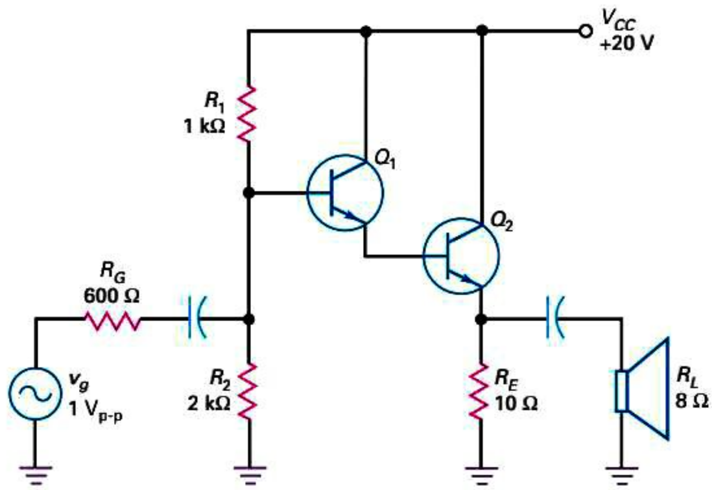


Figure 9-32



SEC. 9-6 DARLINGTON CONNECTIONS

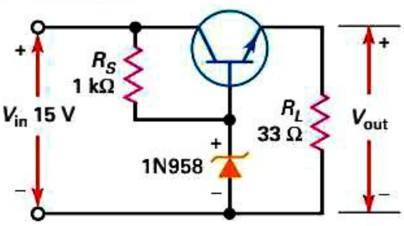
9-20 If the Darlington pair of Fig. 9-31 has an overall current gain of 5000, what is the input impedance of the Q_1 base?

9-21 In Fig. 9-31, what is the ac input voltage to the Q_1 base if the Darlington pair has an overall current gain of 7000?

9-22 Both transistors have a β of 150 in Fig. 9-32. What is the input impedance of the first base?

9-23 In Fig. 9-32, what is the ac input voltage to the Q_1 base if the Darlington pair has an overall current gain of 2000?

Figure 9-33



SEC. 9-7 VOLTAGE REGULATION

9-24 The transistor in Fig. 9-33 has a current gain of 150. If the 1N958 has a zener voltage of 7.5 V, what is the output voltage? The zener current?

9-25 If the input voltage in Fig. 9-33 changes to 25 V, what is the output voltage? The zener current?

9-26 The potentiometer in Fig. 9-34 can vary from 0 to 1 kΩ. What is the output voltage when the wiper is at the center?

9-27 What is the output voltage in Fig. 9-34 if the wiper is all the way up? If it is all the way down?

Figure 9-34

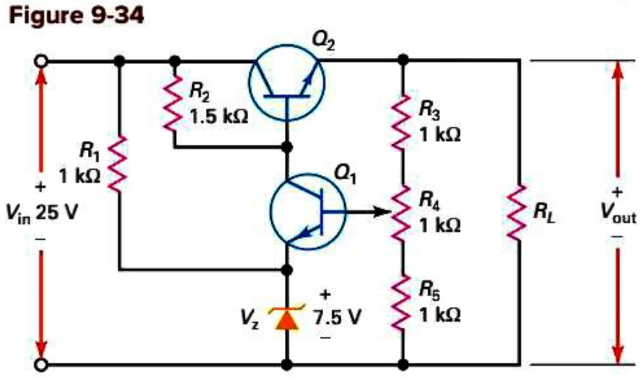
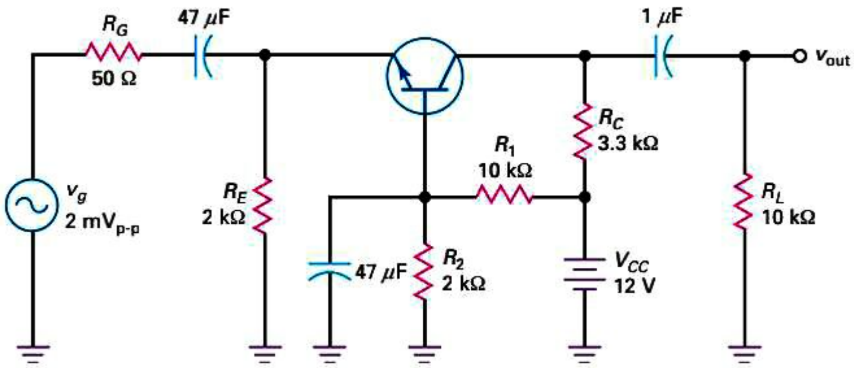


Figure 9-35



SEC. 9-8 COMMON-BASE AMPLIFIER

9-28 In Fig. 9-35, what is the *Q* point emitter current?

9-29 What is the approximate voltage gain in Fig. 9-35?

9-30 In Fig. 9-35, what is the input impedance looking into the emitter? What is the input impedance of the stage?

9-31 In Fig. 9-35, with an input of 2 mV from the generator, what is the value of v_{out}?

9-32 In Fig. 9-35, if the V_{CC} supply voltage were increased to 15 V, what would v_{out} equal?

Critical Thinking

9-33 In Fig. 9-33, what is the power dissipation of the transistor if the current gain is 100 and the zener voltage is 7.5 V?

9-34 In Fig. 9-36a, the transistor has a β_{dc} of 150. Calculate the following dc quantities: V_B, V_E, V_C, I_E, I_C, and I_B.

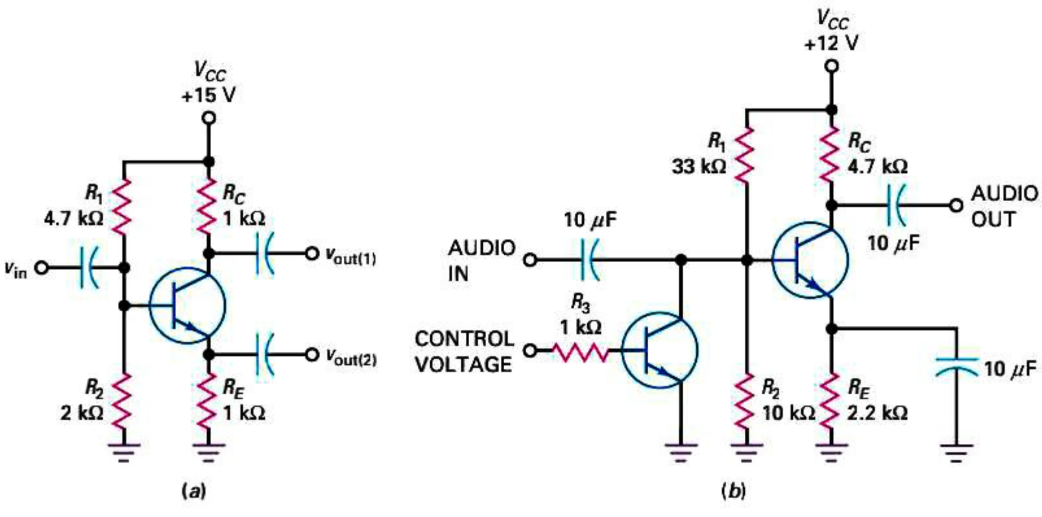
9-35 If an input signal with a peak-to-peak value of 5 mV drives the circuit of Fig. 9-36*a*, what are the two ac output voltages? What do you think is the purpose of this circuit?

9-36 Figure 9-36*b* shows a circuit in which the control voltage can be 0 V or +5 V. If the audio input voltage is 10 mV, what is the audio output voltage when the control voltage is 0 V? When the control voltage is +5 V? What do you think this circuit is supposed to do?

9-37 In Fig. 9-33, what would the output voltage be if the zener diode opened? (Use $\beta_{dc} = 200$)

9-38 In Fig. 9-33, if the 33 Ω load shorts, what is the transistor's power dissipation? (use $\beta_{dc} = 100$)

Figure 9-36



9-39 In Fig. 9-34, what is the power dissipation of Q_2 when the wiper is at the center and the load resistance is 100 Ω?

9-40 Using Fig. 9-31, if both transistors have a β of 100, what is the approximate output impedance of the amplifier?

9-41 In Fig. 9-30, if the input voltage from the generator were 100 $mV_{p\text{-}p}$ and the emitter-bypass capacitor opened, what would the output voltage across the load be?

9-42 In Fig. 9-35, what would be the output voltage if the base-bypass capacitor shorted?

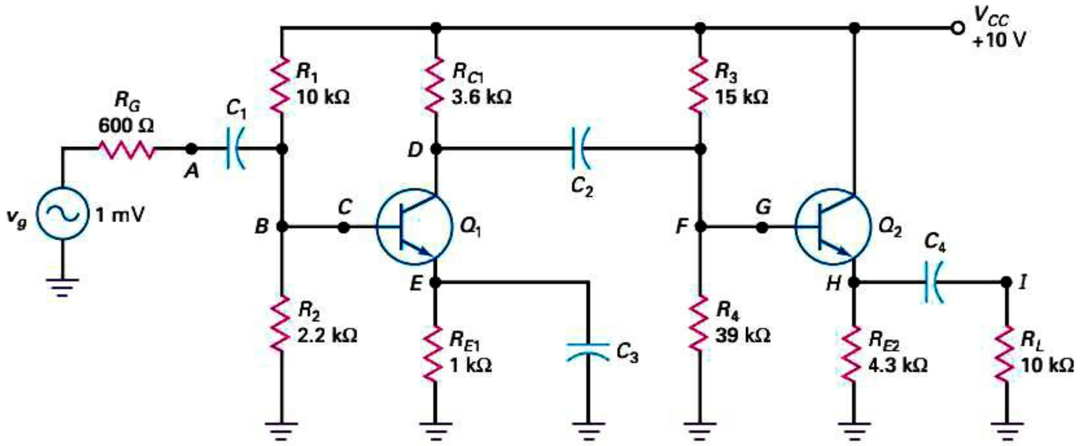
Troubleshooting

Use Fig. 9-37 for the remaining problems. The table labeled "Ac Millivolts" contains the measurements of the ac voltages expressed in millivolts. For this exercise, all resistors are OK. The troubles are limited to open capacitors, open connecting wires, and open transistors.

9-43 Find Troubles T1 to T3.

9-44 Find Troubles T4 to T7.

Figure 9-37



(*a*)

Ac Millivolts

Trouble	V_A	V_B	V_C	V_D	V_E	V_F	V_G	V_H	V_I
OK	0.6	0.6	0.6	70	0	70	70	70	70
*T*1	0.6	0.6	0.6	70	0	70	70	70	0
*T*2	0.6	0.6	0.6	70	0	70	0	0	0
*T*3	1	0	0	0	0	0	0	0	0
*T*4	0.75	0.75	0.75	2	0.75	2	2	2	2
*T*5	0.75	0.75	0	0	0	0	0	0	0
*T*6	0.6	0.6	0.6	95	0	0	0	0	0
*T*7	0.6	0.6	0.6	70	0	70	70	0	0

(*b*)

Multisim Troubleshooting Problems

The Multisim troubleshooting files are found on the Instructor Resources section of *Connect for Electronic Principles*, in a folder named Multisim Troubleshooting Circuits (MTC). See page XVI for more details. For this chapter, the files are labeled MTC09-45 through MTC09-49 and are based on the circuit of Figure 9-37.

Open up and troubleshoot each of the respective files. Take measurements to determine if there is a fault and, if so, determine the circuit fault.

9-45 Open up and troubleshoot file MTC09-45.

9-46 Open up and troubleshoot file MTC09-46.

9-47 Open up and troubleshoot file MTC09-47.

9-48 Open up and troubleshoot file MTC09-48.

9-49 Open up and troubleshoot file MTC09-49.

Job Interview Questions

1. Draw the schematic diagram of an emitter follower. Tell me why this circuit is widely used in power amplifiers and voltage regulators.
2. Tell me all that you know about the output impedance of an emitter follower.
3. Draw a Darlington pair and explain why the overall current gain is the product of the individual current gains.
4. Draw a zener follower and explain why it regulates the output voltage against changes in the input voltage.
5. What is the voltage gain of an emitter follower? This being the case, in what applications would such a circuit be useful?
6. Explain why a Darlington pair has a higher power gain than a single transistor.
7. Why are "follower" circuits so important in acoustic circuits?
8. What is the approximate ac voltage gain for a CC amplifier?
9. What is another name for a common-collector amplifier?
10. What is the relationship between an ac signal phase (output to input) and a common-collector amplifier?
11. If a technician measures unity voltage gain (output voltage divided by input voltage) from a CC amplifier, what is the problem?
12. The Darlington amplifier is used in the final power amplifier (FPA) in most higher-quality audio amplifiers because it increases the power gain. How does a Darlington amplifier increase the power gain?

Self-Test Answers

1. a	**7.** c	**13.** c	**19.** c	**25.** d	**31.** c
2. b	**8.** d	**14.** a	**20.** a	**26.** a	**32.** b
3. c	**9.** c	**15.** c	**21.** c	**27.** d	**33.** d
4. b	**10.** a	**16.** d	**22.** c	**28.** a	**34.** b
5. c	**11.** a	**17.** a	**23.** a	**29.** c	**35.** d
6. b	**12.** d	**18.** c	**24.** a	**30.** d	**36.** b

Practice Problem Answers

9-1 $v_{out} = 2.24$ V

9-3 $r_f = 4.9$ kΩ

9-5 $z_{in(base)} = 303$ kΩ; $z_{in(stage)} = 4.92$ kΩ

9-6 $v_{in} \approx 0.893$ V

9-7 $v_{in} = 0.979$ V; $v_{out} = 0.974$ V

9-8 $z_{out} = 3.33\ \Omega$

9-9 $z_{out} = 2.86\ \Omega$

9-10 $A_v = 222$

9-11 $A_v = 6.28$

9-12 $\beta = 5625$; $I_{B1} = 14.3\ \mu$A; $z_{in(base)} = 112.5$ kΩ

9-13 $V_{out} = 7.5$ V; $I_z = 5$ mA

9-14 $V_{out} = 18.9$ V

9-15 $v_{out} = 76.9$ $mV_{p\text{-}p}$