Chapter 11
Amplifiers: Specifications and External Characteristics

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Amplifiers: Specifications and External Characteristics

1. Use various amplifier models to calculate amplifier performance for given sources and loads.

2. Compute amplifier efficiency.

3. Understand the importance of input and output impedances of amplifiers.

4. Determine the best type of ideal amplifier for various applications.

5. Specify the frequency-response requirements for various amplifier applications.

6. Understand linear and nonlinear distortion in amplifiers.

7. Specify the pulse-response parameters of amplifiers.

8. Work with differential amplifiers and specify common-mode rejection requirements.

9. Understand the various sources of dc offsets and design balancing circuits.

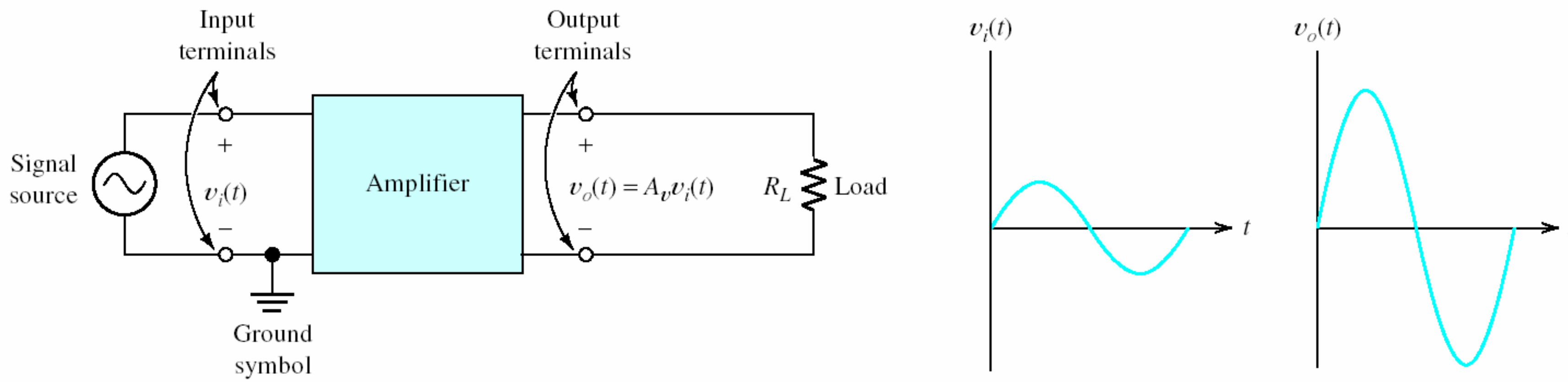
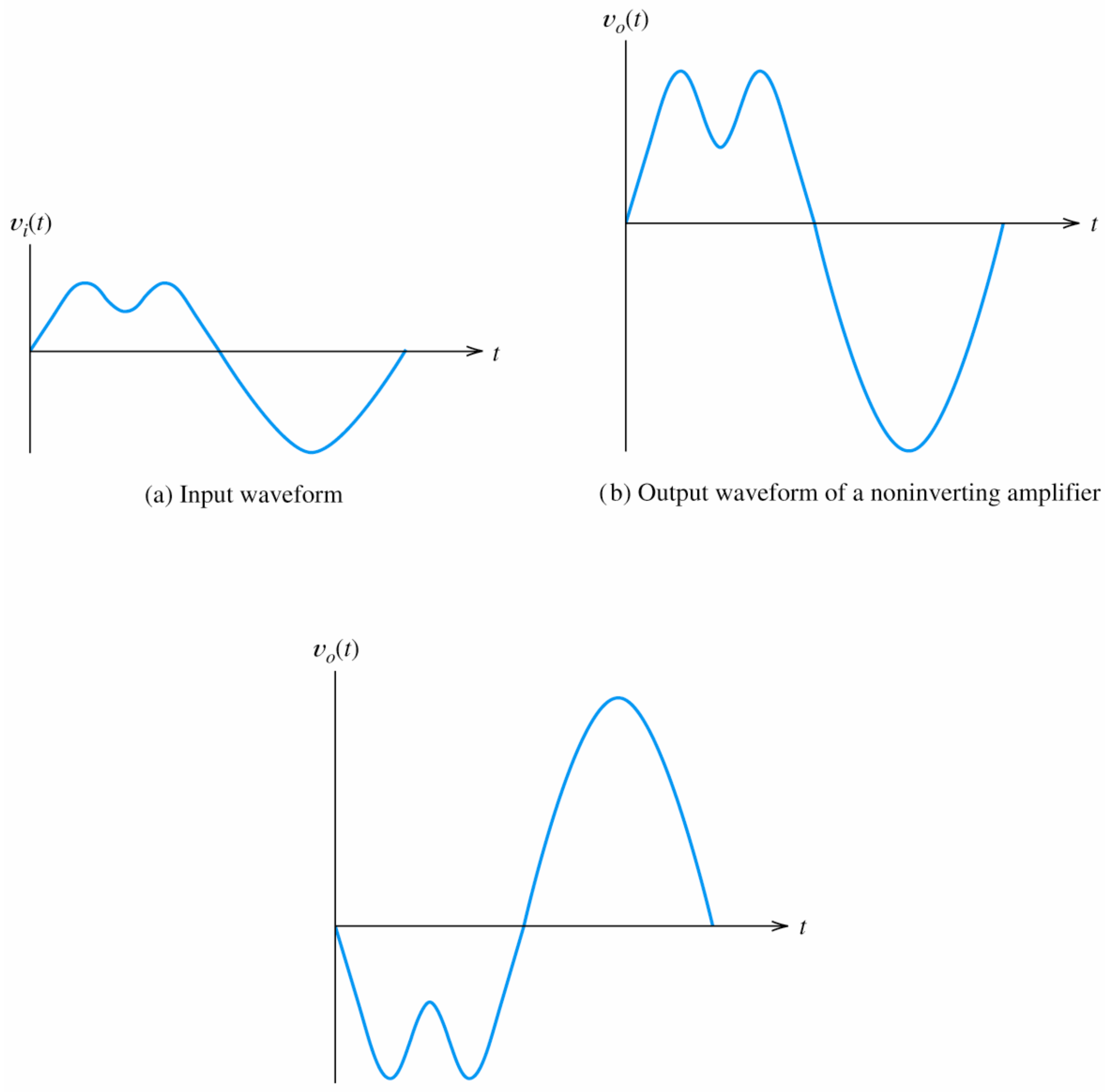


Figure 11.1 Electronic amplifier.

BASIC AMPLIFIER CONCEPTS

Ideally, an amplifier produces an output signal with identical waveshape as the input signal, but with a larger amplitude.

$$v_o(t) = A_v v_i(t)$$



(a) Input waveform

(b) Output waveform of a noninverting amplifier

(c) Output waveform of an inverting amplifier

Figure 11.2 Input waveform and corresponding output waveforms.

Inverting versus Noninverting Amplifiers

Inverting amplifiers have negative voltage gain, and the output waveform is an inverted version of the input waveform. Noninverting amplifiers have positive voltage gain.

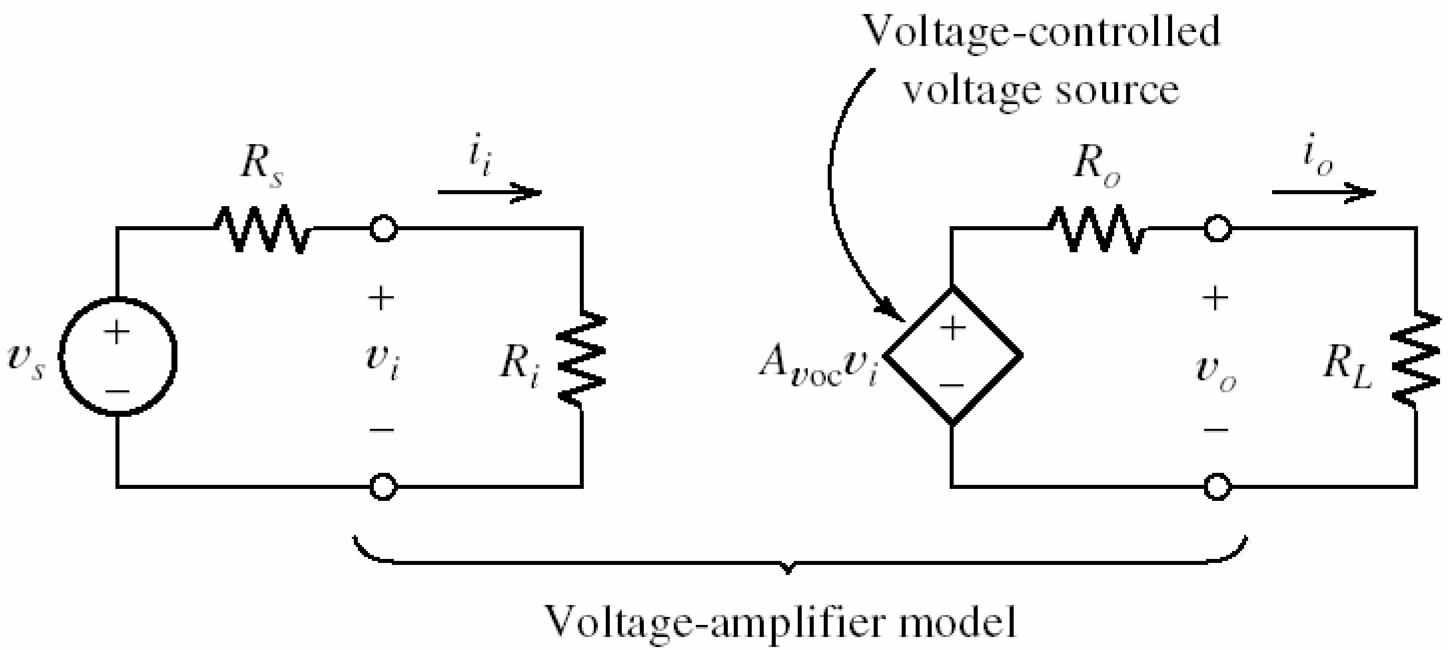
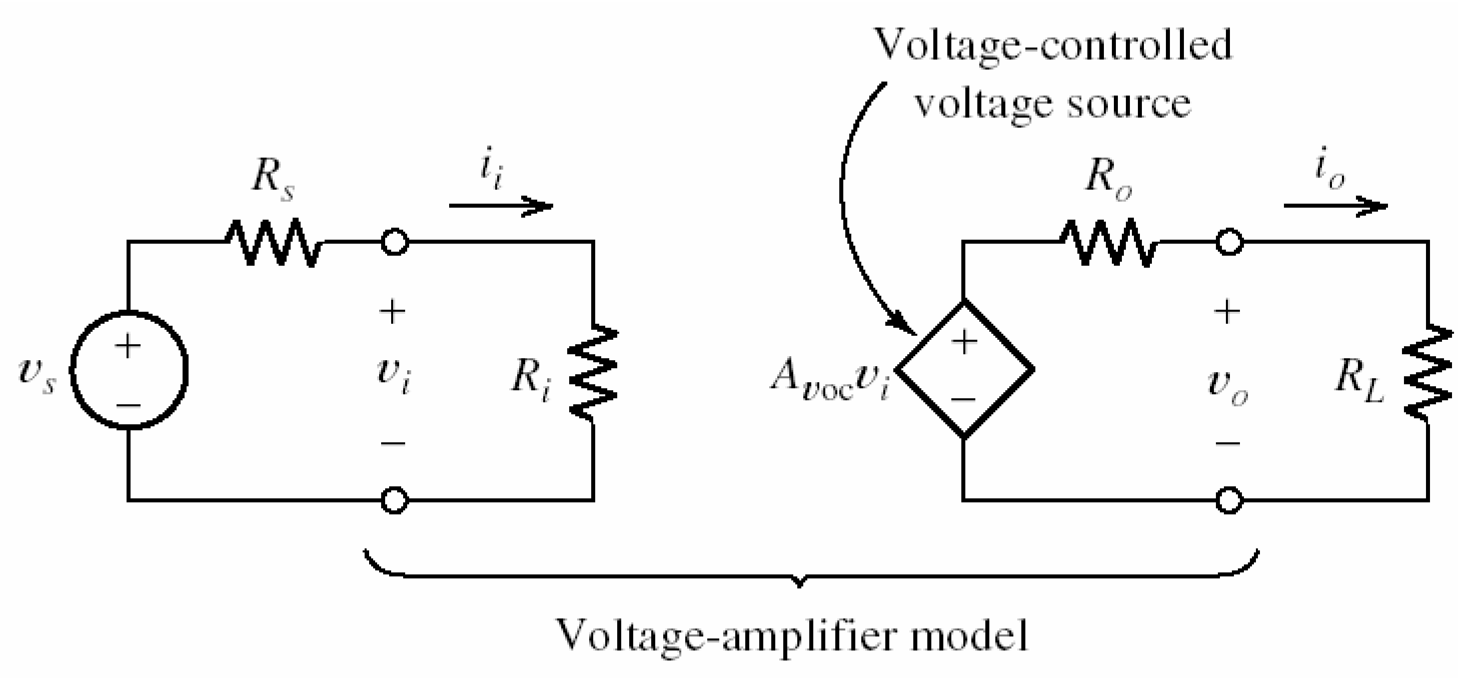


Figure 11.3 Model of an electronic amplifier, including input resistance R_i and output resistance R_o.

Voltage-Amplifier Model



Current Gain

$$A_i = \frac{i_o}{i_i}$$

$$A_i = \frac{i_o}{i_i} = \frac{v_o / R_L}{v_i / R_i} = A_v \frac{R_i}{R_L}$$

Power Gain

$$G = \frac{P_o}{P_i}$$

$$G = \frac{P_o}{P_i} = \frac{V_o I_o}{V_i I_i} = A_v A_i = \left(A_v\right)^2 \frac{R_i}{R_L}$$

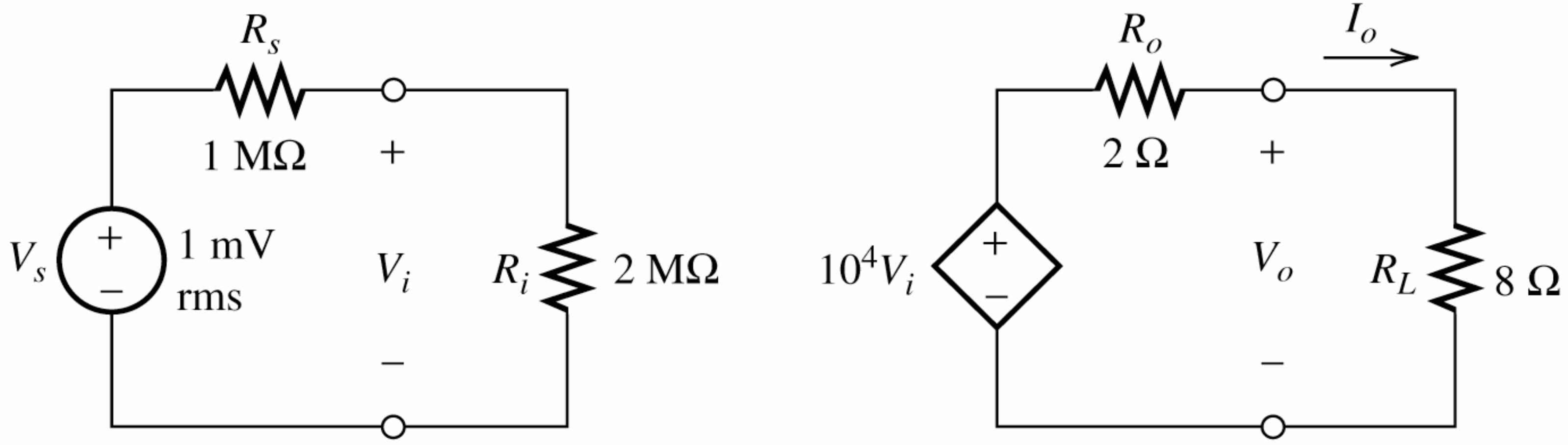


Figure 11.4 Source, amplifier, and load for Example 11.1.

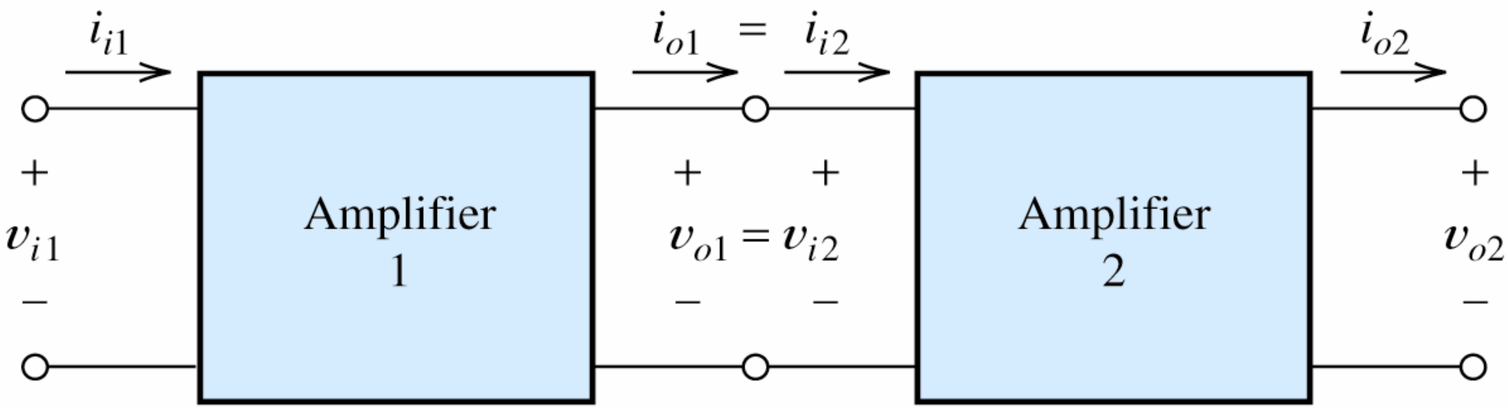
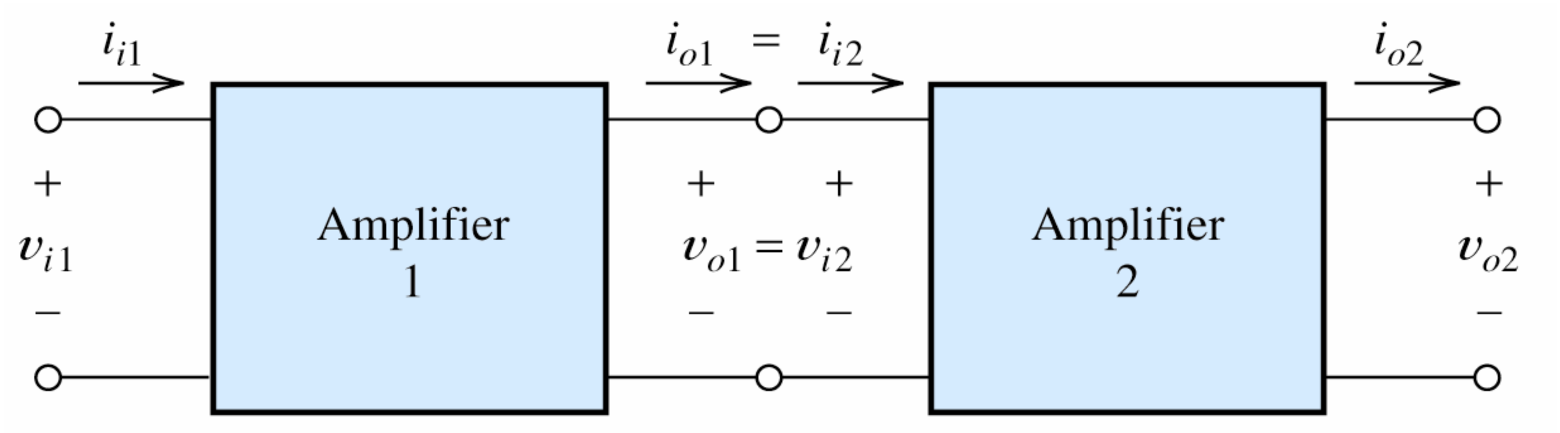


Figure 11.5 Cascade connection of two amplifiers.

CASCADED AMPLIFIERS



$$A_v = A_{v1} A_{v2}$$

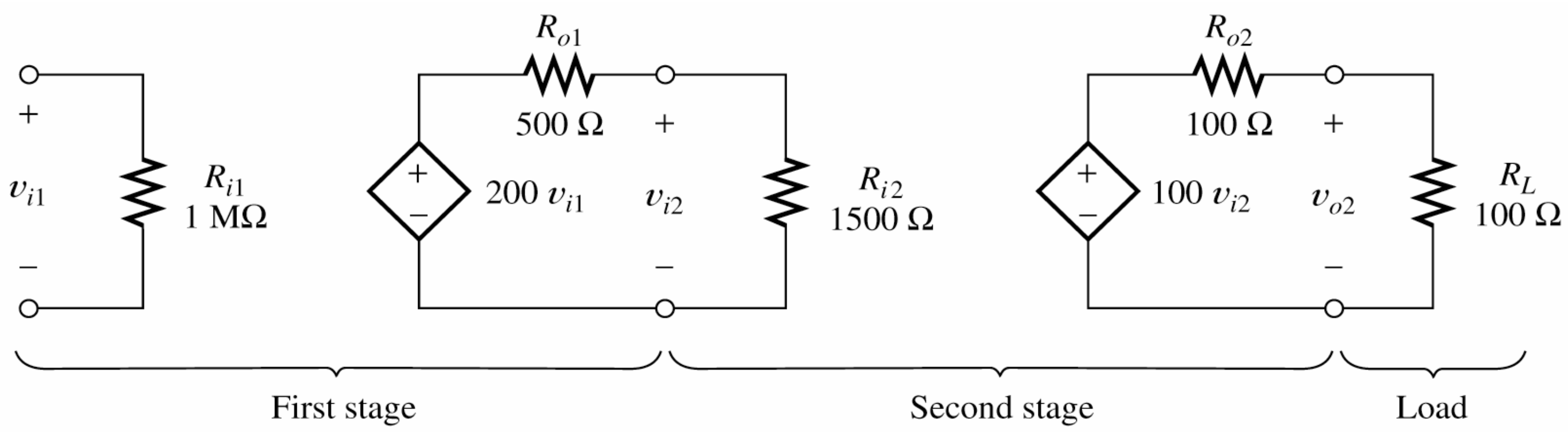


Figure 11.6 Cascaded amplifiers of Examples 11.2 and 11.3.

Simplified Models for Cascaded Amplifier Stages

First, determine the voltage gain of the first stage accounting for loading by the second stage.

The overall voltage gain is the product of the gains of the separate stages.

The input impedance is that of the first stage, and the output impedance is that of the last stage.

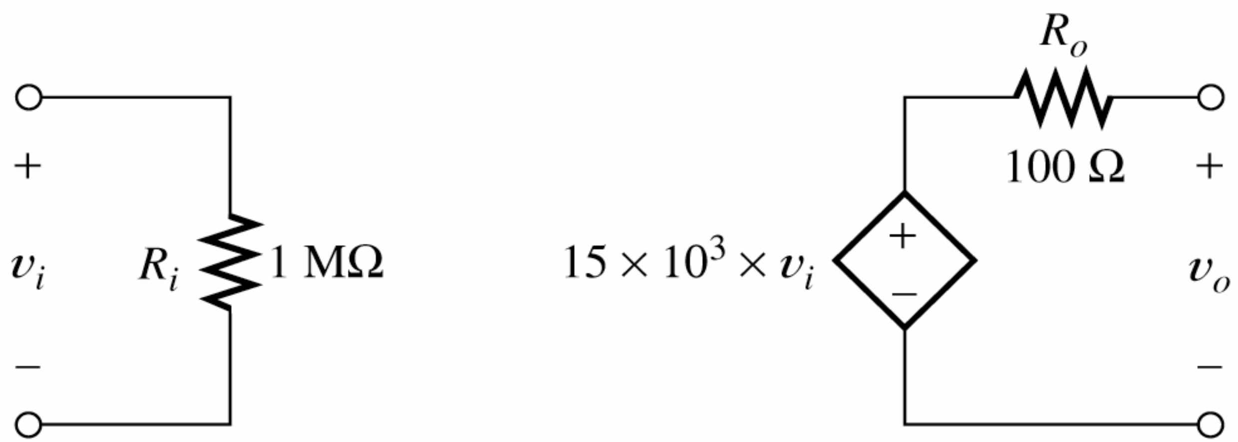


Figure 11.7 Simplified model for the cascaded amplifiers of Figure 11.6. See Example 11.3.

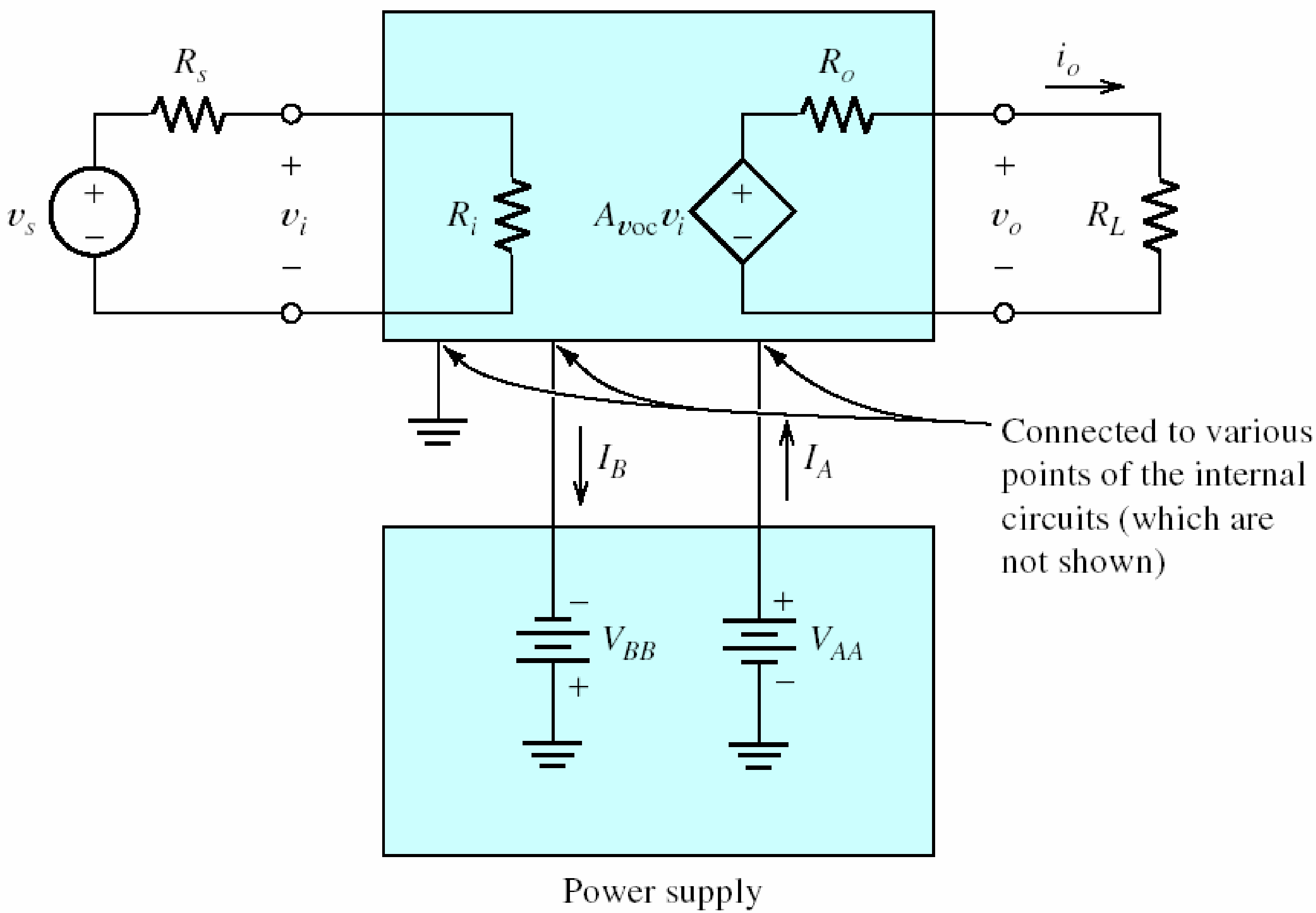
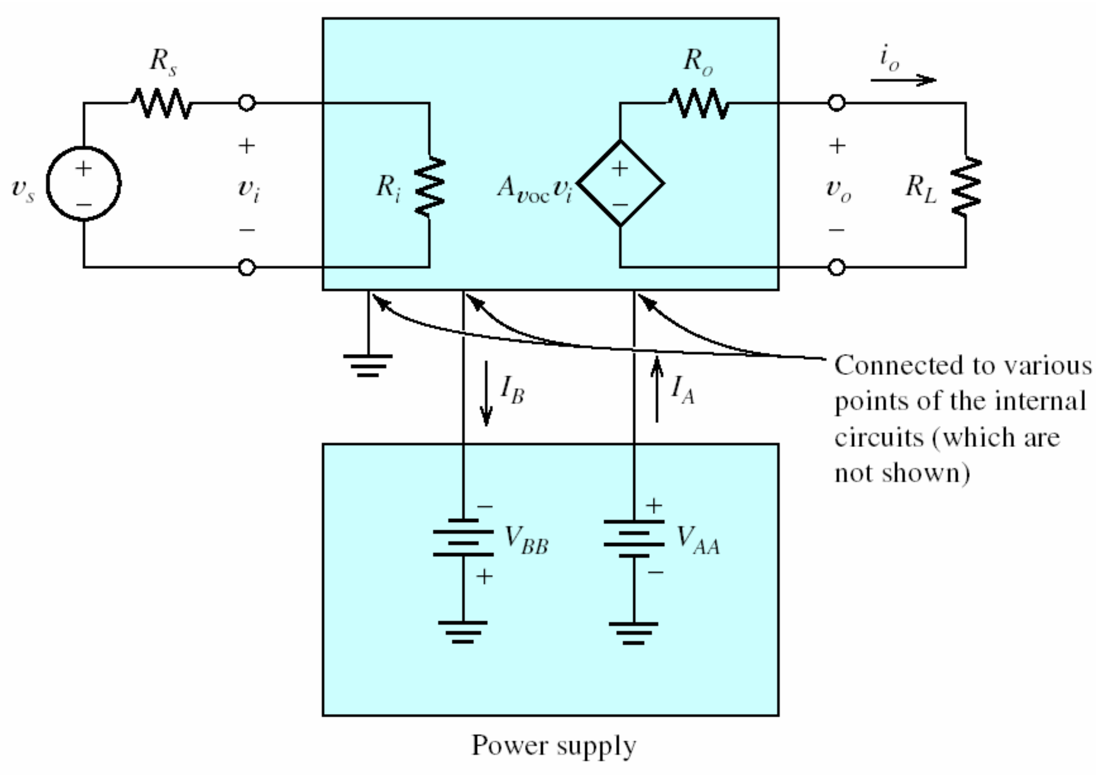


Figure 11.8 The power supply delivers power to the amplifier from several dc voltage sources.

POWER SUPPLIES AND EFFICIENCY



$$P_s = V_{AA}I_A + V_{BB}I_B$$

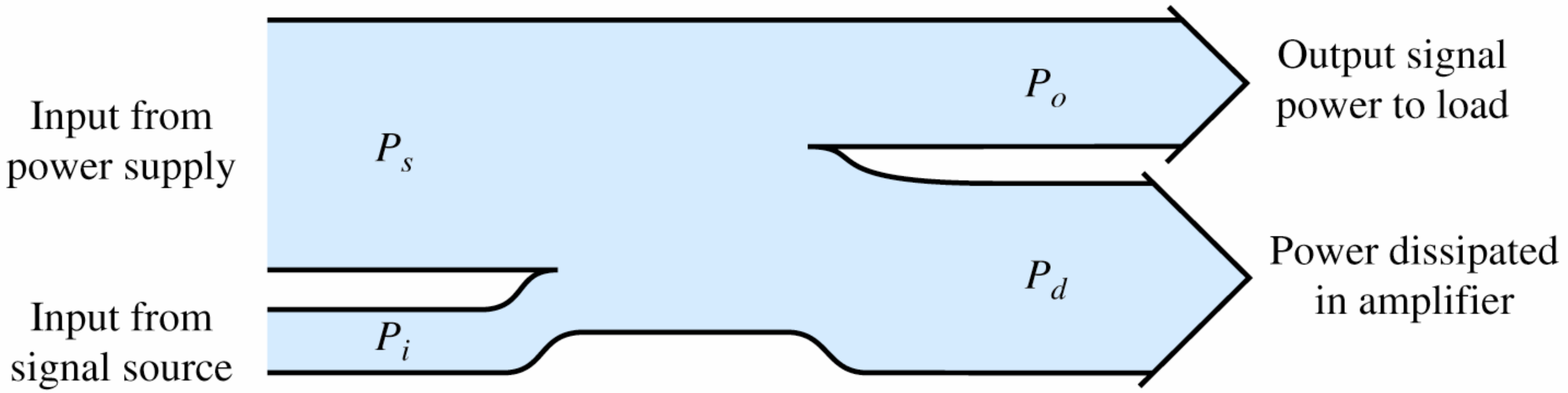


Figure 11.9 Illustration of power flow.

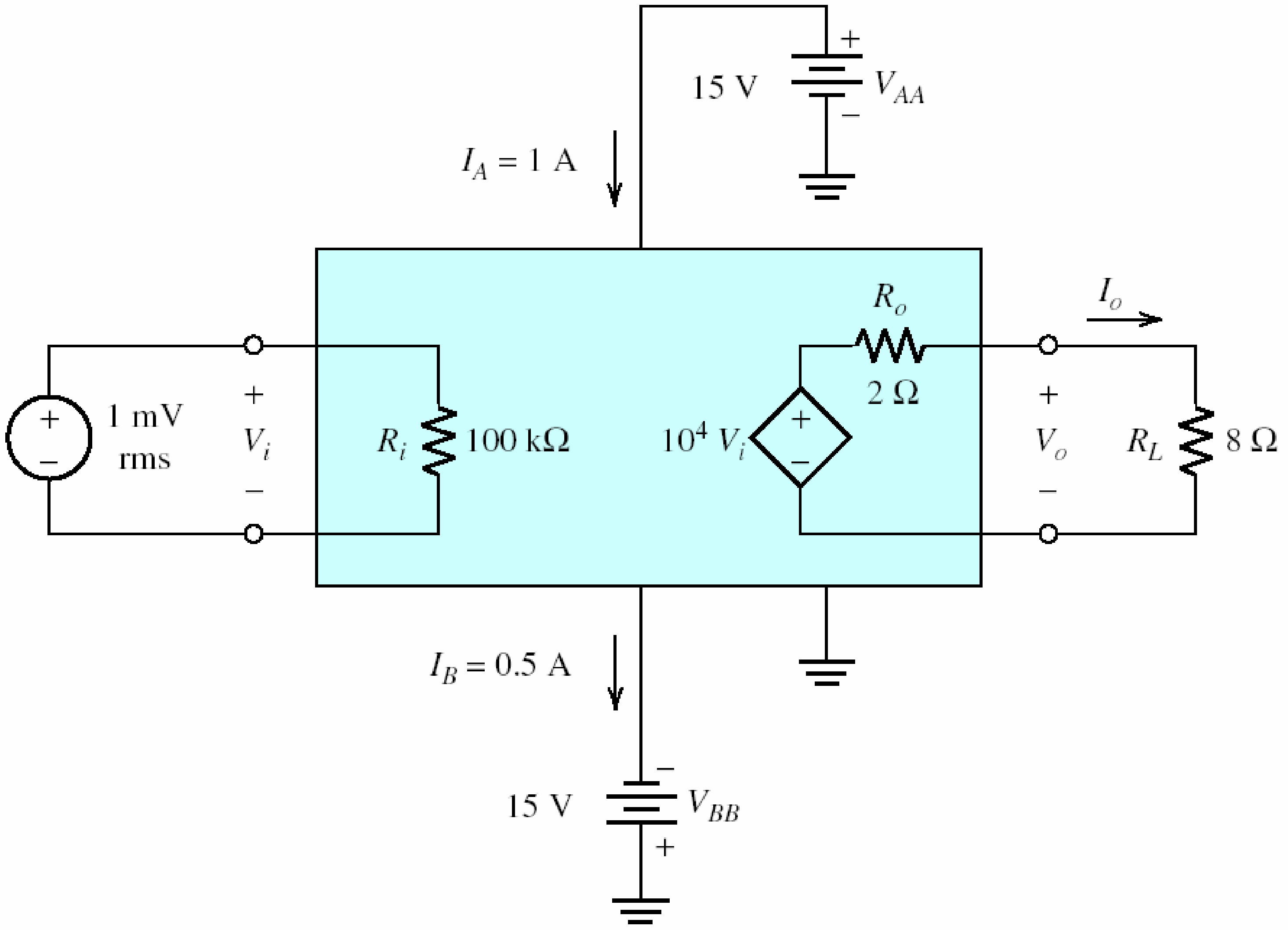


Figure 11.10 Amplifier of Example 11.4.

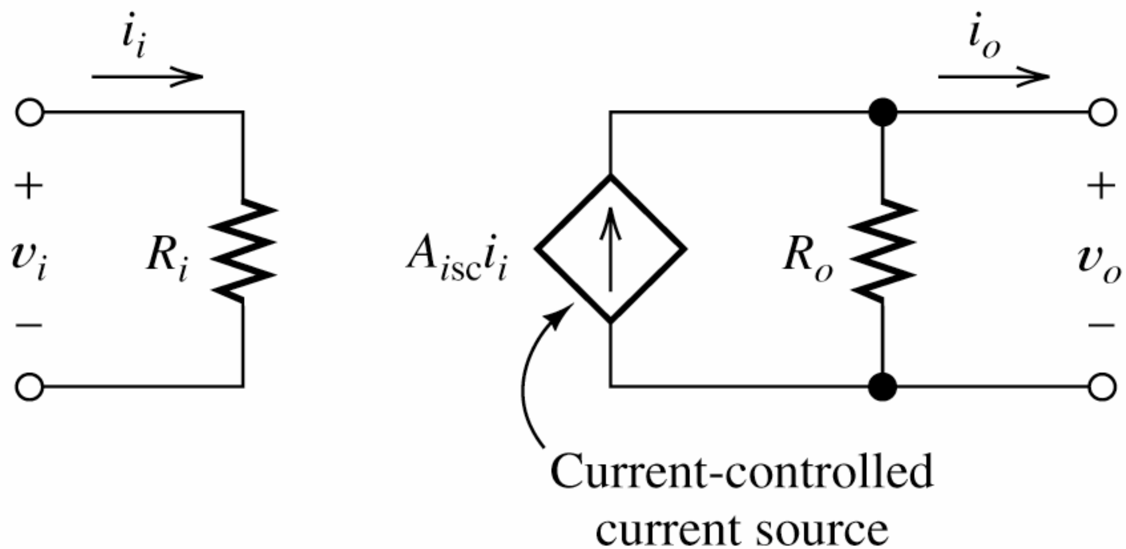
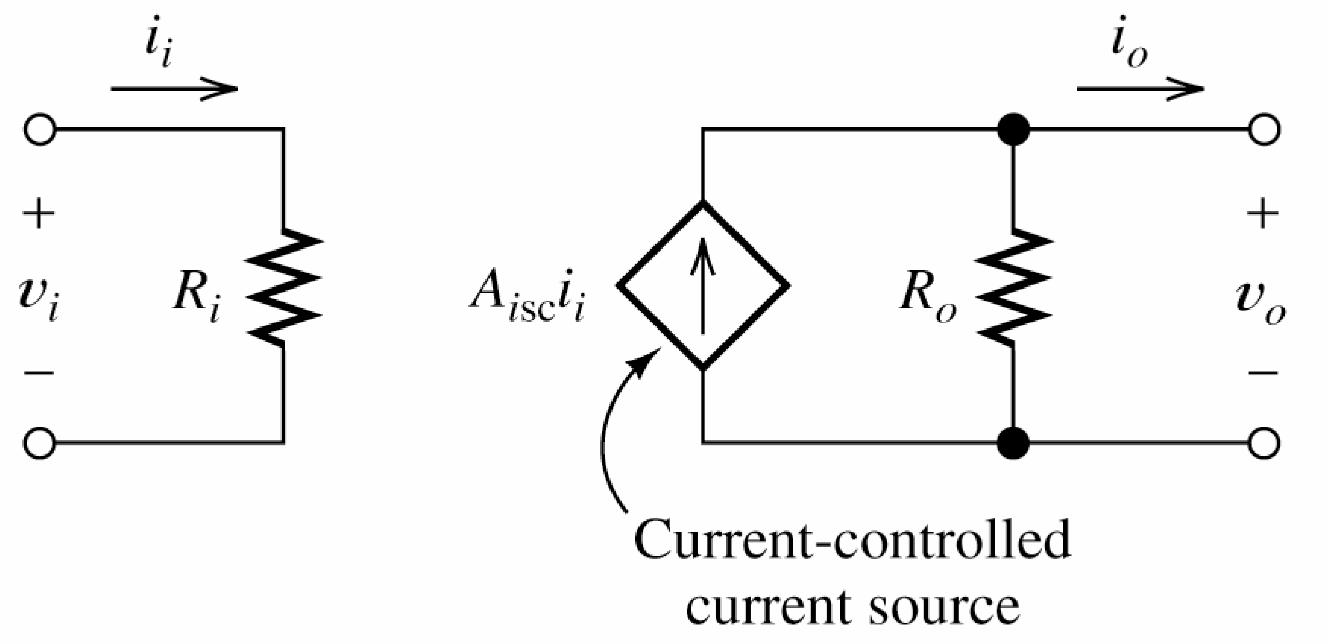


Figure 11.11 Current-amplifier model.

Current-Amplifier Model



A_{isc} is the current gain of the amplifier with the output short circuited.

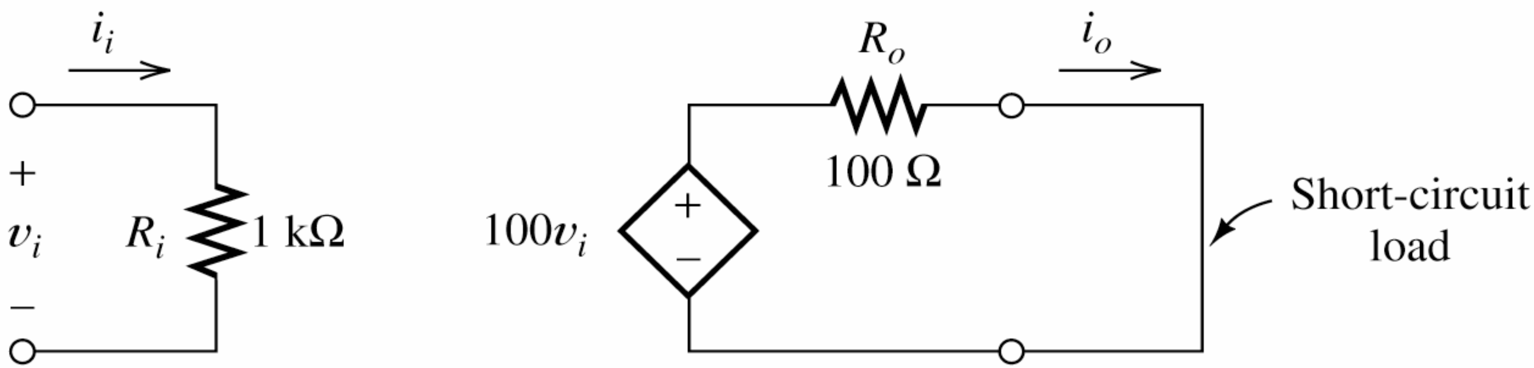


Figure 11.12 Voltage amplifier of Examples 11.5, 11.6, and 11.7.

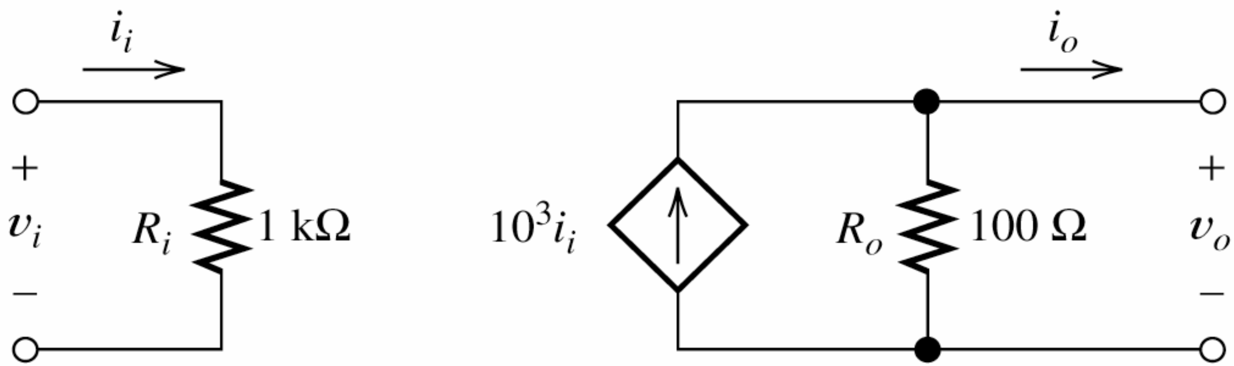


Figure 11.13 Current-amplifier model equivalent to the voltage-amplifier model of Figure 11.12.

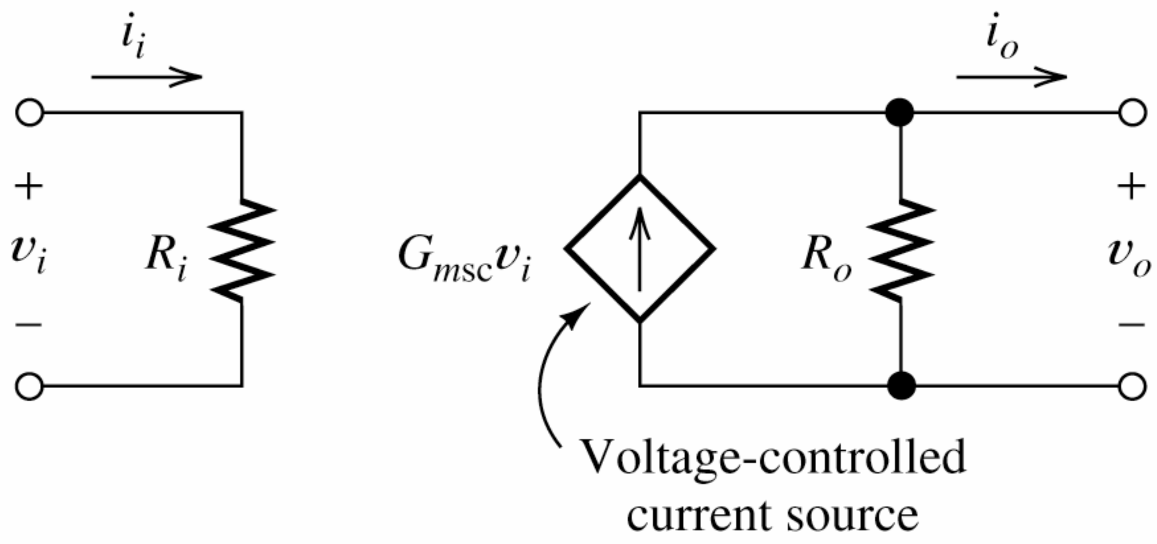
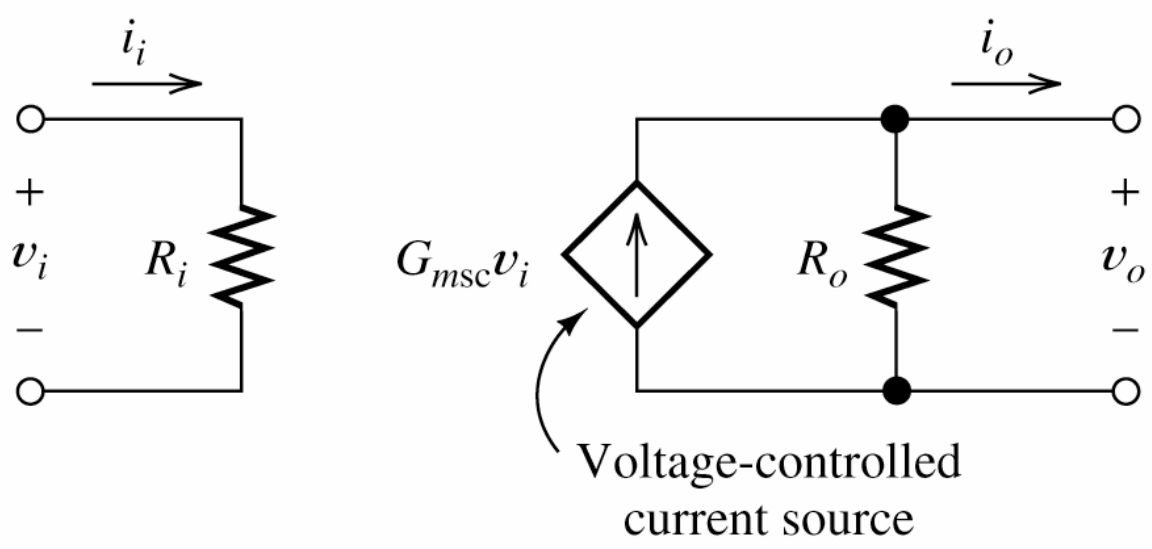


Figure 11.14 Transconductance-amplifier model.

Transconductance-Amplifier Model



$$G_{msc} = \frac{i_{osc}}{v_i}$$

Connect a short circuit across the output terminals and analyze the circuit to determine G_{msc}.

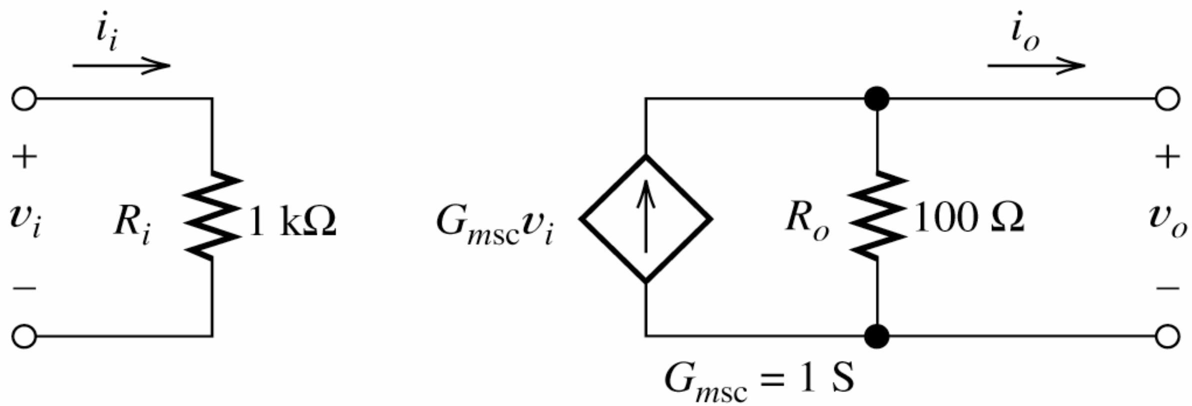


Figure 11.15 Transconductance-amplifier equivalent to the voltage amplifier of Figure 11.12. See Example 11.6.

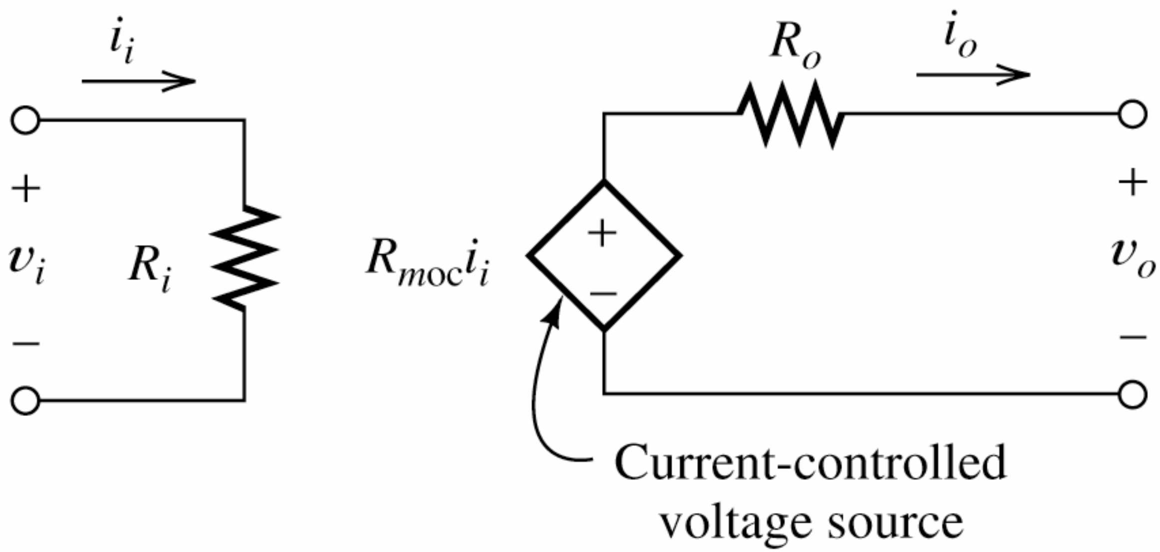
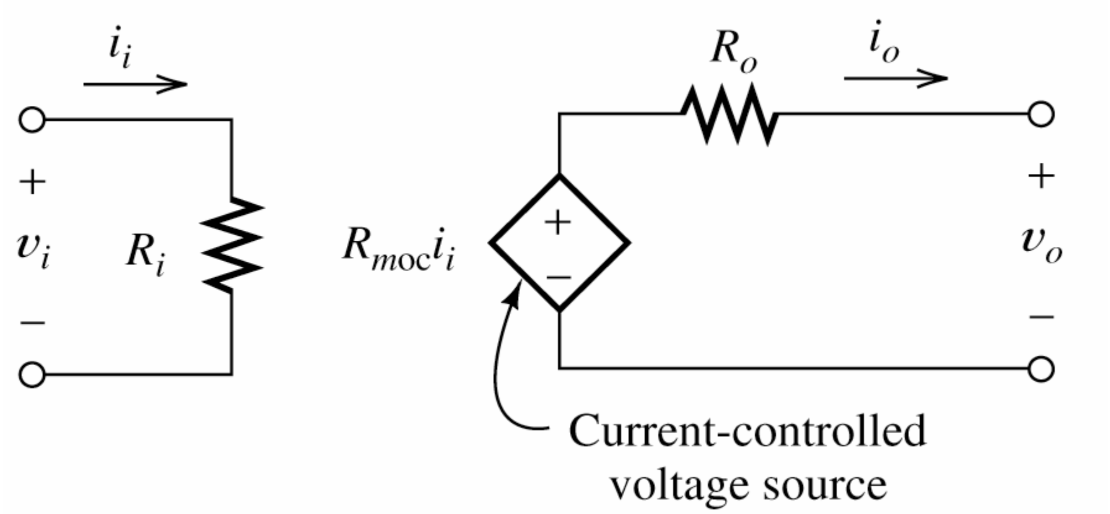


Figure 11.16 Transresistance-amplifier model.

Transresistance-Amplifier Model

$$R_{moc} = \frac{v_{ooc}}{i_i}$$



Open circuit the output terminals and analyze the circuit to determine R_{moc}.

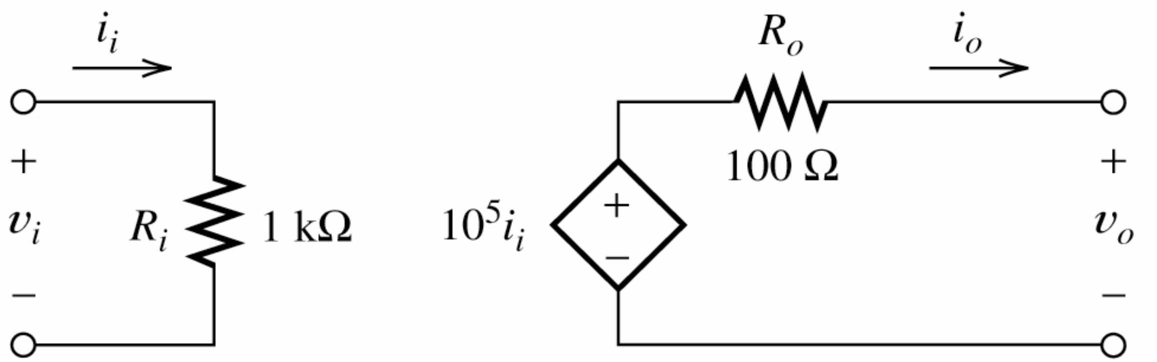
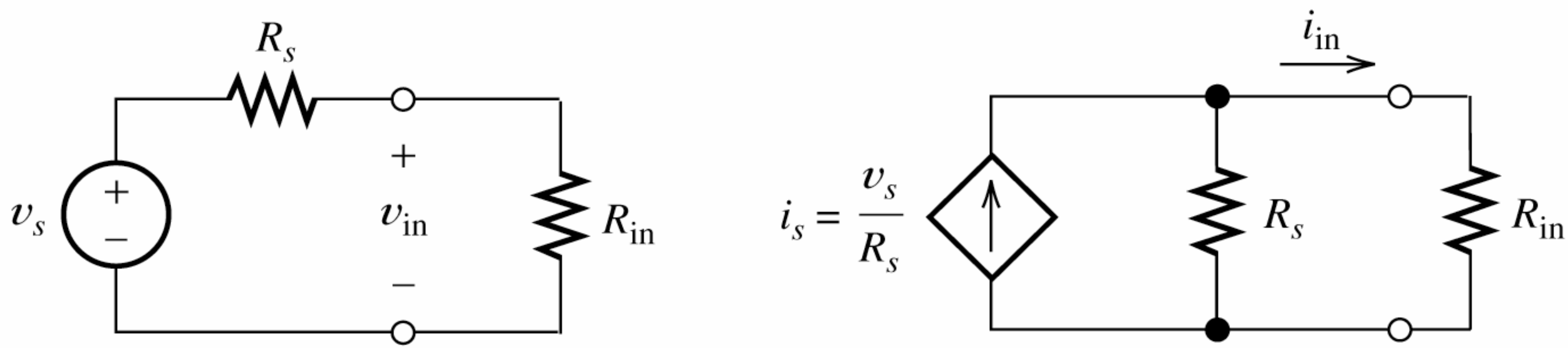


Figure 11.17 Transresistance amplifier that is equivalent to the voltage amplifier of Figure 11.12. See Example 11.7.



(a) If $R_{in} >> R_s$, then $v_{in} \cong v_s$

(b) If $R_{in} << R_s$, then $i_{in} \cong i_s$

Figure 11.18 If we want to sense the open-circuit voltage of a source, the amplifier should have a high input resistance, as in (a). To sense the short-circuit current of the source, low input resistance is called for, as in (b).

IMPORTANCE OF AMPLIFIER IMPEDANCES IN VARIOUS APPLICATIONS

Some applications call for amplifiers with high input (or output) impedance while others call for low input (or output) impedance.

Other applications call for amplifiers that have specific input and/or output impedances.

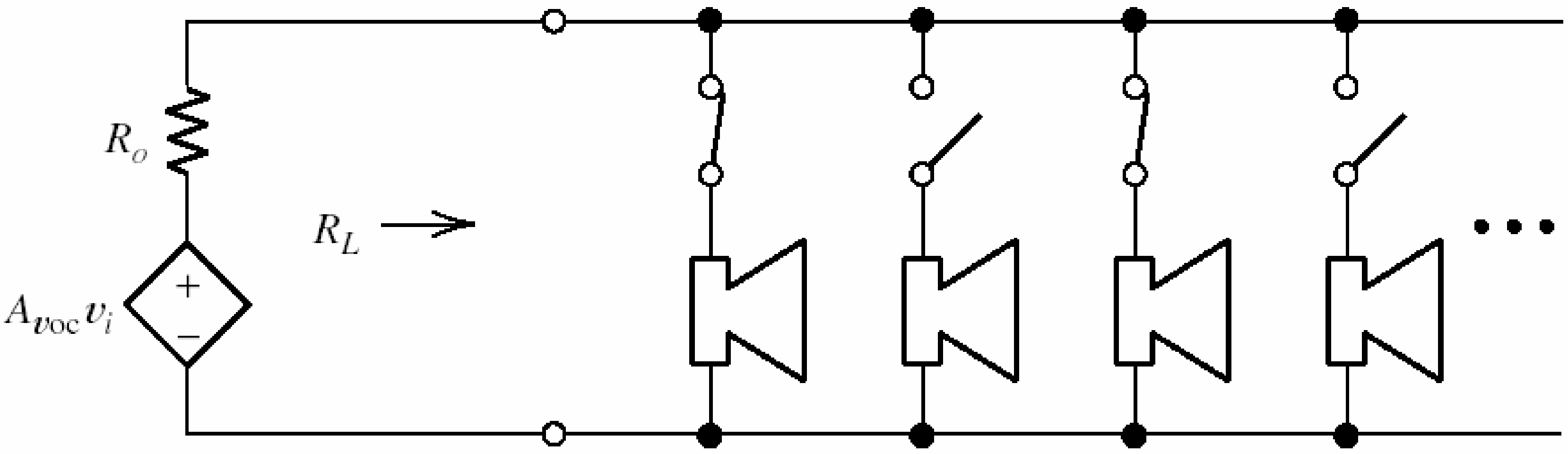


Figure 11.19 If the amplifier output resistance R_o is much less than the (lowest) load resistance, the load voltage is nearly independent of the number of switches closed.

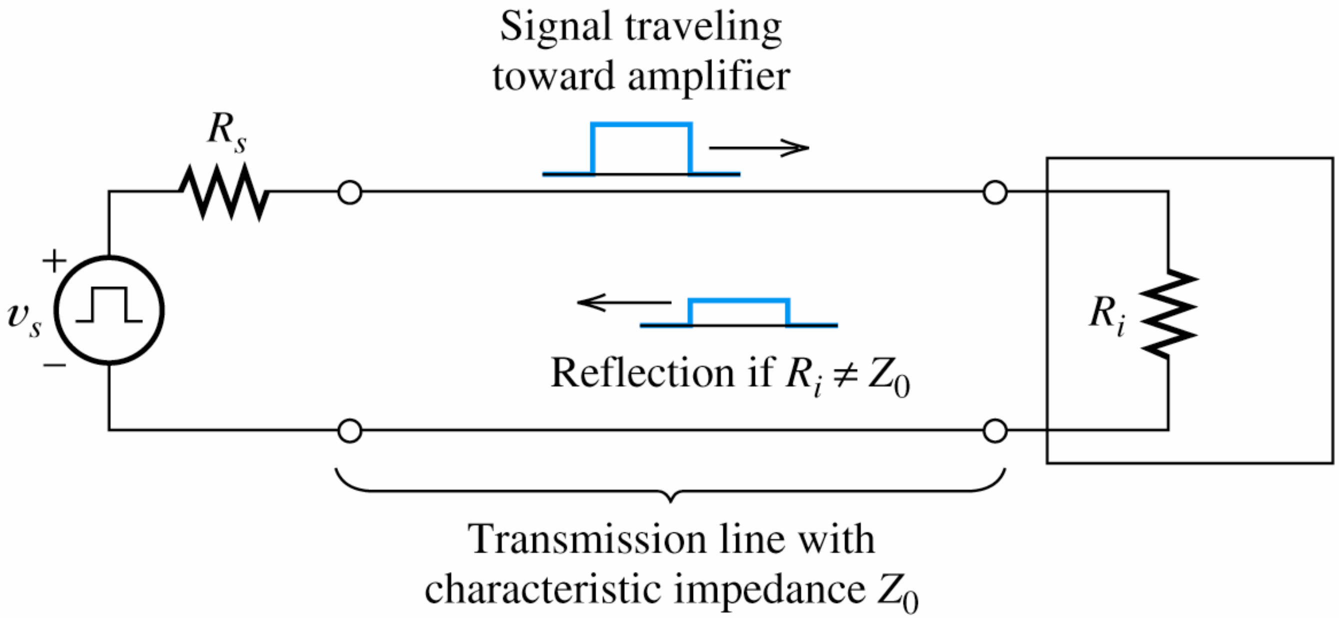


Figure 11.20 To avoid reflections, the amplifier input resistance R_i should equal the characteristic resistance Z_0 of the transmission line.

Table 11.1. Characteristics of Ideal Amplifiers

Amplifier Type	Input Impedance	Output Impedance	Gain Parameter
Voltage	∞	0	A_{voc}
Current	0	∞	A_{isc}
Transconductance	∞	∞	G_{msc}
Transresistance	0	0	R_{moc}

The proper classification of a given amplifier depends on the ranges of source and load impedances with which the amplifier is used.

FREQUENCY RESPONSE

$$A_v = \frac{\mathbf{V}_o}{\mathbf{V}_i}$$

Determining Complex Gain

$$v_i(t) = 0.1\cos\left(2000\pi t - 30^\circ\right)$$

$$v_o(t) = 10\cos\left(2000\pi t + 15^\circ\right)$$

$$A_v = \frac{\mathbf{V}_o}{\mathbf{V}_i} = \frac{10\angle 15^\circ}{0.1\angle -30^\circ}$$

$$= 100\angle 45^\circ$$

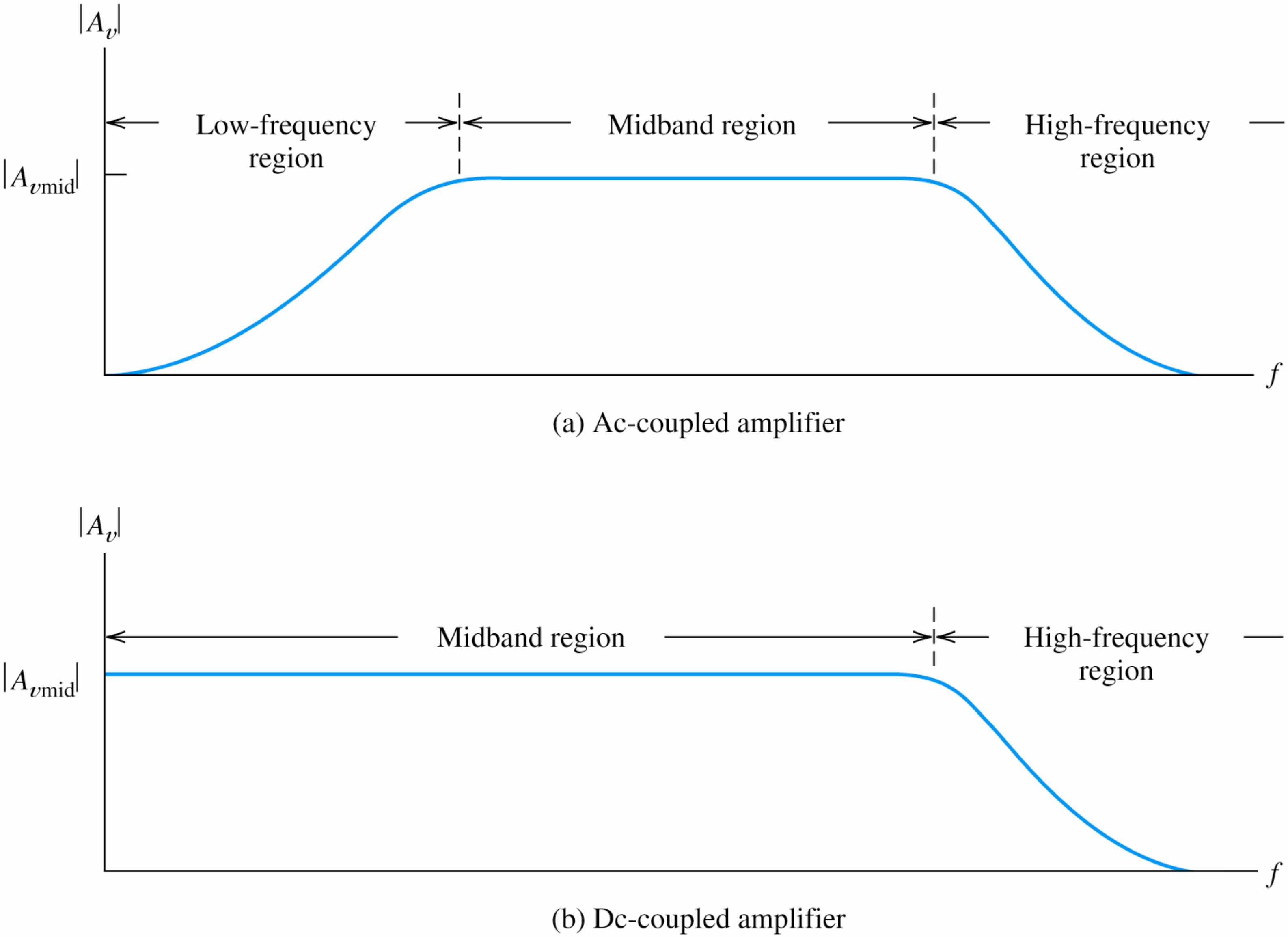


Figure 11.21 Gain magnitude versus frequency.

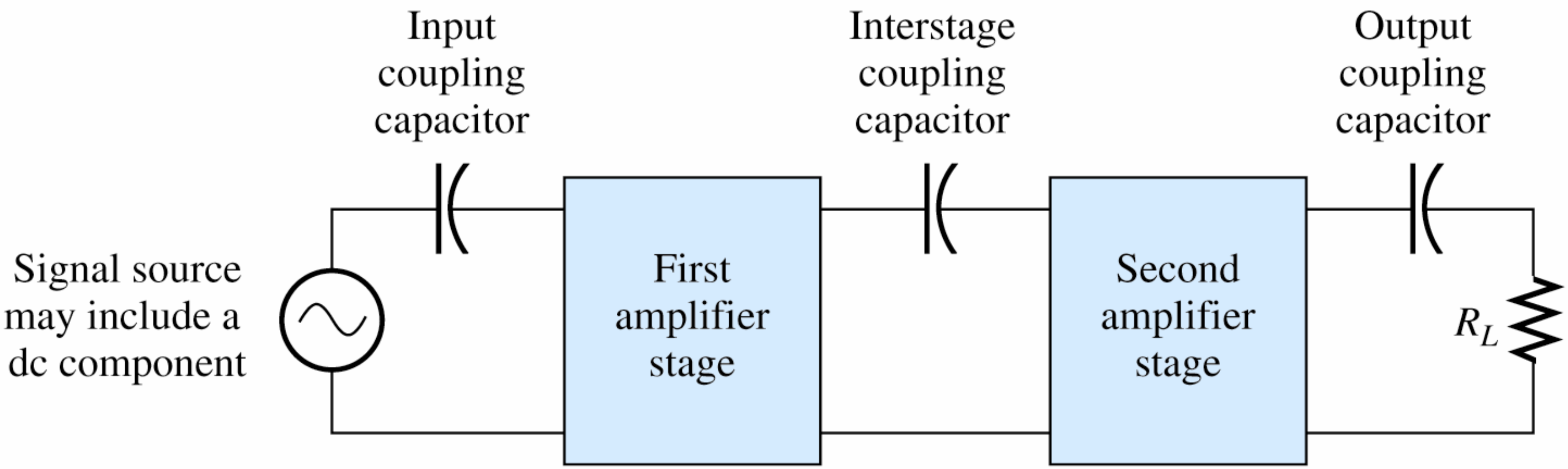


Figure 11.22 Capacitive coupling prevents a dc input component from affecting the first stage, dc voltages in the first stage from reaching the second stage, and dc voltages in the second stage from reaching the load.

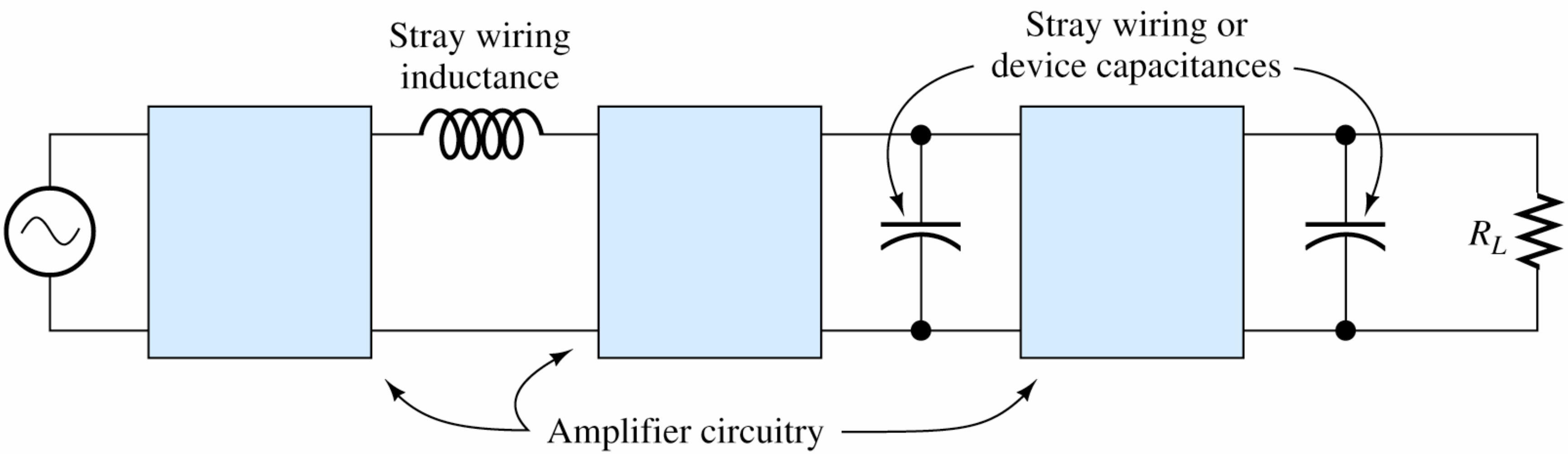


Figure 11.23 Capacitance in parallel with the signal path and inductance in series with the signal path reduce the gain in the high-frequency region.

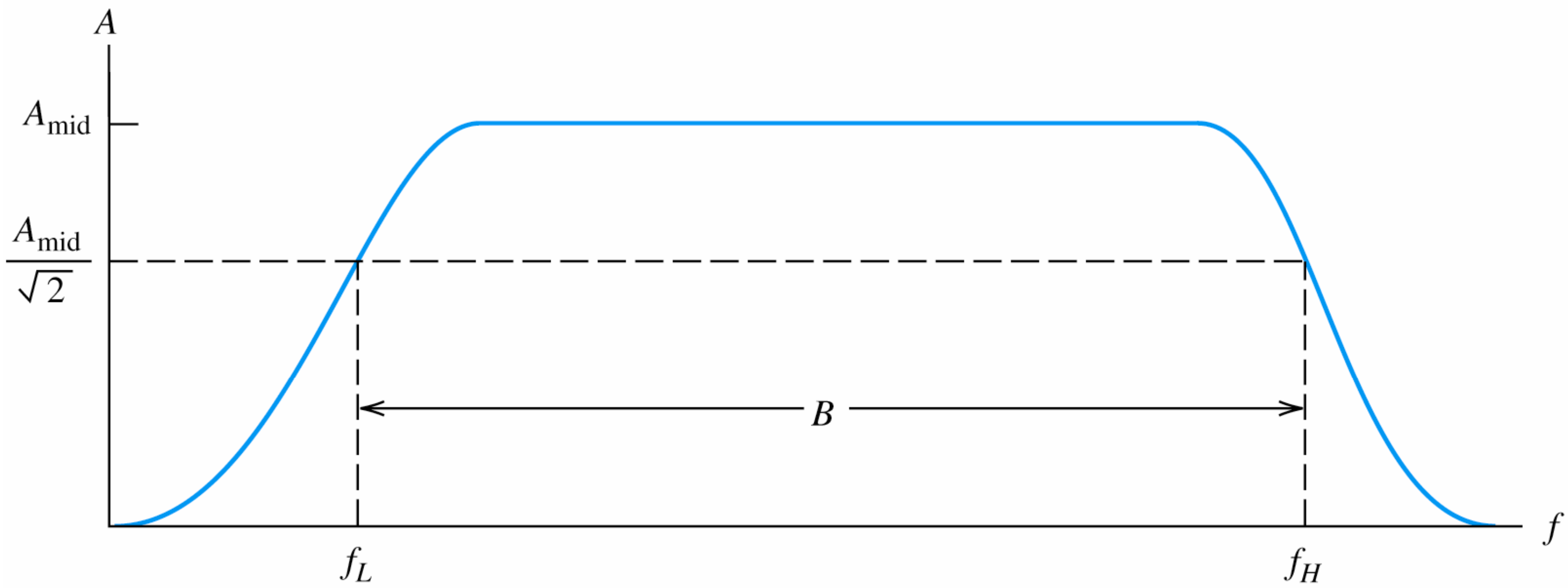


Figure 11.24 Gain versus frequency for a typical amplifier showing the upper and lower half-power (3-dB) frequencies (f_H and f_L) and the half-power bandwidth B.

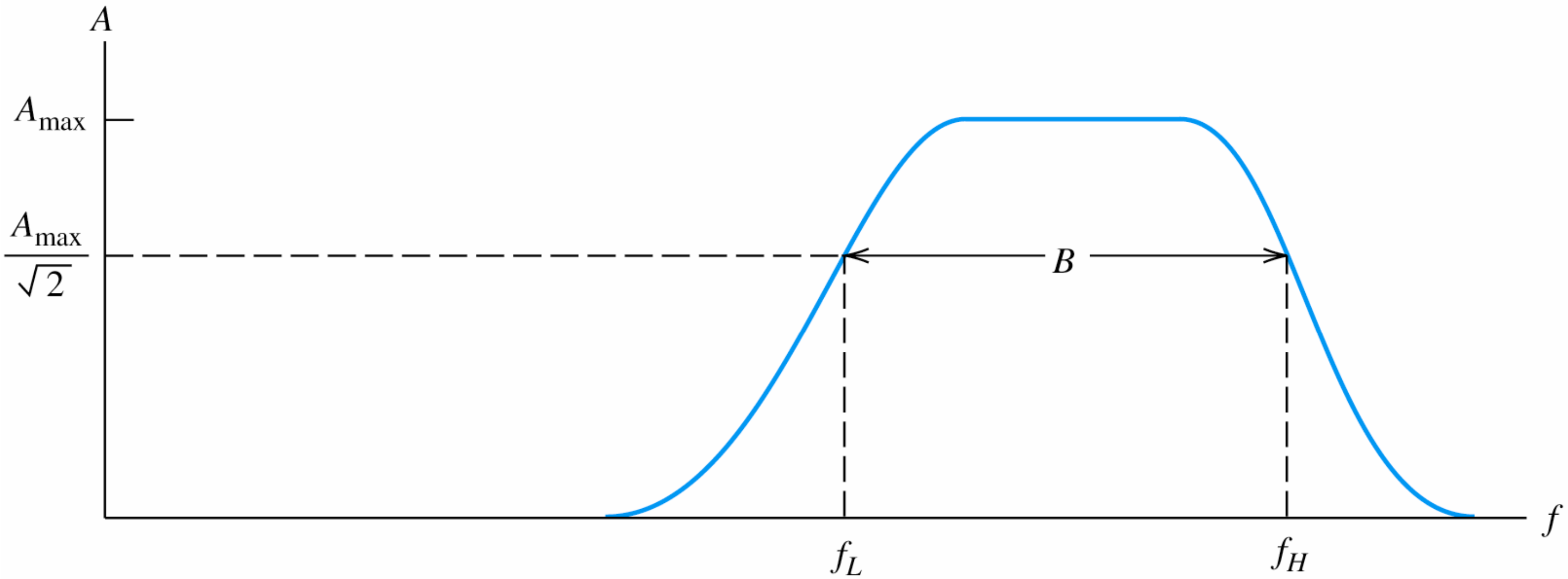
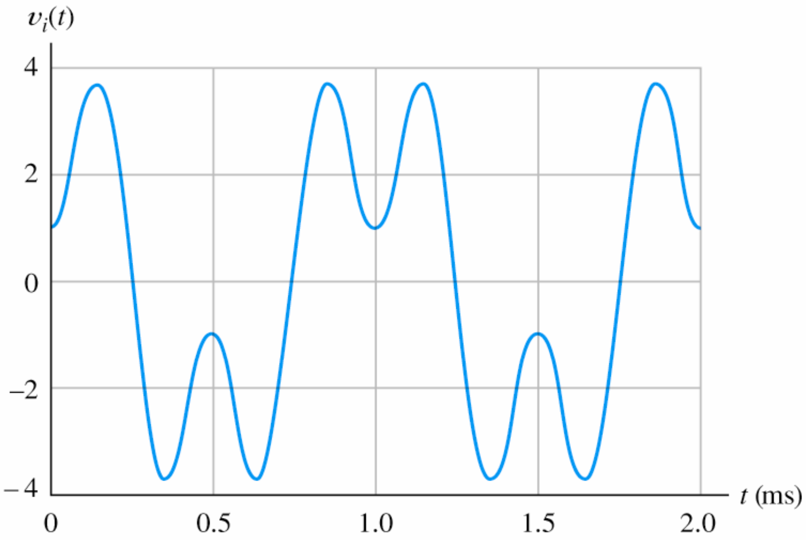


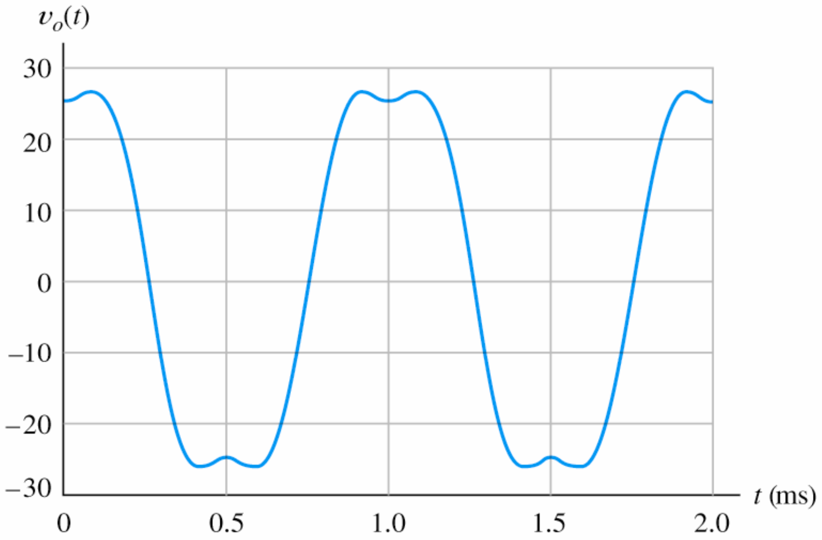
Figure 11.25 Gain magnitude versus frequency for a bandpass amplifier.

LINEAR WAVEFORM DISTORTION

If the gain of an amplifier has a different magnitude for the various frequency components of the input signal, a form of distortion known as **amplitude distortion** occurs.



(a) Input waveform

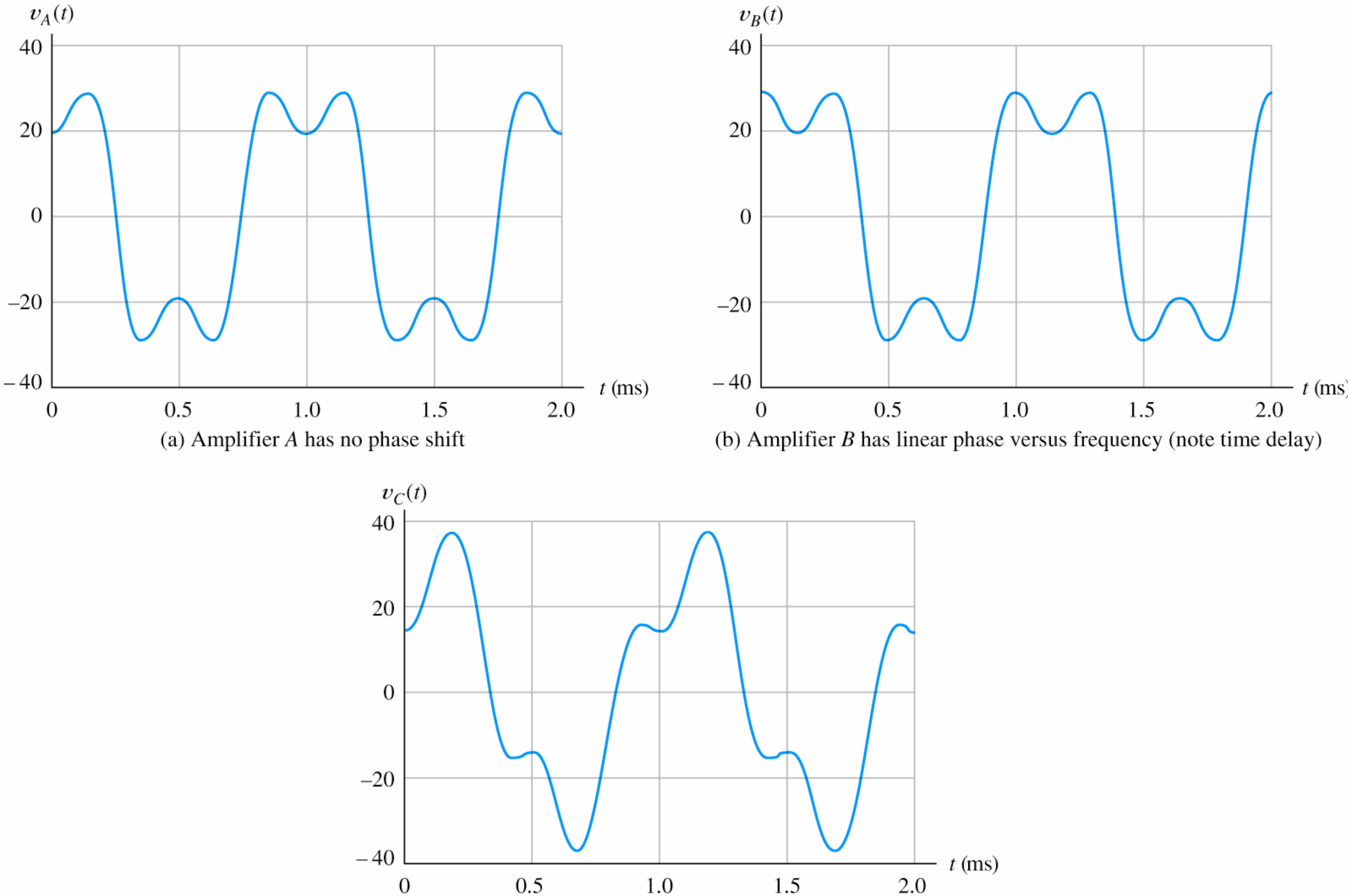


(b) Output distorted because of unequal gain magnitude for various frequency components

Figure 11.26 Linear amplitude distortion. See Example 11.9.

Phase Distortion

If the phase shift of an amplifier is not proportional to frequency, **phase distortion** occurs.



(a) Amplifier *A* has no phase shift

(b) Amplifier *B* has linear phase versus frequency (note time delay)

(c) Amplifier *C* has phase that is not proportional to frequency (note waveform distortion)

Figure 11.27 Effect of amplifier phase response. See Example 11.10. [*Note:* Input waveform has the same shape as $v_A(t)$.]

Requirements for Distortionless Amplification

To avoid linear waveform distortion, an amplifier should have constant gain magnitude and a phase response that is linear versus frequency for the range of frequencies contained in the input signal.

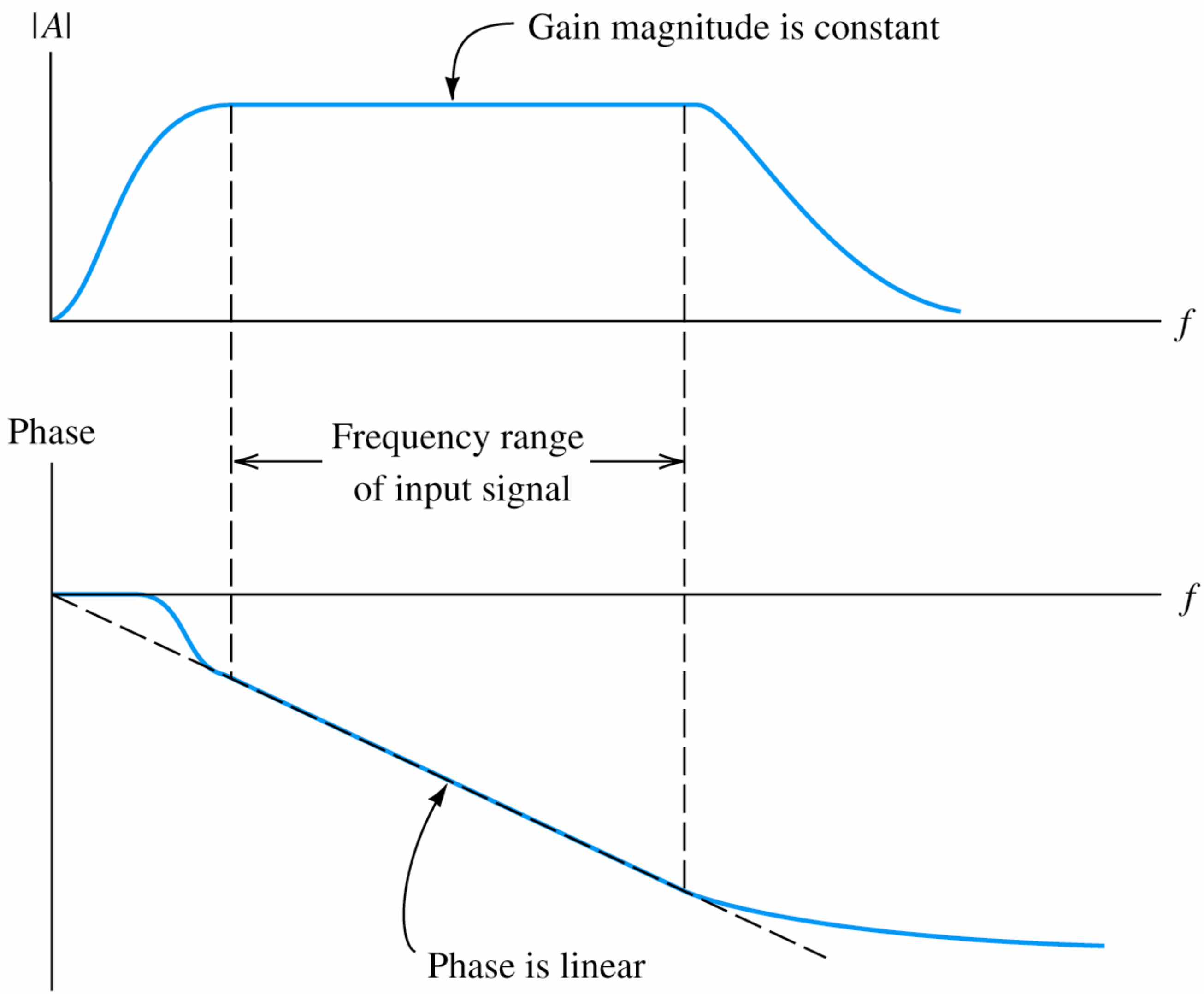


Figure 11.28 Linear distortion does not occur if the gain magnitude is constant and the phase is proportional to frequency over the frequency range of the input signal.

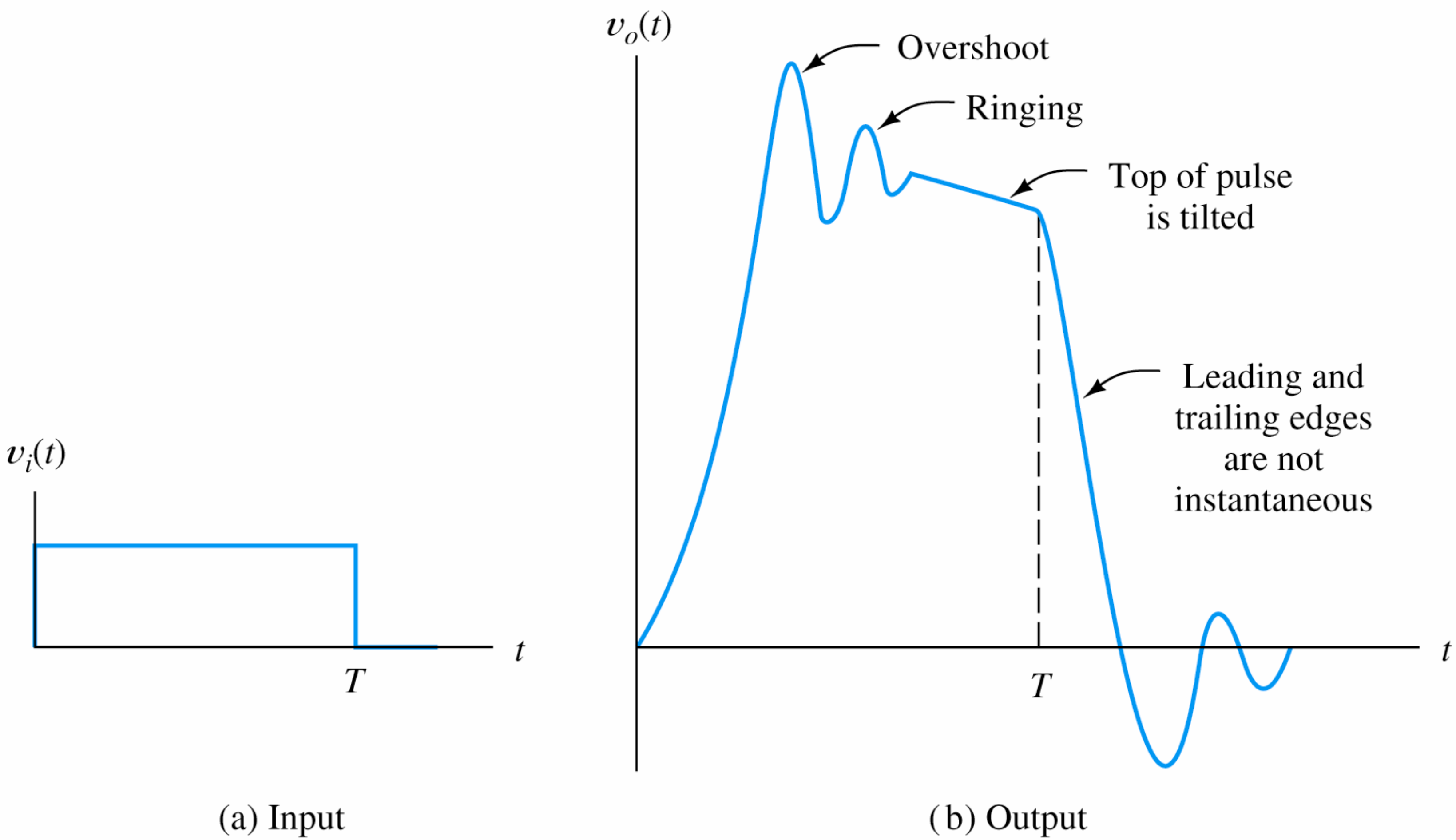
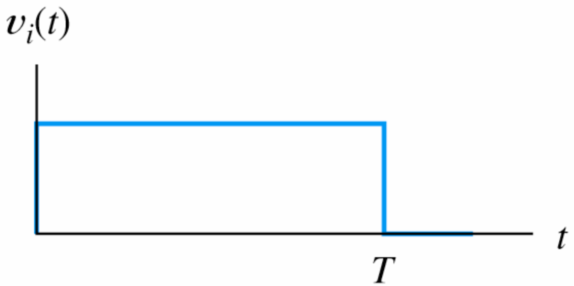
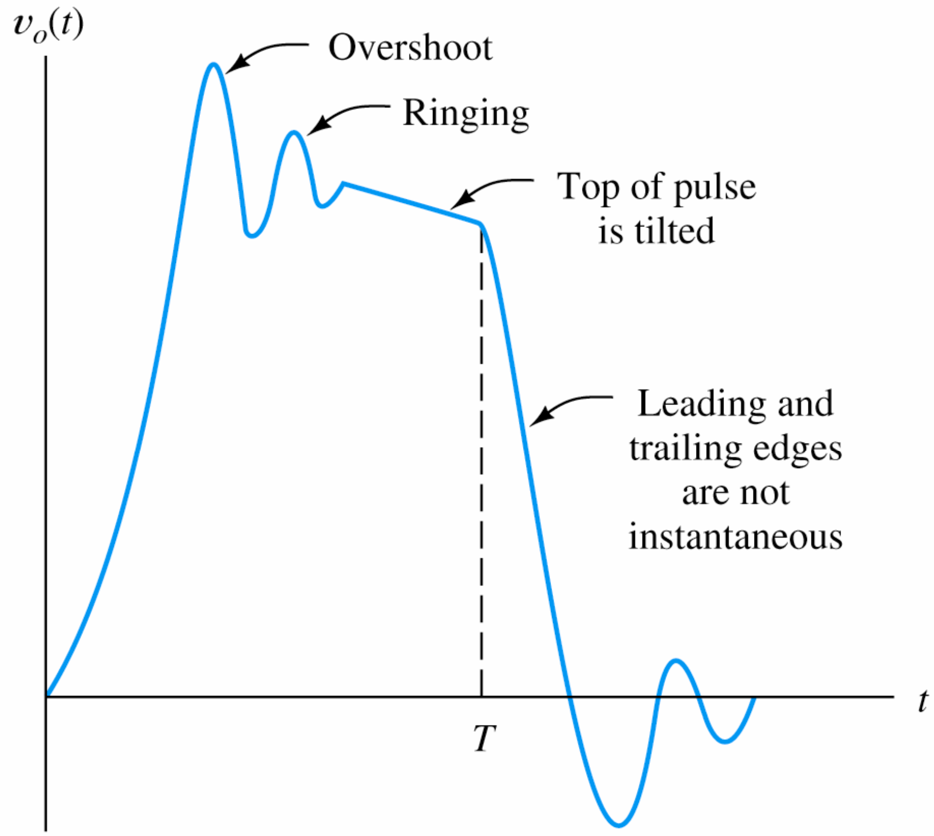


Figure 11.29 Input pulse and the corresponding output of a typical ac-coupled broadband amplifier.

PULSE RESPONSE



(a) Input



(b) Output

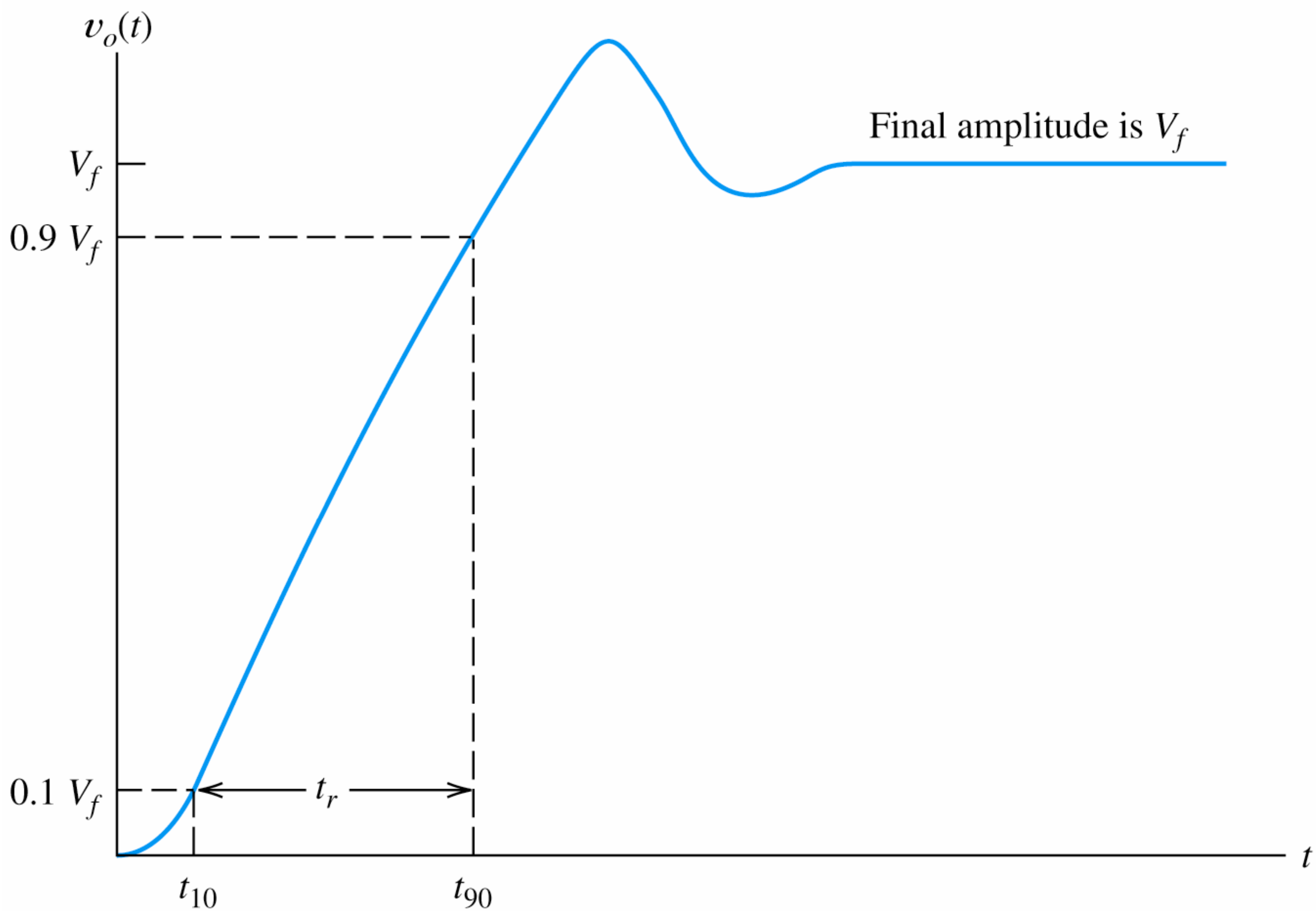
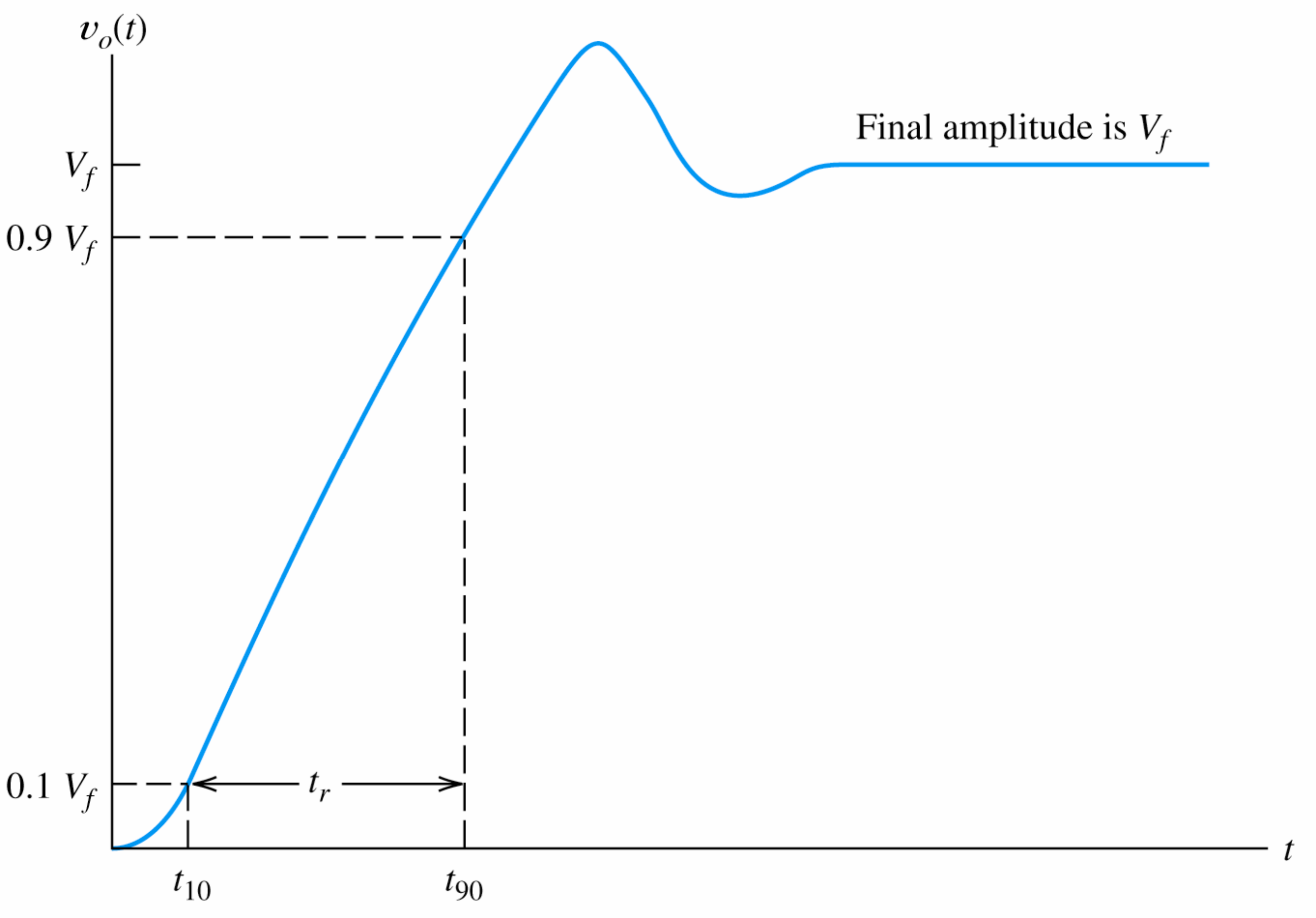


Figure 11.30 Rise time of the output pulse. (*Note:* No tilt is shown. When tilt is present, some judgment is necessary to estimate the amplitude V_f.)

Rise Time



$$t_r \cong \frac{0.35}{B}$$

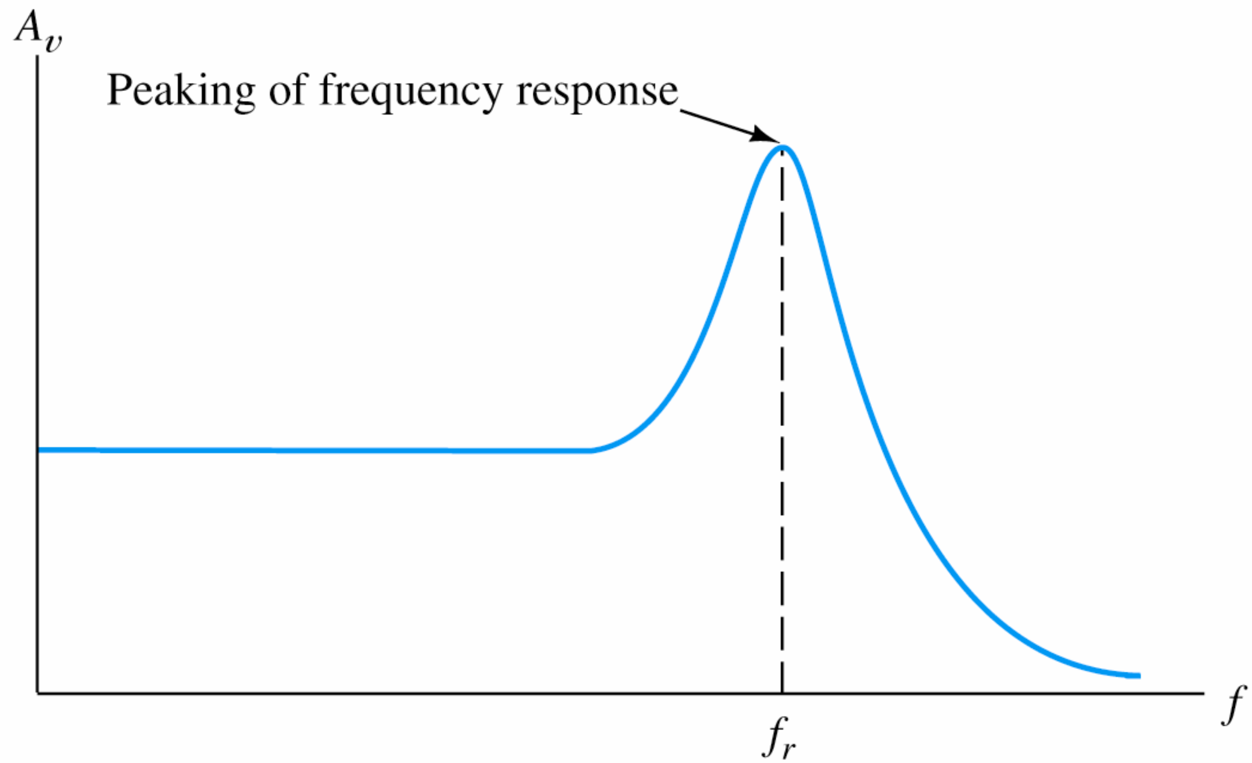


Figure 11.31 Gain versus frequency for an amplifier that displays pronounced ringing in its pulse response. The frequency of the ringing is approximately f_r.

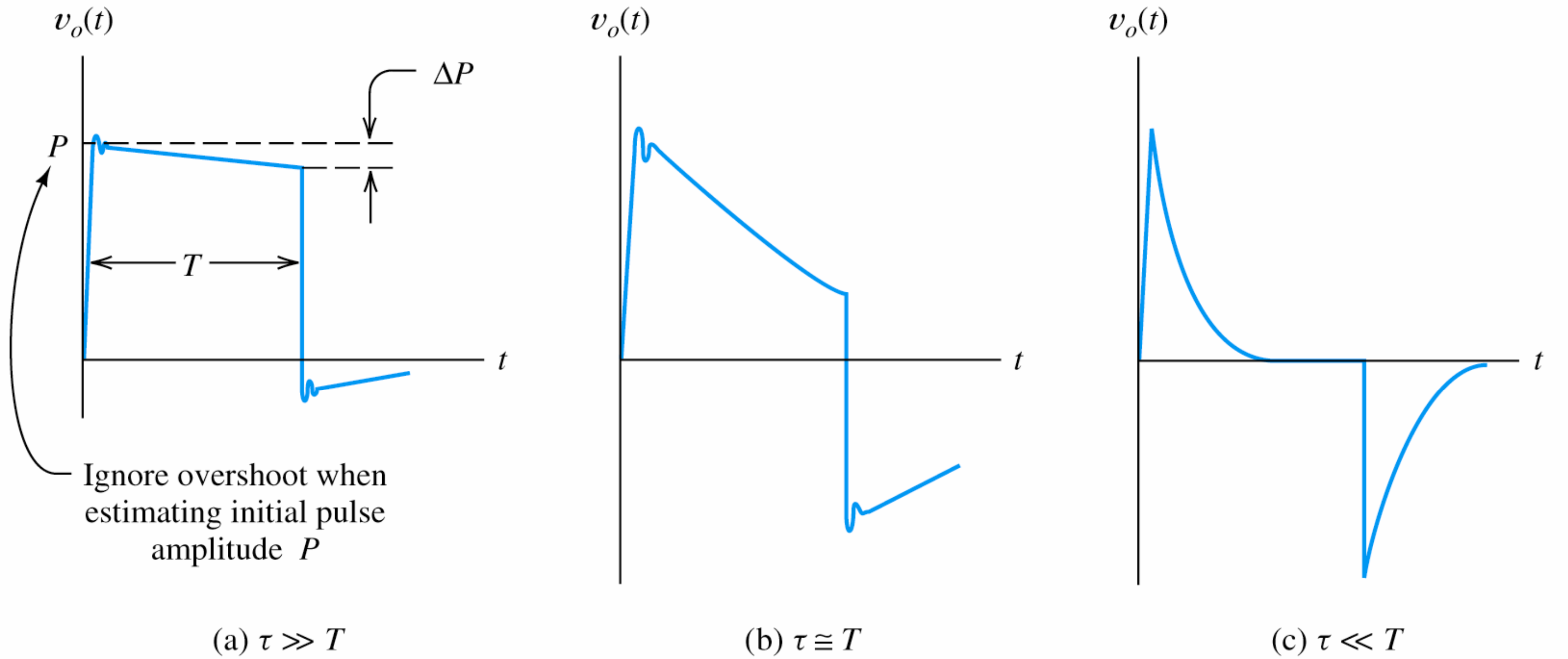
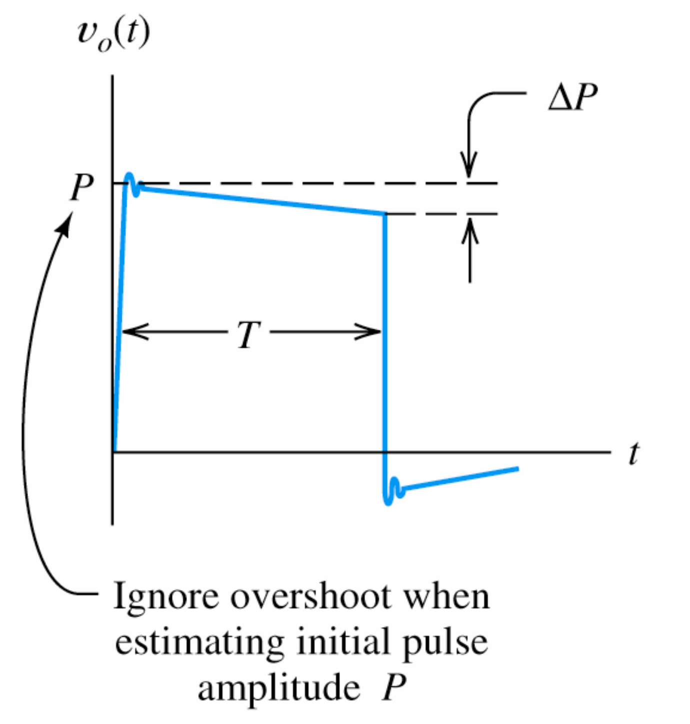


Figure 11.32 Pulse responses of ac-coupled amplifiers. T is the input pulse duration, and τ represents the shortest time constant of the coupling circuits.

Tilt



$$\text{percentage tilt} = \frac{\Delta P}{P} \times 100\%$$

For small amounts of tilt,

$$\text{percentage tilt} \cong 200\pi f_L T$$

TRANSFER CHARACTERISTIC AND NONLINEAR DISTORTION

The transfer characteristic is a plot of instantaneous output amplitude versus instantaneous input amplitude.

Curvature of the transfer characteristic results in nonlinear distortion.

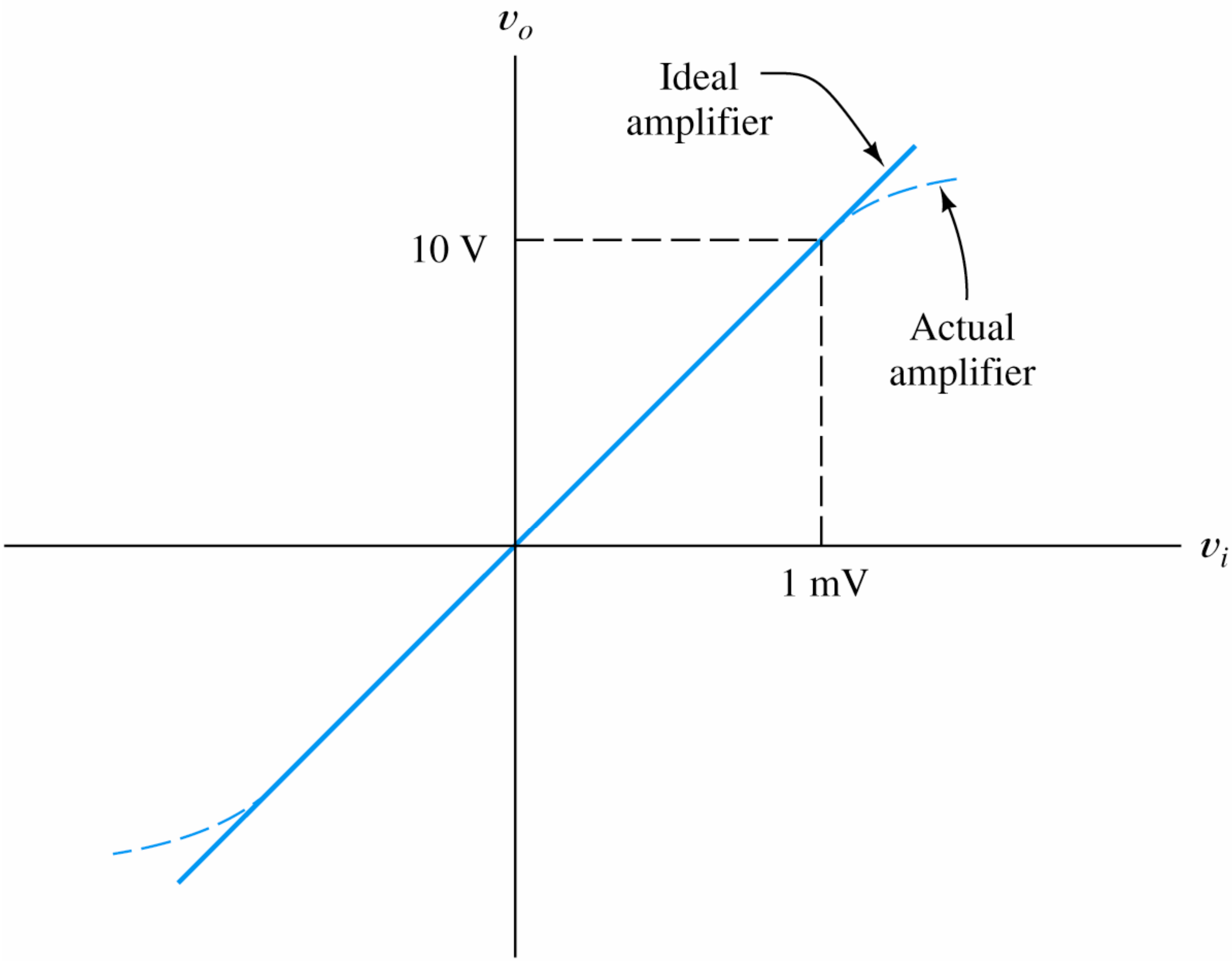


Figure 11.33 Transfer characteristics. $A_v = 10,000$.

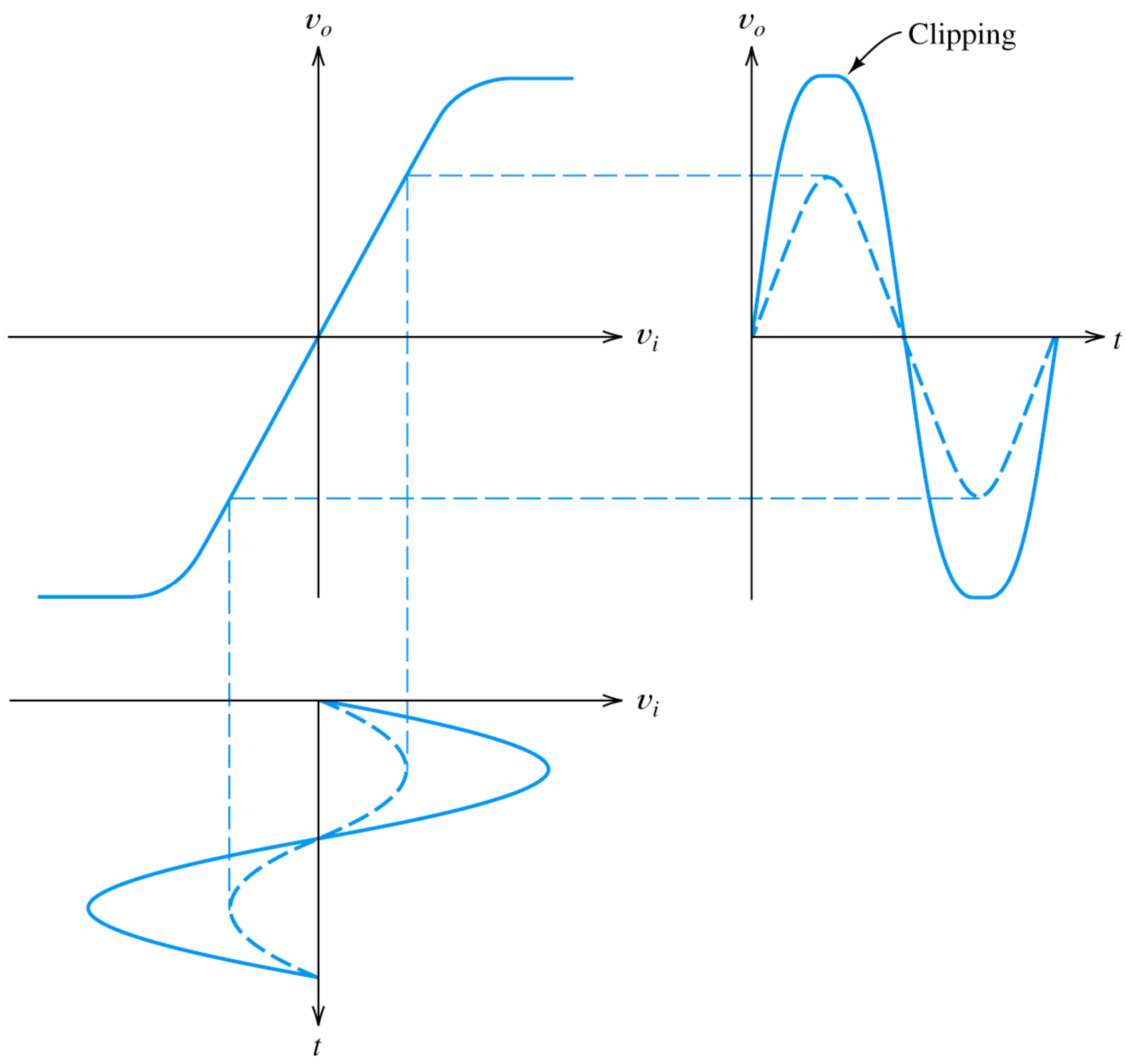


Figure 11.34 Illustration of input signal, amplifier transfer characteristic, and output signal, showing clipping for large signal amplitude.

Harmonic Distortion

For a sinewave input, nonlinear distortion produces output components having frequencies that are integer multiples of the input frequency.

$$v_i(t) = V_a \cos(\omega_a t)$$

$$v_o(t) = V_0 + V_1 \cos(\omega_a t) + V_2 \cos(2\omega_a t) + V_3 \cos(3\omega_a t) + \cdots$$

$$D_2 = \frac{V_2}{V_1} \qquad D_3 = \frac{V_3}{V_1} \qquad D_4 = \frac{V_4}{V_1}$$

Total Harmonic Distortion (THD)

Total harmonic distortion is a specification that indicates the degree of nonlinear distortion produced by an amplifier.

$$D = \sqrt{D_2^2 + D_3^2 + D_4^2 + D_5^2 + \cdots}$$

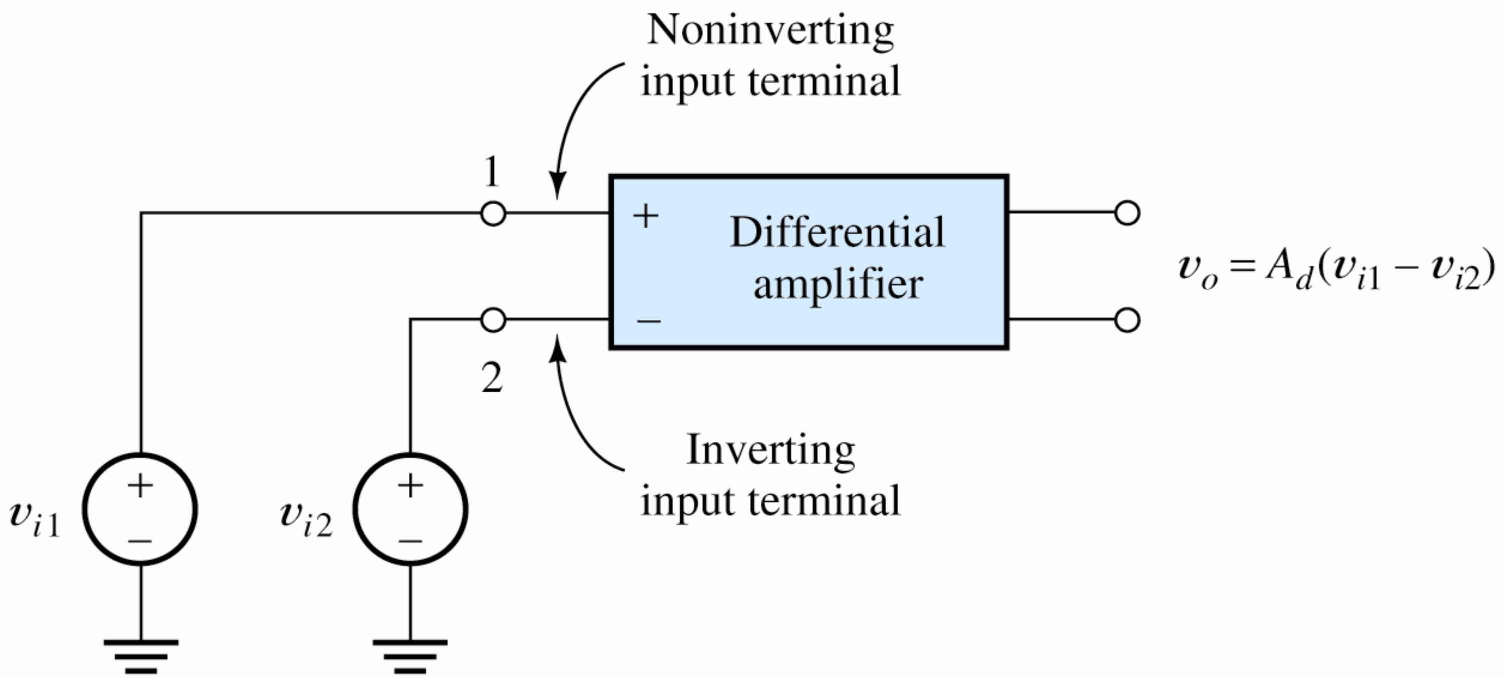


Figure 11.35 Differential amplifier with input sources.

DIFFERENTIAL AMPLIFIERS

A differential amplifier has two input terminals: an inverting input and a noninverting input.

Ideally, a differential amplifier produces an output that is proportional to the difference between two input signals.

$$v_{id} = v_{i1} - v_{i2} \qquad\qquad v_o = A_d v_{id}$$

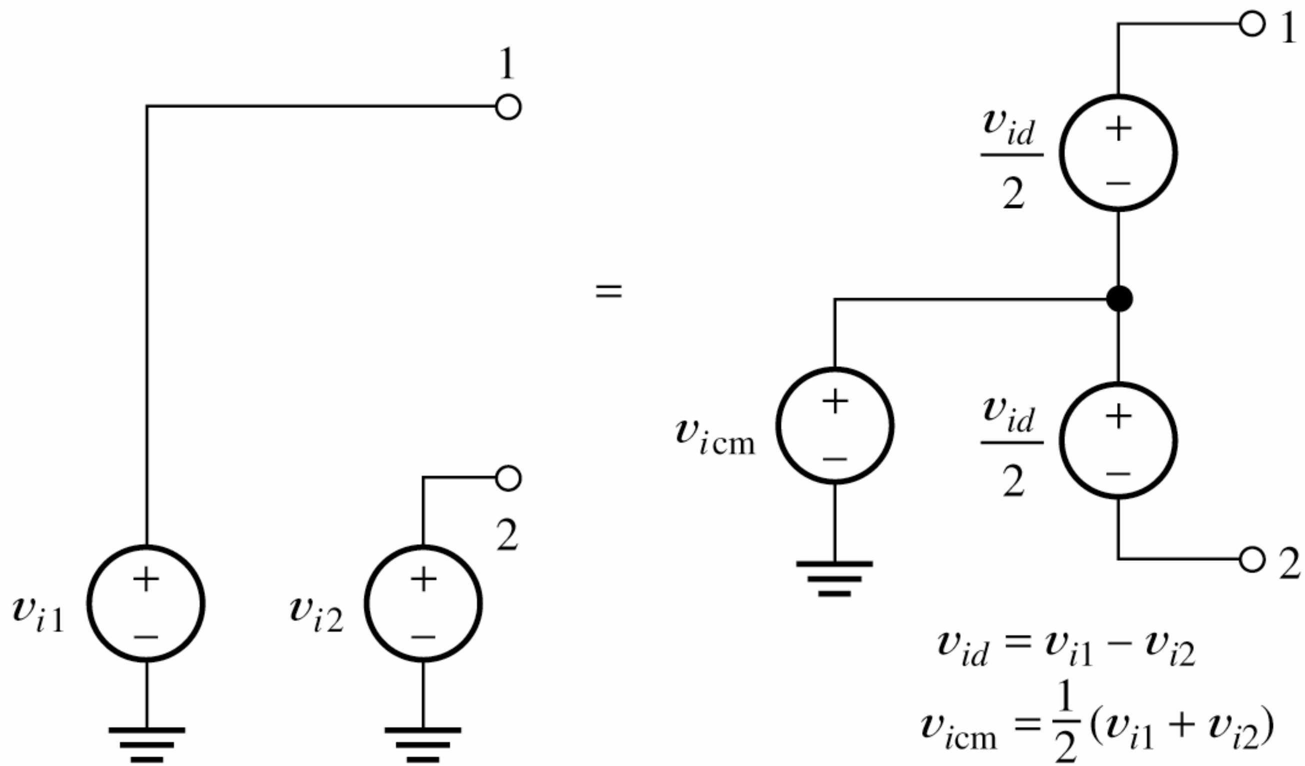
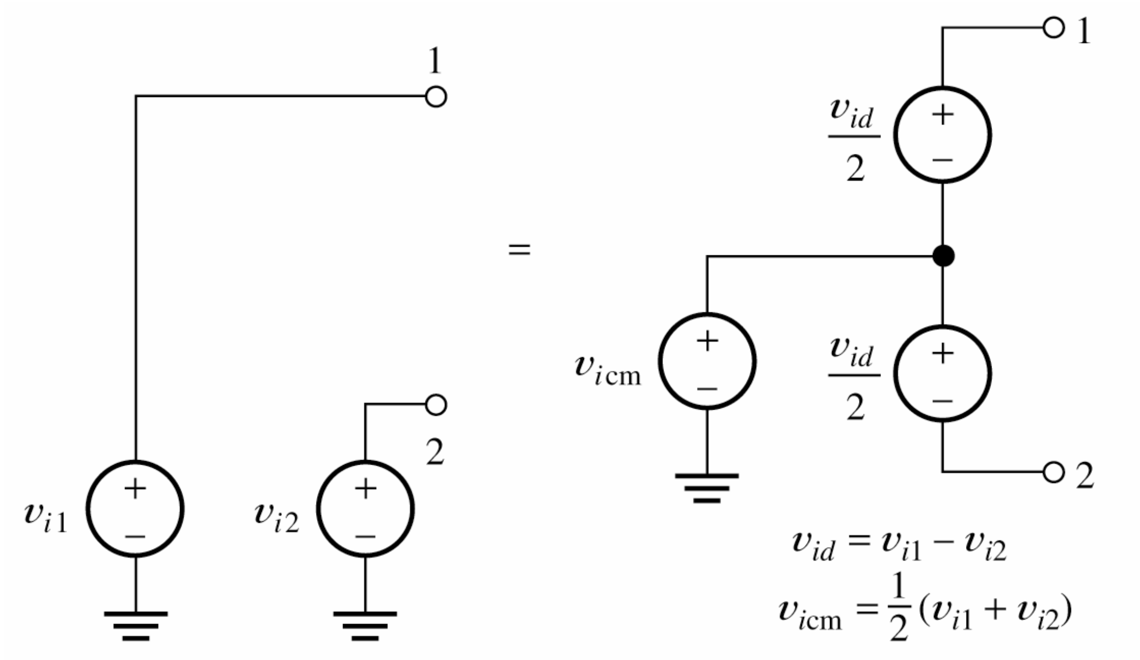


Figure 11.36 The input sources v_{i1} and v_{i2} can be replaced by the equivalent sources v_{icm} and v_{id}.

Common-mode Signal



$$v_{icm} = \frac{1}{2}\left(v_{i1} + v_{i2}\right)$$

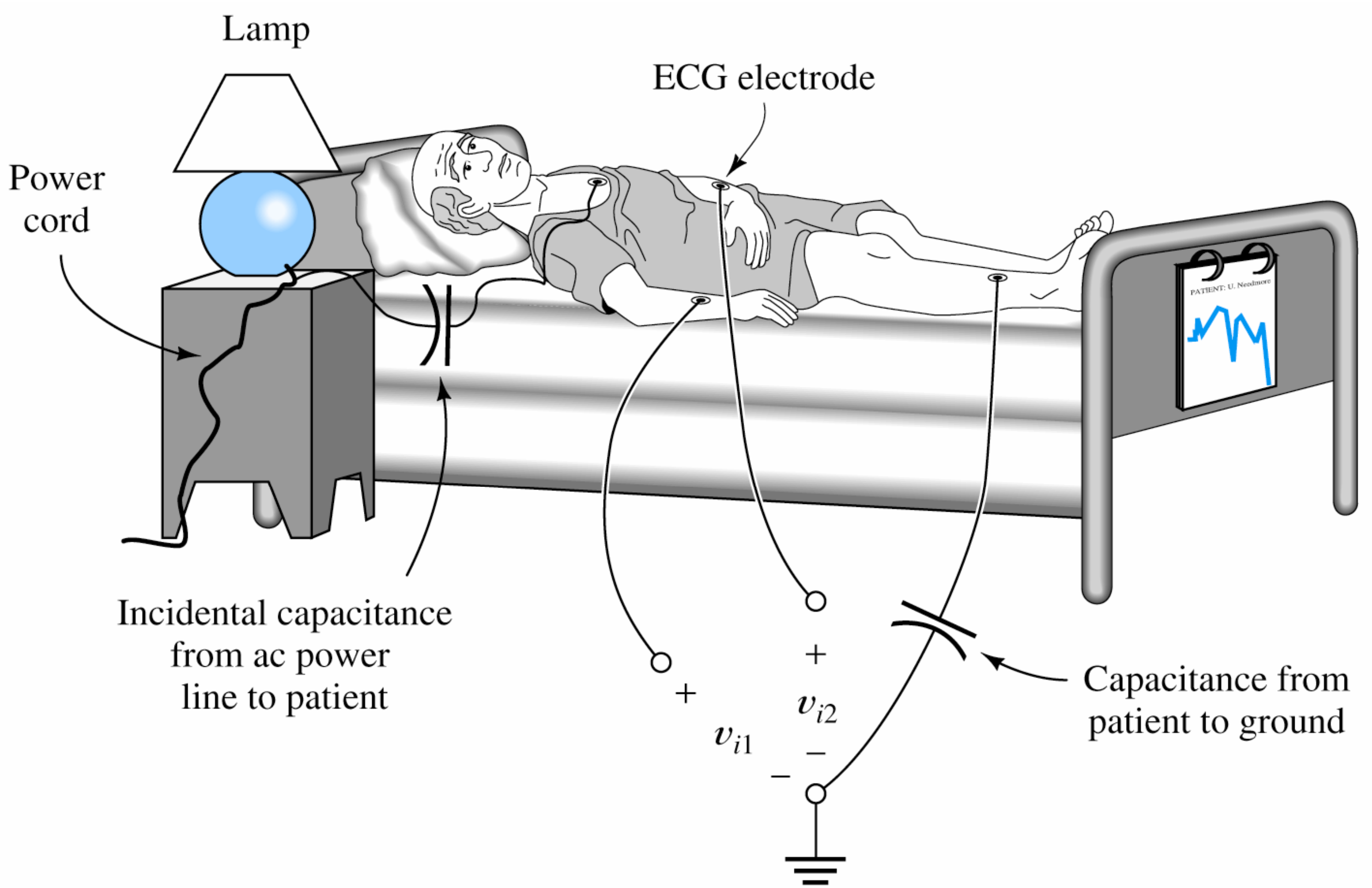


Figure 11.37 Electrocardiographs encounter large 60-Hz common-mode signals.

Common-Mode Rejection Ratio

$$v_o = A_d v_{id} + A_{\mathrm{cm}} v_{i\mathrm{cm}}$$

$$\mathrm{CMRR} = 20 \log \frac{|A_d|}{|A_{\mathrm{cm}}|}$$

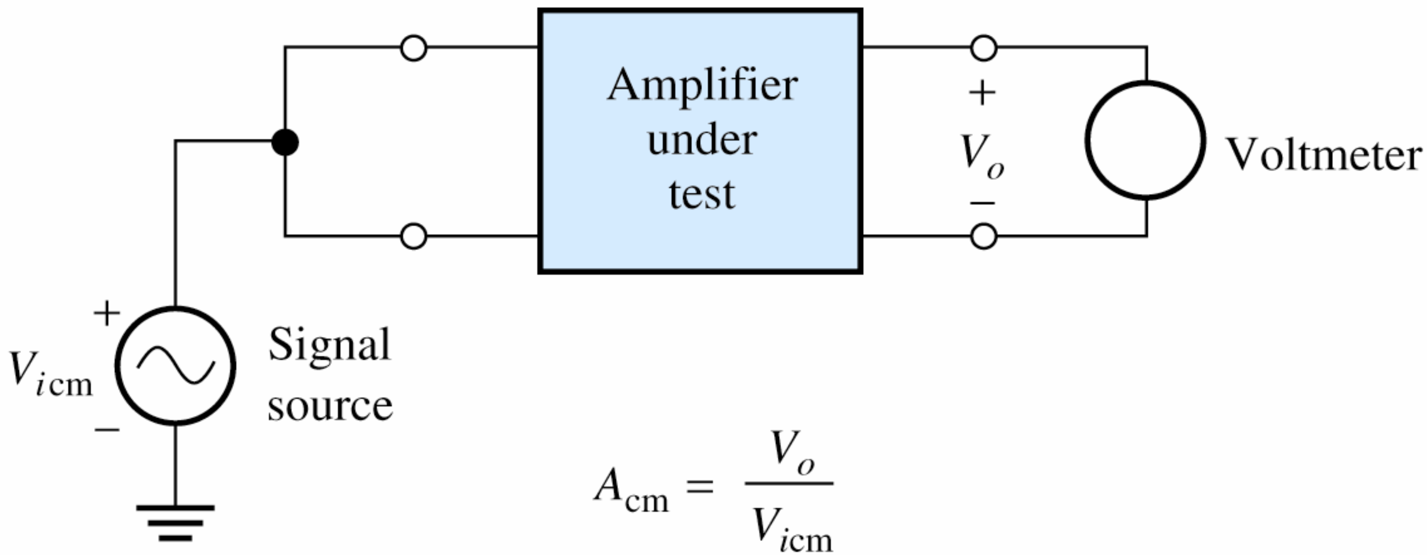
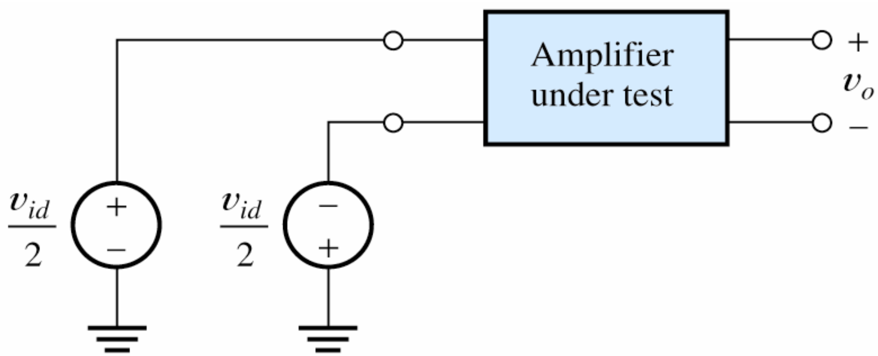
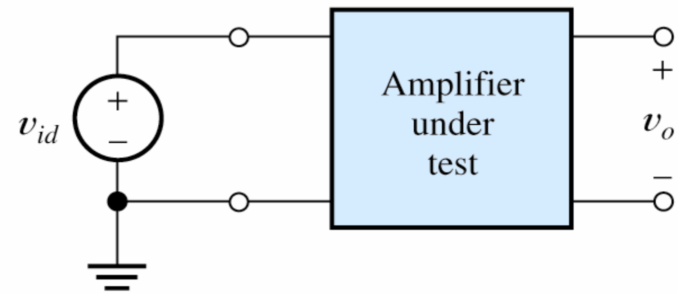


Figure 11.38 Setup for measurement of common-mode gain.



(a) Theoretically required sources to measure differential gain



(b) Practical equivalent if $A_d >> A_{cm}$

Figure 11.39 Setup for measuring differential gain. $A_d = v_o/v_{id}$.

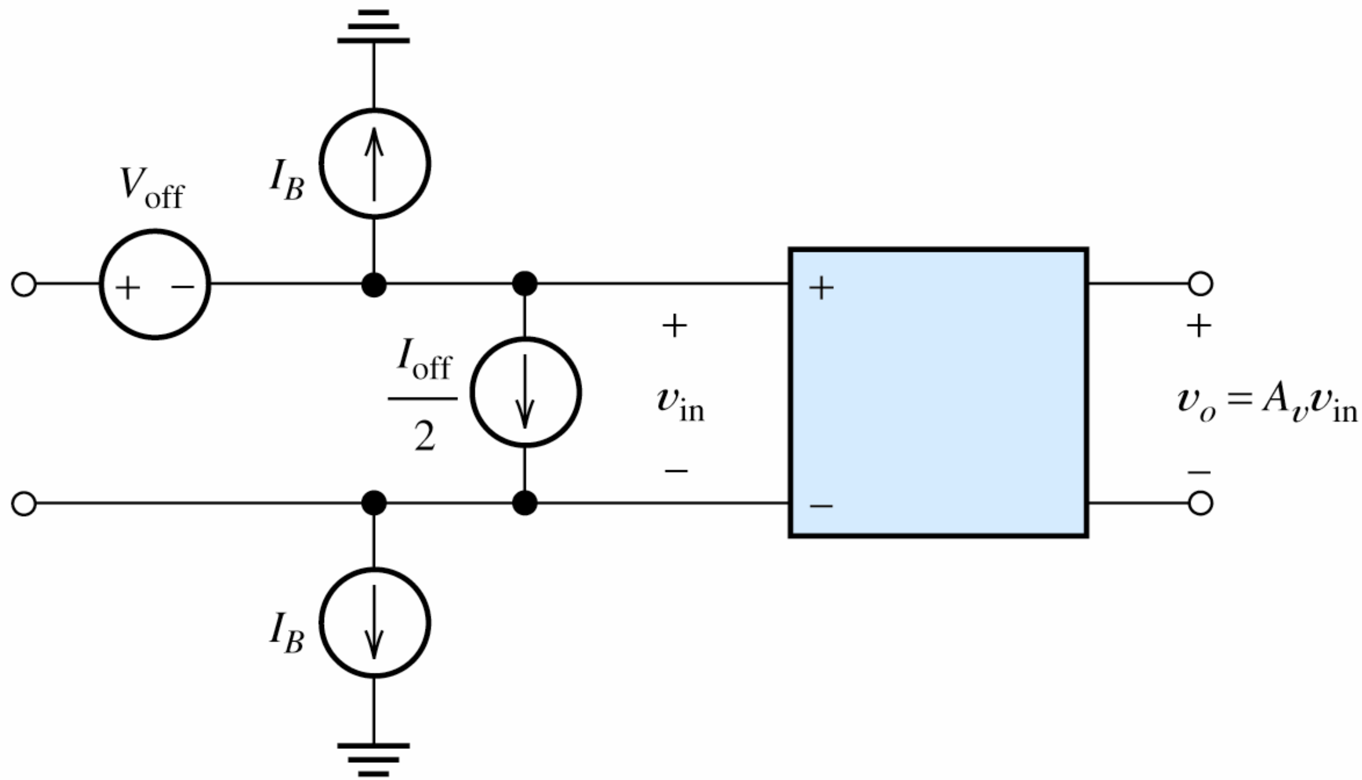
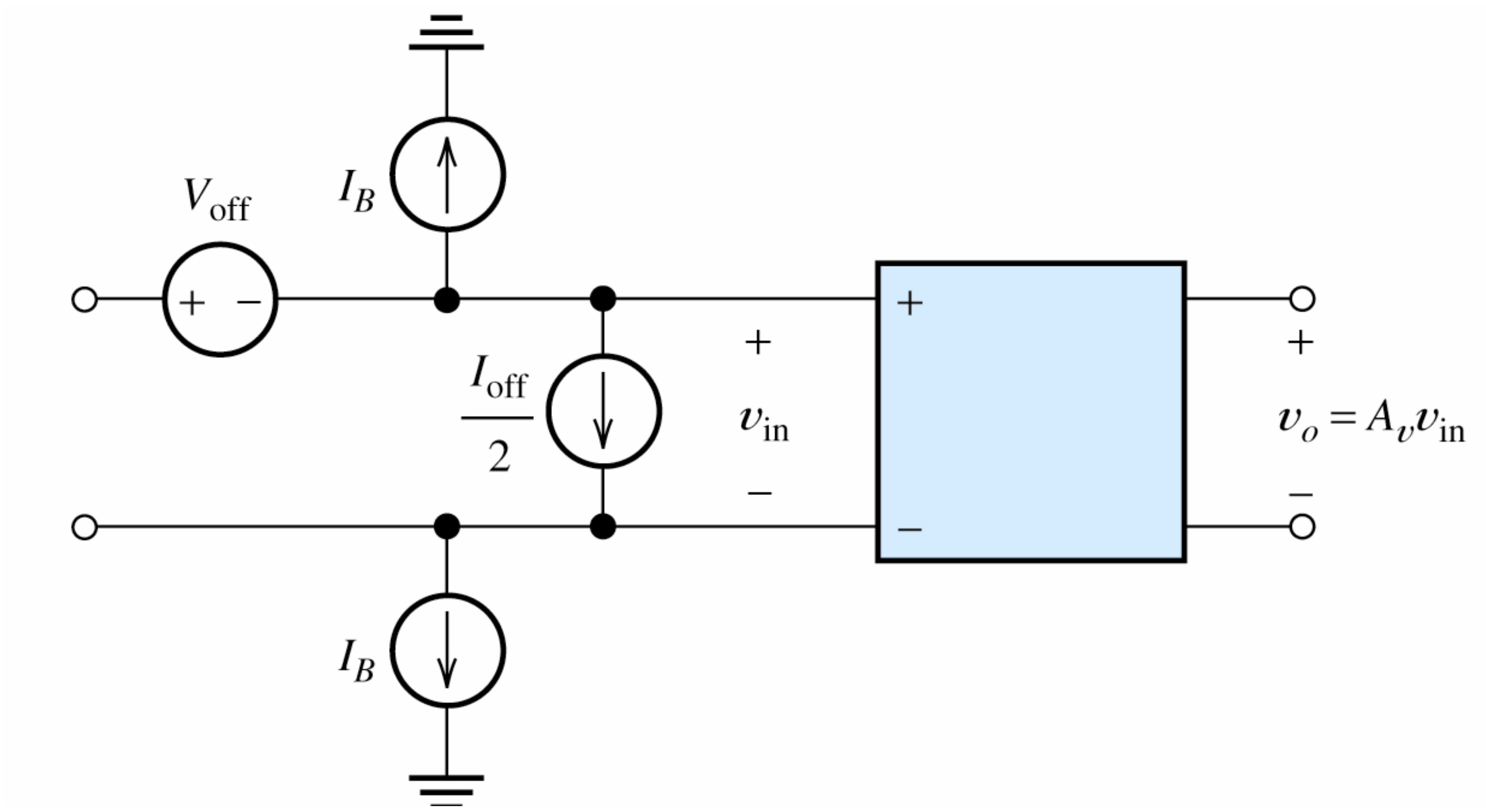


Figure 11.40 Differential amplifier, including dc sources to account for the dc output that exists even when the input signals are zero.

OFFSET VOLTAGE, BIAS CURRENT, AND OFFSET CURRENT



Real differential amplifiers suffer from imperfections that can be modeled by several dc sources: two bias-current sources, an offset current source, and an offset voltage source. The effect of these sources is to add a (usually undesirable) dc term to the ideal output.

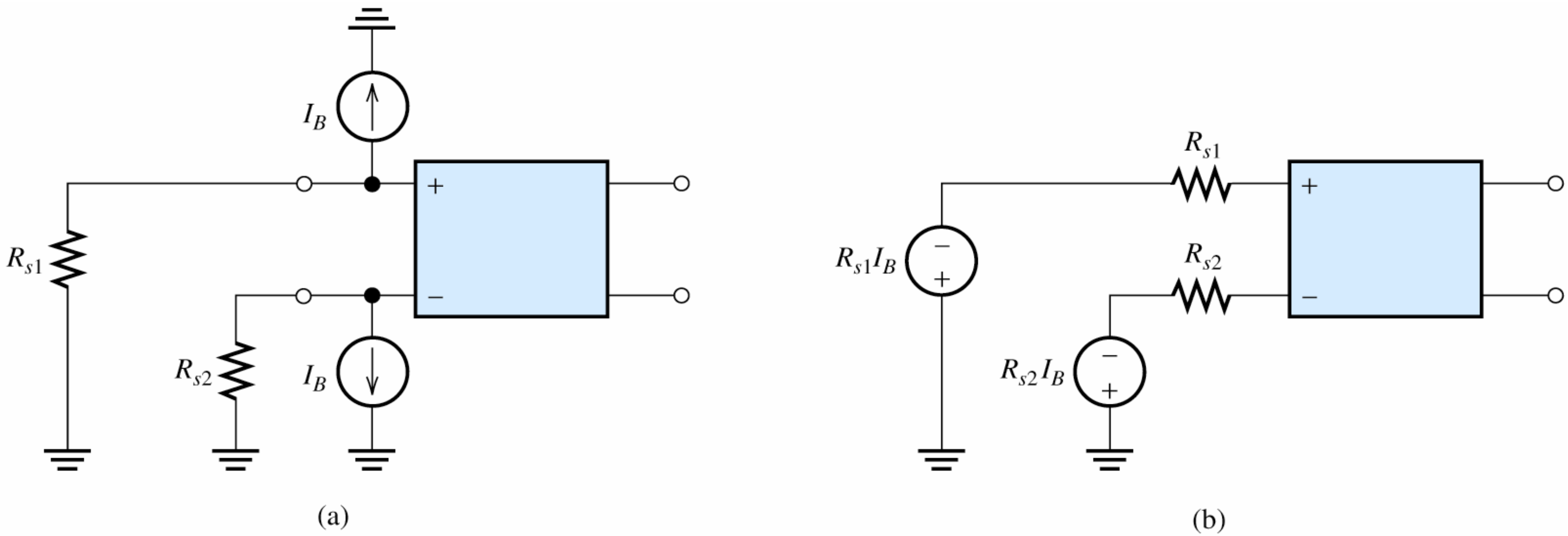


Figure 11.41 The effects of the bias-current sources cancel if $R_{s1} = R_{s2}$.

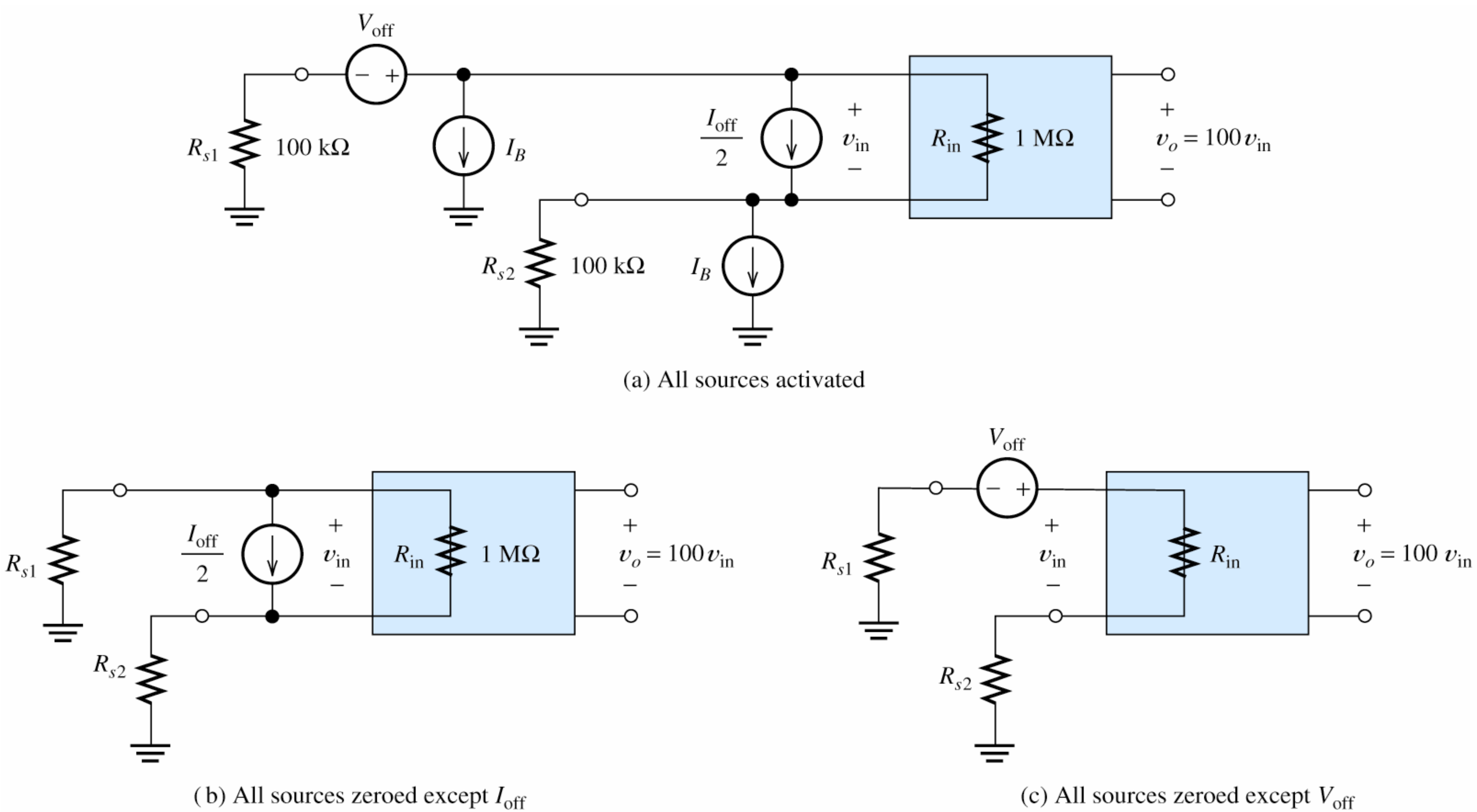


Figure 11.42 Amplifier of Example 11.13.

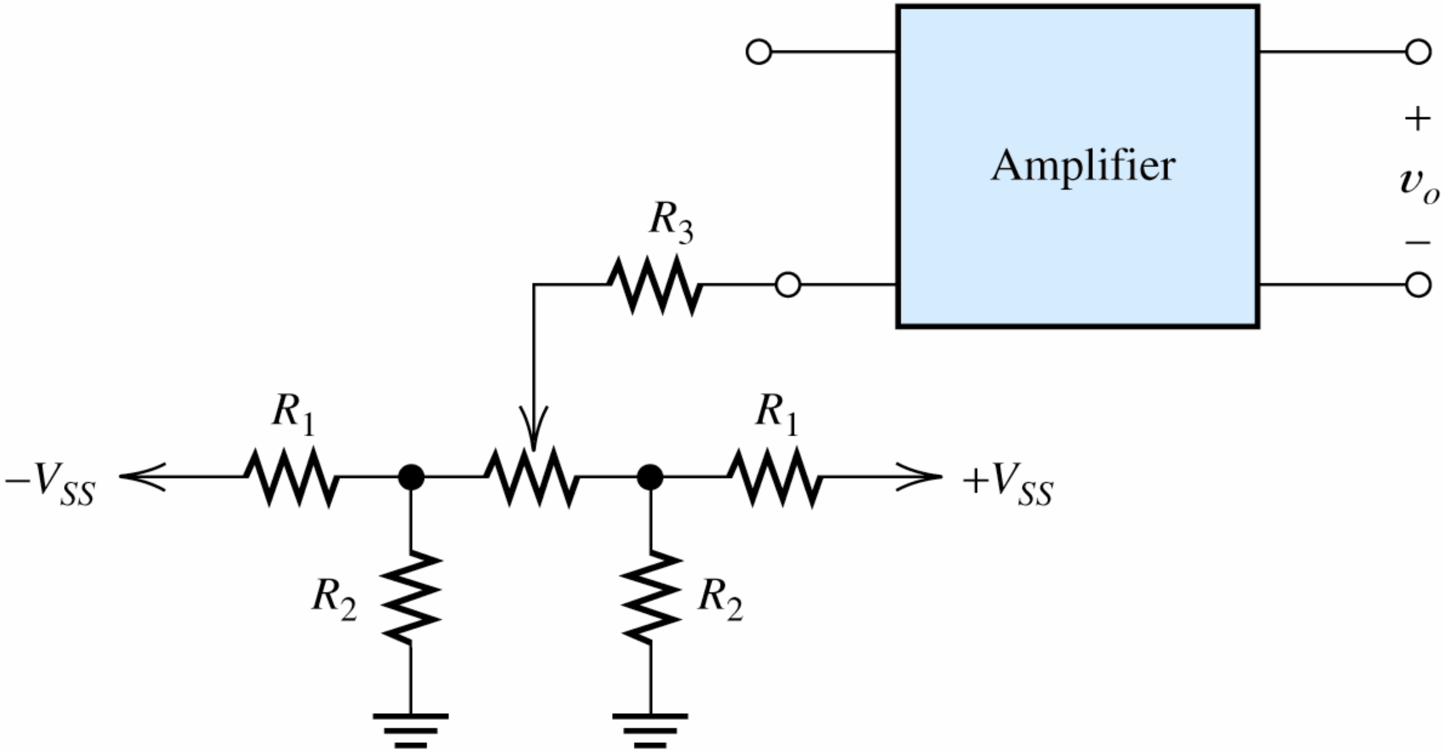


Figure 11.43 Network that can be adjusted to cancel the effects of offset and bias sources.

Problem Set

- 4, 13, 17, 22, 25, 34, 40, 47, 55, 58, 67, 68, 74, 78, 82.