Chapter 14
Operational Amplifiers

1. List the characteristics of ideal op amps.
2. Identify negative feedback in op-amp circuits.
3. Analyze ideal op-amp circuits that have negat
   feedback using the summing-point constraint.

4. Select op-amp circuit configurations suitable for various applications.

5. Design useful circuits using op amps.

6. Identify practical op-amp limitations and recognize potential inaccuracies in instrumentation applications.

7. Work with instrumentation amplifiers.

8. Apply integrators, differentiators, and active filters.

IDEAL OPERATIONAL AMPLIFIERS

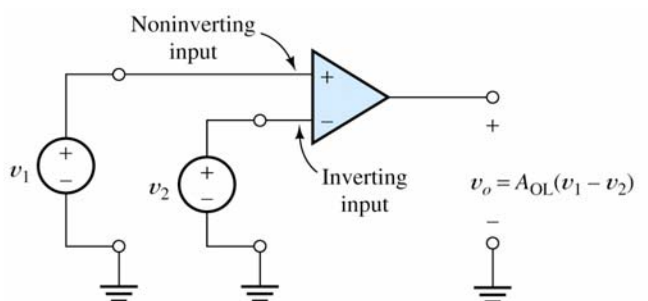

Figure 14.1 Circuit symbol for the op amp.

The input signal of a differential amplifier consists of a differential component and a common-mode component.

$$v_{id} = v_1 - v_2$$

$$v_{icm} = \frac{1}{2}\left(v_1 + v_2\right)$$

Characteristics of Ideal Op Amps

- Infinite gain for the differential input signal
- Zero gain for the common-mode input signal
- Infinite input impedances
- Zero output impedance
- Infinite bandwidth

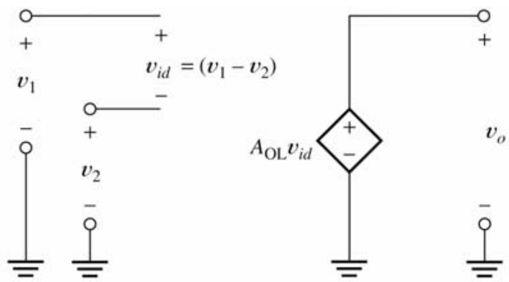

Figure 14.2 Equivalent circuit for the ideal op amp. The open-loop gain A_{OL} is very large (approaching infinity).

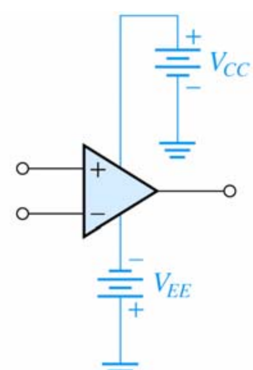

Figure 14.3 Op-amp symbol showing the dc power supplies, V_{CC} and V_{EE}.

SUMMING-POINT CONSTRAINT

Operational amplifiers are almost always used with negative feedback, in which part of the output signal is returned to the input in opposition to the source signal.

In a negative feedback system, the ideal op-amp output voltage attains the value needed to force the differential input voltage and input current to zero. We call this fact the **summing-point constraint.**

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Ideal op-amp circuits are analyzed by the following steps:

1. Verify that *negative* feedback is present.

2. Assume that the differential input voltage and the input current of the op amp are forced to zero. (This is the summing-point constraint.)

3. Apply standard circuit-analysis principles, such as Kirchhoff's laws and Ohm's law, to solve for the quantities of interest.

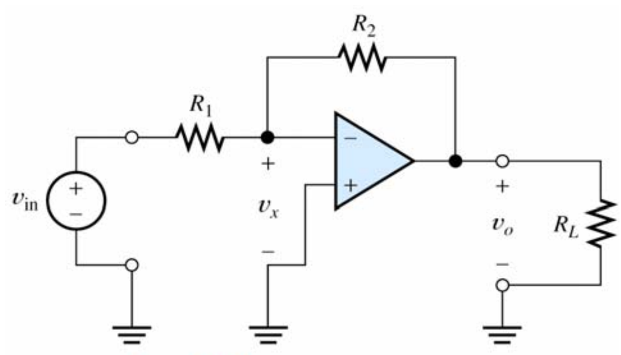

Figure 14.4 The inverting amplifier.

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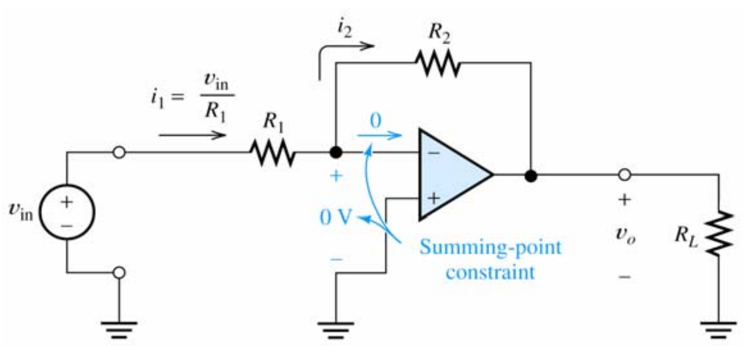

Figure 14.5 We make use of the summing-point constraint in the analysis of the inverting amplifier.

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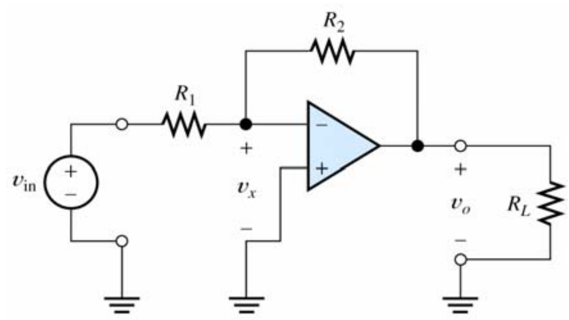
INVERTING AMPLIFIERS



$$A_v = \frac{v_o}{v_{\text{in}}} = -\frac{R_2}{R_1}$$

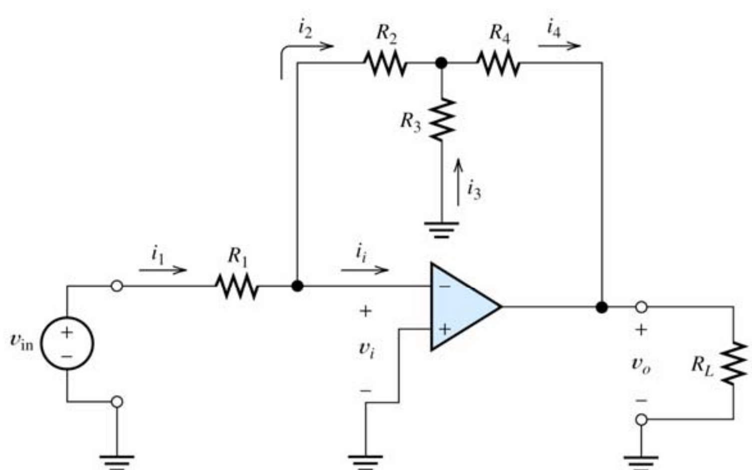


Figure 14.6 An inverting amplifier that achieves high gain magnitude with a smaller range of resistance values than required for the basic inverter. See Example 14.1.

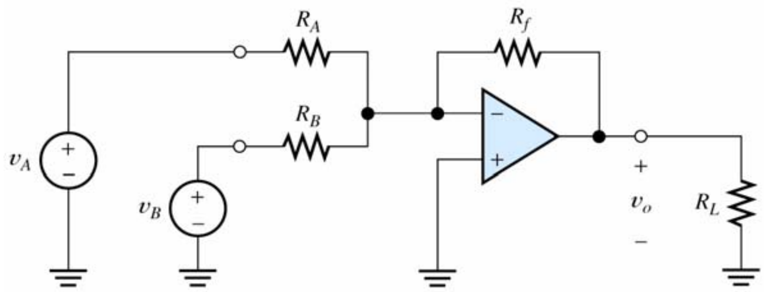


Figure 14.7 Summing amplifier. See Exercise 14.1.

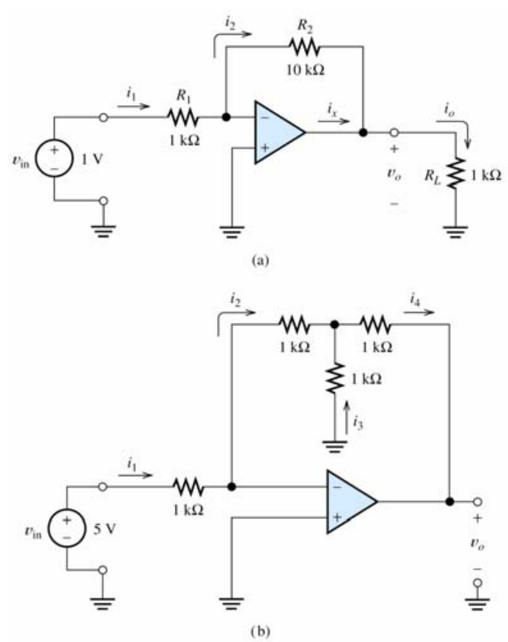


Figure 14.8 Circuits for Exercise 14.2.

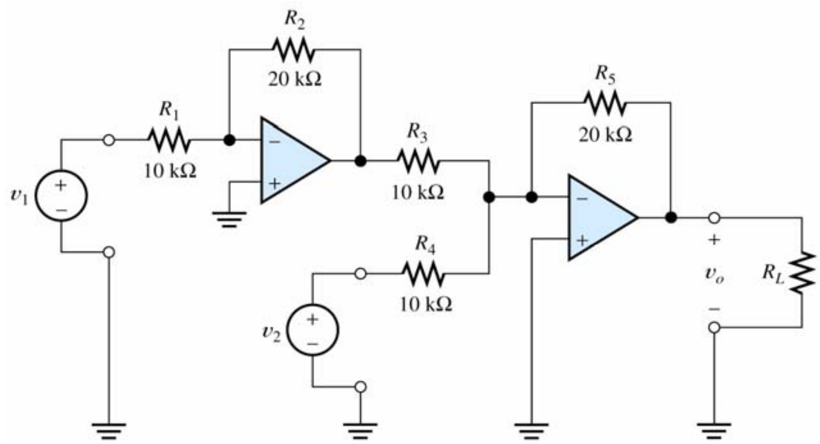


Figure 14.9 Circuit for Exercise 14.3.

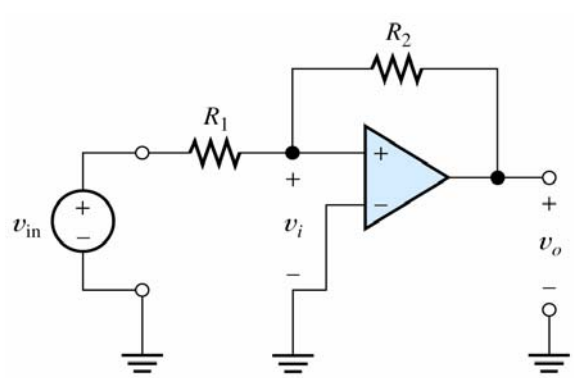
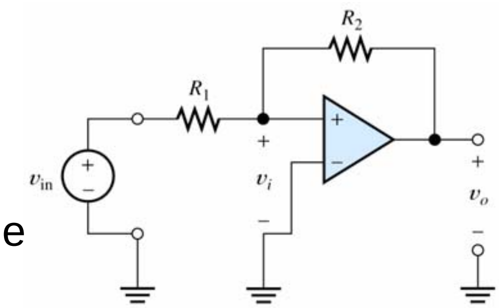


Figure 14.10 Circuit with positive feedback.

Positive Feedback

With positive feedback, the op amp's input and output voltages increase in magnitude until the output voltage reaches one of its extremes.



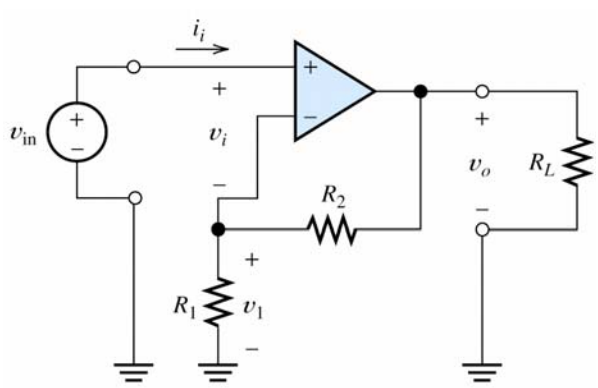
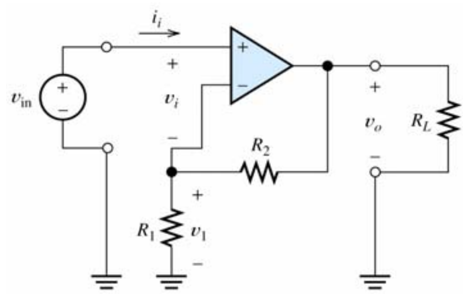


Figure 14.11 Noninverting amplifier.

NONINVERTING AMPLIFIERS

Under the ideal-op-amp assumption, the non-inverting amplifier is an ideal voltage amplifier having infinite input resistance and zero output resistance.



$$A_v = \frac{v_o}{v_{in}} = 1 + \frac{R_2}{R_1}$$

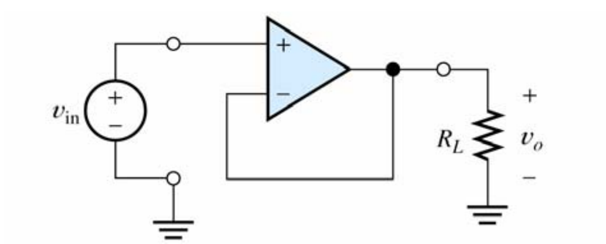
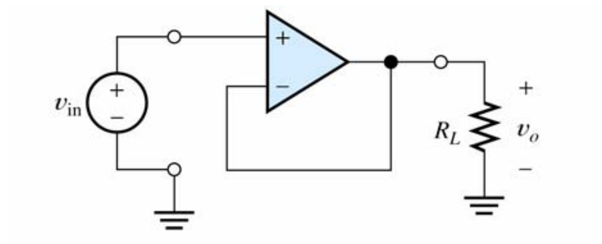


Figure 14.12 The voltage follower which has $A_v = 1$.

Voltage Follower



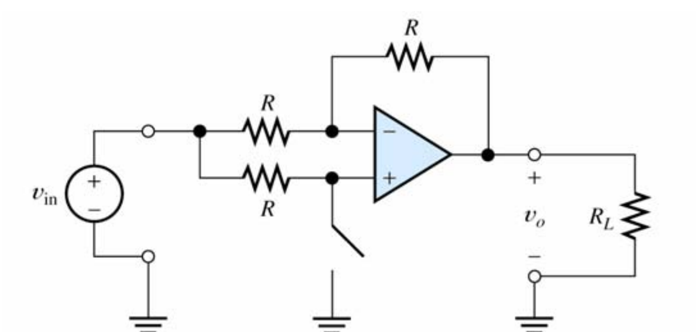


Figure 14.13 Inverting or noninverting amplifier. See Exercise 14.4.

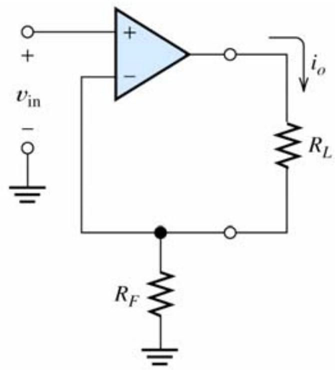


Figure 14.14 Voltage-to-current converter (also known as a transconductance amplifier). See Exercise 14.5.

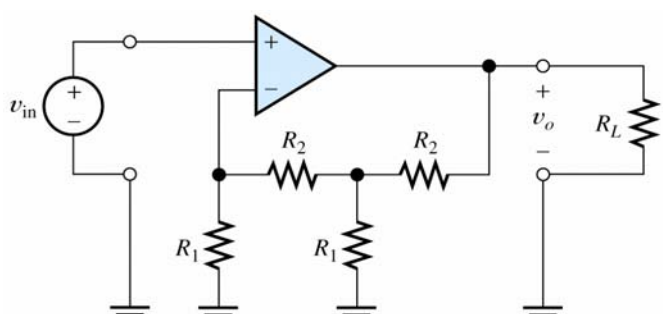


Figure 14.15 Circuit for Exercise 14.6.

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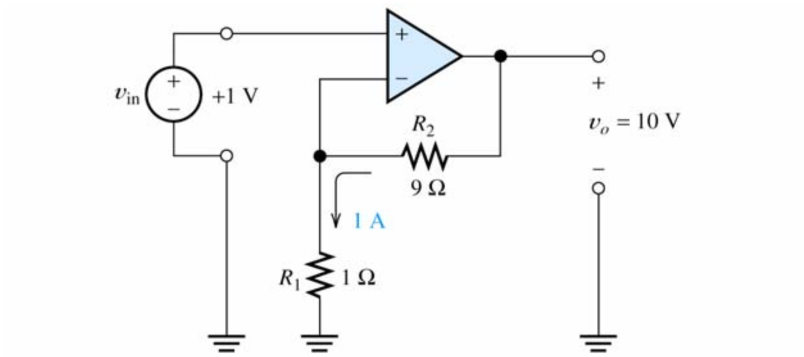

Figure 14.16 If low resistances are used, an excessively large current is required.

DESIGN OF SIMPLE AMPLIFIERS

Amplifier design using op amps mainly consists of selecting a suitable circuit configuration and values for the feedback resistors.

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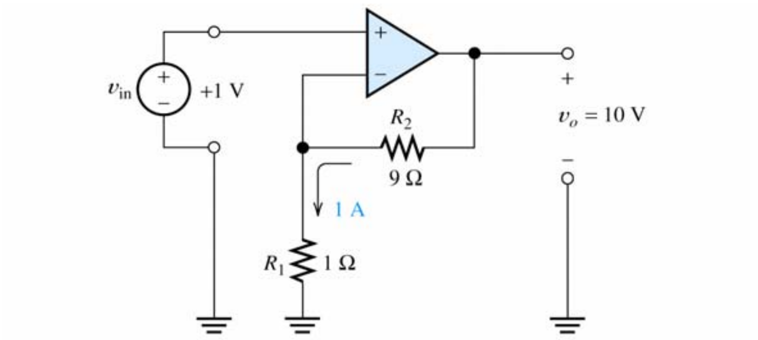
If the resistances are too small, an impractical amount of current and power will be needed to operate the amplifier.



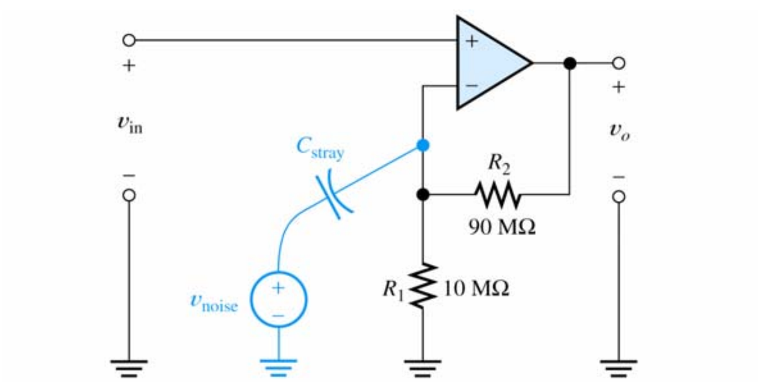
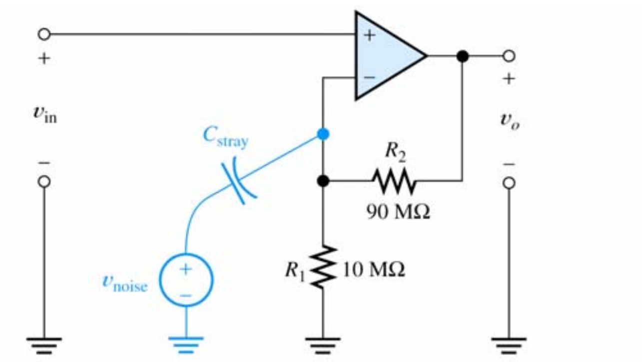


Figure 14.17 If very high resistances are used, stray capacitance can couple unwanted signals into the circuit.

Very large resistance may be unstable in value and lead to stray coupling of undesired signals.



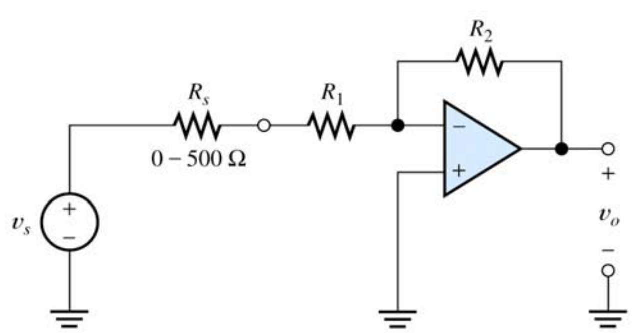


Figure 14.18 Circuit of Example 14.3.

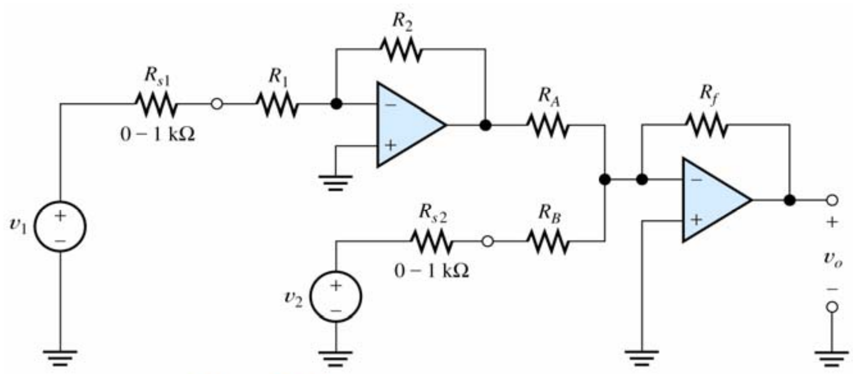


Figure 14.19 Amplifier designed in Example 14.4.

OP-AMP IMPERFECTIONS IN THE LINEAR RANGE OF OPERATION

Real op amps have several categories of imperfections compared to ideal op amps.

Real op amps have finite input impedance and nonzero output impedance.

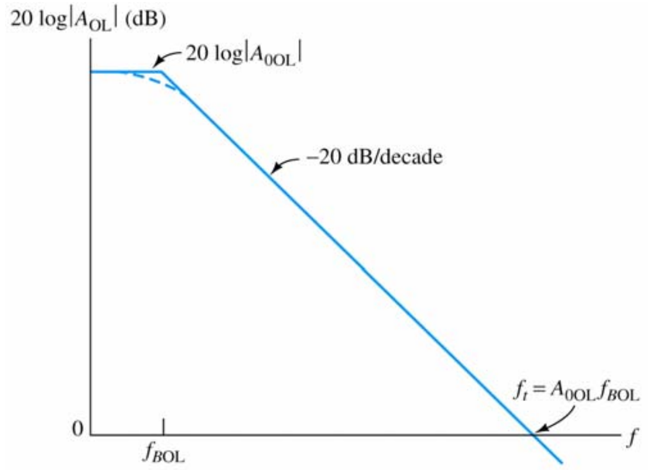
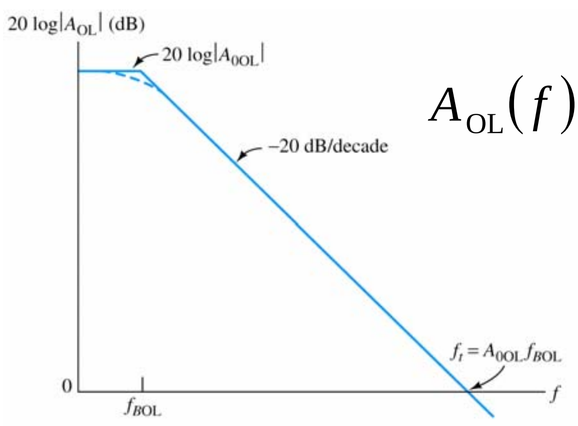


Figure 14.20 Bode plot of open-loop gain for a typical op amp.

Gain and Bandwidth Limitations



$$A_{\mathrm{OL}}(f) = \frac{A_{0\mathrm{OL}}}{1 + j(f / f_{B\mathrm{OL}})}$$

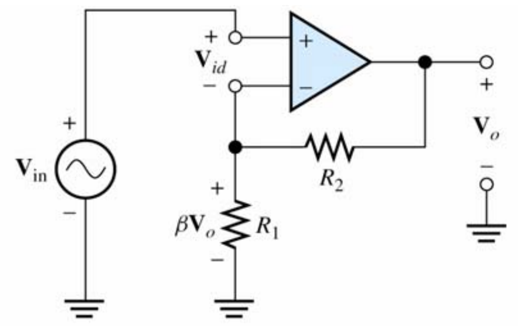


Figure 14.21 Noninverting amplifier circuit used for analysis of closed-loop bandwidth.

Closed-Loop Bandwidth

$$\beta = \frac{R_1}{R_1 + R_2}$$

$$f_{BCL} = f_{BOL}\left(1 + \beta A_{0OL}\right)$$

$$A_{0CL} = \frac{A_{0OL}}{1 + \beta A_{0OL}}$$

$$A_{CL}(f) = \frac{A_{0CL}}{1 + j\left(f / f_{BCL}\right)}$$

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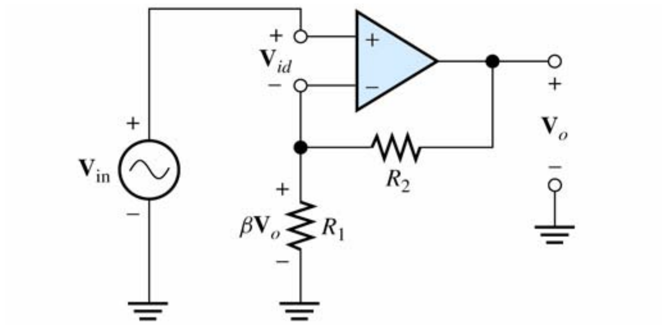

Gain–Bandwidth Product

$$f_t = A_{0\mathrm{CL}} f_{B\mathrm{CL}} = A_{0\mathrm{OL}} f_{B\mathrm{OL}}$$

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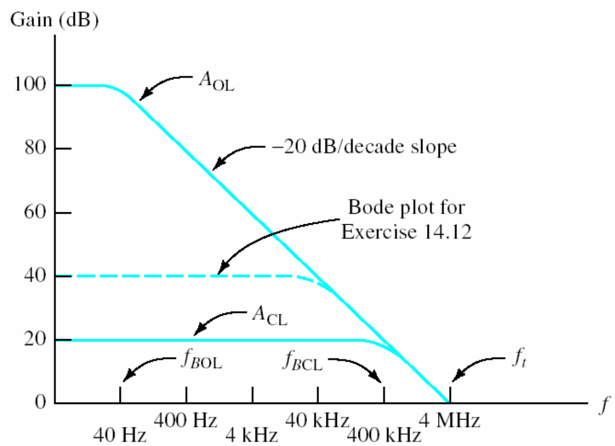

Figure 14.22 Bode plots for Example 14.5 and Exercise 14.12.

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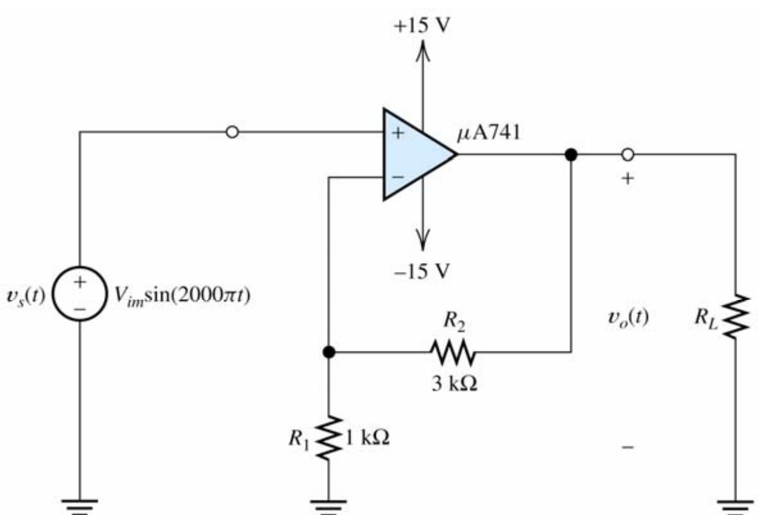

Figure 14.23 Noninverting amplifier used to demonstrate various nonlinear limitations of op amps.

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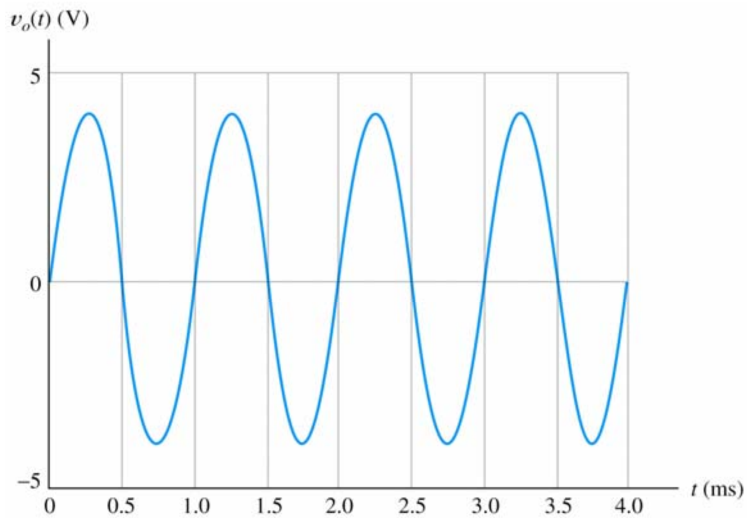

Figure 14.24 Output of the circuit of Figure 14.23 for $R_L = 10\ \text{k}\Omega$ and $V_{im} = 1$ V. None of the limitations are exceeded, and $v_o(t) = 4v_s(t)$.

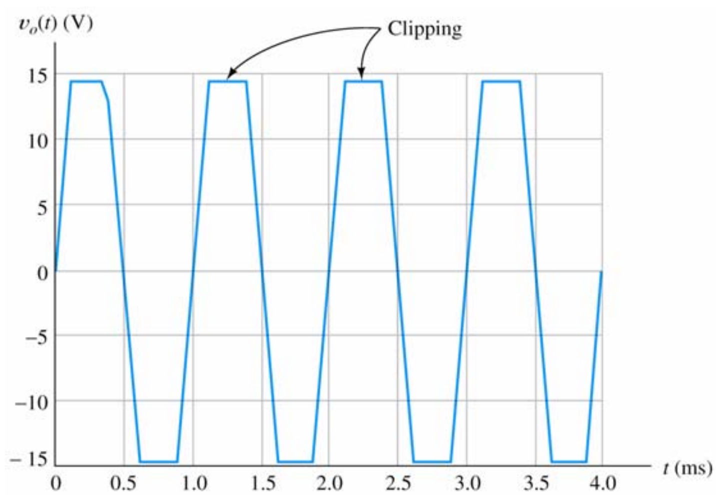

Figure 14.25 Output of the circuit of Figure 14.23 for $R_L = 10\ \text{k}\Omega$ and $V_{im} = 5$ V. Clipping occurs because the maximum possible output voltage magnitude is reached.

NONLINEAR LIMITATIONS

The output voltage of a real op amp is limited to the range between certain limits that depend on the internal design of the op amp. When the
output voltage tries to exceed these limits, clipping occurs.

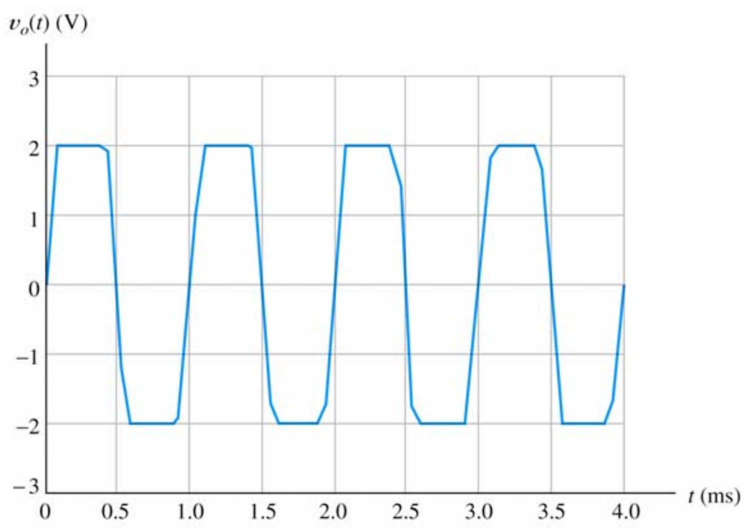

Figure 14.26 Output of the circuit of Figure 14.23 for $R_L = 50\ \Omega$ and $V_{im} = 1$ V. Clipping occurs because the maximum output current limit is reached.

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The output current range of a real op amp is limited. If an input signal is sufficiently large that the output current would be driven beyond
these limits, clipping occurs.

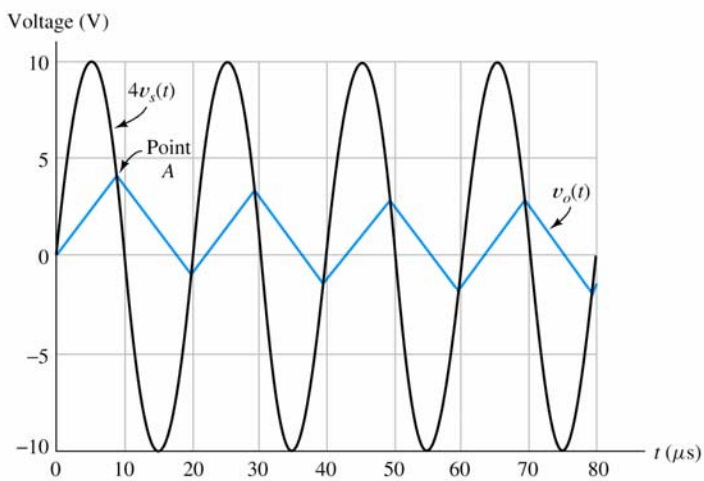

Figure 14.27 Output of the circuit of Figure 14.23 for $R_L = 10$ kΩ and $v_s(t) = 2.5\sin(10^5\pi t)$. The output waveform is a triangular waveform because the slew-rate limit is exceeded. The output for an ideal op amp, which is equal to $4v_s(t)$, is shown for comparison.

Slew-Rate Limitation

Another nonlinear limitation of actual op amps is that the magnitude of the rate of change of the output voltage is limited.

$$\left|\frac{dv_o}{dt}\right| \le \mathrm{SR}$$

Full-Power Bandwidth

The full-power bandwidth of an op amp is the range of frequencies for which the op amp can produce an undistorted sinusoidal output with peak amplitude equal to the guaranteed maximum output voltage.

$$f_{\mathrm{FP}} = \frac{\mathrm{SR}}{2\pi V_{om}}$$

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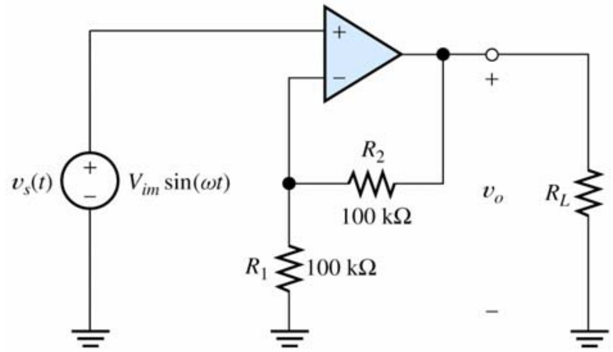

Figure 14.28 Circuit for Exercise 14.13.

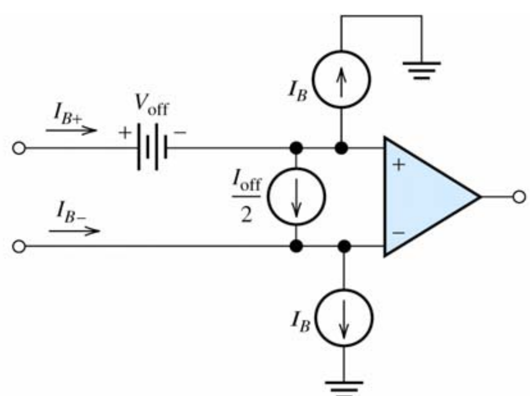

Figure 14.29 Three current sources and a voltage source model the dc imperfections of an op amp.

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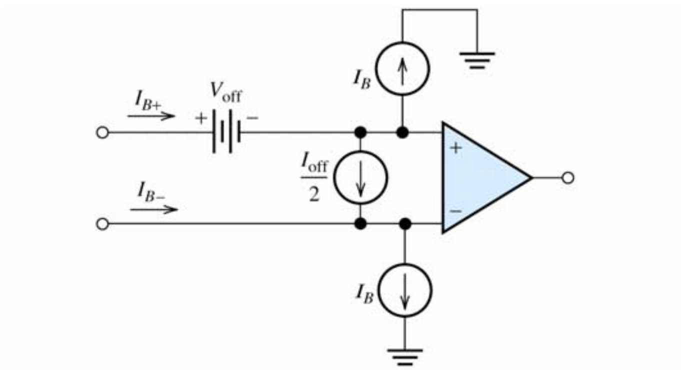
DC IMPERFECTIONS



The three dc imperfections (bias current, offset current, and offset voltage) can be modeled by placing dc sources at the input of the op amp as shown in Figure 14.29.

The effect of bias current, offset current, and offset voltage on inverting or noninverting amplifiers is to add a (usually undesirable) dc
voltage to the intended output signal.

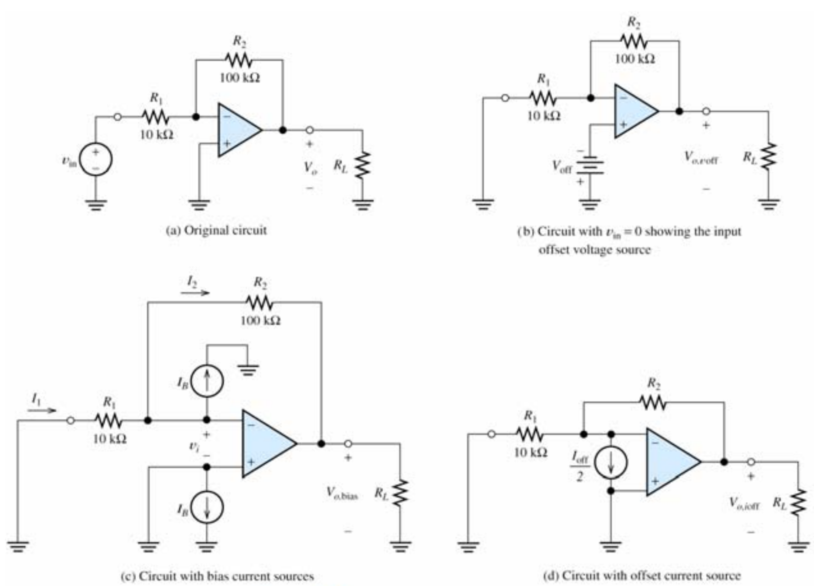


Figure 14.30 Circuits of Example 14.7.

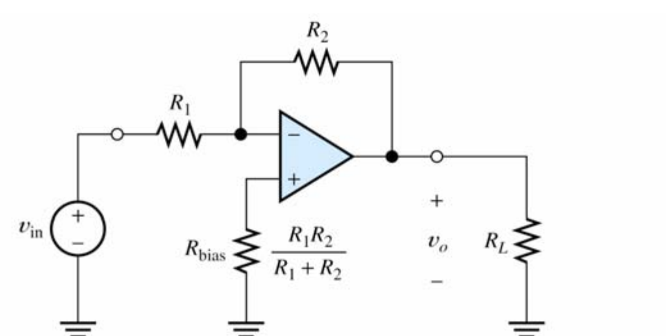


Figure 14.31 Adding the resistor R_{bias} to the inverting amplifier circuit causes the effects of bias currents to cancel.

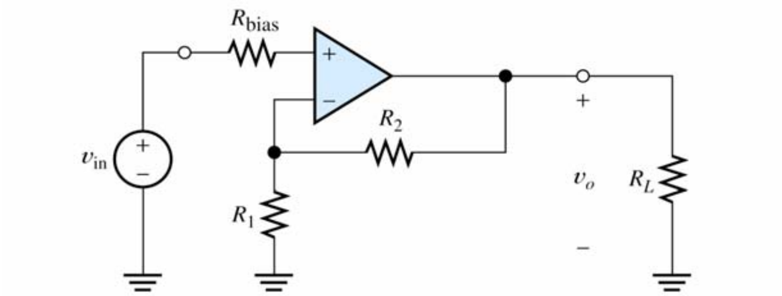


Figure 14.32 Noninverting amplifier, including resistor R_{bias} to balance the effects of the bias currents. See Exercise 14.15.

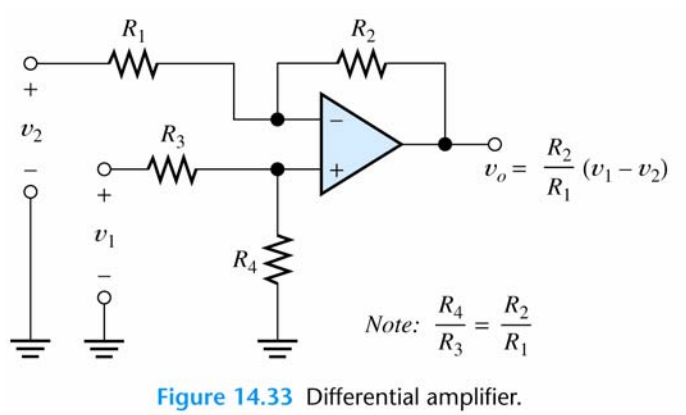
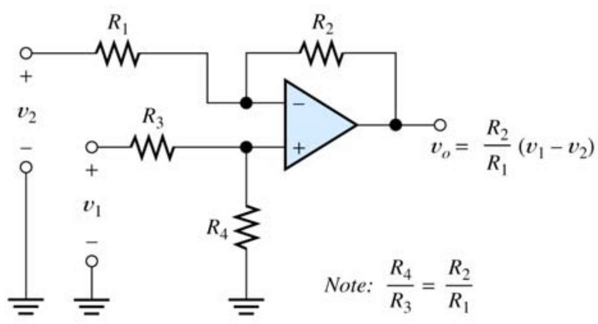


Figure 14.33 Differential amplifier.

DIFFERENTIAL AND INSTRUMENTATION AMPLIFIERS



Differential amplifiers are widely used in engineering instrumentation.

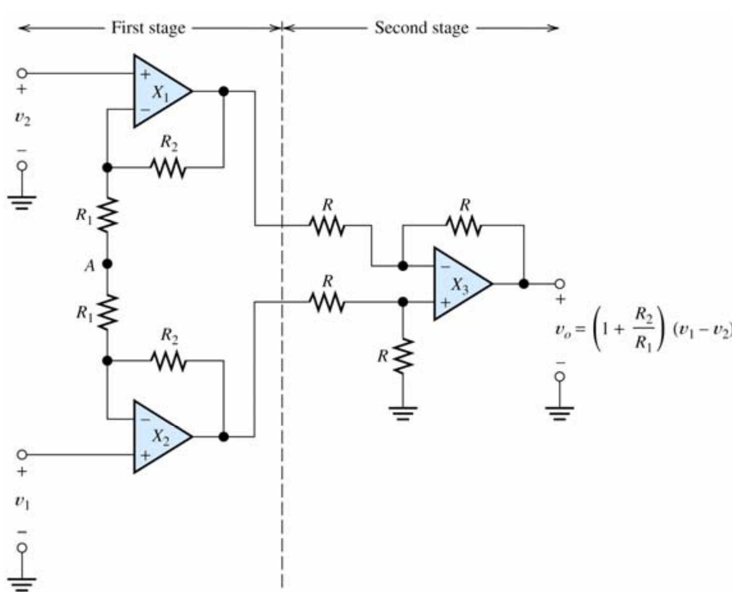


Figure 14.34 Instrumentation-quality differential amplifier.

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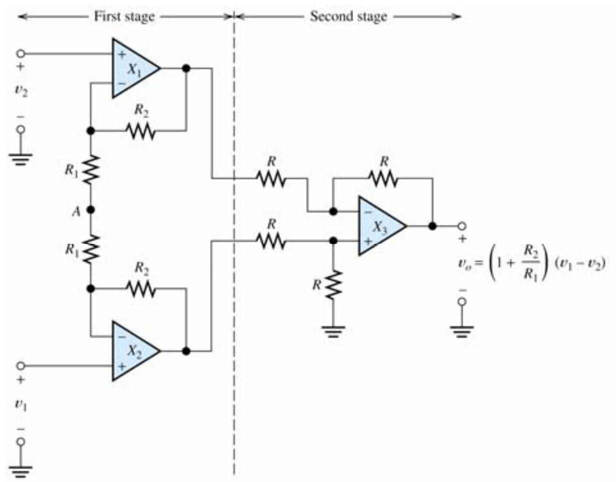
Instrumentation-Quality Differential Amplifier



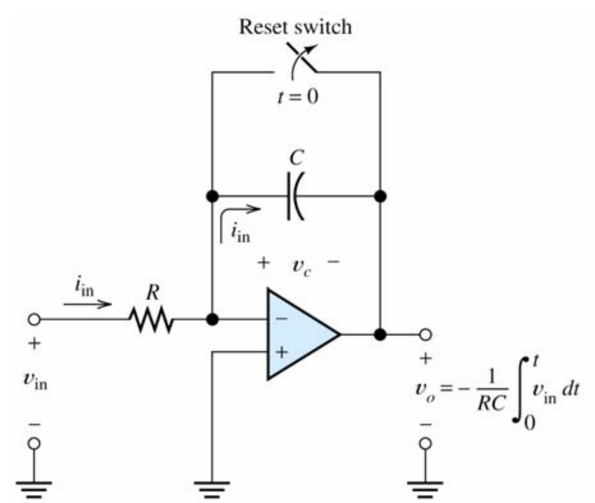
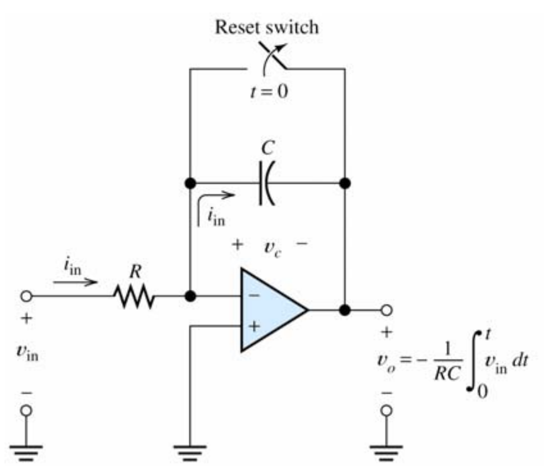


Figure 14.35 Integrator.

INTEGRATORS AND DIFFERENTIATORS

Integrators produce output voltages that are proportional to the running time integral of the input voltages. In a running time integral, the upper limit of integration is *t* .



$$v_o(t) = -\frac{1}{RC}\int_0^t v_{\text{in}}(t)dt$$

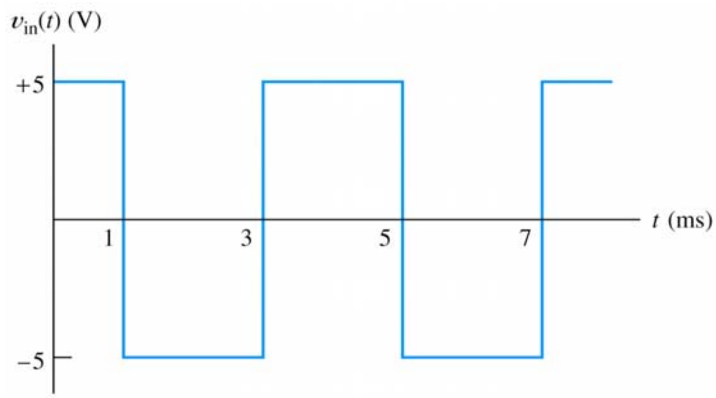


Figure 14.36 Square-wave input signal for Exercise 14.17.

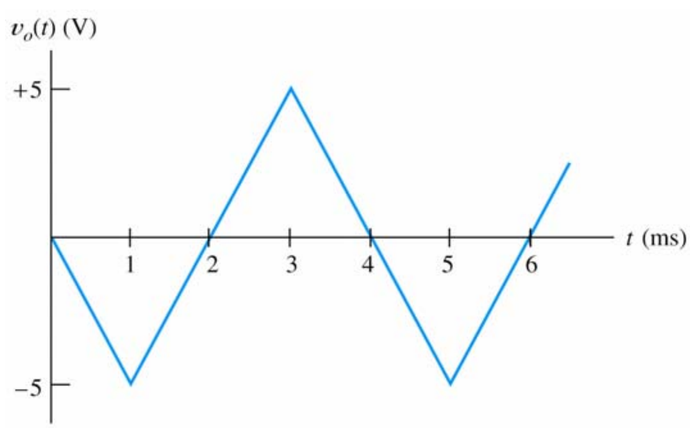


Figure 14.37 Answer for Exercise 14.17.

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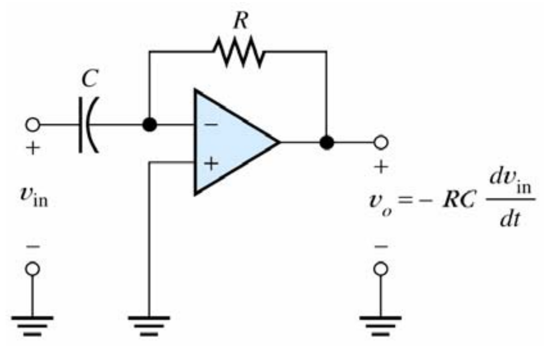
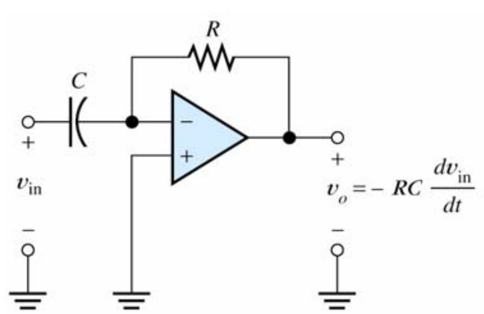


Figure 14.38 Differentiator.

Differentiator Circuit



$$v_o(t) = -RC\frac{dv_{\text{in}}}{dt}$$

ACTIVE FILTERS

Filters can be very useful in separating desired signals from noise.

Ideally, an active filter circuit should:

1. Contain few components
2. Have a transfer function that is insensitive to component tolerances

3**.** Place modest demands on the op amp's gain–
bandwidth product, output impedance, slew
rate, and other specifications

4**.** Be easily adjusted

5**.** Require a small spread of component values

6**.** Allow a wide range of useful transfer functions

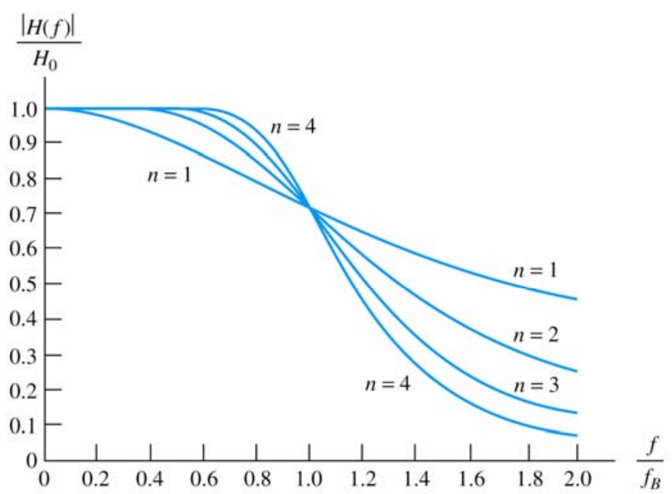


Figure 14.39 Transfer-function magnitude versus frequency for lowpass Butterworth filters.

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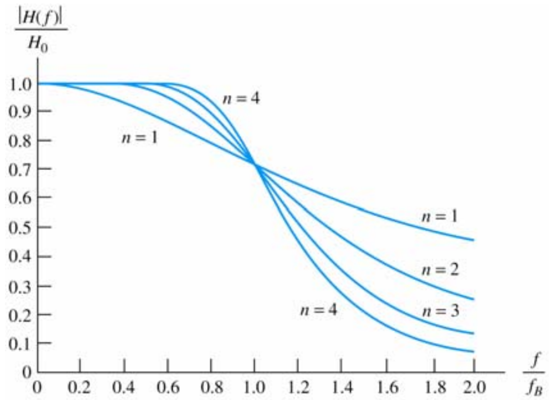
Butterworth Transfer



$$\left|H(f)\right| = \frac{H_0}{\sqrt{1+\left(f/f_B\right)^{2n}}}$$

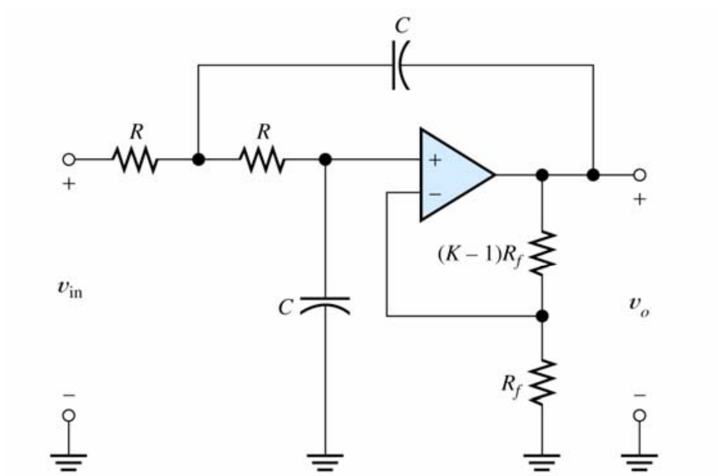


Figure 14.40 Equal-component Sallen–Key lowpass active-filter section.

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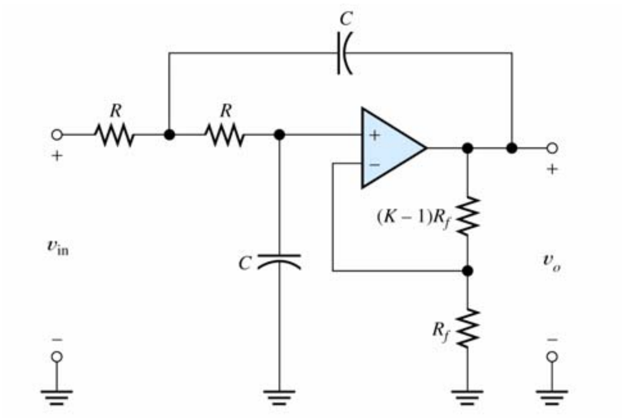
Sallen–Key Circuits



$$f_B = \frac{1}{2\pi RC}$$

Table 14.1. *K* Values for Lowpass or Highpass Butterworth Filters of Various Orders

Order	*K*
2	1.586
4	1.152
	2.235
6	1.068
	1.586
	2.483
8	1.038
	1.337
	1.889
	2.610

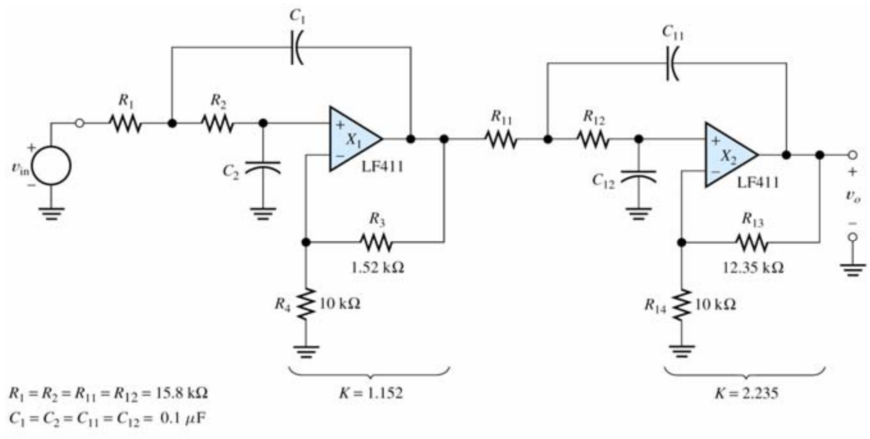
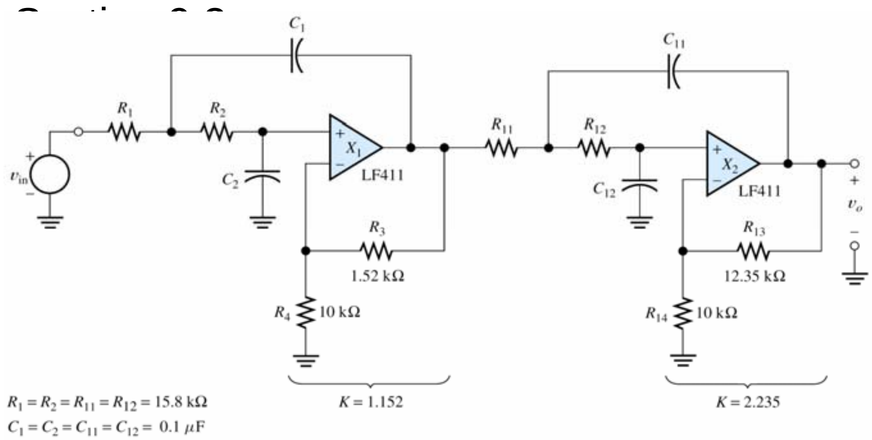


Figure 14.41 Fourth-order Butterworth lowpass filter designed in Example 14.8.

Active lowpass filters such as this are useful as antialias filters in computer-based instrumentation systems as discussed in



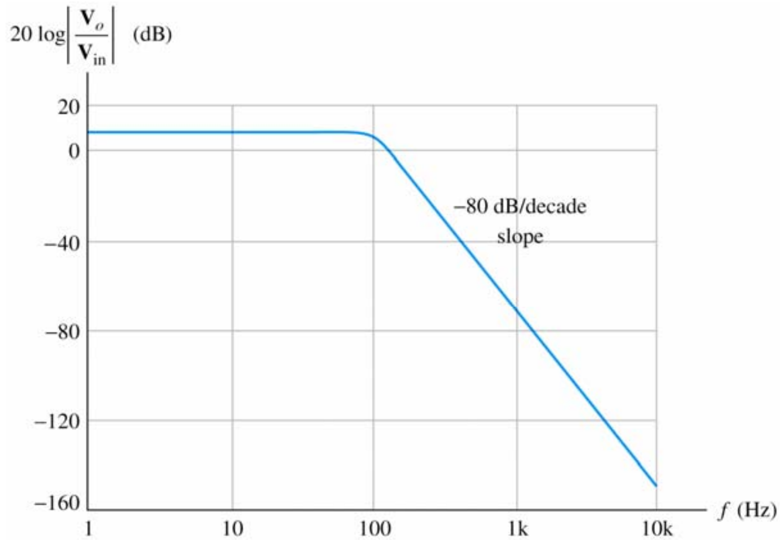


Figure 14.42 Bode magnitude plot of the gain for the fourth-order lowpass filter of Example 14.8.