9. In a difference amplifier, the output is proportional to the difference of the two inputs.
10. Op amp circuits may be cascaded without changing their input-output relationships.
11. *PSpice* can be used to analyze an op amp circuit.
12. Typical applications of the op amp considered in this chapter include the digital-to-analog converter and the instrumentation amplifier.

REVIEW QUESTIONS

5.1 The two input terminals of an op amp are labeled as:
(a) high and low.
(b) positive and negative.
(c) inverting and noninverting.
(d) differential and nondifferential.

5.2 For an ideal op amp, which of the following statements are not true?
(a) The differential voltage across the input terminals is zero.
(b) The current into the input terminals is zero.
(c) The current from the output terminal is zero.
(d) The input resistance is zero.
(e) The output resistance is zero.

5.3 For the circuit in Fig. 5.39, voltage v_o is:
(a) −6 V (b) −5 V
(c) −1.2 V (d) −0.2 V

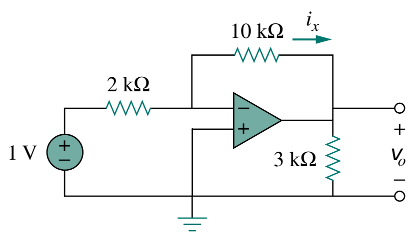


Figure 5.39 For Reivew Questions 5.3 and 5.4.

5.4 For the circuit in Fig. 5.39, current i_x is:
(a) 0.6 A (b) 0.5 A
(c) 0.2 A (d) 1/12 A

5.5 If $v_s = 0$ in the circuit of Fig. 5.40, current i_o is:
(a) −10 A (b) −2.5 A
(c) 10/12 A (d) 10/14 A

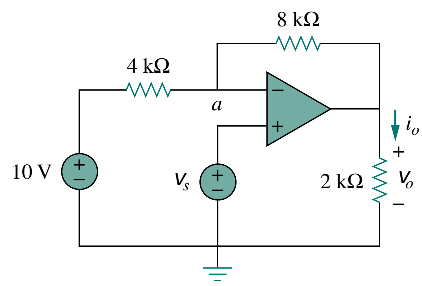


Figure 5.40 For Review Questions 5.5 to 5.7.

5.6 If $v_s = 8$ V in the circuit of Fig. 5.40, the output voltage is:
(a) −44 V (b) −8 V
(c) 4 V (d) 7 V

5.7 Refer to Fig. 5.40. If $v_s = 8$ V, voltage v_a is:
(a) −8 V (b) 0 V
(c) 10/3 V (d) 8 V

5.8 The power absorbed by the 4-kΩ resistor in Fig. 5.41 is:
(a) 9 mW (b) 4 mW
(c) 2 mW (d) 1 mW

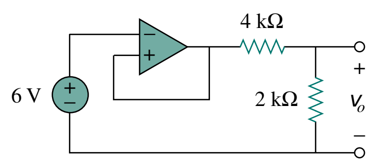


Figure 5.41 For Review Question 5.8.

5.9 Which of these amplifiers is used in a digital-to-analog converter?
(a) noninverter (b) voltage follower
(c) summer (d) difference amplifier

5.10 Difference amplifiers are used in:
(a) instrumentation amplifiers
(b) voltage followers
(c) voltage regulators
(d) buffers
(e) summing amplifiers
(f) subtracting amplifiers

Answers: 5.1c, 5.2c,d, 5.3b, 5.4b, 5.5a, 5.6c, 5.7d, 5.8b, 5.9c, 5.10a,f.

PROBLEMS

Section 5.2 Operational Amplifiers

5.1 The equivalent model of a certain op amp is shown in Fig. 5.42. Determine:
(a) the input resistance
(b) the output resistance
(c) the voltage gain in dB.

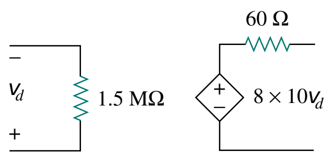


Figure 5.42 For Prob. 5.1.

5.2 The open-loop gain of an op amp is 100,000. Calculate the output voltage when there are inputs of $+10\ \mu$V on the inverting terminal and $+20\ \mu$V on the noninverting terminal.

5.3 Determine the output voltage when $-20\ \mu$V is applied to the inverting terminal of an op amp and $+30\ \mu$V to its noninverting terminal. Assume that the op amp has an open-loop gain of 200,000.

5.4 The output voltage of an op amp is -4 V when the noninverting input is 1 mV. If the open-loop gain of the op amp is 2×10^6, what is the inverting input?

5.5 For the op amp circuit of Fig. 5.43, the op amp has an open-loop gain of 100,000, an input resistance of 10 kΩ, and an output resistance of 100 Ω. Find the voltage gain v_o/v_i using the nonideal model of the op amp.

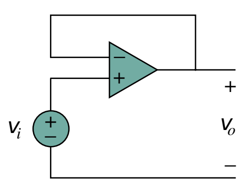


Figure 5.43 For Prob. 5.5.

5.6 Using the same parameters for the 741 op amp in Example 5.1, find v_o in the op amp circuit of Fig. 5.44.

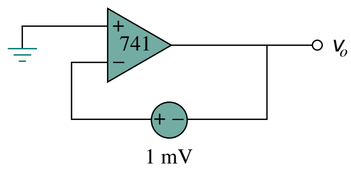


Figure 5.44 For Prob. 5.6.

5.7 The op amp in Fig. 5.45 has $R_i = 100$ kΩ, $R_o = 100\ \Omega$, $A = 100{,}000$. Find the differential voltage v_d and the output voltage v_o.

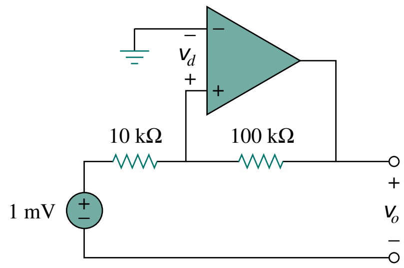


Figure 5.45 For Prob. 5.7.

Section 5.3 Ideal Op Amp

5.8 Obtain v_o for each of the op amp circuits in Fig. 5.46.

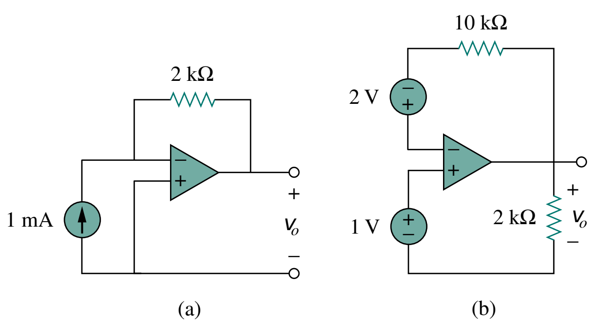
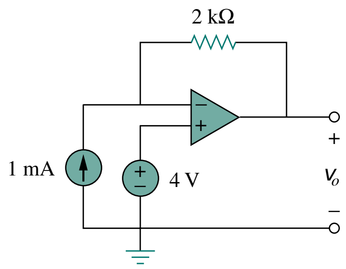


Figure 5.46 For Prob. 5.8.

5.9 Determine v_o for each of the op amp circuits in Fig. 5.47.



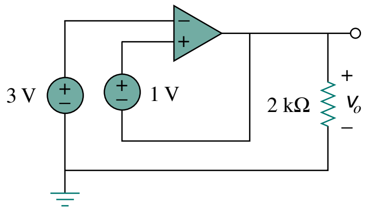


Figure 5.47 For Prob. 5.9.

5.10 Find the gain v_o/v_s of the circuit in Fig. 5.48.

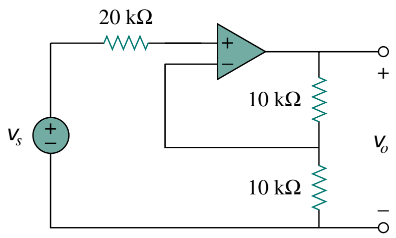


Figure 5.48 For Prob. 5.10.

5.11 Find v_o and i_o in the circuit in Fig. 5.49.

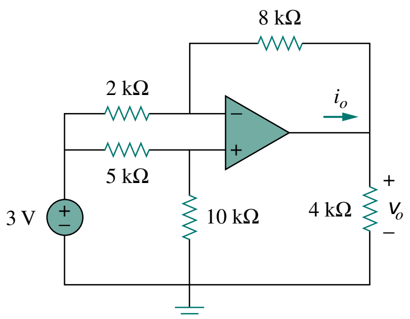


Figure 5.49 For Prob. 5.11.

5.12 Refer to the op amp circuit in Fig. 5.50. Determine the power supplied by the voltage source.

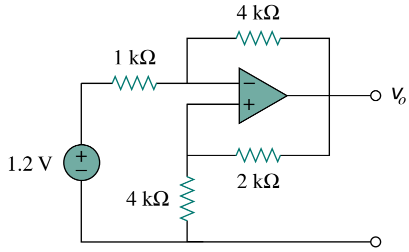


Figure 5.50 For Prob. 5.12.

5.13 Find v_o and i_o in the circuit of Fig. 5.51.

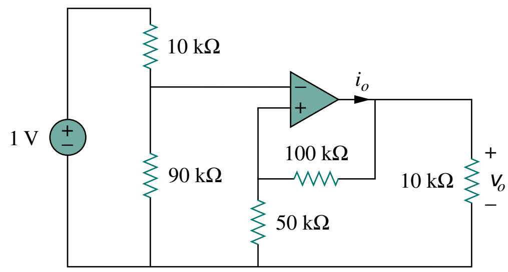


Figure 5.51 For Prob. 5.13.

5.14 Determine the output voltage v_o in the circuit of Fig. 5.52.

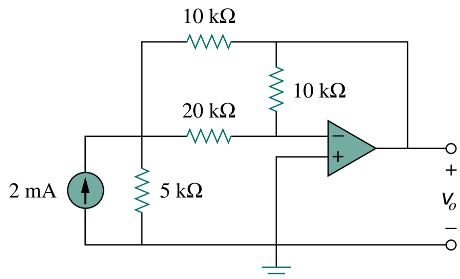


Figure 5.52 For Prob. 5.14.

Section 5.4 Inverting Amplifier

5.15 (a) For the circuit shown in Fig. 5.53, show that the gain is

$$\frac{v_o}{v_i} = -\frac{1}{R}\left(R_1 + R_2 + \frac{R_1 R_2}{R_3}\right)$$

(b) Evaluate the gain when $R = 10\ \text{k}\Omega$, $R_1 = 100\ \text{k}\Omega$, $R_2 = 50\ \text{k}\Omega$, $R_3 = 25\ \text{k}\Omega$.

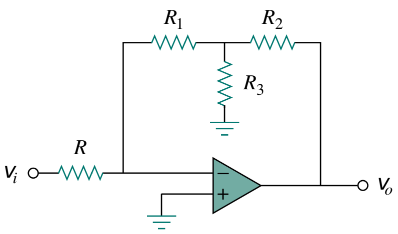


Figure 5.53 For Prob. 5.15.

5.16 Calculate the gain v_o/v_i when the switch in Fig. 5.54 is in:
(a) position 1 (b) position 2 (c) position 3

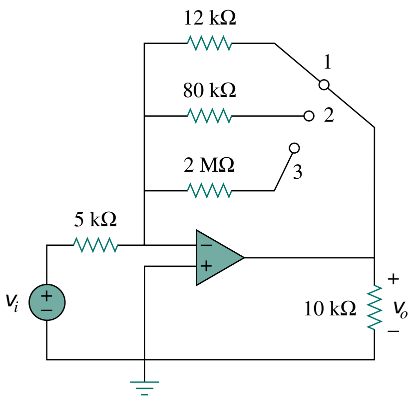


Figure 5.54 For Prob. 5.16.

5.17 Calculate the gain v_o/v_i of the op amp circuit in Fig. 5.55.

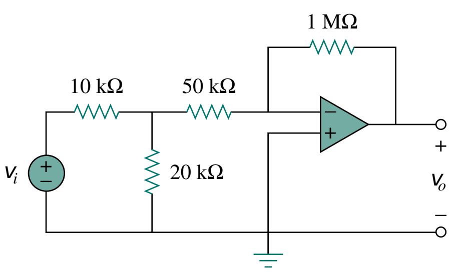


Figure 5.55 For Prob. 5.17.

5.18 Determine i_o in the circuit of Fig. 5.56.

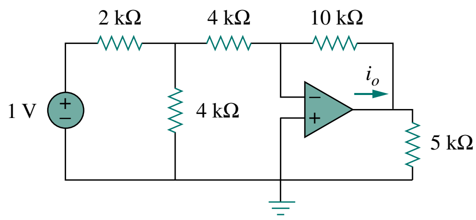


Figure 5.56 For Prob. 5.18.

5.19 In the circuit in Fig. 5.57, calculate v_o if $v_s = 0$.

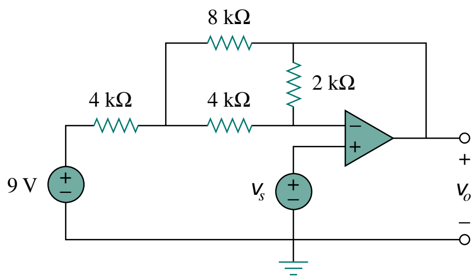


Figure 5.57 For Prob. 5.19.

5.20 Repeat the previous problem if $v_s = 3$ V.

5.21 Design an inverting amplifier with a gain of -15.

Section 5.5 Noninverting Amplifier

5.22 Find v_a and v_o in the op amp circuit of Fig. 5.58.

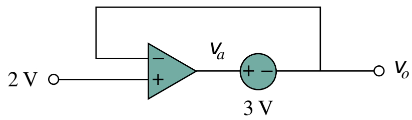


Figure 5.58 For Prob. 5.22.

5.23 Refer to Fig. 5.59.
(a) Determine the overall gain v_o/v_i of the circuit.
(b) What value of v_i will result in $v_o = 15 \cos 120\pi t$?

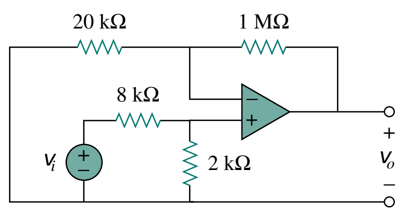


Figure 5.59 For Prob. 5.23.

5.24 Find i_o in the op amp circuit of Fig. 5.60.

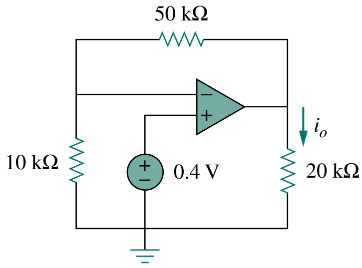


Figure 5.60 For Prob. 5.24.

5.25 In the circuit shown in Fig. 5.61, find i_x and the power absorbed by the 20-Ω resistor.

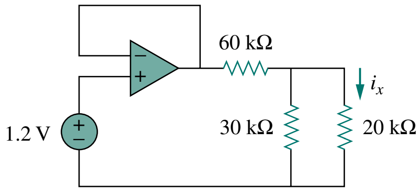


Figure 5.61 For Prob. 5.25.

5.26 For the circuit in Fig. 5.62, find i_x.

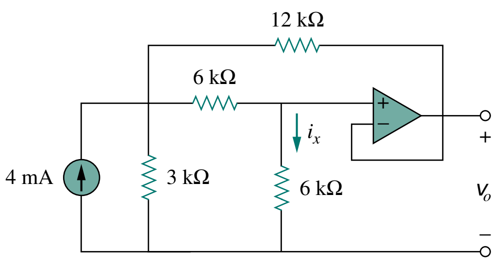


Figure 5.62 For Prob. 5.26.

5.27 Calculate i_x and v_o in the circuit of Fig. 5.63. Find the power dissipated by the 60-kΩ resistor.

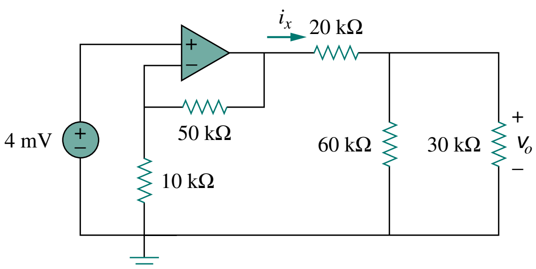


Figure 5.63 For Prob. 5.27.

5.28 Refer to the op amp circuit in Fig. 5.64. Calculate i_x and the power dissipated by the 3-kΩ resistor.

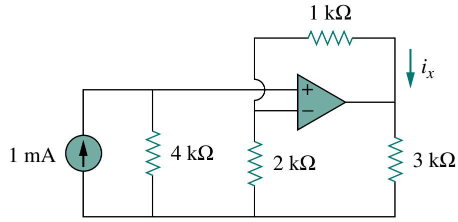


Figure 5.64 For Prob. 5.28.

5.29 Design a noninverting amplifier with a gain of 10.

Section 5.6 Summing Amplifier

5.30 Determine the output of the summing amplifier in Fig. 5.65.

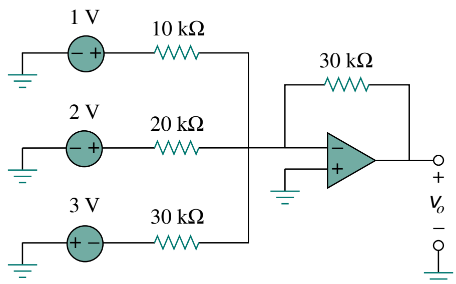


Figure 5.65 For Prob. 5.30.

5.31 Calculate the output voltage due to the summing amplifier shown in Fig. 5.66.

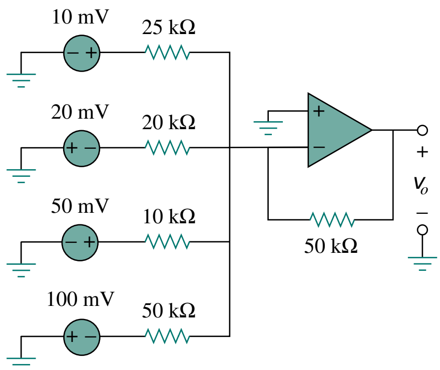


Figure 5.66 For Prob. 5.31.

5.32 An *averaging amplifier* is a summer that provides an output equal to the average of the inputs. By using proper input and feedback resistor values, one can get

$$-v_{out} = \frac{1}{4}(v_1 + v_2 + v_3 + v_4)$$

Using a feedback resistor of 10 kΩ, design an averaging amplifier with four inputs.

5.33 A four-input summing amplifier has $R_1 = R_2 = R_3 = R_4 = 12$ kΩ. What value of feedback resistor is needed to make it an averaging amplifier?

5.34 Show that the output voltage v_o of the circuit in Fig. 5.67 is

$$v_o = \frac{(R_3 + R_4)}{R_3(R_1 + R_2)}(R_2 v_1 + R_1 v_2)$$

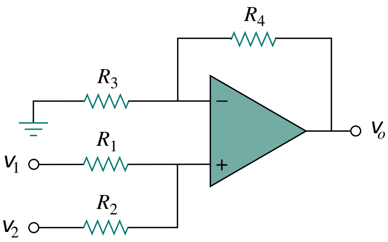


Figure 5.67 For Prob. 5.34.

5.35 Design an op amp circuit to perform the following operation:

$$v_o = 3v_1 - 2v_2$$

All resistances must be $\leq$ 100 kΩ.

5.36 Using only two op amps, design a circuit to solve

$$-v_{out} = \frac{v_1 - v_2}{3} + \frac{v_3}{2}$$

Section 5.7 Difference Amplifier

5.37 Find v_o and i_o in the differential amplifier of Fig. 5.68.

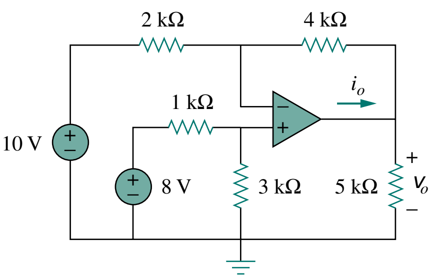


Figure 5.68 For Prob. 5.37.

5.38 The circuit in Fig. 5.69 is a differential amplifier driven by a bridge. Find v_o.

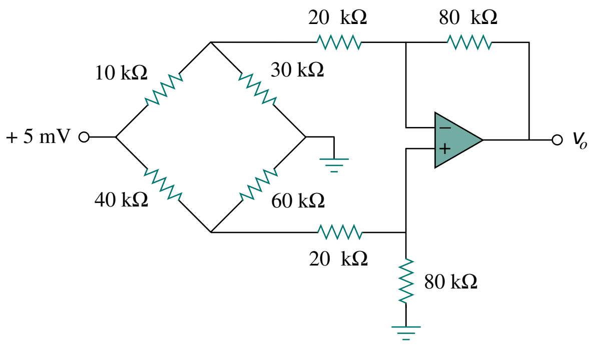


Figure 5.69 For Prob. 5.38.

5.39 Design a difference amplifier to have a gain of 2 and a common mode input resistance of 10 kΩ at each input.

5.40 Design a circuit to amplify the difference between two inputs by 2.

(a) Use only one op amp.

(b) Use two op amps.

5.41 Using two op amps, design a subtractor.

***5.42** The ordinary difference amplifier for fixed-gain operation is shown in Fig. 5.70(a). It is simple and reliable unless gain is made variable. One way of providing gain adjustment without losing simplicity and accuracy is to use the circuit in Fig. 5.70(b). Another way is to use the circuit in Fig. 5.70(c). Show that:

(a) for the circuit in Fig. 5.70(a),

$$\frac{v_o}{v_i} = \frac{R_2}{R_1}$$

Fg5_70b

(b) for the circuit in Fig. 5.70(b),

$$\frac{v_o}{v_i} = \frac{R_2}{R_1}\frac{1}{1 + \dfrac{R_1}{2R_G}}$$

Fg5_70c

(c) for the circuit in Fig. 5.70(c),

$$\frac{v_o}{v_i} = \frac{R_2}{R_1}\left(1 + \frac{R_2}{2R_G}\right)$$

*An asterisk indicates a challenging problem.

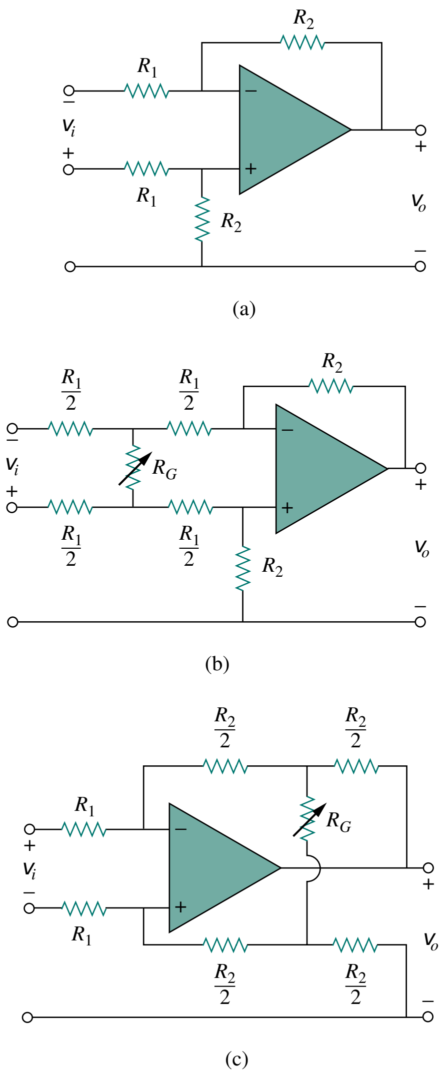


Figure 5.70 For Prob. 5.42.

Section 5.8 Cascaded Op Amp Circuits

5.43 The individual gains of the stages in a multistage amplifier are shown in Fig. 5.71.

(a) Calculate the overall voltage gain v_o/v_i.

(b) Find the voltage gain that would be needed in a fourth stage which would make the overall gain to be 60 dB when added.

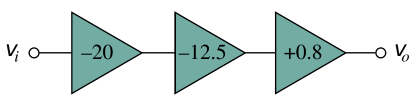


Figure 5.71 For Prob. 5.43.

5.44 In a certain electronic device, a three-stage amplifier is desired, whose overall voltage gain is 42 dB. The individual voltage gains of the first two stages are to be equal, while the gain of the third is to be one-fourth of each of the first two. Calculate the voltage gain of each.

5.45 Refer to the circuit in Fig. 5.72. Calculate i_o if:

(a) $v_s = 12$ mV (b) $v_s = 10\cos 377t$ mV.

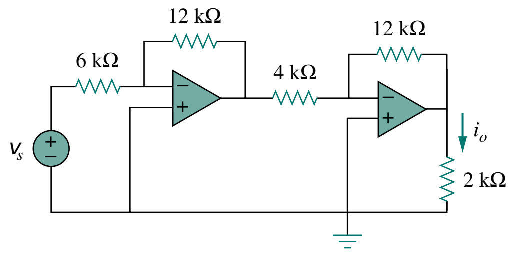


Figure 5.72 For Prob. 5.45.

5.46 Calculate i_o in the op amp circuit of Fig. 5.73.

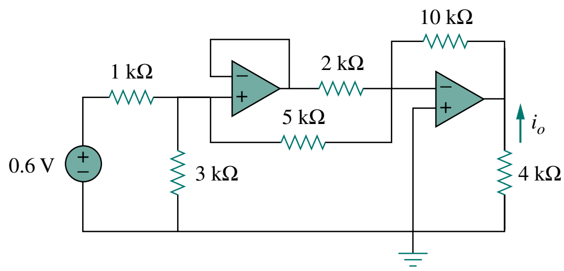


Figure 5.73 For Prob. 5.46.

5.47 Find the voltage gain v_o/v_s of the circuit in Fig. 5.74.

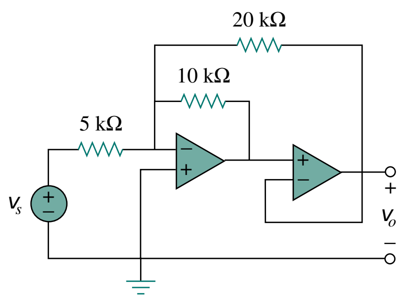


Figure 5.74 For Prob. 5.47.

5.48 Calculate the current gain i_o/i_s of the op amp circuit in Fig. 5.75.

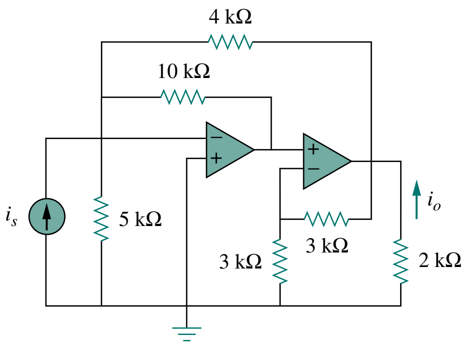


Figure 5.75 For Prob. 5.48.

5.49 Find v_o in terms of v_1 and v_2 in the circuit in Fig. 5.76.

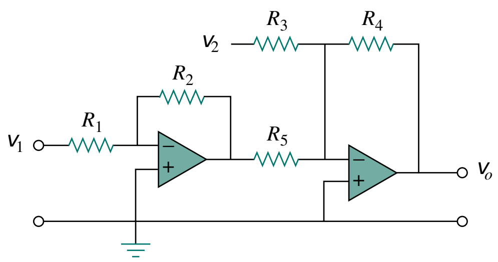


Figure 5.76 For Prob. 5.49.

5.50 Obtain the closed-loop voltage gain v_o/v_i of the circuit in Fig. 5.77.

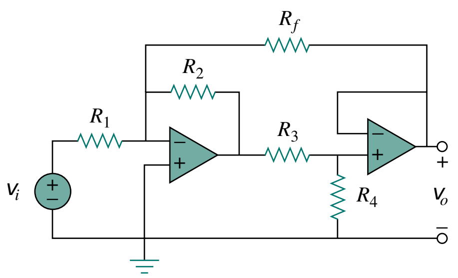


Figure 5.77 For Prob. 5.50.

5.51 Determine the gain v_o/v_i of the circuit in Fig. 5.78.

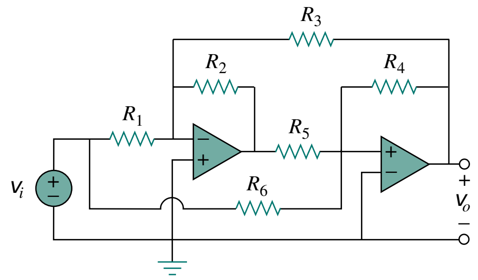


Figure 5.78 For Prob. 5.51.

5.52 For the circuit in Fig. 5.79, find v_o.

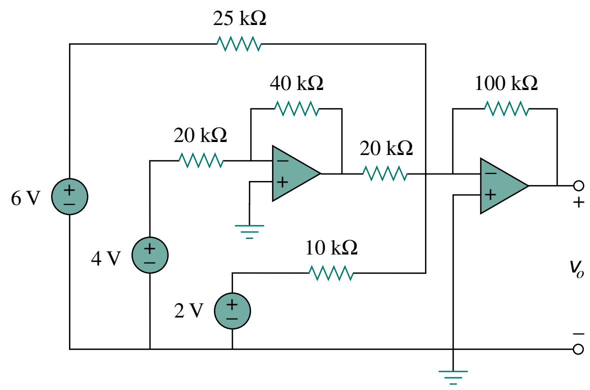


Figure 5.79 For Prob. 5.52.

5.53 Obtain the output v_o in the circuit of Fig. 5.80.

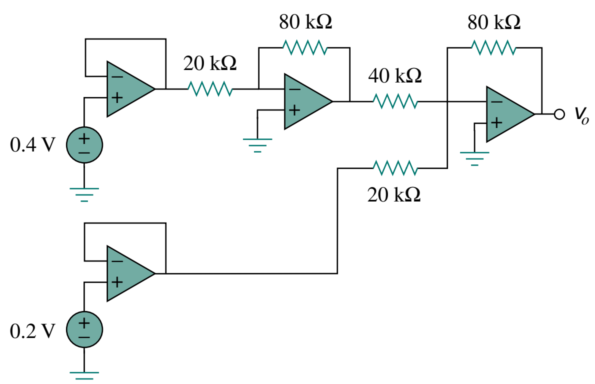


Figure 5.80 For Prob. 5.53.

5.54 Find v_o in the circuit in Fig. 5.81, assuming that $R_f = \infty$ (open circuit).

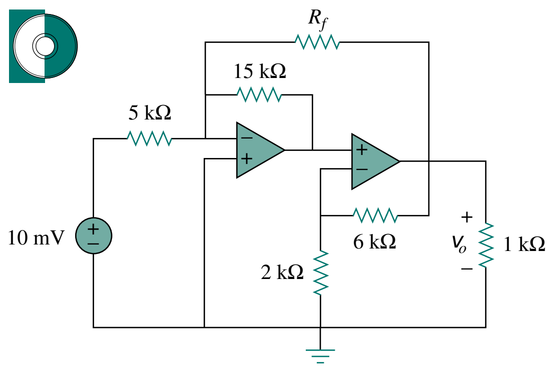


Figure 5.81 For Probs. 5.54 and 5.55.

5.55 Repeat the previous problem if $R_f = 10$ kΩ.

5.56 Determine v_o in the op amp circuit of Fig. 5.82.

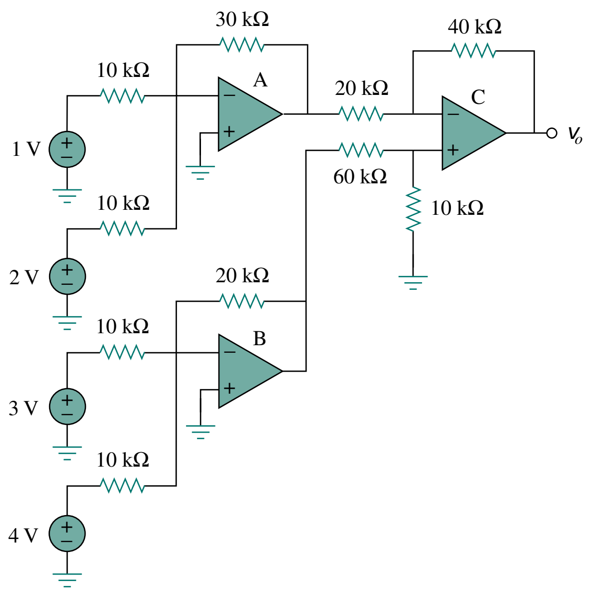


Figure 5.82 For Prob. 5.56.

5.57 Find the load voltage v_L in the circuit of Fig. 5.83.

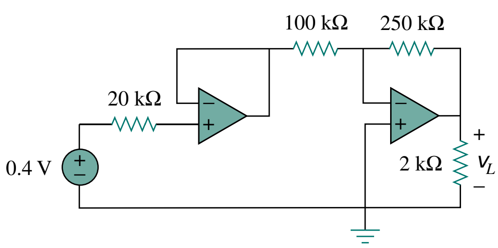


Figure 5.83 For Prob. 5.57.

5.58 Determine the load voltage v_L in the circuit of Fig. 5.84.

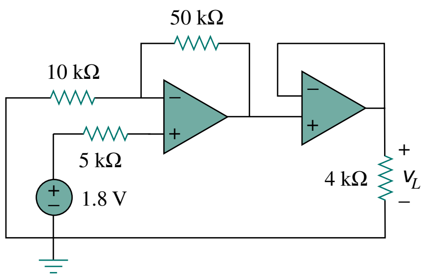


Figure 5.84 For Prob. 5.58.

5.59 Find i_o in the op amp circuit of Fig. 5.85.

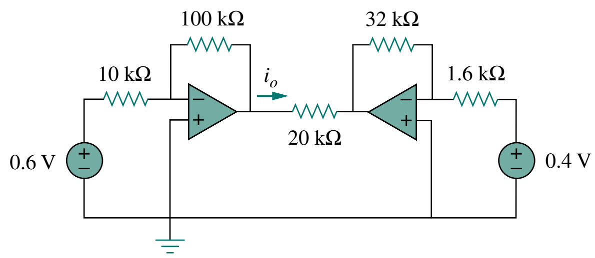


Figure 5.85 For Prob. 5.59.

Section 5.9 Op Amp Circuit Analysis with *PSpice*

5.60 Rework Example 5.11 using the nonideal op amp LM324 instead of uA741.

5.61 Solve Prob. 5.18 using *PSpice* and op amp uA741.

5.62 Solve Prob. 5.38 using *PSpice* and op amp LM324.

5.63 Use *PSpice* to obtain v_o in the circuit of Fig. 5.86.

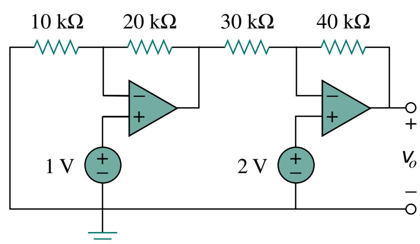


Figure 5.86 For Prob. 5.63.

5.64 Determine v_o in the op amp circuit of Fig. 5.87 using *PSpice*.

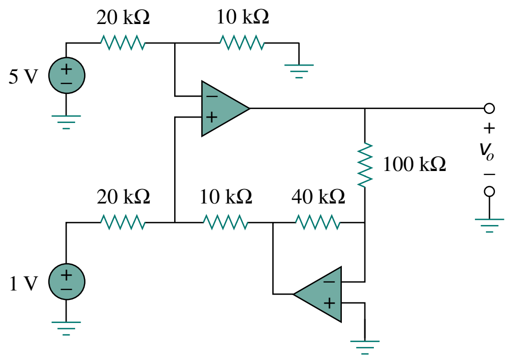


Figure 5.87 For Prob. 5.64.

5.65 Use *PSpice* to solve Prob. 5.56, assuming that the op amps are uA741.

5.66 Use *PSpice* to verify the results in Example 5.9. Assume nonideal op amps LM324.

Section 5.10 Applications

5.67 A five-bit DAC covers a voltage range of 0 to 7.75 V. Calculate how much voltage each bit is worth.

5.68 Design a six-bit digital-to-analog converter.

(a) If $|V_o| = 1.1875$ V is desired, what should $[V_1 V_2 V_3 V_4 V_5 V_6]$ be?

(b) Calculate $|V_o|$ if $[V_1 V_2 V_3 V_4 V_5 V_6] = [011011]$.

(c) What is the maximum value $|V_o|$ can assume?

***5.69** A four-bit *R-2R ladder* DAC is presented in Fig. 5.88.

(a) Show that the output voltage is given by

$$-V_o = R_f\left(\frac{V_1}{2R} + \frac{V_2}{4R} + \frac{V_3}{8R} + \frac{V_4}{16R}\right)$$

(b) If $R_f = 12$ kΩ and $R = 10$ kΩ, find $|V_o|$ for $[V_1 V_2 V_3 V_4] = [1011]$ and $[V_1 V_2 V_3 V_4] = [0101]$.

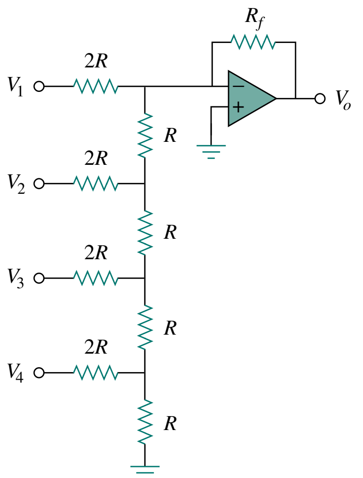


Figure 5.88 For Prob. 5.69.

5.70 If $R_G = 100$ Ω and $R = 20$ kΩ, calculate the voltage gain of the IA in Fig. 5.37.

5.71 Assuming a gain of 200 for an IA, find its output voltage for:

(a) $v_1 = 0.402$ V and $v_2 = 0.386$ V

(b) $v_1 = 1.002$ V and $v_2 = 1.011$ V.

5.72 Figure 5.89 displays a two-op-amp instrumentation amplifier. Derive an expression for v_o in terms of v_1 and v_2. How can this amplifier be used as a subtractor?

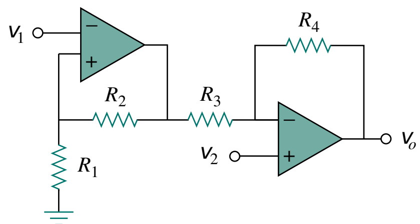


Figure 5.89 For Prob. 5.72.

***5.73** Figure 5.90 shows an instrumentation amplifier driven by a bridge. Obtain the gain v_o/v_i of the amplifier.

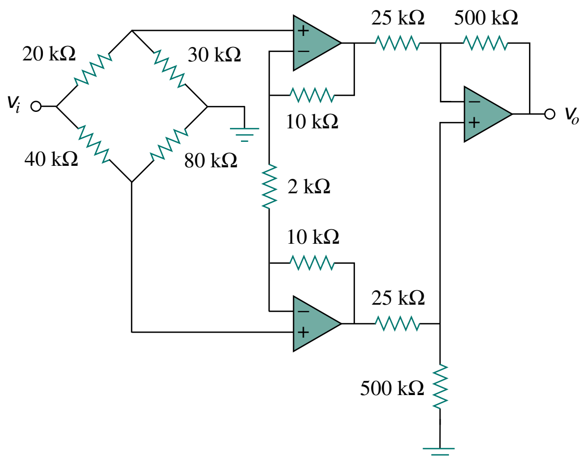


Figure 5.90 For Prob. 5.73.

COMPREHENSIVE PROBLEMS

5.74 A gain of 6 (+ or −, it does not matter) is required in an audio system. Design an op amp circuit to provide the gain with an input resistance of 2 kΩ.

5.75 The op amp circuit in Fig. 5.91 is a *current amplifier.* Find the current gain i_o/i_s of the amplifier.

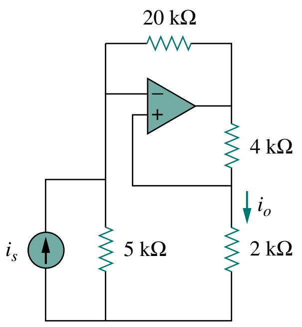


Figure 5.91 For Prob. 5.75.

5.76 A noninverting current amplifier is portrayed in Fig. 5.92. Calculate the gain i_o/i_s. Take $R_1 = 8$ kΩ and $R_2 = 1$ kΩ.

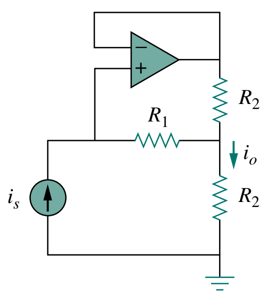


Figure 5.92 For Prob. 5.76.

5.77 Refer to the *bridge amplifier* shown in Fig. 5.93. Determine the voltage gain v_o/v_i.

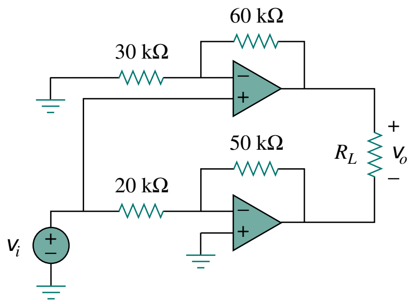


Figure 5.93 For Prob. 5.77.

*__5.78__ A voltage-to-current converter is shown in Fig. 5.94, which means that $i_L = Av_i$ if $R_1R_2 = R_3R_4$. Find the constant term A.

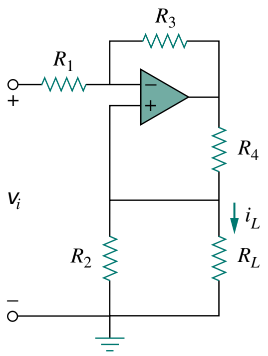


Figure 5.94 For Prob. 5.78.