EE 2010 Circuit Analysis

Module 17: **Op-Amps: Resistive Elements** **Notes**

These notes are drawn from *Alexander and Sadiku*, 2013, *O'Malley*, 2011, WIKIPEDIA, and other sources. They are intended to offer a summary of topics to guide you in focused studies. You should augment this handout with notes taken in class, reading textbook(s), and working additional example problems.

Learning Objective: In this module, we introduce the Operational Amplifier or Op-Amp. We quickly adopt the "ideal model" for an Op-Amp useful in analyzing a wide variety of Op-Amp circuits.

Definition: An *operational amplifier, or op-amp* is a DC-coupled high-gain electronic voltage amplifier with a differential input and a single-ended output. An op-amp produces an output potential (relative to circuit ground) that is typically 100000 times larger than the potential difference between its input terminals.

Due to its *extremely large open-loop gain* $\sim 10^5$, when (almost exclusively) configured in one of several *negative feedback* modes, the characteristics of an op-amp circuit, its gain, input and output impedance, bandwidth etc. **are determined by external components and have little dependence on temperature coefficients or manufacturing variations in the op-amp itself!** Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices.

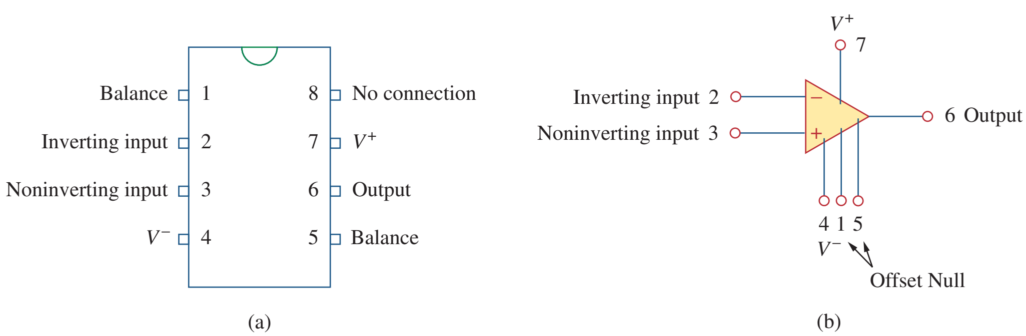
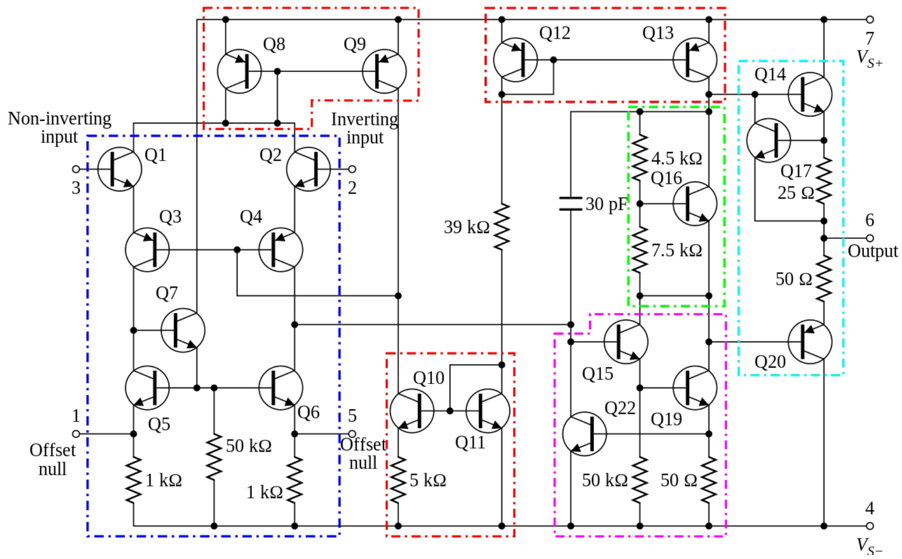


Figure 5.2
A typical op amp: (a) pin configuration, (b) circuit symbol.



Equivalent Circuit:

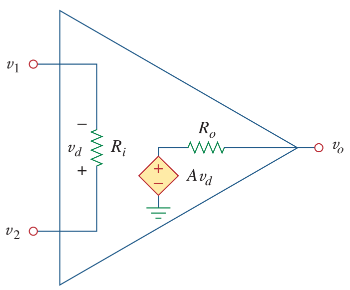


Figure 5.4
The equivalent circuit of the nonideal op amp.

So that $v_0 = Av_d = A(v_2 - v_1)$. With *open-loop gain* $A \sim 10^5$.

Input-output characteristics:

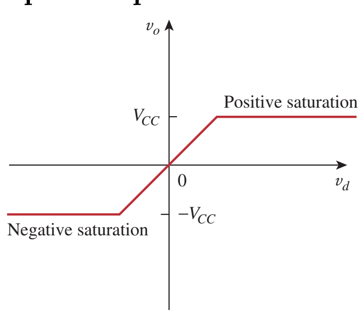
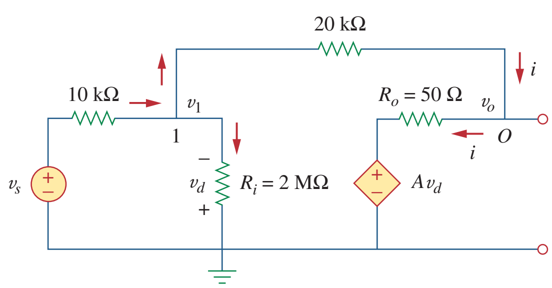


Figure 5.5
Op amp output voltage v_o as a function of the differential input voltage v_d.

Non-ideal Op-Amp Model: Find v_0 due to v_s, i.e., find the *transfer function* ($\frac{v_0}{v_s} = ?$) with open-loop gain $A = 5 * 10^5$.



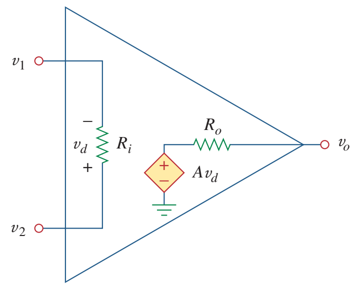


Figure 5.4
The equivalent circuit of the nonideal op amp.

```
%% Example 5.1 Non-ideal Op-amp model
clear all
% Declare symbolic variables
syms v1 vs vo A
% Node equations in solve function for ouput vo in terms of input vs
% Note: v0 = -vd
[vo,v1] = solve(v1/(2*10^6) + (v1-vs)/10000 + (v1 - vo)/20000 == 0,...
  (vo-v1)/20000 + (vo + A * v1)/50 == 0, vo, v1)
H = vo/vs
% Substitute A = 5*10^5
eval(subs(H, A, 5*10^5))
%
```

... *which yields* ...

```
vo = -(200*vs*(400*A - 1))/(40000*A + 120601)
v1 = (80200*vs)/(40000*A + 120601)
H = -(200*(400*A - 1))/(40000*A + 120601)
ans = -2
```

So that, more simply,

$$\frac{v_o}{v_s} = -2 = -\frac{20k}{10k}$$

... the negative of the ratio of the feedback resistor to the input resistor.

Ideal Op Amp Model: An op amp is *ideal* if it has the following characteristics:

1. Infinite open-loop gain, A
2. Infinite input resistance, R_i
3. Zero output resistance, $R_o = 0$.

with corollaries:

1. Virtual open circuit: $i_0 = 0$, $i_1 = 0$
2. Virtual short circuit: $v_d = 0$

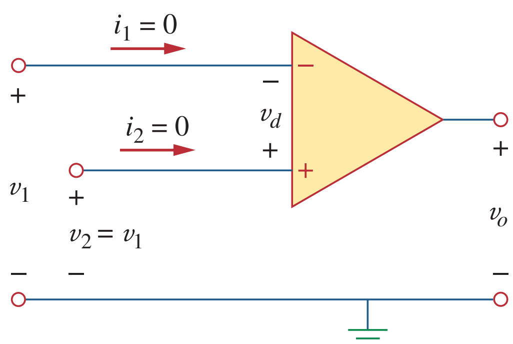
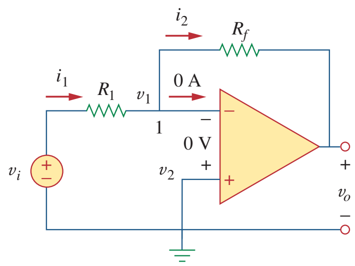


Figure 5.8
Ideal op amp model.

(Almost) Every ideal op-amp problem on the planet is solved by writing a node equation at the inverting input.

Four common configurations:

Most resistor op-amp circuits are simple enough to solve by inspection or in one node equation. We'll use a solver to continue being proficient in writing directly to Matlab. And we'll need a solver when we add dynamic elements.



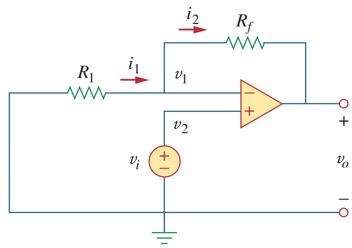
1. Inverting amplifier:

```
%% Ideal Op-amp model: 1. Inverting Amplifier
clear all
% Declare symbolic variables
syms vi vo R1 Rf
% Node equations and solve for ouput vo in terms of input vs
vo = solve((0-vi)/R1 + (0-vo)/Rf == 0, vo)
H = vo/vi
%
```

... *which yields* ...

```
vo = -(Rf*vi)/R1
H = -Rf/R1
```

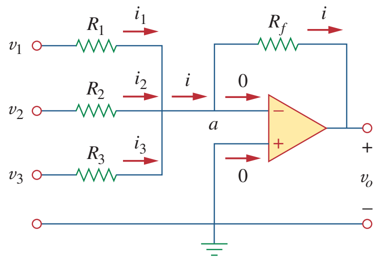
2. Non-Inverting amplifier:




```
%% Ideal Op-amp model: 2. Non-Inverting Amplifier
clear all
% Declare symbolic variables
syms vi vo R1 Rf
% Node equations and solve for ouput vo in terms of input vs
vo = solve(vi/R1 + (vi-vo)/Rf == 0, vo)
H = simplify(vo/vi)
%
```

... *which yields* ...

```
vo = (R1*vi + Rf*vi)/R1
H = (R1 + Rf)/R1
```



3. Summing amplifier:

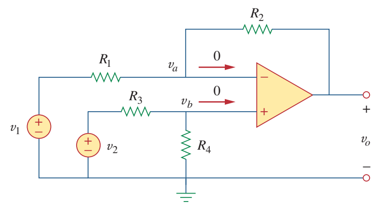
```
%% Ideal Op-amp model: 3. Summing Amplifier
clear all
% Declare symbolic variables
syms v1 v2 v3 vo R1 R2 R3 Rf
% Node equations and solve for ouput vo in terms of input vs
vo = solve((0-v1)/R1 + (0-v2)/R2 +(0-v3)/R3 + (0-vo)/Rf == 0, vo)
```

... *which yields* ...

```
vo = -Rf*(v1/R1 + v2/R2 + v3/R3)
%
```

And so we again see the results of *Superposition*.

4. Difference amplifier:




```
%% Ideal Op-amp model: 4. Difference Amplifier
clear all
% Declare symbolic variables - with a sensible relabeling of resistors
syms v1 v2 vx vo R1 R2 R3 Rf
% Node equations and solve for ouput vo in terms of input vs
[vo, vx] = solve((vx-v1)/R1 + (vx-vo)/Rf == 0,...
  vx == v2*R2/(R2+R3), vo, vx)
vo = (R1*R2*v2 - R2*Rf*v1 + R2*Rf*v2 - R3*Rf*v1)/(R1*(R2 + R3))
vx = (R2*v2)/(R2 + R3)
collect(vo, [v1,v2])
%
```

... *which yields* ...

```
vx = (R2*v2)/(R2 + R3)
vo = (-(R2*Rf + R3*Rf)/(R1*(R2 + R3)))*v1 + ((R1*R2 + R2*Rf)/(R1*(R2 + R3)))*v2
```

Which is yet another *Superposition* result.

Procedure for Solving Ideal Op-Amp Problems

Most resistor-only op-amp circuits are simple enough to solve by inspection or by writing a single one node equation. A solver is helpful when the circuit includes dynamic elements.

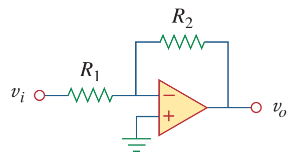
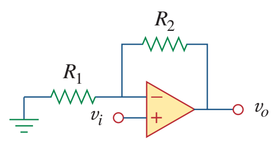
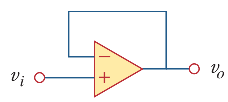
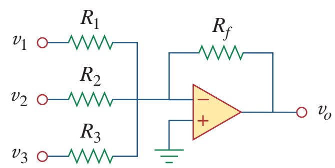
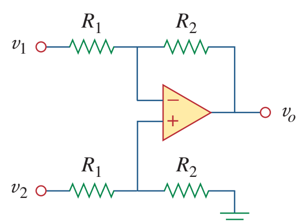
Ideal Op-Amp Solution:

1. Replace the independent source inputs with symbolic inputs V_{in} and I_{in} except in the simplest problems.
2. Make note of every observation that follows from the properties of the Ideal Model.
3. Many resistor-only circuits can be solved by inspection.
4. *Or* ... write a node equation at the inverting input.
5. Observe the result in terms of a *Transfer Function* when appropriate.
6. Answer whatever question(s) are posed concerning the circuit quantity of interest.

Homework: Chapter 5 # 8, 12, 17, 22, 23, 27, 29, 32, 38, 40, 45, 54, 57, 59, 60, 65, 71, 73

TABLE 5.3

Summary of basic op amp circuits.

Op amp circuit	Name/output-input relationship
	Inverting amplifier $v_o = -\frac{R_2}{R_1} v_i$
	Noninverting amplifier $v_o = \left(1 + \frac{R_2}{R_1}\right) v_i$
	Voltage follower $v_o = v_i$
	Summer $v_o = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3\right)$
	Difference amplifier $v_o = \frac{R_2}{R_1}(v_2 - v_1)$

3. An ideal op amp has an infinite input resistance, a zero output resistance, and an infinite gain.
4. For an ideal op amp, the current into each of its two input terminals is zero, and the voltage across its input terminals is negligibly small.
5. In an inverting amplifier, the output voltage is a negative multiple of the input.
6. In a noninverting amplifier, the output is a positive multiple of the input.
7. In a voltage follower, the output follows the input.
8. In a summing amplifier, the output is the weighted sum of the inputs.
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. 5.40, voltage v_o is:

(a) −6 V (b) −5 V
(c) −1.2 V (d) −0.2 V

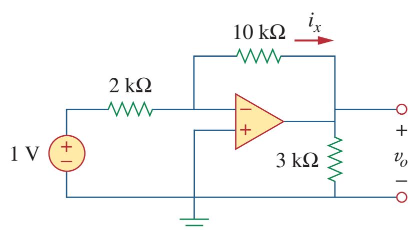


Figure 5.40
For Review Questions 5.3 and 5.4.

5.4 For the circuit in Fig. 5.40, current i_x is:

(a) 0.6 mA (b) 0.5 mA
(c) 0.2 mA (d) 1/12 mA

5.5 If $v_s = 0$ in the circuit of Fig. 5.41, current i_o is:

(a) −10 mA (b) −2.5 mA
(c) 10/12 mA (d) 10/14 mA

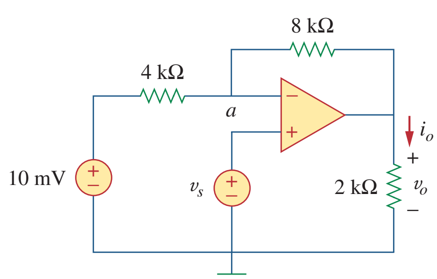


Figure 5.41
For Review Questions 5.5, 5.6, and 5.7.

5.6 If $v_s = 8$ mV in the circuit of Fig. 5.41, the output voltage is:

(a) −44 mV (b) −8 mV
(c) 4 mV (d) 7 mV

5.7 Refer to Fig. 5.41. If $v_s = 8$ mV, voltage v_a is:

(a) −8 mV (b) 0 mV
(c) 10/3 mV (d) 8 mV

5.8 The power absorbed by the 4-kΩ resistor in Fig. 5.42 is:

(a) 9 mW (b) 4 mW
(c) 2 mW (d) 1 mW

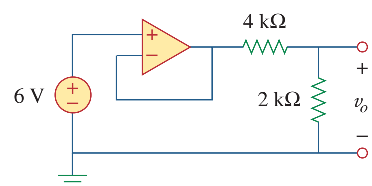


Figure 5.42
For Review Questions 5.8.

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 (please check all that apply):

(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. 5.43. Determine:

(a) the input resistance

(b) the output resistance

(c) the voltage gain in dB

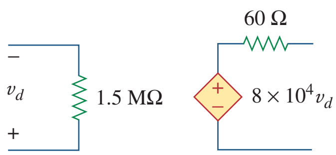


Figure 5.43
For Prob. 5.1.

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. 5.44, 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.

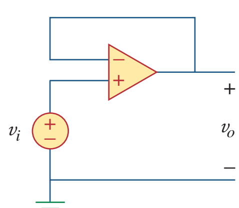


Figure 5.44
For Prob. 5.5.

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. 5.45.

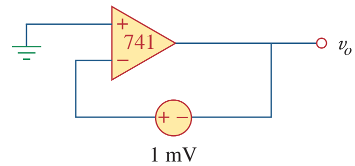


Figure 5.45
For Prob. 5.6.

5.7 The op amp in Fig. 5.46 has $R_i = 100$ kΩ, $R_o = 100\ \Omega$, $A = 100{,}000$. Find the differential voltage v_d and the output voltage v_o.

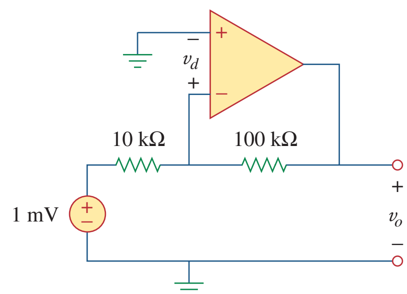


Figure 5.46
For Prob. 5.7.

Section 5.3 Ideal Op Amp

5.8 Obtain v_o for each of the op amp circuits in Fig. 5.47.

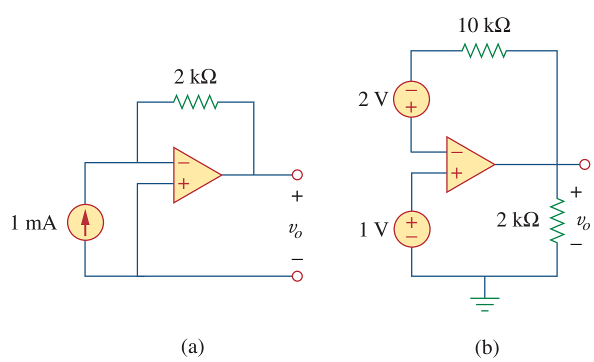


Figure 5.47
For Prob. 5.8.

5.9 Determine v_o for each of the op amp circuits in Fig. 5.48.

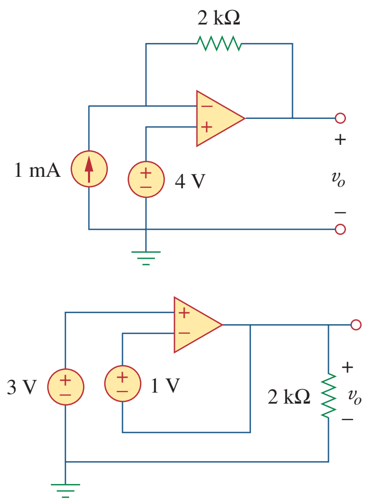


Figure 5.48
For Prob. 5.9.

5.10 Find the gain v_o/v_s of the circuit in Fig. 5.49.

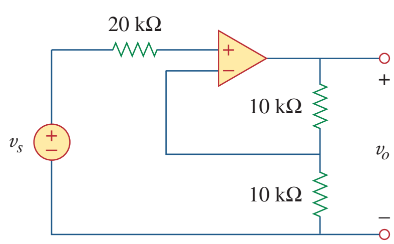


Figure 5.49
For Prob. 5.10.

5.11 Using Fig. 5.50, design a problem to help other students better understand how ideal op amps work.

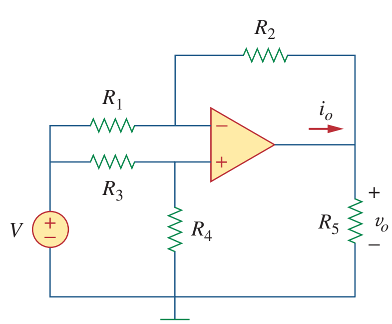


Figure 5.50
For Prob. 5.11.

5.12 Calculate the voltage ratio v_o/v_s for the op amp circuit of Fig. 5.51. Assume that the op amp is ideal.

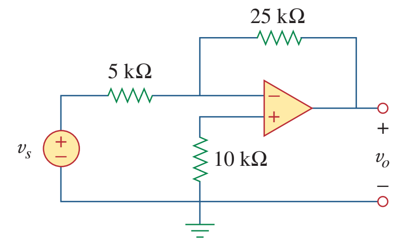


Figure 5.51
For Prob. 5.12.

5.13 Find v_o and i_o in the circuit of Fig. 5.52.

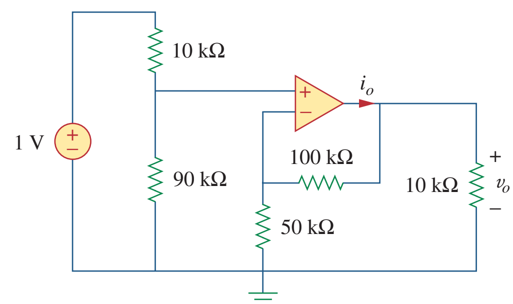


Figure 5.52
For Prob. 5.13.

5.14 Determine the output voltage v_o in the circuit of Fig. 5.53.

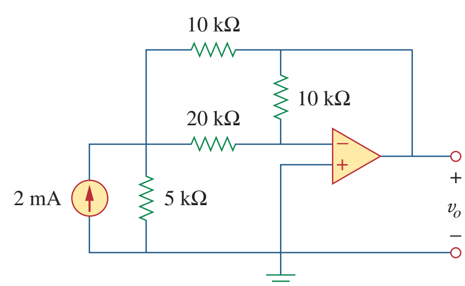


Figure 5.53
For Prob. 5.14.

Section 5.4 Inverting Amplifier

5.15 (a) Determine the ratio v_o/i_s in the op amp circuit of Fig. 5.54.

(b) Evaluate the ratio for $R_1 = 20$ kΩ, $R_2 = 25$ kΩ, $R_3 = 40$ kΩ.

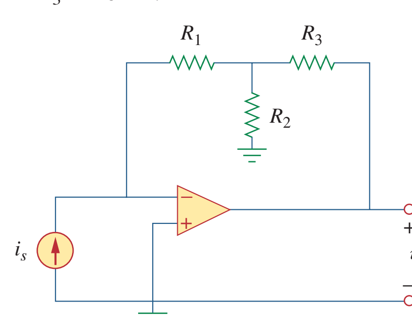


Figure 5.54
For Prob. 5.15.

5.16 Using Fig. 5.55, design a problem to help students better understand inverting op amps.

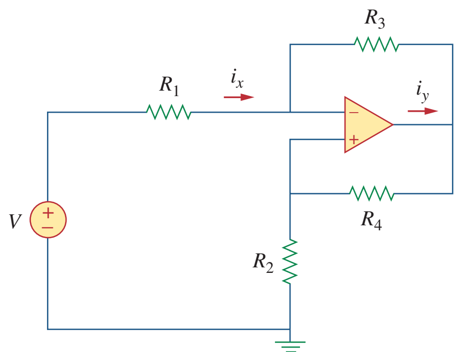


Figure 5.55
For Prob. 5.16.

5.17 Calculate the gain v_o/v_i when the switch in Fig. 5.56 is in:

(a) position 1 (b) position 2 (c) position 3.

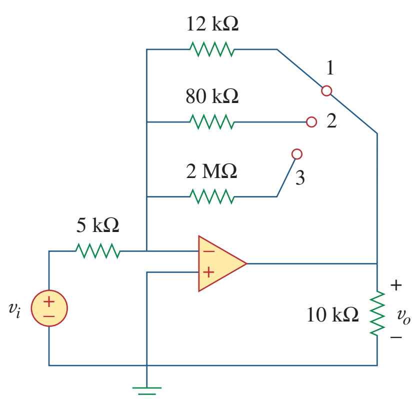


Figure 5.56
For Prob. 5.17.

***5.18** For the circuit shown in Figure 5.57, solve for the Thevenin equivalent circuit looking into terminals A and B.

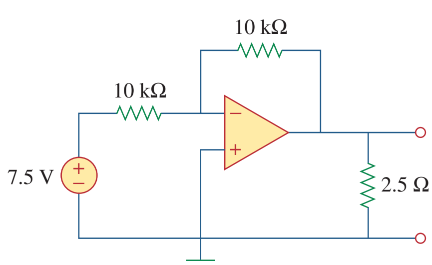


Figure 5.57
For Prob. 5.18.

5.19 Determine i_o in the circuit of Fig. 5.58.

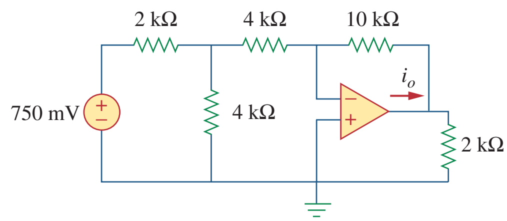


Figure 5.58
For Prob. 5.19.

5.20 In the circuit of Fig. 5.59, calculate v_o of $v_s = 2$ V.

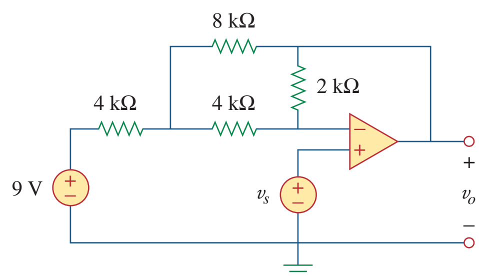


Figure 5.59
For Prob. 5.20.

5.21 Calculate v_o in the op amp circuit of Fig. 5.60.

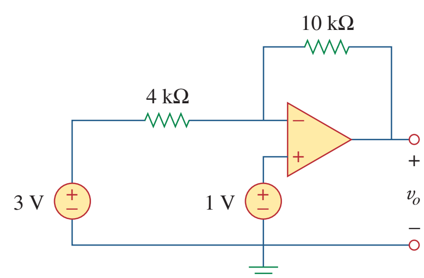


Figure 5.60
For Prob. 5.21.

5.22 Design an inverting amplifier with a gain of −15.

5.23 For the op amp circuit in Fig. 5.61, find the voltage gain v_o/v_s.

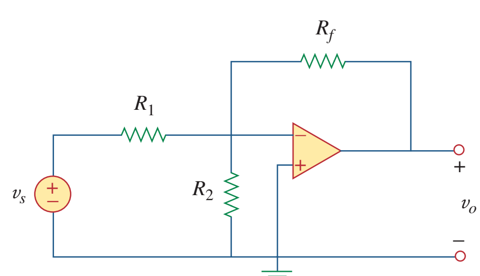


Figure 5.61
For Prob. 5.23.

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* An asterisk indicates a challenging problem.

5.24 In the circuit shown in Fig. 5.62, find k in the voltage transfer function $v_o = kv_s$.

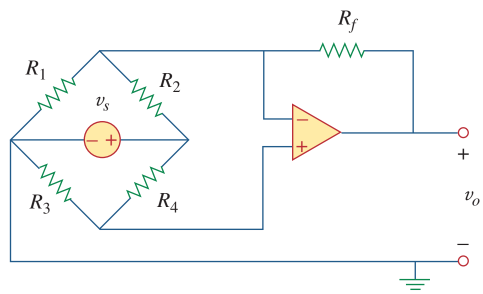


Figure 5.62
For Prob. 5.24.

Section 5.5 Noninverting Amplifier

5.25 Calculate v_o in the op amp circuit of Fig. 5.63.

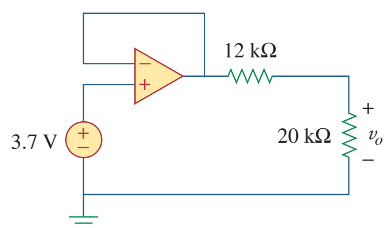


Figure 5.63
For Prob. 5.25.

5.26 Using Fig. 5.64, design a problem to help other
e⊘d students better understand noninverting op amps.

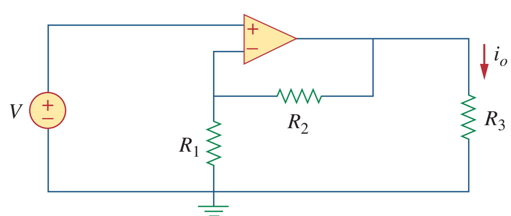


Figure 5.64
For Prob. 5.26.

5.27 Find v_o in the op amp circuit of Fig. 5.65.

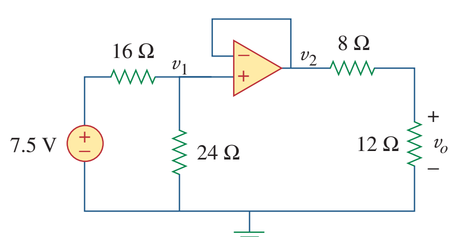


Figure 5.65
For Prob. 5.27.

5.28 Find i_o in the op amp circuit of Fig. 5.66.

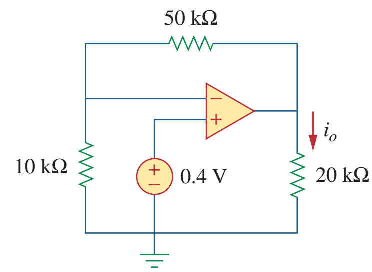


Figure 5.66
For Prob. 5.28.

5.29 Determine the voltage gain v_o/v_i of the op amp circuit in Fig. 5.67.

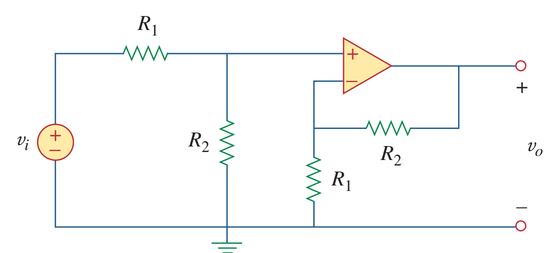


Figure 5.67
For Prob. 5.29.

5.30 In the circuit shown in Fig. 5.68, find $\boldsymbol{i_x}$ and the power absorbed by the 20-kΩ resistor.

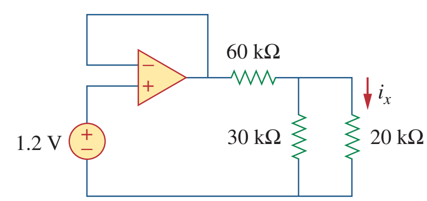


Figure 5.68
For Prob. 5.30.

5.31 For the circuit in Fig. 5.69, find i_x.

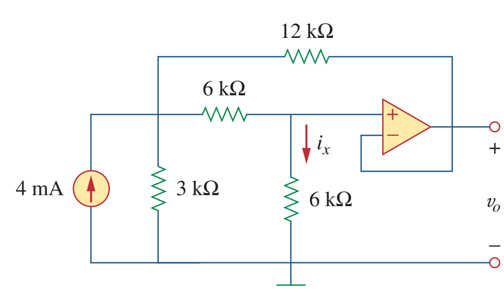


Figure 5.69
For Prob. 5.31.

5.32 Calculate i_x and v_o in the circuit of Fig. 5.70. Find the power dissipated by the 60-kΩ resistor.

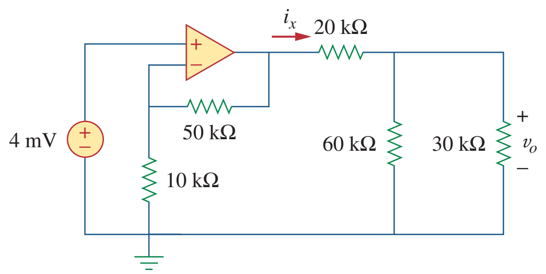


Figure 5.70
For Prob. 5.32.

5.33 Refer to the op amp circuit in Fig. 5.71. Calculate i_x and the power absorbed by the 3-kΩ resistor.

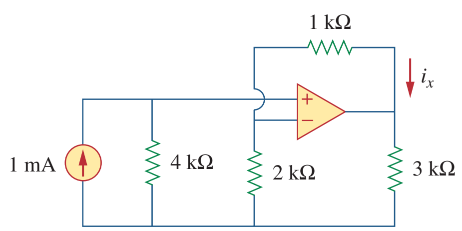


Figure 5.71
For Prob. 5.33.

5.34 Given the op amp circuit shown in Fig. 5.72, express v_o in terms of v_1 and v_2.

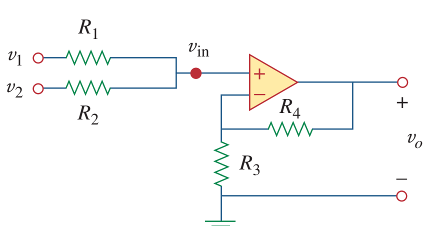


Figure 5.72
For Prob. 5.34.

5.35 Design a noninverting amplifier with a gain of 7.5.
e⁄d

5.36 For the circuit shown in Fig. 5.73, find the Thevenin equivalent at terminals *a-b*. (*Hint:* To find R_{Th}, apply a current source i_o and calculate v_o.)

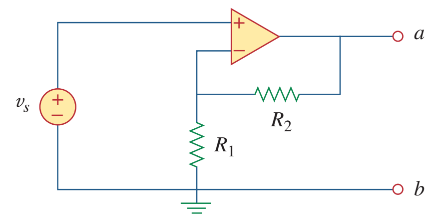


Figure 5.73
For Prob. 5.36.

Section 5.6 Summing Amplifier

5.37 Determine the output of the summing amplifier in Fig. 5.74.

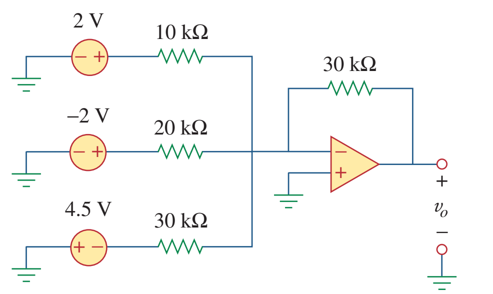


Figure 5.74
For Prob. 5.37.

5.38 Using Fig. 5.75, design a problem to help other students better understand summing amplifiers.
e⁄d

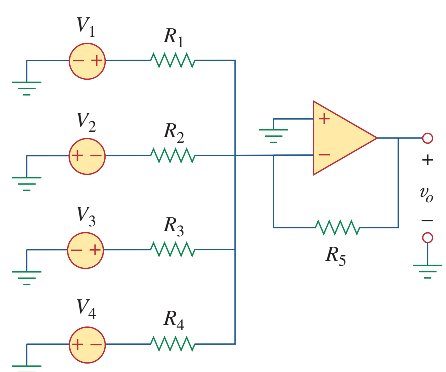


Figure 5.75
For Prob. 5.38.

5.39 For the op amp circuit in Fig. 5.76, determine the value of v_2 in order to make $v_o = -16.5$ V.

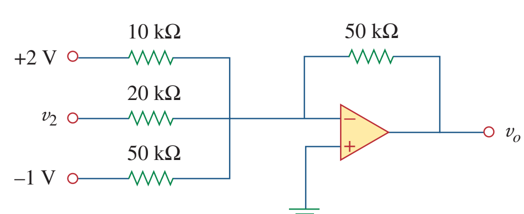


Figure 5.76
For Prob. 5.39.

5.40 Referring to the circuit shown in Fig. 5.77, determine V_o in terms of V_1 and V_2.

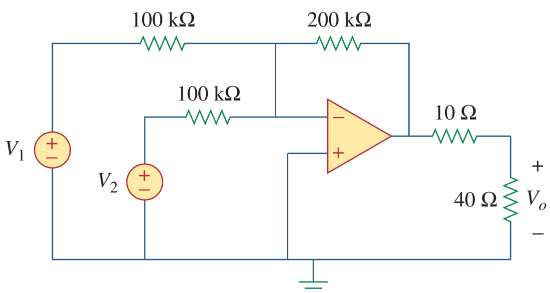


Figure 5.77
For Prob. 5.40.

5.41 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

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

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

5.42 A three-input summing amplifier has input resistors with $R_1 = R_2 = R_3 = 75$ kΩ. To produce an averaging amplifier, what value of feedback resistor is needed?

5.43 A four-input summing amplifier has $R_1 = R_2 = R_3 = R_4 = 80$ kΩ. What value of feedback resistor is needed to make it an averaging amplifier?

5.44 Show that the output voltage v_o of the circuit in Fig. 5.78 is

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

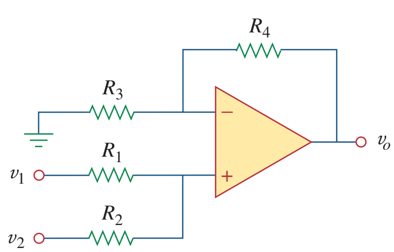


Figure 5.78
For Prob. 5.44.

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

$$v_o = 3v_1 - 2v_2$$

All resistances must be ≤ 100 kΩ.

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

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

Section 5.7 Difference Amplifier

5.47 The circuit in Fig. 5.79 is for a difference amplifier. Find v_o given that $v_1 = 1$ V and $v_2 = 2$ V.

vb: (vx-v1)/2k+(vx-vo)/30k=0

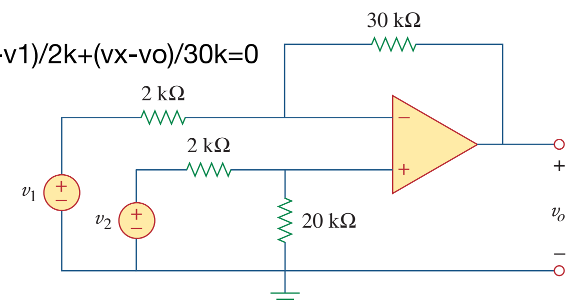


Figure 5.79
For Prob. 5.47.

vx: vx/20k+(vx-v2)/2k=0

5.48 The circuit in Fig. 5.80 is a differential amplifier driven by a bridge. Find v_o.

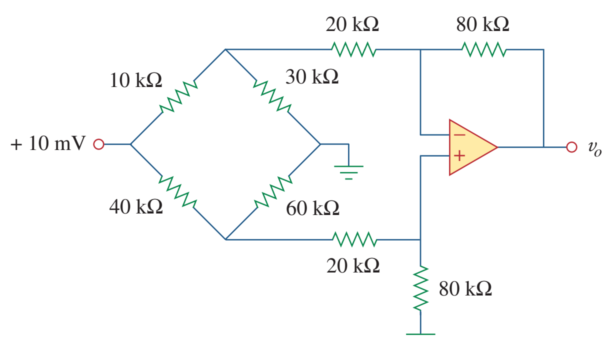


Figure 5.80
For Prob. 5.48.

5.49 Design a difference amplifier to have a gain of 4 and a common-mode input resistance of 20 kΩ at each input.

5.50 Design a circuit to amplify the difference between two inputs by 2.5.

(a) Use only one op amp.

(b) Use two op amps.

5.51 Using two op amps, design a subtractor.
e2d

***5.52** Design an op amp circuit such that
e2d

$$v_o = 4v_1 + 6v_2 - 3v_3 - 5v_4$$

Let all the resistors be in the range of 20 to 200 kΩ.

***5.53** The ordinary difference amplifier for fixed-gain operation is shown in Fig. 5.81(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. 5.81(b). Another way is to use the circuit in Fig. 5.81(c). Show that:

(a) for the circuit in Fig. 5.81(a),

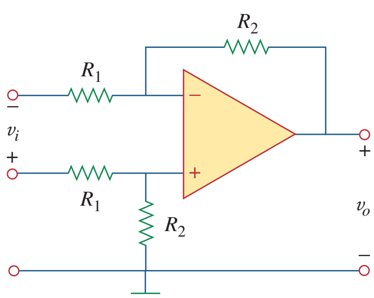
$$\frac{v_o}{v_i} = \frac{R_2}{R_1}$$

(b) for the circuit in Fig. 5.81(b),

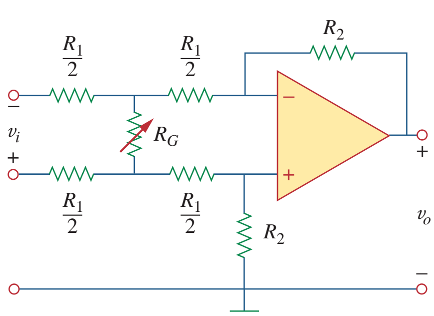
$$\frac{v_o}{v_i} = \frac{R_2}{R_1} \frac{1}{1 + \dfrac{R_1}{2R_G}}$$

(c) for the circuit in Fig. 5.81(c),

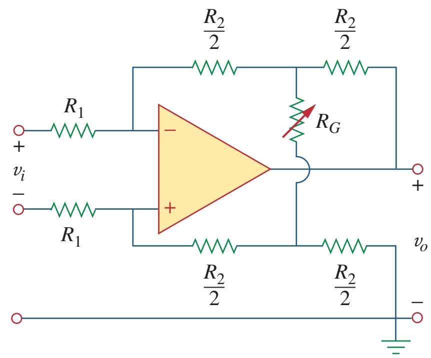
$$\frac{v_o}{v_i} = \frac{R_2}{R_1}\left(1 + \frac{R_2}{2R_G}\right)$$



(a)



(b)



(c)

Figure 5.81
For Prob. 5.53.

Section 5.8 Cascaded Op Amp Circuits

5.54 Determine the voltage transfer ratio v_o/v_s in the op amp circuit of Fig. 5.82, where R = 10 kΩ.

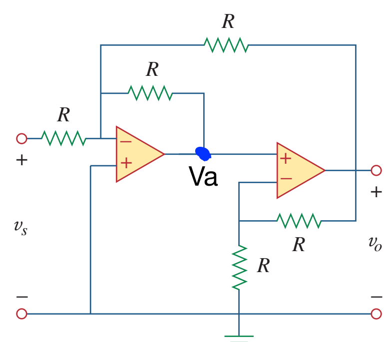


Figure 5.82
For Prob. 5.54.

5.55 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.

5.56 Using Fig. 5.83, design a problem to help other students better understand cascaded op amps.
e2d

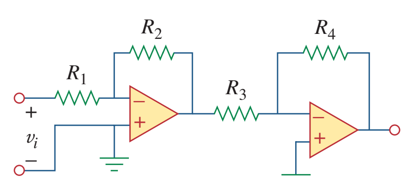


Figure 5.83
For Prob. 5.56.

5.57 Find v_o in the op amp circuit of Fig. 5.84.

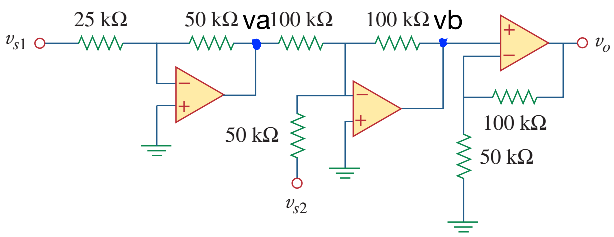


Figure 5.84
For Prob. 5.57.

5.58 Calculate i_o in the op amp circuit of Fig. 5.85.

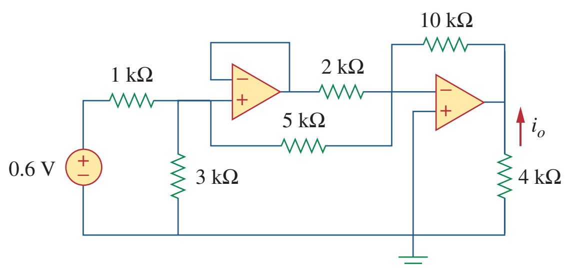


Figure 5.85
For Prob. 5.58.

5.59 In the op amp circuit of Fig. 5.86, determine the voltage gain v_o/v_s. Take $R = 10$ kΩ.

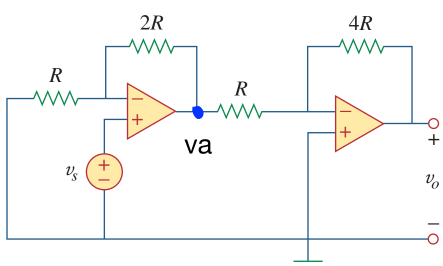


Figure 5.86
For Prob. 5.59.

5.60 Calculate v_o/v_i in the op amp circuit of Fig. 5.87.

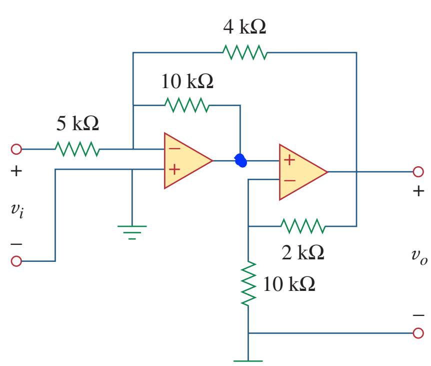


Figure 5.87
For Prob. 5.60.

5.61 Determine v_o in the circuit of Fig. 5.88.

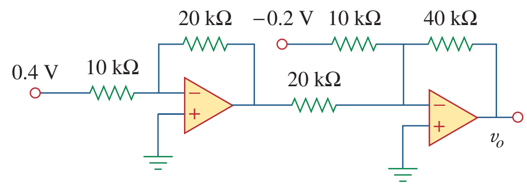


Figure 5.88
For Prob. 5.61.

5.62 Obtain the closed-loop voltage gain v_o/v_i of the circuit in Fig. 5.89.

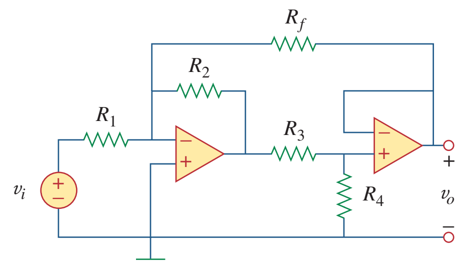


Figure 5.89
For Prob. 5.62.

5.63 Determine the gain v_o/v_i of the circuit in Fig. 5.90.

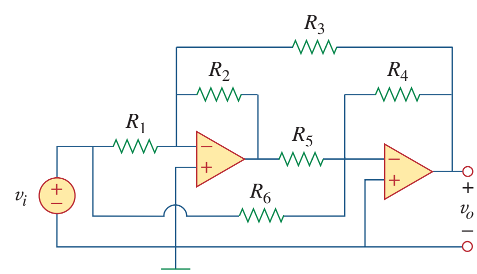


Figure 5.90
For Prob. 5.63.

5.64 For the op amp circuit shown in Fig. 5.91, find v_o/v_s.

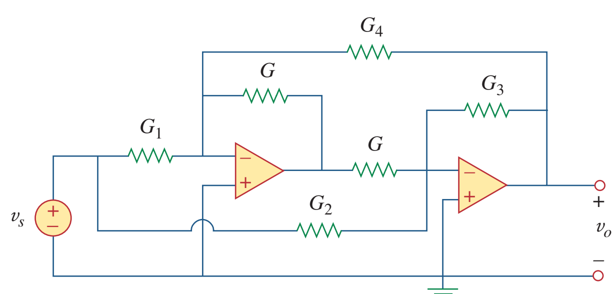


Figure 5.91
For Prob. 5.64.

5.65 Find v_o in the op amp circuit of Fig. 5.92.

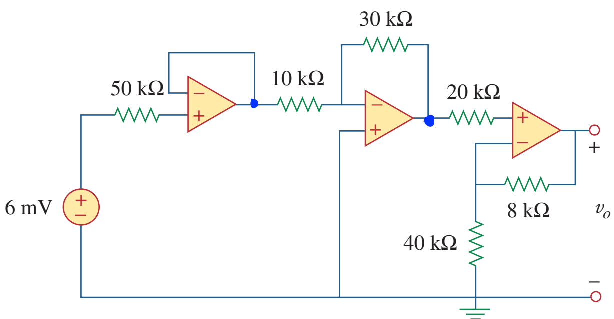


Figure 5.92
For Prob. 5.65.

5.66 For the circuit in Fig. 5.93, find v_o.

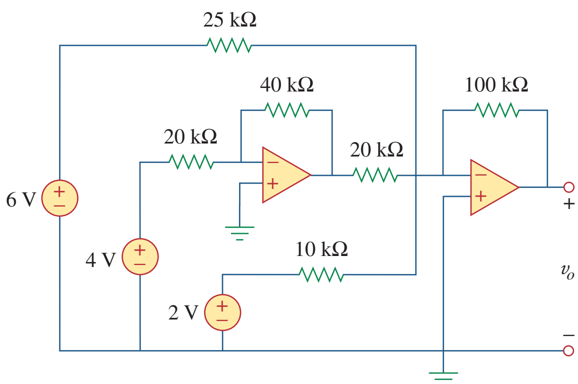


Figure 5.93
For Prob. 5.66.

5.67 Obtain the output v_o in the circuit of Fig. 5.94.

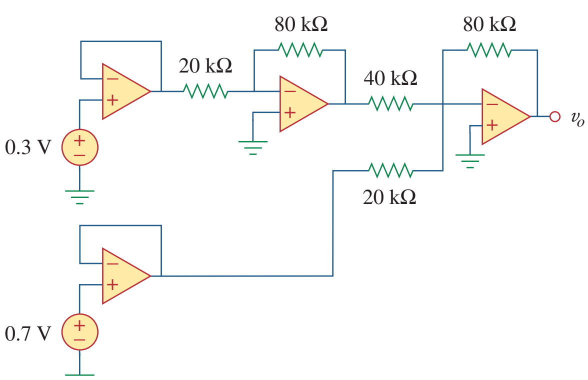


Figure 5.94
For Prob. 5.67.

5.68 Find v_o in the circuit of Fig. 5.95, assuming that $R_f = \infty$ (open circuit).

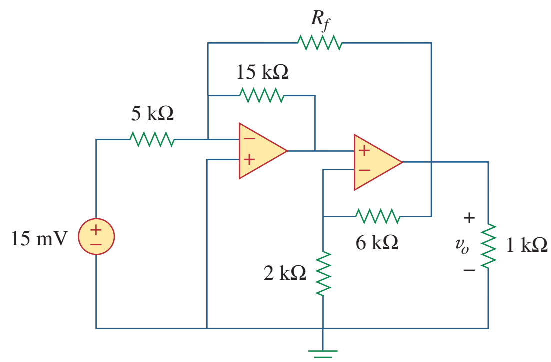


Figure 5.95
For Probs. 5.68 and 5.69.

5.69 Repeat the previous problem if $R_f = 10\ \text{k}\Omega$.

5.70 Determine v_o in the op amp circuit of Fig. 5.96.

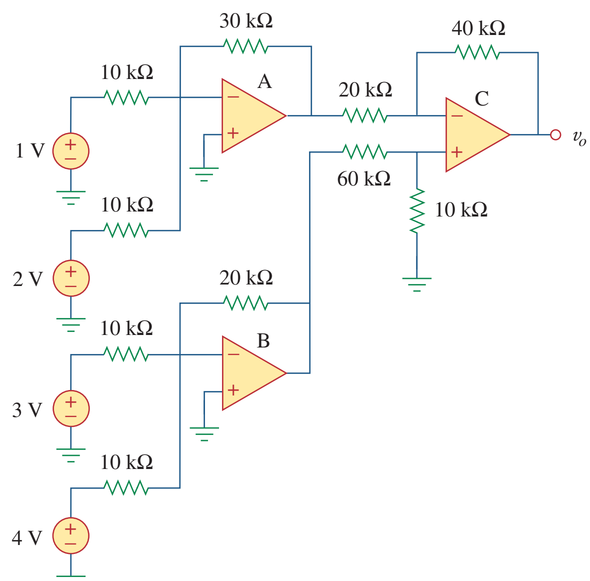


Figure 5.96
For Prob. 5.70.

5.71 Determine v_o in the op amp circuit of Fig. 5.97.

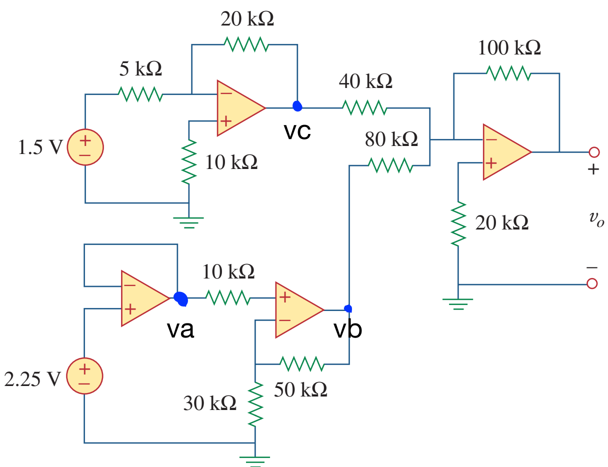


Figure 5.97
For Prob. 5.71.

5.72 Find the load voltage v_L in the circuit of Fig. 5.98.

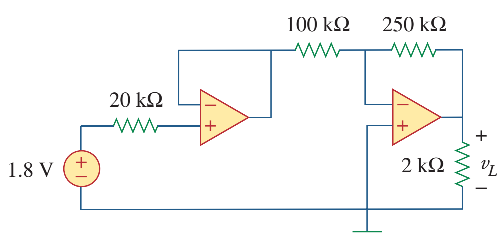


Figure 5.98
For Prob. 5.72.

5.73 Determine the load voltage v_L in the circuit of Fig. 5.99.

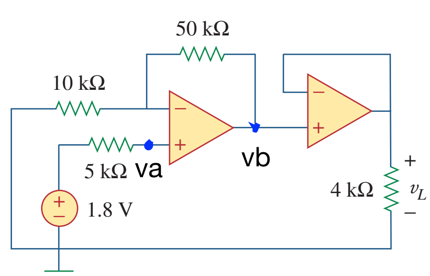


Figure 5.99
For Prob. 5.73.

5.74 Find i_o in the op amp circuit of Fig. 5.100.

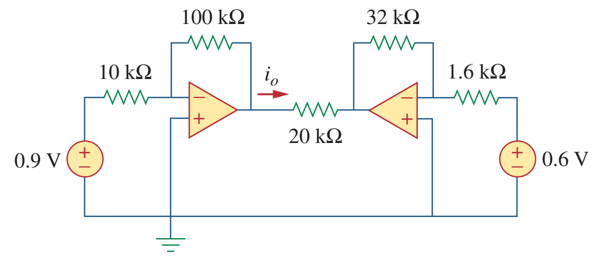


Figure 5.100
For Prob. 5.74.

Section 5.9 Op Amp Circuit Analysis with *PSpice*

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

5.76 Solve Prob. 5.19 using *PSpice* or *MultiSim* and op amp uA741.

5.77 Solve Prob. 5.48 using *PSpice* or *MultiSim* and op amp LM324.

5.78 Use *PSpice* or *MultiSim* to obtain v_o in the circuit of Fig. 5.101.

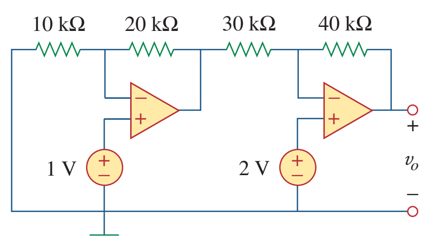


Figure 5.101
For Prob. 5.78.

5.79 Determine v_o in the op amp circuit of Fig. 5.102, using *PSpice* or *MultiSim.*

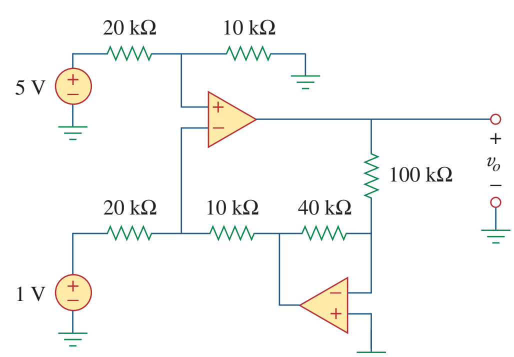


Figure 5.102
For Prob. 5.79.

5.80 Use *PSpice* or *MultiSim* to solve Prob. 5.70.

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

Section 5.10 Applications

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

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

(a) If $|V_o| = 1.1875$ V is desired, what should $[V_1V_2V_3V_4V_5V_6]$ be?

(b) Calculate $|V_o|$ if $[V_1V_2V_3V_4V_5V_6] = [011011]$.

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

***5.84** A four-bit *R-2R ladder* DAC is presented in Fig. 5.103.

(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 $[V_1V_2V_3V_4] = [1011]$ and $[V_1V_2V_3V_4] = [0101]$.

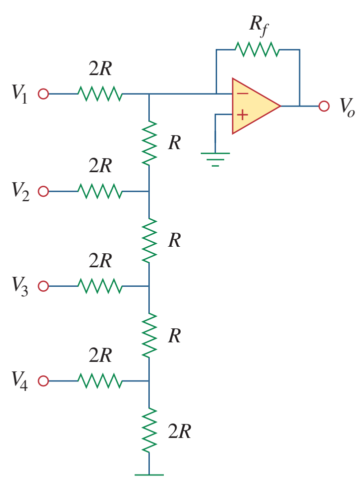


Figure 5.103
For Prob. 5.84.

5.85 In the op amp circuit of Fig. 5.104, find the value of R so that the power absorbed by the 10-kΩ resistor is 10 mW. Take $v_s = 2$ V.

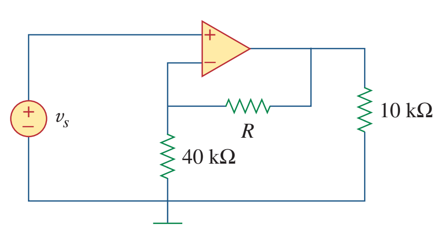


Figure 5.104
For Prob. 5.85.

5.86 Design a voltage controlled ideal current source (within the operating limits of the op amp) where the output current is equal to $200\, v_s(t)$ μA.

5.87 Figure 5.105 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?

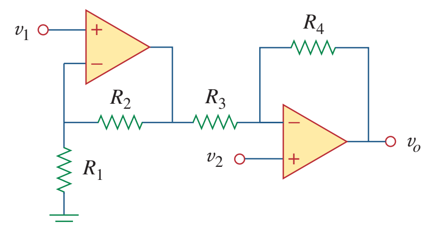


Figure 5.105
For Prob. 5.87.

***5.88** Figure 5.106 shows an instrumentation amplifier driven by a bridge. Obtain the gain v_o/v_i of the amplifier.

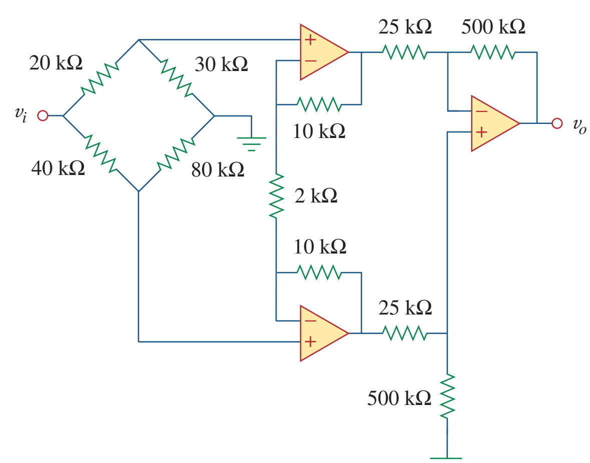


Figure 5.106
For Prob. 5.88.

Comprehensive Problems

5.89 Design a circuit that provides a relationship between output voltage v_o and input voltage v_s such that $v_o = 12v_s - 10$. Two op amps, a 6-V battery, and several resistors are available.

5.90 The op amp circuit in Fig. 5.107 is a *current amplifier*. Find the current gain i_o/i_s of the amplifier.

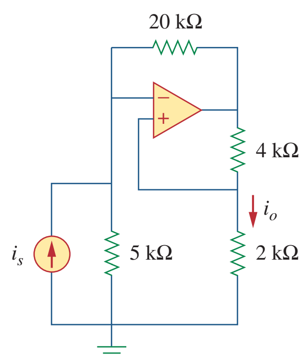


Figure 5.107
For Prob. 5.90.

5.91 A noninverting current amplifier is portrayed in Fig. 5.108. Calculate the gain i_o/i_s. Take $R_1 = 8$ kΩ and $R_2 = 1$ kΩ.

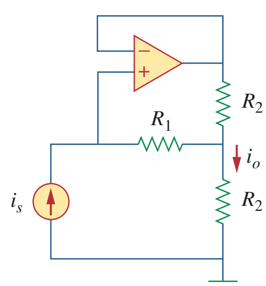


Figure 5.108
For Prob. 5.91.

5.92 Refer to the *bridge amplifier* shown in Fig. 5.109. Determine the voltage gain v_o/v_i.

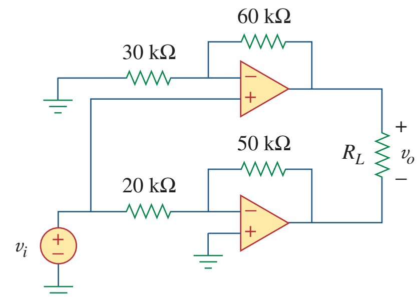


Figure 5.109
For Prob. 5.92.

***5.93** A voltage-to-current converter is shown in Fig. 5.110, which means that $i_L = Av_i$ if $R_1R_2 = R_3R_4$. Find the constant term A.

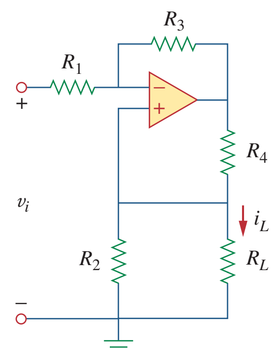


Figure 5.110
For Prob. 5.93.