Solution 5.1

(a) R_{in} = **1.5 MΩ**

(b) R_{out} = **60 Ω**

(c) $A = 8x10^4$

Therefore $A_{dB} = 20 \log 8x10^4$ = **98.06 dB**

Solution 5.2

The open-loop gain of an op amp is 50,000. Calculate the output voltage when there are inputs of +10 μV on the inverting terminal and + 20 μV on the noninverting terminal.

Solution

$$v_0 = Av_d = A(v_2 - v_1)$$
$$= 2\text{x}10^4 (20–10) \text{ x } 10^{-6} = \mathbf{100\ mV}$$

Solution 5.3

Determine the voltage input to the inverting terminal of an op amp when –40 µvolts is applied to the noninverting terminal and the output through an open-loop gain of 150,000 is 15 volts.

Solution

$$v_0 = Av_d = A(v_2 - v_1)$$
$$= 1.5 \text{ x } 10^5 (v_2 + 40\text{x } 10^{-6}) = 15 \text{ V or}$$

$$v_2 = (15 - 6)/(\ 0.15\text{x}10^6) = 9/(0.15\text{x}10^6) = \mathbf{60\ \mu V}.$$

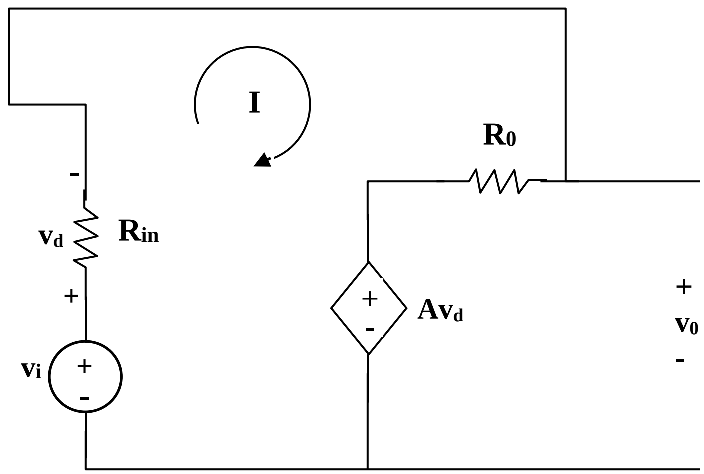
Solution 5.4

$v_0 = Av_d = A(v_2 - v_1)$

$$v_2 - v_1 = \frac{v_0}{A} = \frac{-4}{2x10^6} = -2\mu V$$

$v_2 - v_1 = -2\ \mu V = -0.002\ mV$
$1\ mV - v_1 = -0.002\ mV$
$v_1 =$ **1.002 mV**

Solution 5.5



$-v_i + Av_d + (R_i + R_0)\, I = 0 \qquad\qquad (1)$

But $\quad v_d = R_i I,$

$-v_i + (R_i + R_0 + R_i A)\, I = 0$

$$I = \frac{v_i}{R_0 + (1 + A)R_i} \qquad (2)$$

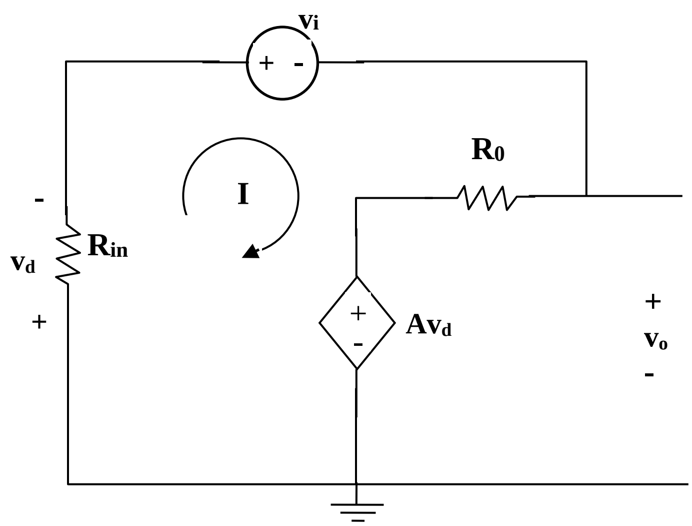
$-Av_d - R_0 I + v_0 = 0$

$$v_0 = Av_d + R_0 I = (R_0 + R_i A)I \;=\; \frac{(R_0 + R_i A)v_i}{R_0 + (1 + A)R_i}$$

$$\frac{v_0}{v_i} = \frac{R_0 + R_i A}{R_0 + (1 + A)R_i} = \frac{100 + 10^4\,x10^5}{100 + (1 + 10^5)} \cdot 10^4$$

$$\cong \frac{10^9}{\left(1 + 10^5\right)} \cdot 10^4 = \frac{100{,}000}{100{,}001} = \mathbf{0.9999990}$$

Solution 5.6



$$(R_0 + R_i)R + v_i + Av_d = 0$$

But $\quad v_d = R_iI,$

$$v_i + (R_0 + R_i + R_iA)I = 0$$

$$I = \frac{-v_i}{R_0 + (1+A)R_i} \qquad (1)$$

$$-Av_d - R_0I + v_o = 0$$

$$v_o = Av_d + R_0I = (R_0 + R_iA)I$$

Substituting for I in (1),

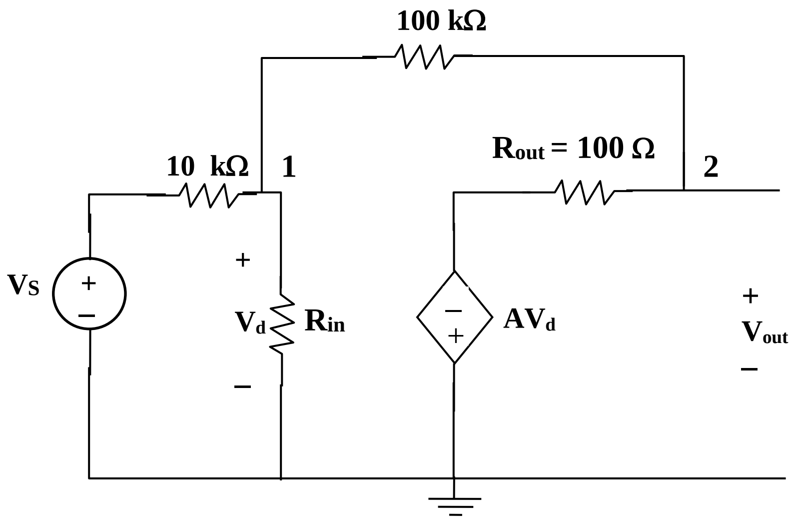
$$v_0 = -\left(\frac{R_0 + R_iA}{R_0 + (1+A)R_i}\right)v_i$$

$$= -\frac{\left(50 + 2x10^6\,x2x10^5\right)\cdot 10^{-3}}{50 + \left(1 + 2x10^5\right)x2x10^6}$$

$$\cong \frac{-200{,}000x2x10^6}{200{,}001x2x10^6}\,\text{mV}$$

$v_0 =$ **-0.999995 mV**

Solution 5.7



At node 1, $(V_S - V_1)/10\text{ k} = [V_1/100\text{ k}] + [(V_1 - V_0)/100\text{ k}]$

$10\,V_S - 10\,V_1 = V_1 + V_1 - V_0$

which leads to $V_1 = (10V_S + V_0)/12$

At node 2, $(V_1 - V_0)/100\text{ k} = (V_0 - (-AV_d))/100$

But $V_d = V_1$ and $A = 100{,}000$,

$V_1 - V_0 = 1000\,(V_0 + 100{,}000V_1)$

$0 = 1001V_0 + 99{,}999{,}999[(10V_S + V_0)/12]$

$0 = 83{,}333{,}332.5\,V_S + 8{,}334{,}334.25\,V_0$

which gives us $(V_0/V_S) = -10$ (for all practical purposes)

If $V_S = 1$ mV, then $V_0 = $ **-10 mV**

Since $V_0 = A\,V_d = 100{,}000\,V_d$, then $V_d = (V_0/10^5)\text{ V} = $ **-100 nV**

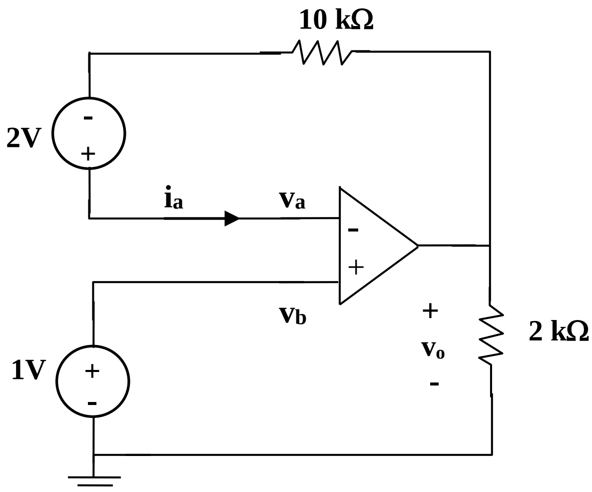
Solution 5.8

(a) If v_a and v_b are the voltages at the inverting and noninverting terminals of the op amp.

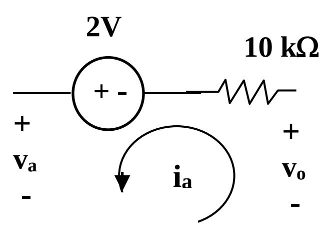
$v_a = v_b = 0$

$$1\text{mA} = \frac{0 - v_0}{2\text{k}} \longrightarrow v_0 = \mathbf{-2\ V}$$

(b)



(a)



(b)

Since $v_a = v_b = 1\text{V}$ and $i_a = 0$, no current flows through the 10 kΩ resistor. From Fig. (b),

$$-v_a + 2 + v_0 = 0 \longrightarrow v_0 = v_a - 2 = 1 - 2 = \mathbf{-1V}$$

Solution 5.9

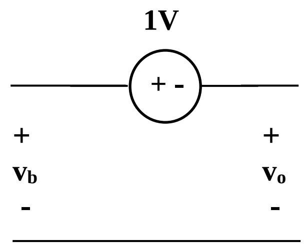
(a) Let v_a and v_b be respectively the voltages at the inverting and noninverting terminals of the op amp

$$v_a = v_b = 4V$$

At the inverting terminal,

$$1mA = \frac{4 - v_0}{2k} \longrightarrow v_0 = \mathbf{2V}$$

(b)



Since $v_a = v_b = 3V$,

$$-v_b + 1 + v_o = 0 \longrightarrow v_o = v_b - 1 = \mathbf{2V}$$

Solution 5.10

Since no current enters the op amp, the voltage at the input of the op amp is v_s. Hence

$$v_s = v_o \left(\frac{10}{10+10}\right) = \frac{v_o}{2} \longrightarrow \frac{v_o}{v_s} = \mathbf{2}$$

Solution 5.11

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

Although there are many ways to work this problem, this is an example based on the same kind of problem asked in the third edition.

Problem

Find v_o and i_o in the circuit in Fig. 5.50.

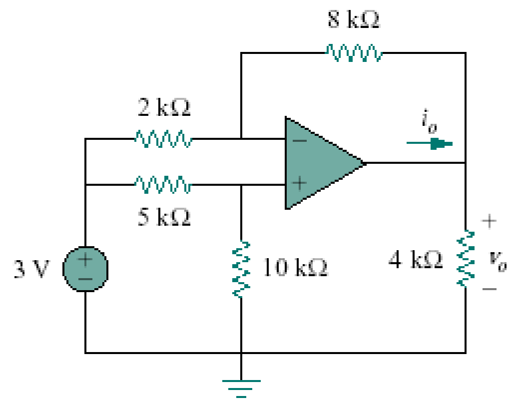
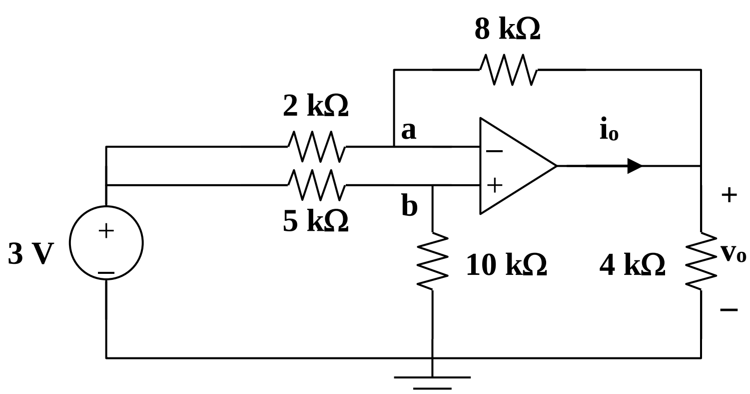


Figure 5.50 for Prob. 5.11

Solution



$$v_b = \frac{10}{10+5}(3) = 2V$$

At node a,

$$\frac{3-v_a}{2} = \frac{v_a - v_o}{8} \longrightarrow 12 = 5v_a - v_o$$

But $v_a = v_b = 2V$,

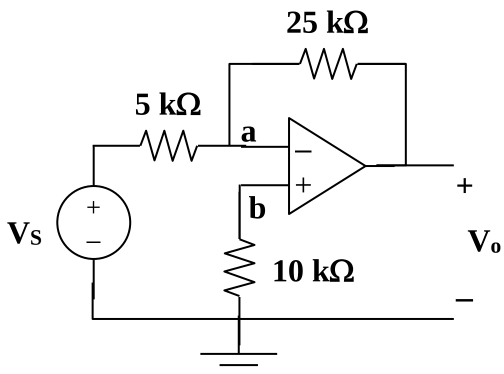
$$12 = 10 - v_o \longrightarrow v_o = \mathbf{-2V}$$

$$-i_o = \frac{v_a - v_o}{8} + \frac{0 - v_o}{4} = \frac{2+2}{8} + \frac{2}{4} = 1\text{mA}$$

$$i_o = \mathbf{-1mA}$$

Solution 5.12

Step 1. Label the unknown nodes in the op amp circuit. Next we write the node equations and then apply the constraint, $V_a = V_b$. Finally, solve for V_o in terms of V_s.



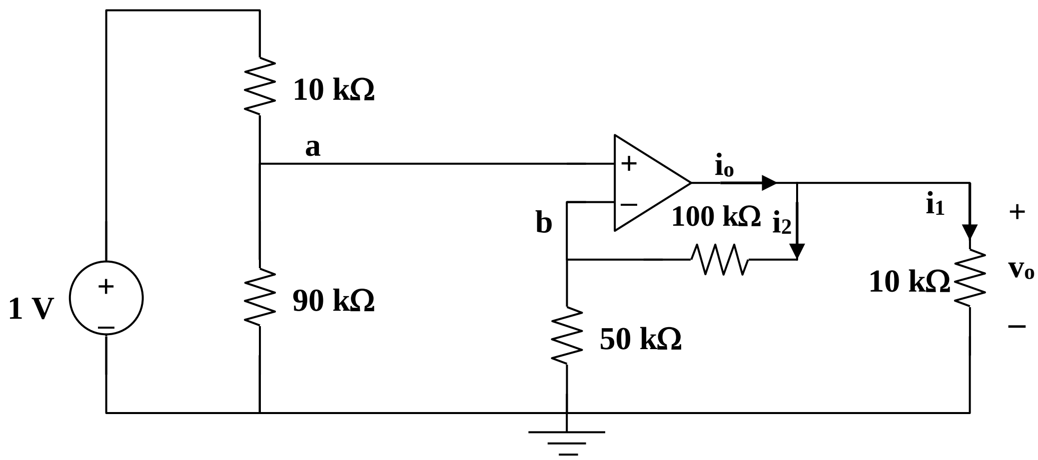
Step 2. $[(V_a\text{-}V_s)/5k] + [(V_a\text{-}V_o)/25k] + 0 = 0$ and

$[(V_b\text{-}0)/10k] + 0 = 0$ or $V_b = 0 = V_a$! Thus,

$[(\text{-}V_s)/5k] + [(\text{-}V_o)/25k] = 0$ or,

$$V_o = (\,-25/5)V_s \text{ or } V_o/V_s = \mathbf{-5}.$$

Solution 5.13



By voltage division,

$$v_a = \frac{90}{100}(1) = 0.9\text{V}$$

$$v_b = \frac{50}{150}v_o = \frac{v_o}{3}$$

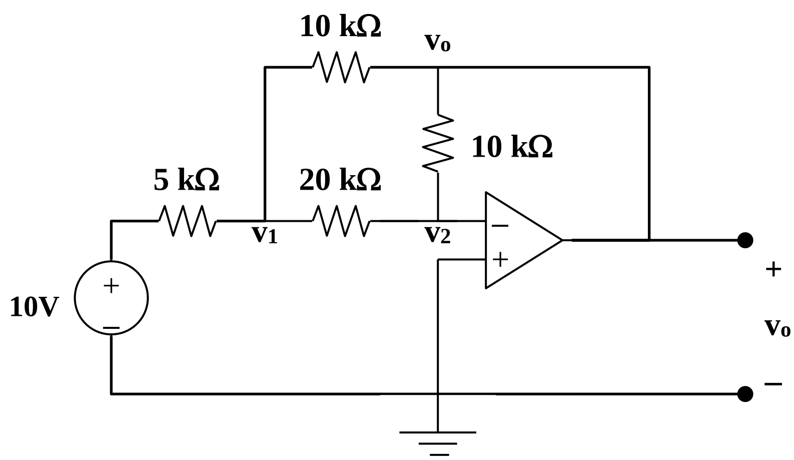
But $v_a = v_b \longrightarrow \frac{v_0}{3} = 0.9 \longrightarrow v_o =$ **2.7V**

$$i_o = i_1 + i_2 = \frac{v_o}{10\text{k}} + \frac{v_o}{150\text{k}} = 0.27\text{mA} + 0.018\text{mA} = \mathbf{288\ \mu A}$$

Solution 5.14

Transform the current source as shown below. At node 1,

$$\frac{10 - v_1}{5} = \frac{v_1 - v_2}{20} + \frac{v_1 - v_o}{10}$$



But $v_2 = 0$. Hence $40 - 4v_1 = v_1 + 2v_1 - 2v_o \longrightarrow$ $40 = 7v_1 - 2v_o$ (1)

At node 2, $\frac{v_1 - v_2}{20} = \frac{v_2 - v_o}{10}$, $v_2 = 0$ or $v_1 = -2v_o$ (2)

From (1) and (2), $40 = -14v_o - 2v_o \longrightarrow$ $v_o = \mathbf{-2.5V}$

Solution 5.15

(a) Let v_1 be the voltage at the node where the three resistors meet. Applying KCL at this node gives

$$i_s = \frac{v_1}{R_2} + \frac{v_1 - v_o}{R_3} = v_1\left(\frac{1}{R_2} + \frac{1}{R_3}\right) - \frac{v_o}{R_3} \qquad (1)$$

At the inverting terminal,

$$i_s = \frac{0 - v_1}{R_1} \quad \longrightarrow \quad v_1 = -i_s R_1 \qquad (2)$$

Combining (1) and (2) leads to

$$\boldsymbol{i_s\left(1 + \frac{R_1}{R_2} + \frac{R_1}{R_3}\right) = -\frac{v_o}{R_3} \quad \longrightarrow \quad \underline{\frac{v_o}{i_s} = -\left(R_1 + R_3 + \frac{R_1 R_3}{R_2}\right)}}$$

(b) For this case,

$$\frac{v_o}{i_s} = -\left(20 + 40 + \frac{20x40}{25}\right)\text{k}\Omega = \underline{-92\ \text{k}\Omega}$$

= **–92 kΩ**

Solution 5.16

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

Although there are many ways to work this problem, this is an example based on the same kind of problem asked in the third edition.

Problem

Obtain i_x and i_y in the op amp circuit in Fig. 5.55.

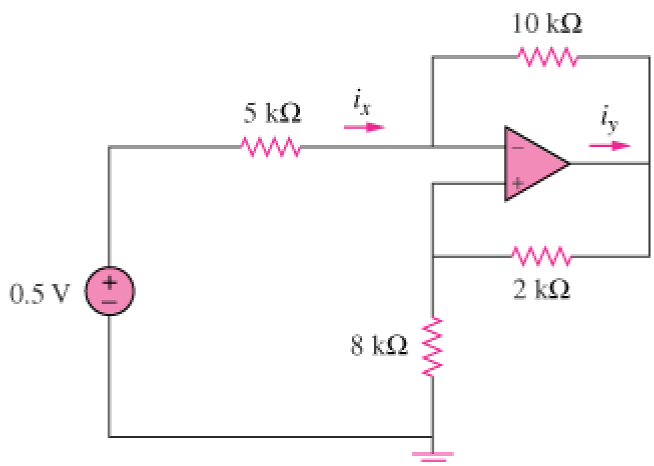
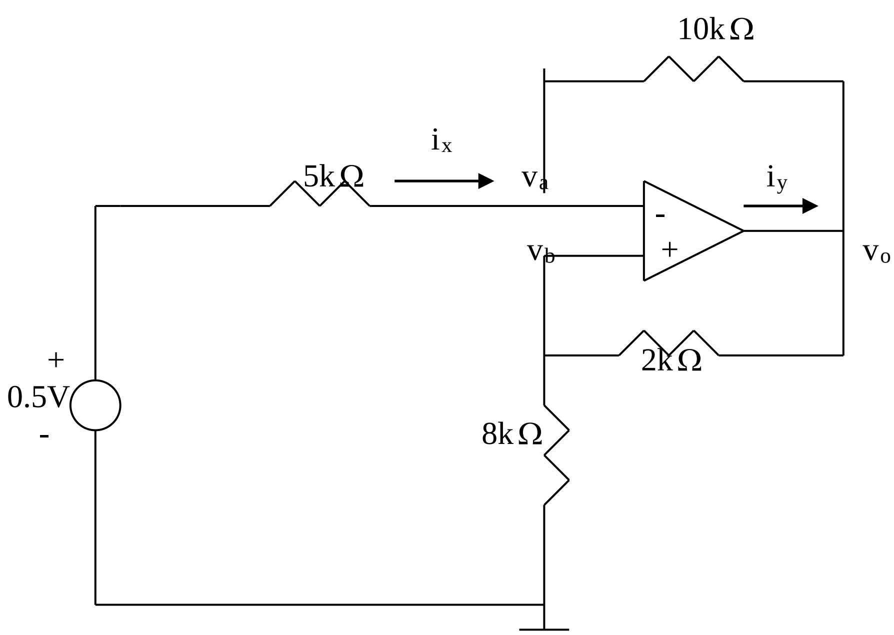


Figure 5.55

Solution



Let currents be in mA and resistances be in kΩ. At node a,

$$\frac{0.5 - v_a}{5} = \frac{v_a - v_o}{10} \longrightarrow 1 = 3v_a - v_o \qquad (1)$$

But

$$v_a = v_b = \frac{8}{8+2} v_o \longrightarrow v_o = \frac{10}{8} v_a \qquad (2)$$

Substituting (2) into (1) gives

$$1 = 3v_a - \frac{10}{8} v_a \longrightarrow v_a = \frac{8}{14}$$

Thus,

$$i_x = \frac{0.5 - v_a}{5} = -1/70 \text{ mA} = \underline{-14.28\ \mu\text{A}}$$

$$\boldsymbol{i_y = \frac{v_o - v_b}{2} + \frac{v_o - v_a}{10} = 0.6(v_o - v_a) = 0.6(\frac{10}{8} v_a - v_a) = \frac{0.6}{4}\ x\ \frac{8}{14}\ \textbf{mA}}$$

= **85.71 μA**

Solution 5.17

(a) $$G = \frac{v_o}{v_i} = -\frac{R_f}{R_i} = -\frac{12}{5} = \mathbf{-2.4}$$

(b) $$\frac{v_o}{v_i} = -\frac{80}{5} = \mathbf{-16}$$

(c) $$\frac{v_o}{v_i} = -\frac{2000}{5} = \mathbf{-400}$$

(a) **–2.4**, (b) **–16**, (c) **–400**

Solution 5.18

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

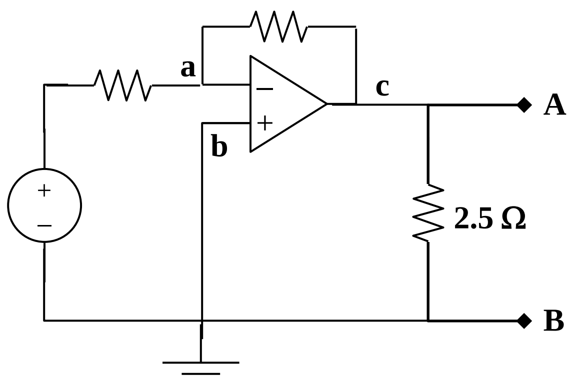


Figure 5.57
For Prob. 5.18.

Solution

Write a node equation at a. Since node b is tied to ground, $v_b = 0$. Since writing a node equation at c adds an additional unknown, the current from the op amp, we need to use the constraint equation, $v_a = v_b$. Once, we know v_c, we then proceed to solve for V_{oc} and I_{sc}. This will lead to $V_{Thev} = V_{oc}$ and $R_{eq} = V_{oc}/I_{sc}$.

$[(v_a – 9)/10k] + [(v_a – v_c)/10k] + 0 = 0$

Our constraint equation leads to,

$v_a = v_b = 0$ or $v_c = –9$ volts

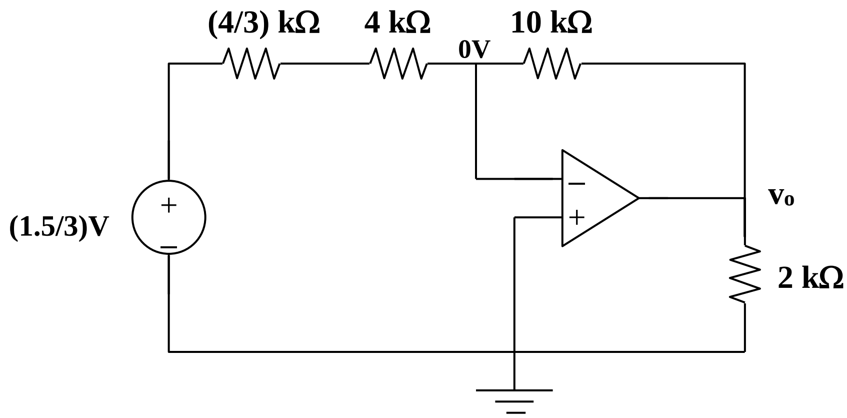
This is also the open circuit voltage (note, the op-amp keeps the output voltage at –9 volts in spite of any connection between A and B. Since this means that even a short from A to B would theoretically then produce an infinite current, $R_e = 0\ \Omega$. In real life, the short circuit current will be limited to whatever the op-amp can put out into a short circuited output.

V_{Thev} = **–9 volts**; R_{eq} = **0 Ω**.

Solution 5.19

We convert the current source and back to a voltage source.

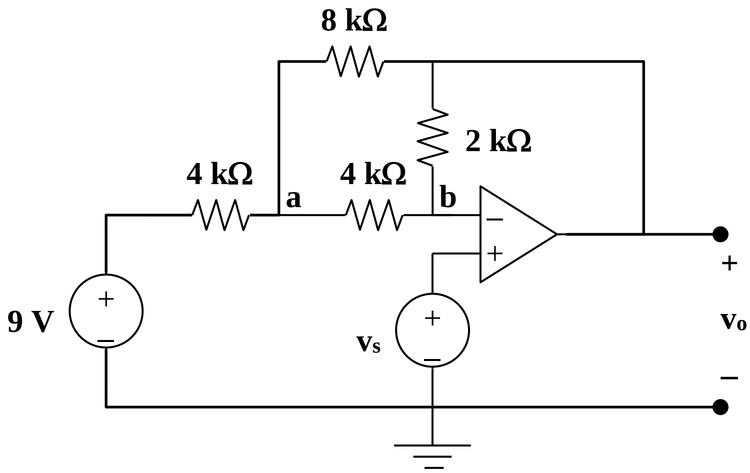
$$2 \| 4 = \frac{4}{3}$$



$$v_o = -\frac{10k}{\left(4+\frac{4}{3}\right)k}\left(\frac{1.5}{3}\right) = -937.5 \text{ mV}.$$

$$i_o = \frac{v_o}{2k} + \frac{v_o - 0}{10k} = \mathbf{-562.5\ \mu A}.$$

Solution 5.20



At node a,

$$\frac{9 - v_a}{4} = \frac{v_a - v_o}{8} + \frac{v_a - v_b}{4} \longrightarrow 18 = 5v_a - v_o - 2v_b \qquad (1)$$

At node b,

$$\frac{v_a - v_b}{4} = \frac{v_b - v_o}{2} \longrightarrow v_a = 3v_b - 2v_o \qquad (2)$$

But $v_b = v_s = 2$ V; (2) becomes $v_a = 6 - 2v_o$ and (1) becomes

$$-18 = 30 - 10v_o - v_o - 4 \qquad v_o = -44/(-11) = \mathbf{4\ V}.$$

Solution 5.21

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

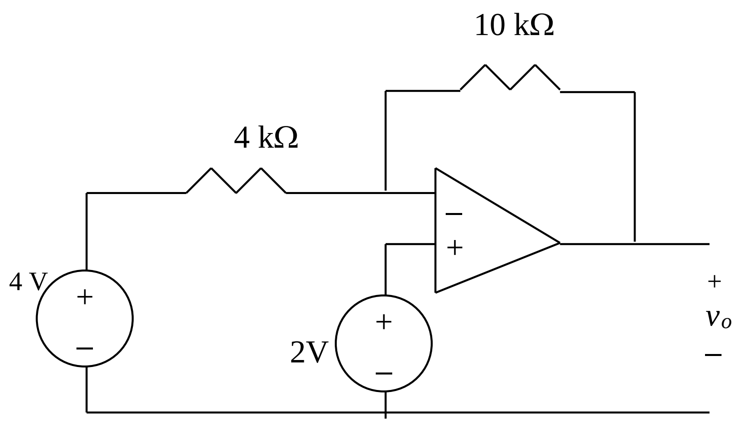


Figure 5.60
For Prob. 5.21.

Solution

Let the voltage at the inverting input of the op amp be v_a and at the noninverting input v_b. This leads to,

$[(v_a–4)/4k] + [(v_a–v_o)/10k] + 0 = 0$ with the constraint equation, $v_b = 2 = v_a$.

$v_o/10k = (–2/4k) + (2/10k) = (–0.5+0.2)/1k$ or

$v_o =$ **–3 V**.

Solution 5.22

$A_v = -R_f/R_i = -15.$

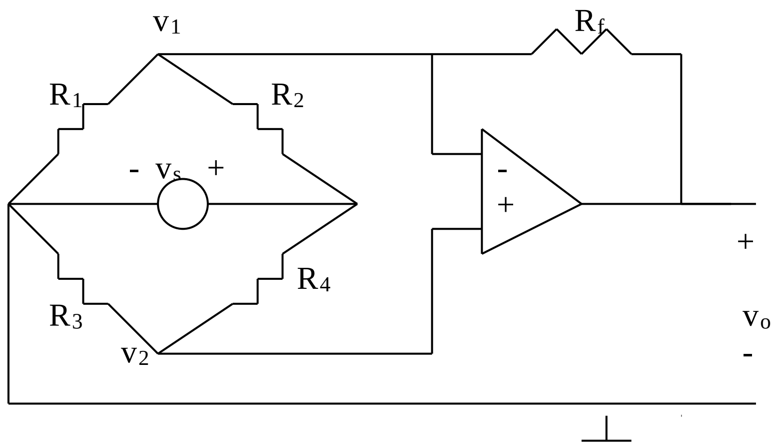
If $R_i = 10\text{k}\Omega$, then R_f = **150 kΩ.**

Solution 5.23

At the inverting terminal, v=0 so that KCL gives

$$\frac{v_s - 0}{R_1} = \frac{0}{R_2} + \frac{0 - v_o}{R_f} \longrightarrow \underline{\frac{v_o}{v_s} = -\frac{R_f}{R_1}}$$

Solution 5.24



We notice that $v_1 = v_2$. Applying KCL at node 1 gives

$$\frac{v_1}{R_1}+\frac{(v_1-v_s)}{R_2}+\frac{v_1-v_o}{R_f}=0 \quad\longrightarrow\quad \left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_f}\right)v_1-\frac{v_s}{R_2}=\frac{v_o}{R_f} \qquad (1)$$

Applying KCL at node 2 gives

$$\frac{v_1}{R_3}+\frac{v_1-v_s}{R_4}=0 \quad\longrightarrow\quad v_1=\frac{R_3}{R_3+R_4}v_s \qquad (2)$$

Substituting (2) into (1) yields

$$v_o=R_f\left[\left(\frac{R_3}{R_1}+\frac{R_3}{R_f}-\frac{R_4}{R_2}\right)\left(\frac{R_3}{R_3+R_4}\right)-\frac{1}{R_2}\right]v_s$$

i.e.

$$\underline{\boldsymbol{k=R_f\left[\left(\frac{R_3}{R_1}+\frac{R_3}{R_f}-\frac{R_4}{R_2}\right)\left(\frac{R_3}{R_3+R_4}\right)-\frac{1}{R_2}\right]}}$$

Solution 5.25

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

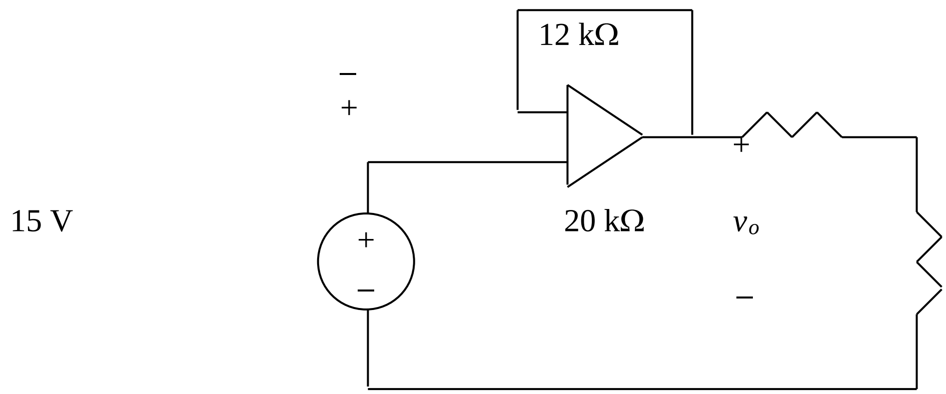


Figure 5.63
For Prob. 5.25.

Solution

This is a voltage follower. If v_c is the output of the op amp,

$v_c = 15$ V

$v_o = [20k/(20k+12k)]v_c = [20/32]15 =$ **9.375 V**.

Solution 5.26

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

Although there are many ways to work this problem, this is an example based on the same kind of problem asked in the third edition.

Problem

Determine $\boldsymbol{i_o}$ in the circuit of Fig. 5.64.

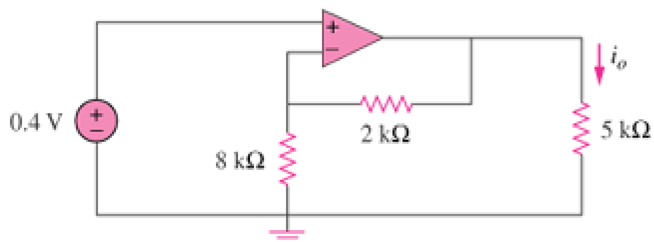
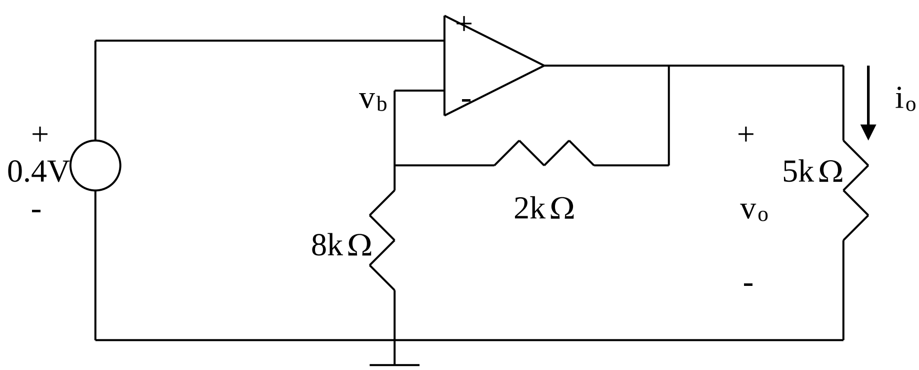


Figure 5.64

Solution



$$v_b = 0.4 = \frac{8}{8+2}v_o = 0.8v_o \longrightarrow v_o = 0.4/0.8 = 0.5\,\text{V}$$

Hence,

$$\boldsymbol{i_o = \frac{v_o}{5k} = \frac{0.5}{5k} = \underline{0.1\,\text{mA}}}$$

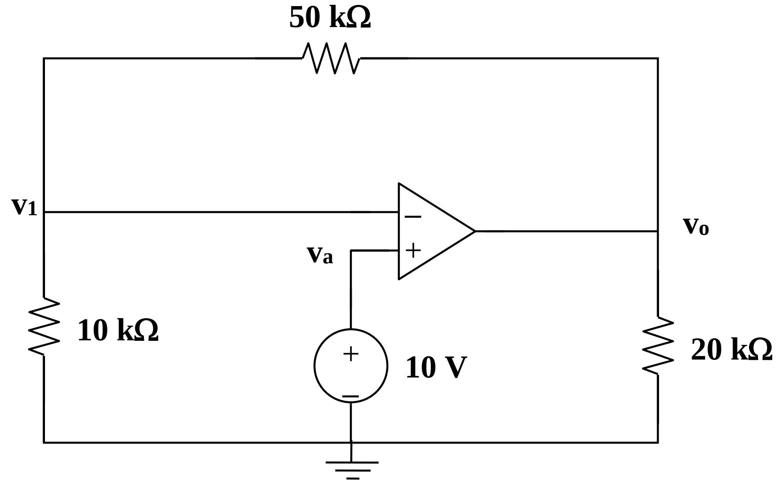
Solution 5.27

This is a voltage follower.

$v_1 = [24/(24+16)]7.5 = 4.5$ V; $v_2 = v_1 = 4.5$ V; and

$v_o = [12/(12+8)]4.5 =$ **2.7 V**.

Solution 5.28



At node 1, $\frac{0 - v_1}{10k} = \frac{v_1 - v_o}{50k}$

But v_1 = 10V,

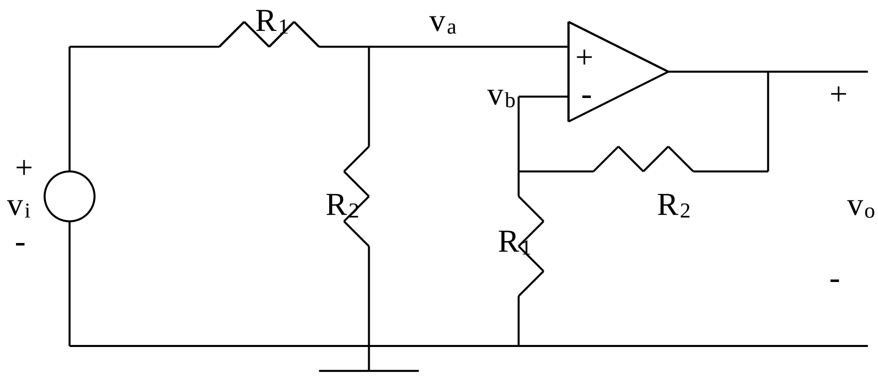
$-5v_1 = v_1 - v_o$, leads to $v_o = 6v_1 =$ **60V**

Alternatively, viewed as a noninverting amplifier,

$v_o = (1 + (50/10))\ (10V) =$ **60V**

$i_o = v_o/(20k) = 60/(20k) =$ **3 mA**.

Solution 5.29



$$v_a = \frac{R_2}{R_1 + R_2} v_i, \qquad v_b = \frac{R_1}{R_1 + R_2} v_o$$

But $v_a = v_b \quad \longrightarrow \quad \dfrac{R_2}{R_1 + R_2} v_i = \dfrac{R_1}{R_1 + R_2} v_o$

Or

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

Solution 5.30

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

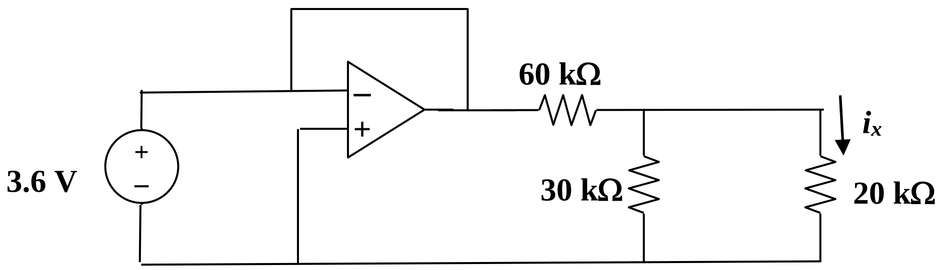


Figure 5.68
For Prob. 5.30.

Solution

The op amp is clearly a voltage follower with an output voltage equal to 3.6 V.

If we combine the parallel resistors together we get [20kx30k/(20k+30k)] = 12k.

The current through the 60 kΩ resistor is equal to 3.6/(60k+12k) = 50 µA. We now have a current divider and $i_x = 50\text{x}10^{-6}\text{x}30\text{k}/(30\text{k}+20\text{k})$ = **30 µA.**

Now we can calculate the power absorbed by the 20 kΩ resistor,

$p_{20} = (i_x)^2\text{x}20\text{k}$ = **18 µW**.

Solution 5.31

For the circuit in Fig. 5.69, find i_x.

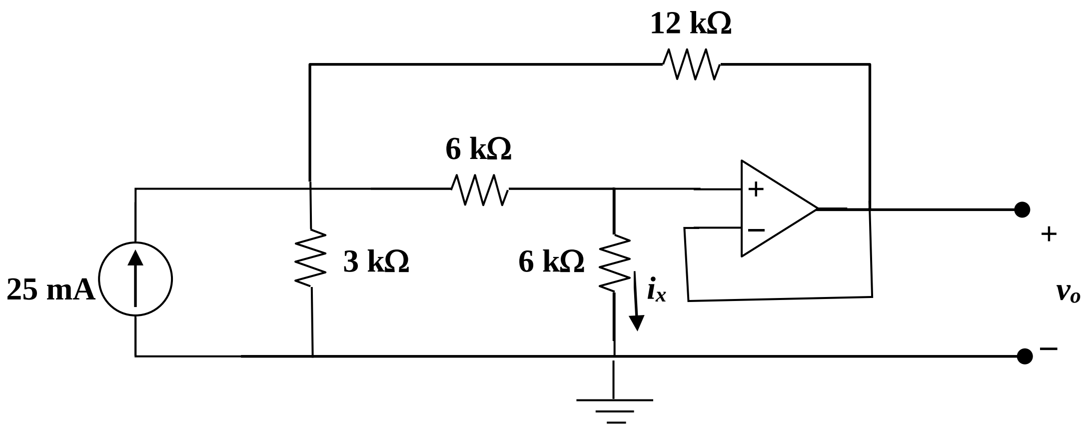
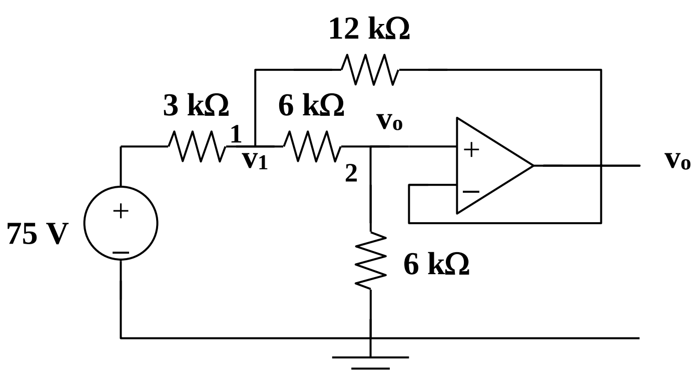


Figure 5.69
For Prob. 5.31.

Solution

After converting the current source to a voltage source, the circuit is as shown below:



At node 1, $[(v_1–75)/3k] + [(v_1–v_o)/6k] + [(v_1–v_o)/12k] = 0$ or

$$7v_1 – 3v_o = 300 \quad (1)$$

At node 2, $[(v_o–v_1)/6k] + [(v_o–0)/6k] + 0 = 0$ or $v_1 = 2v_o$ (2)

Finally, $i_x = [(v_o–0)/6k]$ (3)

From (1), (2), and (3) $14v_o – 3v_o = 300$ or $v_o = 27.27$ V and

$i_x =$ **4.545 mA**.

Solution 5.32

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

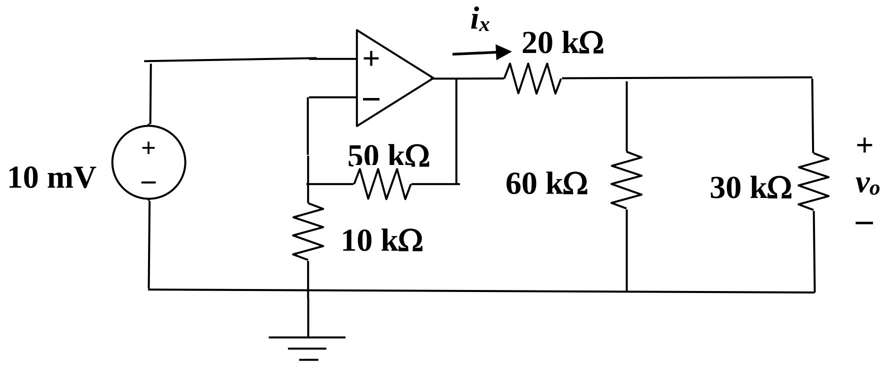


Figure 5.70
For Prob. 5.32.

Solution

Let
v_x = the voltage at the output of the op amp. The given circuit is a non-inverting amplifier.

$$v_x = \left(1+\frac{50}{10}\right)(10\text{ mV}) = 60\text{ mV}$$

$$60\|30 = 20\text{k}\Omega$$

By voltage division,

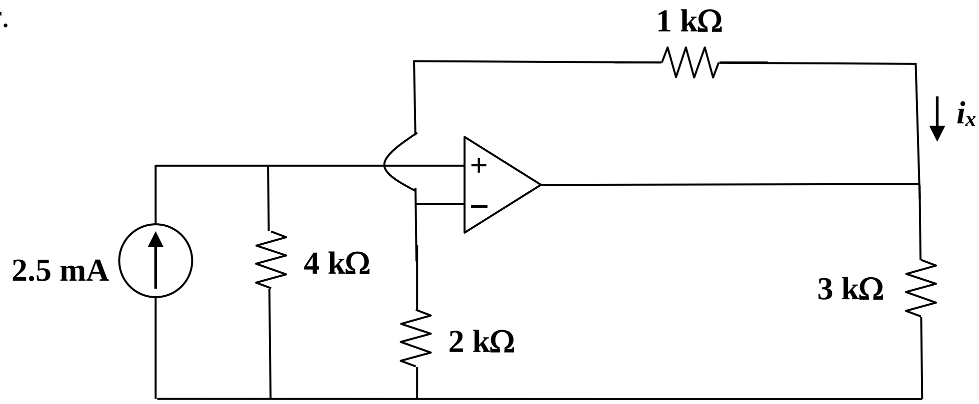
$$v_o = \frac{20}{20+20}v_x = \frac{v_x}{2} = 30\text{ mV}$$

$$i_x = \frac{v_x}{(20+20)k} = \frac{60mV}{40k} = \mathbf{1.5\ \mu A}$$

$$p = \frac{v_o^2}{R} = \frac{900x10^{-6}}{60x10^3} = \mathbf{15\ nW}.$$

Solution 5.33

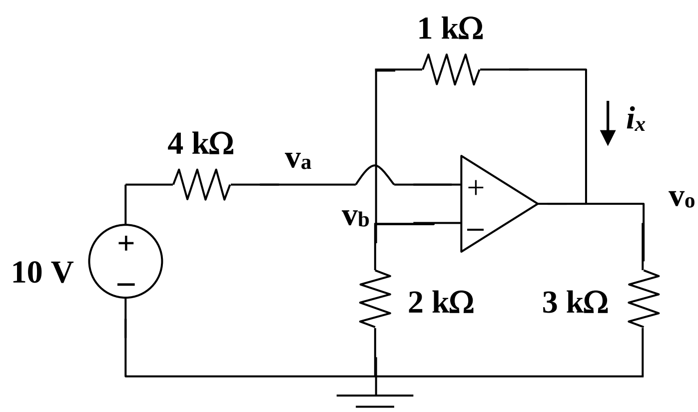
Refer to the op amp circuit in Fig. 5.71. Calculate i_x and the power absorbed by the 3-kΩ resistor.



igure 5.71
For Prob. 5.33.

Solution

After transforming the current source, the current is as shown below:



This is a noninverting amplifier which means that $[(v_b–0)/2k] + [(v_b–v_o)/1k] + 0 = 0$ and $v_a = 10 = v_b$. Thus, $2v_o = 3v_b = 30$ or $v_o = 15$ V.

Now $i_x = [(v_b–v_o)/1k] = –5/1k =$ **–1 mA** and $p_{3k} = (v_o)^2/3k =$ **75 mW**.

Solution 5.34

$$\frac{v_1 - v_{in}}{R_1} + \frac{v_1 - v_{in}}{R_2} = 0 \qquad (1)$$

but

$$v_a = \frac{R_3}{R_3 + R_4} v_o \qquad (2)$$

Combining (1) and (2),

$$v_1 - v_a + \frac{R_1}{R_2} v_2 - \frac{R_1}{R_2} v_a = 0$$

$$v_a \left(1 + \frac{R_1}{R_2}\right) = v_1 + \frac{R_1}{R_2} v_2$$

$$\frac{R_3 v_o}{R_3 + R_4}\left(1 + \frac{R_1}{R_2}\right) = v_1 + \frac{R_1}{R_2} v_2$$

$$v_o = \frac{R_3 + R_4}{R_3\left(1 + \frac{R_1}{R_2}\right)}\left(v_1 + \frac{R_1}{R_2} v_2\right)$$

$$v_O = \underline{\boldsymbol{\frac{R_3 + R_4}{R_3(R_1 + R_2)}(v_1 R_2 + v_2)}}$$

Solution 5.35

$$A_v = \frac{v_o}{v_i} = 1 + \frac{R_f}{R_i} = 7.5 \longrightarrow R_f = 6.5R_i$$

If R_i = **60 kΩ**, R_f = **390 kΩ**.

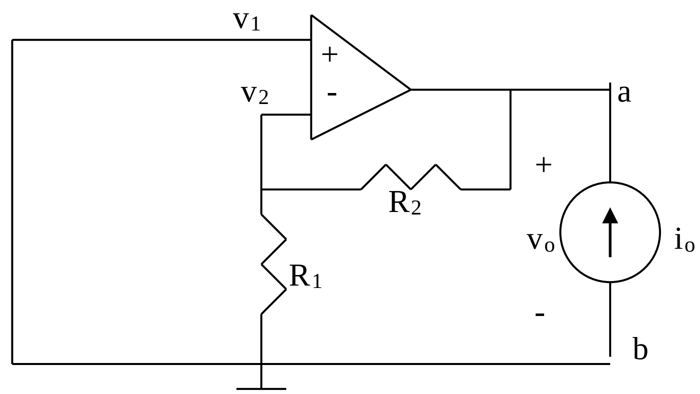
Solution 5.36

$V_{Th} = V_{ab}$

But $\quad v_s = \dfrac{R_1}{R_1 + R_2} V_{ab}$. Thus,

$V_{Th} = V_{ab} = \dfrac{R_1 + R_2}{R_1} v_s = \underline{(1 + \dfrac{R_2}{R_1}) v_s}$

To get R_{Th}, apply a current source I_o at terminals a-b as shown below.



Since the noninverting terminal is connected to ground, $v_1 = v_2 = 0$, i.e. no current passes through R_1 and consequently R_2. Thus, $v_o = 0$ and

$$\underline{\boldsymbol{R_{Th} = \frac{v_o}{i_o} = 0}}$$

Solution 5.37

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

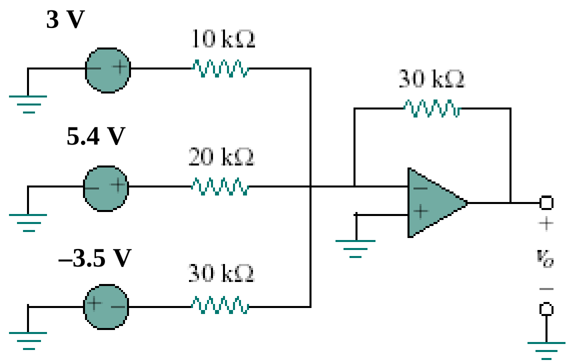


Figure 5.74
For Prob. 5.37.

Solution

$$v_o = -\left[\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right]$$

$$= -\left[\frac{30}{10}(3) + \frac{30}{20}(5.4) + \frac{30}{30}(-3.5)\right]$$

v_o = **–13.6 V**.

Solution 5.38

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

Although there are many ways to work this problem, this is an example based on the same kind of problem asked in the third edition.

Problem

Calculate the output voltage due to the summing amplifier shown in Fig. 5.75.

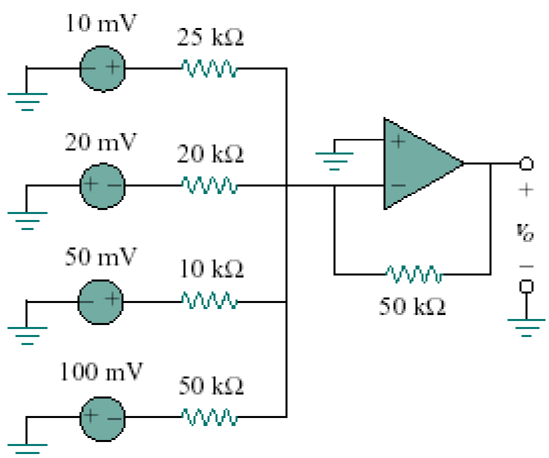


Figure 5.75

Solution

$$v_o = -\left[\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3 + \frac{R_f}{R_4}v_4\right]$$

$$= -\left[\frac{50}{25}(10) + \frac{50}{20}(-20) + \frac{50}{10}(50) + \frac{50}{50}(-100)\right]$$

= **-120mV**

Solution 5.39

For the op amp circuit in Fig. 5.76, determine the value of v_2 in order to make v_o = –7.5 V.

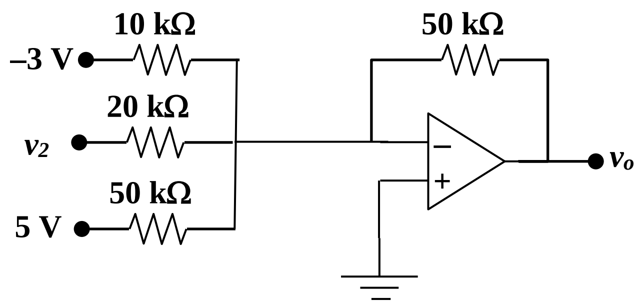


Figure 5.76
For Prob. 5.39.

Solution

This is a summing amplifier.

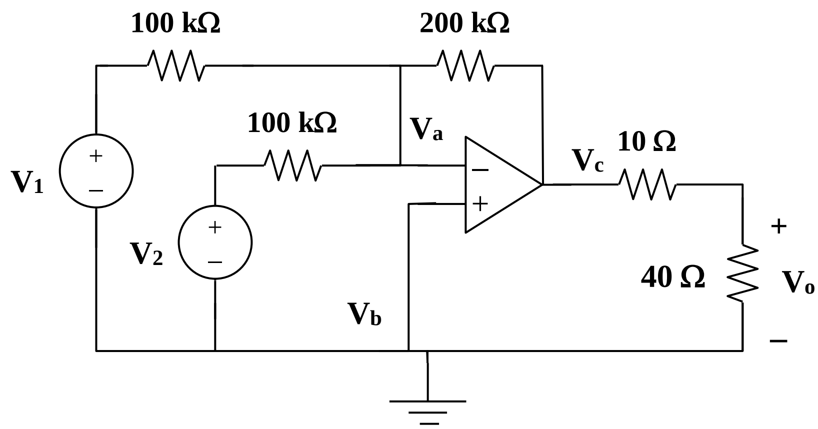
$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right) = -\left(\frac{50}{10}(-3) + \frac{50}{20}v_2 + \frac{50}{50}(5)\right) = 10 - 2.5v_2 =$$

15 – 2.5v2 – 5 = 10 – 2.5v2 = –7.5 or v2 = 17.5/2.5 or

v2 = **7 V**.

Solution 5.40

Determine V_o in terms of V_1 and V_2.



Step 1. Label the reference and node voltages in the circuit, see above. Note we now can consider nodes a and b, we cannot write a node equation at c without introducing another unknown. The node equation at a is $[(V_a–V_1)/10^5] + [(V_a–V_2)/10^5] + 0 + [(V_a–V_c)/2x10^5] = 0$. At b it is clear that $V_b = 0$. Since we have two equations and three unknowns, we need another equation. We do get that from the constraint equation, $V_a = V_b$. After we find V_c in terms of V_1 and V_2, we then can determine V_o which is equal to $[(V_c–0)/50]$ times 40.

Step 2. Letting $V_a = V_b = 0$, the first equation can be simplified to,

$$[–V_1/10^5] + [–V_2/10^5] + [–V_c/2x10^5] = 0$$

Taking V_c to the other side of the equation and multiplying everything by $2x10^5$, we get,

$$V_c = –2V_1 – 2V_2$$

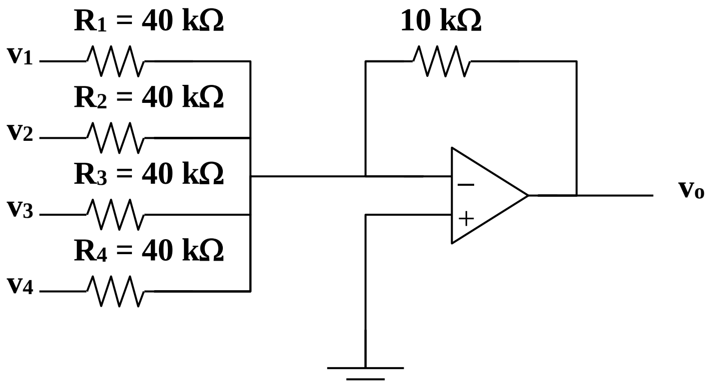
Now we can find V_o which is equal to $(40/50)V_c = 0.8[–2V_1–2V_2]$

V_o = $\mathbf{–1.6V_1–1.6V_2}$.

Solution 5.41

$R_f/R_i = 1/(4) \longrightarrow R_i = 4R_f = 40k\Omega$

The averaging amplifier is as shown below:



Solution 5.42

The feedback resistor of a three-input averaging summing amplifier is 50 kΩ. What are the values of R_1, R_2, and R_3?

Solution

Since the average of three numbers is the sum of those numbers divided by three, the value of the feedback resistor needs to be equal to one-third of the input resistors or, $R_i = 3R_f$ where i = 1, 2, and 3. Therefore,

$R_1 = R_2 = R_3 = 3x50{,}000 =$ **150 kΩ**.

Solution 5.43

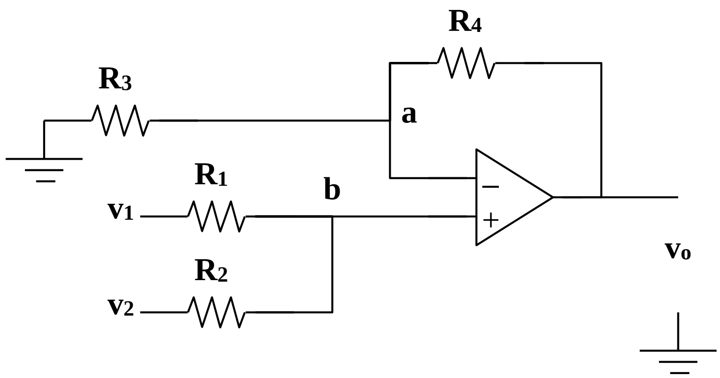
The feedback resistor of a five-input averaging summing amplifier is 40 k**Ω**. What are the values of R_1, R_2, R_3, R_4, and R_5?

Solution

In order to find the average of five inputs each input resistor needs to be five times the feedback resistor or,

$R_1 = R_2 = R_3 = R_4 = R_5 = 5x40{,}000 =$ **200 kΩ**.

Solution 5.44



At node b, $\frac{v_b - v_1}{R_1} + \frac{v_b - v_2}{R_2} = 0 \longrightarrow v_b = \frac{\frac{v_1}{R_1} + \frac{v_2}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2}}$ (1)

At node a, $\frac{0 - v_a}{R_3} = \frac{v_a - v_o}{R_4} \longrightarrow v_a = \frac{v_o}{1 + R_4 / R_3}$ (2)

But $v_a = v_b$. We set (1) and (2) equal.

$$\frac{v_o}{1 + R_4 / R_3} = \frac{R_2 v_1 + R_1 v_2}{R_1 + R_2}$$

or

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

Solution 5.45

Design an op amp circuit to perform the following operation:

$v_o = 3.5v_1 - 2.5v_2$

All resistances must be $\leq$ 100 kΩ.

Solution

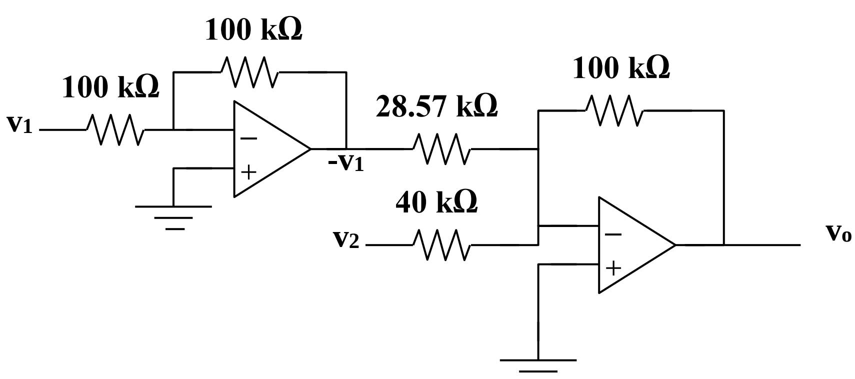
This can be achieved as follows:

$$v_o = -\left[\frac{R}{R/3}(-v_1) + \frac{R}{R/2}v_2\right]$$

$$= -\left[\frac{R_f}{R_1}(-v_1) + \frac{R_f}{R_2}v_2\right]$$

i.e. $R_f = R$, $R_1 = R/3.5$, and $R_2 = R/2.5$

Thus we need an inverter to invert v_1, and a summer, as shown below ($R \leq 100k\Omega$). Let us pick R = 100 kΩ. Note, we can have an infinite number of values that satisfy the conditions. We will use the value of R = 100 kΩ for our design.



Solution 5.46

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

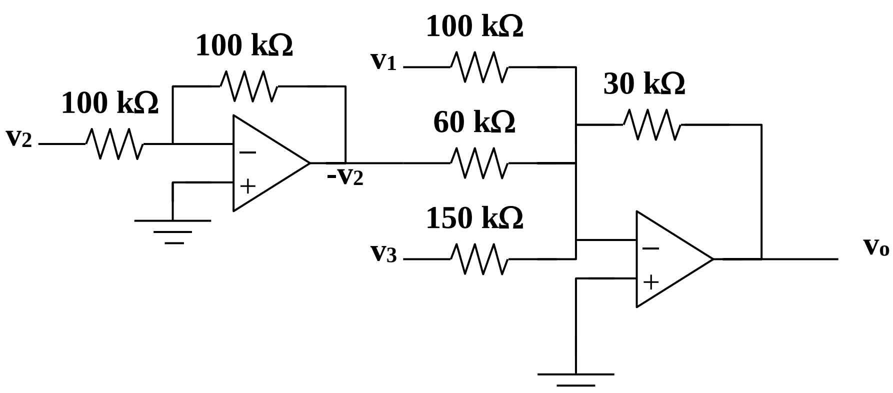
$$-v_{out} = \frac{v_3 - v_1}{5} + \frac{v_1 - v_2}{2}.$$

Solution

Although there are several ways to accomplish this, the easiest way is to simplify the above equation and then design the circuit. Thus,

$-v_{out} = (-0.2+0.5)v_1 - 0.5v_2 + 0.2v_3$ or $-v_{out} = 0.3v_1 - 0.5v_2 + 0.2v_3$.

Let us pick $R_f = 30$ kΩ. To obtain the proper gains, $R_1 = 100$ kΩ, $R_2 = 60$ kΩ, and $R_3 = 150$ kΩ. (30,000/10,000) = 0.3, (30,000/60,000) = 0.5, and (30,000/150,000) = 0.2.



Solution 5.47

Using eq. (5.18), $R_1 = 2k\Omega,\ \mathrm{R}_2 = 30k\Omega,\ \ \mathrm{R}_3 = 2k\Omega,\ \ \mathrm{R}_4 = 20k\Omega$

$$v_o = \frac{30(1+2/30)}{2(1+2/20)}v_2 - \frac{30}{2}V_1 = \frac{32}{2.2}(2) - 15(1) = \underline{14.09\ \mathrm{V}}$$

= **14.09 V**.

Solution 5.48

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

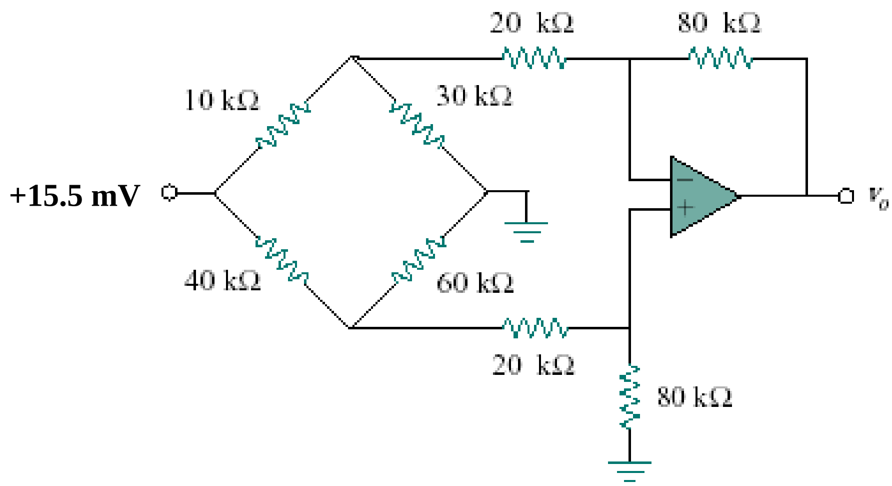


Figure 5.80
For Prob. 5.48.

Solution

We can break this problem up into parts. The 15.5 mV source separates the lower circuit from the upper. In addition, there is no current flowing into the input of the op amp which means we now have the 40-kohm resistor in series with a parallel combination of the 60-kohm resistor and the equivalent 100-kohm resistor.

Thus, $\quad 40k + (60x100k)/(160) = 77.5k$

which leads to the current flowing through this part of the circuit,

$$i = 15.5\ m/77.5k = 200x10^{-9}\ A$$

The voltage across the 60k and equivalent 100k is equal to,

$$v = ix37.5k = 7.5\ mV$$

We can now calculate the voltage across the 80-kohm resistor.

$$v_{80} = 0.8x7.5\ m = 6\ mV$$

which is also the voltage at both inputs of the op amp and the voltage between the 20-kohm and 80-kohm resistors in the upper circuit. Let v_1 be the voltage to the left of the 20-kohm resistor of the upper circuit and we can write a node equation at that node.

$$(v_1 - 15.5m)/(10k) + v_1/30k + (v_1 - 6m)/20k = 0$$

or $\quad 6v_1 - 93 + 2v_1 + 3v_1 - 18 = 0$ or $v_1 = 10.091$ mV.

The current through the 20k-ohm resistor, left to right, is,

$$i_{20} = (10.091m - 6m)/20k = 204.55\text{x}10^{-9} \text{ A}$$

thus, $\quad v_o = 6m - 204.55\text{x}10^{-9}\text{x}80k =$ **-10.364 mV**.

Solution 5.49

$$R_1 = R_3 = 20\text{k}\Omega,\ R_2/(R_1) = 4$$

i.e. $$R_2 = 4R_1 = 80\text{k}\Omega = R_4$$

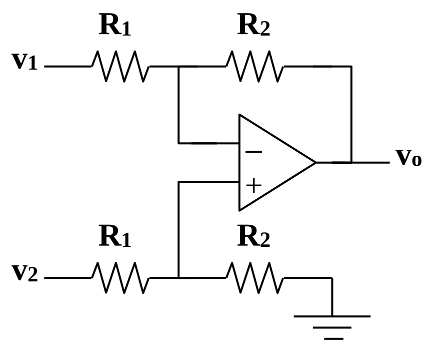
Verify: $$v_o = \frac{R_2}{R_1}\frac{1+R_1/R_2}{1+R_3/R_4}v_2 - \frac{R_2}{R_1}v_1$$

$$= 4\frac{(1+0.25)}{1+0.25}v_2 - 4v_1 = 4(v_2 - v_1)$$

Thus, $R_1 = R_3 =$ **20 kΩ**, $R_2 = R_4 =$ **80 kΩ**.

Solution 5.50

(a) We use a difference amplifier, as shown below:



$$v_o = \frac{R_2}{R_1}(v_2 - v_1) = 2.5(v_2 - v_1),$$ i.e. $R_2/R_1 = 2.5$

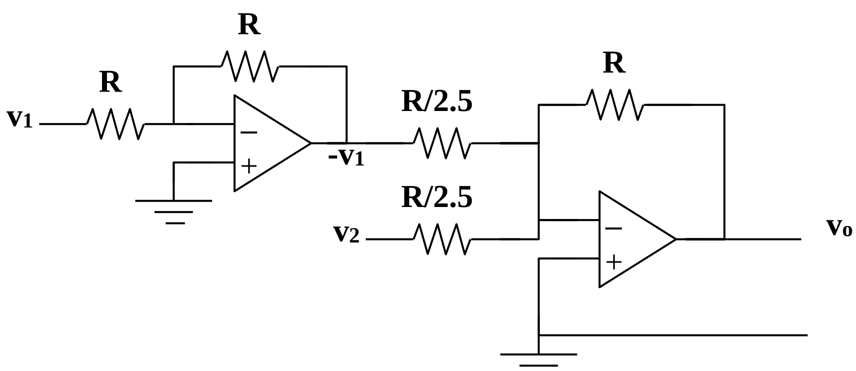
If R_1 = **100 kΩ** then R_2 = **250kΩ**

(b) We may apply the idea in Prob. 5.35.

$$v_0 = 2.5v_1 - 2.5v_2$$
$$= -\left[\frac{R}{R/2}(-v_1) + \frac{R}{R/2}v_2\right]$$
$$= -\left[\frac{R_f}{R_1}(-v_1) + \frac{R_f}{R_2}v_2\right]$$

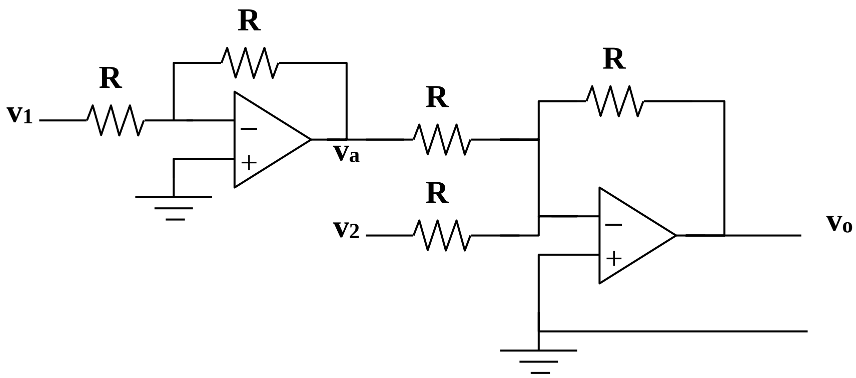
i.e. $R_f = R$, $R_1 = R/2.5 = R_2$

We need an inverter to invert v_1 and a summer, as shown below. We may let R = 100 kΩ.



Solution 5.51

We achieve this by cascading an inverting amplifier and two-input inverting summer as shown below:



Verify:

$$v_o = -v_a - v_2$$

But $\quad v_a = -v_1$. Hence

$$v_o = v_1 - v_2.$$

Solution 5.52

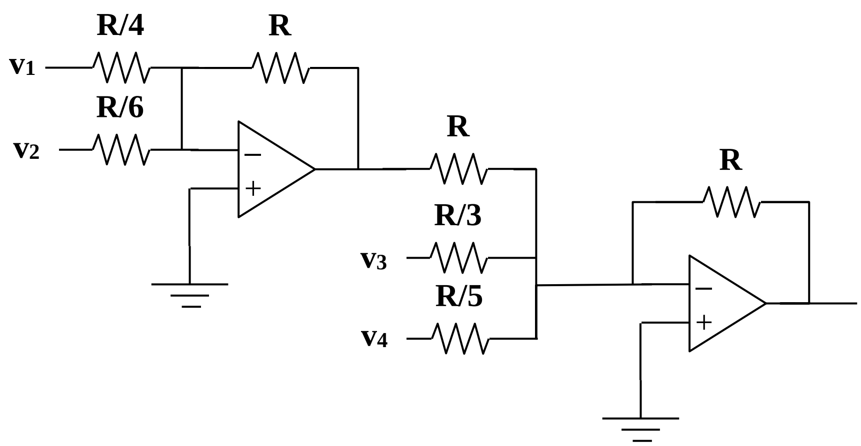
Design an op amp circuit such that

$v_o = 4v_1 + 6v_2 – 3v_3 – 5v_4$

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

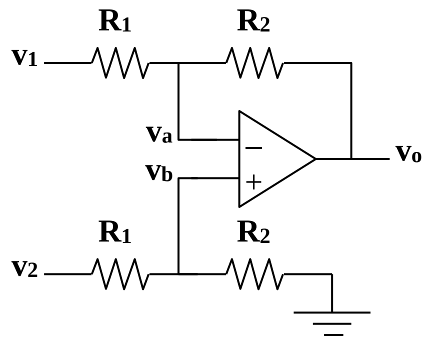
Solution

A summing amplifier shown below will achieve the objective. An inverter is inserted to invert v_2. Since the smallest resistance must be at least 20 kΩ, then let R/6 = 20kΩ therefore let R = **120 kΩ**.



Solution 5.53

(a)



At node a,

$$\frac{v_1 - v_a}{R_1} = \frac{v_a - v_o}{R_2} \longrightarrow v_a = \frac{R_2 v_1 + R_1 v_o}{R_1 + R_2} \qquad (1)$$

At node b, $$v_b = \frac{R_2}{R_1 + R_2} v_2 \qquad (2)$$

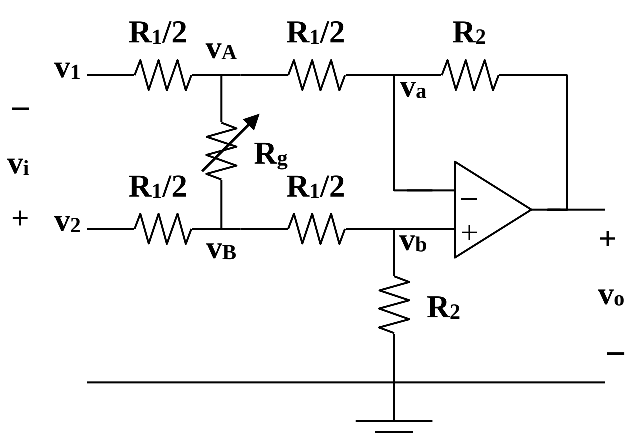
But $v_a = v_b$. Setting (1) and (2) equal gives

$$\frac{R_2}{R_1 + R_2} v_2 = \frac{R_2 v_1 + R_1 v_o}{R_1 + R_2}$$

$$v_2 - v_1 = \frac{R_1}{R_2} v_o = v_i$$

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

(b)



At node A, $\dfrac{v_1 - v_A}{R_1/2} + \dfrac{v_B - v_A}{R_g} = \dfrac{v_A - v_a}{R_1/2}$

or $$v_1 - v_A + \frac{R_1}{2R_g}(v_B - v_A) = v_A - v_a \qquad (1)$$

At node B, $\dfrac{v_2 - v_B}{R_1/2} = \dfrac{v_B - v_A}{R_1/2} + \dfrac{v_B - v_b}{R_g}$

or $$v_2 - v_B - \frac{R_1}{2R_g}(v_B - v_A) = v_B - v_b \qquad (2)$$

Subtracting (1) from (2),

$$v_2 - v_1 - v_B + v_A - \frac{2R_1}{2R_g}(v_B - v_A) = v_B - v_A - v_b + v_a$$

Since, $v_a = v_b$,

$$\frac{v_2 - v_1}{2} = \left(1 + \frac{R_1}{2R_g}\right)(v_B - v_A) = \frac{v_i}{2}$$

or $$v_B - v_A = \frac{v_i}{2} \cdot \frac{1}{1 + \dfrac{R_1}{2R_g}} \qquad (3)$$

But for the difference amplifier,

$$v_o = \frac{R_2}{R_1/2}(v_B - v_A)$$

or $$v_B - v_A = \frac{R_1}{2R_2} v_o \qquad (4)$$

Equating (3) and (4), $\dfrac{R_1}{2R_2} v_o = \dfrac{v_i}{2} \cdot \dfrac{1}{1 + \dfrac{R_1}{2R_g}}$

$$\underline{\frac{v_o}{v_i} = \frac{R_2}{R_1} \cdot \frac{1}{1 + \dfrac{R_1}{2R_g}}}$$

(c) At node a, $\dfrac{v_1 - v_a}{R_1} = \dfrac{v_a - v_A}{R_2/2}$

$$v_1 - v_a = \frac{2R_1}{R_2} v_a - \frac{2R_1}{R_2} v_A \qquad (1)$$

At node b, $$v_2 - v_b = \frac{2R_1}{R_2} v_b - \frac{2R_1}{R_2} v_B \qquad (2)$$

Since $v_a = v_b$, we subtract (1) from (2),

$$v_2 - v_1 = \frac{-2R_1}{R_2}(v_B - v_A) = \frac{v_i}{2}$$

or $$v_B - v_A = \frac{-R_2}{2R_1} v_i \qquad (3)$$

At node A,

$$\frac{v_a - v_A}{R_2/2} + \frac{v_B - v_A}{R_g} = \frac{v_A - v_o}{R/2}$$

$$v_a - v_A + \frac{R_2}{2R_g}(v_B - v_A) = v_A - v_o \qquad (4)$$

At node B, $\dfrac{v_b - v_B}{R/2} - \dfrac{v_B - v_A}{R_g} = \dfrac{v_B - 0}{R/2}$

$$v_b - v_B - \frac{R_2}{2R_g}(v_B - v_A) = v_B \qquad (5)$$

Subtracting (5) from (4),

$$v_B - v_A + \frac{R_2}{R_g}(v_B - v_A) = v_A - v_B - v_o$$

$$2(v_B - v_A)\left(1 + \frac{R_2}{2R_g}\right) = -v_o \qquad (6)$$

Combining (3) and (6),

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

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

Solution 5.54

The first stage is a summer (please note that we let the output of the first stage be v_1).

$$v_1 = -\left(\frac{R}{R}v_s + \frac{R}{R}v_o\right) = -v_s - v_o$$

The second stage is a noninverting amplifier

$$v_o = (1 + R/R)v_1 = 2v_1 = 2(-v_s - v_o) \quad \text{or } 3v_o = -2v_s$$

$$v_o/v_s = \mathbf{-0.6667}.$$

Solution 5.55

Let $A_1 = k$, $A_2 = k$, and $A_3 = k/(4)$

$$A = A_1A_2A_3 = k^3/(4)$$

$$20\text{Log}_{10}A = 42$$

$$\text{Log}_{10}A = 2.1 \longrightarrow A = 10^{2.1} = 125.89$$

$k^3 = 4A = 503.57$

$k = \sqrt[3]{503.57} = 7.956$

Thus

$A_1 = A_2 =$ **7.956**, $A_3 =$ **1.989**

Solution 5.56

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

Although there are many ways to work this problem, this is an example based on the same kind of problem asked in the third edition.

Problem

Calculate the gain of the op amp circuit shown in Fig. 5.83.

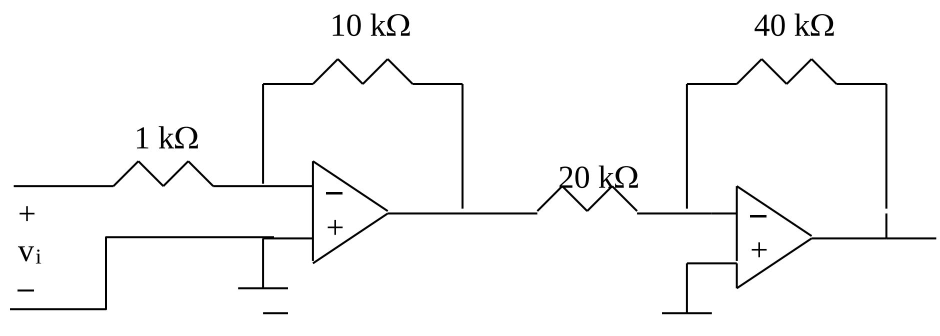


Figure 5.83 **For Prob. 5.56.**

Solution

Each stage is an inverting amplifier. Hence,

$$\frac{v_o}{v_s} = \left(-\frac{10}{1}\right)\left(-\frac{40}{20}\right) = \underline{20}$$

Solution 5.57

Let v_1 be the output of the first op amp and v_2 be the output of the second op amp.

The first stage is an inverting amplifier.

$$v_1 = -\frac{50}{25}v_{s1} = -2v_{s1}$$

The second state is a summer.

$$v_2 = -(100/50)v_{s2} - (100/100)v_1 = -2v_{s2} + 2v_{s1}$$

The third state is a noninverting amplifier

$$v_o = (1+\frac{100}{50})v_2 = 3v_2 = \underline{6v_{s1} - 6v_{s2}}$$

Solution 5.58

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

1.8 V

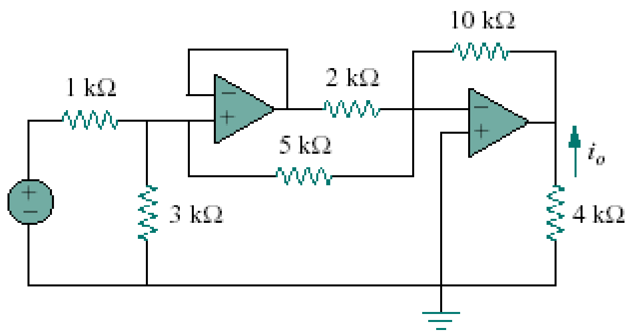


Figure 5.85
For Prob. 5.58.

Solution

Looking at the circuit, the voltage at the right side of the 5-kΩ resistor must be at 0V if the op amps are working correctly. Thus the 1-kΩ is in series with the parallel combination of the 3-kΩ and the 5-kΩ. By voltage division, the input to the voltage follower is:

$$v_1 = \frac{3\|5}{1+3\|5}(1.8) = 1.1739V = \text{to the output of the first op amp.}$$

Thus,

$$v_o = -10((1.1739/5)+(1.1739/2)) = -8.217\text{ V.}$$

$$i_o = \frac{0-v_o}{4k} = \mathbf{2.054\ mA}.$$

Solution 5.59

The first stage is a noninverting amplifier. If v_1 is the output of the first op amp,

$$v_1 = (1 + 2R/R)v_s = 3v_s$$

The second stage is an inverting amplifier

$$v_o = -(4R/R)v_1 = -4v_1 = -4(3v_s) = -12v_s$$

$v_o/v_s = \mathbf{-12}$.

Solution 5.60

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

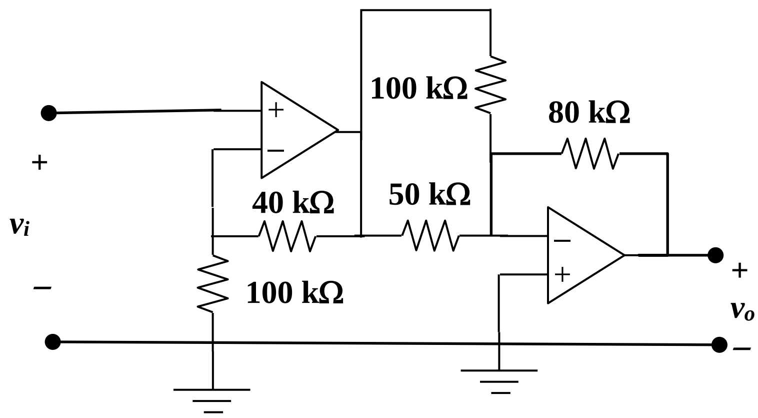


Figure 5.87
For Prob. 5.60.

Solution

The first stage is a noninverting amp with an output voltage equal to $[140k/100k]v_i = 1.4v_i$.

At the negative input of the second op amp we get $[(0–1.4v_i)/100k] + [(0–1.4v_i)/50k] + [(0–v_o)/80k] + 0 = 0$. Thus, $v_o = –[80k(3/100k)]1.4v_i = –3.36v_i$. This leads to,

$v_o/v_i =$ **–3.36**.

Solution 5.61

Determine v_o in the circuit of Fig. 5.88.

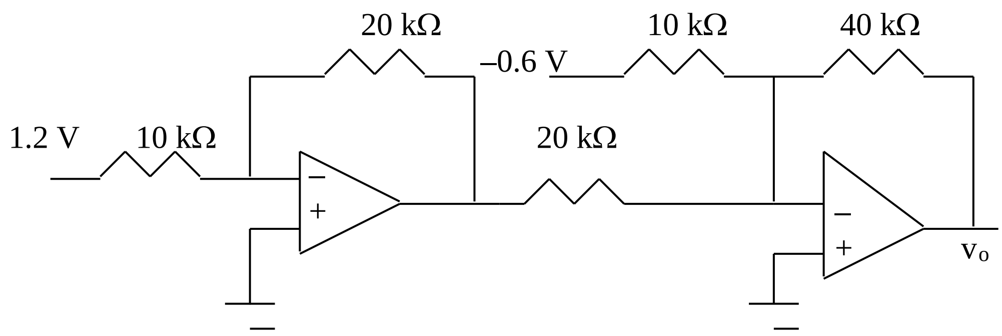


Figure 5.88
For Prob. 5.61.

Solution

The first op amp is an inverter. If v_1 is the output of the first op amp,

$$v_1 = -(20/10)(1.2) = -2.4 \text{ V}$$

The second op amp is a summer

$$V_o = -(40/10)(-0.6) - (40/20)(-2.4) = 2.4 + 4.8$$

$$= \mathbf{7.2\ V}.$$

Solution 5.62

Let v_1 = output of the first op amp
v_2 = output of the second op amp

The first stage is a summer

$$v_1 = -\frac{R_2}{R_1} v_i - \frac{R_2}{R_f} v_o \qquad (1)$$

The second stage is a follower. By voltage division

$$v_o = v_2 = \frac{R_4}{R_3 + R_4} v_1 \longrightarrow v_1 = \frac{R_3 + R_4}{R_4} v_o \qquad (2)$$

From (1) and (2),

$$\left(1 + \frac{R_3}{R_4}\right) v_o = -\frac{R_2}{R_1} v_i - \frac{R_2}{R_f} v_o$$

$$\left(1 + \frac{R_3}{R_4} + \frac{R_2}{R_f}\right) v_o = -\frac{R_2}{R_1} v_i$$

$$\frac{v_o}{v_i} = -\frac{R_2}{R_1} \cdot \frac{1}{1 + \frac{R_3}{R_4} + \frac{R_2}{R_f}} = \boldsymbol{\frac{-R_2 R_4 R_f}{R_1 (R_2 R_4 + R_3 R_f + R_4 R_f)}}$$

Solution 5.63

The two op amps are summers. Let v_1 be the output of the first op amp. For the first stage,

$$v_1 = -\frac{R_2}{R_1}v_i - \frac{R_2}{R_3}v_o \qquad (1)$$

For the second stage,

$$v_o = -\frac{R_4}{R_5}v_1 - \frac{R_4}{R_6}v_i \qquad (2)$$

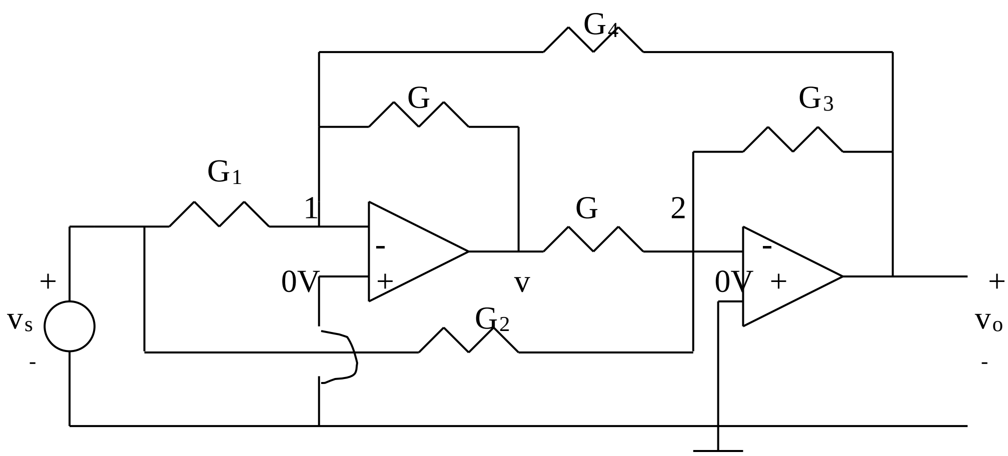
Combining (1) and (2),

$$v_o = \frac{R_4}{R_5}\left(\frac{R_2}{R_1}\right)v_i + \frac{R_4}{R_5}\left(\frac{R_2}{R_3}\right)v_o - \frac{R_4}{R_6}v_i$$

$$v_o\left(1 - \frac{R_2R_4}{R_3R_5}\right) = \left(\frac{R_2R_4}{R_1R_5} - \frac{R_4}{R_6}\right)v_i$$

$$\boldsymbol{\frac{v_o}{v_i} = \frac{\frac{R_2R_4}{R_1R_5} - \frac{R_4}{R_6}}{1 - \frac{R_2R_4}{R_3R_5}}}$$

Solution 5.64



At node 1, v_1=0 so that KCL gives

$$G_1 v_s + G_4 v_o = -Gv \qquad (1)$$

At node 2,

$$G_2 v_s + G_3 v_o = -Gv \qquad (2)$$

From (1) and (2),

$$G_1 v_s + G_4 v_o = G_2 v_s + G_3 v_o \longrightarrow (G_1 - G_2) v_s = (G_3 - G_4) v_o$$

or

$$\underline{\boldsymbol{\frac{v_o}{v_s} = \frac{G_1 - G_2}{G_3 - G_4}}}$$

Solution 5.65

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

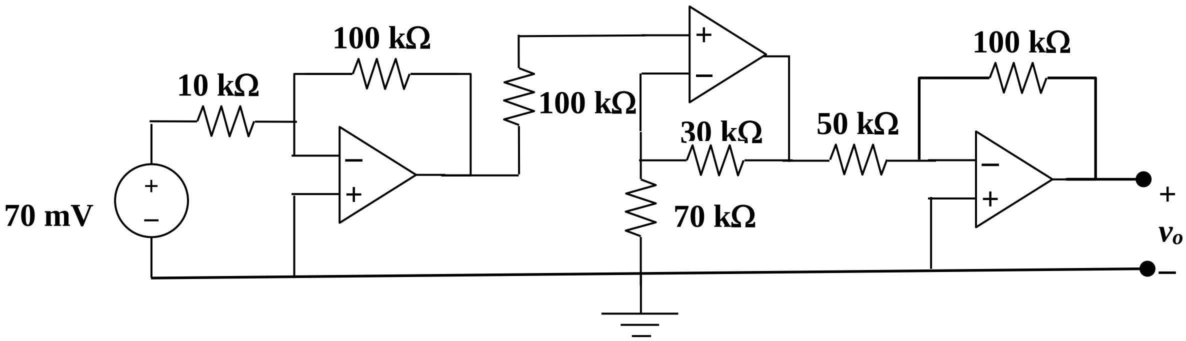


Figure 5.92
For Prob. 5.65.

Solution

The output of the first op amp (to the left) is –(100k/10k)0.07 = –700 mV. The output of the second op amp has to be equal to –0.7[100k/70k] = –1 V. Finally the output of the third op amp is –[100k/50k](–1) = **2 V**.

Solution 5.66

We can start by looking at the contributions to v_o from each of the sources and the fact that each of them go through inverting amplifiers.

The 6 V source contributes –[100k/25k]6; the 4 V source contributes –[40k/20k][–(100k/20k)]4; and the 2 V source contributes –[100k/10k]2 or

$$v_o = \frac{-100}{25}(6) - \frac{40}{20}\left(-\frac{100}{20}\right)(4) - \frac{100}{10}(2)$$

$$= -24 + 40 - 20 = \mathbf{-4V}$$

Solution 5.67

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

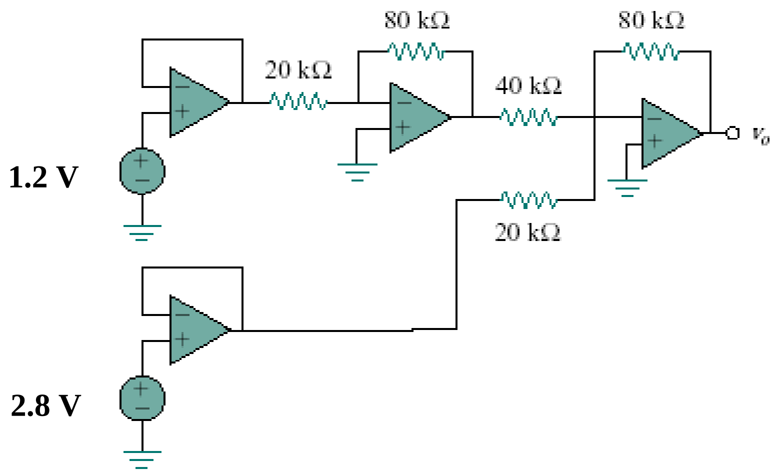


Figure 5.94
For Prob. 5.67.

Solution

$$v_o = -\frac{80}{40}\left(-\frac{80}{20}\right)(1.2) - \frac{80}{20}(2.8) = 9.6 - 11.2 = \mathbf{-1.6\ V}.$$

Solution 5.68

If $R_q = \infty$, the first stage is an inverter.

$$V_a = -\frac{15}{5}(15) = -45\,\text{mV}$$

when V_a is the output of the first op amp.

The second stage is a noninverting amplifier.

$$v_o = \left(1 + \frac{6}{2}\right)v_a = (1+3)(-45) = \mathbf{-180mV}.$$

Solution 5.69

In this case, the first stage is a summer

$$v_a = -\frac{15}{5}(15) - \frac{15}{10}v_o = -45 - 1.5v_o$$

For the second stage,

$$v_o = \left(1 + \frac{6}{2}\right)v_a = 4v_a = 4\left(-45 - 1.5v_o\right)$$

$$7v_o = -180 \quad v_o = -\frac{180}{7} = \mathbf{-25.71\ mV}.$$

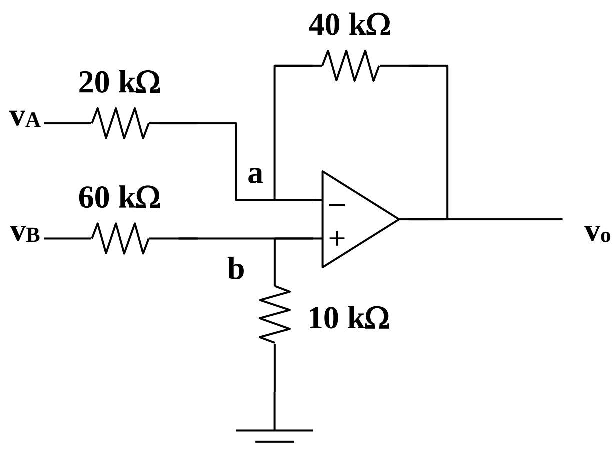
Solution 5.70

The output of amplifier A is

$$v_A = -\frac{30}{10}(1) - \frac{30}{10}(2) = -9$$

The output of amplifier B is

$$v_B = -\frac{20}{10}(3) - \frac{20}{10}(4) = -14$$



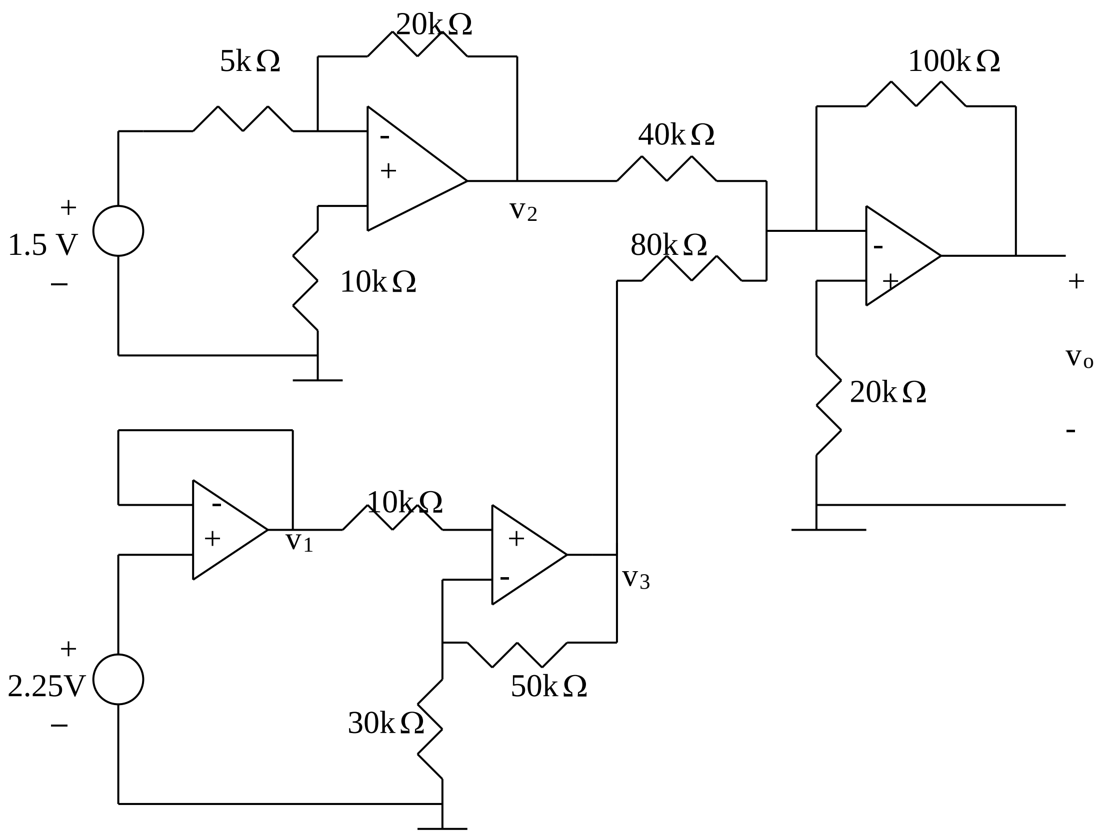
$$v_b = \frac{10}{60+10}(-14) = -2V$$

At node a, $\frac{v_A - v_a}{20} = \frac{v_a - v_o}{40}$

But $v_a = v_b = -2V$, $2(-9+2) = -2-v_o$

Therefore, $v_o =$ **12V**

Solution 5.71



$$v_1 = 2.25, \qquad v_2 = -\frac{20}{5}(1.5) = -6, \qquad v_3 = (1+\frac{50}{30})v_1 = 6$$

$$v_o = -\left(\frac{100}{40}v_2 + \frac{100}{80}v_3\right) = -(-15+7.5) = \mathbf{7.5\ V}.$$

Solution 5.72

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

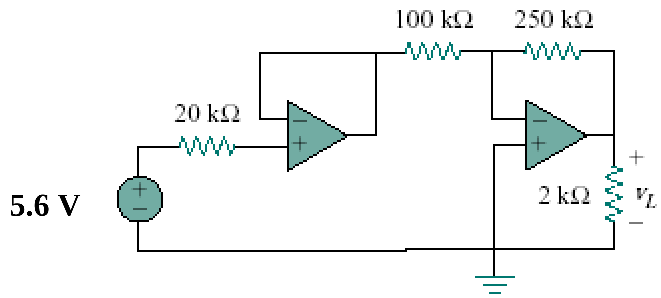


Figure 5.98
For Prob. 5.72.

Solution

Since no current flows into the input terminals of ideal op amp, there is no voltage drop across the 20 kΩ resistor. As a voltage follower, the output of the first op amp is

$$v_{01} = 5.6 \text{ V}$$

The second stage is an inverter

$$v_2 = -\frac{250}{100} v_{01}$$
$$= -2.5(5.6) = \mathbf{-14\ V}.$$

Solution 5.73

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

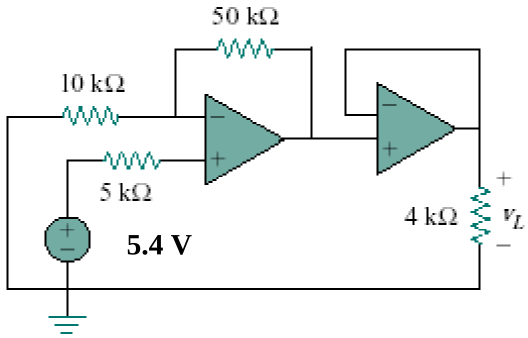


Figure 5.99
For Prob. 5.73.

Solution

The first stage is a noninverting amplifier. The output is

$$v_{o1} = \frac{50}{10}(5.4) + 5.4 = 32.4V$$

The second stage is a voltage follower whose output is

$$v_L = v_{01} = \mathbf{32.4\ V}.$$

Solution 5.74

Let v_1 = output of the first op amp
v_2 = input of the second op amp.

The two sub-circuits are inverting amplifiers

$$v_1 = -\frac{100}{10}(0.9) = -9V$$

$$v_2 = -\frac{32}{1.6}(0.6) = -12V$$

$$i_o = \frac{v_1 - v_2}{20k} = -\frac{-9+12}{20k} = \mathbf{150\ \mu A}.$$

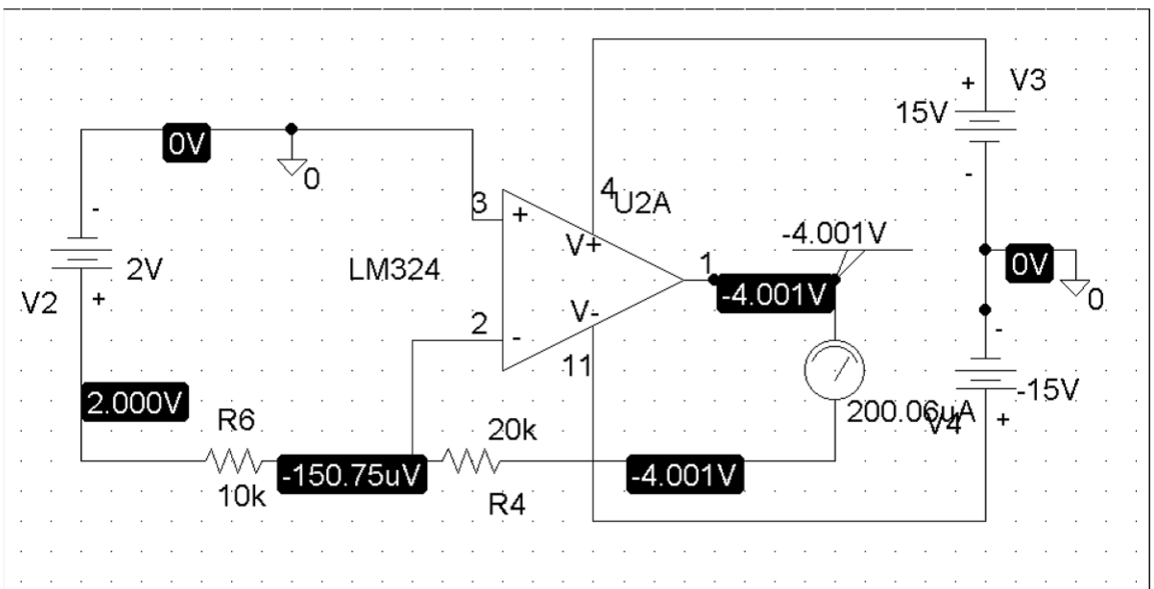
Solution 5.75

The schematic is shown below. Pseudo-components VIEWPOINT and IPROBE are involved as shown to measure v_o and i respectively. Once the circuit is saved, we click Analysis | Simulate. The values of v and i are displayed on the pseudo-components as:

$$i = \mathbf{200\ \mu A}$$

$$(v_o/v_s) = -4/2 = \mathbf{-2}$$

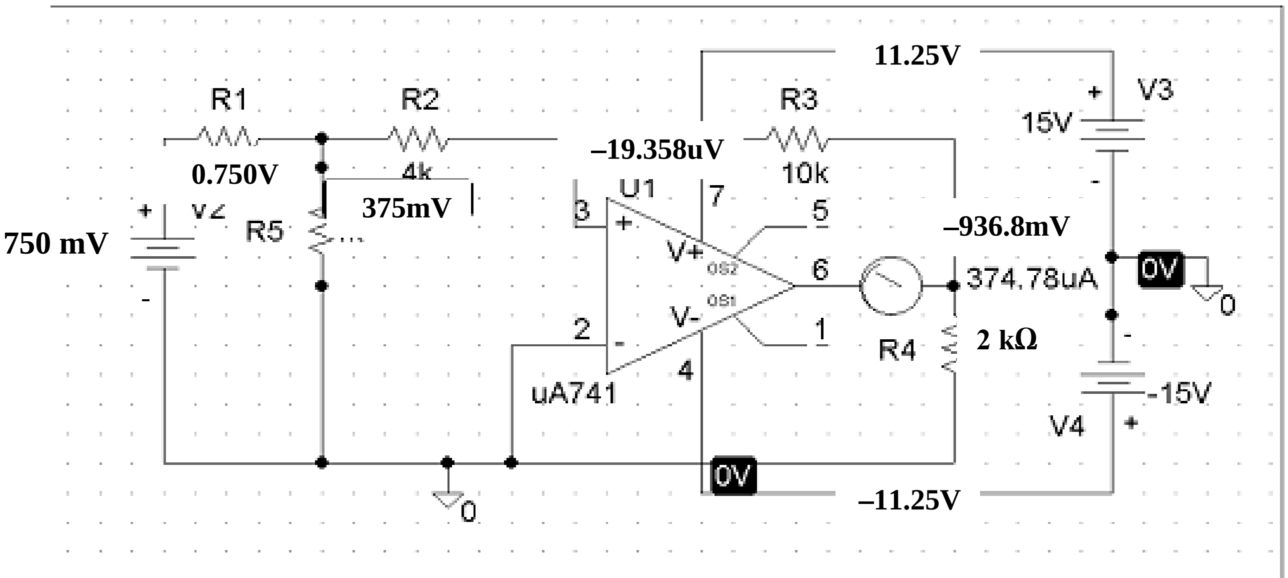
The results are slightly different than those obtained in Example 5.11.



Solution 5.76

The schematic is shown below. IPROBE is inserted to measure i_o. Upon simulation, the value of i_o is displayed on IPROBE as

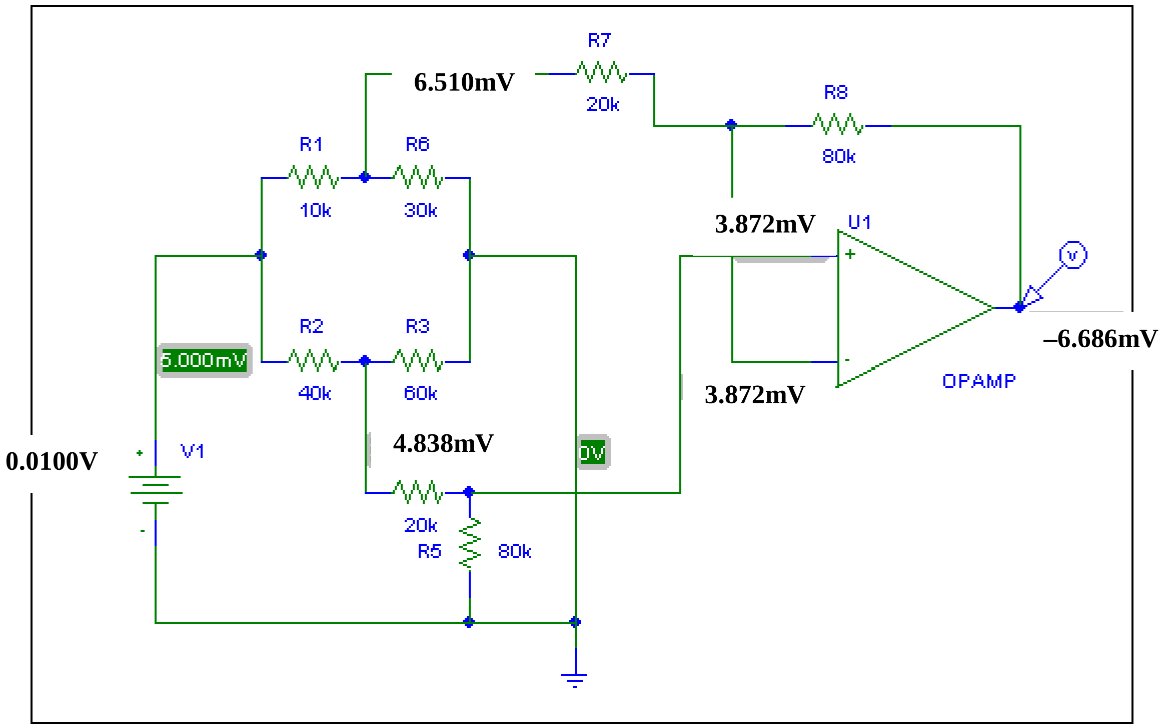
$$i_o = \mathbf{-562.5\ \mu A}$$



Solution 5.77

The schematic for the PSpice solution is shown below.

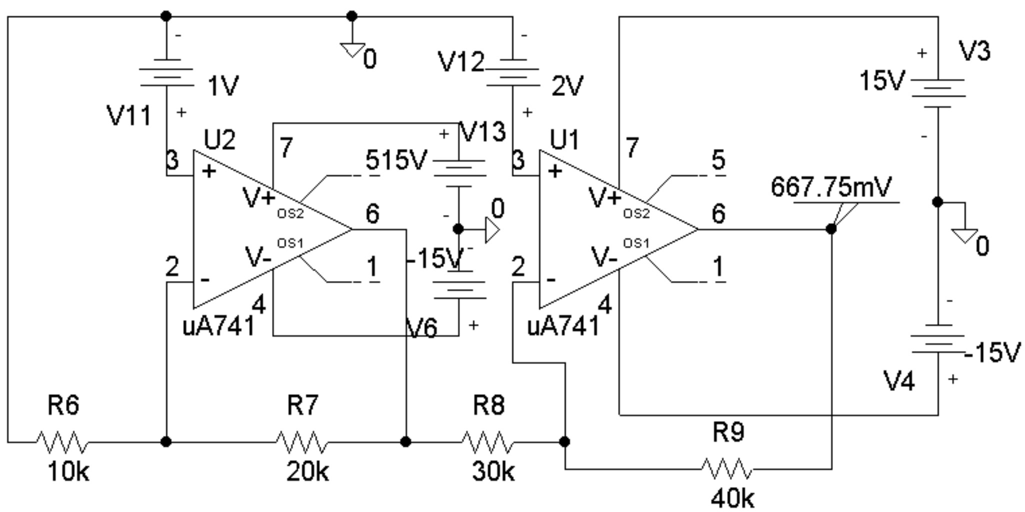
Note that the output voltage, **–6.686 mV**, agrees with the answer to problem, 5.48.



Solution 5.78

The circuit is constructed as shown below. We insert a VIEWPOINT to display v_o. Upon simulating the circuit, we obtain,

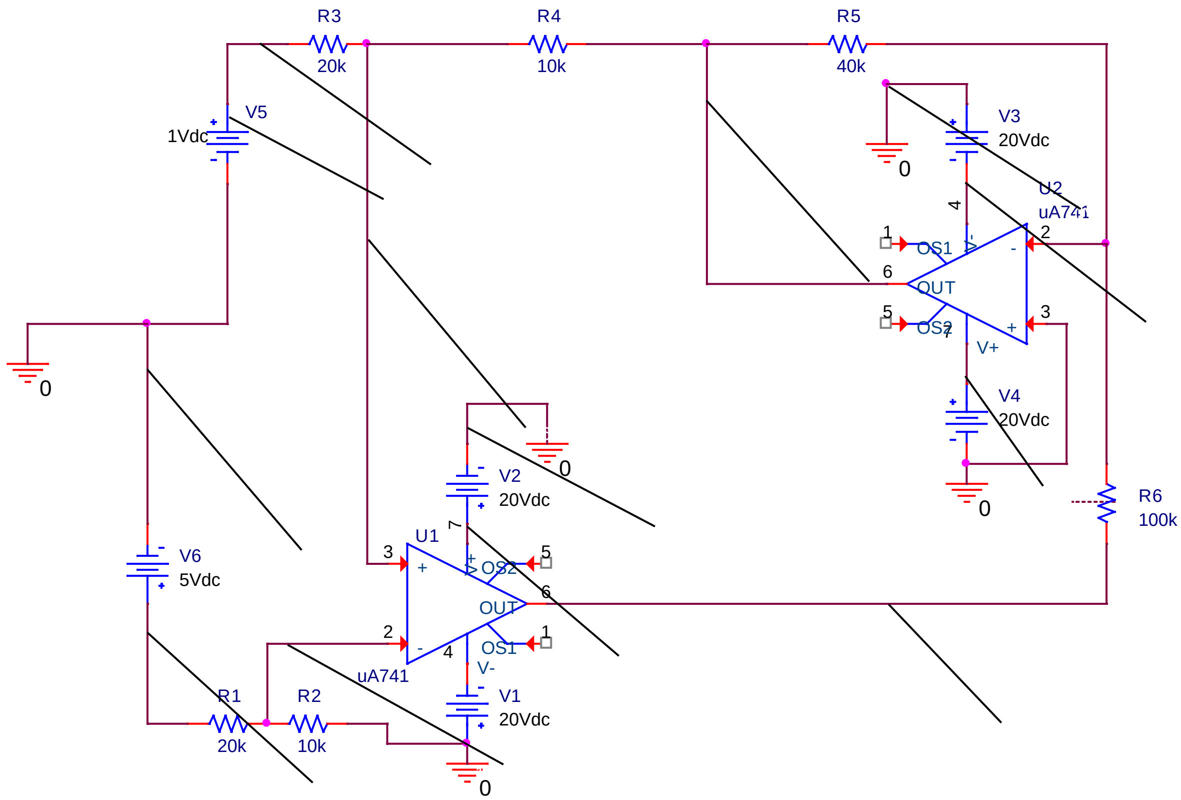
$$v_o = \mathbf{667.75\ mV}$$



Solution 5.79

The schematic is shown below.

$$v_o = \mathbf{-4.992\ V}$$



Checking using nodal analysis we get,

For the first op-amp we get $v_{a1} = [5/(20+10)]10 = 1.6667\ \text{V} = v_{b1}$.

For the second op-amp, $[(v_{b1} - 1)/20] + [(v_{b1} - v_{c2})/10] = 0$ or $v_{c2} = 10[1.6667-1)/20] + 1.6667 = 2\ \text{V}$;

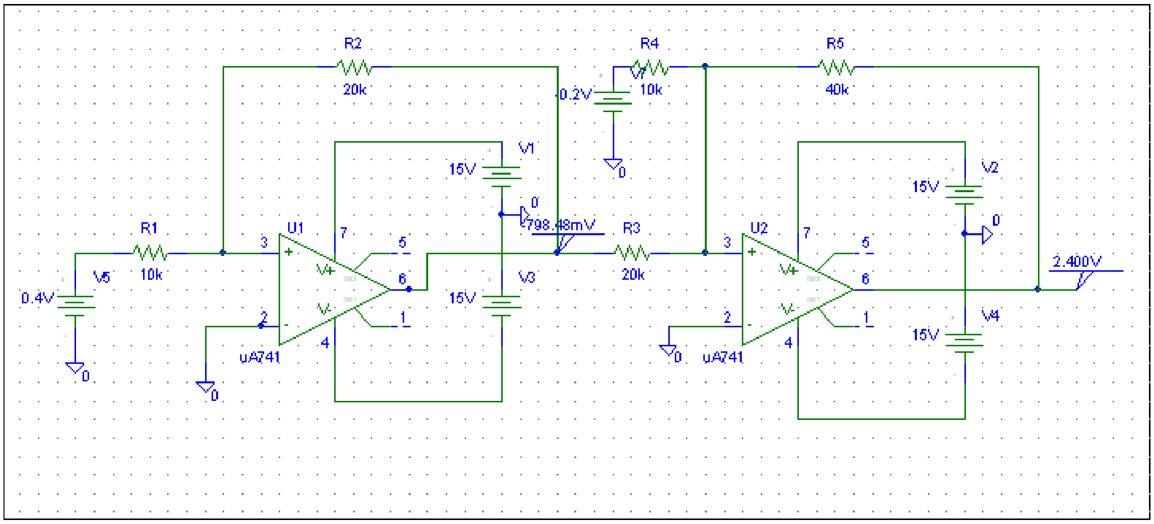
$[(v_{a2} - v_{c2})/40] + [(v_{a2} - v_{c1})/100] = 0$; and $v_{b2} = 0 = v_{a2}$. This leads to $v_{c1} = -2.5v_{c2}$. Thus,

$$= \mathbf{-5\ V}.$$

Solution 5.80

The schematic is as shown below. After it is saved and simulated, we obtain

$$v_o = \mathbf{2.4\ V}.$$

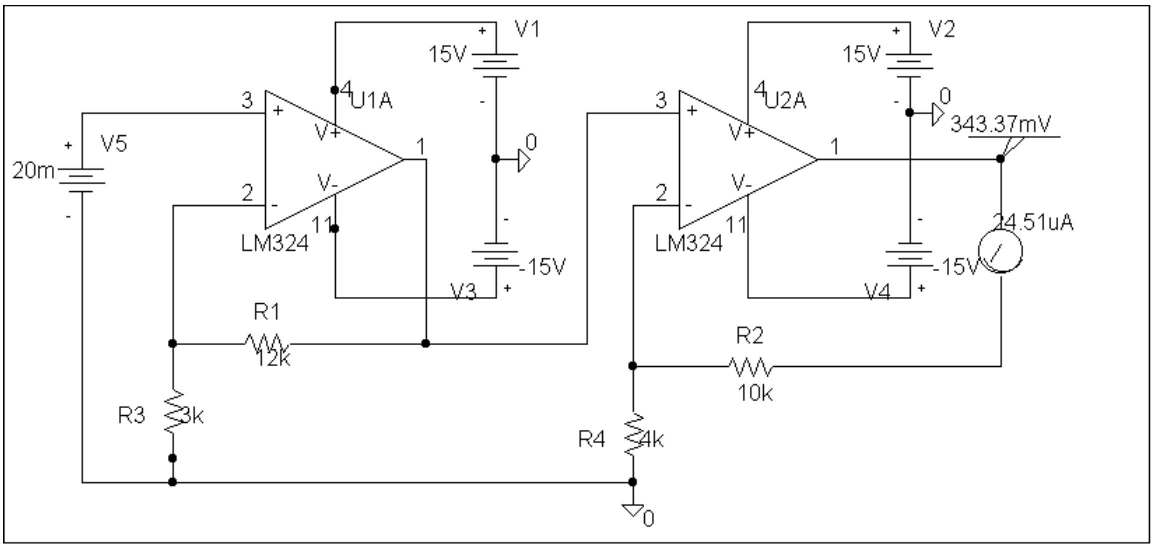


Solution 5.81

The schematic is shown below. We insert one VIEWPOINT and one IPROBE to measure v_o and i_o respectively. Upon saving and simulating the circuit, we obtain,

$$v_o = \mathbf{343.4\ mV}$$

$$i_o = \mathbf{24.51\ \mu A}$$



Solution 5.82

A four-bit DAC covers a voltage range of 0 to 10 V. Calculate the resolution of the DAC in volts per discrete binary step.

Solution

The maximum voltage level corresponds to

$$1111 = 2^4 - 1 = 15.$$

Hence, each bit is worth $(10/15) = \mathbf{666.7\ mV}$

Solution 5.83

The result depends on your design. Hence, let R_G = 10 k ohms, R_1 = 10 k ohms, R_2 = 20 k ohms, R_3 = 40 k ohms, R_4 = 80 k ohms, R_5 = 160 k ohms, R_6 = 320 k ohms, then,

$$-v_o = (R_f/R_1)v_1 + \text{---------} + (R_f/R_6)v_6$$

$$= v_1 + 0.5v_2 + 0.25v_3 + 0.125v_4 + 0.0625v_5 + 0.03125v_6$$

(a) $|v_o| = 1.1875 = 1 + 0.125 + 0.0625 = 1 + (1/8) + (1/16)$ which implies,

$[v_1\ v_2\ v_3\ v_4\ v_5\ v_6]$ = **[100110]**

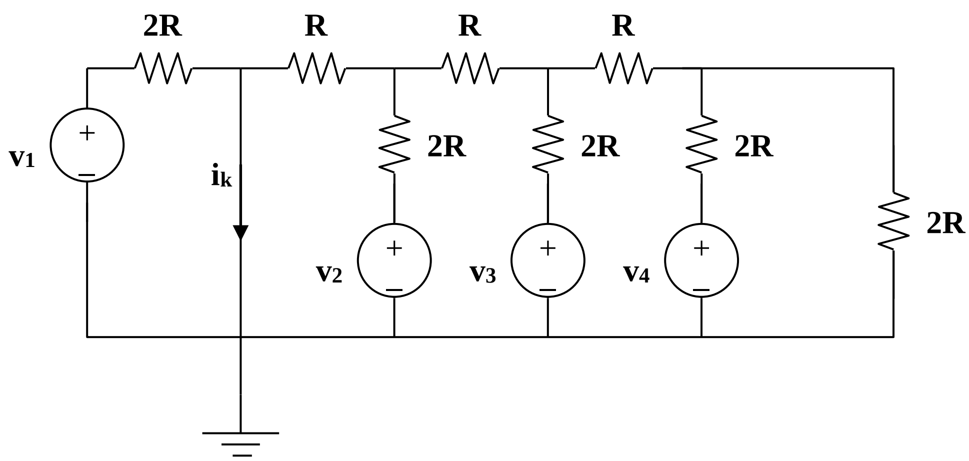
(b) $|v_o| = 0 + (1/2) + (1/4) + 0 + (1/16) + (1/32) = (27/32) =$ **843.75 mV**

(c) This corresponds to [1 1 1 1 1 1].

$|v_o| = 1 + (1/2) + (1/4) + (1/8) + (1/16) + (1/32) = 63/32 =$ **1.96875 V**

Solution 5.84

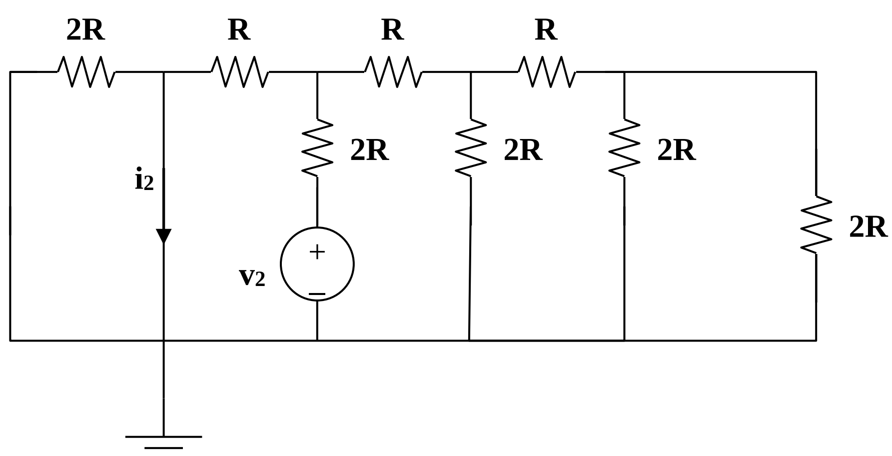
(a) The easiest way to solve this problem is to use superposition and to solve for each term letting all of the corresponding voltages be equal to zero. Also, starting with each current contribution (i_k) equal to one amp and working backwards is easiest.



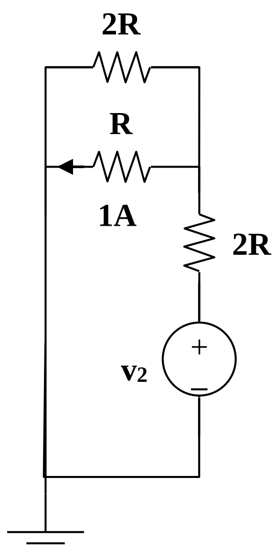
For the first case, let $v_2 = v_3 = v_4 = 0$, and $i_1 = 1A$.

Therefore, $v_1 = 2R$ volts or $i_1 = v_1/(2R)$.

Second case, let $v_1 = v_3 = v_4 = 0$, and $i_2 = 1A$.

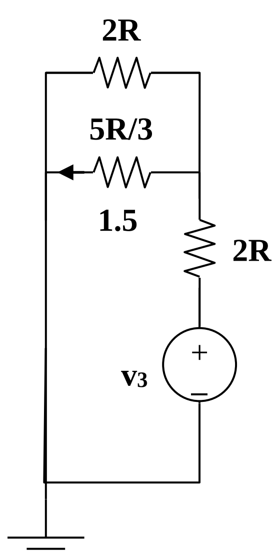


Simplifying, we get,



Therefore, $v_2 = 1xR + (3/2)(2R) = 4R$ volts or $i_2 = v_2/(4R)$ or $i_2 = 0.25v_2/R$. Clearly this is equal to the desired $1/4^{th}$.

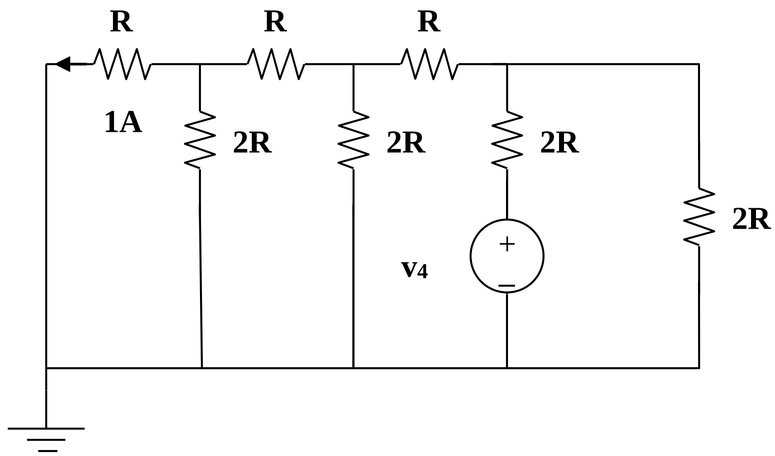
Now for the third case, let $v_1 = v_2 = v_4 = 0$, and $i_3 = 1A$.

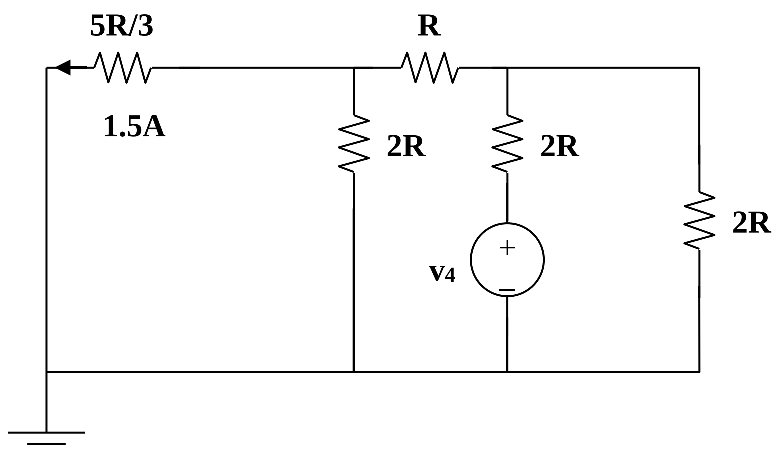


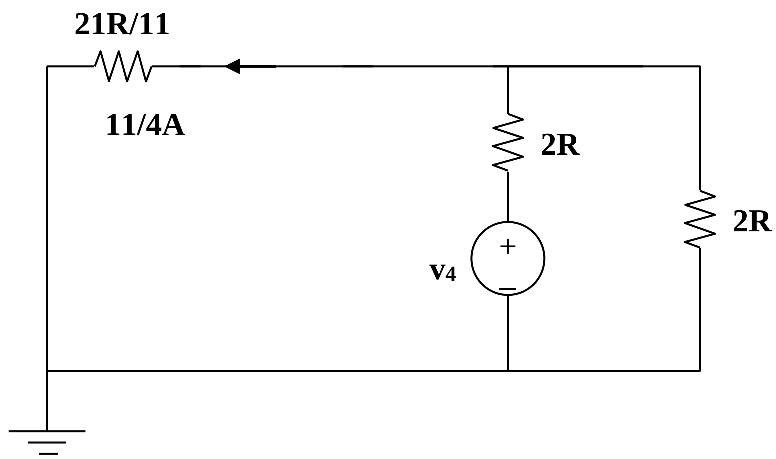
The voltage across the 5R/3-ohm resistor is 5R/2 volts. The current through the 2R resistor at the top is equal to (5/4) A and the current through the 2R-ohm resistor in series with the source is (3/2) + (5/4) = (11/4) A. Thus,

$v_3 = (11/2)R + (5/2)R = (16/2)R = 8R$ volts or $i_3 = v_3/(8R)$ or $0.125v_3/R$. Again, we have the desired result.

For the last case, $v_1 = v_2 = v_3$ and $i_4 = 1A$. Simplifying the circuit we get,







Since the current through the equivalent 21R/11-ohm resistor is (11/4) amps, the voltage across the 2R-ohm resistor on the right is (21/4)R volts. This means the current going through the 2R-ohm resistor is (21/8) A. Finally, the current going through the 2R resistor in series with the source is ((11/4)+(21/8)) = (43/8) A.

Now, $v_4 = (21/4)R + (86/8)R = (128/8)R = 16R$ volts or $i_4 = v_4/(16R)$ or $0.0625v_4/R$. This is just what we wanted.

(b) If $R_f = 12$ k ohms and $R = 10$ k ohms,

$$-v_o = (12/20)[v_1 + (v_2/2) + (v_3/4) + (v_4/8)]$$

$$= 0.6[v_1 + 0.5v_2 + 0.25v_3 + 0.125v_4]$$

For $[v_1\ v_2\ v_3\ v_4] = [1\ 0\ 11]$,

$$|v_o| = 0.6[1 + 0.25 + 0.125] = \mathbf{825\ mV}$$

For $[v_1\ v_2\ v_3\ v_4] = [0\ 1\ 0\ 1]$,

$$|v_o| = 0.6[0.5 + 0.125] = \mathbf{375\ mV}$$

Solution 5.85

In the op amp circuit of Fig. 5.104, find the value of R so that the power absorbed by the 1-kΩ resistor is 10 W. Determine the power gain.

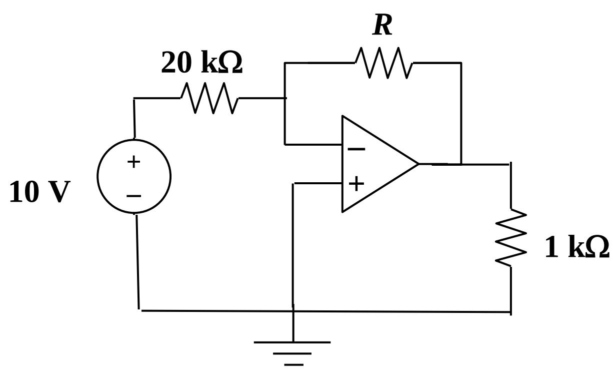


Figure 5.104
For Prob. 5.85.

Solution

This is an inverting amplifier. $v_o = –(R/20k)10 = –0.5R/1,000$

The power being delivered to the 1-kΩ give us

$P = 10\text{ W} = (v_o)^2/1k$ or $v_o = \sqrt{10,000} = \pm 100\text{V}$ in this case we will use the negative value because of the inverting op amp.

Returning to our first equation we get $–100 = –0.5R/1,000$.

Thus, R = **200 kΩ**.

The input power is = $(10)^2/20k = 5$ mW which leads to the power gain,

10/(0.005) = **2,000**.

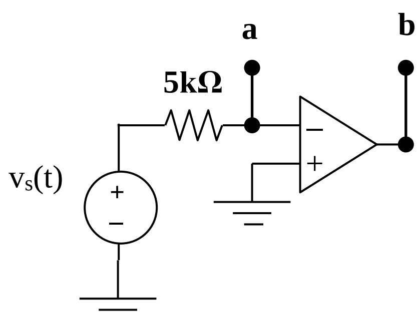
Solution 5.86

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

The easiest way to solve this problem is to understand that the op amp creates an output voltage so that the current through the feedback resistor remains equal to the input current.

In the following circuit, the op amp wants to keep the voltage at a equal to zero. So, the input current is $v_s/R = 200v_s(t)$ µA $= v_s(t)/5k$.

Thus, this circuit acts like an ideal voltage controlled current source no matter what (within the operational parameters of the op amp) is connected between a and b. Note, you can change the direction of the current between a and b by sending $v_s(t)$ through an inverting op amp circuit.



Solution 5.87

The output, v_a, of the first op amp is,

$$v_a = (1 + (R_2/R_1))v_1 \qquad (1)$$

Also, $$v_o = (-R_4/R_3)v_a + (1 + (R_4/R_3))v_2 \qquad (2)$$

Substituting (1) into (2),

$$v_o = (-R_4/R_3)\,(1 + (R_2/R_1))v_1 + (1 + (R_4/R_3))v_2$$

Or, $$v_o = \mathbf{(1 + (R_4/R_3))v_2 - (R_4/R_3 + (R_2R_4/R_1R_3))v_1}$$

If $R_4 = R_1$ and $R_3 = R_2$, then,

$$v_o = (1 + (R_4/R_3))(v_2 - v_1)$$

which is a subtractor with a gain of **$(1 + (R_4/R_3))$**.

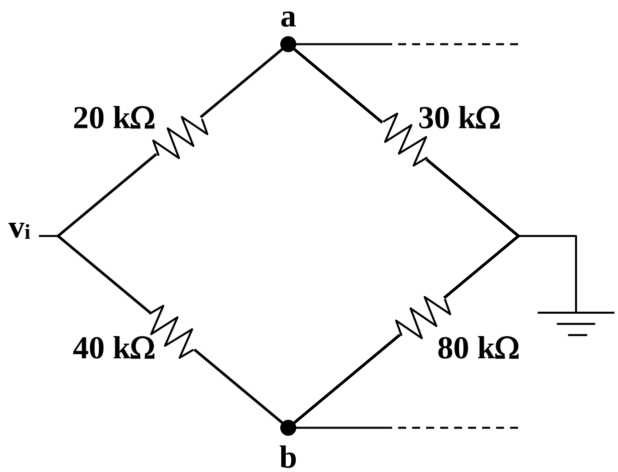
Solution 5.88

We need to find V_{Th} at terminals a – b, from this,

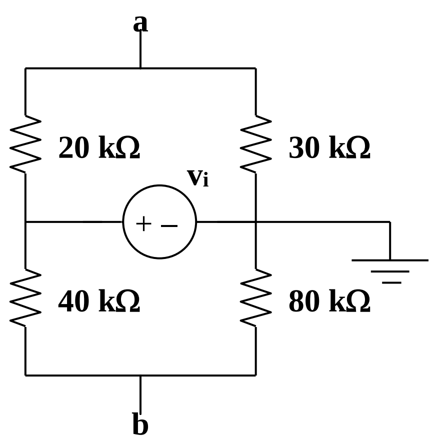
$v_o = (R_2/R_1)(1 + 2(R_3/R_4))V_{Th} = (500/25)(1 + 2(10/2))V_{Th}$

$= 220V_{Th}$

Now we use Fig. (b) to find V_{Th} in terms of v_i.



(a)



(b)

$v_a = (3/5)v_i, \; v_b = (2/3)v_i$

$V_{Th} = v_b – v_a \;\; (1/15)v_i$

$(v_o/v_i) = A_v = -220/15 =$ **-14.667**

Solution 5.89

A **summer** with $\mathbf{v_o = -v_1 - (5/3)v_2}$ where v_2 = **6-V battery** and an **inverting amplifier** with $\mathbf{v_1 = -12v_s}$.

Solution 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.

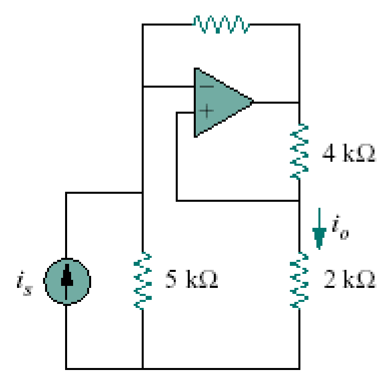
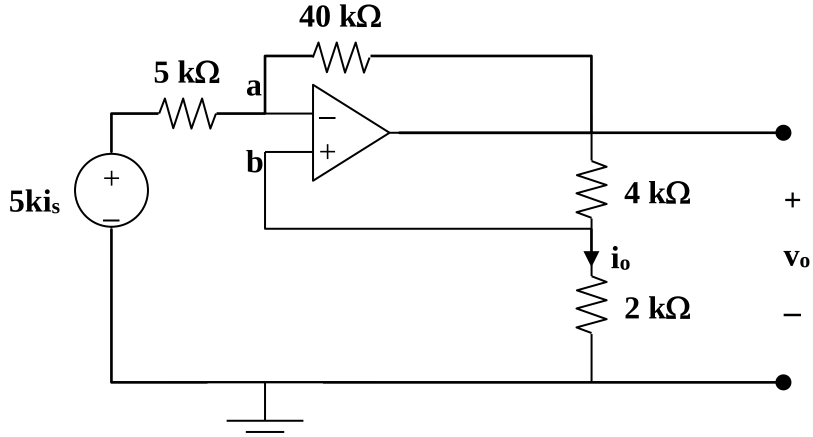


Figure 5.107
For Prob. 5.90.

Solution

Transforming the current source to a voltage source produces the circuit below,

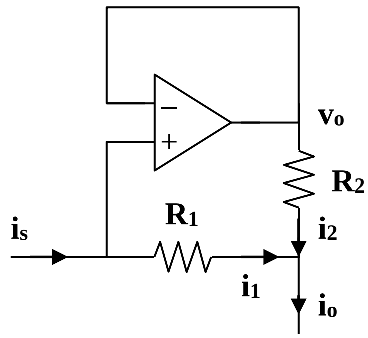
At node b, $v_b = (2/(2+4))v_o = v_o/3$



At node a, $[(v_a–5ki_s)/5k] + [(v_a–v_o)/40k] + 0 = 0$ where $v_a = v_b = v_o/3$. This gives us $8v_a – 40ki_s + v_a – v_o = 0 = (9/3)v_o – v_o – 40ki_s = 2v_o – 40ki_s$ or $i_s = v_o/20k$. Finally, $i_o = v_b/2k = v_o/6k$ which leads to,

$i_o/i_s = (v_o/6k)/(v_o/20k) =$ **3.333**.

Solution 5.91



$$i_o = i_1 + i_2 \qquad (1)$$

But $$i_1 = i_s \qquad (2)$$

R_1 and R_2 have the same voltage, v_o, across them.

$$R_1 i_1 = R_2 i_2, \text{ which leads to } i_2 = (R_1/R_2)i_1 \qquad (3)$$

Substituting (2) and (3) into (1) gives,

$$i_o = i_s(1 + R_1/R_2)$$

$$i_o/i_s = 1 + (R_1/R_2) = 1 + 8/1 = \mathbf{9}$$

Solution 5.92

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

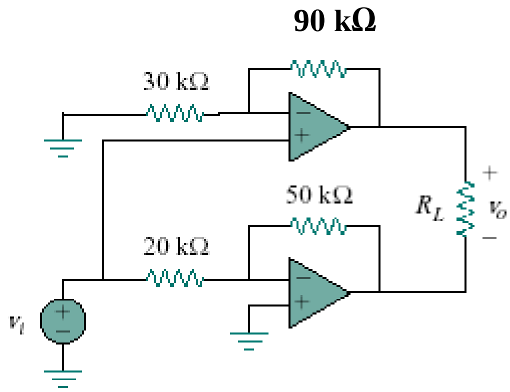


Figure 5.109
For Prob. 5.92.

Solution

The top op amp circuit is a non-inverter, while the lower one is an inverter. The output at the top op amp is

$$v_1 = (1 + 90/30)v_i = 4v_i$$

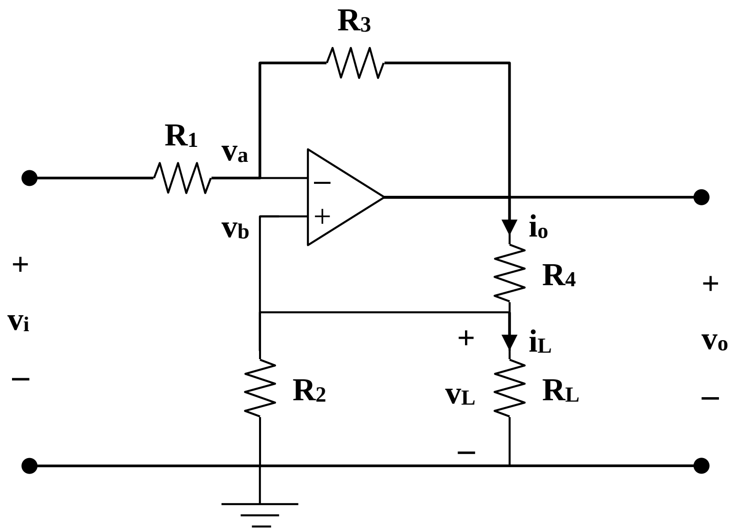
while the output of the lower op amp is

$$v_2 = -(50/20)v_i = -2.5v_i.$$

Hence, $v_o = v_1 - v_2 = 4v_i + 2.5v_i = 6.5v_i$

$$v_o/v_i = \mathbf{6.5}$$

Solution 5.93



At node a, $(v_i - v_a)/R_1 = (v_a - v_o)/R_3$

$v_i - v_a = (R_1/R_2)(v_a - v_o)$

$v_i + (R_1/R_3)v_o = (1 + R_1/R_3)v_a$ (1)

But $v_a = v_b = v_L$. Hence, (1) becomes

$v_i = (1 + R_1/R_3)v_L - (R_1/R_3)v_o$ (2)

$i_o = v_o/(R_4 + R_2||R_L)$, $i_L = (R_2/(R_2 + R_L))i_o = (R_2/(R_2 + R_L))(v_o/(R_4 + R_2||R_L))$

Or, $v_o = i_L[(R_2 + R_L)(R_4 + R_2||R_L)/R_2$ (3)

But, $v_L = i_L R_L$ (4)

Substituting (3) and (4) into (2),

$v_i = (1 + R_1/R_3)\, i_L R_L - R_1[(R_2 + R_L)/(R_2R_3)](R_4 + R_2||R_L)i_L$

$= [((R_3 + R_1)/R_3)R_L - R_1((R_2 + R_L)/(R_2R_3)(R_4 + (R_2R_L/(R_2 + R_L))]i_L$
$= (1/A)i_L$

Thus,

$$A = \frac{\mathbf{1}}{\left(\mathbf{1}+\frac{\mathbf{R_1}}{\mathbf{R_3}}\right)\mathbf{R_L} - \mathbf{R_1}\left(\frac{\mathbf{R_2}+\mathbf{R_L}}{\mathbf{R_2 R_3}}\right)\left(\mathbf{R_4}+\frac{\mathbf{R_2 R_L}}{\mathbf{R_2}+\mathbf{R_L}}\right)}$$

Please note that A has the units of mhos. An easy check is to let every resistor equal 1-ohm and v_i equal to one amp. Going through the circuit produces i_L = 1A. Plugging into the above equation produces the same answer so the answer does check.