Chapter Four:

Operational Amplifiers

4.1 An amplifier has a gain of 15 and the input waveform shown in Fig. P4.1. Draw the output waveform.

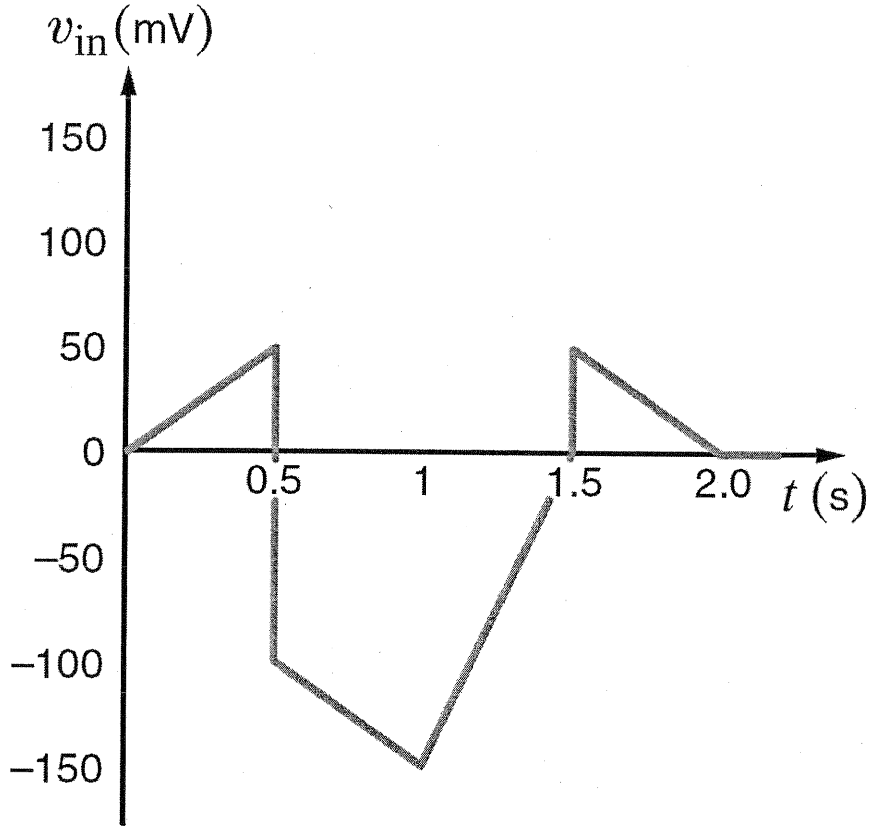
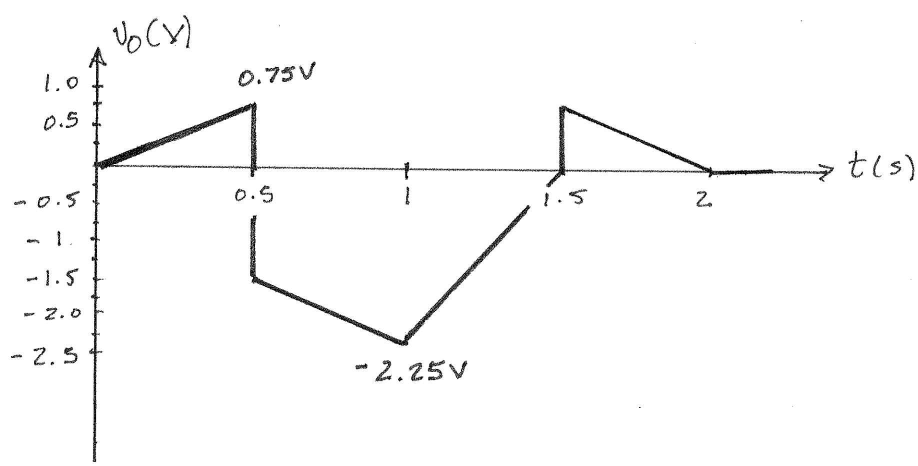


Figure P4.1

SOLUTION:



4.2 An amplifier has a gain of -5 and the output waveform shown in Fig. P4.2. Sketch the input waveform.

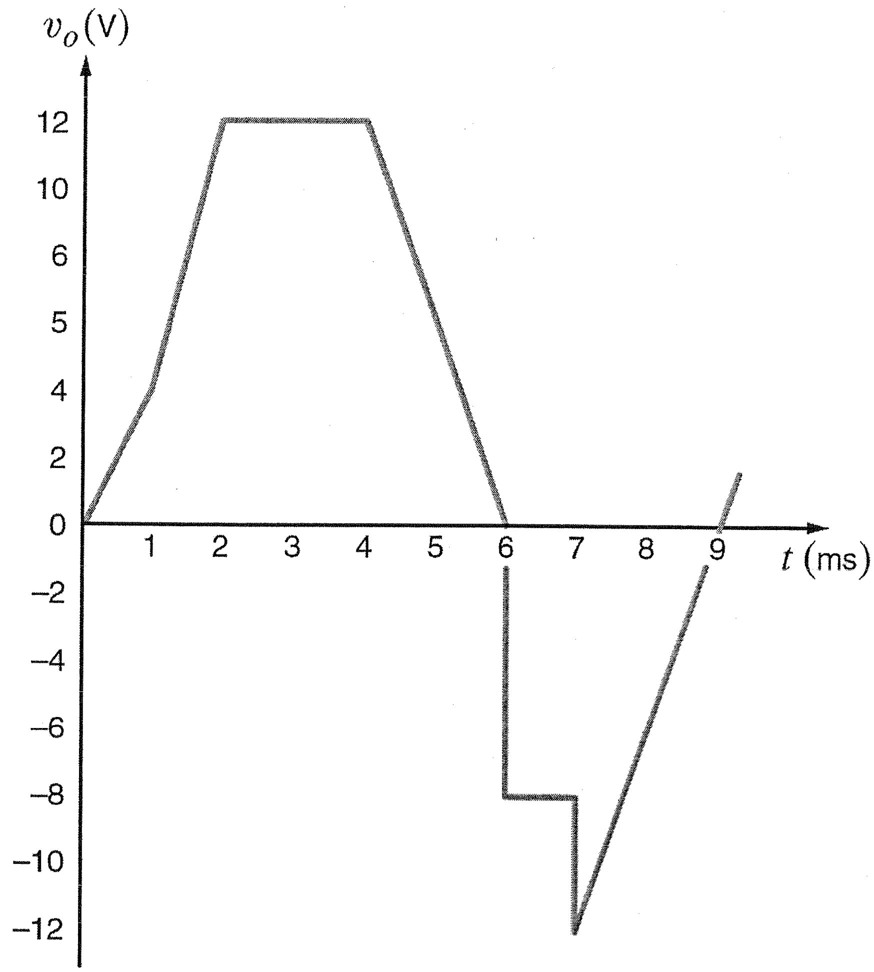
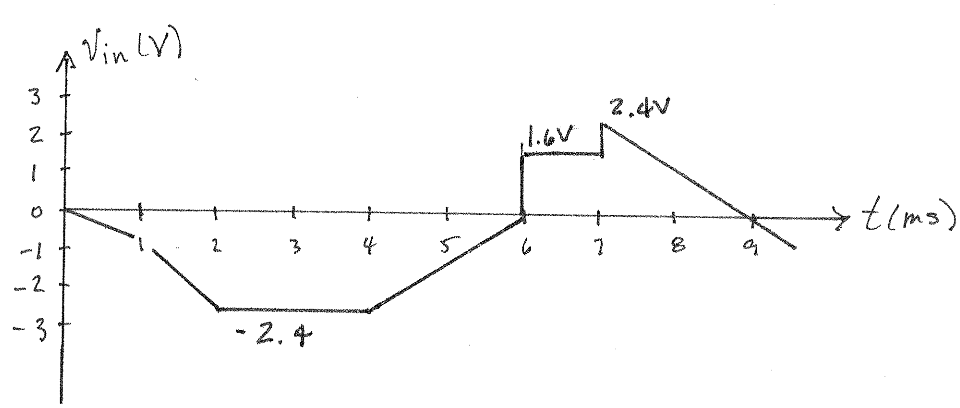


Figure P4.2

SOLUTION:



4.3 An op-amp base amplifier has supply voltages of ± 5 V and a gain of 20.

(a) Sketch the input waveform from the output waveform in Fig. P4.3.

(b) Double the amplitude of your results in (a) and sketch the new output waveform.

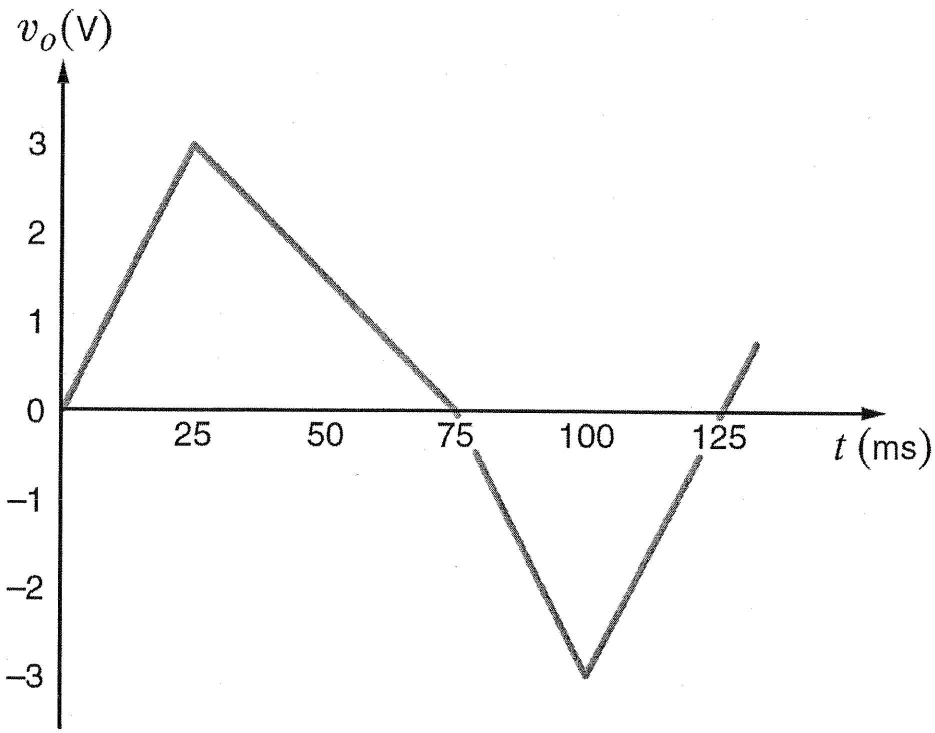
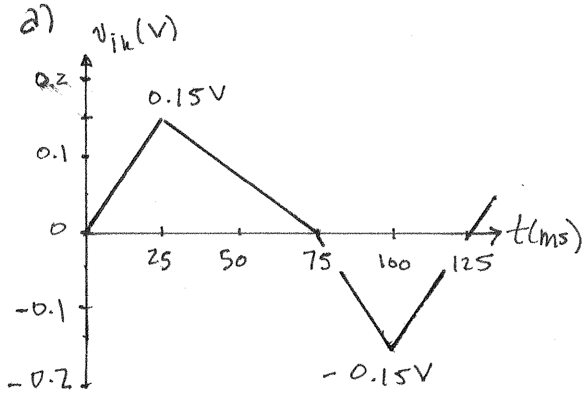


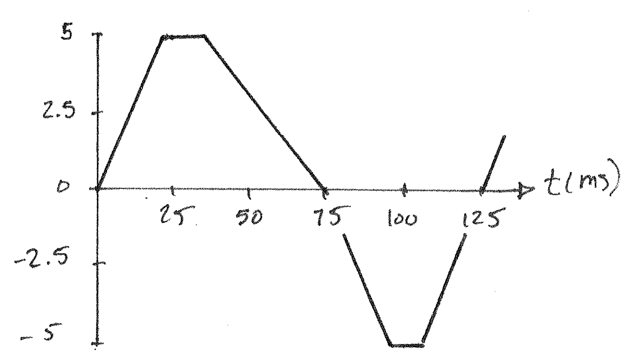
Figure P4.3

SOLUTION:

a)



b)



4.4 For an ideal op-amp, the voltage gain and input resistance are infinite while the output resistance is zero. What are the consequences for

(a) the op-amp's input voltage?

(b) the op-amp's input currents?

(c) the op-amp's output current?

SOLUTION:

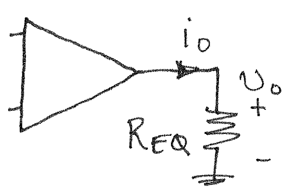
a) Since gain is infinite, an input voltage of zero can produce a finite output voltage.

$v_{in} = 0$

b) Since $R_{in} = \infty$, no input current flows.

$i_{in} = 0$

c) Since $R_{OUT} = 0$, the output current is limited only by external circuitry



$$i_o = \frac{v_o}{R_{EQ}}$$

4.5 Revisit your answers in Problem 4.4 under the following nonideal scenarios. **CS**

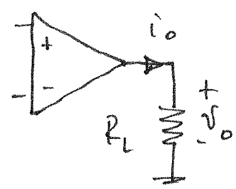
(a) $R_{\text{in}} = \infty$, $R_{\text{out}} = 0$, $A_o \neq \infty$.

(b) $R_{\text{in}} = \infty$, $R_{\text{out}} > 0$, $A_o = \infty$.

(c) $R_{\text{in}} \neq \infty$, $R_{\text{out}} = 0$, $A_o = \infty$.

SOLUTION:

a) Since $R_{in} = \infty$, $i_{in} = 0$
Since $R_{OUT} = 0$, $i_{OUT} = v_{OUT}/R_L$
Since $A_o \neq \infty$, $v_{in} \neq 0$



b) Since $R_{in} = \infty$, $i_{in} = 0$
Since $A_o = \infty$, $v_{in} = 0$
Since $R_{OUT} > 0$, i_{OUT} is limited by both R_{OUT} & R_L

c) Since $A_o = \infty$, $v_{in} = 0$
Since $R_{in} \neq \infty$, $i_{in} = v_{in}/R_{in}$
$i_{in} = 0$ only because $v_{in} = 0$

Since $R_o = 0$, i_{OUT} limited only by R_L

4.6 Revisit the exact analysis of the inverting configuration in Section 4.3.

(a) Find an expression for the gain if $R_{in} = \infty$, $R_{out} = 0$, $A_o \neq \infty$.

(b) Plot the ratio of the gain in (a) to the ideal gain versus A_o for $1 \leq A_o \leq 1000$ for an ideal gain of -10.

(c) From your plot, does the actual gain approach the ideal value as A_o increases or decreases?

(d) From your plot, what is the minimum value of A_o if the actual gain is within 5% of the ideal case?

SOLUTION:

a) From Section 4.3

$$\frac{v_o}{v_S} = \frac{-R_2/R_1}{1 - \dfrac{\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_{in}}\right)\left(\frac{1}{R_2}+\frac{1}{R_o}\right)}{\frac{1}{R_2}\left(\frac{1}{R_2}-\frac{A_o}{R_o}\right)}}$$

For $R_{in} = \infty$, $R_{out} = 0$, $A_o \neq \infty$ we have

$$\frac{1}{R_{in}} \ll \frac{1}{R_1} \text{ and } \frac{1}{R_2} \quad \& \quad \frac{1}{R_o} \gg \frac{1}{R_2}$$

yields,

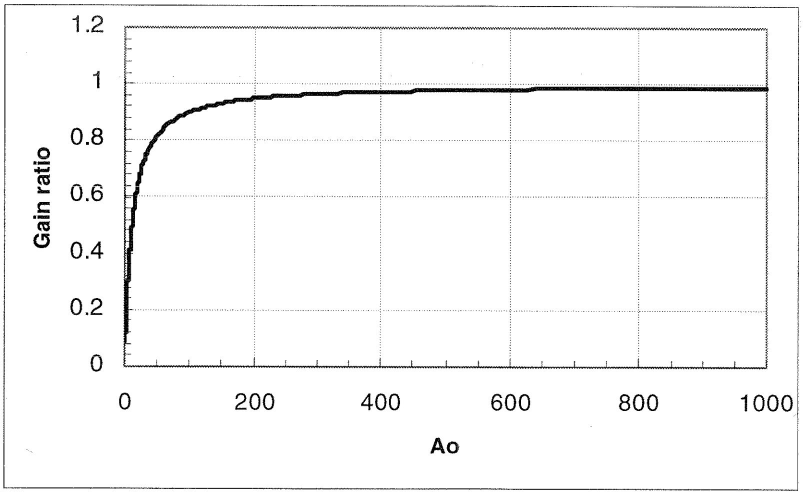
$$\frac{v_o}{v_S} = \frac{-R_2/R_1}{1 + \dfrac{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)\frac{1}{R_o}}{\frac{1}{R_2}\left(A_o/R_o\right)}} = \frac{-R_2/R_1}{1+\left(\frac{R_1+R_2}{R_1}\right)\frac{1}{A_o}}$$

or,

$$\boxed{\frac{v_o}{v_S} = \frac{-R_2/R_1}{1+\frac{1}{A_o}\left(1+R_2/R_1\right)}}$$

b) $A_{ideal} = -\frac{R_2}{R_1} = -10$

$A_{actual} = \frac{v_o}{v_s} = \frac{-10}{1 + \frac{11}{A_o}}$



c) As A_o increases, A_{actual} approaches A_{ideal}

d) from b, $\frac{A_{actual}}{A_{ideal}} = \frac{\frac{-10}{1+\frac{11}{A_o}}}{-10} \leq 0.95$

$$\boxed{A_o \geq 209}$$

4.7 Revisit the exact analysis of the inverting amplifier in Section 4.3.

(a) Find an expression for the voltage gain if $R_{\text{in}} \neq \infty$, $R_{\text{out}} = 0$, $A_o \neq \infty$.

(b) For $R_2 = 27\ \text{k}\Omega$ and $R_1 = 3\ \text{k}\Omega$, plot the ratio of the actual gain to the ideal gain for $A_o = 1000$ and $1\ \text{k}\Omega \leq R_{\text{in}} \leq 100\ \text{k}\Omega$.

(c) From your plot, does the ratio approach unity as R_{in} increases or decreases?

(d) From your plot in (b), what is the minimum value of R_{in} if the gain ratio is to be at least 0.98?

SOLUTION:

a)

$$\frac{v_o}{v_s} = A_{actual} = \frac{-R_2/R_1}{1 - \dfrac{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i}\right)\left(\frac{1}{R_2} + \frac{1}{R_o}\right)}{\frac{1}{R_2}\left(\frac{1}{R_2} - \frac{A_o}{R_o}\right)}}$$

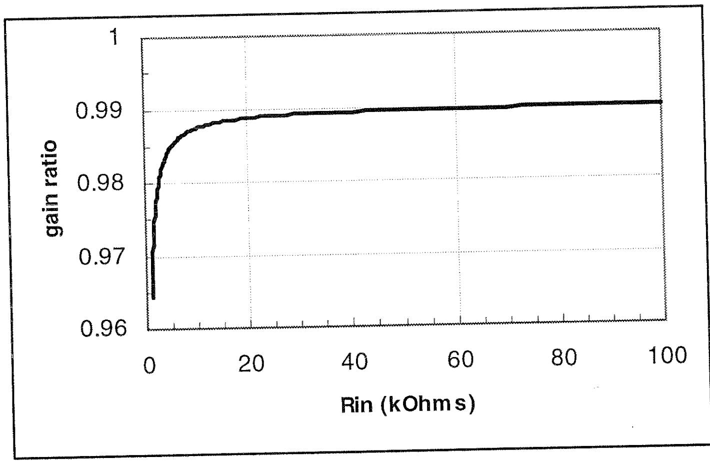
For $R_o = 0$, $\frac{1}{R_o} >> \frac{1}{R_2}$ and $\frac{A_o}{R_o} >> \frac{1}{R_2}$

$$A_{actual} = -\frac{R_2/R_1}{1 + \dfrac{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i}\right)}{A_o/R_2}}$$

$$\boxed{A_{actual} = \frac{-R_2/R_1}{1 + \frac{1}{A_o}\left(1 + \frac{R_2}{R_1} + \frac{R_2}{R_i}\right)}}$$

b) $R_2 = 27\,k\Omega$ $R_1 = 3\,k\Omega$ $A_0 = 1000$ $A_{ideal} = -9$

$$\frac{A_{actual}}{A_{ideal}} = \frac{-9/-9}{1 + \dfrac{10 + \dfrac{27000}{R_i}}{1000}}$$



c) The ratio approaches unity as R_i increases.

d) $$0.98 \leq \frac{1}{1 + 0.01 + \dfrac{27}{R_i}}$$ $\boxed{R_i \geq 2.59\,k\Omega}$

4.8 An op-amp based amplifier has ±18 V supplies and a gain of −80. Over what input range is the amplifier linear?

SOLUTION:

For linear operation

$$\frac{v_o}{v_{in}} = -80$$

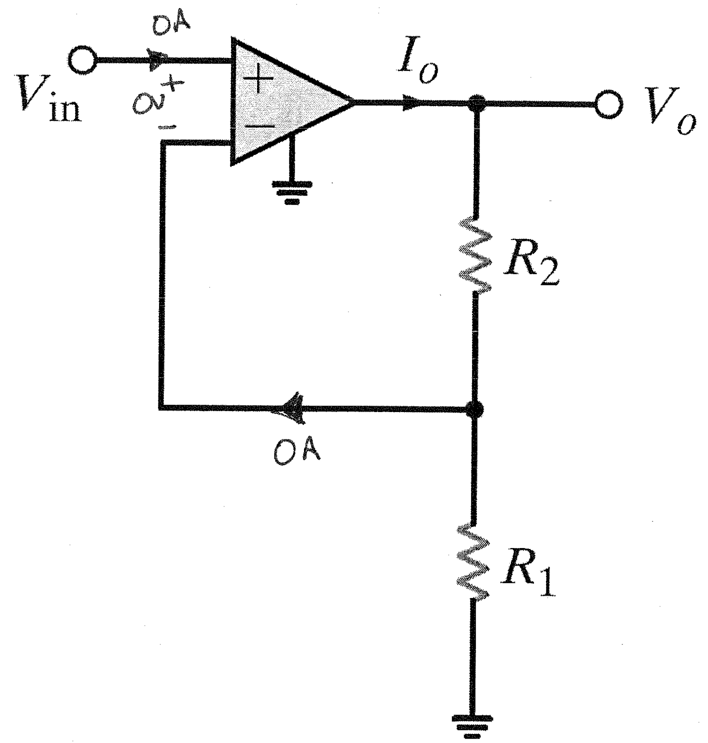
Due to output limits, $|v_o| \leq 18V$

Linear region limited to

$$v_{in} \leq \frac{v_o}{-80}$$

$$\boxed{|v_{in}| \leq 0.225V}$$

4.9 Determine the gain of the amplifier in Fig. P4.9. What is the value of I_o? **CS**



$R_2 = 20$ kΩ

$R_1 = 3.3$ kΩ

$V_{in} = 2$ V

Figure P4.9

SOLUTION:

Basic noninverting configuration

$$\frac{V_o}{V_{in}} = 1 + \frac{R_2}{R_1} \Rightarrow \boxed{\frac{V_o}{V_{in}} = 7.06}$$

If $V_{in} = 2V$, $V_o = 14.12 V$

$$I_o = \frac{V_o}{R_1 + R_2} = 606 \mu A \qquad \boxed{I_o = 606 \mu A}$$

4.10 For the amplifier in Fig. P4.10, find the gain and I_o?

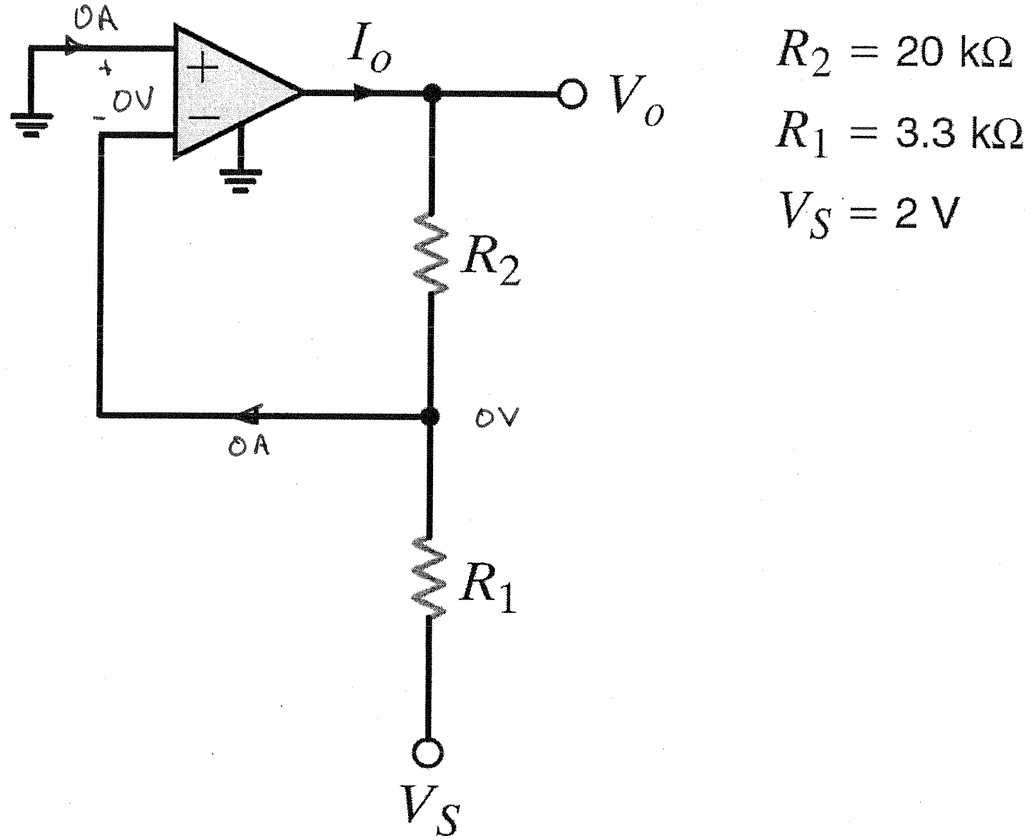


Figure P4.10

SOLUTION:

Basic inverting configuration, $\frac{V_o}{V_S} = -\frac{R_2}{R_1} \Rightarrow \boxed{-6.06 = \frac{V_o}{V_S}}$

$I_o = V_o / R_2$ $V_o = (-6.06) V_S = -12.12$

$\boxed{I_o = -606\mu A}$

4.11 Using the ideal op-amp assumptions, determine the values of V_o and I_1 in Fig. P4.11.

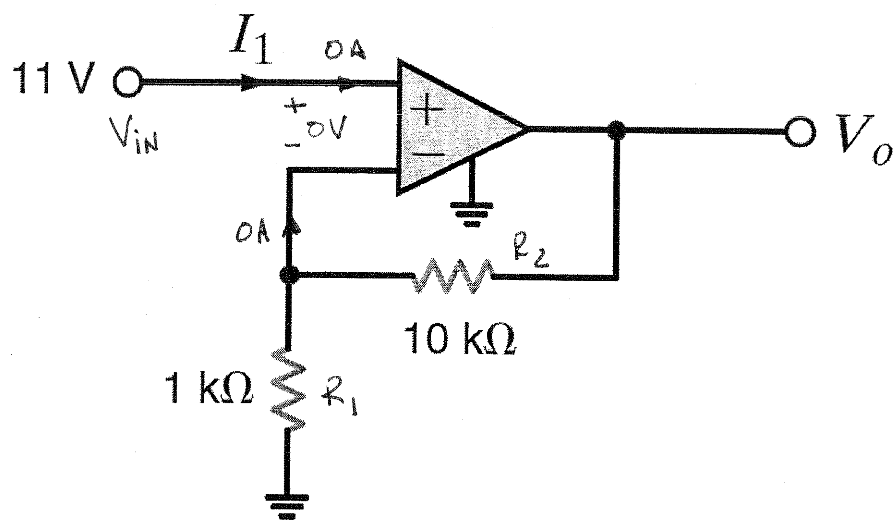


Figure P4.11

SOLUTION:

Basic non-inverting configuration,

$\frac{V_o}{V_{IN}} = 1 + \frac{R_2}{R_1} = 11 \Rightarrow V_o = 11 V_{IN}$ $\boxed{V_o = 121V}$

Since $R_{in} = \infty$, $I_{in} = 0$ $\boxed{I_1 = 0A}$

4.12 Using the ideal op-amp assumptions, determine I_1, I_2, and I_3 in Fig. P4.12. **PSV**

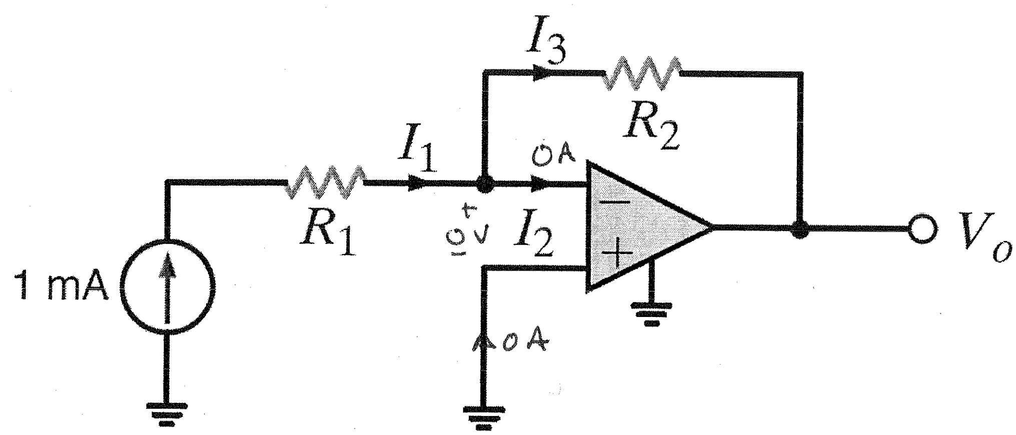


Figure P4.12

SOLUTION:

$\boxed{I_1 = 1\text{mA}}$ $\boxed{I_2 = 0\text{A}}$ (ideal op-amp)

By KCL,

$I_3 = I_1 - I_2$ $\boxed{I_3 = 1\text{mA}}$

4.13 In a useful application, the amplifier drives a load. The circuit in Fig. P4.13 models this scenario. **CS**

(a) Sketch the gain V_o/V_S for $10\ \Omega \leq R_L \leq \infty$.

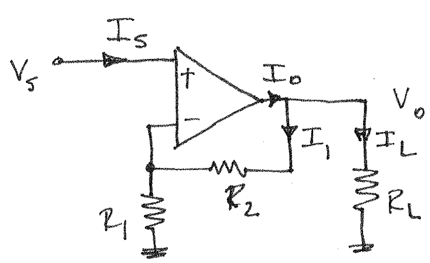
(b) Sketch I_o for $10\ \Omega \leq R_L \leq \infty$ if $V_S = 0.1$ V.

(c) Repeat (b) if $V_S = 1.0$ V.

(d) What is the minimum value of R_L if $|I_o|$ must be less than 100 mA for $|V_S| < 0.5$ V?

(e) What is the current I_S if R_L is 100 Ω? Repeat for $R_L = 10$ kΩ.

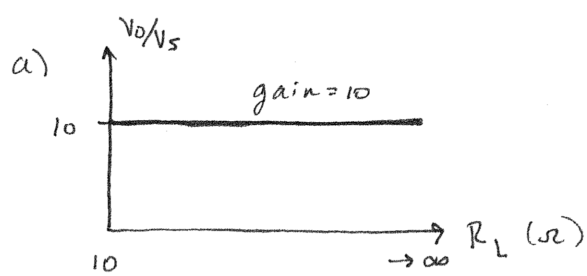
SOLUTION:



$R_2 = 27\,k\Omega \qquad R_1 = 3\,k\Omega$

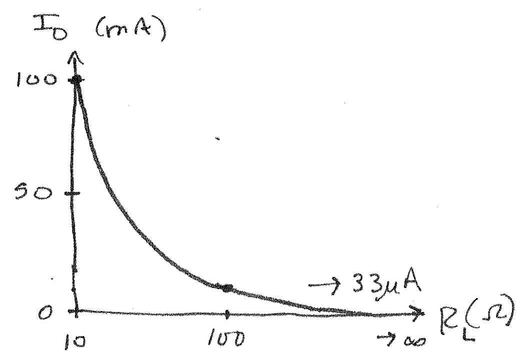
$$\frac{V_o}{V_S} = 1 + \frac{R_2}{R_1} = 10$$

a)

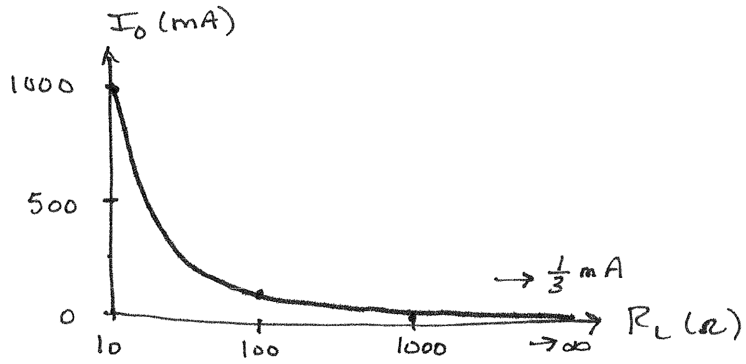


b) $V_S = 0.1\,V$, $V_o = 1\,V$

$$I_o = I_L + I_1 = \frac{V_o}{30\times10^3} + \frac{V_o}{R_L}$$



c. $V_S = 1V$, $V_o = 10V$, $I_o = \frac{10}{30 \times 10^3} + \frac{10}{R_L}$



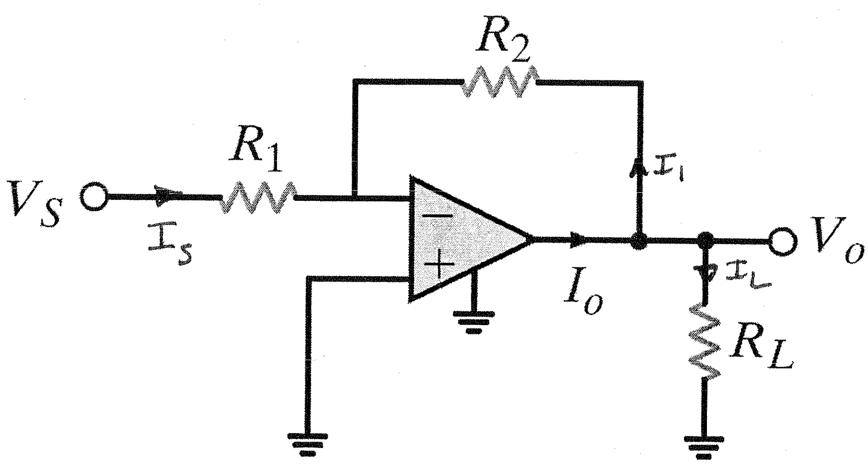
d) $V_S = 0.5V$, $V_o = 5V$, $I_o = \frac{5}{30 \times 10^3} + \frac{5}{R_L} < 100mA$

$$\boxed{R_L > 50.1\Omega}$$

e) I_S flows directly into the opamp's non-inverting input. I_S is zero regardless of R_L

$$\boxed{I_S = 0}$$

4.14 Repeat Problem 4.13 for the circuit in Fig. P4.14.



$R_2 = 27\ \text{k}\Omega$

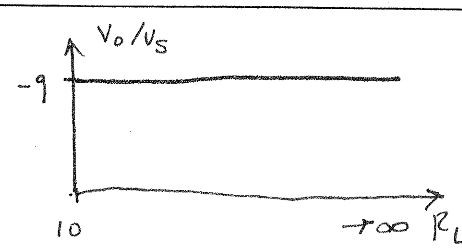
$R_1 = 3\ \text{k}\Omega$

Figure P4.14

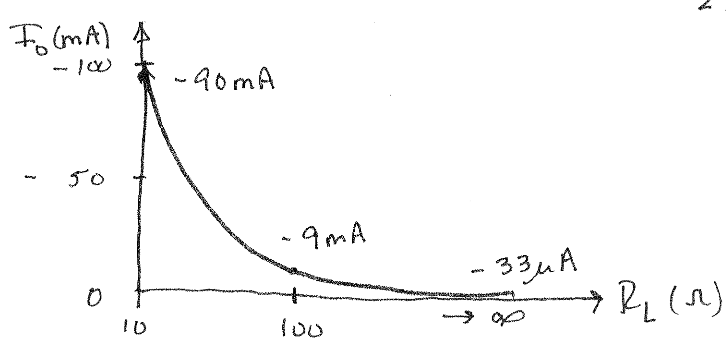
SOLUTION:

a) $V_o = -R_2/R_1\, V_s = -9\,V_s$

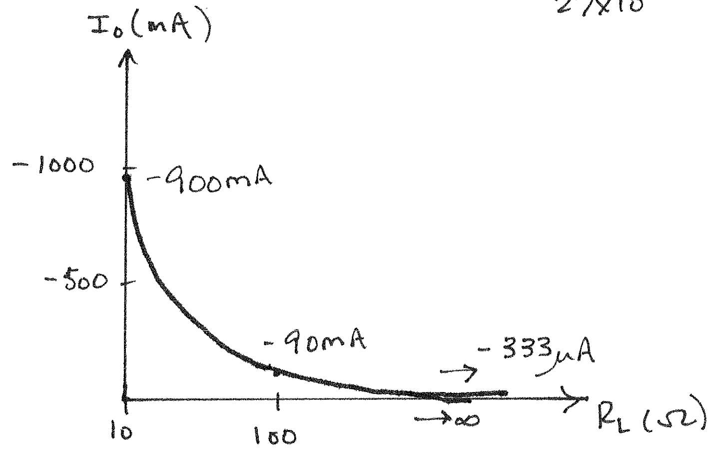
$I_o = I_1 + I_L = \frac{V_o}{R_2} + \frac{V_o}{R_L}$



b) $V_s = 0.1\text{V}$, $V_o = -0.9\text{V}$ $I_o = \frac{-.9}{27\times10^{+3}} - \frac{.9}{R_L}$



c) $V_S = 1V$, $V_o = -9V$ $\quad I_o = \dfrac{-9}{27\times10^3} - \dfrac{9}{R_L}$



d) $I_o = \dfrac{-9V_s}{27\times10^3} - \dfrac{9V_s}{R_L}$

at $V_s = 0.5V$, $|I_o| = +\dfrac{4.5}{27\times10^3} + \dfrac{4.5}{R_L} < 100mA$

$\boxed{R_L > 45.1\Omega}$

e) $I_s = \dfrac{V_s}{R_1} = \dfrac{V_s}{3000}$ $\quad I_s$ is independent of R_L

at $V_s = 0.5V$, $\boxed{I_s = 167\mu A}$

4.15 The op-amp in the amplifier in Fig. P4.15 operates with ±15 V supplies and can output no more than 200 mA. What is the maximum gain allowable for the amplifier if the maximum value of V_S is 1 V?

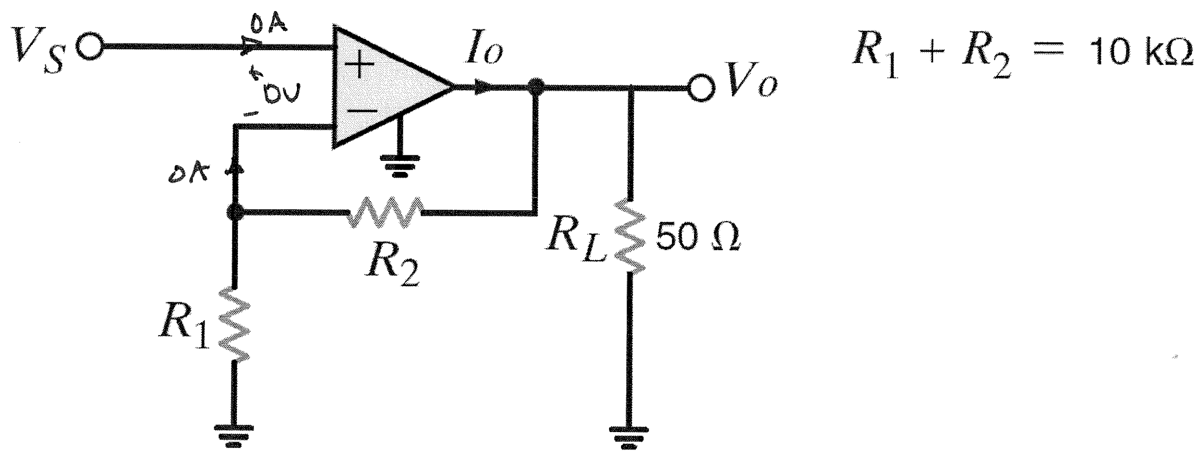


Figure P4.15

SOLUTION:

Basic non-inverting configuration: $\frac{V_o}{V_s} = 1 + \frac{R_2}{R_1} = \frac{R_1 + R_2}{R_1} = \frac{10^4}{R_1}$

$|V_o| = |V_s| \left(\frac{10^4}{R_1} \right) \leq 15$ Since $V_s = 1\,V$, $\frac{10^4}{R_1} = V_o$

Also, $I_o = \frac{V_o}{R_1 + R_2} + \frac{V_o}{50} = \frac{1}{R_1} + \frac{10^4}{50 R_1} = \frac{1}{R_1}\left[201\right] \leq 200\text{mA}$

$R_1 \geq 1005\,\Omega$ for $I_o \leq 200\text{mA}$

$R_2 \leq 8995\,\Omega$

Check gain limit: $1 + R_2/R_1 = 9.95$ Is < 15!

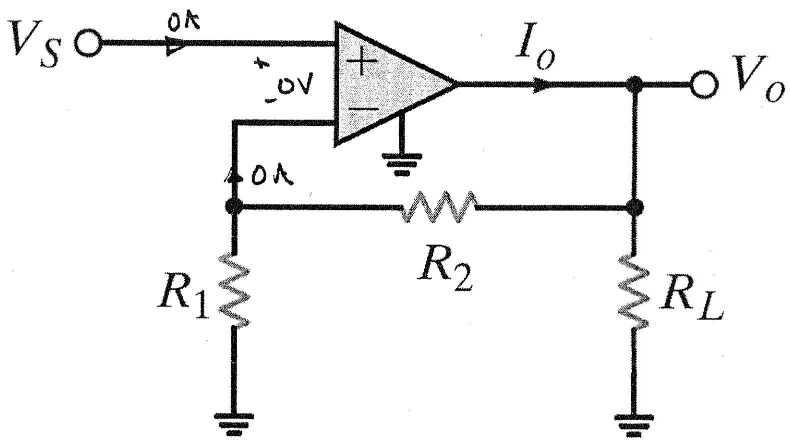
Final answer $\boxed{R_1 = 1005\,\Omega \quad R_2 = 8995\,\Omega \quad A_v = 9.95}$

4.16 For the amplifier in Fig. P4.16, the maximum value of V_S is 2 V and the op-amp can deliver no more than 100 mA.

(a) If ±10 V supplies are used, what is the maximum allowable value of R_2?

(b) Repeat for ±3 V supplies.

(c) Discuss the impact of the supplies on the maximum allowable gain.



R_L = 10 kΩ

R_1 = 100 kΩ

Figure P4.16

SOLUTION:

a) Basic non-inverting configuration: $V_o = V_s\left[1+\frac{R_2}{R_1}\right]$ & $I_o = \frac{V_o}{R_L // (R_1+R_2)}$

For $V_s = 2V$, $V_o = 2\left(1+\frac{R_2}{R_1}\right) \leq 10V$

$\boxed{R_2 \leq 400k\Omega}$

Check I_o limit: $\frac{10}{10^4 // (10^5 + 4\times10^5)} \leq 100mA$? yes!

b) $V_o = 2\left(1+R_2/R_1\right) \leq 3V$ $\boxed{R_2 \leq 50k\Omega}$ $I_o = \frac{3}{9.375\times10^3} = 320\,\mu A$ ✓

c) For a given Vs value, Av max is linearly related to supply voltage until I_o limit becomes an issue.

4.17 For the circuit in Fig. P4.17, **PSV**

(a) find V_o in terms of V_1 and V_2.

(b) If $V_1 = 2$ V and $V_2 = 6$ V, find V_o.

(c) If the op-amp supplies are ± 12 V, and $V_1 = 4$ V, what is the allowable range of V_2?

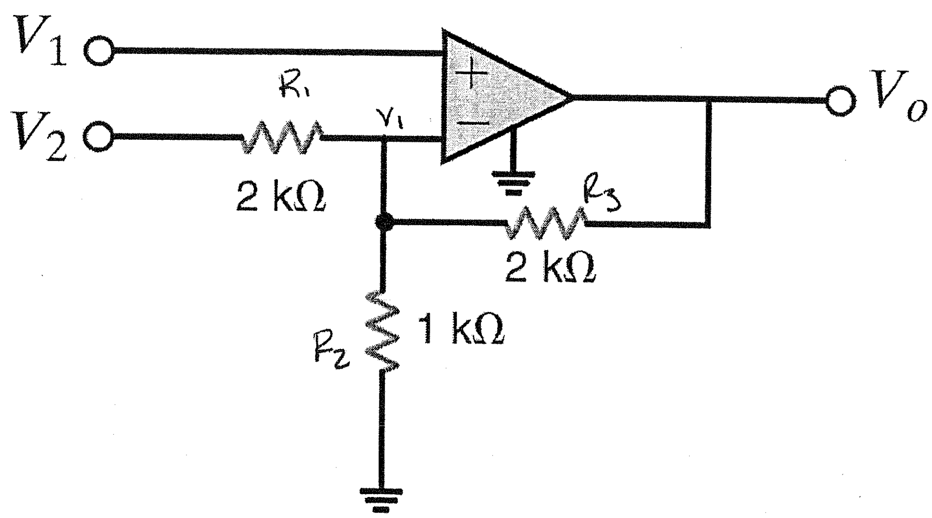


Figure P4.17

SOLUTION:

a) KCL at v_- input: (remember $v_+ = v_- = V_1$)

$$\frac{V_2 - V_1}{R_1} = \frac{V_1}{R_2} + \frac{V_1 - V_o}{R_3} \Rightarrow V_o = V_1\left(1 + \frac{R_3}{R_1} + \frac{R_3}{R_2}\right) - v_2\left(\frac{R_3}{R_1}\right)$$

$$\boxed{v_o = 4V_1 - V_2}$$

b) $V_o = 4(2) - 6$ $\quad \boxed{V_o = 2\text{ V}}$

c) $V_o = |4(4) - V_2| \leq 12\text{ V}$ $\quad \boxed{4\text{ V} \leq V_2 \leq 28\text{ V}}$

4.18 Find V_o in the circuit in Fig. P4.18 assuming the op-amp is ideal.

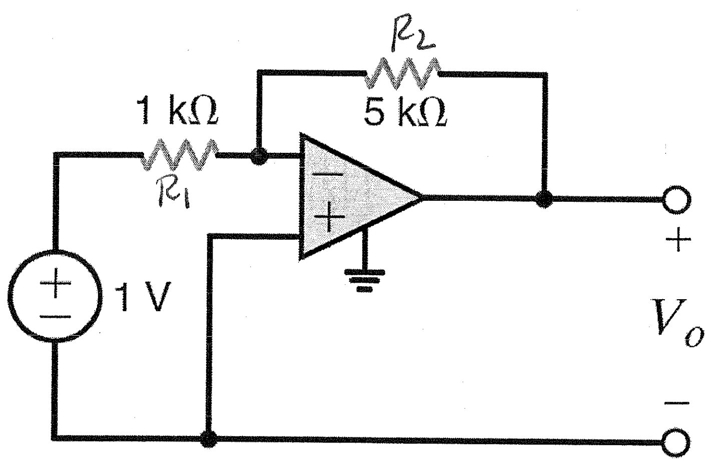


Figure P4.18

SOLUTION:

Basic inverting configuration.

$$V_o = V_s\left[-R_2/R_1\right] \qquad V_o = 1\left(-\frac{5000}{1000}\right) \qquad \boxed{V_o = -5V}$$

4.19 The network in Fig. P4.19 is a current-to-voltage converter or transconductance amplifier. Find v_o / i_S for this network.

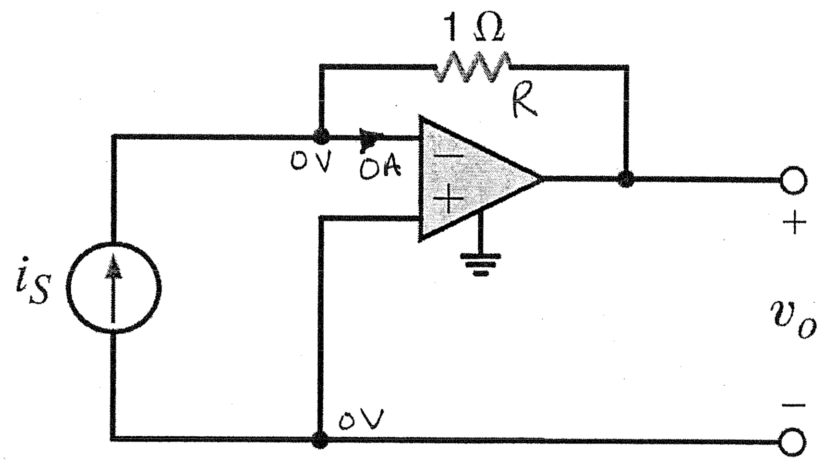


Figure P4.19

SOLUTION:

KCL at v_- input: $\quad i_S = \dfrac{0 - v_o}{R}$

$\dfrac{v_o}{i_S} = -R \qquad \boxed{\dfrac{v_o}{i_S} = -1}$

4.20 Calculate the transfer function i_o/v_1 for the network shown in Fig. P4.20.

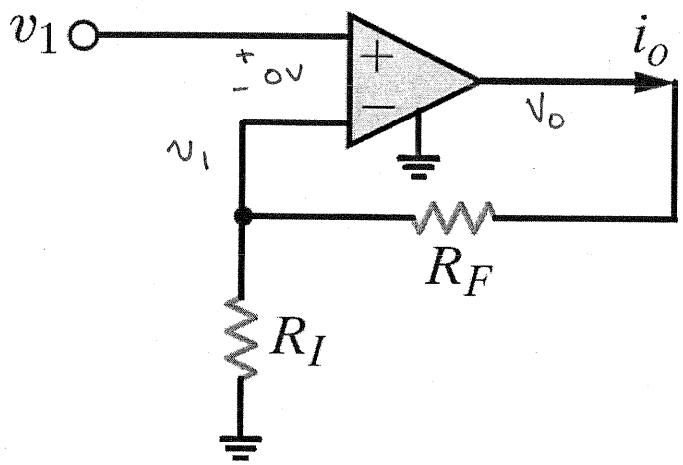


Figure P4.20

SOLUTION:

KCL at v_- input: $\quad \dfrac{v_1}{R_I} = \dfrac{V_o - V_1}{R_F}$

$$\frac{V_o}{V_1} = 1 + \frac{R_F}{R_I} = \frac{R_I + R_F}{R_I}$$

$$i_o = \frac{V_o}{R_I + R_F} = V_1/R_I \qquad \boxed{\frac{i_o}{V_1} = \frac{1}{R_I}}$$

4.21 Determine the relationship between v_1 and i_o in the circuit shown in Fig. P4.21. **CS**

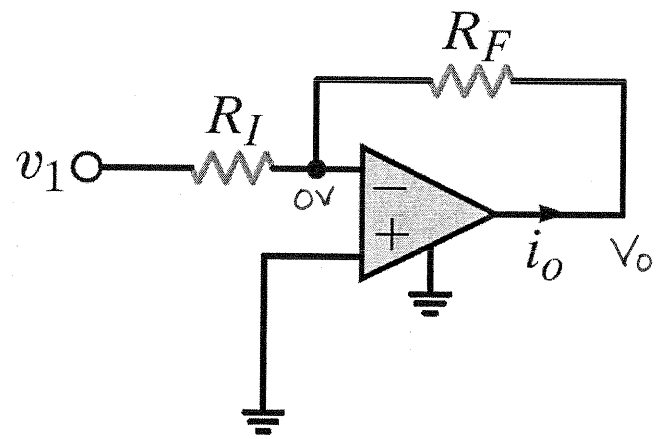


Figure P4.21

SOLUTION:

Basic inverting configuration:

$$\frac{v_o}{v_1} = -\frac{R_F}{R_I} \qquad i_o = \frac{v_o}{R_F} = -v_1/R_I$$

$$\boxed{\frac{i_o}{v_1} = -\frac{1}{R_I}}$$

4.22 Find V_o in the network in Fig. P4.22 and explain what effect R_1 has on the output.

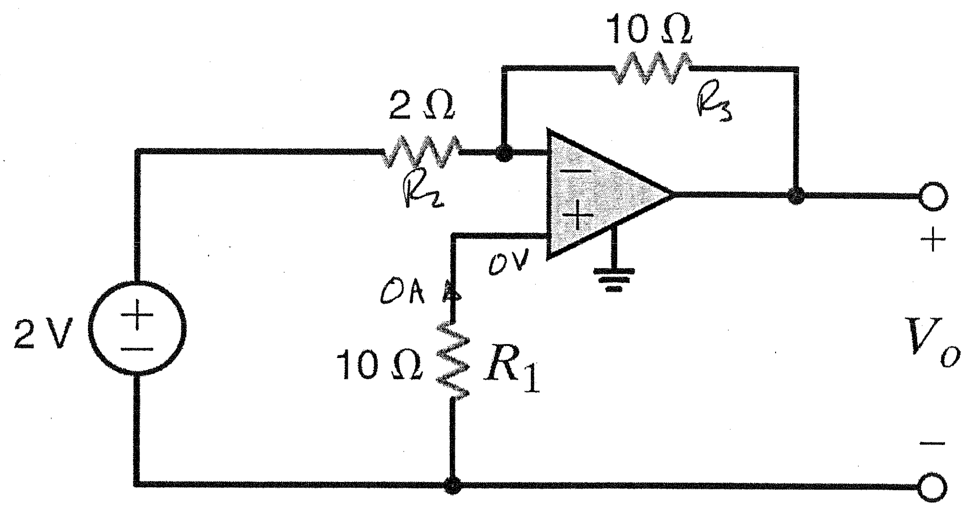


Figure P4.22

SOLUTION:

Since $i_{in} = 0$ for ideal op amp, voltage across $R_1 = 0$ and v_+ input is at 0V as well. Result is a basic inverting configuration.

$$V_o = -2\left(R_3/R_2\right) \Rightarrow \boxed{V_o = -10\,V}$$

R_1 has no impact on the circuit at all!

4.23 Determine the expression for v_o in the network in Fig. P4.23.

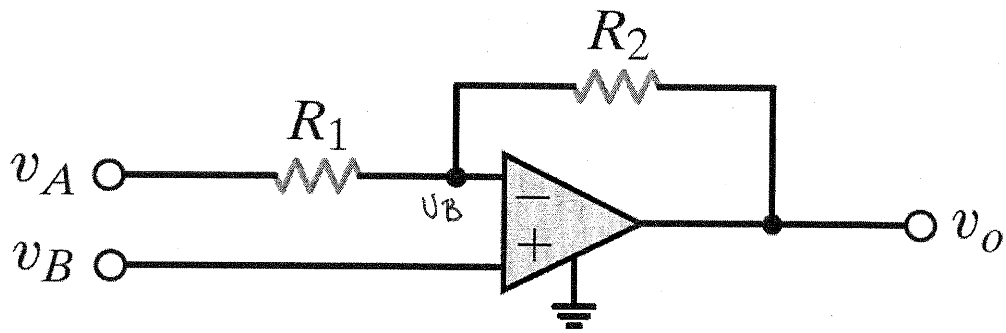


Figure P4.23

SOLUTION:

KCL at V- node:

$$\frac{V_A - V_B}{R_1} + \frac{V_o - V_B}{R_2} = 0$$

$$\boxed{V_o = V_B\left(1 + \frac{R_2}{R_1}\right) - V_A\left(R_2/R_1\right)}$$

4.24 Show that the output of the circuit in Fig. P4.24 is

$$V_o = \left[1 + \frac{R_2}{R_1}\right]V_1 - \frac{R_2}{R_1}V_2$$

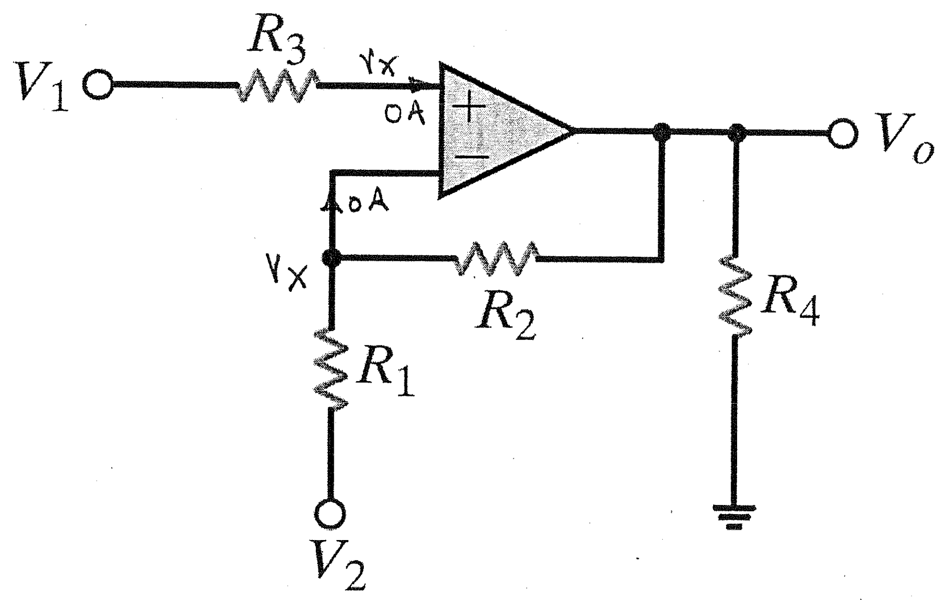


Figure P4.24

SOLUTION:

KCL at v_+ input: $\Rightarrow \dfrac{V_1 - V_x}{R_3} = 0 \Rightarrow V_1 = V_x$

$$\frac{V_2 - V_x}{R_1} + \frac{V_o - V_x}{R_2} = 0 \qquad V_o = V_x\left(1 + \frac{R_2}{R_1}\right) - V_2\left(R_2/R_1\right)$$

$$\boxed{V_o = \left[1 + \frac{R_2}{R_1}\right]V_1 - \frac{R_2}{R_1}V_2}$$

4.25 Find V_o in the network in Fig. P4.25. CS

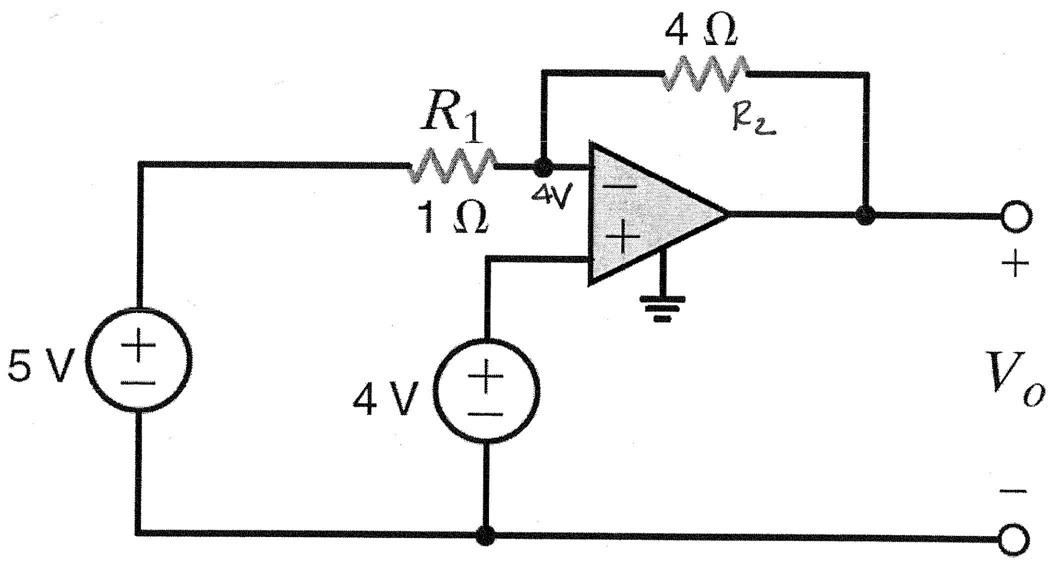


Figure P4.25

SOLUTION:

KCL at V_- input: $\dfrac{5-4}{R_1} + \dfrac{V_o - 4}{R_2} = 0$

$\boxed{V_o = 0\,V}$

4.26 Find the voltage gain of the op-amp circuit shown in Fig. P4.26.

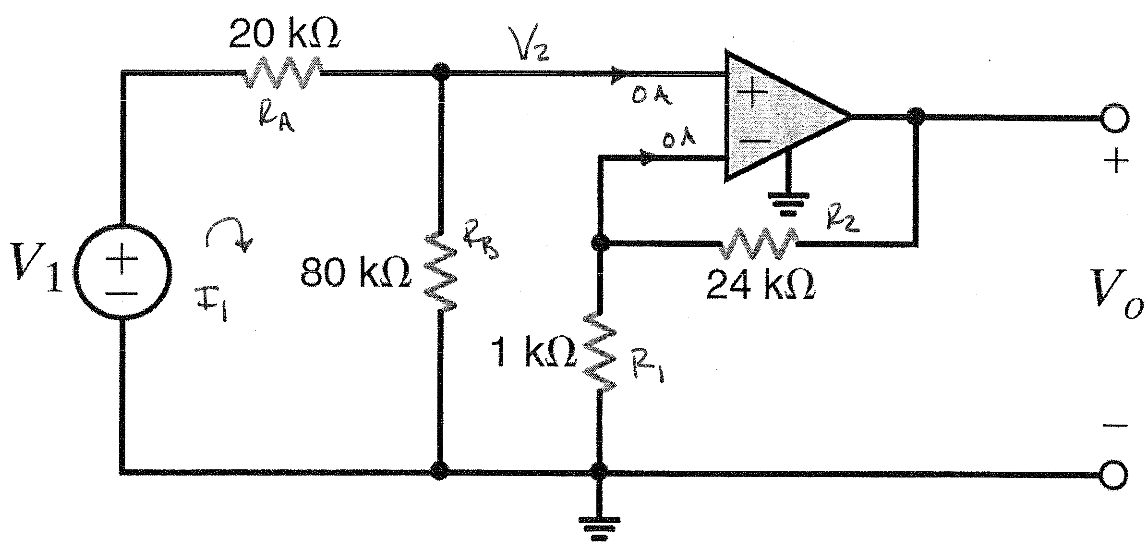


Figure P4.26

SOLUTION:

Two step solution: 1) Find V_2/V_1
2) Find V_o/V_2

1) Loop analysis:

$V_1 = I_1 R_A + I_1 R_B$ & $V_2 = I_1 R_B$

$I_1 = V_2/R_B$ $\qquad \frac{V_2}{V_1} = \frac{R_B}{R_A+R_B} = 0.8$

2) Op-amp is in basic non-inverting configuration.

$$\frac{V_o}{V_2} = 1 + \frac{R_2}{R_1} = 25$$

Overall gain is $V_o/V_1 = (V_2/V_1)(V_o/V_2)$ $\qquad \boxed{\frac{V_o}{V_1} = 20}$

4.27 For the circuit in Fig. 4.27 find the value of R_1 that produces a voltage gain of 10.

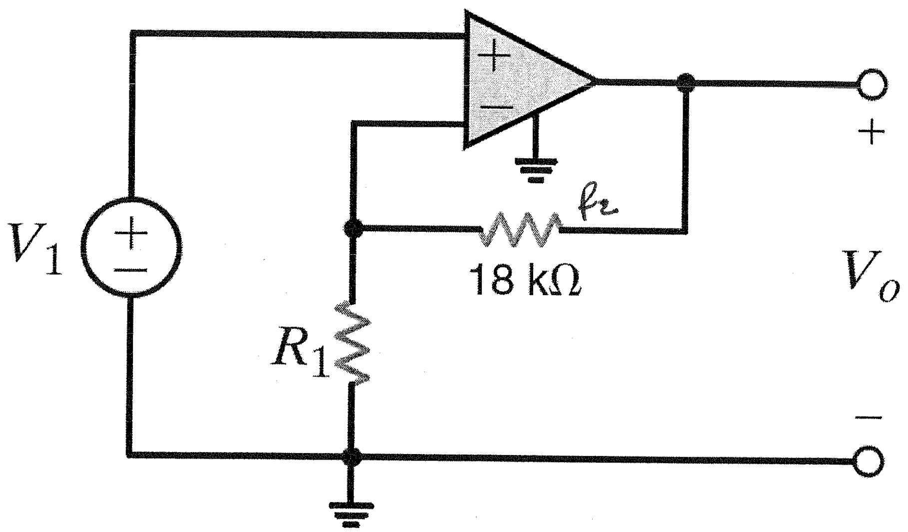


Figure P4.27

SOLUTION:

Basic non-inverting configuration:

$$\frac{V_o}{V_1} = 1 + \frac{R_2}{R_1} = 1 + \frac{18 \times 10^3}{R_1} = 10$$

$$\boxed{R_1 = 2k\Omega}$$

4.28 Determine the relationship between v_o and v_{in} in the circuit in Fig. P4.28.

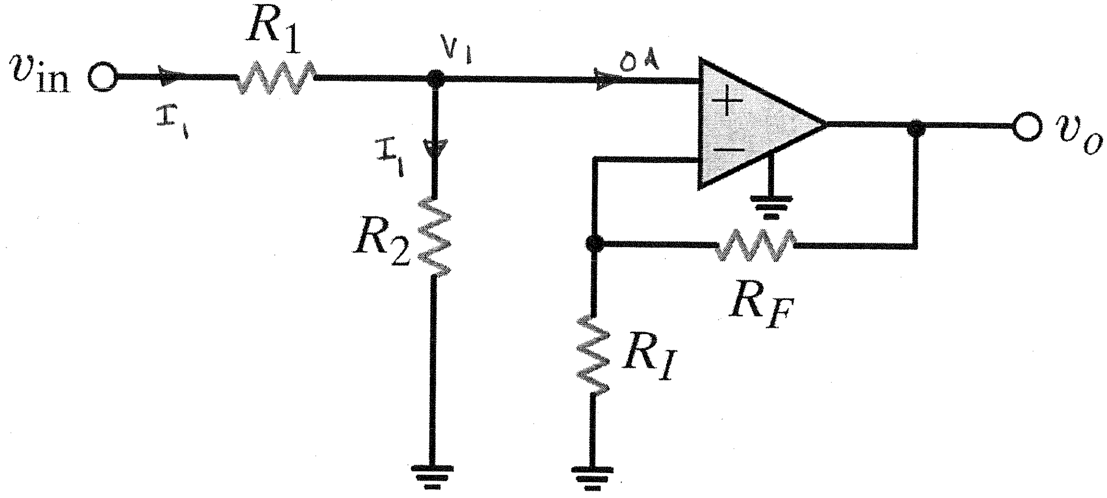


Figure P4.28

SOLUTION: Two step solution: 1) find V_1/V_{in}
2) find V_o/V_1

1) $V_{in} = I_1 R_1 + I_1 R_2$ $\qquad V_1 = I_1 R_2 \Rightarrow \dfrac{V_1}{V_{in}} = \dfrac{R_2}{R_1+R_2}$

2) Opamp is in basic non-inverting configuration

$$\frac{V_o}{V_1} = 1 + \frac{R_F}{R_I}$$

Overall gain $\dfrac{V_o}{V_{in}} = \left(\dfrac{V_o}{V_1}\right)\left(\dfrac{V_1}{V_{in}}\right)$.

$$\boxed{\frac{V_o}{V_{in}} = \left(\frac{R_2}{R_1+R_2}\right)\left(\frac{R_I+R_F}{R_I}\right)}$$

4.29 In the network in Fig. P4.29 derive the expression for v_o in terms of the inputs v_1 and v_2. **CS**

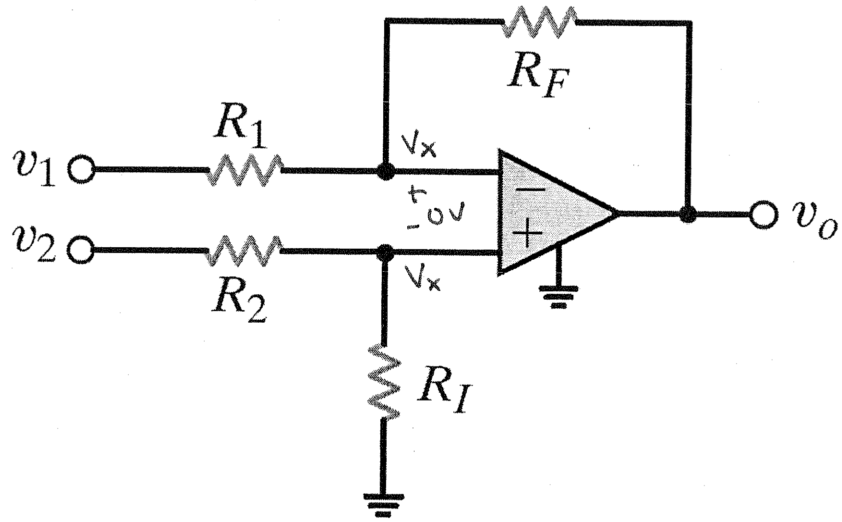


Figure P4.29

SOLUTION:

KCL at V_+ input: $\frac{V_2 - V_x}{R_2} = \frac{V_x}{R_I} \Rightarrow V_x = V_2\left(\frac{R_I}{R_I + R_2}\right)$

KCL at V_- input: $\frac{V_1 - V_x}{R_1} = \frac{V_x - V_o}{R_F} \Rightarrow V_o = V_x\left(1 + \frac{R_F}{R_1}\right) - \frac{R_F}{R_1} V_1$

$$\boxed{V_o = V_2\left(\frac{R_I}{R_I + R_2}\right)\left(\frac{R_1 + R_F}{R_1}\right) - \frac{R_F}{R_1} V_1}$$

4.30 Find V_o in the circuit in Fig. P4.30.

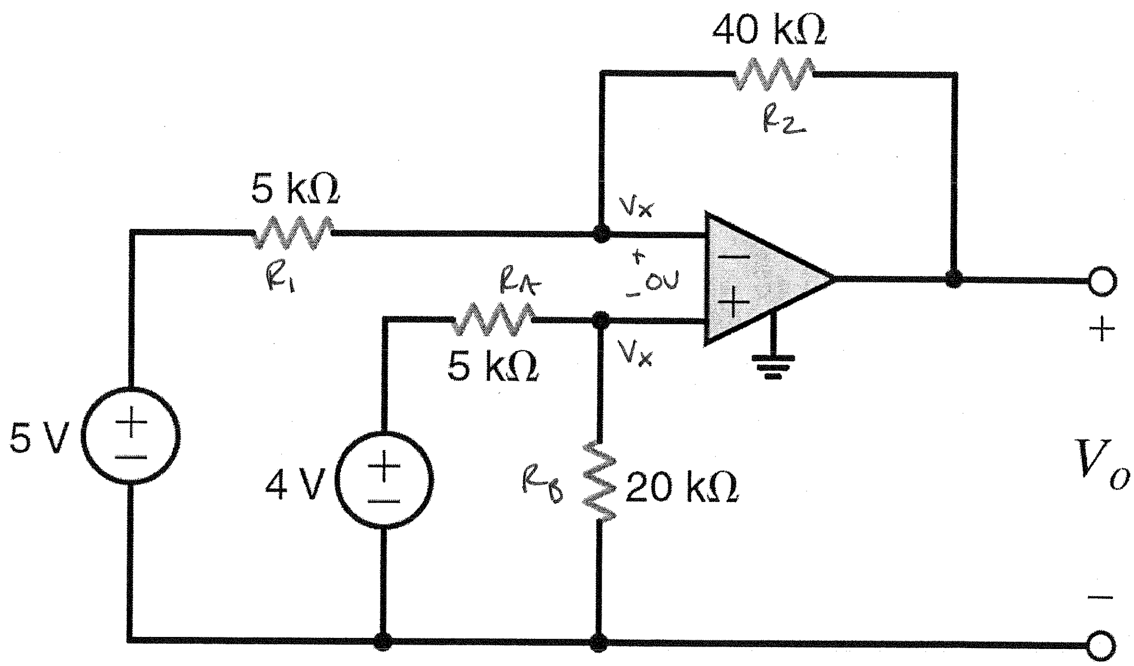


Figure P4.30

SOLUTION:

KCL at v_- input: $\frac{5 - V_x}{R_1} = \frac{V_x - V_o}{R_2} \Rightarrow V_x = 5\left(\frac{R_2}{R_1+R_2}\right) + V_o\left(\frac{R_1}{R_1+R_2}\right)$

KCL @ v_+ input: $\frac{4 - V_x}{R_A} = \frac{V_x}{R_B} \Rightarrow V_x = \frac{4R_B}{R_A+R_B}$

$$5\left(\frac{R_2}{R_1+R_2}\right) + V_o\left(\frac{R_1}{R_1+R_2}\right) = \frac{4R_B}{R_A+R_B}$$

$$V_o = \left(\frac{4R_B}{R_A+R_B} - \frac{5R_2}{R_1+R_2}\right)\frac{R_1+R_2}{R_1}$$

$$\boxed{V_o = -11.2\text{V}}$$

4.31 Find V_o in the circuit in Fig. P4.31.

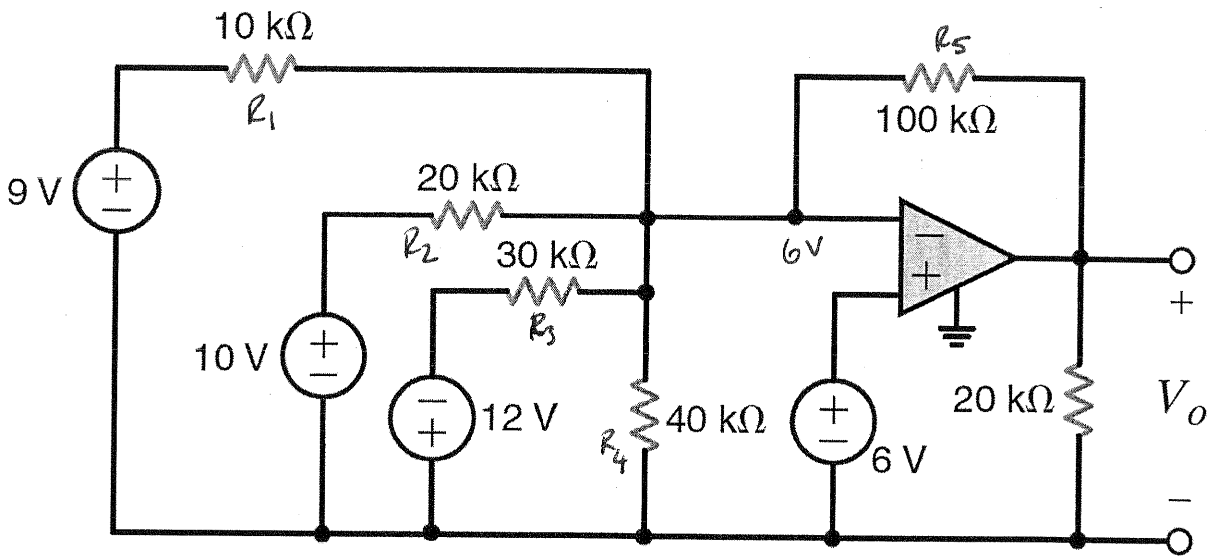


Figure P4.31

SOLUTION:

KCL at v_- input:

$$\frac{9-6}{R_1} + \frac{10-6}{R_2} + \frac{-12-6}{R_3} = \frac{6}{R_4} + \frac{6-V_o}{R_5}$$

$$\frac{3}{10^4} + \frac{4}{2\times10^4} - \frac{18}{3\times10^4} = \frac{6}{4\times10^4} + \frac{6}{10^5} - \frac{V_o}{10^5}$$

$$\boxed{V_o = 31\text{V}}$$

4.32 Determine the expression for the output voltage, v_o, of the inverting summer circuit shown in Fig. P4.32.

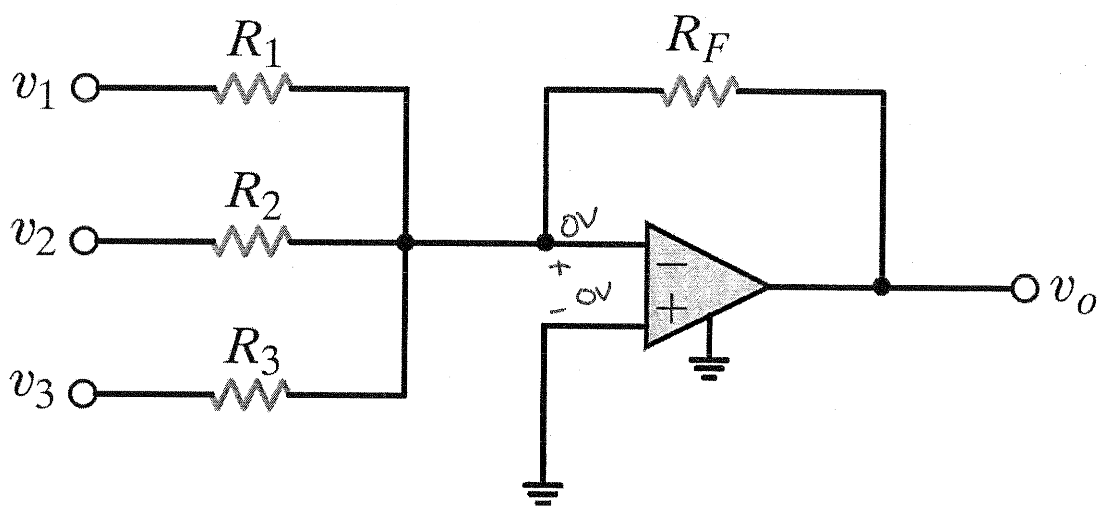


Figure P4.32

SOLUTION:

KCL at V_- input:

$$\frac{v_1 - 0}{R_1} + \frac{v_2 - 0}{R_2} + \frac{v_3 - 0}{R_3} = \frac{0 - v_o}{R_F}$$

$$\boxed{v_o = -\frac{R_F}{R_1}v_1 - \frac{R_F}{R_2}v_2 - \frac{R_F}{R_3}v_3}$$

4.33 Determine the output voltage, v_o, of the noninverting averaging circuit shown in Fig. P4.33. CS

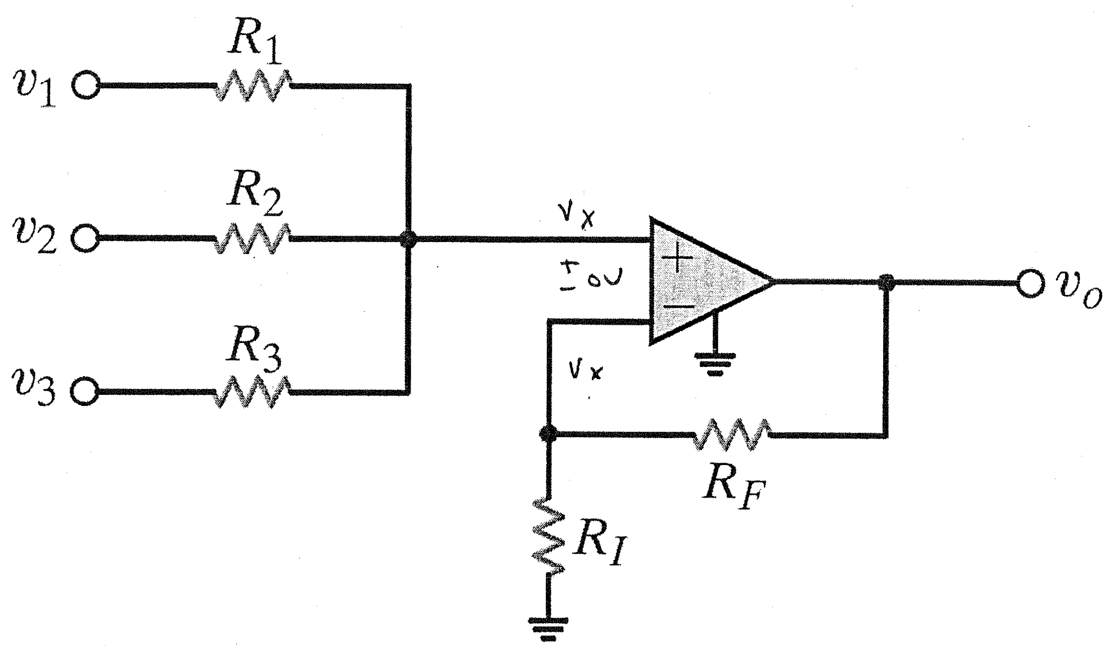


Figure P4.33

SOLUTION:

KCL at v_+ input: $\frac{v_1 - v_x}{R_1} + \frac{v_2 - v_x}{R_2} + \frac{v_3 - v_x}{R_3} = 0$

KCL at v_- input: $\frac{v_o - v_x}{R_F} = \frac{v_x}{R_I}$ $\quad v_x = v_o\left(\frac{R_I}{R_I + R_F}\right)$

Eliminate v_x,

$$\boxed{v_o = \left(\frac{R_I + R_F}{R_I}\right)\left[\frac{R_2 R_3 v_1 + R_1 R_3 v_2 + R_1 R_2 v_3}{R_1 R_2 + R_2 R_3 + R_1 R_3}\right]}$$

4.34 Find the input/output relationship for the current amplifier shown in Fig. P4.34.

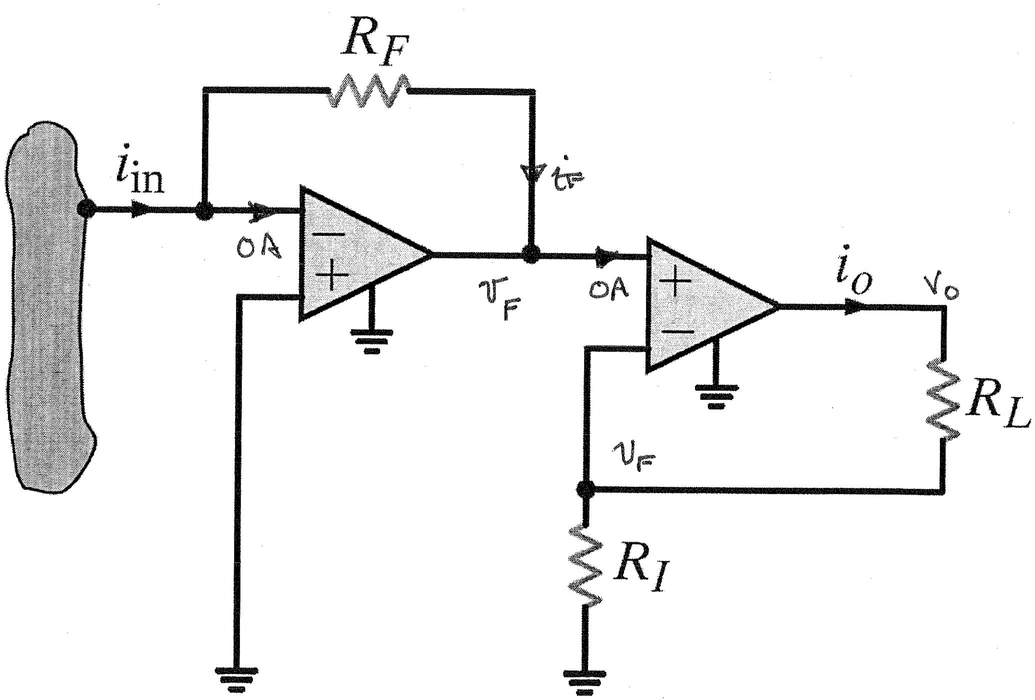


Figure P4.34

SOLUTION: KCL at v_- input w/ 1st op amp.

$$i_{in} = \frac{0 - v_F}{R_F} \qquad v_F = -R_F\, i_{in}$$

2nd op-amp in classic inverting configuration

$$v_o = v_F\left(1 + \frac{R_L}{R_I}\right) \qquad i_o = \frac{v_o - v_F}{R_L} = \frac{v_F}{R_I}$$

$$i_o/i_{in} = (v_F/i_{in})(i_o/v_F) \qquad \frac{i_o}{i_{in}} = -\frac{R_F}{R_I}$$

4.35 Find V_o in the circuit in Fig. P4.35. **PSV**

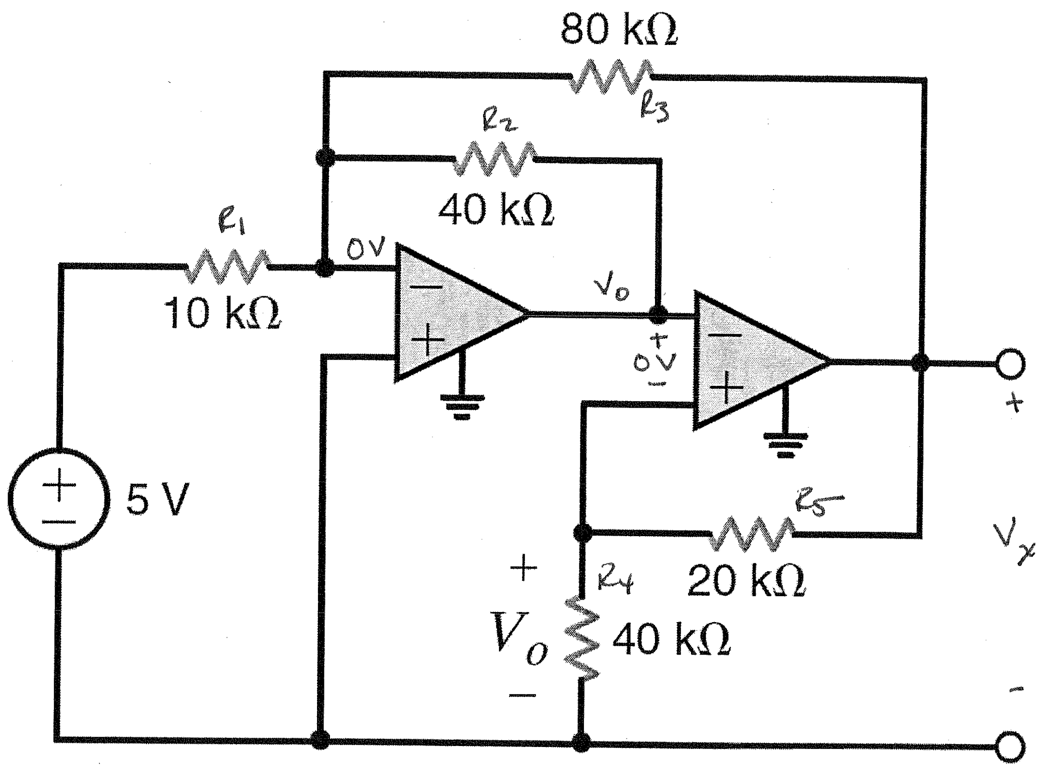


Figure P4.35

SOLUTION:

KCL at v_- of 1st op amp: $\frac{5}{R_1} + \frac{V_o}{R_2} + \frac{V_x}{R_3} = 0 \Rightarrow V_x = -\frac{R_3}{R_1}(5) - \frac{R_3}{R_2}V_o$

KCL at v_+ of 2nd op amp: $\frac{v_o}{R_4} + \frac{v_o - v_x}{R_5} = 0 \Rightarrow V_x = v_o\left(1 + R_5/R_4\right)$

Put in numbers,

$v_x = -40 - 2V_o$ & $v_x = 1.5v_o$

Eliminate V_x,

$$\boxed{V_o = -11.43\text{ V}}$$

4.36 Find v_o in the circuit in Fig. P4.36.

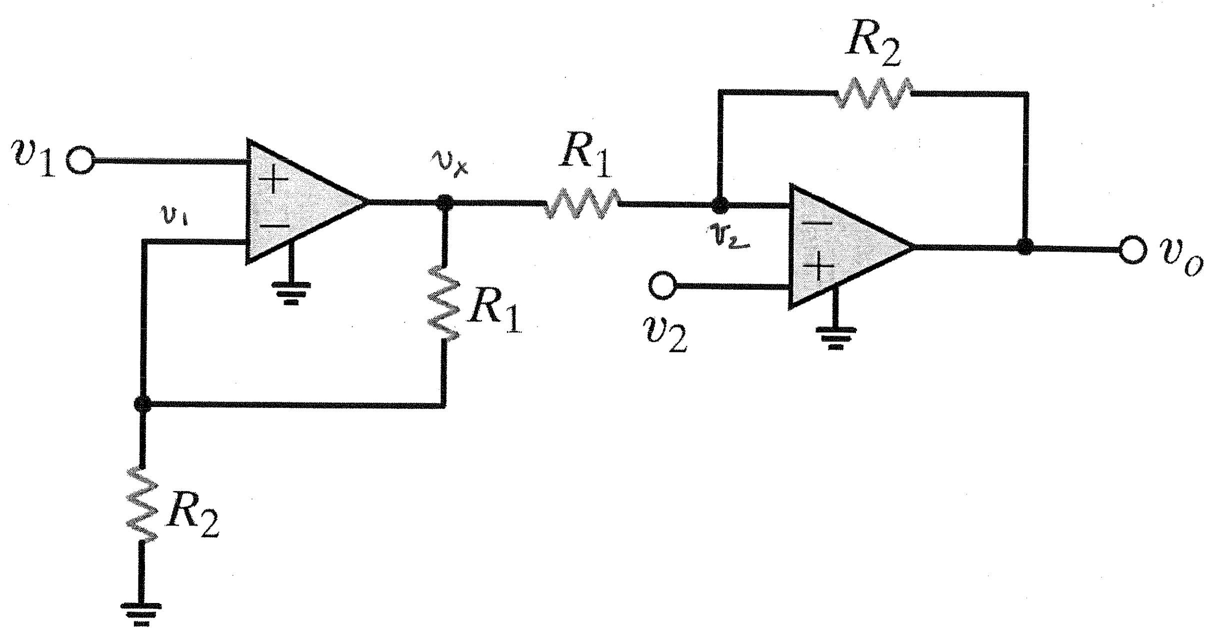


Figure P4.36

SOLUTION:

1st Op amp in basic non-inverting configuration:

$$\frac{v_x}{v_1} = 1 + \frac{R_1}{R_2} \Rightarrow v_x = v_1\left(\frac{R_2+R_1}{R_2}\right)$$

KCL at v_- of 2nd op amp: $\frac{v_x - v_2}{R_1} + \frac{v_o - v_2}{R_2} = 0$

$$v_o = v_2\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1} v_x$$

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

4.37 Find the expression for v_o in the differential amplifier circuit shown in Fig. P4.37. **CS**

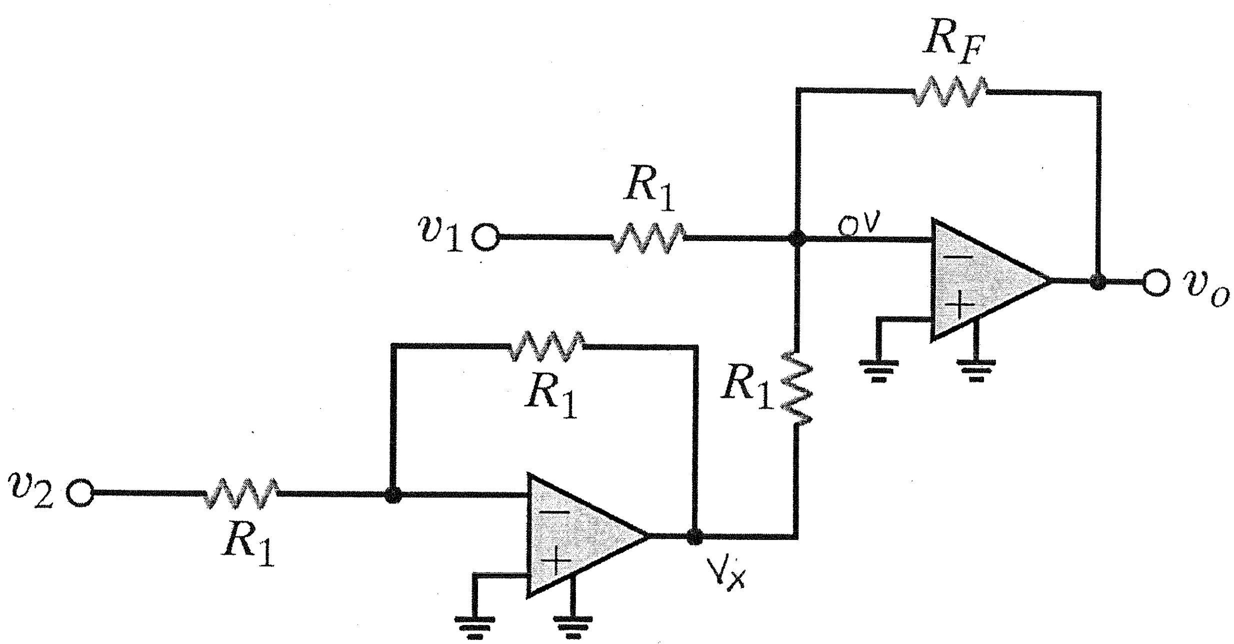


Figure P4.37

SOLUTION:

1st op-amp in classic inverting configuration:

$$v_x = -\frac{R_1}{R_1} v_2 \qquad v_x = -v_2$$

KCL at v_- of 2nd op amp: $\frac{v_1}{R_1} + \frac{v_x}{R_1} + \frac{v_o}{R_F} = 0$

$$\boxed{v_o = \frac{R_F}{R_1}\left[v_2 - v_1\right]}$$

4.38 Find v_o in the circuit in Fig. P4.38. **PSV**

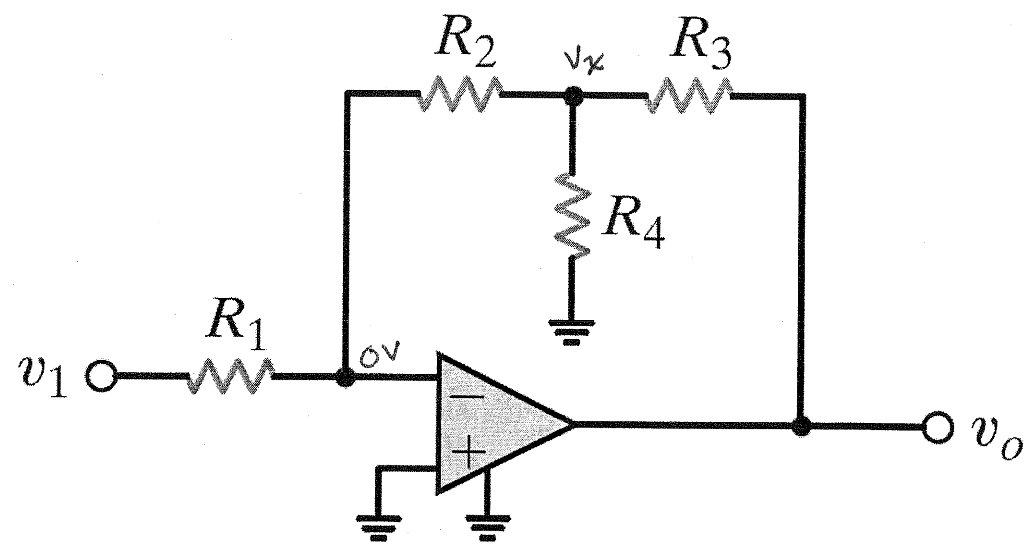


Figure P4.38

SOLUTION:

KCL at v_- input: $\frac{v_1}{R_1} + \frac{v_x}{R_2} = 0$ $\quad v_x = -\frac{R_2}{R_1} v_1$

KCL at v_x node: $\frac{v_x}{R_2} + \frac{v_x}{R_4} + \frac{v_x - v_o}{R_3} = 0$ $\quad v_o = v_x\left(\frac{R_3}{R_2} + \frac{R_3}{R_4} + 1\right)$

$$\boxed{v_o = v_1\left[1 + \frac{R_3}{R_2} + \frac{R_3}{R_4}\right]\left(-\frac{R_2}{R_1}\right)}$$

4.39 Find the output voltage, v_o, in the circuit in Fig. P4.39.

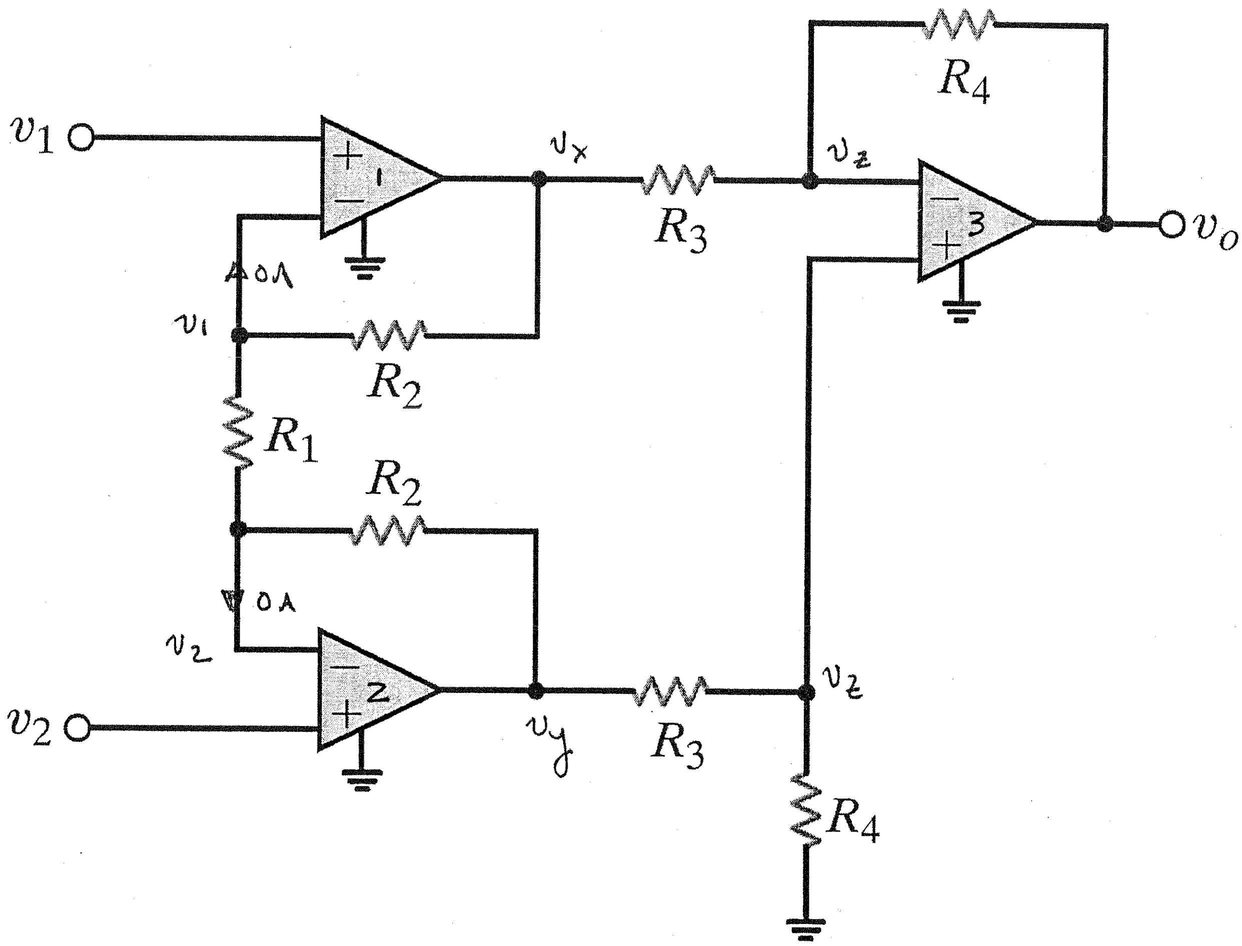


Figure P4.39

SOLUTION:

KCL at v_- of op amp 1: $\dfrac{v_x - v_1}{R_2} = \dfrac{v_1 - v_2}{R_1} \Rightarrow v_x = v_1\left(1 + \dfrac{R_2}{R_1}\right) - \dfrac{R_2}{R_1} v_2$

KCL at v_- of op amp 2: $\dfrac{v_y - v_2}{R_2} = \dfrac{v_2 - v_1}{R_1} \Rightarrow v_y = v_2\left(1 + \dfrac{R_2}{R_1}\right) - \dfrac{R_2}{R_1} v_1$

KCL at v_+ of op amp 3: $\dfrac{v_y - v_z}{R_3} = \dfrac{v_z}{R_4} \Rightarrow v_z = v_y\left(\dfrac{R_4}{R_3 + R_4}\right)$

KCL at v_- of op amp 3: $\dfrac{v_x - v_z}{R_3} + \dfrac{v_o - v_z}{R_4} = 0 \Rightarrow v_o = v_z\left(1 + R_4/R_3\right) - v_x \dfrac{R_4}{R_3}$

$$\boxed{v_o = \frac{R_4}{R_3}\left(1 + 2\frac{R_2}{R_1}\right)(v_2 - v_1)}$$

4.40 The electronic ammeter in Example 4.9 has been modified and is shown in Fig. P4.40. The selector switch allows the user to change the range of the meter. Using values for R_1 and R_2 from Example 4.9, find the values of R_A and R_B that will yield a 10-V output when the current being measured is 100 mA and 10 mA, respectively.

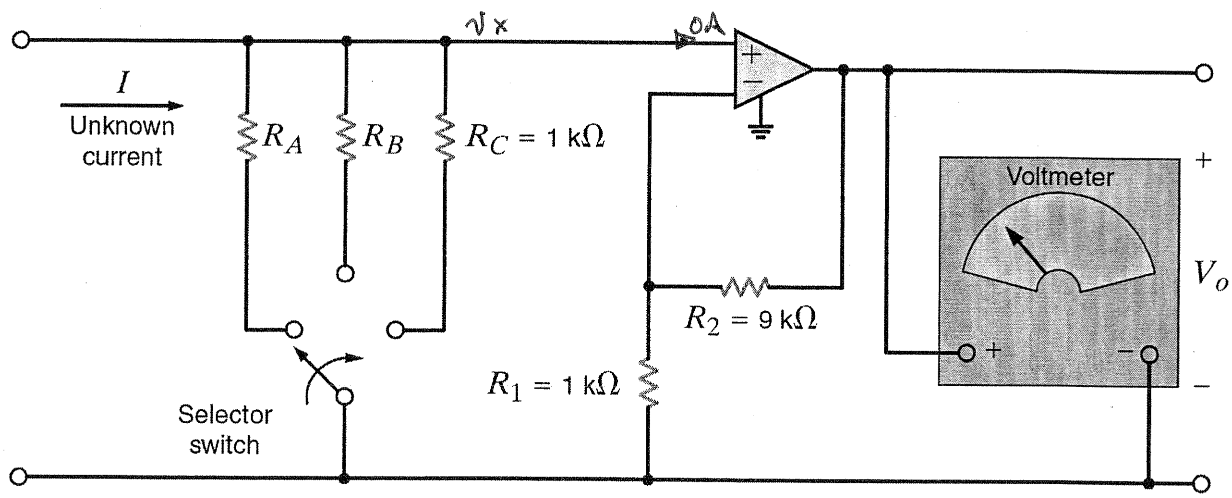


Figure P4.40

SOLUTION:

Op amp in non-inverting configuration: $V_o = V_x\left(1 + \frac{R_2}{R_1}\right) = 10V_x$

$v_x = I R_A = 0.1 R_A$

$V_o = 10V_x = 10(0.1 R_A) = R_A = 10$ $\boxed{R_A = 10\,\Omega}$

$v_x = I R_B = 0.01 R_B$

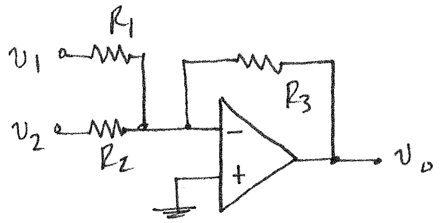
$V_o = 10V_x = 10(0.01 R_B) = \frac{R_B}{10} = 10$ $\boxed{R_B = 100\,\Omega}$

4.41 Given a box of 10-kΩ resistors and an op-amp, design a circuit that will have an output voltage of

$$V_o = -2V_1 - 4V_2 \quad \boxed{CS}$$

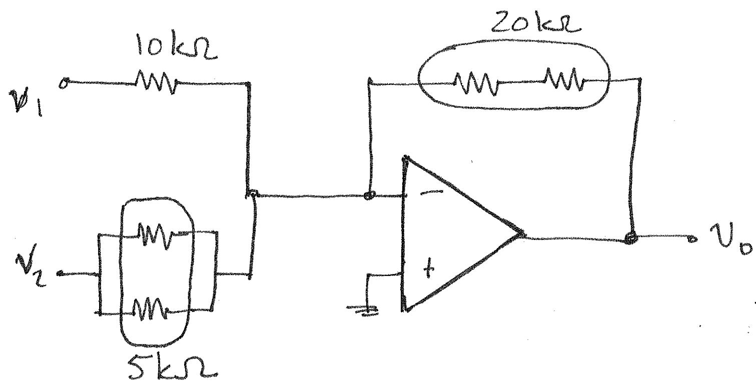
SOLUTION:

Since signs on gains associated with V_1 & V_2 are both negative, a simple summer will suffice.



$$V_o = -\frac{R_3}{R_1} V_1 - \frac{R_3}{R_2} V_2 = -2V_1 - 4V_2$$

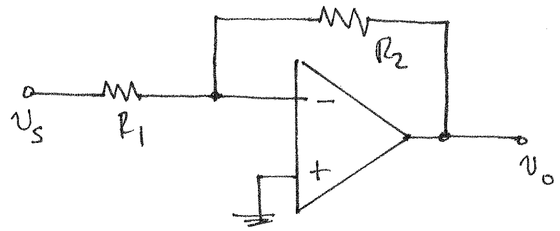
the following circuit with all resistors = 10kΩ works.



4.42 Design an op-amp circuit that has a gain of −50 using resistors no smaller than 1 kΩ.

SOLUTION:

Since gain is negative, use inverting configuration:



$$\frac{v_o}{v_s} = -\frac{R_2}{R_1} = -50$$

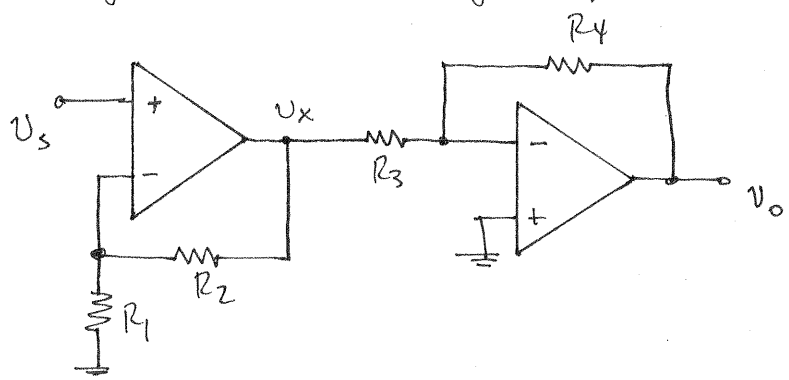
$$\boxed{\text{Choose } R_1 = 2k\Omega \Rightarrow R_2 = 100k\Omega}$$

4.43 Design a two-stage op-amp network that has a gain of −50,000 while drawing no current into its input terminal. Use no resistors smaller than 1 kΩ.

SOLUTION:

For no input current, a non-inverting configuration is needed

For negative, one inverting stage is needed.



$$\frac{v_x}{v_s} = 1 + \frac{R_2}{R_1} \qquad \frac{v_o}{v_x} = -\frac{R_4}{R_3} \qquad \frac{v_o}{v_s} = -\frac{R_4}{R_3}\left(1 + \frac{R_2}{R_1}\right)$$

Choose $\frac{v_x}{v_s} = 250$ and $\frac{v_o}{v_x} = -200$ & $\boxed{R_1 = R_3 = 2\,k\Omega}$

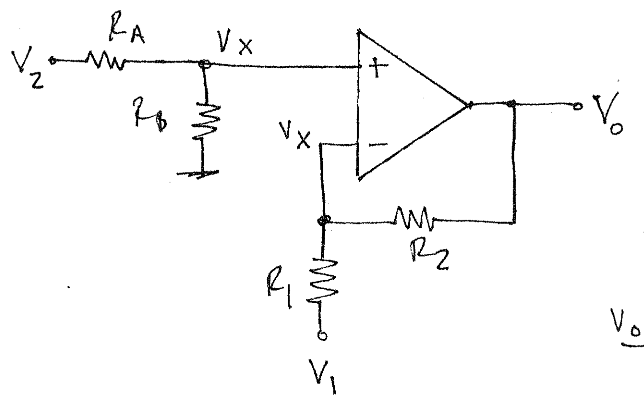
$\boxed{R_2 = 498\,k\Omega}$ $\boxed{R_4 = 400\,k\Omega}$

4.44 Design an op-amp circuit that has the following input/output relationship:

$$V_o = -5\,V_1 + 0.5\,V_2$$

SOLUTION:

A single op-amp will do if we use both + & - inputs.



KCL at V_+,

$$\frac{V_2 - V_x}{R_A} = \frac{V_x}{R_B} \Rightarrow \frac{V_x}{V_2} = \frac{R_B}{R_A + R_B}$$

KCL at V_-,

$$\frac{V_o - V_x}{R_2} = \frac{V_x - V_1}{R_1}$$

$$V_o = V_x\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1} V_1$$

$$V_o = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_B}{R_A + R_B}\right)V_2 - \frac{R_2}{R_1} V_1$$

So, $R_2/R_1 = 5$

Now, $\dfrac{6 R_B}{R_A + R_B} = \dfrac{1}{2}$

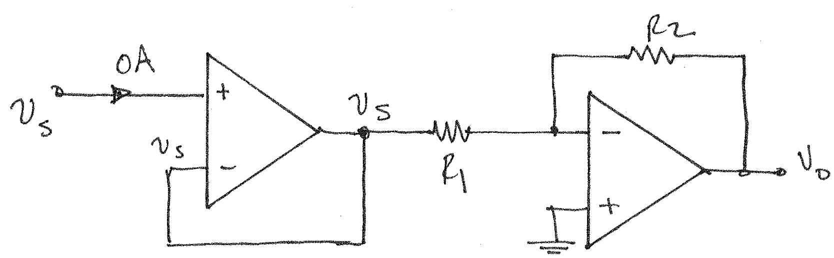
$$\boxed{\begin{array}{l} \text{Choose } R_1 = 1\,k\Omega \Rightarrow R_2 = 5\,k\Omega \\ \text{Choose } R_B = 1\,k\Omega \Rightarrow R_A = 11\,k\Omega \end{array}}$$

4.45 A voltage waveform with a maximum value of 200 mV must be amplified to a maximum of 10 V and inverted. However, the circuit that produces the waveform can provide no more than 100 μA. Design the required amplifier. **CS**

SOLUTION:

Best to use 2 stages: non-inverting followed by inverting.

Required gain $= -\frac{10}{0.2} = -50$

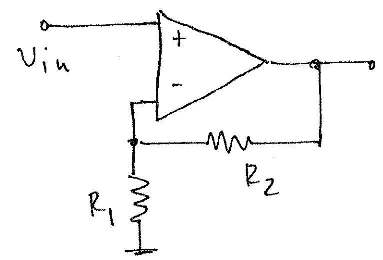


$$\frac{v_o}{v_s} = -\frac{R_2}{R_1}$$

$$\boxed{\text{Choose } R_1 = 1\,k\Omega \Rightarrow R_2 = 50\,k\Omega}$$

4.46 An amplifier with a gain of $\pi \pm 1\%$ is needed. Using resistor values from Table 2.1, design the amplifier. Use as few resistors as possible.

SOLUTION: For positive gain, use non-inverting config.



$$\frac{V_o}{V_{in}} = 1 + \frac{R_2}{R_1} = A$$

for $A = \pi \pm 1\%$, $2.110 \le \frac{R_2}{R_1} \le 2.173$

Best choices are

$$\boxed{R_1 = 20\,k\Omega \qquad R_2 = 43\,k\Omega}$$

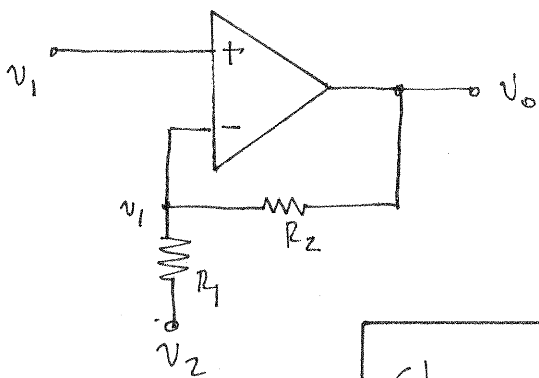
$A = 3.15$ within 0.27% of π.

4.47 Design an op-amp-based circuit to produce the function

$$V_o = 5\,V_1 - 4\,V_2$$

SOLUTION:

To get + & - gains, we can use both + & - inputs,



KCL @ V- input,

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

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

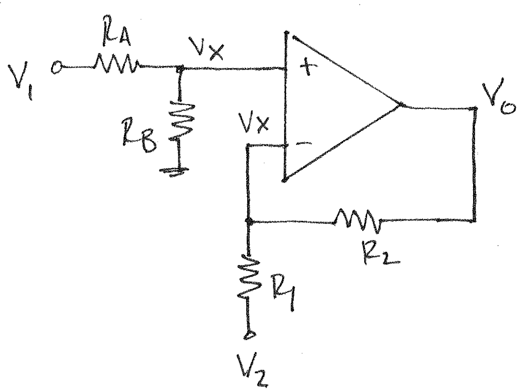
$\boxed{\text{Choose } R_1 = 5\text{k}\Omega \Rightarrow R_2 = 20\text{k}\Omega}$

4.48 Design an op-amp-based circuit to produce the function

$$V_o = 5V_1 - 7V_2$$

SOLUTION:

Use both + & - inputs to get + & - gains.



KCL at V_+ input,

$$\frac{V_1 - V_x}{R_A} = \frac{V_x}{R_B} \Rightarrow \frac{V_x}{V_1} = \frac{R_B}{R_A + R_B}$$

KCL at V_- input

$$\frac{V_o - V_x}{R_2} = \frac{V_x - V_2}{R_1}$$

$$V_o = V_x\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}V_2$$

$$V_o = V_1\left(\frac{R_B}{R_A + R_B}\right)\left(1 + \frac{R_2}{R_1}\right) - \frac{R_2}{R_1}V_2$$

$$R_2/R_1 = 7$$

$$\left(\frac{R_B}{R_A + R_B}\right)8 = 5$$

$$\boxed{\begin{array}{l} \text{Choose } R_1 = 1k\Omega \Rightarrow R_2 = 7k\Omega \\ \text{Choose } R_B = 5k\Omega \Rightarrow R_A = 3k\Omega \end{array}}$$

4.49 Show that the circuit in Fig. P4.49 can produce the output

$$V_o = K_1 V_1 - K_2 V_2$$

only for $0 \le K_1 \le K_2 + 1$. **CS**

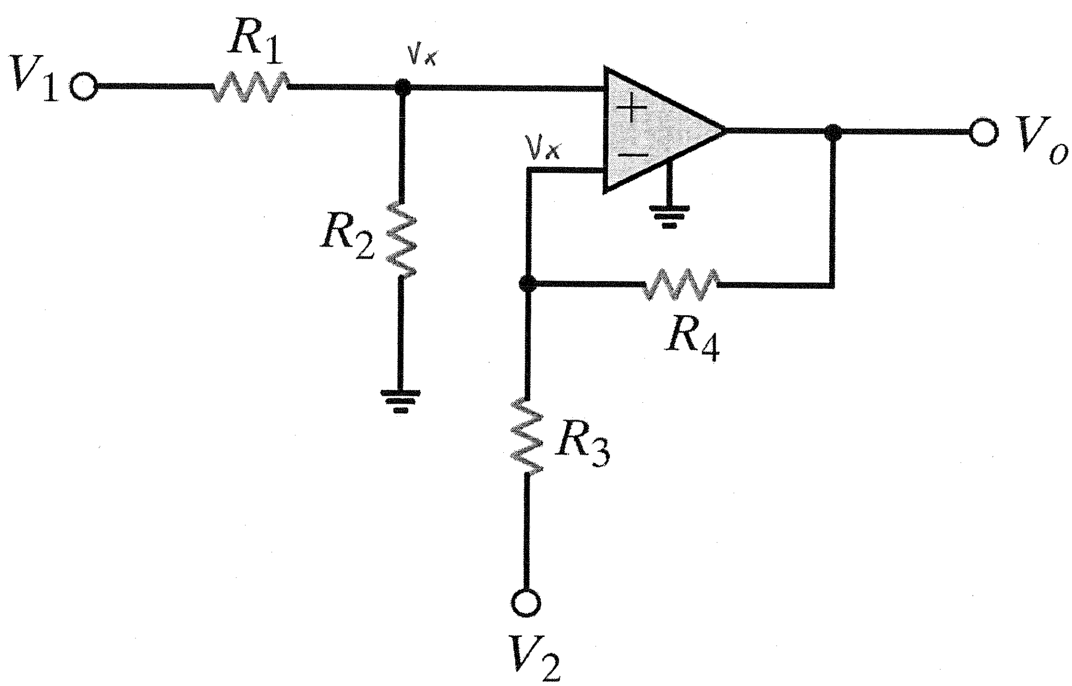


Figure P4.49

SOLUTION:

KCL at V_+ input: $\frac{V_1 - V_x}{R_1} = \frac{V_x}{R_2} \Rightarrow V_x = \frac{V_1 R_2}{R_1 + R_2}$

KCL at V_- input: $\frac{V_o - V_x}{R_4} = \frac{V_x - V_2}{R_3} \Rightarrow V_o = V_x\left(1 + \frac{R_4}{R_3}\right) - \frac{R_4}{R_3} V_2$

$V_o = V_1\left(\frac{R_2}{R_1 + R_2}\right)\left(1 + \frac{R_4}{R_3}\right) - \frac{R_4}{R_3} V_2 = K_1 V_1 - K_2 V_2 \Rightarrow K_2 = R_4/R_3$

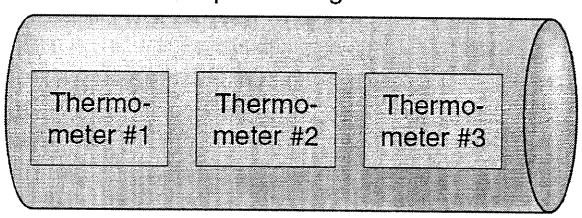
If $R_2 = 0$, $K_1 = 0$

If $R_2 \neq 0$ but $R_1 = 0$, $K_1 = 1 + R_4/R_3 = 1 + K_2$

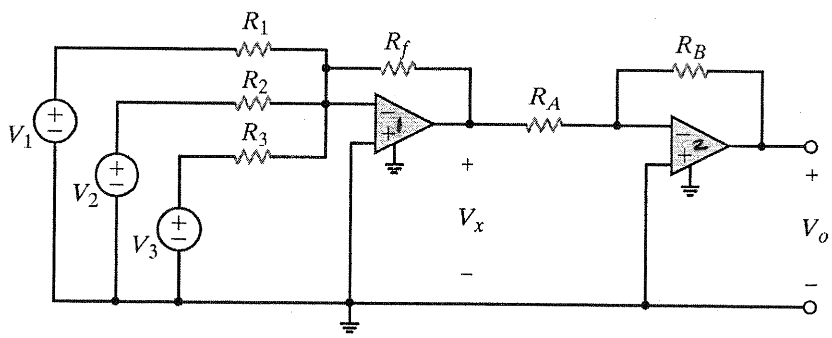
$$\boxed{0 \le K_1 \le (K_2 + 1)}$$

4.50 A 170°C maximum temperature digester is used in a paper mill to process wood chips that will eventually become paper. As shown in Fig. P4.50a, three electronic thermometers are placed along its length. Each thermometer outputs 0 V at 0°C, and the voltage changes 25 mV/°C. We will use the average of the three thermometer voltages to find an aggregate digester temperature. Furthermore, 1 volt should appear at V_o for every 10°C of average temperature. Design such an averaging circuit using the op-amp configuration shown in Fig. 4.50b if the final output voltage must be positive.

Paper mill digester



(a)



(b)

SOLUTION: Op amp 1 is a summer. Op amp 2 is a inverting configuration.

$$V_x = -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right] \quad \& \quad V_o = -\frac{R_B}{R_A}V_x$$

$$V_o = \frac{R_B}{R_A}\left[\frac{R_f V_1}{R_1} + \frac{R_f V_2}{R_2} + \frac{R_f V_3}{R_3}\right]$$

Choose $\frac{R_f}{R_1} = \frac{R_f}{R_2} = \frac{R_f}{R_3} = \frac{1}{3}$

$$V_o = \frac{R_B}{R_A}\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

If $\Delta T_1 = 10°C$, $\Delta V_1 = 0.25V$ & $\Delta V_o = 1V$

$$\frac{\Delta V_o}{\Delta V_1} = \frac{R_B}{R_A}\left(\frac{1}{3}\right) = \frac{1}{0.25} = 4$$

$$\boxed{\text{Choose } R_A = R_f = 1k\Omega \Rightarrow R_B = 12k\Omega \quad R_1 = R_2 = R_3 = 3k\Omega}$$

4.51 A 0.1-Ω shunt resistor is used to measure current in a fuel-cell circuit. The voltage drop across the shunt resistor is to be used to measure the current in the circuit. The maximum current is 20 A. Design the network shown in Fig. P4.51 so that a voltmeter attached to the output will read 0 volts when the current is 0 A and 20 V when the current is 20 A. Be careful not to load the shunt resistor, since loading will cause an inaccurate reading.

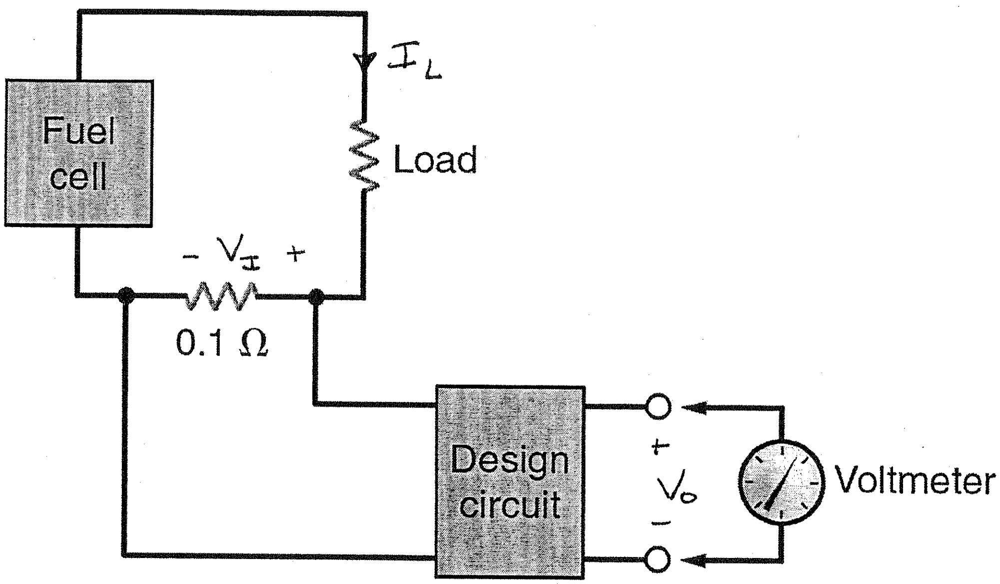
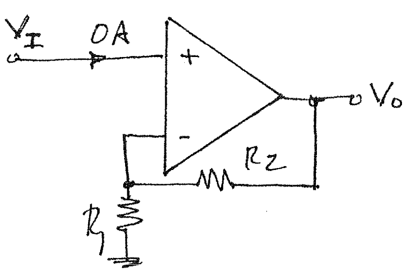


Figure P4.51

SOLUTION:

When $I_L = 20A$, $V_I = (0.1) I_L = 2V$ and $V_o = 20V$.

Need gain of 10 with a buffered input ⇒ non-inverting conf!



$$\frac{V_o}{V_I} = 1 + \frac{R_2}{R_1} = 10$$

$\boxed{\text{Chose } R_1 = 1k\Omega \text{ \& } R_2 = 9k\Omega}$

4.52 Wood pulp is used to make paper in a paper mill. The amount of lignin present in pulp is called the kappa number. A very sophisticated instrument is used to measure kappa, and the output of this instrument ranges from 1 to 5 volts, where 1 volt represents a kappa number of 12 and 5 volts represents a kappa number of 20. The pulp mill operator has asked to have a kappa meter installed on his console. Design a circuit that will employ as input the 1- to 5-volt signal and output the kappa number. An electronics engineer in the plant has suggested the circuit shown in Fig. P4.52.

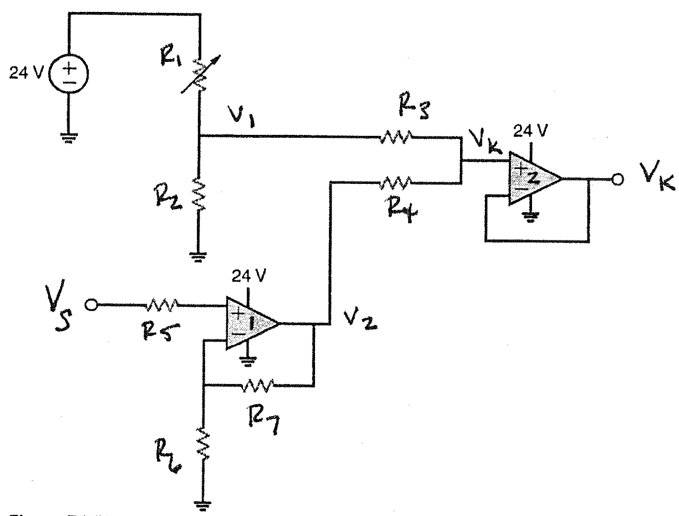


Figure P4.52

SOLUTION:

KCL at V_1: $$\frac{24-V_1}{R_1} = \frac{V_1}{R_2} + \frac{V_1 - V_K}{R_3}$$

KCL at V_K: $$\frac{V_1 - V_K}{R_3} = \frac{V_K - V_2}{R_4}$$

Op amp 1 is in non-inverting configuration: $V_2 = V_s\left(1 + \frac{R_7}{R_6}\right) = g\, V_s$

Let $R_2 = R_3 = R_4 = R_5 = R$ and $R_1 = 1k\Omega$. Eliminate V_1 in KCL eqs.

@ V_K: $V_1 = 2V_K - V_2$

@ V_1: $24R = V_1(2R_1 + R) - V_K R_1$

yields $$V_K = \frac{24R}{3R_1 + 2R} + V_S \frac{g(2R_1 + R)}{3R_1 + 2R}$$

Also,
$$V_K = b + mV_S$$

and at $V_S = 1V$, $V_K = 12V$ and at $V_S = 5V$, $V_K = 20V$.

So, $$m = \frac{\Delta V_K}{\Delta V_S} = \frac{20-12}{5-1} = 2 \quad \text{and} \quad b = 10$$

$$V_K = 10 + 2V_S = \frac{24R}{3R_1 + 2R} + \frac{g(2R_1 + R)}{3R_1 + 2R} V_S$$

yields,
$$R = 7.5k\Omega \ \& \ g = 3.79$$

Let $R_6 = 1k\Omega \Rightarrow R_7 = 2.79k\Omega$.

Results:	$R_1 = 1k\Omega$	$R_7 = 2.79k\Omega$	$R_6 = 1k\Omega$
	Chose: $R_2 = R_3 = R_4 = R_5 =$		$7.5k\Omega$

4.53 An operator in a chemical plant would like to have a set of indicator lights that indicate when a certain chemical flow is between certain specific values. The operator wants a RED light to indicate a flow of at least 10 GPM (gallons per minute), RED and YELLOW lights to indicate a flow of 60 GPM, and RED, YELLOW, and GREEN lights to indicate a flow rate of 80 GPM. The 4–20 mA flow meter instrument outputs 4 mA when the flow is zero and 20 mA when the flow rate is 100 GPM.

An experienced engineer has suggested the circuit shown in Fig. P4.53. The 4–20 mA flow meter and 250 Ω resistor provide a 1–5 V signal, which serves as one input for the three comparators. The light bulbs will turn on when the negative input to a comparator is higher than the positive input. Using this network, design a circuit that will satisfy the operator's requirements. **CS**

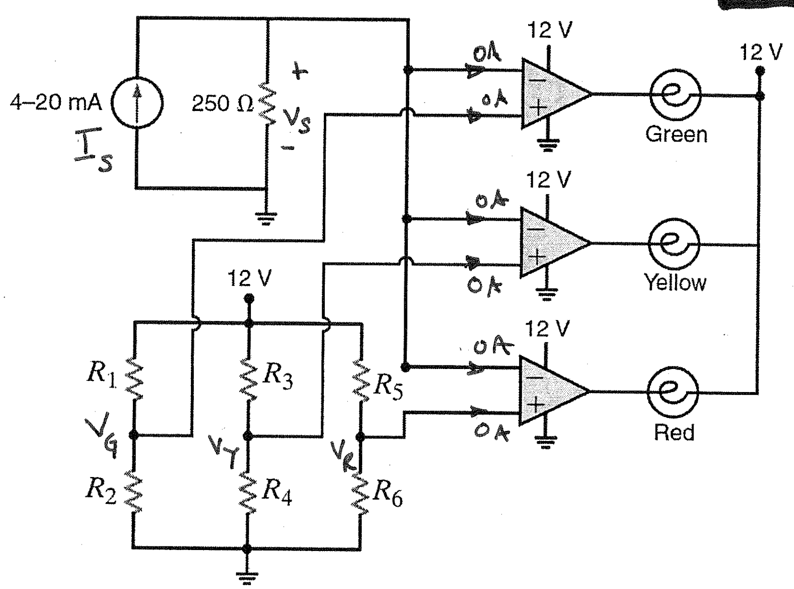


Figure P4.53

SOLUTION:

Desire $V_G = V_S$ when flow = 80 GPM

$I_S = m(\text{flow}) + b$ $\quad$ $4\,mA = m(0) + b \Rightarrow b = 4\,mA$

$\quad 20\,mA = m(100) + b \Rightarrow m = 0.16\ mA/GPM$

At flow = 80 GPM, $I_S = 16.8\,mA$ & $V_S = 250\, I_S = 4.2V$

$V_G = \left(\frac{R_2}{R_1 + R_2}\right) 12 \Rightarrow$ Choose $R_2 = 1k\Omega \Rightarrow R_1 = 1.86k\Omega$

Similarly, at flow = 60 GPm, $I_s = 13.6\,mA$ and $V_s = 3.4V$

Need $V_Y = 3.4V = \dfrac{12 R_4}{R_4 + R_3}$ Choose $R_4 = 1k\Omega \Rightarrow R_3 = 2.53k\Omega$

Finally, at flow = 10 GPM, $I_s = 5.6\,mA$ and $V_s = 1.4V$

For $V_R = 1.4V = \dfrac{12 R_6}{R_6 + R_5}$ choose $R_6 = 1k\Omega \Rightarrow R_5 = 7.57k\Omega$

$$\boxed{\begin{array}{ll} \text{Choosing} & R_2 = R_4 = R_6 = 1k\Omega \\ \text{yields} & R_1 = 1.86k\Omega \\ & R_3 = 2.53k\Omega \\ & R_5 = 7.57k\Omega \end{array}}$$

4.54 An industrial plant has a requirement for a circuit that uses as input the temperature of a vessel and outputs a voltage proportional to the vessel's temperature. The vessel's temperature ranges from 0°C to 500°C, and the corresponding output of the circuit should range from 0 to 12 V. A RTD (resistive thermal device), which is a linear device whose resistance changes with temperature according to the plot in Fig. P4.54a, is available. The problem then is to use this RTD to design a circuit that employs this device as an input and produces a 0- to 12-V signal at the output, where 0 V corresponds to 0°C and 12 V corresponds to 500°C. An engineer familiar with this problem suggests the use of the circuit shown in Fig. P4.54b in which the RTD bridge circuit provides the input to a standard instrumentation amplifier. Determine the component values in this network needed to satisfy the design requirements.

SOLUTION: Need relationships for v_1, v_2, v_o and T.

KCL at RTD: $\frac{12-v_1}{R_1} = \frac{v_1}{R_{RTD}} \Rightarrow 12R_{RTD} = v_1(R_1 + R_{RTD})$

$v_1 = 12R_{RTD}/(R_1 + R_{RTD})$

KCL at v_{2+}: $v_2 = 12R_3/(R_2+R_3)$

$R_{RTD}(T)$: $R_{RTD} = K_1 + K_2 T$

At $T=0°C$, $R_{RTD} = K_1 = 100\,\Omega$

At $T=500°C$, $R_{RTD} = 600\Omega = 100 + K_2(500)$

$K_2 = 1.\ \Omega/°C \Rightarrow R_{RTD} = 100 + T$

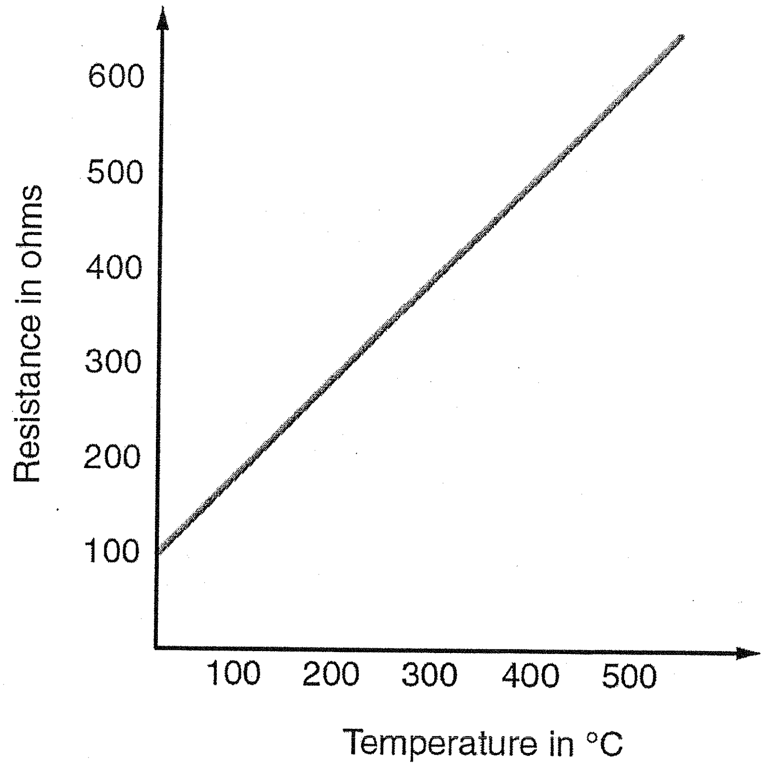


Figure P4.54a

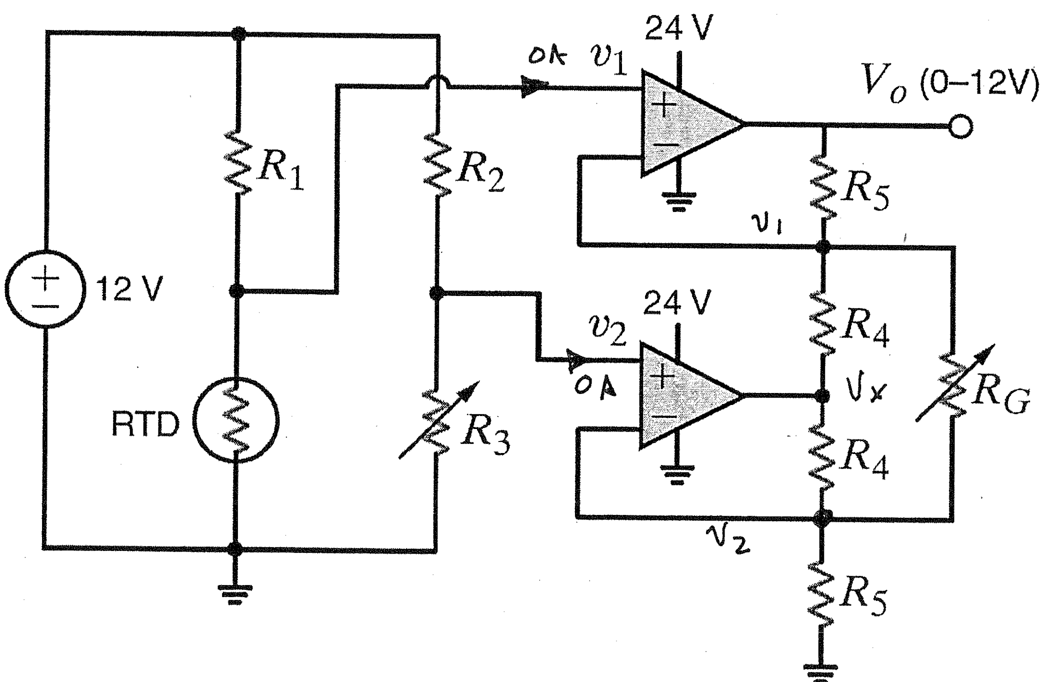


Figure P4.54b

Let $R_1 = R_2 = R_3 = 100\Omega$ (An arbitrary but good choice.

Now,

$$12 - v_1 = \frac{v_1}{1 + T/100} \quad \& \quad v_2 = 6V \quad \leftarrow eq. 1$$

KCL at v_1 at R_4-R_5 node:

$$\frac{v_o - v_1}{R_5} = \frac{v_1 - v_2}{R_G} + \frac{v_1 - v_x}{R_4}$$

KCL at v_2 at R_5-R_4 node:

$$\frac{v_x - v_2}{R_4} + \frac{v_1 - v_2}{R_G} = \frac{v_2}{R_5}$$

Let $R_4 = R_5 = 10k\Omega$ (Again, arbitrary)

$$v_o = \left(2 + \frac{R_4}{R_G}\right)v_1 - v_2 \frac{R_4}{R_G} - v_x \quad \& \quad v_x = v_2\left(2 + \frac{R_4}{R_G}\right) - v_1 \frac{R_4}{R_G}$$

Eliminate $v_x \Rightarrow \quad v_o = 2(v_1 - v_2)\left(1 + \frac{10^4}{R_G}\right)$

But, $v_1 = 12\left(\frac{100+T}{200+T}\right)$ (Solve eq 1. for v_1)

Now,

$$v_o = 24\left(\frac{100+T}{200+T} - \frac{1}{2}\right)\left(1 + \frac{10^4}{R_G}\right)$$

At $T = 0°C$, $v_o = 24\left(\frac{1}{2} - \frac{1}{2}\right)\left(1 + \frac{10^4}{R_G}\right) = 0V$ good!

At $T = 500°C$, $v_o = 24\left(\frac{600}{700} - \frac{1}{2}\right)\left(1 + \frac{10^4}{R_G}\right) = 12V$

$$\boxed{R_G = 25\,k\Omega \qquad R_1 = R_2 = R_3 = 100\Omega \qquad R_4 = R_5 = 10\,k\Omega}$$

4FE-1 Given the summing amplifier shown in Fig. 4PFE-1 select the values of R_2 that will produce an output voltage of −3 V. CS

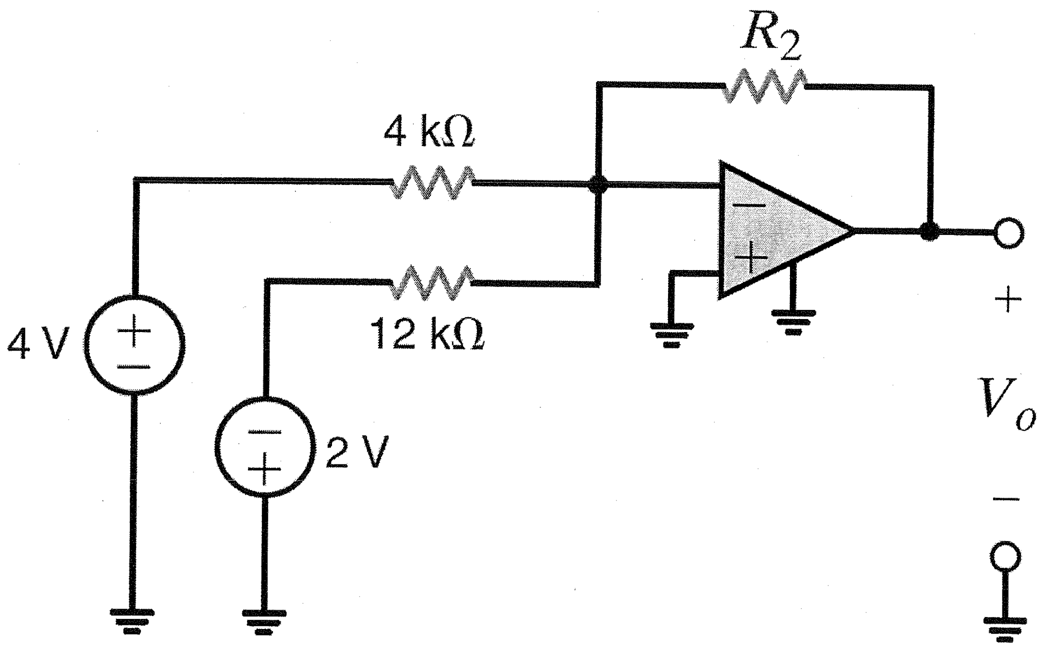


Figure 4PFE-1

SOLUTION: For summing amp:

$$v_o = -\left(\frac{R_2}{4000}\right)4 - \left(\frac{R_2}{12000}\right)(2) = -3$$

$$\boxed{R_2 = 2.57k\Omega}$$

4FE-2 Determine the output voltage V_o of the summing op-amp circuit shown in Fig. 4PFE-2.

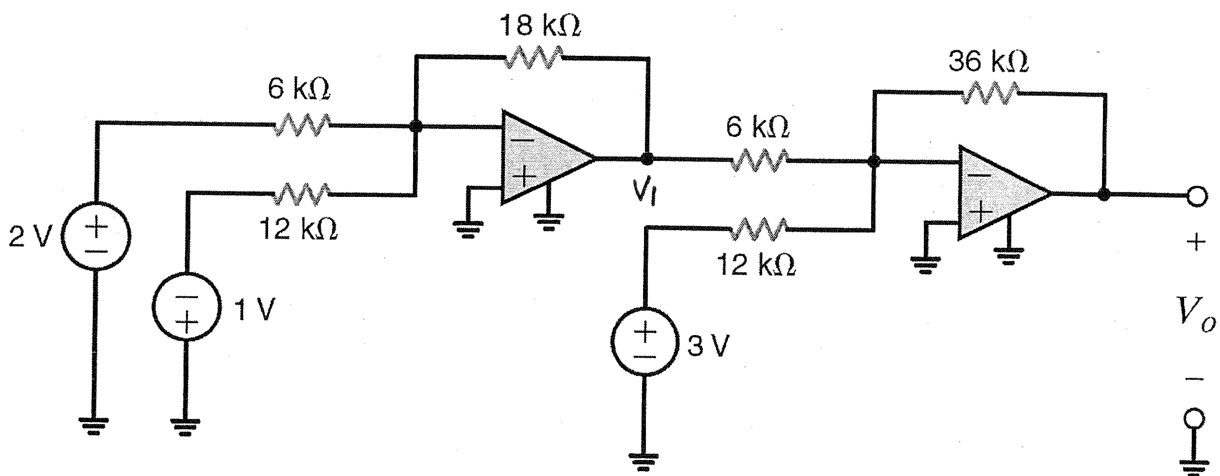


Figure 4PFE-2

SOLUTION:

$$V_1 = -2\left(\frac{18\times10^3}{6\times10^3}\right) + 1\left(\frac{18\times10^3}{12\times10^3}\right) = -4.5\,V$$

$$V_o = -V_1\left(\frac{36\times10^3}{6\times10^3}\right) - 3\left(\frac{36\times10^3}{12\times10^3}\right) \Rightarrow \boxed{V_o = 18\,V}$$