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

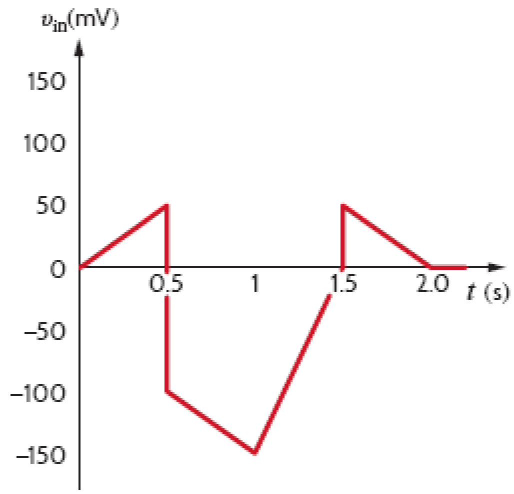
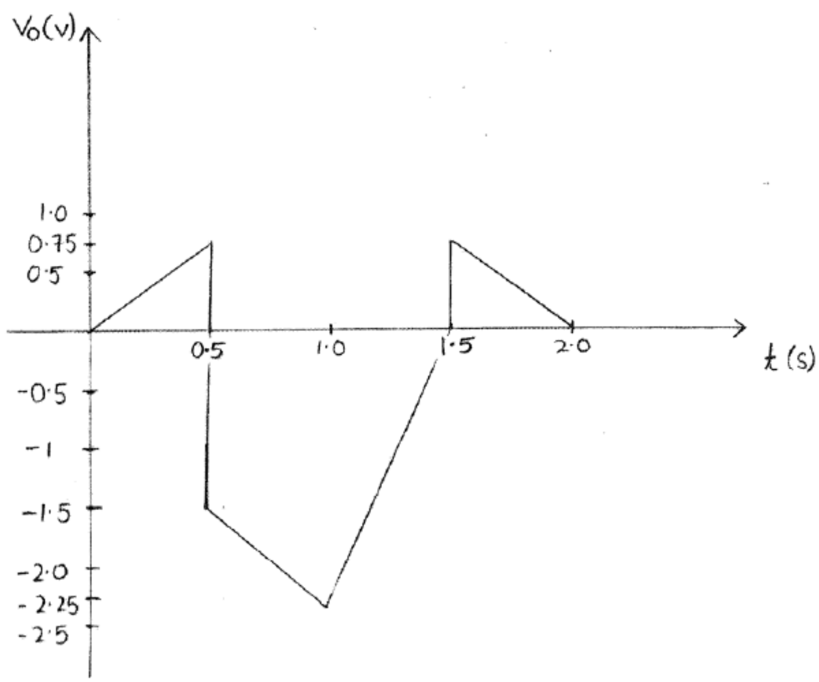


Figure P4.1

SOLUTION:



4.2 An op-amp base amplifier has supply voltages of ± 5V and a gain of 10. Sketch the input waveform from the output waveform in Fig. P4.2. What are (a) the minimum and (b) the maximum values of the input voltage?

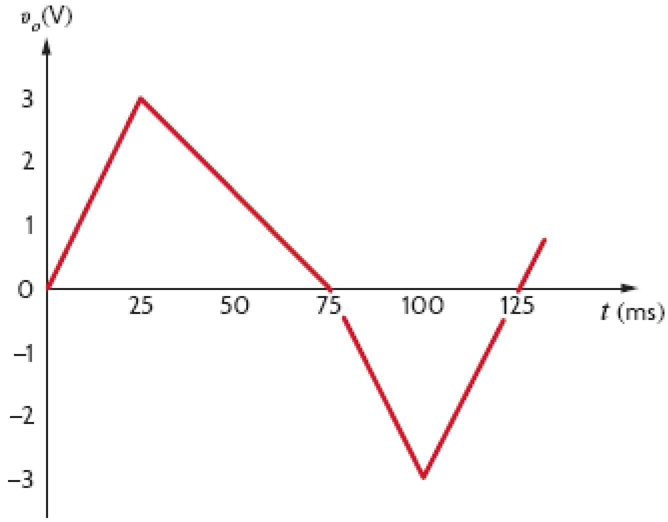


Figure P4.2

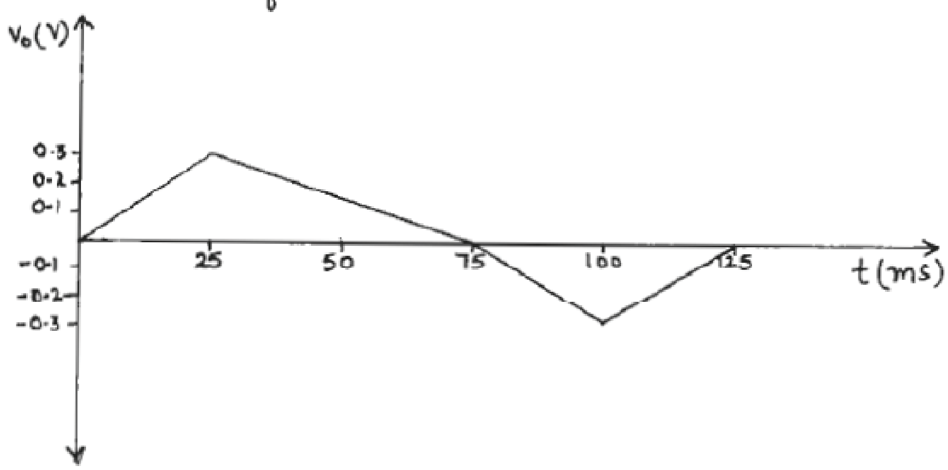
SOLUTION:

$$G = \frac{V_o}{V_s} \qquad \therefore \quad V_s = \frac{V_o}{G}$$

At $t = 25$ ms, $V_o = 3$V, $V_s = 0.3$V

At $t = 100$ ms, $V_o = -3$V, $V_s = -0.3$ V

The input waveform is drawn



(a) The minimum value of the input voltage is −0.3 V.

(b) The maximum value of the input voltage is +0.3 V.

4.3 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) With infinite gain, an input voltage of zero will produce a finite output voltage,

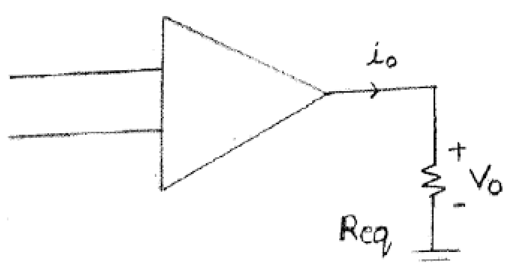
$V_{in} = 0V$ and, if V_{in} is a finite value the $V_{out} = \pm\infty$.

(b) No input current flows;

$R_{in} = \infty$

$i_{in} = 0A$

(c) With $R_{out} = 0\ \Omega$, the output current is limited only by external circuit variables,



$$i = \frac{V_o}{R_{eq}}$$

4.4 Revisit your answers in Problem 4.5 under the following non-ideal scenarios.

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

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

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

SOLUTION:

(a) $R_{in} = \infty$, $R_{out} = 0$, $A_0 \neq \infty$

If $R_{in} = \infty$, then $i_{in} = 0A$

If $R_{out} = 0$, then $i_{out} = \dfrac{V_{out}}{R_L}$ (R_L = external resistor)

If $A_0 \neq \infty$, $V_{in} \neq 0$

(b) $R_{in} = \infty$, $R_{out} > 0$, $A_0 = \infty$

If $R_{in} = \infty$, $i_{in} = 0A$

If $A_0 = \infty$, $V_{in} = 0V$

If $R_{out} > 0$, i_{out} will be limited by both R_{out} and R_L

$$\Rightarrow i_{out} = \frac{V_{out}}{(R_L + R_{out})}$$

(c) $R_{in} \neq \infty$, $R_{out} = 0$, $A_0 = \infty$

If $A_0 = \infty$, $V_{in} = 0V$

If $R_{in} \neq \infty$, $i_{in} = \dfrac{V_{in}}{R_{in}}$

$i_{in} = 0A$ due to the fact that $V_{in} = 0V$

If $R_{out} = 0$, then i_{out} is limited only by R_L.

$$\Rightarrow i_{out} = \frac{V_{out}}{R_L}$$

4.5 Revisit the exact analysis of the inverting configuration in Section 4.5.

(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 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_0 if the actual gain is within 5% of the ideal case?

SOLUTION:

(a) From section 4.3:

$$\frac{V_o}{V_s} = \frac{\frac{-R_2}{R_1}}{1 - \frac{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_{in}}\right)\left(\frac{1}{R_2} + \frac{1}{R_o}\right)}{\frac{1}{R_2}\left(\frac{1}{R_2} - \frac{A_o}{R_o}\right)}}$$

When $R_{in} = \infty$, $R_{out} = 0$, and $A_o \neq \infty$

$$\frac{1}{R_{in}} << \frac{1}{R_1} \quad \text{and} \quad \frac{1}{R_{in}} << \frac{1}{R_2}$$

$$\frac{1}{R_o} >> \frac{1}{R_2}$$

$$\frac{V_o}{V_s} = \frac{\frac{-R_2}{R_1}}{1 + \frac{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)\frac{1}{R_o}}{\frac{1}{R_2}\left(\frac{A_o}{R_o}\right)}}$$

$$\frac{V_o}{V_s} = \frac{\frac{-R_2}{R_1}}{1 + \frac{\frac{R_2 + R_1}{R_2 R_1}}{\frac{A_o}{R_2}}}$$

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

$$\frac{V_O}{V_S} = \frac{\frac{-R_2}{R_1}}{1 + \frac{1}{A_O}\left(1 + \frac{R_2}{R_1}\right)}$$

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

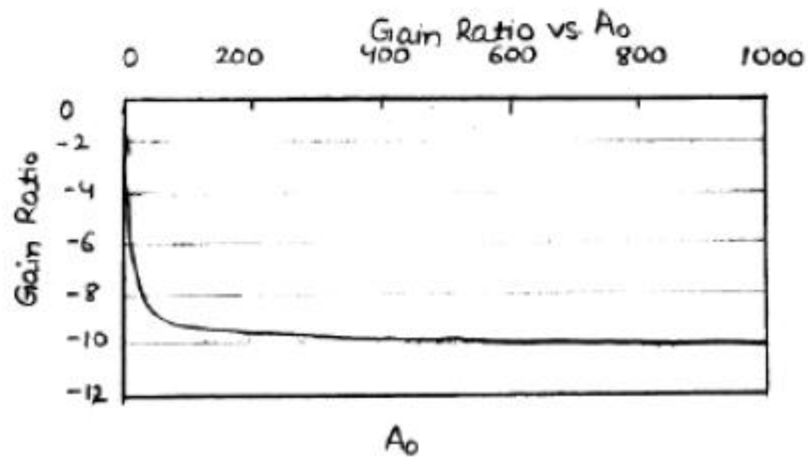
$$A_{ideal} = -10$$

$$A_{actual} = \frac{V_O}{V_S}$$

$$A_{actual} = \frac{-10}{1 + \frac{1}{A_O}(1+10)}$$

$$A_{actual} = \frac{-10}{1 + \frac{11}{A_O}}$$

$$1 \leq A_O \leq 1000$$



(c) When A_o increases, A_{actual} approaches A_{ideal}

(d) $$\frac{A_{actual}}{A_{ideal}} = \frac{\frac{-10}{1+\frac{11}{A_o}}}{-10}$$

$$\frac{\frac{-10}{1+\frac{11}{A_o}}}{-10} \leq 0.95$$

$$A_0 \geqslant 209$$

4.6 Find an expression for the voltage gain of the inverting op-amp if $R_{in} \neq \infty$, $R_{out} = 0$, $A_o \neq \infty$. Find the gain if $R_1 = 15\,\Omega$, $R_2 = 10\,\Omega$, $R_i = 24\,\Omega$, $A_o = 15$.

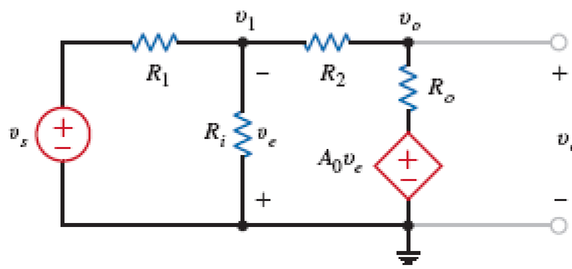


Figure P4.6

SOLUTION:

Since $R_{in} \neq \infty$ and $A_o \neq \infty$, this is a non-ideal inverting op-amp.

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

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

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

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

$R_1 = 15\,\Omega$, $R_2 = 10\,\Omega$, $R_i = 24\,\Omega$, $A_o = 15$

From (1), we get

$$\boxed{A_{actual} = -0.585}$$

4.7 An op-amp based amplifier has ±24 V supplies and a gain of ∞–. –80 Over what input range is the amplifier linear?

Find the (a) minimum and (b) the maximum values.

SOLUTION:

For linear operation

$$\frac{V_o}{V_{in}} = -80$$

Due to output limits, $V_{o(max)} = 24\,V$, $V_{o(min)} = -24\,V$

Therefore, input range of the amplifier over which the amplifier is linear is

$$-\frac{24}{80} \leq V_{in} \leq \frac{24}{80}$$

$$-0.300\,V \leq V_{in} \leq 0.300\,V$$

$$\boxed{V_{in(min)} = -0.300\,V}$$

$$\boxed{V_{in(max)} = 0.300\,V}$$

4.8 Calculate the V_o in the circuit in Fig. P4.8.

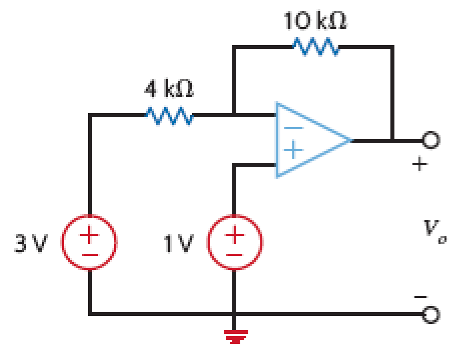


Figure P4.8

SOLUTION:

Let the voltage at the input of the op amp be v_a

$$v_a = 1V, \frac{3 - v_a}{4K} = \frac{(v_a - v_o)}{10K}$$

$$\frac{2}{4} = \frac{1 - v_o}{10}$$

$$v_o = -4\,V$$

4.9 Find the V_o and I_o in the circuit in Fig. P4.9.

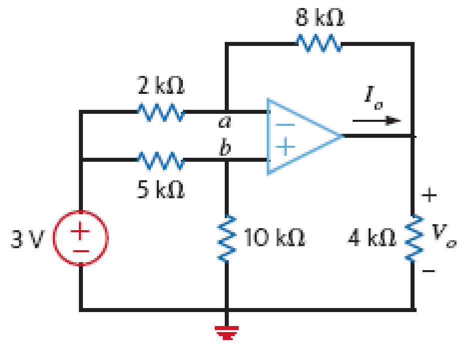


Figure P4.9

SOLUTION:

At node b using voltage divider

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

At node a using nodal analysis

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

So,
$$12 = 10 - v_o$$
$$v_o = -2V$$

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

4.10 Calculate the gain of the op-amp circuit in Fig. P4.10.

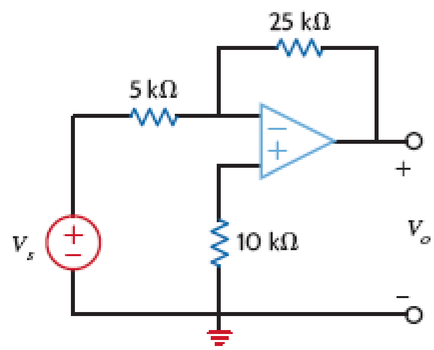


Figure P4.10

SOLUTION:

This the inverting amplifier configuration

$$v_o = -\frac{25}{5} v_s$$

$$\frac{v_o}{v_s} = -5$$

4.11 Find I_o in the following circuit in Fig. P4.11

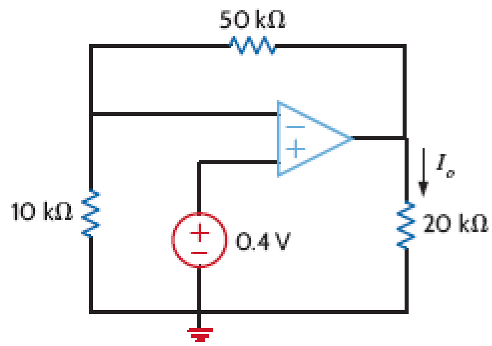


Figure P4.11

SOLUTION:

Applying nodal analysis at the node above 10K

$$\frac{0 - v_1}{10K} = \frac{v_1 - v_o}{50k}$$

$$v_1 = 0.4\ V$$

So

$$-5v_1 = v_1 - v_o$$
$$v_o = 6v_1 = 2.4\ V$$
$$i_o = \frac{v_o}{20K} = 120\,\mu A$$

4.12 Using the ideal op-amp assumptions, determine (a) I_1, (b) I_2, and (a) I_3 in Fig. P4.17.

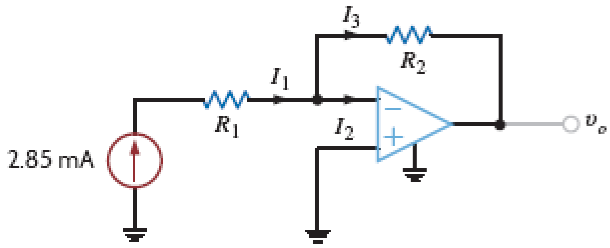


Figure P4.12

SOLUTION:

For ideal op-amp assumption,

$\boxed{I_1 = 2.85 \text{ mA}}$

$\boxed{I_2 = 0}$

Applying KCL at the inverting terminal

$I_3 = I_1 - I_2$

$\boxed{I_3 = 2.85 \text{ mA}}$

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

(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.

$R_2 = 27$ kΩ

$R_1 = 3$ kΩ

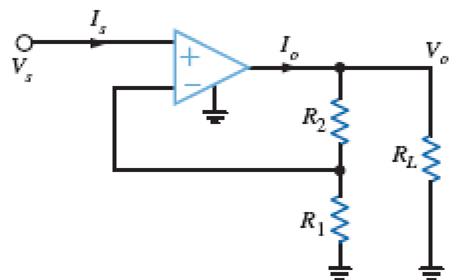
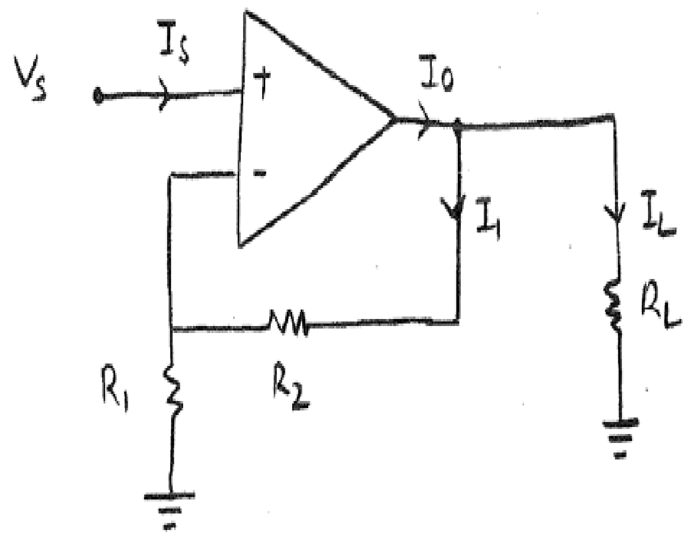


Figure P4.13

SOLUTION:

(See Next Page)



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

$$\frac{V_O}{V_S} = 1 + \frac{R_2}{R_1} = 1 + \frac{27 \times 10^3}{3 \times 10^3}$$

$$\frac{V_O}{V_S} = 10$$

4.14 The op-amp in the amplifier in Fig. P4.14 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?

$R_1 + R_2 = 60\text{ k}\Omega$

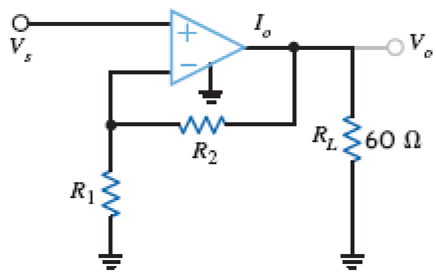


Figure P4.14

SOLUTION:

Basic non-inverting configuration

$$A_v = \frac{V_o}{V_S} = 1 + \frac{R_2}{R_1} = \frac{R_1 + R_2}{R_1} = \frac{60 \times 10^3}{R_1} = \frac{6 \times 10^4}{R_1}$$

$$|V_o| = |V_S| \left(\frac{6 \times 10^4}{R_1}\right) \leq 15 \quad \text{[For linear operation]}$$

$$V_{s\,max} = 1\text{ V}$$

For $V_{s\,max} = 1\text{ V}$, $V_o = \dfrac{6 \times 10^4}{R_1}$

Also, $$I_o = \frac{V_o}{R_1 + R_2} + \frac{V_o}{R_L}$$

$$= \frac{6 \times 10^4}{R_1 \times 60 \times 10^3} + \frac{6 \times 10^4}{R_1 \times 60}$$

$$= \frac{1001}{R_1}$$

$$\therefore \frac{1001}{R_1} \leq 200\text{ mA}$$

$$R_1 \geq \frac{1001}{200 \times 10^{-3}}$$

$\therefore$ $R_1 \geq 5005\ \Omega$ and $R_2 \leq 54995\ \Omega$

$$A_{v\,max} = 1 + \frac{R_{2\,max}}{R_{1\,min}} = 1 + 10.988$$

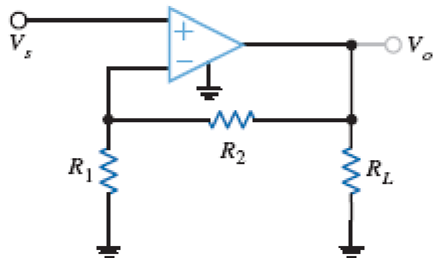
$$\boxed{A_{v\,max} = 12}$$

4.15 For the amplifier in Fig. P4.15, 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.

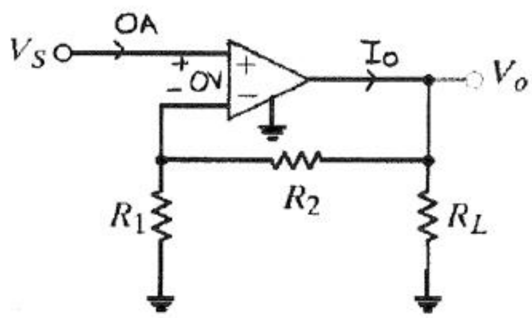
(c) Discuss the impact of the supplies on the maximum allowable gain.



$R_L = 10\text{ k}\Omega$
$R_1 = 100\text{ k}\Omega$

Figure P4.15

SOLUTION:



$R_1 = 100\,k\Omega$

$R_L = 10K\Omega$

(a) Non-inverting op-amp:

$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_S$$

$$I_o = \frac{V_o}{R_L \,||\, (R_1 + R_2)}$$

for $V_S = 2V$

$$V_o = \left(1 + \frac{R_2}{R_1}\right)(2)$$

$$\left(1+\frac{R_2}{R_1}\right)2 \leq 10$$

$$R_2 \leq 400k\Omega$$

$$I_o = \frac{10}{10\times10^3 \parallel (100\times10^3+400\times10^3)}$$

$$I_o = 1.02\ mA \leq 100mA$$

$R_2 = 400$ K Ohms satisfies both current and voltage limit.

(b) $$V_o = \left(1+\frac{R_2}{R_1}\right)(2)$$

$$\left(1+\frac{R_2}{R_1}\right)(2) \leq 3$$

$$R_2 \leq 50K\Omega$$

$$I_o = \frac{3}{10\times10^3 \parallel (100\times10^3+50\times10^3)}$$

$$I_o = 320\ \mu A$$

(C) For any value of V_s, Av_{max} is a linear function of the supply voltage. This relationship exists until the I_o limit is an issue. The limit on I_o is 100mA.

4.16 For the circuit in Fig. P4.16, find V_o, if $V_1 = 3\ V$ and $V_2 = 9\ V$.

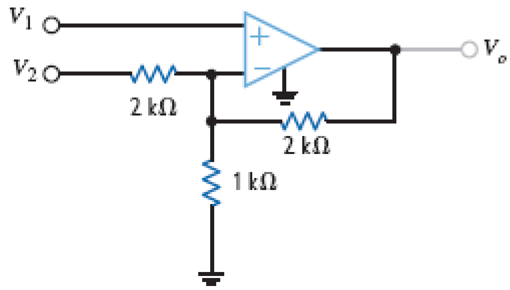
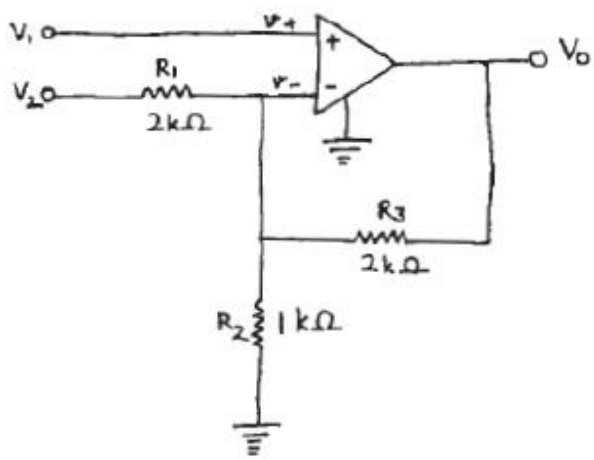


Figure P4.16

SOLUTION:



$v_+ = v_- = V_1$

KCL at v_- input : $\dfrac{V_2 - V_1}{R_1} = \dfrac{V_1}{R_2} + \dfrac{V_1 - V_0}{R_3}$

$$\Rightarrow V_0 = V_1\left(1 + \frac{R_3}{R_2} + \frac{R_3}{R_1}\right) - V_2\left(\frac{R_3}{R_1}\right)$$

$R_1 = 2k\Omega$, $R_2 = 1k\Omega$, $R_3 = 2k\Omega$, $V_1 = 3V$, $V_2 = 9V$

$\therefore\ V_0 = 4V_1 - V_2$

$\boxed{V_0 = 3V}$

4.17 Find V_o in the circuit in Fig. P4.17.

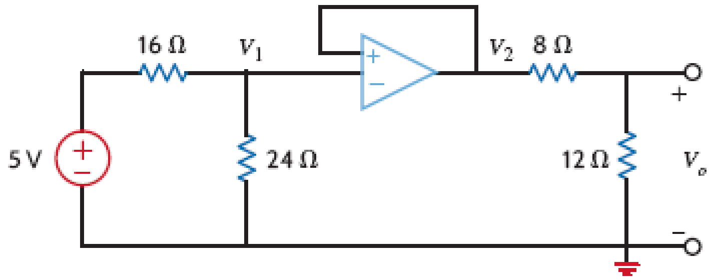


Figure P4.17

SOLUTION:

This configuration is called the voltage follower

$$v_1 = \frac{24}{24+16}(5) = 3V$$
$$v_2 = v_1 = 3V$$
$$v_o = \frac{12}{12+8}(3V) = 1.8\,V$$

4.18 The network in Fig. P4.18 is a current-to-voltage converter or transconductance amplifier. Find v_o/i_S for this network.

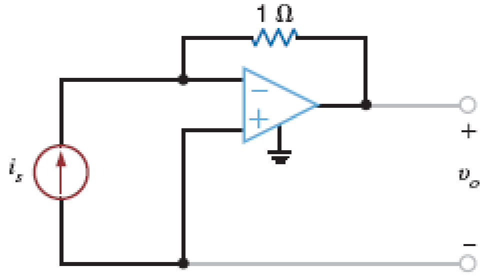
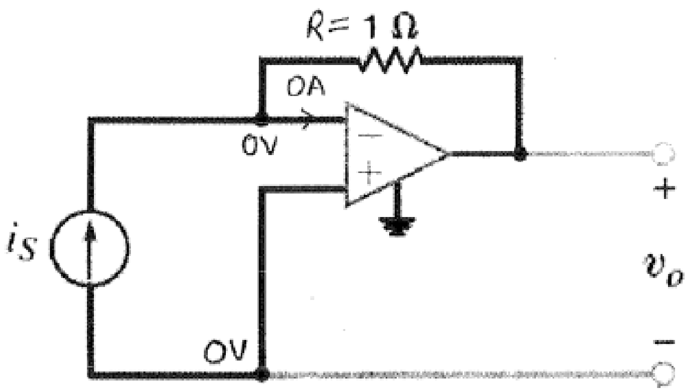


Figure P4.18

SOLUTION:



KCL at V^- : $i_s = 0 + \dfrac{0 - V_o}{R}$

$$i_s = \frac{-V_o}{R}$$

$$\frac{V_o}{i_s} = -R$$

$$\frac{V_o}{i_s} = -1$$

4.19 Determine the V_o and I_x in the circuit in Fig. P4.19.

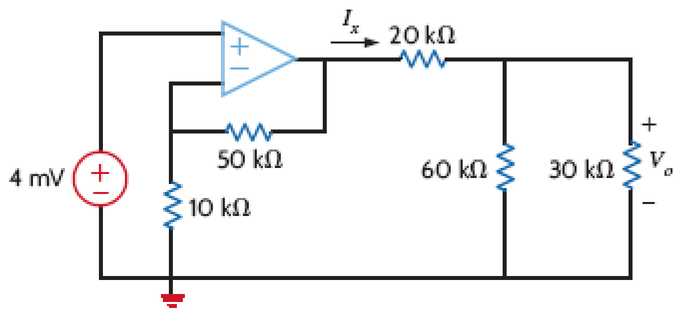


Figure P4.19

SOLUTION:

Let v_a is the voltage at the output the opamp

$$v_a = \left(1 + \frac{50}{10}\right)(4\,mV) = 24mV$$

$$60||30 = 20K$$

By voltage division

$$v_o = \frac{20}{20+20} v_x = 12mV$$

$$i_x = \frac{v_a}{(20+20)K} = \frac{24mV}{40K} = 600nA$$

4.20 Determine V_o in the circuit in Fig. P4.20.

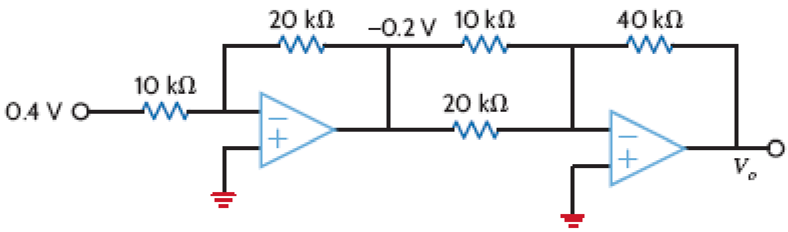


Figure P4.20

SOLUTION:

The first stage is an inverter so the output is

$$v_1 = -\frac{200}{100}(0.4) = -0.8V$$

Second stage is a summer

$$v_o = -\frac{40}{10}(0.2) - \frac{40}{20}(0.8) = 0.8 + 1.6 = 2.4\ V$$

4.21 Show that the output of the circuit in Fig. P4.21 is

$$V_o = \left[1 + \frac{R_2}{R_1}\right] V_1 - kV_2$$

Find k, if $R_1 = 5\ \Omega$, $R_2 = 46\ \Omega$, $R_3 = 6\ \Omega$, $R_4 = 12\ \Omega$.

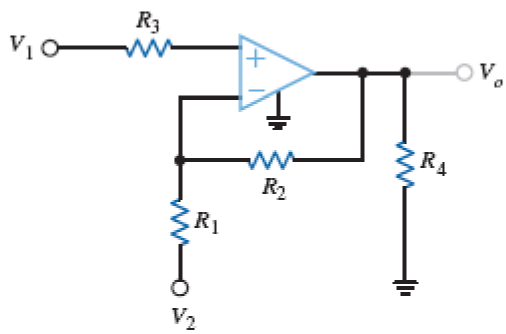
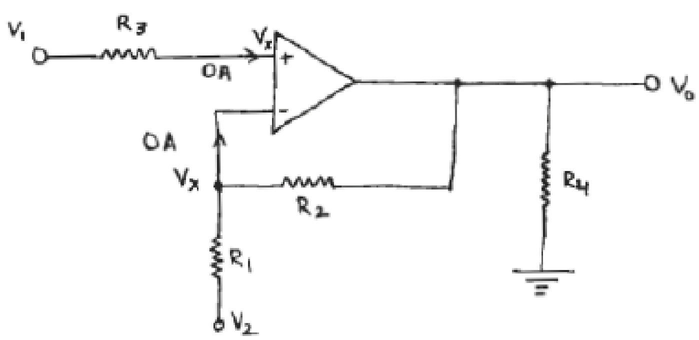


Figure P4.21

SOLUTION:



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

KCL at V_- input: $\dfrac{V_2 - V_x}{R_1} + \dfrac{V_o - V_x}{R_2} = 0$

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

$$\therefore\ V_o = \left[1 + \frac{R_2}{R_1}\right]V_1 - kV_2\ ,\ \text{where } k = \frac{R_2}{R_1}$$

$k = \dfrac{R_2}{R_1} = 9.2$

$\boxed{k = 9.2}$

4.22 Find the voltage gain of the op-amp circuit shown in Fig. P4.22.

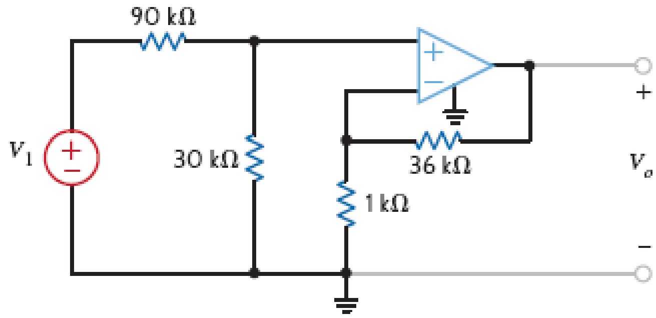
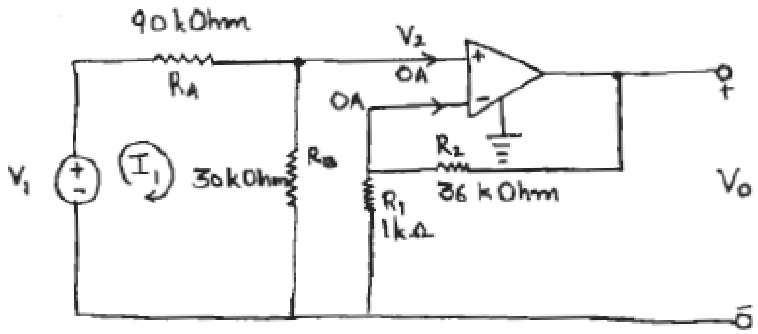


Figure P4.22

SOLUTION:



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

1) Loop analysis : $V_1 = I_1 R_A + I_1 R_B$

$V_2 = I_1 R_B \Rightarrow I_1 = V_2/R_B$

$$\frac{V_2}{V_1} = \frac{R_B}{R_A + R_B} = 0.25 \qquad \frac{V_2}{V_1} = 0.25$$

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

$$\frac{V_o}{V_2} = 1 + \frac{R_2}{R_1} = 37$$

Overall gain is $A = \frac{V_o}{V_1} = \left(\frac{V_2}{V_1}\right)\left(\frac{V_o}{V_2}\right)$

$$\boxed{A = 9.25}$$

4.23 Determine the relationship between v_o and v_{in} in the circuit in Fig. P4.23.

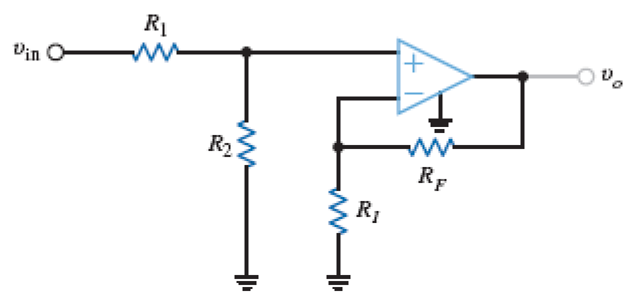
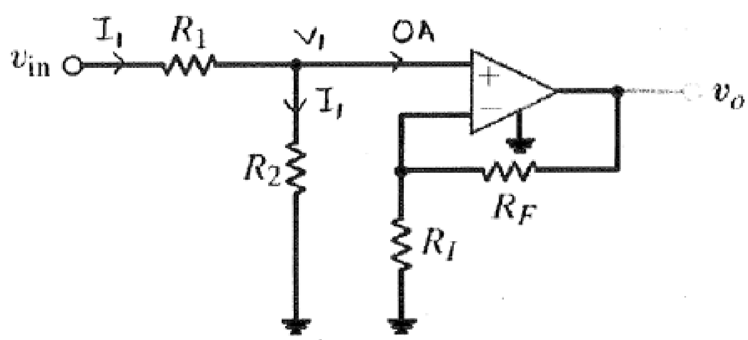


Figure P4.23

SOLUTION:



$$\text{KVL}: \; V_{in} = I_1 R_1 + I_1 R_2$$

$$V_1 = I_1 R_2$$

$$I_1 = \frac{V_1}{R_2}$$

$$V_{in} = \left(\frac{V_1}{R_2}\right)(R_1) + \left(\frac{V_1}{R_2}\right) R_2$$

$$V_{in} = V_1 + \frac{R_1}{R_2} V_1$$

$$\frac{V_1}{V_{in}} = \frac{R_2}{R_1 + R_2}$$

Non-inverting op-amp:

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

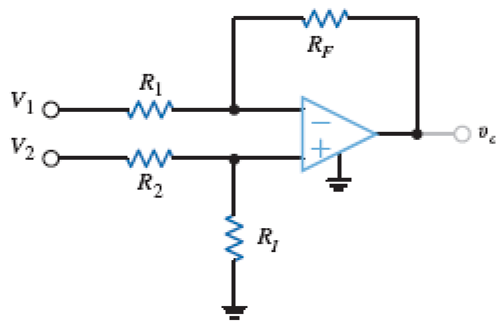
Overall gain:

$$\frac{V_O}{V_{in}} = \left(\frac{V_O}{V_1}\right)\left(\frac{V_1}{V_{in}}\right)$$

$$\frac{V_O}{V_{in}} = \left(1 + \frac{R_F}{R_I}\right)\left(\frac{R_2}{R_1 + R_2}\right)$$

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

4.24 In the network in Fig. P4.32, determine the value of V_o.



$R_1 = 11\ \Omega$

$R_2 = 18\ \Omega$

$R_I = 6\ \Omega$

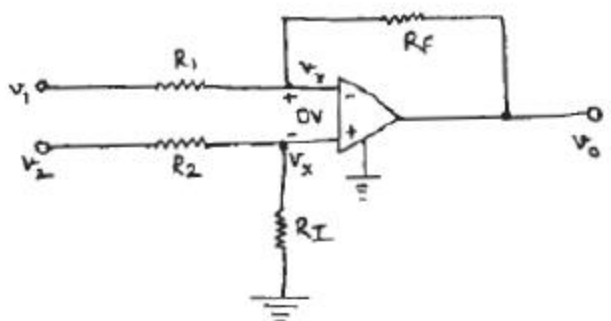
$R_F = 15\ \Omega$

$v_1 = 4\ V$

$v_2 = 6\ V$

Figure P4.24

SOLUTION:



KCL at v_+ input : $\dfrac{v_2 - v_x}{R_2} = \dfrac{v_x}{R_I} \Rightarrow v_x = \dfrac{R_I}{R_I + R_2} v_2$ —— ①

KCL at v_- input : $\dfrac{v_1 - v_x}{R_1} = \dfrac{v_x - v_o}{R_F}$

$$\Rightarrow v_o = v_x\left(1 + \frac{R_F}{R_1}\right) - \frac{R_F}{R_1} v_1 \quad \text{——} \quad ②$$

Substituting the value of v_x from equation ① in ②, we get

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

$$\boxed{V_o = -1.91\ V}$$

4.25 For the circuit in Fig. P4.25, find the value of R_1 that produces a voltage gain of 10.

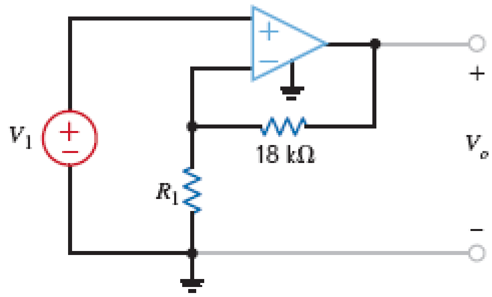
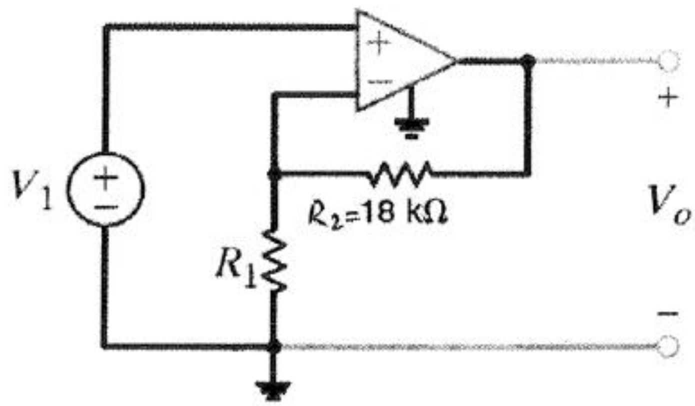


Figure P4.25

SOLUTION:



Non- inverting op-amp:

$$\frac{V_o}{V_1} = 1 + \frac{R_2}{R_1}$$

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

$$R_1 = 2\ k\Omega$$

4.26 Find V_o in the circuit in Fig. P4.26.

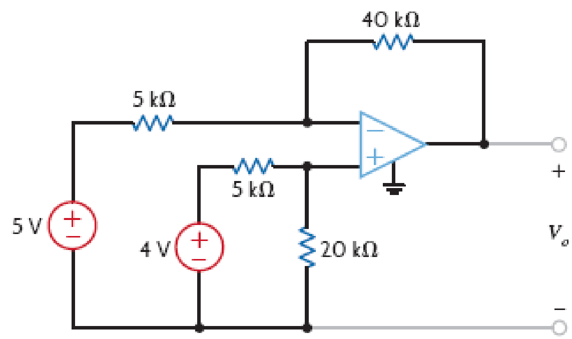
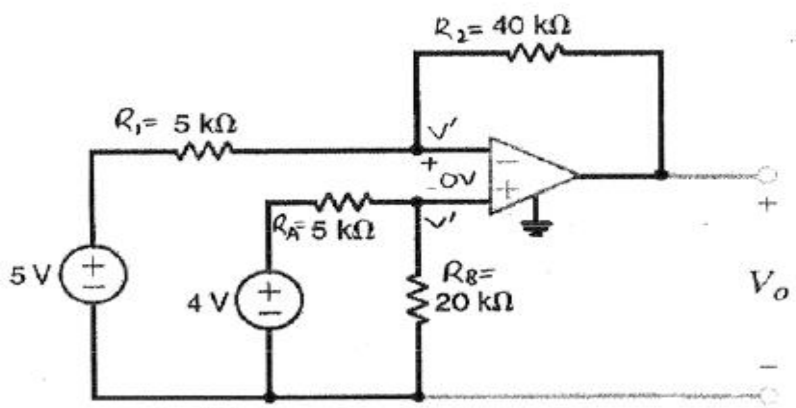


Figure P4.26

SOLUTION:



$$\text{KCL at } V_- : \quad \frac{5-V'}{R_1} = \frac{V'-V_o}{R_2}$$

$$\frac{V'}{R_2} + \frac{V'}{R_1} = \frac{5}{R_1} + \frac{V_o}{R_2}$$

$$V'\left(\frac{R_1+R_2}{R_1R_2}\right) = \frac{5R_2 + R_1V_o}{R_1R_2}$$

$$V' = 5\left(\frac{R_2}{R_1+R_2}\right) + V_o\left(\frac{R_1}{R_1+R_2}\right)$$

KCL at V_+ : $\frac{4-V'}{R_A} = \frac{V'}{R_B}$

$$V' = \frac{4R_B}{R_A+R_B}$$

$$5\left(\frac{R_2}{R_1+R_2}\right) + v_0\left(\frac{R_1}{R_1+R_2}\right) = \frac{4R_B}{R_A+R_B}$$

$$V_0 = \left(\frac{4R_B}{R_A+R_B} - \frac{5R_2}{R_1+R_2}\right)\left(\frac{R_1+R_2}{R_1}\right)$$

$$V_0 = -11.2\,V$$

4.27 Find V_o in the circuit in Fig. P4.27.

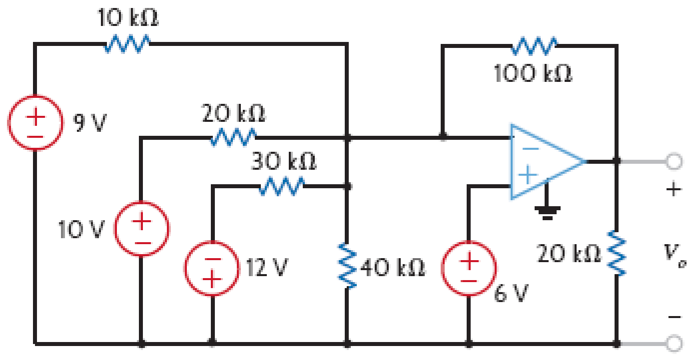
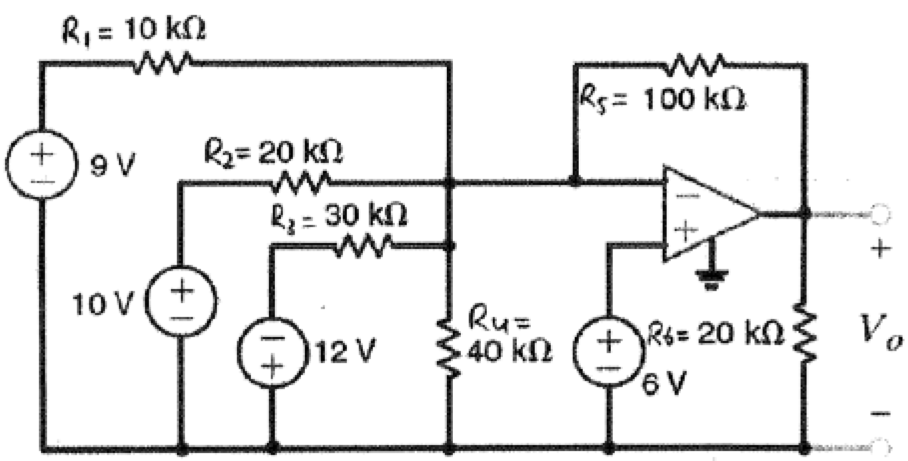


Figure P4.27

SOLUTION:



KCL at V_- : $\dfrac{9-6}{R_1} + \dfrac{10-6}{R_2} + \dfrac{-12-6}{R_3} = \dfrac{6}{R_4} + \dfrac{6-V_o}{R_5}$

$$\frac{3}{R_1} + \frac{4}{R_2} - \frac{18}{R_3} - \frac{6}{R_4} - \frac{6}{R_5} = -\frac{V_o}{R_5}$$

$V_o = 31\text{V}$

4.28 Determine the output of the following summing amplifier in Fig. P4.28

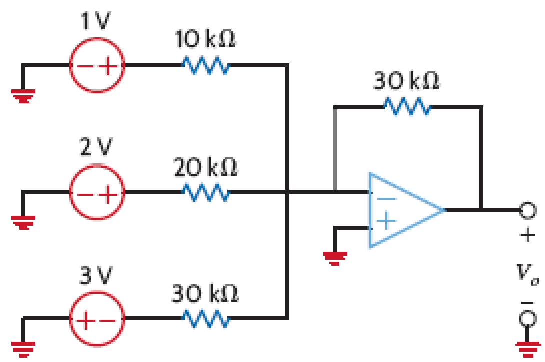


Figure P4.28

SOLUTION:

$$v_o = -\left[\frac{R_f}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_3}V_3\right]$$

$$= -\left[\frac{30}{10}(1) + \frac{30}{20}(2) + \frac{30}{30}(-3)\right]$$

$$V_O = -3V$$

4.29 Show that voltage V_o of the circuit in Fig. P4.29, is given by

$$V_o = \frac{R_3 + R_4}{R_3(R_1 + R_2)}(R_2 V_1 + R_1 V_2)$$

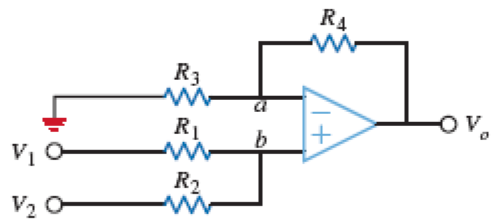


Figure P4.29

SOLUTION:

At node b, applying nodal analysis

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

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

At node a,

$$\frac{0 - v_a}{R_3} = \frac{v_a - v_o}{R_4}$$

$$v_a = \frac{v_o}{1 + \frac{R_4}{R_3}}$$

From ideal op-amp assumption $v_a = v_b$

So,

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

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

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

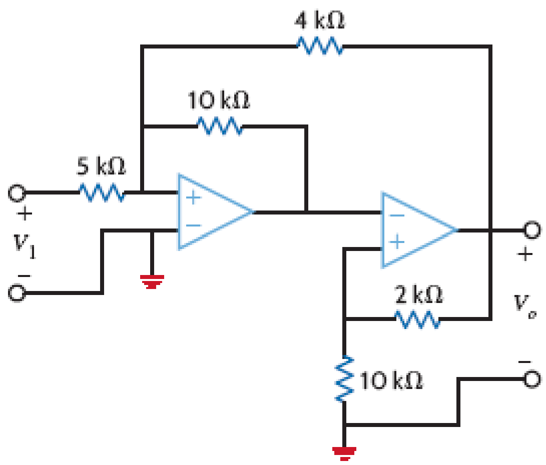


Figure P4.30

SOLUTION:

The first stage of the circuit is summer. Let us assume v_1 be the out put of the first stage.

$$v_1 = -\frac{10}{5}v_1 - \frac{10}{4}v_o$$
$$v_1 = -2v_1 - 2.5v_o$$

By voltage division,

$$v_1 = \frac{10}{10+2}v_o = \frac{5}{6}v_o$$
$$\frac{v_o}{v_1} = -\frac{6}{10} = -0.6$$

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

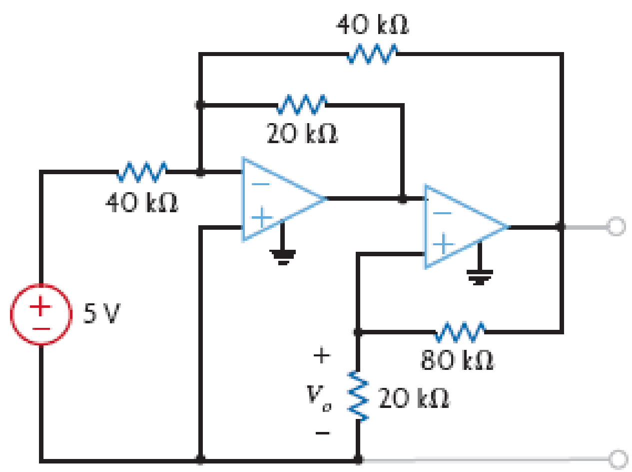
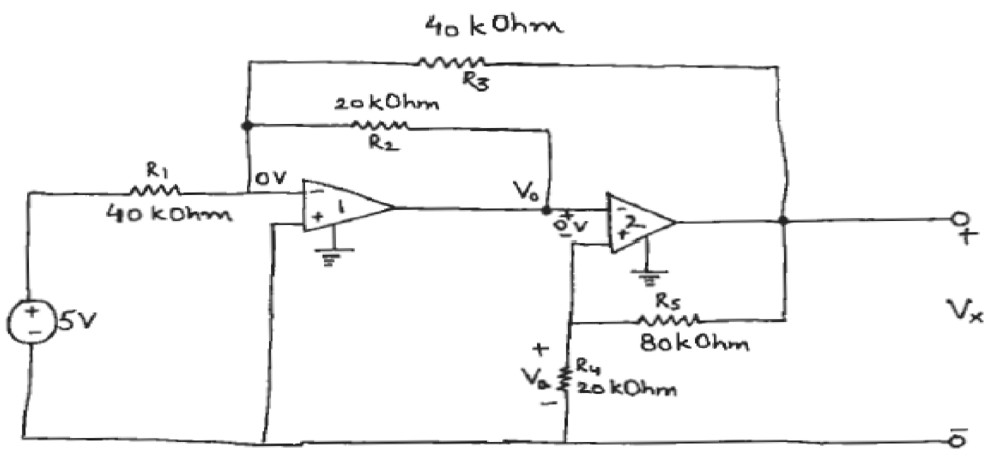


Figure P4.31

SOLUTION:



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

$$\Rightarrow V_x = -\frac{R_3}{R_1}(5) - \frac{R_3}{R_2}V_o \quad \text{— ①}$$

KCL at v_+ input of 2nd op-amp: $\frac{V_o}{R_4} + \frac{V_o - V_x}{R_5} = 0$

$$\Rightarrow V_x = V_o\left(1 + \frac{R_5}{R_4}\right) \quad \text{— ②}$$

From ② $V_x = 5V_0$

Substituting $V_x = 5V_0$ in equation ①, we get

$$\boxed{V_0 = -0.714\ V}$$

4.32 Find V_o/V_s in the circuit in Fig. P4.32.

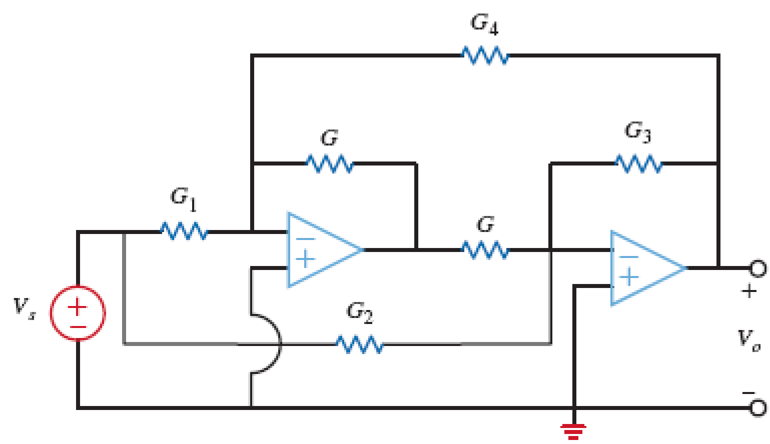


Figure P4.32

SOLUTION:

At the inverting terminal of the first opamp let the voltage be v_1 and $v_1 = 0$ so applying kcl at that node gives

$$G_1 v_s + G_4 v_o = -Gv$$

Similarly at the inverting terminal at second opampkcl gives

$$G_2 v_s + G_3 v_o = -Gv$$

From both the above equation

$$G_1 v_s + G_4 v_o = G_2 v_s + G_3 v_o$$

Arranging the equation gives

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

4.33 Find v_o in the circuit in Fig. P4.33.

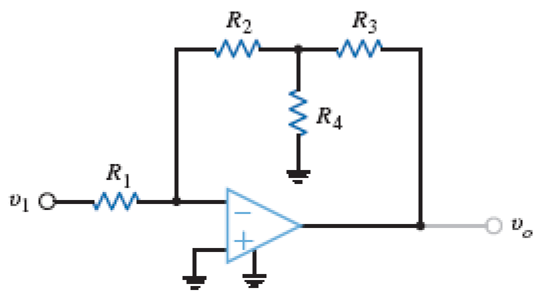
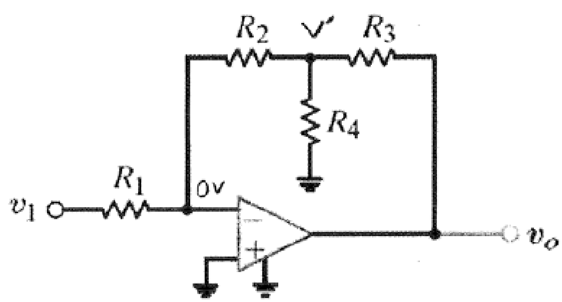


Figure P4.33

SOLUTION:



KCL at V_- : $\dfrac{V_1}{R_1} + \dfrac{V'}{R_2} = 0$

$$V' = -\frac{R_2}{R_1} V_1$$

KCL at V' : $\dfrac{V'}{R_2} + \dfrac{V'}{R_4} + \dfrac{V' - V_0}{R_3} = 0$

$$V_0 = \left(\frac{R_3}{R_2} + \frac{R_3}{R_4} + 1\right) V'$$

$$V_0 = \left(\frac{R_3}{R_2} + \frac{R_3}{R_4} + 1\right)\left(\frac{-R_2}{R_1}\right) V_1$$

4.34 Determine V_o in the circuit in Fig. P4.34.

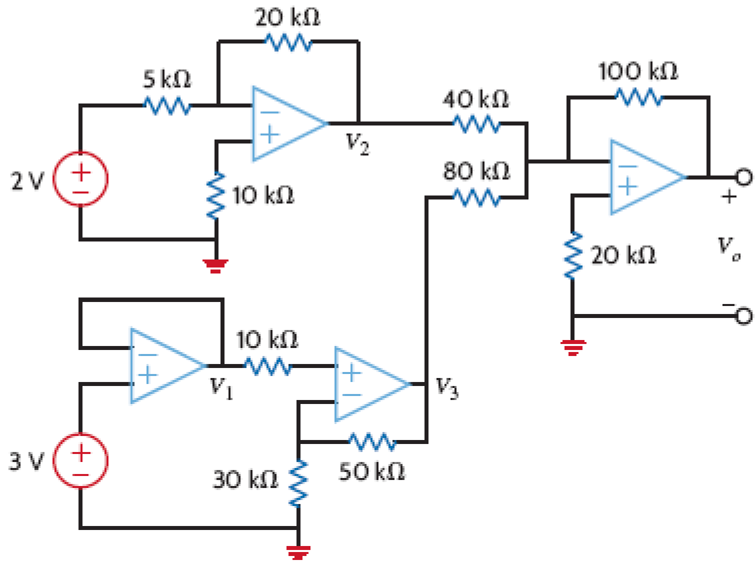


Figure P4.34

SOLUTION:

$$v_1 = 3V,\;\; v_2 = -\frac{20}{5}(2) = -8,\;\; v_3 = \left(1 + \frac{50}{30}\right) v_1 = 8$$

$$v_o = -\left(\frac{100}{40} v_2 + \frac{100}{80} v_3\right) = -(-20 + 10) = 10V$$

4.35 The electronic ammeter in Example 4.9 has been modified and is shown in Fig. P4.35. 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.

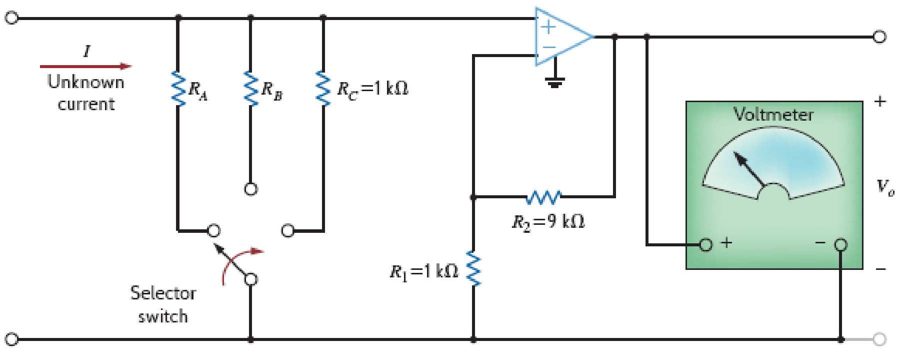
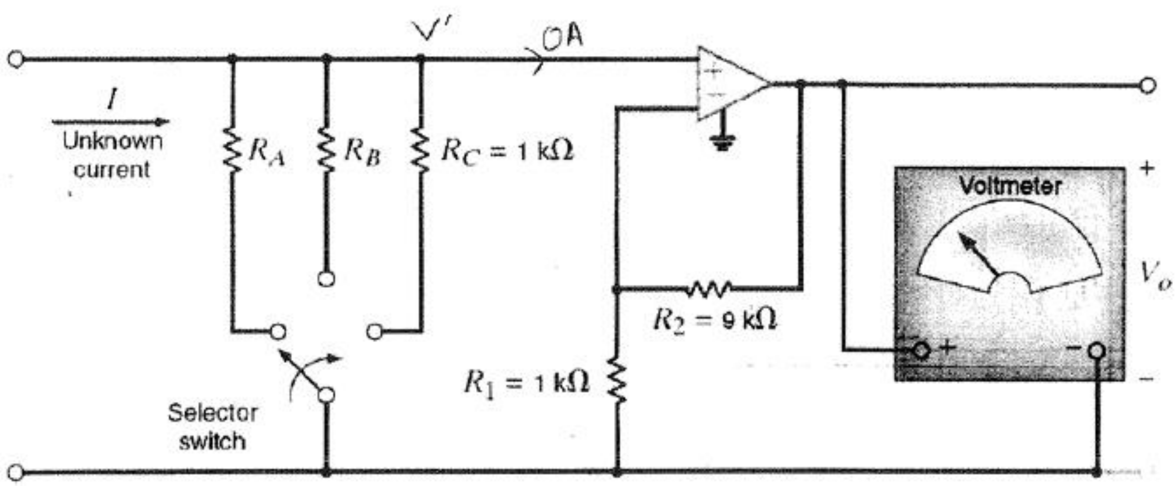


Figure P4.35

SOLUTION:



Non-inverting op-amp:

$$V_o = \left(1 + \frac{R_2}{R_1}\right) V' = 10V'$$

$$V' = IR_A = 0.1 R_A$$

$$V_o = 10V'$$

$$V_0 = 10(0.1 R_A) = 10$$

$$R_A = 10\Omega$$

$$V' = IR_B = 0.01 R_B$$

$$V_0 = 10V' = 10(0.01 R_B) = \frac{R_B}{10}$$

$$\frac{R_B}{10} = 10$$

$$R_B = 100\,\Omega$$

4.36 Design an op-amp circuit that has a gain of –110 using resistors no smaller than 1 kΩ. In the circuit given below,

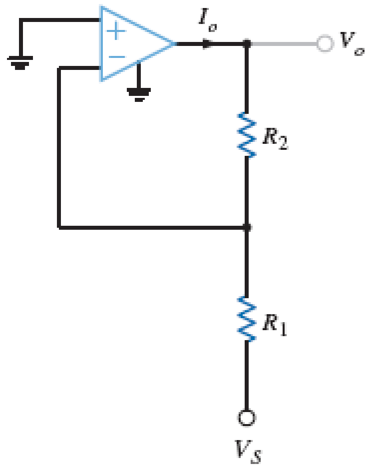
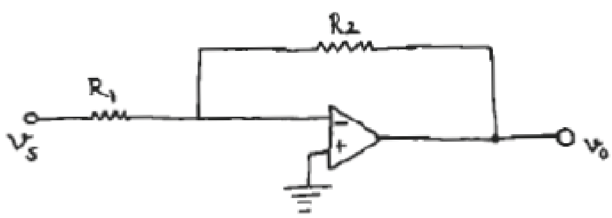


Figure P4.36

if $R_1 = 3\ \text{k}\Omega$, find R_2.

SOLUTION:



Since the gain is negative, use inverting configuration:

$$\frac{V_o}{V_s} = -\frac{R_2}{R_1} = -110$$

$$\frac{R_2}{R_1} = 110$$

Choose $R_1 = 5\,\text{k}\Omega$, then $R_2 = 550\,\text{k}\Omega$

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

$$\boxed{R_2 = 330\ \text{k}\Omega}$$

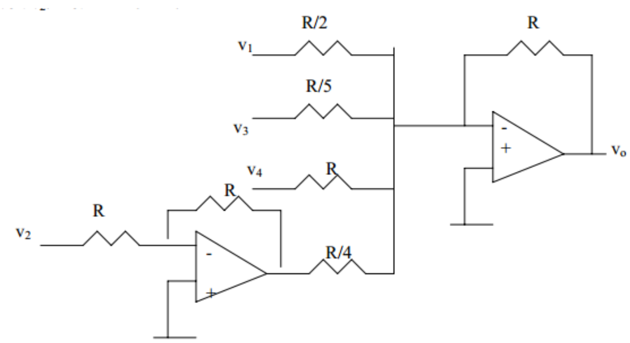
4.37 Design an op-amp circuit such that

$$V_o = -2V_1 + 4V_2 - 5V_3 - V_4$$

Give the value of resistor between 5 to 20 kΩ.

SOLUTION:

Above output can be obtained by summing amplifier. Following arrangement can be used to full fill the purpose. Where R = $10k\Omega$



4.38 Design an op-amp circuit that has the following input/output relationship: $V_o = -18\,V_1 + 0.5\,V_2$ The circuit is given

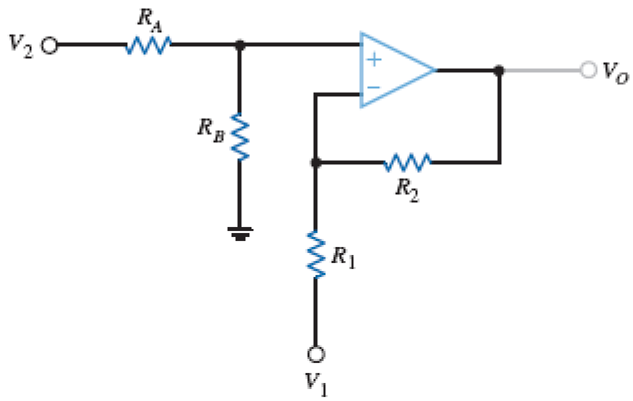
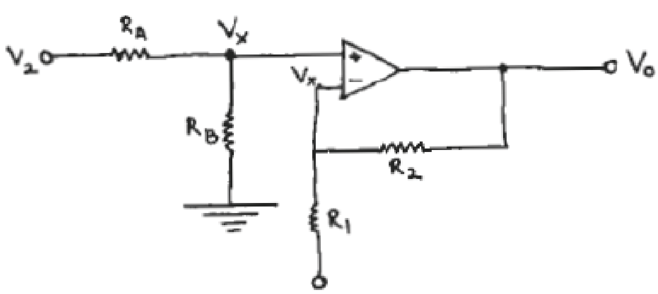


Figure P4.38

If $R_B = 1\ \text{k}\Omega$ and $R_1 = 1\ \text{k}\Omega$, find (a) R_A and R_2.

SOLUTION:



KCL at v_+ : $\dfrac{V_2 - V_x}{R_A} = \dfrac{V_x}{R_B}$

$\Rightarrow \dfrac{V_x}{V_2} = \dfrac{R_B}{R_A + R_B}$ —— ①

KCL at v_- : $\dfrac{V_o - V_x}{R_2} = \dfrac{V_x - V_1}{R_1}$

$\Rightarrow V_o = V_x\left(1 + \dfrac{R_2}{R_1}\right) - \dfrac{R_2}{R_1} V_1$ —— ②

Substituting equation ① in ②, we get

$V_o = -\dfrac{R_2}{R_1} V_1 + \dfrac{R_B}{R_A + R_B}\left(1 + \dfrac{R_2}{R_1}\right) V_2$ —— ③

$$= -18\,V_1 + 0.5\,V_2$$

$\therefore \quad \frac{R_2}{R_1} = 18 \quad$ Choose $R_1 = 2\text{ k}\Omega,\ R_2 = 36\text{ k}\Omega$

Substituting $\frac{R_2}{R_1} = 18$ in equation ③, we get

$$V_o = -18\,V_1 + \frac{R_B}{R_A + R_B}(1 + 18)\,V_2$$

$$= -18\,V_1 + \frac{19\,R_B}{R_A + R_B}\,V_2$$

$$= -18\,V_1 + 0.5\,V_2$$

Therefore $\quad \frac{19\,R_B}{R_A + R_B} = 0.5$

$\Rightarrow \quad \frac{R_A}{R_B} = 37 \quad$ Choose $R_B = 5\text{ k}\Omega,\ R_A = 185\text{ k}\Omega$

Therefore, for the given input/output relationship, we can choose $R_1 = 2\text{ k}\Omega$, $R_2 = 36\text{ k}\Omega$, $R_A = 185\text{ k}\Omega$, $R_B = 5\text{ k}\Omega$

If $R_B = 1\text{ k}\Omega$, $R_1 = 1\text{ k}\Omega$

$\boxed{R_A = 37\text{ k}\Omega}$

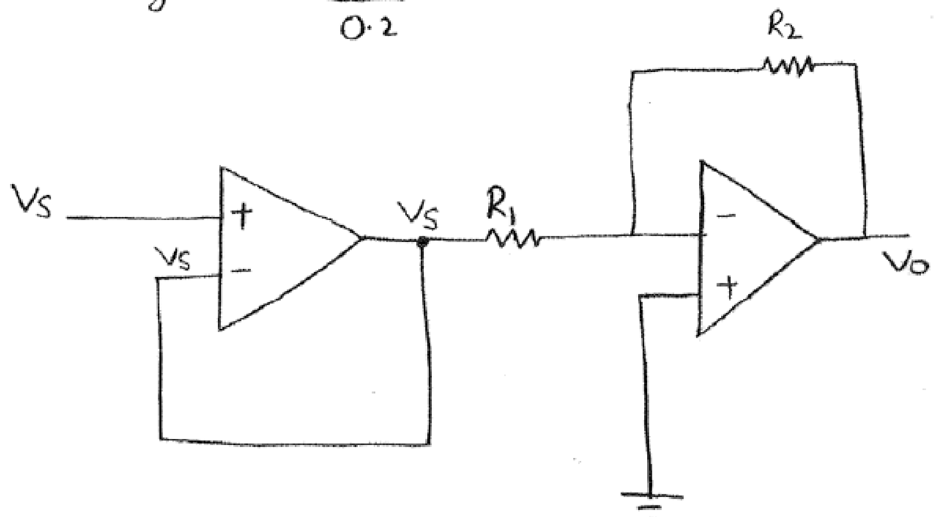
$\boxed{R_2 = 18\text{ k}\Omega}$

4.39 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.

SOLUTION:

A non-inverting op-amp followed by an inverting op-amp will work.

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



$$\frac{V_o}{V_s} = \frac{-R_2}{R_1}$$

Select $R_1 = 1\,K\Omega$

$$R_2 = -50(-1000)$$

$$R_2 = 50\,K\Omega$$

4.40 An amplifier with a gain of $\pi \pm 1\%$ is needed. Design the amplifier using the configuration shown below.

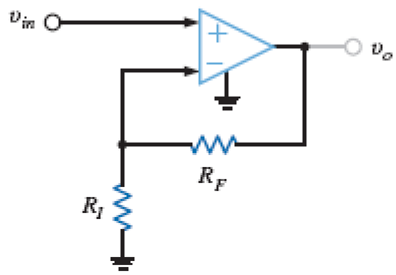
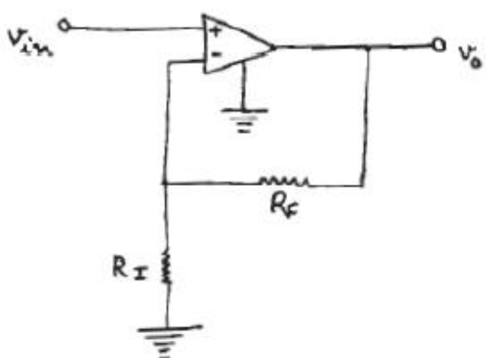


Figure P4.40

If $R_1 = 8$ kΩ, find R_F.

SOLUTION:



For positive gain, use non-inverting configuration

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

For $A = \pi \pm 1\%$, $2.111 \leq \frac{R_F}{R_I} \leq 2.174$

we choose $R_I = 20$ kΩ, $R_F = 45$ kΩ

$A = 3.15$ and this is within the limit $3.111 < A < 3.174$

If $R_I = 8$ kΩ, $1 + \frac{R_F}{R_I} = 3.15$

$$\boxed{R_F = 17.2 \text{ k}\Omega}$$

4.41 Design an op-amp circuit to provide an output $V_o = -\left(3V_1 + \frac{1}{2}V_2\right)$. Use low values of the resisitors but ones for which the input current does not exceed 0.1 mA for 2-V input signals.

SOLUTION:

This input output relation is realisedthorugh summer configuration of op-amp.

Output of op-amp

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

The input resistors can be determined as

$$\frac{R_f}{R_1} = 3 \; and \; \frac{R_f}{R_2} = \frac{1}{2}$$

$$R_2 = 6R_1$$

$$R_1 = \frac{v_1}{i_1} \geq \frac{2V}{0.1mA} = 20K\Omega$$

$$R_2 \geq \frac{2V}{0.1mA} = 120K\Omega, R_f = 60K\Omega$$

4.42 Show that the circuit in Fig. P4.42 can produce the output

$$V_o = K_1V_1 - K_2V_2$$

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

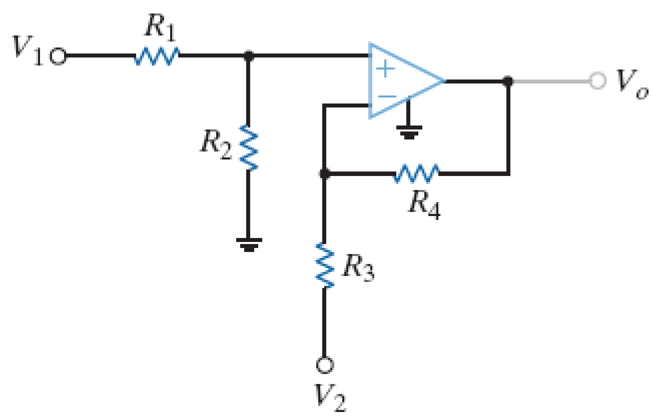
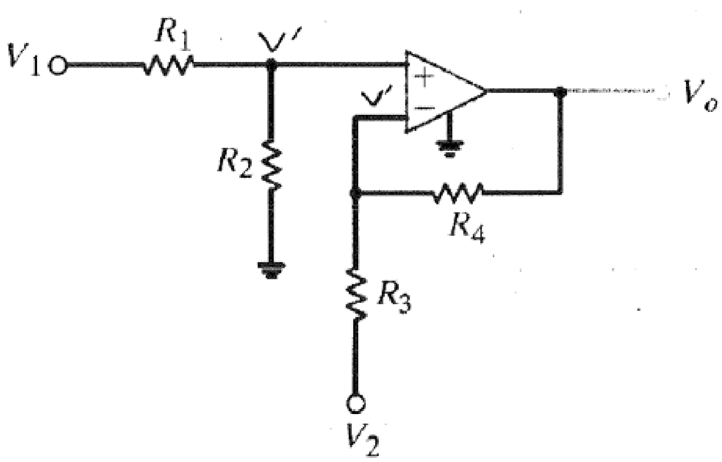


Figure P4.42

SOLUTION:

$$V_o = K_1V_1 - K_2V_2$$

$$0 \le K_1 \le K_2 + 1$$



KCL at V_+ : $\dfrac{V_1 - V'}{R_1} = \dfrac{V'}{R_2}$

$$V'\left(\frac{1}{R_1}+\frac{1}{R_2}\right)=\frac{V_1}{R_1}$$

$$V'=\left(\frac{R_2}{R_1+R_2}\right)V_1$$

KCL at V_- : $\dfrac{V_0-V'}{R_4}=\dfrac{V'-V_2}{R_3}$

$$V_0=\left(\frac{1}{R_3}+\frac{1}{R_4}\right)R_4V'-\frac{R_4}{R_3}V_2$$

$$V_0=\left(1+\frac{R_4}{R_3}\right)V'-\frac{R_4}{R_3}V_2$$

$$V_0=\left(1+\frac{R_4}{R_3}\right)\left(\frac{R_2}{R_1+R_2}\right)V_1-\frac{R_4}{R_3}V_2$$

$$V_0=K_1V_1-K_2V_2$$

$$K_2=\frac{R_4}{R_3}$$

If $R_2=0\,\Omega$, $K_1=0$

If $R_2\neq 0\,\Omega$ and $R_1=0\,\Omega$

$$K_1=1+\frac{R_4}{R_3}$$

$$K_1=1+K_2$$

$$0 \leq k_1 \leq k_2 + 1$$