The virtual ground concept, which depends on A_v being very large, allowed a simple solution to determine the overall voltage gain. It should be understood that although the circuit of Fig. 10.33 is not physically correct, it does allow an easy means for determining the overall voltage gain.

10.5 PRACTICAL OP-AMP CIRCUITS

The op-amp can be connected in a large number of circuits to provide various operating characteristics. In this section, we cover a few of the most common of these circuit connections.

Inverting Amplifier

The most widely used constant-gain amplifier circuit is the inverting amplifier, as shown in Fig. 10.34. The output is obtained by multiplying the input by a fixed or constant gain, set by the input resistor (R_1) and feedback resistor (R_f)—this output also being inverted from the input. Using Eq. (10.8), we can write

$$V_o = -\frac{R_f}{R_1}V_1$$

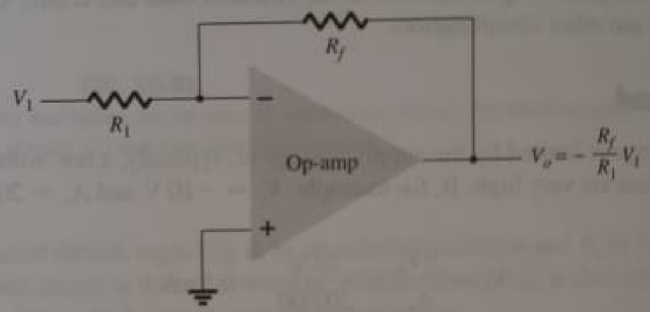


FIG. 10.34
Inverting constant-gain multiplier.

EXAMPLE 10.5 If the circuit of Fig. 10.34 has $R_1 = 100\ \text{k}\Omega$ and $R_f = 500\ \text{k}\Omega$, what output voltage results for an input of $V_1 = 2\ \text{V}$?

Solution:

$$\text{Eq. (10.8):}\quad V_o = -\frac{R_f}{R_1}V_1 = -\frac{500\ \text{k}\Omega}{100\ \text{k}\Omega}(2\ \text{V}) = \mathbf{-10\ V}$$

Noninverting Amplifier

The connection of Fig. 10.35a shows an op-amp circuit that works as a noninverting amplifier or constant-gain multiplier. It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability (discussed later). To determine the voltage gain of the circuit, we can use the equivalent representation shown in Fig. 10.35b. Note that the voltage across R_1 is V_1 since $V_i \approx 0\ \text{V}$. This must be equal to the output voltage, through a voltage divider of R_1 and R_f, so that

$$V_1 = \frac{R_1}{R_1 + R_f}V_o$$

which results in

$$\boxed{\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}} \tag{10.9}$$

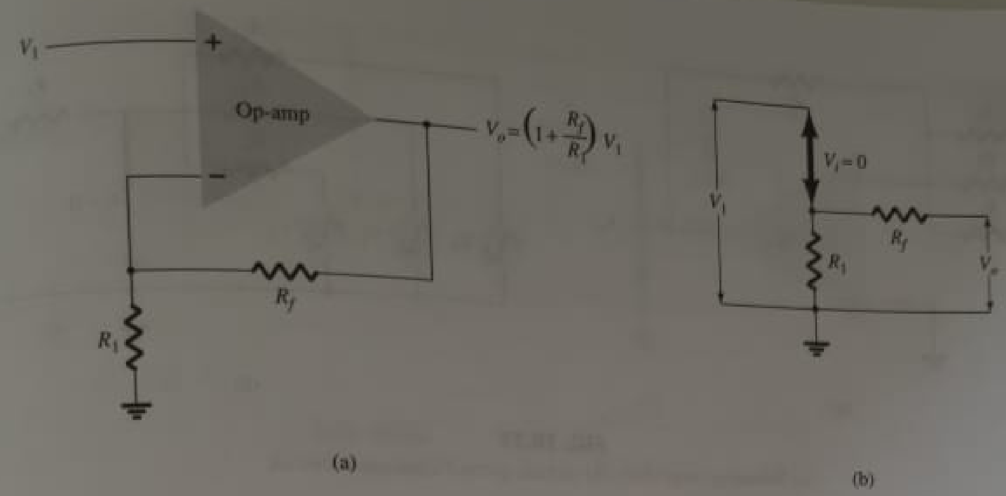


FIG. 10.35
Noninverting constant-gain multiplier.

EXAMPLE 10.6 Calculate the output voltage of a noninverting amplifier (as in Fig. 10.35) for values of $V_1 = 2\text{ V}$, $R_f = 500\text{ k}\Omega$, and $R_1 = 100\text{ k}\Omega$.

Solution:

Eq. (10.9): $$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = \left(1 + \frac{500\text{ k}\Omega}{100\text{ k}\Omega}\right)(2\text{ V}) = 6(2\text{ V}) = \mathbf{+12\text{ V}}$$

Unity Follower

The unity-follower circuit, as shown in Fig. 10.36a, provides a gain of unity (1) with no polarity or phase reversal. From the equivalent circuit (see Fig. 10.36b) it is clear that

$$\boxed{V_o = V_1} \tag{10.10}$$

and that the output is the same polarity and magnitude as the input. The circuit operates like an emitter- or source-follower circuit except that the gain is exactly unity.

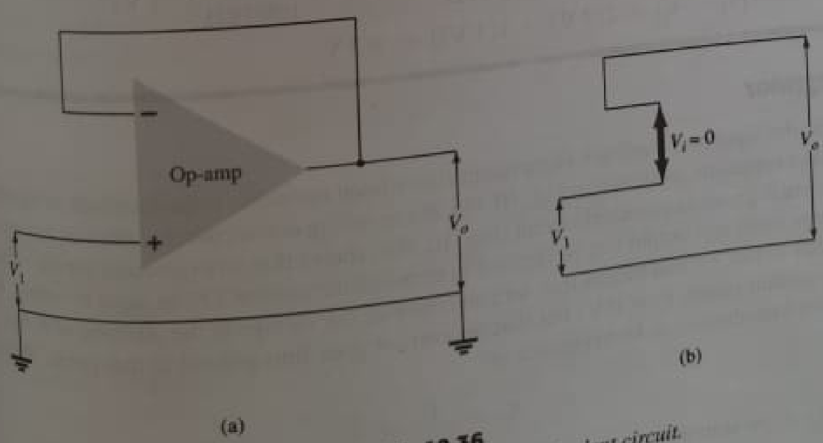
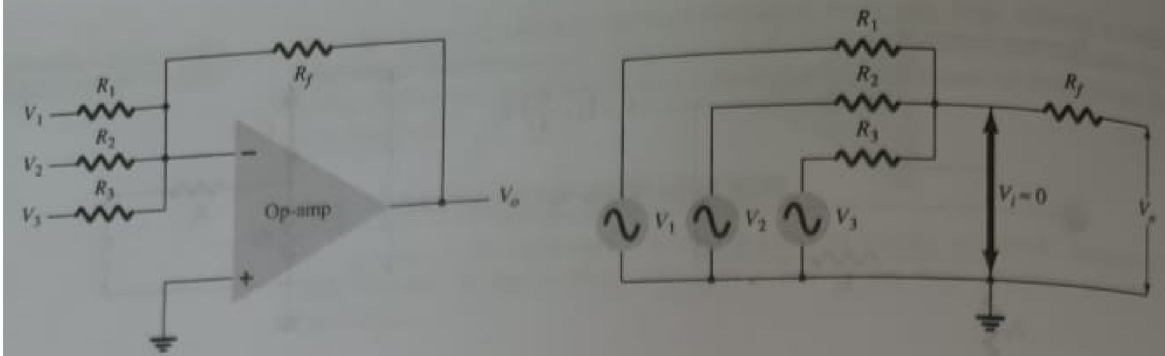


FIG. 10.36
(a) Unity follower; (b) virtual-ground equivalent circuit.

Summing Amplifier

Probably the most used of the op-amp circuits is the summing amplifier circuit shown in Fig. 10.37a. The circuit shows a three-input summing amplifier circuit, which provides a means of al... (adding) three voltages, each multiplied by a constant-gain



(a) (b)

FIG. 10.37
(a) Summing amplifier; (b) virtual-ground equivalent circuit.

factor. Using the equivalent representation shown in Fig. 10.37b, we can express the output voltage in terms of the inputs as

$$\boxed{V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)} \qquad \textbf{(10.11)}$$

In other words, each input adds a voltage to the output multiplied by its separate constant-gain multiplier. If more inputs are used, they each add an additional component to the output.

EXAMPLE 10.7 Calculate the output voltage of an op-amp summing amplifier for the following sets of voltages and resistors. Use $R_f = 1\ \text{M}\Omega$ in all cases.

a. $V_1 = +1\text{ V}, V_2 = +2\text{ V}, V_3 = +3\text{ V}, R_1 = 500\text{ k}\Omega, R_2 = 1\text{ M}\Omega, R_3 = 1\text{ M}\Omega$.
b. $V_1 = -2\text{ V}, V_2 = +3\text{ V}, V_3 = +1\text{ V}, R_1 = 200\text{ k}\Omega, R_2 = 500\text{ k}\Omega, R_3 = 1\text{ M}\Omega$.

Solution: Using Eq. (10.11), we obtain

$$\text{a. } V_o = -\left[\frac{1000\text{ k}\Omega}{500\text{ k}\Omega}(+1\text{ V}) + \frac{1000\text{ k}\Omega}{1000\text{ k}\Omega}(+2\text{ V}) + \frac{1000\text{ k}\Omega}{1000\text{ k}\Omega}(+3\text{ V})\right]$$
$$= -[2(1\text{ V}) + 1(2\text{ V}) + 1(3\text{ V})] = \mathbf{-7\text{ V}}$$

$$\text{b. } V_o = -\left[\frac{1000\text{ k}\Omega}{200\text{ k}\Omega}(-2\text{ V}) + \frac{1000\text{ k}\Omega}{500\text{ k}\Omega}(+3\text{ V}) + \frac{1000\text{ k}\Omega}{1000\text{ k}\Omega}(+1\text{ V})\right]$$
$$= -[5(-2\text{ V}) + 2(3\text{ V}) + 1(1\text{ V})] = \mathbf{+3\text{ V}}$$

Integrator

So far, the input and feedback components have been resistors. If the feedback component used is a capacitor, as shown in Fig. 10.38a, the resulting connection is called an *integrator*. The virtual-ground equivalent circuit (Fig. 10.38b) shows that an expression for the voltage between input and output can be derived in terms of the current I from input to output. Recall that virtual ground means that we can consider the voltage at the junction of R and X_C to be ground (since $V_i \approx 0$ V) but that no current goes into ground at that point. The capacitive impedance can be expressed as

$$X_C = \frac{1}{j\omega C} = \frac{1}{sC}$$

where $s = j\omega$ is in the Laplace notation.* Solving for V_o/V_1 yields

$$I = \frac{V_1}{R} = -\frac{V_o}{X_C} = \frac{-V_o}{1/sC} = -sCV_o$$

*Laplace notation allows expressing differential or integral operations, which are part of calculus, in algebraic form using the operator s. Readers unfamiliar ... to Eq. (10.13) and follow the ...

EXAMPLE 11.1 Determine the output voltage for the circuit of Fig. 11.2 with a sinusoidal input of 2.5 mV.

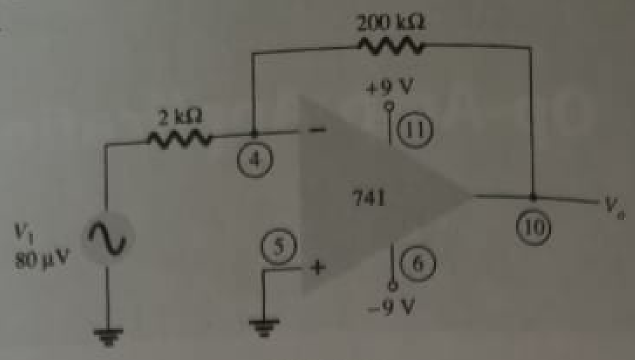


FIG. 11.2
Circuit for Example 11.2.

Solution: The circuit of Fig. 11.2 uses a 741 op-amp to provide a constant or fixed gain, calculated from Eq. (11.1) to be

$$A = -\frac{R_f}{R_1} = -\frac{200\,\text{k}\Omega}{2\,\text{k}\Omega} = -100$$

The output voltage is then

$$V_o = AV_i = -100(2.5\,\text{mV}) = -250\,\text{mV} = \mathbf{-0.25\,V}$$

A noninverting constant-gain multiplier is provided by the circuit of Fig. 11.3, with the gain given by

$$\boxed{A = 1 + \frac{R_f}{R_1}} \qquad (11.2)$$

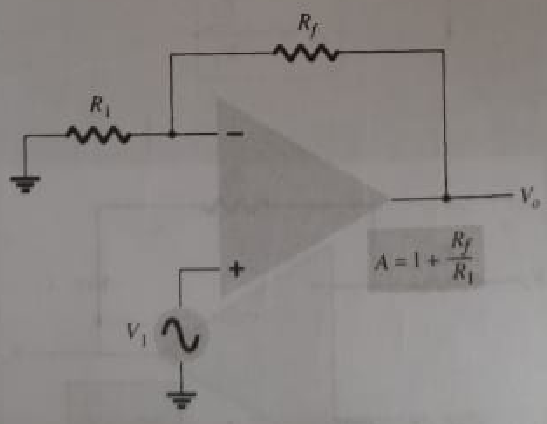


FIG. 11.3
Noninverting fixed-gain amplifier.

EXAMPLE 11.2 Calculate the output voltage from the circuit of Fig. 11.4 for an input of 120 μV.

Solution: The gain of the op-amp circuit is calculated using Eq. (11.2) to be

$$A = 1 + \frac{R_f}{R_1} = 1 + \frac{240\,\text{k}\Omega}{2.4\,\text{k}\Omega} = 1 + 100 = 101$$

The output voltage is then

$$V_o = AV_i = 101(120\,\mu\text{V}) = \mathbf{12.12\,mV}$$

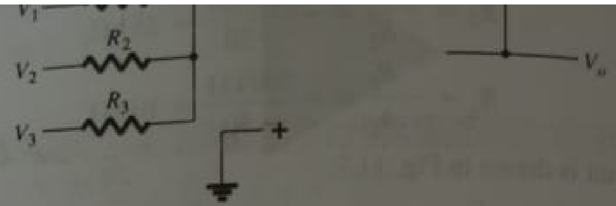


FIG. 11.8
Summing amplifier.

EXAMPLE 11.6 Calculate the output voltage for the circuit of Fig. 11.9. The inputs are $V_1 = 50\text{ mV}\sin(1000t)$ and $V_2 = 10\text{ mV}\sin(3000t)$.

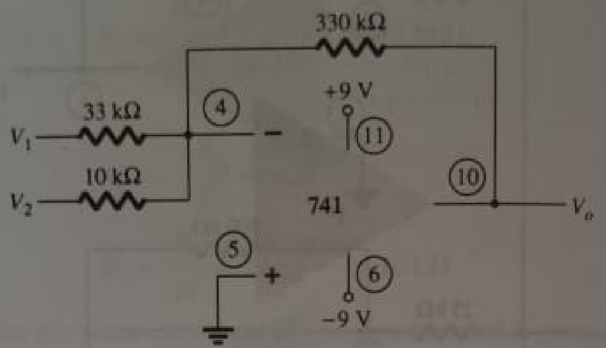


FIG. 11.9
Circuit for Example 11.6.

Solution: The output voltage is

$$V_o = -\left(\frac{330\text{ k}\Omega}{33\text{ k}\Omega}V_1 + \frac{330\text{ k}\Omega}{10\text{ k}\Omega}V_2\right) = -(10\,V_1 + 33\,V_2)$$
$$= -[10(50\text{ mV})\sin(1000t) + 33(10\text{ mV})\sin(3000t)]$$
$$= \mathbf{-[0.5\sin(1000t) + 0.33\sin(3000t)]}$$

Voltage Subtraction

Two signals can be subtracted from one another in a number of ways. Figure 11.10 shows two op-amp stages used to provide subtraction of input signals. The resulting output is given by

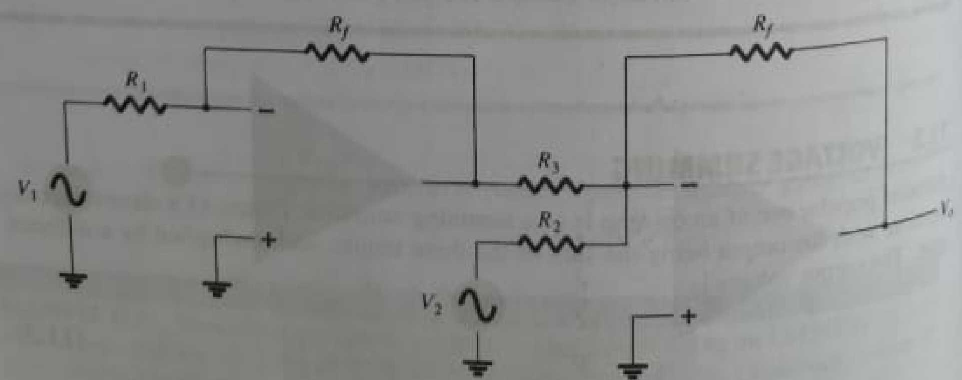


FIG. 11.10
Circuit for subtracting two signals.

$$V_o = -\left[\frac{R_f}{R_3}\left(-\frac{R_f}{R_1}V_1\right) + \frac{R_f}{R_2}V_2\right]$$

$$\boxed{V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right)} \tag{11.4}$$

EXAMPLE 11.7 Determine the output for the circuit of Fig. 11.10 with components $R_f = 1\,\text{M}\Omega$, $R_1 = 100\,\text{k}\Omega$, $R_2 = 50\,\text{k}\Omega$, and $R_3 = 500\,\text{k}\Omega$.

Solution: The output voltage is calculated to be

$$V_o = -\left(\frac{1\,\text{M}\Omega}{50\,\text{k}\Omega}V_2 - \frac{1\,\text{M}\Omega}{500\,\text{k}\Omega}\frac{1\,\text{M}\Omega}{100\,\text{k}\Omega}V_1\right) = -(20\,V_2 - 20\,V_1) = \mathbf{-20(V_2 - V_1)}$$

The output is seen to be the difference of V_2 and V_1 multiplied by a gain factor of -20.

Another connection to provide subtraction of two signals is shown in Fig. 11.11. This connection uses only one op-amp stage to provide subtracting two input signals. Using superposition, we can show the output to be

$$\boxed{V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2} \tag{11.5}$$

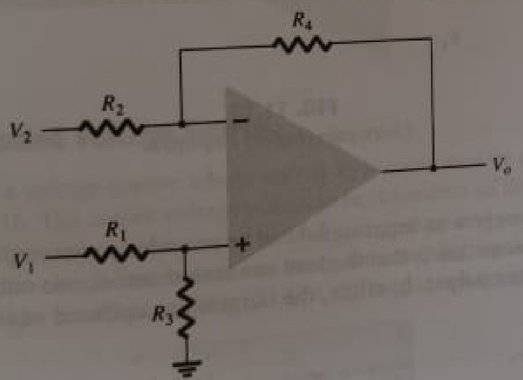


FIG. 11.11
Subtraction circuit.

EXAMPLE 11.8 Determine the output voltage for the circuit of Fig. 11.12.

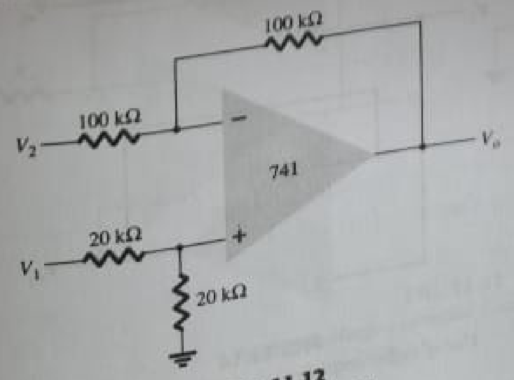


FIG. 11.12
Circuit for Example 11.8.

so that the output can be obtained from

$$\boxed{V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = k(V_1 - V_2)} \tag{11.12}$$

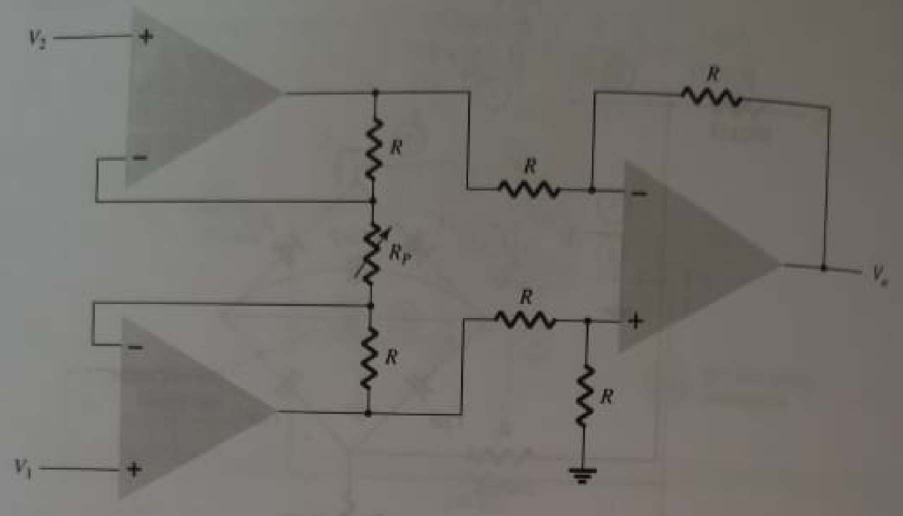


FIG. 11.28
Instrumentation amplifier.

EXAMPLE 11.11 Calculate the output voltage expression for the circuit of Fig. 11.29.

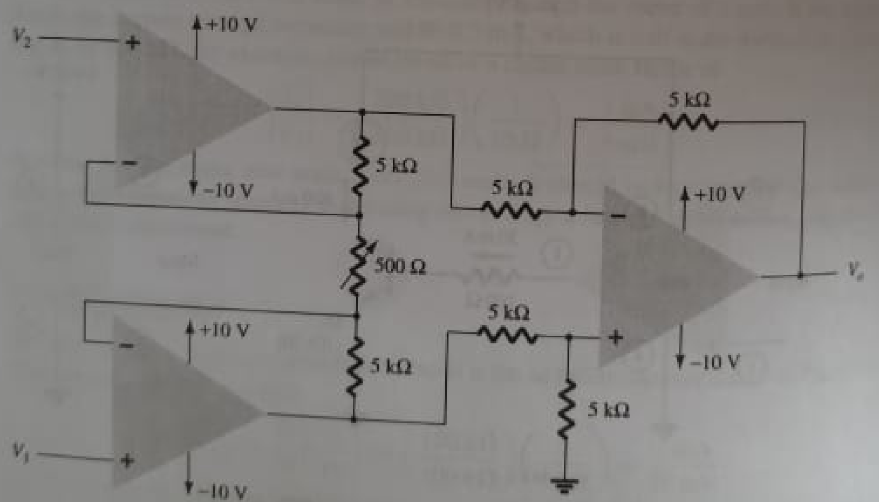


FIG. 11.29
Circuit for Example 11.11.

Solution: The output voltage can then be expressed using Eq. (11.12) as

$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = \left[1 + \frac{2(5000)}{500}\right](V_1 - V_2)$$
$$= \mathbf{21(V_1 - V_2)}$$

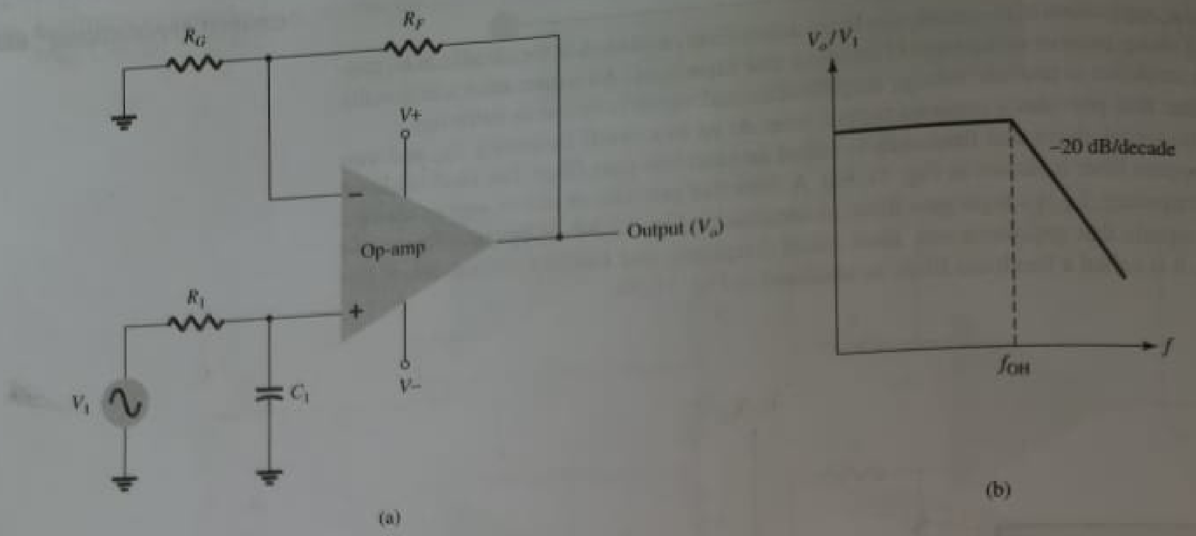


FIG. 11.31
First-order low-pass active filter.

Connecting two sections of filter as in Fig. 11.32 results in a second-order low-pass filter with cutoff at −40 dB per decade—closer to the ideal characteristic of Fig. 11.30a. The circuit voltage gain and the cutoff frequency are the same for the second-order circuit as for the first-order filter circuit, except that the filter response drops at a faster rate for a second-order filter circuit.

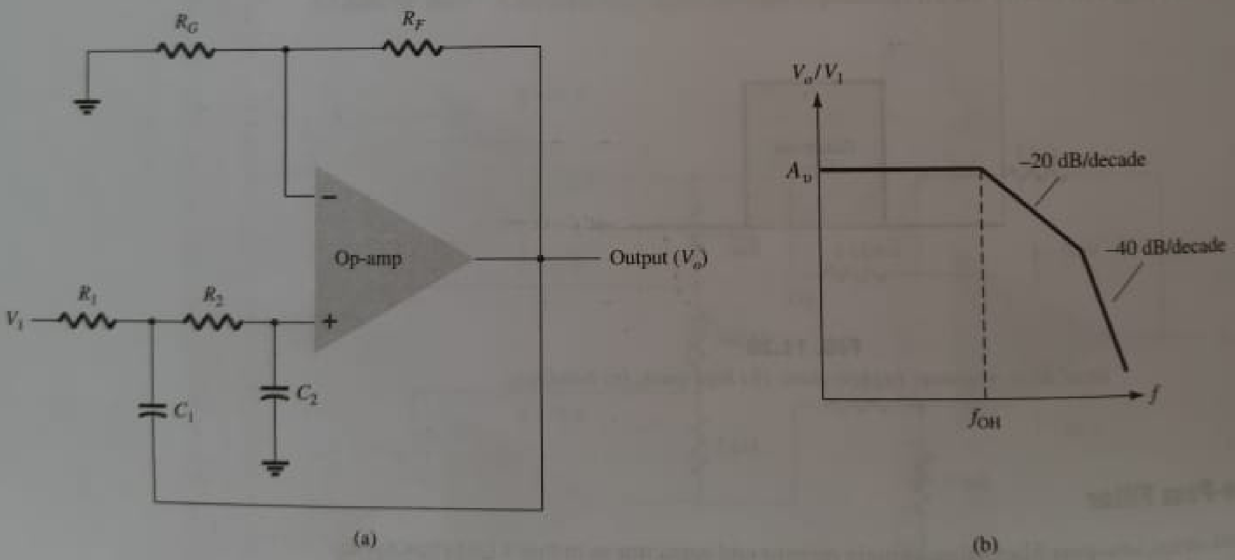


FIG. 11.32
Second-order low-pass active filter.

EXAMPLE 11.12 Calculate the cutoff frequency of a first-order low-pass filter for $R_1 = 1.2\ \text{k}\Omega$ and $C_1 = 0.02\ \mu\text{F}$.

Solution:

$$f_{OH} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi(1.2 \times 10^3)(0.02 \times 10^{-6})} = \mathbf{6.63\ kHz}$$

15. Calculate V_o in the circuit of Fig. 10.74.

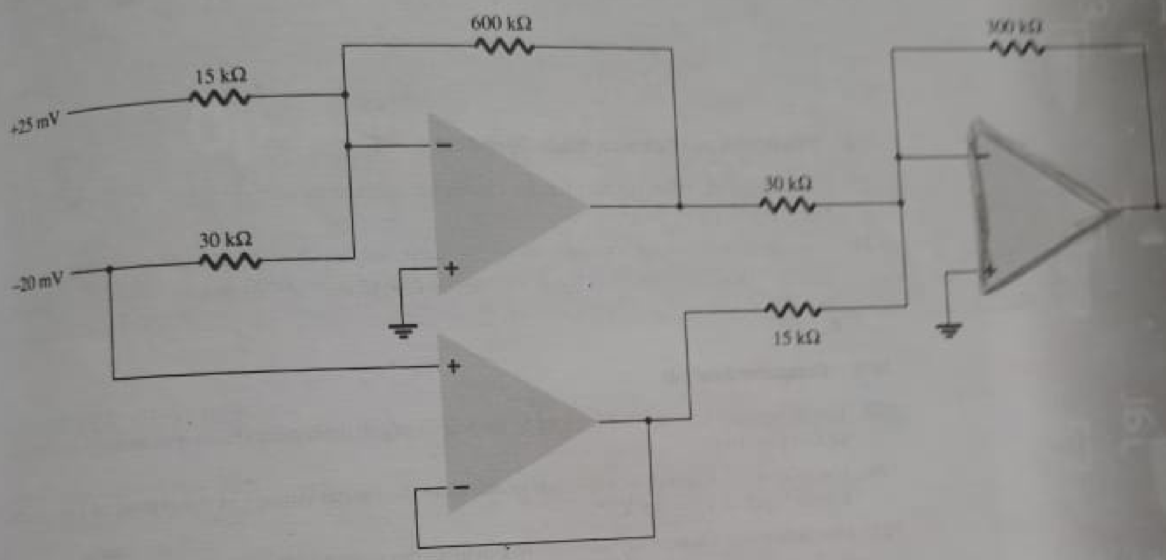


FIG. 10.74
Problem 15.

10.6 Op-Amp Specifications—DC Offset Parameters

*16. Calculate the total offset voltage for the circuit of Fig. 10.75 for an op-amp with specified values of input offset voltage $V_{IO} = 6$ mV and input offset current $I_{IO} = 120$ nA.

*17. Calculate the input bias current at each input of an op-amp having specified values of $I_{IO} = 4$ nA and $I_{IB} = 20$ nA.

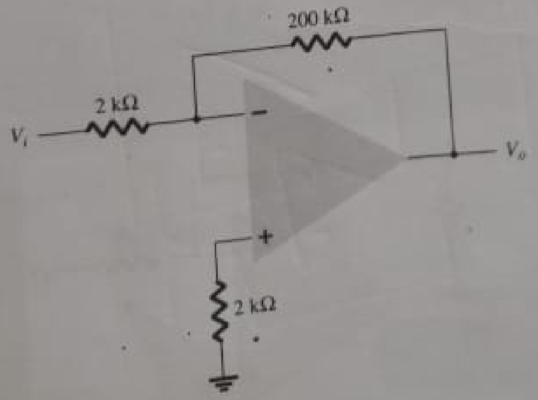


FIG. 10.75
Problems 16, 20, 21, and 22.

…ations—Frequency Parameters

… specified values B_1 = 800 kHz and

13. Calculate the output voltages V_2 and V_3 in the circuit of Fig. 10.72.

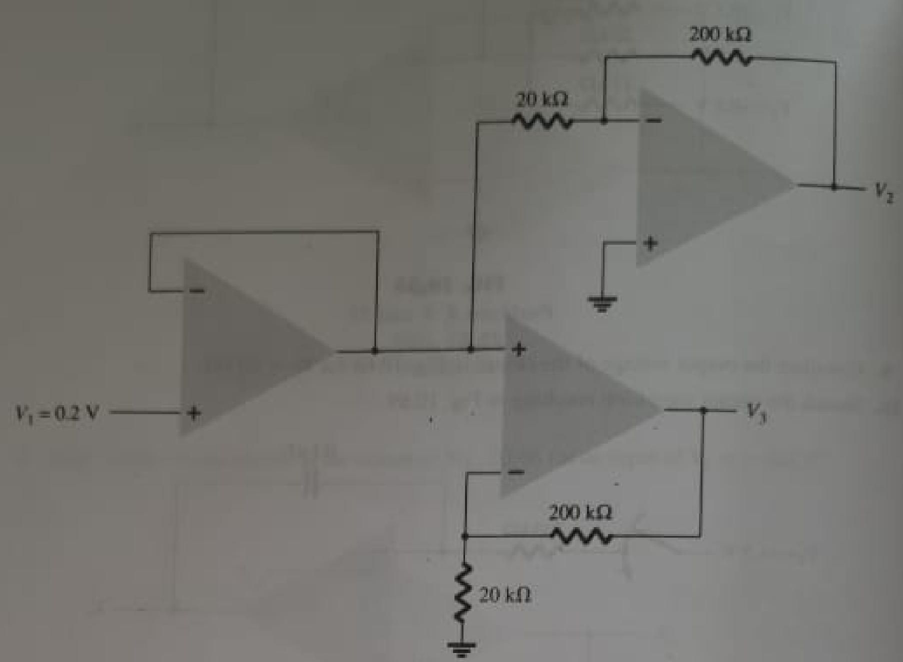


FIG. 10.72
Problem 13.

14. Calculate the output voltage, V_o, in the circuit of Fig. 10.73.

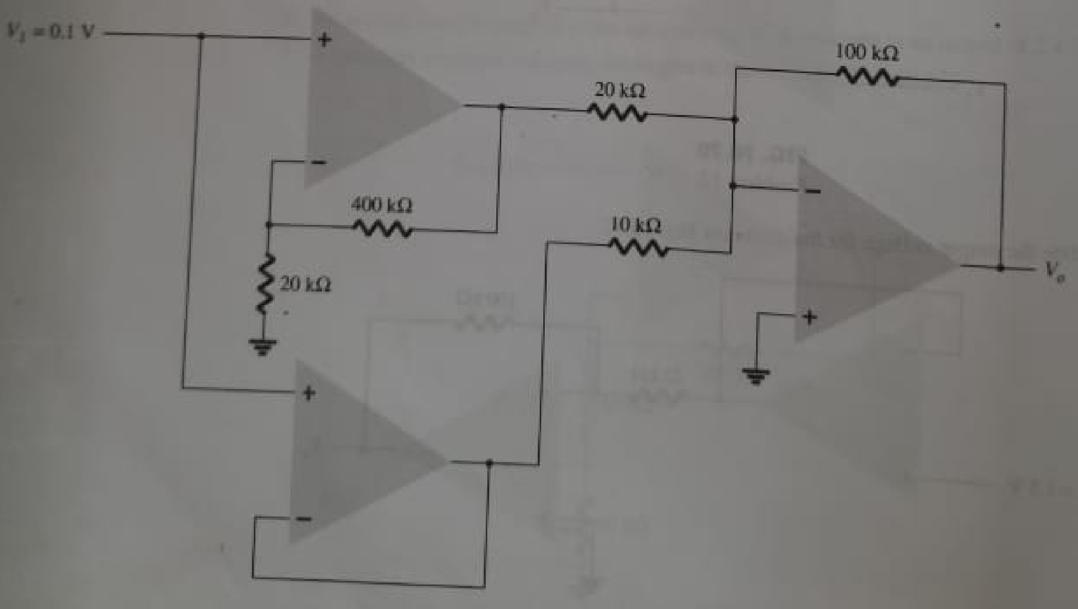
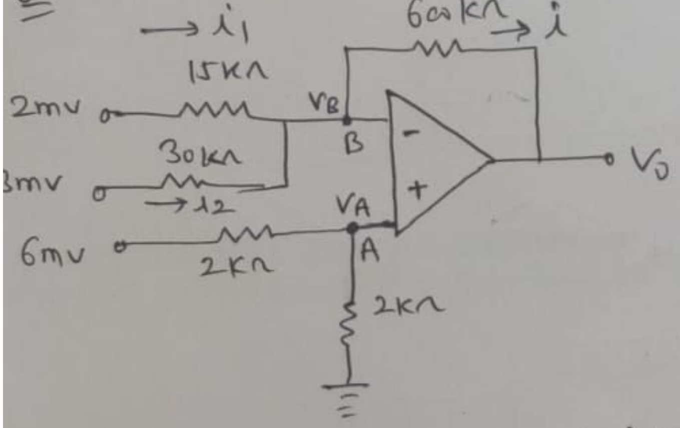


FIG. 10.73
Problems 14 and 27.

Q3



we will calculate the potential at point V_A by voltage divider rule

$$V_A = \frac{2\,k\Omega}{(2+2)\,k\Omega} \times 6\,mv$$

According to virtual ground concept the same potential will be at point B. say that potential is V_B

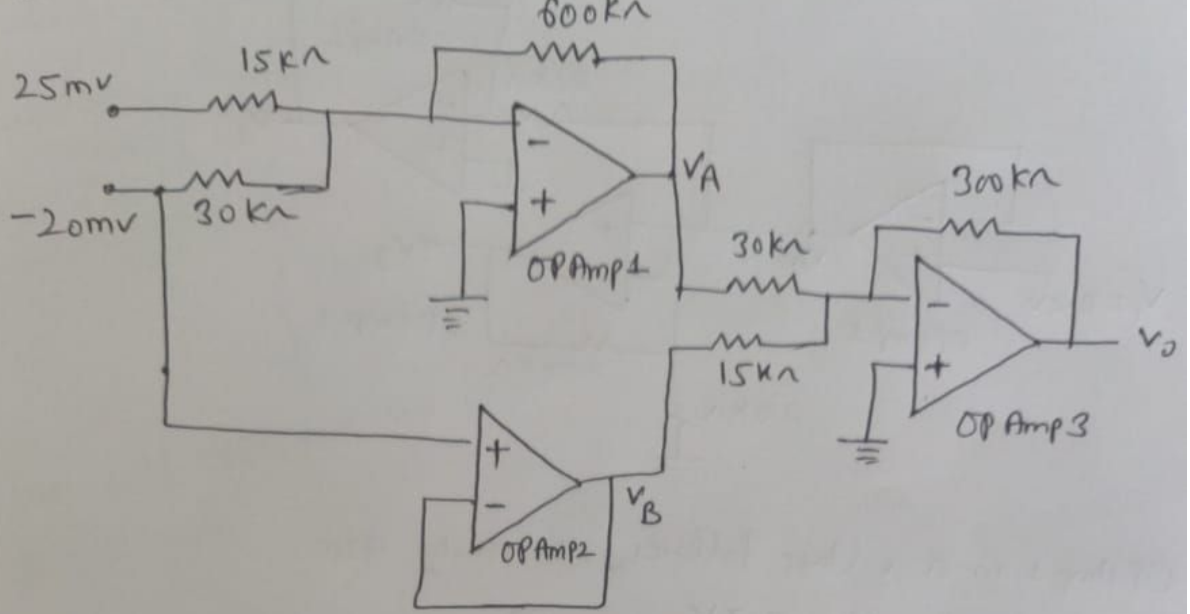
Applying KCL at point B

$$i_1 + i_2 = i$$

$$\frac{2 - V_B}{15} + \frac{3 - V_B}{30} = \frac{V_B - V_o}{600}$$

We can calculate V_o

Q2



OP Amp 1 is a summing Amplifier in inverting mode

$$V_A = \left(\frac{-600}{15}\right)25mV - \left(\frac{600}{30}\right) \times -20mV$$

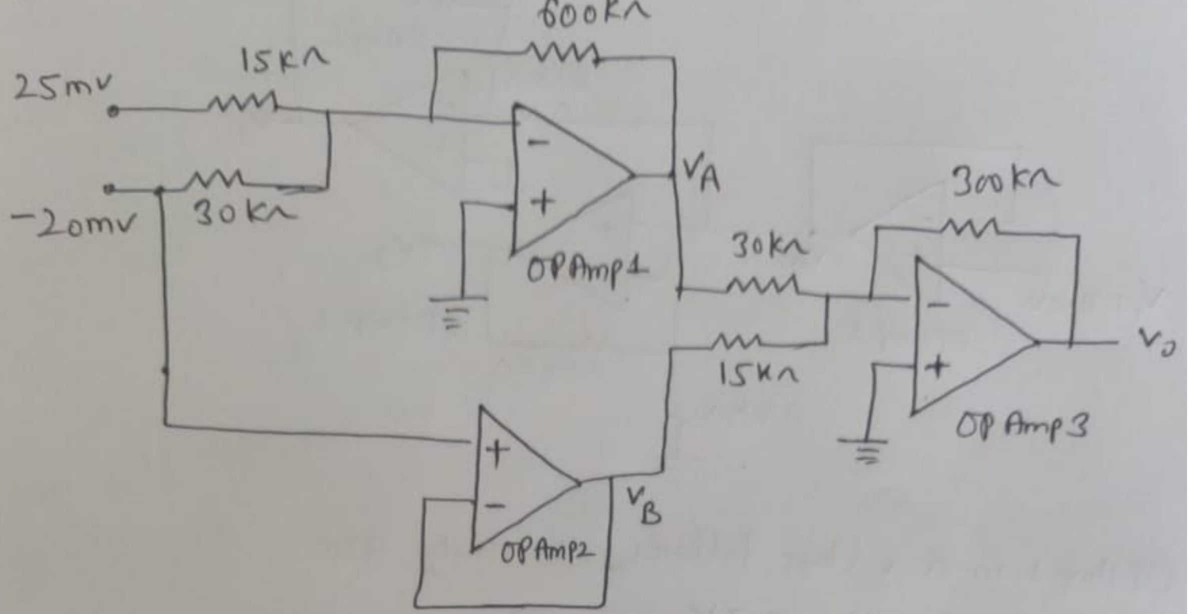
OP Amp 2 is a voltage follower with unity gain

$$\therefore \quad V_B = -20mV$$

OP Amp 3 is again a summing Amplifier in inverting mode

$$V_o = -\left(\frac{300}{30}\right)V_A - \left(\frac{300}{15}\right)V_B$$

Q2



OP Amp 1 is a summing Amplifier in inverting mode

$$V_A = \left(\frac{-600}{15}\right)25mv - \left(\frac{600}{30}\right)\times -20mv$$

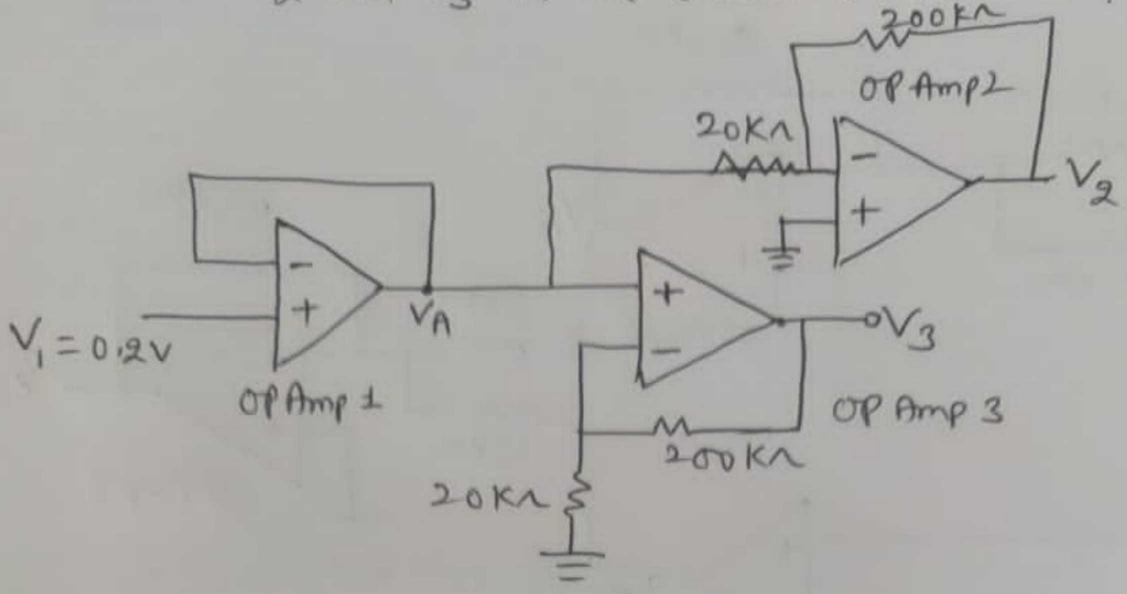
OP Amp 2 is a voltage follower with unity gain

$$\therefore \; V_B = -20mv$$

OP Amp3 is again a summing Amplifier in inverting mode

$$V_o = -\left(\frac{300}{30}\right)V_A - \left(\frac{300}{15}\right)V_B$$

4 Calculate V_2 and V_3 in the circuit shown below:



OP Amp 1 is a voltage follower with unity gain

$$\therefore \quad V_A = V_1 = 0.2V$$

OP Amp 2 is in inverting mode

$$\therefore \quad V_2 = -\left(\frac{200\,k\Omega}{20\,k\Omega}\right) \times V_A$$

Also OP Amp 3 is in non inverting mode

$$\therefore \quad V_3 = \left(1 + \frac{200}{20}\right) 0.2$$

Circuit for Example 11.6.

Solution: The output voltage is

$$V_o = -\left(\frac{330\,\text{k}\Omega}{33\,\text{k}\Omega}V_1 + \frac{330\,\text{k}\Omega}{10\,\text{k}\Omega}V_2\right) = -(10\,V_1 + 33\,V_2)$$
$$= -[10(50\,\text{mV})\sin(1000t) + 33(10\,\text{mV})\sin(3000t)]$$
$$= \mathbf{-[0.5\sin(1000t) + 0.33\sin(3000t)]}$$

Voltage Subtraction

Two signals can be subtracted from one another in a number of ways. Figure 11.10 shows two op-amp stages used to provide subtraction of input signals. The resulting output is given by

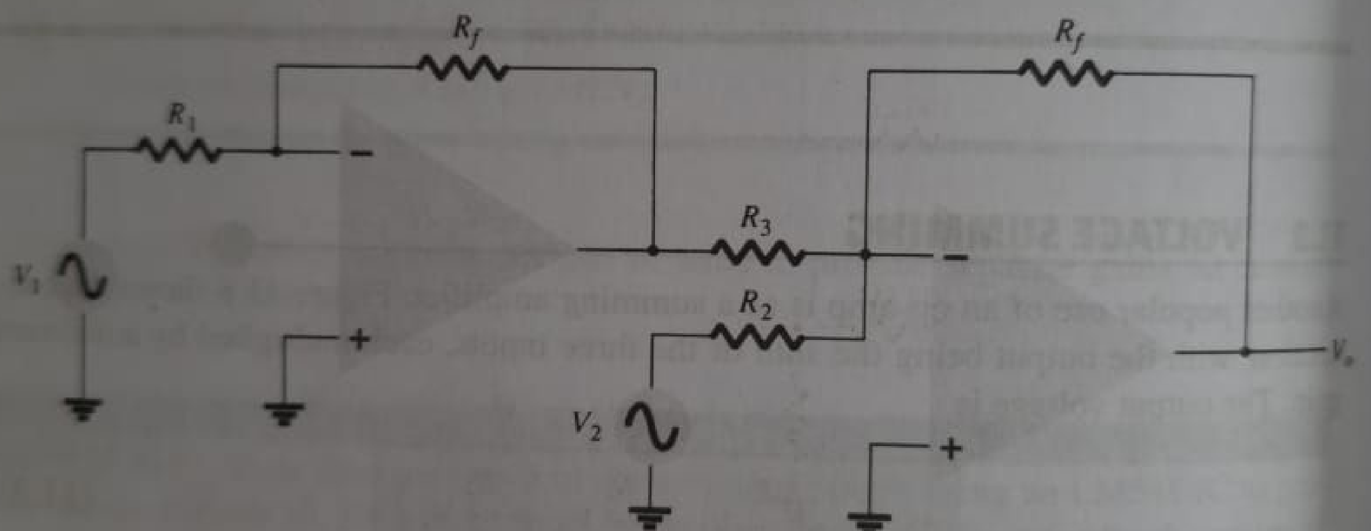


FIG. 11.10
Circuit for subtracting two signals.