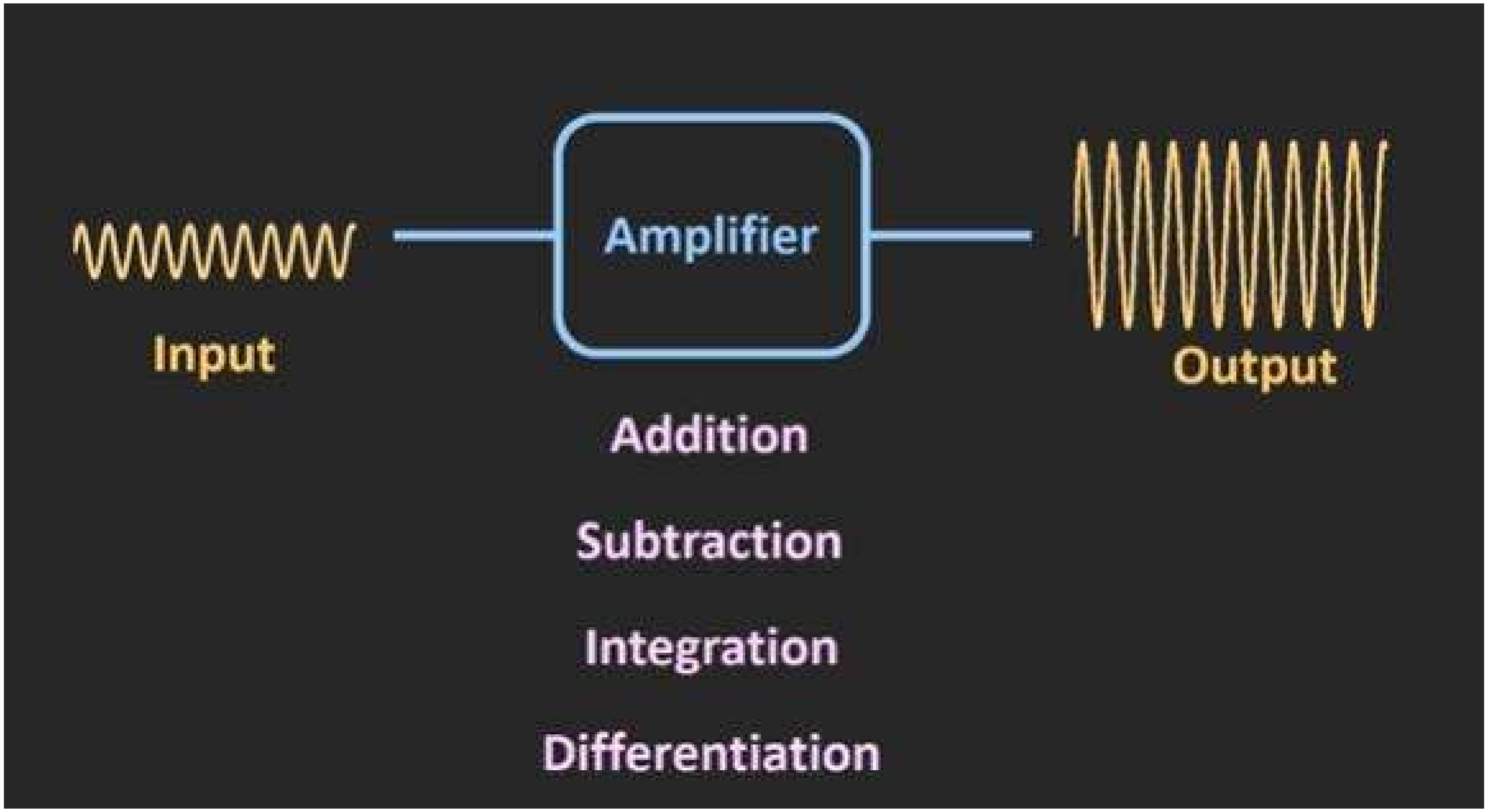
Operational Amplifier (OP-AMP)



Op-Amp?

Operational Amplifier, also known as op-amp, is basically a voltage amplifying device which was originally designed to perform mathematical operations like addition, subtraction, multiplication, division, differentiation and integration.

The ability of the op-amp to perform these mathematical operations is the reason it is called an operational amplifier.

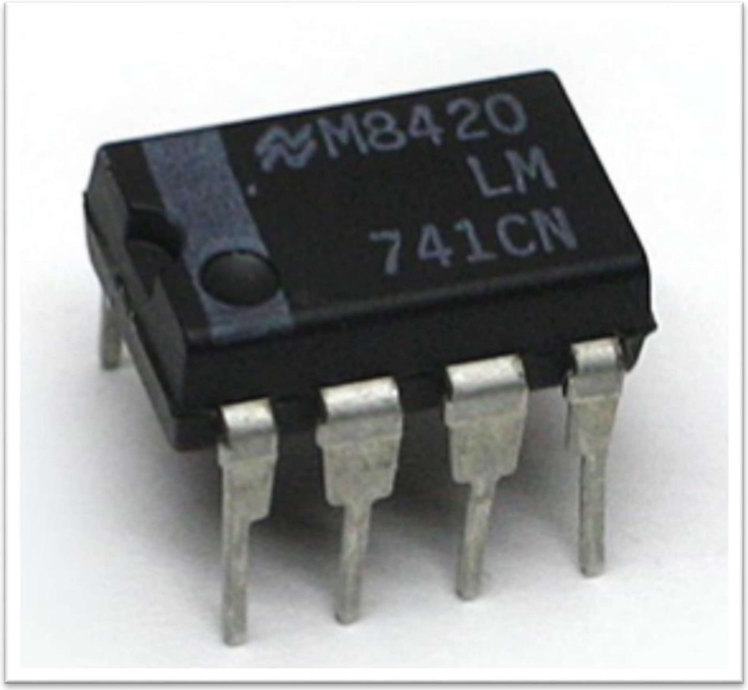


Fig: 741C Op-Amp IC

Op-Amp Circuit

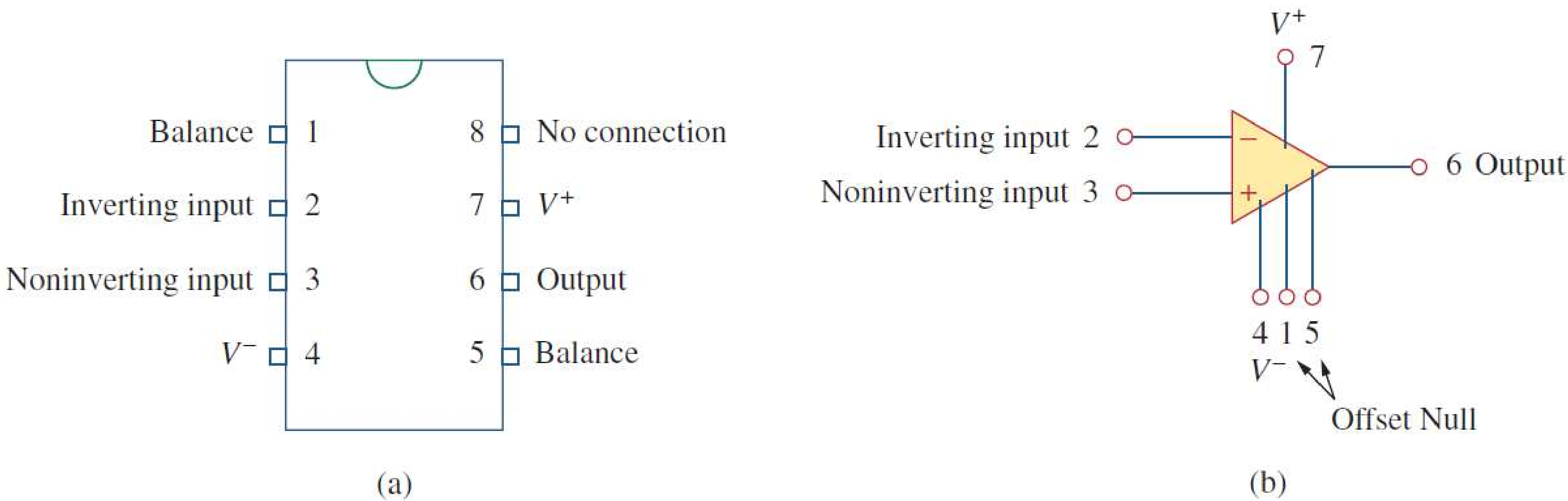


Fig: A typical op amp: (a) pin configuration, (b) circuit symbol.

Op-Amp Circuit

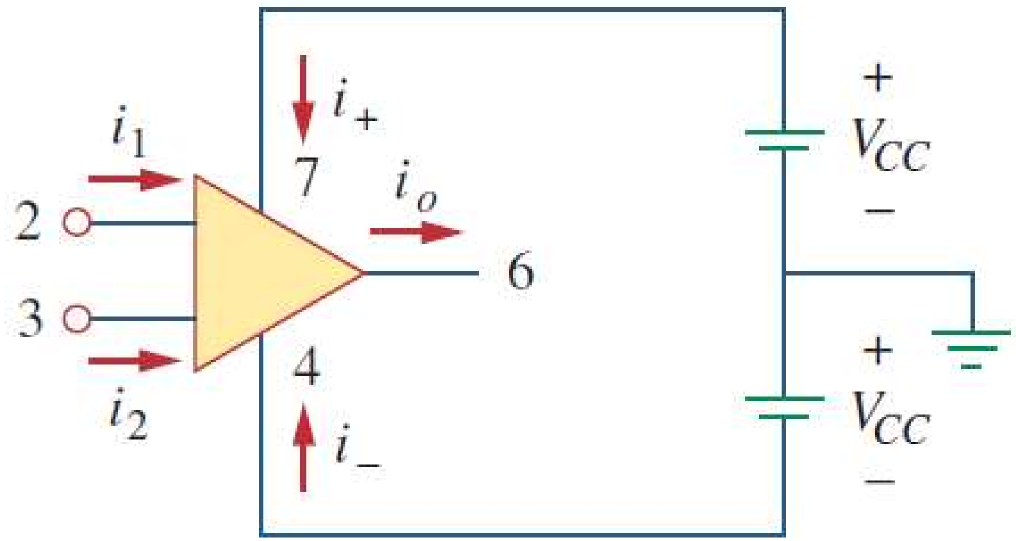


Fig: Powering the op-amp.

How does it work?

Here, v_d is called the differential input voltage. v_d is given by-

$$v_d = v_2 - v_1$$

The op amp senses the difference between the two inputs, multiplies it by the gain A, and causes the resulting voltage to appear at the output. Thus, the output v_o is given by-

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

A is called the **open-loop voltage gain**.

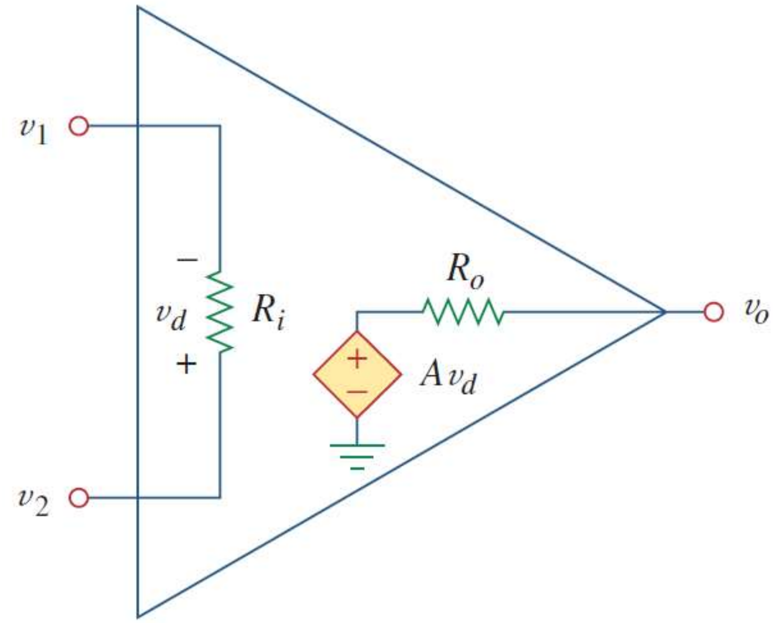


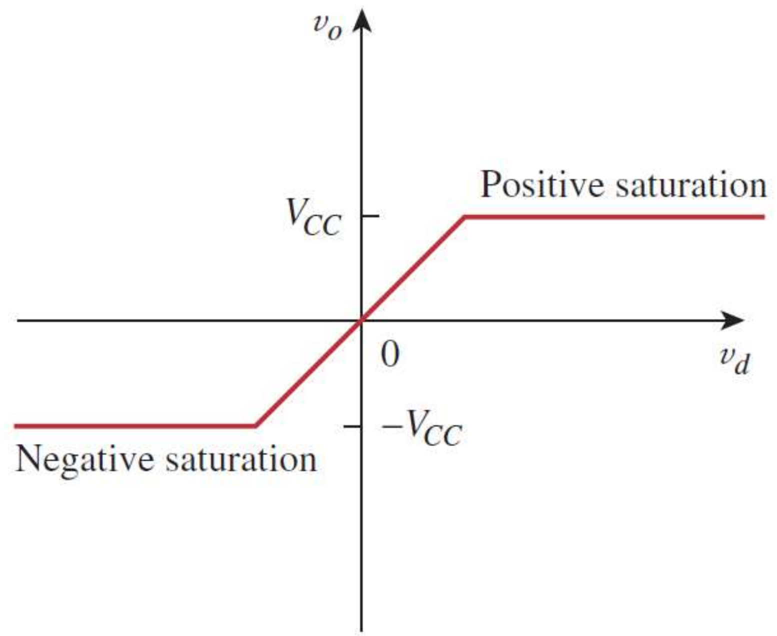
Fig: Equivalent circuit of an op-amp.

Concept of Negative Feedback

Op-amp has a very high open loop gain, A. Typically this value is as high as 10^5. A is called the open-loop voltage gain because it is the gain of the op amp without any external feedback from output to input.

As we can see in the figure, if we operate op-amp in open loop configuration, it goes to saturation very quickly.

We introduce feedback in the op-amp circuit so that we can operate in the linear region depicted in the figure here.



1. Positive saturation, $v_o = V_{CC}$.
2. Linear region, $-V_{CC} \le v_o = Av_d \le V_{CC}$.
3. Negative saturation, $v_o = -V_{CC}$.

Fig: Op amp output voltage v_o as a function of the differential input voltage v_d.

Concept of Negative Feedback

A negative feedback is achieved when the output is fed back to the inverting terminal of the op amp.

For negative feedback circuits, the ratio of the output voltage to the input voltage is called the **closed-loop gain**.

As a result of the negative feedback, it can be shown that the closed-loop gain is almost insensitive to the open-loop gain A of the op-amp. For this reason, op amps are used in circuits with feedback paths.

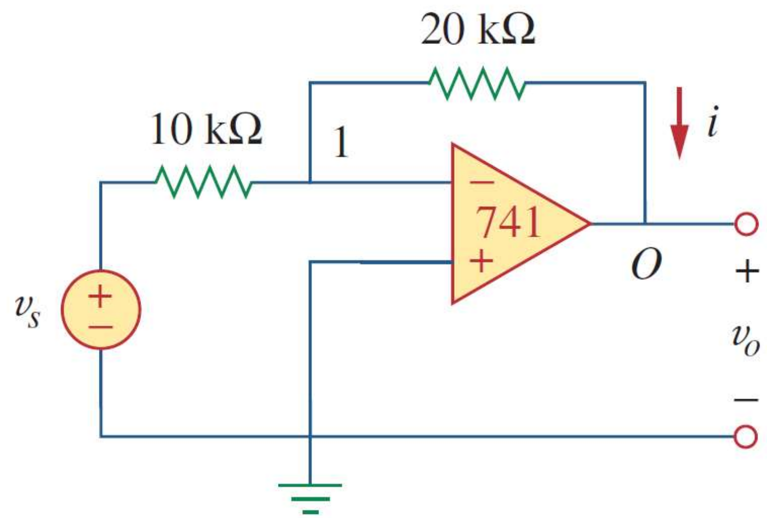


Fig: Example of a op-amp circuit with negative feedback.

Ideal Op-Amp

Ideally op-amp parameters have the following characteristics:

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

Based on these characteristics, there's two important rules for analysis of op-amp circuit-

1. The currents into both input terminals are zero:

$$i_1 = 0 \text{ and } i_2 = 0$$

2. The voltage across the input terminals is zero:

$$v_d = v_2 - v_1 = 0 \quad \text{or} \quad v_2 = v_1$$

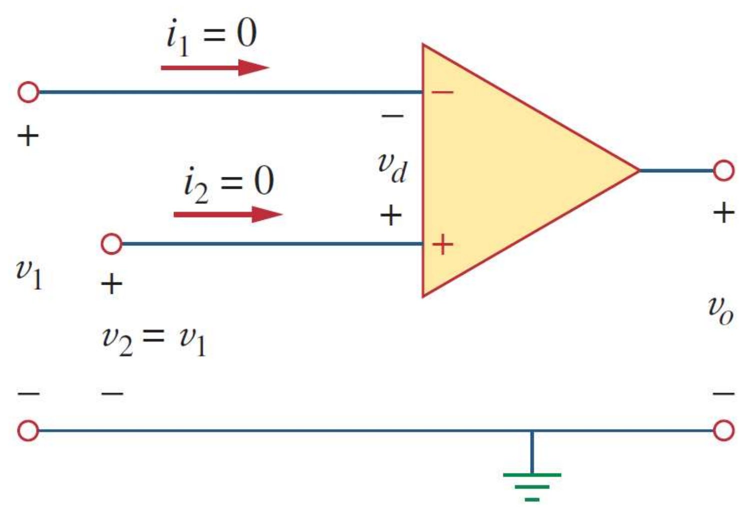


Fig: Ideal op-amp model.

Inverting Amplifier

In this circuit, the noninverting input is grounded, v_i is connected to the inverting input through R_1, and the feedback resistor R_f is connected between the inverting input and output. Applying KCL at node 1,

An inverting amplifier reverses the polarity of the input signal while amplifying it.

$$i_1 = i_2 \quad \Rightarrow \quad \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

But, $v_1 = v_2 = 0$ for an ideal op amp, since the noninverting terminal is grounded. Hence,

$$\frac{v_i}{R_1} = -\frac{v_o}{R_f}$$

or

$$v_o = -\frac{R_f}{R_1} v_i$$

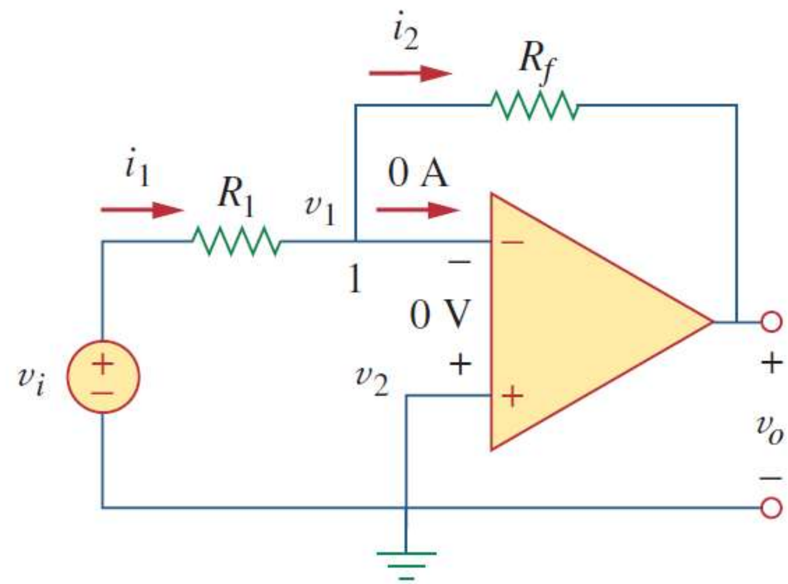


Fig: The inverting amplifier.

Example 5.3

Refer to the op amp in Fig. 5.12. If $v_i = 0.5$ V, calculate: (a) the output voltage v_o, and (b) the current in the 10-kΩ resistor.

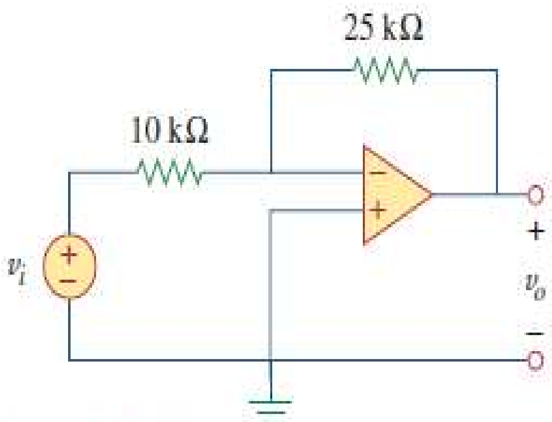


Figure 5.12
For Example 5.3.

Solution:

(a) Using Eq. (5.9),

$$\frac{v_o}{v_i} = -\frac{R_f}{R_1} = -\frac{25}{10} = -2.5$$

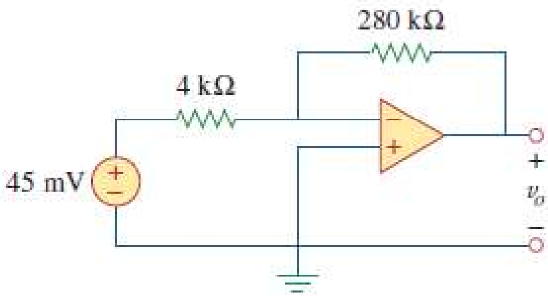
$$v_o = -2.5v_i = -2.5(0.5) = -1.25 \text{ V}$$

(b) The current through the 10-kΩ resistor is

$$i = \frac{v_i - 0}{R_1} = \frac{0.5 - 0}{10 \times 10^3} = 50\ \mu\text{A}$$

Practice Problem 5.3

Find the output of the op amp circuit shown in Fig. 5.13. Calculate the current through the feedback resistor.



Answer: −3.15 V, 26.25 μA.

Example 5.4

Determine v_o in the op amp circuit shown in Fig. 5.14.

Solution:

Applying KCL at node a,

$$\frac{v_a - v_o}{40 \text{ k}\Omega} = \frac{6 - v_a}{20 \text{ k}\Omega}$$

$$v_a - v_o = 12 - 2v_a \quad \Rightarrow \quad v_o = 3v_a - 12$$

But $v_a = v_b = 2$ V for an ideal op amp, because of the zero voltage drop across the input terminals of the op amp. Hence,

$$v_o = 6 - 12 = -6 \text{ V}$$

Notice that if $v_b = 0 = v_a$, then $v_o = -12$, as expected from Eq. (5.9).

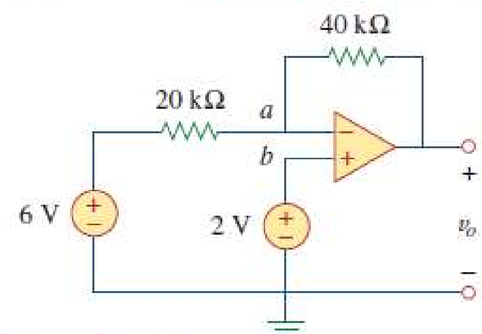


Figure 5.14
For Example 5.4.

Non-inverting Amplifier

Only difference in this circuit from the inverting amplifier is that, the inverting input is grounded and v_i is connected to the non-inverting input. Applying KCL at the inverting terminal gives, A noninverting amplifier is an op amp circuit designed to provide a positive voltage gain.

$$i_1 = i_2 \quad \Rightarrow \quad \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

But, $v_1 = v_2 = v_i$

Hence,

$$\frac{-v_i}{R_1} = \frac{v_i - v_o}{R_f}$$

or

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

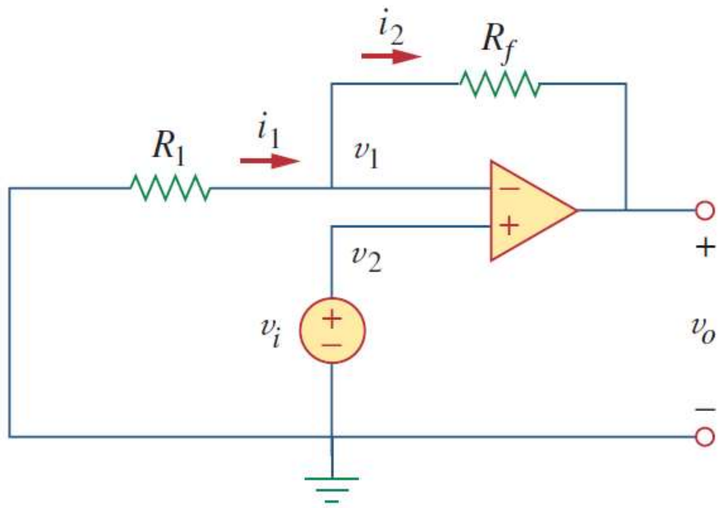
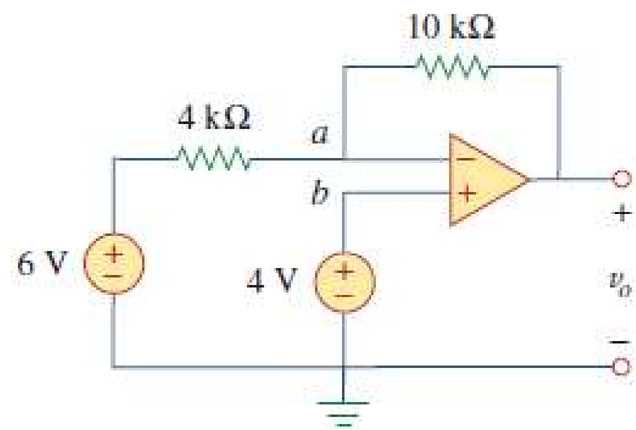


Fig: The non-inverting amplifier.

Example 5.5

For the op amp circuit in Fig. 5.19, calculate the output voltage v_o.



Applying KCL at node a,

$$\frac{6 - v_a}{4} = \frac{v_a - v_o}{10}$$

But $v_a = v_b = 4$, and so

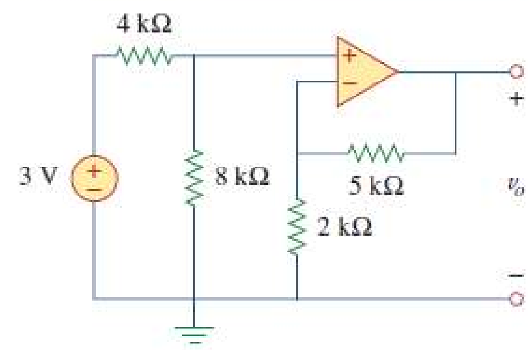
$$\frac{6 - 4}{4} = \frac{4 - v_o}{10} \quad \Rightarrow \quad 5 = 4 - v_o$$

or $v_o = -1$ V, as before.

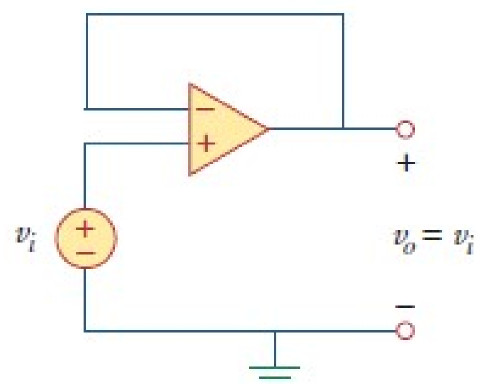
Practice Problem 5.5

Calculate v_o in the circuit of Fig. 5.20.

Answer: 7 V.



The voltage follower



Notice that if feedback resistor $R_f = 0$ (short circuit) or $R_1 = \infty$ (open circuit) or both, the gain becomes 1. Under these conditions ($R_f = 0$ and $R_1 = \infty$), the circuit in Fig. 5.16 becomes that shown in Fig. 5.17, which is called a *voltage follower* (or *unity gain amplifier*) because the output follows the input. Thus, for a voltage follower

$$\boxed{v_o = v_i} \tag{5.12}$$

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

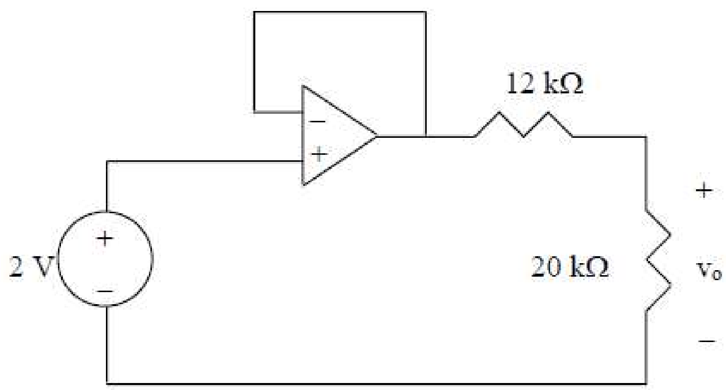


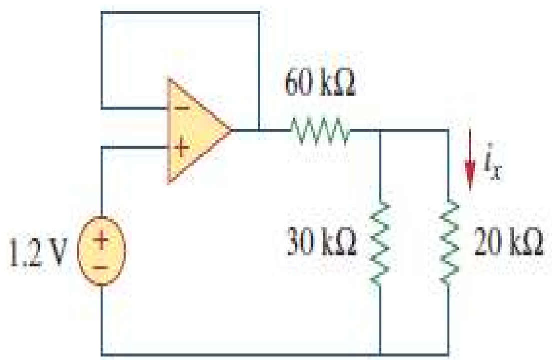
Figure 5.63 For Prob. 5.25.

This is a voltage follower. If v_1 is the output of the op amp,

$$v_1 = 2V$$

$$v_o = \frac{20k}{20k+12k} v_1 = \frac{20}{32}(2) = \underline{1.25\ V}$$

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



The output of the voltage becomes

$$v_o = v_i = 12$$
$$30 \| 20 = 12k\Omega$$

By voltage division,

$$v_x = \frac{12}{12+60}(1.2) = 0.2V$$

$$i_x = \frac{v_x}{20k} = \frac{0.2}{20k} = \underline{\mathbf{10\mu A}}$$

$$p = \frac{v_x^2}{R} = \frac{0.04}{20k} = \underline{\mathbf{2\mu W}}$$

Summing Amplifier

Op-amp can be used to perform addition and subtraction, and that is exactly what old analog computers used to do!

Today we will see op-amp's ability to perform addition. The amplifier designed to do that is called Summing Amplifier.

A summing amplifier is an op amp circuit that combines several inputs and produces an output that is the weighted sum of the inputs.

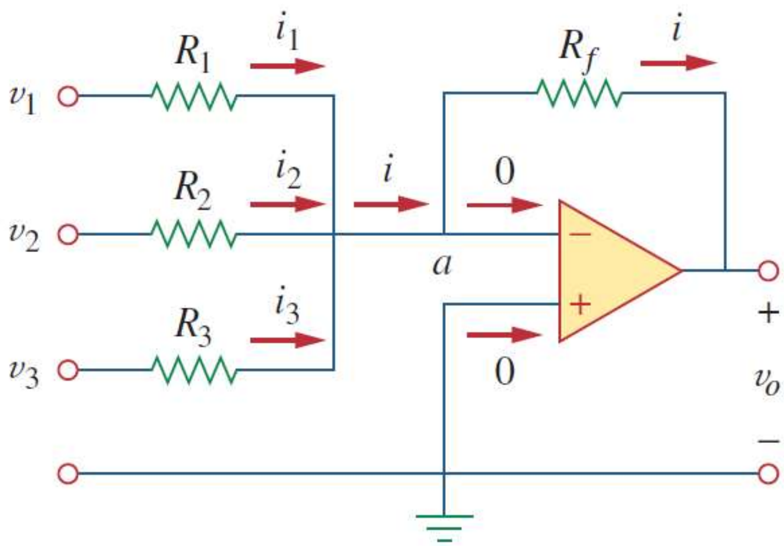


Fig: The summing amplifier.

$$i = i_1 + i_2 + i_3$$

$$i_1 = \frac{v_1 - v_a}{R_1}, \quad i_2 = \frac{v_2 - v_a}{R_2}$$

$$i_3 = \frac{v_3 - v_a}{R_3}, \quad i = \frac{v_a - v_o}{R_f}$$

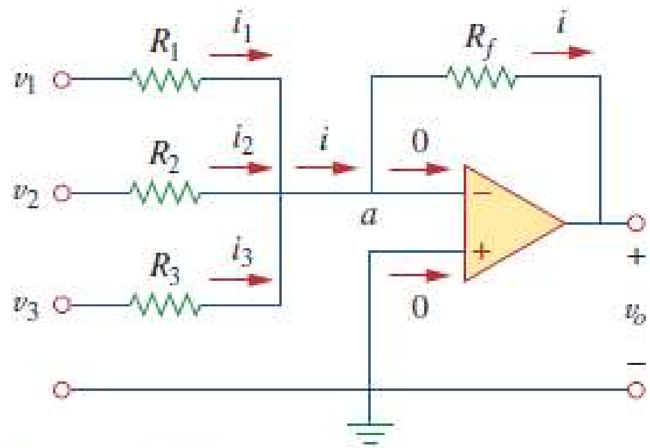


Figure 5.21
The summing amplifier.

$$\boxed{v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)} \qquad \textbf{(5.15)}$$

indicating that the output voltage is a weighted sum of the inputs. For this reason, the circuit in Fig. 5.21 is called a *summer*. Needless to say, the summer can have more than three inputs.

Example 5.6

Calculate v_o and i_o in the op amp circuit in Fig. 5.22.

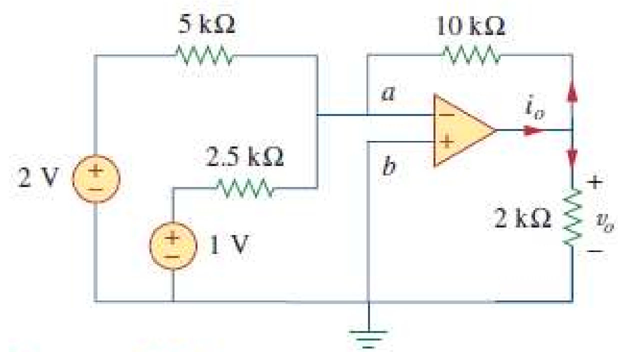


Figure 5.22
For Example 5.6.

Solution:

This is a summer with two inputs. Using Eq. (5.15) gives

$$v_o = -\left[\frac{10}{5}(2) + \frac{10}{2.5}(1)\right] = -(4 + 4) = -8 \text{ V}$$

The current i_o is the sum of the currents through the 10-kΩ and 2-kΩ resistors. Both of these resistors have voltage $v_o = -8$ V across them, since $v_a = v_b = 0$. Hence,

$$i_o = \frac{v_o - 0}{10} + \frac{v_o - 0}{2} \text{ mA} = -0.8 - 4 = -4.8 \text{ mA}$$

Find v_o and i_o in the op amp circuit shown in Fig. 5.23.

Practice Problem 5.6

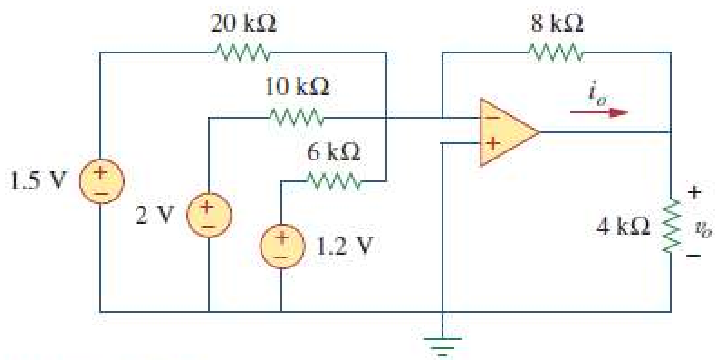


Figure 5.23
For Practice Prob. 5.6.

Answer: −3.8 V, −1.425 mA.

$$V_0 = -\left[\frac{8}{20}(1.5) + \frac{8}{10}(2) + \frac{8}{6}(1.2)\right] = \underline{-3.8\ \mathrm{V}}$$

$$i_0 = \frac{V_0}{8} + \frac{V_0}{4} = -\frac{3.8}{8} - \frac{3.8}{4} = \underline{-1.425\ \mathrm{mA}}$$

Difference Amplifier

A difference amplifier is a device that amplifies the difference between two inputs but rejects any signals common to the two inputs.

The equation that relates output with input in a difference amplifier is given below-

$$v_o = \frac{R_f}{R_1}(v_1 - v_2)$$

Now we will derive this simple equation using its circuit diagram.

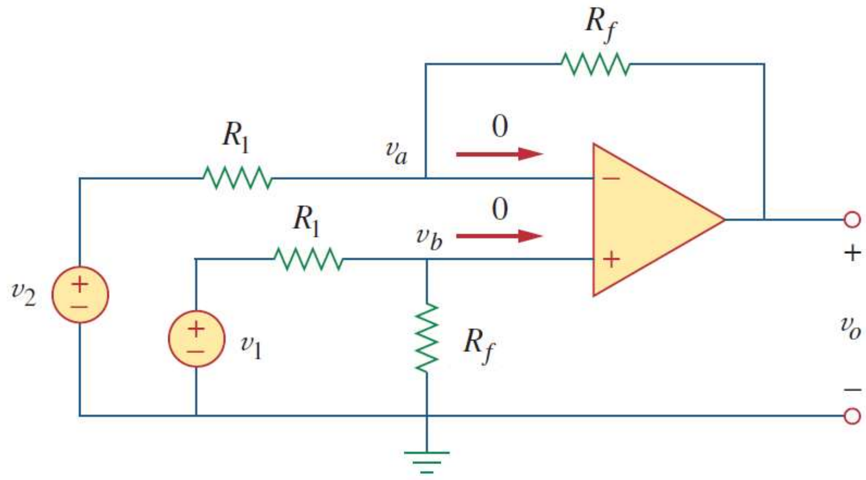


Fig: Difference amplifier.

Step -1

$$v_b = \frac{R_4}{R_3 + R_4} v_2$$

Step -2 Applying KCL at a node

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

Step -3

But $v_a = v_b$. Substituting

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

$$\boxed{v_o = \frac{R_2(1 + R_1/R_2)}{R_1(1 + R_3/R_4)} v_2 - \frac{R_2}{R_1} v_1} \qquad (5.18)$$

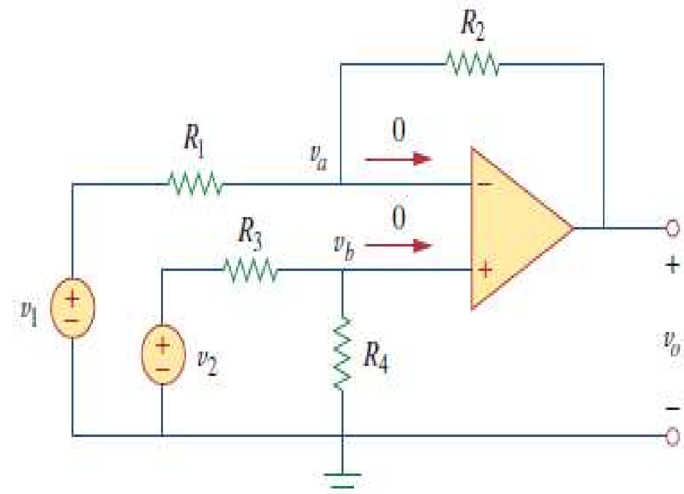


Figure 5.24
Difference amplifier.

Since a difference amplifier must reject a signal common to the two inputs, the amplifier must have the property that $v_o = 0$ when $v_1 = v_2$. This property exists when

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \tag{5.19}$$

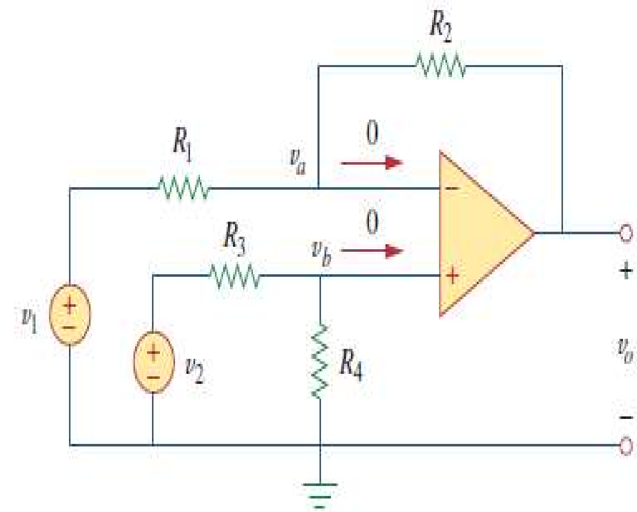


Figure 5.24
Difference amplifier.

Thus, when the op amp circuit is a difference amplifier, Eq. (5.18) becomes

$$v_o = \frac{R_2}{R_1}(v_2 - v_1) \tag{5.20}$$

If $R_2 = R_1$ and $R_3 = R_4$, the difference amplifier becomes a *subtractor*, with the output

$$v_o = v_2 - v_1 \tag{5.21}$$

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

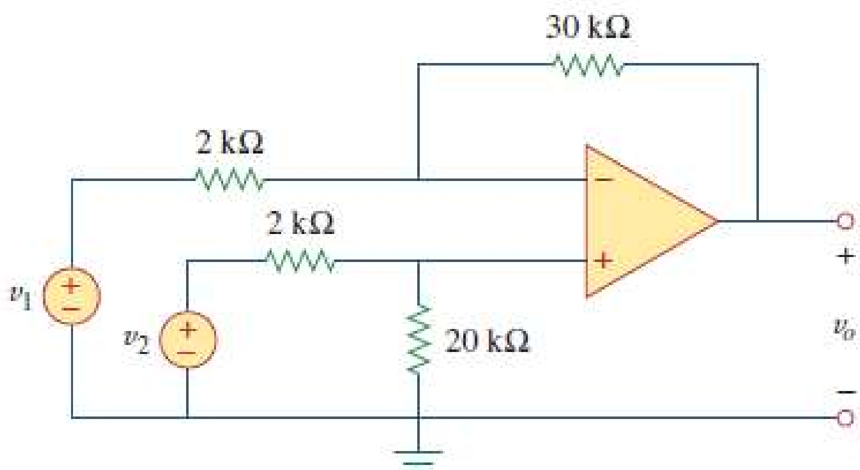


Figure 5.79
For Prob. 5.47.

Using eq. (5.18), $R_1 = 2k\Omega$, $R_2 = 30k\Omega$, $R_3 = 2k\Omega$, $R_4 = 20k\Omega$

$$V_o = \frac{30(1+2/30)}{2(1+2/20)} V_2 - \frac{30}{2} V_1 = \frac{32}{2.2}(2) - 15(1) = \underline{14.09\text{ V}}$$

Example 5.9

Find v_o and i_o in the circuit in Fig. 5.29.

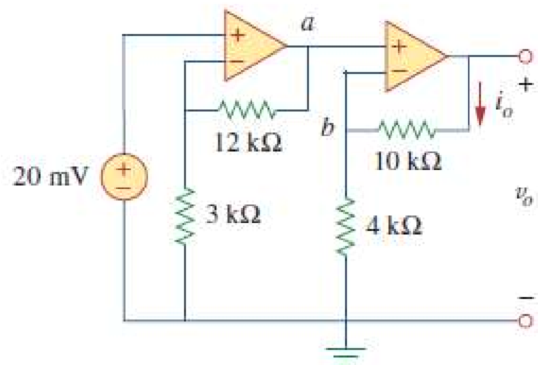


Figure 5.29
For Example 5.9.

Solution:

This circuit consists of two noninverting amplifiers cascaded. At the output of the first op amp,

$$v_a = \left(1 + \frac{12}{3}\right)(20) = 100 \text{ mV}$$

At the output of the second op amp,

$$v_o = \left(1 + \frac{10}{4}\right)v_a = (1 + 2.5)100 = 350 \text{ mV}$$

The required current i_o is the current through the 10-kΩ resistor.

$$i_o = \frac{v_o - v_b}{10} \text{ mA}$$

But $v_b = v_a = 100$ mV. Hence,

$$i_o = \frac{(350 - 100) \times 10^{-3}}{10 \times 10^3} = 25\ \mu\text{A}$$

Practice Problem 5.9

Determine v_o and i_o in the op amp circuit in Fig. 5.30.

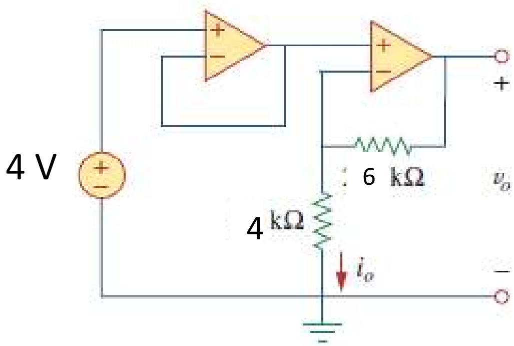


Figure 5.30
For Practice Prob. 5.9.

Answer: .

$$v_a = 4V$$

For the noninverting amplifier,

$$v_0 = \left(1 + \frac{6}{4}\right) v_a = (1 + 1.5)\,(4) = \underline{\mathbf{10V}}$$

$$i_0 = \frac{v_b}{4}\,\text{mA}$$

But $v_b = v_a = 4$

$$i_0 = \frac{4}{4} = \underline{\mathbf{1mA}}$$

Practice Problem 5.10

If $v_1 = 7$ V and $v_2 = 3.1$ V, find v_o in the op amp circuit of Fig. 5.33.

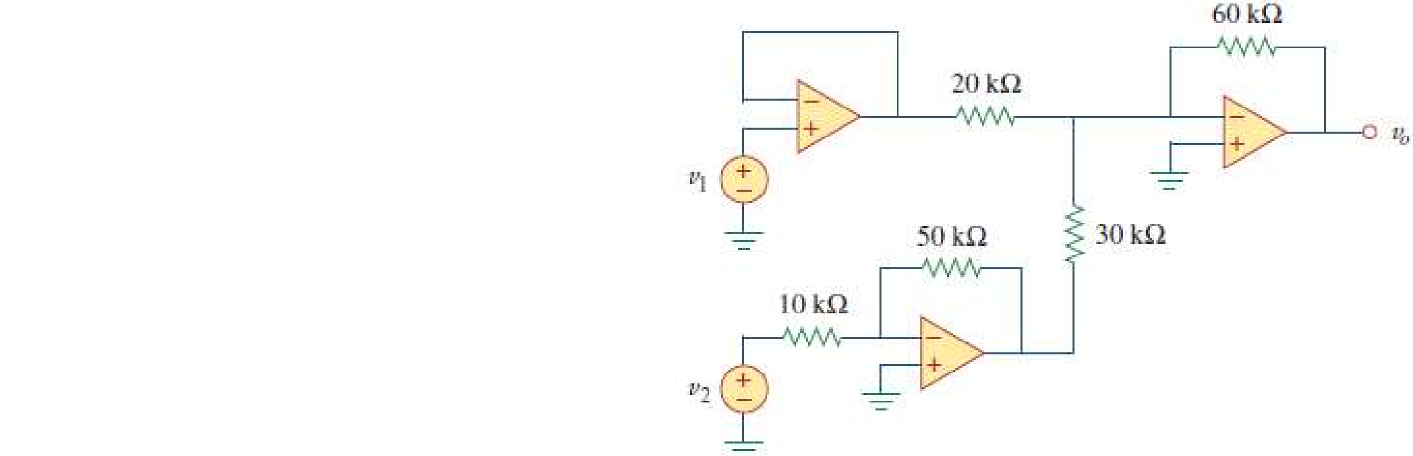
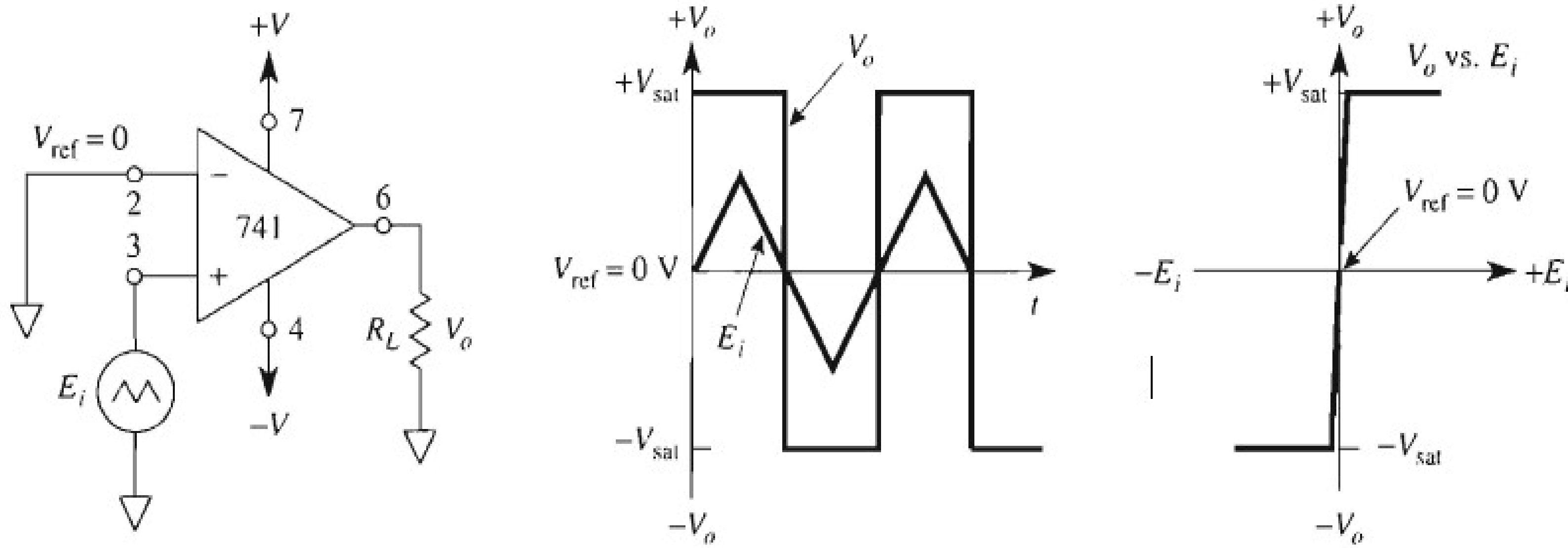


Figure 5.33
For Practice Prob. 5.10.

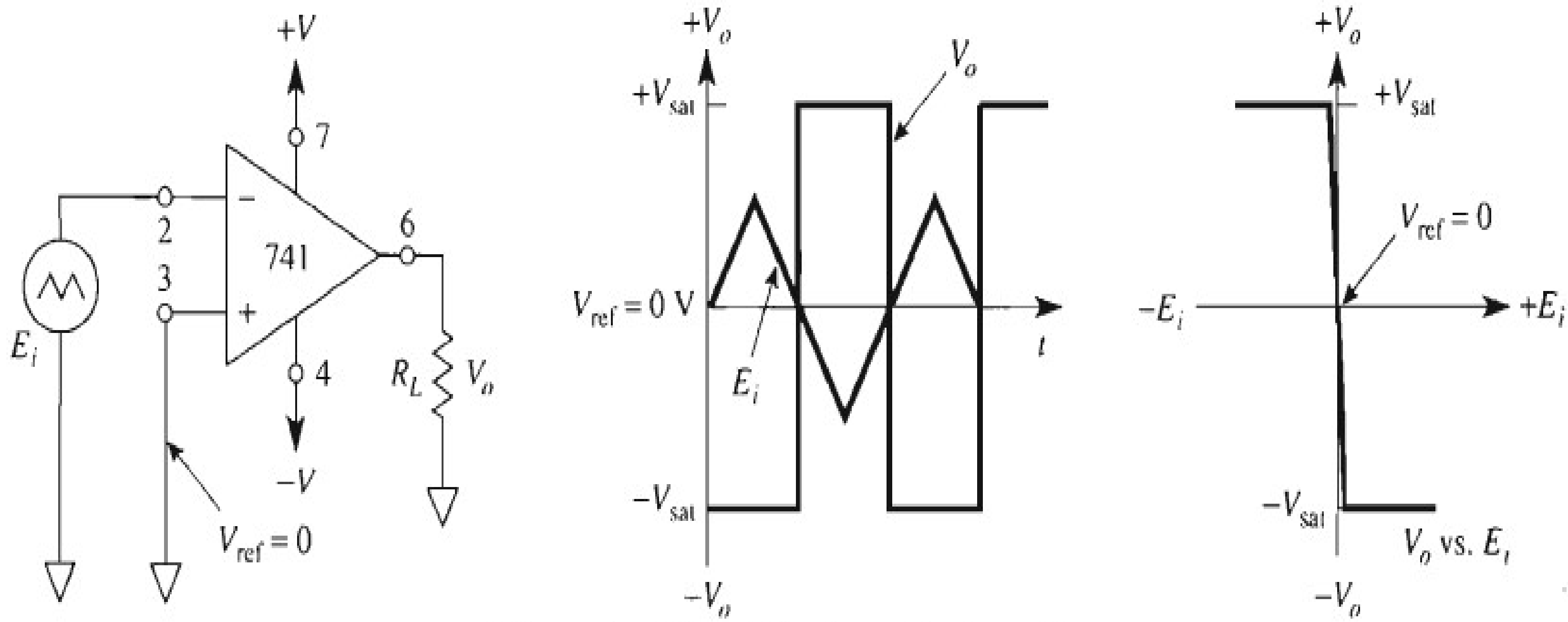
Answer: 10 V.

2-3.1 Noninverting Zero-Crossing Detector

The op amp in Fig. 2-4(a) operates as a comparator. Its (+) input compares voltage E_i with a reference voltage of 0 V ($V_{ref} = 0$ V). When E_i is above V_{ref}, V_o equals $+V_{sat}$. This is because the voltage at the (+) input is more positive than the voltage at the (−) input. Therefore, the sign of E_d in Eq. (2-1) is positive. Consequently, V_o is positive, from Eq. (2-2).



(a) Noninverting: When E_i is above V_{ref}, $V_o = +V_{sat}$.



(b) Inverting: When E_i is above V_{ref}, $V_o = -V_{sat}$.

FIGURE 2-4 Zero-crossing detectors, noninverting in (a) and inverting in (b). If the signal E_i is applied to the (+) input, the circuit action is noninverting. If the signal E_i is applied to the (−) input, the circuit action is inverting.

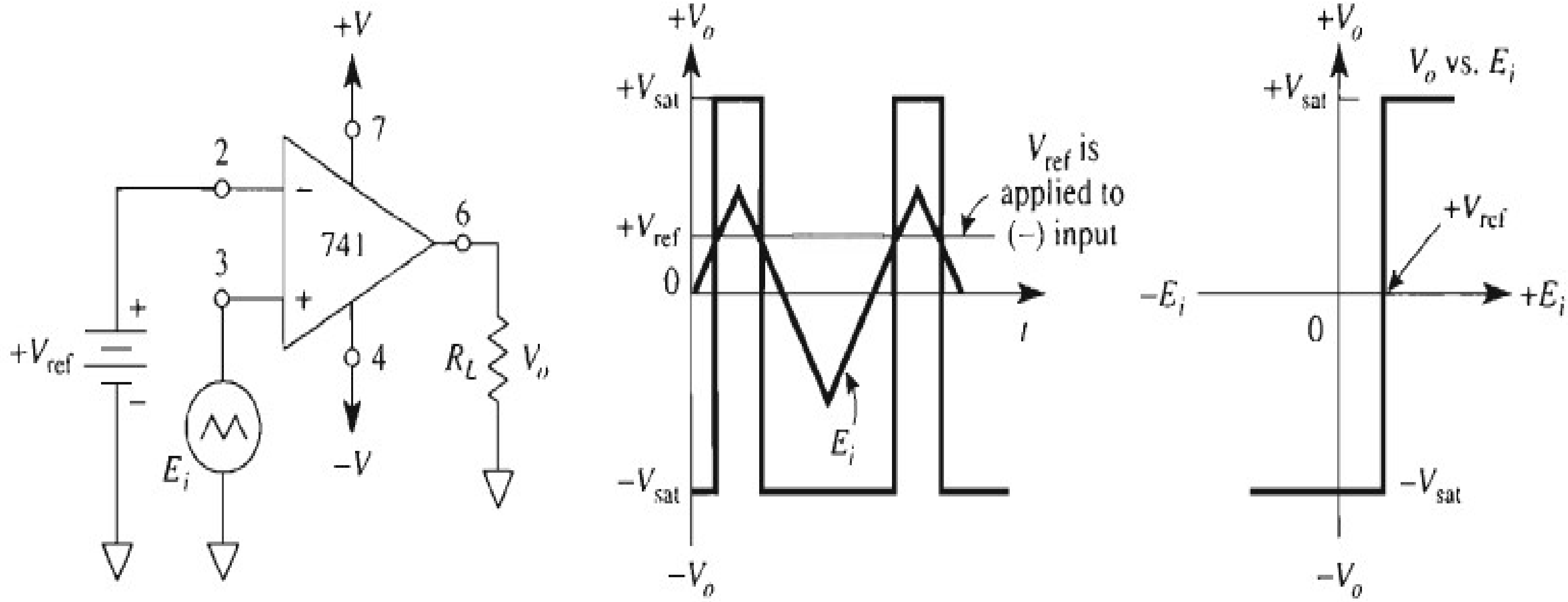
2-3.2 Inverting Zero-Crossing Detector

The op amp's (−) input in Fig. 2-4(b) compares E_i with a reference voltage of 0 V (V_{ref} = 0 V). This circuit is an *inverting zero-crossing detector.* The waveshapes of V_o versus time and V_o versus E_i in Fig. 2-4(b) can be explained by the following summary:

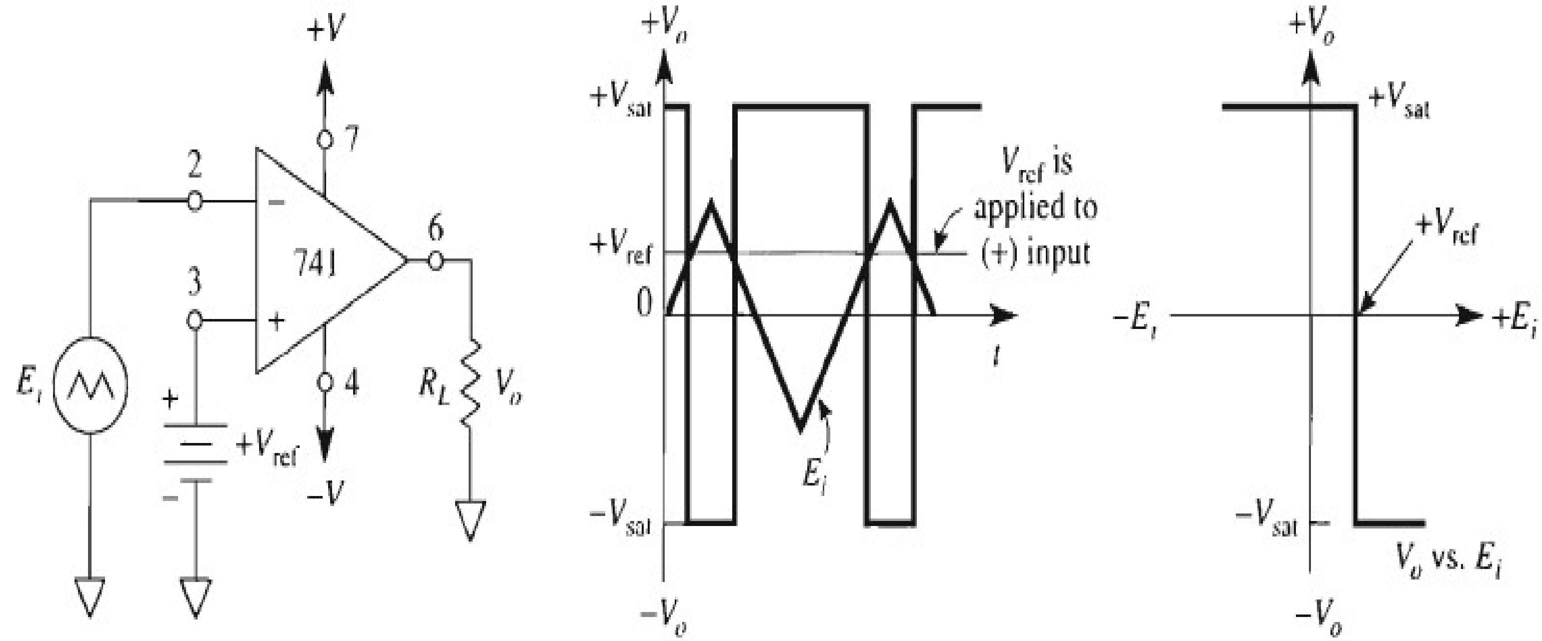
1. If E_i is more positive than V_{ref}, then V_o equals $-V_{sat}$.
2. Where E_i crosses the reference going positive, V_o makes a negative-going transition from $+V_{sat}$ to $-V_{sat}$.

Summary. If the signal or voltage to be monitored is connected to the (+) input, a noninverting comparator results. If the signal or voltage to be monitored is connected to the (−) input, an inverting comparator results.

When $V_o = +V_{sat}$, the signal is *above* (more positive than) V_{ref} in a noninverting comparator and *below* (more negative than) V_{ref} in an inverting comparator.



(a) Noninverting: When E_i is above V_{ref}, $V_o = +V_{sat}$.



(b) Inverting: When E_i is above V_{ref}, $V_o = -V_{sat}$.

FIGURE 2-5 Positive-voltage-level detector, noninverting in (a) and inverting in (b). If the signal E_i is applied to the (+) input, the circuit action is noninverting. If the signal E_i is applied to the (−) input, the circuit action is inverting.