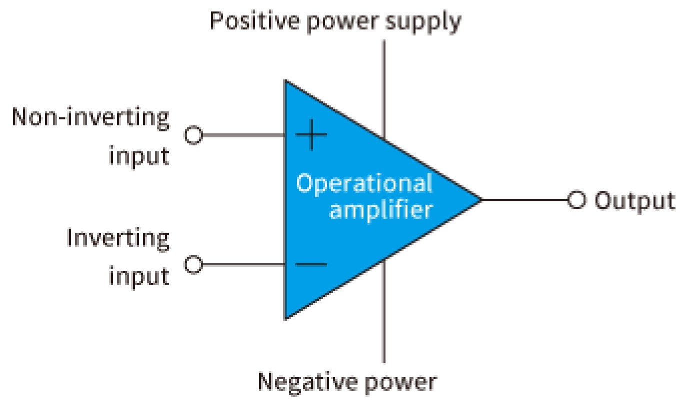
Operational Amplifier (Op –Amp)

Operational Amplifier: An operational amplifier (op-amp) is an integrated circuit (IC) that amplifies the difference in voltage between two inputs.

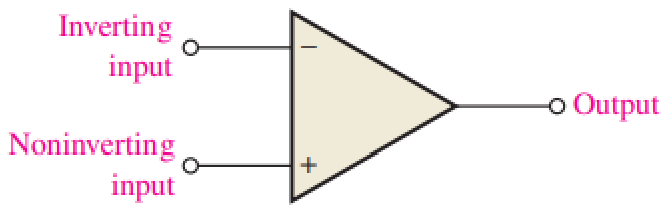
Why Operational?

Operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term operational.

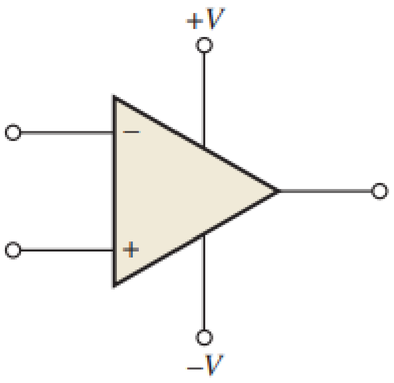
Symbol of Operational Amplifier:



- It has two input terminals, the inverting (-) input and the noninverting (+) input.
- One output terminal.
- Two dc supply voltages, one positive and the other negative.

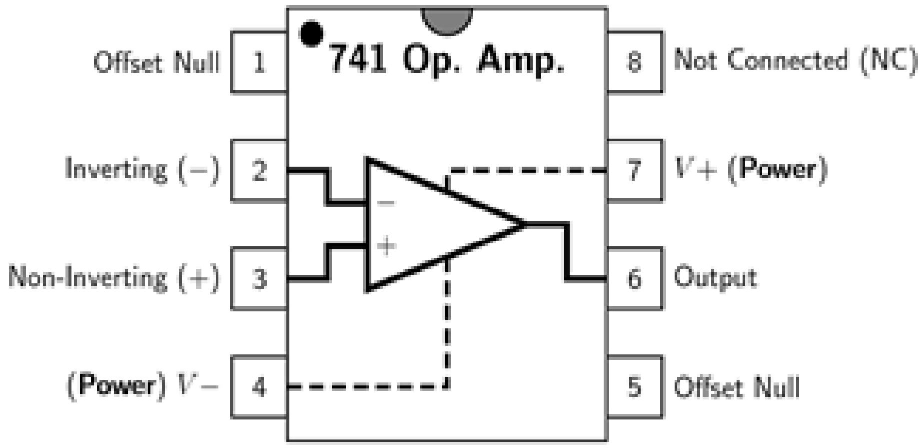


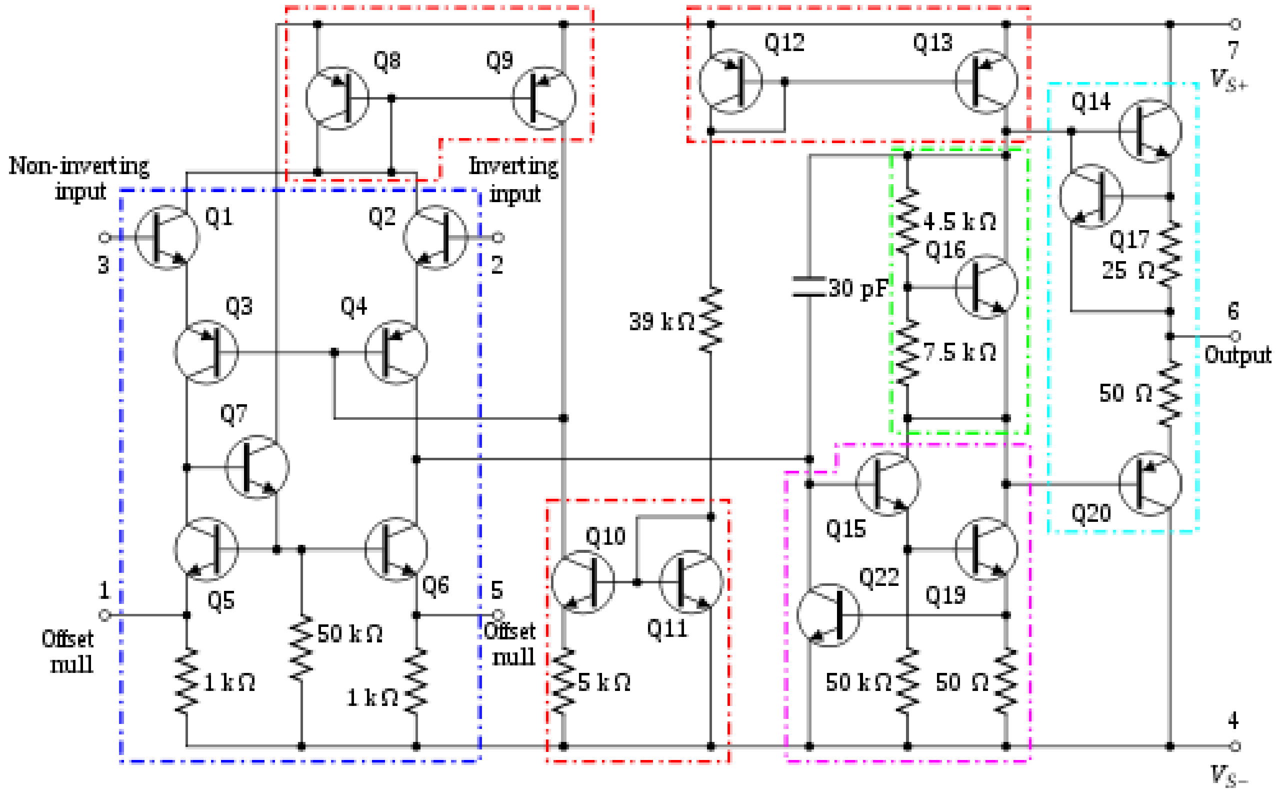
(a) Symbol

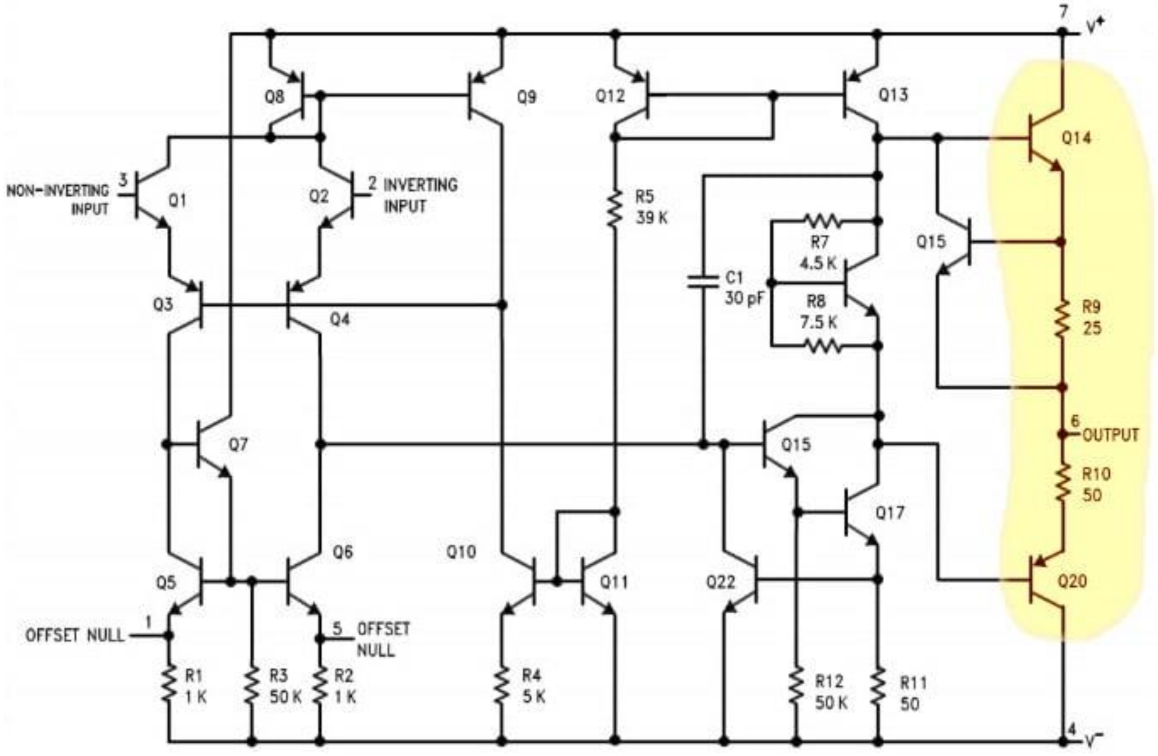


(b) Symbol with dc supply connections

Pin Diagram of Operational Amplifier:

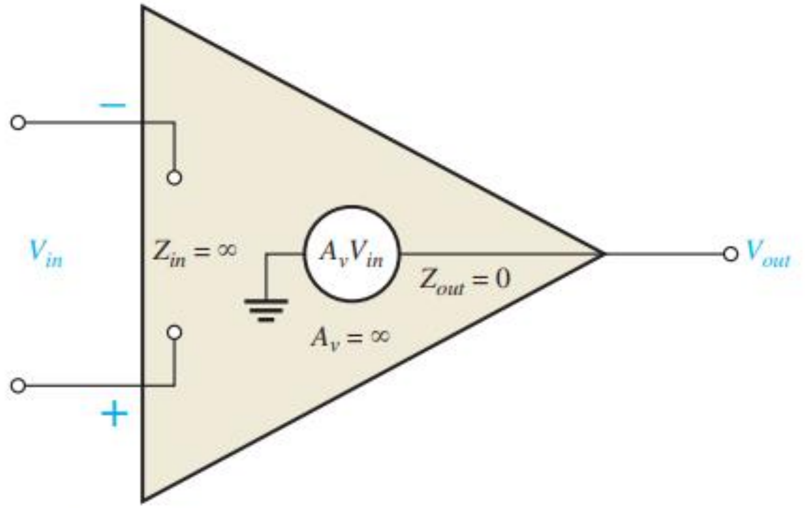



Q8
Q9
Q12
Q13
Q14
Non-inverting input
Inverting input
Q1
Q2
3
2
Q3
Q4
Q7
Q5
Q6
1
Offset null
5
Offset null
50 kΩ
1 kΩ
1 kΩ
39 kΩ
30 pF
4.5 kΩ
Q16
7.5 kΩ
Q17
25 Ω
6
Output
50 Ω
7
Q10
Q11
5 kΩ
Q15
Q22
Q19
Q20
50 kΩ
50 Ω
4


7
V+
Q8
Q9
Q12
Q13
Q14
NON-INVERTING INPUT
3
Q1
Q2
2 INVERTING INPUT
R5 39 K
R7 4.5 K
R8 7.5 K
C1 30 pF
Q15
R9 25
Q3
Q4
Q7
6 OUTPUT
Q15
R10 50
Q17
Q6
Q10
Q5
Q11
Q22
Q20
OFFSET NULL 1
5 OFFSET NULL
R1 1 K
R3 50 K
R2 1 K
R4 5 K
R12 50 K
R11 50
4
V-

Characteristics of Ideal Operational Amplifier:

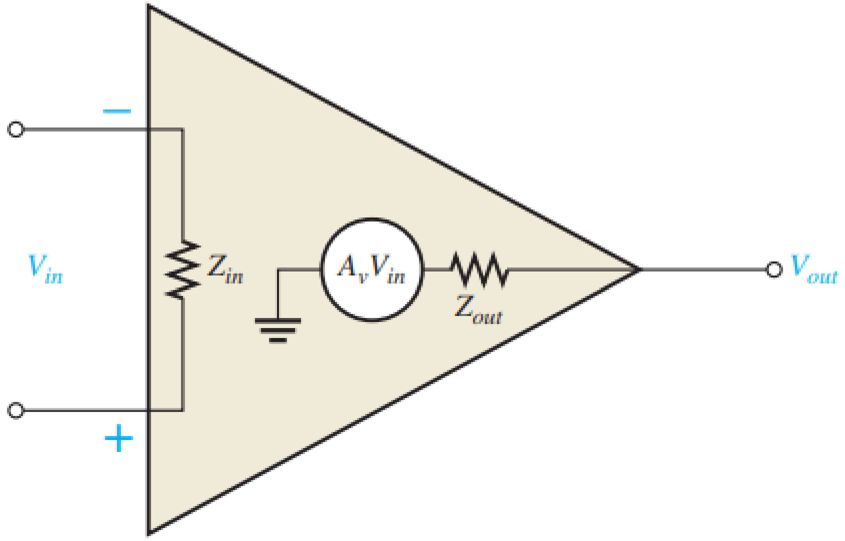
- Op-Amp has an infinite input impedance, Z_{in}=∞ (open).
- Zero output impedance, Z_{out}=0 (Short).
- It has infinite voltage gain, A_v=∞ .
- Infinite bandwidth.



(a) Ideal op-amp representation

Characteristics of Practical Operational Amplifier:

- Op-Amp has very high input impedance.
- Very low output impedance.
- It has very high voltage gain.
- Very high bandwidth.



(b) Practical op-amp representation

Features of Practical Op-Amp:

- Low Cost.
- Flexible.
- Small in size.
- Versatile.

Mathematics of Op-Amp:

- The gain of the Op-Amp is calculated as:

$$V_{out} = G \times (V_+ - V_-)$$

$$G = \frac{V_{out}}{V_+ - V_-}$$

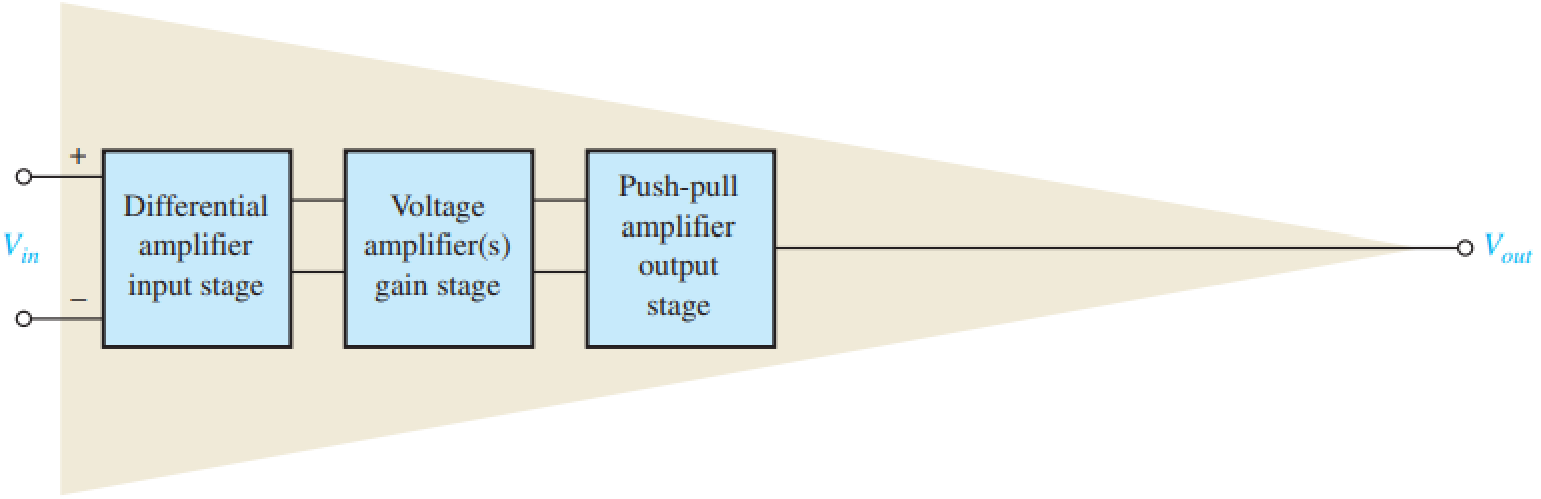
$$V_{in} = V_d = V_+ - V_-$$

- The maximum output is the power supply voltage $(\pm V)$

Internal Block Diagram of an Op-Amp:

A typical op-amp is made up of three types of amplifier circuits:

- A differential amplifier.
- A voltage amplifier.
- A push-pull amplifier.



Basic internal arrangement of an op-amp.

Differential amplifier: Differential amplifier is the input stage for the op-amp. It provides amplification of the difference voltage between the two inputs.

Voltage amplifier: The second stage, i.e. voltage amplifier is usually a class A amplifier that provides additional gain. Some op-amps may have more than one voltage amplifier stage.

Push-pull amplifier: A push-pull class B amplifier is typically used for the output stage.

Input Signals Mode of Op-Amp:

The differential amplifier exhibits three modes of operation based on the type of input signals. These are:

1. Single-ended differential mode.
2. Double-ended differential mode.
3. Common mode.

Single-ended differential mode:

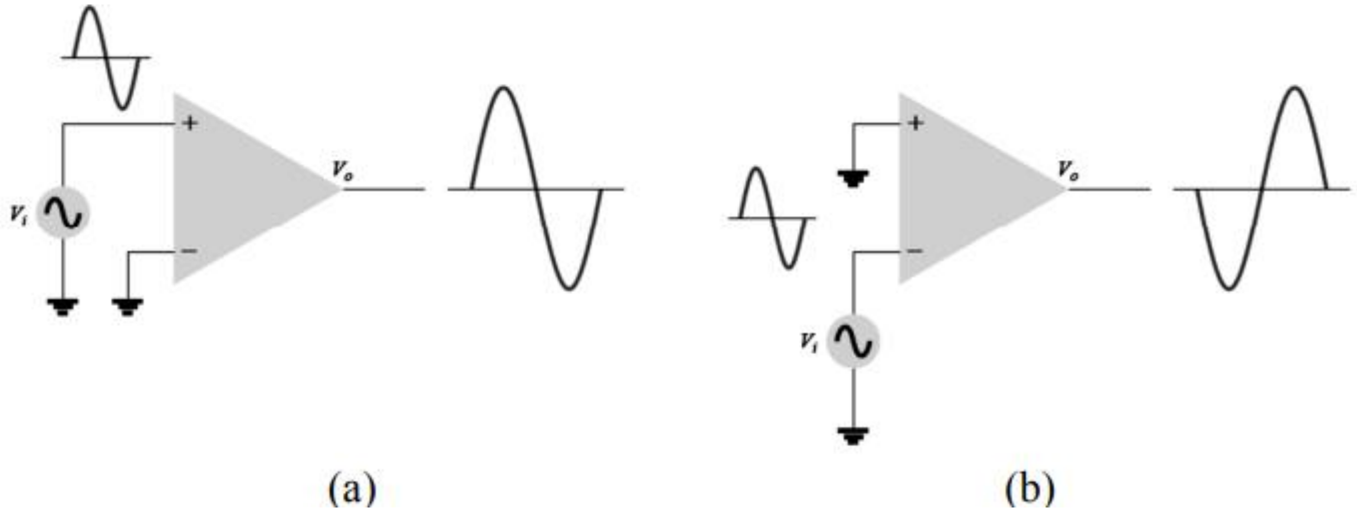


Figure: 1.

- When an op-amp is operated in the single-ended differential mode, one input is grounded and a signal voltage is applied to the other input, as shown in Figure:1.
- In the case where the signal voltage is applied to the noninverting input as in Figure:1(a), a noninverted, amplified signal voltage appears at the output. In the case where the signal is applied to the inverting input with the noninverting input grounded, as in Figure:1(b), an inverted, amplified signal voltage appears at the output.

Double-ended differential mode:

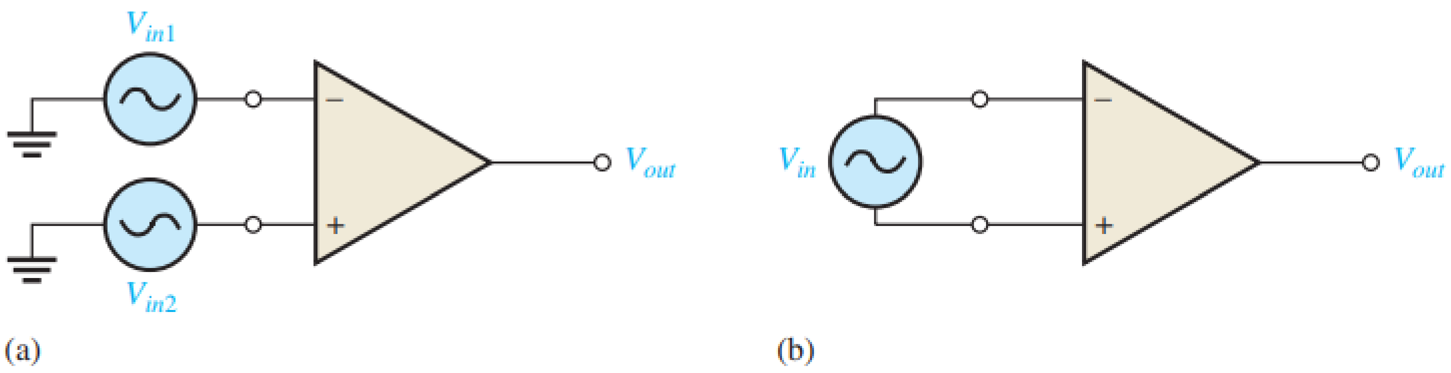


Figure: 2.

- In the double-ended differential mode, two opposite-polarity (out-of-phase) signals are applied to the inputs, as shown in Figure:2(a).
- The amplified difference between the two inputs appears on the output.
- Equivalently, the double-ended differential mode can be represented by a single source connected between the two inputs, as shown in Figure 2(b).

Common mode:

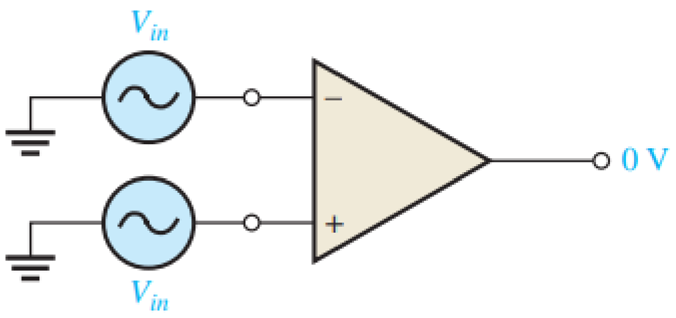


Figure: 3.

In the common mode, two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in Figure:3. When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage.

This action is called common-mode rejection. **Its importance lies in the situation where an unwanted signal appears commonly on both op-amp inputs. Common-mode rejection means that this unwanted signal will not appear on the output and distort the desired signal. Common-mode signals (noise) generally are the result of the pick-up of radiated energy on the input lines, from adjacent lines, the 60 Hz power line, or other sources.

Open Loop Gain : The open-loop voltage gain, A_{ol}, of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components. The open-loop voltage gain is set entirely by the internal design. Open-loop voltage gain can range up to 200,000 (106 dB) and is not a well-controlled parameter. Datasheets often refer to the open-loop voltage gain as the large-signal voltage gain.

$$Open\ loop\ Gain : A_{ol} = \frac{V_o}{V_{in}}$$

$$\text{Or, } A_{ol} = \frac{V_o}{V_+ - V_-}$$

Common Mode Rejection Ratio :

- ❖Desired signals can appear on only one input or with opposite polarities on both input lines. These desired signals are amplified and appear on the output.
- ❖Unwanted signals (noise) appearing with the same polarity on both input lines are essentially cancelled by the op-amp and do not appear on the output.

CMRR: The measure of an amplifier's ability to reject common-mode signals is a parameter called the CMRR (common-mode rejection ratio).

Ideally, an op-amp provides a very high gain for differential-mode signals and zero gain for common-mode signals. **Practical op-amps, however, do exhibit a very small common-mode gain (usually much less than 1), while providing a high open-loop differential voltage gain (usually several thousand). **The higher the open-loop gain with respect to the common-mode gain, the better the performance of the op-amp in terms of rejection of common-mode signals.**

CMRR: The ratio of the open-loop differential voltage gain, A_{ol}, to the common-mode gain, A_{cm} is called the common-mode rejection ratio, CMRR.

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}}$$

** A very high value of CMRR means that the open-loop gain, A_{ol}, is high and the common-mode gain, A_{cm} , is low.

***A CMRR of 100,000, for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common-mode).

The CMRR is often expressed in decibels (dB) as :

$$\text{CMRR} = 20 \log \left(\frac{A_{ol}}{A_{cm}}\right)$$

EXAMPLE 12–1 A certain op-amp has an open-loop differential voltage gain of 100,000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibels.

Solution $A_{ol} = 100{,}000$, and $A_{cm} = 0.2$. Therefore,

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} = \frac{100{,}000}{0.2} = \mathbf{500{,}000}$$

Expressed in decibels,

$$\text{CMRR} = 20 \log (500{,}000) = \mathbf{114\ dB}$$

*Related Problem** Determine the CMRR and express it in dB for an op-amp with an open-loop differential voltage gain of 85,000 and a common-mode gain of 0.25.

**Electronic Devices. By- Floyd (9th edition)
Chapter-12
Example 12-1

Some Important Terms in Op-Amp:

Maximum Output Voltage Swing ($V_{O(p-p)}$):

- With no input signal, the output of an op-amp is ideally 0 V. This is called the quiescent output voltage.
- When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{cc}$.
- In practice, however, this ideal can be approached but never reached. varies with the load connected to the op-amp and increases directly with load resistance.
- For example, the Fairchild KA741 datasheet shows a typical $V_{O(p-p)}$ of $\pm$ 13 V for V_{cc}= $\pm$15 V ,when R_L=2 KΩ .$V_{O(p-p)}$ increases to $\pm$14 V when R_L=10 KΩ.

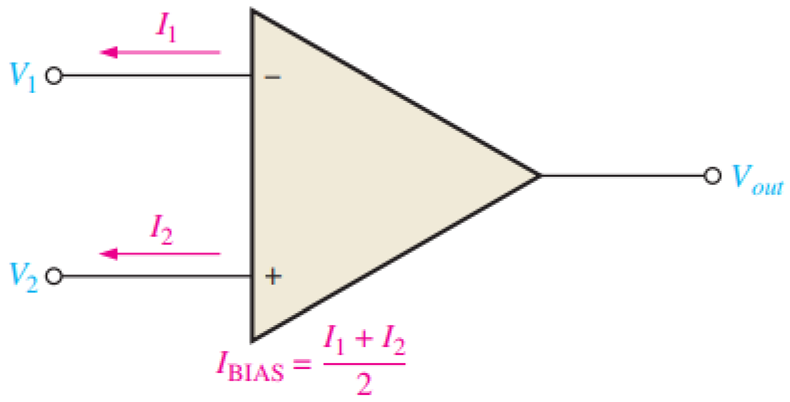
Input Offset Voltage:**

- The ideal op-amp produces zero volts out for zero volts in. In a practical op-amp, however, a small dc voltage, V_{out}(error), appears at the output when no differential input voltage is applied. Its primary cause is a slight mismatch of the base-emitter voltages of the differential amplifier input stage of an op-amp.
- ***As specified on an op-amp datasheet, the input offset voltage, V_{OS}, is the differential dc voltage required between the inputs to force the output to zero volts. Typical values of input offset voltage are in the range of 2 mV or less. In the ideal case, it is 0 V.***
- The input offset voltage drift is a parameter related to V_{OS} that specifies how much change occurs in the input offset voltage for each degree change in temperature. Typical values range anywhere from about per degree Celsius to about per degree Celsius. Usually, an op-amp with a higher nominal value of input offset voltage exhibits a higher drift.

Input Bias Current:

The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage. By definition, the input bias current is the average of both input currents and is calculated as follows:

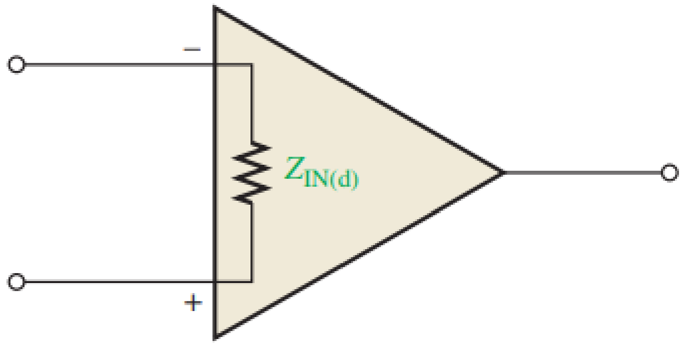
$$I_{\text{BIAS}} = \frac{I_1 + I_2}{2}$$



Input Impedance:

Two basic ways of specifying the input impedance of an op-amp are the differential and the common mode.

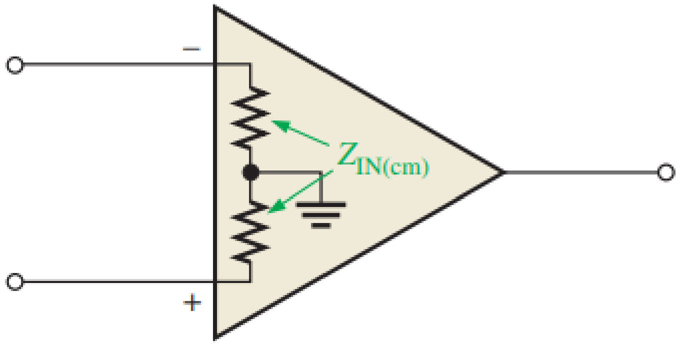
- The differential input impedance is the total resistance between the inverting and the noninverting inputs, as illustrated in Figure:4(a). Differential impedance is measured by determining the change in bias current for a given change in differential input voltage.



(a) Differential input impedance

Figure:4(a)

- The common-mode input impedance is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage. It is depicted in Figure:4(b).



(b) Common-mode input impedance

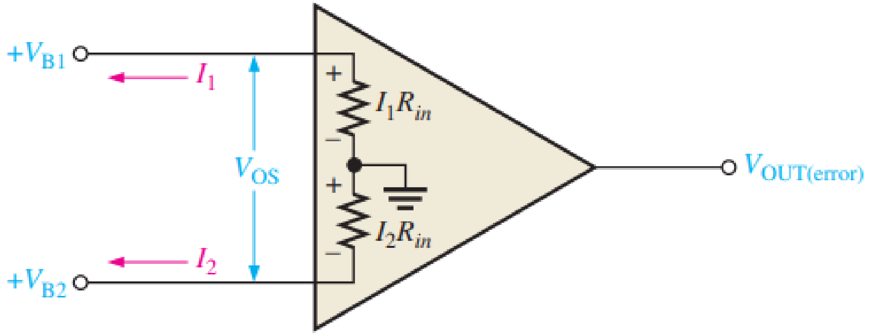
Figure:4(b)

Input Offset Current Ideally, the two input bias currents are equal, and thus their difference is zero. In a practical op-amp, however, the bias currents are not exactly equal.

The *input offset current,* I_{OS}, is the difference of the input bias currents, expressed as an absolute value.

$$\boldsymbol{I_{OS} = |I_1 - I_2|}$$

Actual magnitudes of offset current are usually at least an order of magnitude (ten times) less than the bias current. In many applications, the offset current can be neglected. However, high-gain, high-input impedance amplifiers should have as little I_{OS} as possible because the difference in currents through large input resistances develops a substantial offset voltage, as shown in Figure 12–9.



The offset voltage developed by the input offset current is

$$V_{OS} = I_1R_{in} - I_2R_{in} = (I_1 - I_2)R_{in}$$

$$\boldsymbol{V_{OS} = I_{OS}R_{in}}$$

The error created by I_{OS} is amplified by the gain A_v of the op-amp and appears in the output as

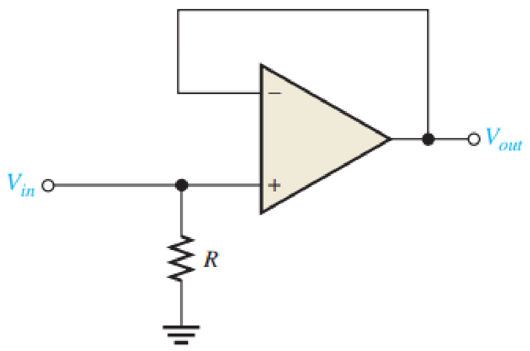
$$\boldsymbol{V_{OUT(error)} = A_vI_{OS}R_{in}}$$

A change in offset current with temperature affects the error voltage. Values of temperature coefficient for the offset current in the range of 0.5 nA per degree Celsius are common.

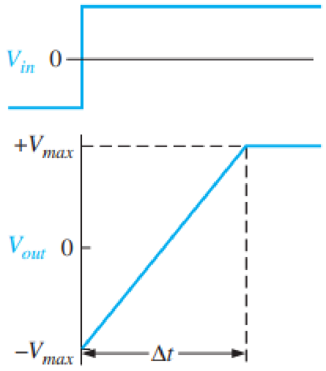
Slew Rate:

Slew Rate The maximum rate of change of the output voltage in response to a step input voltage is the **slew rate** of an op-amp. The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

Slew rate is measured with an op-amp connected as shown in Figure 12–11(a). This particular op-amp connection is a unity-gain, noninverting configuration that will be discussed in Section 12–4. It gives a worst-case (slowest) slew rate. Recall that the high-frequency components of a voltage step are contained in the rising edge and that the upper critical frequency of an amplifier limits its response to a step input. For a step input, the slope on the output is inversely proportional to the upper critical frequency. Slope increases as upper critical frequency decreases.



(a) Test circuit



(b) Step input voltage and the resulting output voltage

FIGURE 12–11

Slew-rate measurement.

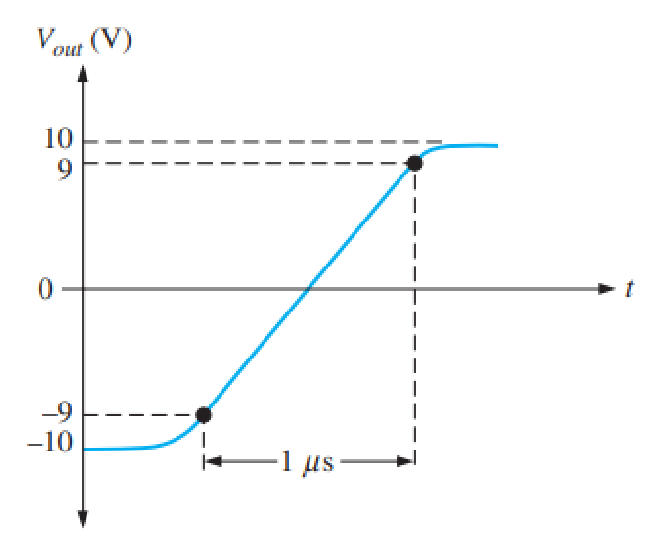
A pulse is applied to the input and the resulting ideal output voltage is indicated in Figure 12–11(b). The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit. A certain time interval, Δt, is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$, once the input step is applied. The slew rate is expressed as

$$\textbf{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

where $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond (V/μs).

EXAMPLE 12–2 The output voltage of a certain op-amp appears as shown in Figure 12–12 in response to a step input. Determine the slew rate.

▶ **FIGURE 12–12**



Solution The output goes from the lower to the upper limit in 1 μs. Since this response is not ideal, the limits are taken at the 90% points, as indicated. So, the upper limit is +9 V and the lower limit is −9 V. The slew rate is

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t} = \frac{+9\text{ V} - (-9\text{ V})}{1\ \mu\text{s}} = \mathbf{18\ V/\mu s}$$

Related Problem When a pulse is applied to an op-amp, the output voltage goes from −8 V to +7 V in 0.75 μs. What is the slew rate?

Negative feedback:

Negative feedback is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.

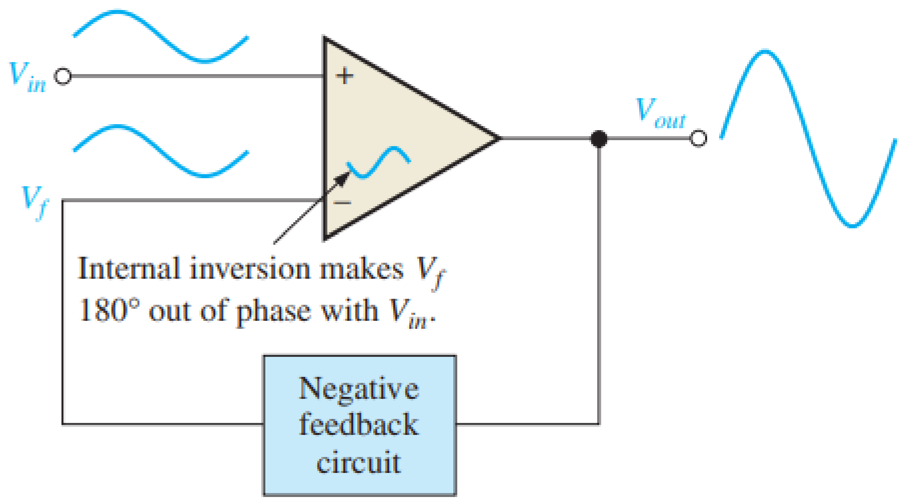


Figure: Illustration of Negative Feedback.

The inverting input effectively makes the feedback signal 180° out of phase with the input signal.

Why Use Negative Feedback?

- With negative feedback, the closed loop voltage gain (Acl) can be reduced and controlled so that the op-amp can function as a linear amplifier.

Negative feedback takes a portion of the output and applies it back out of phase with the input, creating an effective reduction in gain

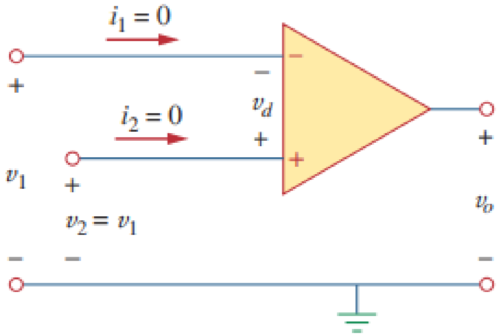
- In addition to providing a controlled, stable voltage gain, negative feedback also provides for control of the input and output impedances and amplifier bandwidth.

Negative feedback is used to stabilize the gain and increase frequency response.

**The usefulness of an op-amp operated without negative feedback is generally limited to comparator applications.

Op-Amp : with and without negative feedback

	VOLTAGE GAIN	INPUT *Z*	OUTPUT *Z*	BANDWIDTH
Without negative feedback	A_{ol} is too high for linear amplifier applications	Relatively high (see Table 12–1)	Relatively low	Relatively narrow (because the gain is so high)
With negative feedback	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider



Two important characteristics of the ideal op amp are:

1. The currents into both input terminals are zero:

$$\boxed{i_1 = 0, \qquad i_2 = 0}$$

This is due to infinite input resistance. An infinite resistance between the input terminals implies that an open circuit exists there and current cannot enter the op amp. But the output current is not necessarily zero.

2. The voltage across the input terminals is equal to zero; i.e.,

$$v_d = v_2 - v_1 = 0$$

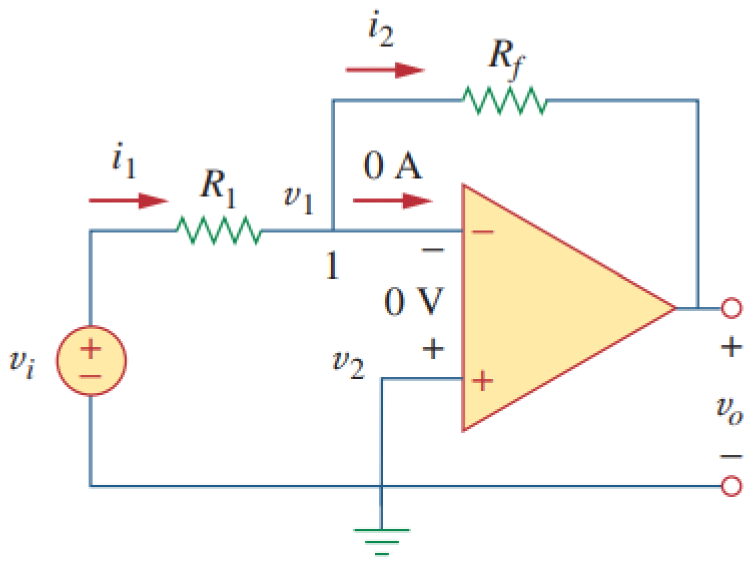
or

$$\boxed{v_1 = v_2}$$

Thus, an ideal op amp has zero current into its two input terminals and the voltage between the two input terminals is equal to zero.

Inverting Amplifier:

In this circuit, the noninverting input is grounded, vi is connected to the inverting input through R1, and the feedback resistor Rf is connected between the inverting input and output. Our goal is to obtain the relationship between the input voltage vi and the output voltage vo. Applying KCL at node 1,



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

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

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

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.

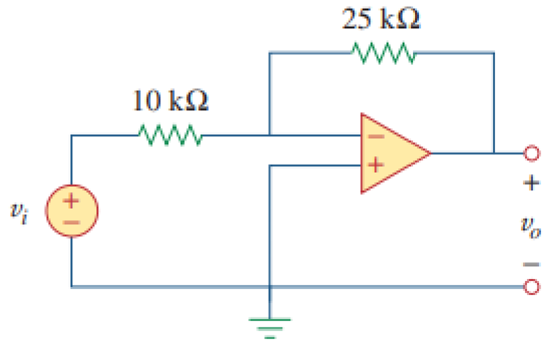


Figure 5.12
For Example 5.3.

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

$$i = \frac{v_i - 0}{} = \frac{0.5 - 0}{} = 50\ \mu\text{A}$$

Practice Problem 5.3

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

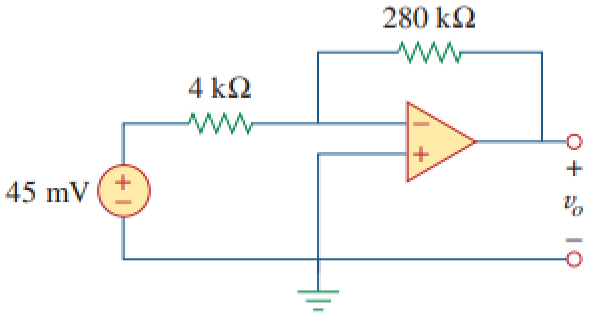


Figure 5.13
For Practice Prob. 5.3.

Answer: -3.15 V, 26.25 μA.

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

Example 5.4

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).

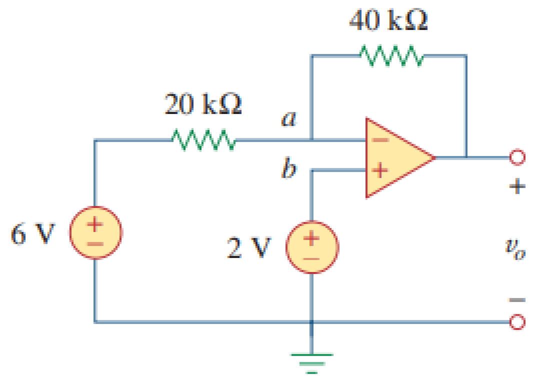
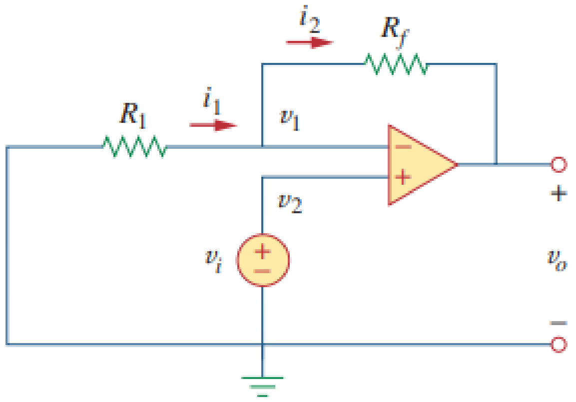


Figure 5.14
For Example 5.4.

Book: Fundamental of Electric Circuits(Chapter 12)
Article:5.4

Non-inverting Amplifier:

In this case, the input voltage v_i is applied directly at the noninverting input terminal, and resistor R_1 is connected between the ground and the inverting terminal. We are interested in the output voltage and the voltage gain. Application of KCL at the inverting terminal gives:



$$i_1 = i_2 \quad \Rightarrow \quad \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f} \qquad \ldots\ldots\ldots\ldots(1)$$

But $v_1 = v_2 = v_i$. Equation (1) becomes

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

or

$$\boxed{v_o = \left(1 + \frac{R_f}{R_1}\right)v_i} \qquad \ldots\ldots\ldots(2)$$

**A noninverting amplifier is an op amp circuit designed to provide a positive voltage gain.

The voltage gain is $A_v = \frac{v_o}{v_i} = 1 + \frac{R_f}{R_1}$, which does not have a negative sign. Thus, the output has the same polarity as the input.

Again we notice that the gain depends only on the external resistors.

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

$$\boxed{v_o = v_i}$$

Such a circuit has a very high input impedance and is therefore useful as an intermediate-stage (or buffer) amplifier to isolate one circuit from another, as portrayed in Fig. 5.18. The voltage follower minimizes interaction between the two stages and eliminates interstage loading.

Example 5.5

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

*(Fundamental of Electrical Engineering(By- Alexender, 5th Edition)

Solution:

We may solve this in two ways: using superposition and using nodal analysis.

METHOD 1 Using superposition, we let

$$v_o = v_{o1} + v_{o2}$$

where v_{o1} is due to the 6-V voltage source, and v_{o2} is due to the 4-V input. To get v_{o1}, we set the 4-V source equal to zero. Under this condition, the circuit becomes an inverter. Hence Eq. (5.9) gives

$$v_{o1} = -\frac{10}{4}(6) = -15 \text{ V}$$

To get v_{o2}, we set the 6-V source equal to zero. The circuit becomes a noninverting amplifier so that Eq. (5.11) applies.

$$v_{o2} = \left(1 + \frac{10}{4}\right)4 = 14 \text{ V}$$

Thus,

$$v_o = v_{o1} + v_{o2} = -15 + 14 = -1 \text{ V}$$

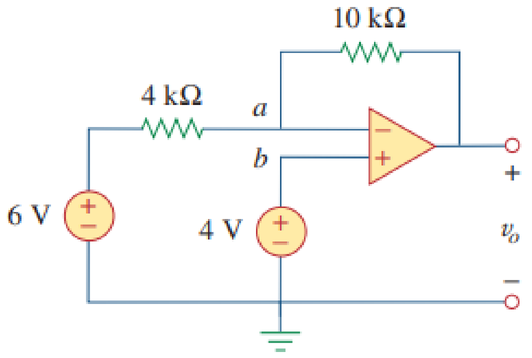


Figure 5.19
For Example 5.5.

METHOD 2 Applying KCL at node a,

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

But $v_a = v_b = 4$, and so

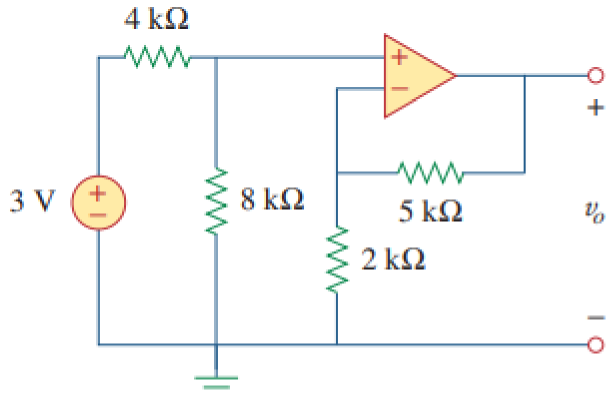
$$\frac{6 - 4}{4} = \frac{4 - v_o}{10} \quad \Rightarrow \quad 5 = 4 - v_o$$

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

Practice Problem 5.5

Calculate v_o in the circuit of Fig. 5.20.

Answer: 7 V.



Voltage Follower:

The **voltage-follower** configuration is a special case of the noninverting amplifier where all of the output voltage is fed back to the inverting (−) input by a straight connection, as shown in Figure 12–19. As you can see, the straight feedback connection has a voltage gain of 1 (which means there is no gain). The closed-loop voltage gain of a noninverting amplifier is $1/B$ as previously derived. Since $B = 1$ for a voltage-follower, the closed-loop voltage gain of the voltage-follower is

$$A_{cl(VF)} = 1$$

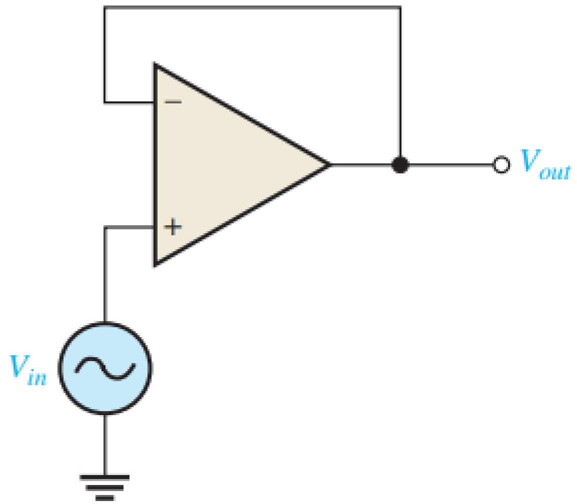


FIGURE 12–19

Op-amp voltage-follower.

The most important features of the voltage-follower configuration are its very high input impedance and its very low output impedance. These features make it a nearly ideal buffer amplifier for interfacing high-impedance sources and low-impedance loads. This is discussed further in Section 12–5.

Impedances of the Noninverting Amplifier:

Input Impedance The input impedance of a noninverting amplifier can be developed with the aid of Figure 12–23. For this analysis, assume a small differential voltage, V_d, exists between the two inputs, as indicated. This means that you cannot assume the op-amp's input impedance to be infinite or the input current to be zero. Express the input voltage as

$$V_{in} = V_d + V_f$$

Substituting BV_{out} for the feedback voltage, V_f, yields

$$V_{in} = V_d + BV_{out}$$

Remember, B is the attenuation of the negative feedback circuit and is equal to $R_i/(R_i + R_f)$.

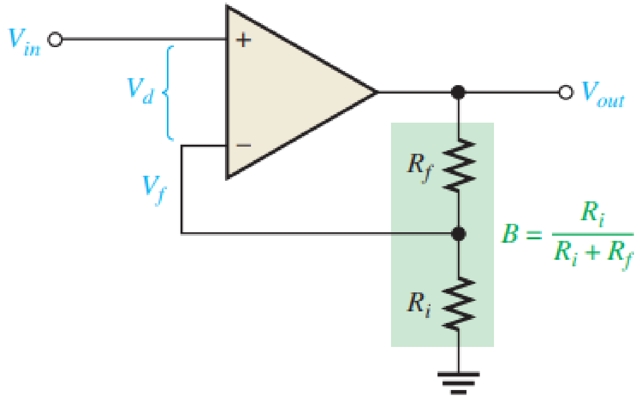


FIGURE 12–23

Since $V_{out} \cong A_{ol}V_d$ (A_{ol} is the open-loop gain of the op-amp),

$$V_{in} = V_d + A_{ol}BV_d = (1 + A_{ol}B)V_d$$

Now substituting $I_{in}Z_{in}$ for V_d,

$$V_{in} = (1 + A_{ol}B)I_{in}Z_{in}$$

where Z_{in} is the open-loop input impedance of the op-amp (without feedback connections).

$$\frac{V_{in}}{I_{in}} = (1 + A_{ol}B)Z_{in}$$

V_{in}/I_{in} is the overall input impedance of a closed-loop noninverting amplifier configuration.

$$\mathbf{Z_{in(NI)} = (1 + A_{ol}B)Z_{in}}$$

This equation shows that the input impedance of the noninverting amplifier configuration with negative feedback is much greater than the internal input impedance of the op-amp itself (without feedback).

Output Impedance An expression for output impedance of a noninverting amplifier can be developed with the aid of Figure 12–24.

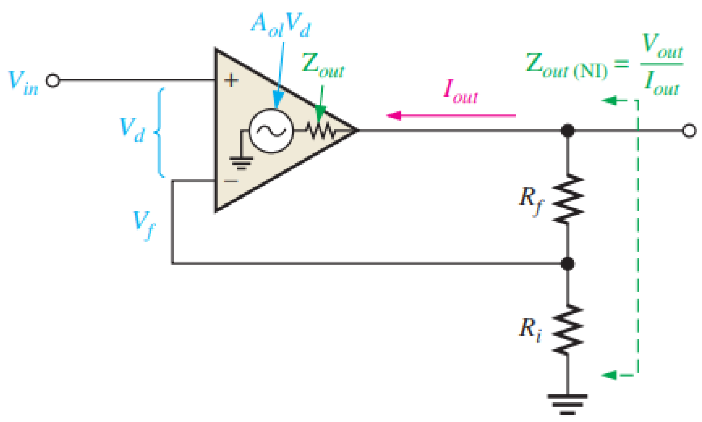


FIGURE 12–24

By applying Kirchhoff's voltage law to the output circuit,

$$V_{out} = A_{ol}V_d - Z_{out}I_{out}$$

The differential input voltage is $V_d = V_{in} - V_f$; therefore, by assuming that $A_{ol}V_d \gg Z_{out}I_{out}$, you can express the output voltage as

$$V_{out} \cong A_{ol}(V_{in} - V_f)$$

Substituting BV_{out} for V_f,

$$V_{out} \cong A_{ol}(V_{in} - BV_{out})$$

Expanding and factoring yields

$$V_{out} \cong A_{ol}V_{in} - A_{ol}BV_{out}$$

$$A_{ol}V_{in} \cong V_{out} + A_{ol}BV_{out} \cong (1 + A_{ol}B)V_{out}$$

Since the output impedance of the noninverting amplifier configuration is $Z_{out(NI)} = V_{out}/I_{out}$, you can substitute $I_{out}Z_{out(NI)}$ for V_{out}; therefore,

$$A_{ol}V_{in} = (1 + A_{ol}B)I_{out}Z_{out(NI)}$$

Dividing both sides of the previous expression by I_{out},

$$\frac{A_{ol}V_{in}}{I_{out}} = (1 + A_{ol}B)Z_{out(NI)}$$

The term on the left is the internal output impedance of the op-amp (Z_{out}) because, without feedback, $A_{ol}V_{in} = V_{out}$. Therefore,

$$Z_{out} = (1 + A_{ol}B)Z_{out(NI)}$$

Thus,

$$\mathbf{Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B}}$$

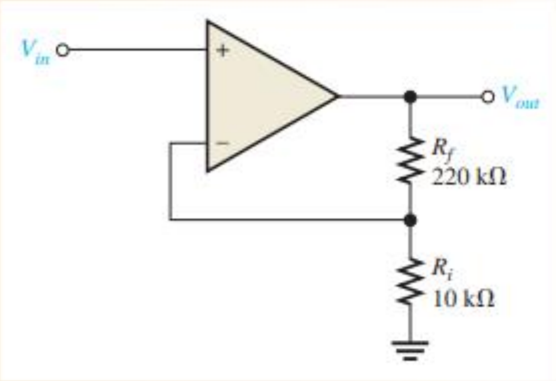
This equation shows that the output impedance of the noninverting amplifier configuration with negative feedback is much less than the internal output impedance, Z_{out}, of the op-amp itself (without feedback) because Z_{out} is divided by the factor $1 + A_{ol}B$.

EXAMPLE 12–5

(a) Determine the input and output impedances of the amplifier in Figure 12–25. The op-amp datasheet gives $Z_{in} = 2\ \text{M}\Omega$, $Z_{out} = 75\ \Omega$, and $A_{ol} = 200{,}000$.

(b) Find the closed-loop voltage gain.

FIGURE 12–25



Solution

(a) The attenuation, B, of the feedback circuit is

$$B = \frac{R_i}{R_i + R_f} = \frac{10\ \text{k}\Omega}{230\ \text{k}\Omega} = 0.0435$$

$$Z_{in(NI)} = (1 + A_{ol}B)Z_{in} = [1 + (200{,}000)(0.0435)](2\ \text{M}\Omega)$$
$$= (1 + 8700)(2\ \text{M}\Omega) = \mathbf{17.4\ G\Omega}$$

This is such a large number that, for all practical purposes, it can be assumed to be infinite as in the ideal case.

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75\ \Omega}{1 + 8700} = \mathbf{8.6\ m\Omega}$$

This is such a small number that, for all practical purposes, it can be assumed to be zero as in the ideal case.

(b) $A_{cl(NI)} = 1 + \dfrac{R_f}{R_i} = 1 + \dfrac{220\ \text{k}\Omega}{10\ \text{k}\Omega} = \mathbf{23.0}$

- Try by yourselves:
  - Impedances of the Inverting Amplifier.
  - Impedances of the voltage follower circuit.

Solve the problems from exercise:
5.9, 5.10, 5.11, 5.18, 5.37, 5.39


Thank
you