TEC 201 - Basic Electronics Engineering

Unit IV: Operational Amplifiers

Electronics & Communication Engineering

Unit IV: Operational Amplifier (Op-Amp)

INTRODUCTION TO OPERATIONAL AMPLIFIERS

Ideal op-amp,

Inverting and Non-inverting op-amp circuits,

Op-amp applications:

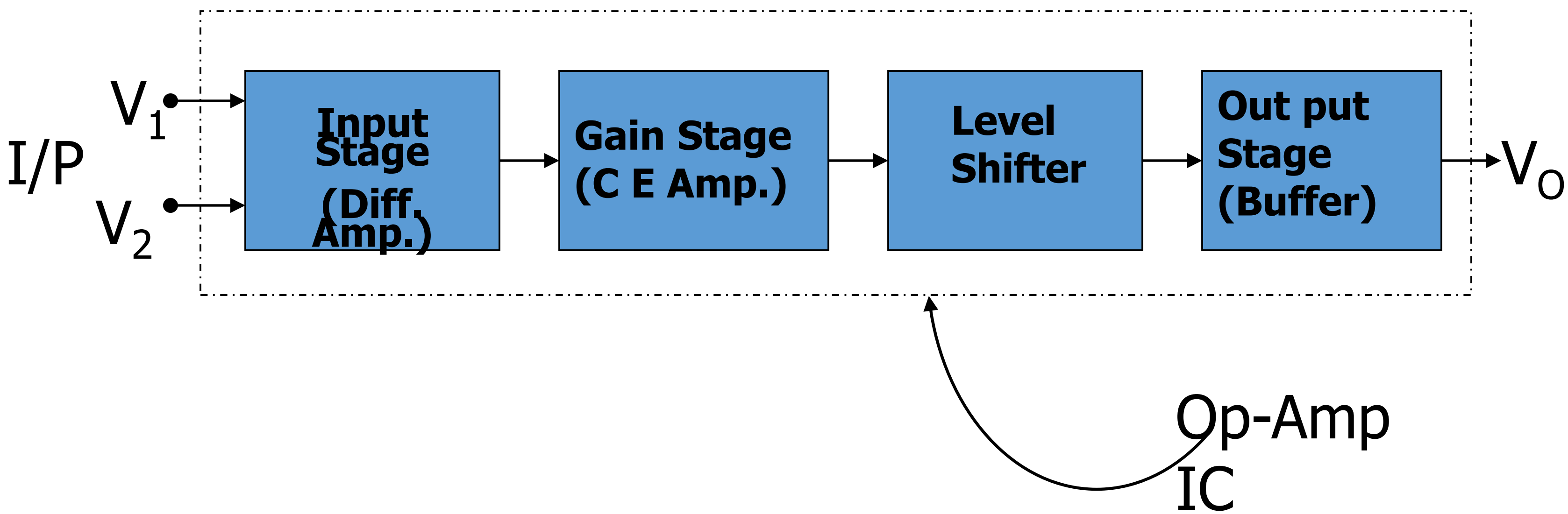
- Voltage follower,
- Addition,
- Subtraction,
- Integration,
- Differentiation.

Basic Block Diagram of Op-Amp

An Op-Amp can be conveniently divided in to four main blocks

1. An Input Stage or Input Diff. Amp.
2. The Gain Stage
3. The Level Translator
4. An Out put Stage

Note:→ It can be used to perform various mathematical operations such as Addition, Subtraction, Integration, Differentiation, log etc.



An IDEAL OP AMP

An ideal op amp has the following characteristics:

1. Infinite open-loop voltage gain, $A_V \approx \infty$.
2. Infinite input resistance, $R_i \approx \infty$.
3. Zero output resistance, $R_o \approx 0$.
4. Infinite CMRR, $\rho = \infty$
5. The output voltage Vo=0; when $V_d = V_2 - V_1 = 0$
6. Change of output with respect to input, slew rate = ∞
7. Change in out put voltage with Temp., $\partial V_o / \partial V_i = 0$

Operational Amplifiers

My belief is that "operational" was used as a descriptor early-on because this form of amplifier can perform operations of

- adding signals
- subtracting signals
- integrating signals, $\int x(t)dt$

The applications of operational amplifiers (shortened to op amp) have grown beyond those listed above.

Operational Amplifiers

At this level of study we will be concerned with *how to use the op amp as a device.*

The internal configuration (design) is beyond basic circuit theory and will be studied in later electronic courses. The complexity is illustrated in the following circuit.

Operational Amplifiers

The op amp is built using VLSI techniques. The circuit diagram of an LM 741 from National Semiconductor is shown below.

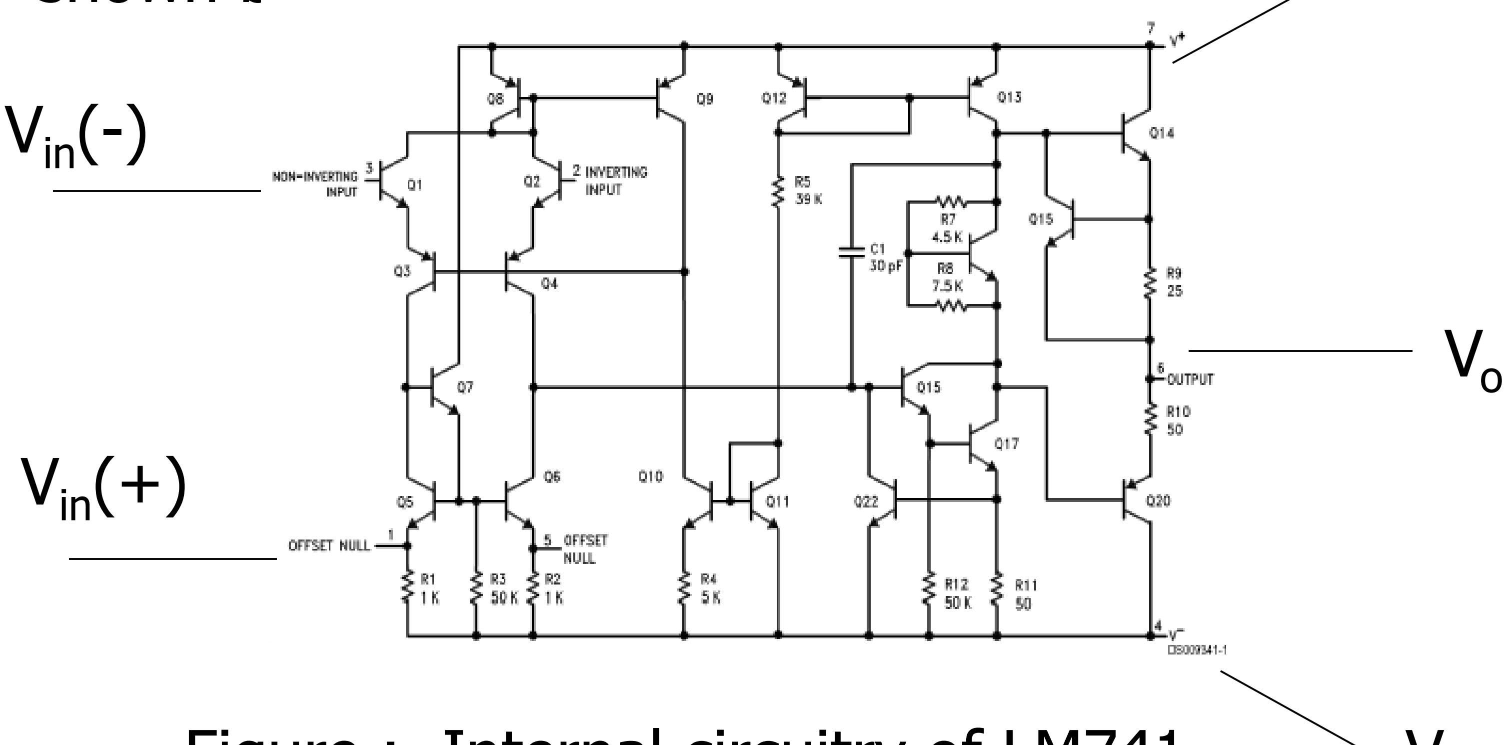


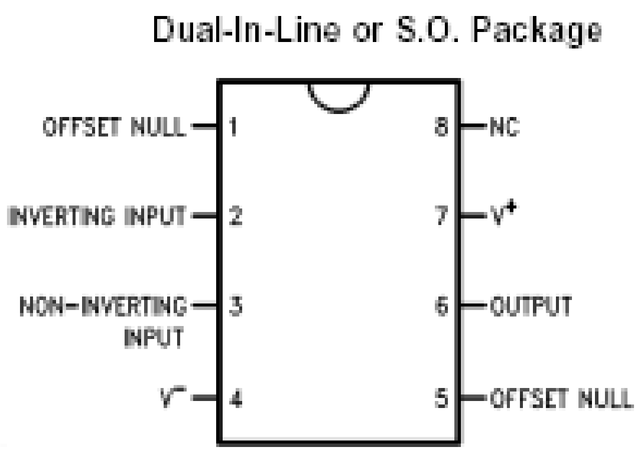
Figure : Internal circuitry of LM741.

Taken from National Semiconductor data sheet as shown on the web.

Operational Amplifiers

Fortunately, we do not have to *sweat* a circuit with 22 transistors and twelve resistors in order to use the op amp

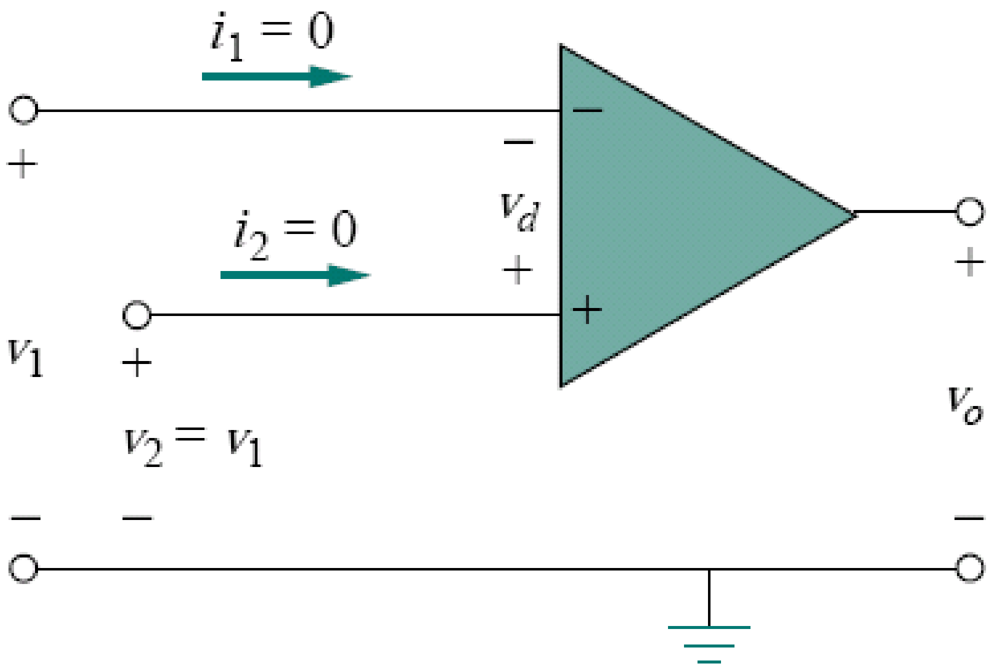
The circuit in the previous slide is usually encapsulated into a dual in-line pack (DIP). For a single LM741, the pin connections for the chip are shown below.



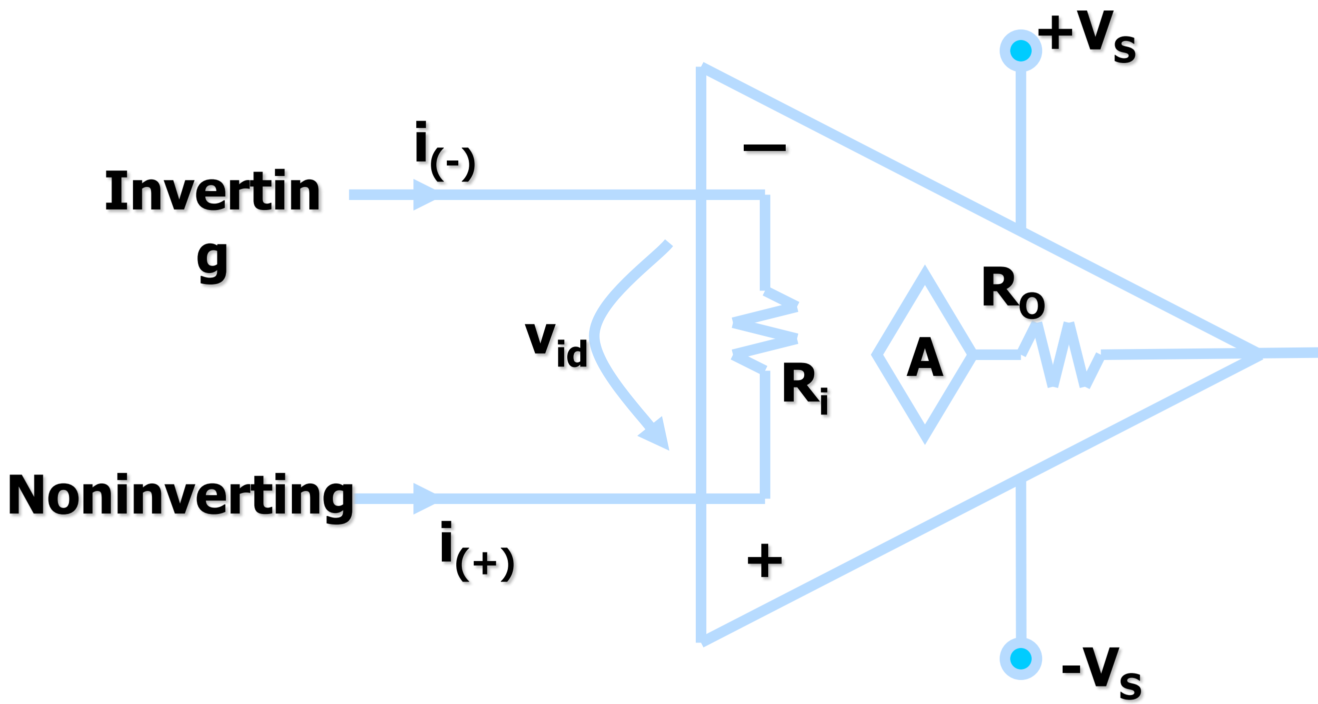
Taken from National Semiconductor data sheet as shown on the web.

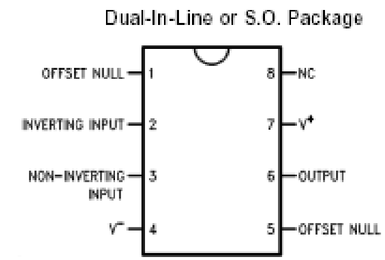
Figure: Pin connection, LM741.

An Electrical Representation of Op Amp.



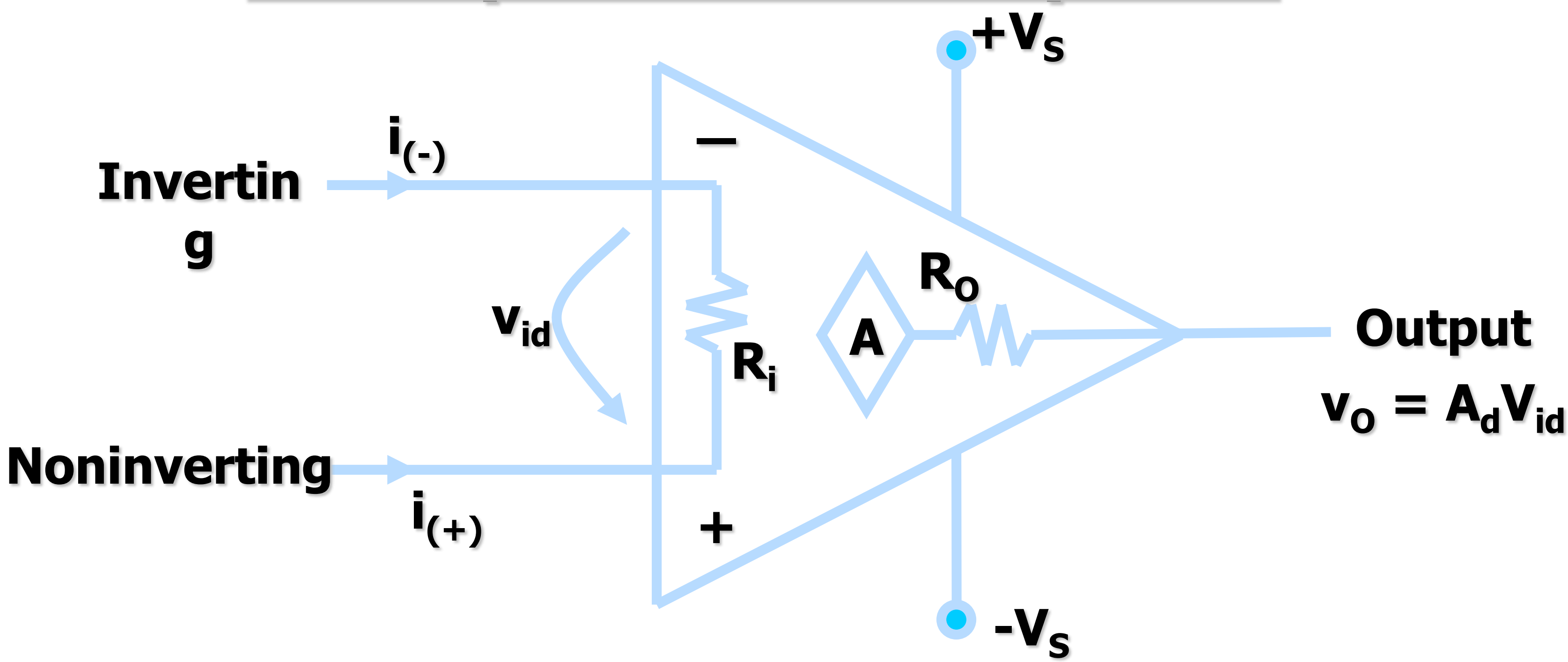
The Operational Amplifier





- $i_{(+)}$, $i_{(-)}$: Currents into the amplifier on the inverting and non-inverting lines respectively
- v_{id} : The input voltage from inverting to non-inverting inputs
- $+V_S$, $-V_S$: DC source voltages, usually +15V and –15V
- R_i : The input resistance, ideally infinity

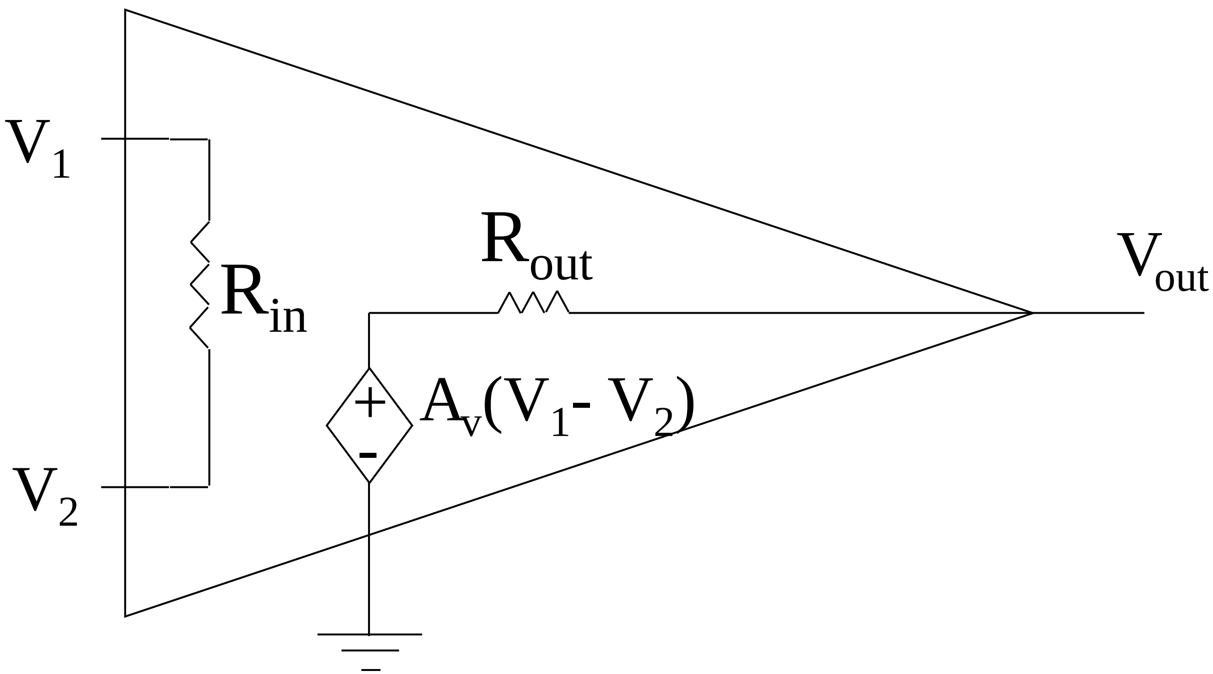
The Operational Amplifier



- R_i : The input resistance, ideally infinity
- A : The gain of the amplifier. Ideally very high, in the $1x10^{10}$ range.
- R_O: The output resistance, ideally zero
- v_O: The output voltage; $v_O = A_{OL}v_{id}$ where A_{OL} is the open-loop voltage gain

Operational Amplifier Model

- An operational amplifier circuit is designed so that
  1) $V_{out} = A_v (V_1 - V_2)$ (**A_v** is a very large gain)
  2) Input resistance (**R_{in}**) is very large
  3) Output resistance (**R_{out}**) is very low



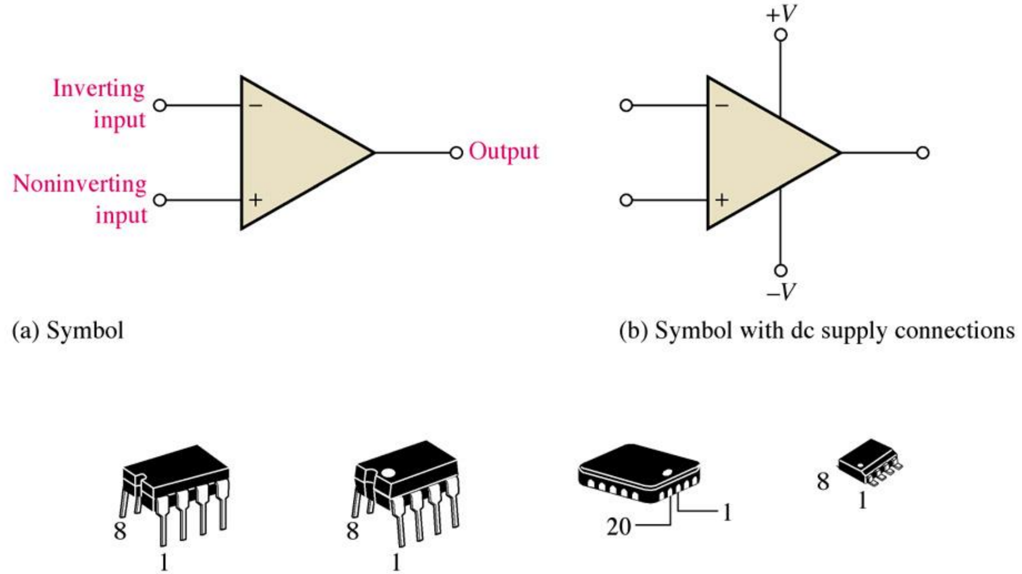
Practical Op-Amp Circuits

These Op-amp circuits are commonly used:

- Inverting Amplifier
- Noninverting Amplifier
- Unity Follower
- Summing Amplifier
- Integrator
- Differentiator

Introduction To Operational Amplifiers

The **operational amplifier** or op-amp is a circuit of components integrated into one chip. We will study the op-amp as a singular device. A typical op-amp is powered by two dc voltages and has an inverting(-) and a noninverting input (+) and an output. Note that for simplicity the power terminals are not shown but understood to exist.



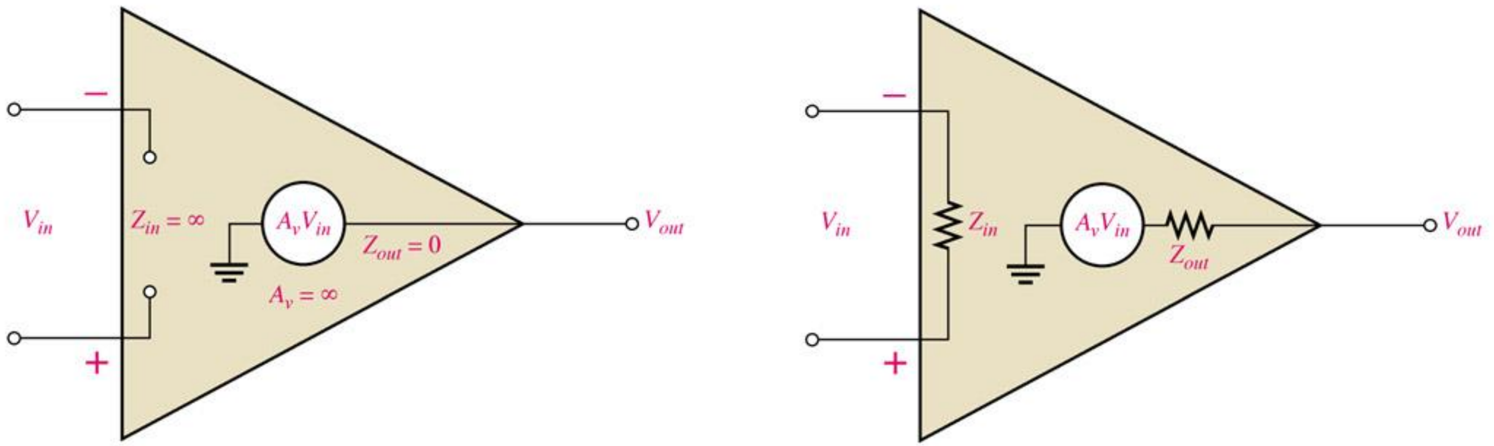
(a) Symbol

(b) Symbol with dc supply connections

(c) Typical packages. Pin 1 is indicated by a notch or dot on dual-in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Introduction To Op-Amps – The Ideal & Practical Op-Amp

While an **ideal op-amp** has infinite voltage gain and infinite bandwidth. Also, it has infinite input impedance (open) and zero output impedance. We know this is impossible. However, **Practical op-amps** do have very high voltage gain, very high input impedance, very low output impedance, and wide bandwidth.

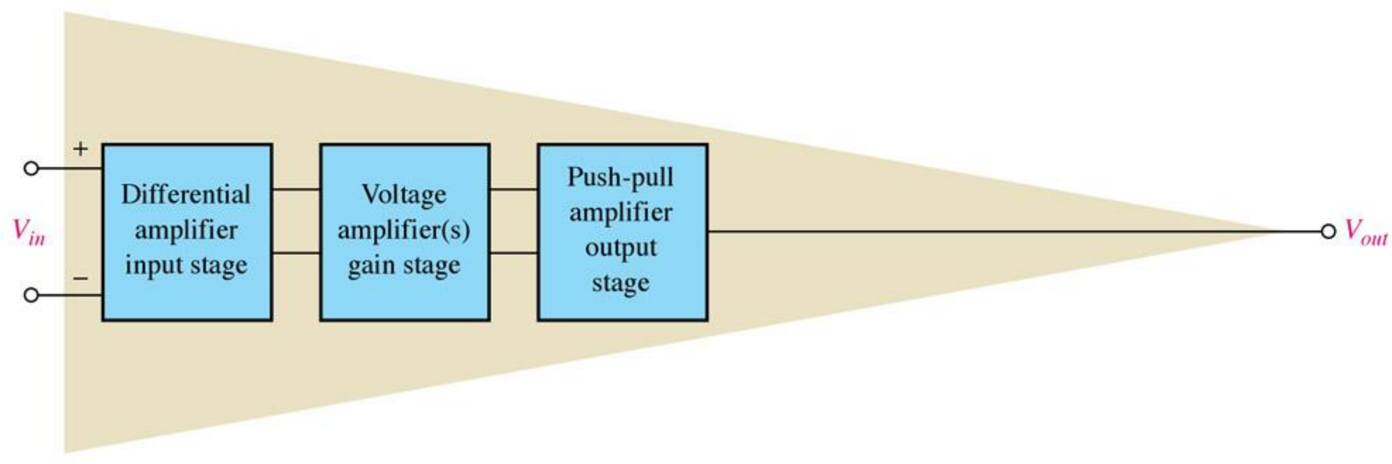


(a) Ideal op-amp representation

(b) Practical op-amp representation

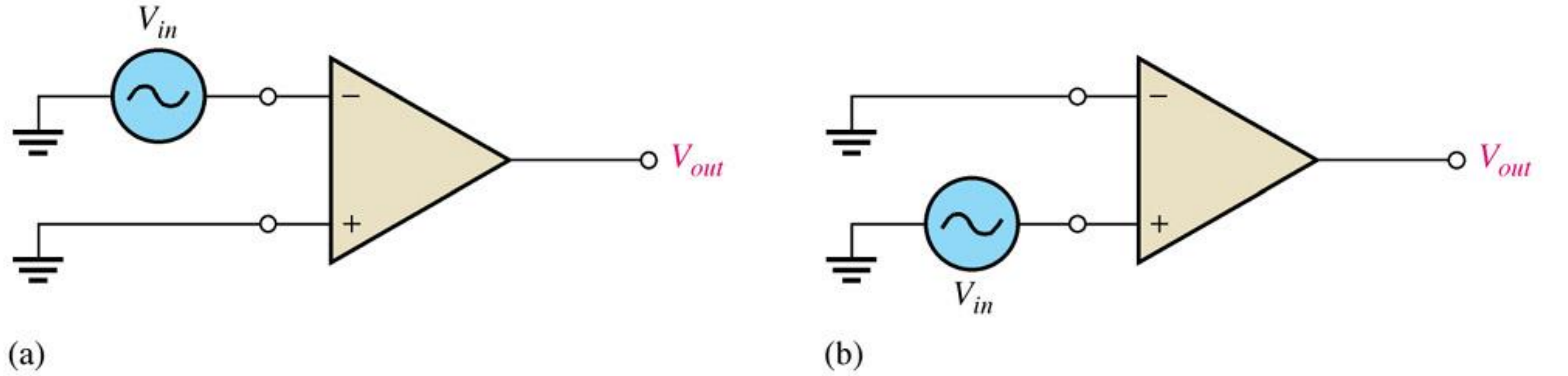
Introduction To Op-Amps – Internal Block Diagram of an Op-Amp

A typical op-amp is made up of three types of amplifier circuit: a *differential amplifier*, a *voltage amplifier*, and a *push-pull amplifier*, as shown in Figure. A differential amplifier is the input stage for the op-amp. It has two inputs and provides amplification of the difference voltage between the two inputs. The voltage amplifier provides additional op-amp gain. Some op-amps may have more than one voltage amplifier stage.



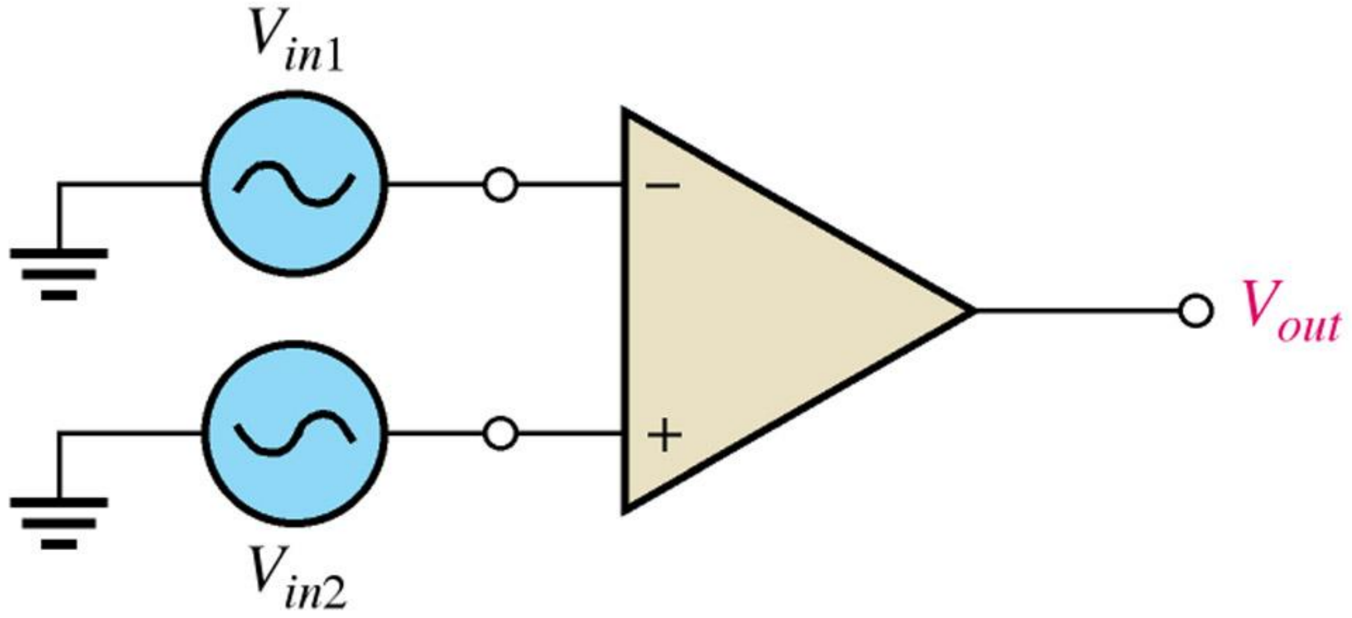
Op-Amp Input Modes and Parameters –
Input Signal Modes – Signal-Ended Input

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



Op-Amp Input Modes and Parameters – Input Signal Modes - Differential Input

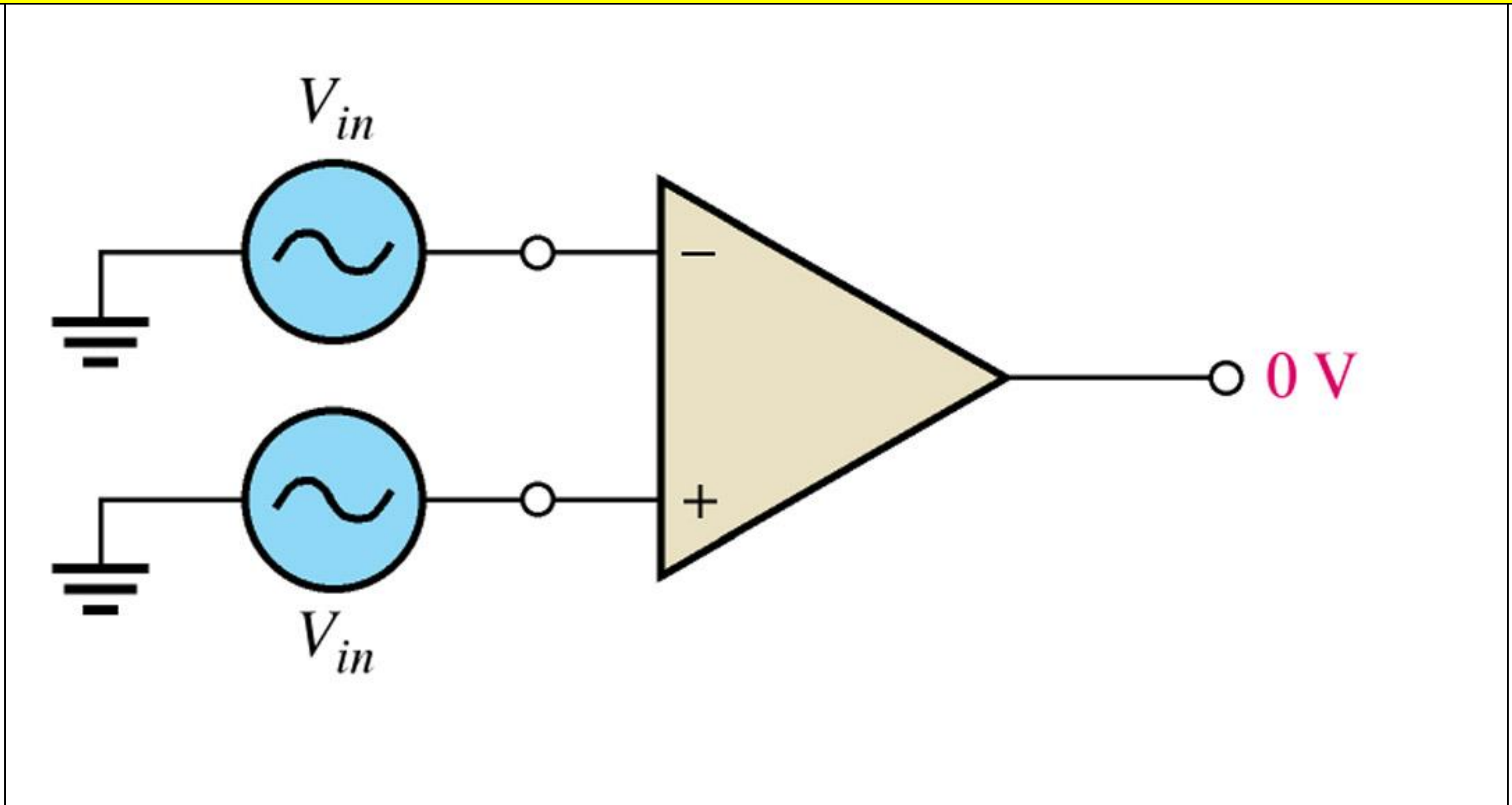
In the **differential mode**, two opposite-polarity (out-of-phase) signals are applied to the inputs, as shown in Figure. This type of operation is also referred to as double-ended. The amplified difference between the two inputs appears on the output.



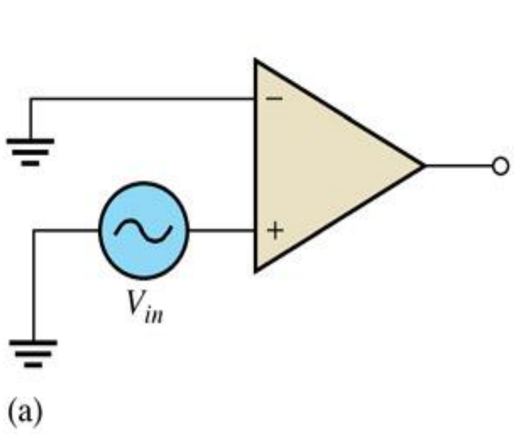
Op-Amp Input Modes and Parameters –

Input Signal Modes - Common-Mode Input

In the common mode, two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown in Figure. When equal input signals are applied to both inputs, they cancel, resulting in a zero output voltage. This action is called common-mode rejection.



Ex. 12-1 Identify the type of input mode for each op-amp in Figure.



(a) Single-ended input **(b)** Differential input **(c)** Common-mode

Op-Amp Input Modes and Parameters – Common-Mode Rejection Ratio

The **common-mode rejection ratio (CMRR)** is the measure for how well it rejects an unwanted the signal. It is the ratio of open loop gain (A_{ol}) to common-mode gain (A_{cm}). The open loop gain is a data sheet value.

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

The CMRR is often expressed in decibel (dB) as

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

Ex. 12-2 A certain op-amp has an open-loop voltage gain of 100,000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibel.

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

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

Expressed in decibels,

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

Ex. 12-3 An op-amp data sheet specifies a CMRR of 300,000 and an A_{ol} of 90,000. What is the common-mode gain?

$$A_{cm} = \frac{A_{ol}}{CMRR} = \frac{90{,}000}{300{,}000} = 0.3$$

Op-Amp Input Modes and Parameters

Op-amps tend to produce a small dc voltage called output error voltage ($V_{OUT(error)}$). The data sheet provides the value of dc differential voltage needed to force the output to exactly zero volts. This is called the **input offset voltage (V_{OS})**. This can change with temperature and the **input offset drift** is a parameter given on the data sheet.

Op-Amp Input Modes and Parameters

There are other input parameters to be considered for op-amp operation. The **input bias current** is the dc current required to properly operate the first stage within the op-amp. The **input impedance** is another. Also, the **input offset current** which can become a problem if both dc input currents are not the same.

Output impedance and **slew rate**, which is the response time of the output with a given pulse input are two other parameters.

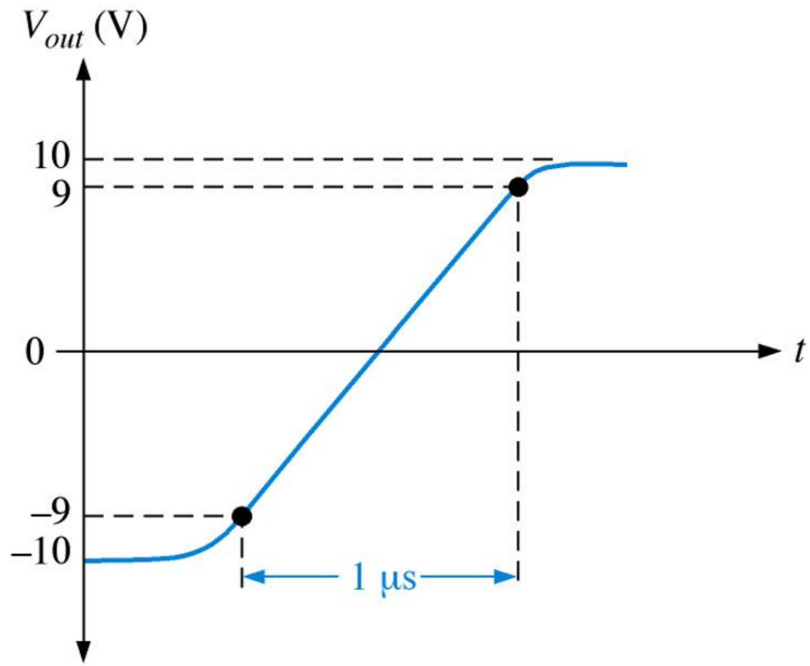
Op-amp low **frequency response** is all the way down to dc. The high frequency response is limited by the internal capacitances within the op-amp stages.

An IDEAL OP AMP

An ideal op amp has the following characteristics:

1. Infinite open-loop voltage gain, $A_V \approx \infty$.
2. Infinite input resistance, $R_i \approx \infty$.
3. Zero output resistance, $R_o \approx 0$.
4. Infinite CMRR, $\rho = \infty$
5. The output voltage Vo=0; when $V_d = V_2 - V_1 = 0$
6. Change of output with respect to input, slew rate = ∞
7. Change in out put voltage with Temp., $\partial V_o / \partial V_i = 0$

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

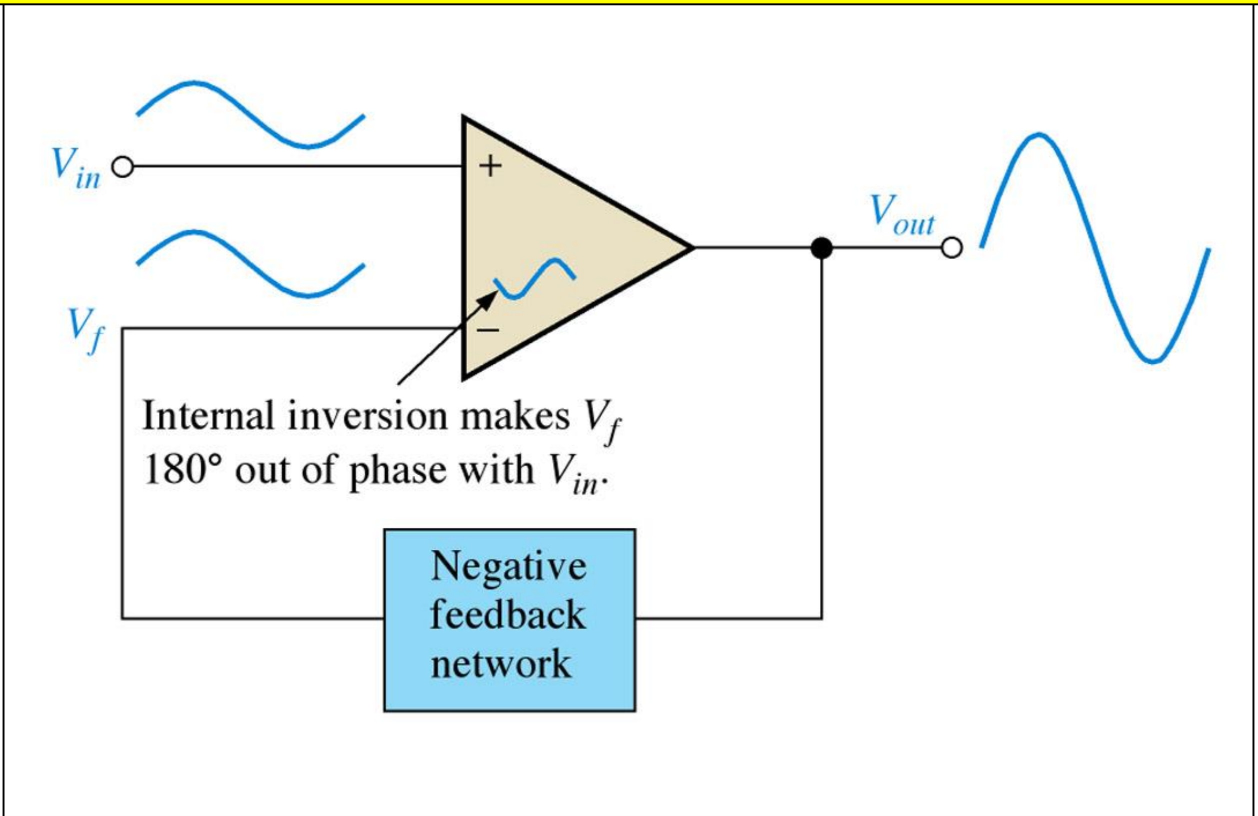


The output goes from the lower to the upper limit in 1 μs. Since this response is not ideal, the limits are taken at the 90% points, as indicated. So, the upper limit is +9 V and the lower limit is -9 V. The slew rate is

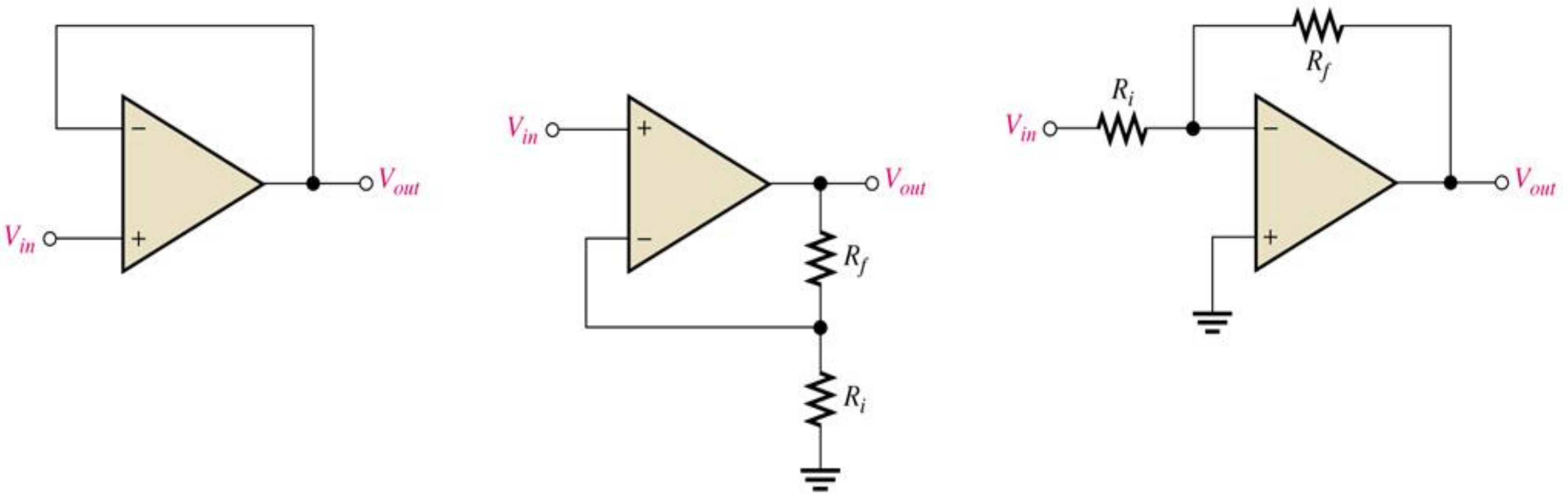
$$Slew\ rate = \frac{\Delta V_{out}}{\Delta t} = \frac{+9V-(-9V)}{1\mu s} = 18\,V/\mu s$$

Negative Feedback

Negative feedback is feeding part of the output back to the input to limit the overall gain. This is used to make the gain more realistic so that the op-amp is not driven into saturation. Remember regardless of gain there are limitations of the amount of voltage that an amplifier can produce.



Ex. Identify each of the op-amp configurations in Figure.

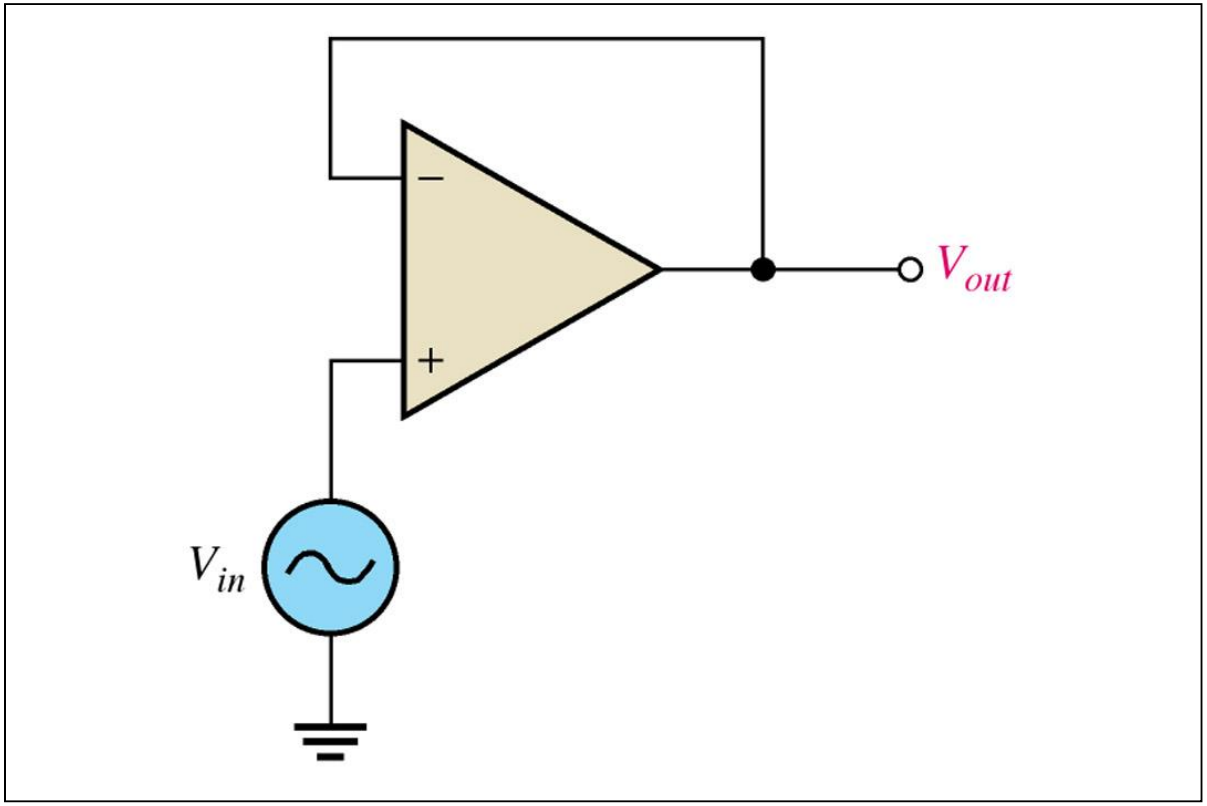


(a) (b) (c)

(a) Voltage-follower **(b)** Non-inverting **(c)** Inverting

Op-Amps With Negative Feedback – Voltage-follower

The **voltage-follower amplifier** configuration has all of the output signal fed back to the inverting input. The voltage gain is **1**. This makes it useful as a buffer amp since it has a high input impedance and low output impedance.

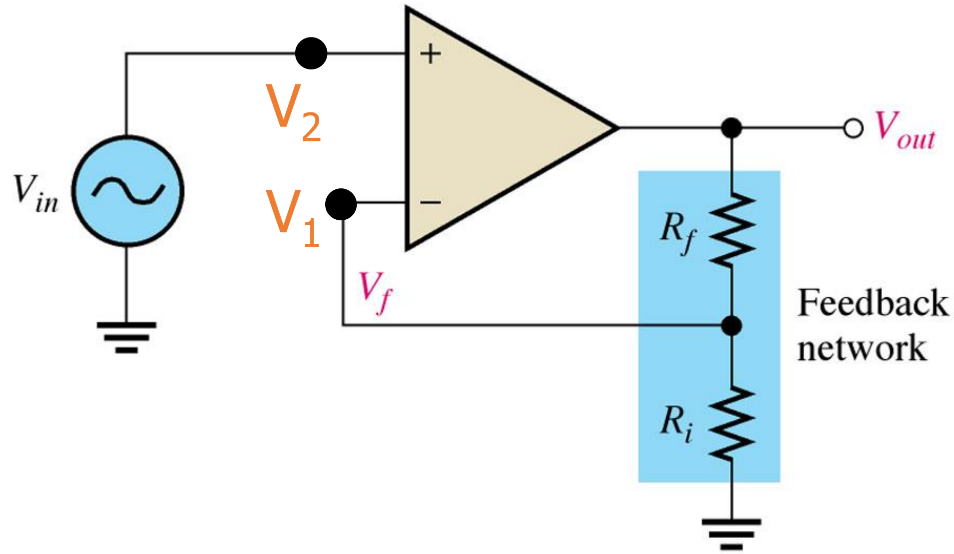


Op-Amps With Negative Feedback – noninverting Amplifier

The **closed-loop voltage gain (A_{cl})** is the voltage gain of an op-amp with external feedback. The gain can be controlled by external component values. Closed loop gain for a **non-inverting amplifier** can be determined by the formula below.

Ideal Op-Amp

$V_1 = V_2 = V_{in}$



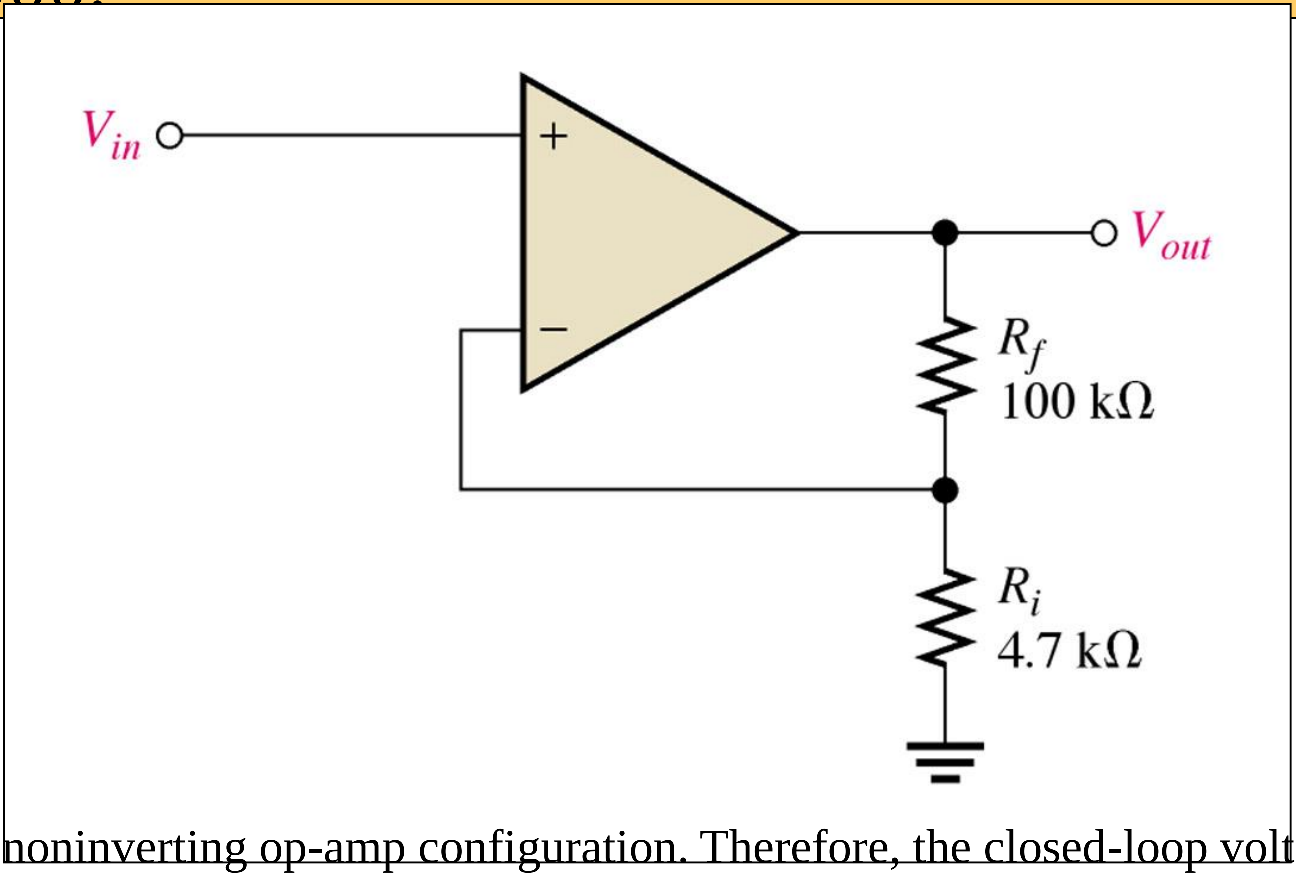
$$\frac{V_1}{R_i} + \frac{V_1 - V_{out}}{R_f} = 0$$

$$V_{in} \cdot R_f + R_i (V_{in} - V_{out}) = 0$$

$$V_{in}(R_i + R_f) = R_i \cdot V_{out}$$

$$V_{out} = \frac{R_i + R_f}{R} \cdot V_{in} = (1 + \frac{R_f}{R_i}) \cdot V_{in}$$

Ex. Determine the gain of the amplifier in Figure. The open-loop voltage gain of the op-amp is 100,000.



This is a noninverting op-amp configuration. Therefore, the closed-loop voltage gain is

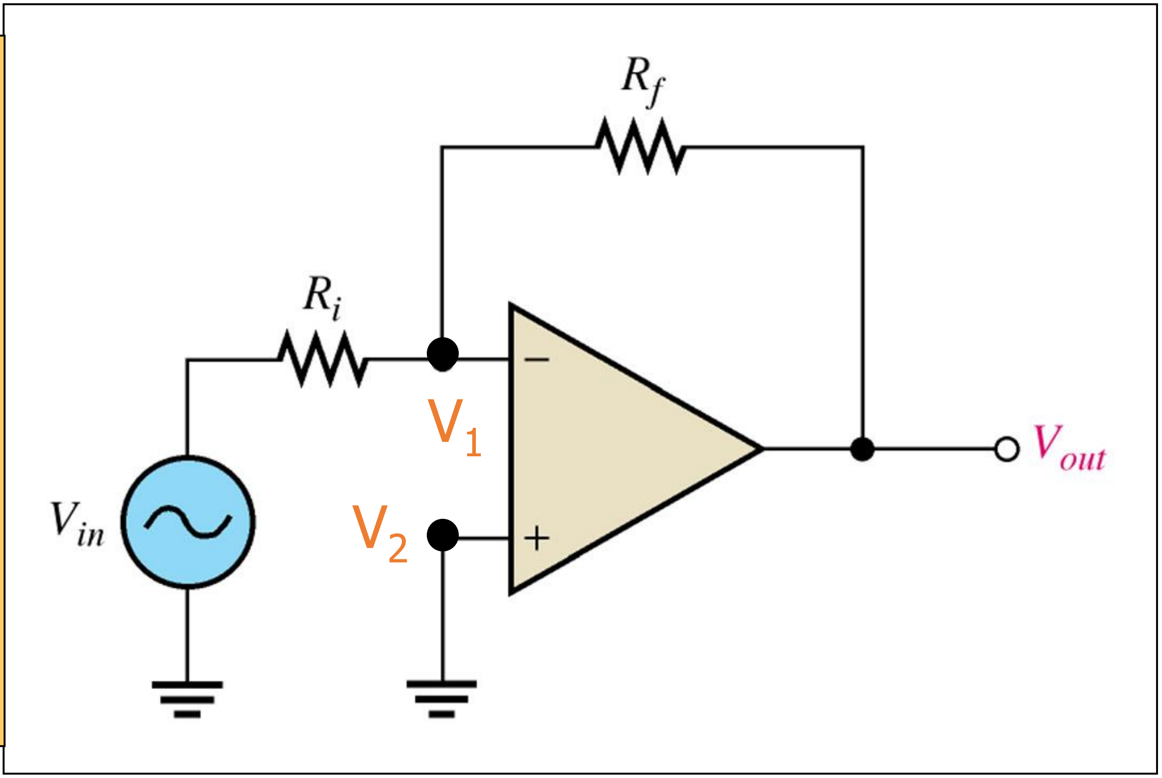
$$A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{100\,k\Omega}{4.7\,k\Omega} = 22.3$$

Op-Amps With Negative Feedback – Inverting Amplifier

The **inverting amplifier** has the output fed back to the inverting input for gain control. The gain for the inverting op-amp can be determined by the formula below.

Ideal Op-Amp

$$V_1 = V_2 = 0$$

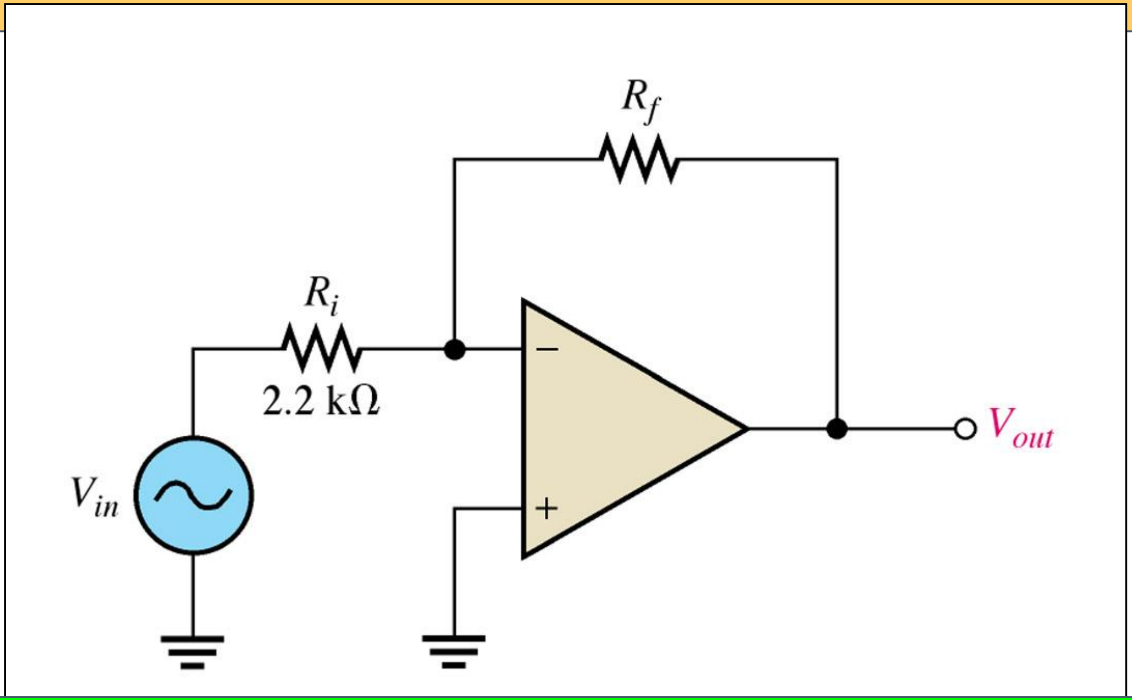


$$\frac{\cancel{V_1} - V_{in}}{R_i} + \frac{\cancel{V_1} - V_{out}}{R_f} = 0$$

$$-V_{in}R_f - V_{out}R_i = 0$$

$$V_{out} = -\left(\frac{R_f}{R_i}\right)V_{in}$$

Ex. Given the op-amp configuration in Figure, determine the value of R_f required to produce a closed-loop voltage gain of -100.

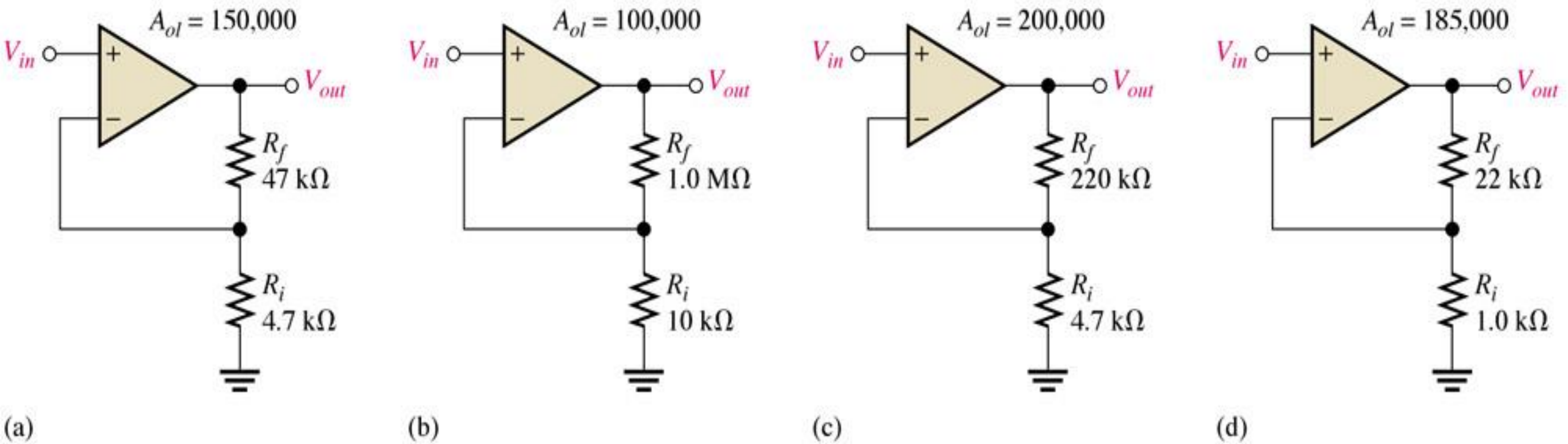


Knowing that R_i = 2.2 kΩ and the absolute value of the closed-loop gain is $|A_{cl(I)}| = 100$, calculate R_f as follows:

$$\left|A_{cl(I)}\right| = \frac{R_f}{R_i}$$

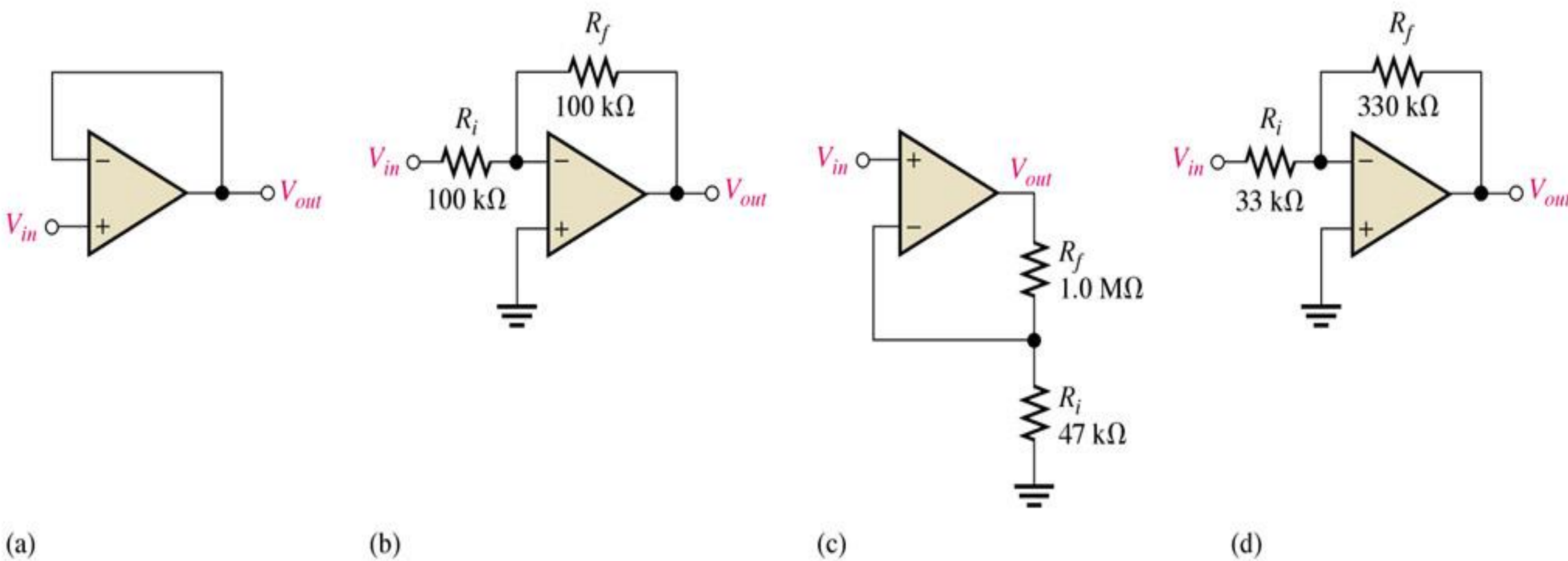
$$R_f = \left|A_{cl(I)}\right| R_i = (100)(2.2k\Omega) = 220k\Omega$$

Ex. Determine the closed-loop gain of each amplifier in Figure.



(a) 11 **(b)** 101 **(c)** 47.8 **(d)** 23

Ex. If a signal voltage of 10 mV_{rms} is applied to each amplifier in Figure, what are the output voltages and what is there phase relationship with inputs?.



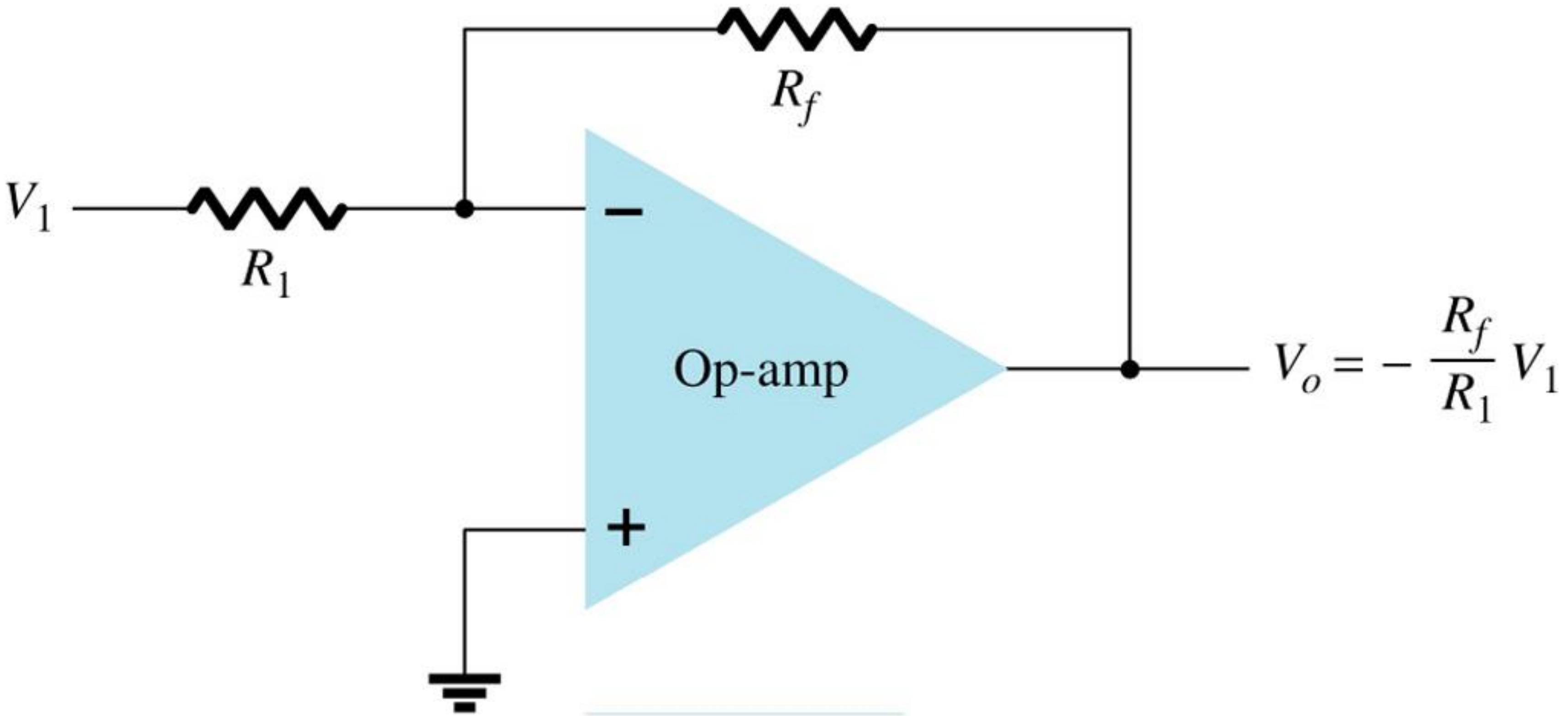
(a) $V_{out} \cong V_{in}$ = 10 mV, in phase **(b)** $V_{out} = A_{cl}V_{in}$ = – 10 mV, 180º out of phase **(c)** V_{out} = 233 mV, in phase **(d)** V_{out} = – 100 mV, 180º out of phase

Practical Op-Amp Circuits

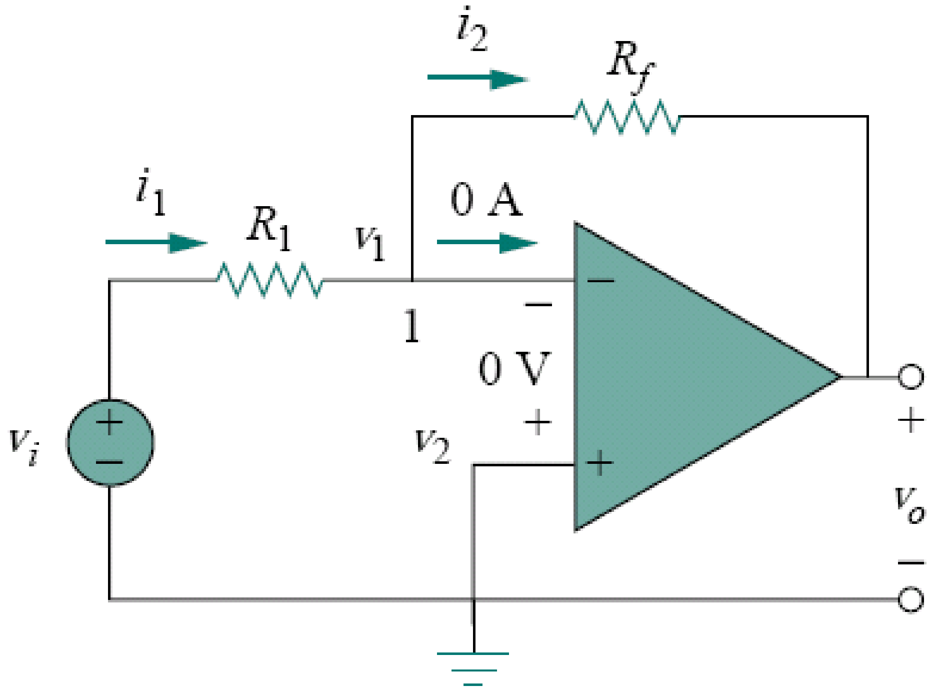
These Op-amp circuits are commonly used:

- Inverting Amplifier
- Noninverting Amplifier
- Unity Follower
- Summing Amplifier
- Integrator
- Differentiator

Inverting Op-Amp

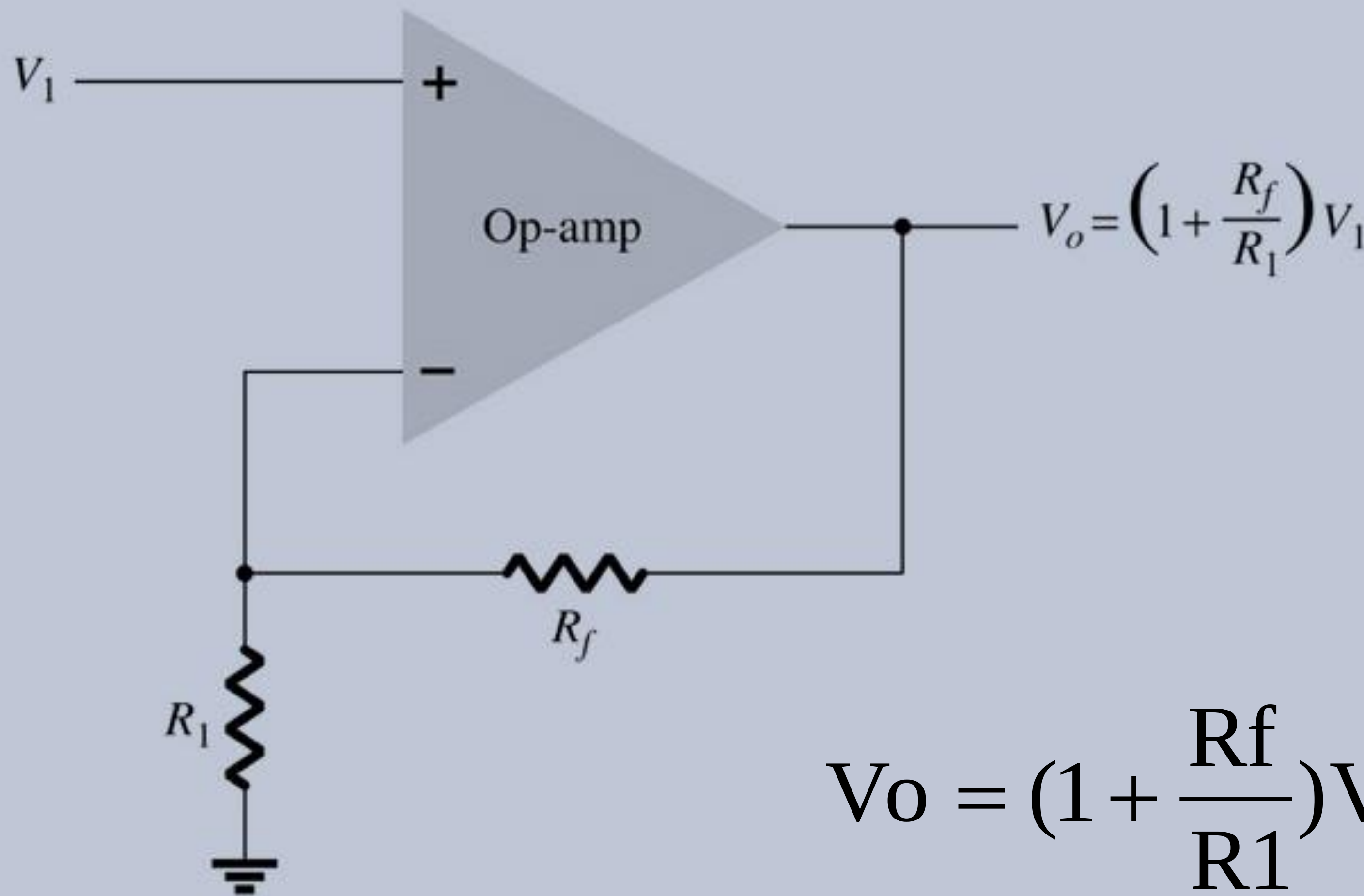


$$Vo = \frac{-Rf}{R1} V1$$



i2
Rf
i1
R1
v1
0 A
1
0 V
vi
v2
vo

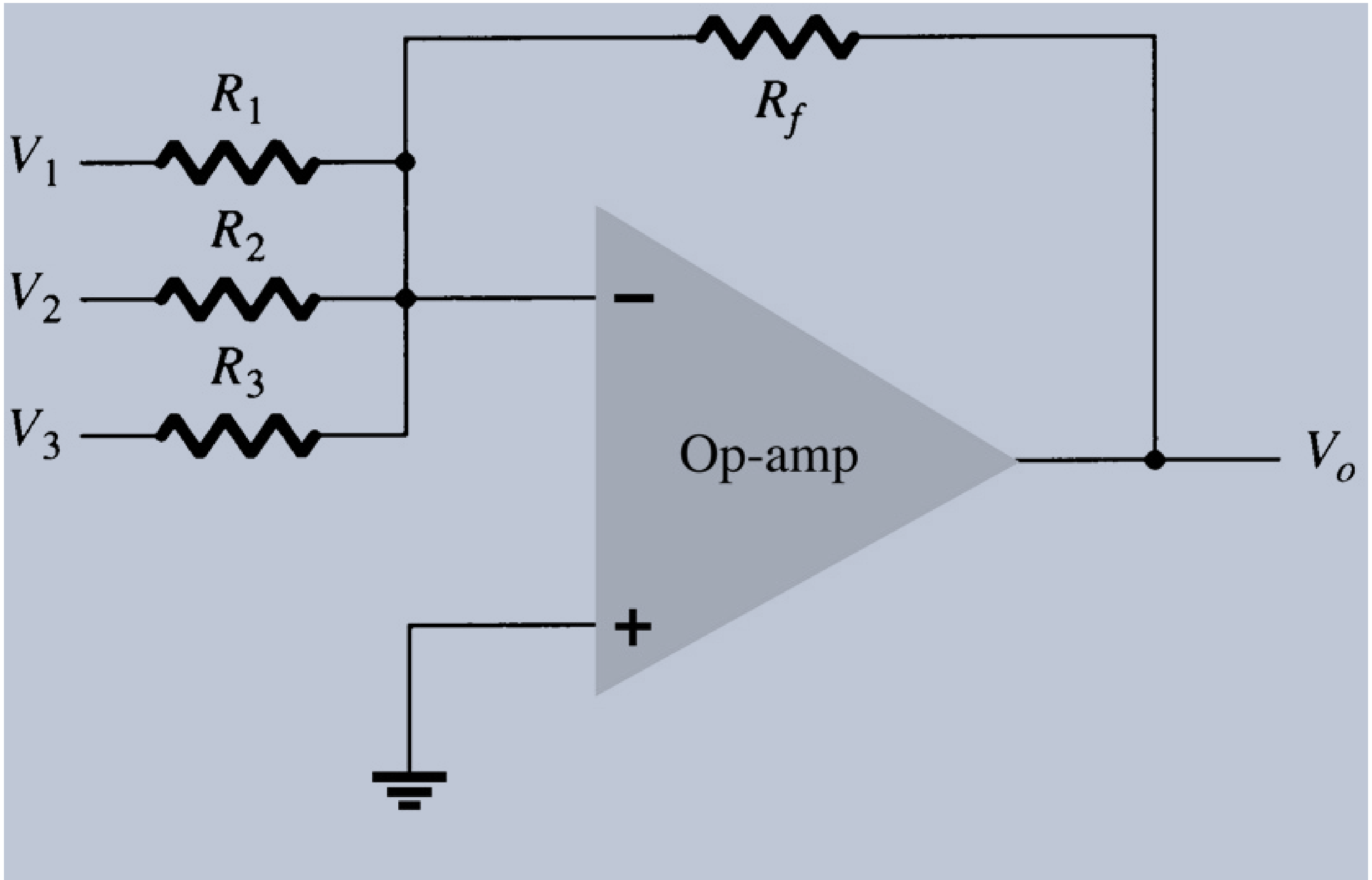
Noninverting Amplifier



$$Vo = (1 + \frac{Rf}{R1})V1$$

Notice the output formula is similar to Inverting Amplifier, but they are not the same.

Summing Amplifier

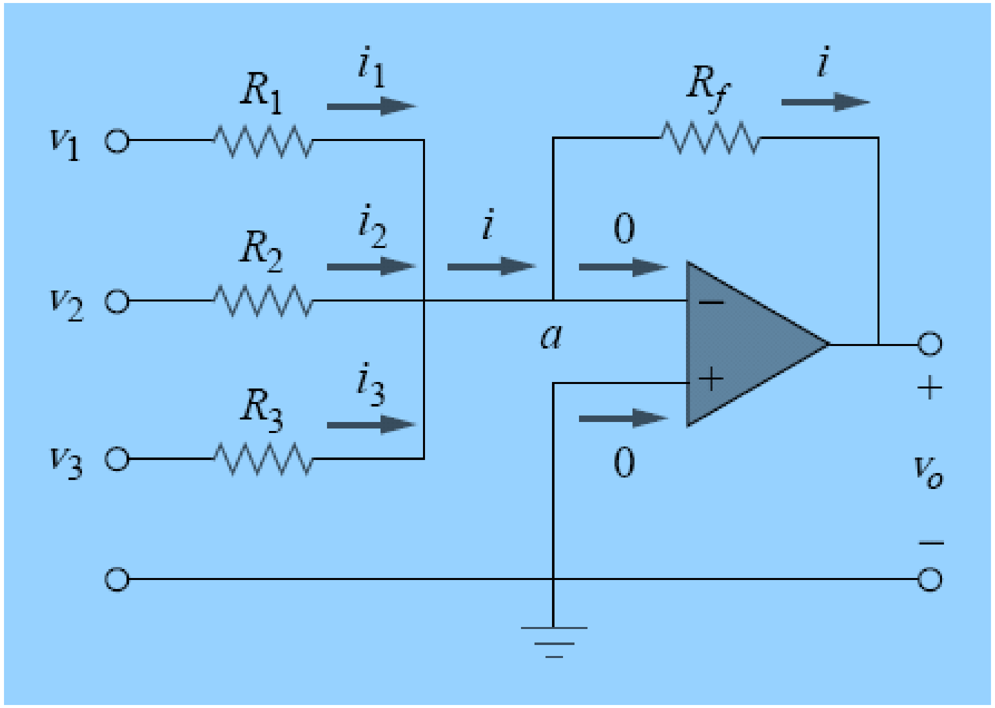


(a)

Because the op-amp has a high input impedance the multiple inputs are treated as separate inputs.

$$Vo = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 \right)$$

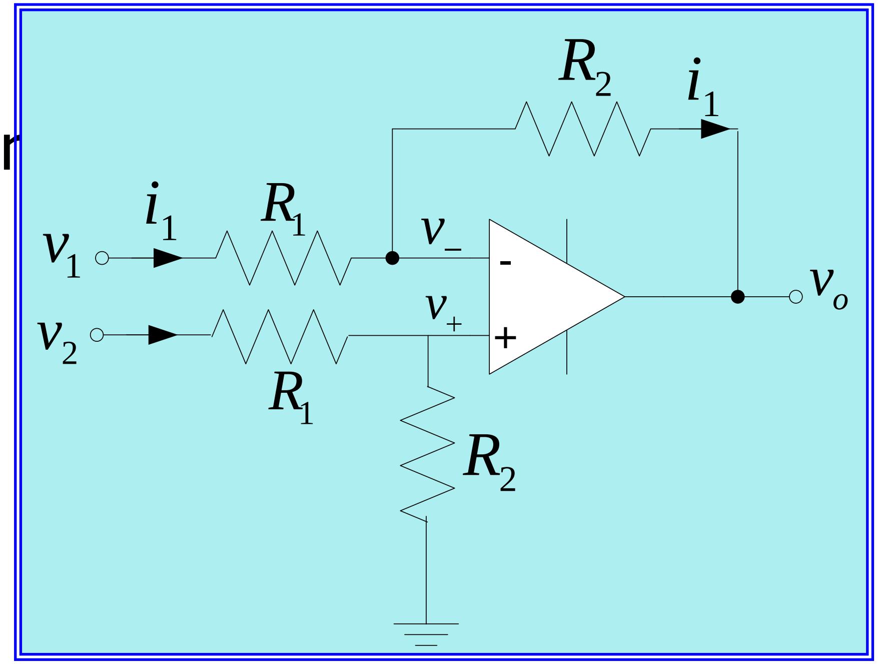
Summing Amplifier



Differential Amplifier Using Op Amp

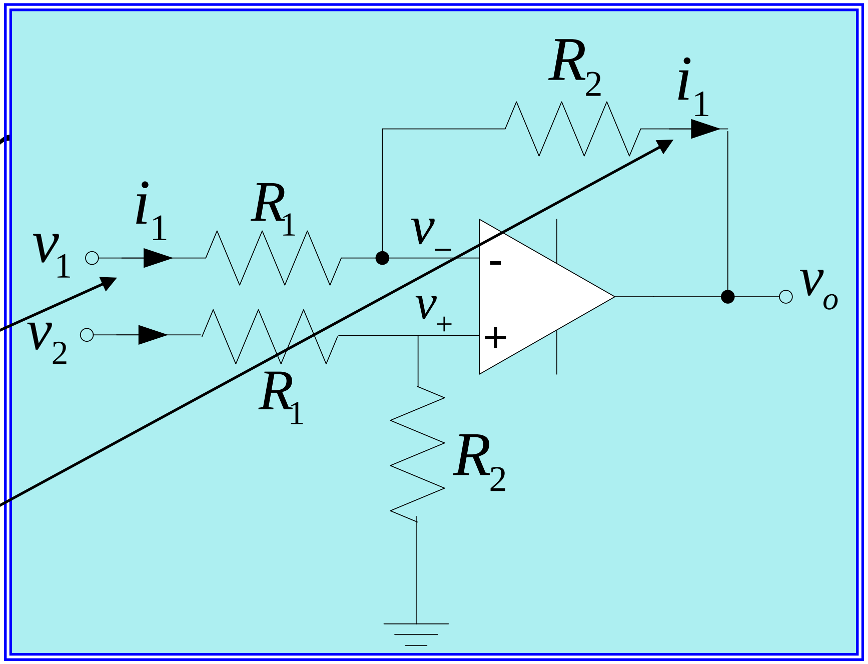
I/P Current to op amp is zer

$$v_- = v_+$$



Differential Amplifier Using Op Amp

I/P Current to op amp is zer



$$v_- = v_+$$

$$i_1 = \frac{v_1 - v_-}{R_1}$$

$$i_1 = \frac{v_- - v_0}{R_2}$$

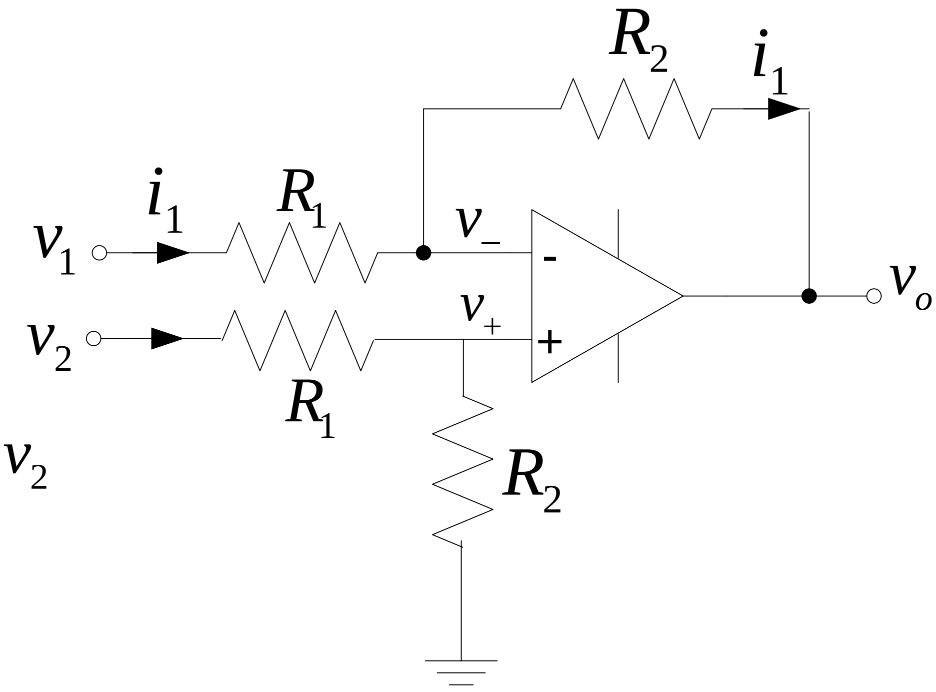
$$v_+ = \frac{R_2}{R_1 + R_2} v_2$$

$$\frac{v_1 - v_+}{R_1} = \frac{v_+ - v_0}{R_2}$$

$$\frac{v_1 - \dfrac{R_2}{R_1 + R_2} v_2}{R_1} = \frac{\dfrac{R_2}{R_1 + R_2} v_2 - v_0}{R_2}$$

Differential Amplifier Using Op Amp

$$\frac{v_1 - \frac{R_2}{R_1 + R_2} v_2}{R_1} = \frac{\frac{R_2}{R_1 + R_2} v_2 - v_0}{R_2}$$

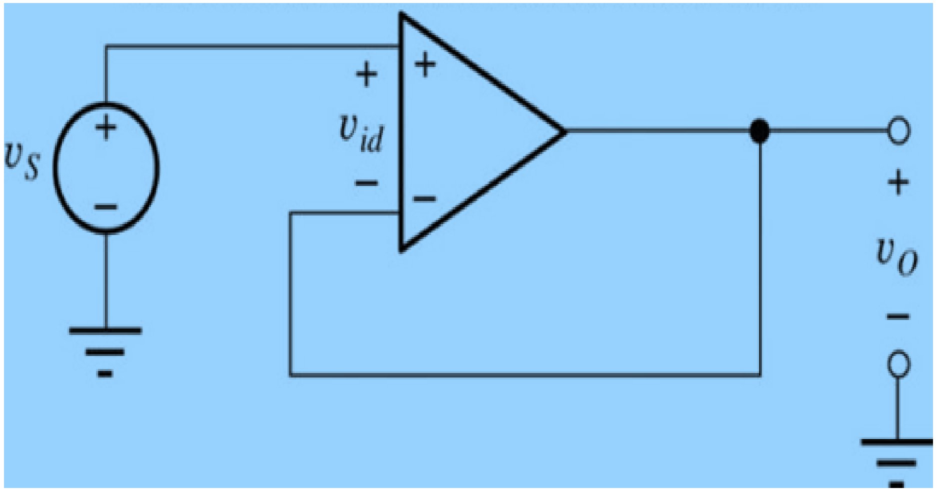


$$v_0 = -\frac{R_2}{R_1} v_1 + \frac{R_2}{R_1 + R_2} v_2 + \frac{R_2^2}{R_1 \left(R_1 + R_2 \right)} v_2$$

$$v_0 = -\frac{R_2}{R_1} v_1 + \frac{R_2}{R_1 + R_2} \left(1 + \frac{R_2}{R_1} \right) v_2$$

$$v_0 = \frac{R_2}{R_1} \left(v_2 - v_1 \right)$$

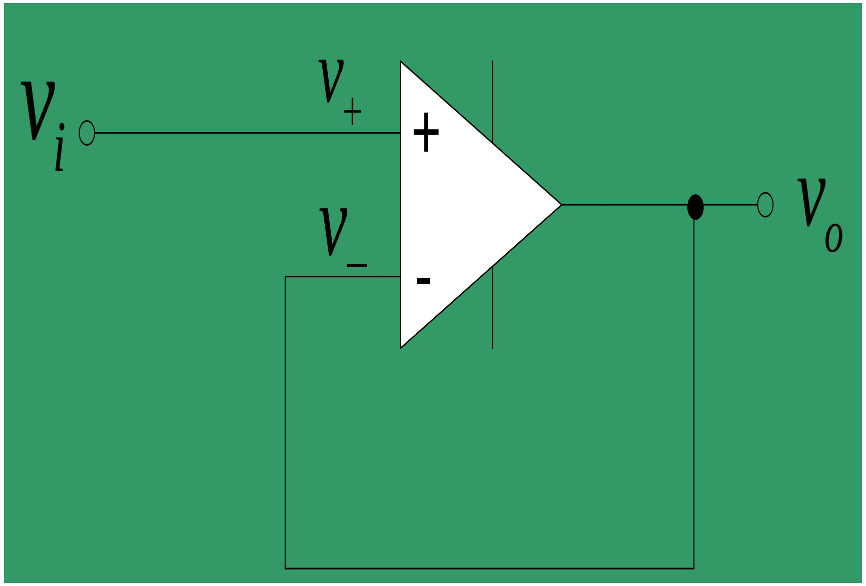
The Unity-Gain Amplifier or “Buffer”



- This is a special case of the non-inverting amplifier, which is also called a voltage follower, with infinite R_1 and zero R_2.

  Hence $A_v = 1$.
- It provides an excellent electrical isolation while maintaining the signal voltage level.
- The “ideal” buffer requires no input current and can drive any desired load resistance without loss of signal voltage.
- Such a buffer is used in many sensor and data acquisition system applications.

Unity-Gain Buffer



Closed-loop voltage gain

$$A_F = \frac{v_o}{v_i}$$

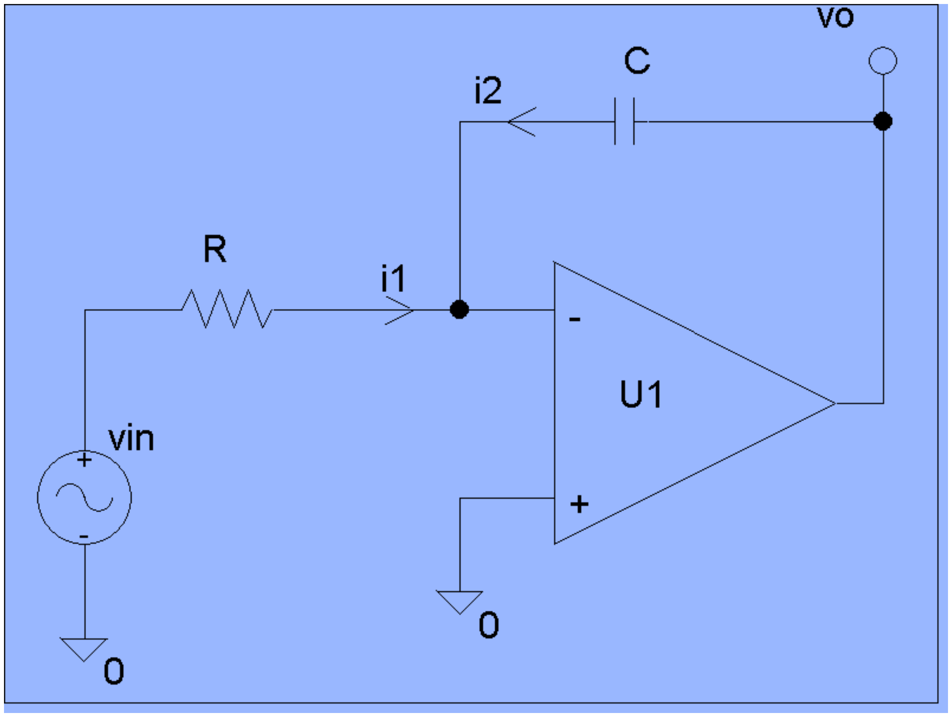
$$v_i = v_+ = v_- = v_o$$

$$v_i = v_+ = v_- = v_o$$

$$A_F = \frac{v_o}{v_i} = 1$$

Used as a "line driver" that transforms a high input impedance (resistance) to a low output impedance. Can provide substantial current gain.

Op-Amp Integrator



Op-Amp Integrator Cont…

Since the inverting input is at virtual ground

$$i_1 = \frac{v_{in}}{R}$$

$$i_2 = C\frac{dv_o}{dt}$$

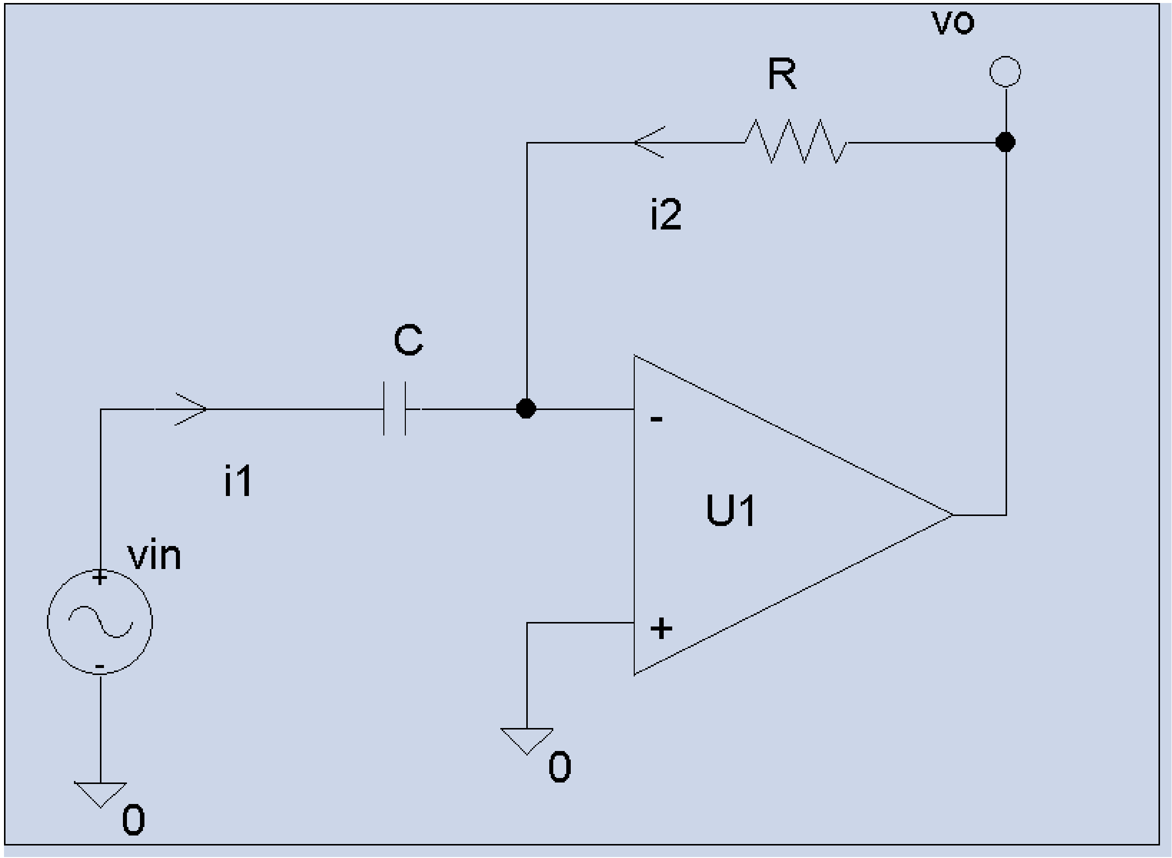
Applying KCL at the inverting input

$$i_1 + i_2 = 0$$

$$\therefore \quad C\frac{dv_o}{dt} + \frac{v_{in}}{R} = 0$$

$$\Rightarrow \quad v_o = -\frac{1}{RC}\int v_{in}\,dt + v_o(\mathrm{initial})$$

Op-Amp Differentiator Circuit



Op-Amp Differentiator Cont…

Since the inverting input is at virtual ground

$$i_1 = C\frac{dv_{in}}{dt}$$

$$i_2 = \frac{v_o}{R}$$

Applying KCL at the inverting input

$$i_1 + i_2 = 0$$

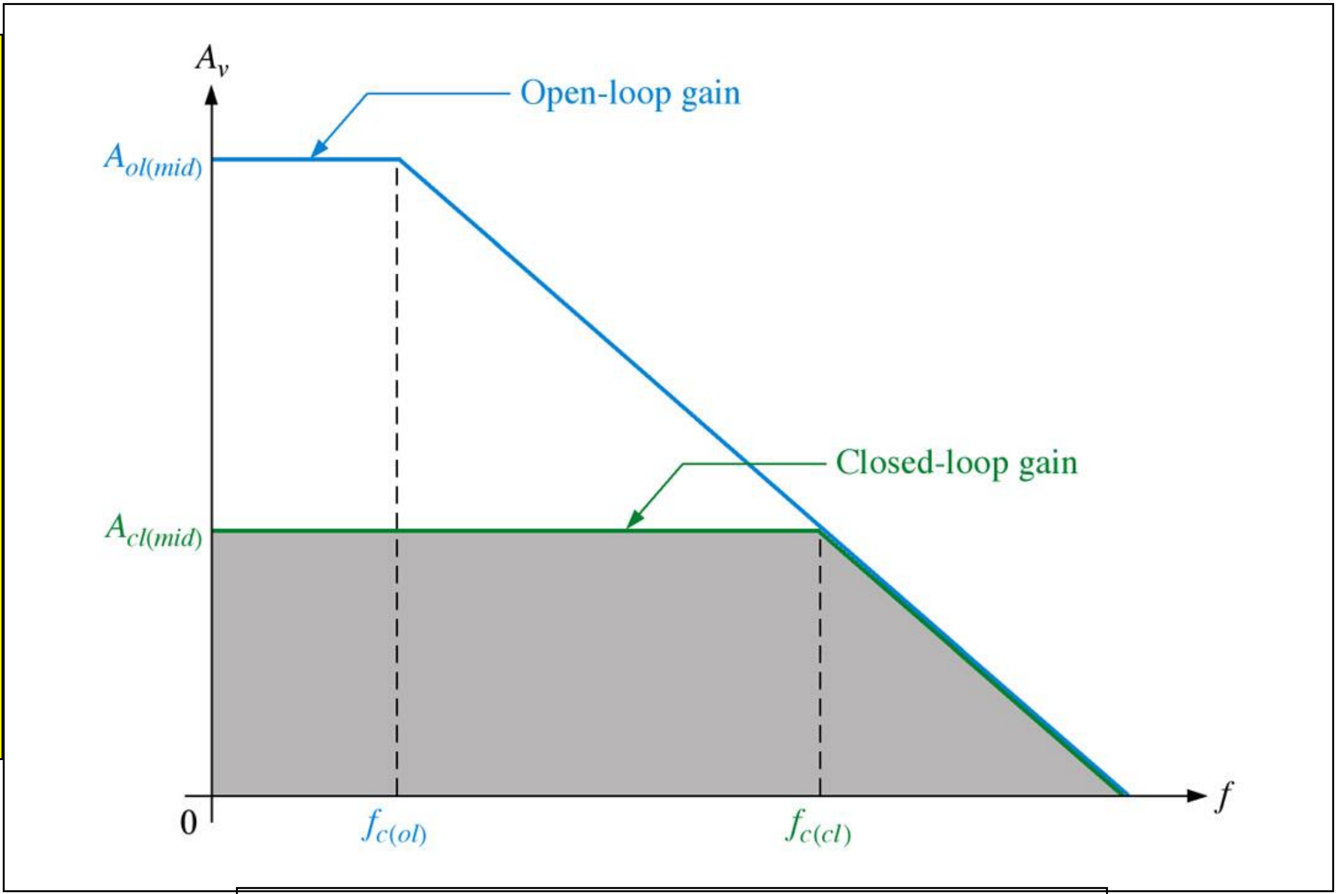
$$\therefore \quad C\frac{dv_{in}}{dt} + \frac{v_o}{R} = 0$$

$$\Rightarrow \quad v_o = -RC\frac{dv_{in}}{dt}$$

Differentiators are avoided in practice as they amplify noise

Gain-Bandwidth Product

The **gain-bandwidth product** is always equal to the frequency at which the op-amp's open-loop gain is 0dB (unity-gain bandwidth).



Closed-loop gain compared to open-loop gain.

$$BW_{cl} = BW_{ol}(1 + BA_{ol(mid)})$$

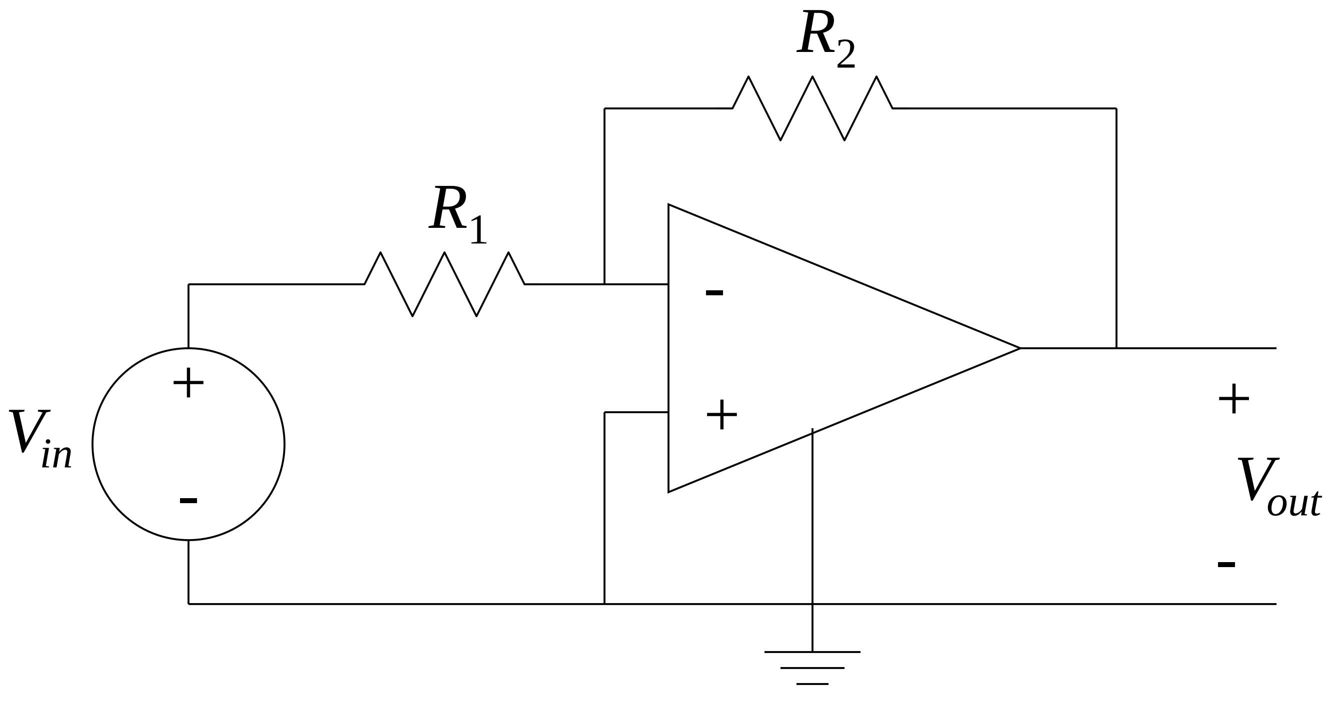
How to solve Op Amp Circuit?

- Nodal analysis or other methods to solve for the output voltage in terms of the input(s).
- Keep in mind that the ideal op amp model leads to the following conditions:

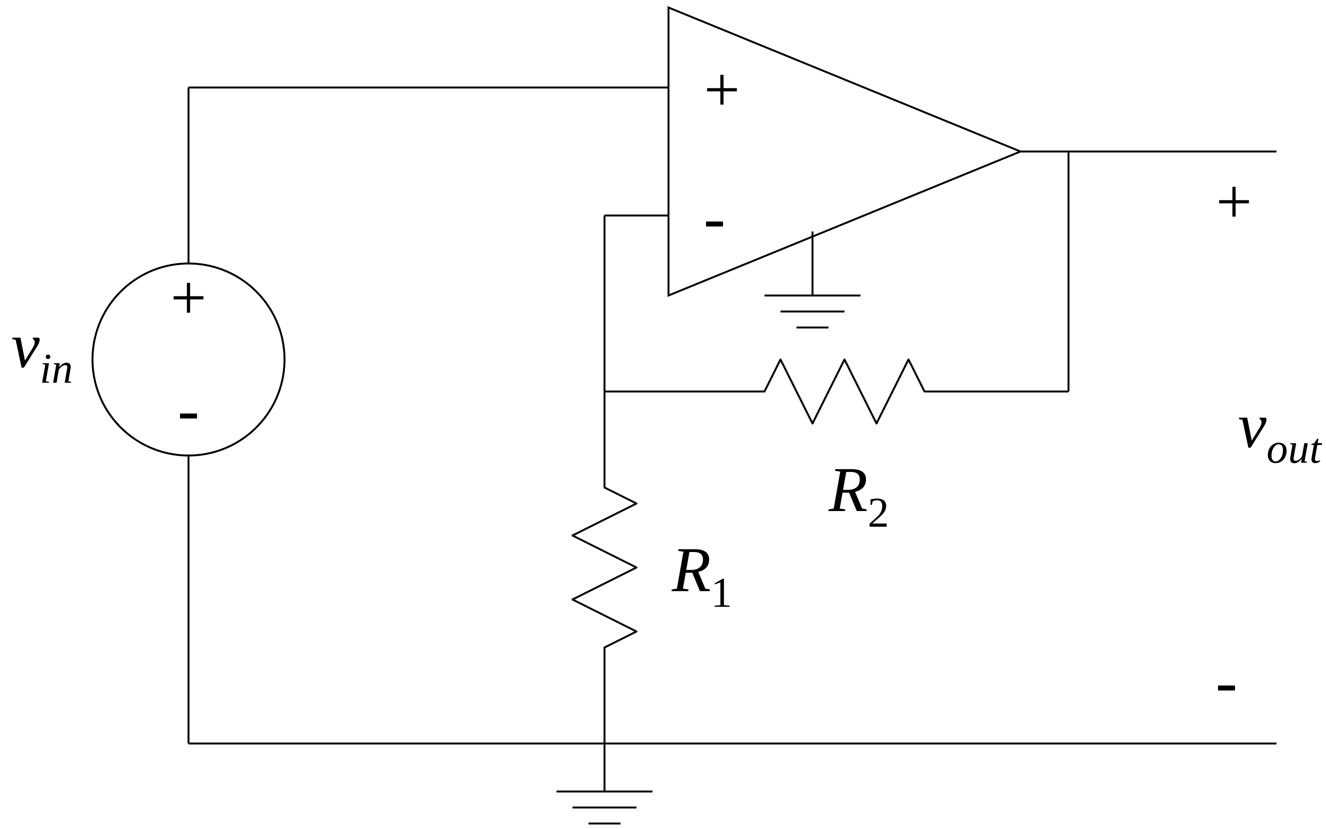
$$i_- = 0$$

$$v_+ = v_-$$

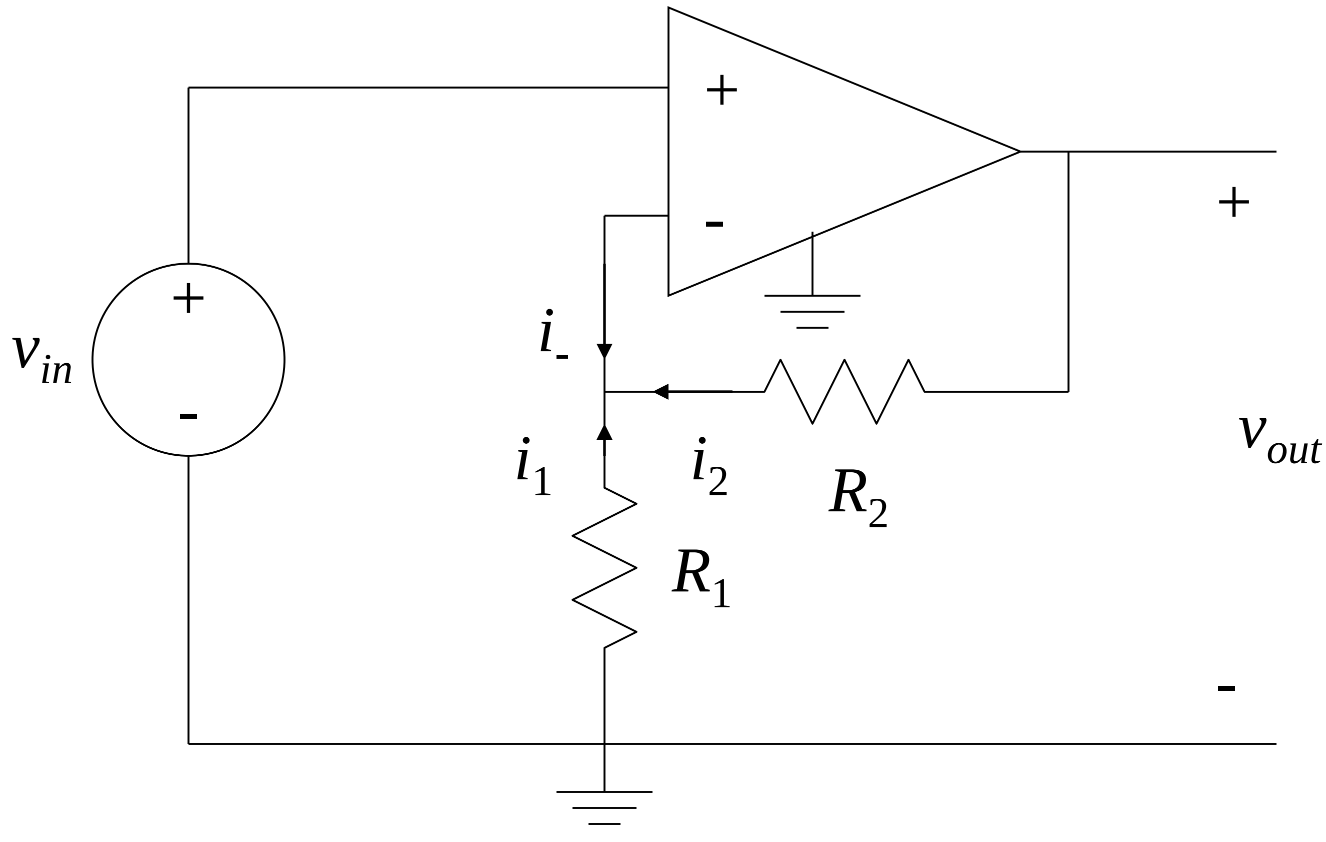
Where is the Feedback?



The Non-Inverting Amplifier



Nodal Analysis: Finding the nodes



Nodal Analysis: Apply KCL

$$i_- = 0$$

$$i_1 = \frac{-v_-}{R_1} = \frac{-v_{in}}{R_1}$$

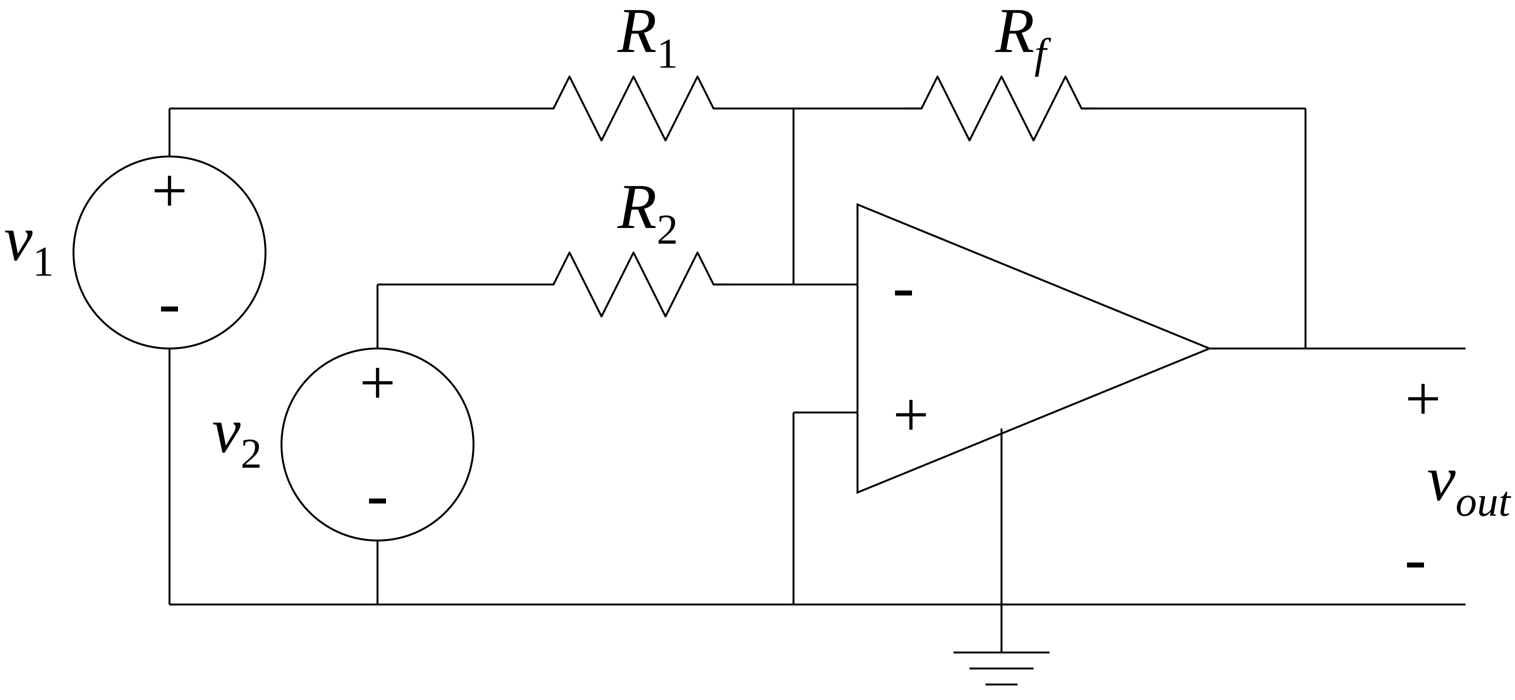
$$i_2 = \frac{v_{out} - v_-}{R_2} = \frac{v_{out} - v_{in}}{R_2}$$

Nodal Analysis: Solve for V_{out}

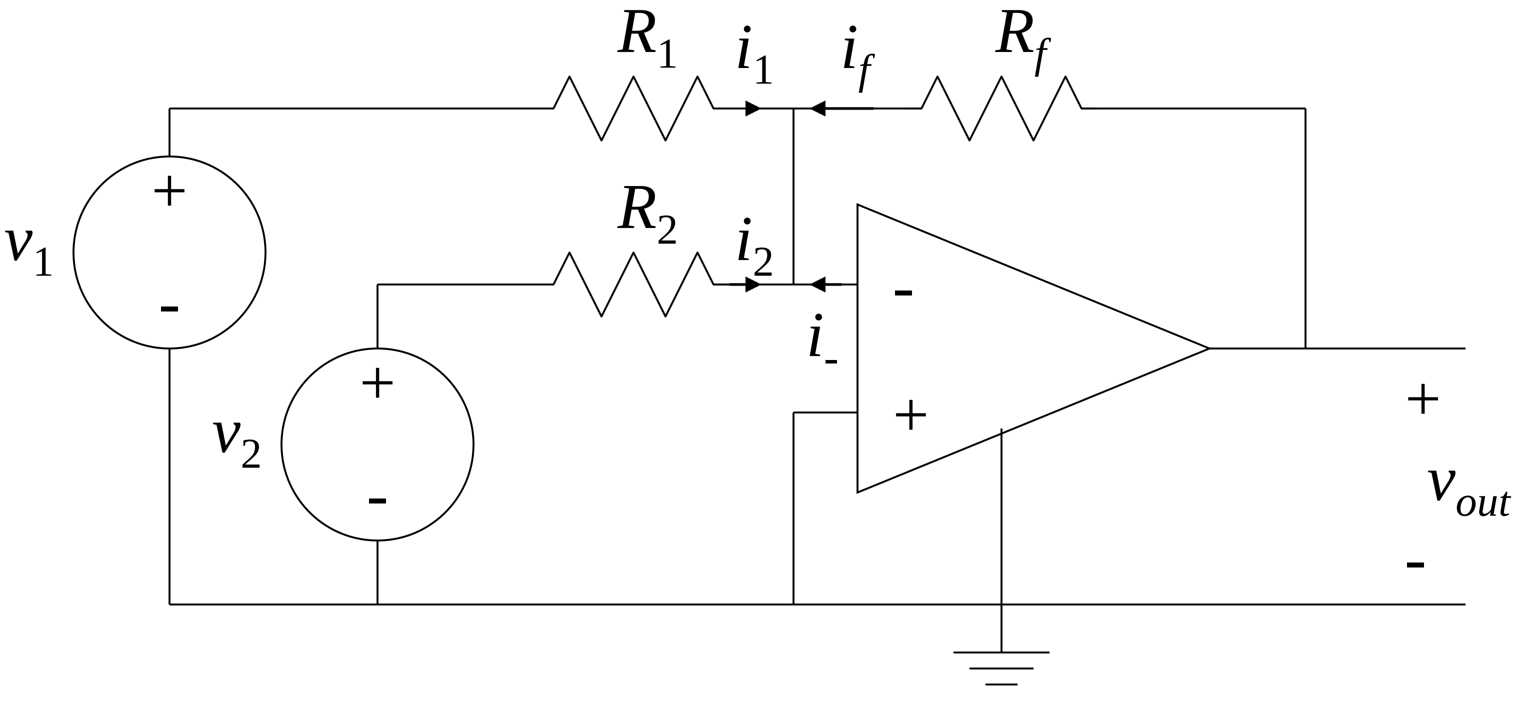
$$\frac{-v_{in}}{R_1} + \frac{v_{out} - v_{in}}{R_2} = 0$$

$$v_{out} = v_{in}\left(1 + \frac{R_2}{R_1}\right)$$

A Mixer Circuit



Nodal Analysis: Finding the nodes



Nodal Analysis: Apply KCL

$$i_1 = \frac{v_1 - v_-}{R_1} = \frac{v_1}{R_1}$$

$$i_2 = \frac{v_2 - v_-}{R_2} = \frac{v_2}{R_2}$$

$$i_- = 0$$

$$i_f = \frac{v_{out} - v_-}{R_f} = \frac{v_{out}}{R_f}$$

Nodal Analysis: Solve for V_{out}

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_{out}}{R_f} = 0$$

$$v_{out} = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2$$

BASIC OP-AMP CIRCUITS

Objectives:

- Describe and analyze the operation of several types of summing amplifiers.

- Describe and analyze the operation of integrators and differentiators.

SUMMING AMPLIFIERS

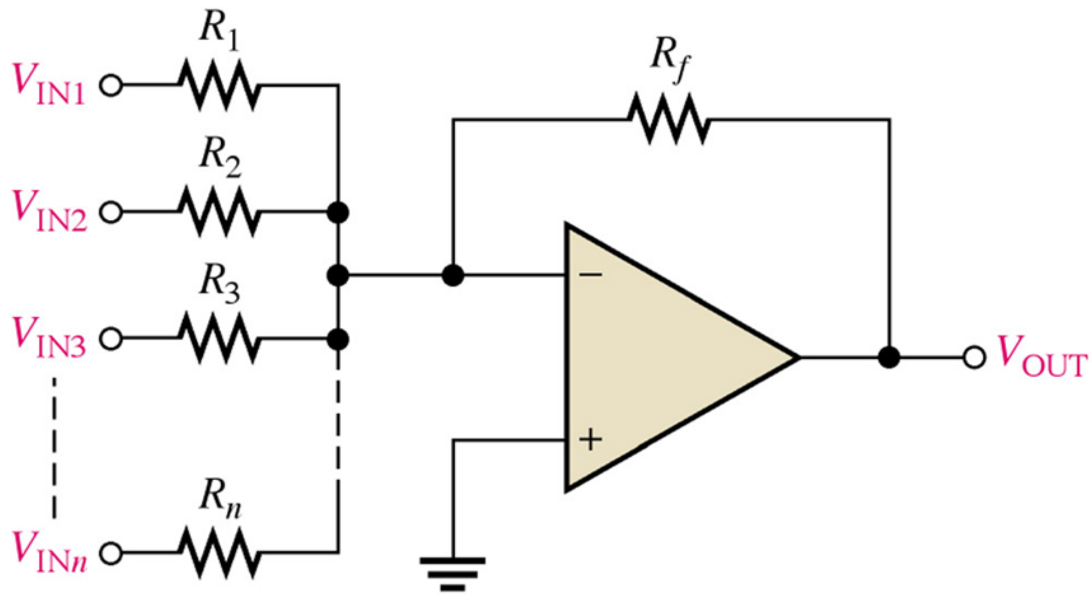


Figure 9: Summing amplifier with *n* inputs

- Summing amplifier has two or more inputs.
- Its output voltage is proportional to the negative sum of its input voltages.

$$V_{OUT} = -(V_{IN1} + V_{IN2} + V_{IN3} + \ldots + V_{INn})$$

Summing amplifier with gain greater than unity

- When Rf is larger than the input resistors, the amplifier has a gain of Rf/R.

$$V_{out} = -\frac{R_f}{R_1}\left(V_1 + V_2 + ... + V_N\right)$$

Averaging Amplifier

- A summing amplifier can be made to produce the average of the input voltages.
- n = number of inputs

$$\mathbf{R_f/R = 1/n}$$

Scaling adder

- Is a summing adder with each input having different gain
- The Rf to input resistance ratio would determine what the voltage output would be with a signal present at each output.

$$V_{OUT} = -\left(\frac{R_f}{R_1} V_{IN1} + \frac{R_f}{R_2} V_{IN2} + \ldots + \frac{R_f}{R_n} V_{INn} \right)$$

Example 4

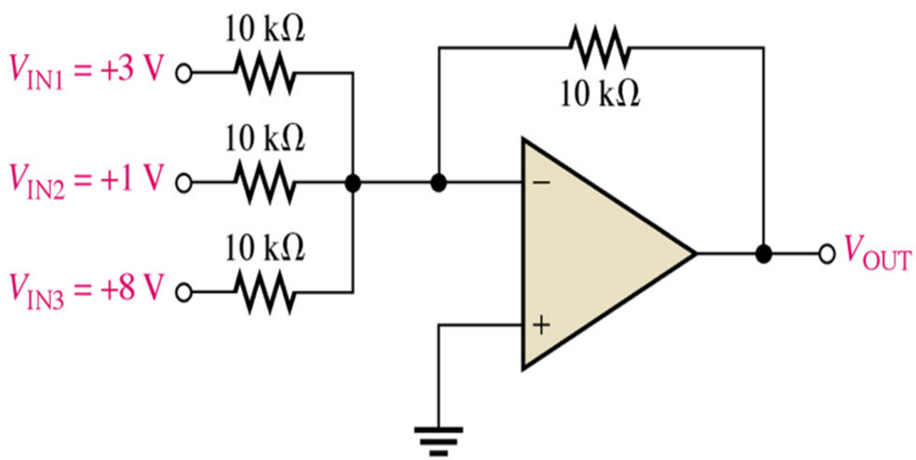


Figure (a)

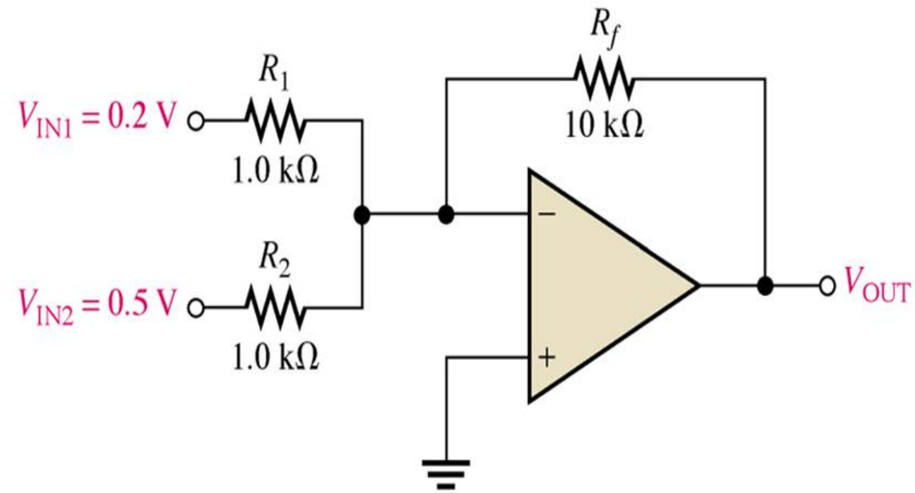
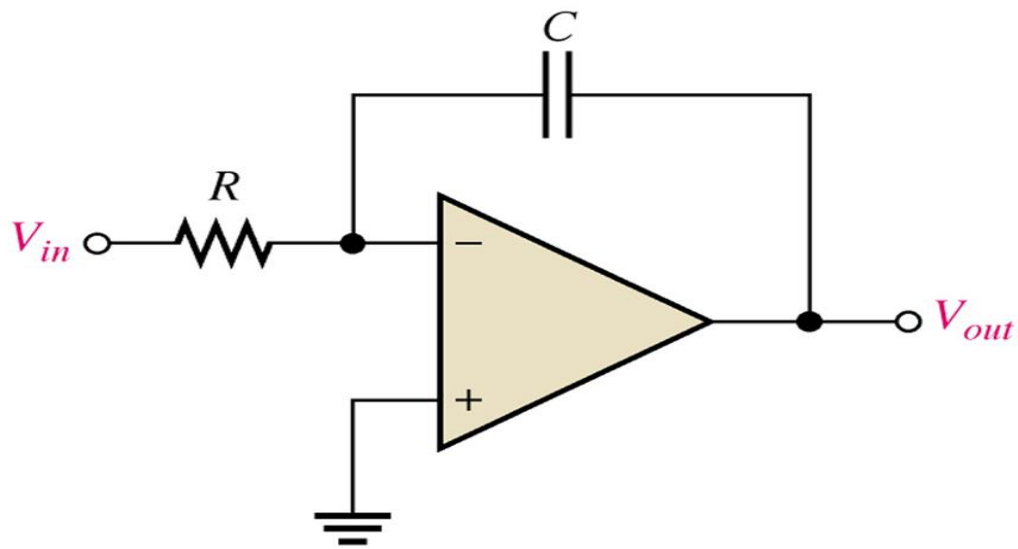


Figure (b)

Determine the output voltage for the summing amplifier in Figure (a) and (b).

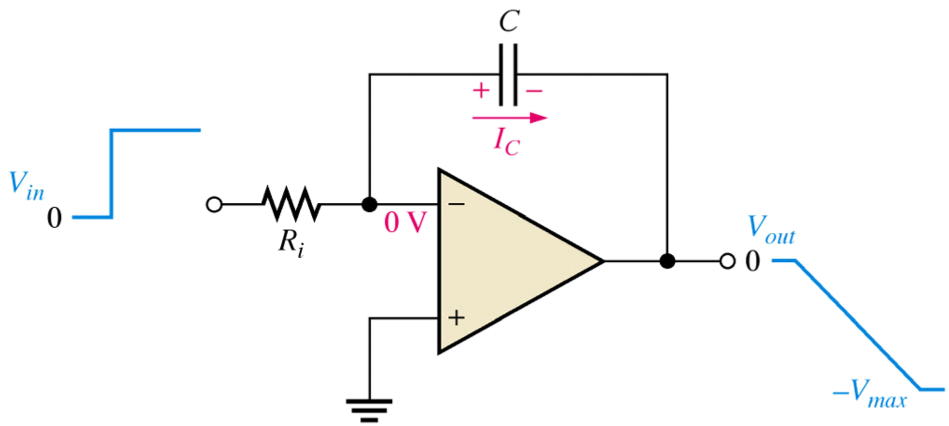
OP-AMP INTEGRATOR

Ideal Integrator



- The feedback element is a capacitor that forms an RC circuit with the input resistor.

Ideal Integrator

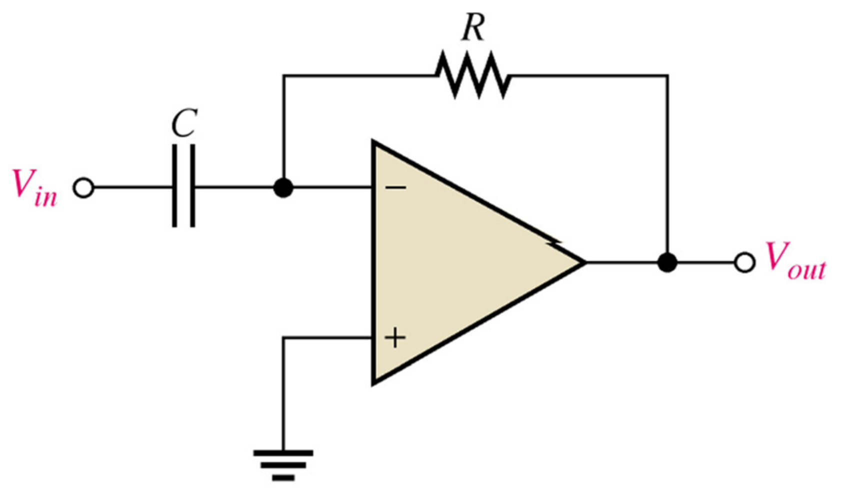


- When a constant positive step input voltage is applied, the output ramp decreases negatively until the op-amp saturates at its maximum negative level.
- The integrator can be used to change a square wave input into a triangular wave output.
- The rate of change of the output voltage:

$$\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{in}}{R_i C}$$

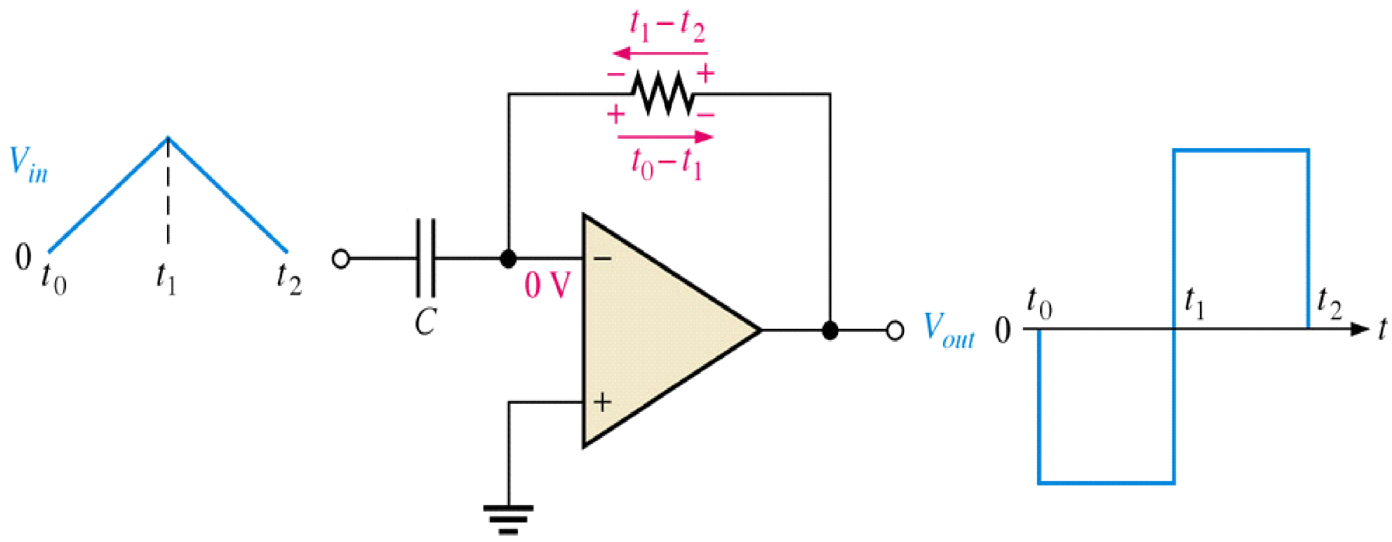
OP-AMP DIFFERENTIATOR

Ideal Differentiator



- The capacitor is the input element, and the resistor is the feedback element.
- A differentiator produces an output that is proportional to the rate of change of the input voltage.

$$V_{out} = -\left(\frac{V_C}{t}\right) R_f C$$



- When input is a positive-going ramp, the output is negative (capacitor is charging)
- When input is a negative-going ramp, the output is positive (capacitor is discharging) – current is the opposite direction