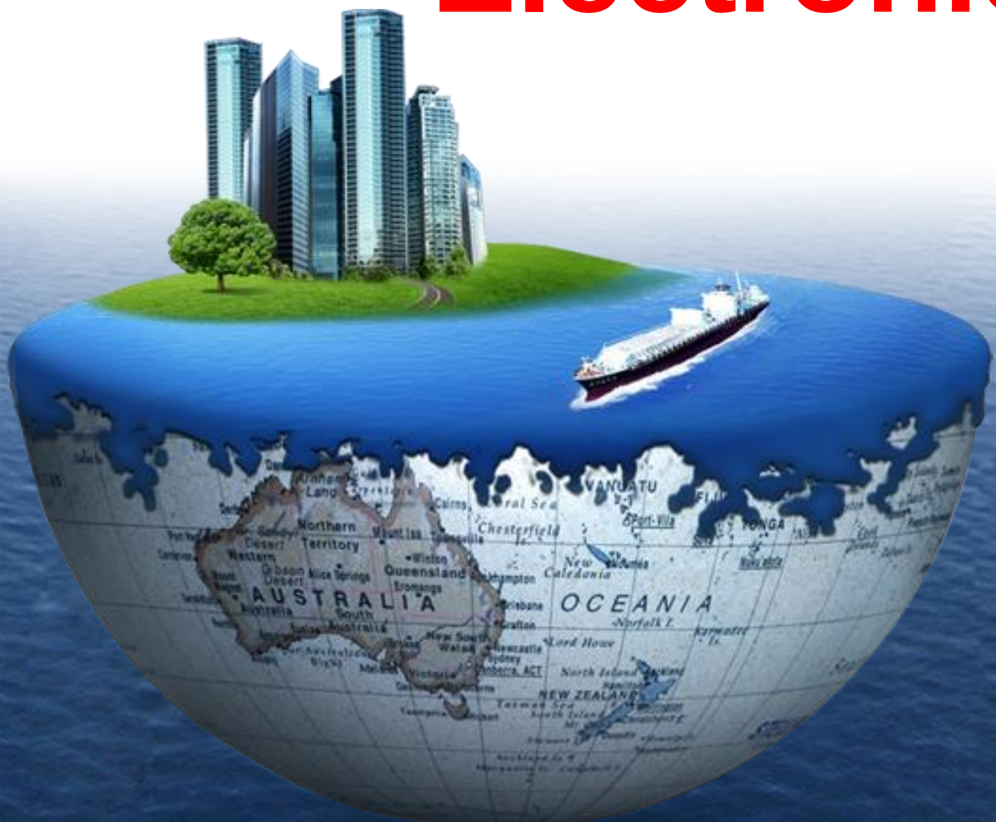
Electronic Engineering
COM 121



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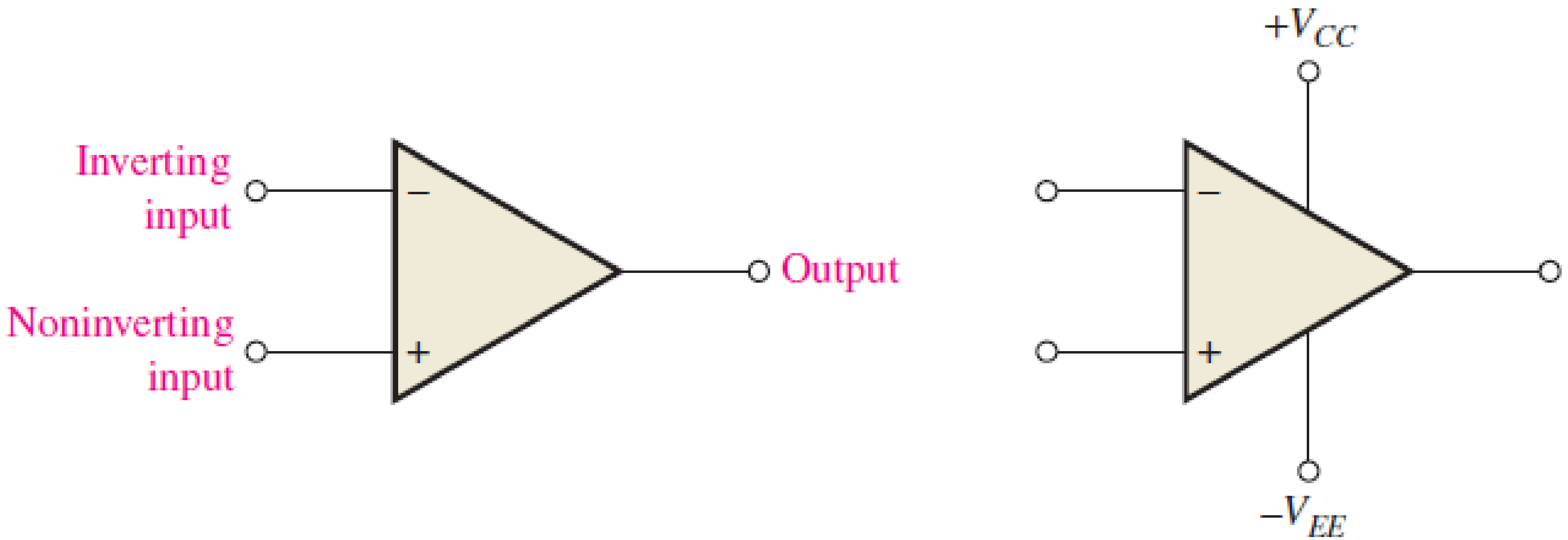
Electronics

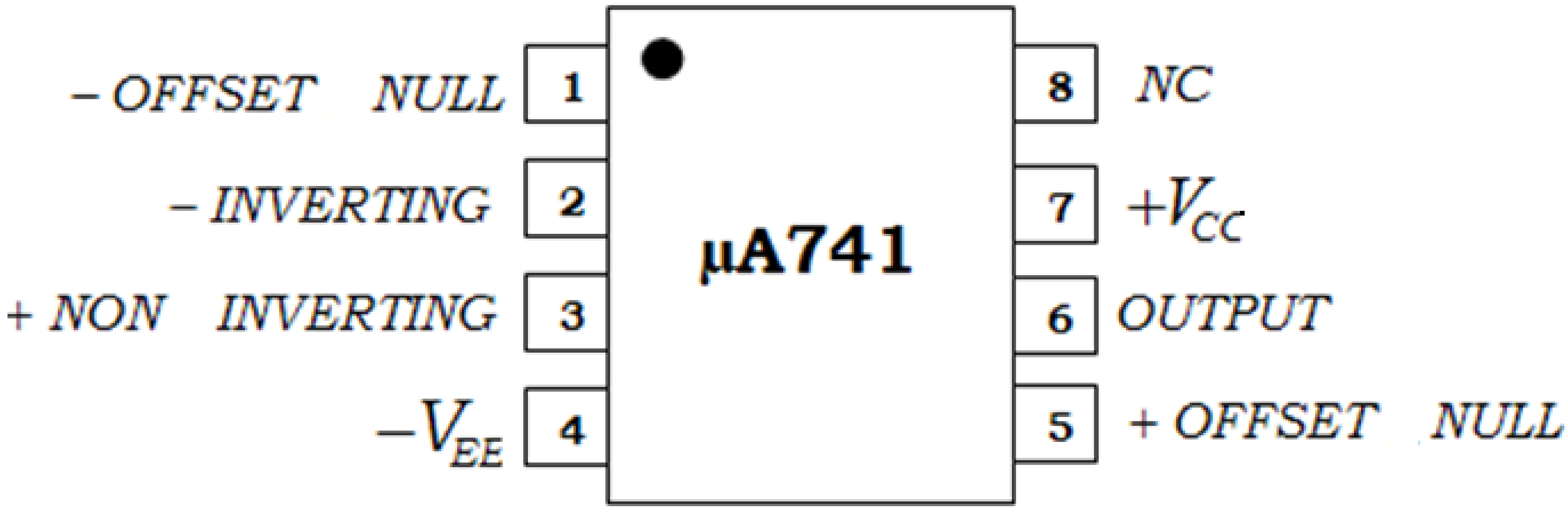
Operational Amplifiers

Introduction to operational Amplifier

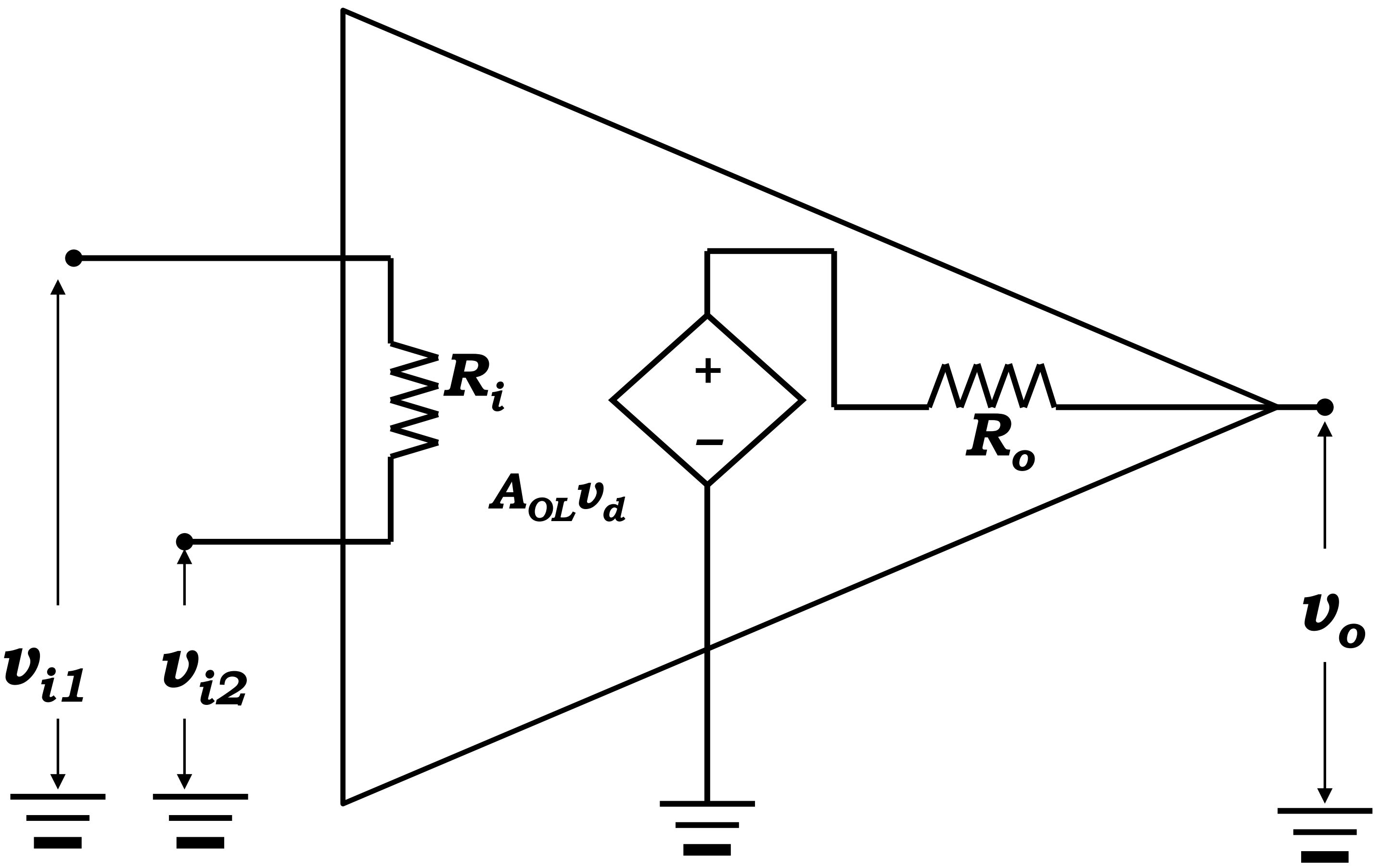
- Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation - thus the term operational.
- The standard operational amplifier (op-amp) symbol is shown in below



The 741 Op Amp



- The electric equivalent model of Practical Op-Amp:

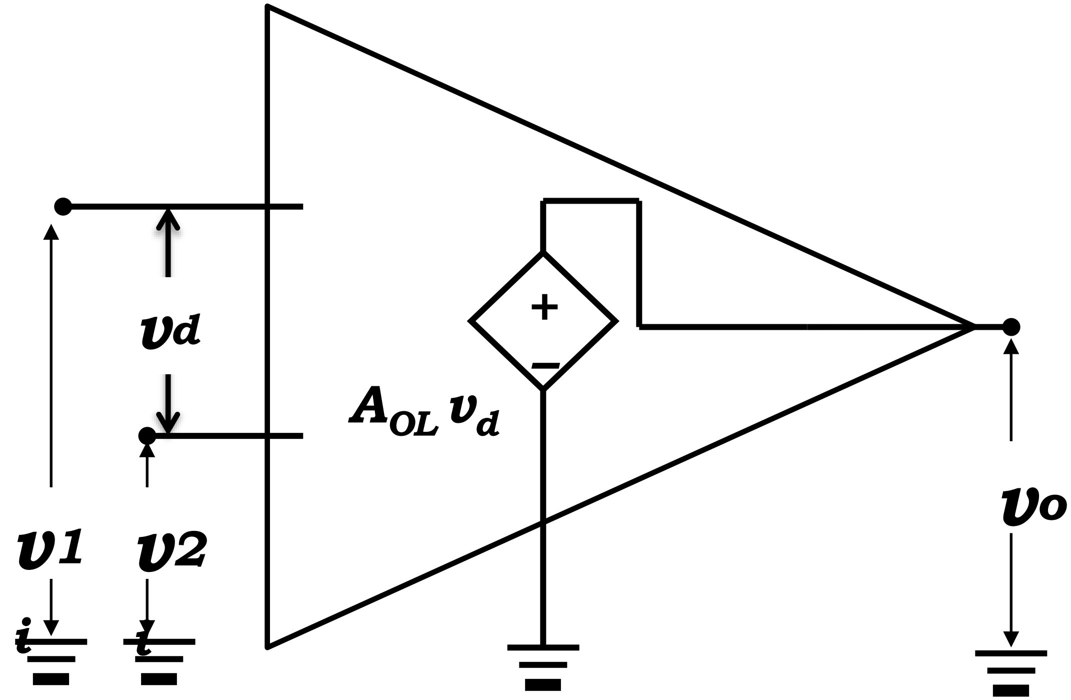


Introduction to Operational Amplifier

- **The electric equivalent model of Ideal Op-Amp:**

- For Ideal Op-Amp

Infinite input resistance (R_i) and Zero output resistance (R_o).

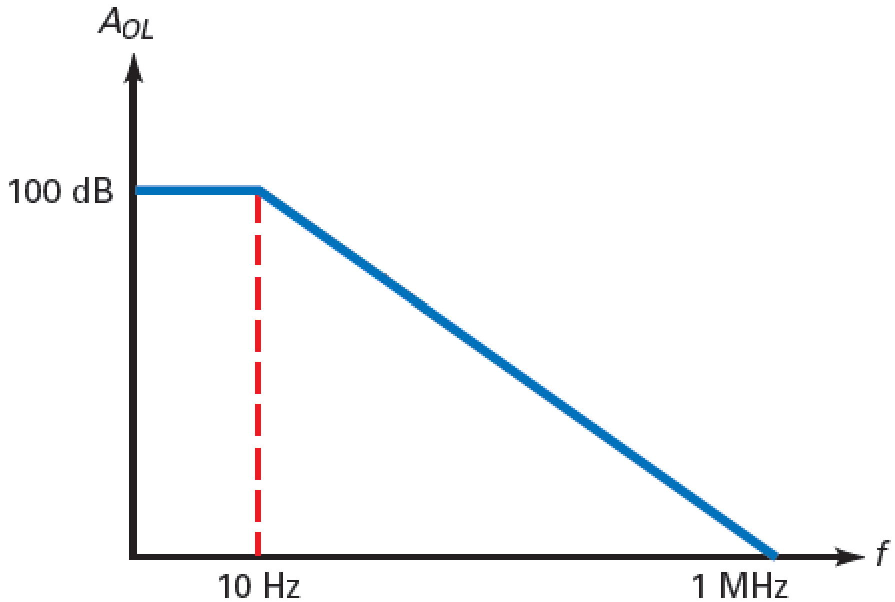


Performance Parameters of Op-Amp.

- **Key op-amp parameters includes the following:**
  - Bandwidth (BW)
  - Slew Rate (SR)
  - Open loop gain (A_{OL})
  - Common Mode Rejection Ratio (CMRR)
  - Power Supply Rejection Ratio (PSRR)
  - Input impedance (R_i)
  - Output impedance (R_o)

Bandwidth (BW) of Op-Amp.

- An ideal operational amplifier has an infinite frequency response so it is therefore assumed to have an infinite bandwidth.
- With real op-amps, the bandwidth is limited by the Gain-Bandwidth product (GB), which is equal to the frequency where the amplifiers gain becomes unity.
- The 741C has an open-loop voltage gain of 100,000, equivalent to 100 dB.



Slew Rate (SR) of Op-Amp.

- Slew rate equals the change in output voltage divided by the change in time.

$$SR = \frac{\Delta v_{out}}{\Delta t}$$

- For example, the slew rate of a 741C is 0.5 V/µs. This means that the output of a 741C can change no faster than 0.5 V in a microsecond.

Open loop gain (A_{OL}) of Op-Amp.

- When no feedback path (or loop) is used, the voltage gain is maximum and is called the open-loop voltage gain, designated A_{OL}.
- 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.
- Open-loop voltage gain can range up to 200,000 (10^6 dB).

Common Mode Rejection Ratio (CMRR) of Op-Amp.

- The ratio of differential gain to common-mode gain in an amplifier.
- The measure of an amplifier's ability to reject unwanted signal.
- 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.

Power Supply Rejection Ratio (PSRR):

- The PSRR is equals the change in the power supply voltage to corresponding change in the output voltage.

Input and Output impedance of Op-Amp.

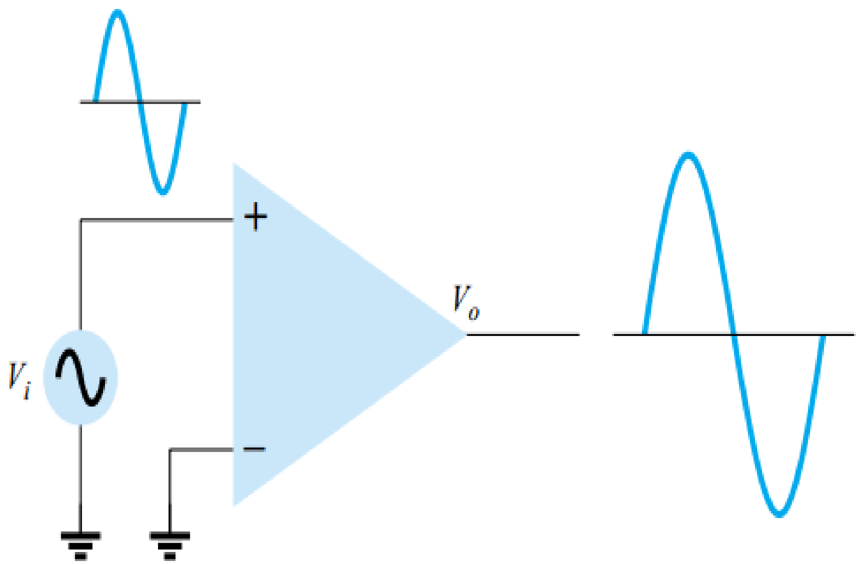
- **Input impedance (R_i):**
- It is the impedance looking into the input terminal of the op-amp.
- **Output impedance (R_o):**
- It is the impedance looking into the output terminal of the op-amp and ground.
- **Offset and Offset Drifts:**
- A diff amp has input bias and offsets that produce an output error when there is no input signal.

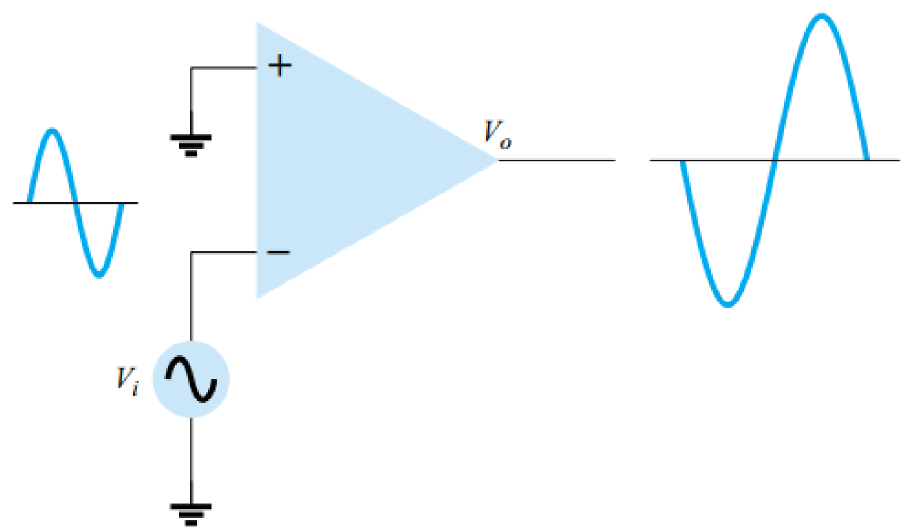
Difference between Ideal and Practical Op-Amp

Parameters	Ideal Op-Amp	Practical Op-Amp (E.g. LM 741)
Bandwidth (BW)	Infinite	1MHz
Slew Rate (SR)	Infinite	0.5 V / µs
Open loop gain (A_{OL})	Infinite	200,000
Common Mode Rejection Ratio (CMRR)	Infinite	90 dB
Power Supply Rejection Ratio (PSRR)	Zero	120 dB (+Supply) 110 dB (-Supply)
Input impedance (Ri)	Infinite	2 MΩ
Output impedance (Ro)	Zero	75 Ω
Offset and Offset Drifts	Zero	1mV, 20nA

Op-amp input modes and parameters.

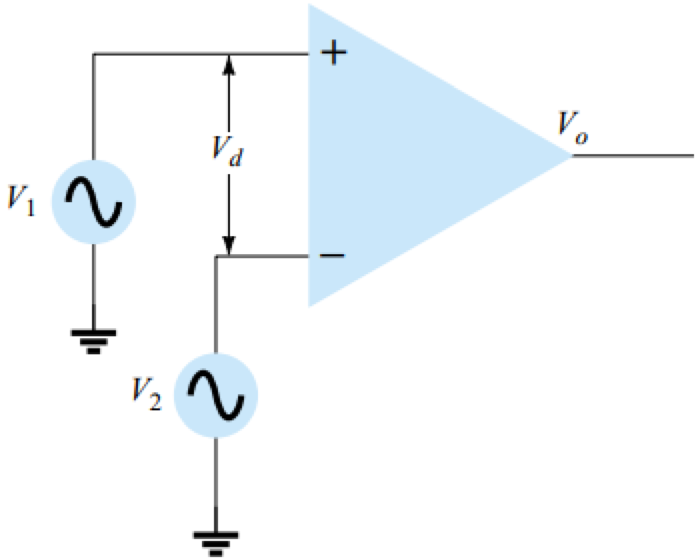
- **Single-Ended Mode :**one input is grounded and a signal is applied to the other input.

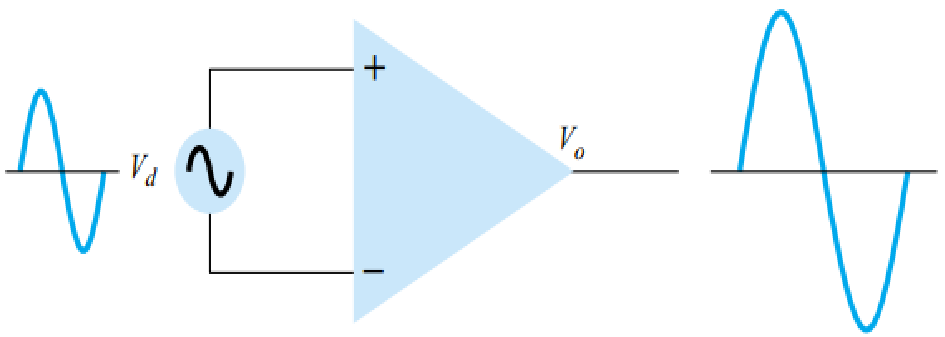




- **Double-Ended (Differential) Input**:

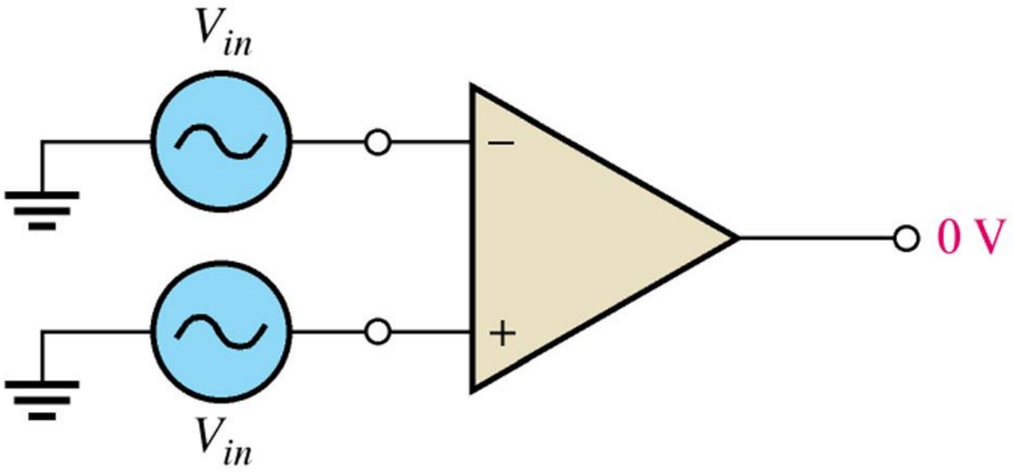
Two out-of-phase signals are applied and the difference of the two amplified and produced at the output.





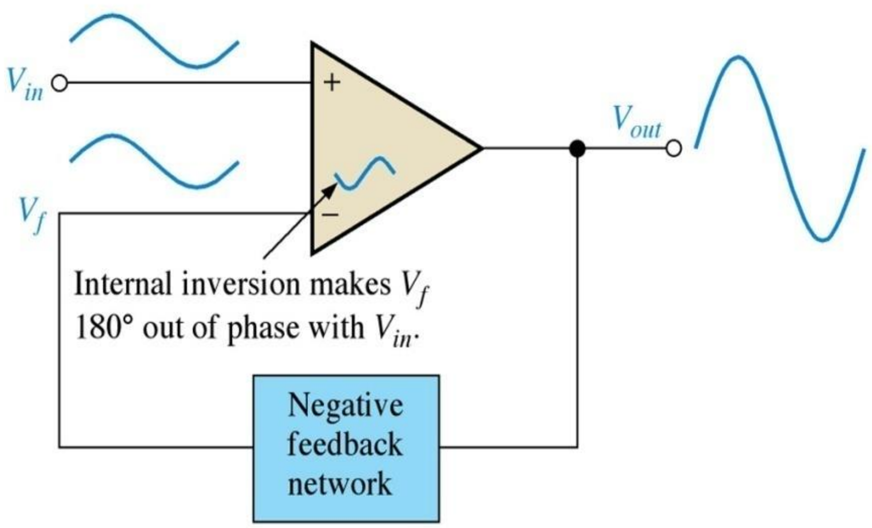
Op-amp input modes and parameters.

- **Common-Mode Operation**
- When the same input signals are applied to both inputs
- The two inputs are equally amplified, and since they result in opposite polarity signals at the output, these signals cancel, resulting in 0-V output.



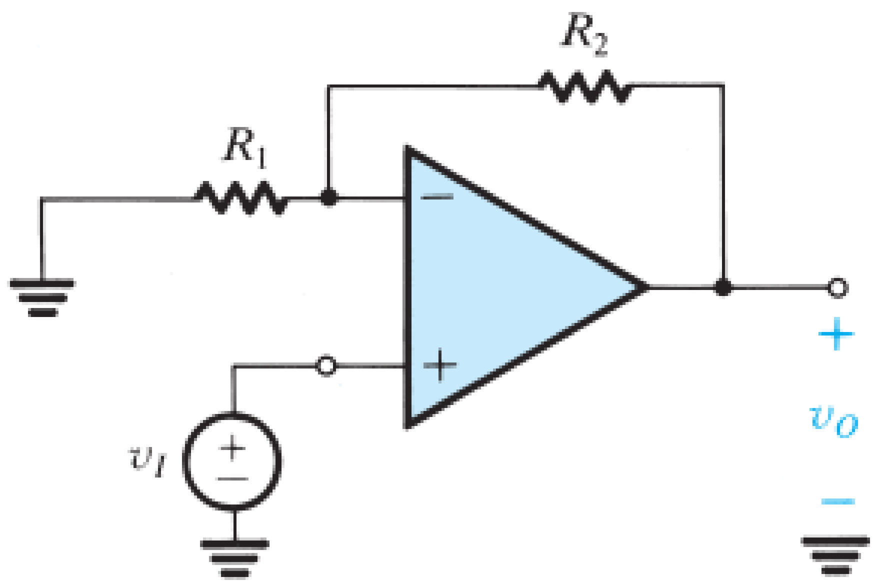
Op-Amps With Negative Feedback

- Negative feedback is feeding part of the output back to the input to limit the overall gain.
- The *closed-loop voltage gain* (A_{cl}) can be reduced and controlled , so the op-amp can function as a linear amplifier.
- providing a controlled, stable voltage gain.
- provide control of the input and output impedances and amplifier bandwidth.



Non-inverting Amplifier Configuration

- The voltage at the inverting input terminal will be equal to that at the non-inverting input terminal, which is the applied voltage v_1.



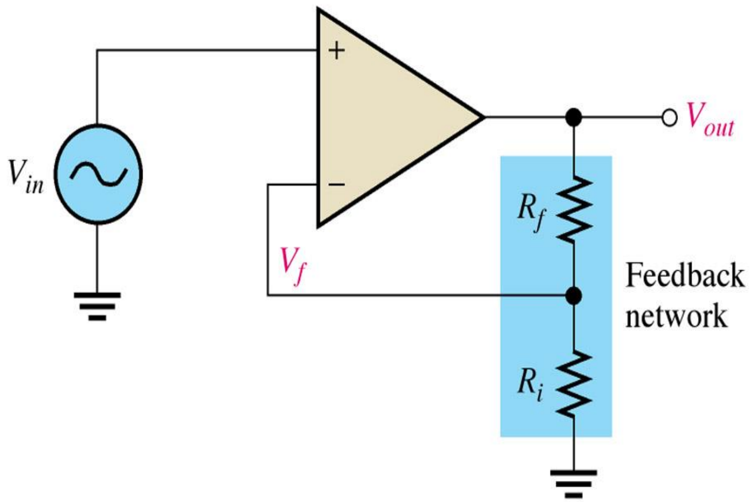
Closed-loop voltage gain of Non-Inverting Op-Amp

$$V_{out} = A_{ol}\left(V_{in} - V_f\right)$$

$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

$$B = \frac{R_i}{R_i + R_f}$$

$$\therefore \qquad V_f = BV_{out}$$



$$\therefore \qquad V_{out} = A_{ol}\left(V_{in} - BV_{out}\right)$$

$$= A_{ol}V_{in} - A_{ol}BV_{out}$$

Closed-loop voltage gain of Non-Inverting Op-Amp

$$\therefore \quad A_{ol}V_{in} = V_{out} + A_{ol}BV_{out}$$

$$= V_{out}\left(1 + A_{ol}B\right)$$

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$

$$\because \quad A_{ol}B >> 1$$

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{A_{ol}B} = \frac{1}{B}$$

$$A_{cl(NI)} = \frac{V_{out}}{V_{in}} = \frac{1}{B} = \frac{R_i + R_f}{R_i}$$

Closed-loop voltage gain of Non-Inverting Op-Amp

- **The closed loop voltage gain :**

$$A_{cl(NI)} = \frac{v_o}{v_i}$$

$$\boxed{\therefore A_{cl(NI)} = 1 + \frac{R_f}{R_i}}$$

- **Note:**

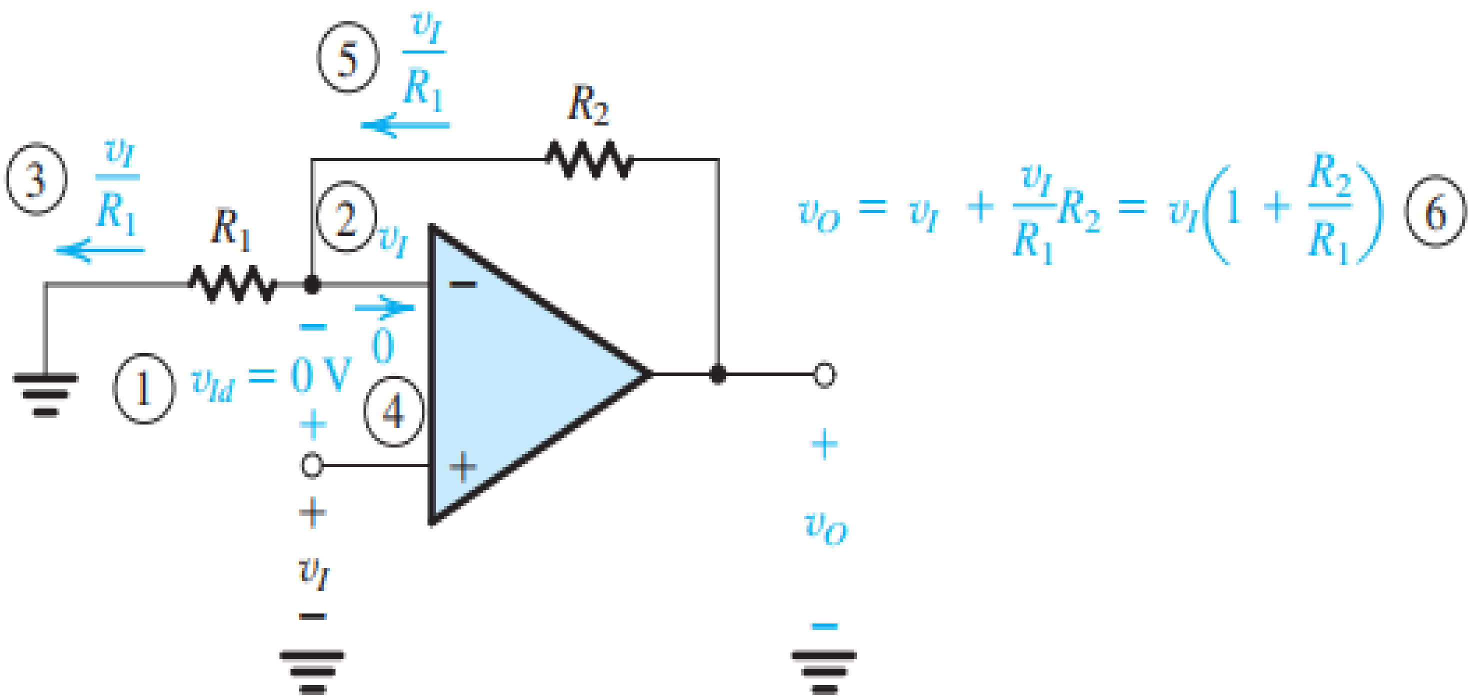
The closed-loop voltage gain is not at all dependent on the op-amp's open-loop voltage gain

Non-inverting Amplifier Configuration

- By applying KCL at node 2:

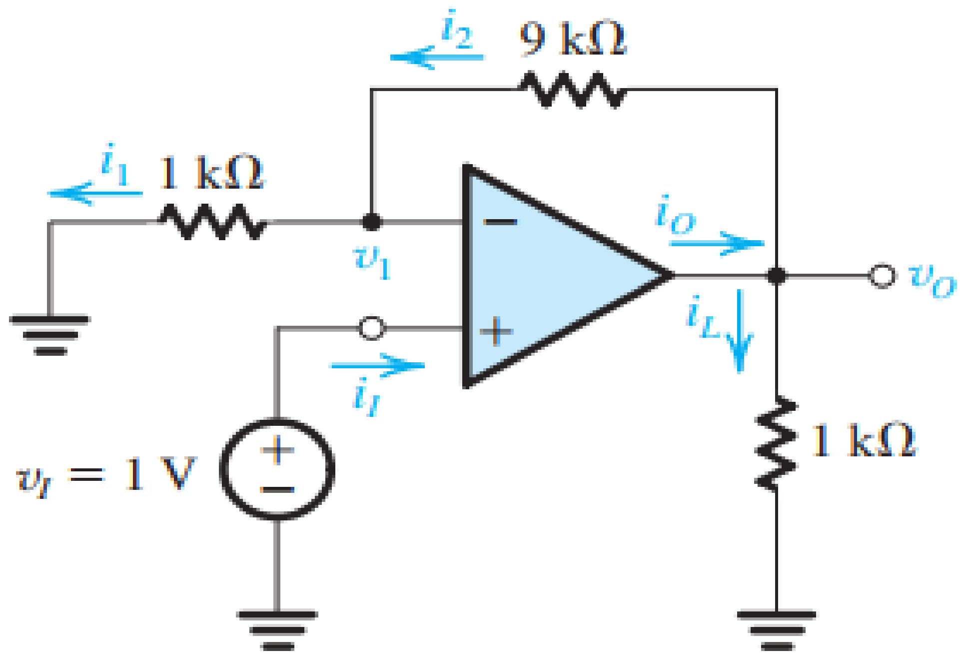
$$\therefore\ I_1 = I_2$$

$$\therefore\ \frac{(v_o - v_1)}{R_2} = \frac{v_1}{R_1}$$



Assignment

- For the circuit shown in figure, find the values of $i_I, v_1, i_1, i_2, v_O, i_L,$ *and* i_O.
- Also find the voltage gain v_O/v_I, the current gain i_L/i_I.



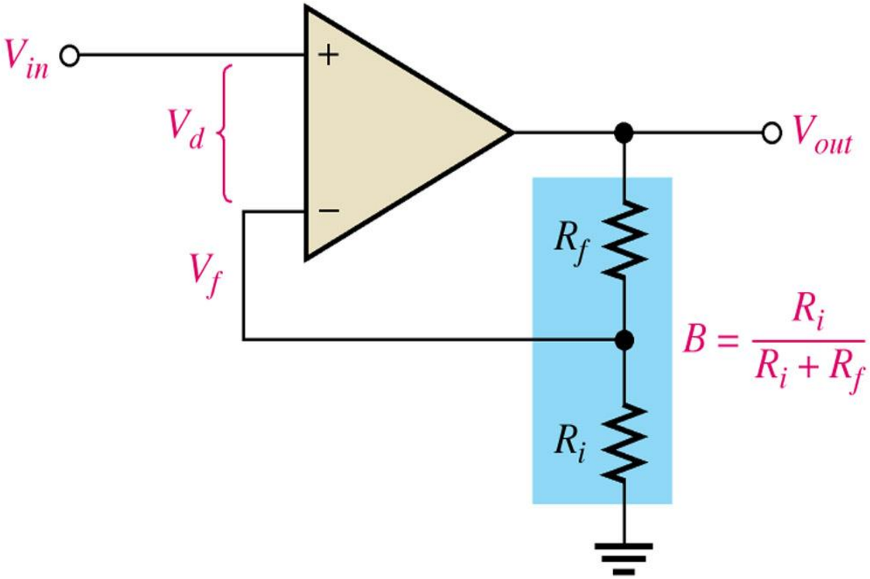
Impedances of a Non-inverting Amplifier

Input impedance

Assume a small differential voltage, V_d , exists between the two inputs. *So* $Z_{in} \neq \infty$ *and* $I_{in} \neq 0$ **. the input voltage is**

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

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



Impedances of a Non-inverting Amplifier

$$Since, \qquad V_{out} \cong A_{ol} V_d$$

$$V_{in} = V_d + A_{ol} B V_d = V_d \left(1 + A_{ol} B\right)$$

$$\because \qquad V_d = I_{in} Z_{in}$$

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

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

Impedances of a Non-inverting Amplifier

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

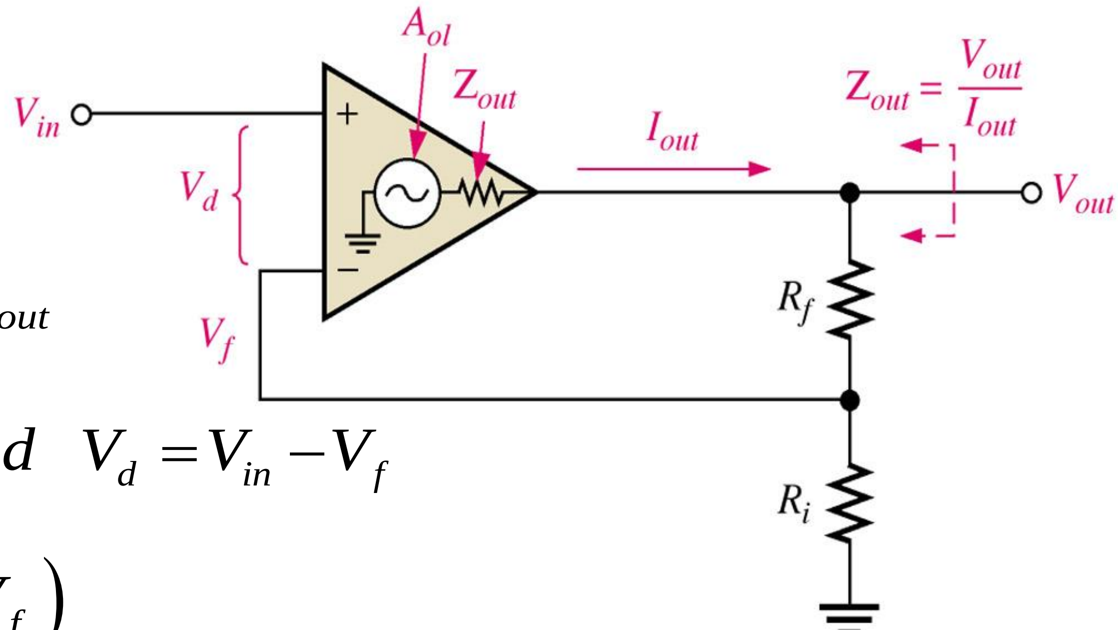
$$\boxed{Z_{in(NI)} = Z_{in}\left(1 + A_{ol}B\right)}$$

$Z_{in(NI)}$ is the overall input impedance of a closed-loop non-inverthg amplifier configuration. and $Z_{in(NI)} >> Z_{in}$

Impedances of a Non-inverting Amplifier

Output Impedance

By applying Kirchhoff's law to the output circuit,



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

$$\because \quad A_{ol} V_d >> Z_{out} I_{out} \quad , \quad and \quad V_d = V_{in} - V_f$$

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

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

Impedances of a Non-inverting Amplifier

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

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

Since the output impedance of the non-inverting amp is

$$Z_{out(NI)} = {V_{out}}/{I_{out}}$$

$$A_{ol}V_{in} \cong I_{out}Z_{out(NI)}\left(1 + A_{ol}B\right)$$

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

Impedances of a Non-inverting Amplifier

the internal output impedance of the op-amp without feedback (Z_{out}), therefore $A_{ol}V_{in}=V_{out}$

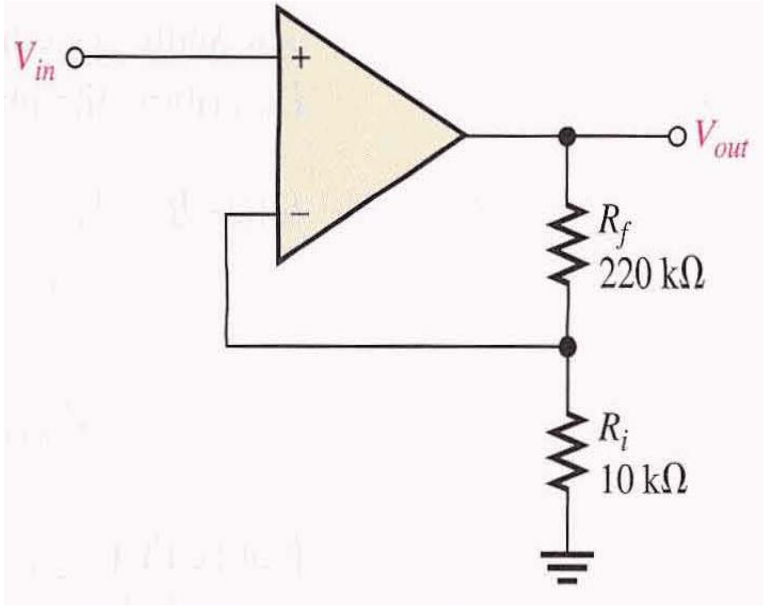
$$Z_{out} \cong Z_{out(NI)}\left(1+A_{ol}B\right) \rightarrow \boxed{Z_{out(NI)} \cong \frac{Z_{out}}{1+A_{ol}B}}$$

Example

For the circuit in the figure:

(a) Determine the input and output impedances of the amplifier. The op-amp data sheet gives Z_{in} = 2 MΩ, Z_{out}= 75 Ω, and A_{ol} = 200,000.

(b) Find the closed-loop voltage gain.



Example

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

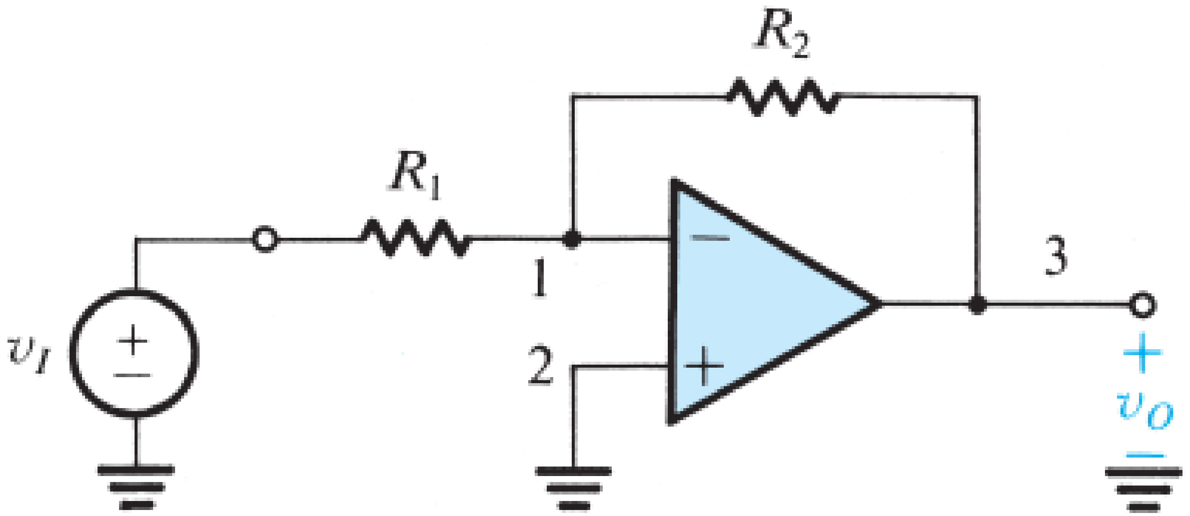
$$\begin{aligned} Z_{in(NI)} &= Z_{in}\left(1 + A_{ol}B\right) \\ &= 2\times10^{6}\left(1 + 200,000\times0.0435\right) \\ &= 17.4G\Omega \end{aligned}$$

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75}{1+8700} = 8.6\times10^{-3}\Omega$$

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{220}{10} = 23$$

Inverting Configuration Op-Amp

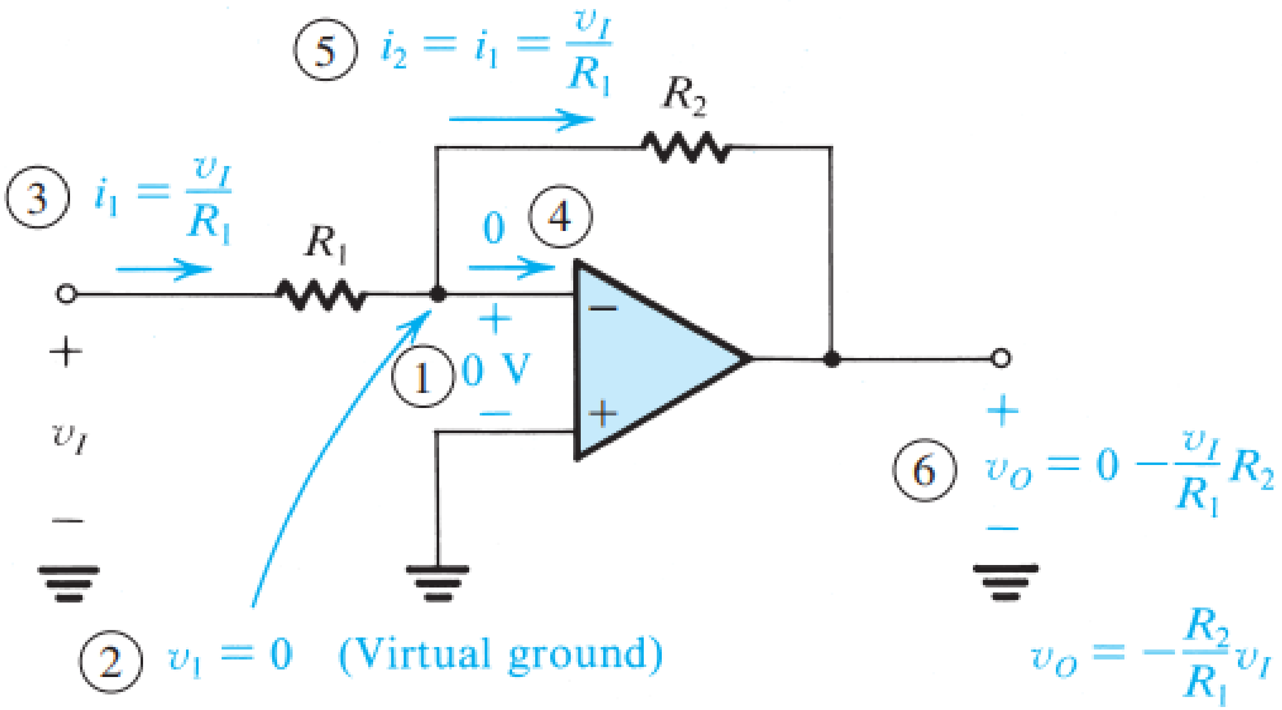
- The input signal is applied through a series input resistor R_1 to the inverting (-) input.
- The output of the overall circuit is taken at terminal 3.



Inverting closed-Loop Gain

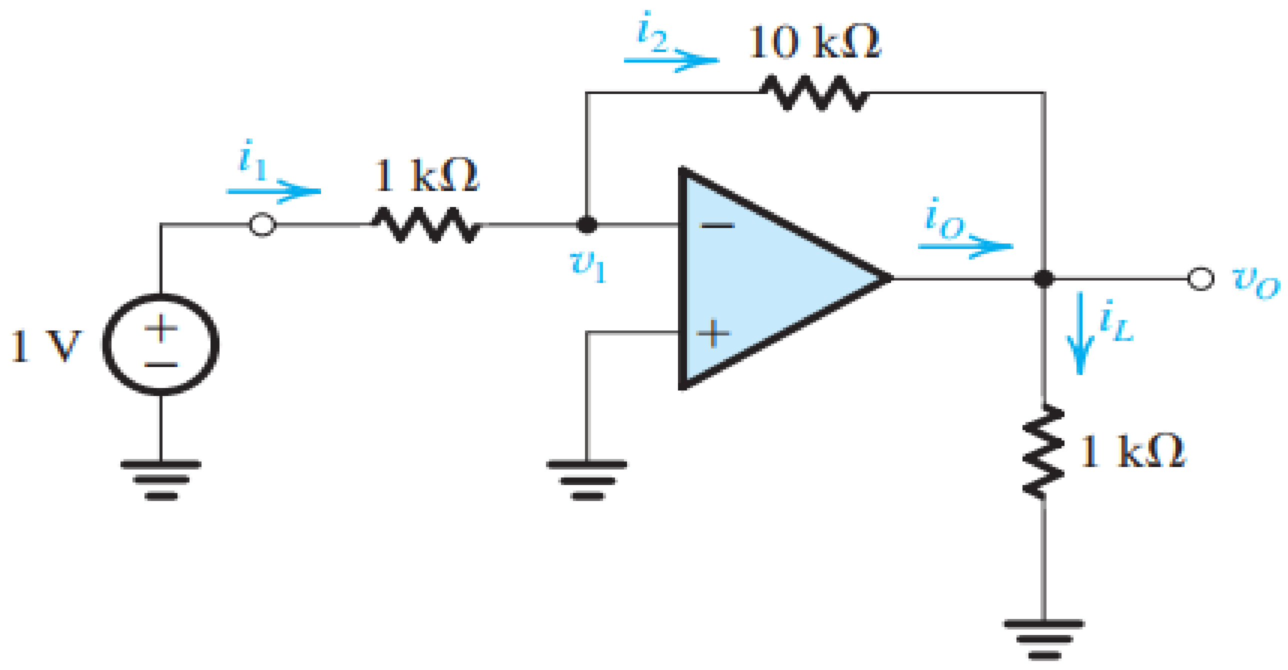
$$i_1 = i_2$$

- $\frac{0-v_1}{R_1} = \frac{v_0-0}{R_2} \Rightarrow \frac{v_o}{v_1} = -\frac{R_2}{R_1} \Rightarrow A_{cl}(IN) = -\frac{R_2}{R_1}$



Example

- For the circuit in Figure determine the values of $v_1, i_1, i_2, vO, iL, and\ i_O$. Also determine the voltage gain v_O/v_I, current gain i_L/i_I, and power gain P_O/PI.



Solution

$$V_1 = 0, \qquad i_1 = \frac{V_i - V_1}{R_1} = \frac{1-0}{1\,k\Omega} = 1\,mA$$

$$i_1 = i_2, \qquad \therefore\ i_2 = 1\,mA$$

$$i_2 = \frac{V_1 - V_o}{R_2}, \qquad \frac{0 - V_o}{10\,k\Omega} = 1\,mA$$

$$\therefore\ V_o = -10\,V$$

$$i_L = \frac{V_0 - V_0}{R_L} = \frac{-10-0}{1\,k\Omega} = -10\,mA$$

Solution

$$i_L = i_o + i_2 \qquad \therefore i_o = i_L - i_2 = -10 - 1$$

$$\therefore i_o = -11\, mA$$

Voltage gain $A_v = \frac{V_o}{V_I} = \frac{-10}{1} = -10$

Current gain $A_c = \frac{i_L}{i_I} = \frac{-10}{1} = -10$

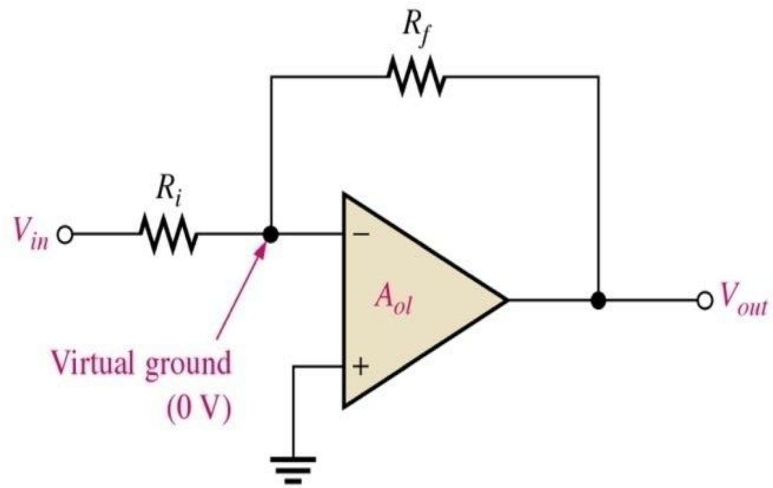
Power gain $A_v = \frac{P_o}{P_I} = \frac{100}{1} = 100$

Impedances of an Inverting Amplifier

➢ *Input Impedance*

The input impedance for an inverting amplifier is

$$Z_{in(I)} \cong R_i$$

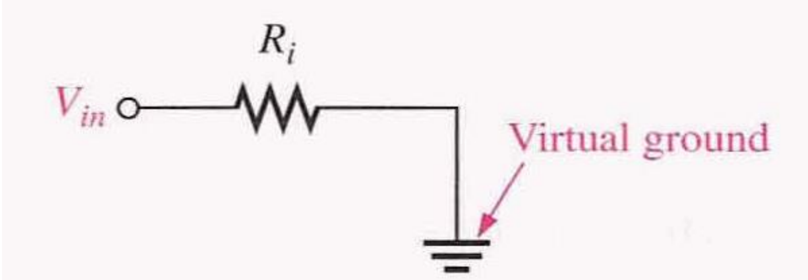


➢ *Output Impedance*

The expression is the same as for

the non-inverting case.

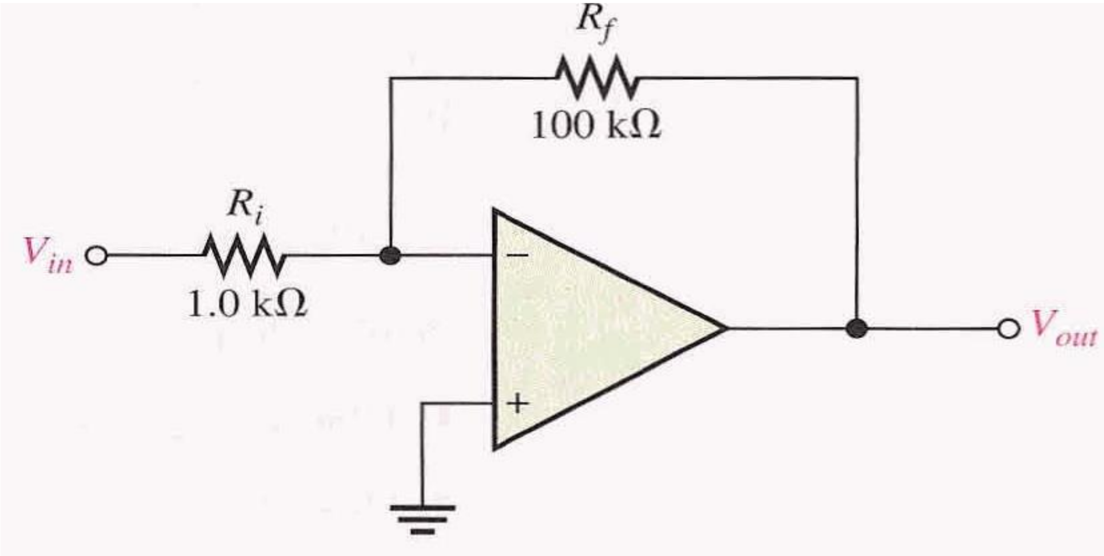
$$Z_{out(I)} \cong \frac{Z_{out}}{1 + A_{ol}B}$$



Example

Find the values of the input and output impedances. Also, determine the closed-loop voltage gain.

(Z_{in} = 4 MΩ, Z_{out}= 50 Ω, A_{ol} = 50,000).



Example

$$Z_{in(I)} \cong R_i = 1k\Omega$$

$$B = \frac{R_i}{R_i + R_f} = \frac{1}{101} = 0.001$$

$$Z_{out(I)} \cong \frac{Z_{out}}{1 + A_{ol}B} = \frac{50\Omega}{1+50} = 980\,m\Omega$$

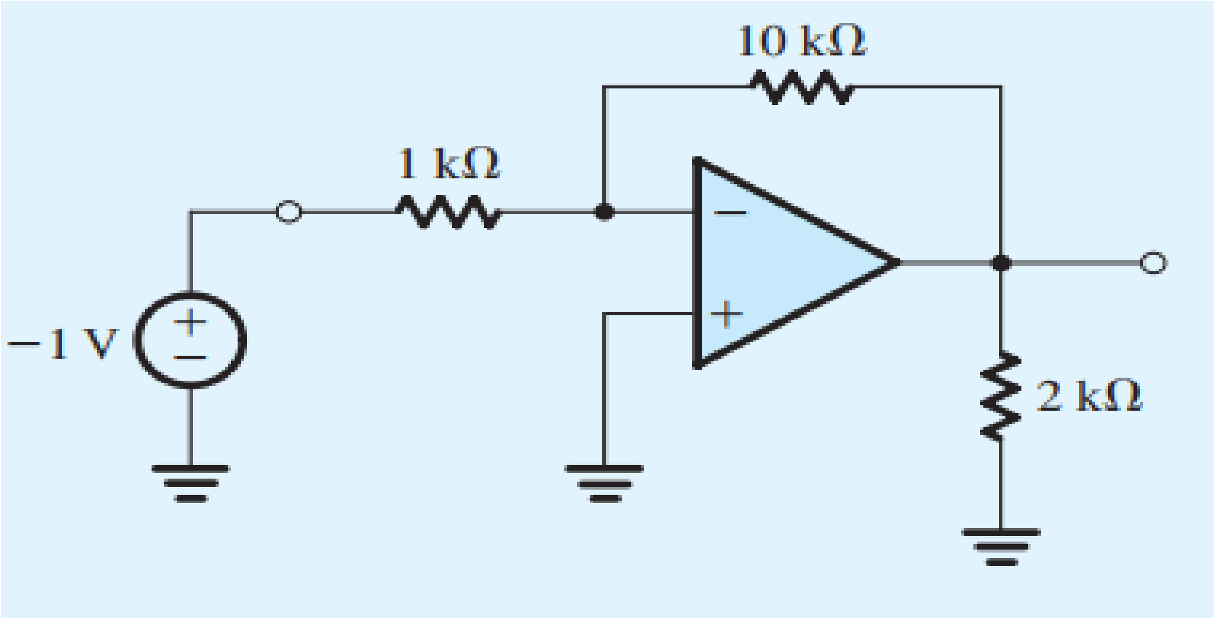
$$A_{cl(I)} = -\frac{R_f}{R_i} = -\frac{100}{1} = -100$$

Assignment

For the circuit in the figure:

(a) Determine the input and output impedances of the amplifier. The op-amp data sheet gives, Z_{out}= 75 Ω, and A_{ol} = 200,000.

(b) Find the closed-loop voltage gain.



Applications of Op-Amp

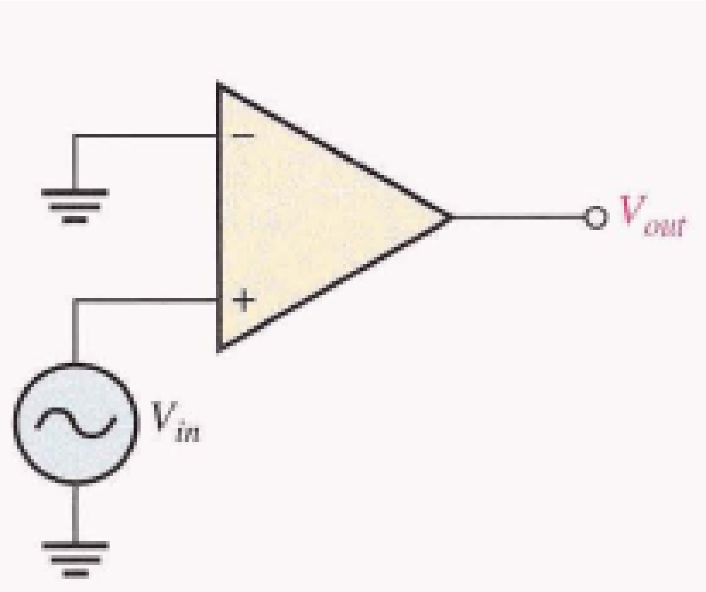
- Operational amplifiers are often used as comparators to compare the amplitude of one voltage with another.

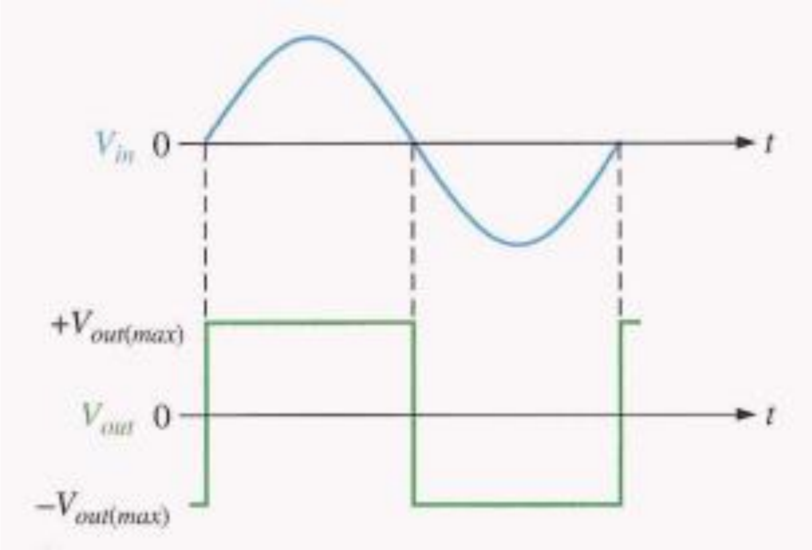
Zero-Level Detection:

- A comparator is a type of op-amp circuit that compares two input voltages and produces an output in either of two states indicating the greater than or less than relationship of the inputs.
- One application of an op-amp used as a comparator is to determine when an input voltage exceeds a certain level.

Comparator Op-amp

- When the sine-wave is positive, the output is at its maximum positive level.
- When the sine wave crosses *0*, the amplifier is driven to its opposite state and the output goes to its maximum negative level



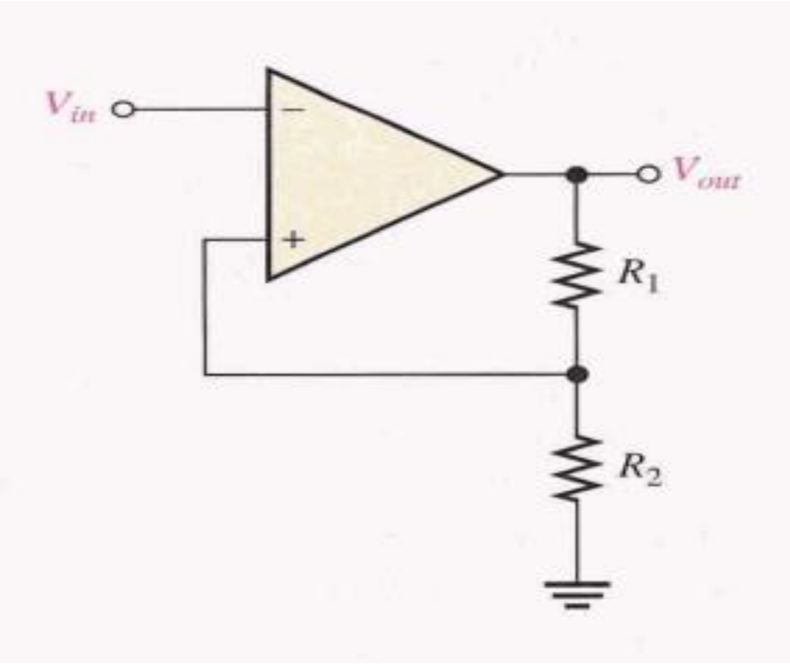


Comparator Op-amp

- In order to make the comparator less sensitive to noise, a technique positive feedback can be used.
- The two reference levels are referred to as the upper trigger point (UTP) and the lower trigger point (LTP).

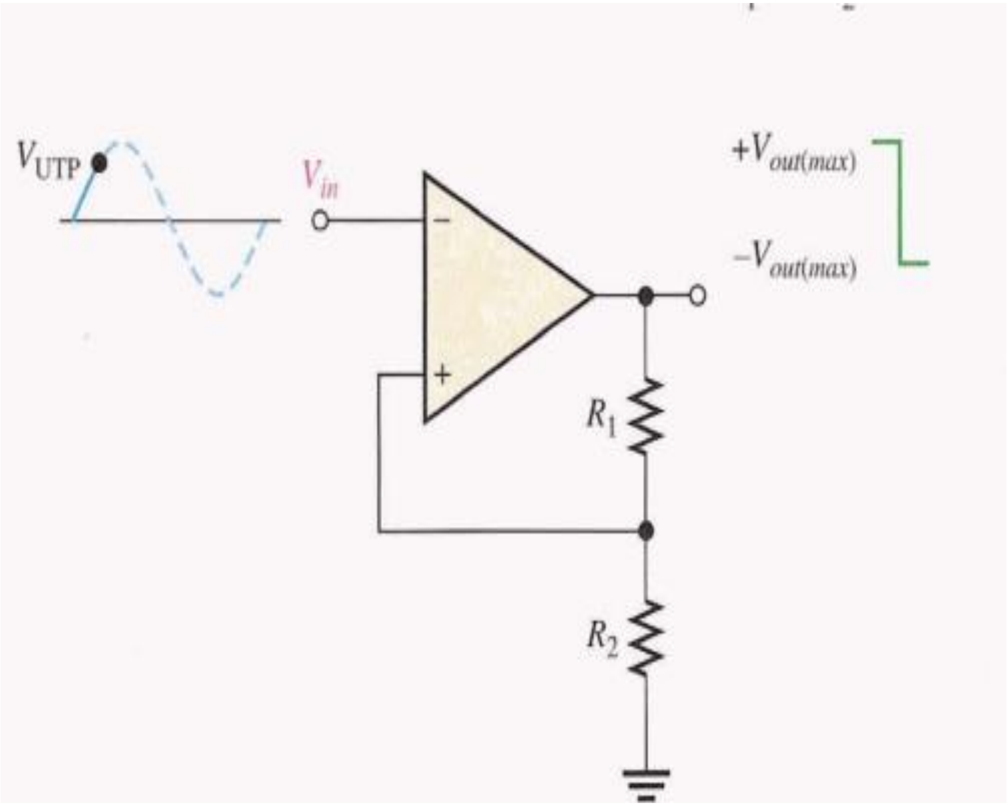
- $$V_{UTP} = \frac{R_2}{R_1+R_2}\,(+V_{out}(max))$$

- $$V_{LTP} = \frac{R_2}{R_1+R_2}\,(-V_{out}(max))$$



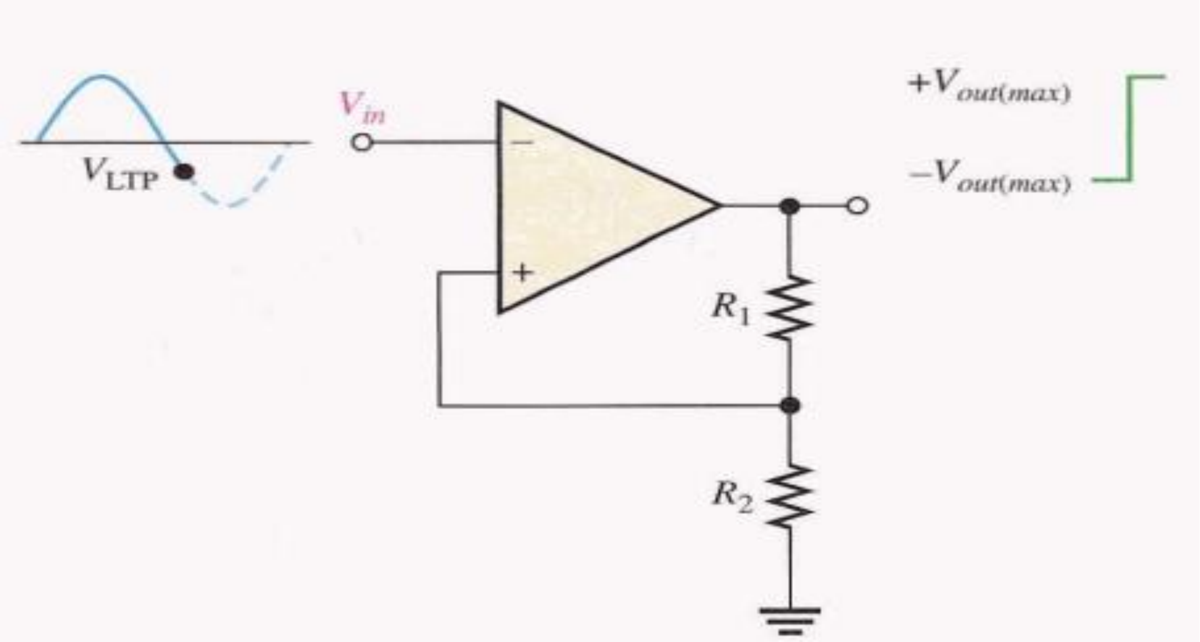
Comparator Op-amp

- When the output voltage is at its positive maximum, $+Vout$ (*max*), the voltage feed back to the noninverting input is V_{UTP} .
- When Vin,exceeds V_{UTP} the output voltage drops to its negative maximum, $-Vout$ (max) as shown in figure



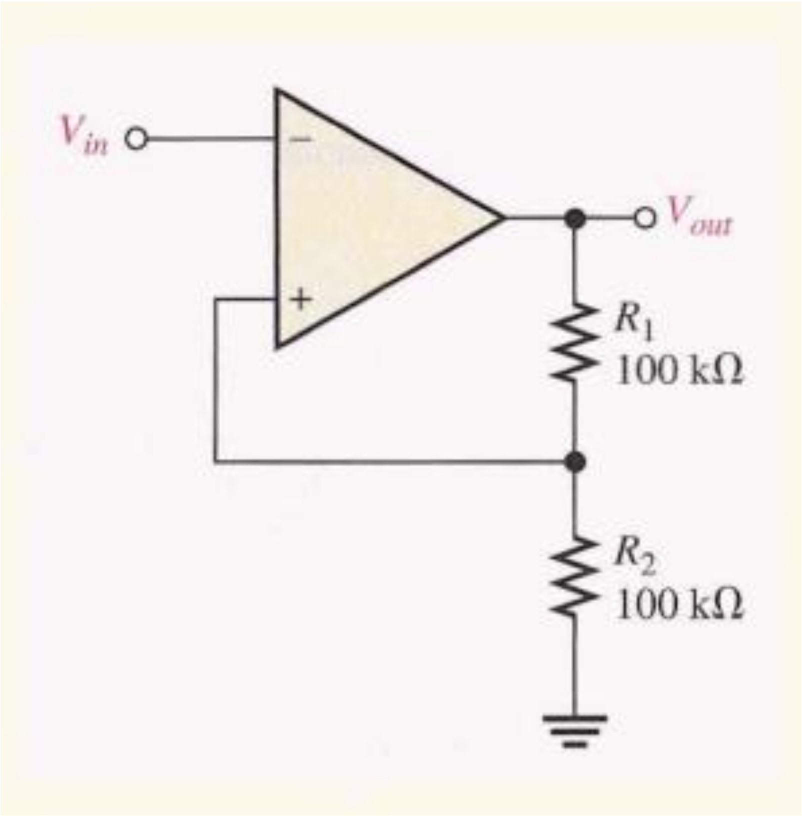
Comparator Op-amp

- Now the voltage feed back to the noninverting input is V_{LTp}.
- The input voltage must now fall below V_{LTP}, as shown in figure before the device will switch from the maximum negative voltage back to the maximum positive voltage.



Example

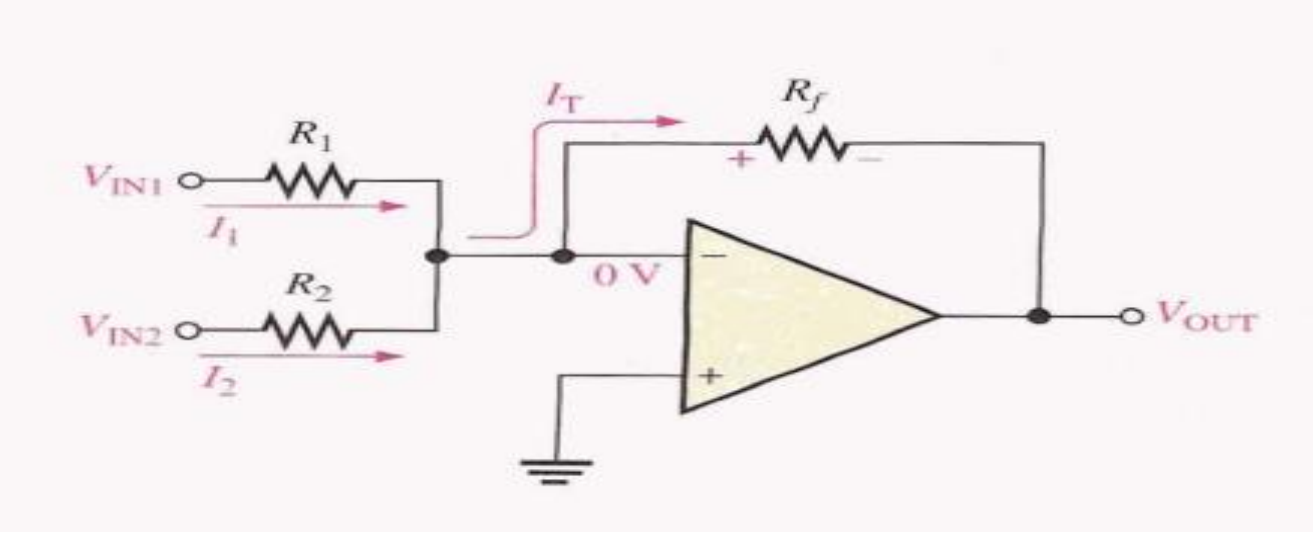
- Determine the upper and lower trigger points for the comparator circuit in figure.
- Assume that $+Vout(max) = +5\,V$ and $-Vout(min) = -5\,V$.



Summing Amplifiers

A summing amplifier: has two or more inputs, and its output voltage is proportional to the negative of the algebraic sum of its input voltage.

- One method of Digital to Analog conversion uses a scaling adder with input resistor values that represent the binary weights of the digital input code.



Summing Amplifiers

Summing amplifier with n inputs

$$I_1 + I_2 + \cdots \ldots \ldots \ldots \ldots \ldots \ldots + I_N = -I_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots + \frac{V_N}{R_n} = -\frac{V_{out}}{R_f}$$

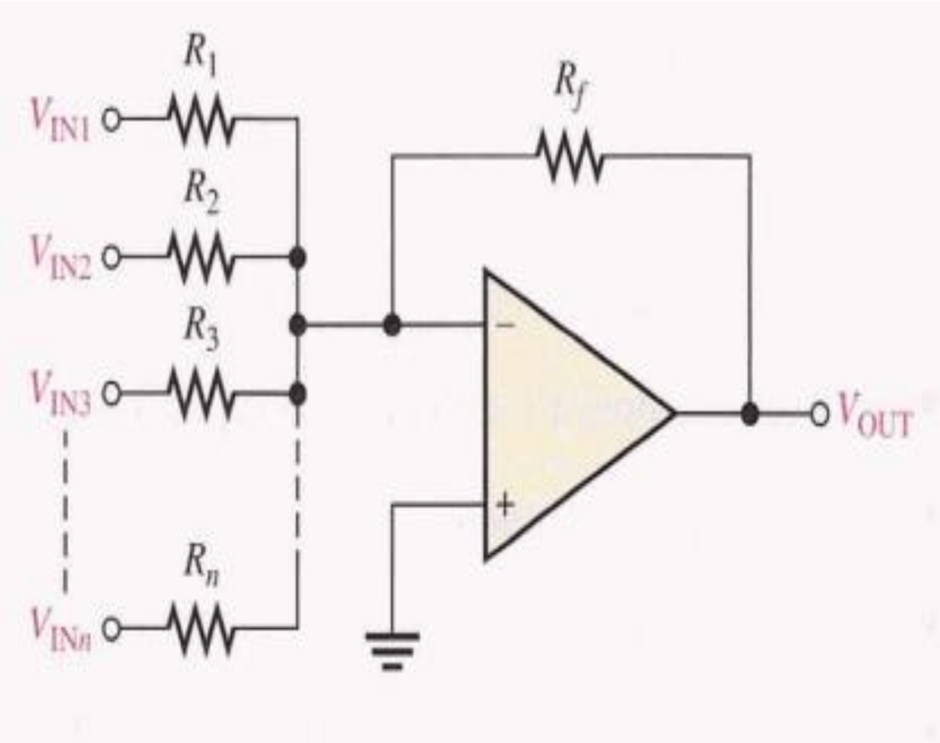
$$V_{out} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots \ldots \ldots \ldots\right.$$

$$\left.\ldots \ldots \ldots + \frac{V_N}{R_n}\right)$$

$$If\ R_1 = R_2 = \cdots \ldots \ldots \ldots \ldots \ldots = R_n = R$$

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + \cdots \ldots \ldots . . + V_N)$$

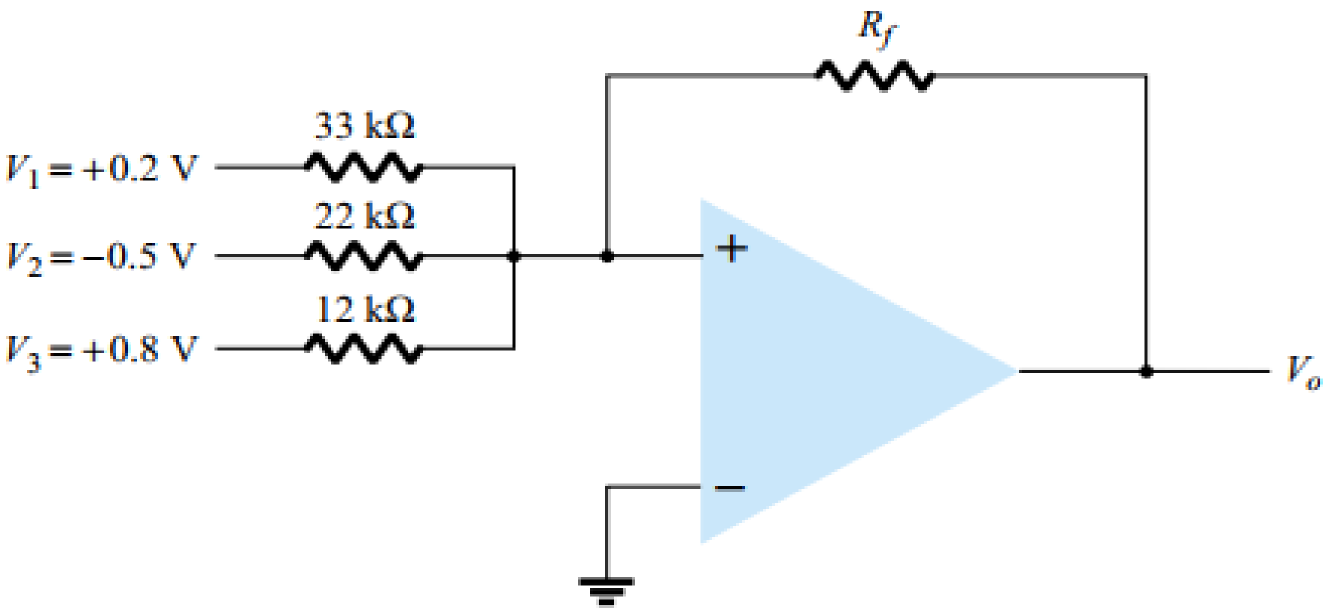
$$Gain = \frac{R_f}{R}$$



Example

Calculate the output voltage developed by the circuit of Figure for

$Rf = 330\ k\Omega$.

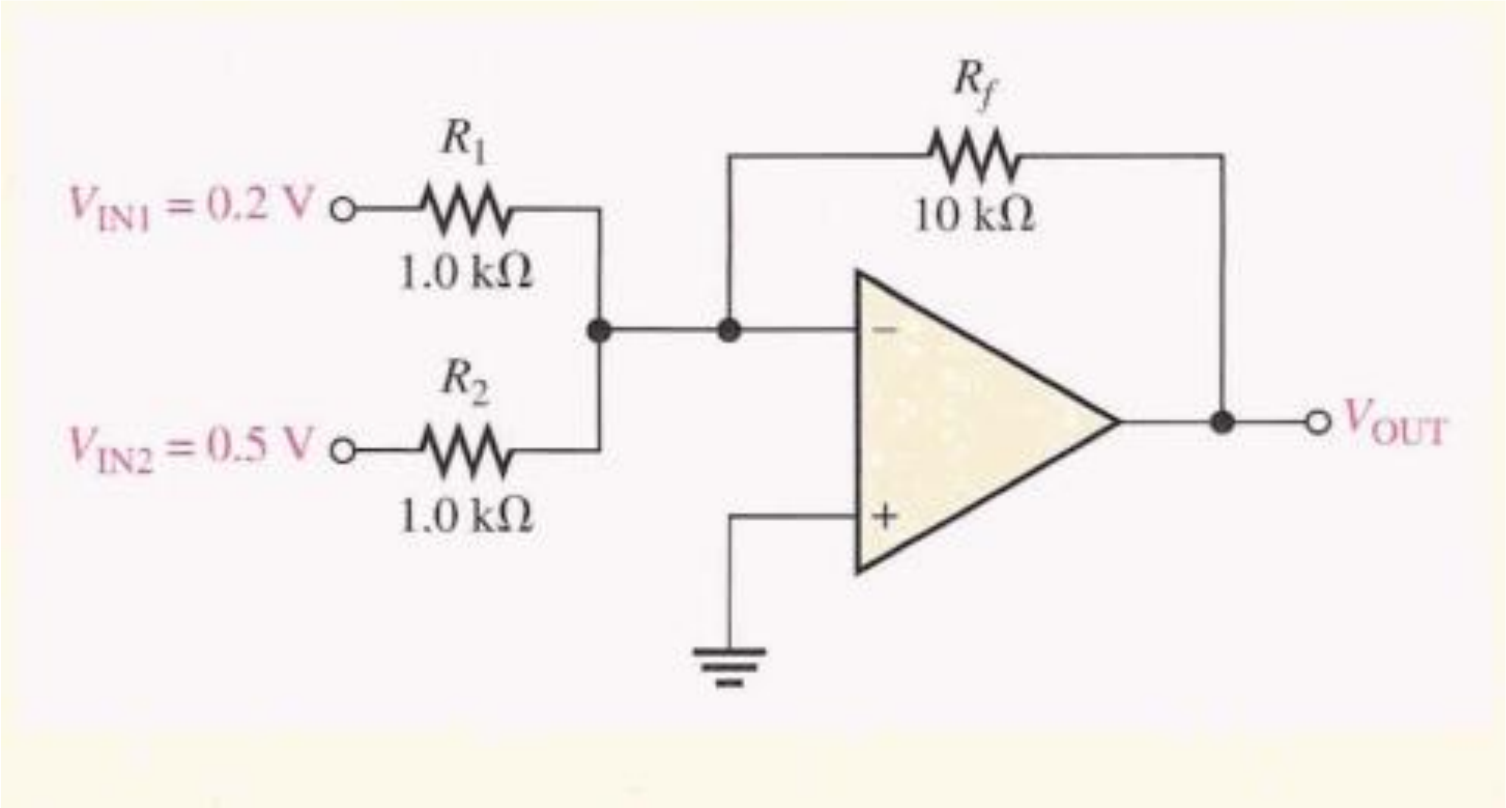


Solution

- $V_{out} = -R_f(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3})$
- $V_{out} = -320\ (\frac{0.2}{33} + \frac{-0.5}{22} + \frac{0.8}{12})$
- $V_{out} =$ **-16 v**

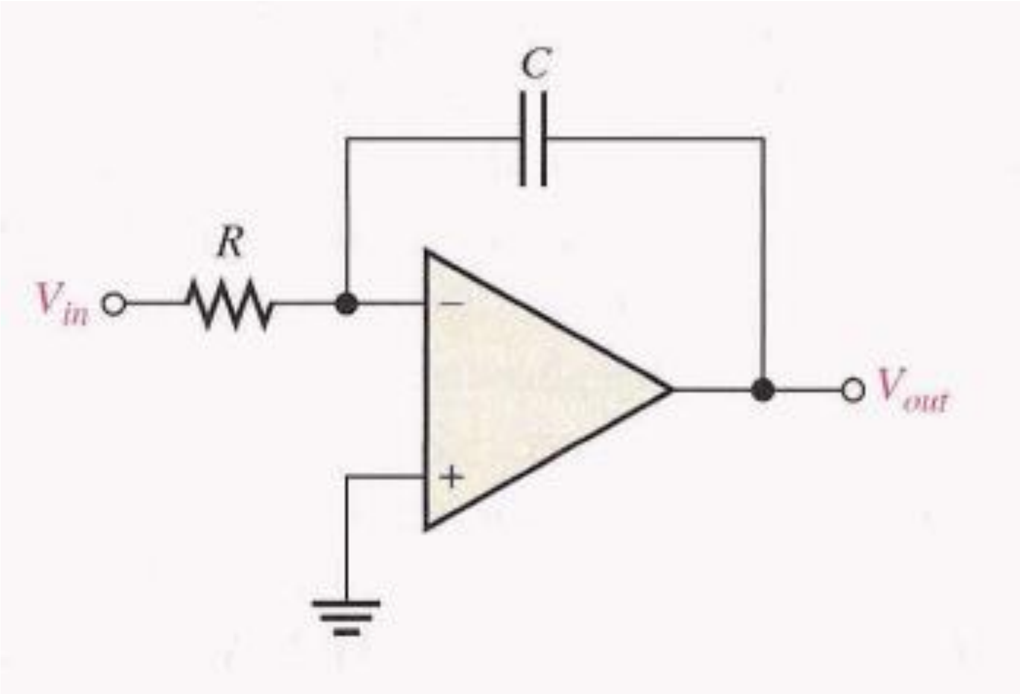
Assignment

- Determine the output voltage for the summing amplifier in figure.



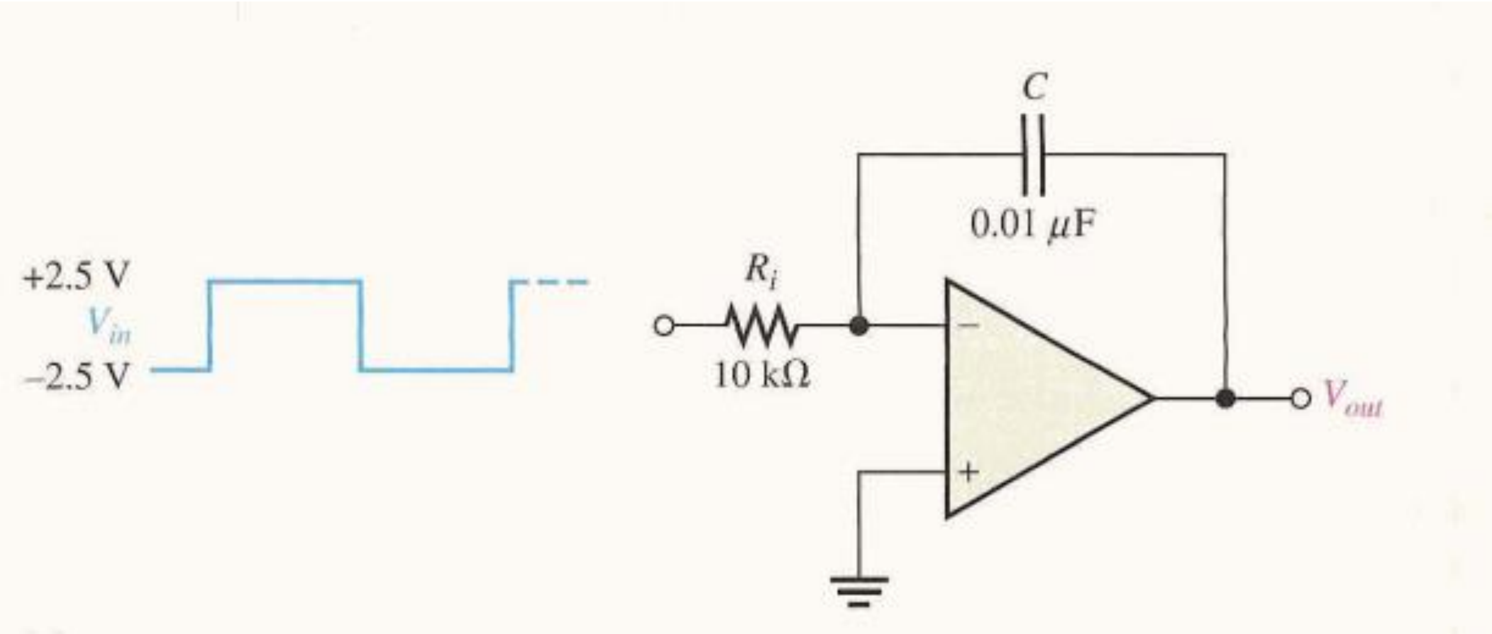
Integrator Amplifier

- If the feedback component used is a capacitor, as shown in figure, the resulting connection is called an integrator.
- $I_R = -I_c$
- $\dfrac{V_{in}}{R} = C_f \ \dfrac{dv_{out}(t)}{dt}.$
- $\dfrac{dv_{out}(t)}{dt} = -\dfrac{1}{RC} \ V_{in}\ (t)$
- $V_{out}(t) = -\frac{1}{RC}\int v_{in}(t)dt$



Example

- Determine the rate of change the output voltage in response to the input square wave, as shown for the integrator in figure. The output voltage is initially zero. The pulse width is 100µs.



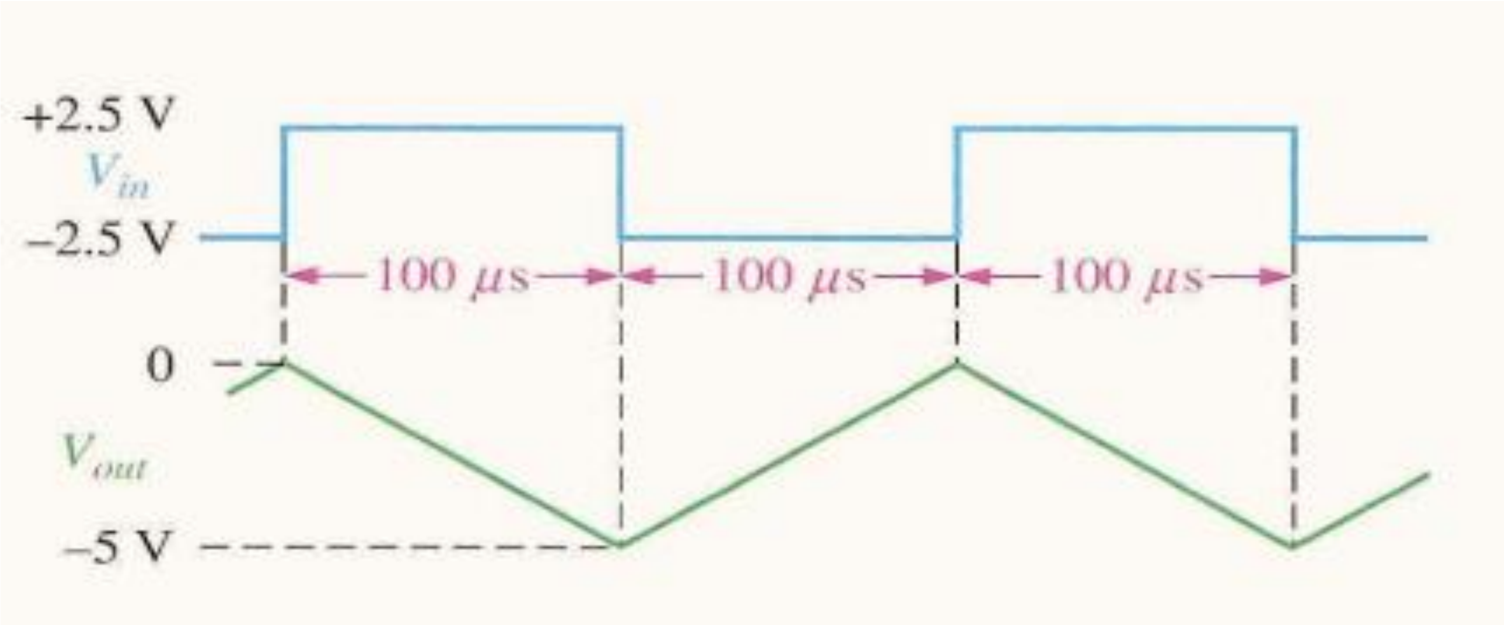
Solution

$$V_{out\,1} = -\frac{1}{10\,k\Omega \times 0.01\mu F}\int_0^{100\mu s} 5\,dt = 50\,000\,t = -50\,000\,(100\mu s)$$

$$V_{out\,1} = -5\,v$$

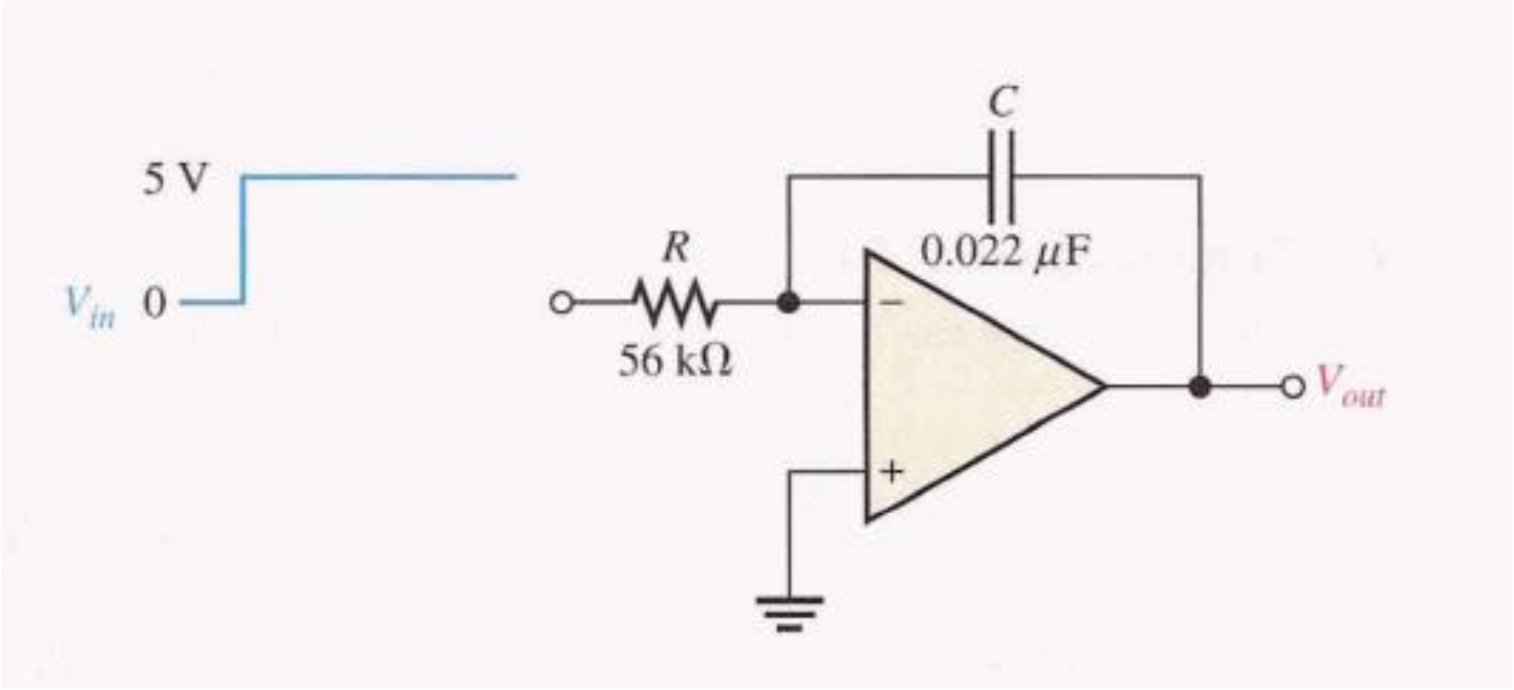
$$V_{out\,2} = -\frac{1}{10\,k\Omega \times 0.01\mu F}\int_0^{100\mu s} -5\,dt = 50\,000\,t = 50\,000\,(100\mu s)$$

$$V_{out\,2} = 5\,v$$



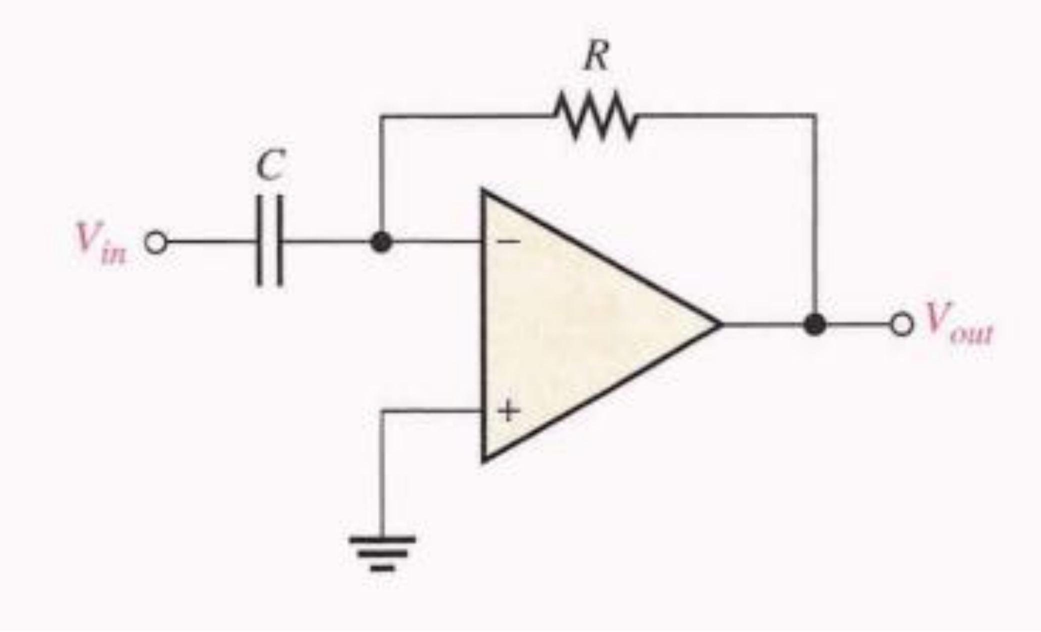
Assignment

- Determine the rate of change of the output voltage in response to the step input to the integrator in figure.



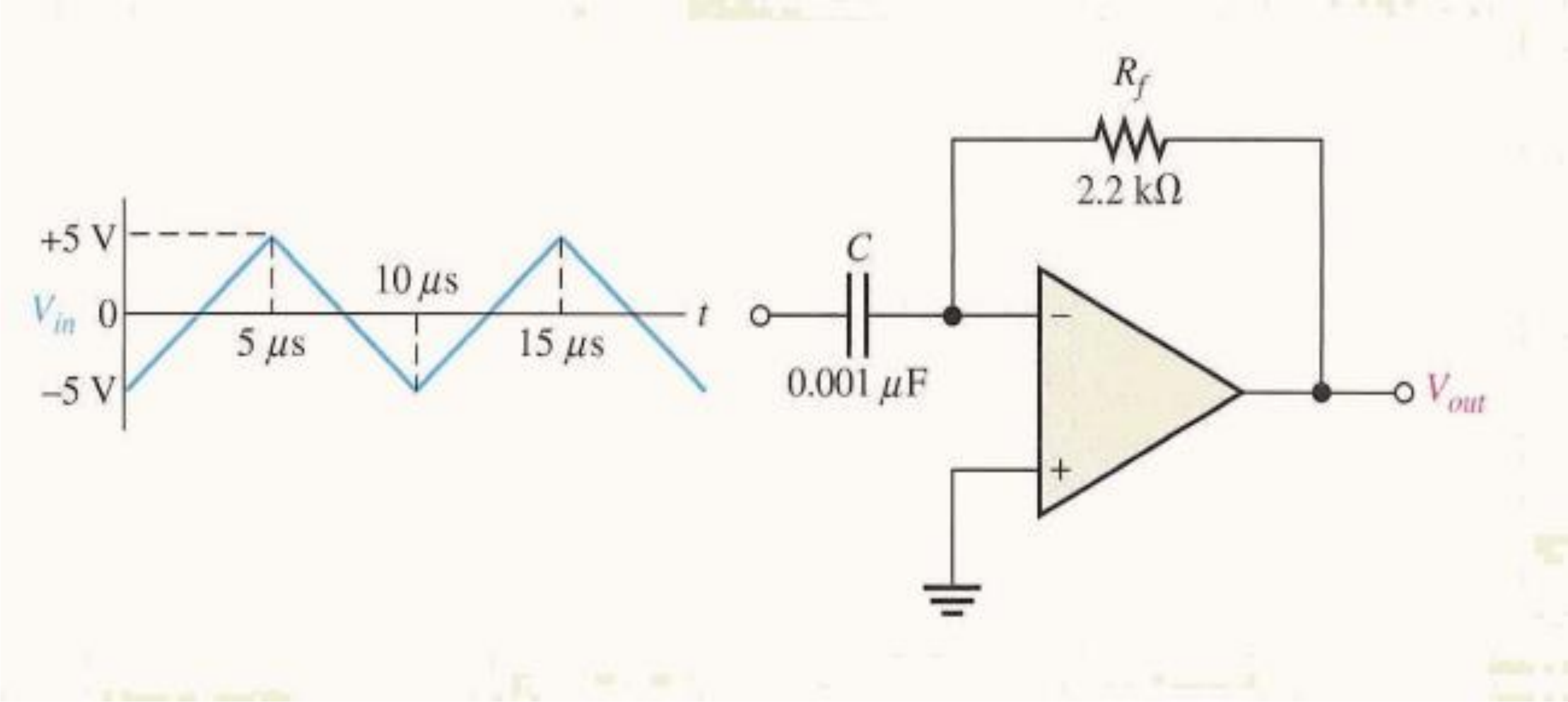
Op-Amp Differentiator

- The capacitor is now 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.
- $I_f = -I_c$
- $\frac{V_{out}(t)}{R_f} = -C\frac{dV_{in}}{dt}$
- $V_{out}(t) = -R_f C\frac{dV_{in}}{dt}$

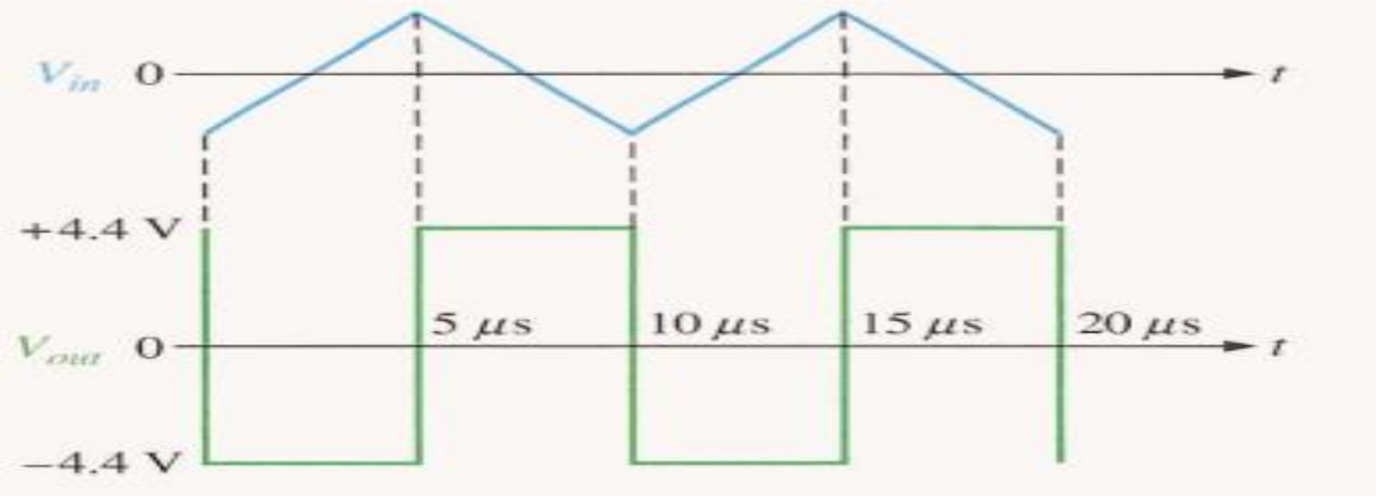


Example

- Determine the output voltage of the op-amp differentiator in figure for the triangular-wave input shown:

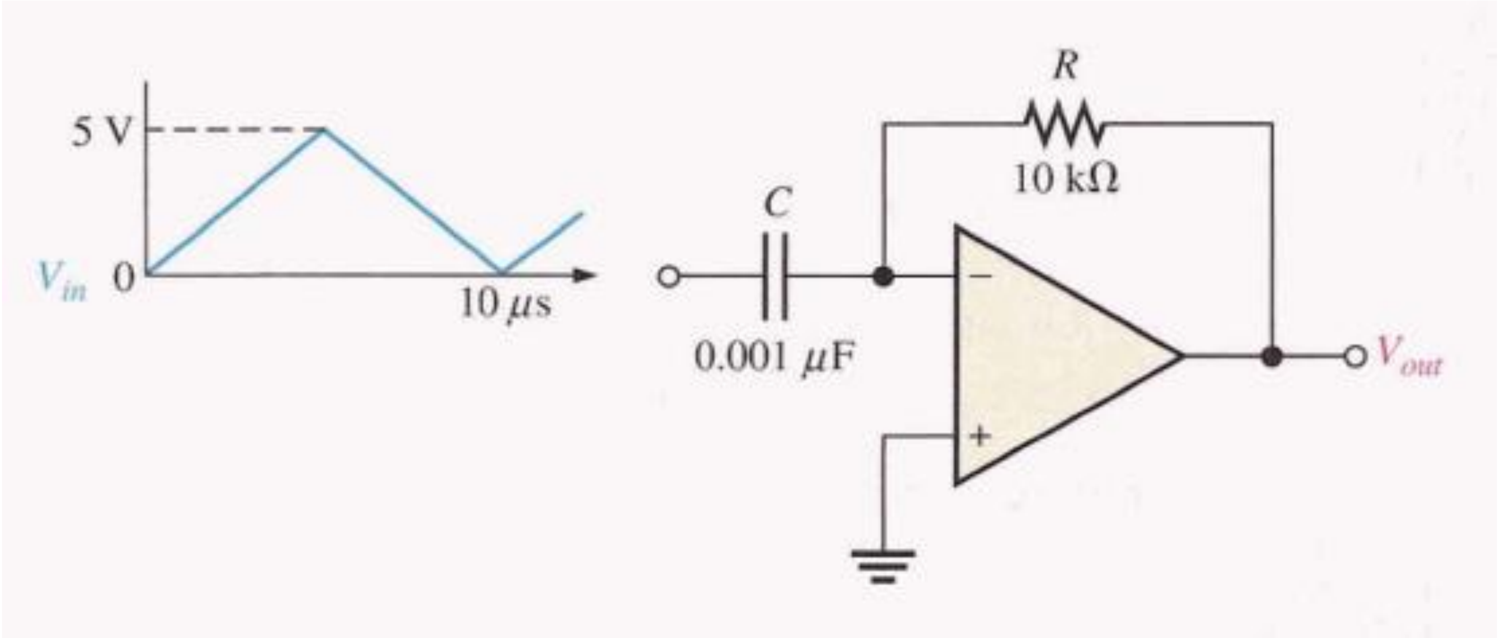


Example

- $R_f C = (2.2\ k\Omega)(0.001\mu F) = 2.2\mu s$
- $\frac{dv_{in}}{dt} = \textit{The slope of the postive} - \textit{going ramp} = (2\ ^{V}/_{\mu s}).$
- $v_{out} = -R_f C \frac{dv(t)}{dt} = -(2\ ^{V}/_{\mu s}) 2.2 \mu s = -4.4V.$
- The slope of the negative-going ramp is -2$^{V}/_{\mu s}$
- $v_{out} = -R_f C \frac{dv(t)}{dt} = -(-2\ ^{V}/_{\mu s}) 2.2 \mu s = 4.4V.$
- 

Assignment

- A triangular waveform is applied to the input of the circuit in Figure as shown. Determine what the output should be and sketch its waveform in relation to the input.



Mini-Project

- **Project #1:**
- Audio Amplifier Circuit or Stereo Amplifier Circuit using Op-Amps or transistors or both.
- **Project #2:**
- High power siren circuit for door bell.
- **Project #3:**
- Function Generator Circuit using Op-Amp with variable frequencies.
- **Project #4:**
- DIY (Do It Yourself) Infrared Motion Detector Circuit (transmitter and receiver).

Mini-Project

- **Note:**
- All those circuits need power supply from $\pm 5V\ to\ \pm 24V$. You must design your power supply circuit.
- Report is required for all parts of your project with short discussion and conclusion (including power supply circuit).
- If you hope to get bonus marks, you should design and fabricate more than one project.

THANK YOU