

Operational Amplifier :- $\star$ An operational-Amplifier (op-amp) is an active element design to perform mathematical operations like addition, subtraction, multiplication, division, differentiation and Integration.

- $\star$ op-amp can be used for AC as well as DC.
- $\star$ Input resistance of op-amp is very high whereas output resistance is very low.
- $\star$ An op-amp is a multistage direct coupled amplifier.

OR

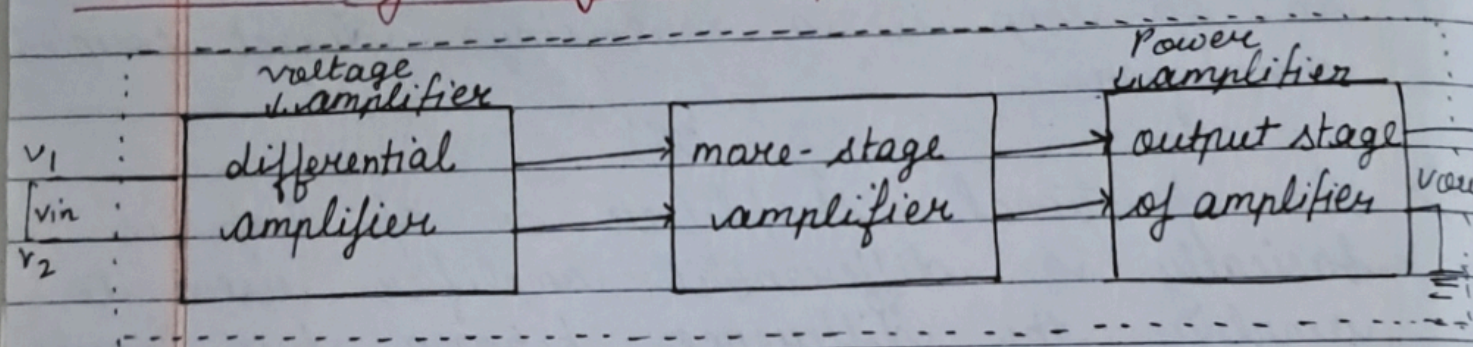
$\Rightarrow$ An operational - Amplifier or op-amp is basically a differential amplifier used to amplify the difference between two input signals. It is characterised by a very high input resistance.

op-amp was first used in an analogue computer to perform mathematical operations but now it is available in high performance, low cost and integrated circuit. Hence it is used to provide voltage change (amplitude and polarity) in oscillators in wave form generators in filter circuit and in many type of instructions circuits.

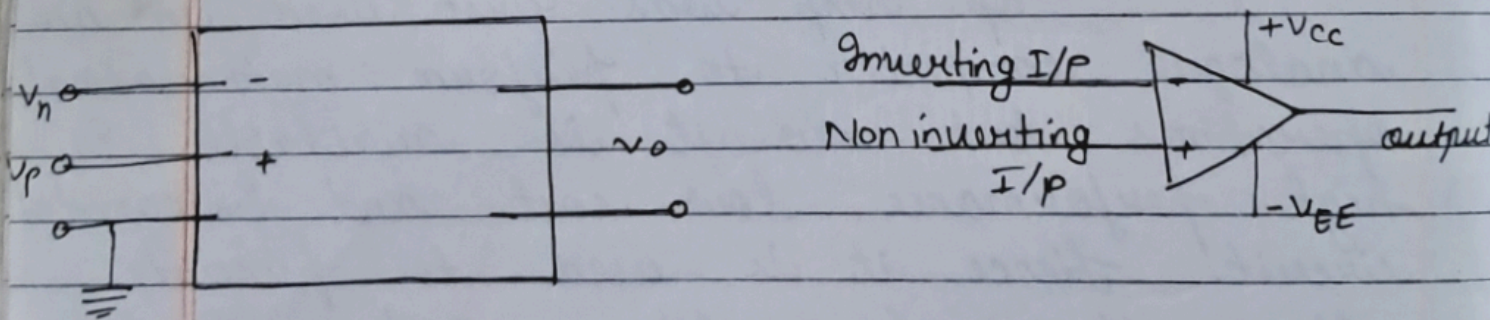
Fig (a) shows a basic op-amp with two input and one output resulting by using the differential amplifier as input stage. Each input results in either the same or an opposite polarity

(or phase) output, depending whether the signal has applied to the -ive or +ive. The op-amp is correspondingly called "Inverting and Non-inverting" amplifier. An ideal op-amp circuit would have Infinite Input Impedance, zero output Impedance, and Infinite voltage gain.

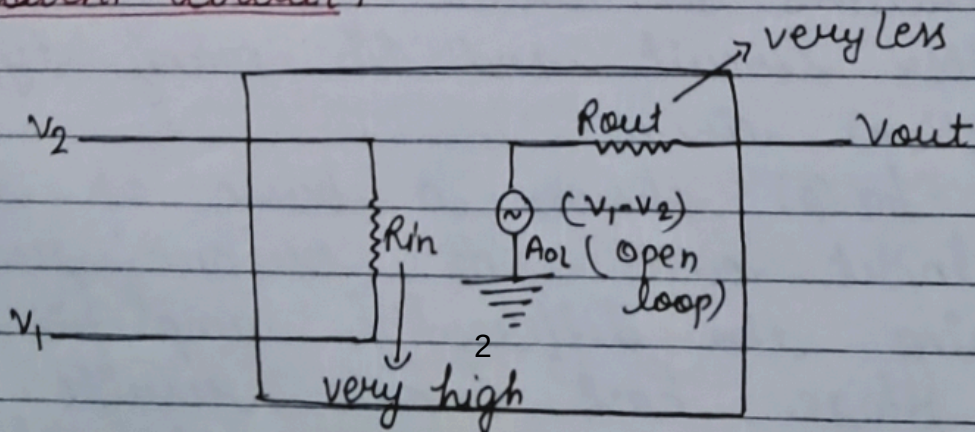
Block Diagram of An Op-Amp :-



Circuit Symbol :-



Equivalent Circuit :-



Characteristics of an Ideal Op-Amp:-

Characteristics	Ideal op-Amp	Practical op-Amp IC (741)
Open loop gain (A_{OL})	∞	10^6
Input resistance (R_i)	∞	$1\text{M}\Omega$ to $2\text{M}\Omega$
Output resistance (R_o)	0	50Ω to 100Ω
open loop band width	∞	$\approx 1\text{MHz}$
off set voltage	0	$< 10\text{mV}$
off set current	0	10nA
Common mode Rejection Ratio (CMRR)	∞	90dB
Slew Rate	∞	$1\text{V}/\mu\text{sec}$

Voltage Transfer Characteristics of Ideal Op-Amp

The basic op-Amp equation in which the output offset voltage is assumed to be zero is given by:-

$$V_o = A(V_p - V_n)$$

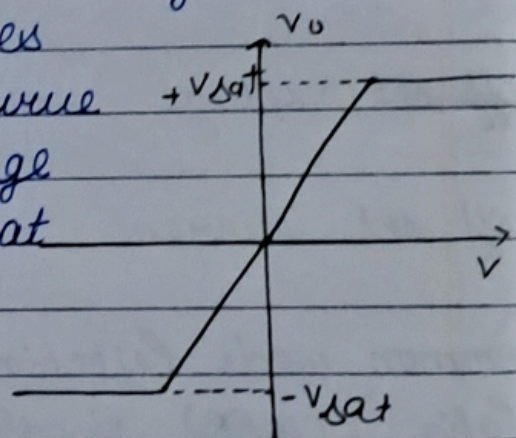
where;

V_o = output voltage
 A = voltage gain

V_p = voltage at noninverting Input terminal
 V_n = voltage at Inverting terminal

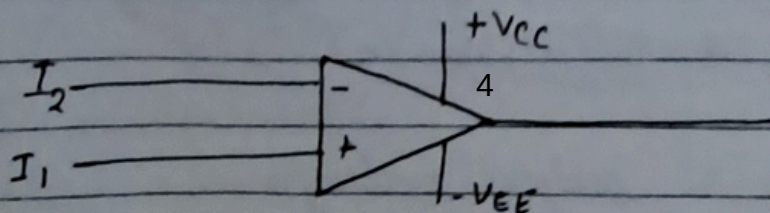
This equation is used in studying the op-amp's characteristics and in analyzing different circuit configurations that employ feedback. The graphic representation of this equation is shown in figure.

Note that the output voltage can't exceeds the +ve and -ve saturation voltages. The output voltage is directly proportional to the input difference voltage only until it reaches the saturation voltages and that there after output voltages remains constant. This curve is called an ideal voltage transfer curve, ideal that output offset voltage is assumed to be zero.



Important Definations :-

1. Input Bias Current :- It is the average of the two current which flow into inverting and non-inverting terminals of op-amp.



According to definition :-

$$I_B = \frac{I_1 + I_2}{2}$$

where I_B = input bias current.

Ideally its value is zero but practically its 100's of nA.

2. Input off set current :-

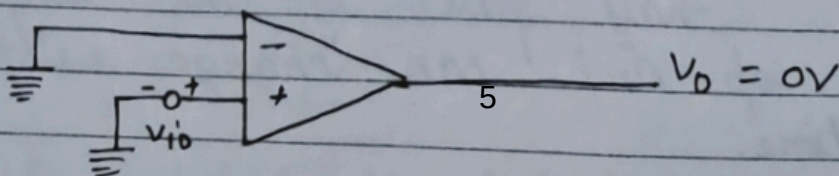
The algebraic difference between the currents into the inverting and non-inverting terminals is called input off-set current.

$$I_{io} = |I_1 - I_2| \longrightarrow \text{few nA.}$$

I_{io} = Input off set current.

3. Input off-set Voltage :-

For ideal operational amplifier output should be zero when both inputs are grounded. But in practical in op-amp the output voltage is not zero when both inputs are grounded. A small amount of voltage is applied at the input terminal to make the output voltage zero this input voltage is called input off set voltage.



4. Output off set Voltage:-

It is the output voltage of an op-amp when $V_1 = 0$ and $V_2 = 0$ and represented by V_{oo} (output off set voltage).

5. Common Mode Rejection Ratio (CMRR):-

The common mode rejection ratio may be defined as the ratio of the differential voltage gain (A_d) to the common mode gain (A_{cm})

$$CMRR = \frac{|A_d|}{|A_{cm}|}$$

$$A_d = \frac{V_o}{(V_1 - V_2)}$$

$$V_1 = V_2 = V_d$$

$$A_{cm} = \frac{V_o}{V_{cm}}$$

$$V_{cm} = \frac{V_1 + V_2}{2}$$

⇒ Higher CMRR indicates better rejection of common input.

For ideal condition $A_{cm} = 0$

Hence:

$$CMRR = \infty$$

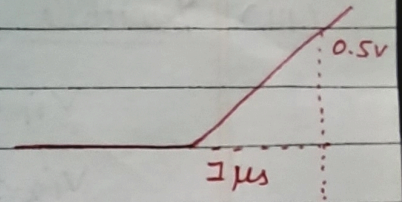
i.e. CMRR should be zero for ideal.

6. Slew Rate:- Slew rate is the measure of how fast of the output voltage of an op-amp can change with respect to time.

Mathematically;

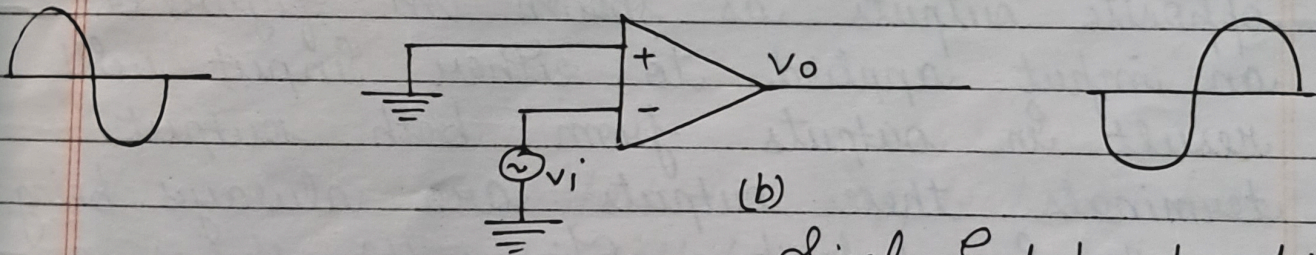
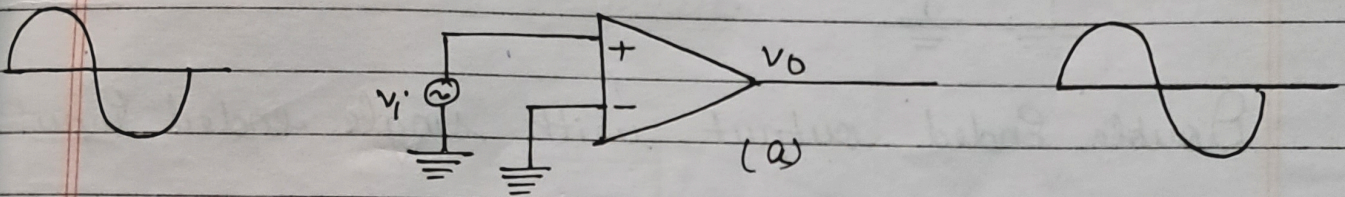
$$Slew Rate (SR) = \frac{dV_o}{dt} / \max$$

It is specifies in $V/\mu s$.
 For ideal op-amp SR is ∞
 Slew rate = $\frac{0.5V}{\mu s}$



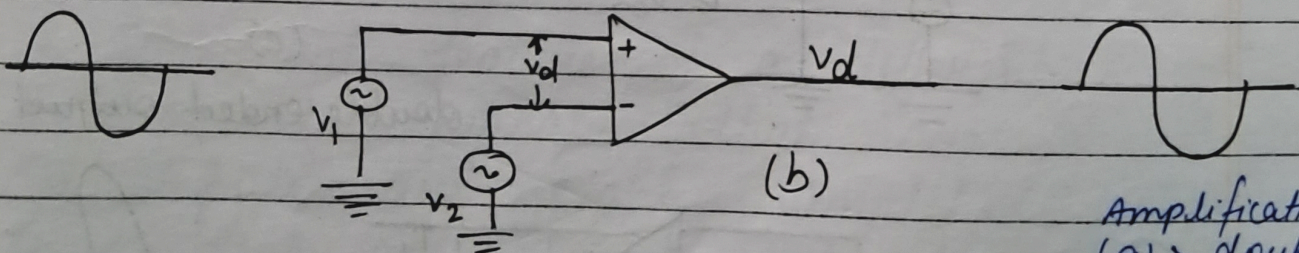
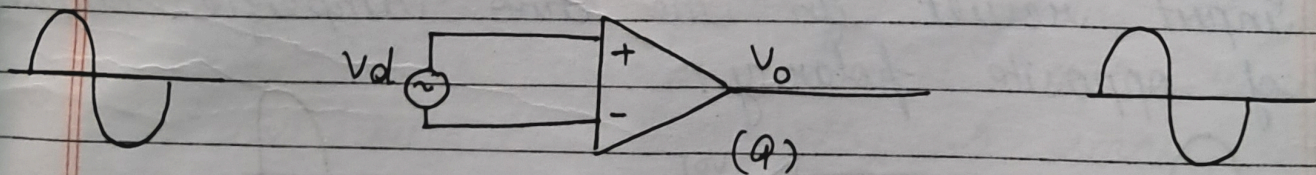
Ideally $SR = \infty$ i.e; output voltage should be ∞ in $1 \mu s$ time.

$\Rightarrow$ (i) Single Ended Input :-



Single Ended operation

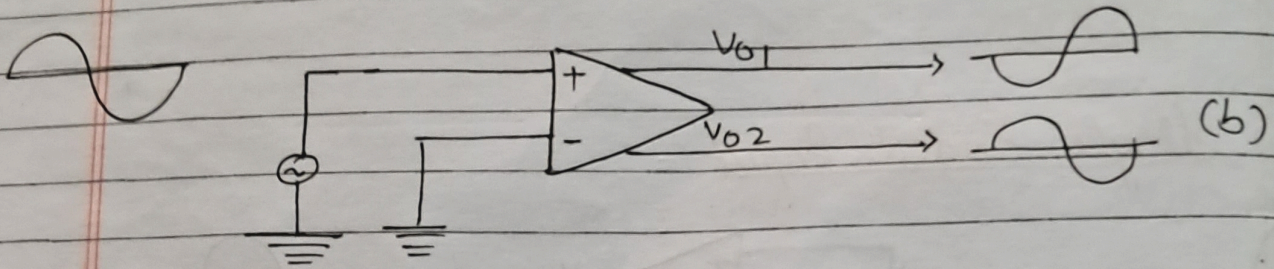
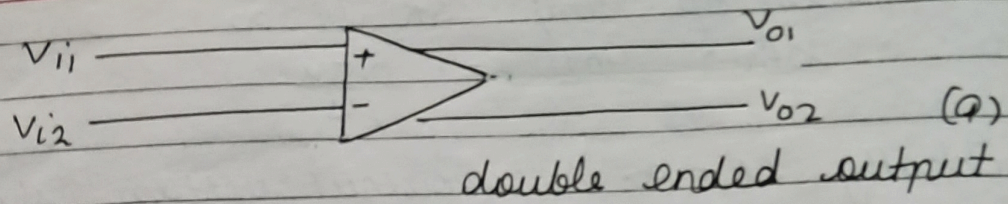
(ii) Double Ended (Differential) Input :-



Double Ended (differential) operation.

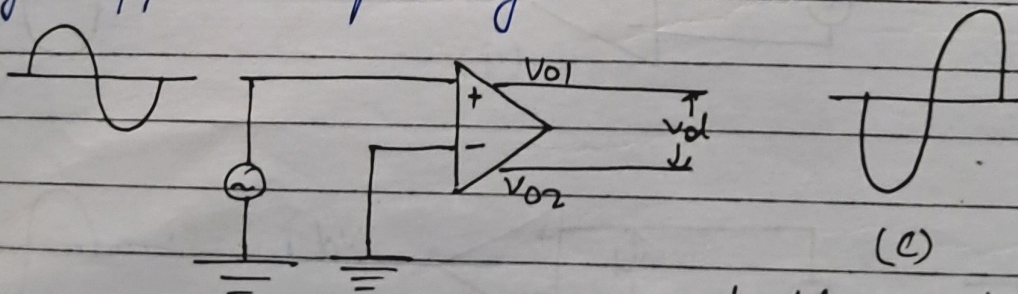
Amplification of (a) > double of amplification of (b)

(iii) Double Ended Output :-

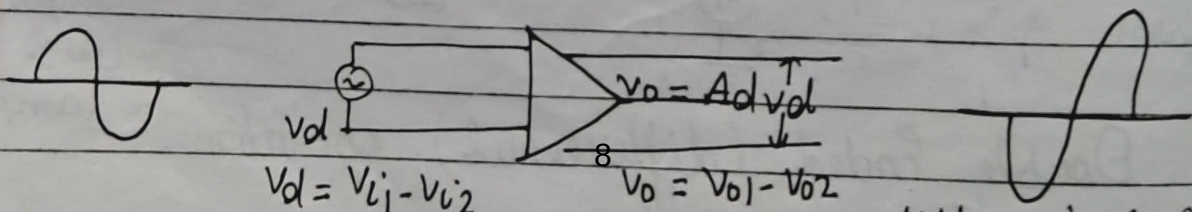


Double Ended output with single ended Input

The op-amp can also be operated with opposite outputs as shown in figure (a) an input applied to either input will result in outputs from both output terminals, these outputs are always being opposite in polarity. Figure (b) shows a single ended input with a double ended output the signal applied to the +ive input result in the two amplified outputs of opposite polarity.



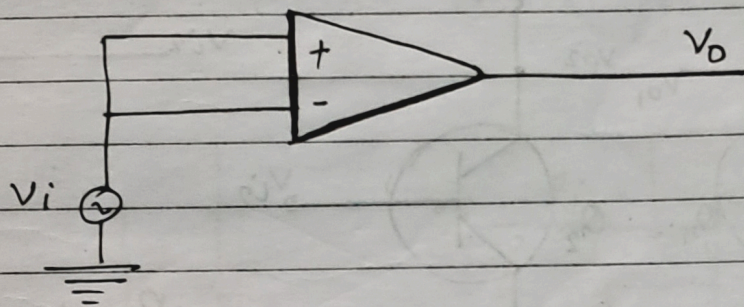
double ended output



differential input
differential o/p operation.

Fig (c) shows the same operation with a single output measured between output terminals not with respect to ground. This difference output signal $V_d = V_{o1} - V_{o2}$ is known as the floating signal because neither output terminal is ground. Fig (d) shows a differential input differential output operation. This is fully differential operation.

Common Mode Operation :-

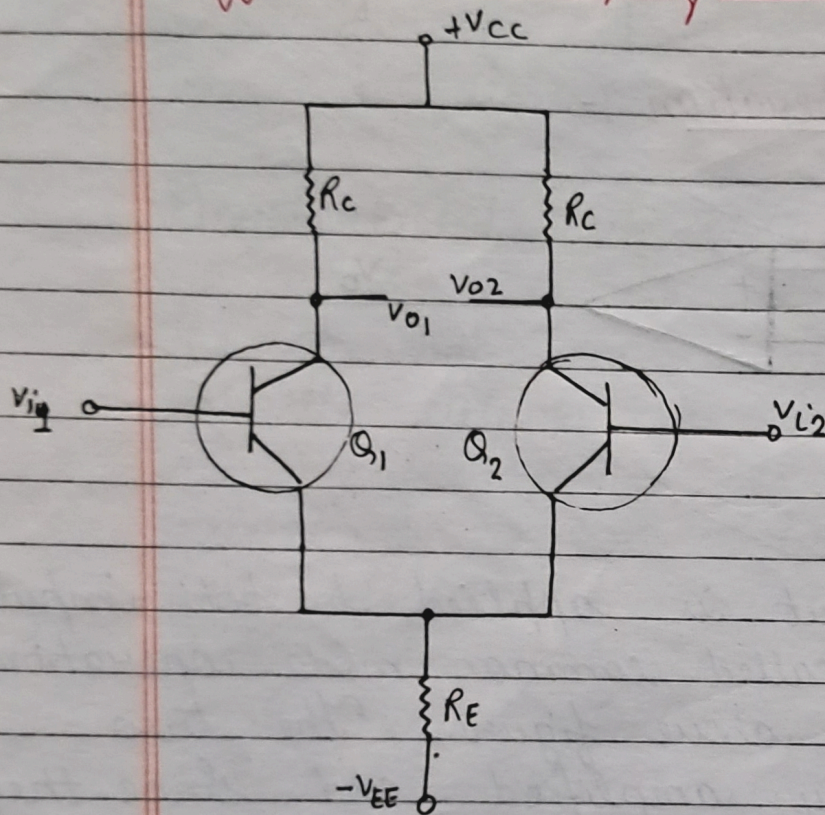


If the same input is applied to both inputs the operation is called common mode operation, as shown in the above figure. The two inputs are equally amplified and since they result in opposite polarity signals at the output these signals cancel out resulting in no output. Practically a small output signal will result.

⇒ A significant feature of a differential connection is that the signals that are opposite at the inputs are highly amplified, whereas those that are common to the two inputs are only slightly amplified. Since noise (any unwanted input signals) is generally common to

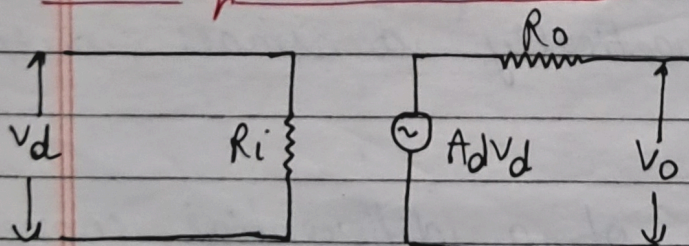
both inputs, the differential connection tends to provides attenuation (to stop the signals) of this unwanted input of the differential signal applied to the input this operation feature is refer to as common mode rejection.

Differential Amplifier Circuit



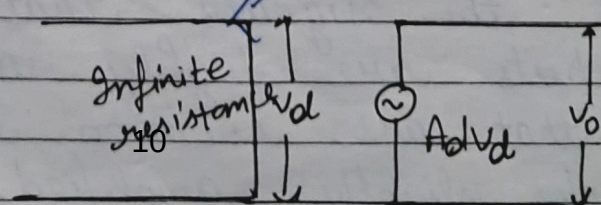
Basic differential amplifier circuit.

Ac Equivalent Circuit:-



(a) Practical

1. Infinite I/p resistance
2. zero o/p impedance
3. Infinite voltage gain



(b) Ideal

Ac - Equivalent Ckt of op- Amp ckt

Basic Operational Amplifier Connection:-

1. Inverting Amplifier:-

The most widely used constant gain amplifier circuit is the Inverting amplifier as shown in figure 1 and its symbol is shown in fig. 2.

The Input signal is applied to the -ve (Inverting) terminal and +ve (non-inverting) terminal is grounded. The Input voltage V_i is applied through a series resistance R_i and the output voltage V_o is feedback through a resistance R_f .

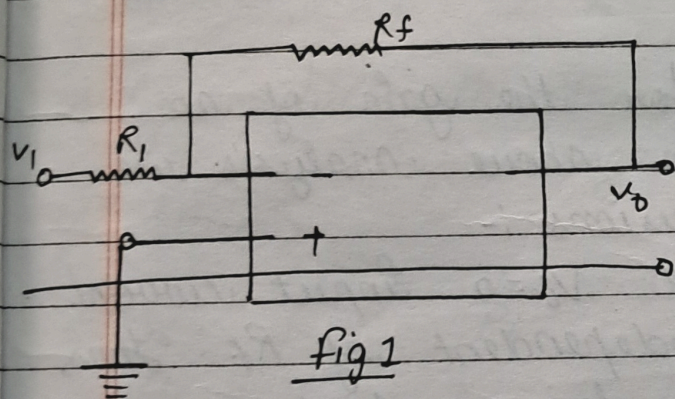


Fig 1

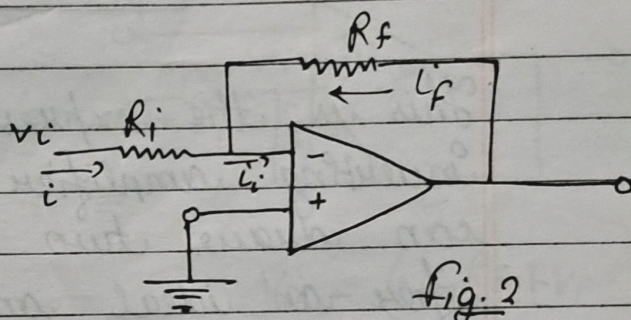


Fig. 2

- Since the op-amp gain is very large, we have

$$V_i = \frac{-V_o}{A} \approx 0$$

Again because the input resistance is very high, we have:

$$I_i = \frac{V_i}{R_i} \approx 0$$

For an ideal amplifier closely approximated by a practical op-amp we have:

$$R_i = \infty, \quad R_o = 0, \quad A = \infty, \quad V_i = 0 \text{ \& } I_i = 0$$

from fig 2 :

$$i_i = i_i - i_f \quad \text{but } i_i = 0$$

$$i_i = -i_f$$

$$\frac{v_i}{R_i} = \frac{-v_o}{R_f} \Rightarrow \boxed{v_o = -\frac{R_f}{R_i} v_i}$$

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

$\therefore \frac{v_o}{v_i} = A_f$ circuit gain with feedback

$$\therefore \boxed{A_f = -\frac{R_f}{R_i}}$$

This is the expression for the gain of an inverting amplifier. From above analysis we can draw two conclusions :-

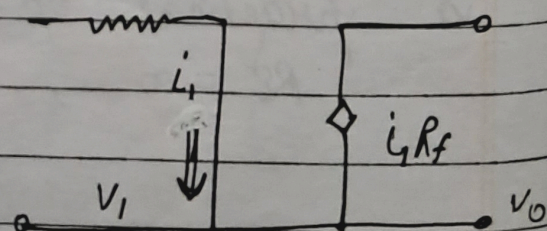
1. For an ideal amplifier $v_i = 0$ Input current $i_i = v_i/R_i$ and is independent of R_f . Thus, the input is isolated from output.
2. For an ideal op-amp with Infinite gain or a practical op-amp with very high gain the gain of amplifier circuit is determined by the external resistance R_i and R_f .

The first conclusion leads to a circuit model for an inverting amplifier circuit. The output voltage is given by:-

$$v_o = - \left(-\frac{v_i}{R_i} \right) R_f = -i_i R_f$$

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is represented by controlled the voltage source.



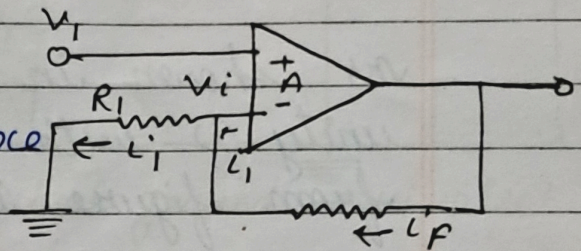
Non-Inverting Amplifier :-

The connections of an op-amp that works as a non-inverting amplifier are shown in figure. The input signal V_i is applied directly to the +ve (non-inverting terminal) terminal and a fraction of the output signal is fed back to the -ve terminal through a feedback resistance R_f , another external resistance R_i is connected between the -ve terminal and earth. Since the op-amp gain is very large;

$$V_i = -\frac{V_o}{A} = 0$$

Again becoz the input resistance R_i is very large we have;

$$I_i = \frac{V_i}{R_i} \approx 0$$



$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_i$$

for an ideal amplifier closely approximated by a practical op-amp we have;

$$R_i = \infty, R_o = 0, A = \infty, V_i = 0 \text{ \& } I_i = 0$$

we see from fig that the voltage across R_i is V_i (because $V_i = 0$). This must be equal to output voltage, through a voltage divider formed by R_i & R_f .

$$V_i = \frac{R_i}{R_i + R_f} V_o$$

$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_i$$

but $\frac{V_o}{V_i} = A_f$ circuit gain with feedback.

$$A_f = 1 + \frac{R_f}{R_i}$$

This is the expression for the gain of a noninverting amplifier.

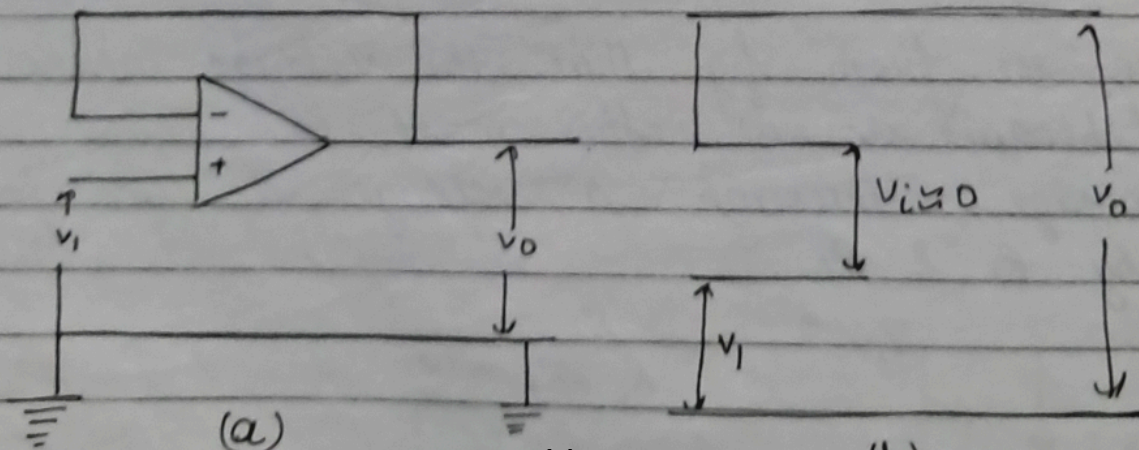
We see that gain is determined only by the feedback circuit element R_i and R_f . The gain is true.

Unity Follower:-

The unity follower circuit as shown in figure provides a gain of unity (1) with no unity or phase reversal from figure it is clear that

$$V_o = V_i$$

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

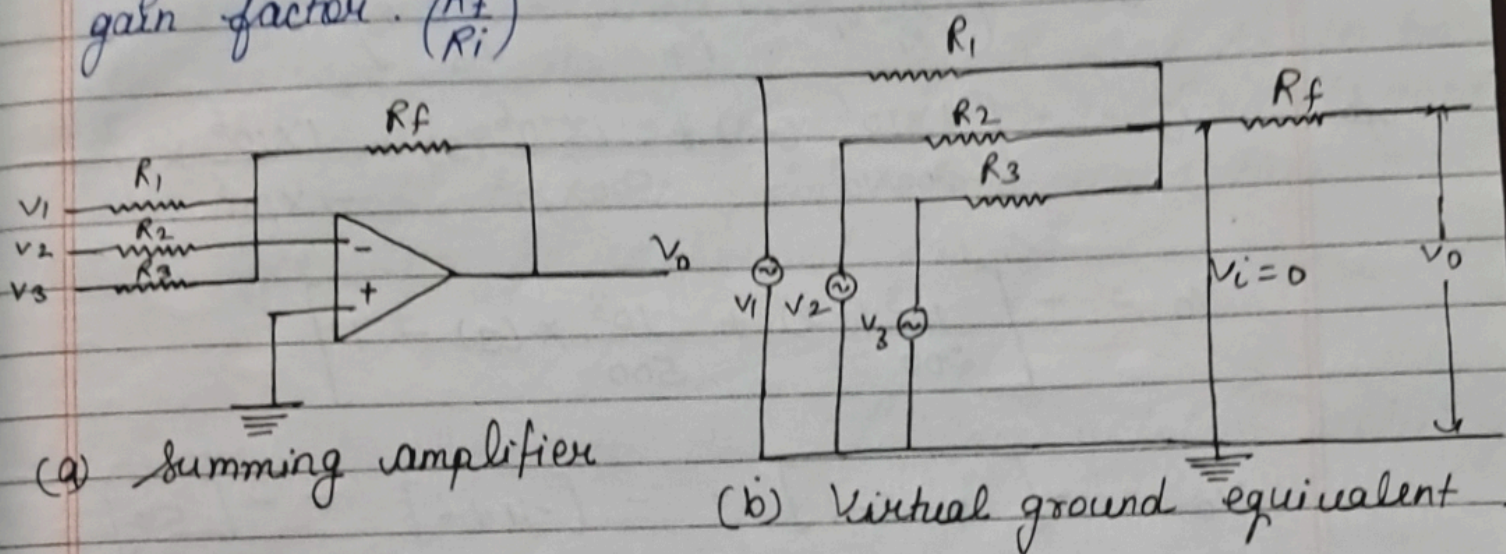


unity follower

equivalent circuit

Summing Amplifier:-

Probably the most used of the op-amp circuit is the summing amplifier circuit shown in figure (a). The circuit shows a three input summing amplifier, which provides a means of algebraically summing (adding) three voltages, each multiplied by a constant gain factor. $\left(\frac{R_f}{R_i}\right)$



Using the equivalent representation as shown in the figure we can express the output voltage in terms of the input as :-

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

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

Example:- Calculate the output voltage (V_o) of an op-amp summing amplifier for the following sets of voltages and resistors $R_f = 1\text{m}\Omega$, $V_1 = -2\text{V}$, $V_2 = +3\text{V}$, $V_3 = +1\text{V}$, $R_1 = 200\text{k}\Omega$, $R_2 = 500\text{k}\Omega$ & $R_3 = -1\text{m}\Omega$.

Solution:- we know that

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

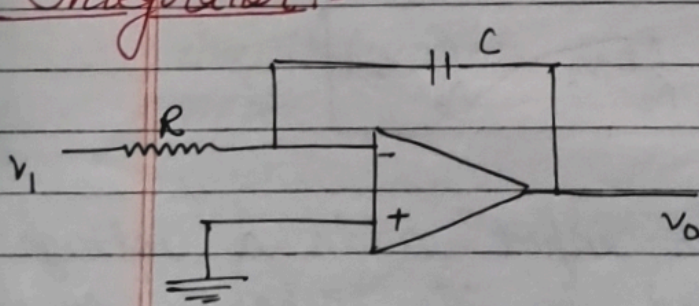
$$\therefore V_o = - \left[\frac{1 \times 10^{-6}}{200 \times 10^3} (-2) + \frac{1 \times 10^{-6}}{500 \times 10^3} (3) + \frac{1 \times 10^{-6}}{-1 \times 10^{-6}} \times 1 \right]$$

$$V_o = - \left[\frac{10^3}{200} (-2) + \frac{10^3}{500} \times (3) - 1 \right]$$

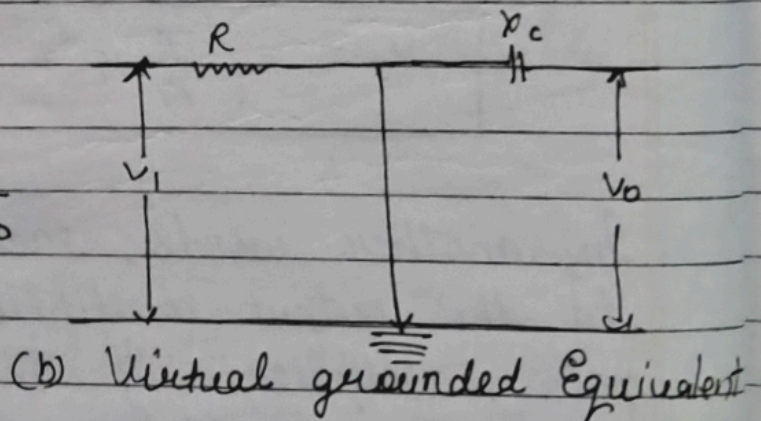
$$V_o = - [10 + 6 - 1] = - [-11 + 6] = - [-5\text{V}]$$

$$\boxed{V_o = 5\text{V}}$$

Integrator:-



(a)



(b) Virtual grounded Equivalent

An integrator is a circuit which has an output voltage that is proportional to the time integral of its input voltage.

So for the input and feedback

components have been resistors. If the feedback component used as a capacitor as in figure, the resulting connection is called an Integrator. The virtual ground equivalent circuit shows that an expression for the voltage between the input and output can be derived in terms of current I from input to output. Recall the virtual ground means that we can consider the voltage at the junction of R and X_c to be grounded (since $V_i \approx 0$) but that no current goes into ground at that point. The capacitive Impedance can be expressed as:-

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

where $sC = j\omega$ is the Laplace notation solving for V_o/V_i yields.

$$I = \frac{V_i}{R}$$

A circuit in which the output voltage waveform is the integrator or Integration amplifier. Such a circuit can be obtained by replacing resistor R_f by capacitor C_f in basic Inverting op-amp configuration.

The expression for output voltage V_o can be obtained by Kirchhoff's current equation:-

$$I_i = I_B + I_f$$

$$I_B \text{ is negligibly small; } I_i = I_f$$

Recall the relationship between the current through and the voltage across the capacitor is:-

$$i_c = C \frac{dv_c}{dt}$$

$$\frac{V_{in} - V_o}{R_i} = C_f \left(\frac{d}{dt} \right) (V_o - V_o)$$

but $V_1 = V_2 = 0$ because A is very large so;

$$\frac{V_{in}}{R_i} = -C_f \frac{d}{dt} (-V_o)$$

The output voltage can be obtained by Integrating circuit on both side w.r. to time

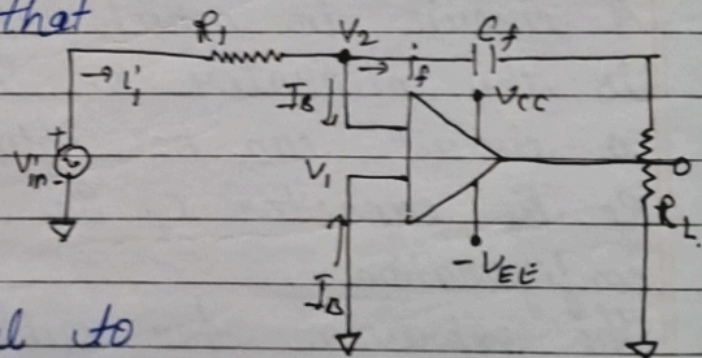
$$\int_0^t \frac{V_{in}}{R_i} dt = \int_0^t -C_f \frac{d}{dt} (-V_o) dt$$

$$= -C_f (-V_o) + V_o \Big|_0^t = 0$$

$$V_o = -\frac{1}{R_i C_f} \int_0^t V_{in} dt + C$$

C is the Integration constant and is proportional to the value of output voltage V_o at $t=0$.

The equation shows that the output voltage is directly proportional to the area of input voltage and inversely proportional to the time constant $R_i C_f$.



Example:- Consider an input voltage $V_i = 1V$ to the Integrator circuit

Given:- $R = 1m\Omega$, $C = 1\mu\Omega$.

Input circuit:-

when $R = 100k\Omega$ the total output

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$V_o = -\frac{1}{R_i C_f} = -10V$ less
-10V inclined.

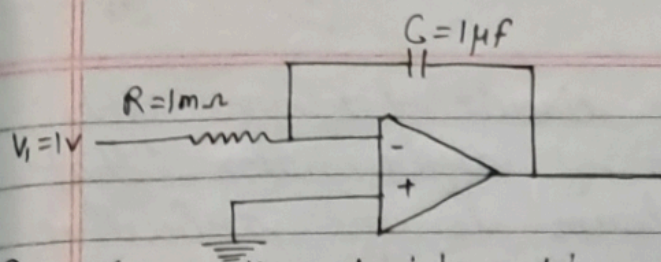
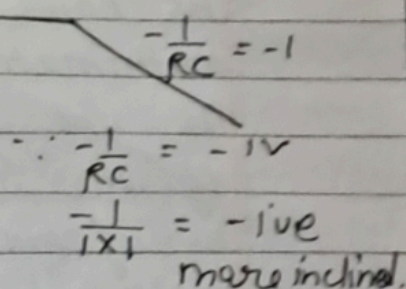


Fig: (operation of integration with step input)

Output

V_o



Note:- As $-\frac{1}{RC}$ value increasing through the $-ve$ side the graph becomes less inclined.

More than one Input may be applied to an Integrator as shown in figure below with the resulting operation given by:-

$$V_o(t) = -\left[\frac{1}{R_1 C} \int V_1(t) dt + \frac{1}{R_2 C} \int V_2(t) dt + \frac{1}{R_3 C} \int V_3(t) dt \right]$$

This is called summing Integrator circuit an example of a summing Integrator are used in analogue computer as given in figure.

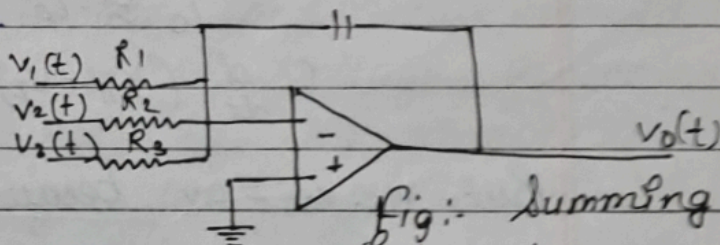
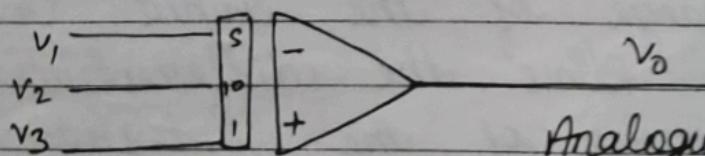


Fig: Summing Integrator circuit

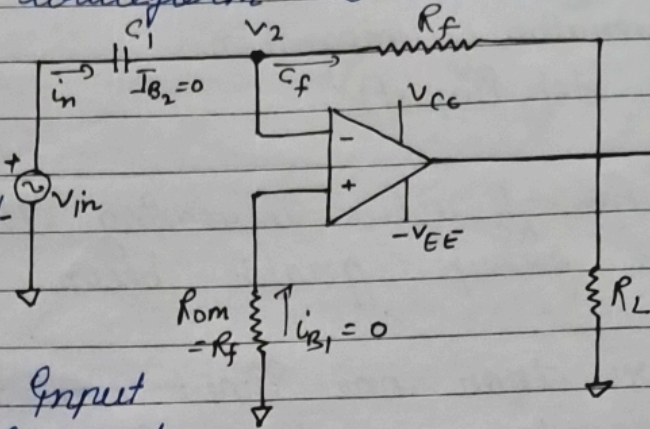
The actual circuit is shown Input resistors and feedback capacitor whereas the analogue computer representation indicates only the scale factor for each input.



Analogue computer Integrated ckt representation.

The Differentiator:- Fig. 19 shows the differentiator or the differentiation amplifier. As its

its name implies, the circuit performs the mathematical operation of differentiation. That is the output waveform is the derivative of the input waveform. The differentiator may be constructed from a basic inverting amplifier if an input resistor R_i is placed by a capacitor C_i .



The expression for the output voltage can be obtained from Kirchhoff's current relation:-

$$i_c = i_B + i_f$$

$$i_c \approx i_f$$

$$i_B \approx 0$$

$$C_i \frac{d}{dt} (V_{in} - V_2) = \frac{V_2 - V_o}{R_f}$$

But $V_1 \approx V_2 = 0V$ because A is very large so;

$$C_i \frac{dV_{in}}{dt} = -\frac{V_o}{R_f}$$

$$V_o = -\frac{R_f C_i dV_{in}}{dt} \quad (1)$$

Thus the output voltage V_o is equal to $R_f C_i$ times the negative instantaneous rate of change of the input voltage V_{in} with time. Since the differentiator performs a reverse of the Integrator's function, a cosine input will produce a sine output; a triangular input will produce a square output.

The frequency response of a differentiator

$$f_a = \frac{1}{2\pi R_f C_1}$$

Op-amp Specification :- Dc off set Parameters

Before going into various practical applications using op-amp we should become familiar with some of the parameters used to define the operation of unit. These are as following :-

Off Set Current And Voltage :-

Although the op-amp should be 0V when the input is 0V. In actual there is some off set voltage at the output. For example :- If one connected 0V to both op-amp inputs and this would represent 26mV of unwanted voltage generated by the circuit and not by the input signal. The output offset voltage can be determined by the input offset voltage and the gain of the amplifier.

The output offset voltage can be shown to be affected by two separate conditions :-

1. An input offset voltage
2. off set current

1. Input off set Voltage (V_{IO}) :-

$$V_o = A V_i$$

from fig:-

$$V_i = V_{IO} - V_o \frac{R_1}{R_1 + R_f}$$

$$V_o = A \left[V_{IO} - V_o \frac{R_1}{R_1 + R_f} \right]$$

