Unit - I

Operational Amplifier

→ An operational Amplifier is an integrated circuit Operates as voltage follower.

→ An op-Amp as a differnitial inputs that is it has two inputs of opposite polarity.

→ An op-Amp as a single output and very high gain which means the output signal voltage is much higher than the input signal voltage.

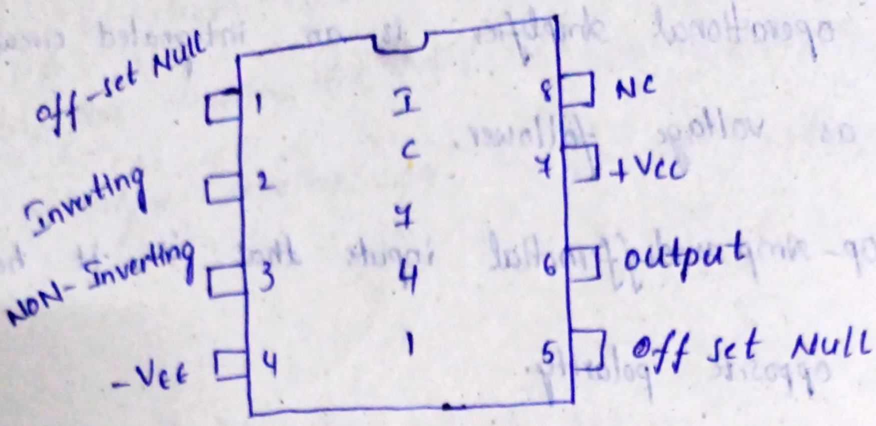
→ It is a voltage control voltage source device.

→ By using op-Amp we can amplifier both AC and DC signals.

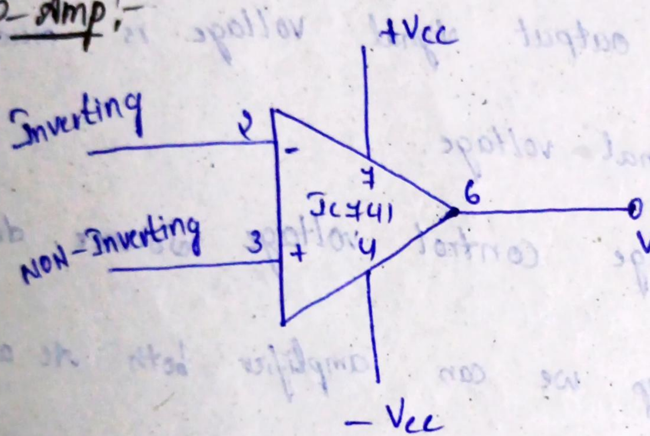
→ each Amplifier are called operational Amplifier because they are initially design for effective devices to perform Arthemetic operations in an analog circuits.

→ the op-Amp has many other applications in signal Processing measurement and instrumentation.

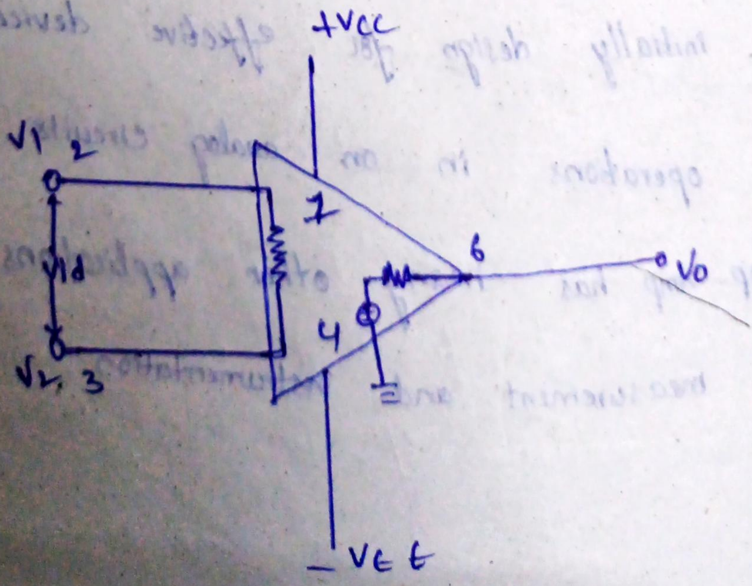
Pin diagram of IC 741 op-Amp:-



Ideal op-Amp:-



equilent circuit of Op-Amp:-



$$\text{gain } (A) = \frac{\text{output voltage}}{\text{Input voltage}}$$

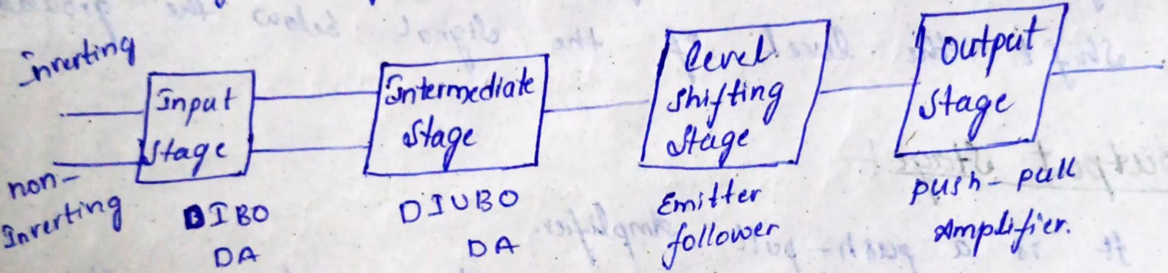
$$V_{id} = V_2 - V_1$$

$$A = \frac{V_o}{V_2 - V_1}$$

$$A = \frac{V_o}{V_{id}}$$

$$\boxed{V_o = A \cdot V_{id}}$$

Block diagram of op-Amp:-



Input Stage:-

→ the input stage is a dual input balanced output and differential Amplifier.

→ It can amplify the difference b/w the input sources.

→ It provides the most of the voltage gain of the amplifier and also establishes input resistance of amplifiers op-amp.

Intermediate stage:-

→ It is a dual input unbalanced output

differential amplifier. It is driven by the output of the first stage.

→ It can amplify the output of the input stage.

→ Because of the Direct-coupling is used, DC voltage at the output of intermediate stage is well above the ground potential.

Level shifting stage:-

→ It is an emitter follower.

→ It will follow the same output only it will change the DC level of the input signal.

→ Shift the level of the signal below the ground.

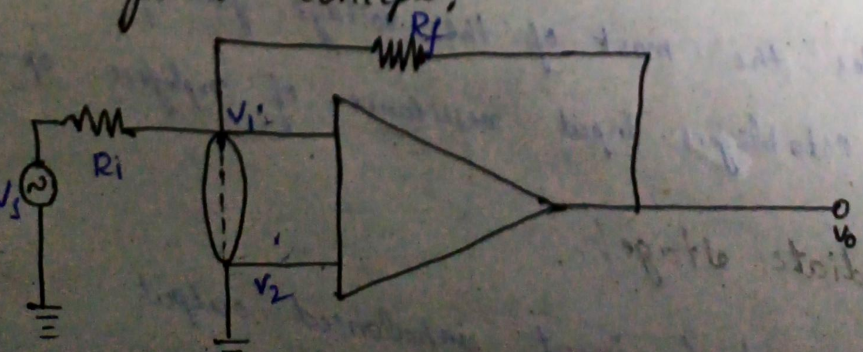
<u>output stage</u>:-

→ It is a push-pull Amplifier.

→ It increases the output voltages and raises the current supplying capabilities of Op-Amp.

→ This stage also provides low output resistance.

Virtual ground concept:-



Here R_i = input resistance.
R_f = feed back resistance.
V_1 = Inverting voltage
V_2 = NON- Inverting voltage.

→ physically inverting and non- inverting terminals are not connected but virtually they are connected.

→ voltage at non- inverting terminal is equal to '0' ($V_2 = 0$).

→ from virtual ground concept $V_1 = V_2$ so; $V_1 = 0$

→ the currents at the inverting and non- inverting terminals are equal to '0'.

$$\text{Gain} = \frac{V_0}{V_{id}}$$

$V_{id} = V_2 - V_1$ (where $V_2 = 0$ & $V_1 = 0$).

$V_{id} = 0$

$$\text{Gain} = \frac{V_0}{0}$$

$$\boxed{A = \infty}$$

Op- Amp parameters:-

i) Input Bias current
ii) Input off set current
iii) Input off set voltage
iv) output off set voltage
v) slew Rate
vi) CMRR.

(i) Input Bias Current :-

→ pratically average of input currents is called as input Bias current

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

(ii) Input off set current :-

→ the algebric difference b/w currents of inverting and non-inverting are refferd as input offset current.

$$\boxed{I_{10} = | I_2 - I_1 |}$$

→ Ideal value of the input offset current is zero but pratically in the order of Nano amperes.

(iii) Input offset voltage :-

→ To make the output voltage is zero some source voltage is applied at the input side then the voltage is called as input offset voltage.

→ for ideal op-amp both inputs are connected to ground then output voltage is equal to zero But pratically op-amp voltage is not equal to zero because some source voltage is applied at the input terminals.

(iv) output offset voltage :-

→ the difference b/w the Inverting and NON-inverting terminals voltage are equal to zero.

$$V_{id} = V_2 - V_1 = 0.$$

→ Infinite band width so that the frequency signal '0' to 'infinite' Hz can be amplified

→ Infinite CMRR so that output common mode noise voltage is 'Zero'.

→ Infinite slew rate so that output voltage changes simutanisoly with input voltage.

5) Slew rate:-

→ the rate of change of the output voltage w.r.t time is called as slew rate.

→ It indicates the how fast op-amp reacts when input changes

$$\boxed{S_R = \frac{dv_o}{dt}}$$

→ Units of slew rate is volts / micro seconds.

6) CMRR:-

→ CMRR means common mode rejection ratio.

→ It can reject the common mode signals and allow the difference signals.

$$\boxed{CMRR = \frac{A_{dm}}{A_{cm}}}$$

Characteristics of Op-Amp:-

→ Infinite voltage gain.

→ Input resistance is infinite.

→ Zero output resistance. so that output can drive infinite no. of other devices.

→ Zero output voltage when the input voltage is zero.

→ Infinite band with so that at any frequency signals zero to infinite Hz can be amplified ettinuation.

→ Infinite CMRR so that output common noise voltage is zero.

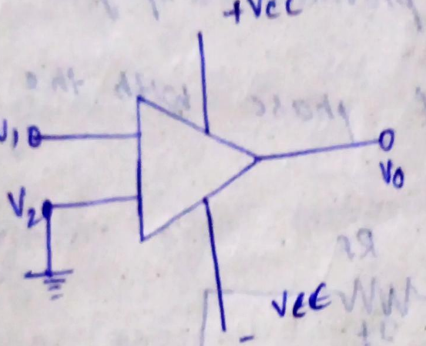
→ Infinite slew rate so that output voltage changes simultanoauly with input voltages.

Parameter	Ideal value	practical value.
→ open loop gain	infinite	10^6
→ Input resistance	infinite	1 Mega-Ω to 2 mega Ω
→ output resistance	0	50 Ω to 100 Ω
→ Band with	infinite	1 mega hz
→ CMRR	infinite	90 decimals (db)
→ slew rate	infinite	—
→ off set voltage	0	less than 10 milli volts
→ off set current	0	10 nano amphered.

Inverting op-Amp:-

→ In inverting ideal op-Amp voltage source is connected to the inverting terminal and non-inverting terminal is connected to the ground is called as Inverting op-Amp.

open loop inverting op-Amp:-



→ from virtual ground concept of the ideal op-Amp. the Inverting terminal voltage is equal to non-inverting terminal voltage.

→ the non-Inverting terminal voltage V_2 is connected to ground so $V_2 = 0$

$$V_1 = V_2$$
$$V_1 = 0$$
$$V_1 = V_2 = 0$$
$$V_{id} = V_2 - V_1$$
$$= 0$$

Now

gain $A = \frac{V_o}{V_{id}}$

$$A = \frac{V_0}{0}$$

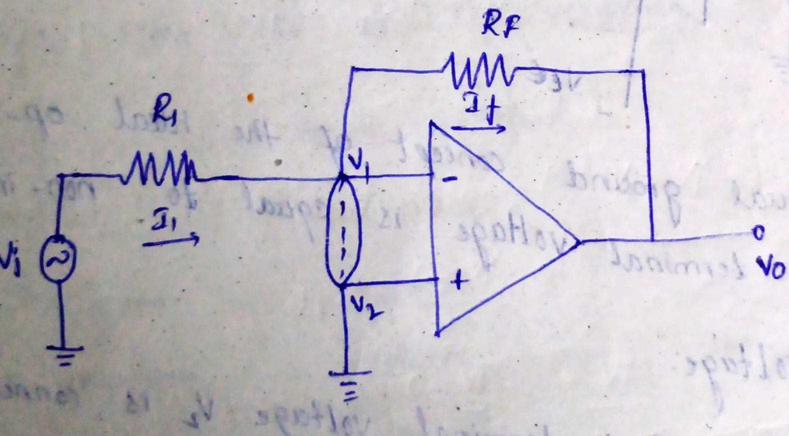
$$\boxed{A = \infty}$$

→ for ideal open loop inverting op-Amp the open loop gain is equal to infinite $\boxed{A = \infty}$

Closed loop inverting op-Amp:-

→ for Amplification purpose the resistors are connected at the feed back path.

→ An op-Amp circuit provides amplified output signal that is 180° out of phase with the input signal.



from virtual ground concept $V_1 = V_2$

$V_2 = 0$

$V_1 = 0$

Apply kcl on the voltage source node $V_1 = 0$.

$$I_1 = I_F$$

Here $I_1 = \frac{V_i - V_1}{R_1}$

and $I_F = \frac{V_1 - V_0}{R_F}$

$$V_1 = 0$$

$$I_1 = I_F$$

$$\frac{V_i - 0}{R_1} = \frac{0 - V_0}{R_F}$$

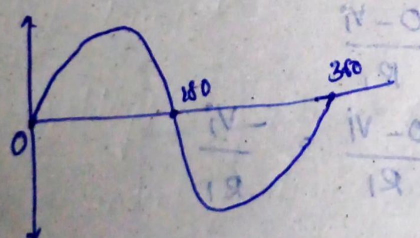
$$\frac{V_i}{R_1} = \frac{-V_0}{R_F}$$

$$\frac{V_0}{V_i} = \frac{-R_F}{R_i}$$

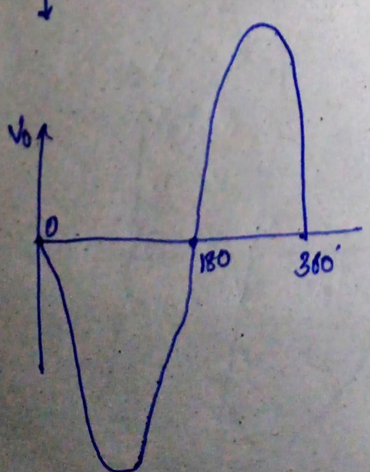
Now gain $A = -\frac{R_F}{R_i}$

→ '–' Negative sign indicates inverting input signal with 180° out of phase.

Input :-



Output :-

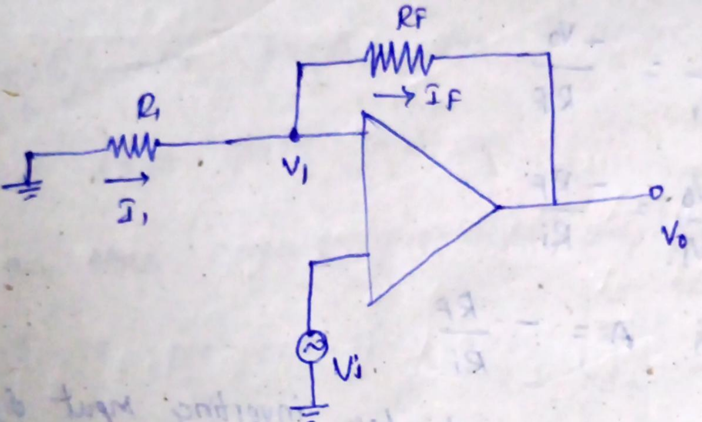


NON - Inverting op-Amp :-

→ Inverting terminal is connected to the ground and non-inverting terminal is connected to the voltage source. then it is called as NON - inverting op-Amp.

→ the phase difference b/w input signal and output signal is 0°.

Circuit :-



Apply KCL at the node V_1

$$I_1 = I_F \longrightarrow ①$$

from virtual ground concept $V_1 = V_i$

$$I_1 = \frac{0 - V_i}{R_1}$$

$$I_1 = \frac{0 - V_i}{R_1} = \frac{-V_i}{R_1}$$

And

$$I_F = \frac{V_1 - V_0}{R_F}$$

$$I_1 = \frac{V_i - V_0}{R_F}$$

Now from ①

$$I_1 = I_F$$

$$-\frac{V_i}{R_1} = \frac{V_i - V_o}{R_F}$$

$$-\frac{V_i}{R_1} = \frac{V_i}{R_F} - \frac{V_o}{R_F}$$

$$\frac{V_o}{R_F} = \frac{V_i}{R_1} + \frac{V_i}{R_F}$$

$$\frac{V_o}{R_F} = V_i\left(\frac{1}{R_F} + \frac{1}{R_1}\right)$$

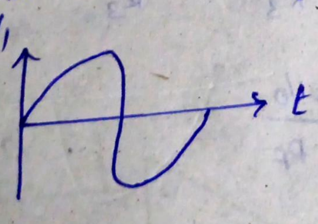
$$\frac{V_o}{V_i} = 1 + \frac{R_F}{R_1}$$

$$A = 1 + \frac{R_F}{R_1}$$

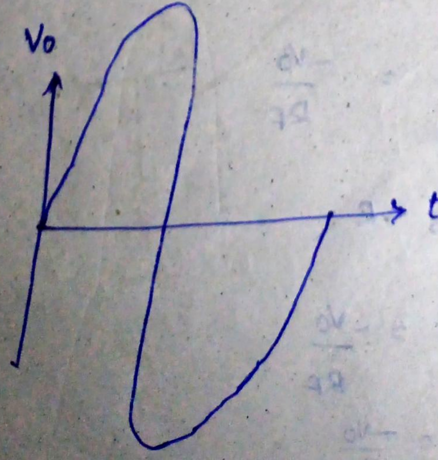
$$V_o = V_i\left[1 + \frac{R_F}{R_1}\right]$$

→ the phase difference b/w input signal and output signal is '0'. that means the gain is in positive.

Input :-

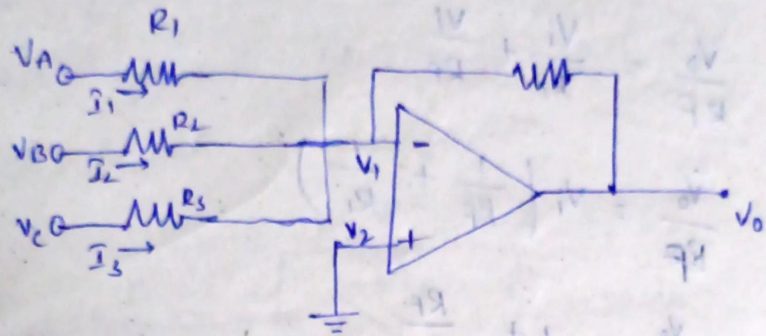


output :-



Op-Amp as a adder (or) summing amplifier :-

→ Op-Amp as an adder circuit provides an output voltage is equal to the sum of the input voltages



from virtual ground concept $V_1 = V_2$

$V_1 = V_2 = 0$

Apply KCL at Node V_1 = $I_1 + I_2 + I_3 = I_f$

Now $I_1 = \dfrac{V_A - V_1}{R_1} = \dfrac{V_A}{R_1}$

[∴ where $V_1 = 0$] $I_2 = \dfrac{V_B - V_1}{R_2} = \dfrac{V_B}{R_2}$

$I_3 = \dfrac{V_C - V_1}{R_3} = \dfrac{V_C}{R_3}$

and $I_f = \dfrac{V_1 - V_0}{R_F} = \dfrac{-V_0}{R_F}$.

Now $I_1 + I_2 + I_3 = I_F$

$$\frac{V_A}{R_1} + \frac{V_B}{R_2} + \frac{V_C}{R_3} = \frac{-V_0}{R_F}$$

Take $R_1 = R_2 = R_3 = R$

$$\frac{V_A}{R} + \frac{V_B}{R} + \frac{V_C}{R} = \frac{-V_0}{R_F}$$

$$\frac{1}{R}(V_A + V_B + V_C) = \frac{-V_0}{R_F}$$

$$\therefore \boxed{V_O = -\frac{R_F}{R}(V_A + V_B + V_C)}$$

Take if $R_F = R$ then

$$\therefore \boxed{V_O = -(V_A + V_B + V_C)}$$

$\therefore$ Here negatives indicate the op-Amp is inverting.

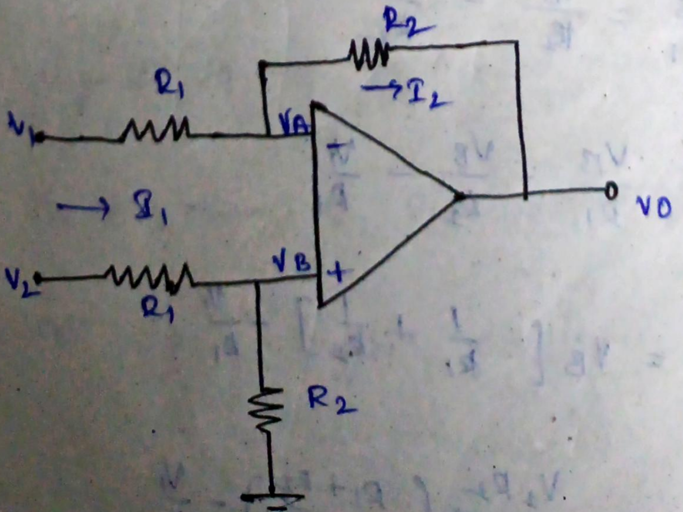
→ the output voltage is equal to the summation of the input voltage.

→ Adder op-Amp also called as Summing amplifier.

Op-Amp as a Substractor:-

→ Op-Amp is an substractor circuit provides an output voltage is equal to the substraction of the input voltages.

→ Substractor op-Amp is also a difference amplifier.



from virtual ground concept $V_A = V_B$

from voltage divider rule $X = \frac{\text{total voltage. corresponding}}{\text{total resistance } (\Omega)}$

$$V_B = \frac{V_2 R_2}{R_1 + R_2}$$

Apply kcl at node V_A

$$I_1 = I_2$$

Now $I_1 = \frac{V_1 - V_A}{R_1}$

$$I_1 = \frac{V_1 - V_B}{R_1}$$

$$I_2 = \frac{V_A - V_0}{R_2}$$

$$I_2 = \frac{V_B - V_0}{R_2}$$

Now $I_1 = I_2$

$$\frac{V_1 - V_B}{R_1} = \frac{V_B - V_0}{R_2}$$

$$\frac{V_1}{R_1} - \frac{V_B}{R_1} = \frac{V_B}{R_2} - \frac{V_0}{R_2}$$

$$\frac{V_0}{R_2} = \frac{V_B}{R_1} + \frac{V_B}{R_2} - \frac{V_1}{R_1}$$

$$\frac{V_0}{R_2} = V_B\left[\frac{1}{R_1} + \frac{1}{R_2}\right] - \frac{V_1}{R_1}$$

$$\frac{V_0}{R_2} = \frac{V_2 R_2}{R_1 + R_2}\left(\frac{R_1 + R_2}{R_1 R_2}\right) - \frac{V_1}{R_1}$$

$$\frac{V_0}{R_2} = \frac{V_2}{R_1} - \frac{V_1}{R_1}$$

$$\frac{V_o}{R_2} = \frac{1}{R_1}(V_2 - V_1)$$

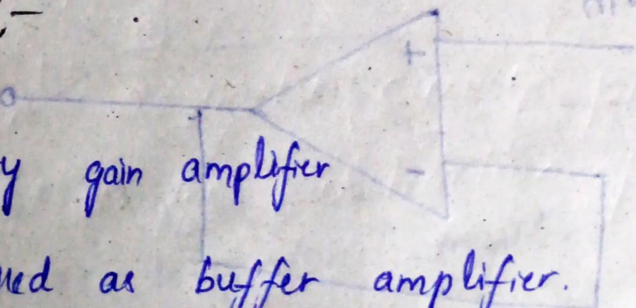
$$V_o = \frac{R_2}{R_1}(V_2 - V_1)$$

if take $R_2 = R_1$ then

$$V_o = (V_2 - V_1)$$

→ the output voltage is equal to the substraction of input voltages so it is called as difference amplifier.

Voltage follower:-



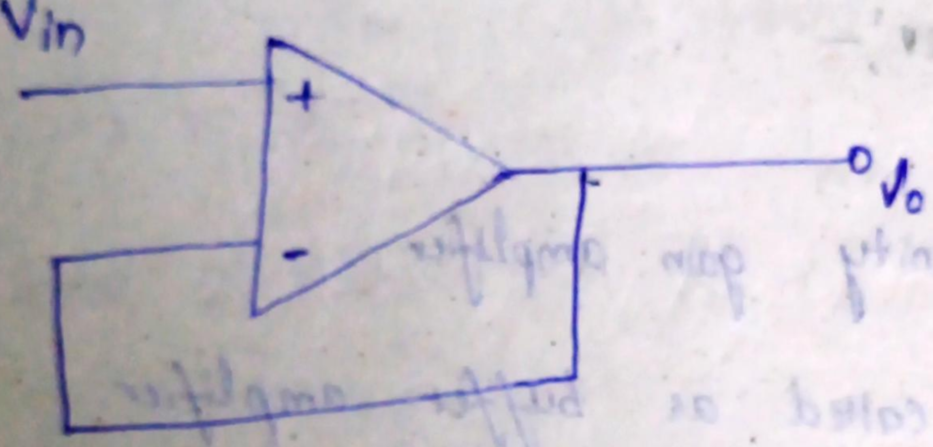
→ It is a unity gain amplifier

→ It is also called as buffer amplifier.

→ It doesn't provide any amplification to the input signal. so it is called as voltage follower.

→ If $V_{id} = 0$ then $V_o = V_i$. So voltage follower is called as buffer amplifier.

Op- Amp as a voltage follower:-



$V_0 = V_{in}$

then gain $(A) = \frac{V_0}{V_{in}}$

$A = \frac{V_{in}}{V_{in}}$

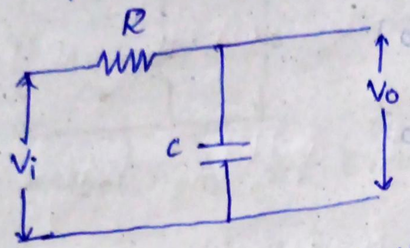
$\boxed{A = 1}$

Op- Amp as a Integrator:-

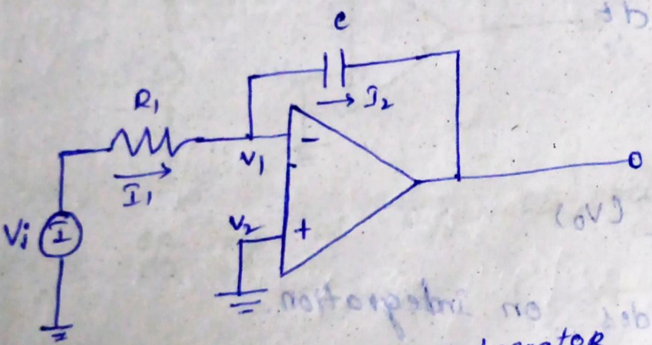
→ Low pass RC circuit act as an integrator

→ In integrator the output voltage is directly proportional to the integration of input voltage.

→ In integrator circuit resistor is connected at the series path and capacitor is connected at the feed back path



Low pass RC circuit.



Op- Amp as integrator circuit

from virtual ground concept $\boxed{V_1 = V_2}$

$V_2 = 0$

$V_1 = V_2 = 0$

$Q = CV$

$i = Q/t$

$i = C \cdot \frac{dv}{dt}$ (current flowing through capacitor).

Apply KCL at Node V_1

$I_1 = I_2$

$$I_1 = \frac{V_i - V_1}{R_1}$$

$$= \frac{V_i - 0}{R_1}$$

$$= \frac{V_i}{R_1}$$

$$I_2 = C \cdot \frac{d}{dt}(V_1 - V_0)$$

$$= C \frac{d}{dt}(0 - V_0)$$

$$= C \frac{d}{dt}(-V_0)$$

$$I_2 = -C \frac{dV_0}{dt}$$

$$I_1 = I_2$$

$$\frac{V_i}{R_1} = -C \cdot \frac{d}{dt}(V_0)$$

Apply both sides on integration.

$$\int \frac{V_i}{R_1} = \int -C \cdot \frac{d}{dt}(V_0)$$

$$V_0 = -\frac{1}{R_1 C} \int V_i \, dt$$

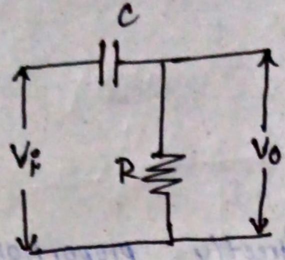
$$V_0 \propto \int V_i dt.$$

Op-Amp as differentiator:-

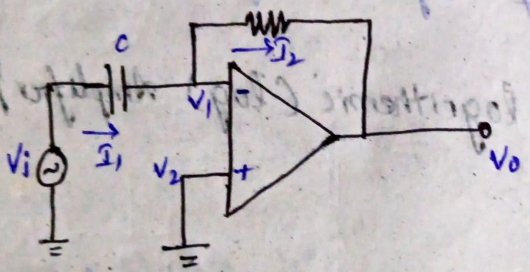
→ High pass RC circuit acts as a differentiator.

→ In differentiator the output voltage is directly proportional to the differentian of Input Voltage.

→ In differentiator circuit capacitor is connected at the series path and resistor is connected at the feedback path.



a) High pass RC circuit.



op-Amp as differentiator circuit

from virtual ground concept $V_1 = V_2$

$V_2 = 0$

$\boxed{V_1 = V_2 = 0}$

Applying KCL at node V_1 - $\underline{I_1 = I_2}$

$$I_1 = C \cdot \frac{d}{dt}(v_i - v_1)$$

$$= C \cdot \frac{dv_i}{dt}$$

$$I_2 = \frac{V_1 - V_0}{R}$$

$$I_2 = \frac{-V_0}{R}$$

$$I_1 = I_2$$

$$C \frac{dv_i}{dt} = \frac{-V_0}{R}$$

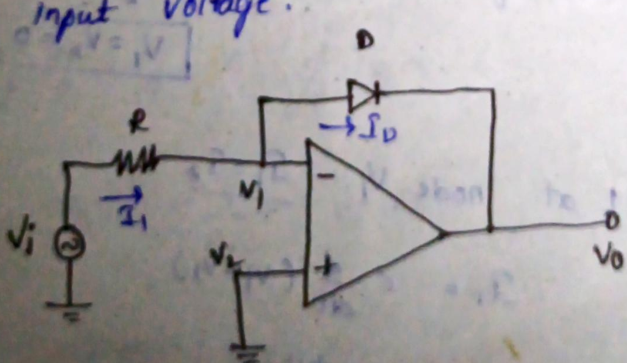
$$V_0 = -RC \frac{dv_i}{dt}$$

$$V_0 \propto \frac{dv_i}{dt}$$

the output voltage is directly proportional to the differention of input voltage.

op-Amp as a logrithemic (log) Amplifier with Diode :-

→ In op-Amp as a logrthemic amplifier the output voltage is directly proportional to the logithemic of the input voltage.



op-Amp as a logAmplifier circuit.

Diode equation - $I_D = I_0 (e^{\frac{V}{nV_T}} - 1)$

from virtual ground concept $V_2 = 0$

So, $\boxed{V_1 = V_2 = 0}$

Apply KCL at node V_1. $I = I_D$

$$I = \frac{V_i - V_1}{R}$$

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

NOW, $I_D = I_0 \left(e^{\frac{V}{\eta V_T}} - 1 \right)$

$$I_D = I_0 \left[e^{\frac{V_i - V_0}{\eta V_T}} - 1 \right]$$

$$I_D = I_0 \left[e^{\frac{-V_0}{\eta V_T}} - 1 \right]$$

$$I = I_D$$

$$\frac{V_i}{R} = I_0 \left[e^{\frac{-V_0}{\eta V_T}} - 1 \right]$$

Neglate '1'

$$\frac{V_i}{I_0 R} = \left[e^{\frac{-V_0}{\eta V_T}} \right]$$

Apply log on both sides.

$$\log\left[\frac{V_i}{I_0 R}\right] = \cancel{\log}\left[\cancel{e}^{\frac{-V_0}{\eta V_T}} \right]$$

$$\log\left[\frac{V_i}{I_0 R}\right] = \frac{-V_0}{\eta V_T}$$

$$\boxed{V_0 = -\eta V_T \log\left(\frac{V_i}{I_0 R}\right)}$$

$$\boxed{V_0 \propto \log(V_i)}$$