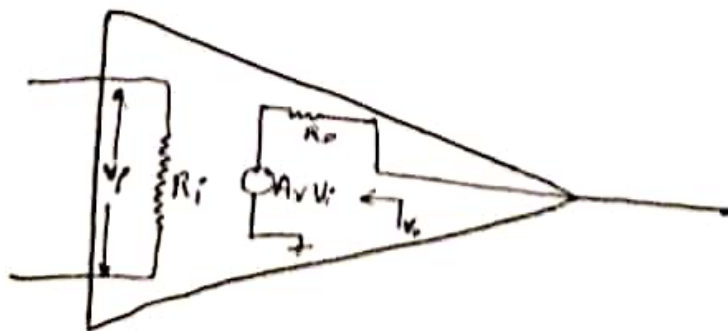
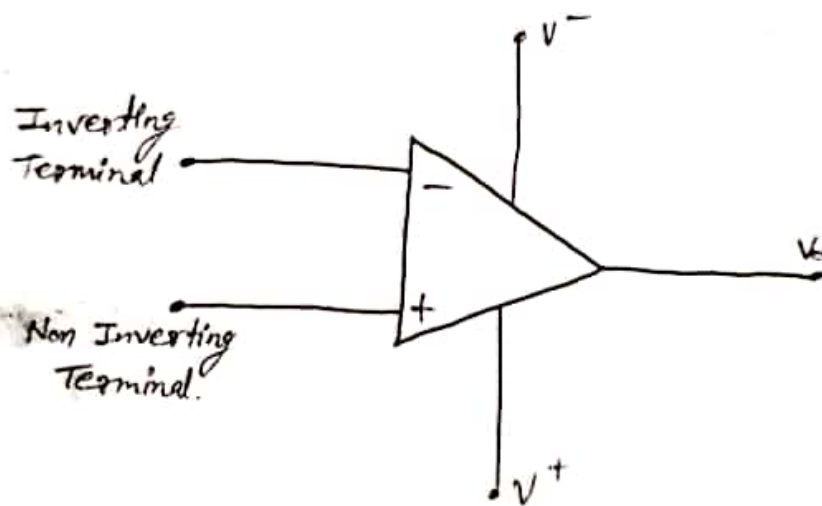


## Operational Amplifier (Op-Amp):

Op-Amp provides,

- ① High Input Impedance,
- ② Low output Impedance,
- ③ Voltage gain very high.

each Op-Amp has 5 basic terminals & other remaining terminals is & depends on type of Op-Amp & also of required application.



for Op-Amp  $R_o$  is very small  
 $R_i \rightarrow$  very large

Ideally  
 $R_i = \infty$ ,  
 $R_o = 0$ .



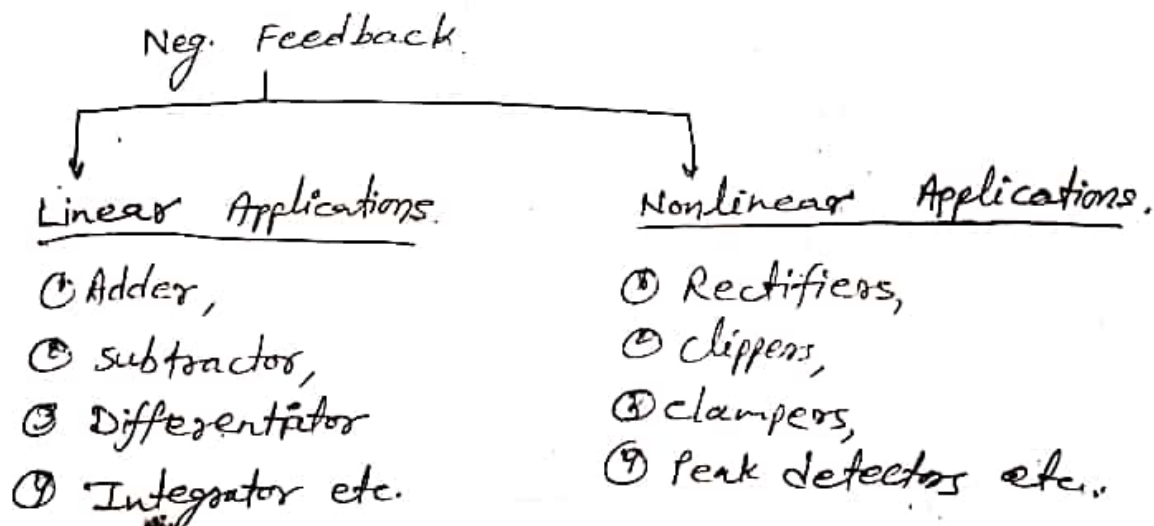
The current entering into the op-amp terminals is zero.

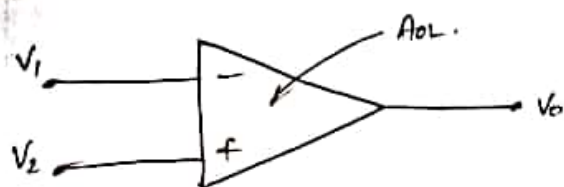
### Ideal characteristics of Op-Amps:-

- ①  $R_i = \infty$
- ②  $R_o = 0$
- ③ Open loop voltage gain  $A_{OL} = \infty$
- ④ B.W. =  $\infty$
- ⑤ Zero offset voltage
- ⑥ CMRR (Common mode rejection Ratio) =  $\infty$ .

The op-amp basically used in 3 configuration,

- ① Negative feedback,
- ② Positive feedback,  $\rightarrow$  oscillators,  $\rightarrow$  Schmitt Trigger.
- ③ open loop configuration  $\rightarrow$  comparators,  $\rightarrow$  Limiters.





$$V_0 = A_{OL}(V_2 - V_1)$$

If  $V_2 > V_1$ ,  $(V_2 - V_1)$  is positive.

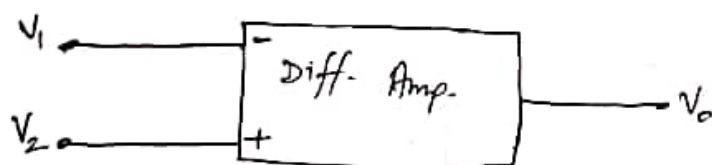
$$V_0 \cong +V_{sat} \quad (\text{op-amp work in saturation region})$$

If  $V_2 < V_1$ , then  $(V_2 - V_1)$  is negative

$$V_0 \cong -V_{sat}$$

Inverted.

\* Op. Amp is basically, a differential or difference Amplifier.



In practically when strength of IP voltage changes then output voltage of op. Amp is also changes

|                          |  |                          |
|--------------------------|--|--------------------------|
| $V_1 = 200 \mu V$        |  | $V_1 = 2000 \mu V$       |
| $V_2 = 150 \mu V$        |  | $V_2 = 1350 \mu V$       |
| $V_0 = A_{OL}(50 \mu V)$ |  | $V_0 = A_{OL}(50 \mu V)$ |

But both are not same or,

$$V_{01} \neq V_{02}$$

$\therefore$  we can say that,  $V_0$  of op. Amp not only depends on difference but also depends on common mode signal also.

Let,  $A_1 \rightarrow$  Voltage Amplification due to  $V_1$   
 $A_2 \rightarrow$  Voltage Amplification due to  $V_2$ .

$$V_o = A_1 V_1 + A_2 V_2 \quad \text{--- (1)}$$

$$\text{Difference signal voltage} = V_2 - V_1 = V_d \quad \text{--- (2)}$$

$$\text{Common mode voltage } V_c = \frac{V_1 + V_2}{2} \quad \text{--- (3)}$$

$$\text{eqn (2), } V_2 = V_1 + V_d$$

$$\text{eqn (3), } V_c = \frac{V_1}{2} + \frac{V_2}{2} = \frac{V_1}{2} + \frac{V_1 + V_d}{2}$$

$$V_c = V_1 + \frac{V_d}{2}$$

$$\boxed{V_1 = V_c - \frac{V_d}{2}} \quad \text{--- (4)}$$

Substitute eqn (4) in  $V_2 = V_1 + V_d$ .

$$= V_c - \frac{V_d}{2} + V_d$$

$$\boxed{V_2 = V_c + \frac{V_d}{2}}$$

Substitute values of  $V_1$  &  $V_2$  in eqn (1).

$$V_o = A_1 \left( V_c - \frac{V_d}{2} \right) + A_2 \left( V_c + \frac{V_d}{2} \right)$$

$$V_o = V_d \left( \underbrace{\frac{A_2 - A_1}{2}}_{\text{Differential mode gain}} \right) + V_c \left( \underbrace{A_1 + A_2}_{\text{Common mode gain}} \right)$$

$$\boxed{V_o = A_d \cdot V_d + A_c \cdot V_c}$$

o/p due to

o/p due to common mode signal.

The ratio of  $A_d$  to  $A_c$  is known as CMRR.

$$\text{CMRR} = \frac{A_d}{A_c}$$

for OP-Amp CMRR should be very high (ideally  $= \infty$ ) This cond<sup>n</sup> can be achieved by connecting  $A_1$  to  $-V_e$  &  $A_2$  to  $+V_e$ .

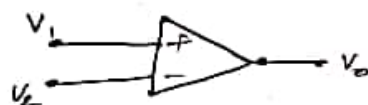
$$A_1 \rightarrow -V_e$$

$$A_2 \rightarrow +V_e$$

$$A_d = \left( \frac{A_2 - A_1}{2} \right) \rightarrow \text{Diff. gain is very high}$$

$$A_c = (A_2 + A_1) \rightarrow \text{very low}$$

Q $\Rightarrow$  A diff. Amp. shown below as diff. mode gain 100 & CMRR is 40 dB. If  $V_1 = 0.55V$  &  $V_2 = 0.45V$ . then  $V_o = ?$



$$A_d = 100, (\text{CMRR})_{dB} = 40 \text{ dB}$$

Sol<sup>n</sup>:

$$V_o = A_d V_d + A_c V_c$$

$$(\text{CMRR})_{dB} = 40 = 20 \log \left( \frac{A_d}{A_c} \right)$$

$$2 = \log \left( \frac{A_d}{A_c} \right)$$

$$\frac{100}{A_c} = 100$$

$$A_c = 1$$

$$V_d = V_1 - V_2 = 0.1 \text{ V}$$

$$V_c = \frac{V_1 + V_2}{2} = 0.5 \text{ V}$$

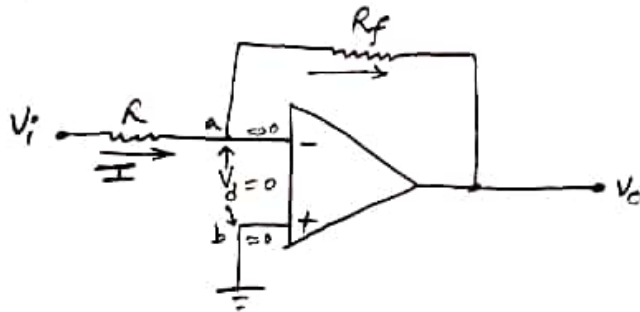
$$V_o = 100 \times 0.1 + 1 \times 0.5$$

$$V_o = 10.5 \text{ Volt}$$

Date  
28/10/2009

## Basic Applications of OP-Amp:-

### Inverting Amplifier:-



The I/P Impedance of Amp  $\Rightarrow$  Very high ideally  $\infty$

The current entering into the op-amp terminals is zero.

$$V_d \approx 0$$

$$V_d = (V_b - V_a) = (0 - V_a) = 0.$$

$\therefore V_a = 0$ .  $\rightarrow$  So, Node 'a' is called Virtual Ground.

$$I = I_f + I_a \rightarrow 0$$

$$I = I_f$$

$$\frac{V_i - V_a}{R} = \frac{V_a - V_o}{R_f}$$

$$\frac{V_i}{R} = -\frac{V_o}{R_f}$$

$$V_o = -V_i \left( \frac{R_f}{R} \right)$$

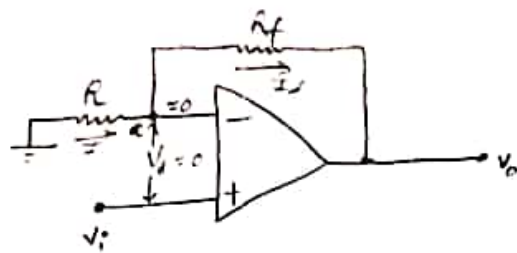
-ve sign  $\rightarrow$   $180^\circ$  of phase shift b/w I/P ( $V_i$ ) & O/P ( $V_o$ ).

Gain:-

$$\frac{V_o}{V_i} = A_v = -\frac{R_f}{R}$$

always  $R_f > R$

## Non-Inverting Amplifier:-



$$V_d = 0 = V_i - V_a$$

$$\boxed{V_a = V_i}$$

Apply KCL at node a,

$$I = I_f + I_a$$

$$I = I_f$$

$$\frac{0 - V_a}{R} = \frac{V_a - V_o}{R_f}$$

$$-\frac{V_a}{R} = \frac{V_a}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_i}{R_f} = V_a \left( \frac{1}{R} + \frac{1}{R_f} \right) = V_a \left( \frac{R + R_f}{R \cdot R_f} \right)$$

$$V_o = V_a \left( \frac{R + R_f}{R} \right)$$

$$\therefore V_a = V_i$$

$$\therefore \boxed{V_o = +V_i \left( 1 + \frac{R_f}{R} \right)}$$

+ve sign represents  $V_o$  &  $V_i$  are in phase or there is no phase shift in non-inverting amp.

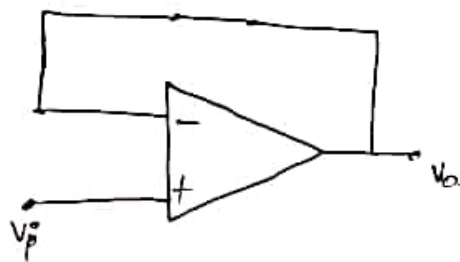
$$\boxed{\frac{V_o}{V_i} = \left[ 1 + \frac{R_f}{R} \right] = A_v}$$

for same ckt,

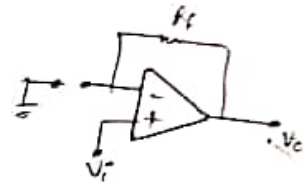
Gain of Non-Inverting Amp.  $>$  Gain of Inverting Amp

$$A_{V(N-I)} > A_{V(I)}$$

when,  $\frac{R_f}{R} = 0$  If  $R_f = 0$  or  $R = \infty$ . then Non-inverting Amplifier becomes Voltage follower ckt.



or



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

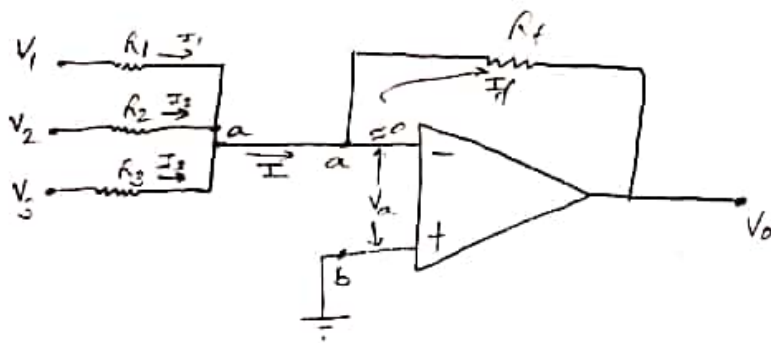
$$V_o = V_i$$

$$\boxed{\frac{V_o}{V_i} = A_V = 1}$$

voltage follower or Buffer Amplifier.

$$\left\{ \begin{array}{l} R_i = \infty \\ R_o = 0 \\ A_V = 1 \end{array} \right\} \text{ Buffer Amplifier}$$

## Inverting Summing Amplifier :-



Since  $V_b = 0$

$$(V_b - V_a) = 0.$$

$$V_a = V_b = 0.$$

Node 'a'  $\rightarrow$  Virtual Ground.

Apply KCL at node -@:-

$$I_1 + I_2 + I_3 = I = I_f.$$

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} = \frac{V_a - V_o}{R_f}$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} - V_a \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) = \frac{V_a}{R_f} - \frac{V_o}{R_f}$$

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

or

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

when,  $R_1 = R_2 = R_3 = R_f$

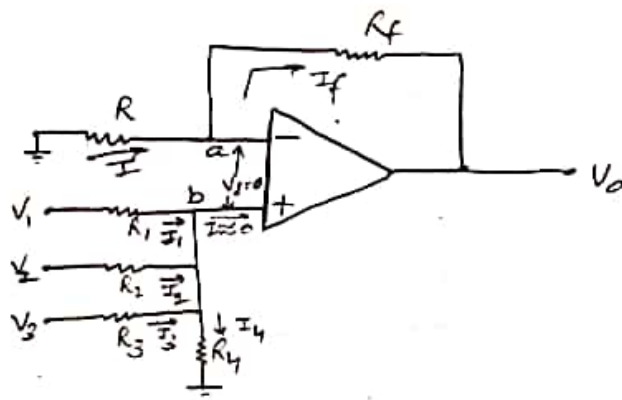
$$V_o = -[V_1 + V_2 + V_3]$$

$\rightarrow$  Inverting Summing Amplifier.

When,  $R_1 = R_2 = R_3 = 3R_f$  then  
 $R_1 = R_2 = R_3 = R_4 = 4R_f$

$$V_o = - \left[ \frac{V_1 + V_2 + V_3}{3} \right] \rightarrow \text{Same ckt for above Resistive value work as Inverting Average Amplifier.}$$

### Non-Inverting Summing Amplifier :-



Since  $V_d = 0 \Rightarrow V_o = V_a$ .

Apply KCL at 'b'

$$I_1 + I_2 + I_3 = I_4$$

$$\frac{V_1 - V_b}{R_1} + \frac{V_2 - V_b}{R_2} + \frac{V_3 - V_b}{R_3} = \frac{V_b - 0}{R_4}$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = V_b \left[ \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right]$$

$$\therefore V_b = \left[ \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} \right]$$

Apply KCL at 'a',

$$I = I_f$$

$$\frac{0 - V_a}{R} = \frac{V_a - V_o}{R_f}$$

$$-\frac{V_a}{R} = \frac{V_a}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = V_a \left[ \frac{1}{R_f} + \frac{1}{R} \right] = V_a \left[ \frac{R + R_f}{R \cdot R_f} \right]$$

$$V_o = V_a \left( 1 + \frac{R_f}{R} \right)$$

∴ By virtual ground concept,

$$V_a = V_b$$

$$\therefore V_o = \left( 1 + \frac{R_f}{R} \right) \left[ \frac{\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}} \right]$$

Let,  $R_1 = R_2 = R_3 = R_4$

$$V_o = \left( 1 + \frac{R_f}{R} \right) \left[ \frac{V_1 + V_2 + V_3}{4} \right]$$

when,  $R_f = 3R$ ,

$$V_o = [V_1 + V_2 + V_3] \rightarrow \text{work as Non-Inverting Summing Amplifier}$$

when,  $R = 3R_f$  then,

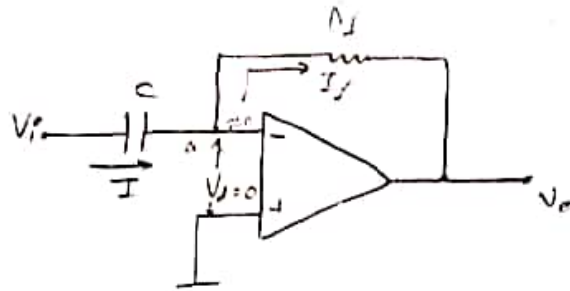
$$V_o = \left( 1 + \frac{R_f}{3R_f} \right) \left[ \frac{V_1 + V_2 + V_3}{4} \right]$$

$$V_o = \frac{4}{3} \left[ \frac{V_1 + V_2 + V_3}{4} \right]$$

$$V_o = \frac{V_1 + V_2 + V_3}{3}$$

→ Average

Differentiator :- (High Pass filter)



Since,  $V_a = 0$ ,  $V_n = 0$ .

Apply KCL at node - 'a' :-

$$I = I_f$$

Capacitor,  
 $\therefore I_C = C \frac{d}{dt} (V_C)$

$$C \frac{d}{dt} (V_i - V_a) = \frac{V_a - V_o}{R_f}$$

$$\frac{-V_o}{R_f} = C \frac{d}{dt} (V_i)$$

$$V_o = -R_f \cdot C \frac{d}{dt} (V_i)$$

The o/p voltage is ( $V_o$ ) is differentiation of i/p voltage ( $V_i$ ).

In for fourier Transform,

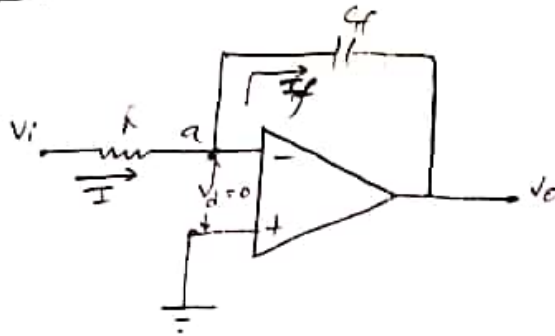
$$x(t) \xleftrightarrow[\text{I.F.T.}]{\text{F.T.}} X(\omega)$$

$$x'(t) \text{ or } \frac{d}{dt} x(t) \longrightarrow j\omega X(\omega)$$

$\therefore$  Take fourier Transform of o/p voltage to find out gain of ckt,

$$\text{F.T. } [V_o(t)] = \text{F.T. } \left[ -C \cdot R_f \cdot \frac{d}{dt} V_i(t) \right]$$

Integrator :- (Low pass filter).



$$V_d = 0 \Rightarrow V_a = 0.$$

$$I = I_f.$$

$$\frac{V_i - V_a}{R} = C_f \frac{d}{dt} (V_a - V_o).$$

$$\frac{V_i}{R} = -C_f \cdot \frac{dV_o}{dt}$$

$$V_o = -\frac{1}{R \cdot C_f} \int V_i dt$$

o/p voltage is proportional to integral of Input.

at low freq<sup>n</sup>,  $\Rightarrow f = 0$  /  $X_C = \infty \rightarrow$  o.c. of feedback path

Practical Integrator ckt :-

