UNIT-3

OPERATIONAL AMPLIFIER

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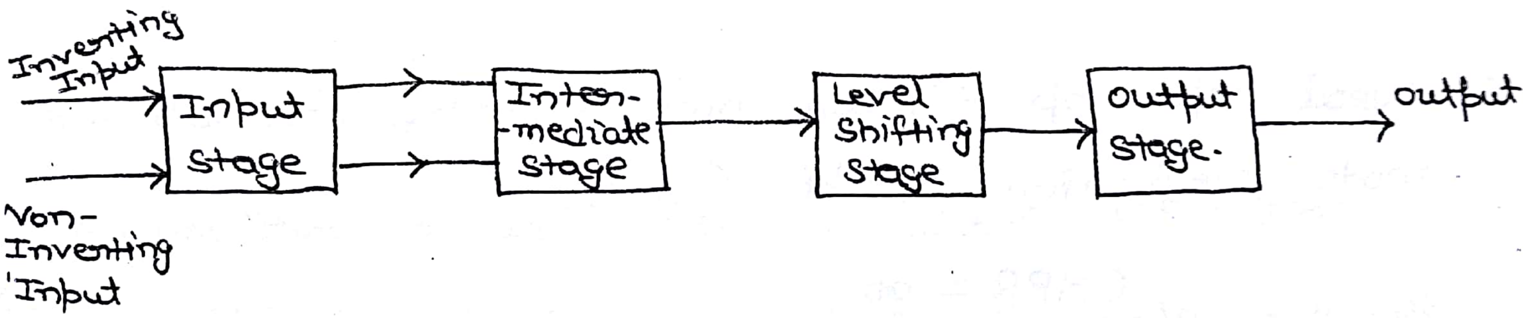
OPERATIONAL AMPLIFIER (OP-AMP):

OP-Amp is a directly coupled very high gain amplifier generally consisting of one (or) more differential Amplifier. An OP-Amp can amplify signals having frequency from 0Hz to 1MHz. It is so named because it can do mathematical operations like addition, subtraction, multiplication and integration. It is available in the form of IC package.

Block diagram of an op-Amp:



Input stage is dual Input, Balanced output differential amplifier. This stage provides most of the voltage gain of the amplifier and also establish the Input resistance of the OP-Amp.

Intermediate stage is a dual Input, unbalanced output differential amplifier. It increases over-all gain of OP-Amp.

Level shifting stage is used to shift dc level downward to zero volts with respect to ground. This stage is emitter follower using constant current source.

The last stage is a complementary Push Pull amplifier. The output stage increase the output voltage swing and current ... capability of OP-Amp. It provide low output resistance

Properties of Ideal OP-Amp:

1. Open loop voltage gain of ideal op-Amp is infinite

$$A_{OL} = \infty$$

2. Input Resistance of ideal OP-Amp is infinite

$$R_i = \infty$$

3. Output Resistance of ideal OP-Amp must be Zero

$$R_o = 0$$

4. Ideal op-Amp should have infinite Bandwidth

$$B = \infty$$

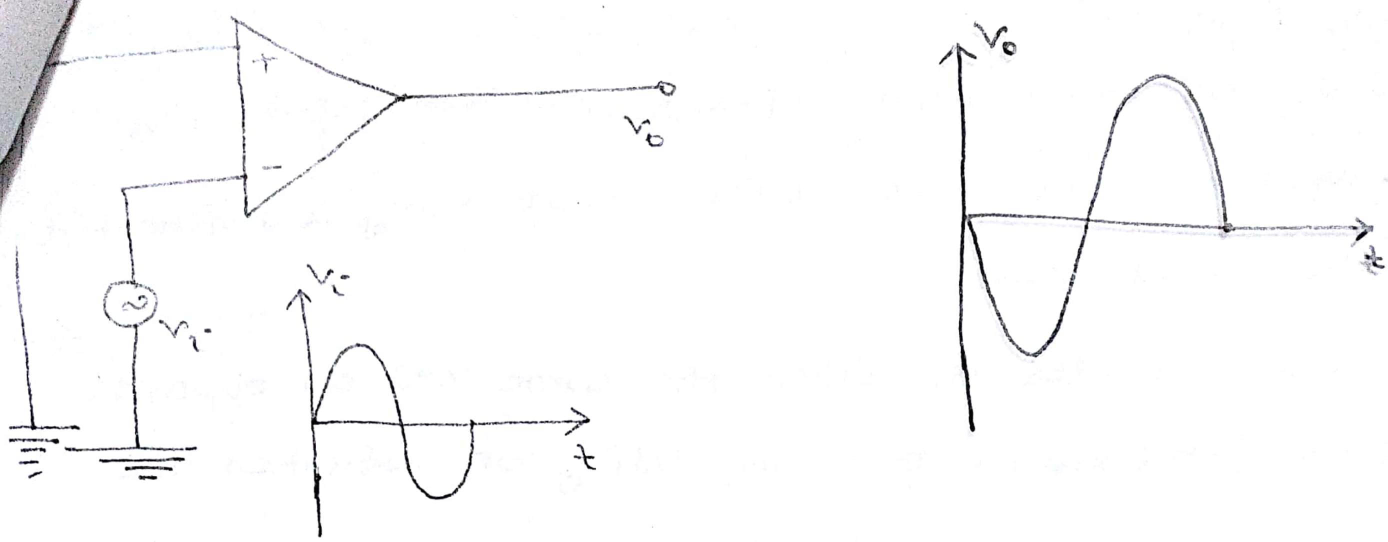
5. Ideal op-Amp should have infinite common mode rejection ratio (CMRR)

$$CMRR = \infty$$

6. Ideal op-Amp should have infinite slew rate.

$$SR = \infty$$

7. Ideal op-Amp should have zero o/p with Zero Input.



In above Figure, An input signal applied to the minus Input, the output then being opposite in phase to the applied signal.

Double Ended Input :

In addition to using only one Input, it is possible to apply signal at each input, this being a double ended operation.

$$V_d = V_{i_1} - V_{i_2}$$

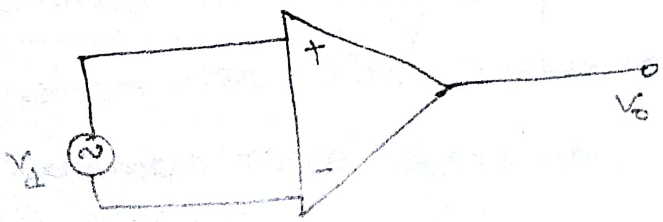


Fig (a)

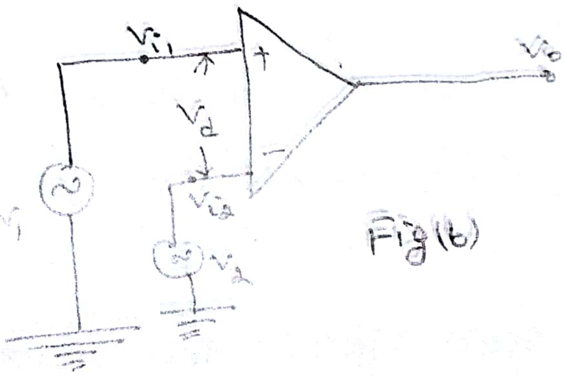
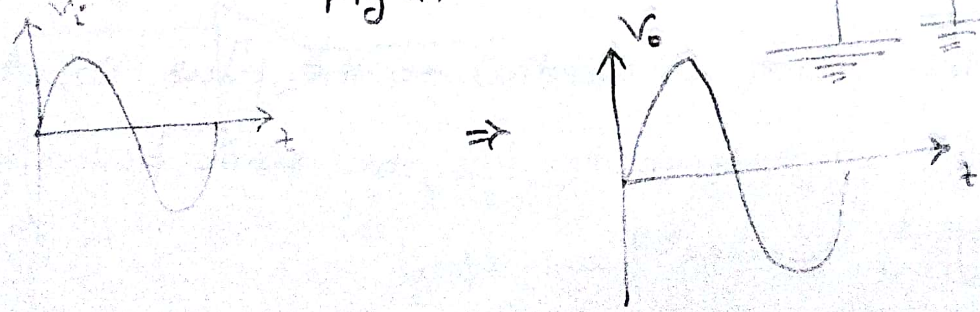


Fig (b)



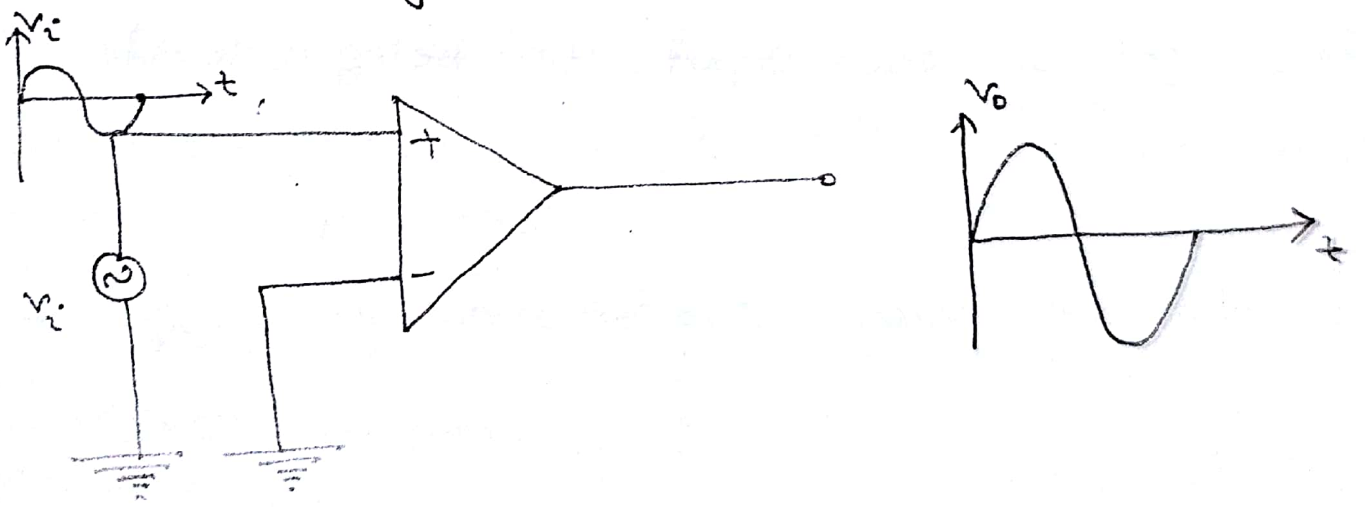
Op-Amp Basics:

Below Figures shows a basic op-Amp with two inputs and ~~input~~ one output as would result using a differential amplifier input stage.

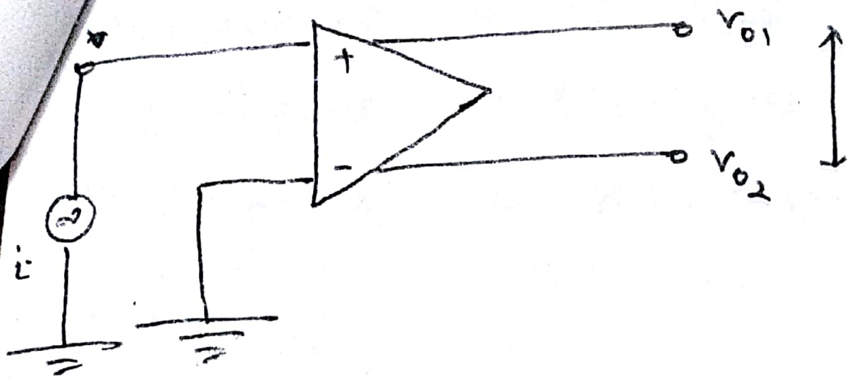
Each Input results in either the same (or) an opposite polarity (or phase) output, depending on whether the signal is applied to the plus (+) or the minus (−) respectively.

Single Ended Input:

Single Ended input operation results when the input signal is connected to one input with the other input connected to ground.



In above figure, the input is applied to the plus input which results in an output having the same polarity as the applied input signal.



$$V_d = V_{01} - V_{02}$$

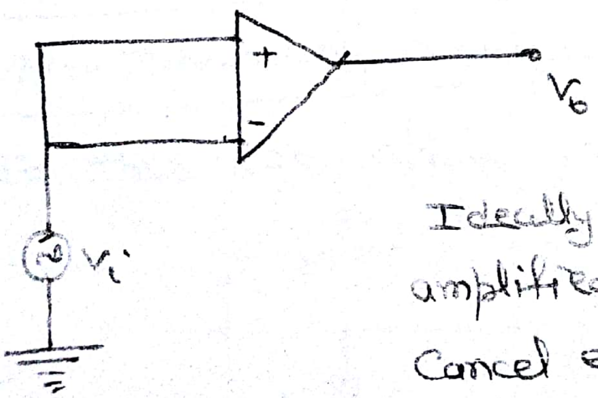
The single output can also be taken from above figure. It will be the difference of two output signal i.e $V_d = V_{01} - V_{02}$.

The difference of output signal is referred to as a floating signal.

The difference o/p is large, because they are of opposite polarity and subtracting them results in twice their ~~mean~~ Amplitude.

<u>Common mode operation:</u>

when the Same Input signal is applied to both the Input common mode operation results as shown in fig.



Ideally the two inputs are equally amplified, But At the output these signal Cancel each other, resulting in an output

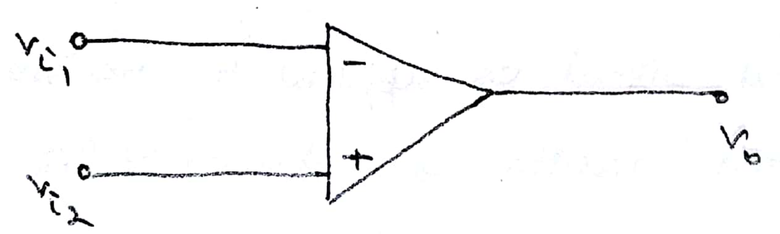
Practically, a small output signal will results.

In Fig (a), an input V_i., applied between the two input terminals, with the resulting amplified output in phase with that applied between the plus and minus inputs.

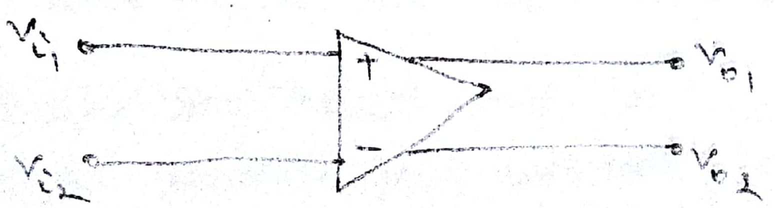
In Fig. (b) the same action resulting when two separate signals are applied to the inputs, the difference signal beings $V_{i_1} - V_{i_2}$.

Double Ended output:

The OP-Amp can also be operated with opposite outputs. An Input applied to either inputs will result in output from both output terminals. These ouputs always being opposite in polarity.



Simple Symbol



Double Ended output.

appear at the inverting terminal, because of infinite voltage gain.

So, Potential at inverting terminal is called virtual ground. virtual ground means that terminal is not connected to ground actually, even then the voltage at terminal is zero.

From Figure $I_2 = 0$ $[\because V_1 = V_2]$

$$I_1 = \frac{V_i - V_2}{R_1} \quad , \quad I_f = \frac{V_2 - V_o}{R_F}$$

$$I_1 = I_F \quad \text{[Because } I_2 = 0A]$$

$$\frac{V_i - V_2}{R_1} = \frac{V_2 - V_o}{R_F}$$

Put $V_2 = 0$

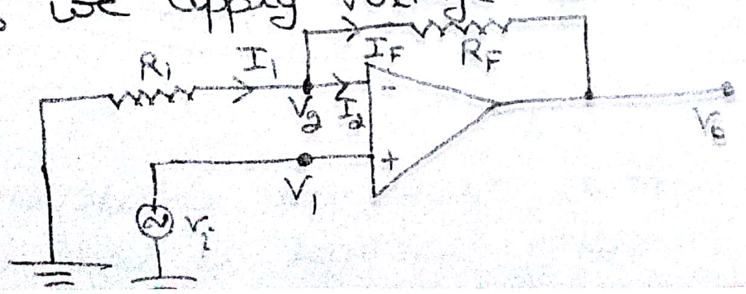
$$\frac{V_i}{R_1} = -\frac{V_o}{R_F} \Rightarrow \frac{V_o}{V_i} = -\frac{R_F}{R_1}$$

(or) $\boxed{A_{CL} \text{ (or) } A_F = -\frac{R_F}{R_1}}$ and $\boxed{V_o = -\frac{R_F}{R_1} V_i}$

* Negative sign indicates that output voltage is with opposite phase with respect to input voltage.

Non-Inverting Amplifier:

In this we apply voltage at non-Inverting terminal

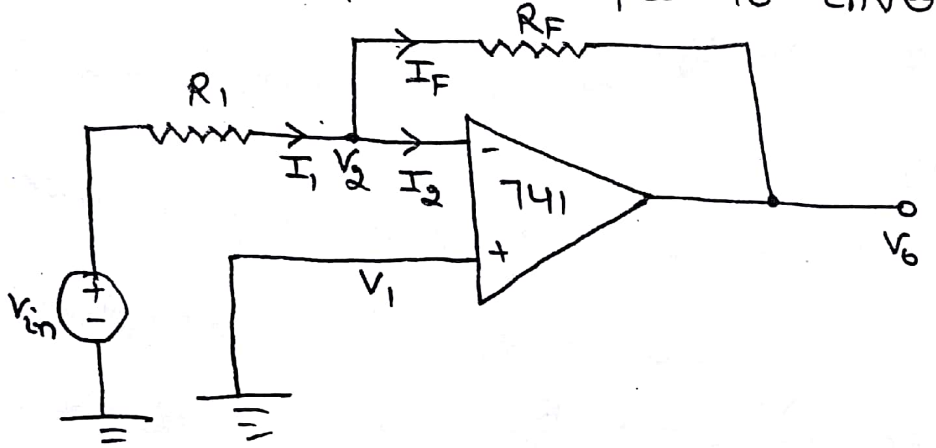


Closed Loop OP-Amp configuration:

As open loop OP-Amp can not be used in linear applic... So, By Introducing feed back we may use it for linear application. If the feedback is provided at negative Input then it will be called negative feedback. If it is provided to Positive terminal then it will be called Positive feedback. An OP-Amp that uses feedback is called closed loop Amplifier.

OP-Amp as Inverting Amplifier:

In this we provide input to inverting terminal.



For an OP-Amp:

$$A = \frac{V_o}{V_{id}} = \frac{V_o}{V_1 - V_2} \qquad [\because V_{id} = V_1 - V_2]$$

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

$$\boxed{A = \infty} \qquad V_1 - V_2 = \frac{V_o}{\infty}$$

$$V_1 - V_2 = 0 \Rightarrow \boxed{V_1 = V_2} \rightarrow \text{Virtual short}$$

$$V_1 = 0 \quad \therefore \quad V_2 = 0$$

A virtual short circuit means that whatever is the voltage at non-Inverting terminal, it will automatically an op-Amp.

$$A = \frac{V_o}{V_{id}} = \frac{V_o}{V_1 - V_2} \quad [\because V_{id} = V_1 - V_2]$$

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

$$A = \infty, \quad V_1 - V_2 = 0 \Rightarrow \boxed{V_1 = V_2} \rightarrow \text{virtual short}$$

$V_1 = V_i$. Hence $\boxed{V_2 = V_i}$

From Figure $I_2 = 0$, Because $V_1 = V_2$

$$I_1 = \frac{0 - V_2}{R_1}, \quad I_f = \frac{V_2 - V_o}{R_F}$$

$I_1 = I_F$ Because $[V_1 = V_2]$

$$\frac{0 - V_2}{R_1} = \frac{V_2 - V_o}{R_F}$$

Put $V_2 = V_i$.

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

And $$\boxed{A_{CL} \text{ (or) } A_F = \frac{V_o}{V_i} = 1 + \frac{R_F}{R_1}}$$

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

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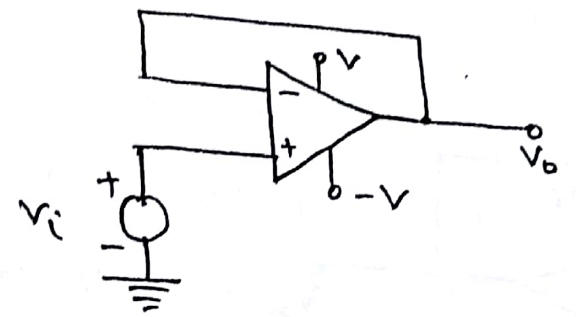
Linear Applications of OP-Amps:

closed loop OP-Amp configurations is widely used in a number of linear applications. It means output of Input of op-Amp are linearly Related.

a) Buffer Amplifier:

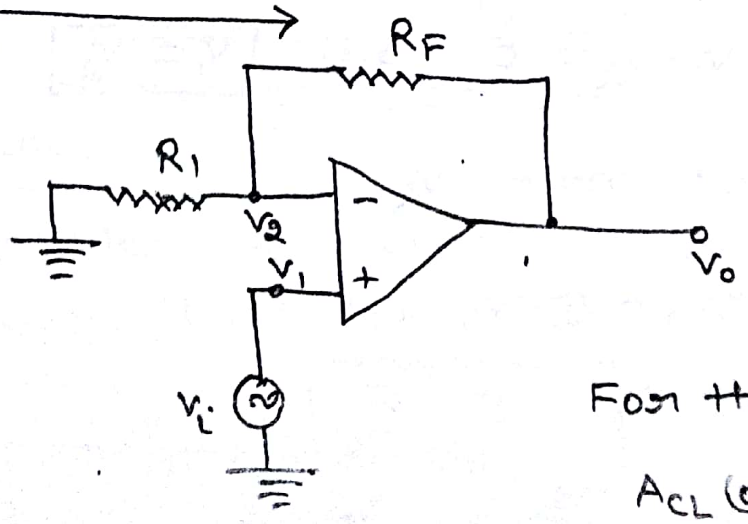
The gain for Amplifier is 1.

$A_F = 1$ So that $\frac{V_o}{V_i} = 1 \Rightarrow \boxed{V_o = V_i}$



The Buffer Amplifier provides a means of isolating an Input signal from load.
Thus it can be made to prevent disturbance of one part of circuit to another part.

b) voltage Follower:



For this circuit

$$A_{CL} \text{ (or) } A_F = 1 + \frac{R_F}{R_1}$$

Let $R_F = 0$ (Shorting) and $R_1 = \infty$ (opening)

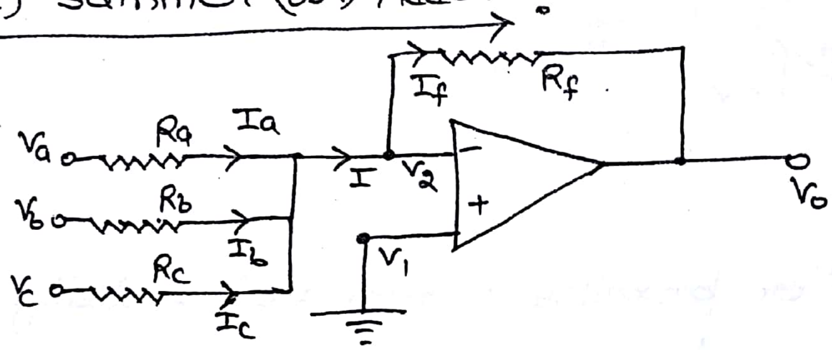
$$A_F = 1 + \frac{0}{\infty} = 1 \Rightarrow \frac{V_o}{V_i} = 1 \Rightarrow \boxed{V_o = V_i}$$

output voltage = Input voltage.

This circuit is called voltage follower because o/p voltage is equal to and in phase with Input. In other words, In voltage follower output follows input.

Hence voltage follower is a special case of the non-inverting amplifier. voltage amplifier is also used as a Buffer Amplifier.

(c) Summer (or) Adder :



$V_o = A V_{id}$ $\quad [\because V_{id} = V_1 - V_2]$

For Ideal op-Amp $\quad V_o = A(V_1 - V_2)$

$$V_1 - V_2 = \frac{V_o}{A} = \frac{V_o}{\infty} \qquad [\because A = \infty]$$

So, $V_1 - V_2 = 0$ and $\boxed{V_1 = V_2}$ and $V_1 = 0$ so that $V_2 = 0$

Applying KCL at node V_2.

$$I_a + I_b + I_c = I$$

and $I = I_f$

$$I = \frac{V_a - V_2}{R_a} + \frac{V_b - V_2}{R_b} + \frac{V_c - V_2}{R_c}$$

$\because V_2 = 0$

Hence $$I = \frac{V_a}{R_a} + \frac{V_b}{R_1} + \frac{V_c}{R_1}$$

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

$\because A = \infty$

Hence $V_1 - V_2 = \frac{V_o}{\infty} \Rightarrow V_1 - V_2 = 0$

$$\boxed{V_1 = V_2}$$

and $V_1 = 0$ (given)

So that $V_2 = 0$

And $I_1 = I_c$

$$I_1 = \frac{V_i - V_2}{R_1} \quad \text{and} \quad I_c = \frac{C\,dV_c}{dt}$$

$$V_c = V_2 - V_o$$

$$V_c = 0 - V_o = -V_o$$

Hence $I_c = -\frac{C\,dV_o}{dt}$

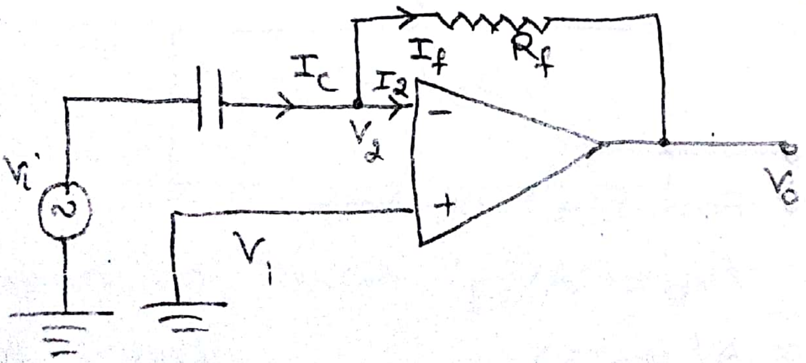
$$\frac{V_i - V_2}{R_1} = -\frac{C\,dV_o}{dt}$$

$$\frac{V_i}{R} = -\frac{C\,dV_o}{dt}$$

$$\boxed{V_o = -\frac{1}{R_1 C}\int_0^t V_i\,dt}$$

Differentiator:

A differentiator is a circuit in which output voltage is the differential of the input voltage waveform.



and $I_f = \dfrac{V_2 - V_o}{R_f}$

$$I_f = \frac{-V_o}{R_f} \qquad [\because V_2 = 0]$$

As we know

$$I = I_f$$

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} = -\frac{V_o}{R_f}$$

Re-arrange the equation

$$\boxed{V_o = -\left[\frac{R_f}{R_a}V_a + \frac{R_f}{R_b}V_b + \frac{R_f}{R_c}V_c\right]}$$

Let us Substitute

$$R_a = R_b = R_c = R_f$$

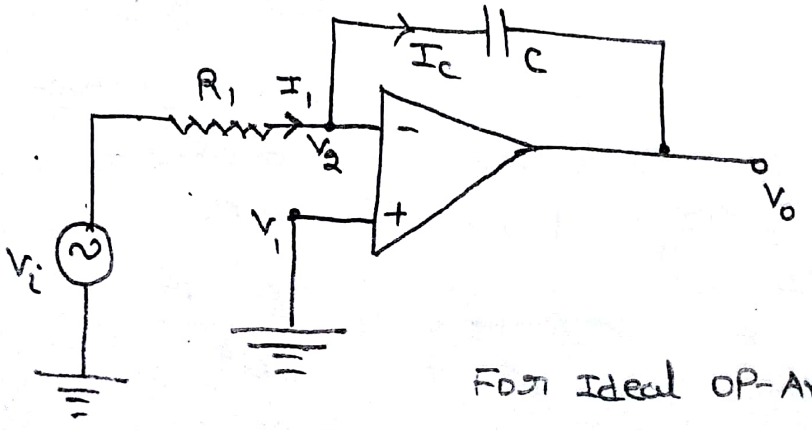
then we obtain

$$\boxed{V_o = -(V_a + V_b + V_c)}$$

output voltage is sum of three inputs.

(i) Integrator:

An Integrator is a circuit in which the output voltage waveform is the integral of the input voltage waveform



For Ideal OP-Amp

$$V_o = AV_{id}$$

$$V_o = A(V_1 - V_2)$$

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For an OP-Amp:

$$A = \frac{V_o}{V_{id}} \quad , \quad V_{id} = V_1 - V_2$$

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

$$A = \infty$$

$$V_1 - V_2 = \frac{V_o}{\infty} \Rightarrow V_1 - V_2 = 0 \Rightarrow \boxed{V_1 = V_2}$$

And $V_1 = 0$

Hence $\boxed{V_2 = 0}$

Due to $V_1 = V_2 \Rightarrow I_2 = 0$

So that $I_c = I_f$

$$I_c = \frac{c\,dV_c}{dt} \qquad \left[\because Q = CV \text{ and } \frac{dQ}{dt} = \frac{c\,dV}{dt}\right]$$

$$V_c = V_i - V_2 \Rightarrow I_c = +\frac{c\,dV_i}{dt}$$

and $V_c = +V_i \quad [\because V_2 = 0]$

$$I_f = \frac{V_2 - V_o}{R_f} \Rightarrow \frac{-V_o}{R_f} \quad [\text{As } V_2 = 0]$$

$$I_c = I_f$$

$$+\frac{c\,dV_o}{dt} = \frac{-V_o}{R_f}$$

$$\boxed{V_o = -R_f C \frac{dV_i}{dt}}$$

This Expression shows that output is the differentiation of the input.

OP-Amp Parameters:

Bias current:

Input Bias current I_b is the average of current that flow into the inverting and non-inverting input termin of the op-Amp.

$$\boxed{I_b = \frac{I_{b_1} + I_{b2}}{2}}$$

1. Slew Rate:

The slew rate is defined as maximum rate of change output voltage with respect to time.

$$\boxed{\text{Slew Rate (SR)} = \left.\frac{dV_o}{dt}\right|_{max.}}$$

3. Common mode rejection Ratio:

Common mode rejection ratio may be defined as rati of the differential voltage gain 'A_d' to the common mode voltage gain.

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

Differential voltage gain is defined as

$$A_d = \frac{V_o}{V_{id}} \qquad V_{id} = V_1 - V_2$$

Common mode voltage gain is defined as

$$A_{CM} = \frac{V_{OCM}}{V_{CM}} \qquad V_{CM} = \frac{1}{2}(V_1 + V_2)$$

The value of CMRR in decibel is

$$(CMRR)_{decibel} = 20 \log_{10} \frac{A_d}{A_c}$$

$$V_{id} = V_1 - V_2 \quad \& \quad V_{CM} = \frac{1}{2}(V_1 + V_2)$$

and, $V_o = A_1 V_1 + A_2 V_2$

write $V_{id} = V_d$

From above $V_1 = V_c + \frac{1}{2} V_d$

$$V_2 = V_c - \frac{1}{2} V_d$$

$$V_o = A_1 V_1 + A_2 V_2$$

$$= A_1 \left[V_c + \frac{1}{2} V_d\right] + A_2 \left[V_c - \frac{1}{2} V_d\right]$$

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

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

where $A_d = \frac{1}{2}[A_1 - A_2]$

$$A_c = \frac{1}{2}(A_1 + A_2)$$

$$V_o = A_d V_d + \frac{A_d}{CMRR} V_c = A_d V_d \left[1 + \frac{1}{CMRR} \frac{V_c}{V_d}\right]$$

$$\boxed{V_o = A_d V_d \left[1 + \frac{1}{CMRR} \frac{V_c}{V_d}\right]}$$

, an Input signal is applied to either input with
the other input Grounded, the operation is
referred to as single-ended.

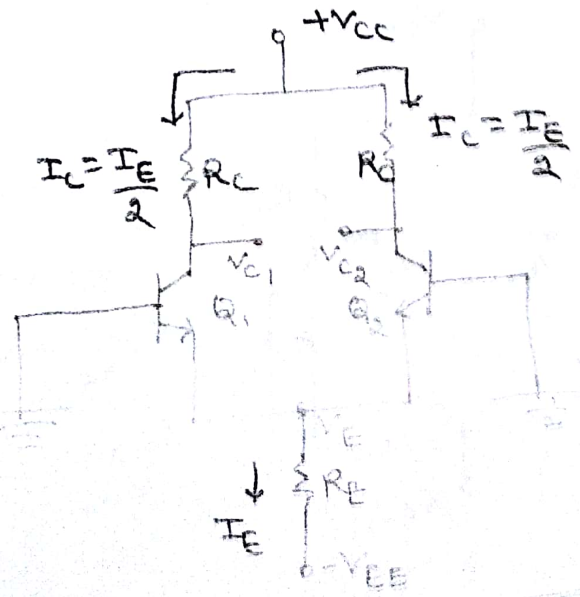
If two opposite polarity Input signal are applied, the
operation is referred as Double ended.

If the same Input is applied to both inputs, the
operation is called "common mode".

The main features of the differential amplifier is the
very large gain when opposite signals are applied
to the inputs as compared to the very small
gain resulting from common inputs.

The ratio of this difference gain to the common gain
is called common-mode rejection.

DC- Bias:



Common mode Rejection:

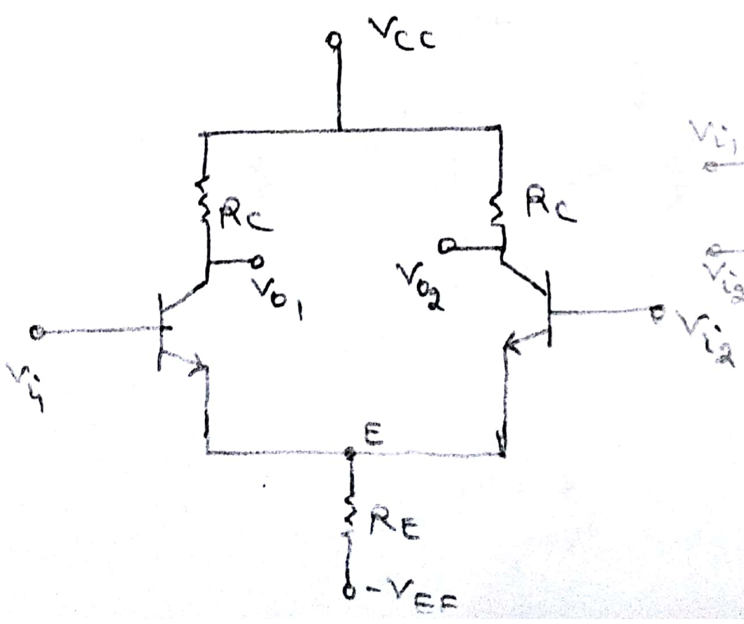
A significant feature of a differential connection is the the signal that are opposite at the inputs are highly amplified, whereas those are common to the two inputs are only slightly amplified.

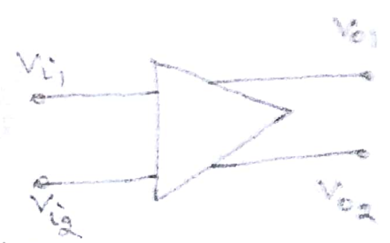
* The overall operation being to amplify the difference signal while rejecting the common signal at the two inputs.

This operating features is referred to as common mode rejection

⇒ Differential Amplifier circuit:

The differential Amplifier circuit is an extremely popular connection used in IC units. This connection can be describe by considering basic differential amplifier shown in fig:





$$V_{BE} = V_B - V_E$$

$$V_E = V_B - V_{BE}$$

$$= 0 - 0.7V$$

$$V_E = 0.7V$$

The emitter DC Bias current is then

$$I_E = \frac{V_E - (-V_{EE})}{R_E} \cong \frac{V_{EE} - 0.7V}{R_E}$$

If Both transistor are well matched

$$I_{C_1} = I_{C_2} \cong \frac{I_E}{2}$$

$$V_{C_1} = V_{C_2} = V_{CC} - I_C R_C$$

$$\boxed{V_{C_1} = V_{C_2} = V_{CC} - \frac{I_E}{2} R_C}$$

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