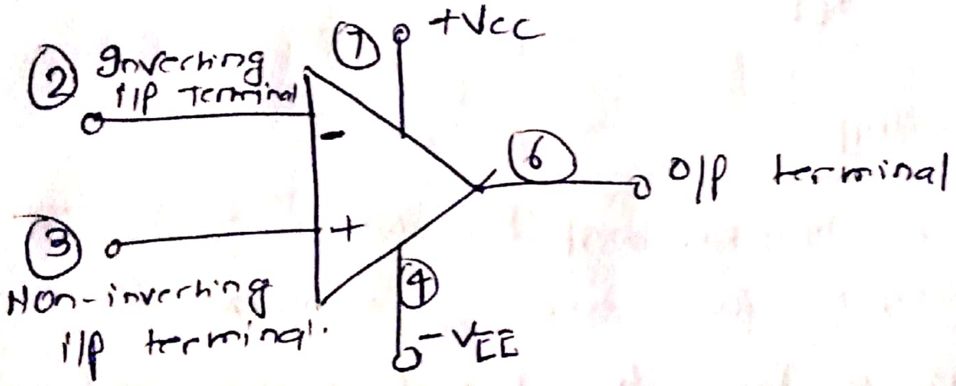
Operational Amplifier

Operational amplifiers are commonly known as "op-amps". It was introduced in 1948 and was used to perform mathematical operations in Analog computers. Hence, the name is operation amplifier.

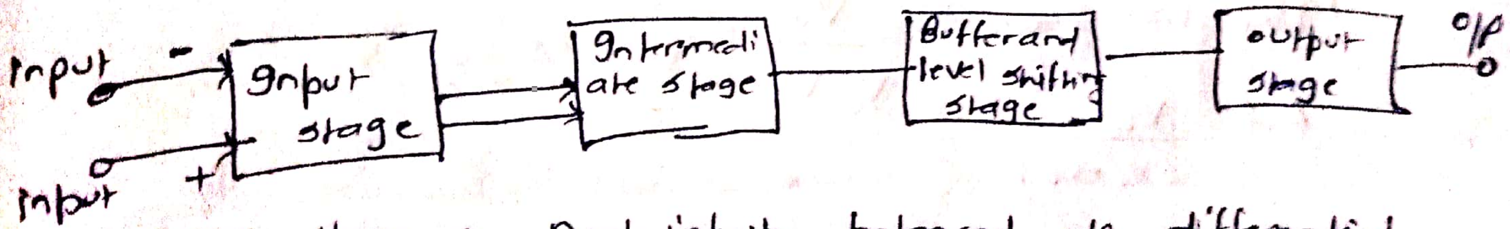
Op-amp symbol

It is a two i/p and one o/p device.



If an Input is given to inverting terminal, the o/p will be of opposite polarity.

Block diagram representation

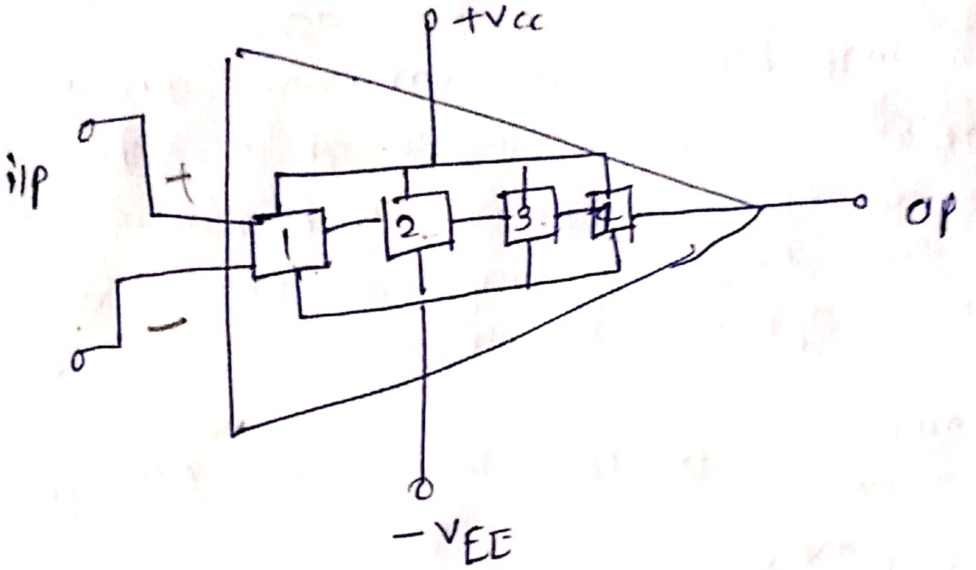


Input stage → Dual input, balanced o/p differential amplifier

Intermediate stage — To have high gain, it has multi-stage cascaded amplifiers.

Output stage :— It has push-pull Complementary amplifier.

So the over all block diagram will be represented like this.

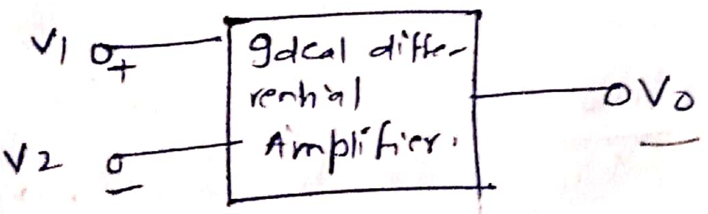


1 - i/p stage
2 - intermediate stage
3 - level shifting
4 - o/p

Ideal op-amp

It is basically an amplifier which will amplify the difference b/w two i/p signals.

Let us understand the basics of an differential amplifier which is a basic building block of an op-amp.



gain = $\frac{o/p}{i/p}$

Differential gain = $\frac{V_o}{V_1 - V_2}$, $V_d = V_1 - V_2$

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

Common mode gain

If $V_1 = V_2$, then $V_o = A_d(V_1 - V_2) = A_d(0)$

$V_o = 0$

But the o/p voltage of the amplifier, not only depends on the difference voltages but also on the average common level of the two inputs.

$V_d = V_1 - V_2$

This average common level of two i/p signals are called common mode signal.

$$V_c = \frac{V_1 + V_2}{2}.$$

The gain with which it amplifies the common signal is known as common mode gain.

$$V_0 = A_c \cdot V_c \quad \text{--- (II)} \qquad A_c = \frac{V_0}{V_c}, \quad V_c = \frac{V_1 + V_2}{2}$$

$$\boxed{V_0 = A_d \cdot V_d \mp A_c \cdot V_c}$$

Common mode rejection ratio (CMRR)

This is the ability of of a differential amplifier to reject a common mode signal.

It is given by ratio of differential mode voltage gain to common mode voltage gain.

$$CMRR = \left| \frac{A_d}{A_c} \right| \quad ; \infty, \quad A_c = 0.$$

Ideal op-amp characteristics

a) Infinite voltage gain → The open loop gain of an op-amp should be infinite.

$$\frac{V_o}{V_{in}} = \infty$$

b). It should have infinite i/p ~~resistance~~ Impedance.

c). It should have zero o/p impedance.

d). Zero offset voltage :- The presence of a small o/p voltage though $V_1 = V_2 = 0$ is called offset voltage. It should be zero for an ideal op-amp.

e). Infinite bandwidth :- The range of frequency over which the amplifier performs is called bandwidth and it should be infinite for an ideal op-amp.

f). Infinite CMRR :- The ideal op-amp have $A_c = 0$, hence $CMRR = \left|\frac{A_d}{A_c}\right| = \left|\frac{A_d}{0}\right| = \infty$.

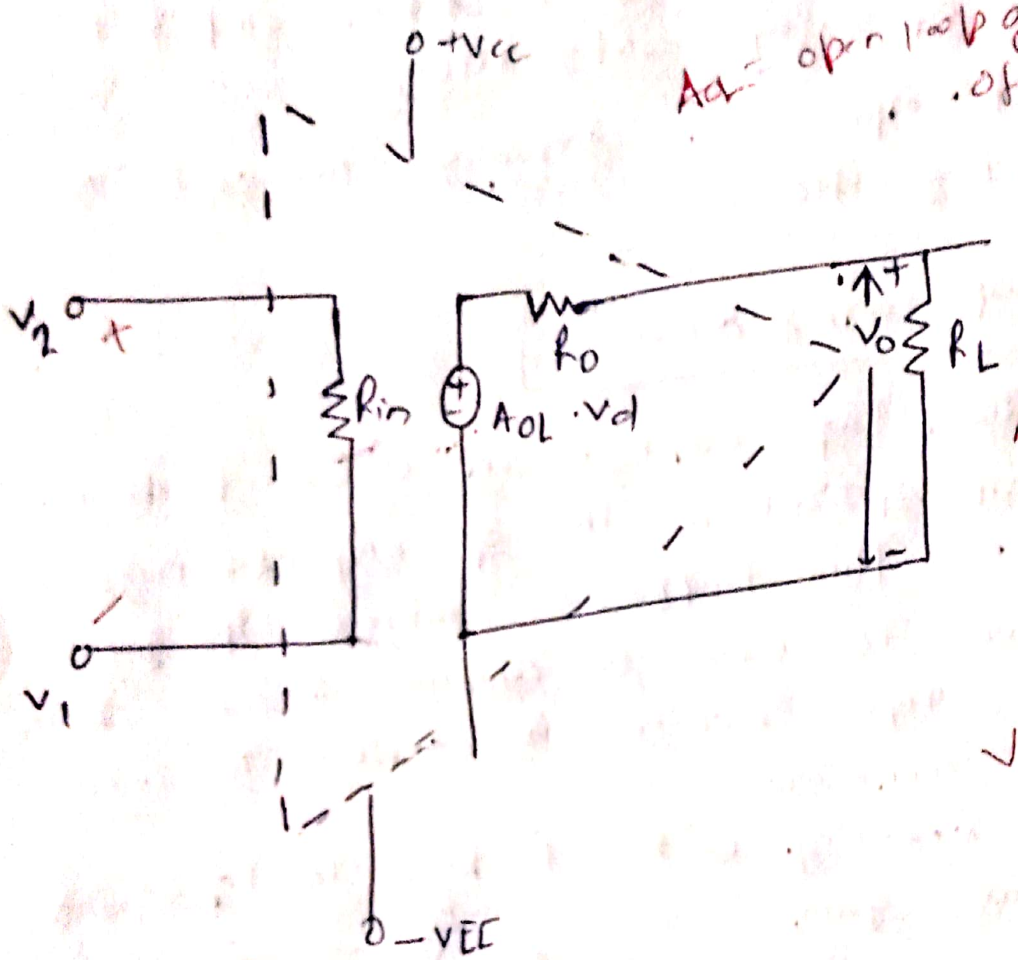
g). Infinite slew rate :-
The slew rate ensures that change in o/p voltage occurs simultaneously with change in i/p voltage. It is given by

$$S = \left.\frac{dV_o}{dt}\right|_{max.} (V/\mu s).$$

It is defined as maximum rate of change of o/p voltage with time.

h). The parameters of op-amp should not be dependent on temperature.

Equivalent circuit of a practical op-amp

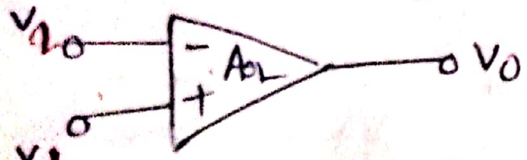


A_{OL} = open loop gain of op-amp

$A_{OL} = \frac{V_{out}}{V_1 - V_2} = \frac{V_{out}}{V_d}$

$V_{out} = V_d \cdot A_{OL}$

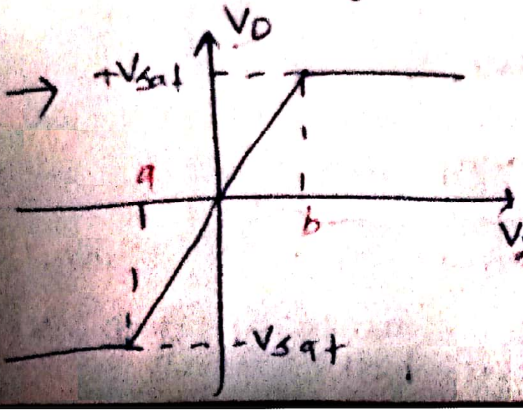
Problems with open loop configuration of an opamp



A_{OL} = open loop gain.

Due to very large open loop gain, a very small noise present at the input gets amplified and it brings the op-amp in saturation.

Voltage Transfer curve →



The curve shows that only for a small i/p level (a-b) it shows linear behaviour, otherwise it is saturated.

This indicates the inability of op-amp to work as a linear small signal amplifier in the open-loop configuration.

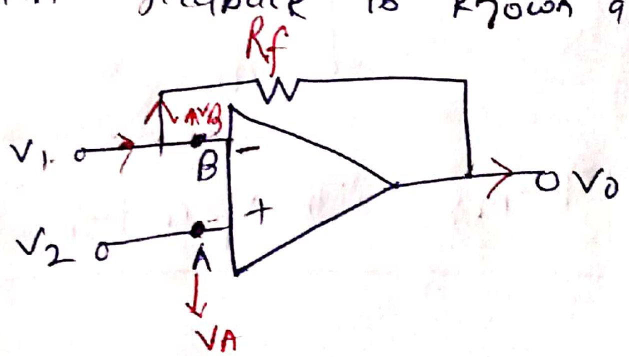
Hence, op-amps are generally not used in this configuration.

Closed loop configuration

The closed loop configuration uses a feedback. In linear applications, the op-amp uses negative feedback. This feedback controls the gain.

A resistor is used to connect the o/p with negative input terminal to ensure negative feedback connection.

The gain resulting with feedback is known as closed loop gain.



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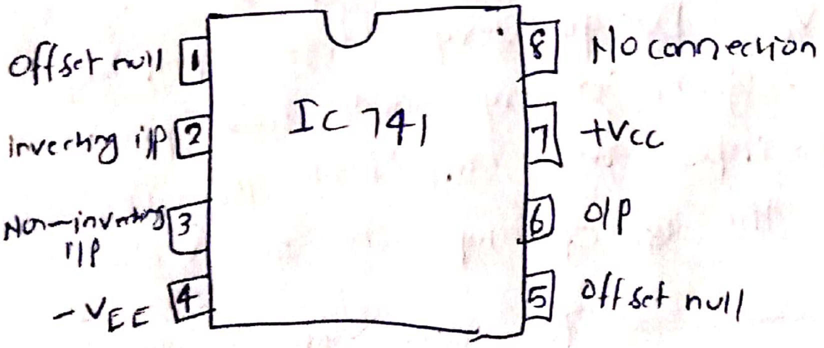
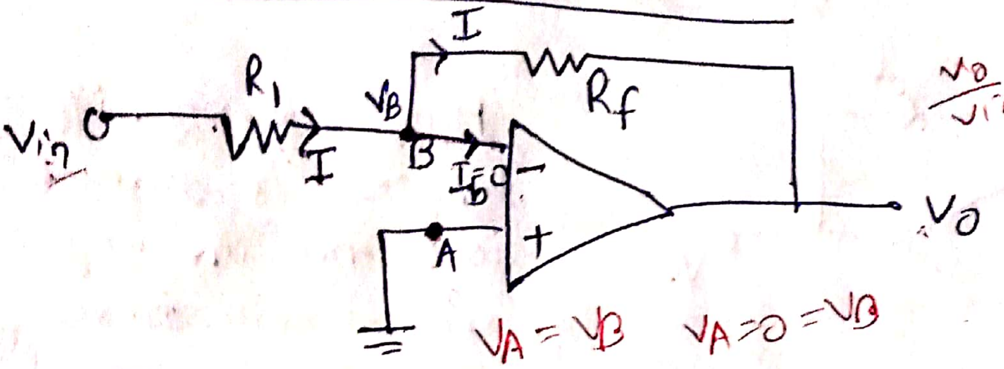


Assumptions in op-amp

(i) $V_A = V_B$ → This is known as virtual ground.

(ii) No current will flow inside op-amp as the i/p resistance is very high.

Inverting amplifier



$\frac{V_o}{V_{in}} = ?$

$V_A = V_B \quad V_A = 0 = V_B$

For inverting op-amp as the name suggests, the o/p has 180° phase shift with i/p. The non-inverting i/p terminal will be grounded.

We have to find closed loop gain $\frac{V_o}{V_{in}}$.

∵ $V_A = 0$ so by the concept of virtual ground, $V_B = 0$

at point B, no current will flow inside the op-amp hence the current I generated by V_{in} will flow towards feed back resistor R_f.

By applying KCL at node B

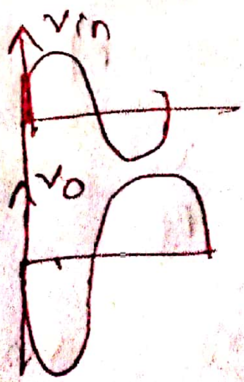
$$\frac{V_{in} - V_B}{R_1} = I = \frac{V_B - V_o}{R_f}$$

$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_o}{R_f}$$

$$\frac{V_{in}}{R_1} = \frac{-V_o}{R_f}$$

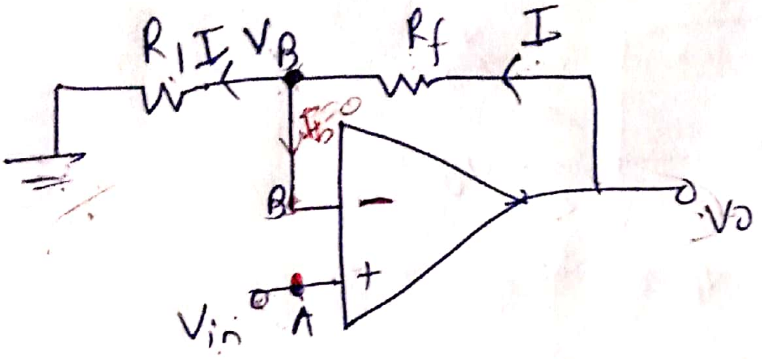
$$\boxed{\frac{V_o}{V_{in}} = -\frac{R_f}{R_1}}$$

$V_o = -\left(\frac{R_f}{R_1}\right) \cdot V_{in}$



The negative sign indicates 180° phase shift b/w i/p and o/p signal. Hence, this is an inverting amp.

Non-inverting Amplifier

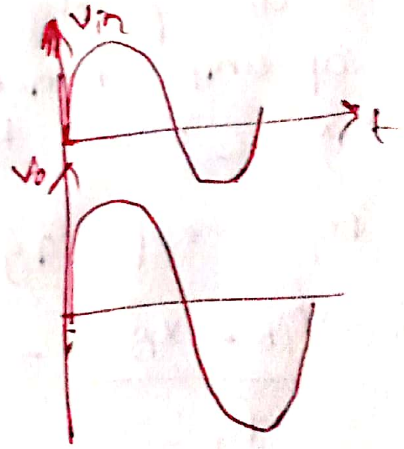


Here, inverting i/p terminal is grounded and non-inverting terminal will have i/p voltage.

$V_A = V_{in} = V_B$ — By the concept of virtual ground.

∵ V_o is +ve, the current will flow from V_o (higher potential) towards R_1 (grounded)

No current will flow inside the op-amp.



By KCL

$$\frac{V_o - V_B}{R_f} = \frac{V_B - 0}{R_1} = I$$

$$\frac{V_o - V_{in}}{R_f} = \frac{V_{in}}{R_f} \quad \Big| \because V_{in} = V_B$$

$$\frac{V_o}{R_f} = \frac{V_{in}}{R_f} + \frac{V_{in}}{R_1}$$

$$\frac{V_o}{R_f} = V_{in}\left(\frac{1}{R_f} + \frac{1}{R_1}\right)$$

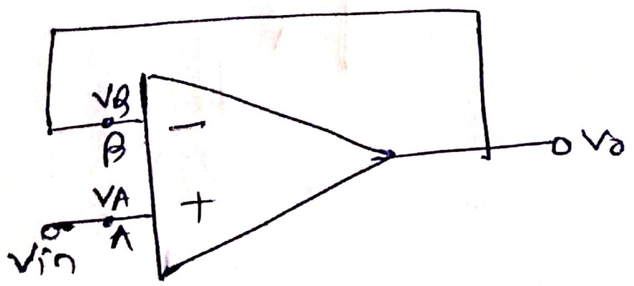
$$\frac{V_o}{V_{in}} = R_f\left(\frac{1}{R_f} + \frac{1}{R_1}\right) = \left(1 + R_f/R_1\right)$$

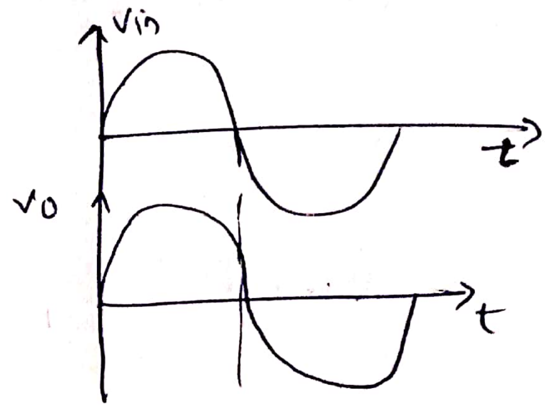
$$\boxed{\frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}}$$

This is the gain of non-inverting amplifier.

Voltage follower

The circuit in which o/p voltage follows the i/p voltage is known as voltage follower





$V_A = V_B = V_{in}$

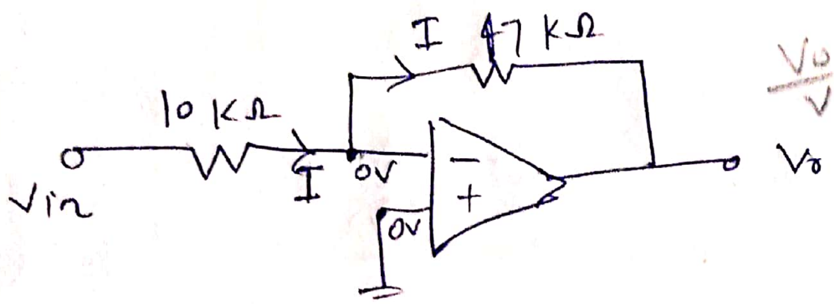
$V_o = V_B$

$$\boxed{V_o = V_{in}}$$

$\frac{V_o}{V_{in}} = 1$, this is also called source follower, unity gain amplifier, buffer amplifier.

Questions on inverting o/p amp

Determine the voltage gain of the op-amp circuit shown below



$\frac{V_o}{V_{in}} = ?$

$$I = \frac{V_{in} - 0}{10 \times 10^3} = \frac{0 - V_o}{47 \times 10^3}$$

$$\frac{V_o}{V_{in}} = -\frac{47 \times \cancel{10^3}}{10 \times \cancel{10^3}}$$

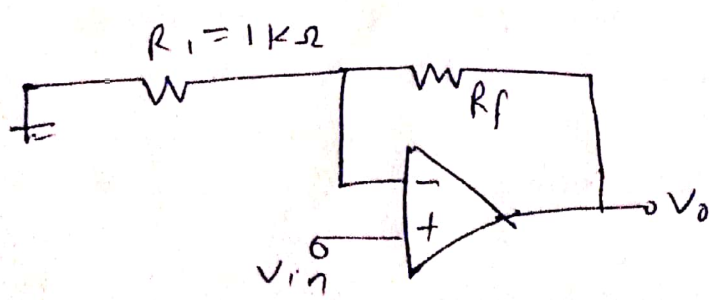
$$\boxed{\frac{V_o}{V_{in}} = -4.7}$$

If $V_{in} = 1V$

$V_o = -4.7 \times 1$

$$\boxed{V_o = -4.7V}$$

2). For a non-inverting amp, determine the R_f if gain is 61.



$$\frac{V_o}{V_{in}} = \text{gain} = 1 + \frac{R_f}{R_1}$$

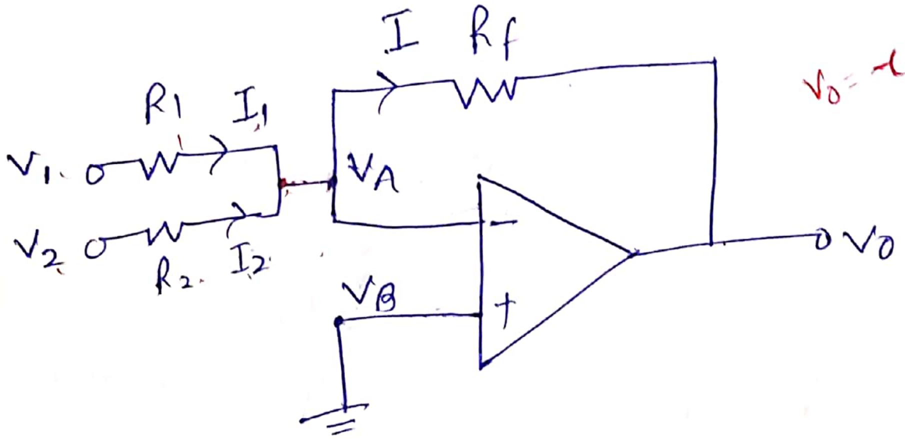
$$61 = 1 + \frac{R_f}{1}$$

$$\boxed{R_f = 60\,K\Omega}$$

Adder or Summer

Inverting Summer

As the input impedance of the op-amp is Extremely large, more than one i/p signals can be applied to the inverting ~~op~~ terminal. Such circuit gives addition of the applied signal at the o/p. Hence it is called summer circuit.



$V_0 = -(V_1+V_2)$

∵ point B is grounded, $V_B = 0$

By the concept of virtual ground, $V_A = V_B = 0$

from i/p side :-

$$I_1 = \frac{V_1 - V_A}{R_1} = \frac{V_1 - 0}{R_1} = \frac{V_1}{R_1}$$

$$I_2 = \frac{V_2 - V_A}{R_2} = \frac{V_2 - 0}{R_2} = \frac{V_2}{R_2}$$

$$I = \frac{V_A - V_o}{R_f} = \frac{0 - V_o}{R_f} = \frac{-V_o}{R_f}$$

$$I = I_1 + I_2$$

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

$$V_0 = -\left[\frac{R_f}{R_1}\cdot V_1 + \frac{R_f}{R_2}\cdot V_2\right]$$

if $R_f = R_1 = R_2$

$$\boxed{V_o = -[V_1 + V_2]}$$

17/18

20/22

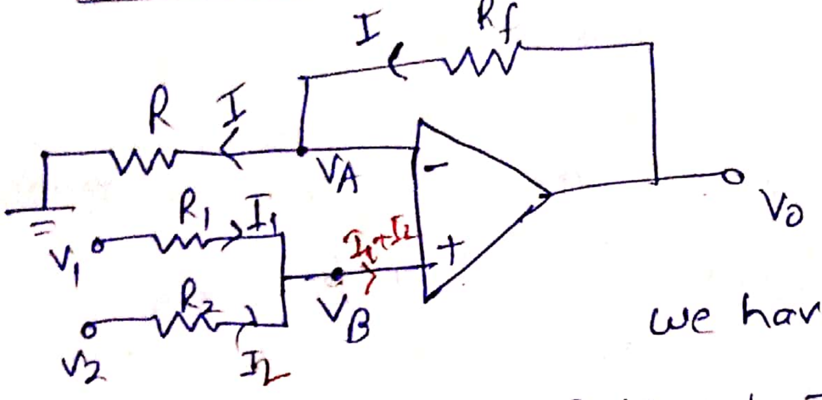
24/25

3:15

4:30

12

Non-inverting summing amplifier



Here, i/p voltages are applied at the non-inverting terminal.

we have to find VB as voltage at point B is not zero.

At non-inverting i/p side

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

$$I_2 = \frac{V_2 - V_B}{R_2}$$

$\because I_1 + I_2 = 0$ as no current will flow inside the o/p amp.

$$\frac{V_1 - V_B}{R_1} + \frac{V_2 - V_B}{R_2} = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} - V_B\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = 0$$

$$V_B\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$

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

By the concept of virtual ground

$$V_A = V_B = \frac{V_1 R_2 + V_2 R_1}{R_1 + R_2} \quad (1)$$

at o/p side

$$I = \frac{V_0 - V_A}{R_f}$$

at inverting i/p side

$$I = \frac{V_A - 0}{R}$$

$$\frac{V_0 - V_A}{R_f} = \frac{V_A}{R}$$

$$\frac{V_0}{R_f} = V_A\left(\frac{1}{R_f} + \frac{1}{R}\right)$$

$$V_0 = V_A\left(1 + \frac{R_f}{R}\right) \quad (11)$$

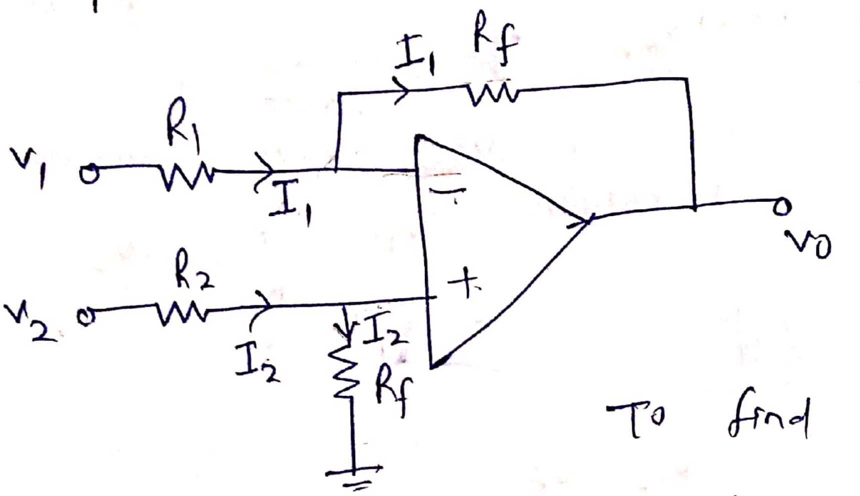
$$V_0 = \left(\frac{V_1 R_2 + V_2 R_1}{R_1 + R_2}\right)\left(1 + \frac{R_f}{R}\right)$$

If $R_f = R_1 = R_2 = R$

$$\boxed{V_0 = V_1 + V_2}$$

Subtractor or difference amplifier

In this type of circuit, two i/p voltages are applied at two i/p terminals and the o/p will be difference of two i/ps.



$V_0 = V_2 - V_1$

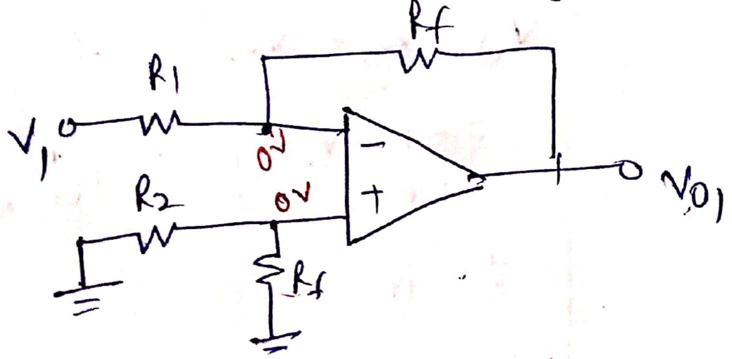
To find the relation b/w i/p and o/p, we have to use superposition theorem.

let us assume that V_{01} is o/p when V_1 is acting and V_{02} is the o/p when V_2 is acting.

$$\boxed{V_0 = V_{01} + V_{02}}$$

case-I

when V_1 is acting and V_2 is grounded,



Here, this amplifier is Just like a inverting amplifier and we know the gain for inverting o/p amp is equal to

gain $= -\frac{R_f}{R_1}$

$\frac{V_{01}}{V_1} = \frac{-R_f}{R_1}$

$$\boxed{V_{01} = -\frac{R_f}{R_1} \cdot V_1} \quad \text{— (1)}$$

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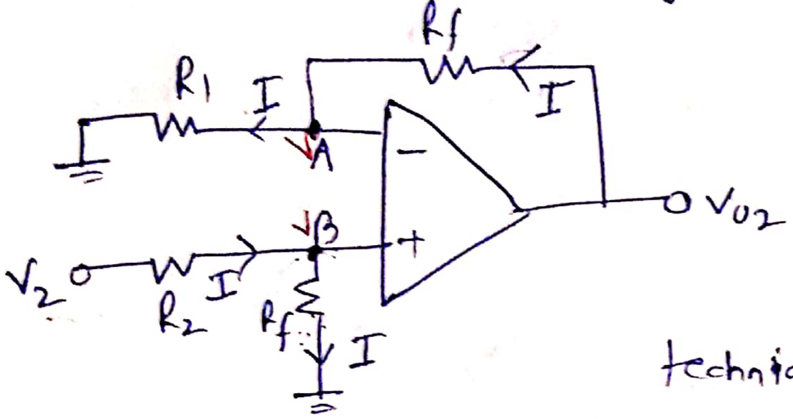
Case – II

when V_2 is acting and V_1 is grounded.



By the concept of virtual ground $V_A = V_B$

To find V_B

By using voltage divider technique, $V_B = \frac{R_f}{R_2 + R_f} \cdot V_2$ —— (I)

Now at o/p side

$$I = \frac{V_{o2} - V_A}{R_f} = \frac{V_{o2} - V_B}{R_f} \quad \because V_A = V_B$$

at inverting i/p side

$$\frac{V_A - 0}{R_1} = I = \frac{V_A}{R_1} = \frac{V_B}{R_1}$$

$$\frac{V_{o2} - V_B}{R_f} = \frac{V_B}{R_1}$$

$$\frac{V_{o2}}{R_f} = V_B \left[\frac{1}{R_1} + \frac{1}{R_f}\right]$$

$$V_{o2} = V_B \left[1 + \frac{R_f}{R_1}\right] \text{ —— (II)}$$

from Eq. (I)

$$V_{o2} = \left[1 + \frac{R_f}{R_1}\right] \cdot \underbrace{\left[\frac{R_f}{R_2 + R_f} \cdot V_2\right]}_{V_B} \text{ —— (V)}$$

$$V_O = V_{o1} + V_{o2}$$

$$= -\frac{R_f}{R_1} V_1 + \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_f \cdot V_2}{R_f + R_2}\right]$$

If $R_f = R_1 = R_2$

$$V_o = -V_1 + [1+1]\left[\frac{1}{2} \cdot V_2\right]$$

$$= -V_1 + V_2$$

$$\boxed{V_o = V_2 - V_1}$$