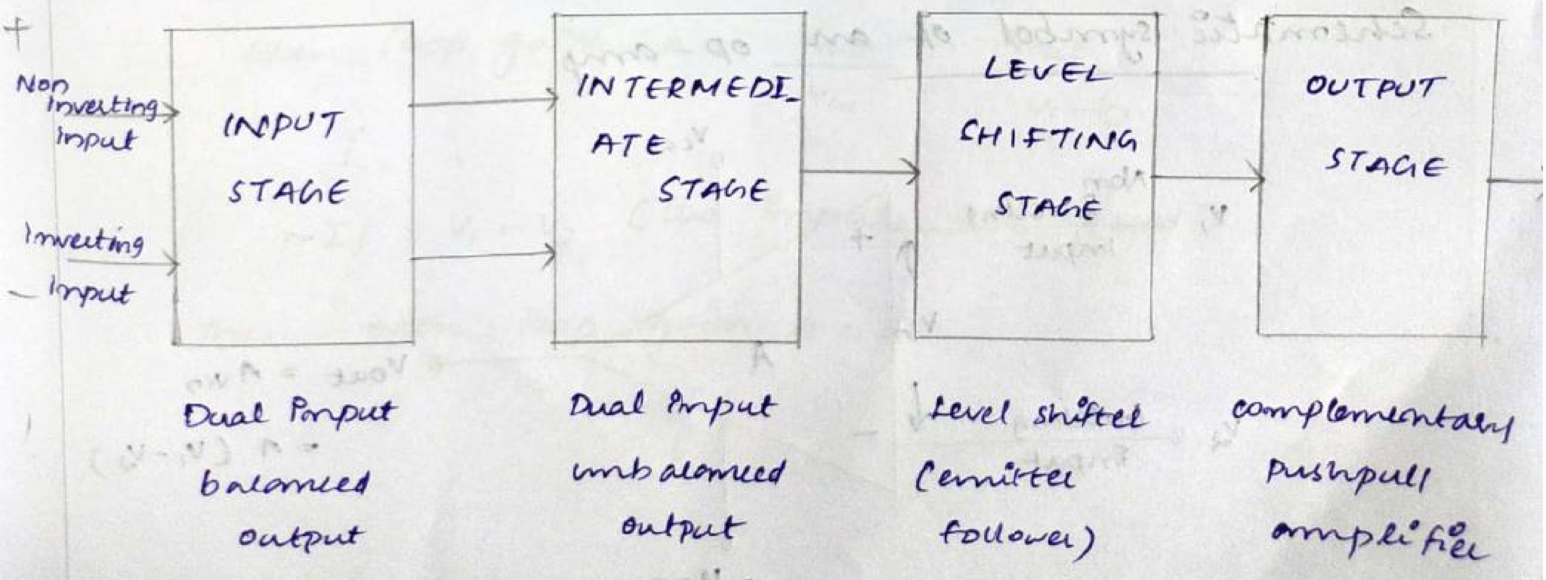
MODULE - 4

OPERATIONAL AMPLIFIERS

* An operational amplifier is a direct coupled high gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output stage.
* It is used for performing operations such as addition, subtraction, multiplication and integration. Thus the name operational amplifiers and are usually called op-amps.
* op-amp is multiterminal device, which has two input and one output terminal. The terminal with -ve sign is called inverting terminal and terminal with +ve sign is called non-inverting terminal.

Block diagram of a typical op-amp



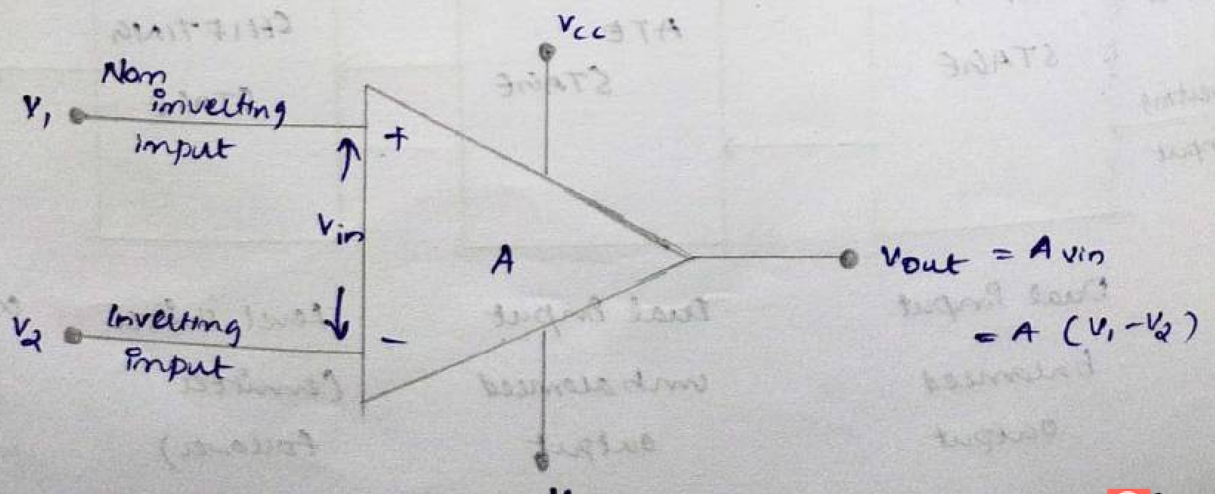
1) Input stage : It is a dual input balanced output differential amplifier with a constant current source. Output is taken between collectors so that output remains balanced.

2) Intermediate stage : It is another differential amplifier which is driven by the output of first stage. This stage is dual input, unbalanced output differential amplifier.

3) Level shifting stage : It is usually an emitter follower circuit inorder to shift the dc level at the output of the intermediate stage downward to zero volts with respect to ground

4) Output stage : It is usually a push-pull complementary amplifier. This stage increases the output voltage swing and the current supplying capability of the amplifier ~~and the current sou~~

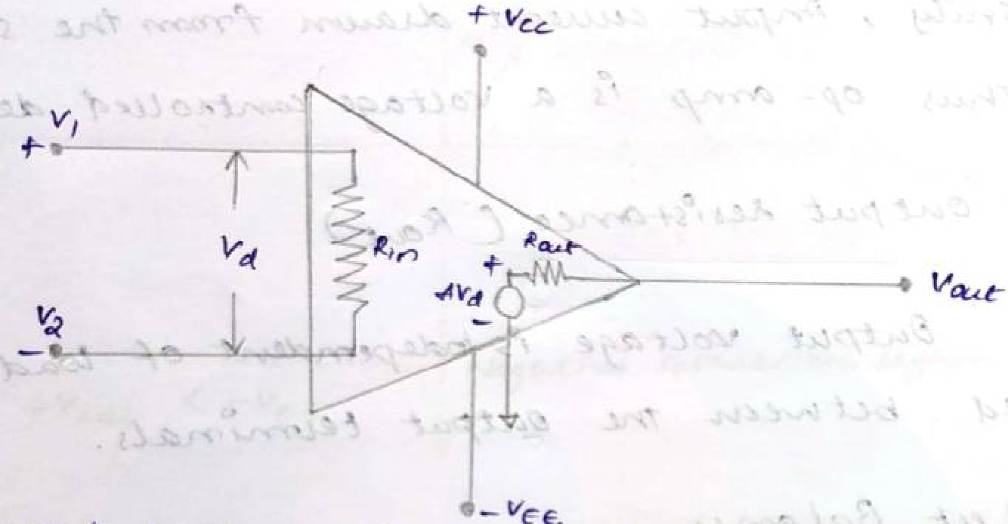
Schematic symbol of an op-amp



Differential input $V_d = V_{in} = V_1 - V_2$

output voltage $V_o = AV_d = AV_{in} = A(V_1 - V_2)$

Equivalent circuit of an op-amp



V_1 : input voltage at non inverting terminal w.r.t ground

V_2 : input voltage at inverting terminal w.r.to ground

V_d : Difference voltage $= V_1 - V_2$

$V_{out} = AV_d = A[V_1 - V_2]$

Ideal op-amp characteristics

1) Infinite open loop gain $(A = \infty)$

open loop gain $A = \dfrac{V_{out}}{V_{in}} = \dfrac{V_{out}}{V_1 - V_2}$

If $V_1 = V_2$ (two inputs are equal)

then open loop gain $A = \infty$

2) Infinite input resistance ($R_{in} = \infty$)

It is the resistance measured between inverting and non-inverting terminals. Since input resistance is infinity, input current drawn from the source is zero. Thus op-amp is a voltage controlled device.

3) Zero output resistance (R_{out})

Output voltage is independent of load resistance connected between the output terminals.

4) Perfect Balance

5) Infinite frequency Bandwidth

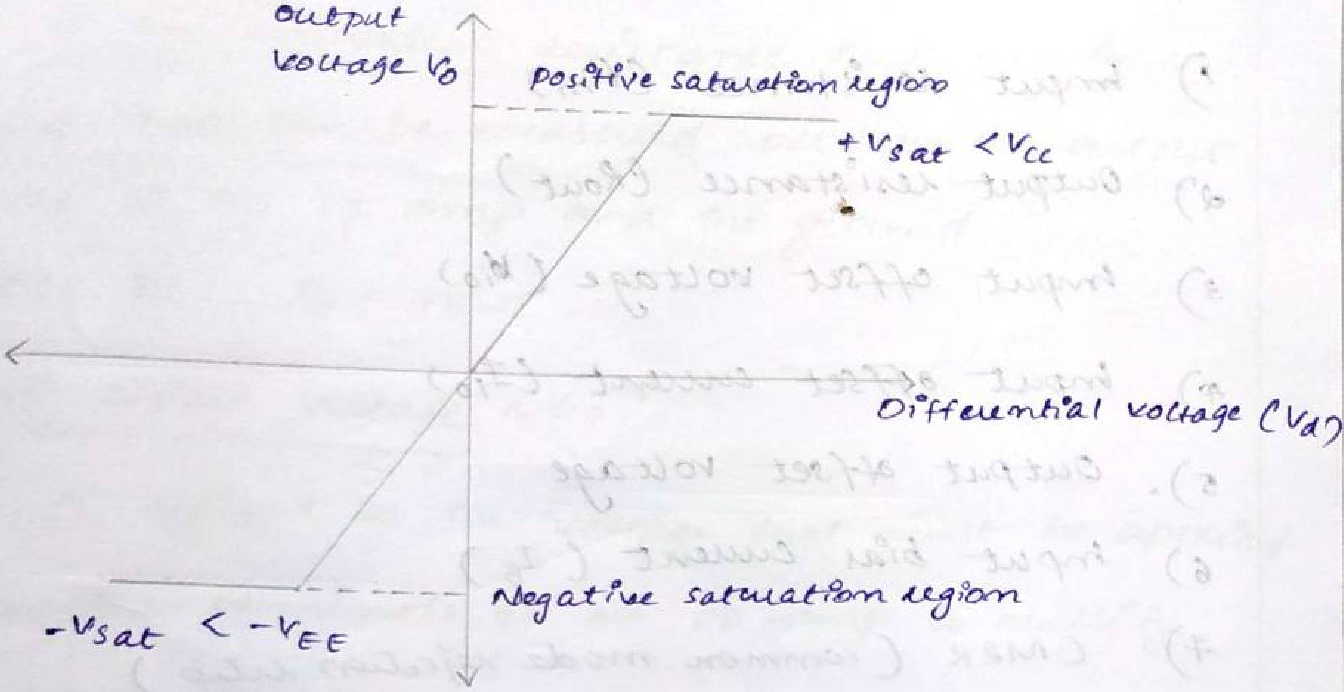
6) Drift of characteristics with temperature is Nil.

7) Common mode ~~of~~ rejection ratio (CMMR) is infinite so that amplifier is free from undesired common mode signals such as thermal noise etc.

8) Slew rate is infinite so that output voltage changes occur simultaneously with input voltage changes.

9) Output voltage is zero when input voltage is zero ie offset voltage is zero.

Ideal voltage Transfer Curve



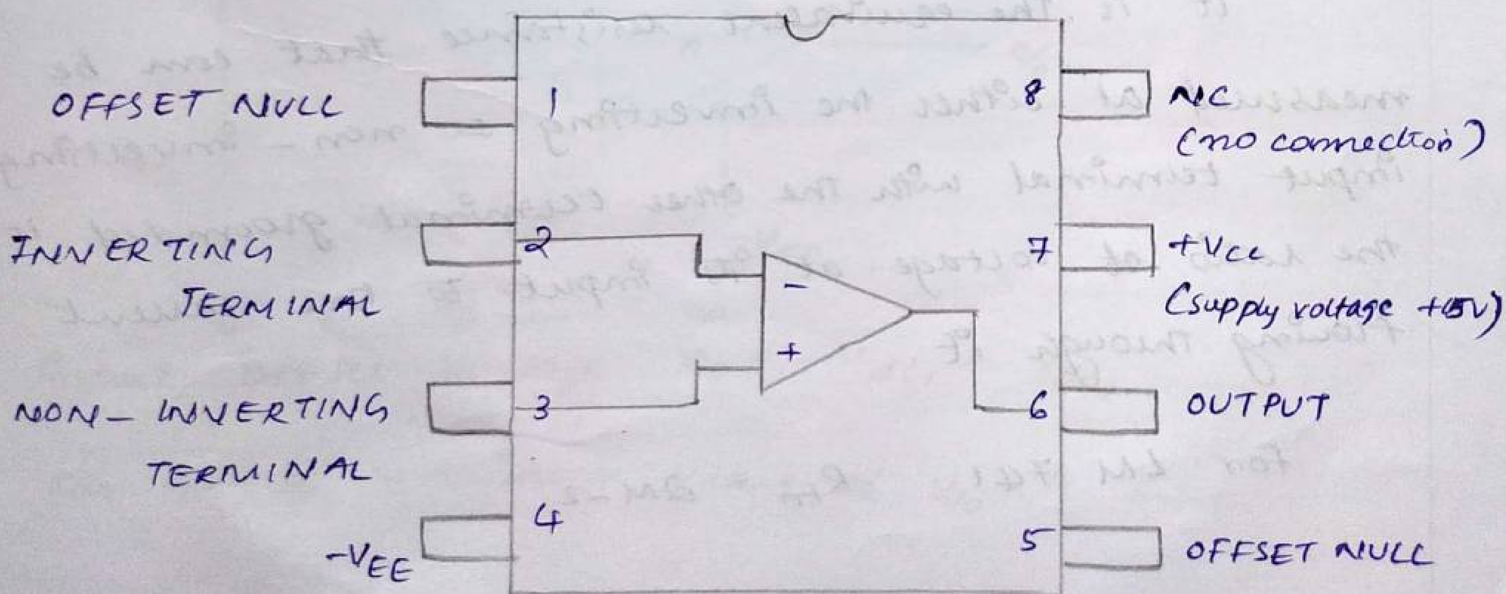
LM 741 IC

LM

National semiconductor (manufacturer)

741

Military grade op amp operating temp range [$55°c - 125°c$]



Supply voltage −15 V

Parameters of op-amp

1) Input resistance (R_{in})
2) Output resistance (R_{out})
3) Input offset voltage (V_{io})
4) Input offset current (I_{io})
5) Output offset voltage
6) Input bias current (I_B)
7) CMRR (common mode rejection ratio)
8) Differential gain
9) Slew rate
10) SVRR
11) Gain bandwidth product
12) Transient response

1) Input resistance (R_{in})

It is the equivalent resistance that can be measured at either the inverting or non-inverting input terminal with the other terminal grounded. It is the ratio of voltage at its input to the current flowing through it.

For LM 741 $R_{in} = 2M\Omega$

2) Output resistance (R_o)

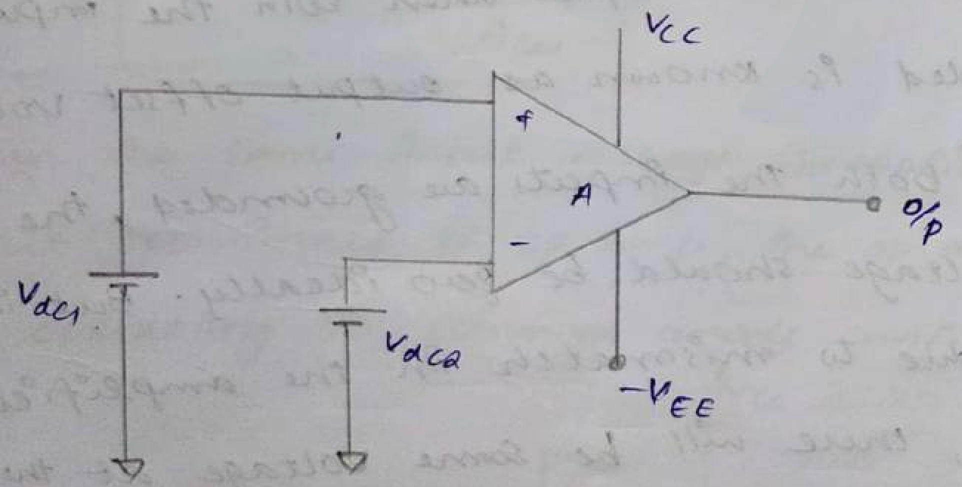
It is the equivalent resistance that can be measured that can be measured between the output terminal of the op amp and the ground.

For 741 IC $R_o = 75\Omega$

3) Input offset voltage (V_{io})

It is defined as the voltage that must be applied between the terminals of an op-amp to nullify the output voltage.

Even the input voltage of an op-amp is zero the output voltage may not be zero. This is because of the circuit imbalances inside the op-amp. In order to compensate this is a small voltage should be applied between the input terminals.

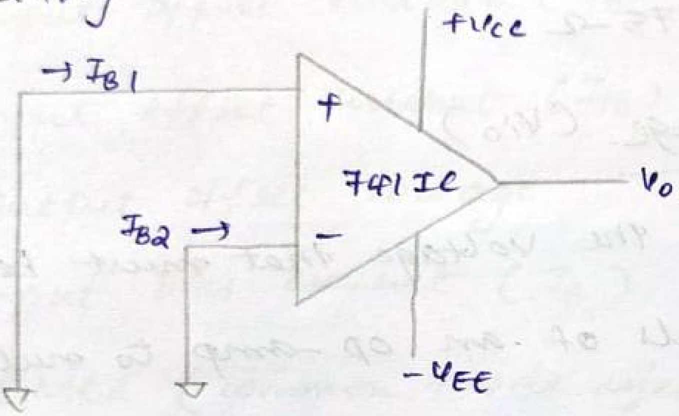


Input offset voltage $V_{io} = V_{dc1} - V_{dc2}$

For 741 IC maximum value of V_{io} is 6mV.

4) Input offset current [I_{io}]

It is the algebraic difference between the currents entering into the inverting and non-inverting terminals.



I_{B1} : current entering to non-inverting terminal

I_{B2} : current entering to inverting terminal

$$\boxed{I_{io} = |I_{B1} - I_{B2}|}$$

For LM 741 IC, I_{io} = 200 nA (max)

5) Output offset voltage

Voltage at the output when both the inputs are grounded is known as output offset voltage.

When both the inputs are grounded, the output voltage should be zero ideally. But in practice, due to mismatch in the amplifier components, there will be some voltage at the output.

6) Input bias current (I_B)

It is the average value of the base currents entering into the terminals of op-amp.

If $I_{B1} \rightarrow$ current entering non inverting terminal

$I_{B2} \rightarrow$ current entering inverting terminal.

Input bias current $\boxed{I_B = \frac{I_{B1} + I_{B2}}{2}}$

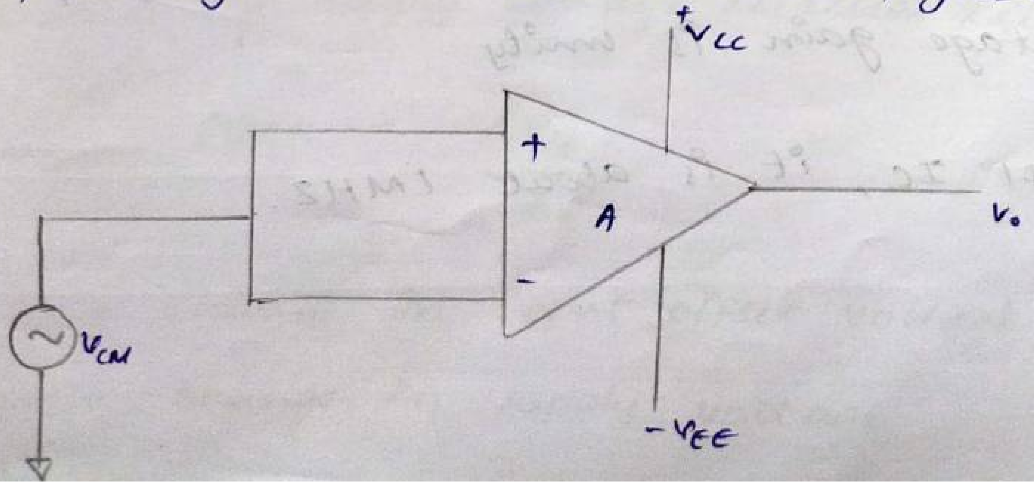
For LM 741 $I_B = 500\ nA$ (max)

7) Common Mode Rejection Ratio (CMRR)

It is the ratio of differential gain (A_d) to the common mode gain (A_{CM}).

$$\boxed{CMRR = \frac{A_d}{A_{CM}}}$$

When the same input voltage is applied to the both input terminals of op amp, the op amp is said to be operating in common mode configuration.



The ability of an op amp to reject a common mode signal is expressed as its common mode rejection ratio (CMRR). Ideally CMRR = ∞

CMRR is usually expressed in dB

$$\boxed{\text{CMRR in dB} = 20 \log \left(\frac{A_d}{A_{CM}} \right)}$$

For 741 IC CMRR = 90 dB (typically)

8) Differential gain (A_d)

$$A = A_d = \frac{\text{output voltage}}{\text{differential input voltage}} = \frac{V_o}{V_{id}}$$

V_{id} = difference btwn the input voltages

Output voltage is greater than input signal.

For 741 IC gain is 200 V/mV or 20,000

9) Gain bandwidth product

It is the bandwidth of an op amp when the voltage gain is unity.

For 741 IC, it is about 1MHZ.

10) Slew rate (SR)

It is defined as the maximum rate of change of output voltage per unit of time and is expressed in volts per microseconds.

$$\boxed{SR = \frac{dV_o}{dt}\Big/_{max} \quad V/\mu s}$$

Slew rate indicates how rapidly the output of an op-amp can change in response to change in input frequency.

$$\boxed{SR = 2\pi f V_{out}}$$

Slew rate of an opamp is fixed.

For LM 741 IC, SR = 0.5 V/μs

11) Supply Voltage Rejection Ratio [SVRR]

The change in an op amp's input offset voltage caused by the variations in supply voltages is called the supply voltage rejection ratio (SVRR)

$$SVRR = \frac{\Delta V_{io}}{\Delta V}$$

ΔV_{io} = change in input offset voltage

ΔV = change in supply voltage

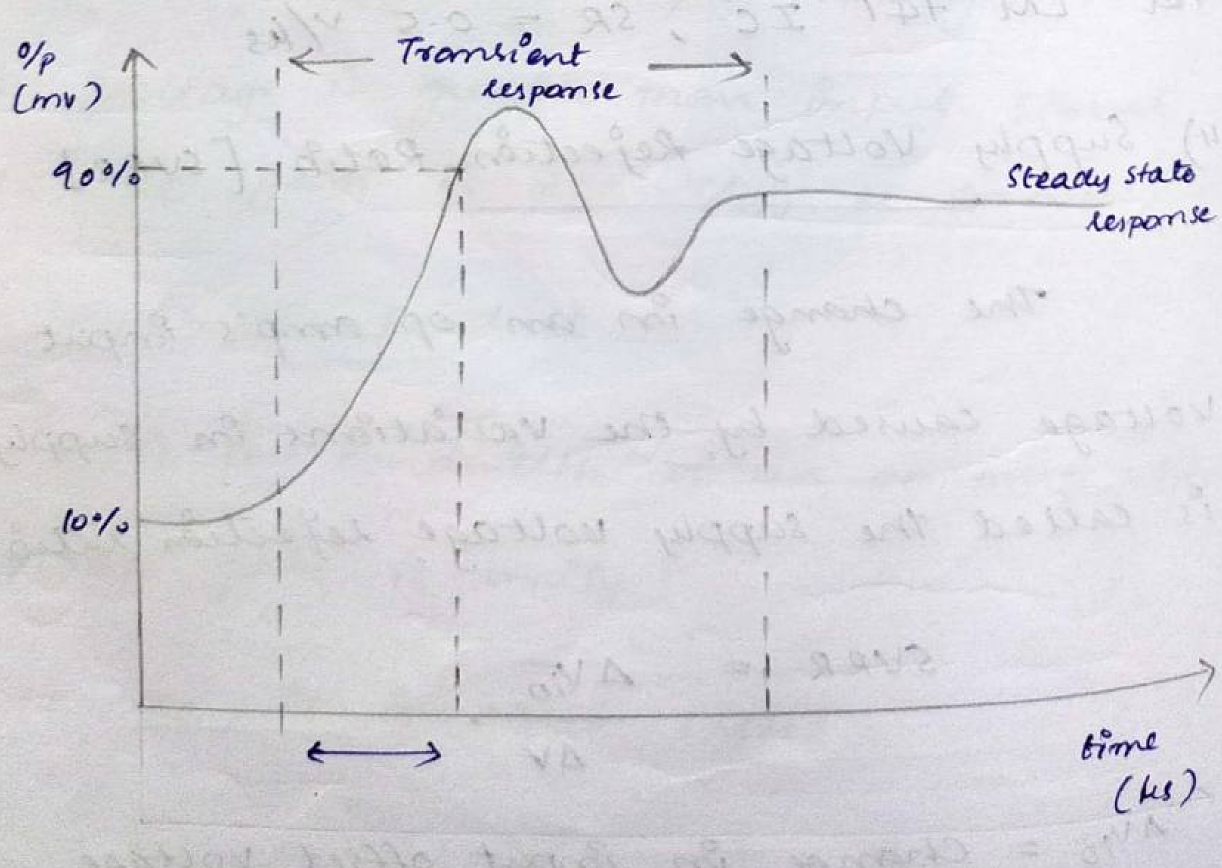
For LM 741 IC SVRR = 150 $\mu V/V$.

SVRR is also called power supply rejection ratio (PSRR).

12) Transient Response

The response of any practical network has two parts ⓐ transient response
ⓑ steady state response

Transient response is that portion of the complete response, before the output attains some fixed value once reached, this fixed value remains at that level and is called the steady state response.



OPEN LOOP AND CLOSED LOOP CONFIGURATIONS OF OP AMP

Open loop op amp configuration

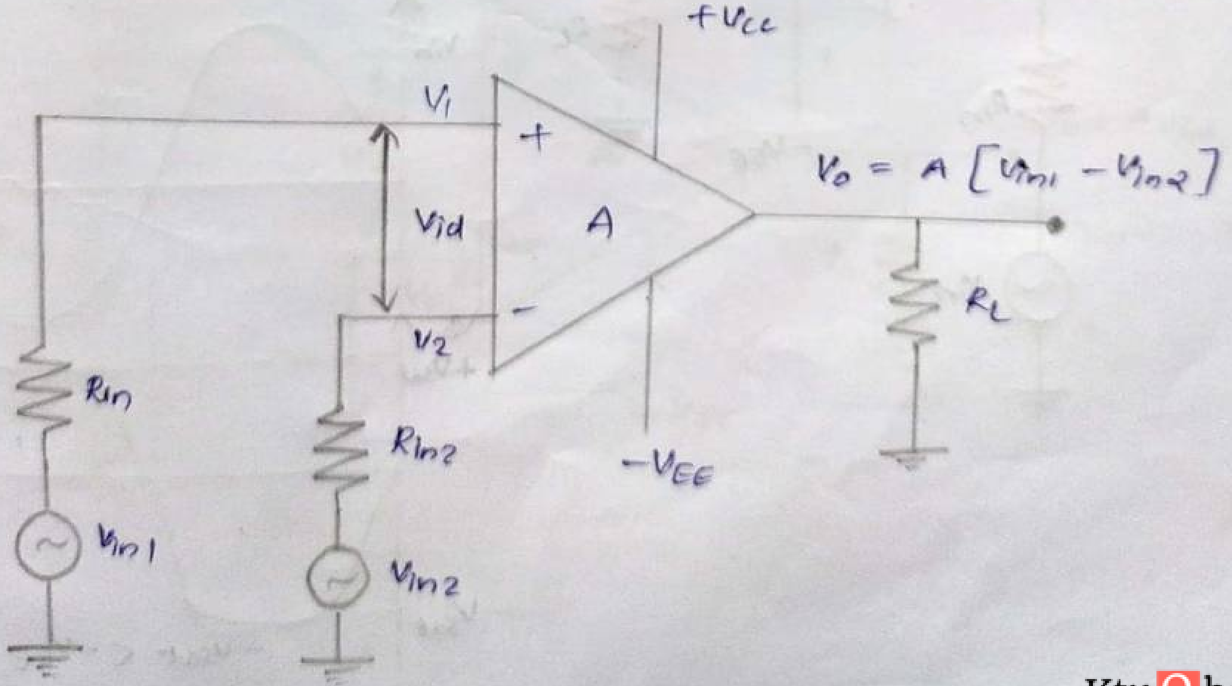
* Open loop means that there is no connection between input and output terminals either direct or through another network.
* In open loop configuration the op amp function as a high gain amplifier..
* There are three open loop amplifiers :-

(1) Differential amplifier

(2) Inverting amplifier

(3) Non-inverting amplifier

Differential amplifier



* Input signals V_{in1} and V_{in2} are applied to the positive and negative input terminals.

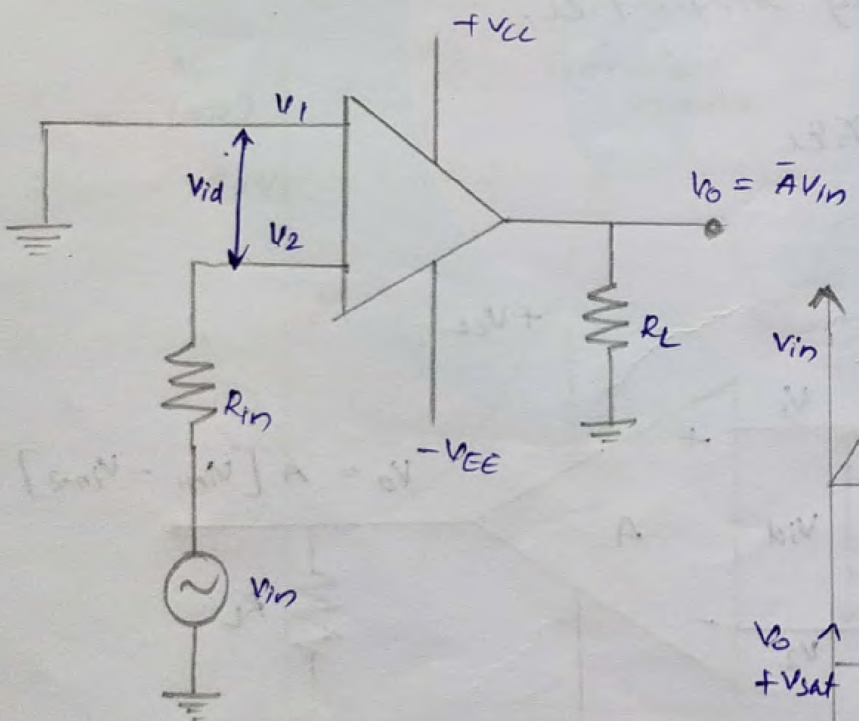
* The op amp amplifies the difference between the two input signals, this configuration is called differential amplifier.

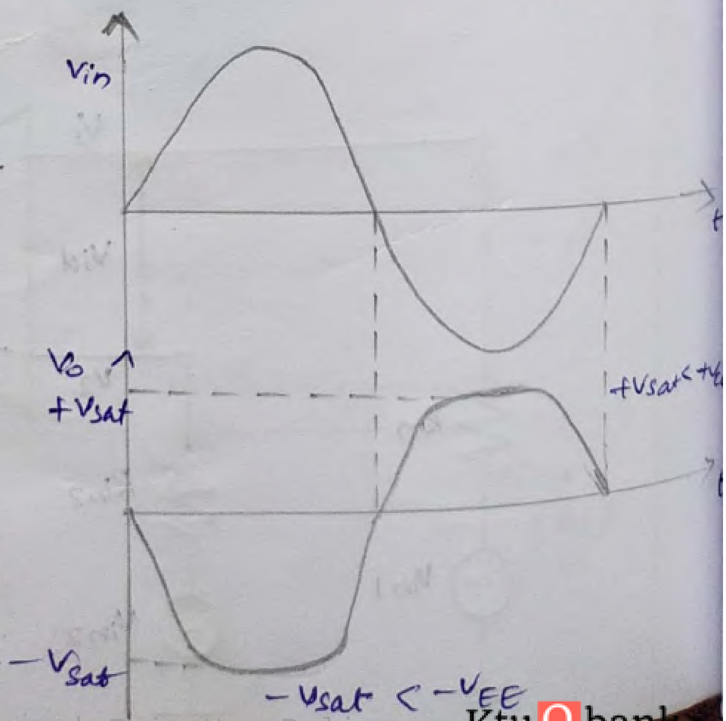
* The o/p voltage $V_o = A V_{id}$

$$\boxed{V_o = A\,[V_{in1} - V_{in2}]}$$

where A = open loop gain

Inverting Amplifier





* In inverting amplifier only one input is applied and it is to the inverting input terminal. Non-inverting terminal is grounded.

ie, $V_1 = 0V$ $V_2 = V_{in}$

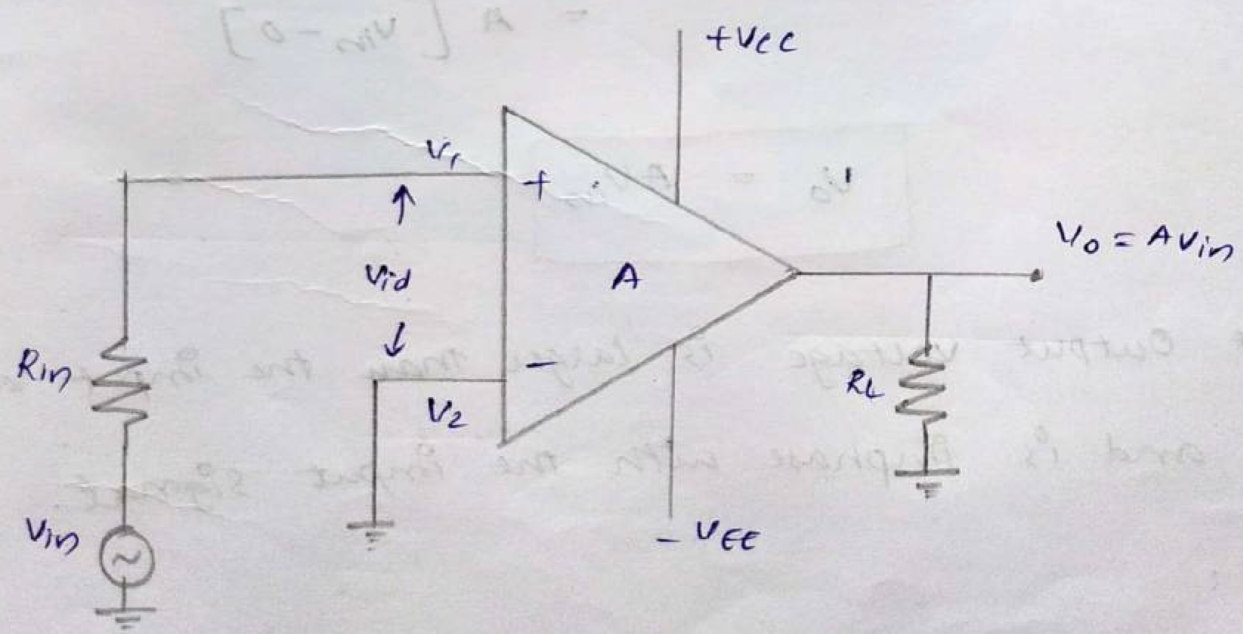
The o/p voltage $V_0 = A[V_1 - V_2]$

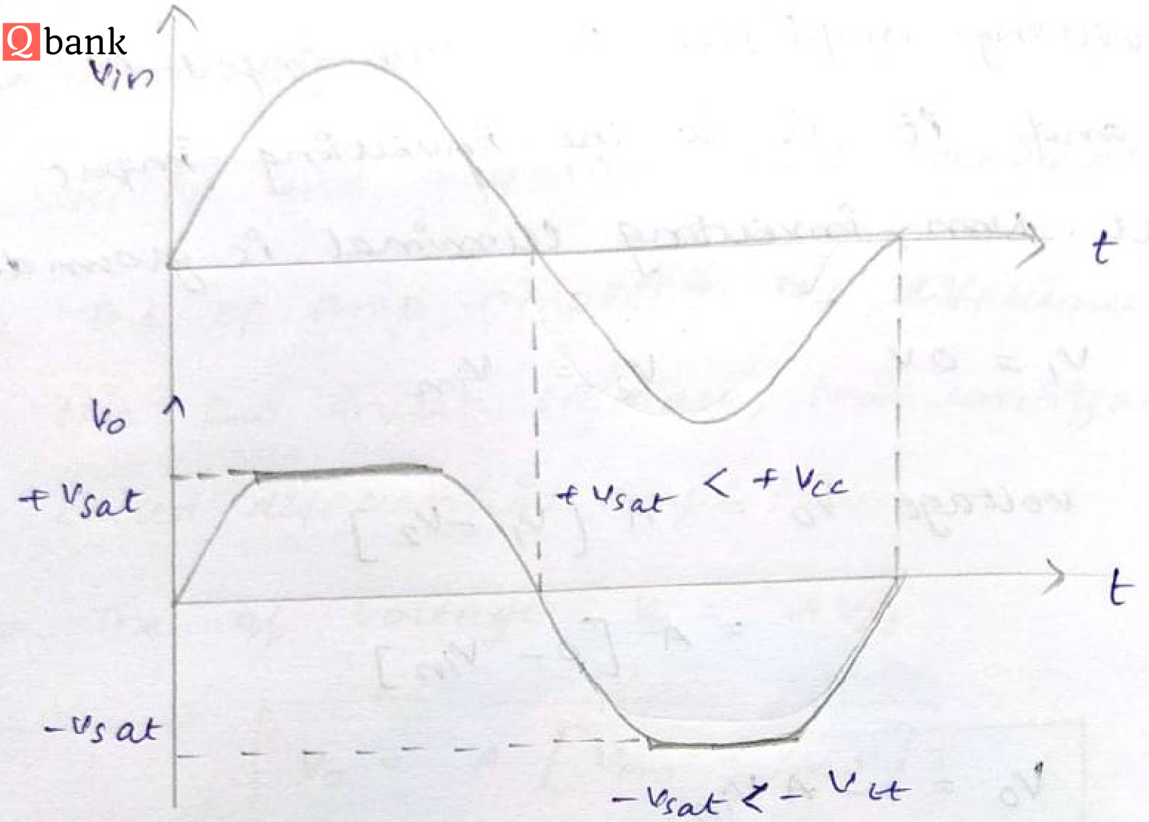
$= A[0 - V_{in}]$

$$\boxed{V_0 = -A V_{in}}$$

* Negative sign indicates that the output voltage is out of phase with the input.

Non-inverting amplifier





* Input is applied to the non-inverting terminal and inverting terminal is grounded.

$V_1 = V_{in}$ $\quad V_2 = 0$

o/p voltage, $V_0 = A[V_1 - V_2]$

$= A[V_{in} - 0]$

$$\boxed{V_0 = AV_{in}}$$

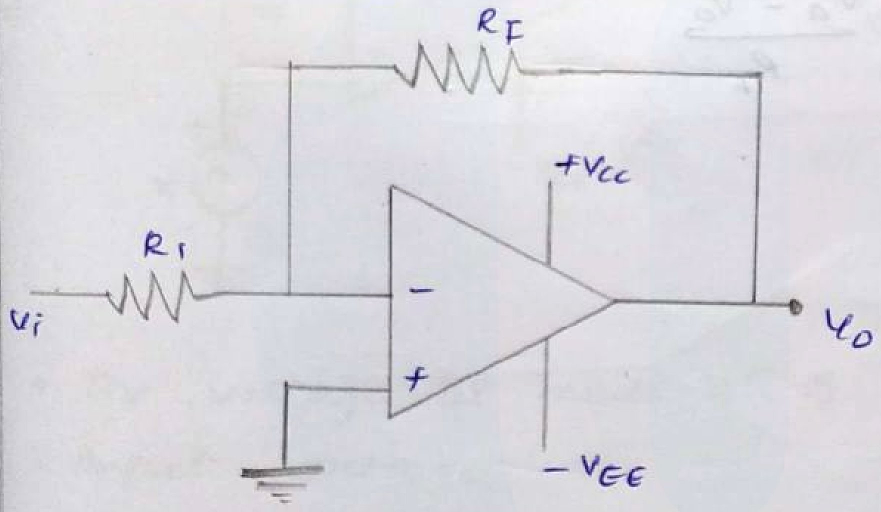
* Output voltage is larger than the input voltage and is inphase with the input signal.

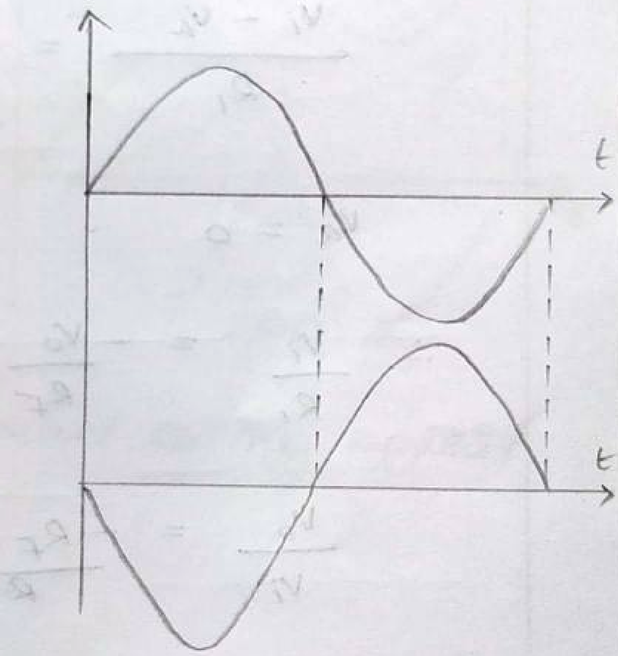
Closed loop op amp configurations

An op amp that uses feedback is called feedback amplifier also refered as closed loop configuration. There are two types of closed loop configurations

1) Inverting amplifiers
2) Non-inverting amplifiers

Inverting amplifier





* It is voltage shunt feedback amplifier.
* Input signal (V_i) is applied to the inverting terminal through R_1 and non inverting terminal of op amp is grounded
* R_F is the feedback resistor.
* Difference voltage (V_d) is ideally zero ie voltage at inverting terminal is approximately equal

to that of non-inverting terminal. The inverting terminal potential is approximately equal to ground potential. Therefore inverting terminal is said to be virtual grounded.

ie, $V_a = 0$

Analysis

Apply KCL (Kirchoff's current law) at node a

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

$$V_a = 0$$

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

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

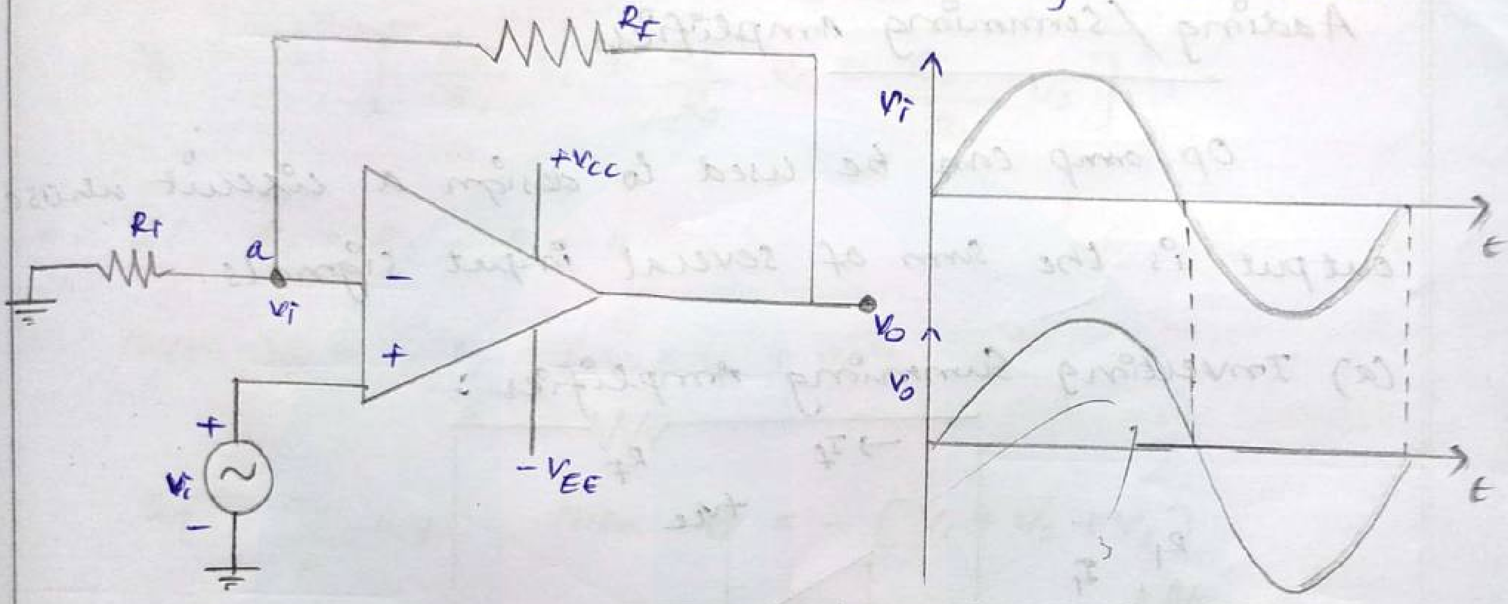
$\therefore$ Closed loop gain $\boxed{A_v = \frac{V_o}{V_i} = \frac{-R_F}{R_1}}$

Negative sign indicates a 180° phase shift between input (V_i) and output (V_o).

$\therefore$ Closed loop gain $A_v = \dfrac{V_o}{V_i} = \dfrac{-R_F}{R_1}$

Non Inverting amplifier

* It is voltage series feedback amplifier.
* Input signal V_i is applied to the non inverting terminal of op amp.
* Feedback is given to the inverting terminal



* The voltage at node 'a' is equal to the applied input voltage

$$ie, \ V_a = V_i$$

* By applying voltage division rule at $R_1 - R_F$ network

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

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

Thus for non-inverting amplifier

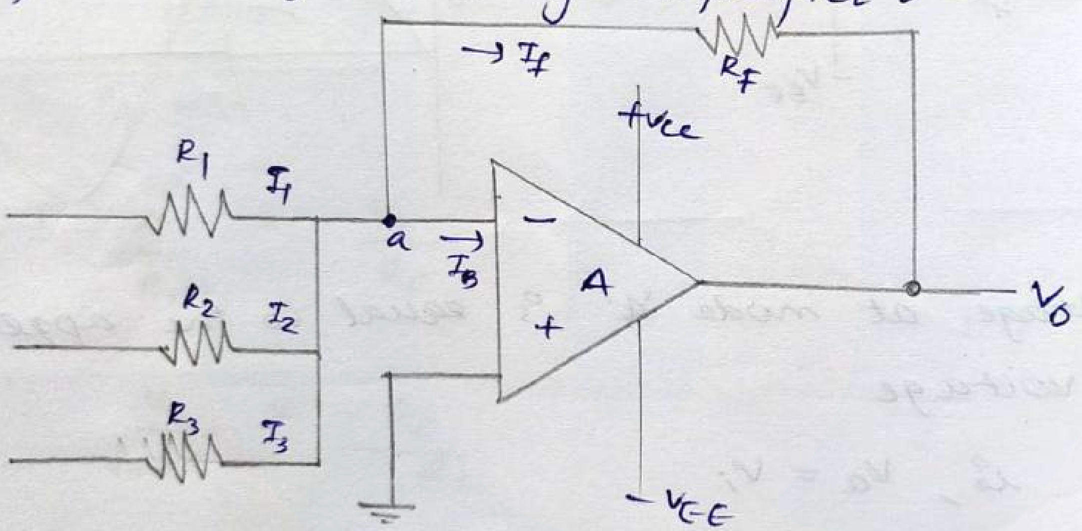
$$\boxed{A_{CL} = \frac{V_o}{V_i} = 1 + \frac{R_F}{R_1}}$$

Both i/p and o/p are in same phase.

Adding / Summing Amplifiers

Op amp can be used to design a circuit whose output is the sum of several input signals.

(a) Inverting Summing Amplifier:



* The circuit consists of three input voltages V_1, V_2, V_3 and input resistors R_1, R_2, R_3 and a feedback resistor R_F.

* Applying KCL at node 'a'.

$V_a = 0$ (Virtual ground concept)

$$I_1 + I_2 + I_3 = I_B + I_f$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{V_a - V_o}{R_f} \quad (I_B = 0)$$

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

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

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

* If $R_1 = R_2 = R_3 = R$

then $V_o = \frac{-R_f}{R}(V_1 + V_2 + V_3)$

If $\frac{R_f}{R} = 1$, then $V_o = -[V_1 + V_2 + V_3]$

* This circuit can be used as an averaging amplifier in which the output voltage is equal to the average of all input voltages.

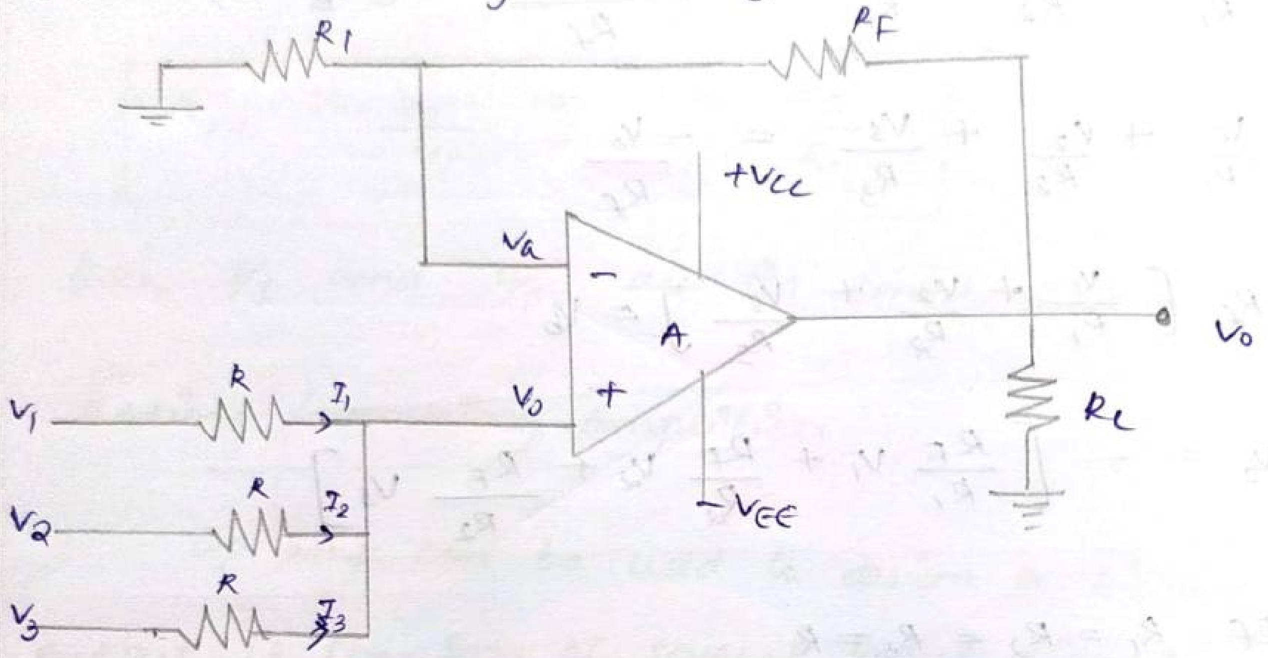
If $R_1 = R_2 = R_3 = R$ and $\frac{R_f}{R} = \frac{1}{n}$

where n is the no: of inputs

If $n = 3$,

then $V_o = -\frac{[V_1 + V_2 + V_3]}{3}$

(b) Non-inverting summing amplifier :



The input voltage sources and resistors are connected to the non inverting terminal.

$$V_a = V_b$$

At node b, $I_1 + I_2 + I_3 = 0$

$$\frac{V_1 - V_b}{R} + \frac{V_2 - V_b}{R} + \frac{V_3 - V_b}{R} = 0$$

$$V_1 + V_2 + V_3 - 3V_b = 0$$

$$V_1 + V_2 + V_3 = 3V_b$$

$$\therefore \quad V_b = \frac{V_1 + V_2 + V_3}{3} = V_a$$

At node a,

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

$$\frac{V_0}{R_F} = \frac{V_a}{R_1} + \frac{V_a}{R_F}$$

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

$$V_0 = V_a \cdot R_F \left[\frac{1}{R_1} + \frac{1}{R_F}\right]$$

$$= \left(\frac{V_1 + V_2 + V_3}{3}\right) R_F \left[\frac{R_1 + R_F}{R_1 R_F}\right]$$

$$\boxed{V_0 = \left[\frac{V_1 + V_2 + V_3}{3}\right]\left[1 + \frac{R_F}{R_1}\right]}$$

Design an adder circuit using op amp to provide

$$V_{out} = -V_1 + 3V_2 - 5V_3$$

Given $V_{out} = -V_1 + 3V_2 - 5V_3$

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

$\therefore \frac{R_F}{R_1} = 1 \Rightarrow R_F = R_1$

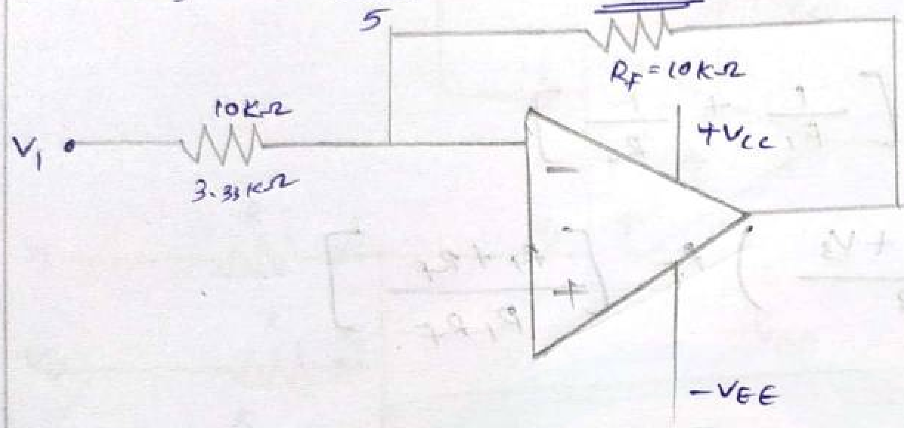
$\frac{R_F}{R_2} = 3 \Rightarrow R_F = 3R_2$

$\frac{R_F}{R_3} = 5 \Rightarrow R_F = 5R_3$

Let $R_1 = 10\,K\Omega$, then $R_F = 10\,K\Omega$

$$R_2 = \frac{R_F}{3} = \frac{10}{3}\ k\Omega = 3.33\ k\Omega$$

$$R_3 = \frac{R_F}{5} = 2\ k\Omega$$



Difference Amplifiers / Subtractor

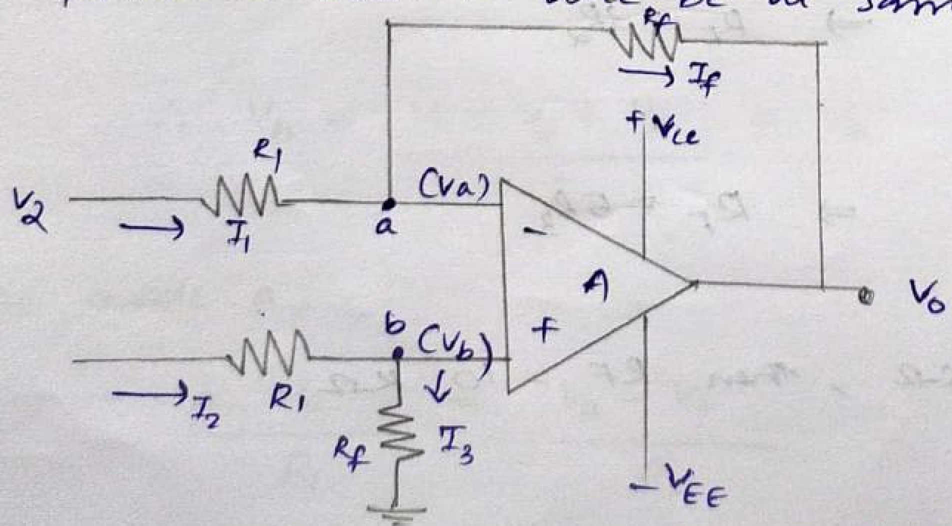
* An amplifier which amplifies the difference between two signals is called difference amplifier or differential amplifier.

* Differential voltage at the input of op amp is zero.

ie, $V_a - V_b = 0$

$$V_a = V_b$$

$\therefore$ point a and b will be at same potential.



Apply KCL at node 'a'

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

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

$$\frac{V_2}{R_1} + \frac{V_o}{R_F} = V_a\left[\frac{1}{R_1} + \frac{1}{R_F}\right] \quad \text{——— (1)}$$

Apply KCL at node 'b'.

$$\frac{V_1 - V_b}{R_1} = \frac{V_b}{R_F} = \frac{V_a}{R_F} \quad (\text{since } V_a = V_b)$$

$$\frac{V_1}{R_1} - \frac{V_b}{R_1} = \frac{V_a}{R_F}$$

$$\frac{V_1}{R_1} = V_a\left[\frac{1}{R_F} + \frac{1}{R_1}\right]$$

$$= V_a\left[\frac{R_1 + R_F}{R_1 R_F}\right]$$

$$\therefore V_a = V_1 \cdot \frac{\cancel{R_1} R_F}{\cancel{R_1}(R_1 + R_F)}$$

$$V_a = \frac{V_1 R_F}{R_1 + R_F} \quad \text{——— (2)}$$

Substitute (2) in (1)

$$\frac{V_2}{R_1} + \frac{V_o}{R_F} = \frac{V_1 R_F}{R_1 + R_F}\left[\frac{1}{R_1} + \frac{1}{R_F}\right]$$

$$= V_1 \frac{R_F}{\cancel{R_1 + R_F}} \left[\frac{\cancel{R_1 + R_F}}{R_F R_1} \right]$$

$$\frac{V_2}{R_1} + \frac{V_0}{R_F} = \frac{V_1}{R_1}$$

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

$$\boxed{V_0 = \frac{R_F}{R_1} [V_1 - V_2]}$$

If $R_1 = R_F = R$

then $\boxed{V_0 = (V_1 - V_2)}$

? Design a difference amplifier using op amp to get the output voltage $V_{out} = 10 [V_2 - V_1]$. Use minimum value of resistance as $10 k\Omega$

Ans:- $V_{out} = \frac{R_F}{R_1} [V_2 - V_1]$

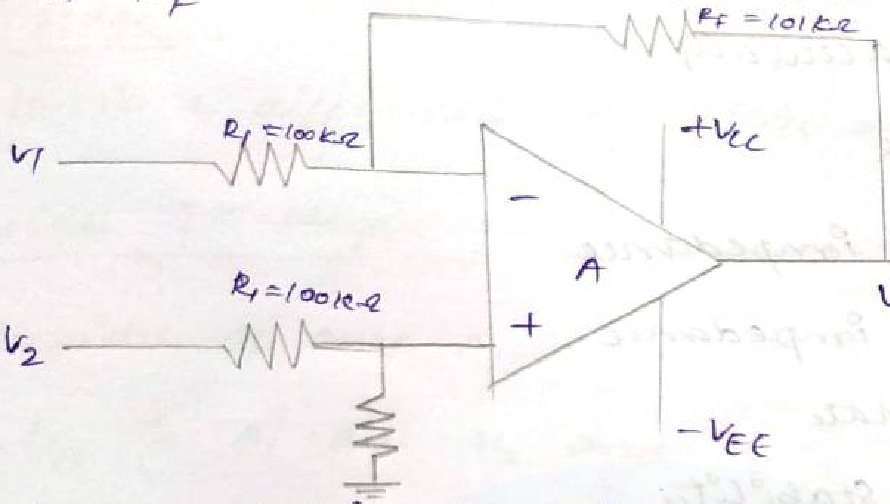
$$V_{out} = 10 [V_2 - V_1]$$

$$\therefore \frac{R_F}{R_1} = 10$$

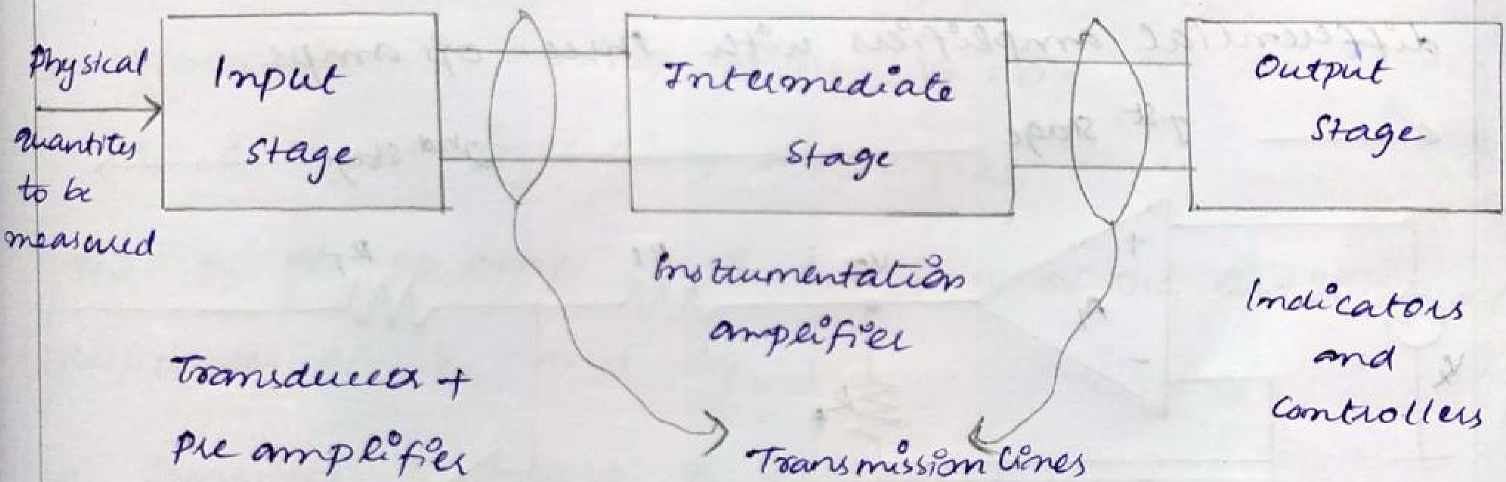
Minimum value of resistance to be used is $10 k\Omega$

Let $R_1 = 10\,k\Omega$

$\therefore R_F = 10 \times 10\,k\Omega = 100\,k\Omega$



Instrumentation Amplifier



BLOCK DIAGRAM OF INSTRUMENTATION S/M

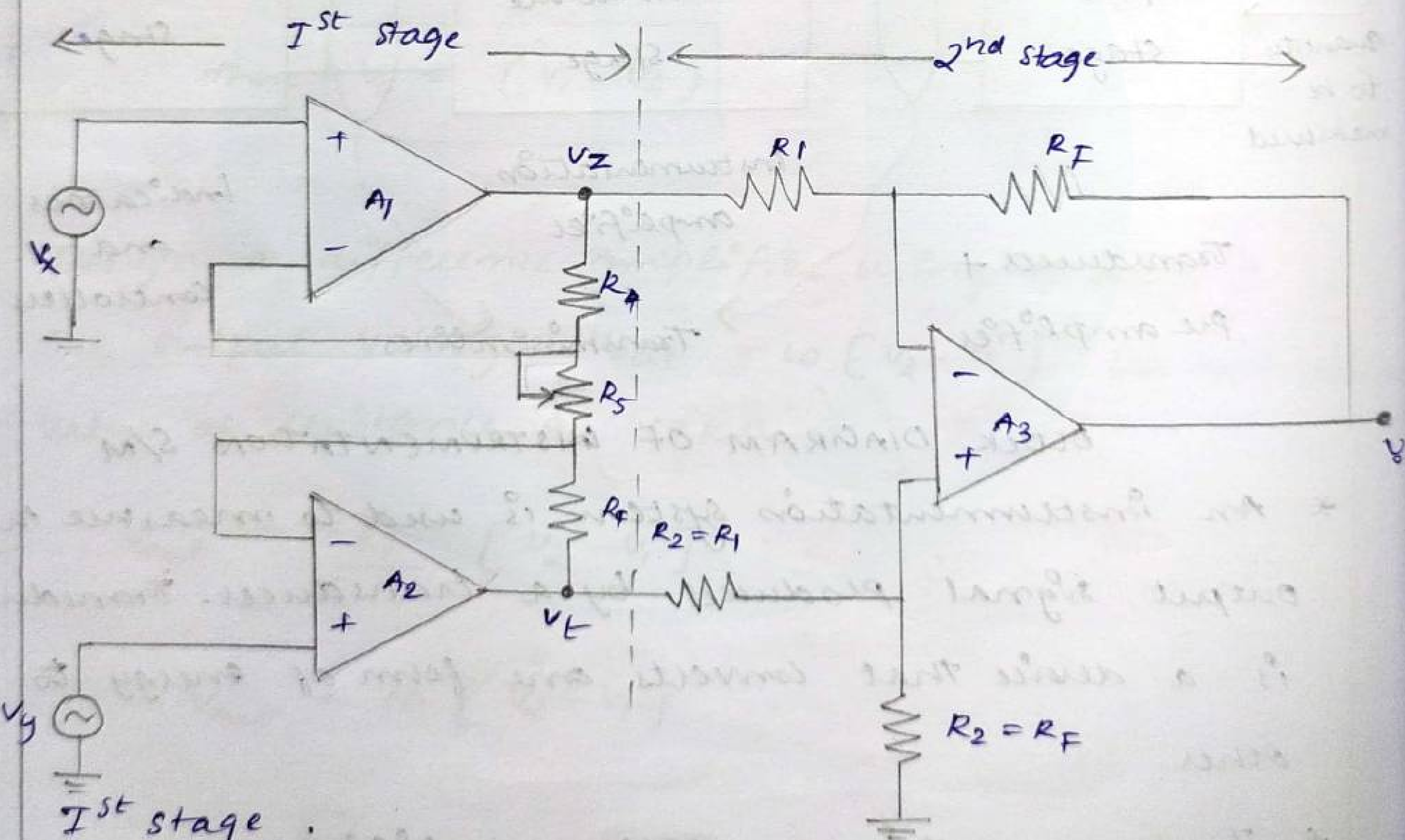
* An instrumentation system is used to measure the output signal produced by a transducer. Transducer is a device that converts one form of energy to other.

* Instrumentation amplifier amplifies the low level of output signal of the transducer inorder to drive indicator or display.

Important features of instrumentation amplifiers are

1. High gain accuracy
2. High CMMR
3. Low output impedance
4. High input impedance
5. High slew rate
6. High gain stability

Instrumentation amplifiers basically consists of differential amplifiers with three - op amps



<u>Ist stage</u> :

Offers high input impedance to both the inputs and allows to set gain with a single resistor.

 R_5 a potentiometer A_1 and A_2 are two op-amps.

2nd stage :

It is a differential amplifier with one op-amp

Consider Ist stage

Consider op amp A_1

* i/ps to A_1 are V_x and V_t.
* When V_x is acting alone, $V_t = 0$

The A_1 act as non-inverting amplifier

* When V_t is acting alone, $V_x = 0$.

A_1 act as inverting amplifier

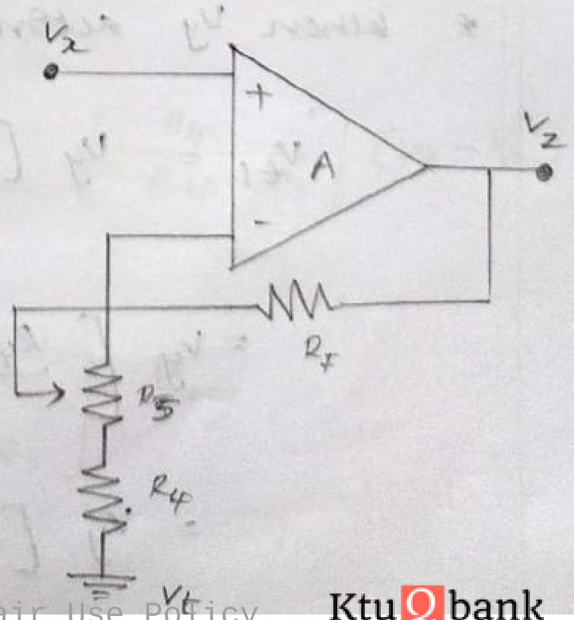
The o/p of op amp A_1 is the sum of the individual responses of V_x and V_t.

* Consider the case V_x acting alone (non-inverting amp)

$$V_{z1} = V_x \cdot \left[1 + \frac{R_4}{R_4 + R_5}\right]$$

$$= V_x \left[\frac{R_4 + R_5 + R_4}{R_4 + R_5}\right]$$

$$= V_x \cdot \left[\frac{2R_4 + R_5}{R_4 + R_5}\right].$$



* when V_t acting alone (inverting amplifier)

$$V_{z2} = V_t\left[-\frac{R_4}{R_4+R_5}\right]$$

$V_z = V_{z1} + V_{z2}$ which is the o/p of A_1.

$$V_{z} = V_x\left[\frac{2R_4+R_5}{R_4+R_5}\right] - V_t\left[\frac{R_4}{R_4+R_5}\right]$$

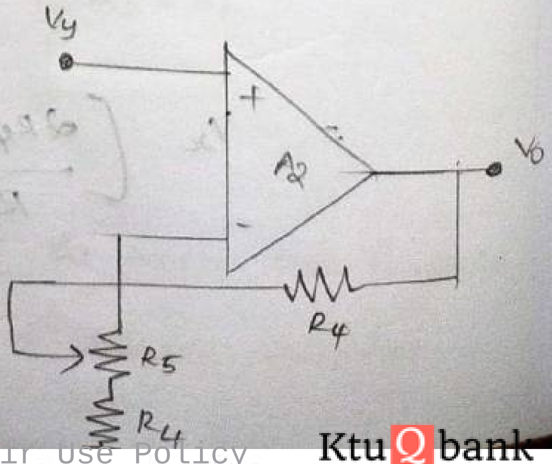
→ For op amp A_2

* i/p to A_2 are V_y and V_z
* when V_y is acting alone, $V_z=0$. so it is non-inverting amplifier.
* when V_z is acting alone, $V_y=0$. it act as inverting amplifier.
* The o/p is summation of the individual response.
* when V_y acting alone (non-inverting amp)

$$V_{t1} = V_y\left[1+\frac{R_4}{R_4+R_5}\right]$$

$$= V_y\left[\frac{R_4+R_5+R_4}{R_4+R_5}\right]$$

$$= V_y\left[\frac{2R_4+R_5}{R_4+R_5}\right]$$



When V_z is acting alone, $V_y = 0$ (Inverting amp)

$$\cancel{V_{t1} = V_y\left[1+\frac{R_4}{R_4+R_5}\right]}$$

$$V_{t2} = \left[\frac{-R_4}{R_5+R_4}\right]\cdot V_z$$

$\therefore V_t = V_{t1} + V_{t2}$ which is the o/p of A_2.

$$V_t = \left[\frac{2R_4+R_5}{R_4+R_5}\right]V_y + \left[-\frac{R_4}{R_5+R_4}\right]V_z$$

$$V_t = \left[\frac{2R_4+R_5}{R_4+R_5}\right]V_y + \left[\frac{-R_4}{R_5+R_4}\right]V_z$$

→ o/p of 1st stage $V_{zt} = V_z - V_t$

$$= V_x\left[\frac{2R_4+R_5}{R_4+R_5}\right] - V_t\left[\frac{R_4}{R_4+R_5}\right] - \left[\frac{2R_4+R_5}{R_4+R_5}\right]V_y$$

$$+\left[\frac{R_4}{R_4+R_5}\right]V_z$$

$$\therefore V_{zt} = \left[\frac{2R_4+R_5}{R_4+R_5}\right](V_x - V_y) - \left[\frac{R_4}{R_4+R_5}\right](V_z - V_t)$$

$$V_{zt} - V_{zt}\left[\frac{R_4}{R_4+R_5}\right] = \left[\frac{2R_4+R_5}{R_4+R_5}\right]\cdot V_{xy}$$

$$V_{zt}\left[1-\frac{R_4}{R_4+R_5}\right]=\left[\frac{2R_4+R_5}{R_4+R_5}\right]V_{xy}$$

$$V_{zt}\left[\frac{R_4+R_5-R_4}{R_4+R_5}\right]=\left[\frac{2R_4+R_5}{R_4+R_5}\right]V_{xy}$$

$$V_{zt}\left[\frac{R_5}{R_4+R_5}\right]=\left[\frac{2R_4+R_5}{R_4+R_5}\right]V_{xy}$$

$$\frac{V_{zt}}{V_{xy}}=\frac{\left[\frac{2R_4+R_5}{R_4+R_5}\right]}{\left[\frac{R_5}{R_4+R_5}\right]}=\frac{2R_4+R_5}{R_5}$$

O/P of second stage : It is a difference amplifier

$$\boxed{V_0=-\frac{R_F}{R_1}V_{zt}}$$

Overall gain $A_D=\frac{V_0}{V_{xy}}=\frac{V_0}{V_{zt}}\cdot\frac{V_{zt}}{V_{xy}}$

$$=-\frac{R_F}{R_1}\times\left[\frac{2R_4+R_5}{R_5}\right]$$

$$\boxed{A_D=-\frac{R_F}{R_1}\left[1+\frac{2R_4}{R_5}\right]}$$

→ Overall o/p voltage V_o = gain × V_{xy} = $A_D \times V_{xy}$

→ Gain can be changed by adjusting potentiometer R_5.

→ R_5 should never set to 0 or ∞.

Applications

1) Used as temperature indicator in transducer

2) Used in light intensity meters.