OPERATIONAL AMPLIFIER –

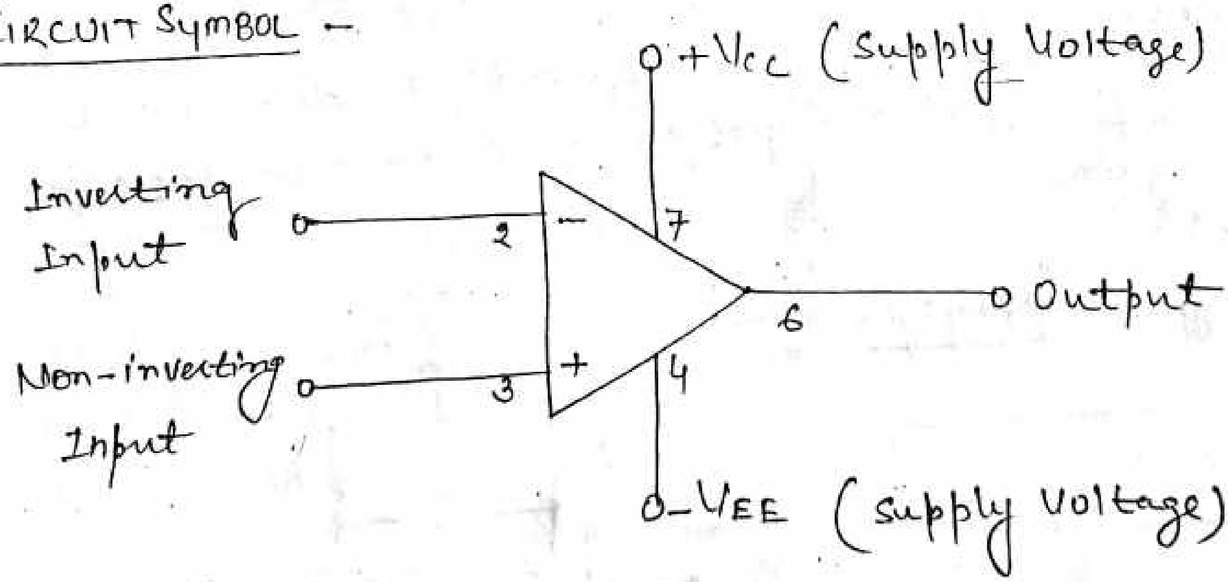
- It is a very high gain amplifier (Differential Amplifier) with high input impedance and low output impedance.
- It is usually known as op-Amp.
- Its name consists two words **Operational + Amplifier.**

Operational → It can perform mathematical operations on ac or dc signals like – Addition, subtraction, multiplication, division, differentiation integration, log, Antilog etc.

Amplifier → It can amplify both ac and dc signals.

- It is also known as voltage controlled voltage source (VCVS)
- Some other applications of op-amp are – comparator, Oscillators, regulators, filters. etc.

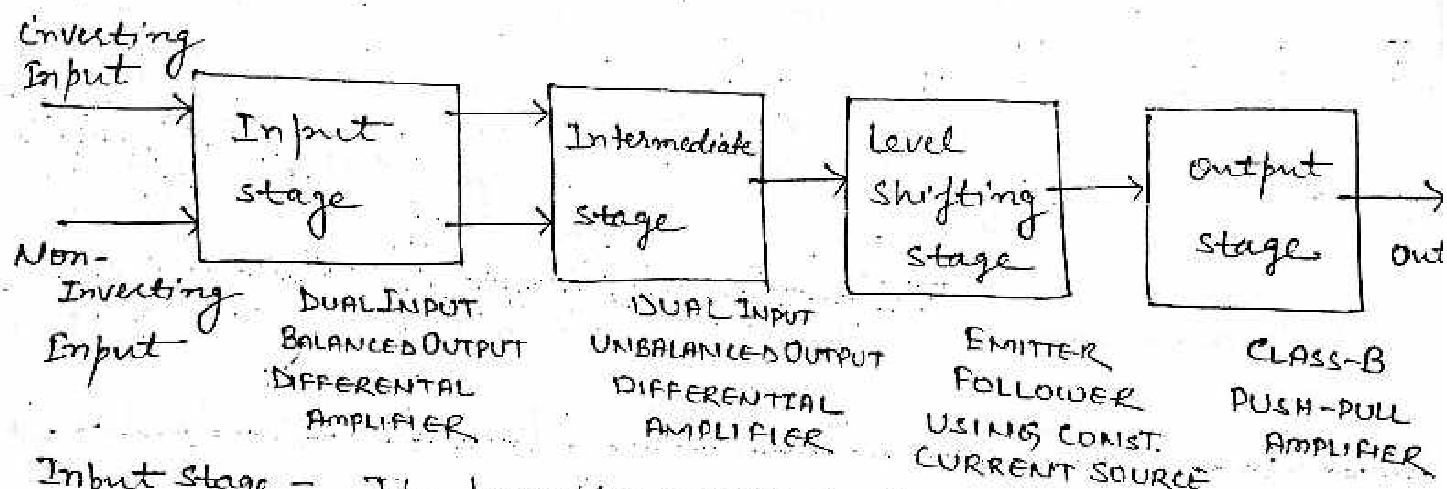
CIRCUIT SYMBOL –



→ It has two inputs (Inverting & Non-inverting), two supply voltage terminals (positive & negative) and one output terminal.

BLOCK DIAGRAM –

- Op-Amp is a multi-stage amplifier.
- It's block diagram representation can be given as–

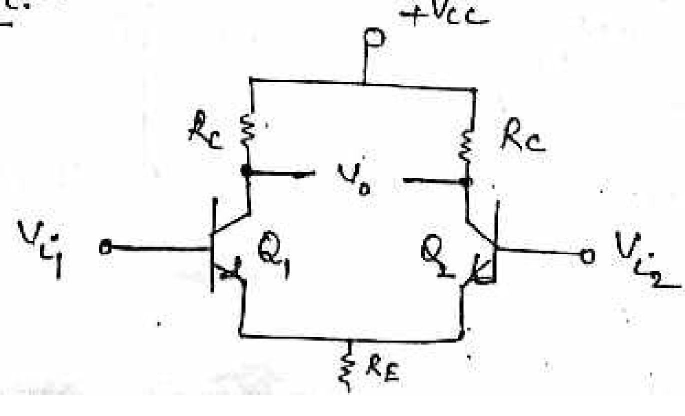


Input Stage – It provides most of the voltage gain and establishes the input resistance of the op-amp.

Intermediate Stage – It is a single output, dual input differential amplifier to provide another stages of gain

Differential Amplifier ckt. –

$$\boxed{V_0 \propto (V_{i_1} - V_{i_2})}$$



Level shifting stage -

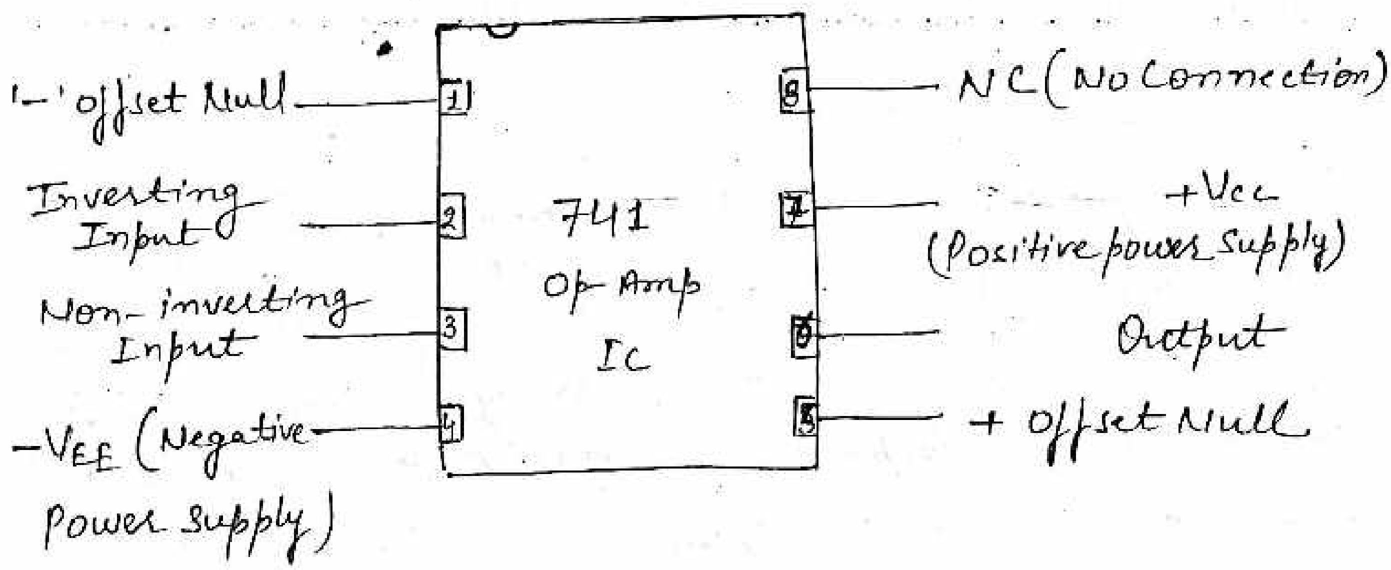
The output of intermediate stage (i.e. Input to level shifting stage) is an amplified signal with some non-zero dc level. This stage is used to bring this dc level to zero level (ie. ground).

Common collector amplifier (i.e. emitter follower) with constant current source is used for this purpose.

Output Stage -

- This stage provides the low output impedance, increases the output voltage magnitude and maximum current supplying capability to drive maximum no. of devices at the output.

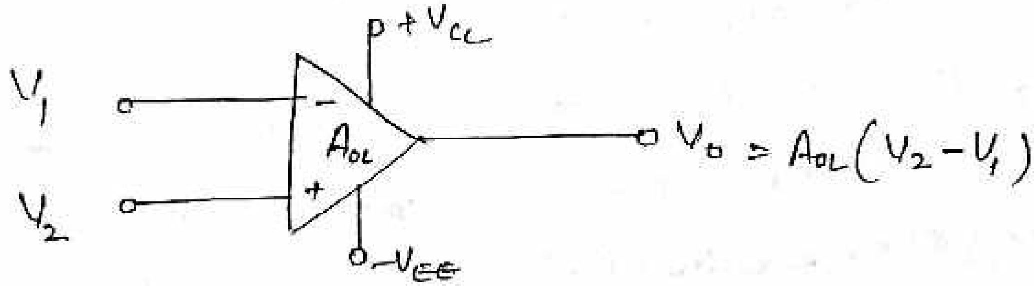
PIN DIAGRAM OF 741-IC Op-Amp →



8-Pin DIP (Dual-in line Package)

(IC- Integrated Circuit)

Op-amp Input Modes and Operation:-



If V_1 and V_2 be the inputs at inverting and non-inverting input terminals, net input to op-amp is

$$V_d = V_2 - V_1$$

V_d - is differential input or difference input voltage

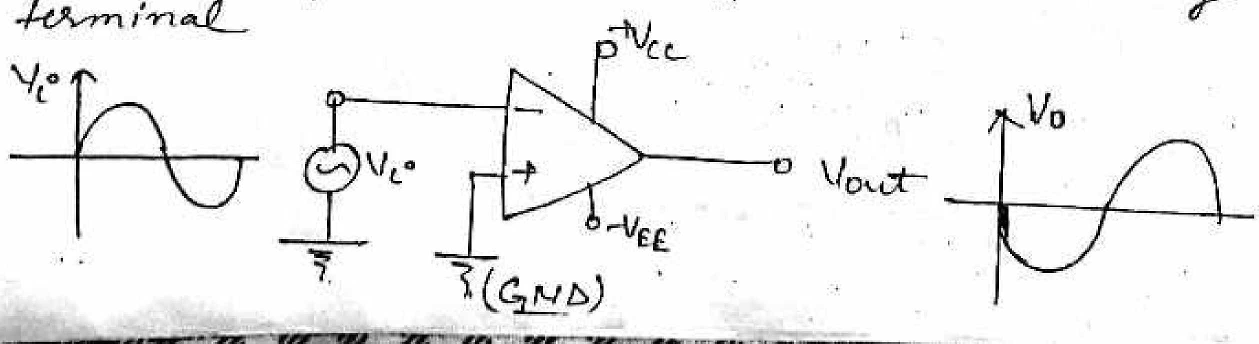
If A_{OL} be the open loop gain of amplifier,

$$V_o = A_{OL}(V_d)$$

$$\boxed{V_o = A_{OL}(V_2 - V_1)}$$

Single ended input mode -

If input is applied only at one input terminal and another terminal is grounded. Op-amp is said to be operating in single ended mode. If input is applied at inverting terminal

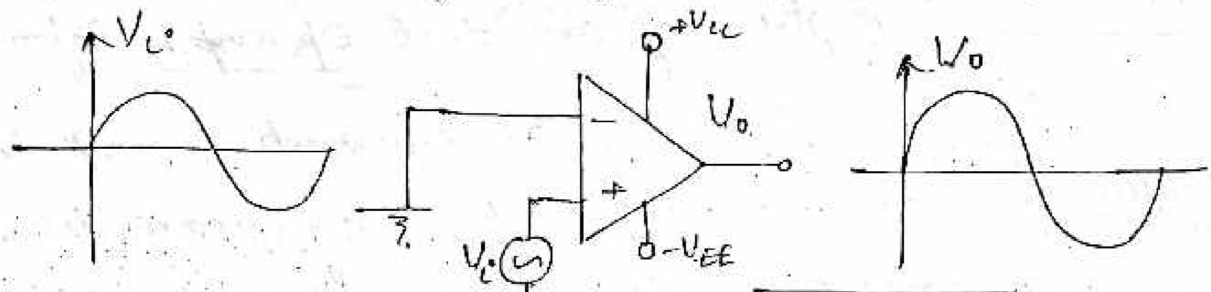


∴ Output is 180° out of phase w.r.t. (with respect to) input signal. hence '−'ve input terminal is called inverting Input terminal.

$$V_2 = 0 \quad , \; V_1 = V_1$$

$$\boxed{V_O = -A_{OL} V_1}$$

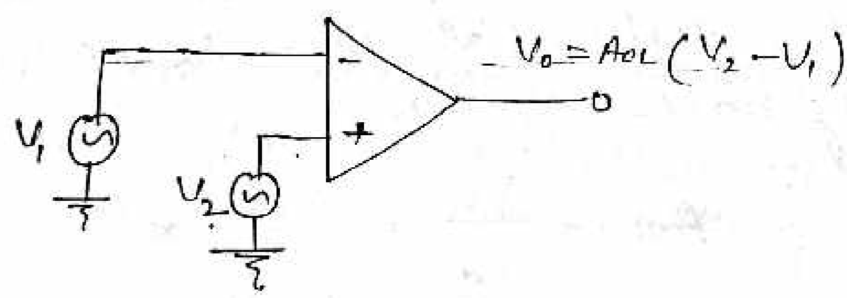
If input is applied at '+'ve Input terminal, there will be no change in phase of output signal



$V_1 = 0$, $\boxed{V_O = A_{OL} V_2}$

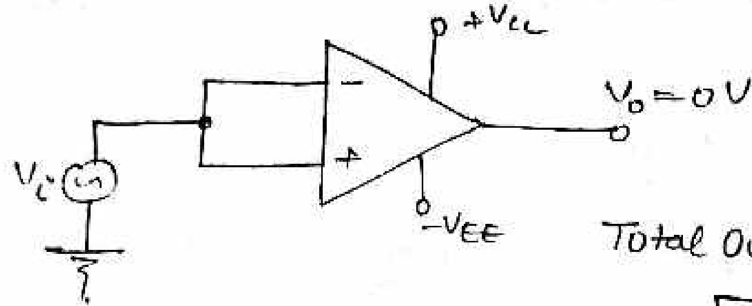
Hence input terminal is <u>non-inverting input terminal</u>.

<u>Differential Mode</u> – If signals are applied at both input terminals, op-amp is said to be working in differential mode or double-ended input mode.



<u>Common mode</u> – The same input is applied at both input terminal and output of the ideal op-amps is supposed to be zero.

Producing a zero output in common mode operation is called as <u>Common-mode rejection</u>.



Common mode Voltage is,

$$\boxed{V_{cm} = \frac{1}{2}(v_1 + v_2)}$$

Total Output of op-amp is,

$$\boxed{V_{out} = A_d V_d + A_{cm} V_{cm}}$$

CHARACTERISTICS OF IDEAL OP-AMP →

An Ideal op-amp should have following characteristi

(1) Open loop gain of an Ideal op-amp is infinite ($A_{OL} = \infty$

→ If output of an op-amp is not connected (feedback) to with its input by any means like resistanc capacitors, diode etc, op-amp is said to be in open-loop condition.

(OR)

→ If output of an op-amp doesn't depend upon its previous output, op-amp is said to be in open loop condition.

→ $A_{OL} = \infty$, means for finite output at output terminal, differential input v_d should be negligibly small ($v_d \simeq 0$).

$$A_{OL} = \frac{V_o}{v_d} = \frac{V_o}{0} = \infty$$

→ for 741 IC-op-amp value of open loop gain is in the order of 10^5.

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(2). INPUT IMPEDANCE IS INFINITE – ($R_i = \infty$)

→ An ideal op-amp has infinite input impedance.

→ It means that op-amp draws no input current from power supply.

→ So why op-amp is called a voltage controlled device.

→ It can amplify a negligibly small input signal.

→ Input impedance of 741 IC op-amp is 2MΩ.

3) OUTPUT IMPEDANCE IS ZERO ($R_o = 0$) –

– An ideal op-amp has zero output impedance.

– It means output voltage is independent of load connected across the output.

– op-amp can drive infinite no. of devices.

– output impedance of 741 IC op-amp is 75Ω

4) INFINITE BANDWIDTH ($BW = \infty$) –

– Bandwidth is known as range (band) of frequencies.

– An ideal op-amp can amplify signal of zero to infinite ($0 \to \infty$) frequency, hence bandwidth is infinite. Band width of 741 IC op-amp is 1MHz.

5) INFINITE CMRR → ($CMRR = \infty$)

– CMRR is Common mode rejection ratio.

– It is defined as the ratio of differential mode gain (A_d) to common mode gain (A_c). It should be infinite so that Input noise (common mode noise) could not be amplified at output. i.e. common mode gain of an ideal op-amp should be zero.

- CMRR of 741 IC op-amp is 90dB.

(6) INFINITE SLEW RATE - (SLEW RATE $= \infty$)

→ Slew rate is defined as the maximum rate of change output voltage per unit time.

→ It should be infinite so that output voltage changes occur simultaneously with input voltage changes.

→ Slew rate of 741 IC Op-amp is 0.5 V/μsec.

(7) ZERO OFFSET VOLTAGE -

→ Whenever input voltage is zero, output voltage should be zero at that time.

→ Hence ideal op-amp should have zero offset voltage.

(8) PSRR should be ZERO (PSRR $= 0$) -

→ It is Power supply rejection ratio.

→ It is defined as the ratio of change in input offset voltage to change in the supply voltage.

$$PSRR = \frac{\Delta V_{ios}}{\Delta V} = \frac{\text{Change in Input Offset Volt}}{\text{Change in input supply volta}}$$

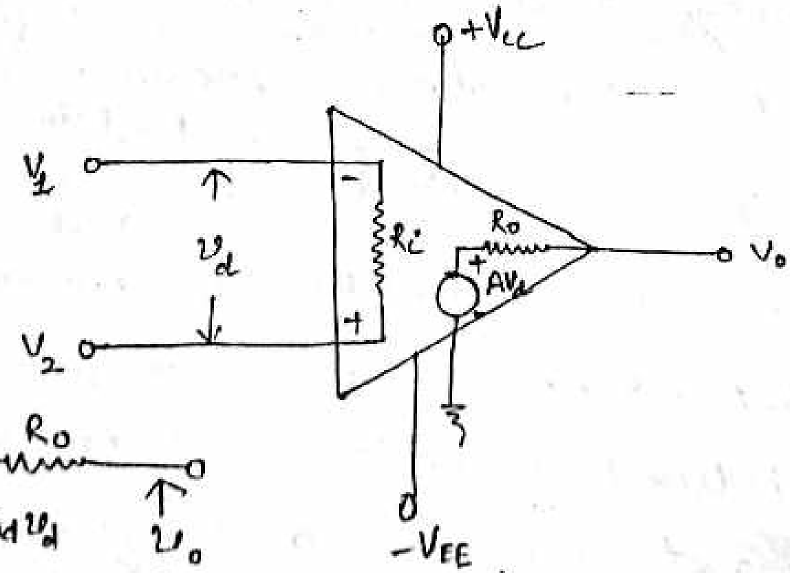
→ It is a parameter which specifies the degree of dependance of output voltage on the changes in power supply voltages.

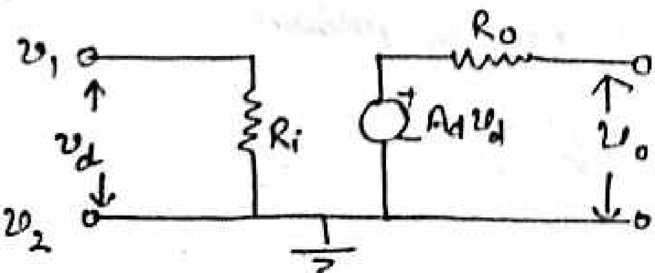
→ It should be zero for ideal op-amp.

Characteristics of Ideal op-amp (List) –

1. It has infinite input impedance. $(Z_i = \infty)$
2. Ideal op-amp has zero output impedance $(Z_0 = 0)$
3. Voltage gain is infinite (Open loop voltage gain is infinite). $(A_{OL} = \infty)$.
4. Bandwidth is infinite. $(BW = \infty)$
5. Ideal op-amp has infinite CMRR. $(CMRR = \infty)$
6. Slew rate is infinite $(SR = \infty)$
7. It has zero offset voltage $(V_{os} = 0)$
8. Power supply rejection ratio is zero for ideal op-amp. $(PSRR = 0)$

PRACTICAL EQUIVALENT CIRCUIT –



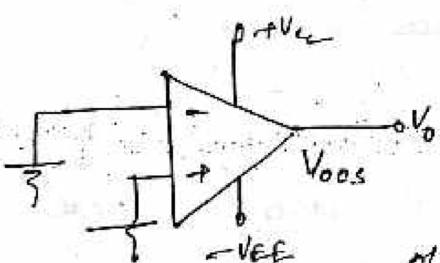


OR –

OP-AMP PARAMETERS -

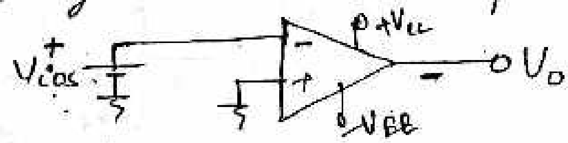
(i) Output offset Voltage (V_{oos})
(ii) Input offset Voltage (V_{ios})
(iii) Input Bias Current (I_B)
(iv) Input offset Current (I_{ios})
(v) Common mode rejection ratio (CMRR)
(vi) Slew Rate (SR)

OUTPUT OFFSET VOLTAGE - If both input terminals of op-amp are at zero (ground), output should be zero. But output is not zero in this case. There exist a little output voltage. This voltage is known as output offset voltage.

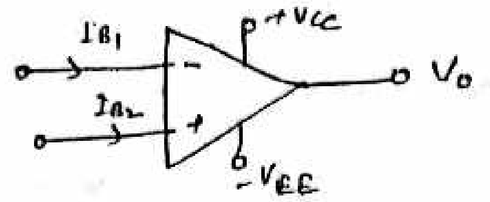


This is because of variations in parameters of transistors of same type.

INPUT OFFSET VOLTAGE - To make output offset voltage zero, we need to apply some voltage at input, this voltage is known as input offset voltage (V_{ios}).



INPUT BIAS CURRENT - For ideal op-amp current in both input terminals should be zero and equal ($I_{B_1} = I_{B_2} = 0$) but due to variations in transistor parameters they are not zero and not equal.



Input bias current is the average of both input currents I_{B_1} & I_{B_2}

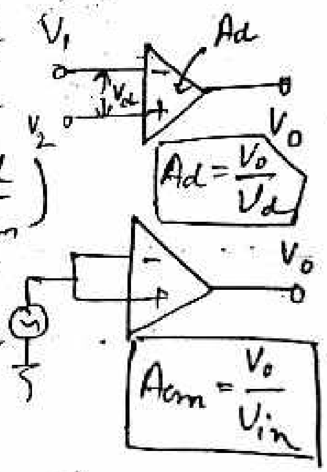
$$\boxed{I_B = \frac{I_{B_1} + I_{B_2}}{2}}$$

INPUT OFFSET CURRENT – Due to imbalances in op-amp circuitary both input currents to op-amp at input terminals I_{B_1} & I_{B_2} are not equal. Difference between both is input offset current

$$\boxed{I_{ios} = |I_{B_1} - I_{B_2}|}$$

CMRR – Common mode rejection ratio (CMRR) is the ratio of differential mode gain (A_d) to common mode gain (A_{cm}).

for numeric value $\quad CMRR = \dfrac{\text{differential mode gain}}{\text{Common mode gain}} = \dfrac{A_d}{A_{cm}}$



for decibal value $\quad CMRR\big|_{dB} = 20\log_{10}\left(\dfrac{A_d}{A_{cm}}\right)$

CMRR is ∞ for ideal op-amp.

SLEWRATE – Slew rate is the maximum rate of change of output w.r.t. time.

$$SR = \frac{\text{Max. change in output Voltage (V)}}{\text{Change in time } (\mu sec.)} = \left.\frac{dV_o}{dt}\right|_{max.}$$

→ unit of slew rate is $V/\mu sec$.

→ It decides the capability of op-amp to change its output rapidly.

→ It also decides the highest frequency of operation.

OPEN LOOP OP-AMP -

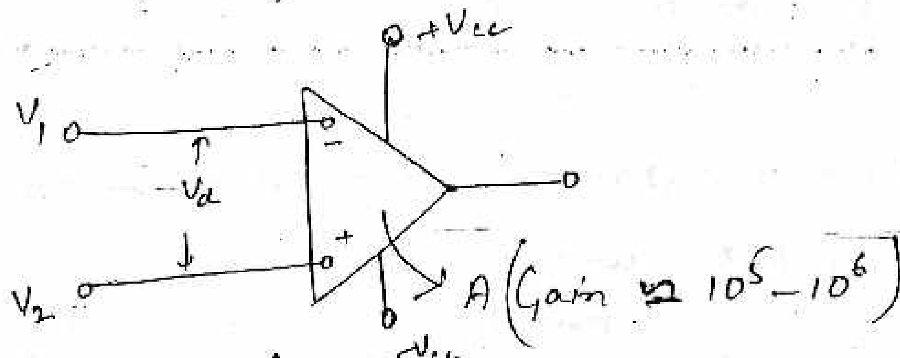
→ If output of op-amp is not fed-back to the input of op-amp, op-amp is called open-loop op-amp.

"OR"

→ If output of op-amp at any time does not depen upon the previous output and depends only upon the input given, op-amp is said to be in open loop condition.

→ No connection between output and input either directly or via any network.

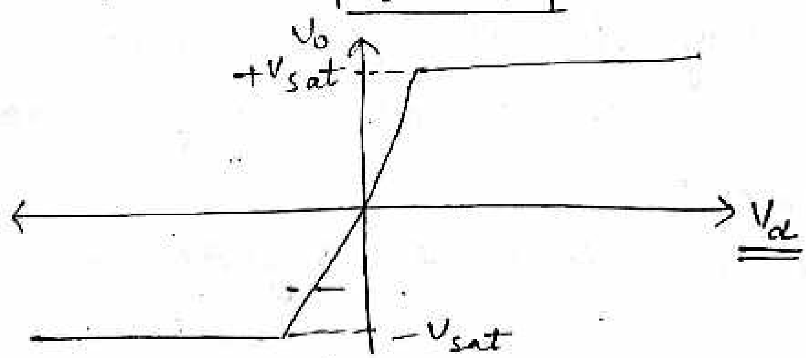
→ Gain of an open-loop ideal op-amp is infinte.



$V_d \simeq (V_2 - V_1)$

$\boxed{V_0 = A \times V_d}$

Operation:-



let the inverting & non-inverting inputs ~~to~~ the op-amp are V_1 and V_2 respectively, differential input

$$v_d = V_2 - V_1$$

let $V_2 = 5V$, $V_1 = 2V$, $V_d = 5-2 = 3V$

Gain of IC 741 is 2×10^5, which is very high

hence output is $V_0 = A \cdot v_d$

$= 2\times10^5 \times 3$

$V_0 = 6\times10^5 V$ (Extremly high Voltage)

hence we can conclude that for very small magnitude of v_d (in mV generally) output will reach the saturation mode and output will be either $+V_{sat}$ or $-V_{sat}$.

if $V_d > 0$, $V_0 = +V_{sat}$
or $(V_2 - V_1) > 0$

if $V_d < 0$, $V_0 = -V_{sat}$
or $V_2 < V_1$

Note:- open loop op-amp is not used as an amplifier because of its extremely high gain; because of its high gain, distortion is introduced at the output. Open-loop gain A_{OL} also varies with temp. and power supply.

Open loop op-amp applications -

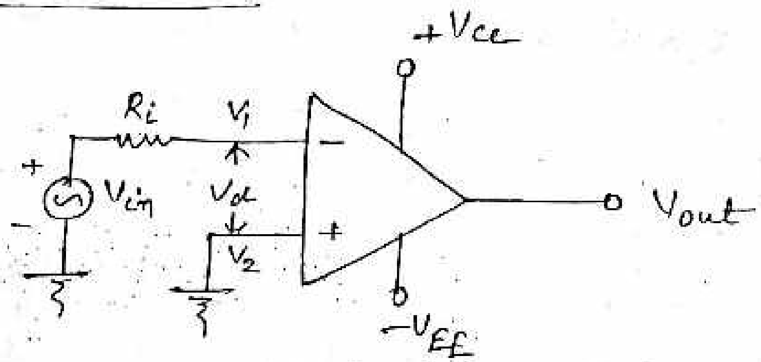
(i) Inverting Amplifier

(ii) Non-inverting Amplifier

Imp. (iii) comparator

** All wave forms are for ideal op-amp having open loop gain infinite (∞).

(I) INVERTING AMPLIFIER →



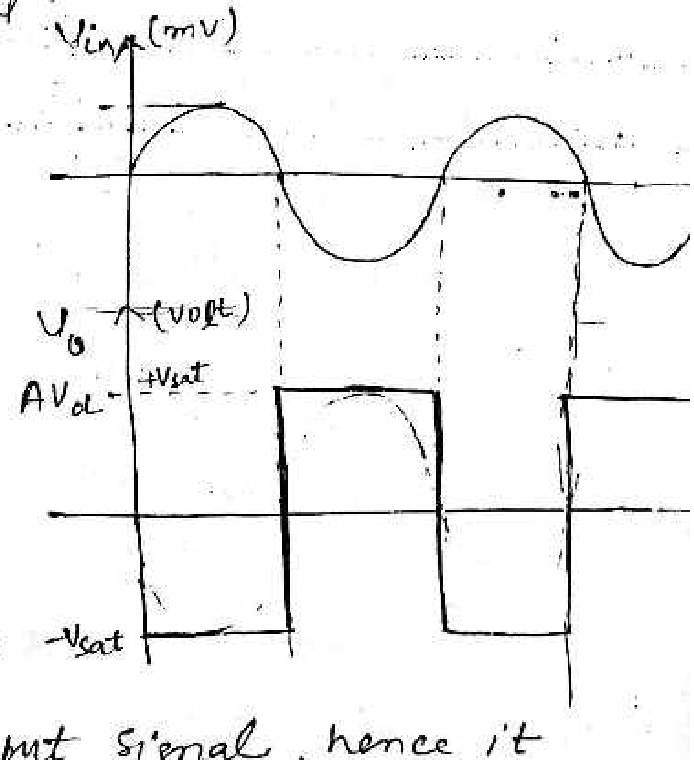
If AC input V_{in} is applied at inverting terminal and another terminal is grounded.

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

$V_0 = A V_d = A(V_2 - V_1)$

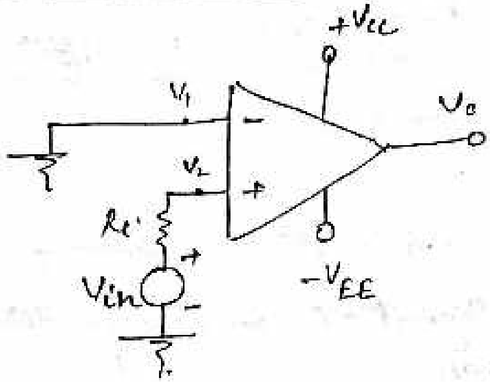
$$\boxed{V_0 = -A V_{in}}$$

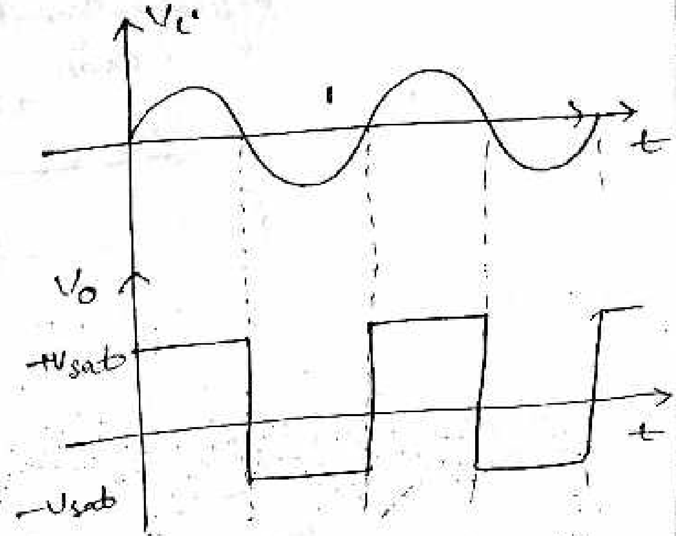
Output Waveform -



Output is an amplified signal whose phase is 180° out of phase with the input signal, hence it is inverting amplifier.

(II) NON-INVERTING AMPLIFIER –





If input is applied at non-inverting terminal and other is grounded, – the output is

as $V_2 = V_{in}$; $V_1 = 0$

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

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

Output is amplified signal and is in phase with input (No phase difference), hence Non-inverting amplifier.

III) COMPARATOR –

Comparators may be of two types depending upon the input signal applied.

(i) Inverting comparator (ii) Non-inverting Comparator

→ Comparator compares one input signal (applied signal) to the other fixed signal (reference signal).

→ Output of open-loop comparator swings between +V_{sat} and –V_{sat}.

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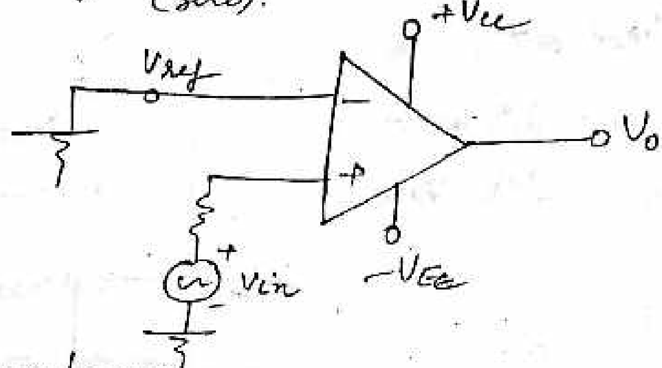
(ZERO CROSSING DETECTORS)

COMPARATOR WITH ZERO REFERENCE SIGNAL –

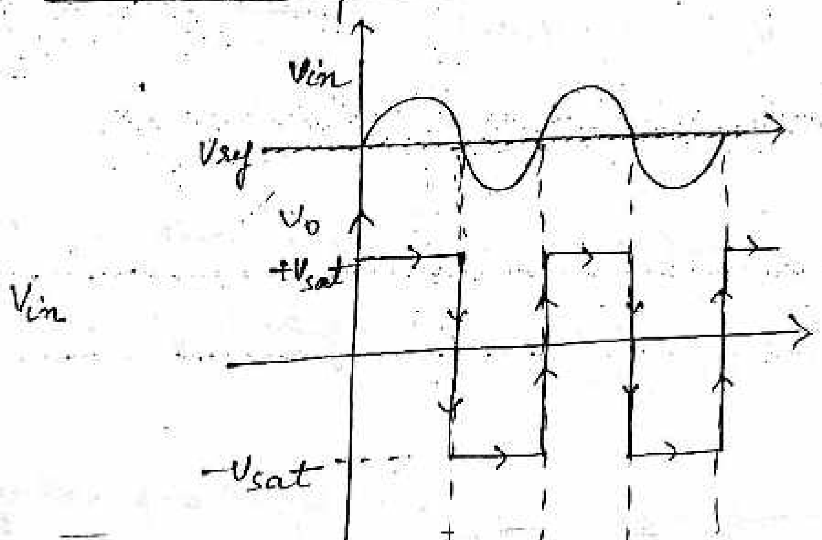
(i) Non-inverting Comparator –

Input at Non-inverting terminal (Pin 3)

Reference Signal at inverting terminal (Pin 2) (zero).



Output wave forms: –



As $V_{in} > V_{ref}$

$V_{in} > 0$

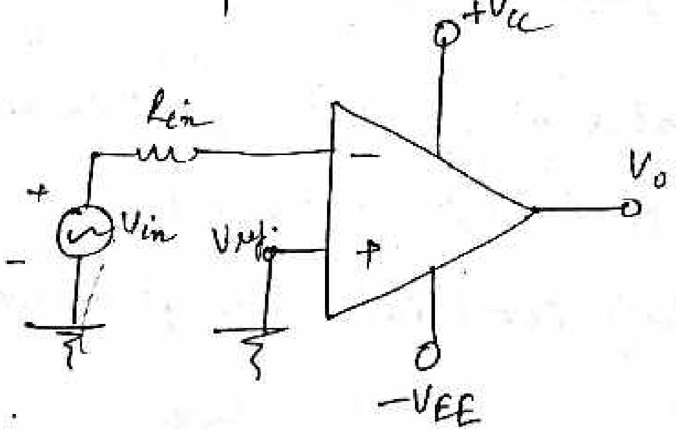
$\boxed{V_O = +V_{sat}}$

As $V_{in} < V_{ref}$

$V_{in} < 0$

$\boxed{V_O = -V_{sat}}$

(ii) Inverting Comparator –



Input Signal at inverting terminal and reference signal (ground) at non inverting terminal.

FEEDBACK AND CLOSED loop OP-AMP -

→ When output of an op-amp is feel back (connected) to the input. it is called feedback. When the phase of input and feedback signal are same, feedback is positive feedback. when phase of input and feedback signal is not same (180° out of phase), feedback is Negative.

→ Feedbacks are of two types:

(i) Positive or Regenerative feedback
(ii) Negative or degenerative feedback

→ Positive feedback is used in "oscillators" and "schmitt triger" while negative feedback is used in amplifier applications.

Why feedback is used → In open-loop op-amp voltage gain is extremely high, hence input signals applied are very small (in mV range) which are sensitive to noise and almost impossible to obtain.

Output of open-loop op-amp swings between $\pm V_{sat}$ and it can not exceed the biasing values $+V_{cc}$, $-V_{EE}$.

Advantages of Negative feedback -

(i) It reduces the infinitesome gain to moderate value and stablizes it.

(ii) Reduces the distortion in small signals and make the output almost independent of temperature and supply voltages variations.

(iii) It increases the bandwidth of op-amp.

(iv) It increases the Input impedance and decreases the output impedance.

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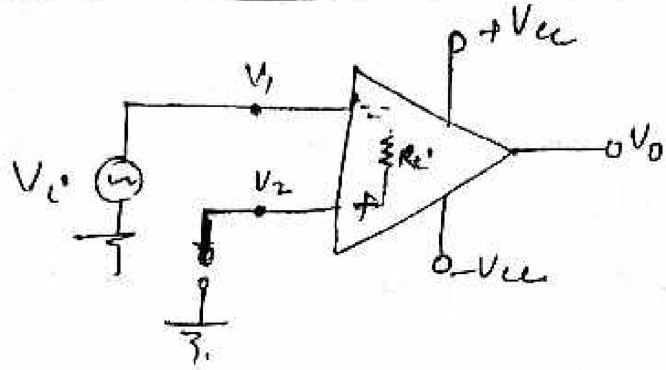
Virtual Short Concept –



$v_d = (V_2 - V_1)$ $V_2 = ?$, $V_1 = V_{in}$

→ for ideal op-amp voltage gain is infinite ($A_{OL} = \infty$) and input resistance ($R_i = \infty$).

→ As $R_i = \infty$, No current will flow into op-amp between V_1 and V_2.

→ i.e. both are at same potential.

→ It means they are virtually short, or

$$A_{OL} = \frac{v_o}{v_d}$$

$$v_d = \frac{V_o}{A_{OL}} = \frac{v_o}{\infty} = 0$$

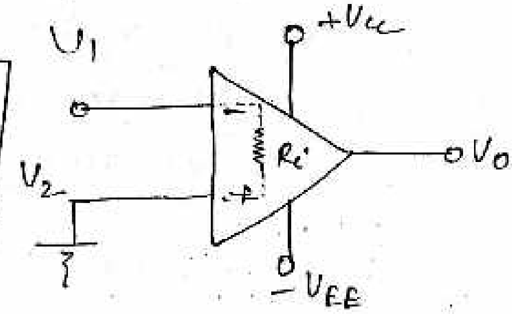
$$V_2 - V_1 = 0$$

$$\boxed{V_2 = V_1 = V_{in}}$$

$$\boxed{V_+ = V_-}$$

Voltage at '+' input terminal = Voltage at '–'ve input terminal

Virtual Ground –



In the figure V_1 can be considered at ground because ideally input resistance is ∞ and no current will flow into the op-amp i.e. V_1 and V_2 have no voltage difference.

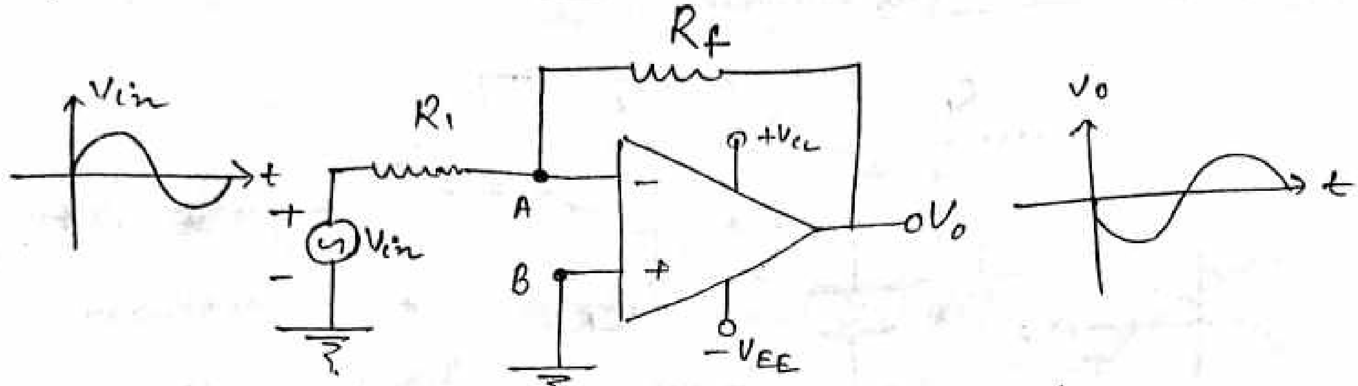
$\boxed{V_1 = V_2}$, As V_2 is at ground V_1 is also at ground.

as $V_2 = V_1$ (from virtual short)

$\boxed{V_2 = 0 = V_1}$

V_1 is also grounded.

INVERTING AMPLIFIER –



→ Input is applied at inverting terminal.

→ Constant gain amplifier.

→ Also known as voltage shunt feedback amplifier.

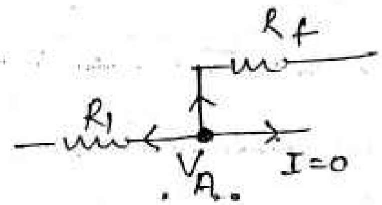
→ Output is 180° out of phase with input.

According to virtual short concept

$$\boxed{V_B = V_A = 0}$$

Nodal analysis at node A (KCL at node A)

$$\frac{V_A - V_{in}}{R_1} + \frac{V_A - V_O}{R_f} + I = 0$$



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

(I=0 as ideally there is no input current to op-amp)

$V_A = 0$ Volt

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

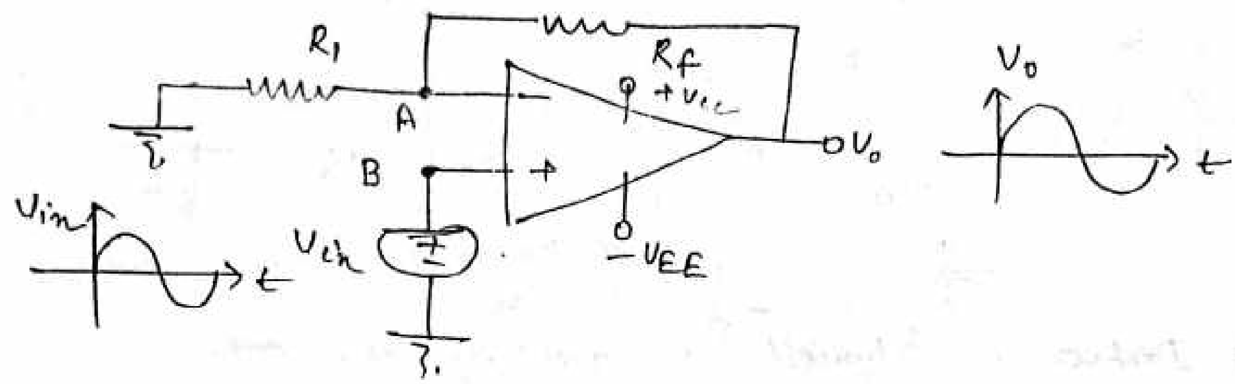
→ output is 180° out of phase, therefore it is called inverting amplifier.

Closed loop Voltage gain.

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

→ Gain is not '∞' now, it depends upon the value of R_f and R_1. (i.e. gain is reduced & stablized.)

Non-Inverting Amplifier -



(i) Negative feedback is used.

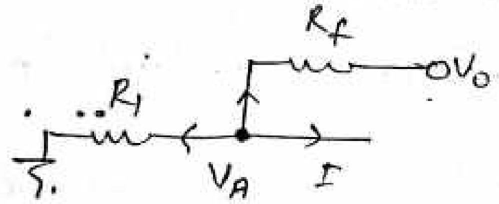
(ii) Input signal is applied at non-inverting terminal.

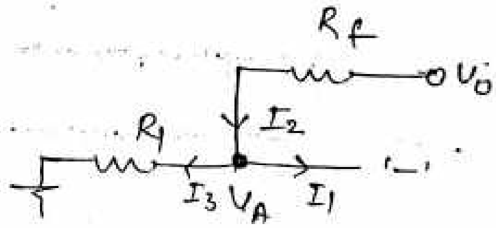
(iii) Output will be in-phase with input, hence it is non-inverting amplifier.

according to virtual short concept

$$\boxed{V_B = V_A = V_{in}}$$

KCL at node A,





$$\frac{V_A - 0}{R_1} + \frac{V_A - V_0}{R_f} + I = 0$$

$$\frac{V_{in}}{R_1} + \frac{V_{in} - V_0}{R_f} + 0 = 0 \quad (\because I = 0)$$

$$\boxed{V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}}$$

OR,

$$I_1 + I_3 = I_2$$

$$0 + \frac{V_{in}}{R_1} = \frac{V_0 - V_{in}}{R_f}$$

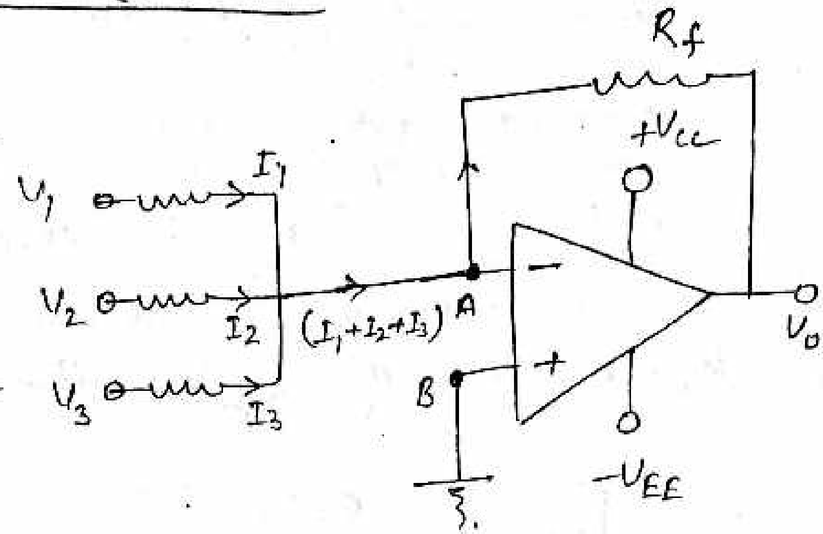
$$V_0 = \left(1 + \frac{R_f}{R_1}\right) V_{in}$$

Closed loop voltage gain

$$\boxed{A_{CL} = \frac{V_0}{V_{in}} = 1 + \frac{R_f}{R_1}}$$

Summing Amplifier (Adder) -

→ Summing amplifier is used to give the output, which is the sum of several inputs.



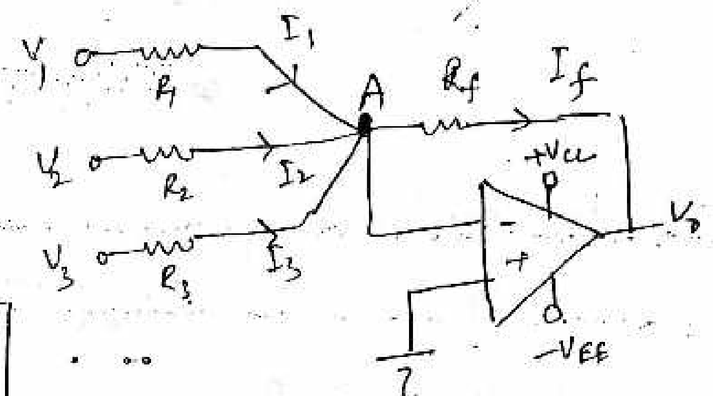
Analysis:-

(i) By virtual short concept,

$V_B = V_A = 0$ (hence $V_A = 0$)

(ii) KCL at Node A.

$I_1 + I_2 + I_3 = I_f$



$$\frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} + \frac{V_3 - 0}{R_3} = \frac{0 - V_0}{R_f}$$

$$\boxed{V_0 = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)}$$

If $R_1 = R_2 = R_3 = R$

$$V_0 = -R_f\left(\frac{V_1}{R} + \frac{V_2}{R} + \frac{V_3}{R}\right) = -\frac{R_f}{R}(V_1 + V_2 + V_3)$$

$$\boxed{V_0 = -\frac{R_f}{R}(V_1 + V_2 + V_3)}$$

If $R_1 = R_2 = R_3 = 3R_f$

$$V_0 = -\frac{R_f}{3R_f}(V_1 + V_2 + V_3)$$

$$\boxed{V_0 = -\left(\frac{V_1 + V_2 + V_3}{3}\right)}$$

Output is average of three input voltages.

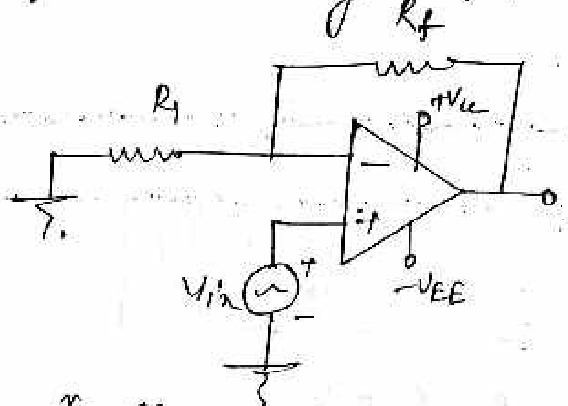
if $R_1 = R_2 = R_3 = R = R_f$

$$\boxed{V_0 = -\frac{R_f}{R_f}(V_1 + V_2 + V_3) = -(V_1 + V_2 + V_3)}$$

(Sum of three voltages.)

VOLTAGE FOLLOWER -

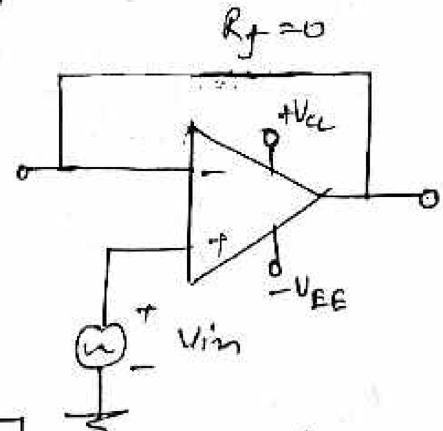
(special case of non-inverting amplifier)



In non-inverting amplifier ckt. is R_1 is removed (open circuited) and R_f is made zero.

output of non-inverting amp.r is

$$V_0 = \left(1 + \frac{R_f}{R_1}\right)V_{in}$$



if $R_f = 0$

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

(Voltage follower)

8. Gain of the amplifier is $\boxed{\frac{V_0}{V_{in}} = 1}$

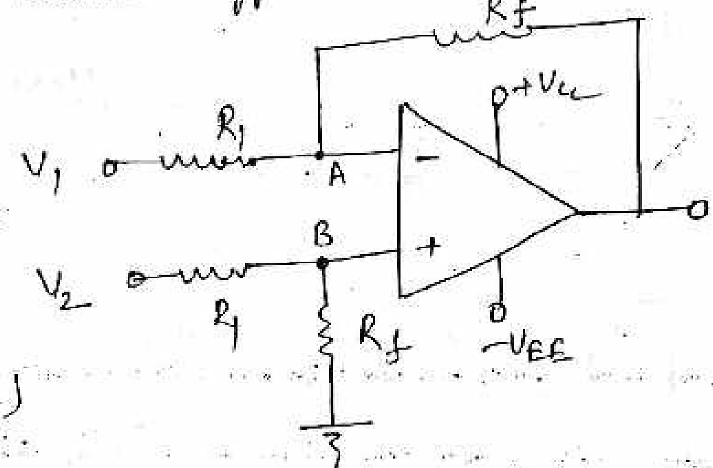
∴ Hence this amplifier is called voltage follower

or unity gain buffer amplifier.

- Output voltage is equal to the input (Both in phase and magnitude)
- Since output exactly follows the input, hence it is called voltage follower.

SUBTRACTOR -

Circuit that amplifies the difference between two input signals is called differential amplifier.



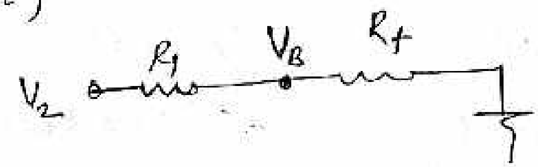
Firstly find V_B.

$$V_B = \frac{R_f}{R_1 + R_f} \cdot V_2$$

(By voltage divider)

As $V_B = V_A$ (Virtual short Concept)

$$V_A = \frac{R_f}{R_1 + R_f} \cdot V_2$$

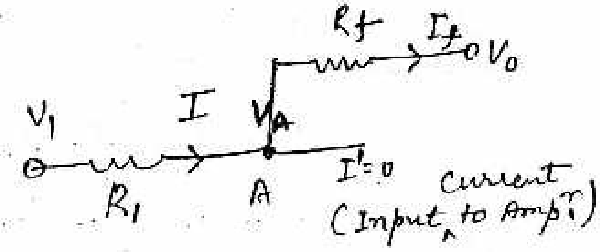


(No current flows into Op-amp).

KCL at Node A:

$$I = I_f$$

$$\frac{V_1 - V_A}{R_1} = \frac{V_A - V_0}{R_f}$$



$$-\frac{V_0}{R_f} = \frac{V_1}{R_1} - \frac{V_A}{R_1} - \frac{V_A}{R_f}$$

$$-\frac{V_0}{R_f} = \frac{V_1}{R_1} - V_A\left(\frac{1}{R_1} + \frac{1}{R_f}\right)$$

$$= \frac{V_1}{R_1} - \frac{\cancel{R_f}}{\cancel{(R_1+R_f)}}\cdot V_2\left(\frac{\cancel{R_1+R_f}}{R_1\cdot \cancel{R_f}}\right)$$

$$-\frac{V_0}{R_f} = \frac{V_1}{R_1} - \frac{1}{R_1}\cdot V_2$$

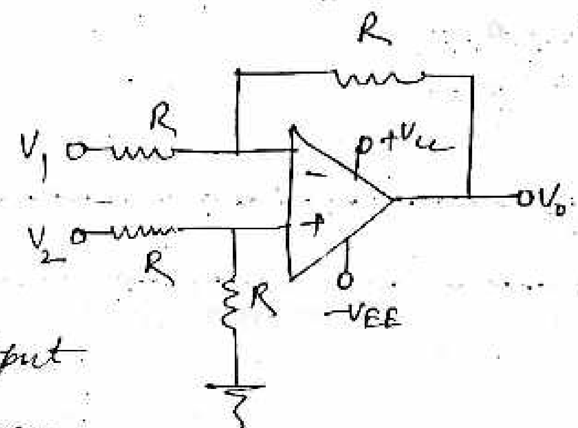
$$V_0 = -\frac{R_f}{R_1}\left(V_1 - V_2\right)$$

$$\boxed{V_0 = \frac{R_f}{R_1}\left(V_2 - V_1\right)}$$

Differential Amplifier.

If $R_f = R_f = R$

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



(Subtractor)

Amplifier is a subtractor now which gives the output exactly the difference between two input voltages.

Differentiator -

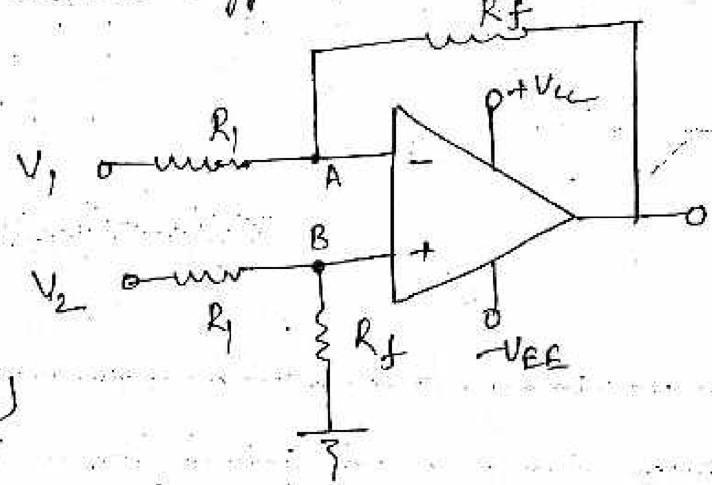
Differentiator gives the amplified signal of differentiation of input signal. Output is proportional to the rate of change of its input signal.

∴ Hence this amplifier is called voltage follower or unity gain buffer amplifier.

- Output voltage is equal to the input (Both in phase and magnitude)
- Since output exactly follows the input, hence it is called voltage follower.

SUBTRACTOR –

Circuit that amplifies the difference between two input signals is called differential amplifier.

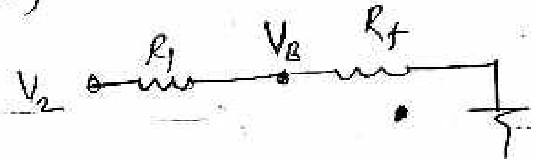


Firstly find V_B.

$$V_B = \frac{R_f}{R_1 + R_f} \cdot V_2$$

(By voltage divider)

As $V_B = V_A$ (Virtual short Concept)

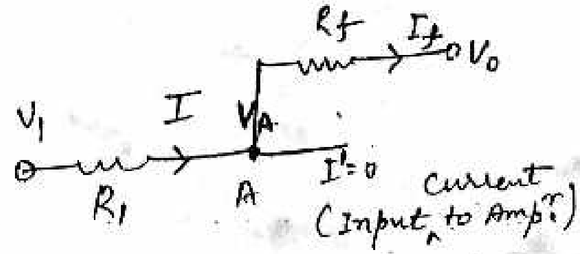


$$V_A = \frac{R_f}{R_1 + R_f} \cdot V_2$$

(No current flows into op-amp).

KCL at Node A.

$$I = I_f$$



$$\frac{V_1 - V_A}{R_1} = \frac{V_A - V_0}{R_f}$$

$$-\frac{V_0}{R_f} = \frac{V_1}{R_1} - \frac{V_A}{R_1} - \frac{V_A}{R_f}$$

$$-\frac{V_0}{R_f} = \frac{V_1}{R_1} - V_A\left(\frac{1}{R_1} + \frac{1}{R_f}\right)$$

$$= \frac{V_1}{R_1} - \frac{\cancel{R_f}}{\cancel{(R_1+R_f)}}\cdot V_2\left(\frac{\cancel{R_1+R_f}}{R_1\cdot\cancel{R_f}}\right)$$

$$-\frac{V_0}{R_f} = \frac{V_1}{R_1} - \frac{1}{R_1}\cdot V_2$$

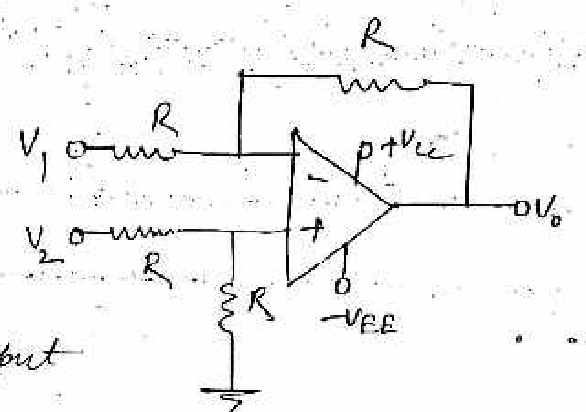
$$V_0 = -\frac{R_f}{R_1}\left(V_1 - V_2\right)$$

$$\boxed{V_0 = \frac{R_f}{R_1}\left(V_2 - V_1\right)}$$

Differential Amplifier.

If $R_f = R_f = R$

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



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B2