

Integrated Circuits

The design of electronic circuits using discrete components is effective for small circuits. When circuit complexity is more, more number of electronic components are required with more number of connections between them. Designing of such circuits may be critical, time consuming and less reliable.

To avoid these problems, all the components with their interconnections are fabricated on the same chip. Such a circuit is called Integrated Circuit (IC).

Classification of Integrated Circuit :-

The integrated circuits can be classified according to mode of operation, process involved, level of integration, package and characteristics.

1. Mode of operation

- Linear

- Digital

2. Process involved

- Monolithic

- Hybrid

- Thick film

- Thin film

3. Level of Integration

- SSI
- MSI
- LSI
- VLSI
- ULSI

4. Package

- DIP
- Flat pack
- Metal can pack
- Ceramic chip carrier pack

5. Characteristics

- Propagation delay
- Noise margin
- Fan-in
- Fan-out
- Power dissipation
- Current / voltage levels
- Figure of merit.

chip size and complexity

Transistor	3-80 gates / chip	1947
SSI	1 - 100 transistors / chip (Logic gates, and flip flops)	1960 - 1965
MSI	30 - 800 gates / chip, 100 - 1k transistors / chip (Counters, Adders & MUX)	1965 - 1970

WSI

900 - 3k gates / chip,
1k - 20k transistors / chip
(8-bit micro processor
RAM, ROM)

VHSI

> 3k gates / chip
20k - 10 lakhs / chip
(16 bit M.P., 32 bit M.P.)

1980 - 1990

UHSI

10^5 - 10^6 transistors / chip
(special purpose process, sensors)

1990 - 2000

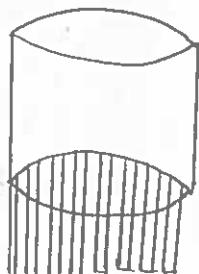
GSI
(Unit scale
Integration)

$> 10^5$ - 10^6 transistors / chip

IC Packages

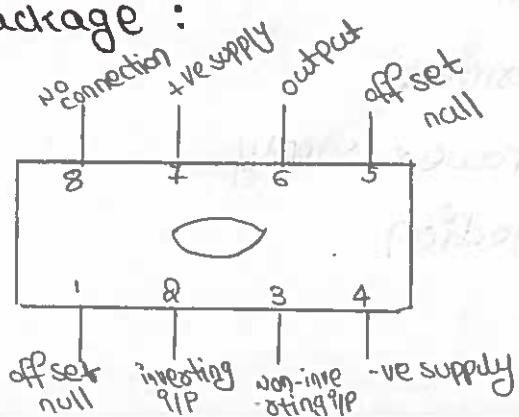
- 1 Metal can package
- 2 Dual in line package
- 3 Flat top package

1. Metal can package :



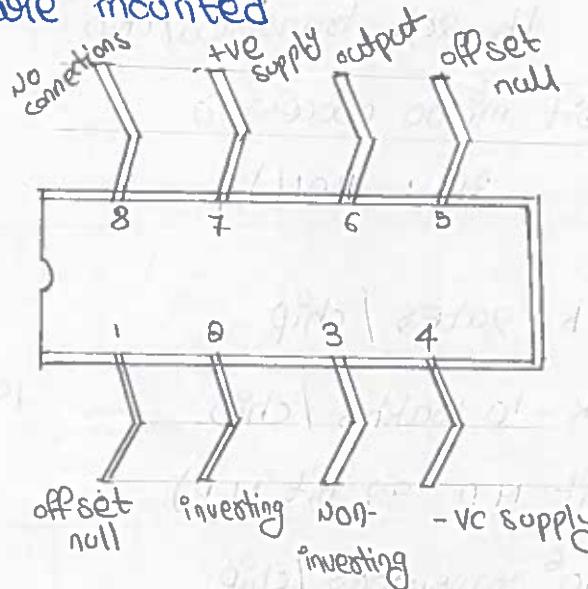
Metal can package

2. Flat top package :



3. Equal inline packages :

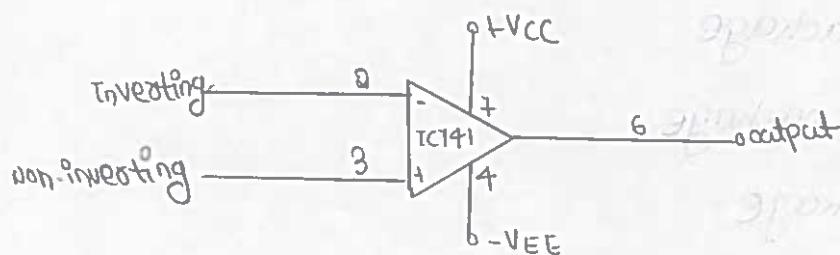
Pins were mounted



Basic information of op-amp :-

The operational amplifier is a high gain differential amplifier. It can do the multiple operations like addition, subtraction, differentiation and Integration.

Symbol of op-amp :-



Pig Description :-

Pin A :- offset null

Pin 2 :- Inverting terminal

Pin 3 :- Non-inverting terminal

Pin 4 :- negative supply terminal

Pin 5 :- offset null

Pin 6 :- output terminal

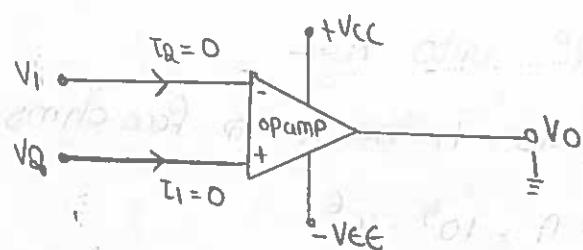
Pin 7:- Positive power supply

Pin 8 :- No connection

Ideal and Practical op-amp

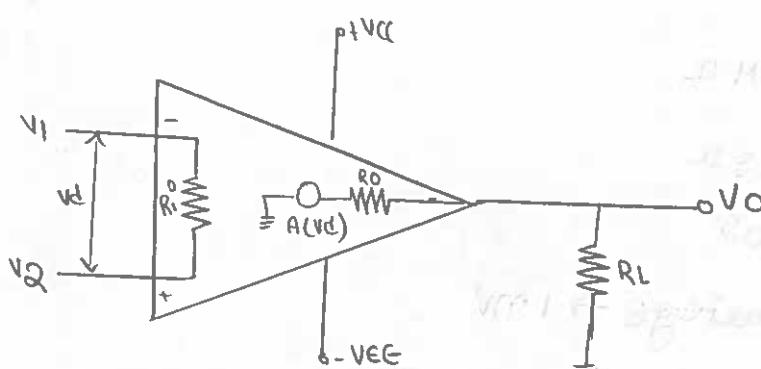
i. Ideal op-amp :-

The below figure shows ideal op amp if it has two input signals v_1 & v_2 applying to non-inverting and inverting terminals respectively.



$$A_{OL} = \infty \text{ [open loop gain]}$$

Equivalent circuit :-



where

R_i^o - Input impedance of a operational amplifier

A_o - output impedance

R_L - load resistance

1) $R_i^o = \infty$

2) $R_o = 0$ (resistance should be minimum)

3) $A = \infty$

4) Band width (B.W) = ∞

5) Slew rate $S = \frac{dV_o}{dt} \mid_{\max} (v/\mu\text{sec})$

Fastness of the op-amp to reach its max value square wave is applicable to the slew rate

6) CMRR (Common mode Rejection Ratio)

$$S = \infty$$

$$\text{CMRR} = \frac{Ad}{Ac} = P$$

$$\text{CMRR in dB} = 20 \log \left| \frac{Ad}{Ac} \right| \text{dB}$$

ii, Practical op-amp

Input impedance R_i = upto $10^12 \Omega$

Output impedance R_o = 1 + maintains few ohms

Gain $A = 10^5 - 10^6$

offset voltage in millivolts

Typical op-amp

$R_p \rightarrow 2M\Omega$

$R_o \rightarrow 75\Omega$

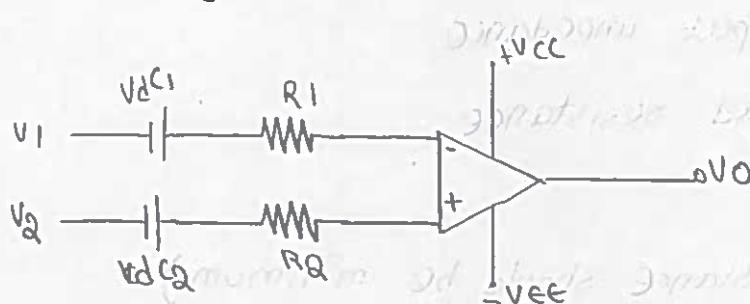
$A \rightarrow 10^5$

offset voltage $\rightarrow 1 \text{ mV}$

slew rate $\rightarrow 0.5 \text{ V}/\mu\text{s}$

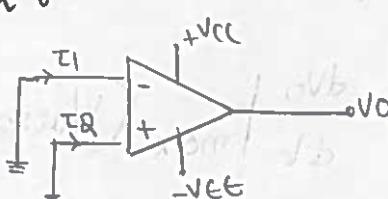
CMRR $\rightarrow 70 - 90 \text{ dB}$

offset voltages :-



$$V_o = V_{dc2} - V_{dc1}$$

offset currents :-



$$I_{io} = |I_1 - I_2|$$

slew rate

$$S = \frac{dV_o}{dA} \Big|_{\text{max}}$$

$$S = V_p \cdot \omega$$

V_p → peak value of the output wave

$$S = V_p \cdot \omega$$

$$= 2\pi f \cdot V_p \text{ (V/sec)}$$

$$S = \frac{2\pi f}{10^5} V_p \text{ (V/μs)}$$

common mode rejection ratio

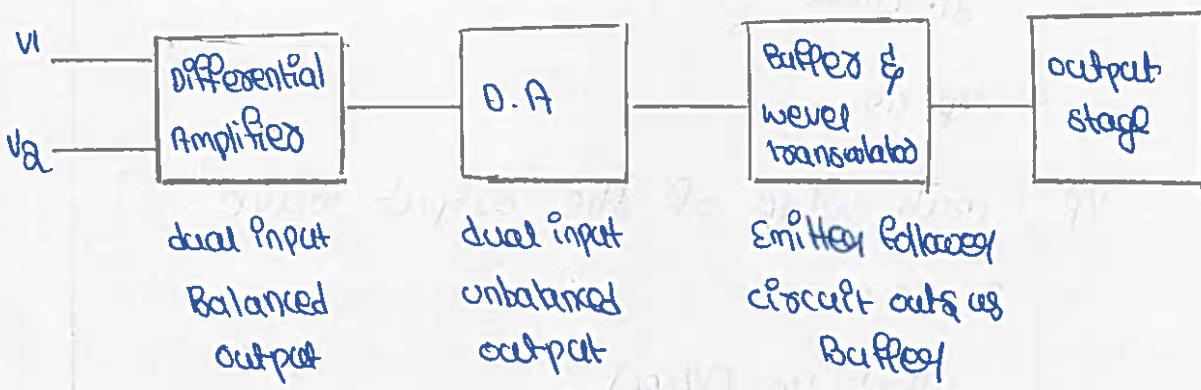
$$\text{CMRR} = \frac{A_d}{A_c}$$

$$A_d = \frac{V_{od}}{V_{id}} \quad A_c = \frac{V_{oc}}{V_{ic}}$$

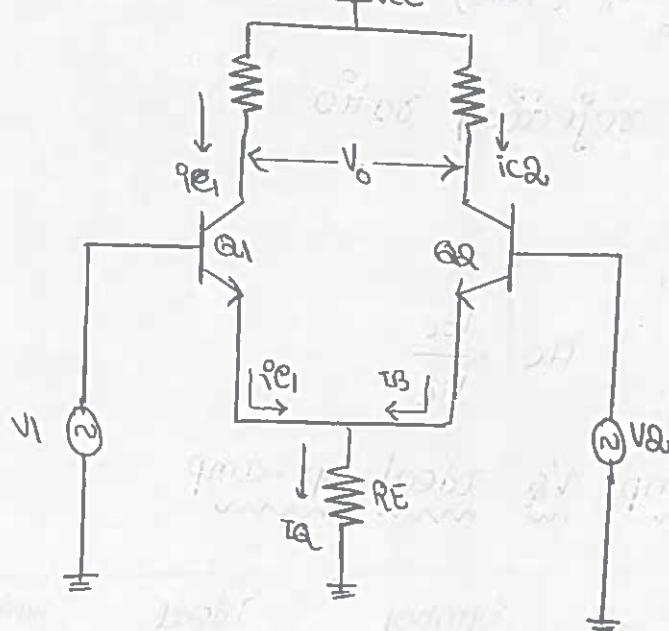
→ Practical op-amp vs Ideal op-amp

Parameter	Symbol	Ideal	Typical op-amp
open loop voltage gain	A_{OL}	infinity	2×10^5
output impedance	Z_{out}	0	75Ω
input impedance	Z_{in}	∞	$2 M\Omega$
input offset current	I_{ios}	0	$20 nA$
input offset voltage	V_{pos}	0	$2 mV$
band width	BW	∞	$1 MHz$
CMRR	P	∞	90dB
slew rate	S	∞	$0.5 V/\mu s$
Input bias current	I_b	0	$80 nA$
Power supply rejection ratio.	$PSRR$	0	$30 dBV$

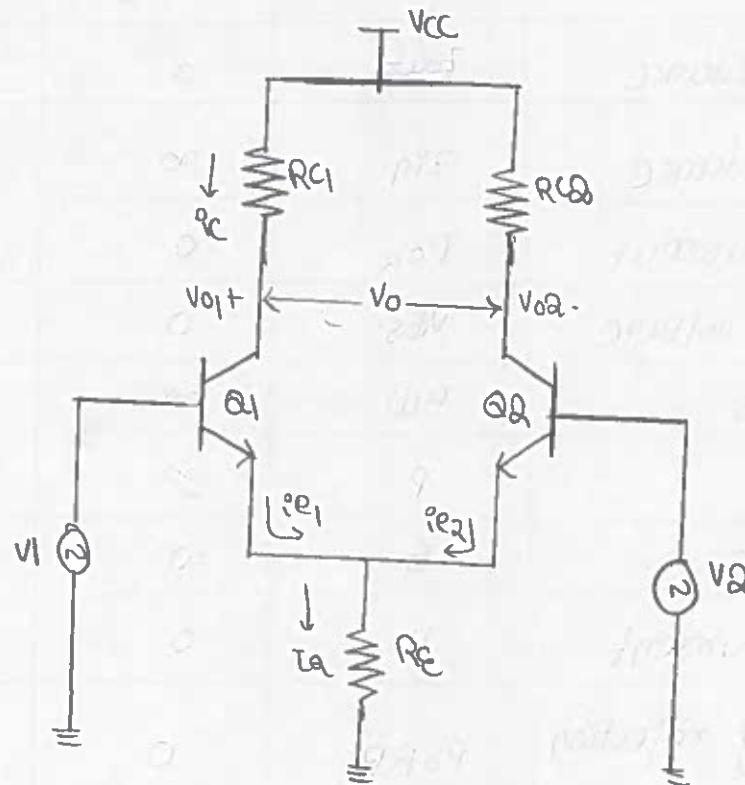
Internal circuits of op-amp



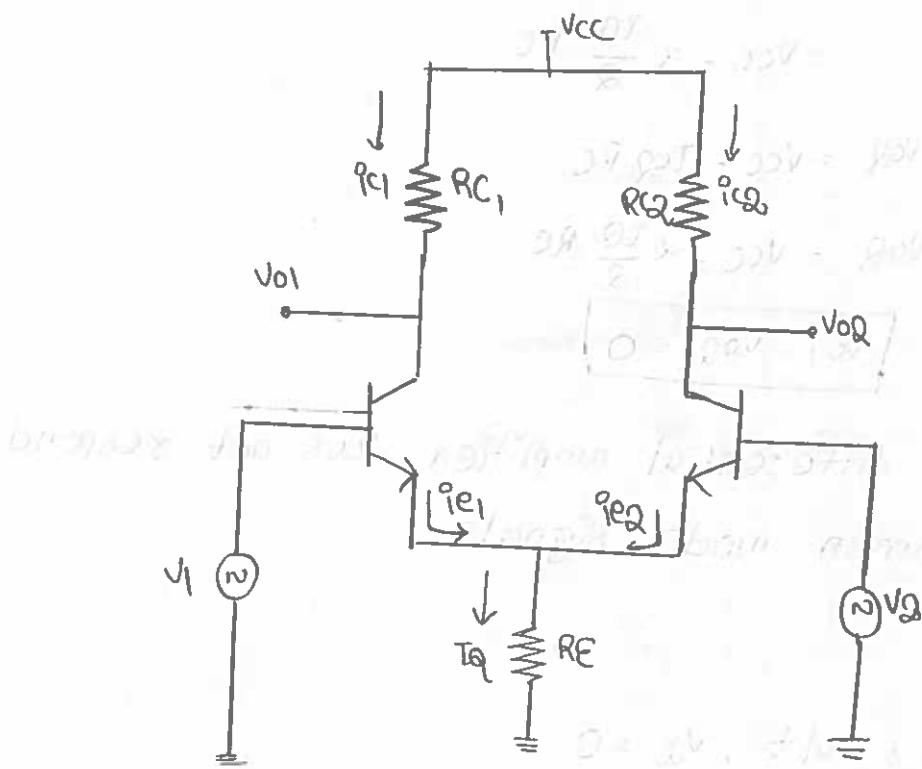
* Differential Amplifier



* Dual input Balanced output

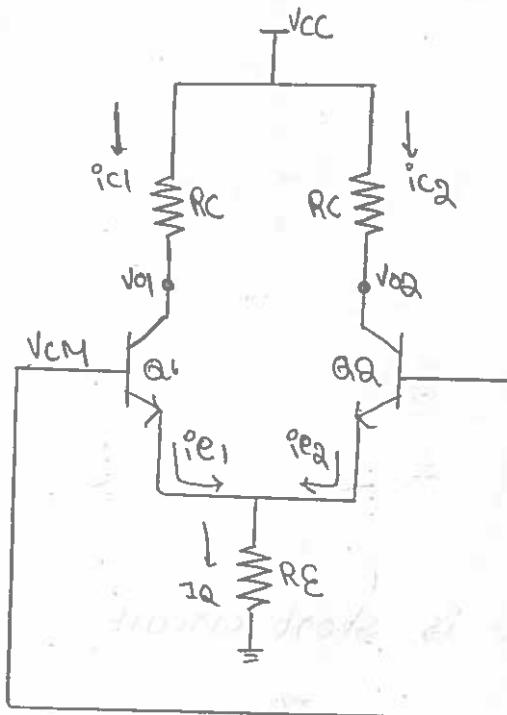


* Dual input unbalanced output



case i :-

If we given common input



$$\tau_{C1} = \tau_{C2} = \frac{\tau_Q}{2}$$

$$\text{wkt } \frac{\tau_C}{\tau_E} = \alpha$$

$$\tau_C = \alpha \tau_E$$

$$\tau_{C1} = \alpha \frac{\tau_Q}{2}$$

$$\tau_{C2} = \alpha \frac{\tau_Q}{2}$$

$$V_{O1} = V_{CC} - I_{C1} R_C$$

$$= V_{CC} - \alpha \frac{I_Q}{2} R_C$$

$$V_{O2} = V_{CC} - I_{C2} R_C$$

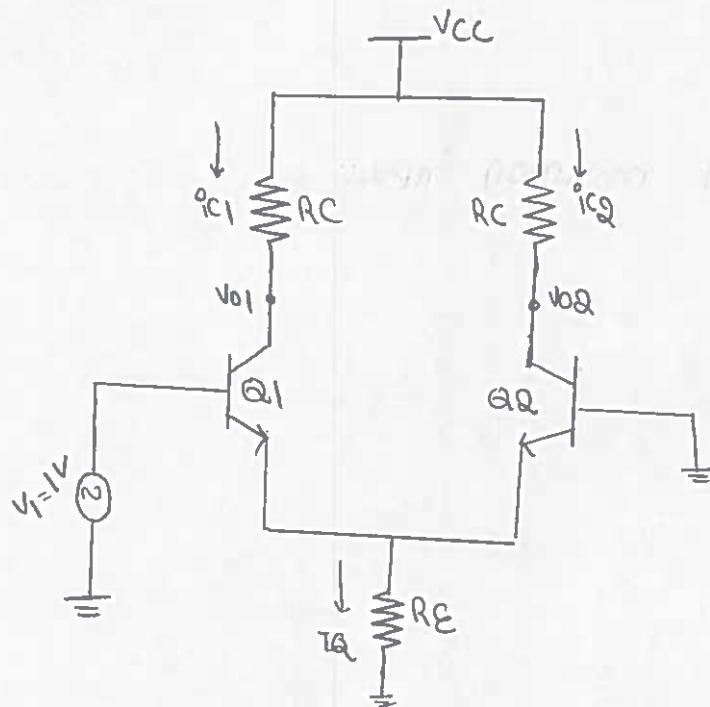
$$V_{O2} = V_{CC} - \alpha \frac{I_Q}{2} R_C$$

$$\boxed{V_{O1} - V_{O2} = 0}$$

The differential amplifier does not respond to the common mode signals.

case ii :-

$$\text{If } V_1 = 1 \text{ Volt}, V_2 = 0$$



$$V_{O2} = V_{CC}$$

Since at Q1 it is short circuit

$$\text{so } V_{O1} = V_{CC} - \alpha \frac{I_Q}{2} R_C$$

at Q2 it is open circuit

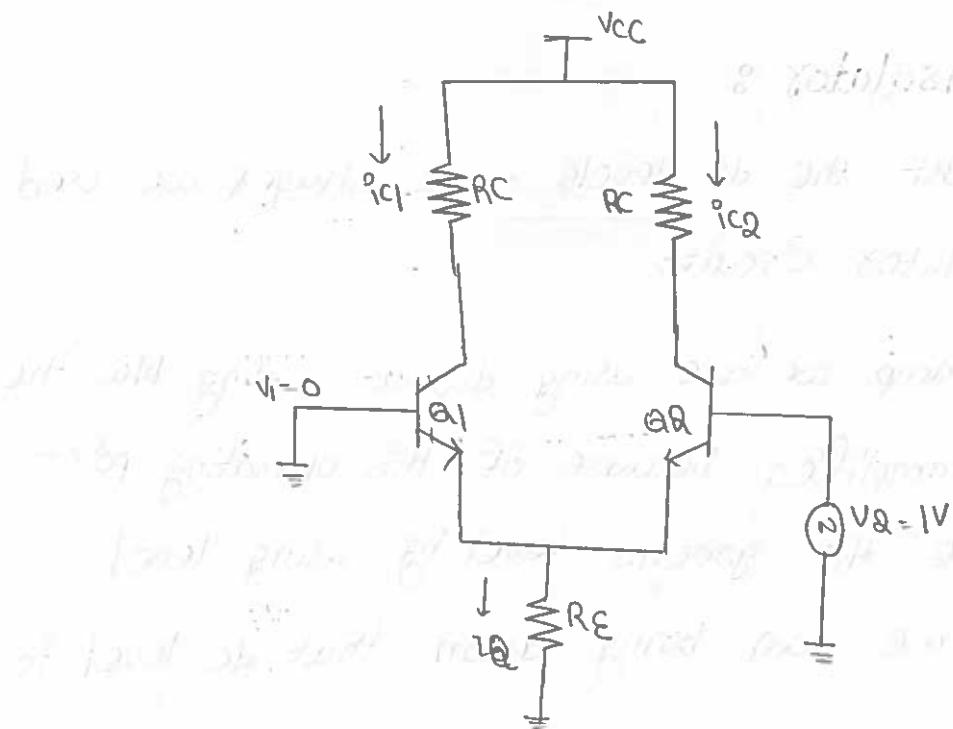
$$\text{so } V_{O2} = V_{CC}$$

$$V_{O1} - V_{O2} = V_{CC} - \alpha \frac{I_Q}{2} R_C - V_{CC}$$

$$= - \alpha \frac{I_Q}{2} R_C$$

case III :-

If $V_1 = 0$, $V_2 = 1$ volt

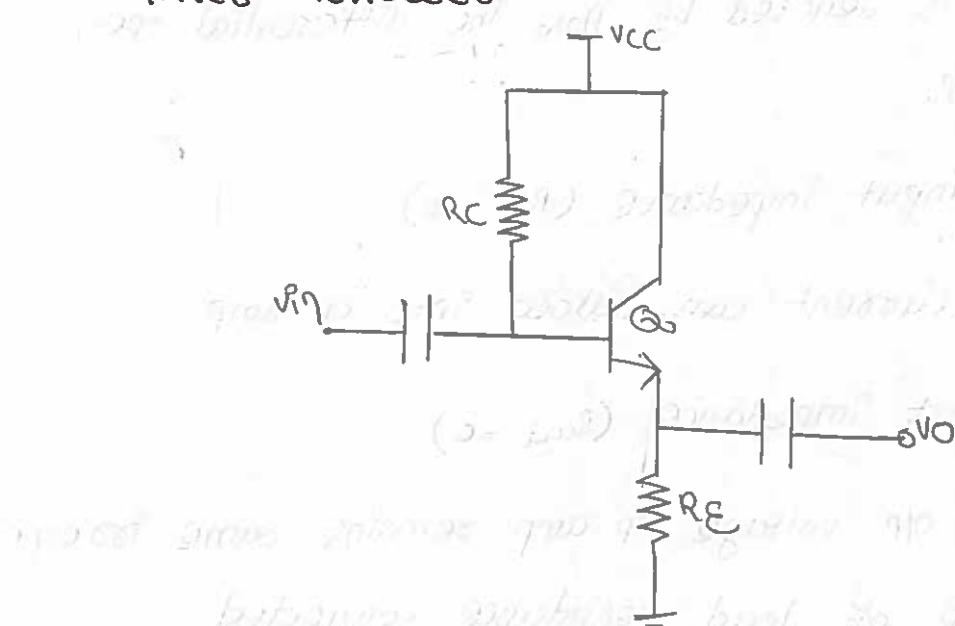


$$V_{O1} = V_{CC},$$

$$V_{O2} = V_{CC} - \alpha \frac{TQ}{2} RC$$

$$\begin{aligned} V_{O1} - V_{O2} &= V_{CC} - V_{CC} + \alpha \frac{TQ}{2} RC \\ &= \alpha \frac{TQ}{2} RC \end{aligned}$$

* Emitter follower circuit



WKT for Si, $V_{BE} = 0.7$ V for i.e., $V_{BE} = 0.3V$

$$V_{in} - V_{BE} = V_O$$

compare to V_{in} & V_O V_{BE} voltages are

Very small $V_{in} = V_o$

so it acts as a Buffer

level Translators :

* To adjust the dc levels or dc voltages we used level translators circuits.

* In op-amp we are using direct coupling b/w the differential amplifier because if this operating point moves above the ground level by using level translators we can bring down that dc level to zero level.

Final stage (Output stage)

It design to provide the low output impedance

Characteristics of op-amp

* Infinity voltage gain ($A_{OL} = \infty$)

It is denoted by A_{OL} . The differential open loop is ' ∞ '.

* Infinity input impedance ($R_{in} = \infty$)

No current can flow into op-amp

* Zero output impedance ($R_{out} = 0$)

The o/p voltage op-amp remains same irrespective value of load resistance connected.

* Zero offset voltage ($V_{ios} = 0$)

It is zero for ideal op-amp. This ensures zero output for zero input signals.

* Infinity bandwidth ($B.W = \infty$).

The gain of op-amp will be constant over the frequency range from '0 to ∞ '. op-amp can amplify DC as well as AC.

* Common Mode Rejection Ratio ($CMRR = \infty$)

Infinity CMRR of op-amp ensures zero mode gain. Due to this common mode noise output voltage is zero.

* Infinity slewrate ($s = \infty$)

Infinity slewrate indicates that output change simultaneously with the change in input voltage.

$$s = \frac{dV_o}{dt} \Big|_{\text{max}}$$

* No effect on temperature

The characteristics of op-amp do not change with temperature.

* Power Supply Rejection Ratio ($PSRR = 0$)

PSRR defined as ratio of change in input offset voltage due to the change in supply voltage keeping the another power supply voltage is constant. It is also called 'Supply Rejection Ratio'.

DC and AC characteristics of operational

Amplifiers :-

→ Input offset voltage

→ Input offset current

- Input Bias current
- Thermal drift.
- An ideal op-amp does not take current or voltage from the source because of input impedance $\infty \text{ ohm}$.
- For practical op-amp it has some currents or voltages delivered from the source to the input terminal of op-amp.
- Here the two input terminals respond differently to the currents or voltages because of mismatching between the transistors.

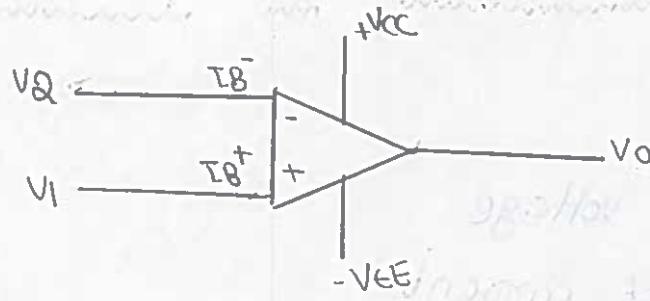
DC characteristics

- Input Bias current
- Input offset current
- Input offset voltage
- Total output offset voltage
- Thermal drift.

i, Input Bias current

* The op-amp input is a differential amplifier which may be made from BJT or FET.

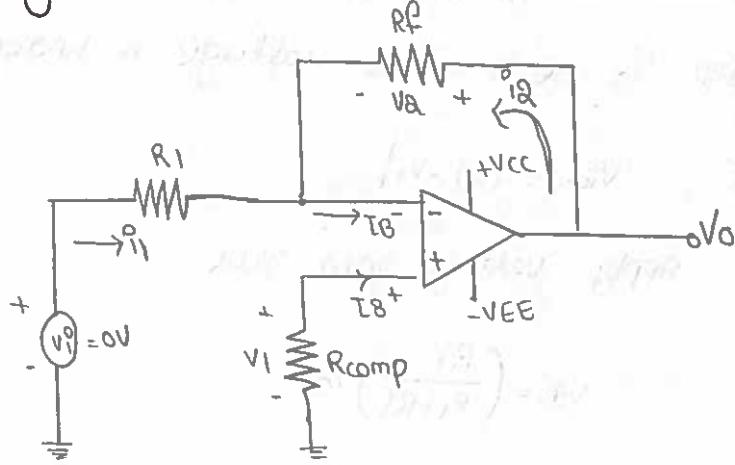
* For practical op-amp the input terminals supply a little bit of DC currents into the operational amplifier because of this the output voltage does not equals to zero.



$$I_B = \frac{I_{B^-} + I_{B^+}}{2}$$

* To provide the input bias current we will add the extra resistor to our op-amp this resistor is known as compensation resistor.

* For inverting op-amp R_{comp}



$$R_{comp} = \frac{R_1 R_F}{R_1 + R_F}$$

R_1 & R_F are parallel with each other i.e. $R_1 \parallel R_F$

* Input offset current

* The bias current compensation will work when the both bias currents I_{B^+} & I_{B^-} are equal. Since the input transistors cannot be made identical

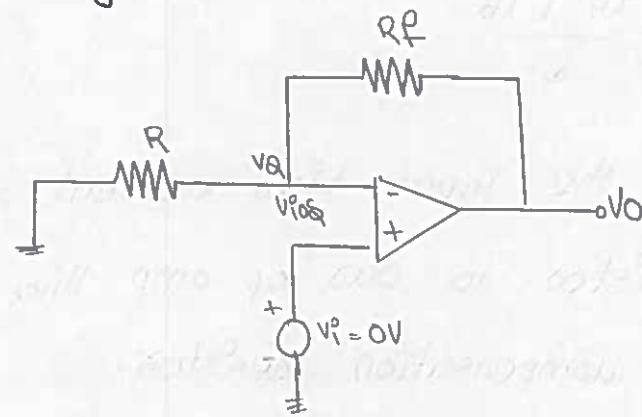
* There will be a some small differences between

I_{B^+} & I_{B^-} . This difference is called as the $\% \text{ offset}$.

$$I_{ios} = |I_{B^+} - I_{B^-}|$$

$$V_o = R_F \cdot I_{ios}$$

3. Input offset voltage :



This small voltage at V_Q terminals to make the output voltage $V_o \neq 0V$. This voltage is known as $^{\circ}\text{IP}$ offset voltage. $V_{\text{ios}} = |V_Q - V_i|$

Apply voltage gain rule

$$V_Q = \left(\frac{R_1}{R_1 + R_F} \right) V_o$$

$$V_o = V_Q \left(\frac{R_1 + R_F}{R_1} \right)$$

$$V_o = V_Q \left(1 + \frac{R_F}{R_1} \right)$$

From equation ①

$$V_{\text{ios}} = V_Q \quad (\because V_i = 0)$$

$$V_o = \left(1 + \frac{R_F}{R_1} \right) V_{\text{ios}}$$

4. Total output offset voltage :

V_{OT} the addition of input offset voltage and input offset current.

$$V_{\text{OT}} = V_o \ ^{\circ}\text{IP} \text{ offset volt} + V_o \ ^{\circ}\text{IP} \text{ offset curr.}$$

$$V_{\text{OT}} = \left(1 + \frac{R_F}{R_1} \right) V_{\text{ios}} + R_F I_{\text{ios}}$$

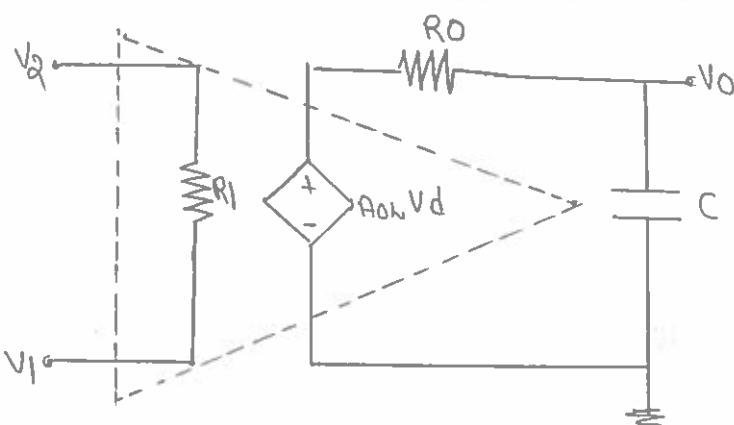
5. Thermal drift :

The op-amp is depends up on the temperature also because of the variation in temperature the input bias current the input offset current and input offset voltage is also changed this variation is called Thermal drift.

AC characteristics

→ Frequency Response of a op-Amp

For ideal op-amp the bandwidth is ∞ and it maintains constant gain over all the frequencies. For practical op-amp at higher frequencies the gain of the op-amp is reduced because of the internal capacitors is called at the output stage of the op-amp.



$$V_o = \frac{X_C}{R_o + X_C} A_{OL} \cdot V_d$$

$$X_C = \frac{1}{j\omega C}$$

$$V_o = \frac{\frac{1}{j\omega C}}{R_o + \frac{1}{j\omega C}} A_{OL} \cdot V_d$$

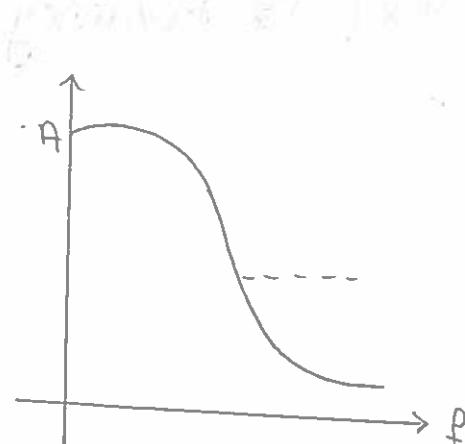
$$= \frac{\frac{1}{j\omega C}}{R_o j\omega C + 1} \times A_{OL} \cdot V_d$$

$$\frac{V_o}{V_d} = \frac{1}{1 + j\omega R_o C} \times A_{OL}$$

$$A = \frac{1}{1 + j2\pi f R_o C} \times A_{OL} \quad [\because f_l = \frac{1}{2\pi R_o C}]$$

$$A = \frac{1}{1 + j(f/f_l)} \times A_{OL}$$

$$|A| = \frac{1}{\sqrt{1 + (f/f_l)^2}} \Rightarrow \phi = -\tan^{-1}(f/f_l)$$



Magnitude

i, $f \ll f_1 \rightarrow A_{OW}$

ii, $f = f_1 \rightarrow A_{OW}/\sqrt{2}$

iii, $f \gg f_1 \rightarrow A_{OW}/f$

Phase

i, $f = f_1$

$$\phi = -\tan^{-1}(1) = -45^\circ \text{ or } -\pi/4$$

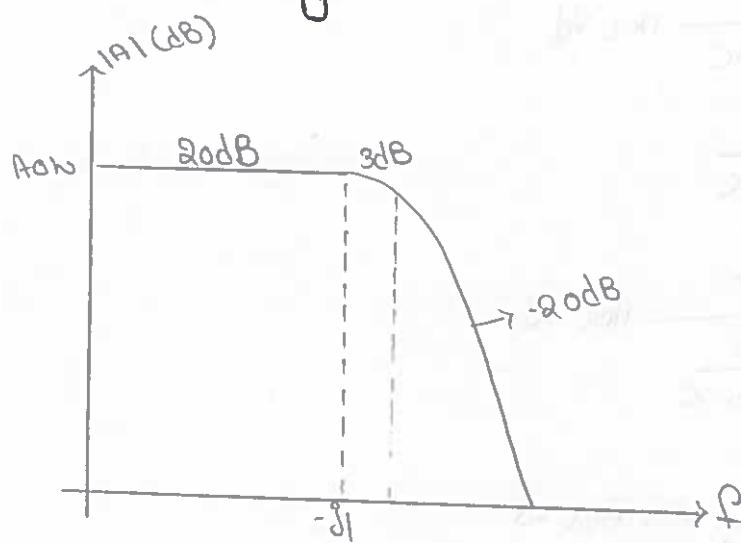
ii, $f \ll f_1$

$$\phi = 0^\circ$$

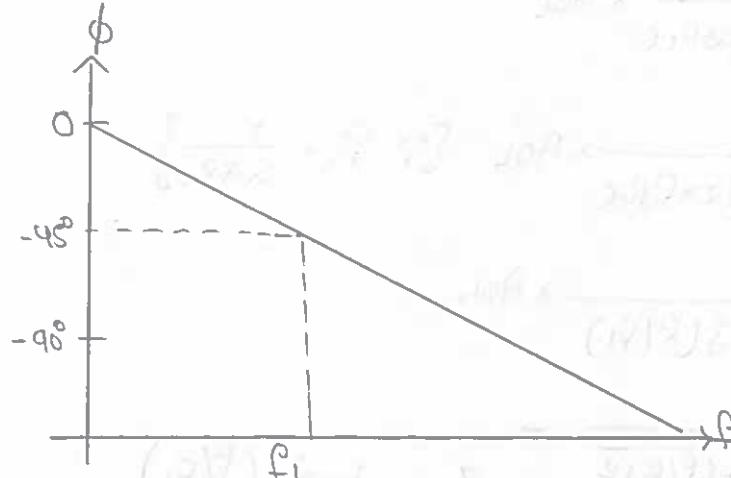
iii, $f \gg f_1$

$$\phi = -\pi/2 \text{ or } -90^\circ$$

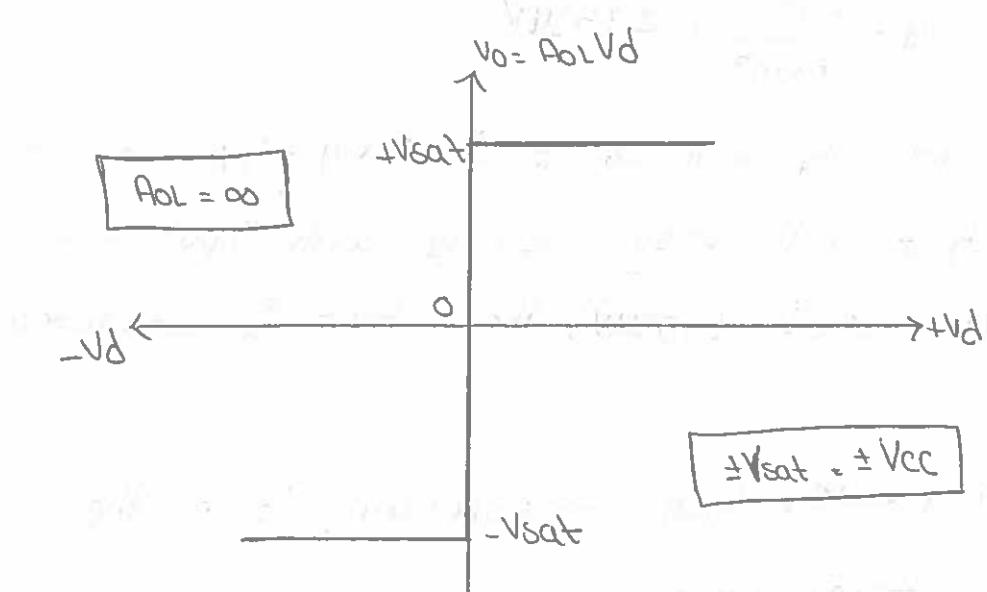
Gain vs Frequency



Phase vs Frequency



\Rightarrow Ideal Voltage Transfer Curve



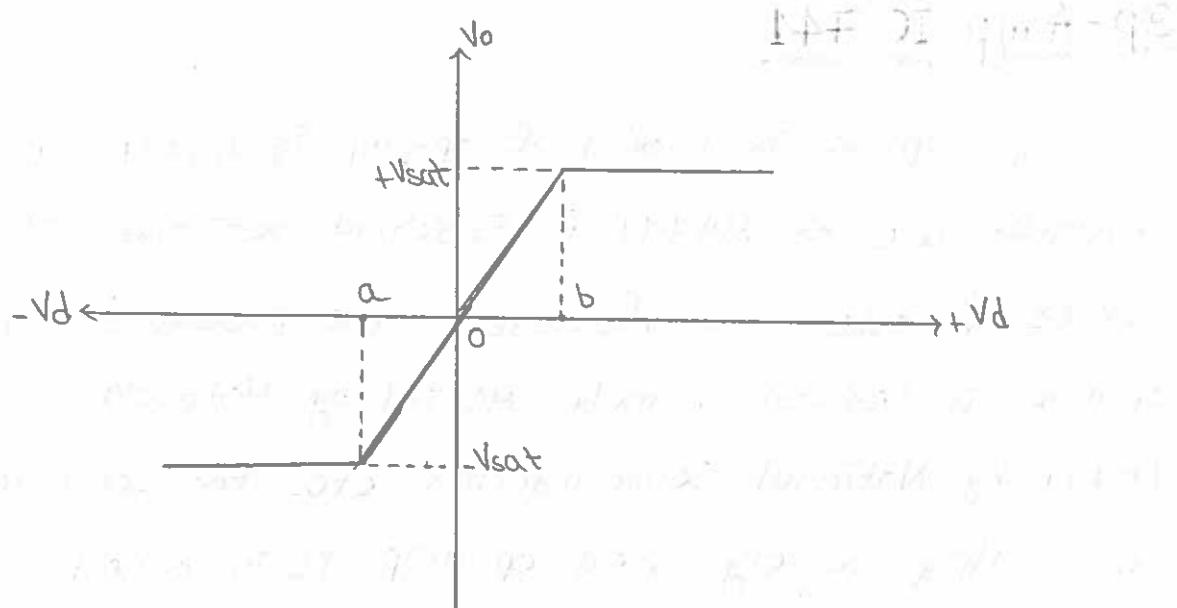
- * Ideally open loop gain of op-amp is ∞ .

$$A_{OL} = \frac{V_o}{V_d} = \infty \text{ i.e., } V_d = \frac{V_o}{\infty} = 0$$

- * Thus for zero input, the output of op-amp is always at saturation level $\pm V_{sat}$ due to infinite gain.

- * Thus ideally range of input for linear operation of the op-amp is zero.

\Rightarrow Practical Voltage Transfer Curve



- * Practically A_{OL} is finite for the op-amp. For op-amp 741C, it is 2×10^5 .

$$\therefore V_o = A_{OL} V_d \text{ i.e., } \pm V_{sat} = 2 \times 10^5 V_d$$

* The saturation voltages are almost $\pm 15V$.

$$V_d = \frac{\pm 15}{2 \times 10^5} = \pm 75 \mu V$$

* Hence practically will V_d is between $-75 \mu V$ and $+75 \mu V$, the output will vary linearly with input. But once V_d exceeds $\pm 75 \mu V$, the output is saturated.

Thus,

i] If V_d is greater than corresponding to b, the output attains $+V_{sat}$.

ii] If V_d is less than corresponding to a, the output attains $-V_{sat}$.

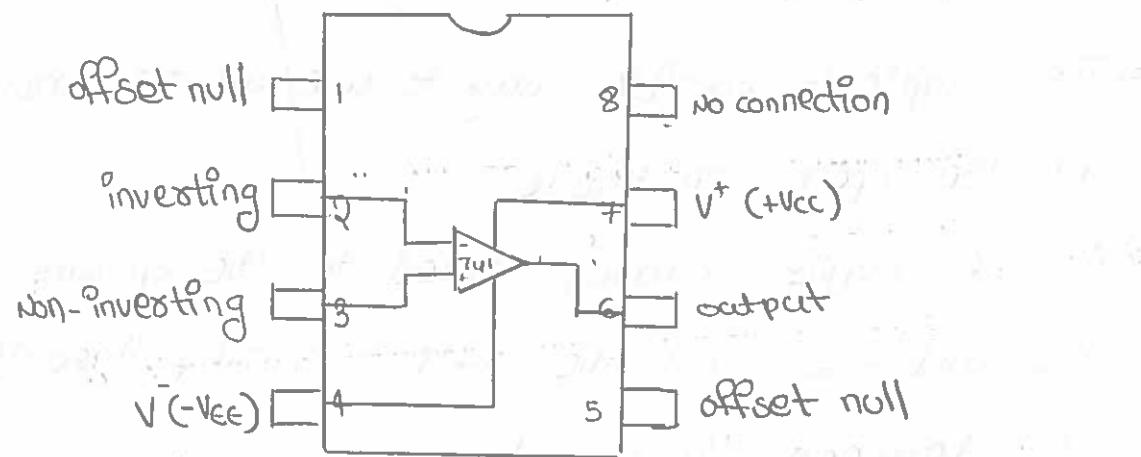
iii] Thus range a-b is input range for which output varies linearly with the input. But as AOL is very high, practically this range is very small.

* Hence op-amp cannot be used in open loop mode for linear applications.

Op-Amp IC 741

→ A very popular IC version of op-amp is MA741. The manufacturer of MA741 is Fairchild Semiconductor.

→ Number of other manufacturers also produced 741 op-amp IC version namely MC1741 by Motorola, LH741 by National Semiconductor etc. For convenience, this widely used op-amp IC is called simply IC741 op-amp dropping the prefixes.



Pin diagram of IC 741 op-amp

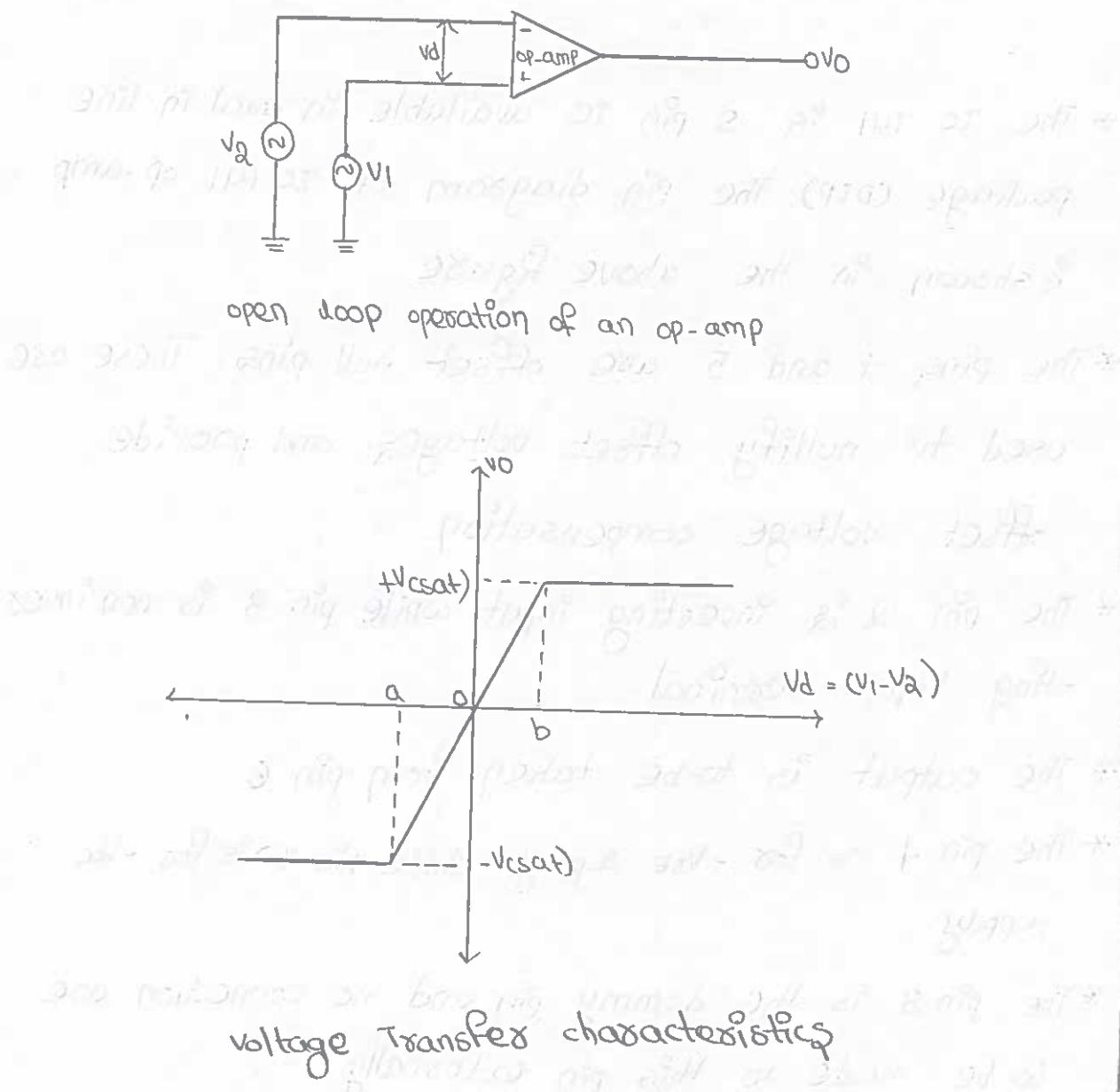
- * The IC 741 is a 8 pin IC available in dual in line package (DIP). The pin diagram of IC 741 op-amp is shown in the above figure.
- * The pins 1 and 5 are offset null pins. These are used to nullify offset voltages and provide offset voltage compensation.
- * The pin 2 is inverting input while pin 3 is non inverting input terminal.
- * The output is to be taken from pin 6.
- * The pin 4 is for -V_{EE} supply while pin 7 is for +V_{CC} supply.
- * The pin 8 is the dummy pin and no connection are to be made to this pin externally.

Features of IC 741

- i. no frequency compensation required.
- ii. short circuit protection provided.
- iii. no latch up.
- iv. large common mode and differential voltage range.
- v. offset voltage null capability.

Op-amp in open loop Mode :-

- ⇒ The simplest possible way to use an op-amp is in the open loop mode.
- ⇒ The d.c supply voltages applied to the op-amp are V_{CC} and $-V_{EE}$ and the output varies linearly only between V_{CC} and $-V_{EE}$.



Open Loop Gain (A_{OL}) :-

The open loop gain (A_{OL}) is very large either its positive saturation voltage or negative saturation voltage for small value of V_d .

This range is very small and practically due to high open loop gain. The op-amp either shows $+V_{sat}$ or $-V_{sat}$. This indicates inability of op-amp to work as linear in small signal amplifiers in open loop model.

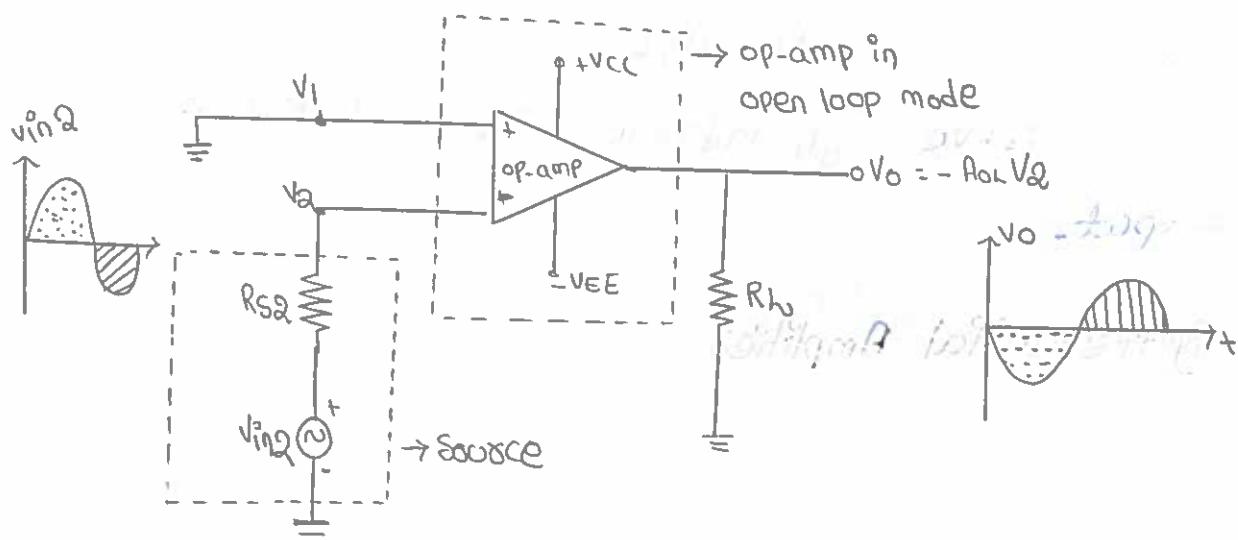
Open loop Configurations of op-AMP :-

These are two types

i. Inverting amplifiers

ii. Non-inverting amplifiers

i. Inverting Amplifiers



open loop Inverting Amplifier

R_{g2} is very small

$$V_2 = V_{in2} \text{ & } V_1 = 0$$

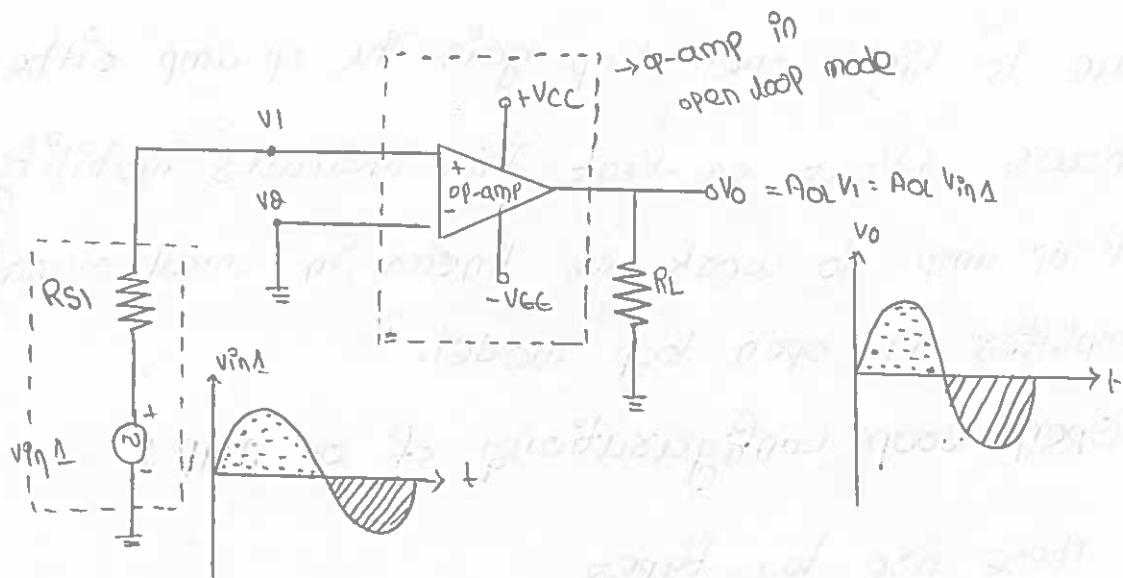
$$V_O = A_{OL} (V_1 - V_2)$$

$$= A_{OL} (0 - V_{in2})$$

$$V_O = -A_{OL} V_{in2}$$

\therefore -ve sign indicates the phase shift of 180° at its output

ii, Non-Inverting Amplifiers



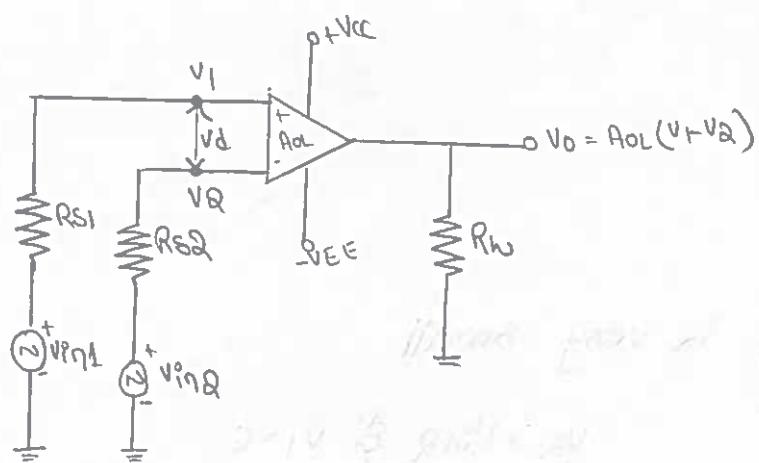
open loop non-inverting amplifiers

R_{SI} is very small $V_1 = V_{in1}$ & $V_Q = 0$

$$\begin{aligned} VO &= AOL(V_1 - V_Q) \\ &= AOL(V_{in1} - 0) \\ &= +AOL V_{in1} \end{aligned}$$

$\therefore +V_Q$ sign indicates the no of shift at its output.

Differential Amplifiers



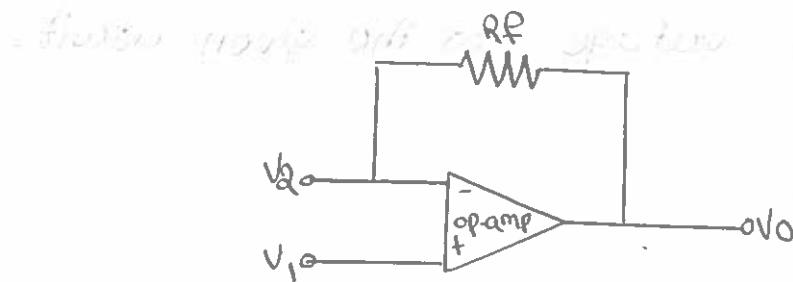
open loop differential amplifier

As op-amp amplifies the difference voltage we can write

$$\begin{aligned} VO &= AOL V_d = AOL(V_1 - V_d) \\ &= AOL(V_{in1} - V_{in2}) \end{aligned}$$

Closed loop configuration of op-amp :-

- * The utility of op-amp increases considerably if it is used in a closed loop mode.
- * The closed loop mode is possible using feedback. The feedback allows to feed some part of the output back to the input.



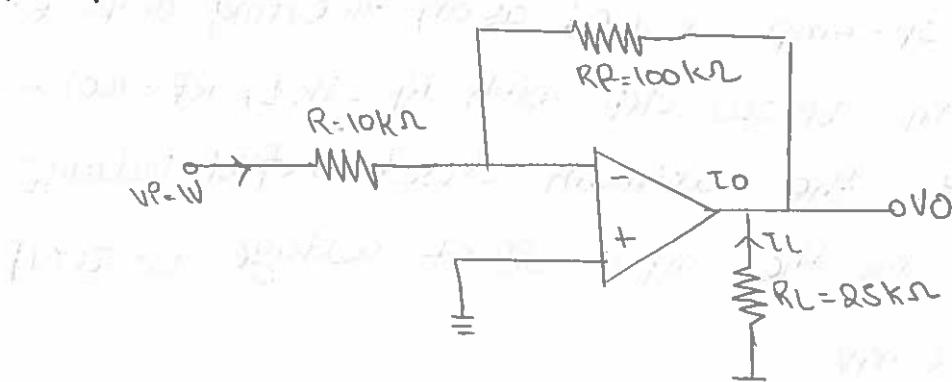
op-amp with negative feedback

- * The negative feedback is possible by adding a resistor. This resistor is called feedback resistor.
- * The feedback is said to be negative as the feedback resistor connects the output to the inverting input terminal.
- * The gain resulting with feedback is called closed loop gain of the op-amp.

Problems 8

If for the given circuit calculate η_{I_1} , η_{V_o} , η_{I_L}

(iv) Total current I_o into the pin.



$$\text{QJ } I_1 = \frac{V_i}{R_1} = \frac{1}{10 \times 10^3} = 0.1 \text{ mA}$$

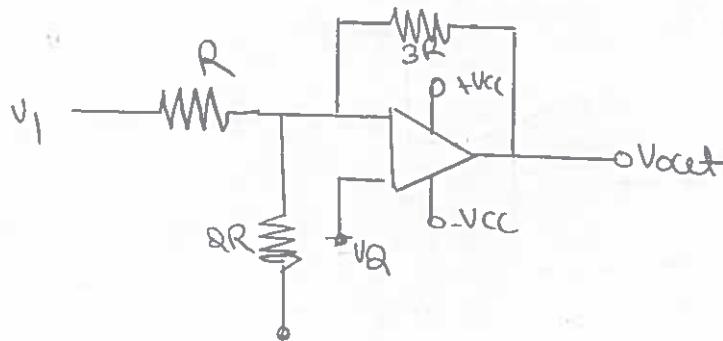
$$\text{QJ } \frac{V_o}{V_{in}} = -\frac{R_F}{R_1} \Rightarrow V_o = \frac{-R_F \cdot V_{in}}{R_1} = \frac{-(400 \times 10^3)}{10 \times 10^3} \times 1$$

$$V_o = -10 \text{ V}$$

$$\text{QJ } I_L = \frac{V_o}{R_L} = \frac{10}{25 \times 10^3} = 0.4 \text{ mA}$$

$$\text{QJ } I_o = I_1 + I_L = (0.1 + 0.4) \text{ mA} = 0.5 \text{ mA}$$

QJ Find the output voltage for the given circuit.



Differential Amplifier

$$V_o = A_1 V_1 + A_2 V_2$$

$$V_o = -3V_1 + 11V_2$$

$$AOM = \frac{A_1 - A_2}{2} = \frac{-3 - 11}{2} = -\frac{14}{2}$$

$$ACM = A_1 + A_2$$

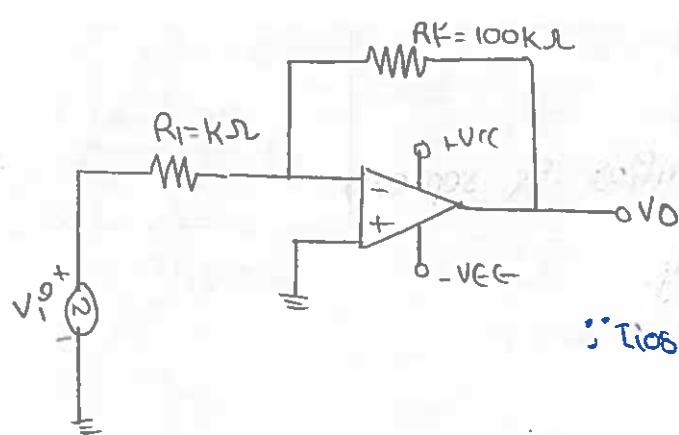
$$= -3 + 11 = \frac{-6 + 11}{2} = \frac{5}{2}$$

$$CMRR = \frac{AOM}{ACM}$$

$$= \frac{-14/4}{5/2} = \frac{-14}{10} = -1.4$$

QJ A 741 op-Amp is used as an inverting amplifier shown in below ckt with $R_1 = 1k\Omega$, $R_F = 100k\Omega$, what is the maximum offset output voltage caused by the input offset voltage for 741

$$V_{ios} = 6 \text{ mV}$$



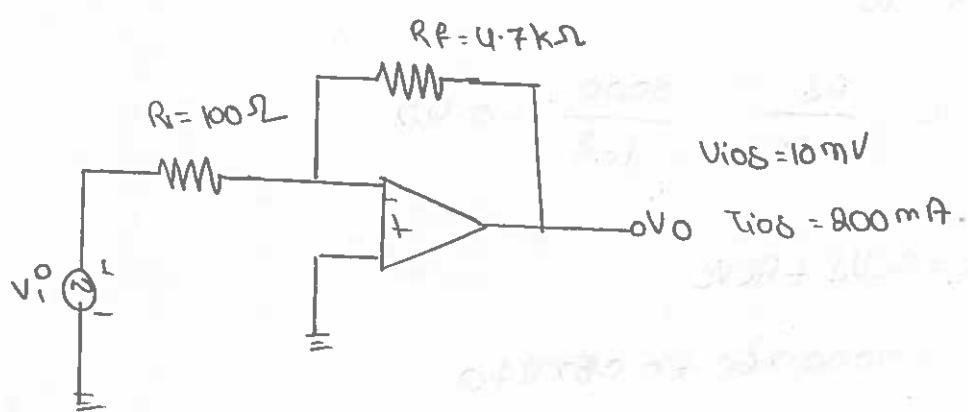
$$V_{OT} = V_O(V_{IO}) + V_O(T_{IO})$$

$$V_O = \left(1 + \frac{R_F}{R_i}\right) V_{IO} \quad , \quad V_O = R_F T_{IO}$$

$$= \left(1 + \frac{R_F}{R_i}\right) 6 \times 10^{-3} + R_F (200 \times 10^{-9})$$

$$= \left(1 + \frac{100 \times 10^3}{1 \times 10^3}\right) 6 \times 10^{-3} + 100 \times 10^3 (200 \times 10^{-9})$$

$$\boxed{V_O = 0.626 \text{ V.}}$$



$$V_{OT} = \left(1 + \frac{R_F}{R_i}\right) 10 \times 10^{-3} + R_F (200 \times 10^{-9})$$

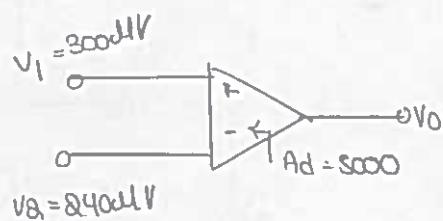
$$= \left(1 + \frac{4.7 \times 10^3}{100}\right) 10 \times 10^{-3} + 4.7 \times 10^3 (200 \times 10^{-9})$$

$$\boxed{V_O = 40.4 \text{ V}}$$

- Q) Determine the output voltage of a differential amplifier for the input voltage of 300 mV and 240 mV. The differential gain of the amplifier is 5000 and the value of the CMRR is i) 100 and ii) 10⁵

Sell

The differential amplifier is represented as shown in fig.



i) CMRR = 100

$$V_d = V_1 - V_2 = 300 - 240 = 60 \text{ mV}$$

$$V_c = \frac{V_1 + V_2}{2} = \frac{300 + 240}{2} = 270 \text{ mV}$$

$$\text{CMRR} = \frac{Ad}{A_c} \text{ i.e., } 100 = \frac{5000}{A_c} \text{ i.e., } A_c = 50$$

$$\therefore V_O = AdV_d + A_cV_c$$

$$= 5000 \times 60 + 50 \times 270$$

$$= 300000 + 1350 = 300135 \text{ mV} = 300.135 \text{ mV}$$

ii) CMRR = 10^5

$$\therefore A_c = \frac{Ad}{\text{CMRR}} = \frac{5000}{10^5} = 0.05$$

$$\therefore V_O = AdV_d + A_cV_c$$

$$= 5000 \times 60 + 0.05 \times 270$$

$$= 300013.5 \text{ mV} = 300.0135 \text{ mV}$$

Ideally A_c must be 20010 and output should be only AdV_d which is $5000 \times 60 \times 10^{-6}$ i.e., 300 mV.