

Date: 29/1/19

OPERATIONAL AMPLIFIER

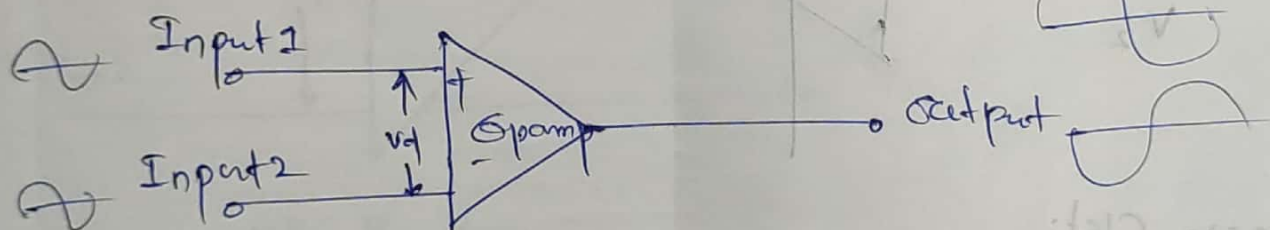
(Mod-5)

Operational amplifier is also known as Mathematical and arithmetical amplifier. As it performs operation like differentiation, Integration, Summation, Inversion, Non-inversion etc.

Opamp is a device having very high gain differential amplifier with a high input impedance (typically in $M\Omega$) and low output impedance.

NOTE: The Opamp has two inputs and one output.

Symbol:



i/p 1 = V_1 = Non inverting i/p

i/p 2 = V_2 = Inverting i/p

$$V_{in} \text{ or } V_d = V_1 - V_2$$

$$V_{out} = A_v V_{in} = A_v V_d$$

$$= A_v (V_1 - V_2)$$

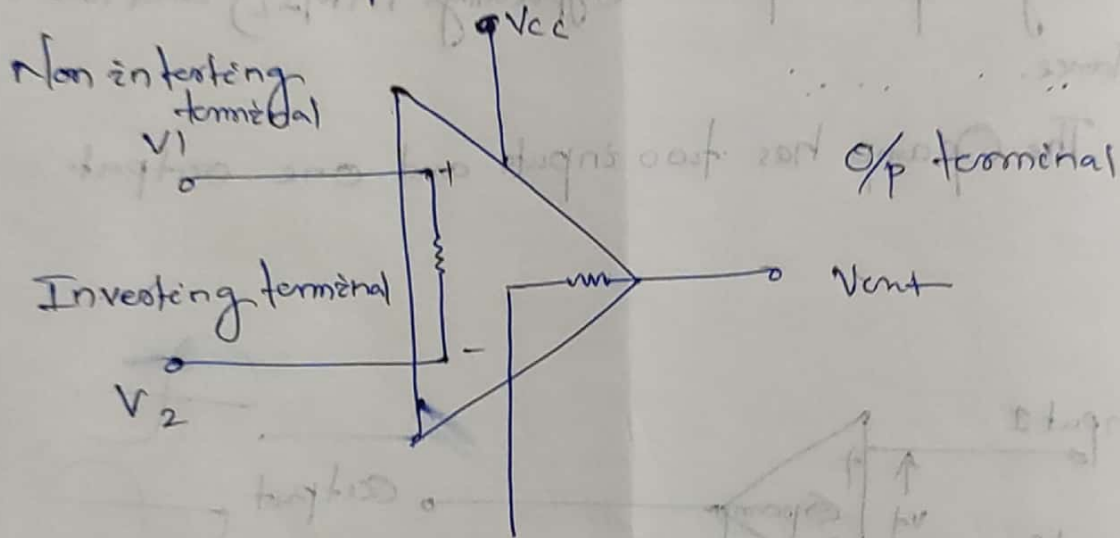
Characteristics of OPAMP:

1. It has high i/p impedance ($\approx \infty$)
2. low o/p impedance (≈ 0)
3. It can amplify dc as well as ac i/p signal
4. It has high band width ($\approx \infty$)

5. It has high value of differential gain.
6. It has high CMRR (Common mode Rejection Ratio)
7. It has high slew Rate.
8. It has stable ϕ/p voltage.

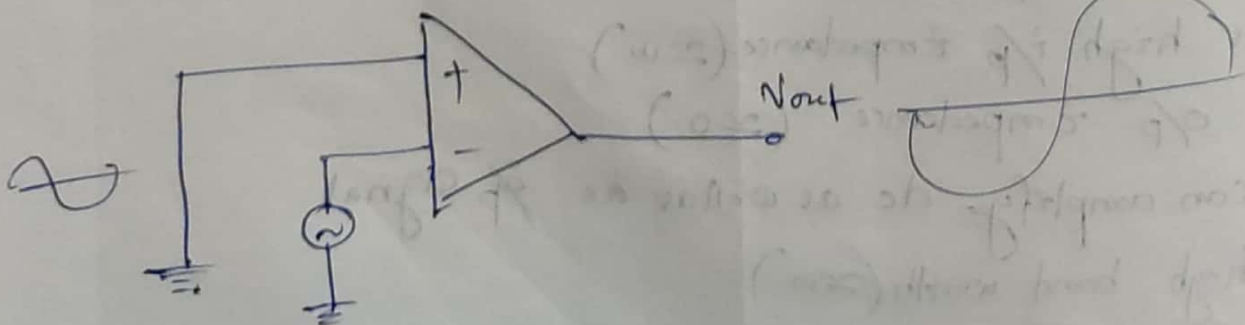
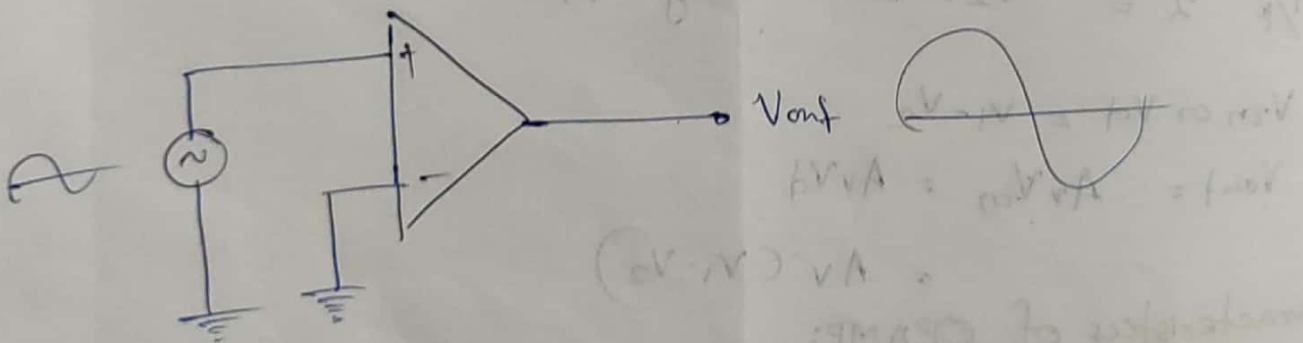
Eqv. ckt of OPAMP:

Eqv. ckt: Any Electrical parameter represented by resistance, inductance, capacitance.

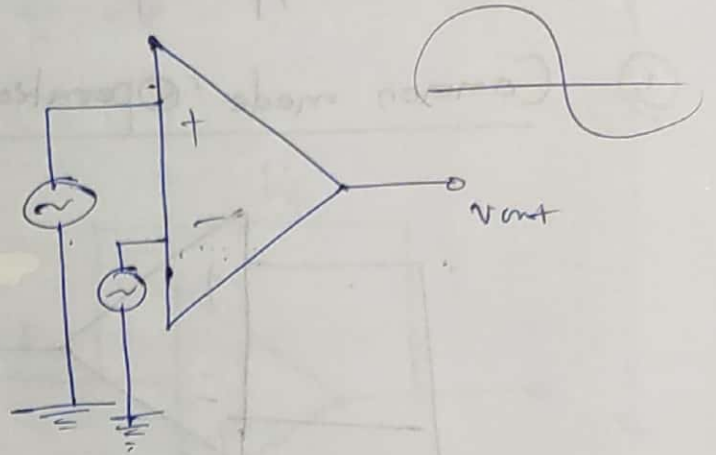
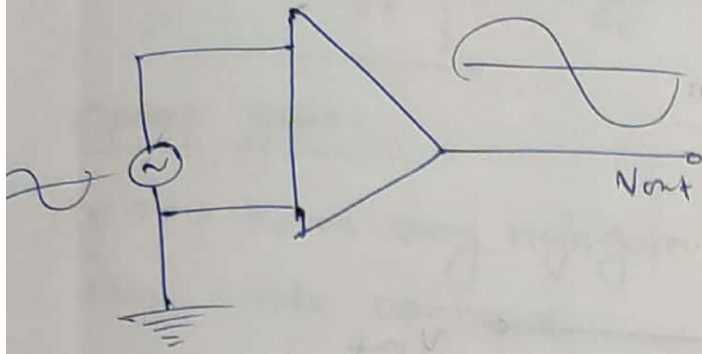


Basic ckt:

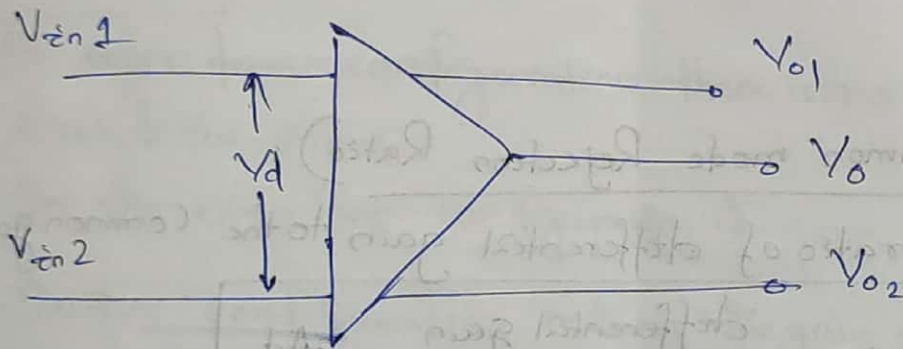
① Single Ended ϕ/p :



② Double ended i/p (Differential Operation)



Double Ended Output:



$$V_d = V_1 - V_2$$

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

V_c = Common mode output voltage.

$$A_{V(e)} = \frac{V_{02}}{V_c}$$

$$V_{02} = A_{V(e)} V_c$$

$$A_{V(d)} = \frac{V_{01}}{V_d}$$

$$V_{01} = A_{V(d)} V_d$$

Here, V_{01} is O/p due to differential i/p

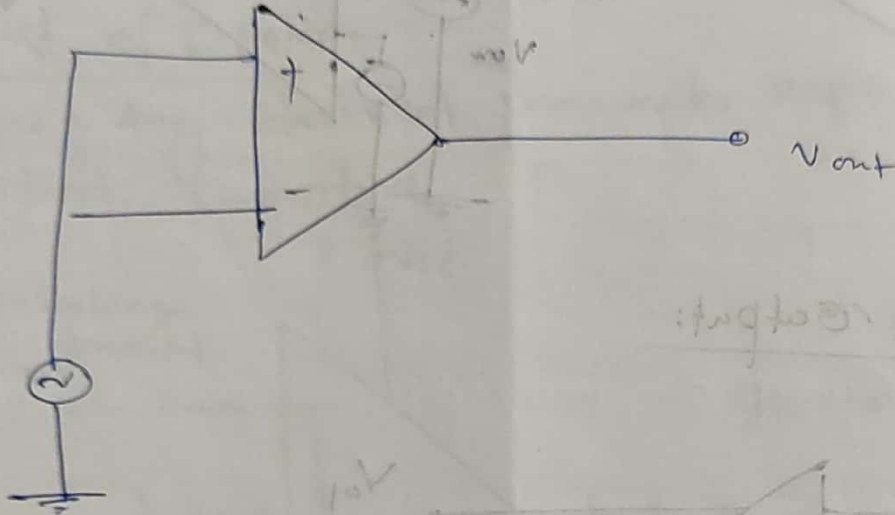
V_{02} is O/p due to common i/p.

$$\begin{aligned} V_{out} &= V_{01} + V_{02} \\ &= A_{V(d)} V_d + A_{V(e)} V_c \end{aligned}$$

Common mode Signal:

When same e/p signal are applied to the both e/p.

① Common mode Operations:



② CMRR (Common mode Rejection Ratio):

CMRR is the ratio of differential gain to the Common gain.

i.e.
$$\text{CMRR} = \frac{\text{differential gain}}{\text{Common gain}} = \frac{A_d}{A_c}$$

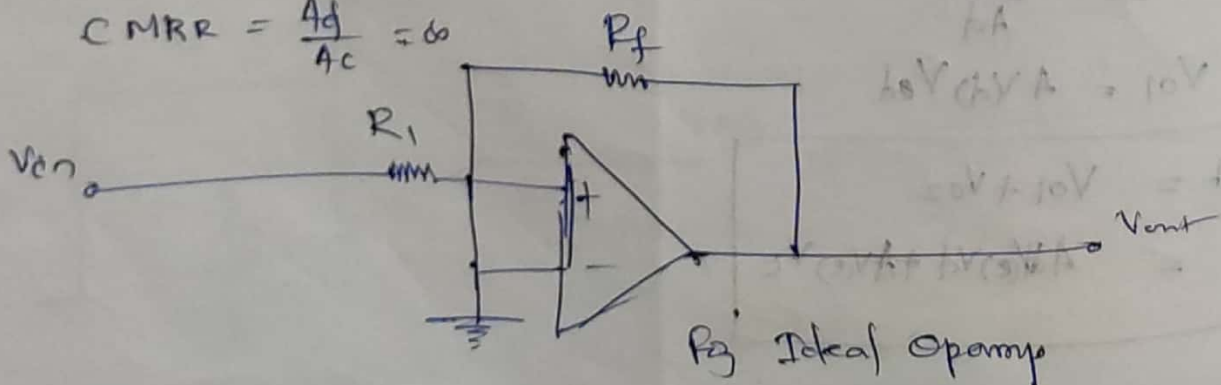
$$\text{CMRR (dB)} = 20 \log_{10} \left(\frac{A_d}{A_c} \right)$$

③ Ideal Case of Opamp: (Ideal Opamp)

$$\text{CMRR} \approx \infty$$

$$A_c \approx 0$$

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



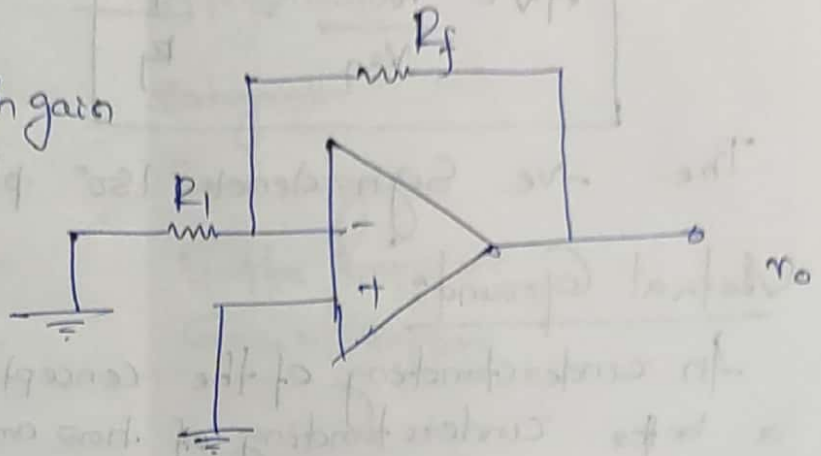
④ Opamp Gain:

$$A_v = \frac{V_o}{V_i} = \frac{A_d}{A_c} + \frac{v}{0} = \infty$$

Opamp gain:

Opamp have very high gain they can be connected

- * Open loop
- * Closed loop,



Open loop:

It refers to a configuration where there is no feedback from output back to the input.

In the open loop configuration, the gain can be exceed 10,000.

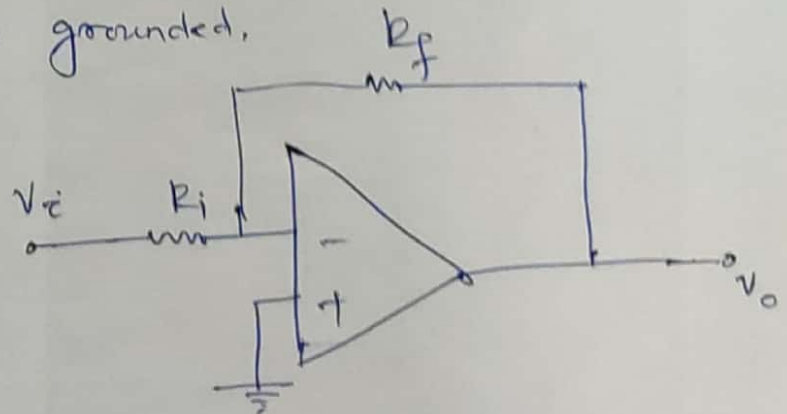
In this configuration reduces the gain, in order to control the gain of an Opamp it must have feedback. This feedback is +ve feedback. -ve feedback reduces gain and improves many characteristics of Opamp.

Inverting Opamp:

The signal i/p is applied to the inverting i/p (-ve i/p).

The non inverting i/p is grounded.

The resistor, R_f is the feedback resistor it is connected from the output to the -ve input. This is -ve feedback.



Inverting Opamp Gain:

Gain can be determined from external resistors R_f and R_i

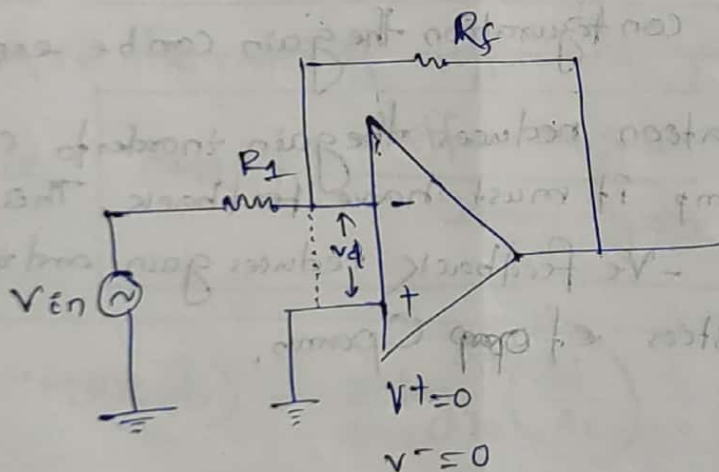
$$A_v = \frac{V_o}{V_{in}} = -\frac{R_f}{R_i}$$

The -ve sign denotes 180° phase shift betⁿ i/p & o/p.

Virtual Ground:

An understanding of the concept of virtual ground provides a better understanding of how an opamp operates.

The noninverting i/p. pin at ground, the inverting is also 0V for an ac signal.



Let, $A_{OL} = 10^6$

$$V_{out} = A \times v_d$$

$$V_{out} = 10V \text{ (let)}$$

$$10 = 10^6 \times v_d$$

$$v_d = 10 \mu V$$

$$v^+ - v^- = 10 \mu V$$

$$\frac{v^+ - v^- \approx 0}{|v^+ = v^-|}$$

Application of Opamp:

- ① Opamp acts as an inverting amplifier.
- ② " " noninverting amplifier
- ③ " " differentiator
- ④ " " integrator
- ⑤ " " Summing
- ⑥ " " Buffer Amplifier
- ⑦ " " Gain Multiplier

① Inverting Amplifier:

Apply KCL at node 'B'

$$I = I_1 + I_2$$

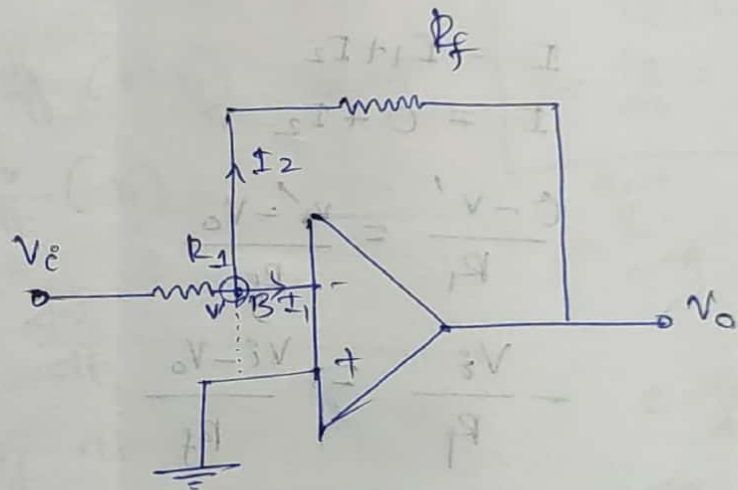
$$= 0 + I_2$$

$$\Rightarrow \boxed{I = I_2}$$

$$\frac{V_i - V'}{R_1} = \frac{V' - V_o}{R_f}$$

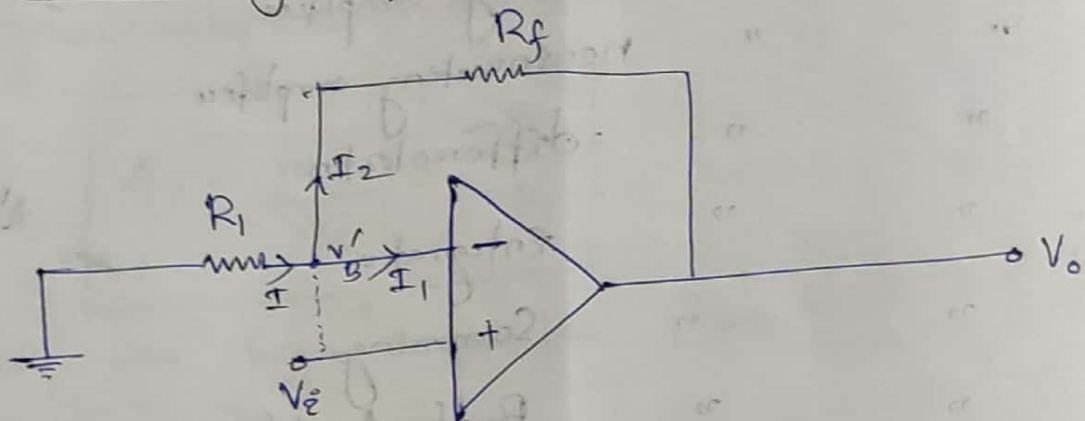
$$\Rightarrow \frac{V_i}{R_1} = \frac{-V_o}{R_f}$$

$$\Rightarrow \boxed{-\frac{R_f}{R_1} = \frac{V_o}{V_i}}$$



($\because V' = 0V$
as it is considered as virtual ground)

② Non Inverting Amplifier:



$$I = I_1 + I_2$$

Applying KCL, at Node B.

$$I = I_1 + I_2$$

$$I = 0 + I_2$$

$$\frac{0 - v'}{R_1} = \frac{v' - V_o}{R_f}$$

$$\frac{V_i}{R_f} = \frac{V_i - V_o}{R_f}$$

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

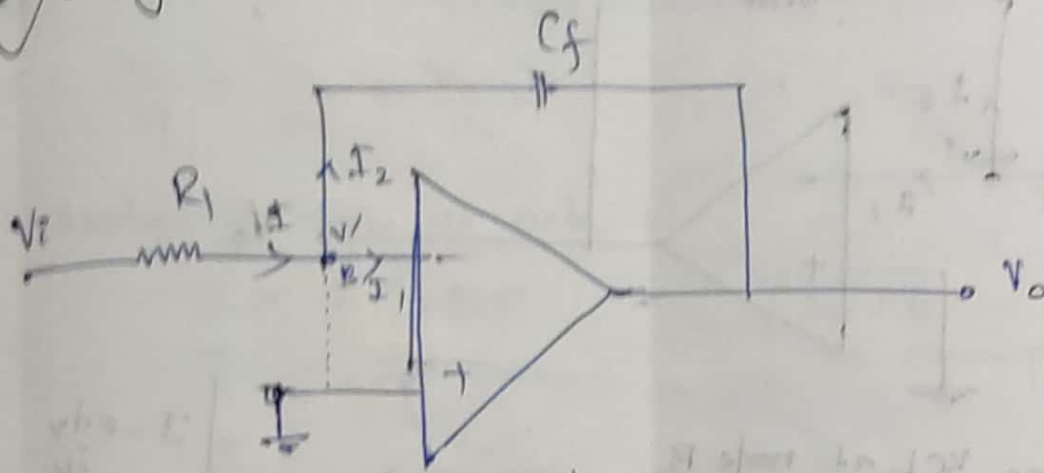
$$\Rightarrow -\frac{R_f}{R_1} \cdot V_i = V_i - V_o$$

$$\Rightarrow V_o = V_i + \frac{R_f}{R_1} V_i$$

$$\Rightarrow V_o = \left(1 + \frac{R_f}{R_1}\right) V_i$$

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

③ Integrator:



Applying KCL at node B.

$$I = I_1 + I_2$$

$$I = I_2$$

$$\frac{V_i - V'}{R_1} = C_f \frac{dV'}{dt} (V' - V_o)$$

$$\frac{V_i}{R_1} = C_f \frac{dV'}{dt} (-V_o)$$

$$\frac{V_i}{R_1} = -C_f \frac{dV_o}{dt}$$

$$dV_o = \frac{-V_i}{R_1 C_f} dt$$

$$V_o = -\frac{1}{R_1 C_f} \int V_i dt$$

$$Q = CV$$

$$I = \frac{dQ}{dt} = C \frac{dV}{dt}$$

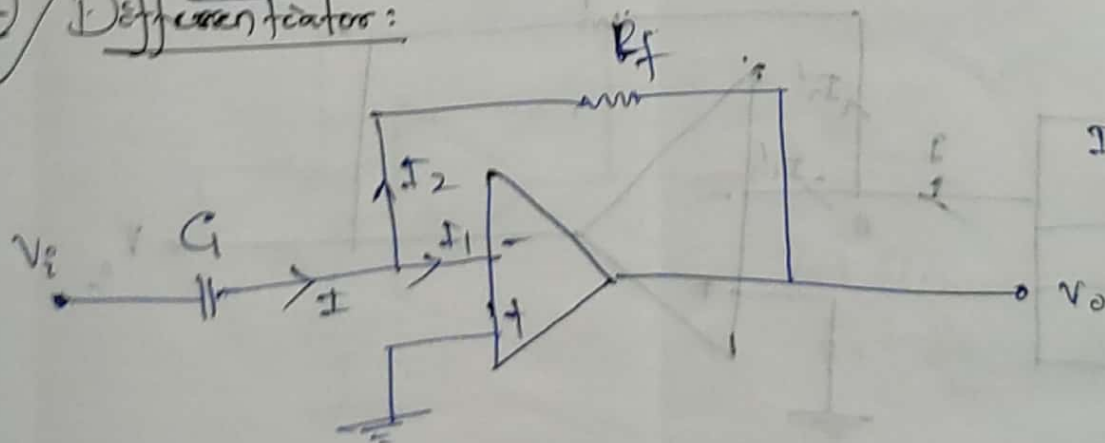
$$Q = CV$$

$$\frac{dQ}{dt} = C \frac{dV}{dt}$$

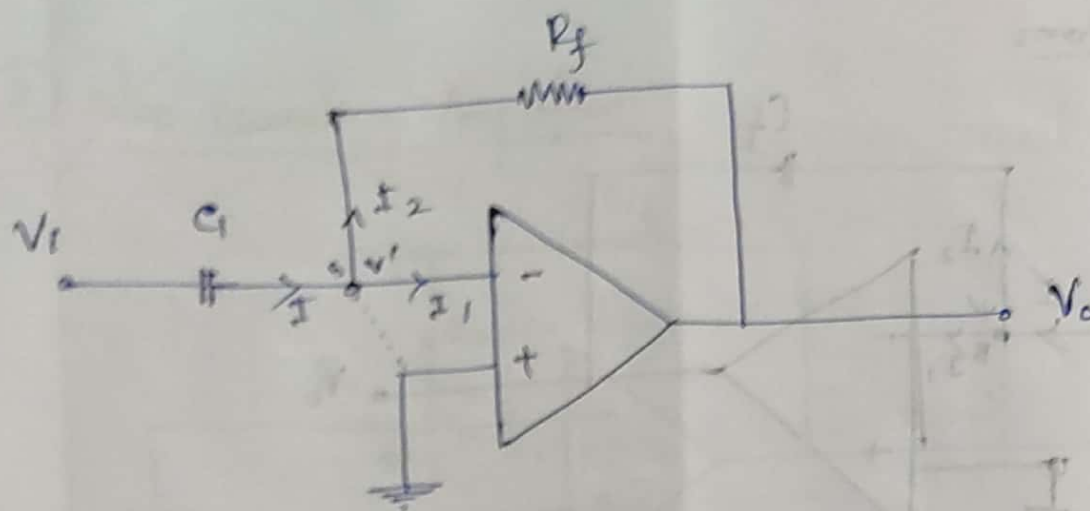
$$I = \frac{dQ}{dt}$$

$$Q = \int I dt$$

④ Differentiator:



$$I = C \frac{dV}{dt}$$



Applying KCL at node B,

$$I = I_1 + I_2$$

$$I = I_2$$

$$e \frac{dv_i}{dt} (v_i - v') = \frac{v' - v_o}{R_f}$$

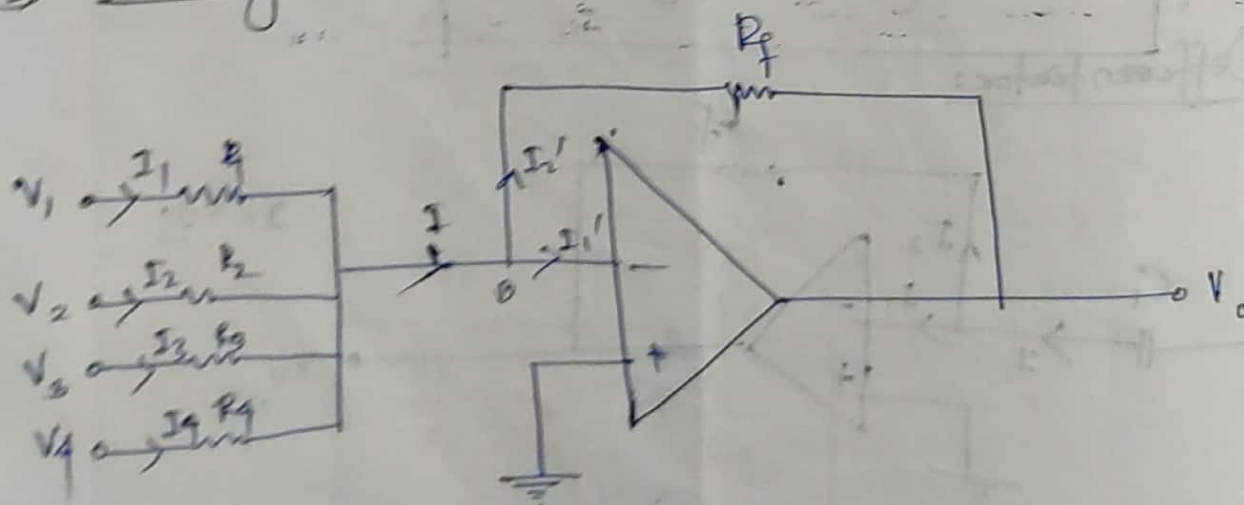
$$e \frac{dv_i}{dt} = -\frac{v_o}{R_f}$$

$$v_o = -R_f e \frac{dv_i}{dt}$$

$$v_o = -R_f e \frac{dv_i}{dt}$$

$$I = e \frac{dv}{dt}$$

⑤ Summing :



$$I = I_1 + I_2 + I_3 + I_4 + I_5 + \dots + I_n$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \dots + \frac{V_n}{R_n}$$

Applying KCL at node 'B'

$$I = I_1' + I_2'$$

$$I = I_2'$$

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

$I_1' = 0$
as Opamp is high ϵ/p impedance

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

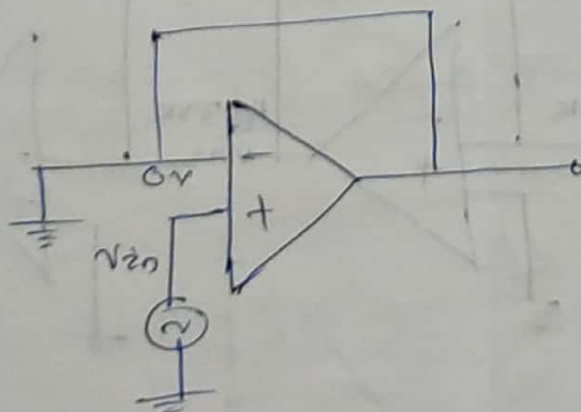
$$V_o = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \dots + \frac{V_n}{R_n} \right)$$

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

if $R_1 = R_2 = R_3 = \dots = R_n = R$

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

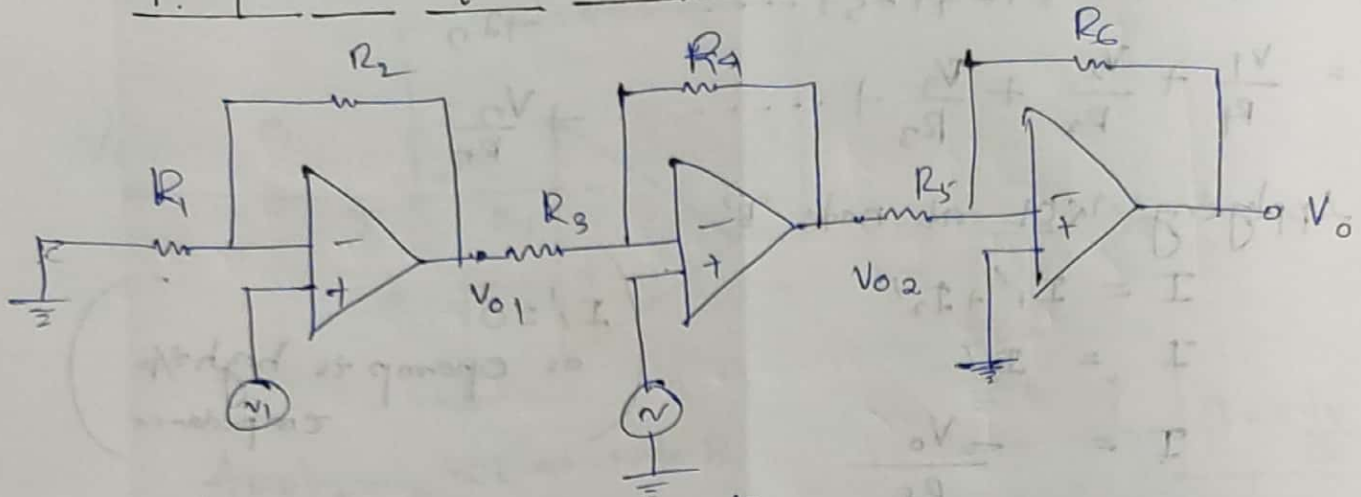
⑥ Opamp. Buffer: (Unit follower ckt)



$$V_o = V_{in}$$

$$A_v = \frac{V_o}{V_{in}} = 1$$

Opamp Base Gain Multiplier:



$$\frac{V_{01}}{V_i} = A_{V1} = 1 + \frac{R_2}{R_1}$$

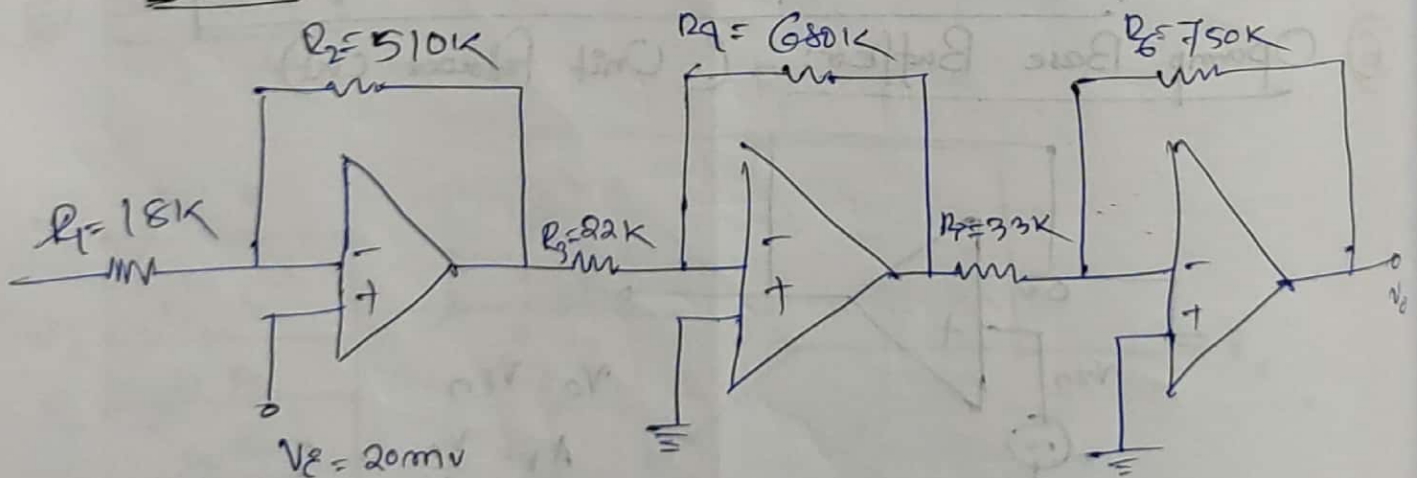
$$\frac{V_{02}}{V_{01}} = A_{V2} = -\frac{R_4}{R_3}$$

$$\frac{V_o}{V_{02}} = A_{V3} = -\frac{R_6}{R_5}$$

$$A_v = A_{V1} \times A_{V2} \times A_{V3}$$

$$= \left(1 + \frac{R_2}{R_1}\right) \left(-\frac{R_4}{R_3}\right) \left(-\frac{R_6}{R_5}\right)$$

Problem:



$$V_o = ?$$

$$A_{V1} = \frac{V_{o1}}{V_{in}} = 1 + \frac{R_2}{R_1} = 1 + \frac{510}{18} = \frac{86}{3} = 29.33$$

$$A_{V2} = \frac{V_{o2}}{V_{o1}} = -\frac{R_4}{R_3} = -\frac{340}{11} = -30.9090$$

$$A_{V3} = \frac{V_o}{V_{o2}} = -\frac{R_6}{R_5} = -\frac{750}{33} = -22.72$$

$$A_V = 20597.065$$

$$A_V = A_{V1} \times A_{V2} \times A_{V3} = (29.33) \times (-30.9090) \times (-22.72) = 20597.06521 \quad \text{Ans}$$

$$\Rightarrow 29.33 = \frac{V_{o1}}{V_{in}}$$

$$29.33 = \frac{V_{o1}}{20} \Rightarrow V_{o1} = 586.6$$

$$\Rightarrow -30.9090 = \frac{V_{o2}}{586.6} \Rightarrow V_{o2} = -18131.2194$$

$$\Rightarrow A_{V3} = \frac{V_o}{V_{o2}} = -22.72$$

$$\Rightarrow V_o = (-22.72) \cdot (-18131.2194)$$

$$= 411941.3048 \quad \text{Ans}$$

Slew Rate: The Max^m rate of change of voltage w.r.t time.

i.e.

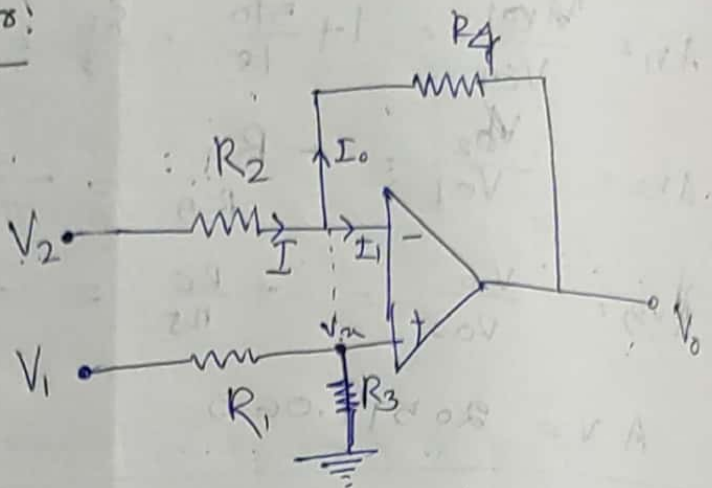
$$SR = \frac{\Delta V}{\Delta t}$$

Voltage Subtractor:

KCL method.

Let $V_n = \frac{V_1 R_3}{R_1 + R_3}$

$\therefore I = I_1 + I_2$



$\Rightarrow I = I_2$

$\Rightarrow \frac{V_2 - V_n}{R_2} = \frac{V_n - V_0}{R_4}$

$\Rightarrow \frac{V_2}{R_2} - \frac{V_n}{R_2} = \frac{V_n}{R_4} - \frac{V_0}{R_4}$

$\Rightarrow \frac{V_2}{R_2} + \frac{V_0}{R_4} = V_n \left(\frac{1}{R_4} + \frac{1}{R_2} \right)$

$\Rightarrow \frac{V_0}{R_4} = \frac{V_1 R_3}{R_1 + R_3} \left(\frac{1}{R_2} + \frac{1}{R_4} \right) - \frac{V_2}{R_2}$

$\Rightarrow V_0 = \frac{R_3 R_4}{R_1 + R_3} \left(\frac{R_2 + R_4}{R_2 R_4} \right) V_1 - \frac{V_2}{R_2}$

Let V_1 is grounded. Only V_2 is applied.

$\therefore V_{01} = -\frac{R_4}{R_2} V_2$

Let V_2 is grounded and V_1 is applied.

$\therefore V_{02} = \left(1 + \frac{R_4}{R_2} \right) V_1$
 $= \left(1 + \frac{R_4}{R_2} \right) \left(\frac{R_3 R_4}{R_1 + R_3} \right)$

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

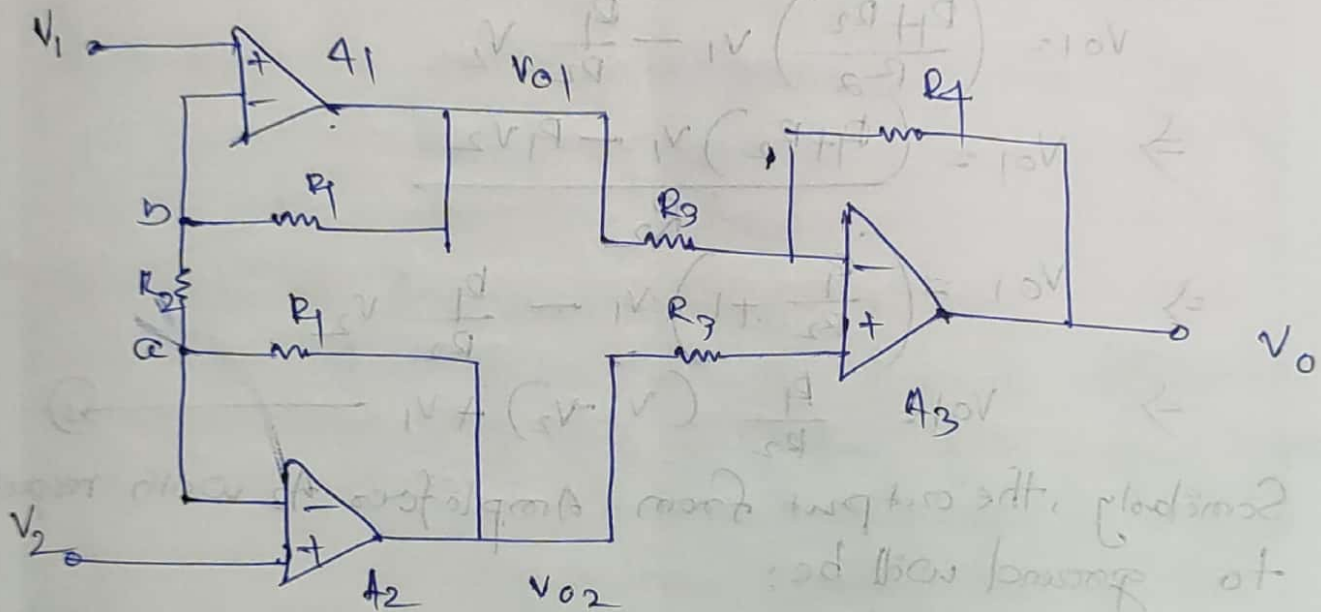
$V_0 = \left(1 + \frac{R_4}{R_2} \right) \left(\frac{R_3 R_4}{R_1 + R_3} \right) V_1 - \frac{R_4}{R_2} V_2$

Instrumentation Amplifier:

Q. Derive an expression for the voltage gain of an instrumentation amplifier? What are its applications? What is the need of current mirror ckt? Draw one ckt?

Ans:

The instrumentation can be drawn as:



First stage is a balanced input, balanced output amplifier formed by A1 & A2 which amplifies the differential signal but passes the common mode signal without amplification. The second stage formed by A3 is a differential amplifier which largely removes the common mode signal.

The voltage V_{01} consists of two components, the voltage due to V_1 & the voltage due to V_2 . If $V_2 = 0$, the point 'e' will be virtual earth & amplifier A1 will act as a non-inverting amplifier with a gain of $V_{01} = V_1 \left(1 + \frac{R_1}{R_2} \right)$

$$V_{o1} = V_1 \left(1 + \frac{R_1}{R_2} \right)$$

If $V_1 = 0$, then point 'b' will be virtual earth & amplifier A_2 will act as an inverting amplifier with a gain of

$$V_{o1} = - \left(\frac{R_1}{R_2} \right) V_2$$

The output from Amplifier A_1 with respect to ground will be

$$V_{o1} = \left(\frac{R_1 + R_2}{R_2} \right) V_1 - \frac{R_1}{R_2} V_2$$

$$\Rightarrow V_{o1} = \left(\frac{R_1 + R_2}{R_2} \right) V_1 - \frac{R_1}{R_2} V_2$$

$$\Rightarrow V_{o1} = \left(\frac{R_1}{R_2} + 1 \right) V_1 - \frac{R_1}{R_2} V_2$$

$$\Rightarrow V_{o1} = \frac{R_1}{R_2} (V_1 + V_2) + V_1 \quad \text{--- (1)}$$

Similarly, the output from Amplifier A_2 with respect to ground will be:

$$V_{o2} = \frac{R_1}{R_2} (V_2 - V_1) + V_2 \quad \text{--- (2)}$$

These two voltages are fed into differential amplifier. The gain of this amplifier is given by

$$V_o = \frac{R_4}{R_3} (V_{o2} - V_{o1}) \quad \text{--- (3)}$$

Substituting Equations for V_{o2} & V_{o1}

$$V_o = \frac{R_4}{R_3} \left\{ \left[\frac{R_1}{R_2} (V_2 - V_1) + V_2 \right] - \left[\frac{R_1}{R_2} (V_1 + V_2) + V_1 \right] \right\}$$

Simplify this.

$$\Rightarrow V_0 = \frac{R_4}{R_3} \frac{R_1 V_2}{R_2} - \frac{R_1 V_1}{R_2} + V_2 - \frac{R_1 V_1}{R_2} + \frac{R_1 V_2}{R_2} - V_1$$

$$\Rightarrow V_0 = \frac{R_4}{R_3} \left\{ \frac{2R_1 V_2}{R_2} + V_2 - 2 \frac{R_1 V_1}{R_2} - V_1 \right\}$$

$$\Rightarrow V_0 = \frac{R_4}{R_3} V_2 \left(1 + \frac{2R_1}{R_2} \right) - V_1 \left(1 + \frac{2R_1}{R_2} \right)$$

$$\Rightarrow V_0 = (V_2 - V_1) \frac{R_4}{R_3} \left(1 + \frac{2R_1}{R_2} \right)$$

Therefore the differential gain, G is $= \frac{V_0}{V_2 - V_1}$

$$\Rightarrow G = \frac{R_4}{R_3} \left(1 + \frac{2R_1}{R_2} \right)$$

Application of Instrumentation amplifier:

Instrumentation amplifier is a type of differential amplifier that has been outfitted with input buffer amplifiers which eliminate the need for input impedance matching & thus make the amplifier particularly suitable for use in measurement & test equipment.

Instrumentation amplifier is used where there is need of high differential gain accuracy, stability must be maintain within a noisy environment & where large common mode signals are present.

Some of the applications are:-

- ① In data acquisition from low output transducer such as strain gauge, Thermocouples, Wheatstone bridge measurement etc.
- ② In medical instrumentation, Navigation, Radar instrumentation etc.

- (iii) In audio applications involving low amplitude audio signals in noisy environments to improve SNR.
- (iv) High Speed signal conditioning for video data acquisition & Imaging.
- (v) High frequency signal amplification in Cable RF system.

Need of Current Mirror Ckt:

A current mirror is a circuit designed to copy a current through one active device by controlling the current in another device of a circuit, keeping the output current constant, regardless of loading. The current being copied can be a sometimes is a varying signal current. The Current mirror ckt can be drawn as follows.

