IES/GATE

Electrical Engineering

VOLUME-IV

Analog & Digital Electronics

Contents

Analog electronics - (2)

Topic - 43

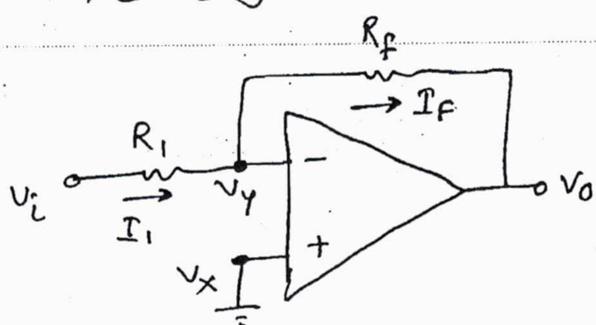
op Amp Applications

- A. RAJKUMAR

Linear applications

Amplifiers

① Inverting Amplifier :



Virtual ground theory

$V_y = V_x$

$I_1 = I_f$

$$\frac{V_i - V_y}{R_1} = \frac{V_y - V_0}{R_f}$$

$$\frac{V_i - 0}{R_1} = \frac{0 - V_0}{R_f}$$

Then $\boxed{\frac{V_0}{V_i} = -\frac{R_f}{R_1}}$ (closed loop gain A_{CL})

practical error

$V_x \neq V_y$

$V_0 = A_d V_d$

$= A_d (V_x - V_y)$

$= A_d (0 - V_y)$

$= -A_d V_y$

Then $\boxed{V_y = -V_0/A_d}$

$I_1 = I_f$

$$\frac{V_i - V_y}{R_1} = \frac{V_y - V_0}{R_f}$$

$$v_y\left[\frac{1}{R_f}+\frac{1}{R_1}\right] = \frac{v_i}{R_1}+\frac{v_o}{R_f}$$

$$v_y\left(\frac{R_1+R_f}{R_1 R_f}\right) - \frac{V_o}{R_f} = \frac{v_i}{R_1}$$

$$-\frac{V_o}{A_d}\left[\frac{R_1+R_f}{R_1 R_f}\right] - \frac{V_o}{R_f} = \frac{V_i}{R_1}$$

$$-\frac{V_o}{R_f}\left[\left[1+\frac{R_f}{R_1}\right]\frac{1}{A_d}+1\right] = \frac{V_i}{R_1}$$

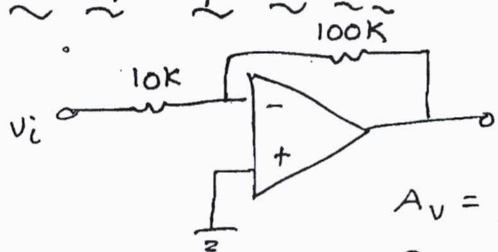
$$\boxed{\frac{V_o}{V_i} = \frac{-R_f/R_1}{1+\frac{1}{A_d}\left[1+\frac{R_f}{R_1}\right]}}$$

practical error

conclusions

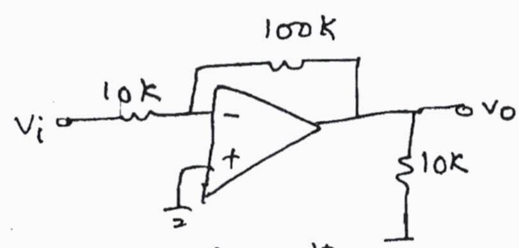
(1) The voltage gain is low
(2) The input impedance is low
} drawbacks

Example problems



$A_v = \underline{-10}$

$R_i = \underline{10K}$



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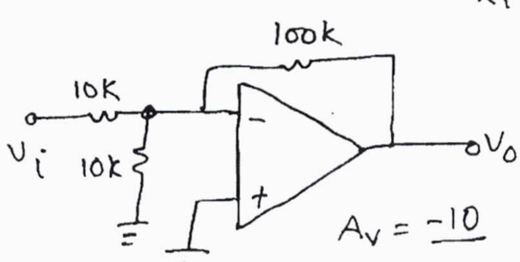

$A_v = \underline{-10}$

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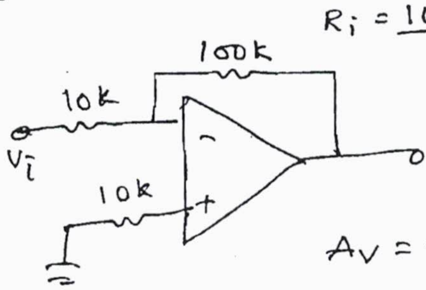
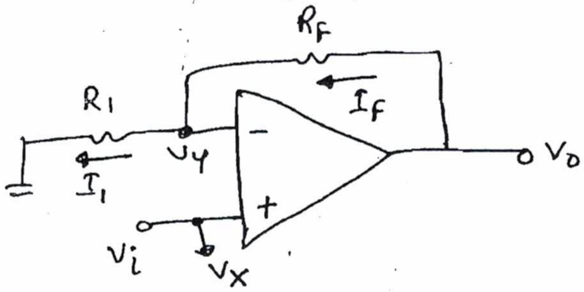


$A_v = \underline{-10}$

$R_i = \underline{10K}$

(2) Non-Inverting Amplifier



Virtual ground theory

$$V_x = V_y = V_i$$

$$I_f = I_1$$

$$\frac{V_0 - V_y}{R_f} = \frac{V_y - 0}{R_1}$$

Then $\frac{V_0 - V_i}{R_f} = \frac{V_i - 0}{R_1}$

$$\boxed{\frac{V_0}{V_i} = 1 + \frac{R_F}{R_1}}$$

practical error

$$V_x \neq V_y$$

$$\boxed{\frac{V_0}{V_i} = \frac{\left[1 + \frac{R_F}{R_1}\right]}{1 + \frac{1}{A_d}\left[1 + \frac{R_F}{R_1}\right]}}$$

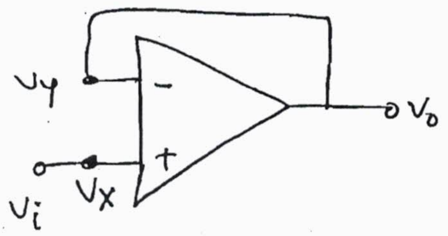
Input impedance

$$Z_i = \frac{V_i}{I_i} = \frac{V_i}{0} = \infty \quad \text{(high impedance)}$$

Conclusions

1. The voltage gain is low (drawback)
2. The input impedance is high (advantage)

③ voltage buffer



virtual ground

$V_x = V_y$

here $V_x = V_i$

$V_y = V_o$

$\therefore \; V_i = V_o$

The voltage gain $= \dfrac{V_o}{V_i} = 1$ (unity gain)

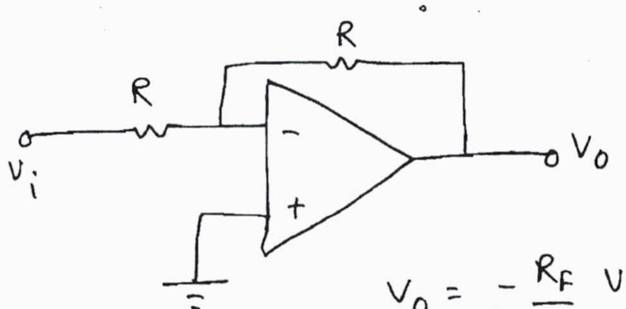
practical error

$V_o = A_d V_d = A_d (V_i - V_o)$

$V_o (1 + A_d) = A_d V_i$

$$\boxed{\frac{V_o}{V_i} = \frac{A_d}{1 + A_d}}$$

④ phase shifter

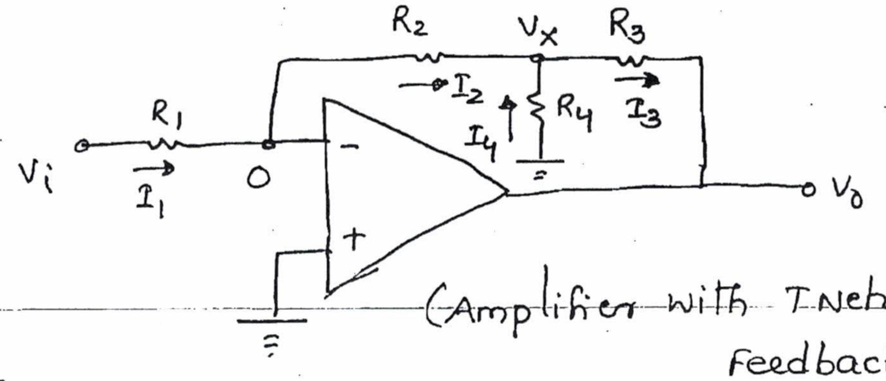


$V_o = -\dfrac{R_F}{R_1} V_i$ (inverting Amplifier)

$= -\dfrac{R}{R} V_i$

$$\boxed{V_o = -V_i}$$

⑤ Improvement of voltage gain in Inverting Amplifier



(Amplifier with T Network Feedback)

$$V_x = -\frac{R_2}{R_1} V_i$$

KCL @ T network

$$I_2 + I_4 = I_3$$

$$\frac{0-V_x}{R_2} + \frac{0-V_x}{R_4} = \frac{V_x - V_0}{R_3}$$

$$\frac{V_0}{R_3} = V_x \left[\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right]$$

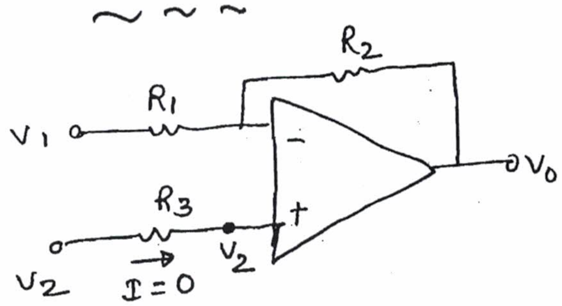
$$\frac{V_0}{R_3} = -\frac{R_2}{R_1} V_i \left[\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right]$$

$$\frac{V_0}{V_i} = -\frac{R_2 R_3}{R_1} \left[\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right]$$

$$\boxed{\frac{V_0}{V_i} = -\frac{R_2}{R_1} \left[1 + \frac{R_3}{R_2} + \frac{R_3}{R_4} \right]}$$

(6) Differential Amplifier

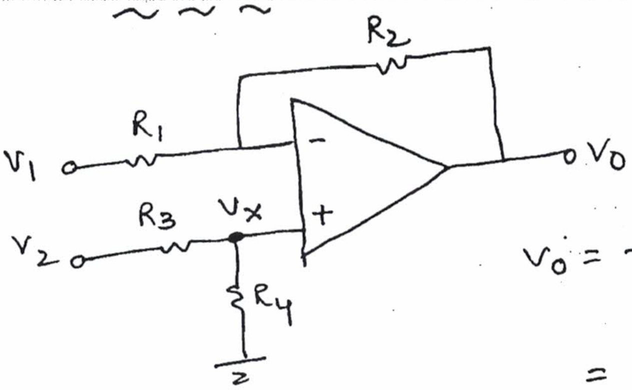
model-1



using Superposition theorem

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

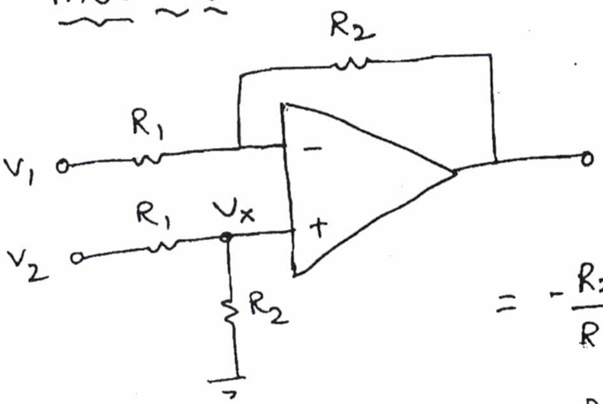
model-2



$$V_0 = -\frac{R_2}{R_1}V_1 + \left[1+\frac{R_2}{R_1}\right]V_x$$

$$= -\frac{R_2}{R_1}V_1 + \left[1+\frac{R_2}{R_1}\right]V_2 \times \frac{R_4}{R_3+R_4}$$

model-3



$$V_0 = -\frac{R_2}{R_1}V_1 + \left[1+\frac{R_2}{R_1}\right]V_x$$

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

$$= -\frac{R_2}{R_1}V_1 + \frac{\cancel{R_1+R_2}}{R_1}V_2 \times \frac{R_2}{\cancel{R_1+R_2}}$$

$$\boxed{V_0 = \frac{R_2}{R_1}(V_2 - V_1)}$$

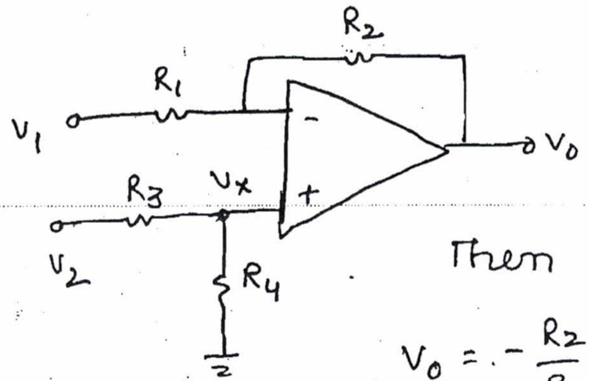
→ CMRR is maintained.

(7) Instrumentational Amplifier

CMRR (common mode Rejection ratio)

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

where $A_d \rightarrow$ differential gain
$A_c \rightarrow$ common mode gain



Then

$$V_o = -\frac{R_2}{R_1} V_1 + \left[1 + \frac{R_2}{R_1}\right] V_x$$

$$= \underbrace{-\frac{R_2}{R_1}}_{A_1} V_1 + \underbrace{\left[1 + \frac{R_2}{R_1}\right] \frac{R_4}{R_3 + R_4}}_{A_2} V_2$$

$$V_o = A_1 V_1 + A_2 V_2$$

$$\left.\begin{aligned} V_d &= V_2 - V_1 \\ V_c &= \frac{V_1 + V_2}{2} \end{aligned}\right\}$$

where $V_d \rightarrow$ differential voltage

$V_c \rightarrow$ common mode voltage

$$\left.\begin{aligned} V_2 &= \frac{V_d}{2} + V_c \\ V_1 &= -V_d/2 + V_c \end{aligned}\right\}$$

$$V_o = A_1 \left[-\frac{V_d}{2} + V_c\right] + A_2 \left[\frac{V_d}{2} + V_c\right]$$

$$= \underbrace{\left[\frac{A_2 - A_1}{2}\right]}_{A_d} V_d + \underbrace{\left[A_1 + A_2\right]}_{A_c} V_c$$

where

$$\left.\begin{aligned} &\boxed{A_d = \frac{A_2 - A_1}{2}} \\ &\boxed{A_c = A_1 + A_2} \end{aligned}\right\}$$

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

output voltage V_0 error

$$V_0 = A_d V_d + A_c V_c$$

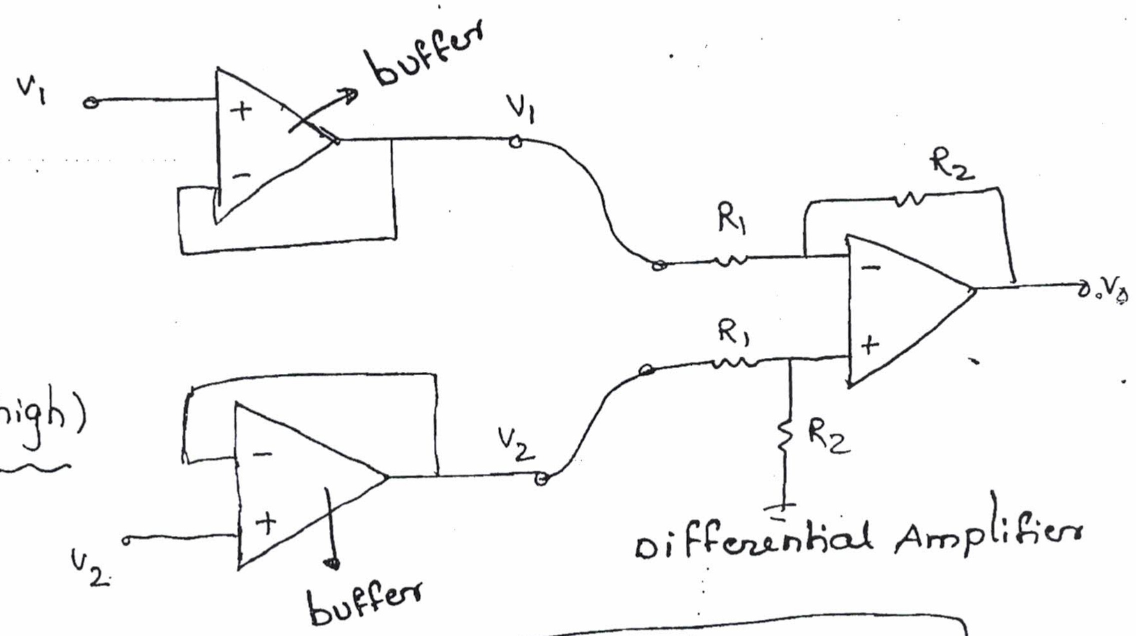
$$= A_d V_d \left[1 + \frac{A_c}{A_d} \frac{V_c}{V_d} \right]$$

$$\boxed{V_0 = A_d V_d \left[1 + \frac{1}{CMRR} \times \frac{V_c}{V_d} \right]}$$

practical error

$$= \frac{1}{CMRR} \frac{V_c}{V_d}$$

Instrumentational Amplifier using 3 opamps



* $z_i = \infty$ (high)

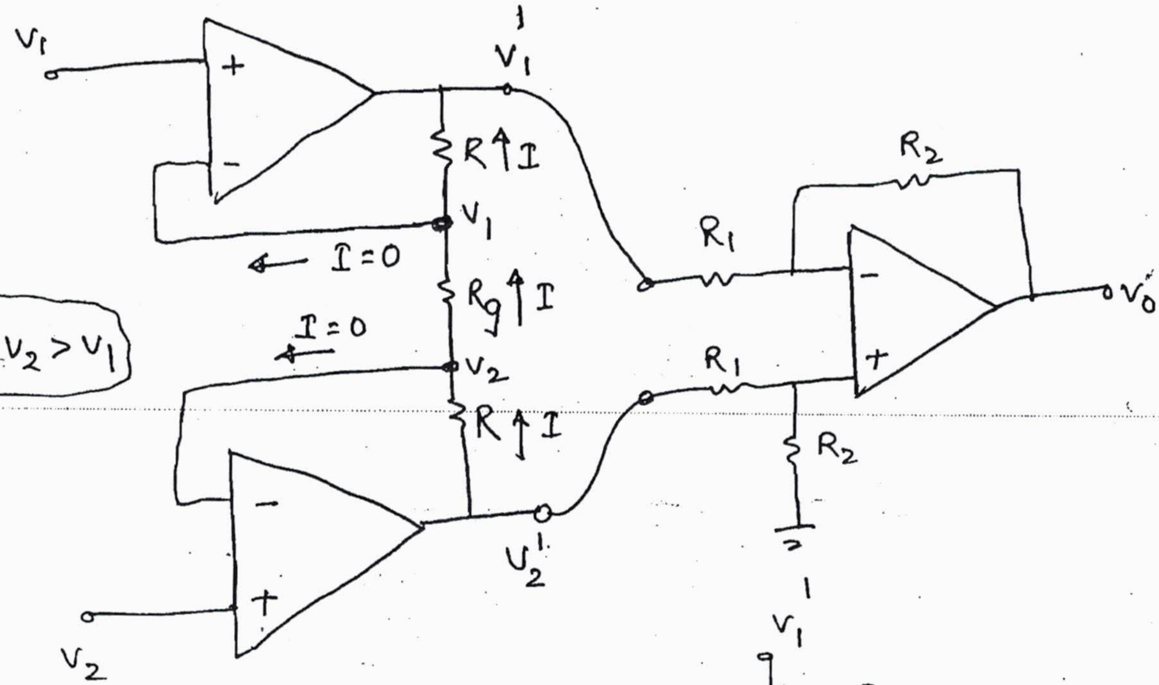
$$\boxed{V_0 = \frac{R_2}{R_1} (V_2 - V_1)}$$

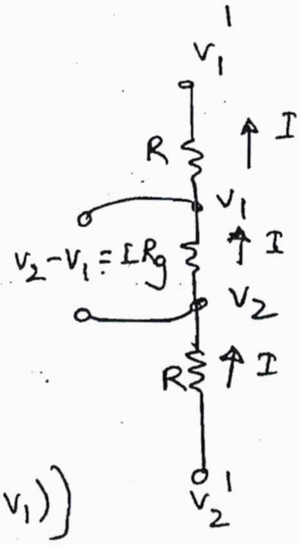
* CMRR is maintained

* voltage gain is low

modified circuit

Let $V_2 > V_1$





$$V_0 = \frac{R_2}{R_1}\left(V_2' - V_1'\right)$$

$$V_1' = -IR + V_1$$

$$V_2' = IR + V_2$$

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

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

$$= \frac{R_2}{R_1}\left[2IR + V_2 - V_1\right]$$

$$= \frac{R_2}{R_1}\left[(V_2 - V_1) + 2\cdot(V_2 - V_1)\cdot\frac{R}{R_g}\right]$$

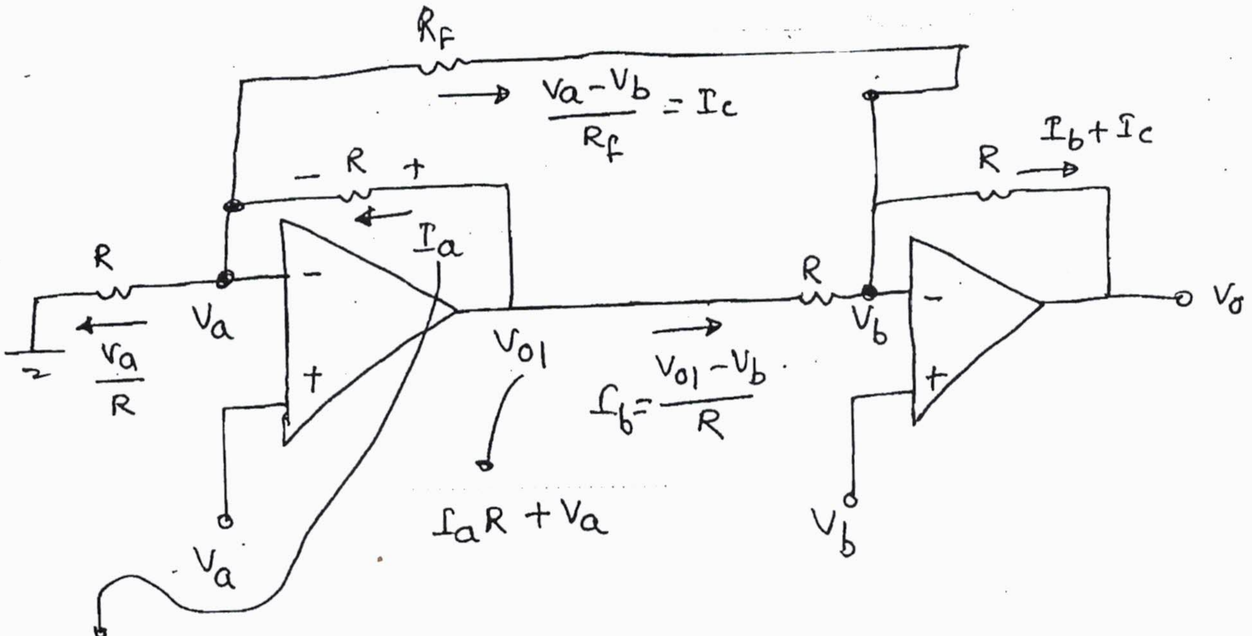
$$V_0 = \frac{R_2}{R_1}(V_2 - V_1)\left[1 + \frac{2R}{R_g}\right]$$

$$\boxed{\frac{V_0}{V_2 - V_1} = \frac{R_2}{R_1}\left[1 + \frac{2R}{R_g}\right]}$$

→ voltage gain is high
→ Input impedance is high
→ CMRR is maintained

} advantages

Instrumentational Amplifier using two op Amps



$$I_a = \frac{V_a}{R} + \frac{V_a - V_b}{R_f}$$

After Simplification

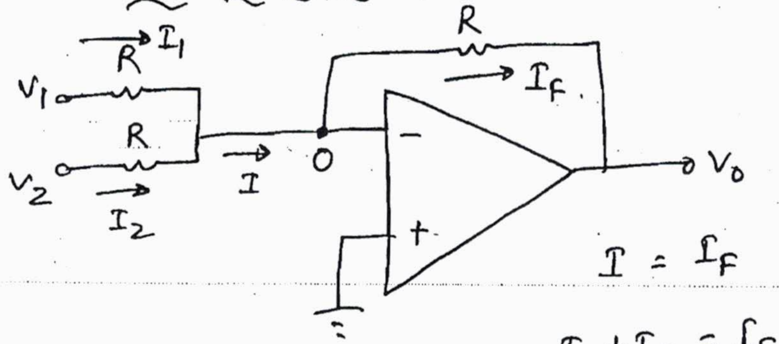
$$\boxed{V_0 = 2(V_b - V_a)\left(1 + \frac{R}{R_f}\right)}$$

$$\boxed{\frac{V_0}{V_b - V_a} = 2\left[1 + \frac{R}{R_f}\right]}$$

mathematical operations

① Adder

Inverting Adder



$$I = I_F$$

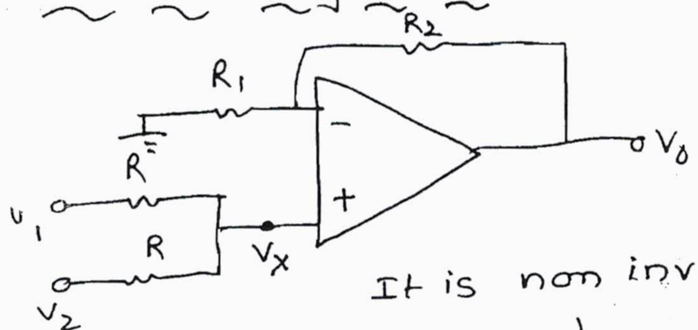
$$I_1 + I_2 = I_F$$

$$\frac{V_1}{R} + \frac{V_2}{R} = \frac{0 - V_0}{R}$$

$$\frac{1}{\cancel{R}}(V_1 + V_2) = -\frac{V_0}{\cancel{R}}$$

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

Non Inverting adder



It is non inverting Amplifier with input V_X where $V_X = V_1 \times \frac{R}{R+R} + V_2 \times \frac{R}{R+R}$

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

$$V_0 = \left[1 + \frac{R_2}{R_1}\right] V_X$$

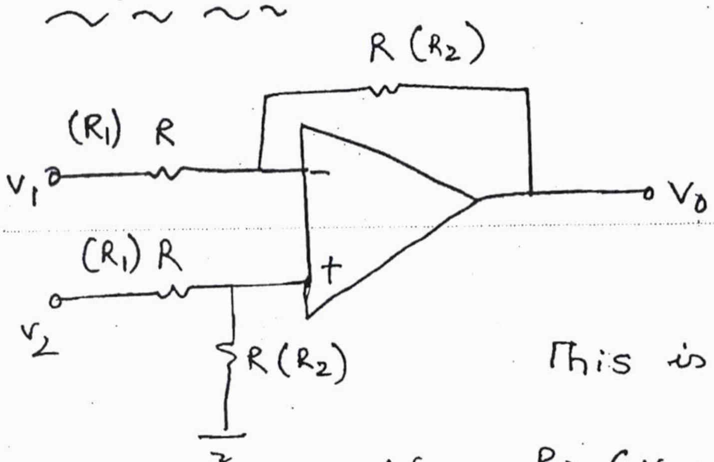
$$= \left(1 + \frac{R_2}{R_1}\right) \frac{V_1 + V_2}{2}$$

Suppose $R_1 = R_2 = R$ Then

$$V_0 = \cancel{2}\cdot \frac{v_1+v_2}{\cancel{2}}$$

$$\boxed{V_0 = v_1 + v_2}$$

② Subtractor



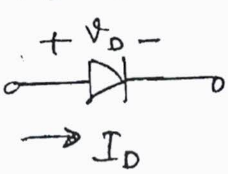
This is differential Amplifier

$$V_0 = \frac{R_2}{R_1}(V_2 - V_1)$$

Now $R_1 = R_2 = R$

Then $\boxed{V_0 = V_2 - V_1}$

③ Logarthmic amplifier

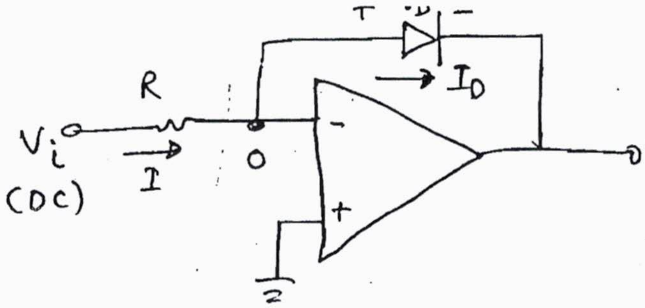


$$I_D = I_0\left(e^{V_D/V_T} - 1\right)$$

In forward bias

$$I_D = I_0\, e^{V_D/V_T}$$

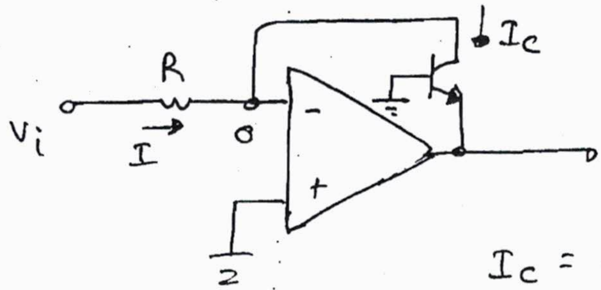
$$\underbrace{V_D = V_T \ln\left(\frac{I_D}{I_0}\right)}_{\text{Logarthmic}}$$



$$V_o = -V_D$$
$$= -V_T \ln\left(\frac{I_D}{I_0}\right)$$
$$= -V_T \ln\left(\frac{I}{I_0}\right)$$

where $I = I_D = \frac{V_i}{R}$

$$\boxed{V_o = -V_T \ln\left(\frac{V_i}{I_0 R}\right)}$$



$$V_o = -V_{BE}$$

$$I_c = I_0\, e^{V_{BE}/V_T}$$

$$V_{BE} = V_T \ln\left(\frac{I_c}{I_0}\right)$$

where $I = I_c = V_i/R$

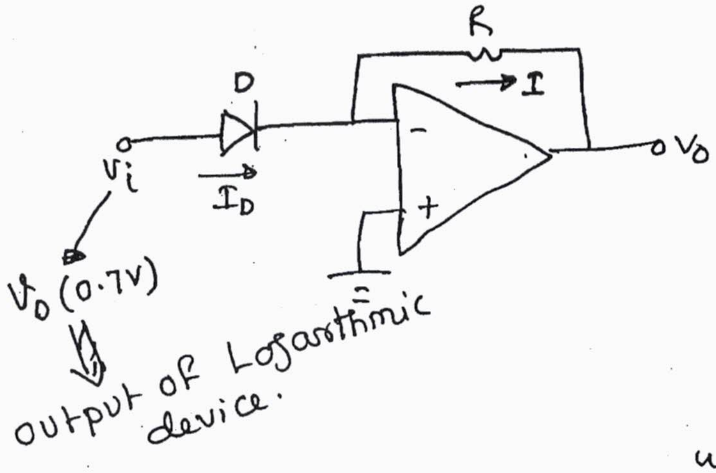
$$\boxed{V_o = -V_T \ln\left(\frac{V_i}{I_0 R}\right)}$$

Note :-

In discrete electronics diode is used as a logarthmic operation

In Integrated electronics BJT is used as a logarthmic operation.

(4) Antilog Amplifier



$$I_D = I_0 e^{V_D/V_T}$$

where $V_D = V_i$

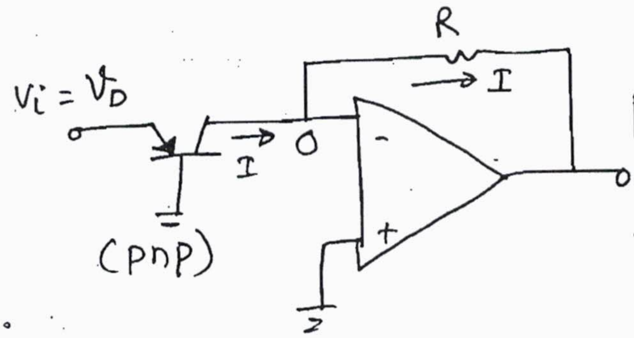
$$I_D = I_0 e^{V_i/V_T}$$

where $I_D = I$

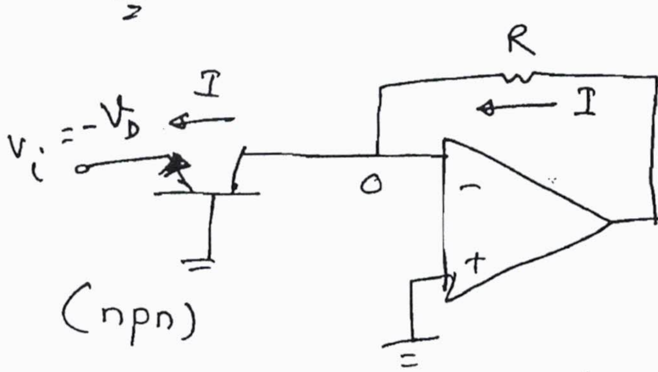
$$I = I_0 e^{V_i/V_T}$$

$$\frac{0 - V_0}{R} = I_0 e^{V_i/V_T}$$

$$\boxed{V_0 = -I_0 R e^{V_i/V_T}}$$

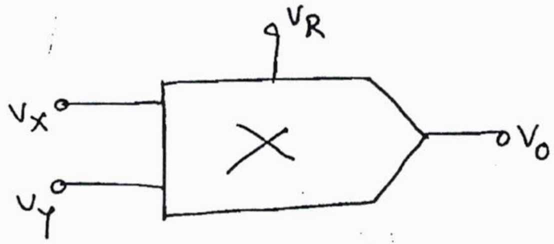


$$\boxed{V_0 = -I_0 R e^{V_i/V_T}}$$



$$\boxed{V_0 = I_0 R e^{V_i/V_T}}$$

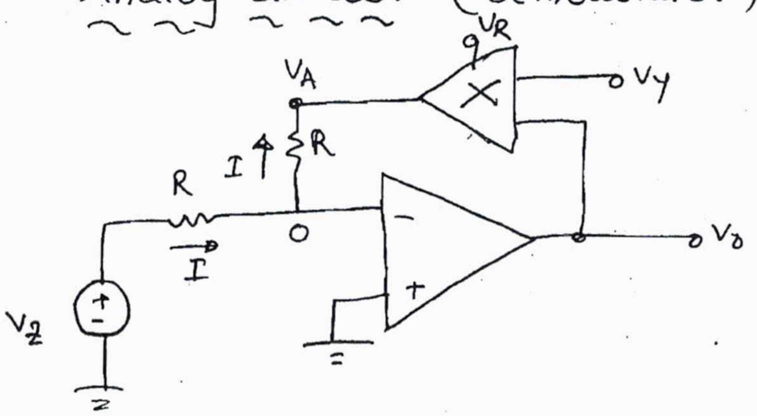
⑤ Analog multiplier (modulator)



$$\boxed{V_o = \frac{V_x \cdot V_y}{V_R}}$$

where $V_R \rightarrow$ Reference voltage (Typically 10V)

⑥ Analog divider (Demodulator)



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

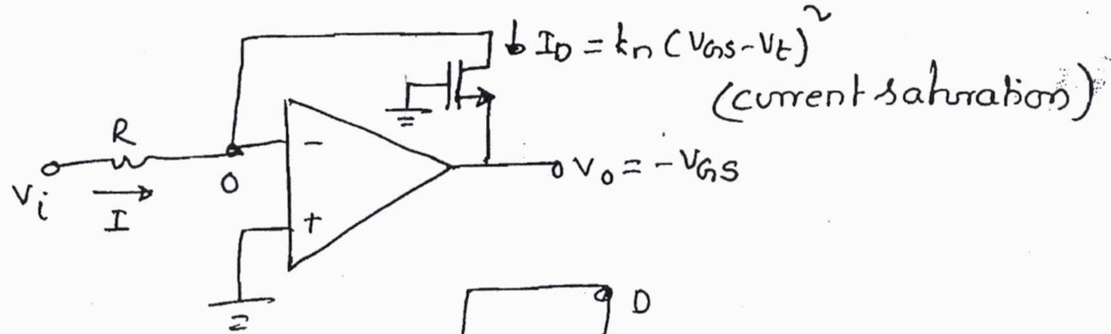
$$\left[V_A = \frac{V_y \cdot V_o}{V_R} \right]$$

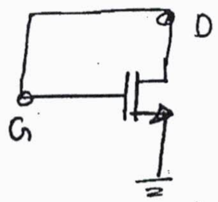
$$V_z = -V_A$$

$$= \frac{-V_y V_o}{V_R}$$

$$\boxed{V_o = -V_R \cdot \left[\frac{V_z}{V_y}\right]}$$

(7) Square root amplifier





Diode connected MOSFET will always works in current saturation.

$$I = I_D = \frac{V_i - 0}{R} = \frac{V_i}{R}$$

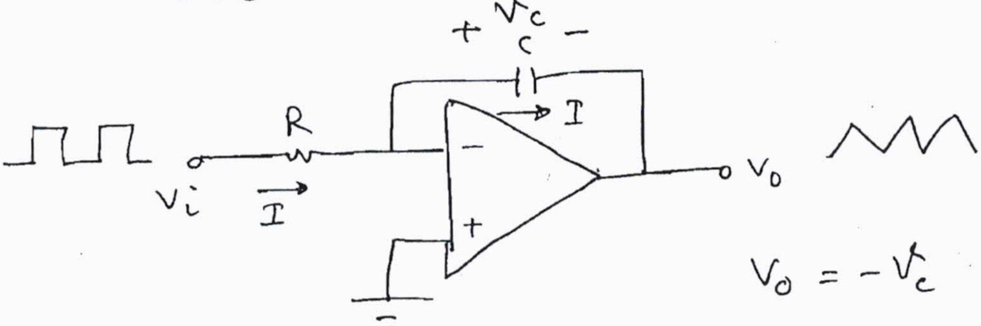
$$V_o = -V_{GS}$$

$$I_D = k_n (V_{GS} - V_t)^2$$

$$\frac{V_i}{R} = k_n (-V_o - V_t)^2$$

$$\boxed{V_o = -\sqrt{\frac{V_i}{R k_n}} - V_t}$$

(8) Integrator:



$$V_o = -V_c$$