OPAMP as Circuit Element

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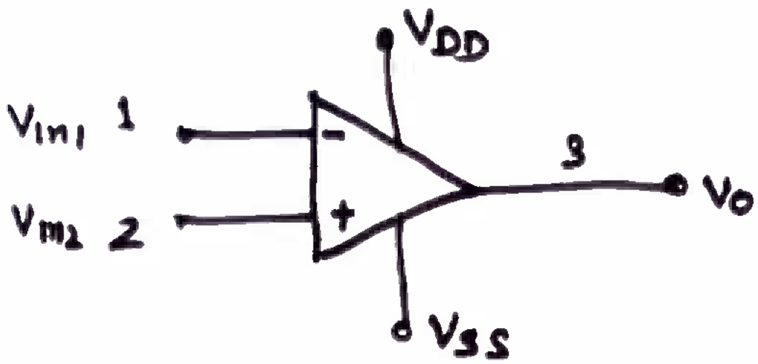
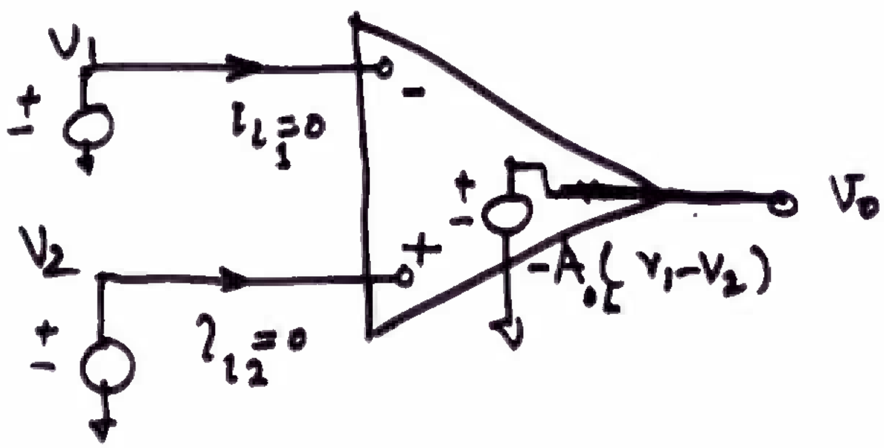
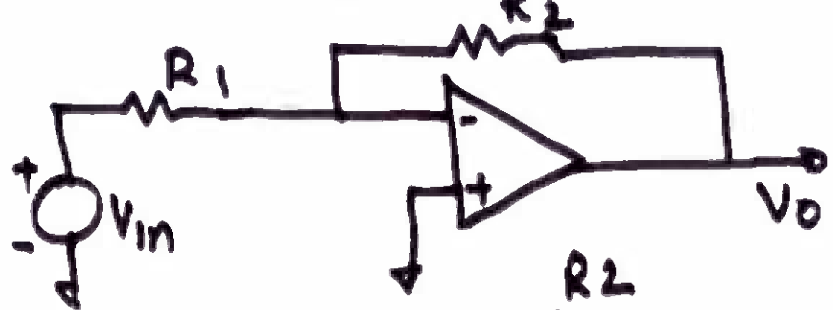
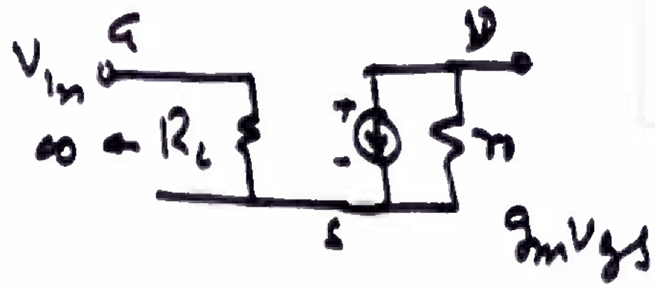


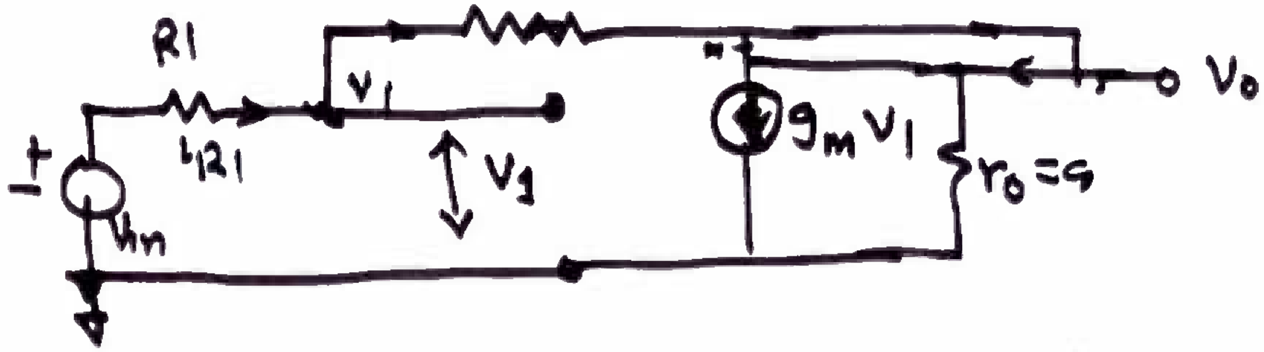
Equivalent Circuit
↓



Inverting & Non Inverting Amplifier







$$\frac{V_{in} - V_1}{R_1} = \frac{V_1 - V_0}{R_2} \quad \text{or} \quad \frac{V_{in}}{R_1} + \frac{V_0}{R_2} = \underline{\underline{V_1}}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

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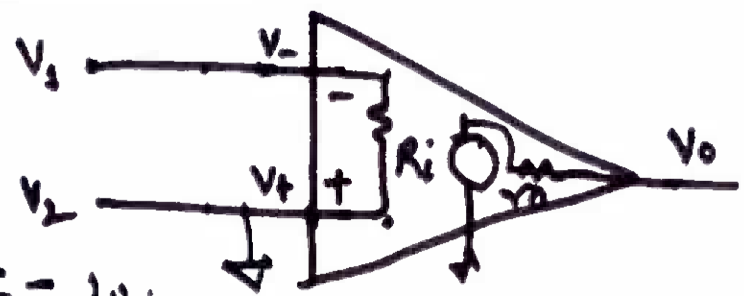
Ideal Parameters

$R_i \to \infty$

$r_o \to 0$

A_v is very large



$\frac{V_1 - V_2}{R_i} = i_{R_i}$

$V_d = V_1 - V_2 = V_- - V_+$

$V_o = -A_V (V_- - V_+) = -A_V V_d$

or $V_d = -\frac{V_o}{A_V}$ If $A_V \to \infty$ $V_d \to 0$

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

Hence if we Ground $\underline{V_+} \Rightarrow 0$

Then $V_- = 0$

This is Concept of Virtual Ground.

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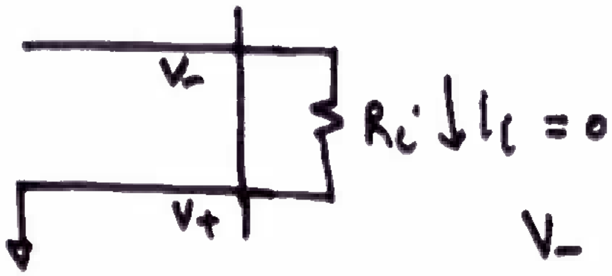
Alternatively as $R_i \to \infty$, no current passes through it



As $i_i = 0$

$\therefore\ V_- = V_+ = 0$

V_- getting 'Zero' potential. This is called Virtual Ground.

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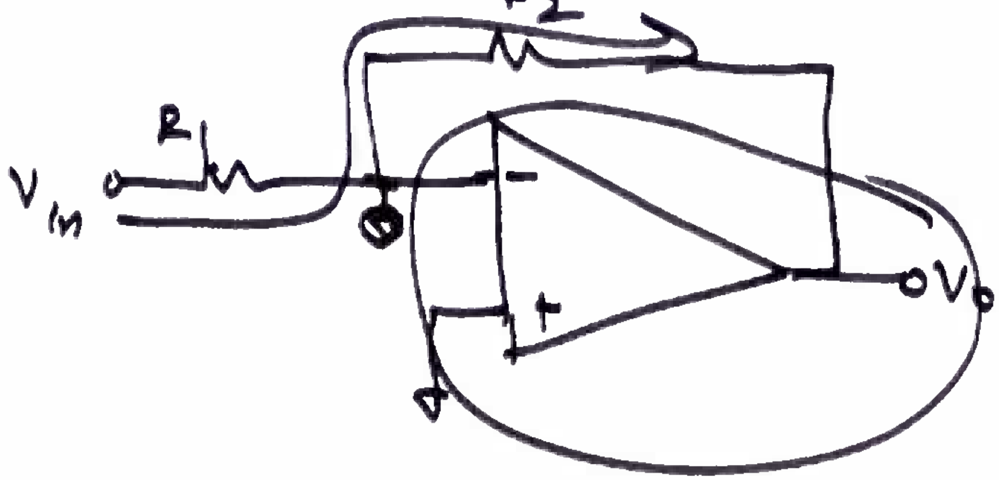

$$V_0 = -\frac{R_2}{R_1} V_{in}$$

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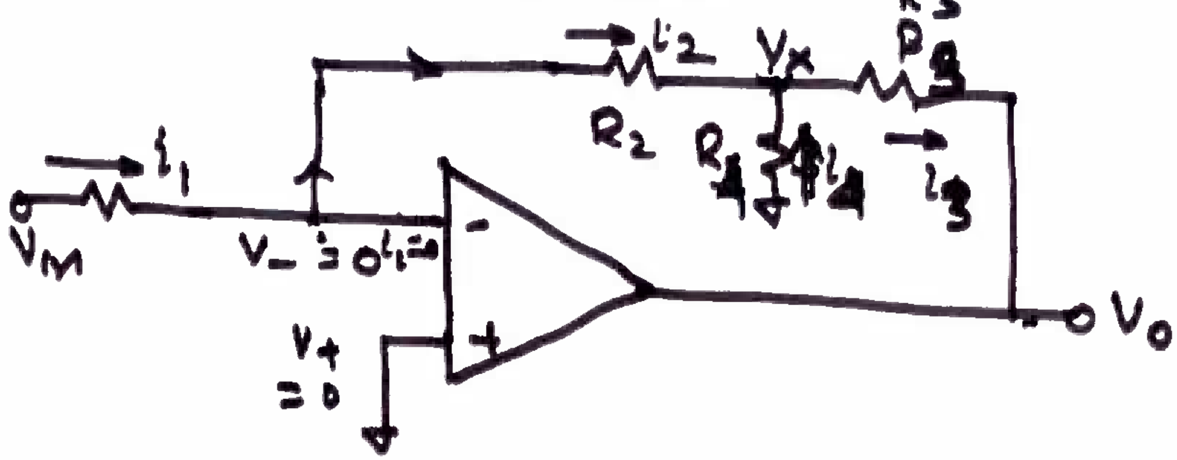
Amplifier with T-network in Feedback



$i_1 = i_2$ as $V_- = 0$ (VG)

No current enters OPAMP inputs.

$$V_x = 0 - i_2 R_2 = -i_1 R_2 = -\frac{V_{in}}{R_1} \cdot R_2$$

At node V_x: $\quad i_2 + i_4 = i_3$

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

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or $-\frac{V_{in}}{R_1} R_2 \left[\frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right] = \frac{V_o}{R_3}$

or $\frac{V_o}{V_{in}} = A_V = -\frac{R_2}{R_1} \left[1 + \frac{R_3}{R_4} + \frac{R_3}{R_2} \right]$

<u>Why T-Network ?</u>

Larger Gain with . . .
values of Resistors.

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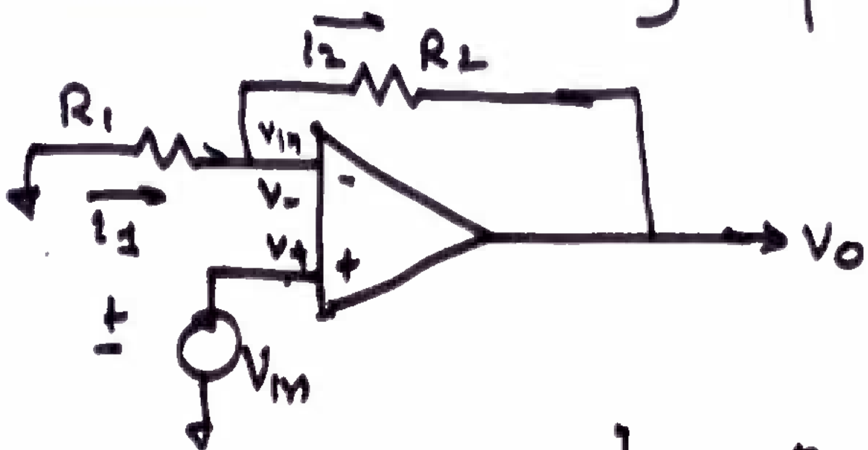
NonInverting Amplifier



Assumption :

$R_i \to \infty$ $\therefore$ no current enters OPAMP inputs. $\therefore V_- = V_+$

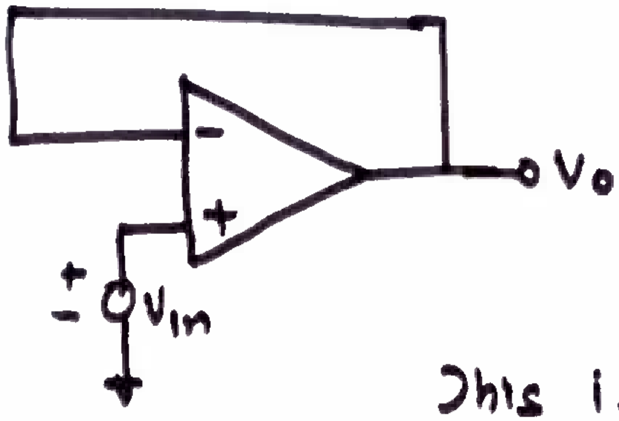
$$i_1 = \frac{0 - V_-}{R_1} = -\frac{V_-}{R_1} = -\frac{V_+}{R_1} = -\frac{V_{in}}{R_1}$$

Then $$i_2 = \frac{V_- - V_o}{R_2} = \frac{V_{in} - V_o}{R_2}$$

But $i_1 = i_2$

or $$\frac{V_{in} - V_o}{R_2} = -\frac{V_{in}}{R_1} \quad \text{or} \quad \frac{V_o}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right)$$

Interesting Circuit

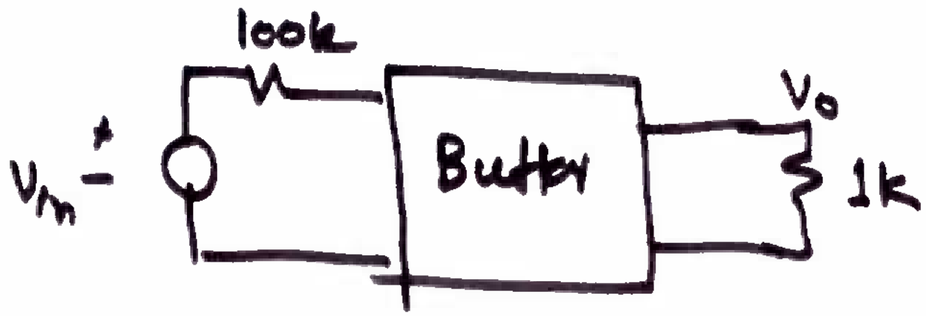


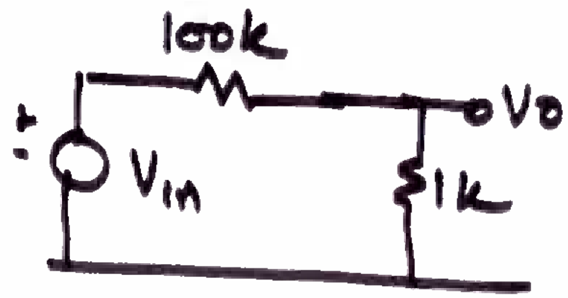
Here $V_o = V_- = V_+$

or $V_o = V_{in}$

$\therefore \quad A_V = \frac{V_o}{V_{in}} = 1$

This is called Voltage Follower or Buffer





$$\frac{V_o}{V_{in}} = \frac{1k}{101k} = 0.01$$

Severe Loading

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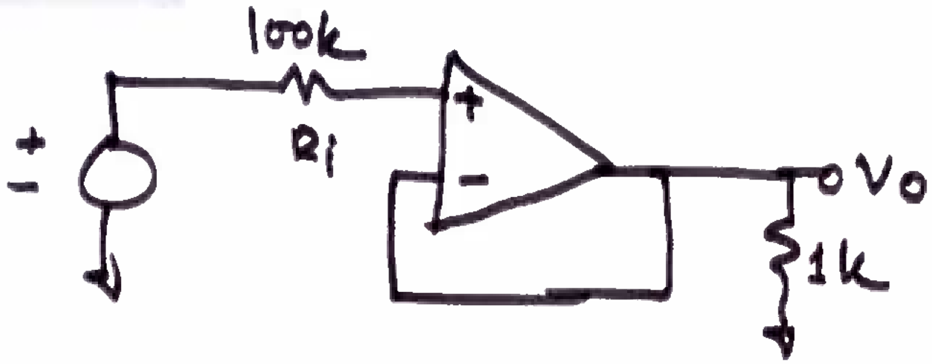
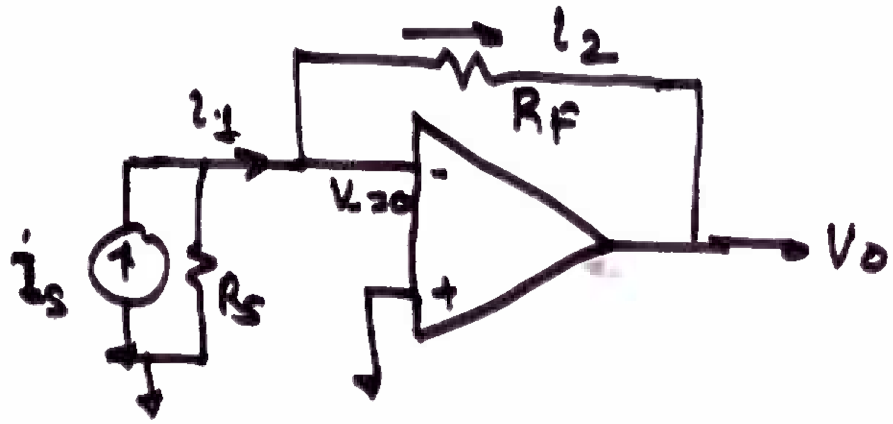


$R_i >> 100k \quad \therefore \quad V_o \simeq V_{in}$

(iii) I-V Convertor



$i_1 = i_2 = i_s \qquad$ But $i_2 = \dfrac{0 - V_o}{R_F} \qquad \therefore V_o = -i_2 R_F = -i_s R_F$

V-I Converter

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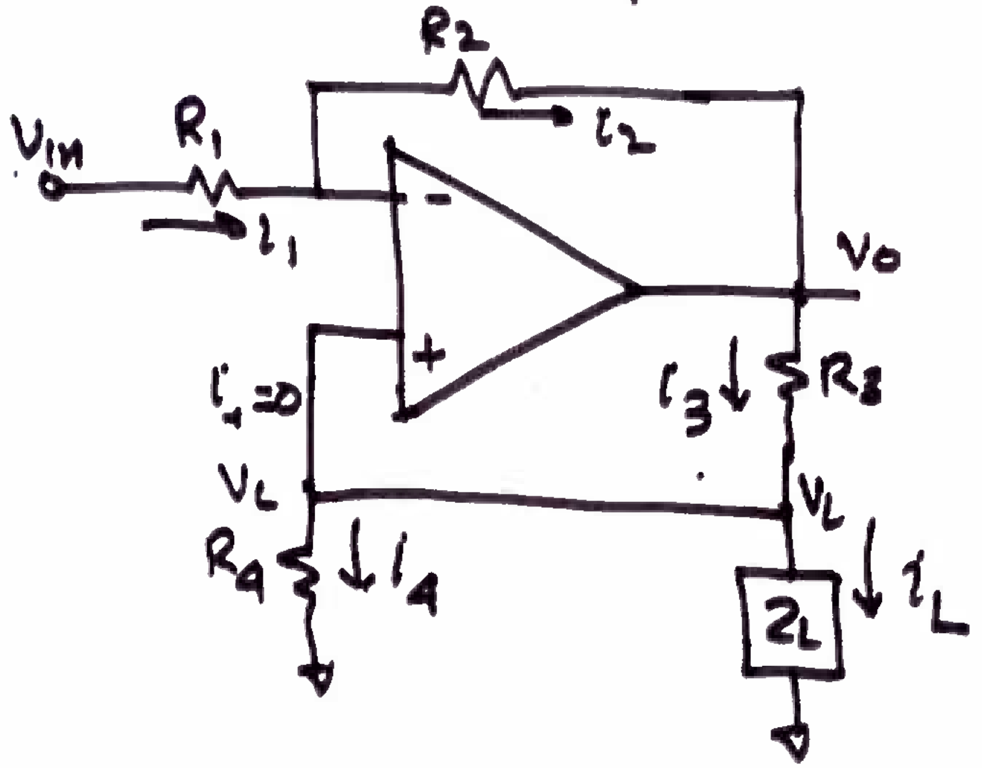
Requirement : I in Load should be independent of Load Value.



Clearly $V_- = V_+ = V_L \neq 0$

$\therefore V_- = V_+ = i_L Z_L = V_L$

Also $i_1 = i_2$

(No current enters inputs)

or $$\frac{R_2}{R_1}\cdot\left(\frac{i_L Z_L - V_{in}}{R_3}\right) = i_L + \frac{i_L Z_L}{R_4}$$

$$i_L\left[\frac{R_2}{R_1}\frac{Z_L}{R_3} - 1 - \frac{Z_L}{R_4}\right] = V_{in}\,\frac{R_2}{R_1 R_3}$$

For i_L to be independent of Z_L

$$\frac{R_2}{R_1 R_3} = \frac{1}{R_4}$$

Then $$\boxed{i_L = -\frac{1}{R_4}\cdot V_{in}}$$

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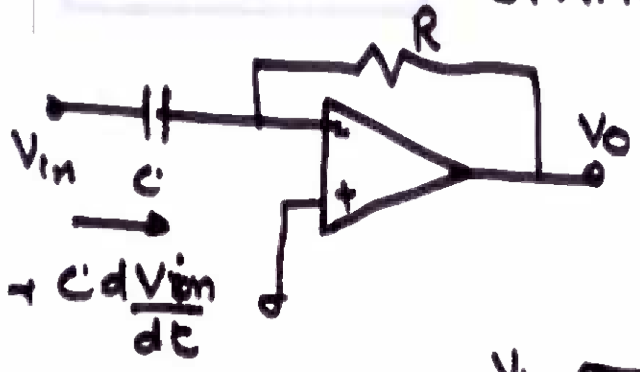
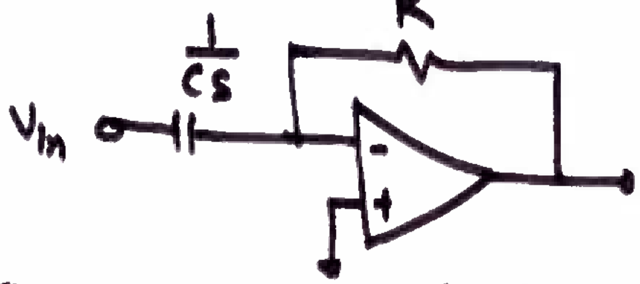
OPAMP Differentiator & Integrator



$$V_o(t) = -RC\frac{dV_{in}}{dt}$$



$$\frac{V_{in}-0}{1/Cs} = \frac{0-V_o}{R}$$

or $V_o = -RCs\,V_{in}$

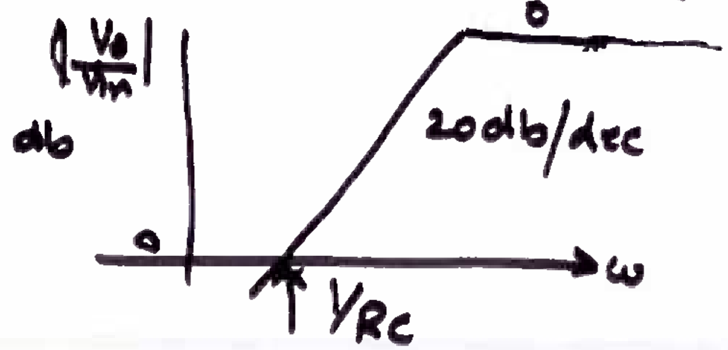
$$\frac{V_o(s)}{V_{in}(s)} = RCs = -j\omega RC$$

$$\left|\frac{V_o(s)}{V_{in}(s)}\right| = \omega CR$$

$$\phi = \tan^{-1}\frac{-\omega RC}{0} = -\tan^{-1}\infty = -\pi/2$$

$$H(s) = \frac{V_o(s)}{V_{in}(s)} = RC\cdot s$$

$RC \Rightarrow$ Time constant



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$$\therefore \quad \frac{V_{in} - V_L}{R_1} = \frac{V_L - V_o}{R_2}$$

$$\text{or} \quad \frac{V_{in} - i_L Z_L}{R_1} = \frac{i_L Z_L - V_o}{R_2} \qquad - (1)$$

$$i_3 = \frac{V_o - V_L}{R_3} = \frac{V_o - i_L Z_L}{R_3} \qquad - (2)$$

$$\text{But} \quad i_3 = i_L + i_4 \qquad \qquad \text{But} \quad i_4 = \frac{i_L Z_L}{R_4}$$

$$\therefore \quad \frac{V_o - i_L Z_L}{R_3} = i_L + \frac{i_L Z_L}{R_4} \qquad - (3)$$

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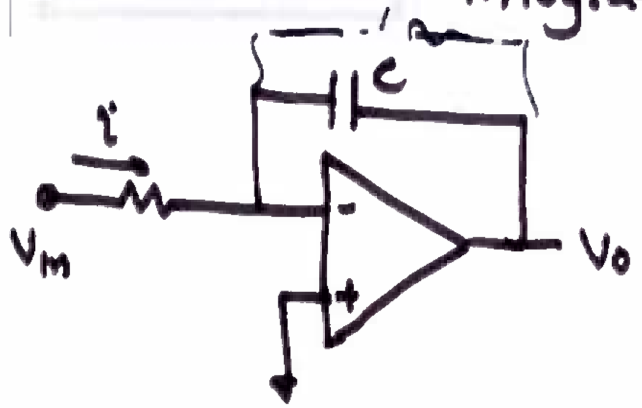
Integrator



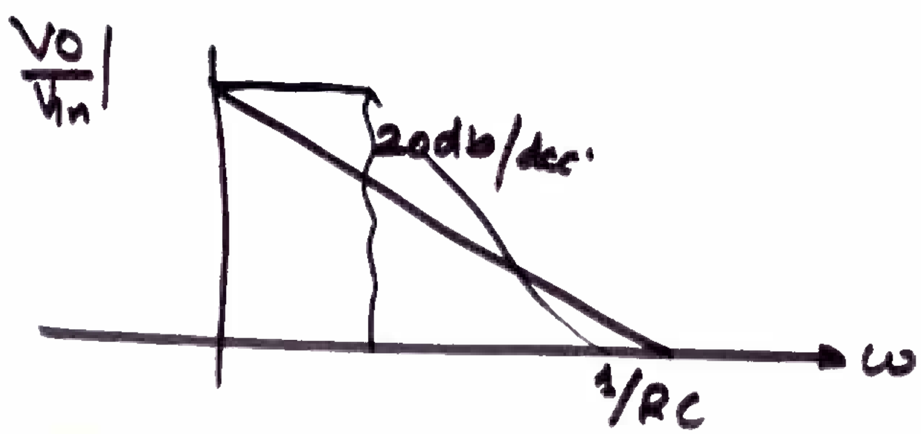
$$\frac{V_{in}}{R} = -C\frac{dV_o}{dt}$$

or $$V_o = -\left[+\frac{1}{RC}\int V_{in}\,dt + V_{co}\right]$$

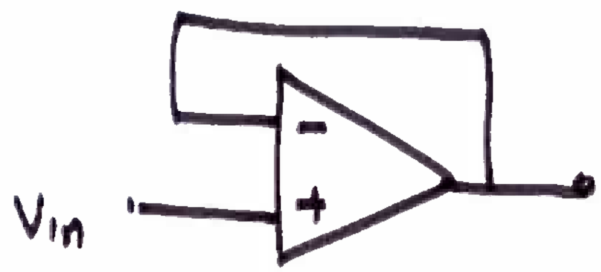
$$\frac{V_o(s)}{V_{in}(s)} = -\frac{1}{sCR} = -\frac{1}{j\omega RC}$$

$$\left|\frac{V_o}{V_{in}}\right| = \frac{1}{\omega RC}$$

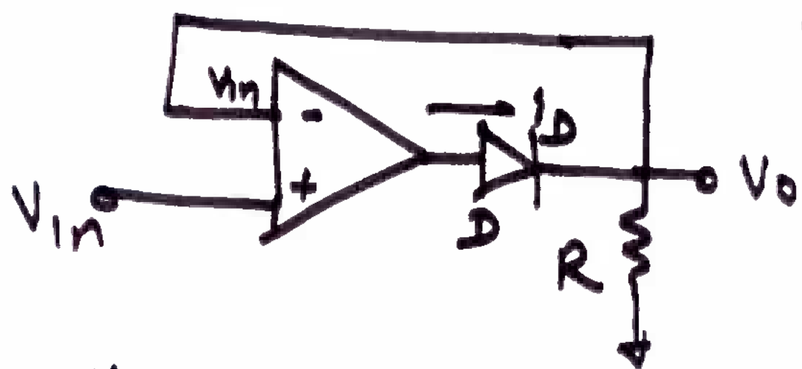
& $\phi = +90^0$



Precision Half Wave Rectifier



Modified V. Follower Circuit



$V_{in} = +\text{tive}$

& $V_{+} = V_{in} = V_{-}$

Diode current $I = I_S\left(e^{\frac{qV_f}{\eta kT}} - 1\right) \simeq I_S\, e^{qV_f/\eta kT}$

$$\therefore \log I = \log I_S + \frac{qV_f}{\eta kT}$$

$$\therefore V_f = \eta\left(\frac{kT}{q}\right)\left[\log I - \log I_S\right]$$

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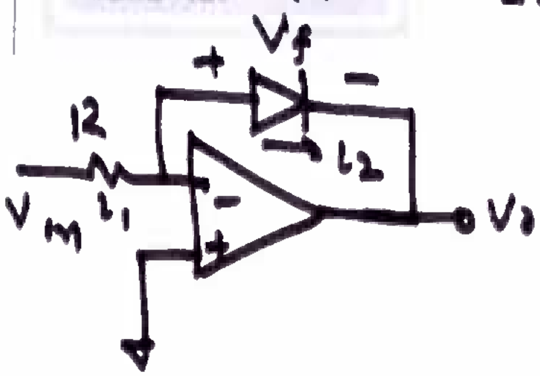
Logarithmic Amplifier



$$i_1 = \frac{v_{in}}{R} = i_2 = i_D$$

If $i_D = 0$ then $i_s = 0$

then $V_0 = 0$

But if Diode conducts ($V_- > V_0$)

Then $V_f + V_0 = 0$ or $V_0 = -V_f = -\frac{\eta KT}{q}\left[\log i_2 - \log I_s\right]$

or $V_0 = -\frac{\eta KT}{q}\left[\log V_{in} - \log R - \log I_s\right]$

$$V_0 = -\frac{\eta KT}{q}\left[\log \frac{V_{in}}{R\, I_s}\right]$$

$\therefore V_0 \propto \log(V_{in})$

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Antilog Amplifier

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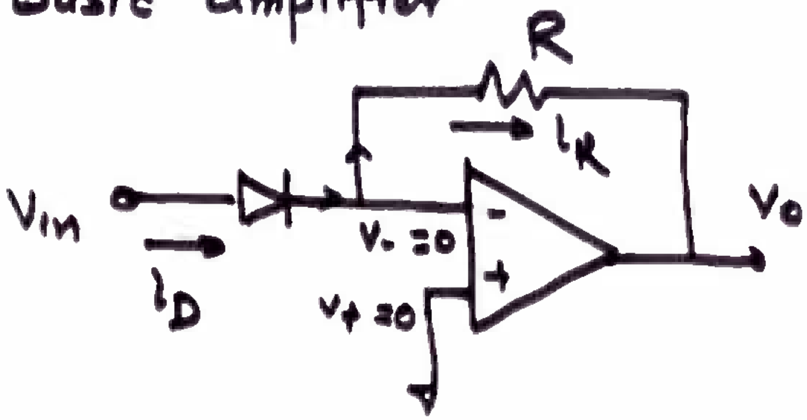
Basic amplifier



We have

$$i_D = I_S \exp\left(\frac{qV_f}{\eta kT}\right)$$

As $V_- = 0$, Hence $i_R \cdot R = -V_o = +\, i_D \cdot R$

$$\therefore \; V_o = -I_S R \exp\left(\frac{qV_f}{\eta kT}\right) \qquad \therefore \; V_o \propto \exp(V_f)$$

Analog Multiplier

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Mathematically $\log(AB) = \log A + \log B$

Also $AB = \text{Antilog}(AB)$

$= \text{Antilog}[\log A + \log B]$

Clearly we can get Multiplication of AB by using three amplifier and an Adder.

(1) Create $\log A$ (2) Create $\log B$

(3) Create $(\log A + \log B)$

(4) Create Antilog of $[\log A + \log B]$

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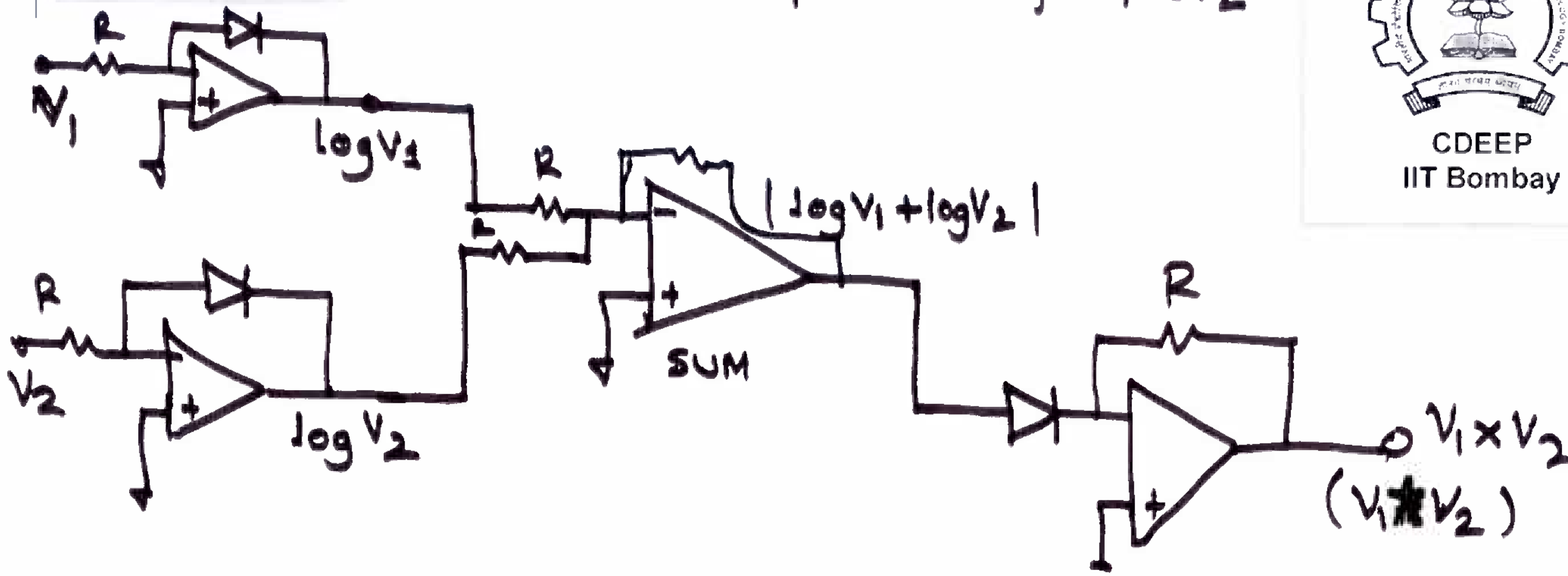
We want Multiplication of V_1 & V_2



Frequency Response of OPAMP

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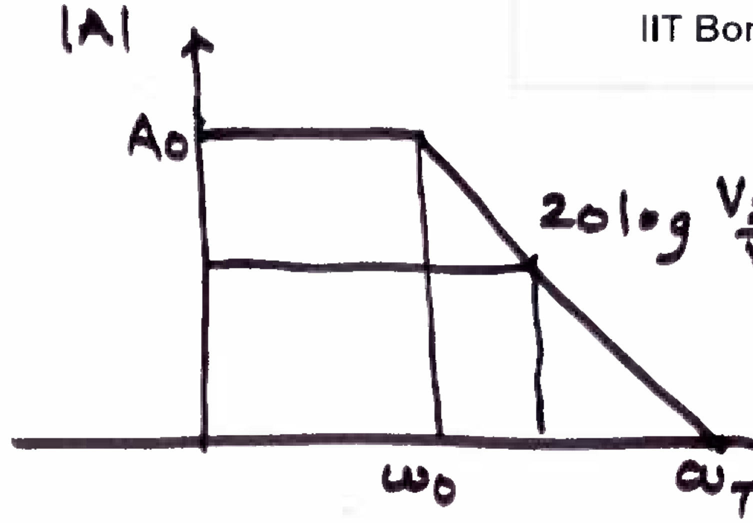
OPEN LOOP

$$A_{OL}(\omega) = \frac{A_0}{1 + j\frac{\omega}{\omega_0}}$$



ω_0 is Dominant Pole.

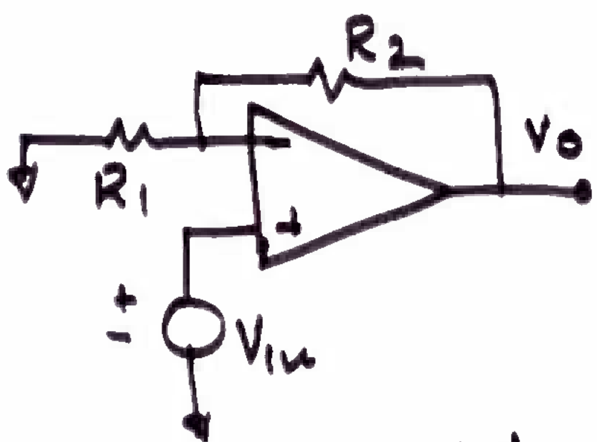
Clearly $\omega_0 \cdot A_0 = \omega_T$ from the Figure (Bode Plot)

$$A_0 \omega_0 = 1 \cdot \omega_T$$

where ω_T is unity Gain Bandwidth or Gain Bandwidth product. (GBW).

Assumptions : Other poles occure at $\omega > \omega_T$ & System is Stable.

<u>Closed Loop</u> : Take a case of Non Inverting Amplifier



With R_2 in feedback, the Amplifier is Shunt Shunt Feedback Amplifier

$$A_{CL} = \frac{A_{OL}}{1 + \beta A_{OL}}$$

Where A_{CL} is Closed Loop Gain

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The feedback factor β is given by $\beta = \frac{R_1}{R_1+R_2} = \frac{1}{1+R_2/R_1}$

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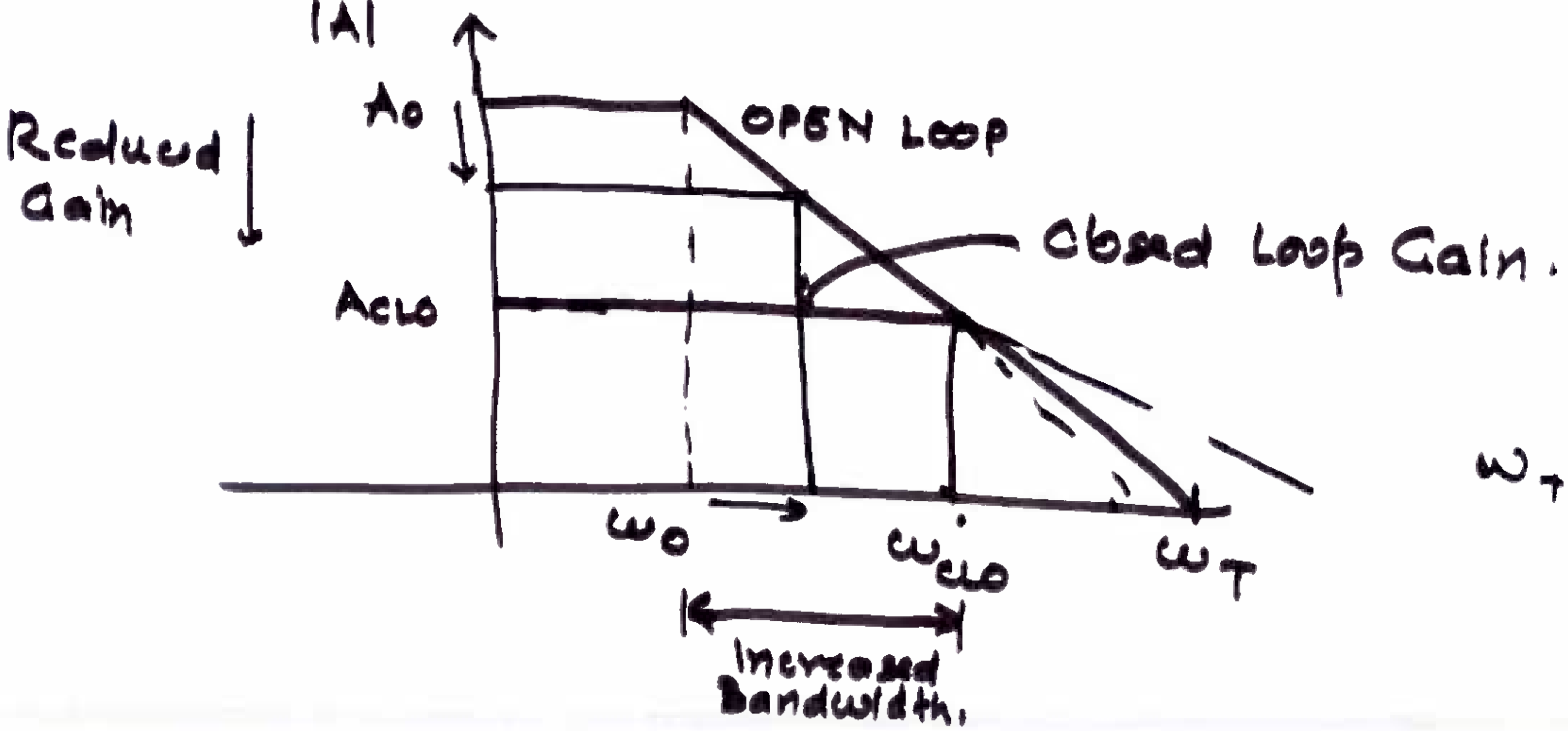
$$\therefore A_{CL}(\omega) = \frac{A_0}{1+\frac{A_0}{1+R_2/R_1}} \cdot \frac{1}{1+j\frac{\omega}{\omega_0\left[1+\frac{A_0}{1+(R_2/R_1)}\right]}}$$

Normally $\boxed{A_0 >> (1+R_2/R_1)}$

Then $A_{CLO} = \frac{A_0}{1+\frac{A_0}{1+R_2/R_1}} \simeq \left(1+\frac{R_2}{R_1}\right)$

or $A_{CL}(\omega) = \dfrac{A_{CLO}}{1 + j\dfrac{\omega}{\omega_o (A_o/A_{CLO})}}$

New Bandwidth $\omega_{CLO} = \omega_o (A_o/A_{CLO})$



$\omega_{T_{CL}} = \omega_{T_{OL}}$

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Proof that :

"ω_T is same for OPEN LOOP & Closed Loop Case"

$$|A_{CL}(\omega = \omega_T')| = 1 = \frac{A_{CLO}}{\sqrt{1 + \left[\frac{\omega_T'}{\omega_0 (A_0/A_{CLO})}\right]^2}}$$

ω_T' = Unity Gain Frequency for Closed Loop.

If square [ ] term is >> 1

Then $A_{CLO} \simeq \dfrac{\omega_T'}{\omega_0 (A_0/A_{CLO})}$

$$\therefore \omega_T' = A_{CLO} \cdot \omega_0 (A_0/A_{CLO}) = A_0 \cdot \omega_0 = \omega_T$$

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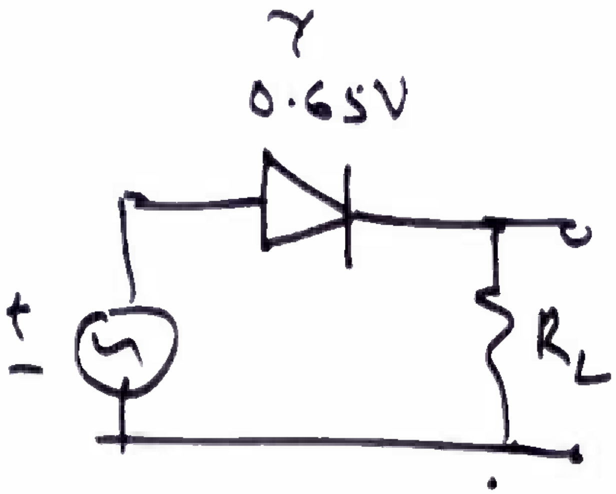

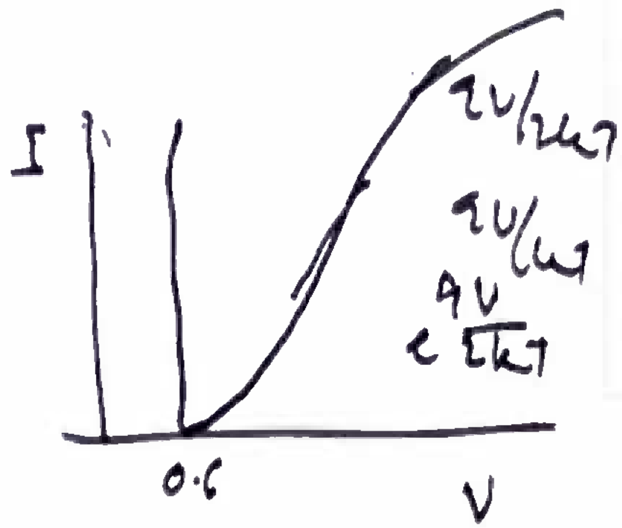

$$v_- - v_+ = v_d$$

$$= \frac{0.6}{10^5}$$

$$= 60\mu$$