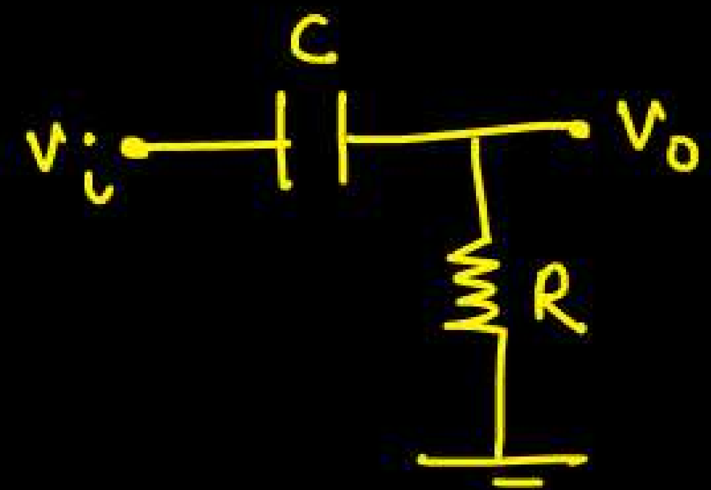
②



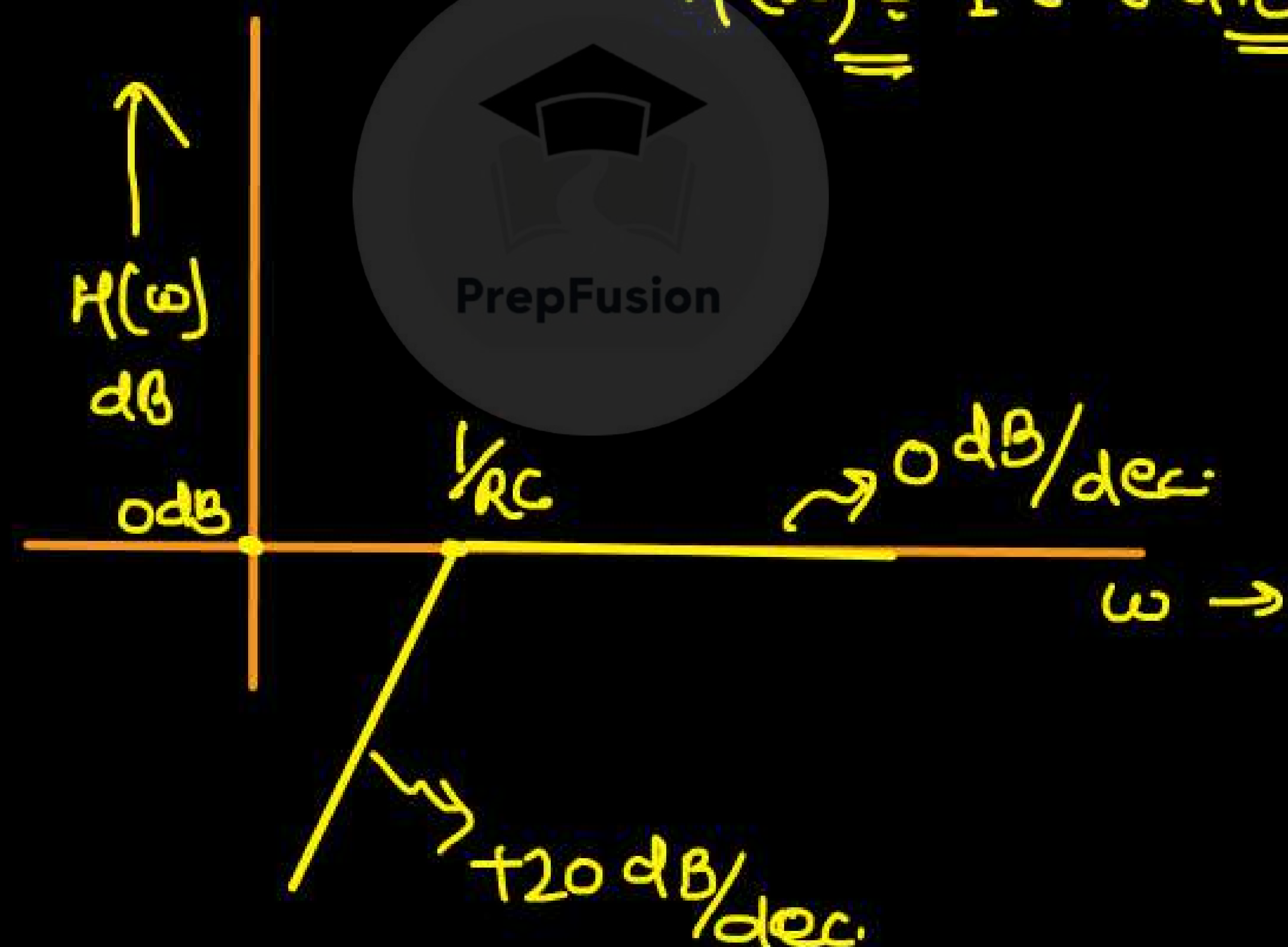
$$H(s) = \frac{sRC}{sRC+1}$$

→ Zero at

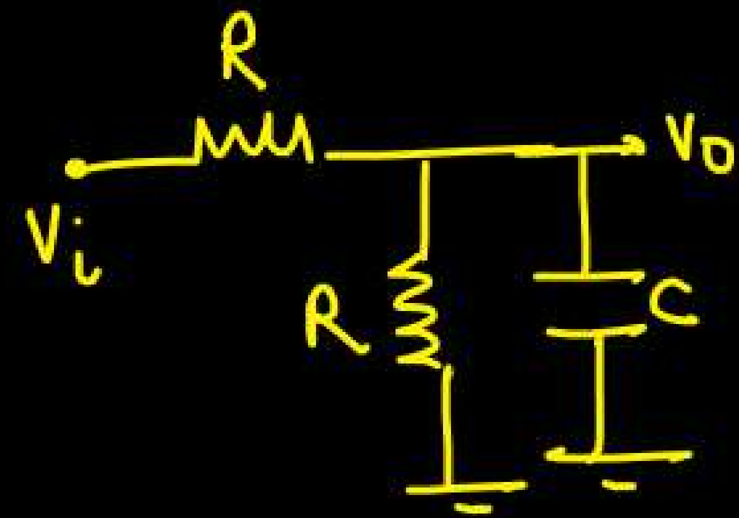
Pole at $-\frac{1}{RC}$

$H(0) = 0 = -\infty\ dB$

$H(\infty) = 1 = 0\ dB$



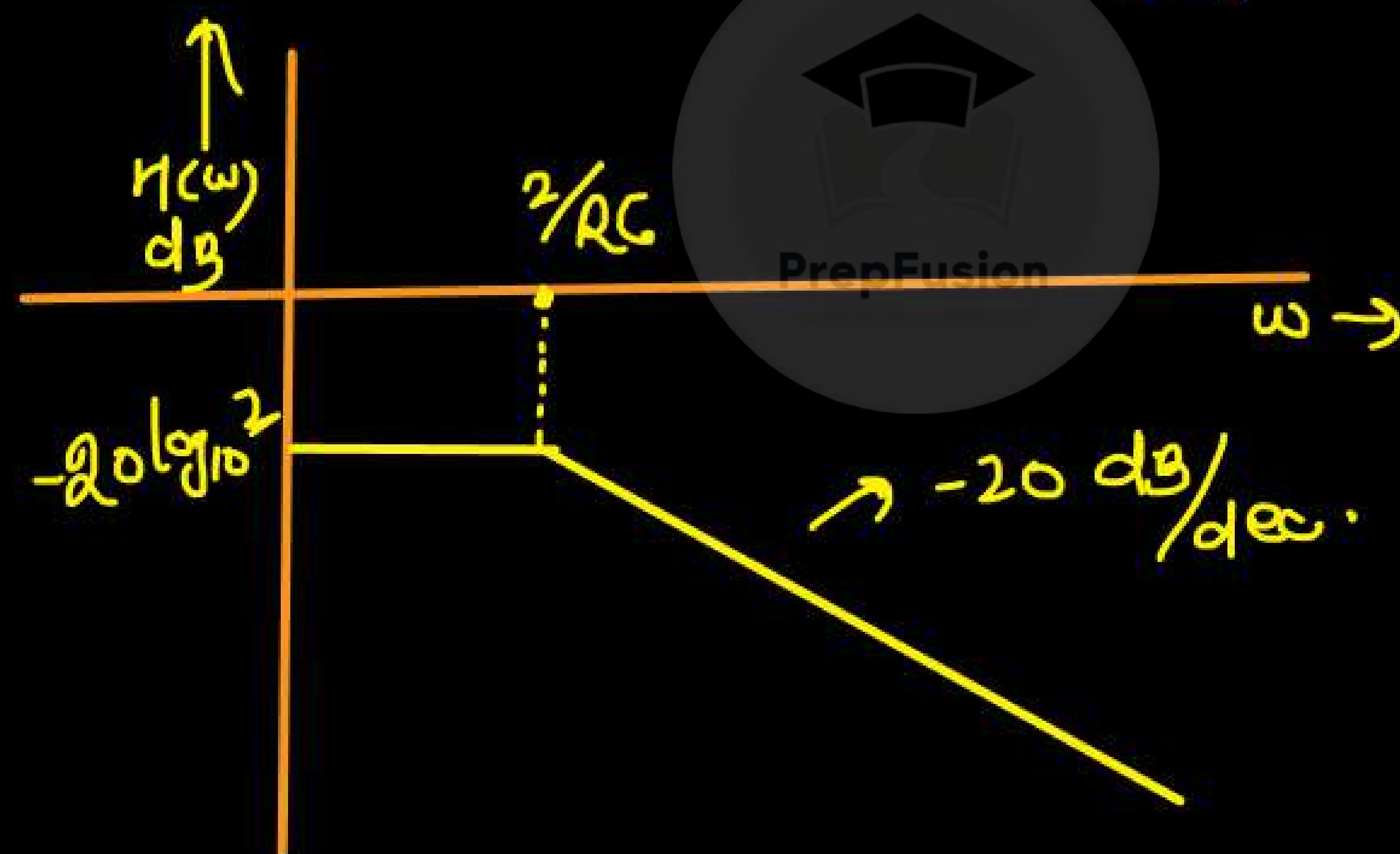
③



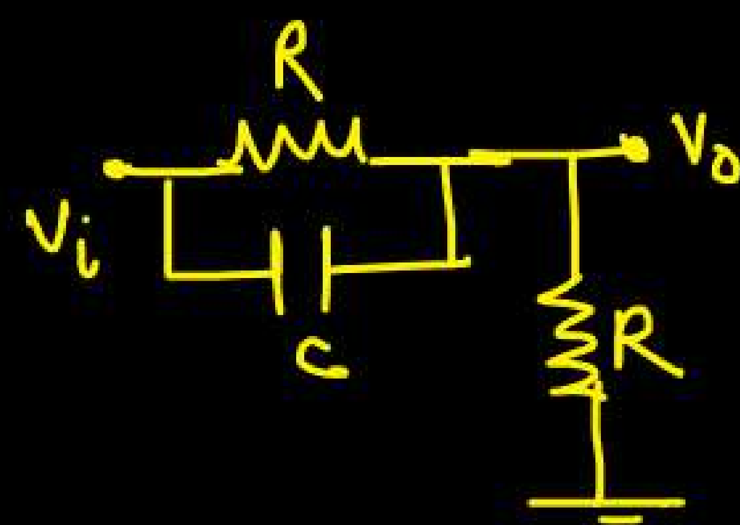
$$H(s) = \frac{1}{sRC+2} \rightarrow \text{pole a} \quad RC$$

$$H(0) = \frac{1}{2} = -20\log_{10} 2 =$$

$$H(\infty) = 0 = -\infty \text{ dB}$$



4



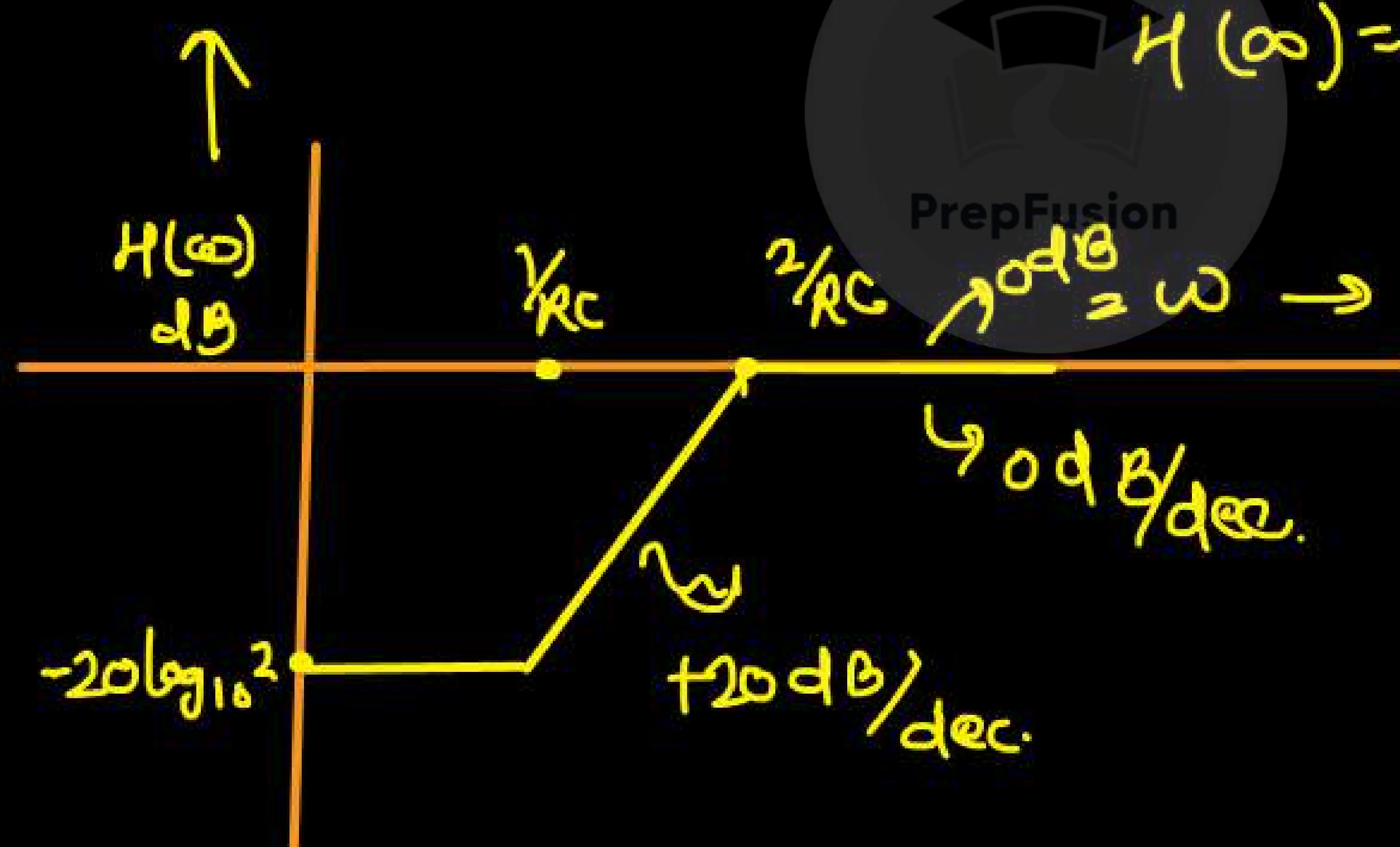
$$H(s) = \frac{sRC+1}{sRC+2}$$

Zero = $1/RC$

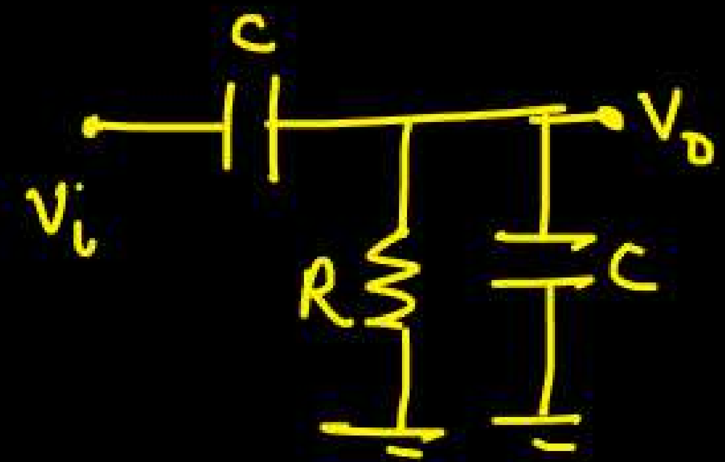
pole = $2/RC$

$$H(0) = \frac{1}{2} = -20\log_{10} 2$$

$$H(\infty) = 1 = 0\ \text{dB}$$



5

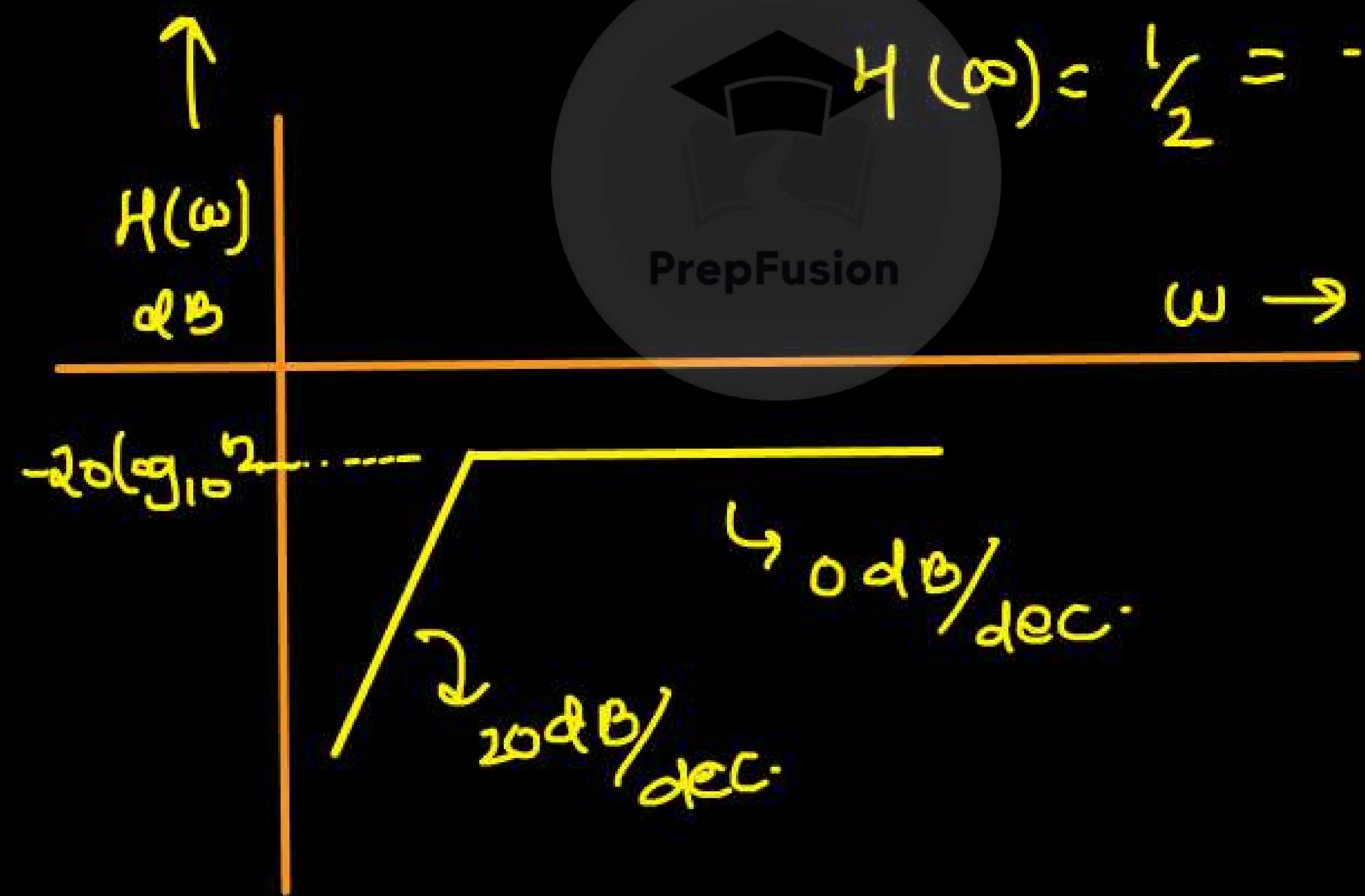


$$H(S) = \frac{SRC}{2SRC + 1} \rightarrow \text{Zer}$$

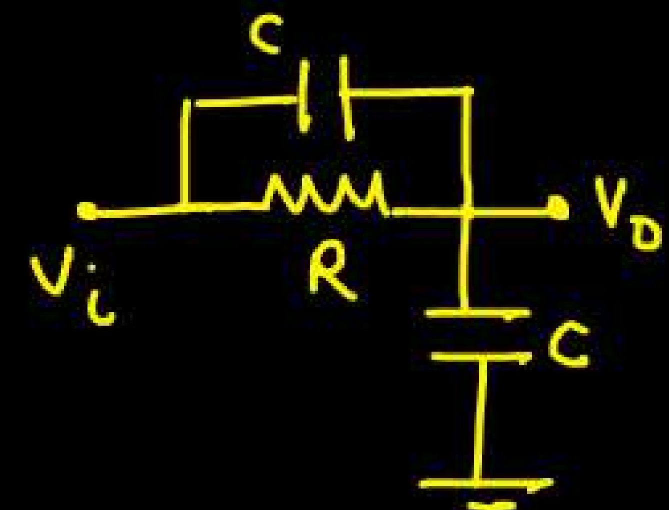
pole at $\frac{1}{2RC}$

$H(0) = 0 = -\infty \text{ dB}$

$H(\infty) = \frac{1}{2} = -20\log_{10}(2)$



6



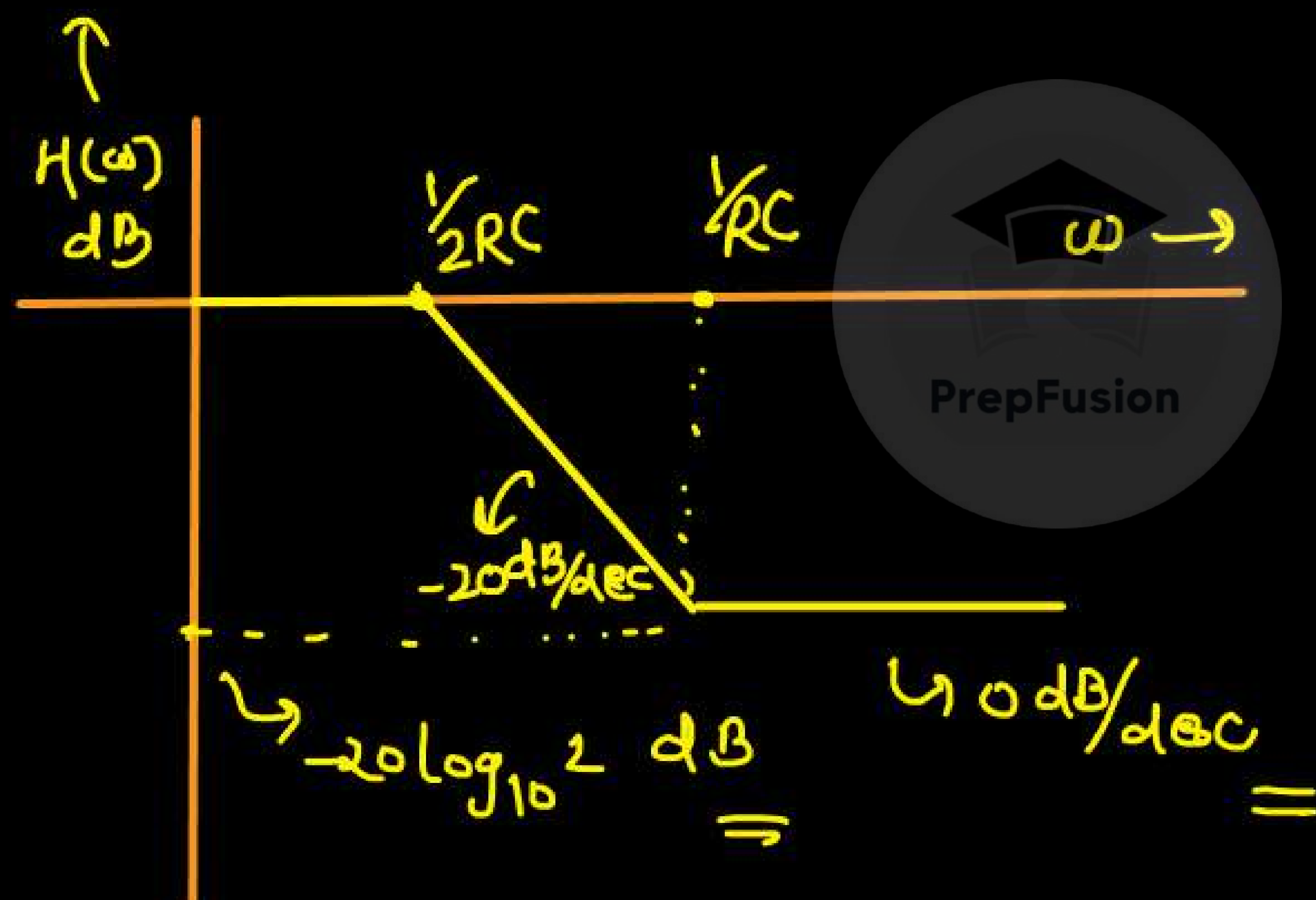
$$H(s) = \frac{sRC + 1}{2sRC + 1}$$

Zero → $\frac{1}{RC}$

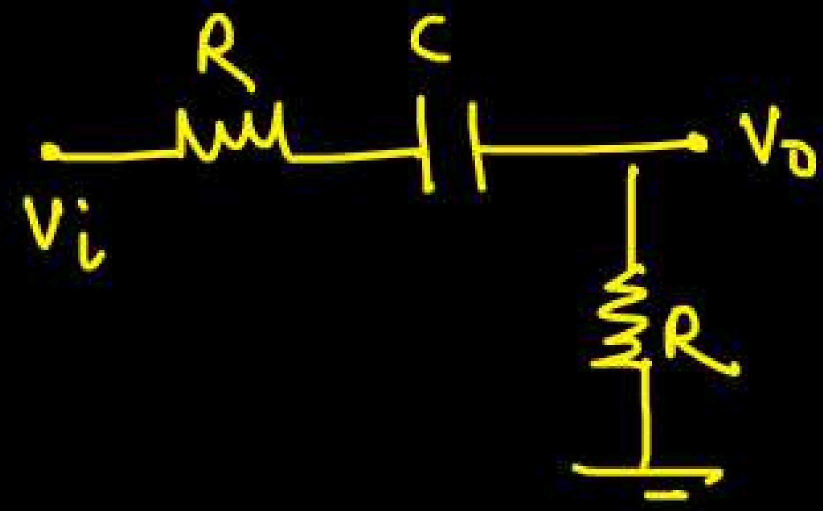
pole → $\frac{1}{2RC}$

$H(0) = 1 = 0\,dB$

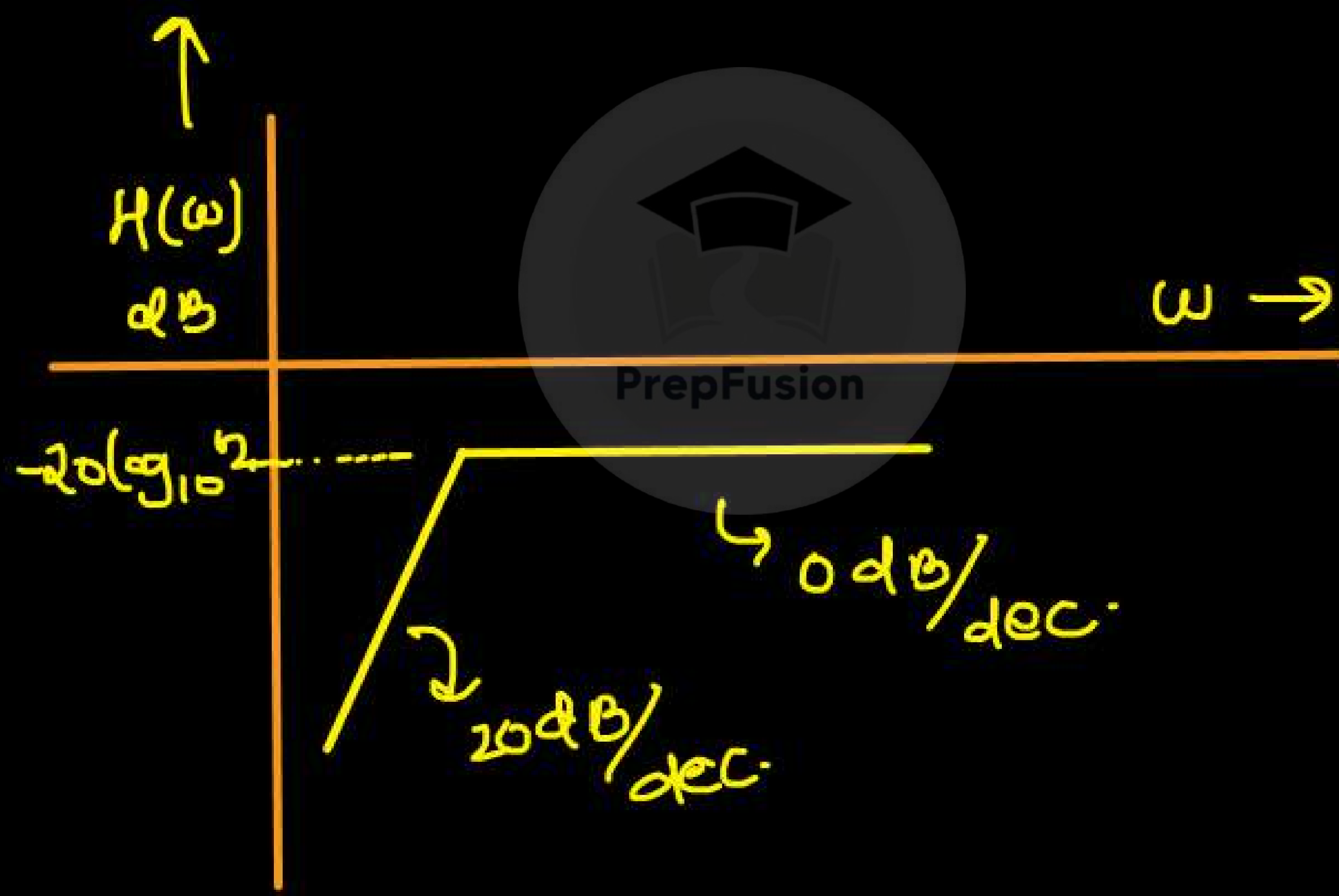
$H(\infty) = \frac{1}{2} = -20\log_{10} 2\ dB$



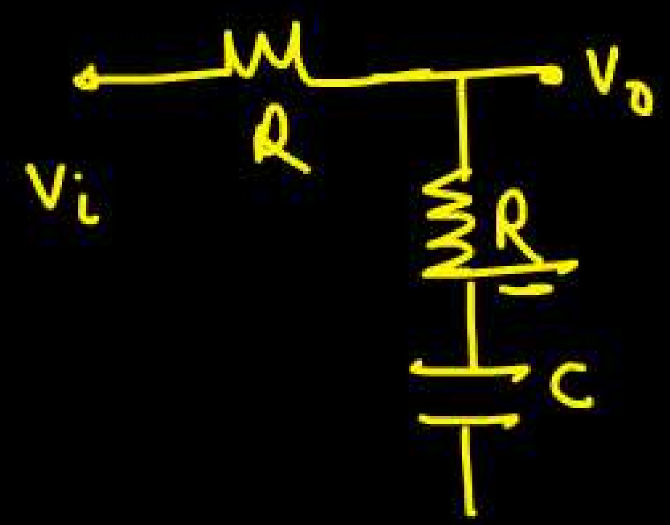
(f)



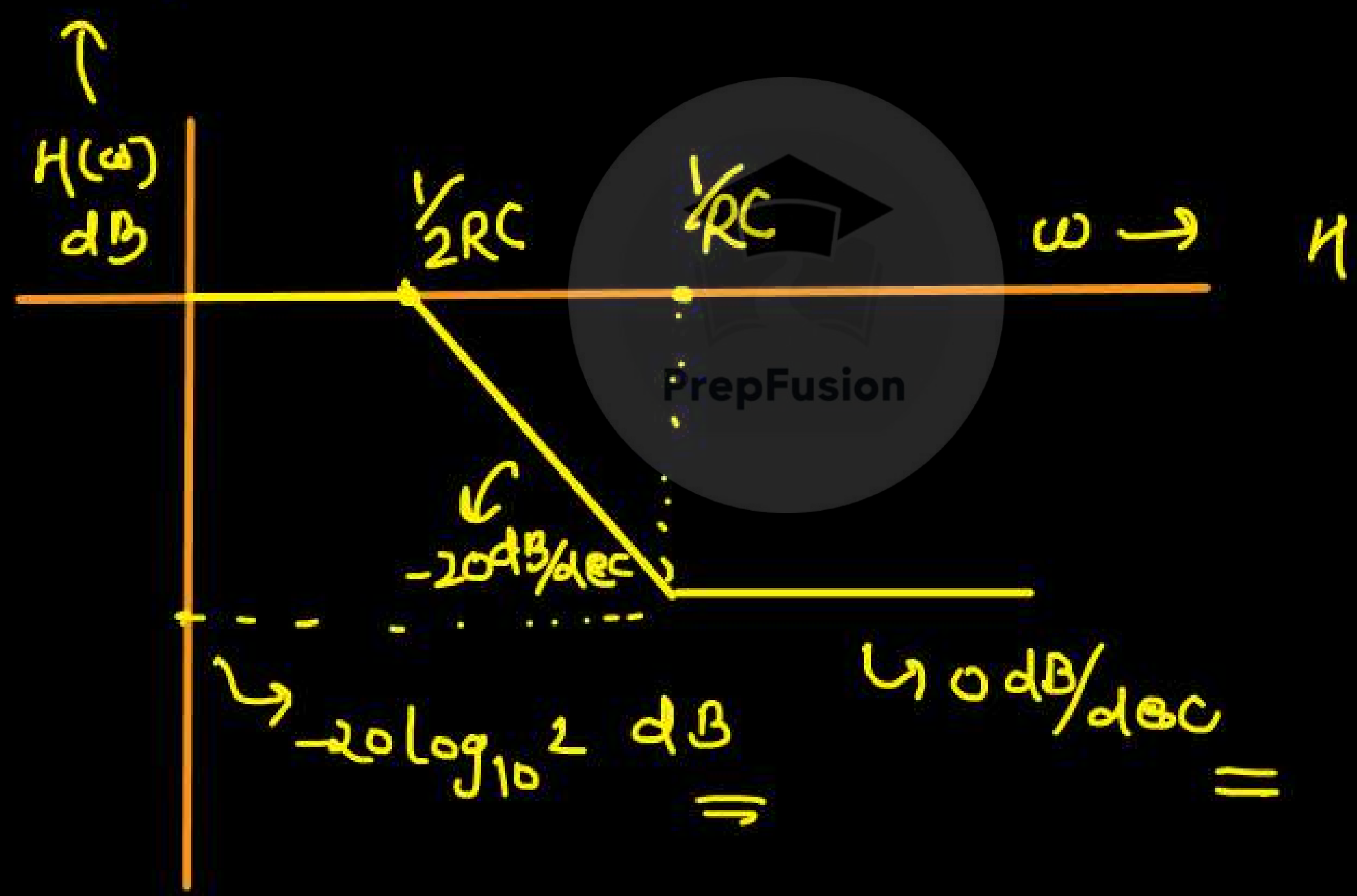
$$H(s) = \frac{sRC}{2sRC+1}$$



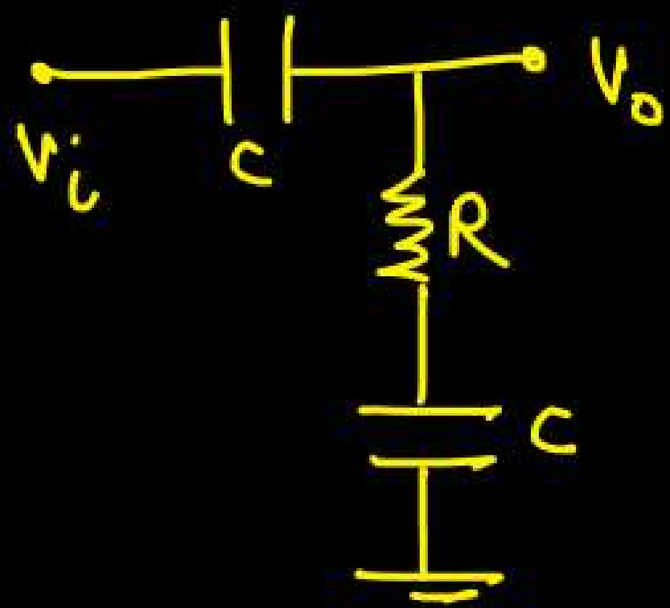
8



$$H(s) = \frac{sRC + 1}{2sRC + 1}$$

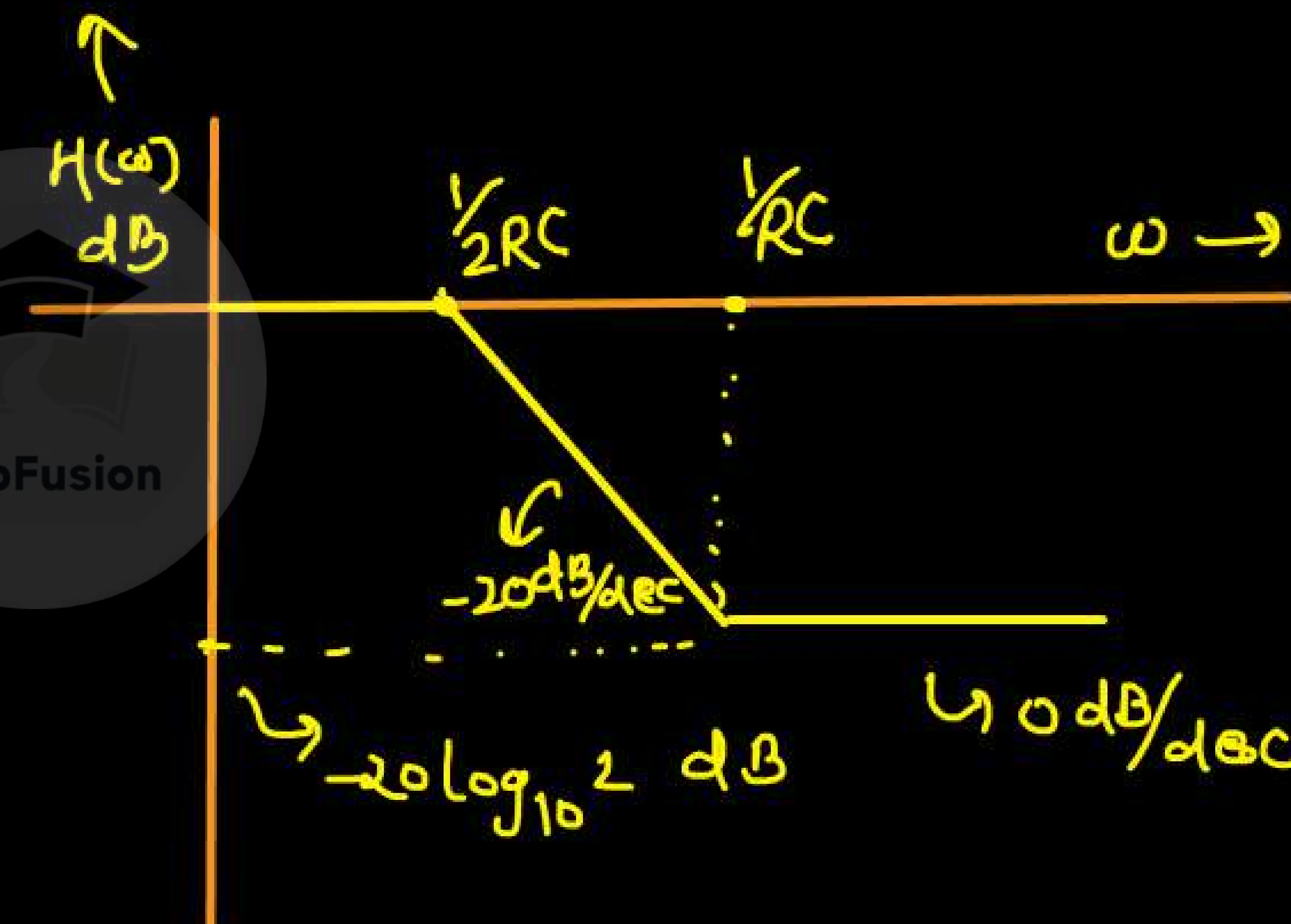


9

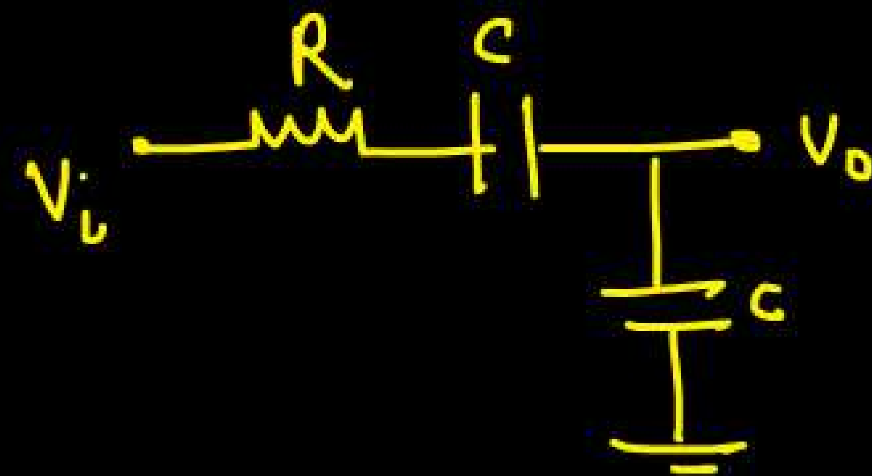


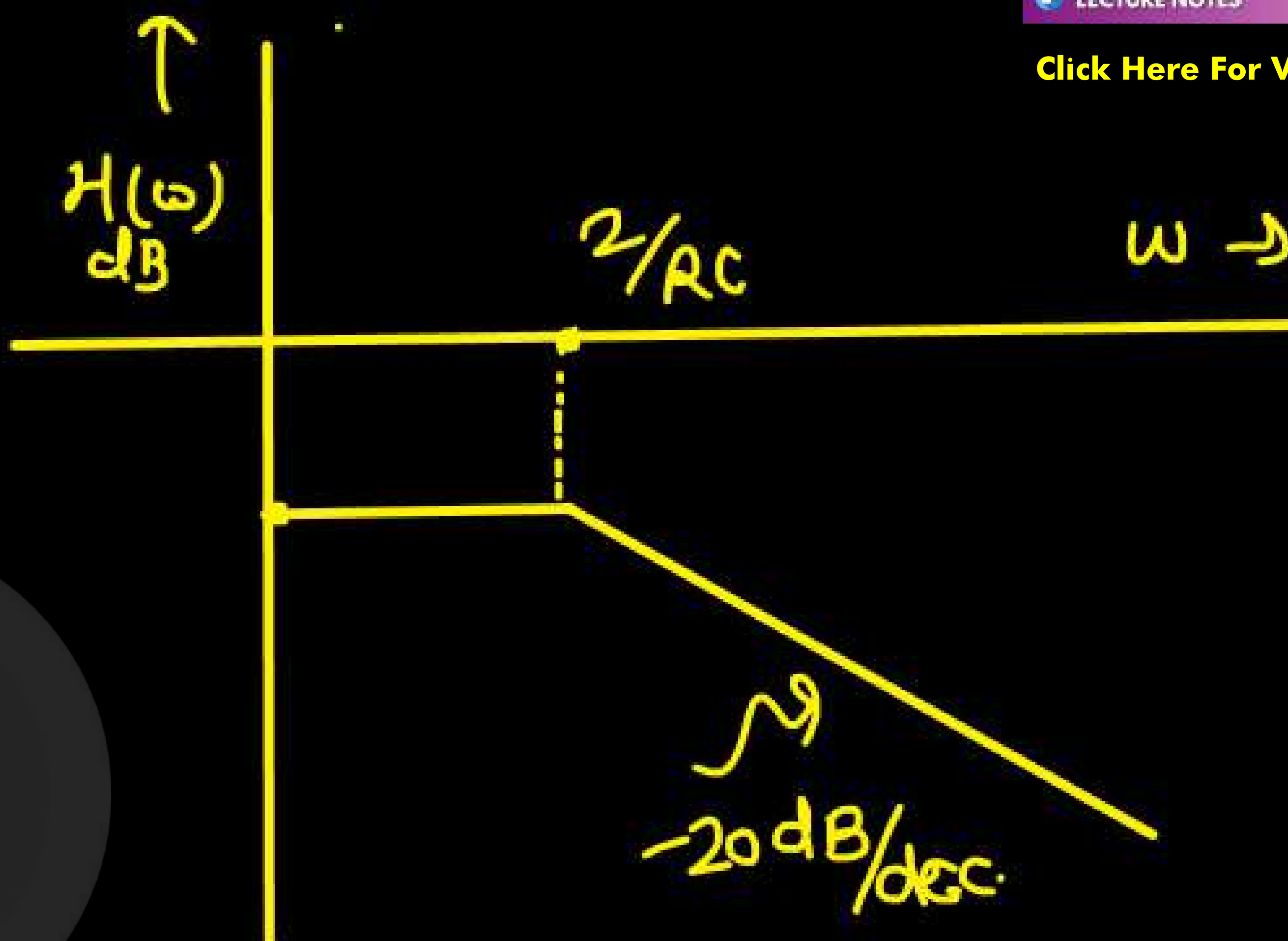
$$H(s) = \frac{sRC + 1}{sRC + 2}$$

$\Rightarrow$



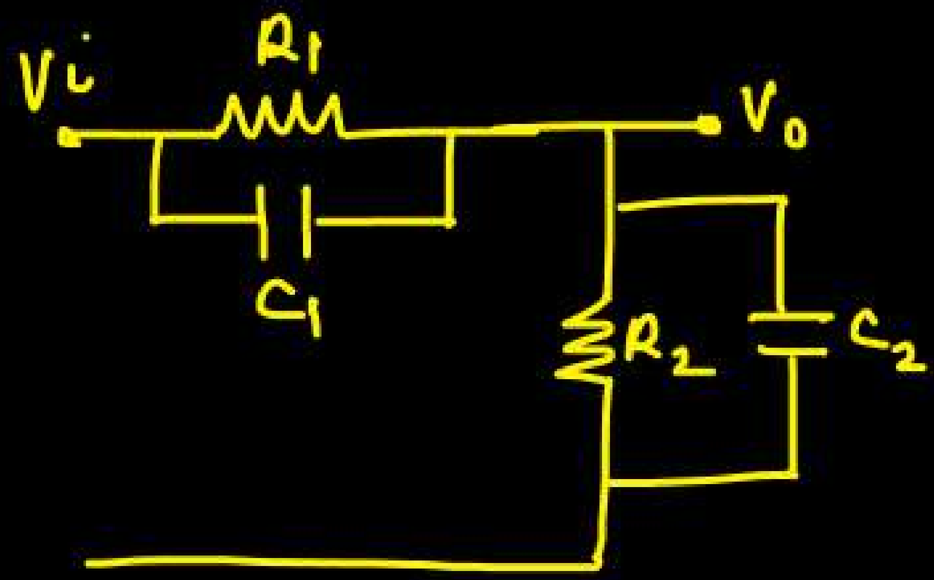
10





$$H(s) = \frac{1}{sRC + 2}$$

Q. Draw Bode plot for the given ckt.



(i) $R_1C_1 > R_2C_2$

(ii) $R_1C_1 < R_2C_2$

(iii) $R_1C_1 = R_2C_2$

→ $$\text{Poles} = \frac{-1}{(R_1 \| R_2)(C_1+C_2)}$$

$$\text{Zero} = \frac{-1}{R_1C_1}$$

(i) $R_1C_1 > R_2C_2 \Rightarrow \frac{R_1}{R_2} > C_2/C_1$

$@ \ \omega=0 \Rightarrow V_0(\omega=0) = \frac{R_2}{R_1+R_2} V_i(\omega=0)$

$$H(\omega=0) = \frac{R_2}{R_1+R_2} = \frac{1}{1+R_1/R_2}$$

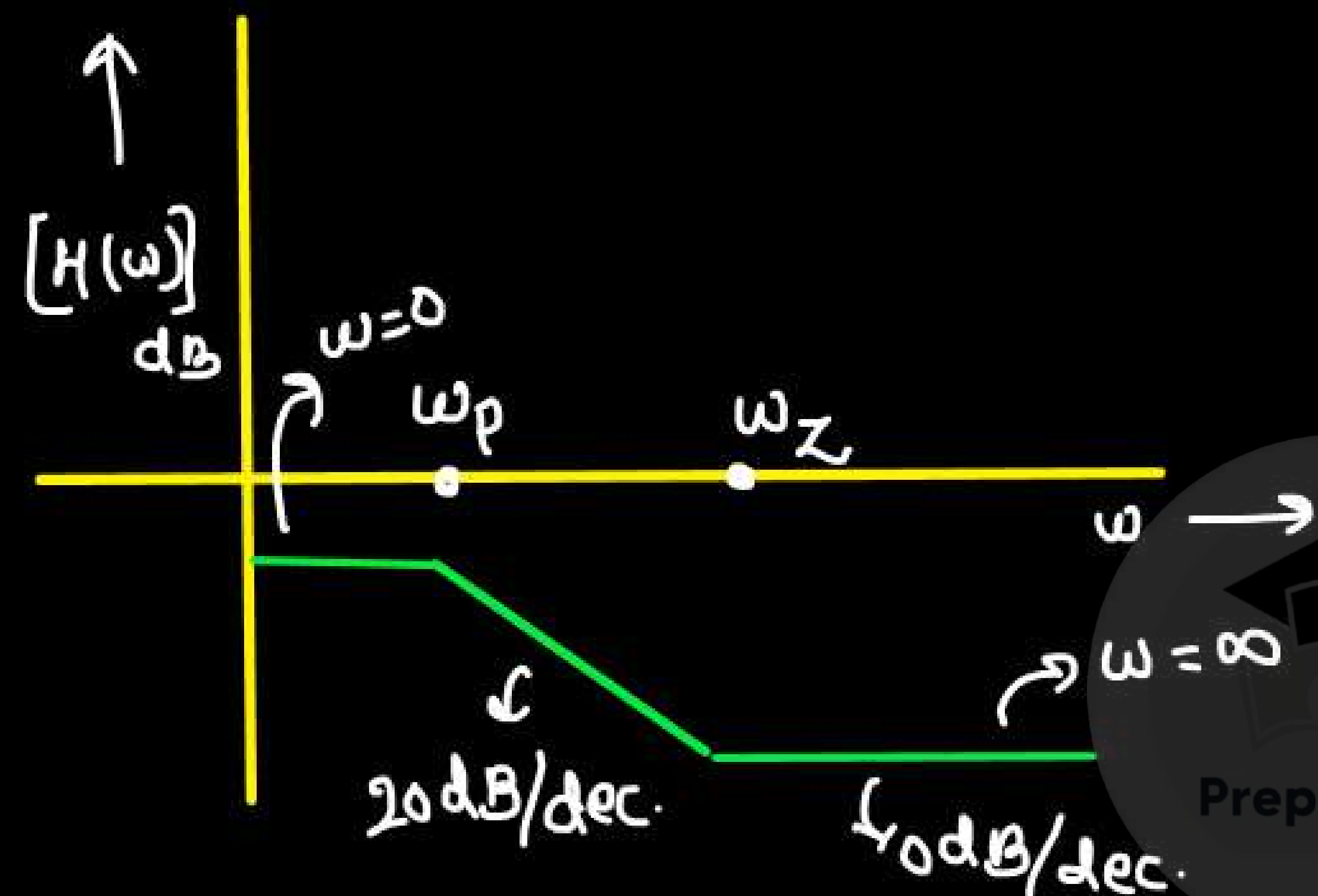
$1/3$

given: $\frac{R_1}{R_2} > \frac{C_2}{C_1}$

$$H(\omega=\infty) = \frac{C_1}{C_1+C_2} = \frac{1}{1+C_2/C_1}$$

$$\boxed{H(\omega=0) < H(\omega=\infty)}$$

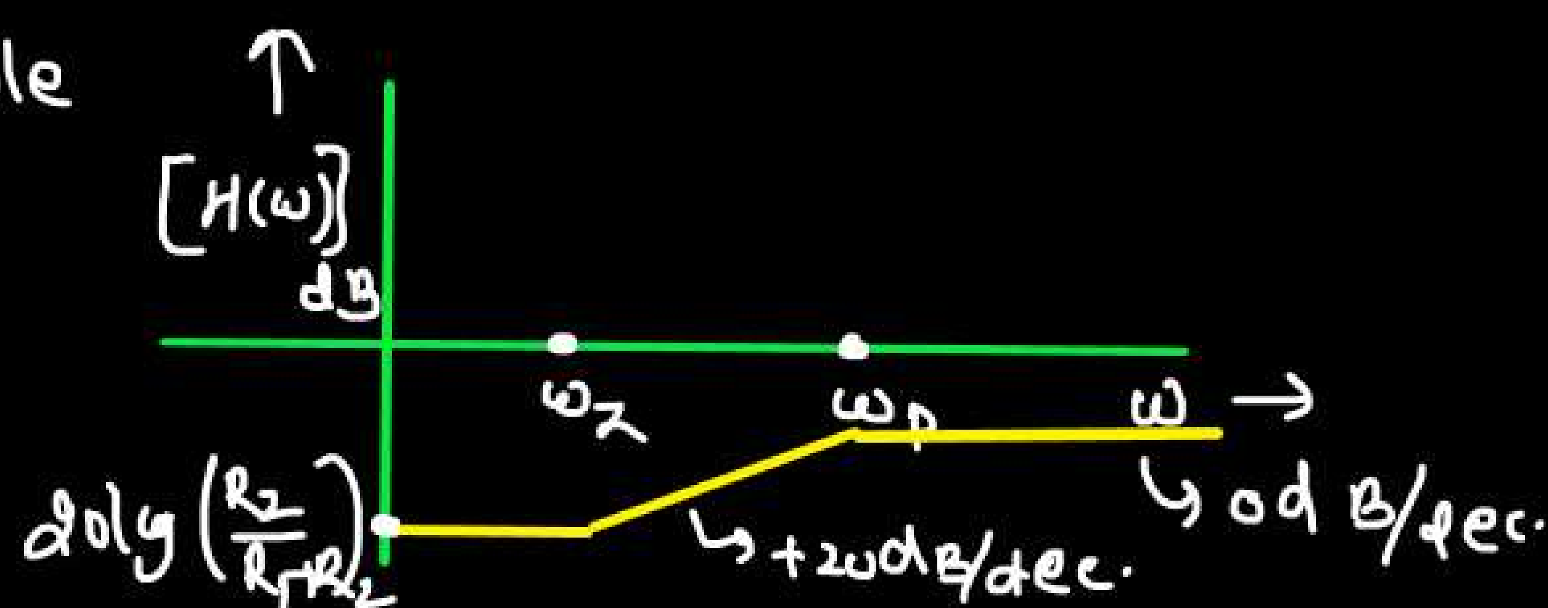
Assume pole < zero



$$\boxed{H(\omega=0) > H(\omega=\infty)}$$

NOT possible

⇒ zero < pole



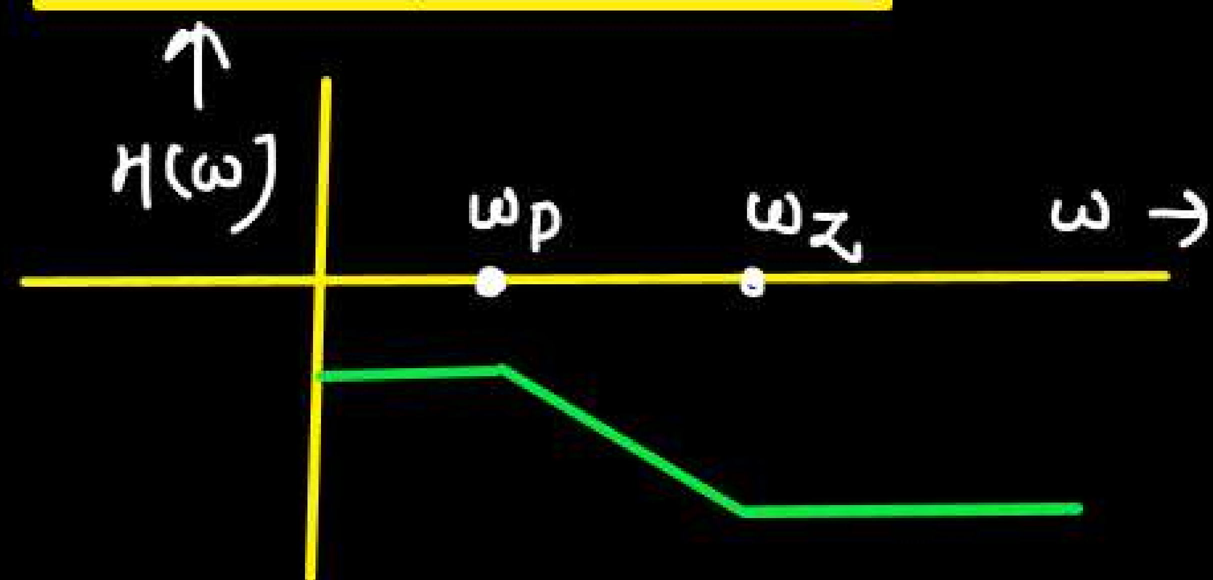
(ii) $R_1C_1 < R_2C_2 \Rightarrow \dfrac{R_1}{R_2} < \dfrac{C_2}{C_1}$

$$H(\omega=0) = \frac{R_2}{R_1+R_2} = \frac{1}{1+\frac{R_1}{R_2}}$$

$$H(\omega=\infty) = \frac{C_1}{C_1+C_2} = \frac{1}{1+\underbrace{C_2/C_1}}$$

$$\frac{R_1}{R_2} < \frac{C_2}{C_1}$$

$$\boxed{H(\omega=\infty) < H(\omega=0)}$$



zero > pole

(iii) $R_1C_1 = R_2C_2$

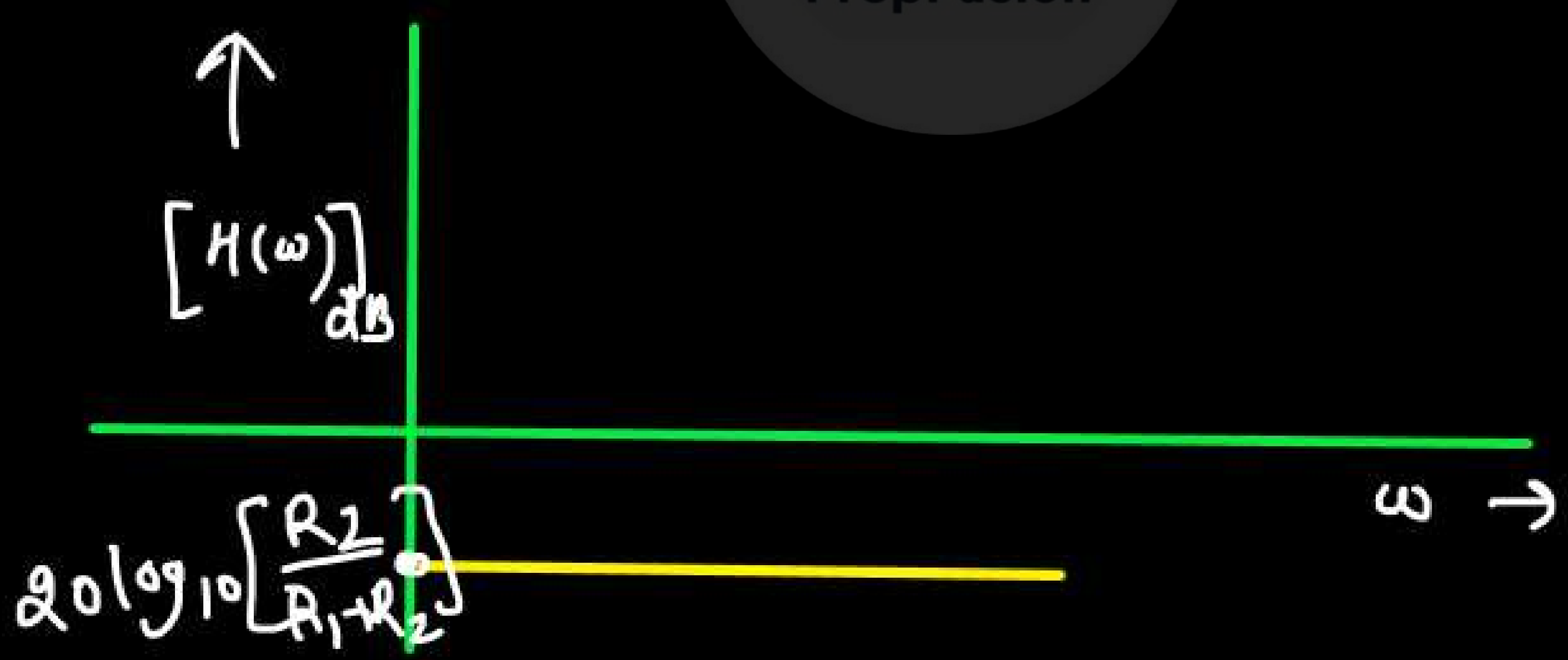
$$H(\omega=0) = \frac{R_2}{R_1+R_2}$$

$$H(\omega=\infty) = \frac{C_1}{C_1+C_2}$$

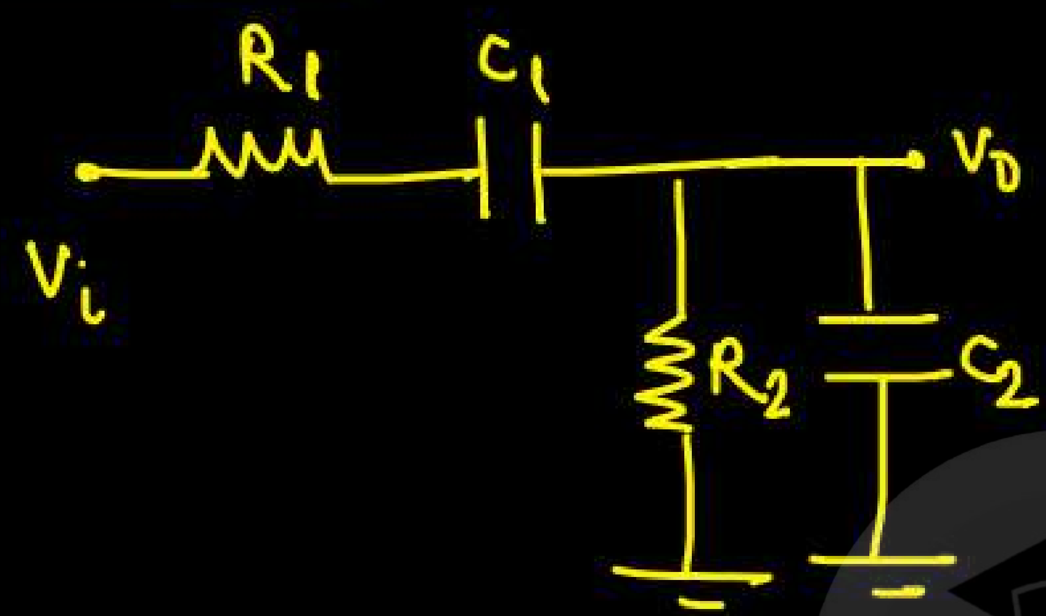
; $R_1C_1 = R_2C_2$

$$\frac{R_1}{R_2} = \frac{C_2}{C_1}$$

$$\Rightarrow \boxed{H(\omega=0) = H(\omega=\infty)}$$



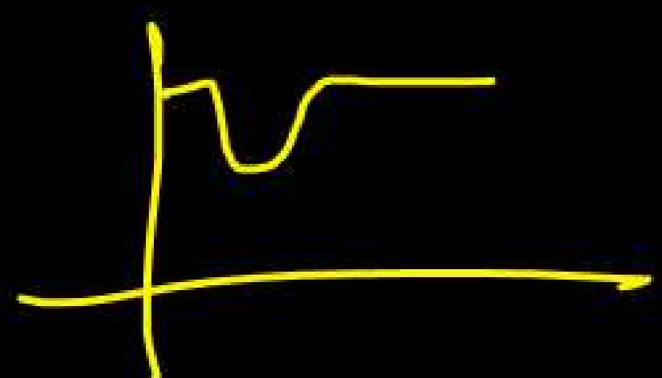
2^{nd} order ckt:-

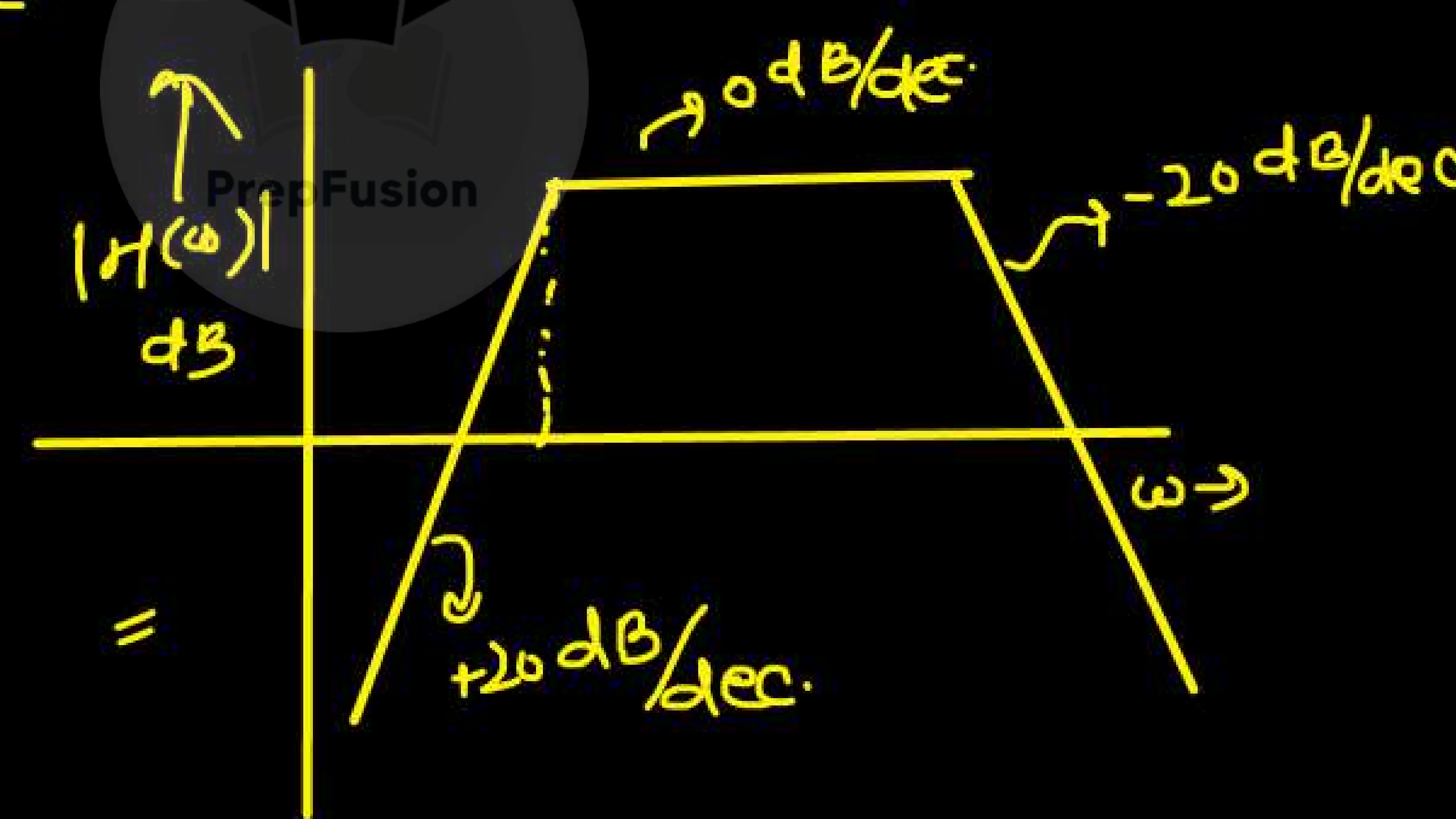


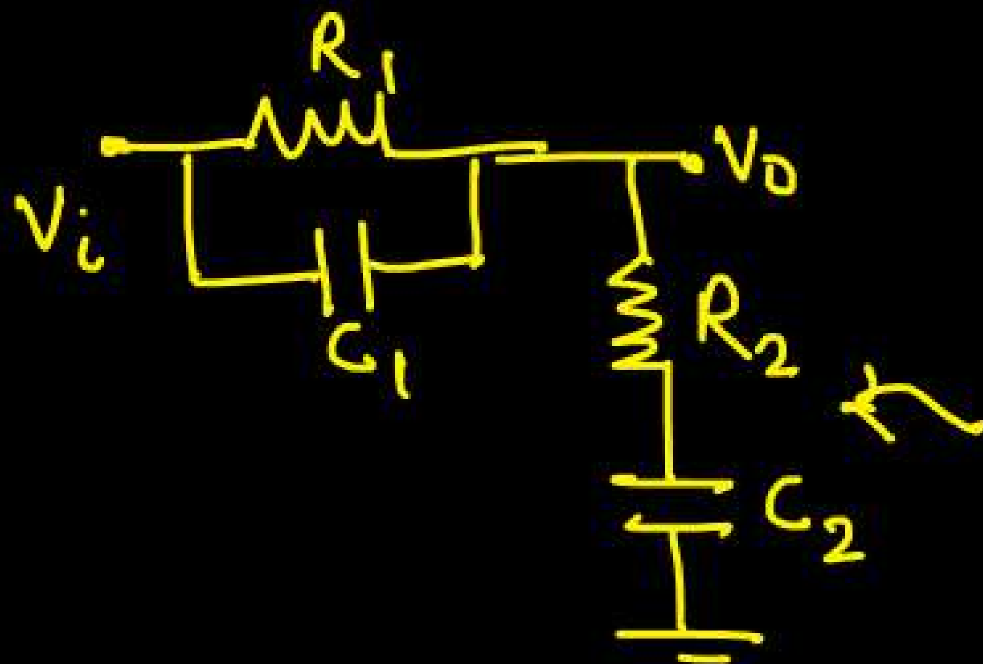
$$H(s) = \frac{AS}{s^2 + bs + C}$$

pole = two

$$H(0) = 0 = -\infty \, dB$$







$$H(s) = \frac{A(sR_1C_1+1)(sR_2C_2+1)}{s^2+bs+c}$$

→ zero at $1/R_1C_1$, $\frac{1}{R_2C_2}$

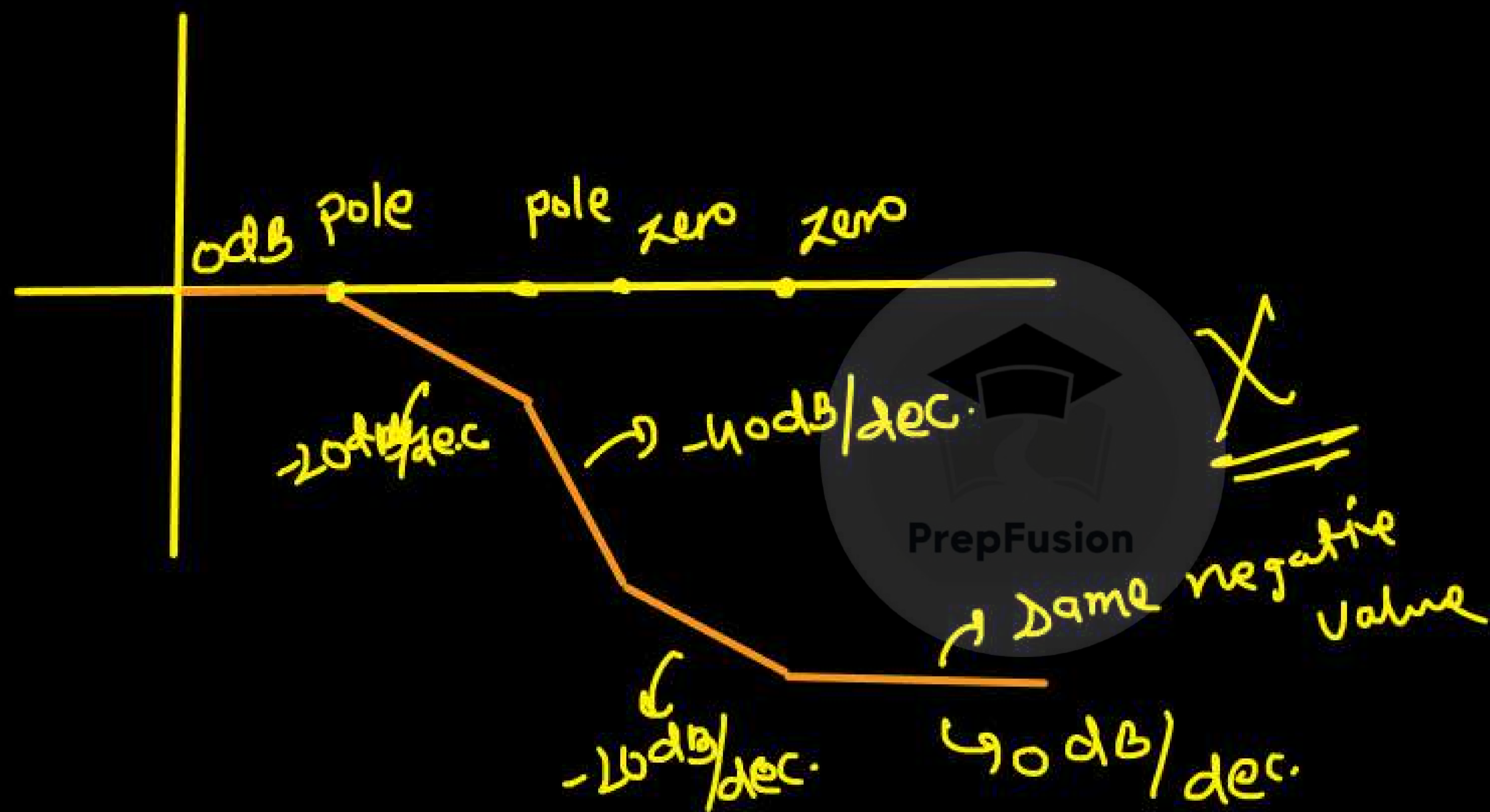
~> poles = two

$H(0) = 1 = 0\ \text{dB}$

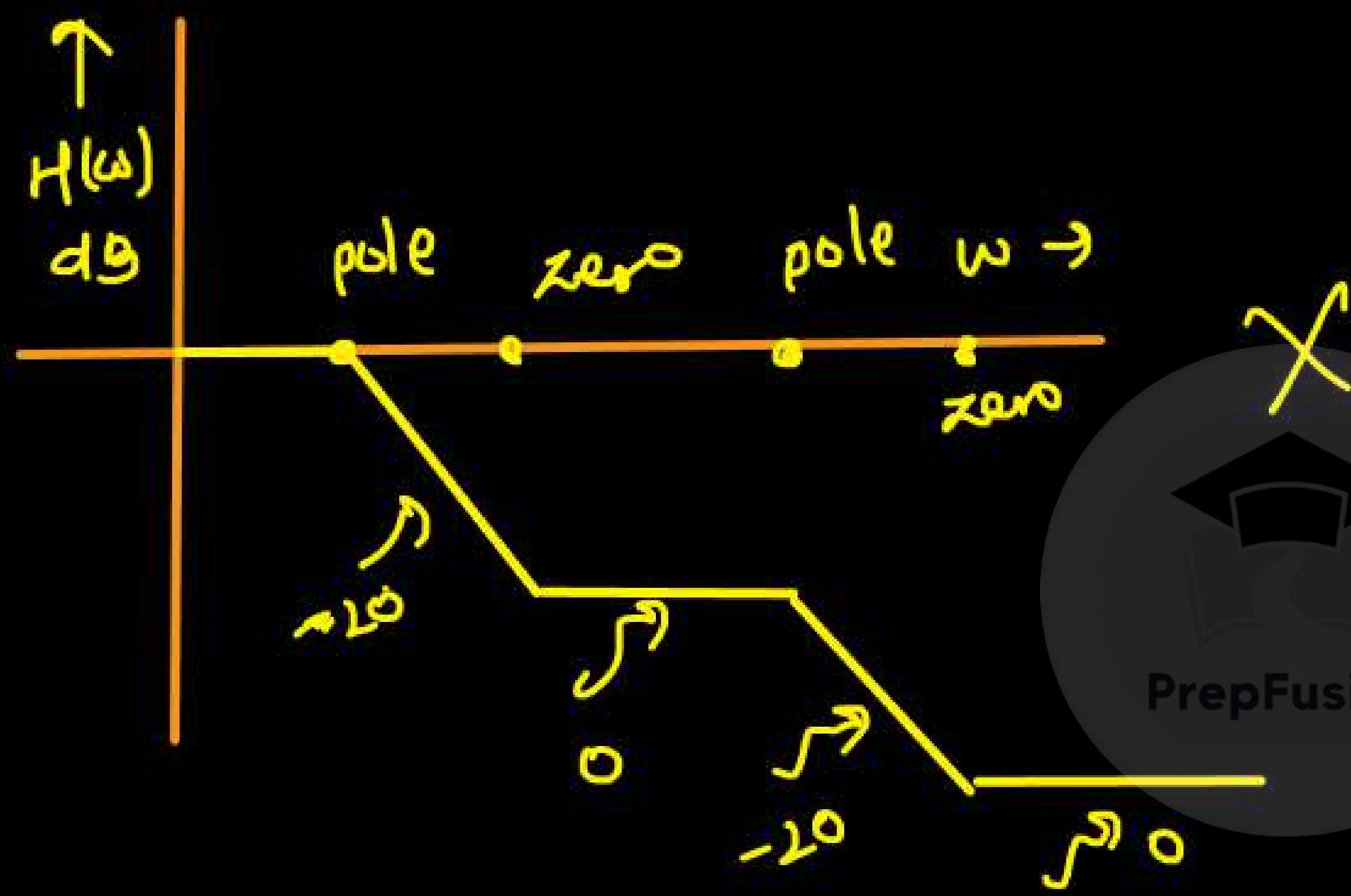
$H(\infty) = 1 = 0\ \text{dB}$

① pole, pole, zero, zero

② zero, zero, p



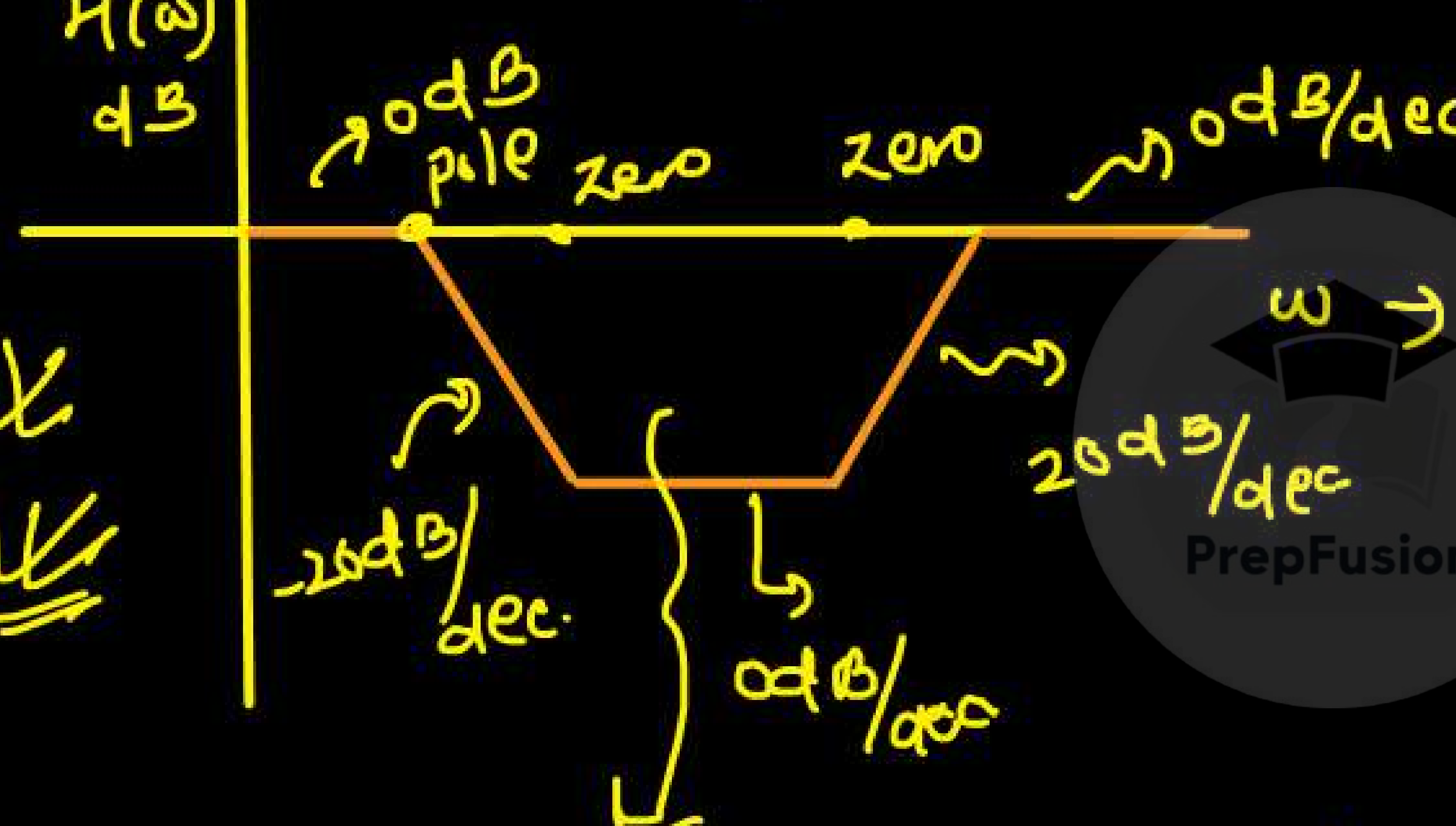
③ pole, zero, pole, zero



④ zero, pole, z

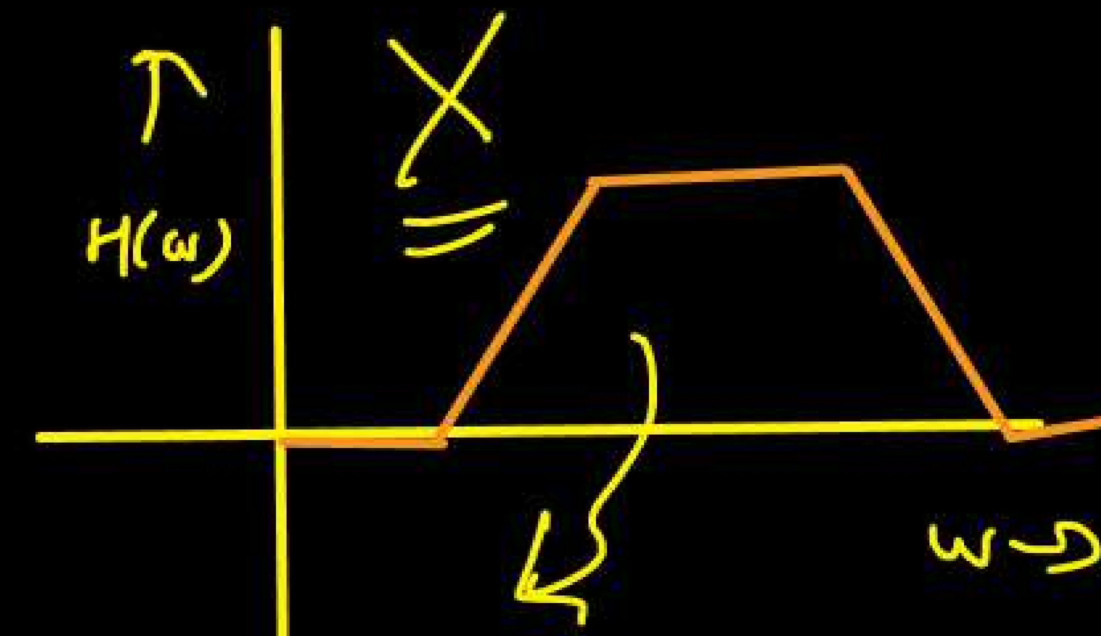
⑤ pole, zero, zero, pole ✓

✓ correct one



gain is always lesser than 1 ($V_0 \leq V_i$)

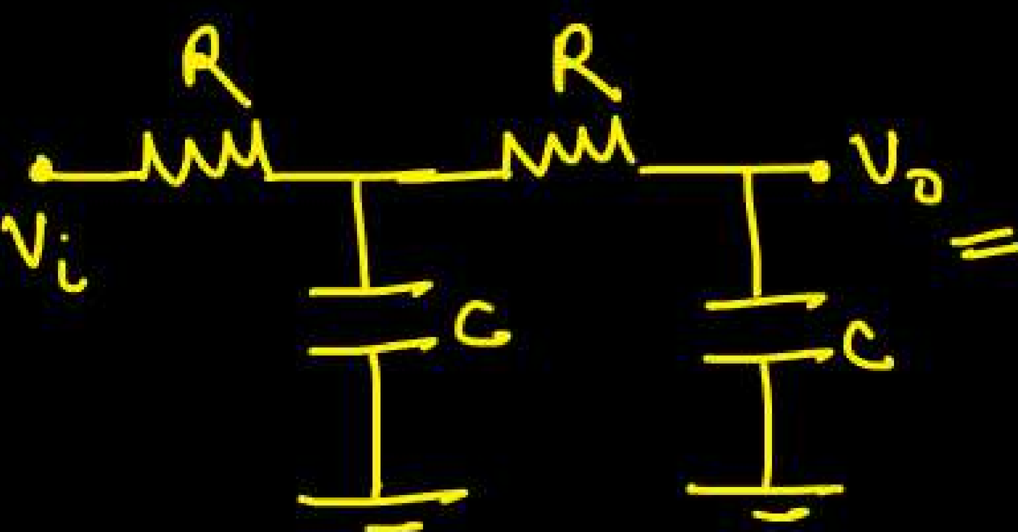
⑥ zero, pole, p



gain goes higher than 1

P, P, Z, Z
Z, Z, P, P
Z, P, Z, P
P, Z, P, Z
P, Z, Z, P ✓
Z, P, P, Z

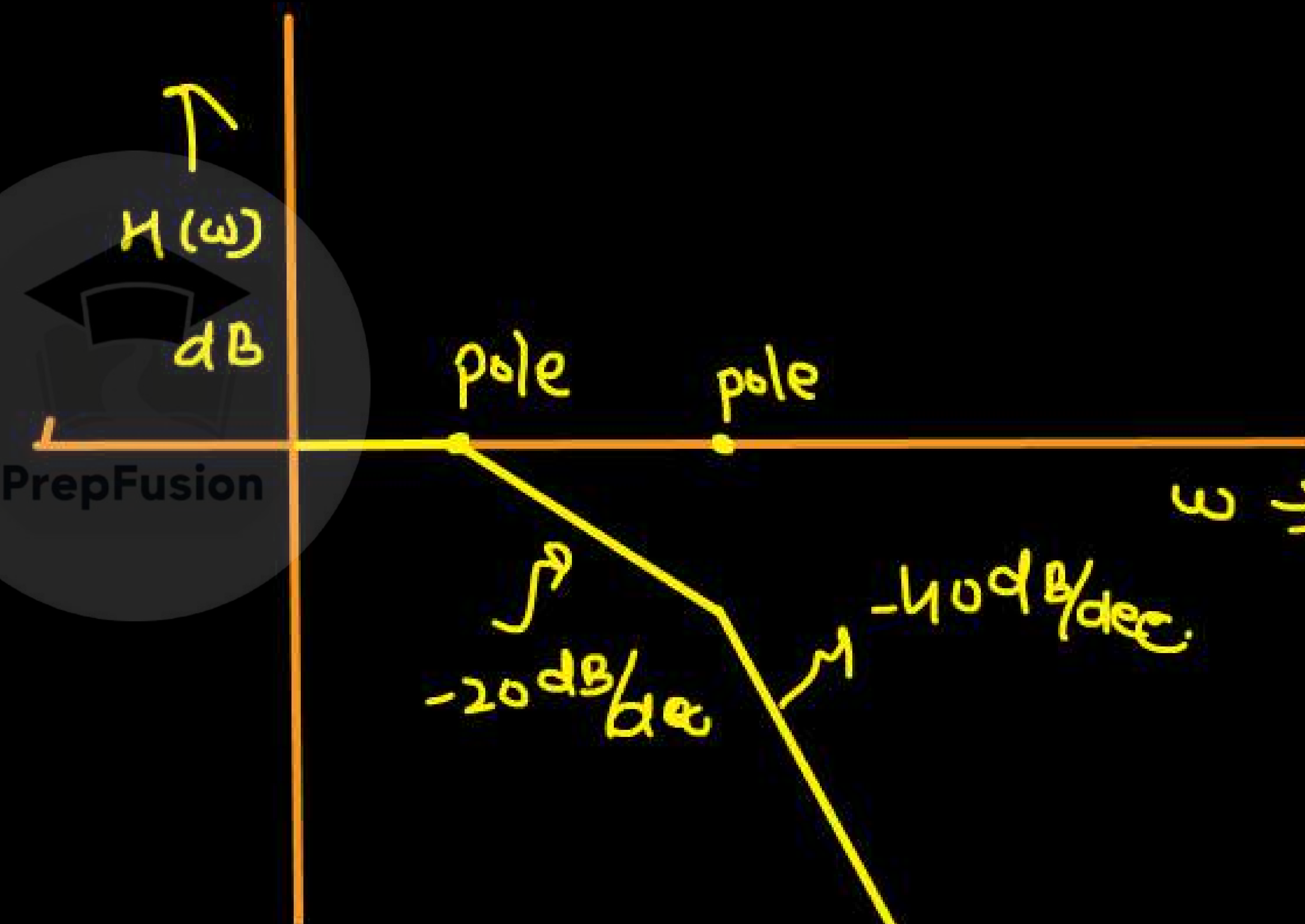
3



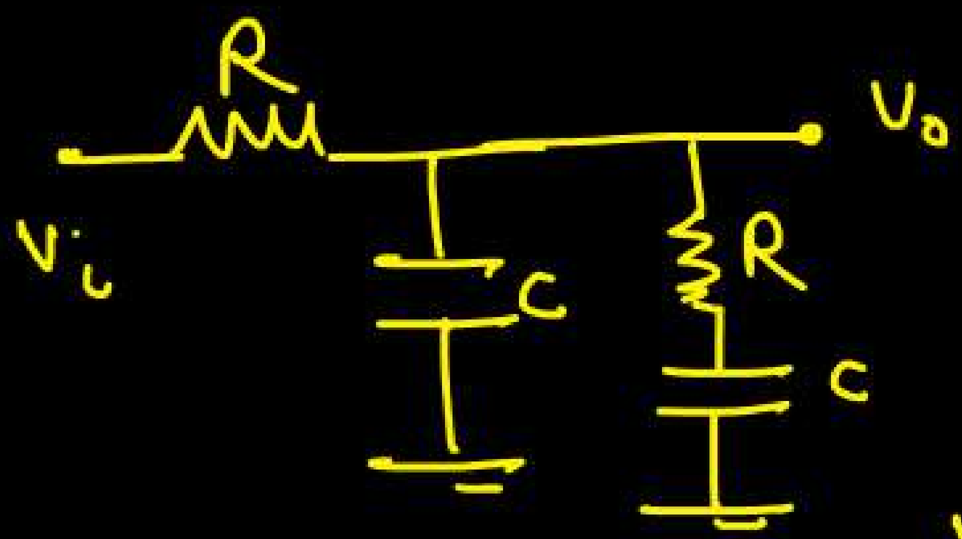
$$H(s) = \frac{A}{s^2 + bs + c}$$

$H(0) = 1 = 0\,dB$

$H(\infty) = 0 = -\infty\,dB$



(4)



Two poles

$V_o < V_i$

(ii) Zeros

$R + \frac{1}{Cs} = 0 \Rightarrow S_Z = -\frac{1}{RC}$

$S = \infty \Rightarrow \frac{1}{Cs} = 0$ ✓

↳ $V_0 = 0 \Rightarrow S_Z = \infty$

$H(0) = 1 = 0\,dB$

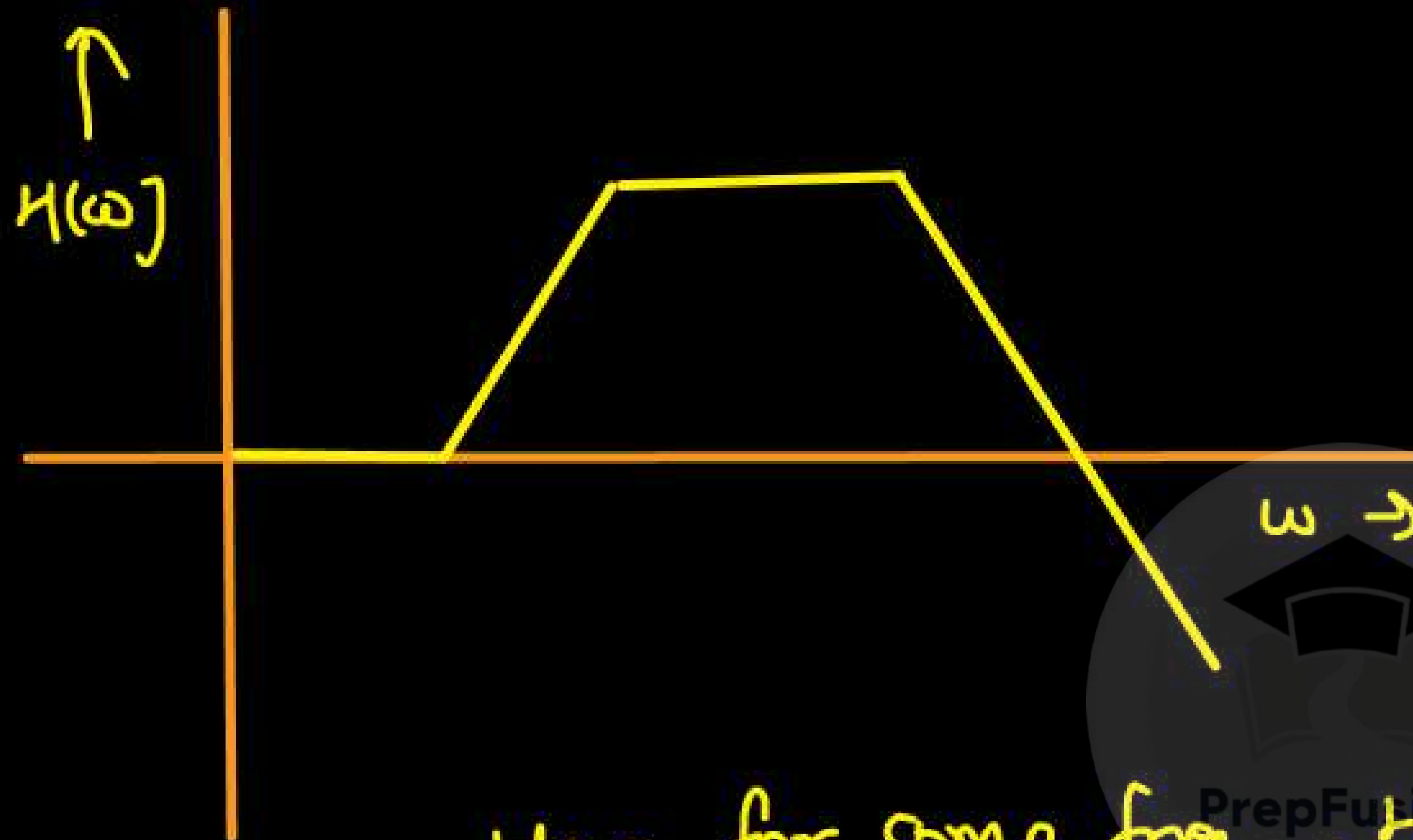
$H(\infty) = -\infty\,dB$

$$H(s) = A\frac{(sRC + 1)}{(s^2 + as + b)}$$

1 zero
2 poles

$V_o < V_i \Rightarrow H(\omega)\Big|_{dB} < 0\,dB$

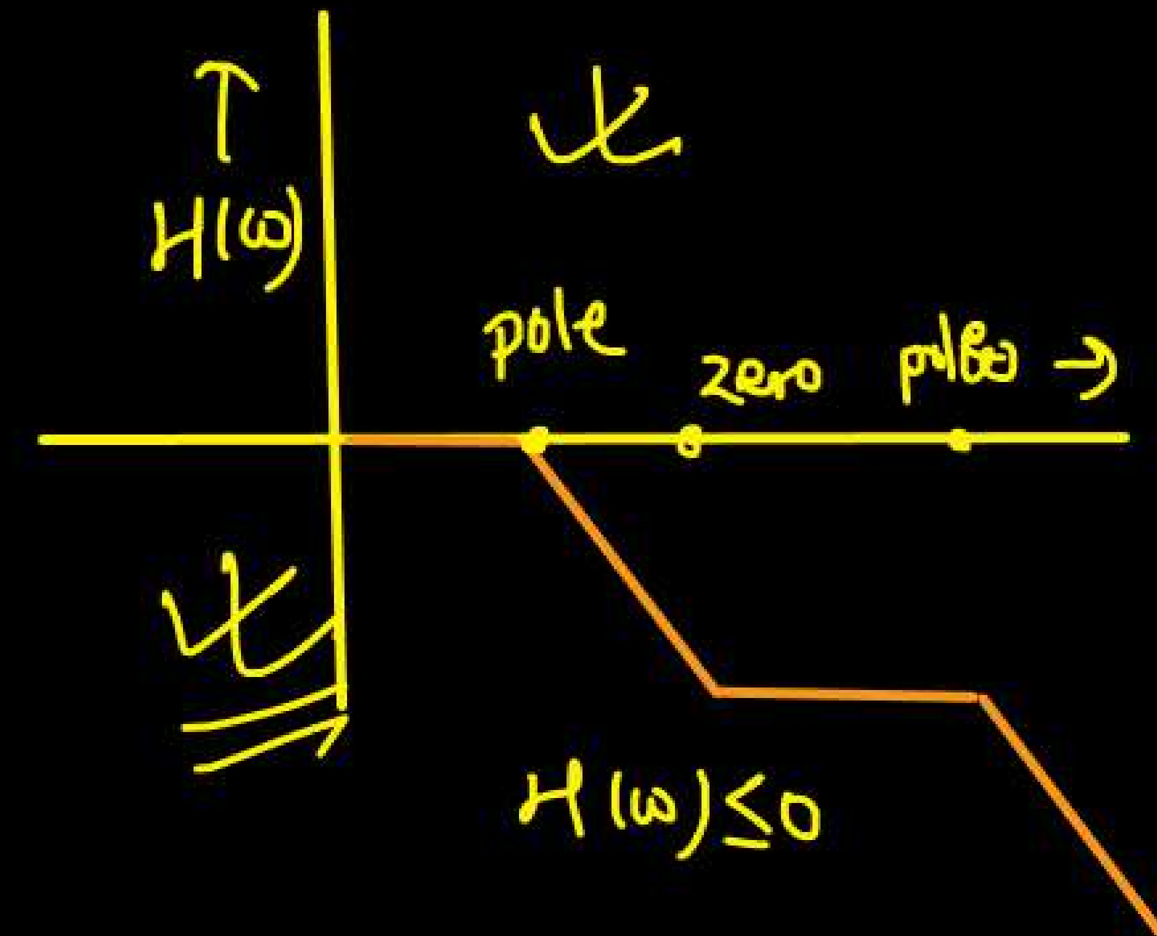
① zero, pole, pole



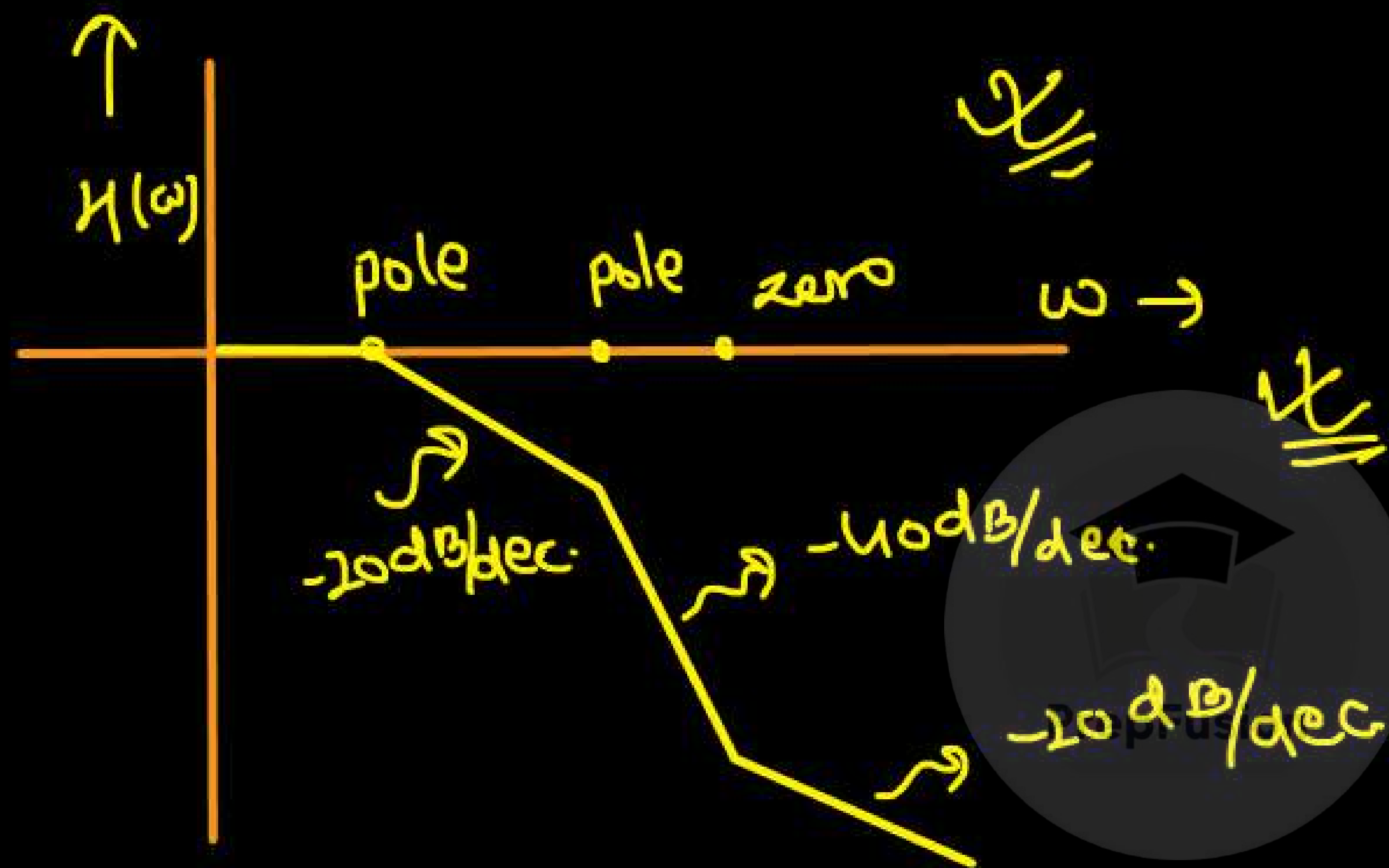
Here for some freq., $H(\omega) > 0$

↳ not possible

② pole, zero



③ pole, pole, zero

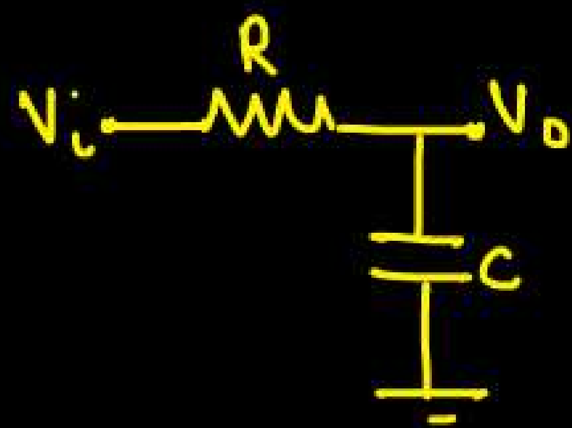


P, P

P, Z, P

Z, P, P

Q. Draw the bode plot for given RC ckt.



$R = 2\Omega$

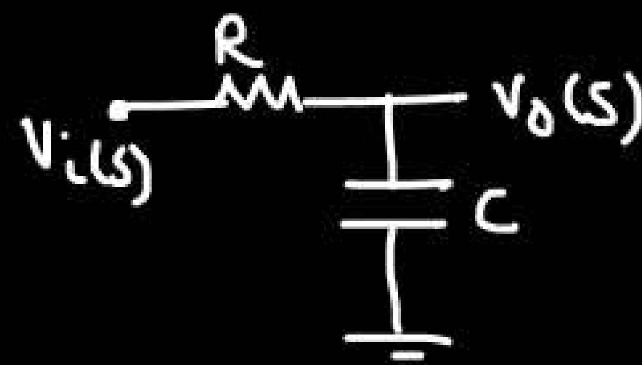
$C = 1F$

For which value of V_i ckt will have the max^m attenuation? and min^m

$V_i = 50mV \sin\left(\frac{t}{4}\right) \rightarrow 0.25$ rad/sec

$V_i = 50mV \sin(2t) \rightarrow 2$ rad/sec

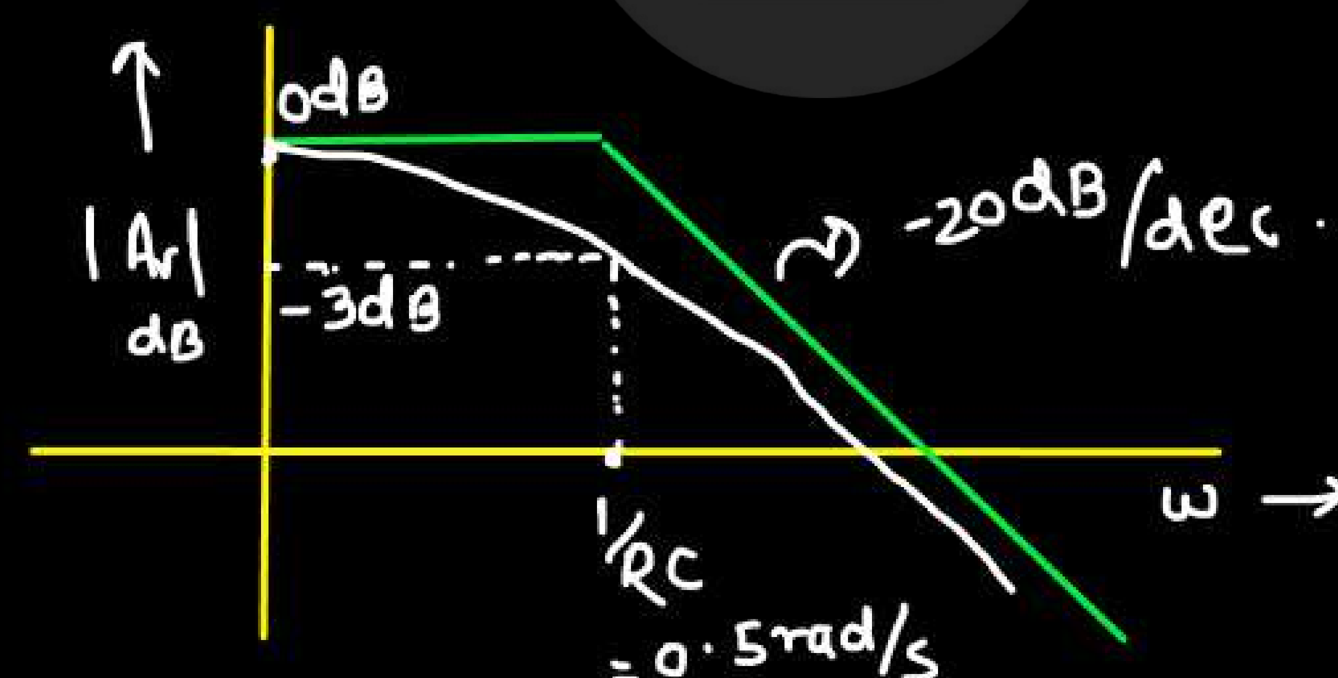
$V_i = 50mV \sin(20t) \rightarrow 20$ rad/sec

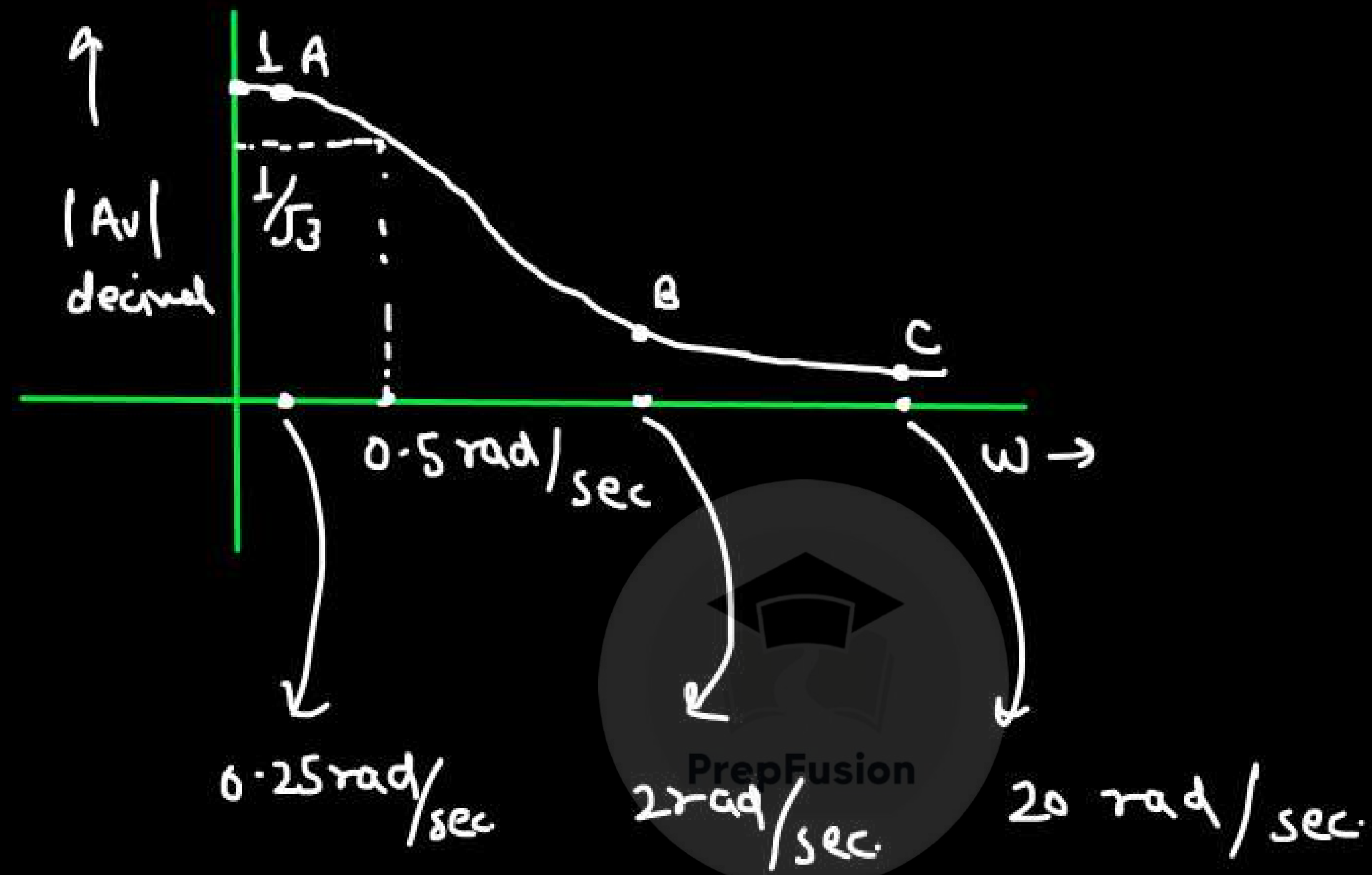


$$\boxed{\frac{V_o(s)}{V_i(s)} = \frac{1}{1+RCs}}$$

$\omega_p = -\frac{1}{RC}$, $\omega_z = \infty$

$\omega_p = -\frac{1}{2\times 1} = -0.5\ \text{rad/sec}$





$$\left(\frac{V_o}{V_i}\right)_{0.25\,r/sec.} > \left(\frac{V_o}{V_i}\right)_{2\,rad/se} > \left(\frac{V_o}{V_i}\right)_{20\,rad/sec.}$$

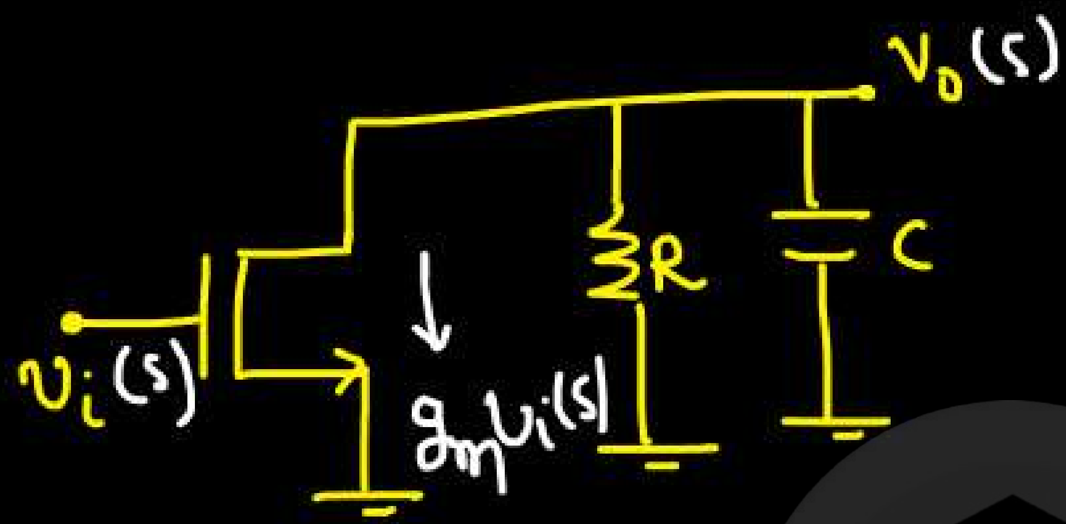
$\Downarrow$

max gain $\Rightarrow$ min attenuation

$\Downarrow$

min gain = max^m attenuation

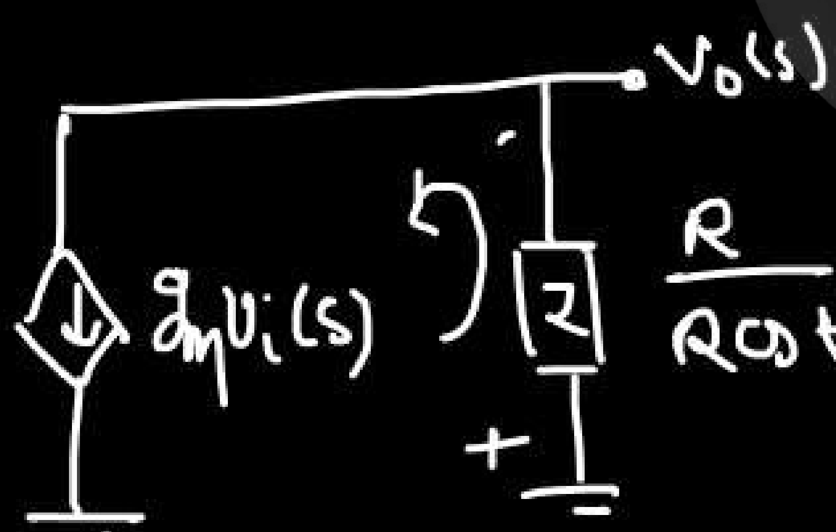
Q. Plot the frequency response.



(a)

$$\frac{v_o(s)}{v_i(s)} = ?$$

→

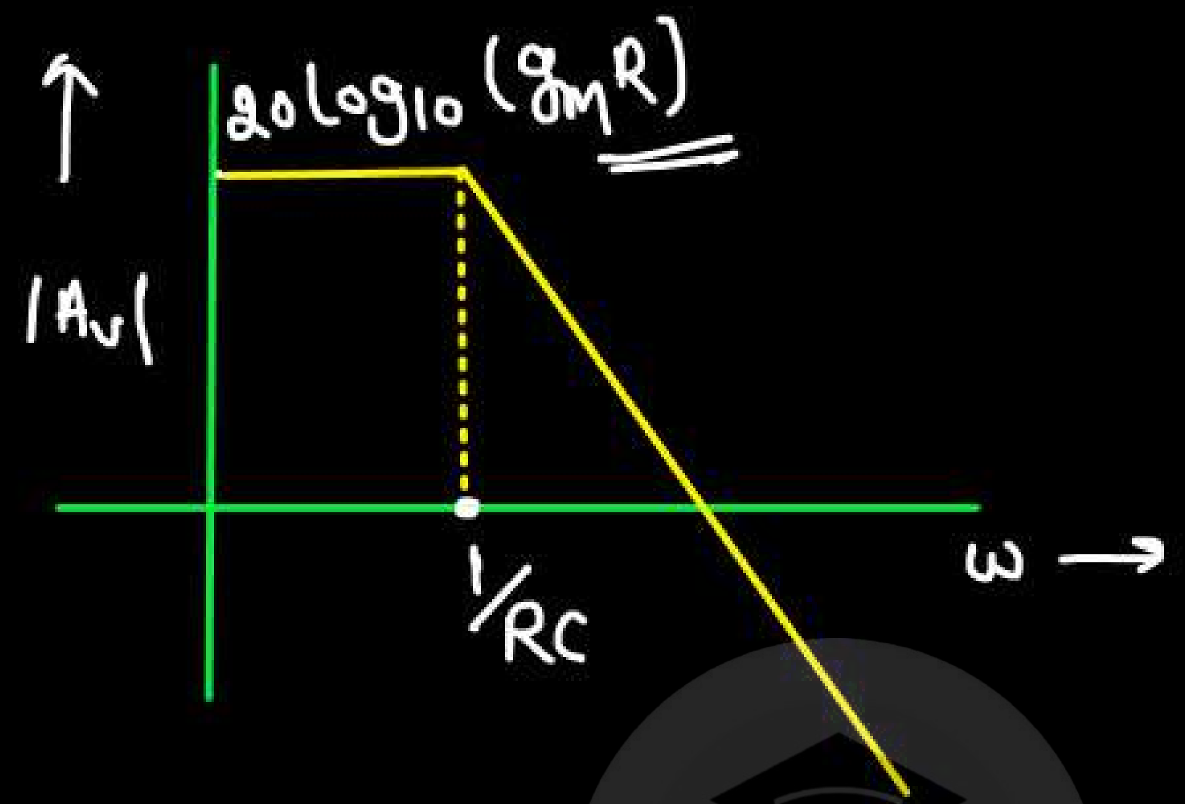


$$\frac{R}{RCs+1}$$

$$v_o(s) = -\frac{g_m \times R}{RCs+1} v_i(s)$$

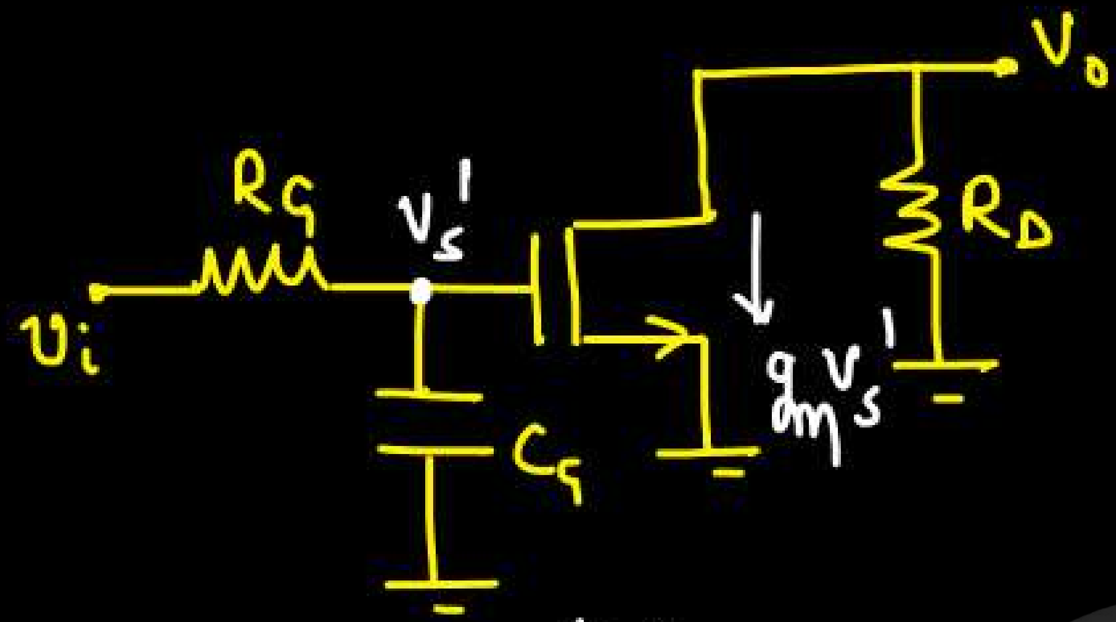
$$\frac{v_o(s)}{v_i(s)} = \frac{-g_m R}{RCs+1}$$

$$\omega_p = -\frac{1}{RC} \qquad |A(\text{DC gain})| = g_m R$$



Let's assume $v_i(s) = 20\,mV \sin(\omega_i t)$

For better amplification, $\boxed{\omega_i \ll \frac{1}{RC}}$

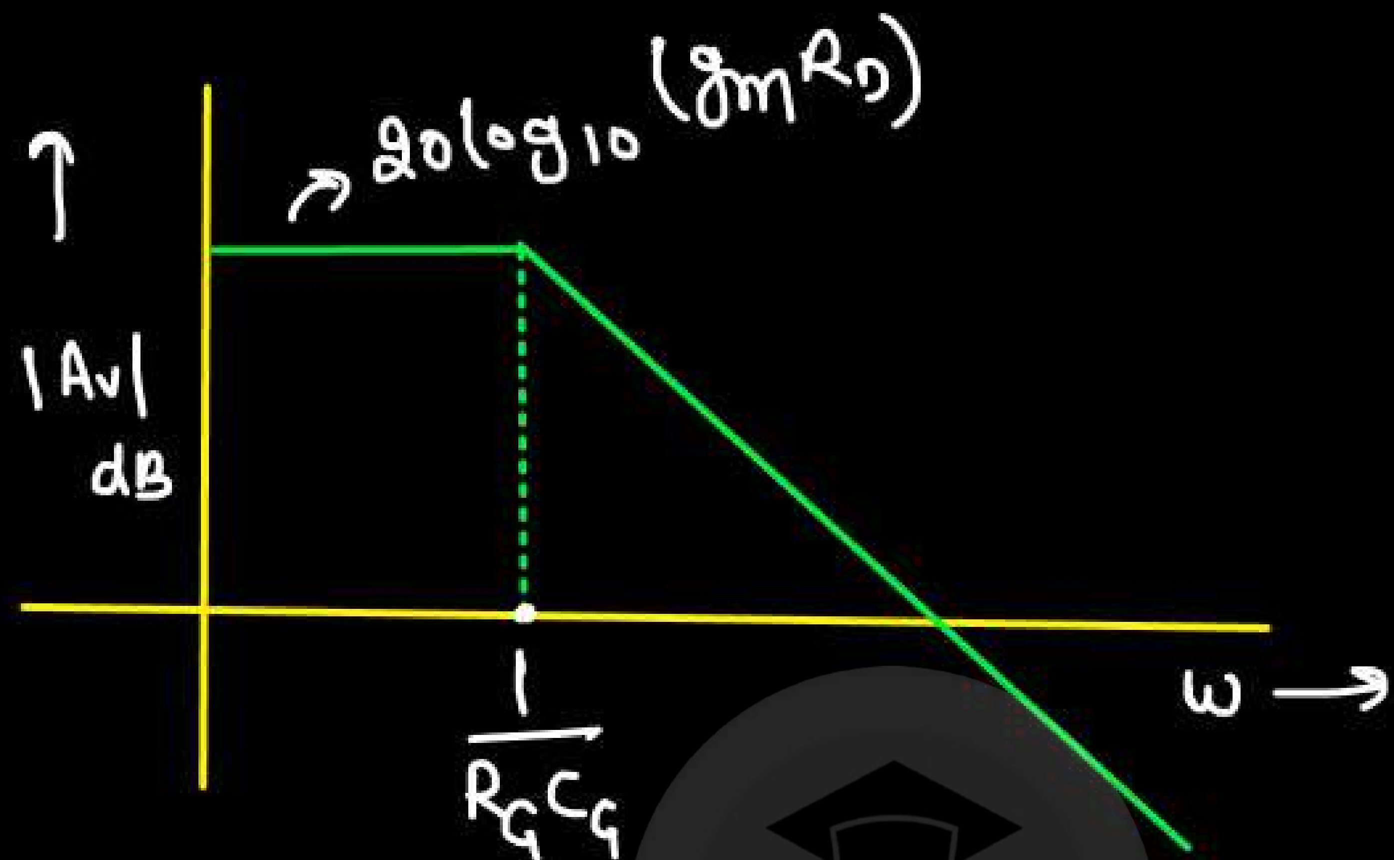


(b)

$$V_0 = -g_m R_D V_s' \quad \text{—(1)}$$

$$V_s' = \frac{\frac{1}{C_G s}}{\frac{1}{C_G s} + R_G} v_i = \frac{1}{R_G C_G s + 1} v_i$$

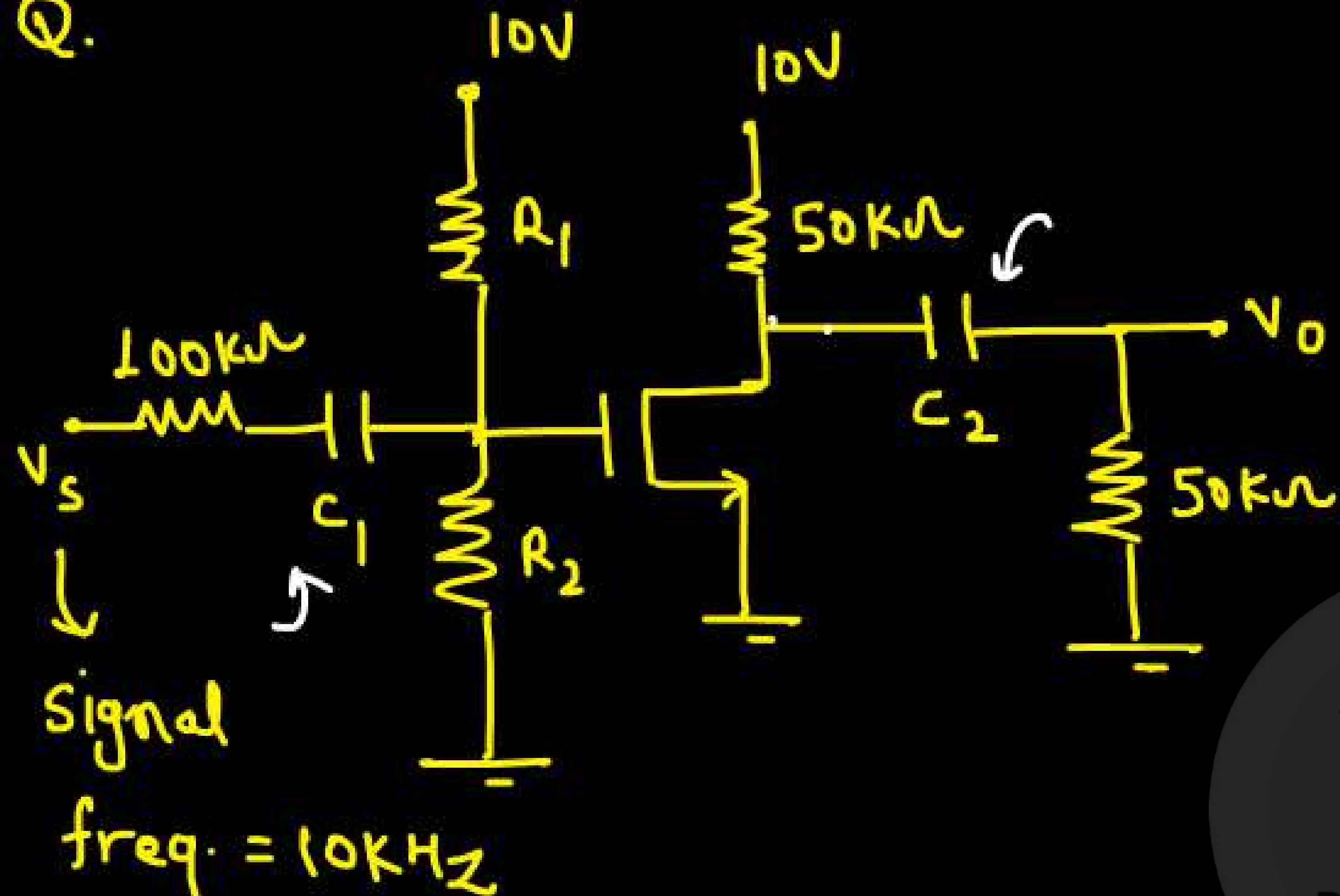
$$\boxed{\frac{V_0}{V_i} = \frac{-g_m R_D}{R_G C_G s + 1}}$$



$$V_i = V_m \sin(\omega_i t)$$

$$\boxed{\omega_i \ll \frac{1}{R_G C_G}}$$ $\Rightarrow$ For better Amplification

Q.



$\boxed{C_1, C_2 \rightarrow \text{coupling cap.}}$

$R_1 = 260k\Omega$

$R_2 = 740k\Omega$

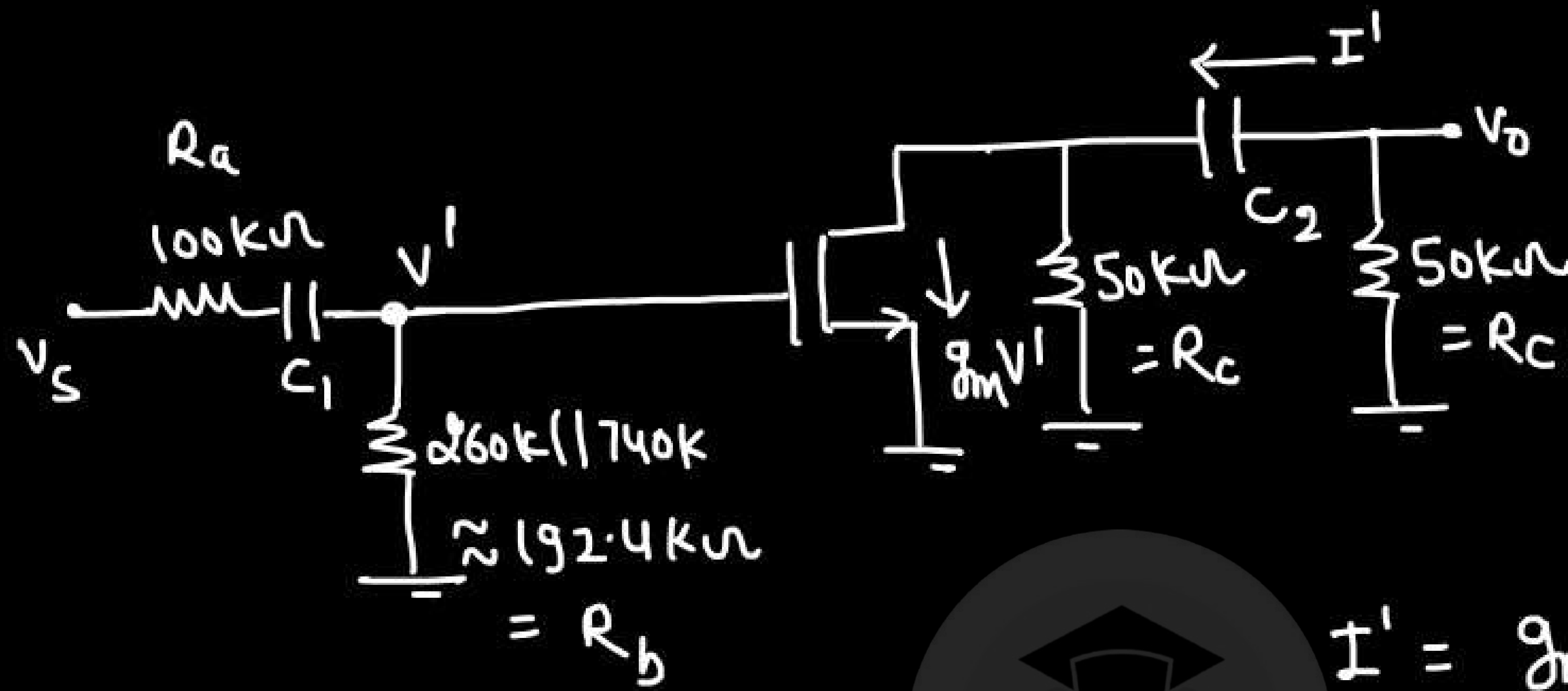
MOS is biased in sat.

How large you should choose C_1 and C_2 such that both cap. acts as short ckt @ signal freq.

$C_1 >> C_{o_1}$

$C_2 >> C_{o_2}$

Determine C_{o_1} and C_{o_2}.



$$V' = \frac{R_b}{R_b + R_a + \frac{1}{C_1 s}} V_s(s)$$

$$\boxed{V' = \frac{R_b C_1 s}{(R_b + R_a) C_1 s + 1} V_s(s)} \quad \text{— (1)}$$

$$I' = g_m V' \times \frac{R_C}{R_C + R_C + \frac{1}{C_2 s}}$$

$$I' = g_m V' \times \frac{R_C C_2 s}{2 R_C C_2 s + 1} \quad \text{— (2)}$$

$$V_o = -I' R_C \quad \text{— (3)}$$

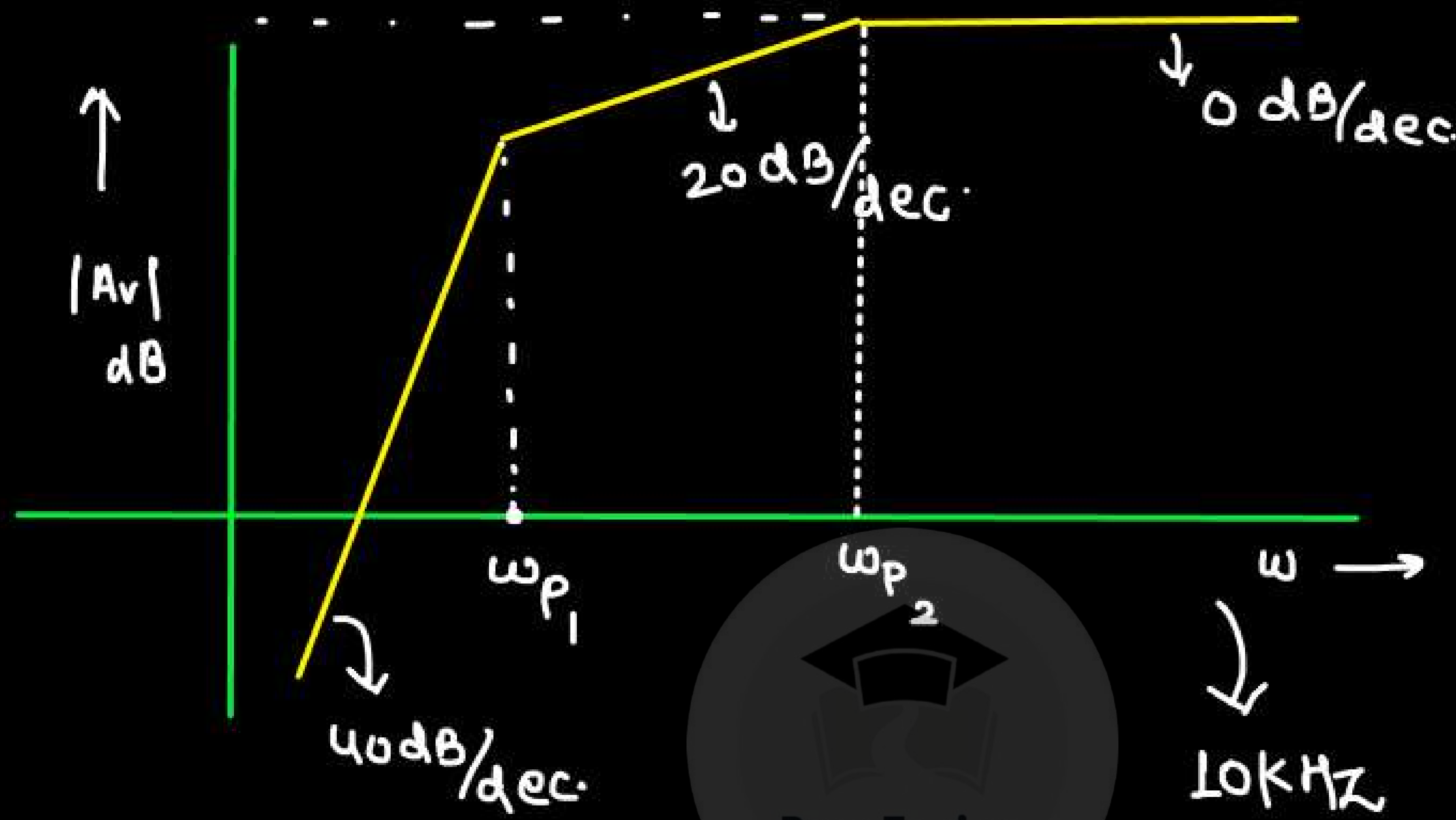
$$V_o(s) = \frac{-g_m R_c C_2 s}{2R_c C_2 s + 1} \times \frac{R_b C_1 s}{(R_b + R_a) C_1 s + 1} V_i(s)$$

$$\boxed{A_v(s) = \frac{V_o(s)}{V_i(s)} = \frac{-g_m R_c R_b C_1 C_2 s^2}{(2R_c C_2 s + 1)\left[(R_b + R_a) C_1 s + 1\right]}}$$ Ans.

$$\omega_{z_1} = \omega_{z_2} = 0$$

$$\boxed{\omega_{p_1} = \frac{-1}{2R_c C_2}}, \quad \boxed{\omega_{p_2} = \frac{-1}{(R_b + R_a) C_1}}$$

$$\omega_p = \frac{-1}{100k \times C_2} \qquad \omega_p = \frac{-1}{292.4k \times C_1}$$



10 kHz

$= 20k\pi$ rad/sec.

$\omega_{p_1} < 20k\pi$

$\omega_{p_2} < 20k\pi$

$\frac{1}{100k \times C_2} < 20k\pi$

$\frac{1}{292.4k \times C_1} < 20k\pi$

$\boxed{C_2 > 159\ pF}$ C_{o_2}

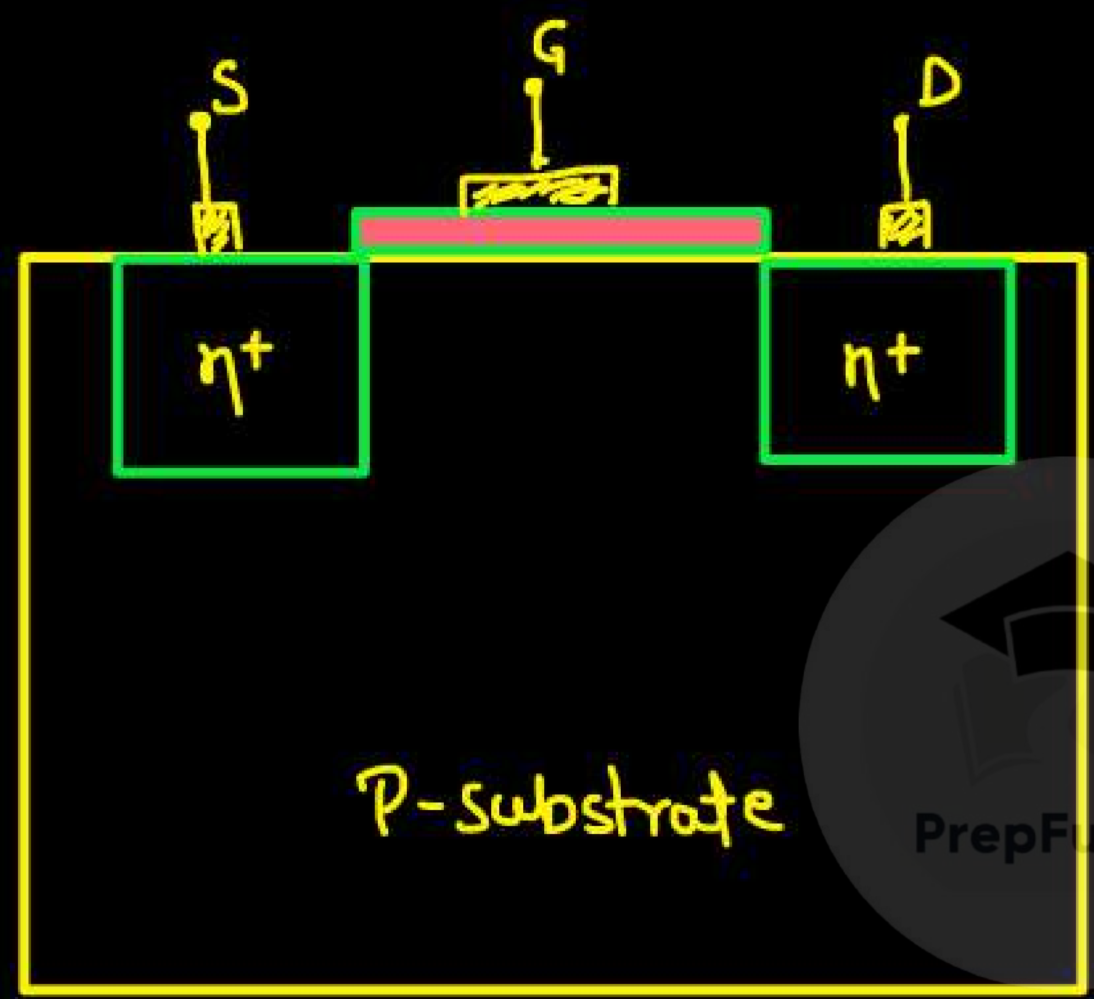
$\boxed{c_1 > 54.4\ pF}$ C_{o_1}

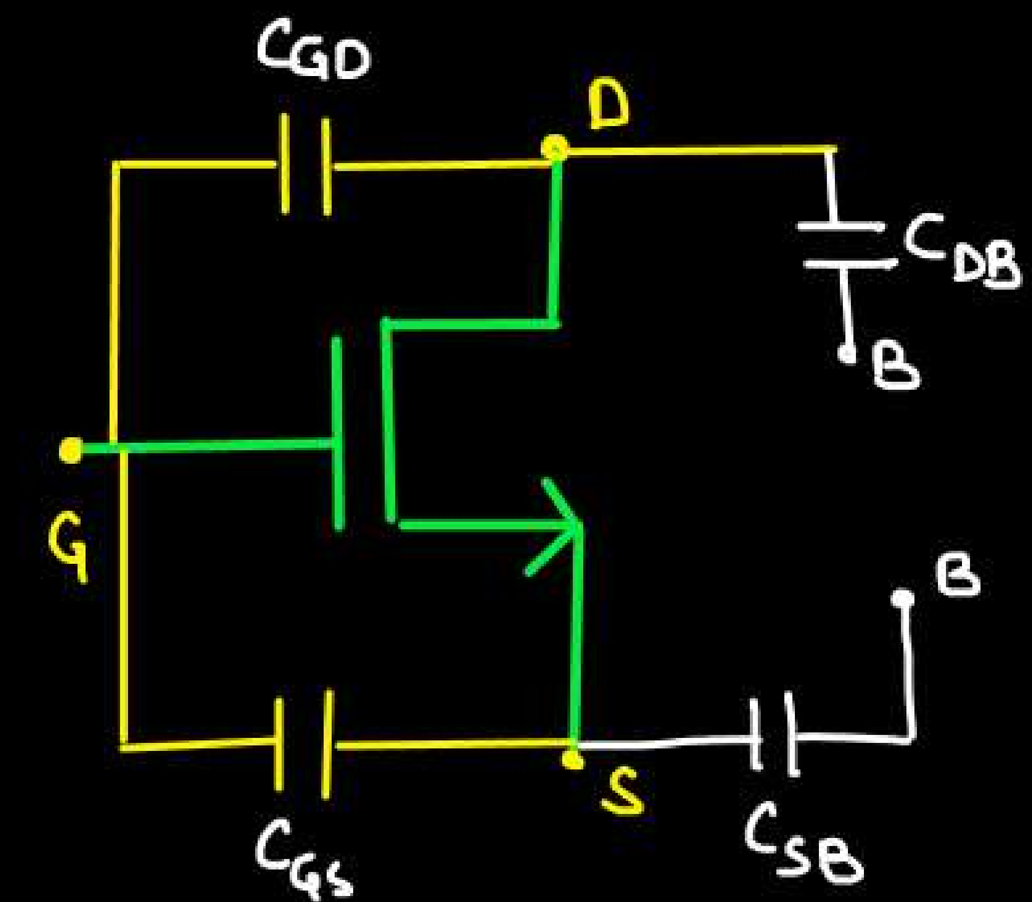
Generally C_2 should be 1590 pF $\quad [C_1, C_2 = 10C_0]$

C_1 should be 544 pF

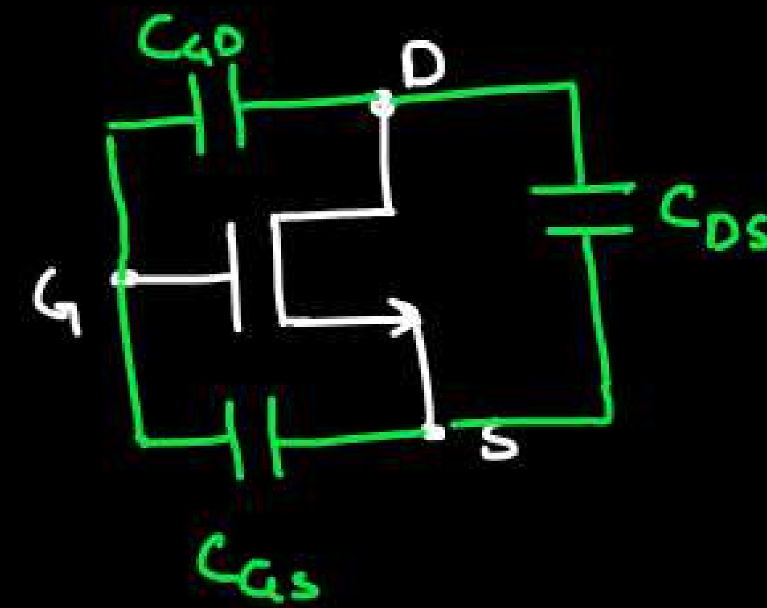
NOT Imp.

⇒ High Freq. Model of MOS:-





☆☆ ⇒



→ +nt @ Higher freq.

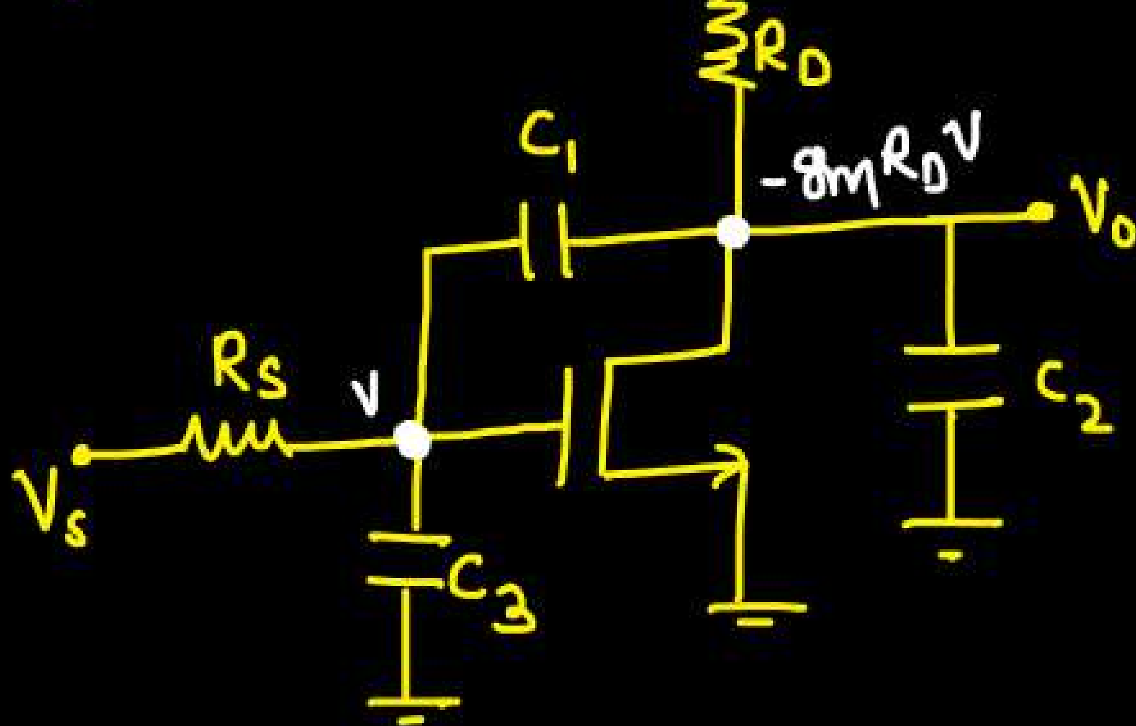
$C_{GS}, C_{GD}, C_{DS} \rightsquigarrow$ pF, fF Range (small)

@ low freq. ⇒ $\frac{1}{C_{GD}S} = \frac{1}{\text{very low} \times \text{very low}} = \frac{1}{0} = \infty \Rightarrow$ O.C.

@ High freq. ⇒ $\frac{1}{C_{GD}S} = \frac{1}{\text{very low} \times \text{very High}} = \frac{1}{\text{considerable}} \Rightarrow$ stays in action

⇒ @ Low and Mid Freq., Parasitic / Internal / J^n cap. are open ckt.
@ High freq., They come in action

Q.

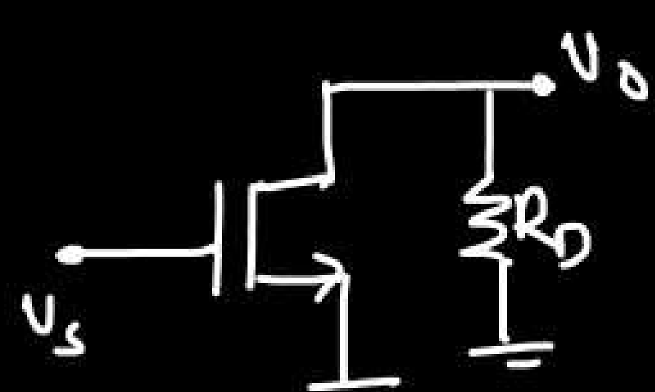


Given that C_1, C_2 & C_3 are parasitic cap.

[$C_1, C_2, C_3 \rightarrow$ very low value pF]

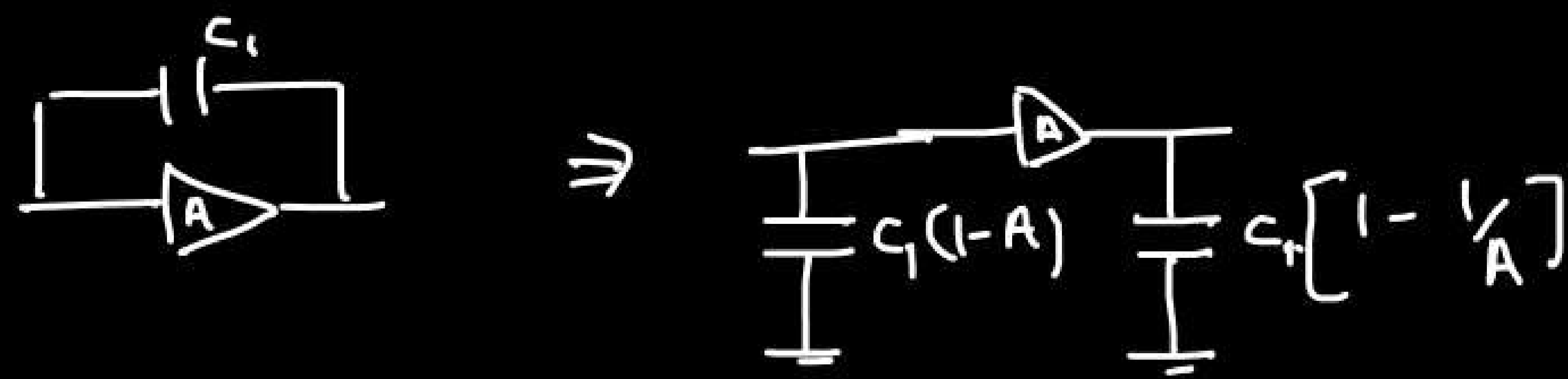
Draw the freq. response.

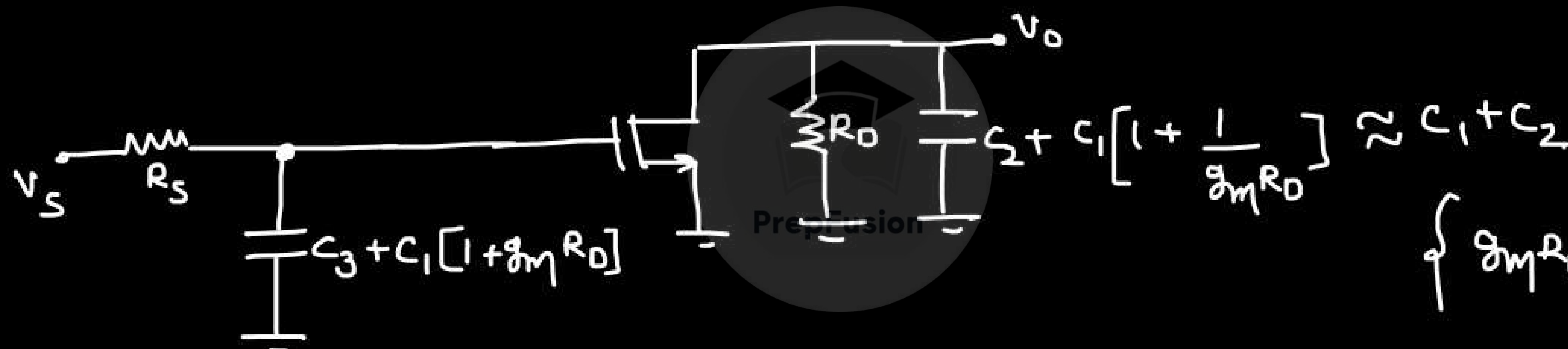
<u>Dc gain:-</u>



$$\boxed{\frac{V_0}{V_s} = -g_m R_D}$$

Applying Miller's Theorem :-





$$\{ g_m R_D >> 1 \}$$

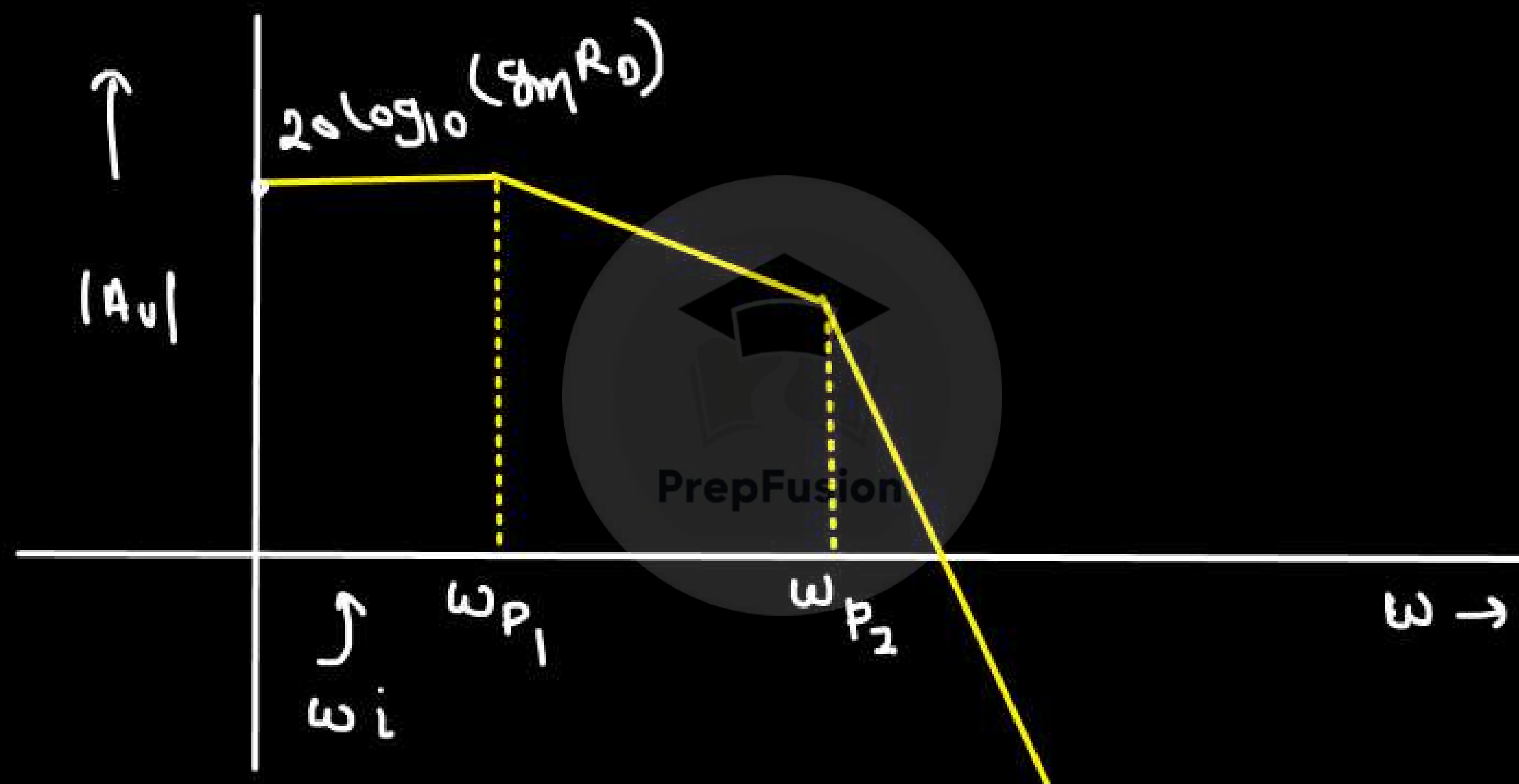
$$\boxed{\frac{V_0(s)}{V_s(s)} = \frac{-g_m R_D}{\{[C_3 + C_1(1+g_m R_D)]R_S s + 1\}\{R_D(C_1+C_2)s + 1\}}}$$

$\omega_{z_1} = \infty$

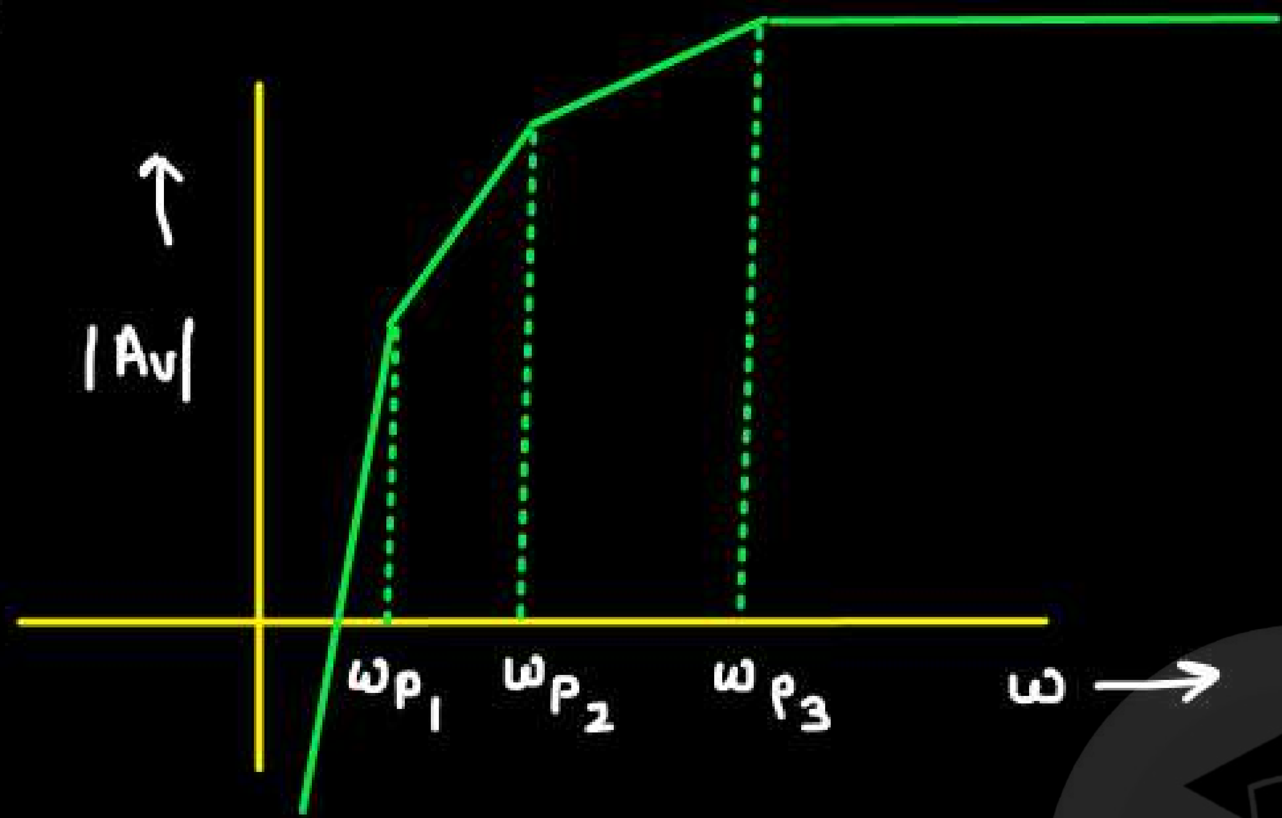
$\omega_{z_2} = \infty$

$$\omega_p = \frac{-1}{R_D(C_1+C_2)}$$

$$\omega_p = \frac{-1}{[C_3 + C_1(1+g_m R_D)]\,R_S}$$

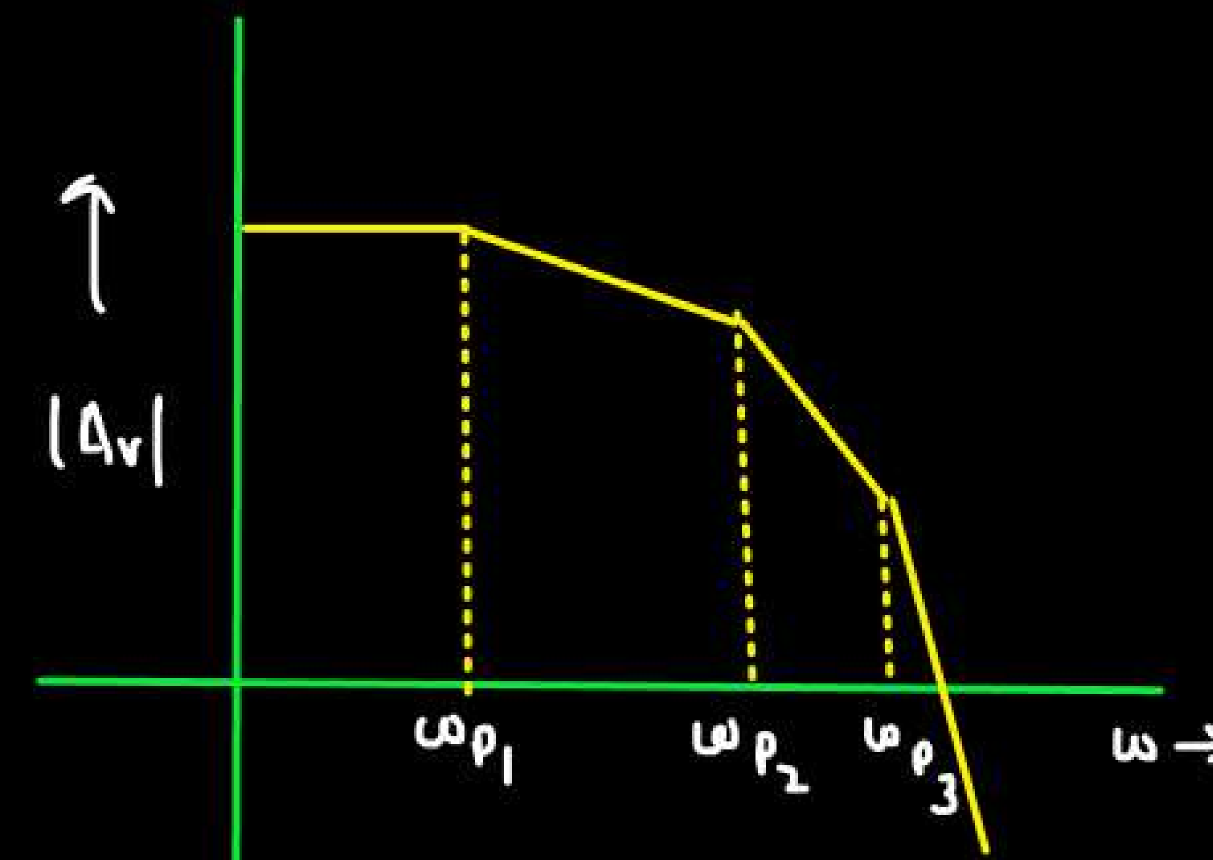


N.B. →



⇓

3-dB cut-off freq. = ω_{P_3}



3-dB cut-off freq. = ω_{P_1}

Low Freq. Model of MOS:-

$\Downarrow$

> coupling cap. will be in action
>
> $\Downarrow$
>
> (ηF or μF $\rightarrow$ High)

@ low freq. $\Rightarrow \dfrac{1}{C_c S} = \dfrac{1}{\text{High} \times \text{low}} = \dfrac{1}{\text{consider}}$ = will be in action

@ High freq. $\Rightarrow \dfrac{1}{\text{High} \times \text{High}} = \dfrac{1}{\infty} = 0$ = cap. will act as s.c.

$\Rightarrow$ @ low freq. $\Rightarrow$ coupling cap. are in action

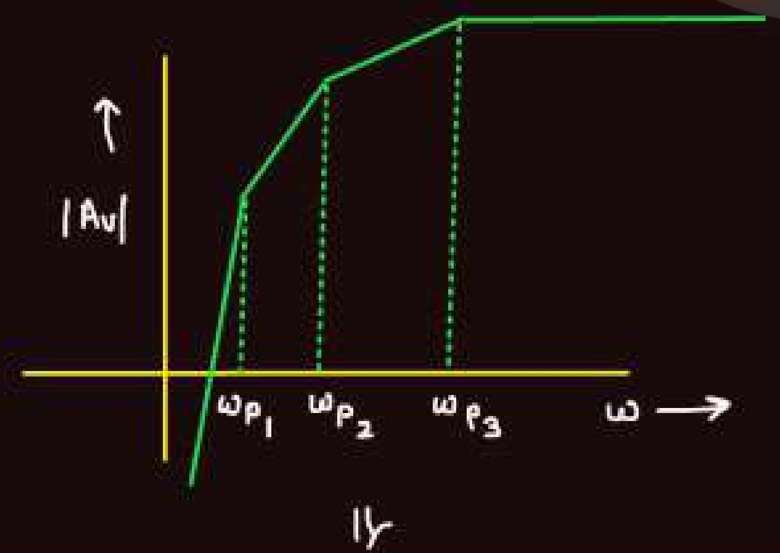
$\Rightarrow$ @ High freq. & Mid Freq. $\Rightarrow$ coupling cap. is s.c.

Conclusion:-

(a) Coupling cap:-

- ↳ Will be in action @ low freq.
- ↳ Response will be of HPF.
- ↳ Will act as s.c. @ High and Mid freq.

Coupling ⇒ Low freq. ⇒ H.P.F. ⇒ 3-dB cut off freq. will be Highest Pole



⇒ @ low freq.

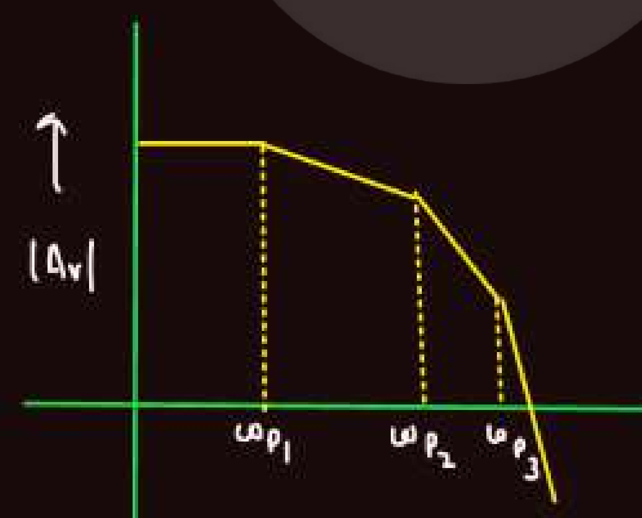
(b) Parasitic / Internal / J^n cap.-

↳ will be in action @ High freq.

↳ Response will be of LPF

↳ Will act as o.c. @ low and Mid freq.

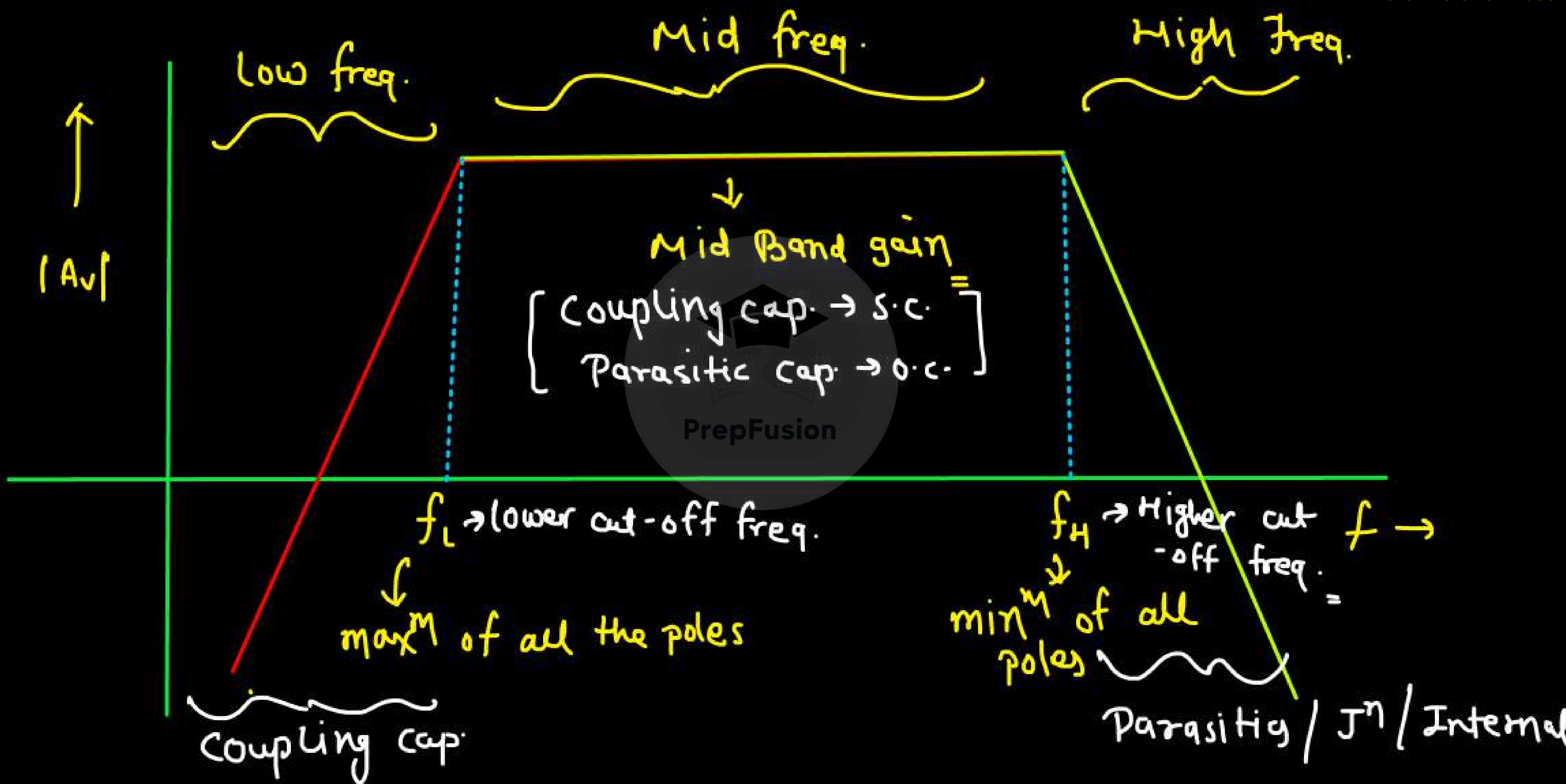
Para / Intern / J^n cap. ⇒ High freq. ⇒ LPF ⇒ Cut-off freq. will be min pole.



⇒ @ High freq.

$\omega \rightarrow$

⇒ Freq. Response of a RC Coupled MOS Amp:-



⇒ How to find a pole in MOS ckt.

① Find the order of the ckt.

② Nullify the i/p and find equivalent resistance across cap. [consider the other cap. shorted]

$$\boxed{\omega_p = \frac{1}{C R_{eq}}}$$

⇒ How to find a zero in MOS ckt:.

① NO Hard and fast rule. Do intelligent Analysis.

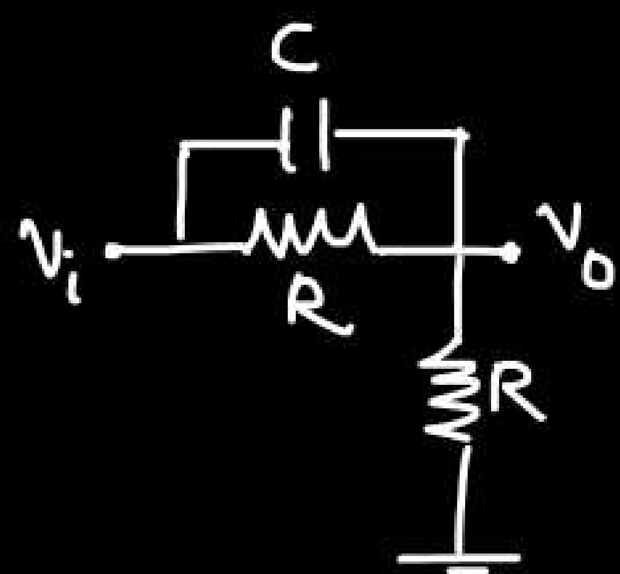
$$\boxed{T(s) = A\,\frac{\left(\frac{s}{z_1}+1\right)\left(\frac{s}{z_2}+1\right) - - - \left(\frac{s}{z_n}+1\right)}{\left(\frac{s}{P_1}+1\right)\left(\frac{s}{P_2}+1\right) - - - \left(\frac{s}{P_n}+1\right)}}$$

⇒ A = dc gain (ω =1)

@ $s = -z_1 \Rightarrow T(s) = 0$

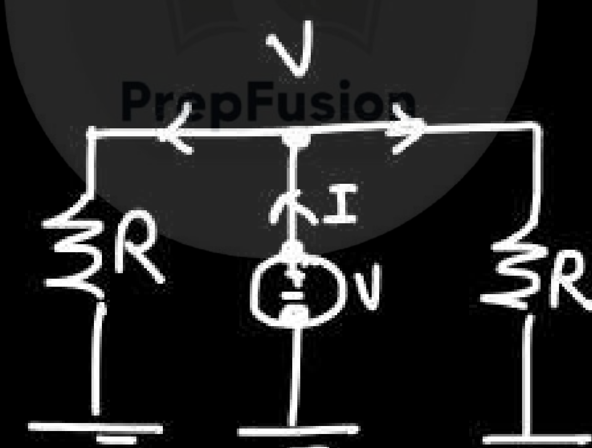
@ zero, T.F. becomes zero. $\frac{V_o(s)}{V_i(s)} \to 0 \Rightarrow V_o(s) \to 0$

Eg. →



① order = 1^{st}

② poles →

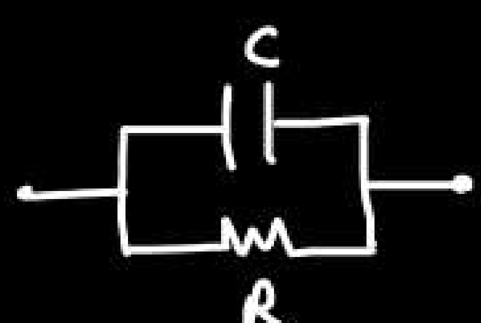


$\Rightarrow R_{eq} = R/2$

$C_{eq} = C$

$$\boxed{\omega_p = \frac{-1}{R/2\, C} = \frac{-2}{RC}}$$

③ zero →



$\equiv$

$= \frac{R}{RCs+1} = 0$

$\Rightarrow$

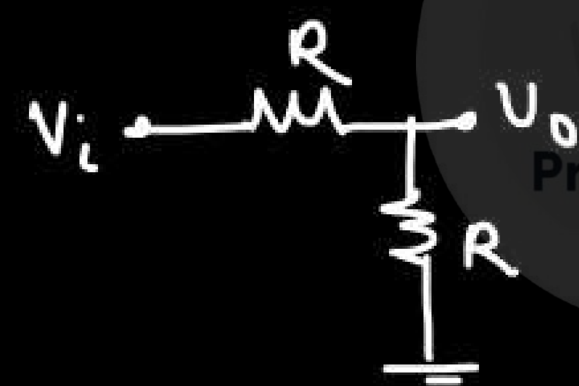
$$\boxed{s_z = -1/RC}$$

$$T.F. = \frac{A\,(SRC + 1)}{\left(\frac{SRC}{2} + 1\right)} = \frac{2A\,(SRC + 1)}{(SRC + 2)}$$

@ $\omega = 0$ $\quad T.F. = A$

in the given ckt

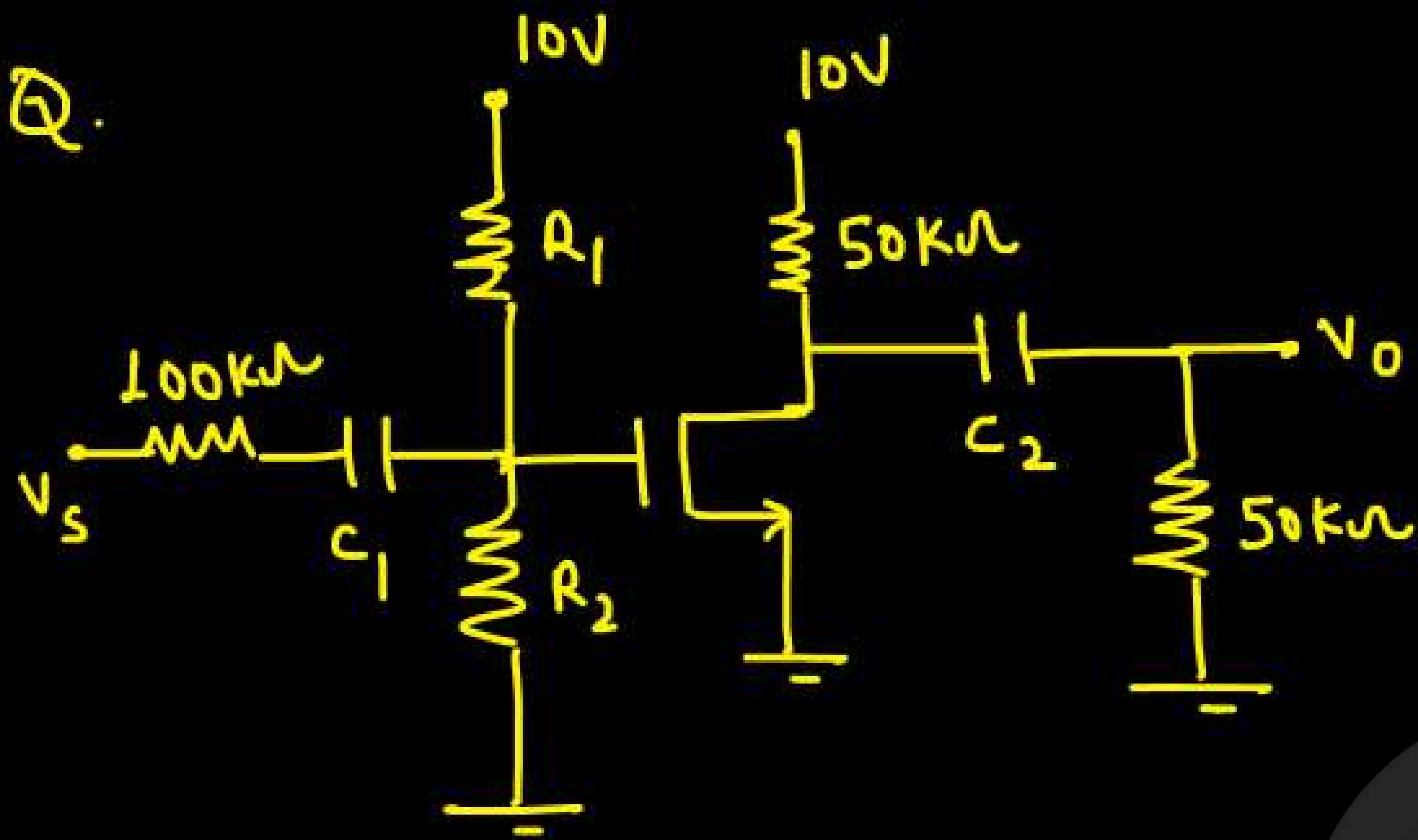
@ $\omega = 0$



$$\frac{V_o}{V_i} = 1/2 = A$$

$$\boxed{T.F. = T(s) = \frac{SRC + 1}{SRC + 2}}$$

Q.



Low freq. operation

(a) Determine the order of ckt.

(b) Find the location of poles.

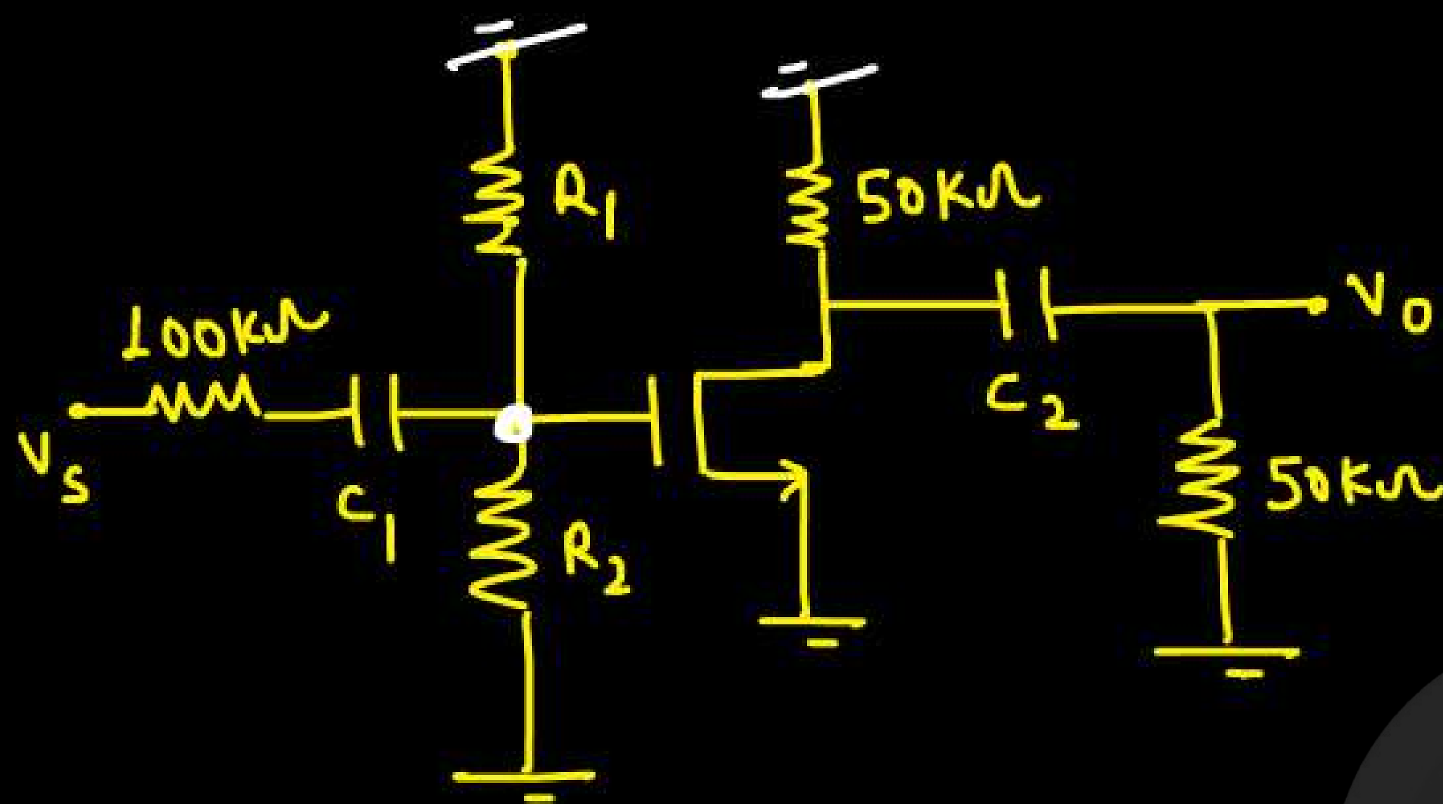
(c) Determine 3-dB cut-off freq. (kHz)

$R_1 = 260\,k\Omega$

$R_2 = 740\,k\Omega$

$C_1 = 100\,pF$

$C_2 = 200\,pF$

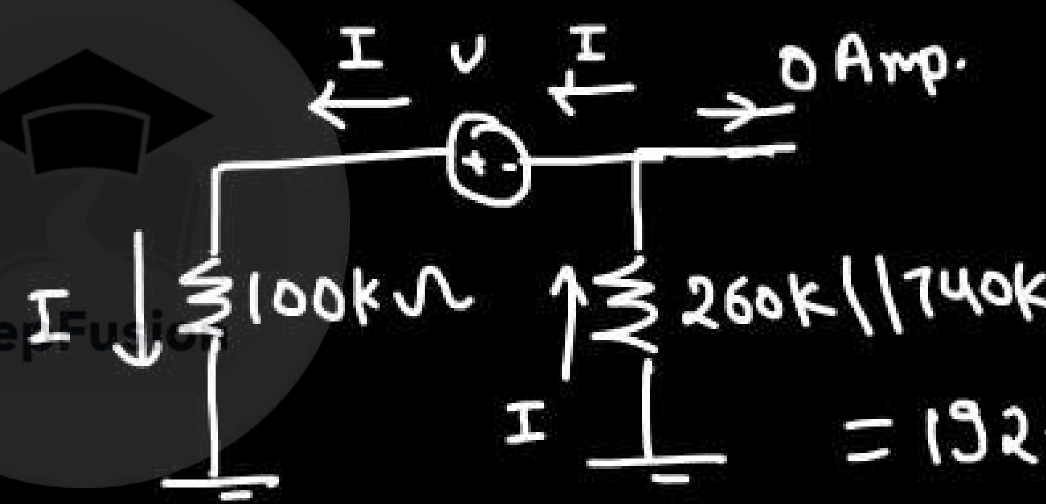


① order = 2^{nd}

② poles :-

$\boxed{\text{Pole because of } C_1}$

→ S.C. C_2 , S.C. input V_s



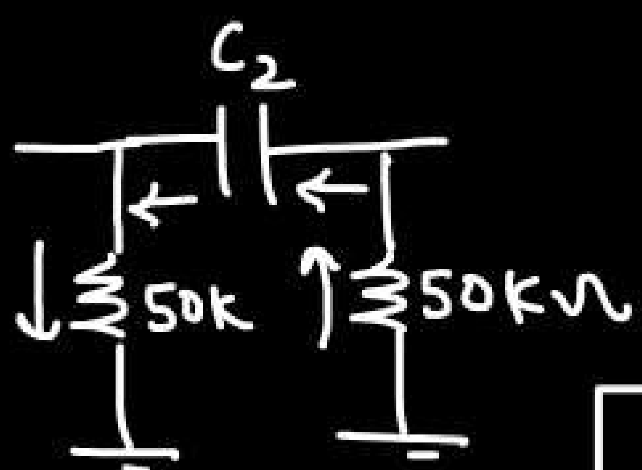
$= 192.4\,k\Omega$

$C_{eq} = C_1 = 100\,pF = 10^{-10}\,F$

$R_{eq} = 192.4 + 100 = 292.4\,k\Omega$

$$\boxed{\omega_{p_1} = \frac{1}{R_{eq}C_1} = 34.2\,K\,rad/sec.}$$

$\boxed{\text{Pole because of } C_2}$



$R_{eq} = 100\,k\Omega$

$C_2 = 100\,pF$

$$\boxed{\omega_{p_2} = \frac{1}{R_{eq}C_2} = 100\,K\,rad/sec.}$$

3-dB cut-off freq. = max^m $(\omega_{p_1}, \omega_{p_2})$

= 100k rad/sec.

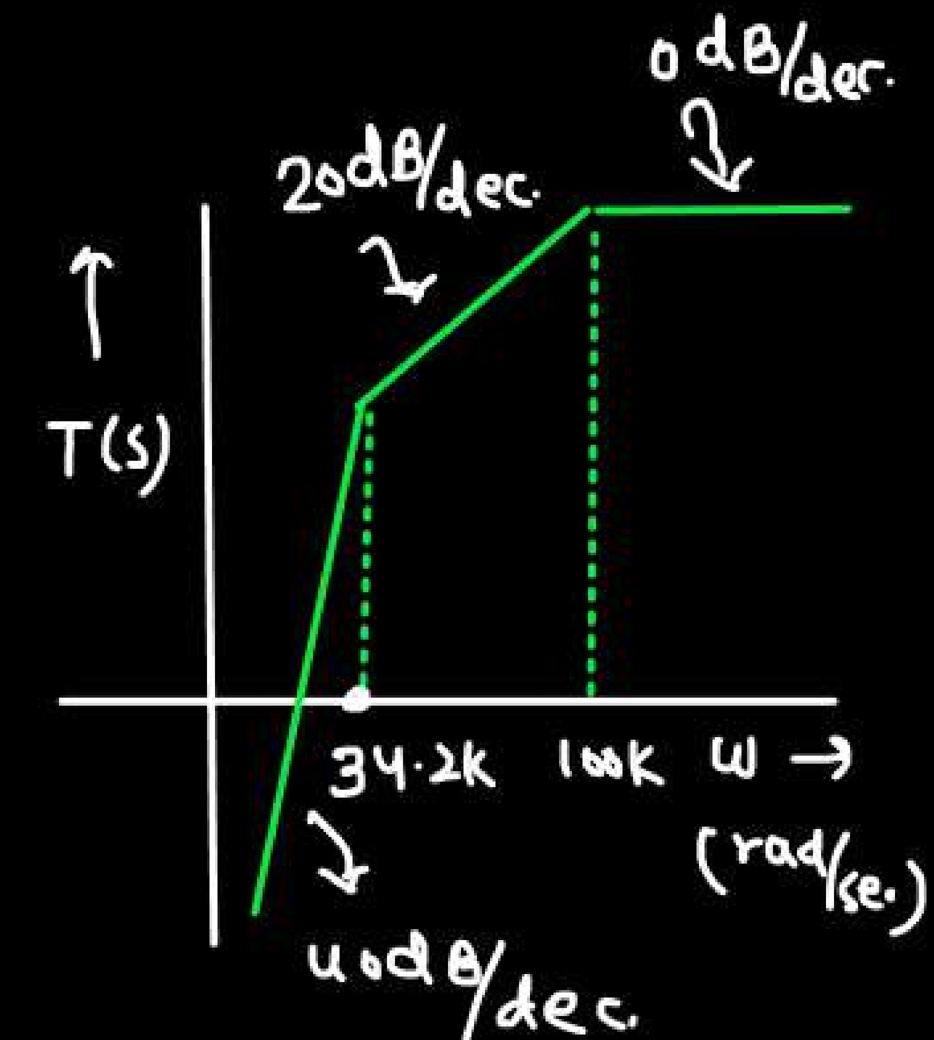
$$\boxed{\omega_{dB} = 15.91 \text{ kHz}}$$

@ $\omega = 0$, Because of C_2, v_o is zero

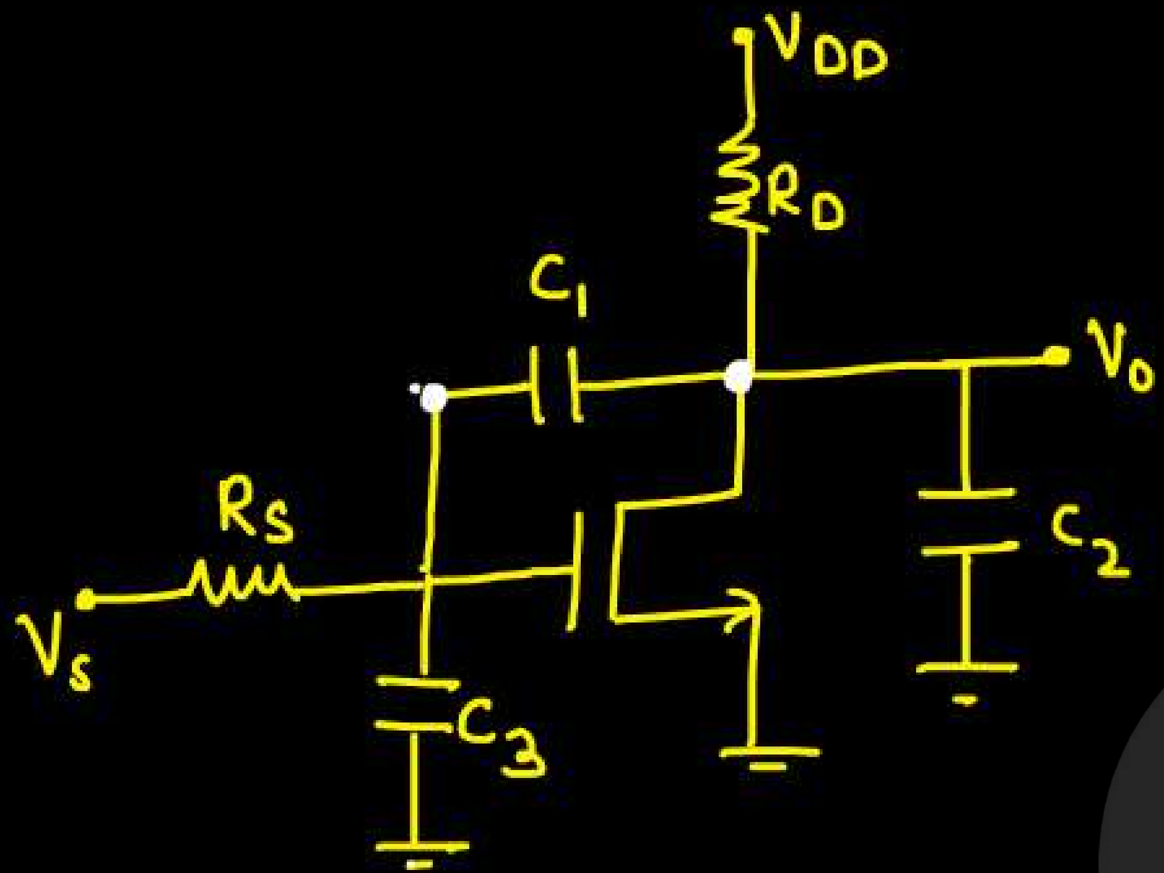
@ $\omega = 0$, Because of C_1, v_o is zero

$\Rightarrow$ you have two zeros @ $\omega = 0$

$$\boxed{T(s) = \frac{K s^2}{\left(\frac{s}{34.2k} + 1\right)\left(\frac{s}{100k} + 1\right)}}$$



Q.



Given that C_1, C_2 & C_3 are parasitic cap.

[$C_1, C_2, C_3 \rightarrow$ very low value. pF]

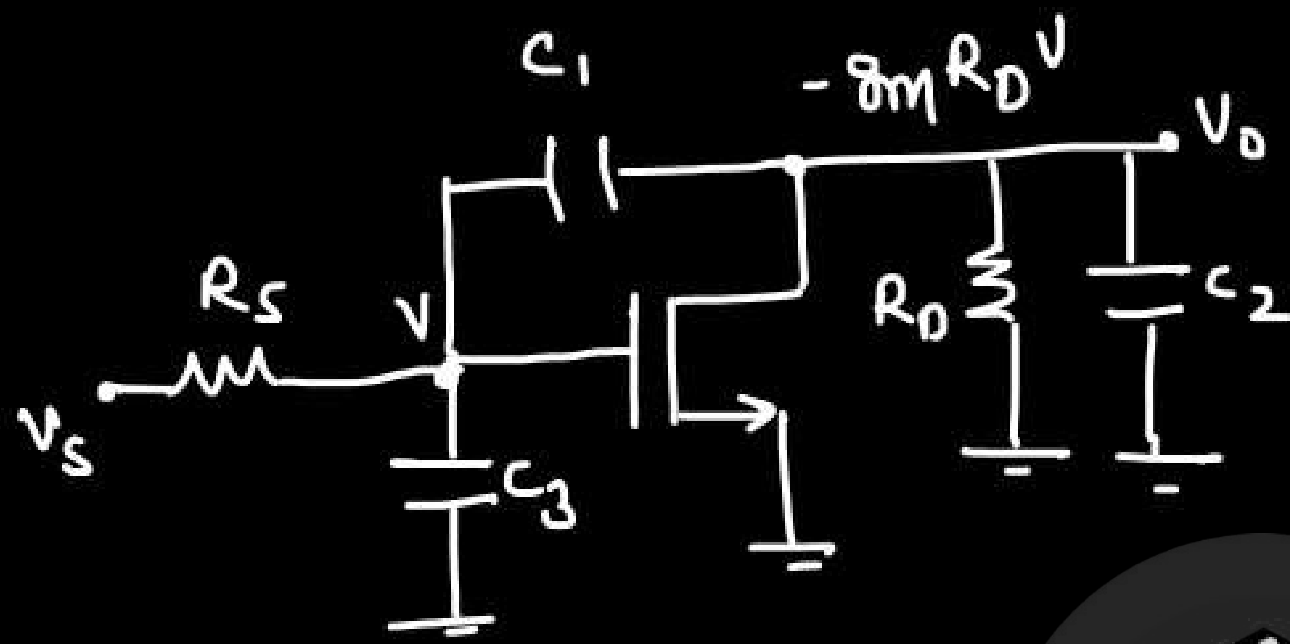
(a) Determine the order of the ckt.

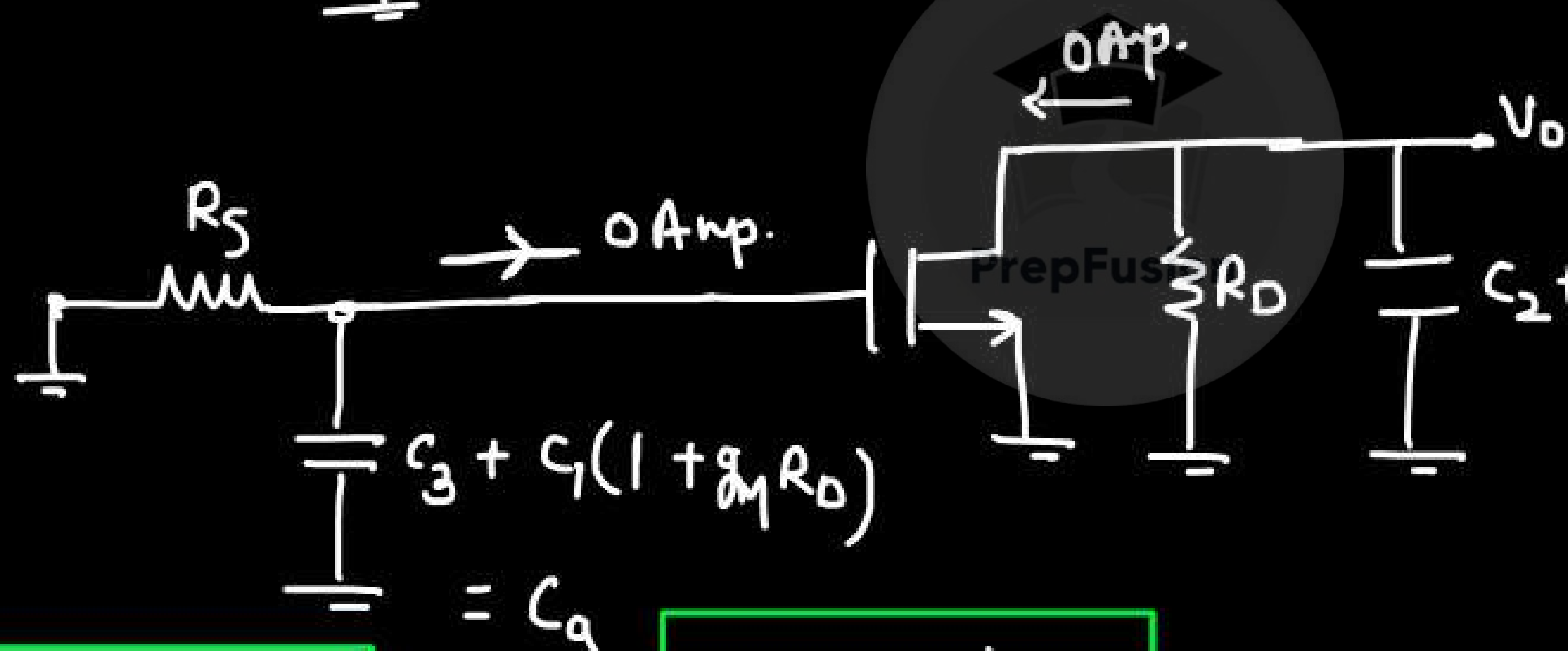
(b) Determine the location of poles.

(c) Draw freq. response.

(d) Tell 3-dB cut-off freq.

(a) 2^{nd} order





$$C_2 + C_1\left[1 + \frac{1}{g_m R_D}\right] \approx C_1 + C_2 = C_b$$

$$\boxed{\omega_{P_1} = \frac{1}{R_S C_a}}$$

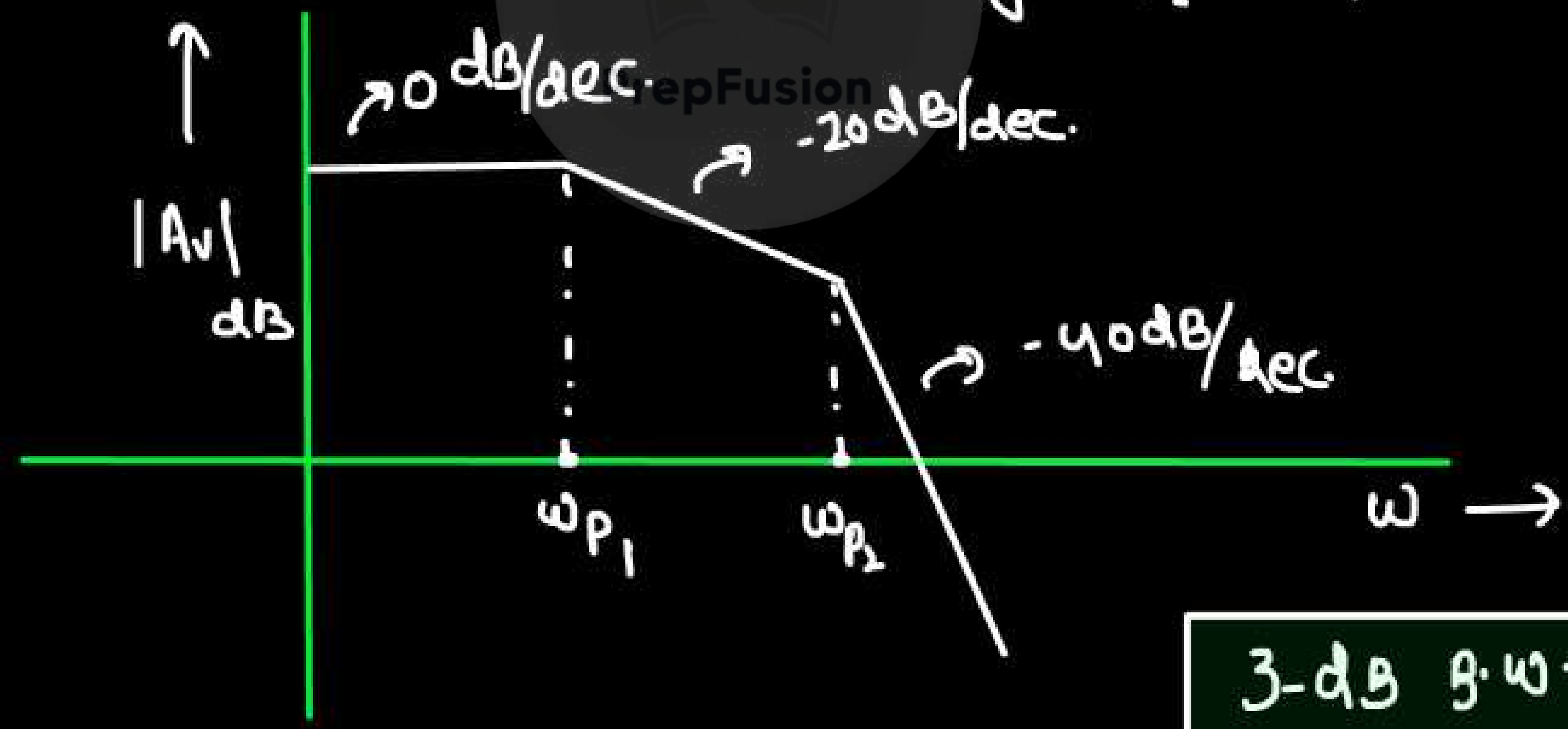
$$\boxed{\omega_{P_2} = \frac{1}{R_D C_b}}$$

Because of C_2, @ $\omega = \infty$, $V_0 = 0$ $\Rightarrow$ zero @ ∞

Because of C_3, @ $\omega = \infty$, $V_0 = 0$ $\Rightarrow$ zero @ ∞

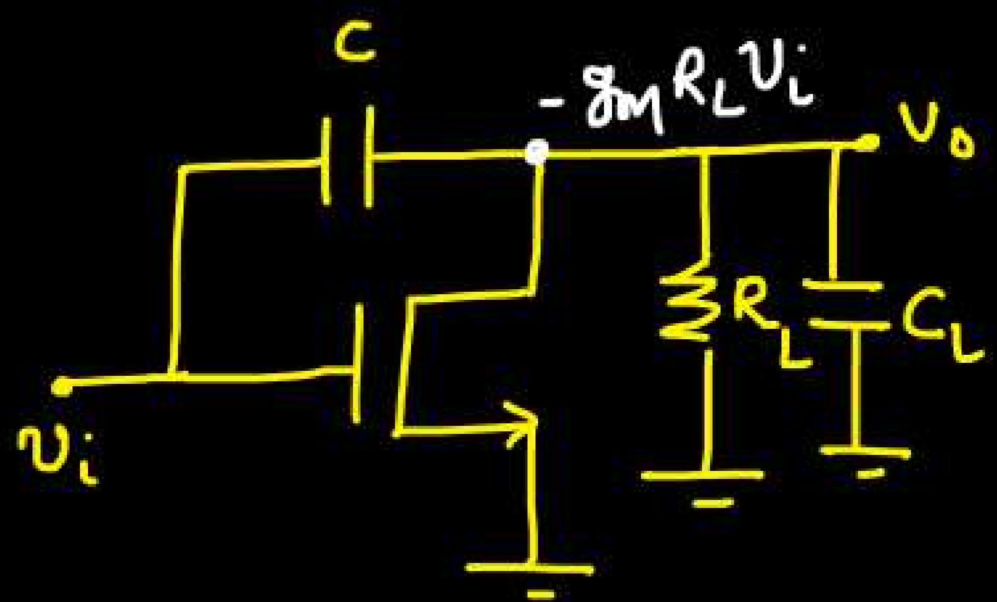
$$\boxed{T \cdot F \cdot = \frac{-g_m R_D}{\left\{ sR_S\left[C_3 + C_1\left(1 + g_m R_D\right)\right] + 1\right\}\left\{ sR_D\left(C_1 + C_2\right) + 1\right\}}}$$

considering $\omega_{P_2} > \omega_{P_1}$



$$\boxed{3\text{-dB } B \cdot W \cdot = \omega_{P_1}}$$

③



Q. Draw Bode plot. Considering

(a) $R_L C_L \gg \frac{C}{g_m}$

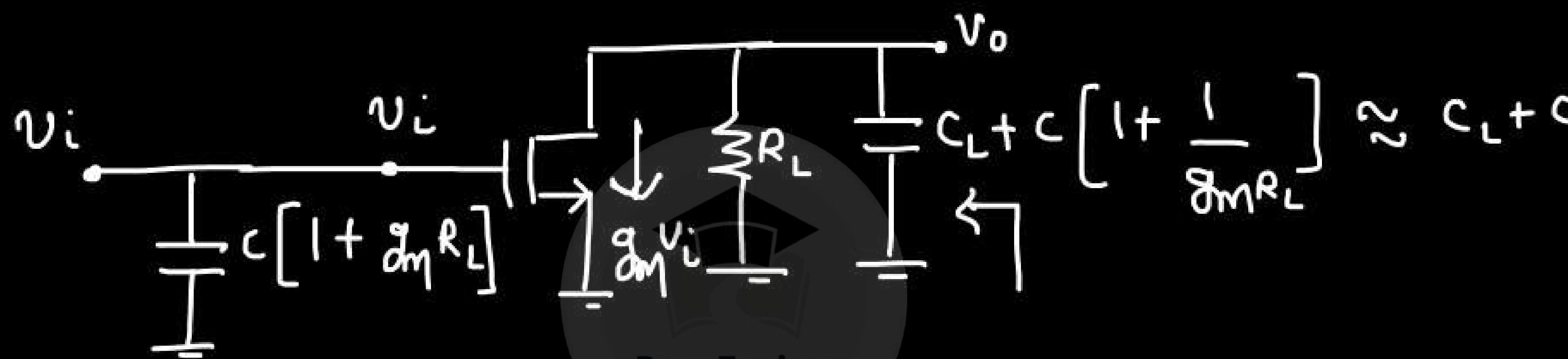
(b) No Cond^n

⇒ Compare your results.

⇒ 1st order

(a) since, C is very low

$\Rightarrow$ I can apply millers Theorem



$$\boxed{A_v = G_m R_{out}}$$

$$\boxed{G_m = -g_m}$$

$$\boxed{R_{out} = R_L \parallel \frac{1}{(C_L + C)s}}$$

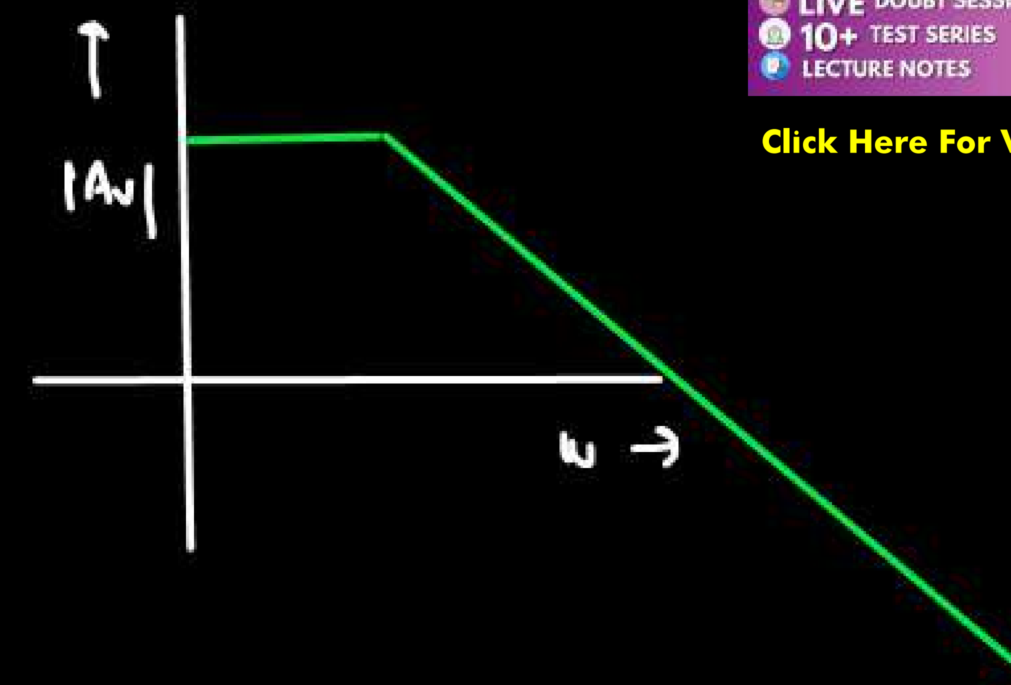
&

$$\boxed{A_v = -g_m\left[R_L \parallel \frac{1}{(C_L + C)s}\right]}$$

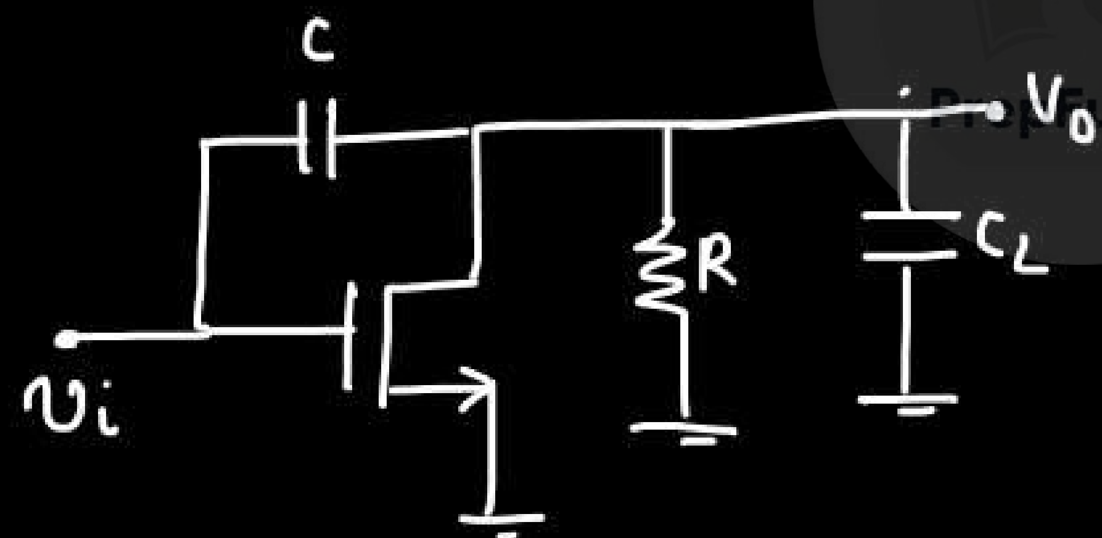
$$A_v = \frac{-g_m R_L}{R_L[C_L + C]s + 1}$$

$$\boxed{\omega_p = \frac{-1}{R_L[C_L + C]}}$$

$$\boxed{\omega_z = \infty}$$



(b)



$$G_m = ?$$

$$I_{out} = -[g_m v_i - v_i Cs]$$

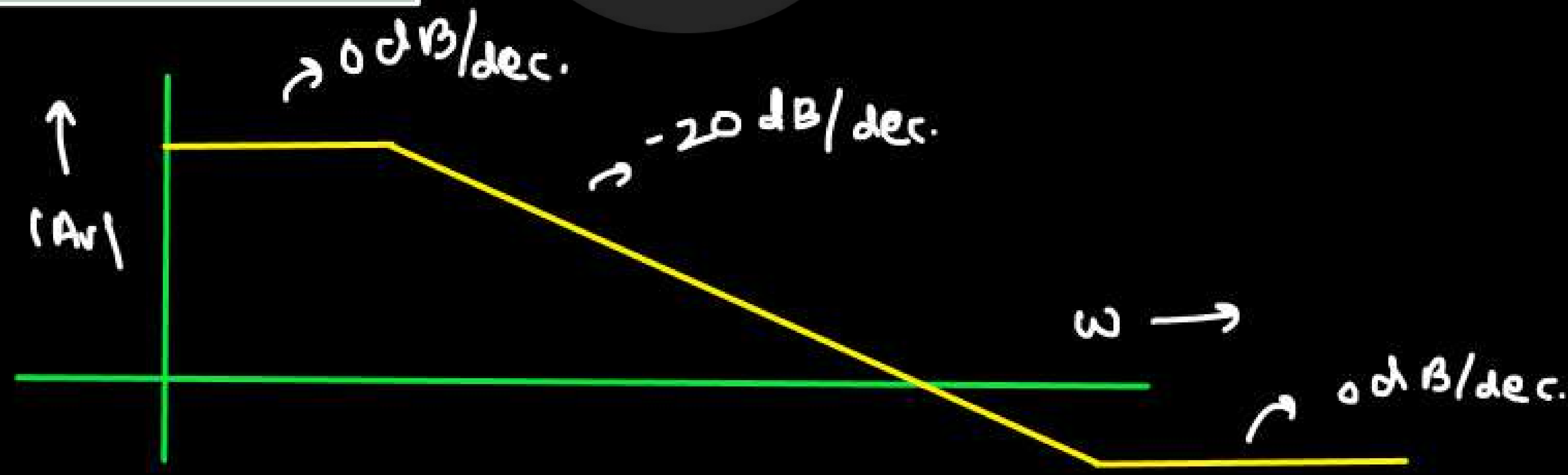
$$\boxed{\frac{I_{out}}{v_{in}} = G_m = -[g_m - Cs]}$$

$$R_{out} = R_L \,||\, \frac{1}{(C_L + C)s}$$

$$A_V = \left[-g_m + Cs\right]\left[\frac{R_L}{R_L(C_L+C)s+1}\right]$$

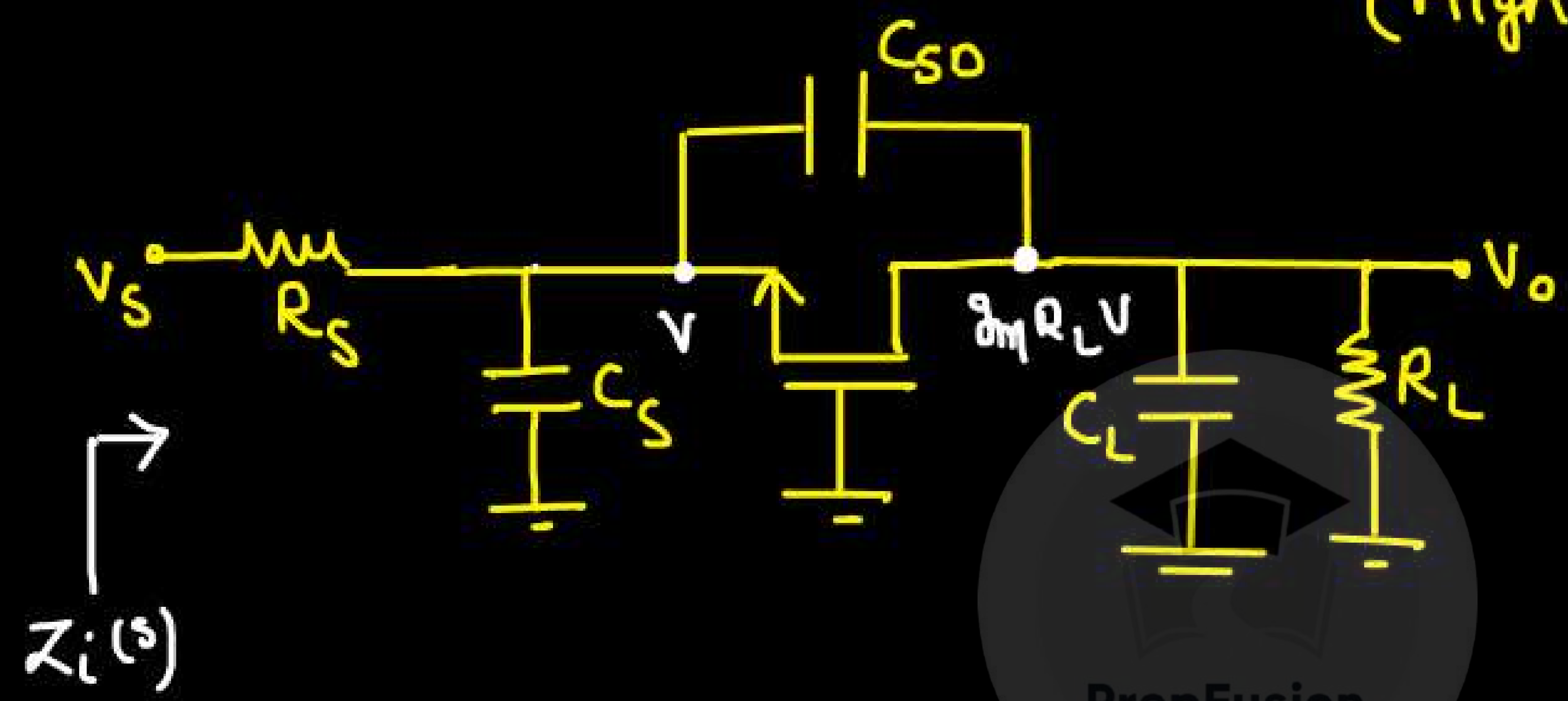
$$\boxed{A_V = \frac{-\left[g_m - Cs\right]R_L}{R_L(C_L+C)s+1}}$$

$$\boxed{\omega_p = \frac{-1}{R_L(C_L+C)}} \quad , \quad \boxed{\omega_z = \frac{g_m}{C}}$$



Frequency Response for Common Gate Amplifiers:-

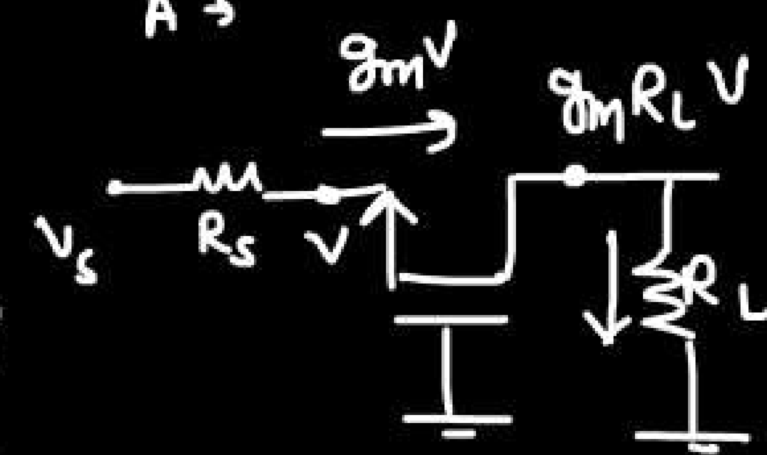
(High frequency)



$$\boxed{\text{order} = 2^{nd}}$$

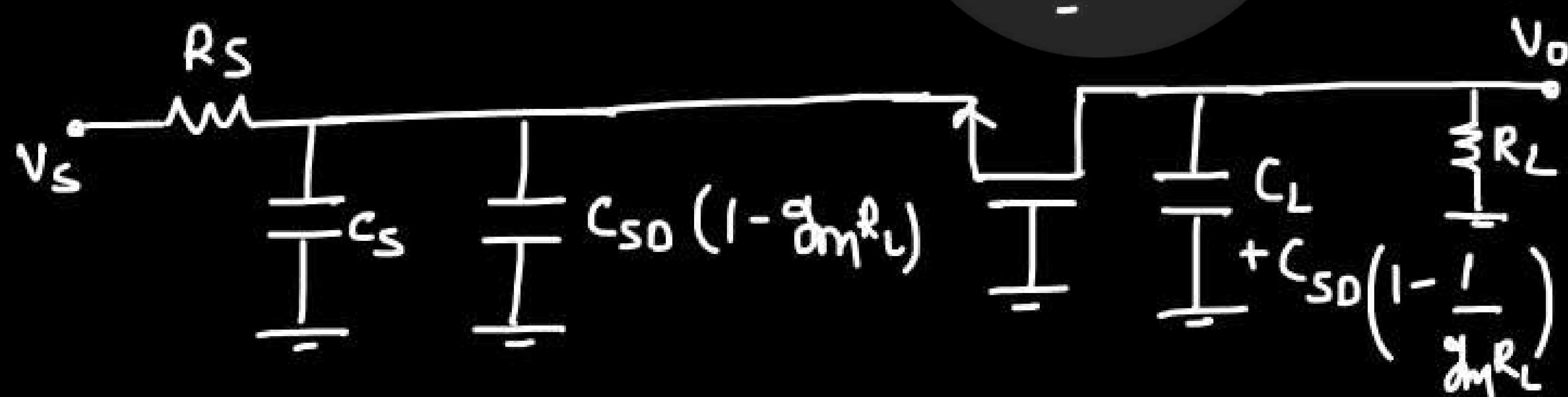
$C_{SD}, C_S, C_L \rightarrow$ Parasitics

$A \rightarrow$



$$\boxed{A = g_m R_L}$$

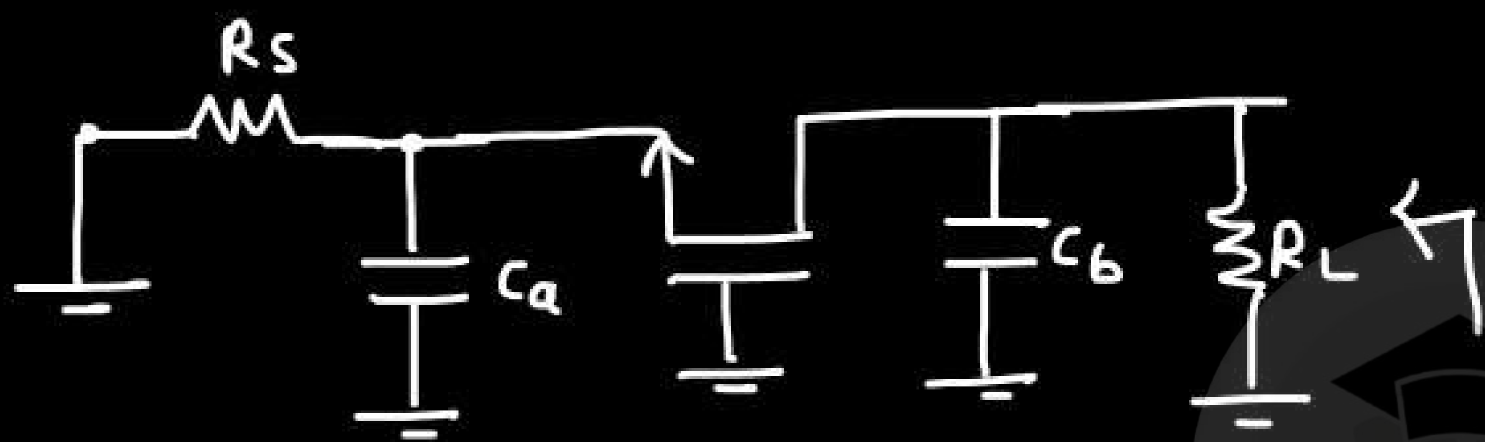
$\rightarrow$



$\simeq C_L + C_{SD}$

$$\omega_{z_1} = \infty \quad , \quad \omega_{z_2} = \infty$$

Poles:-



Equivalent resis. across

$C_b \rightarrow R_L$

$$\boxed{\omega_{p_2} \text{ or } \omega_{p_1} = \frac{1}{C_b R_L}}$$

$$C_a = C_s + C_{SD}[1 - g_m R_L]$$

$$C_b = C_s + C_{SD}\left[1 - \frac{1}{g_m R_L}\right] \approx C_s + C_{SD}$$

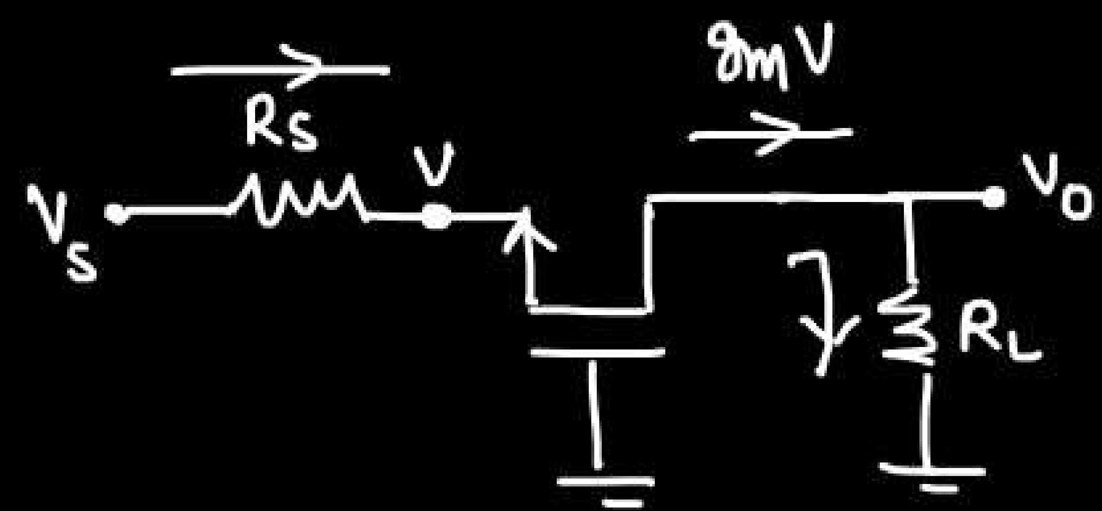
Equivalent res. across $C_a \rightarrow R_s \| 1/g_m$

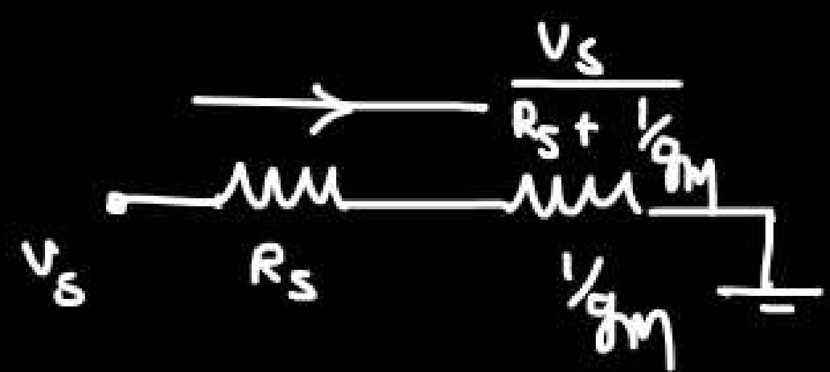
$$\boxed{\omega_{p_1} \text{ or } \omega_{p_2} = \frac{1}{C_a[R_s \| 1/g_m]}}$$

Dc gain:-

$$K = ? = \frac{V_0(\omega = 0)}{V_s(\omega = 0)}$$

K →

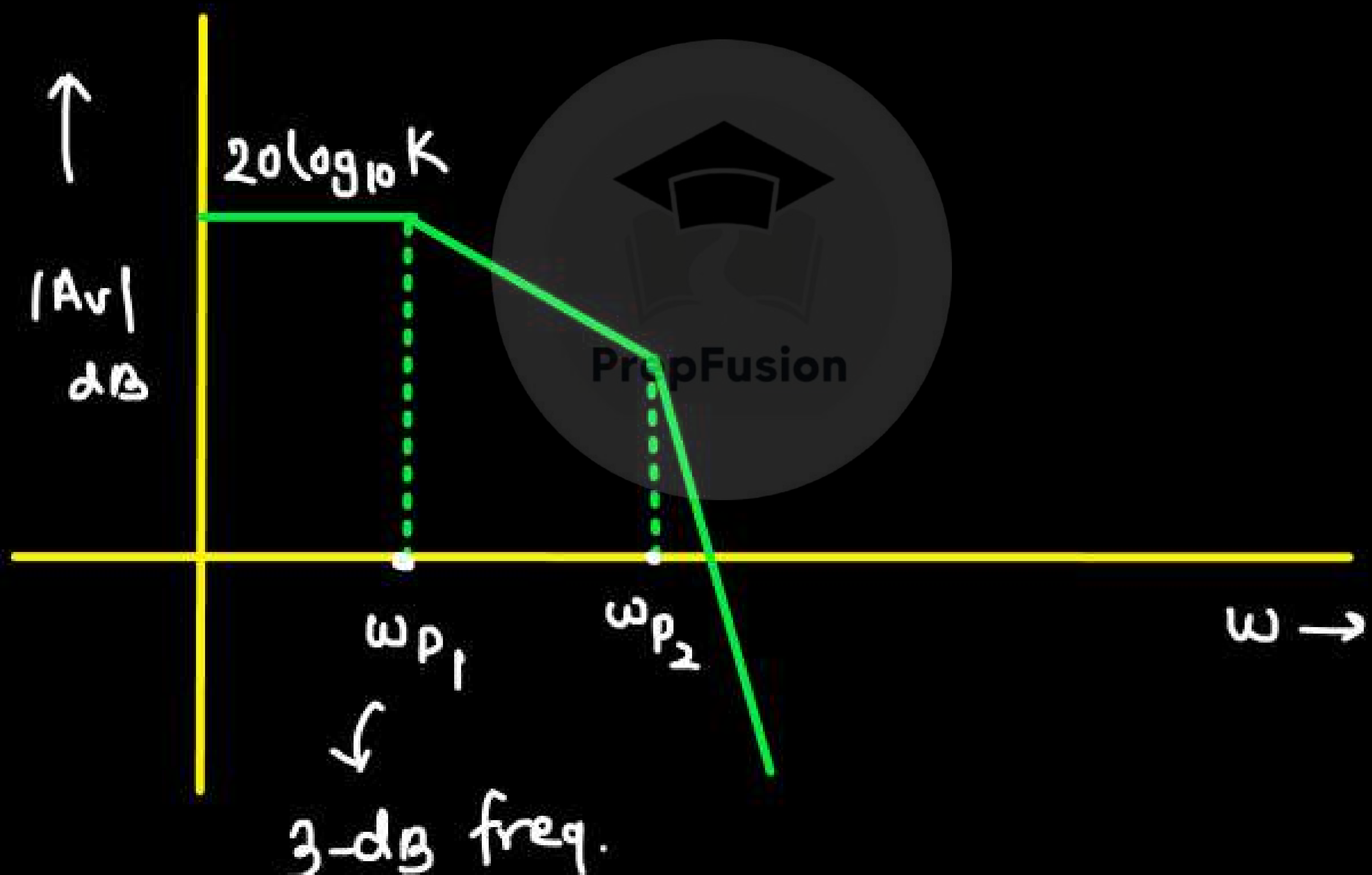




$$V_o = \frac{V_s}{R_s + 1/g_m} \times R_L$$

$$\boxed{\frac{V_o}{V_s} = \frac{g_m R_L}{1 + g_m R_s}} = K$$

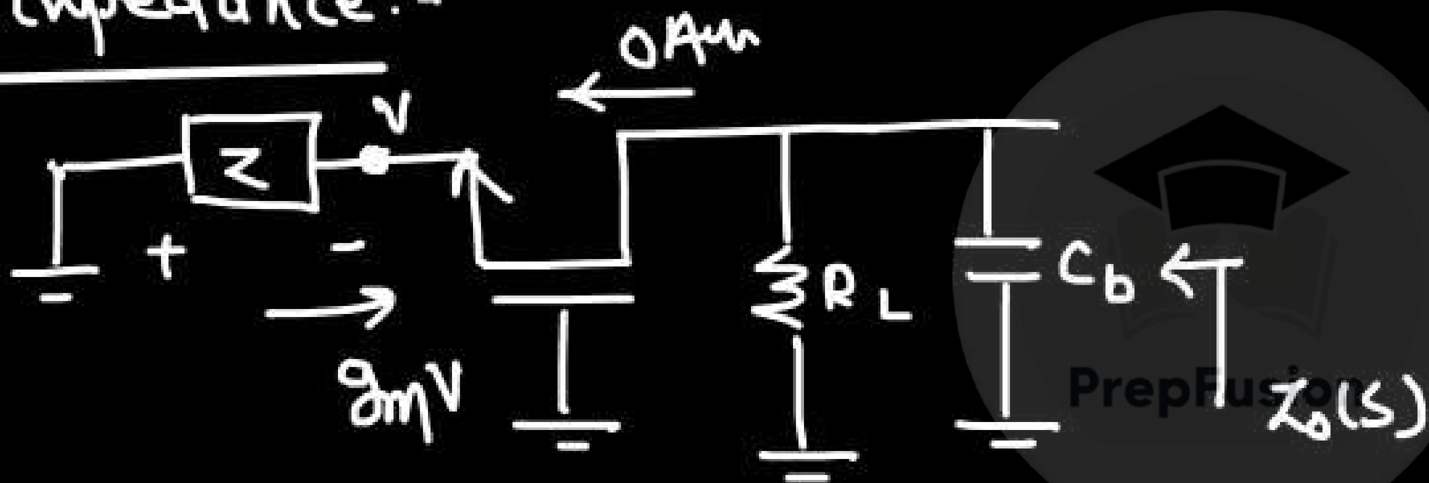
$$T(s) = \frac{K}{\left(\frac{s}{\omega_{p_1}}+1\right)\left(\frac{s}{\omega_{p_2}}+1\right)}$$



input resistance:-

$$\boxed{z_i(s) = R_s + \frac{1}{C_a s} \,||\, \frac{1}{g_m}}$$

output impedance:-



$$\boxed{z_o(s) = \frac{1}{C_b s} \,||\, R_L}$$

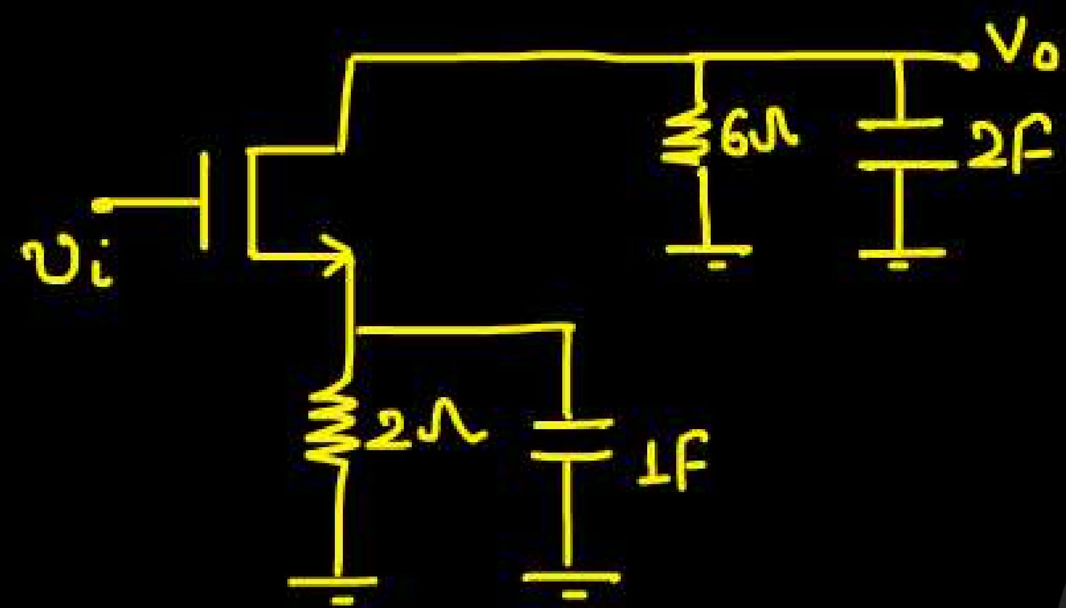
$$-g_m z V = V$$

$$V[1 + g_m z] = 0$$

$$\boxed{V = 0}$$

Assignment - 10

Q.



Given, $g_m = 0.5\,S$

① Find 3-dB B.W. and freq. response.

② Tell the location of poles and zeros.

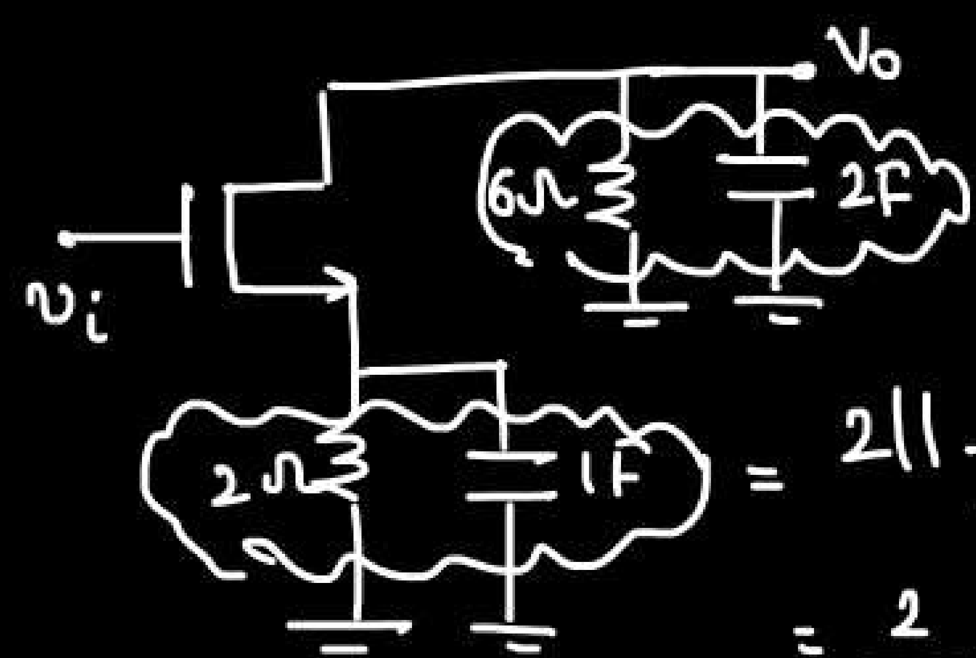
③ If small signal i/p

$$v_i = 20mV \sin\left(\frac{3}{4}t\right)$$

Find v_o?

N.B. → These are not the typical values of g_m, resistance and cap.

$\rightarrow$



$$Z_L(s) = 6 \parallel \frac{1}{2s} = \frac{6}{12s+1}$$

$$= 2 \parallel \frac{1}{s} = \frac{2}{2s+1} = Z(s)$$

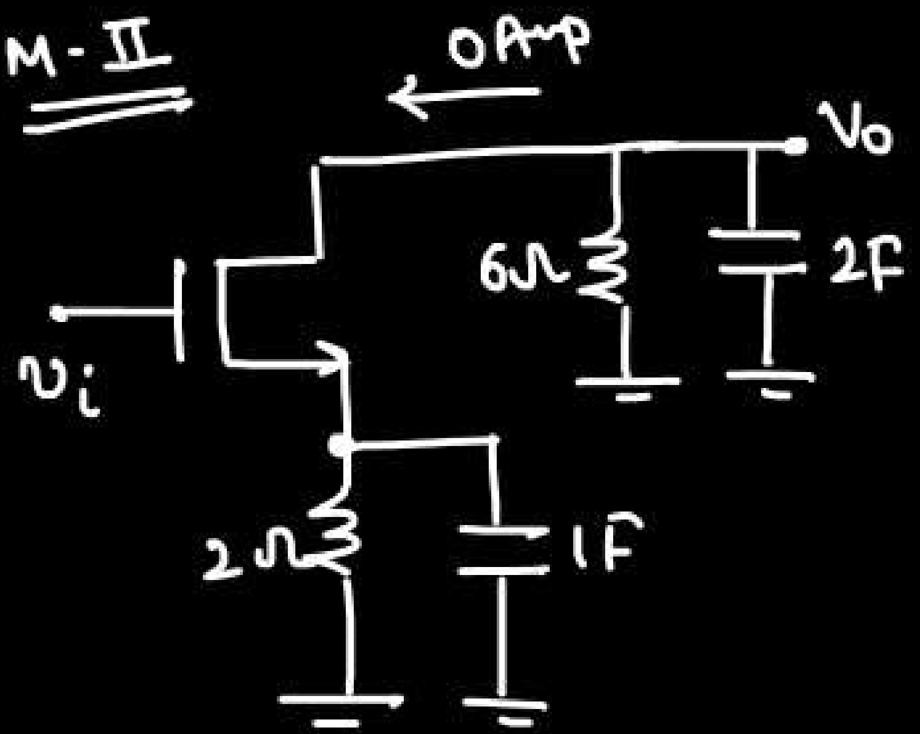
$$\frac{V_o(s)}{V_i(s)} = \frac{-g_m Z_L(s)}{1 + g_m Z(s)}$$

$$= \frac{-0.5\left(\frac{6}{12s+1}\right)}{1 + 0.5\left(\frac{2}{2s+1}\right)}$$

$$\frac{V_o(s)}{V_i(s)} = \frac{-\frac{3}{12s+1}}{1 + \frac{1}{2s+1}} = \frac{-3(2s+1)}{(12s+1)(2s+2)}$$

$$\boxed{\frac{V_o(s)}{v_i(s)} = \frac{-1.5(2s+1)}{(12s+1)(s+1)}}$$

M-II



$$\boxed{\text{order} = 2^{nd}}$$

Poles:-

$$\boxed{\omega_{p_2} = \frac{1}{1F\left(2\Omega \,\|\, \frac{1}{g_m}\right)} = \frac{1}{1F(2\Omega \,\|\, 2\Omega)} = -1 \text{ rad/sec.}}$$

$$\boxed{\omega_{p_1} = \frac{1}{2F(6)} = \frac{-1}{12} \text{ rad/sec.}}$$

DC gain:-

$$\boxed{K = \frac{-g_m R_L}{1 + g_m R_S} = \frac{-3}{1+1} = -1.5}$$

$$\boxed{T(s) = \frac{-1.5(2s+1)}{(12s+1)(s+1)}}$$

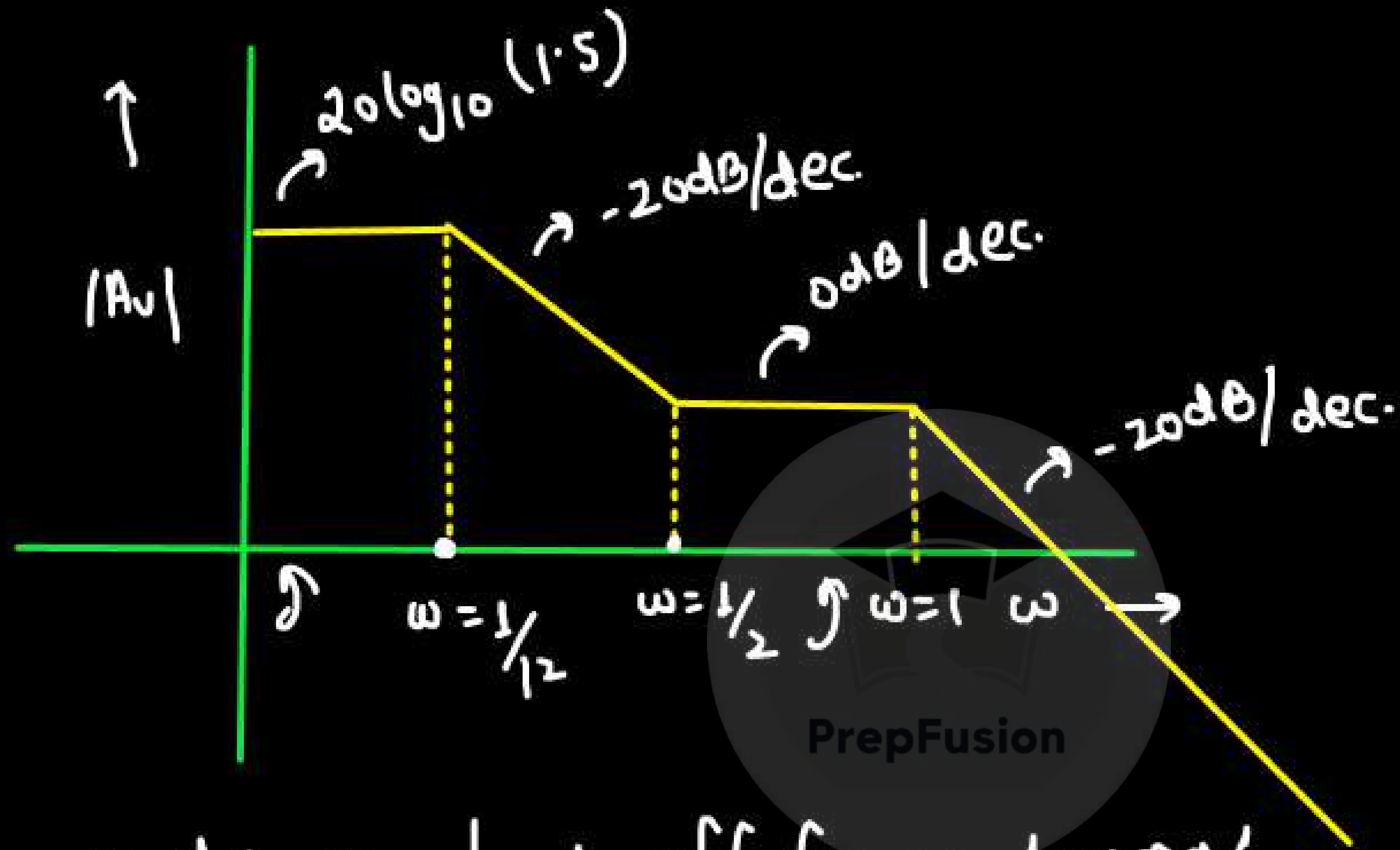
Zeros:-

$$\boxed{\omega_{z_1} = \infty} \;(2F)$$

$$\omega_{z_2} = ? \Rightarrow 2\Omega \,\|\, \frac{1}{1s} = \infty \Rightarrow \frac{2}{2s+1} = \frac{1}{0}$$

$$\boxed{\omega_{z_2} = -1/2}$$

Freq. response:-



3-dB B.W. / cut-off freq = $\frac{1}{12}$ rad/sec.

(iii) $V_i = 20\,mV \sin\left(\frac{3}{4}t\right)$; $\omega_i = \frac{3}{4}$ rad/sec.

$$\frac{V_o(s)}{V_i(s)} = \frac{-1.5(2s+1)}{(12s+1)(s+1)}$$

$$20\,mV \sin\left(\tfrac{3}{4}t\right) \longrightarrow \boxed{\frac{-1.5(2s+1)}{(12s+1)(s+1)}} \longrightarrow ?$$

$$\rightarrow \quad T\left(j\tfrac{3}{4}\right) = \frac{-1.5\left(2j\times\frac{3}{4}+1\right)}{\left(12\times j\frac{3}{4}+1\right)\left(j\frac{3}{4}+1\right)} = \frac{-1.5(6j+4)\times 4}{(j36+4)(j3+4)}$$

$$\left|T\left(j\tfrac{3}{4}\right)\right| = -0.24$$

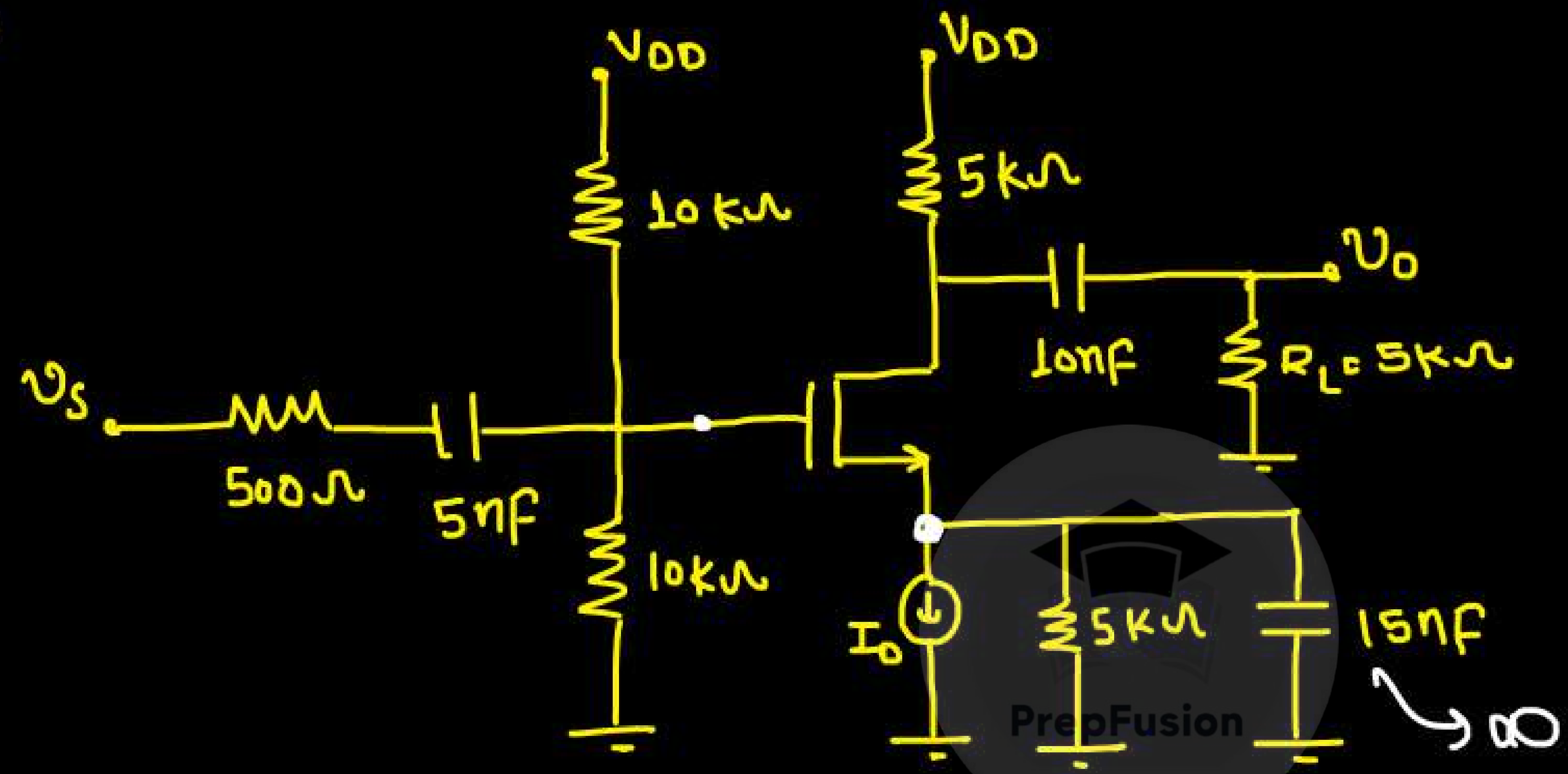
$$\angle T\left(j\tfrac{3}{4}\right) = -244.2^\circ$$

$$\left[-180^\circ + \tan^{-1}\left(\frac{6}{4}\right) - \tan^{-1}\left(\frac{36}{4}\right) - \tan^{-1}\left(\frac{3}{4}\right)\right]$$

**

$$\Rightarrow \quad \boxed{v_0(t) = 4.8\,mV \sin\left(\frac{3}{4}t - 244.2^\circ\right)}$$

Q.



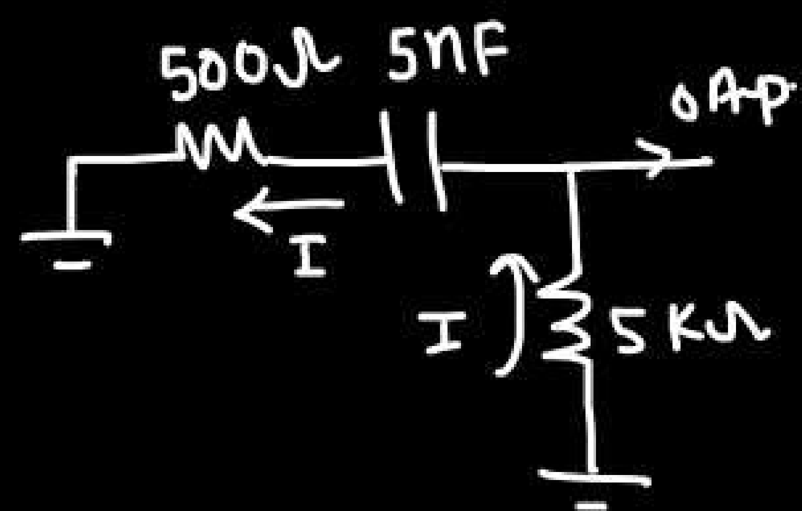
$g_m = 200\,\mu S$

(a) Find the location of poles and zeros.

(b) Find the 3-dB cut-off frequency.

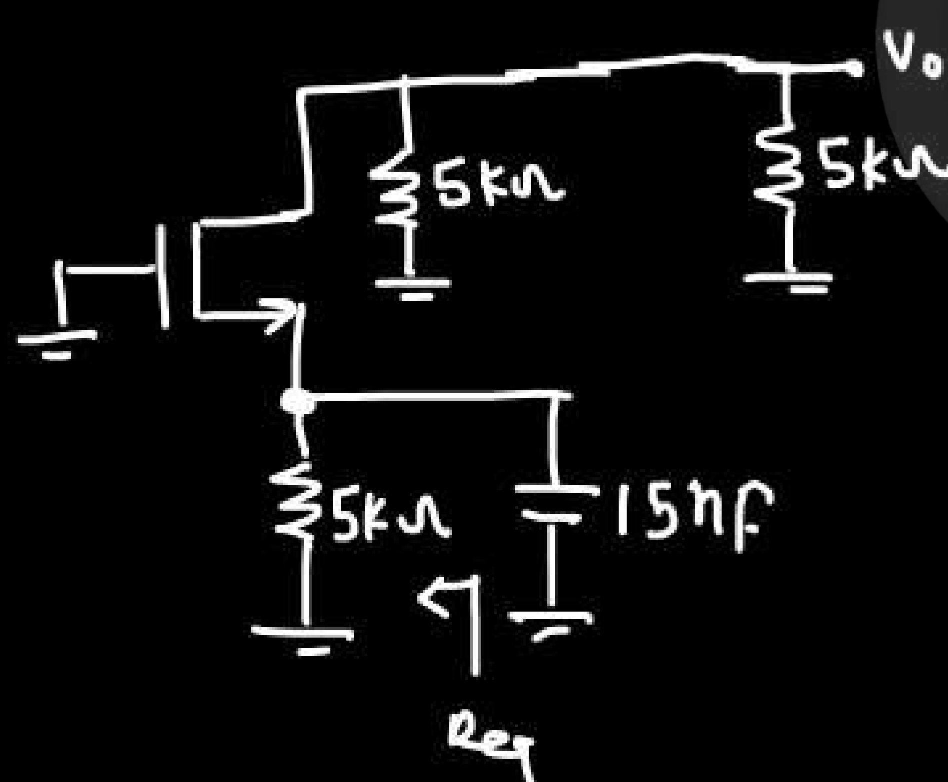
→ $\omega_{z_1} = 0$, $\omega_{z_2} = 0$ $\qquad \omega_{z_3} = \dfrac{-1}{15n \times 5K} = -13.33\,\text{K rad/sec.}$

Req. across 5nF:-



$$\omega_{p_3} = \frac{1}{5n \times 5.5K} = -36.36\ \text{krad/sec.}$$

15nF:-



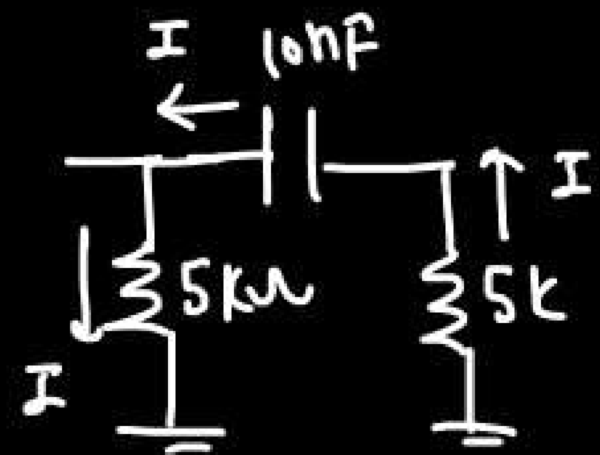
$$R_{eq} = 5K \,||\, \frac{1}{g_m} = 5k \,||\, 5k = 2.5K$$

$$[g_m = 200\mu S]$$

$$\omega_p = \frac{1}{15n \times 2.5K}$$

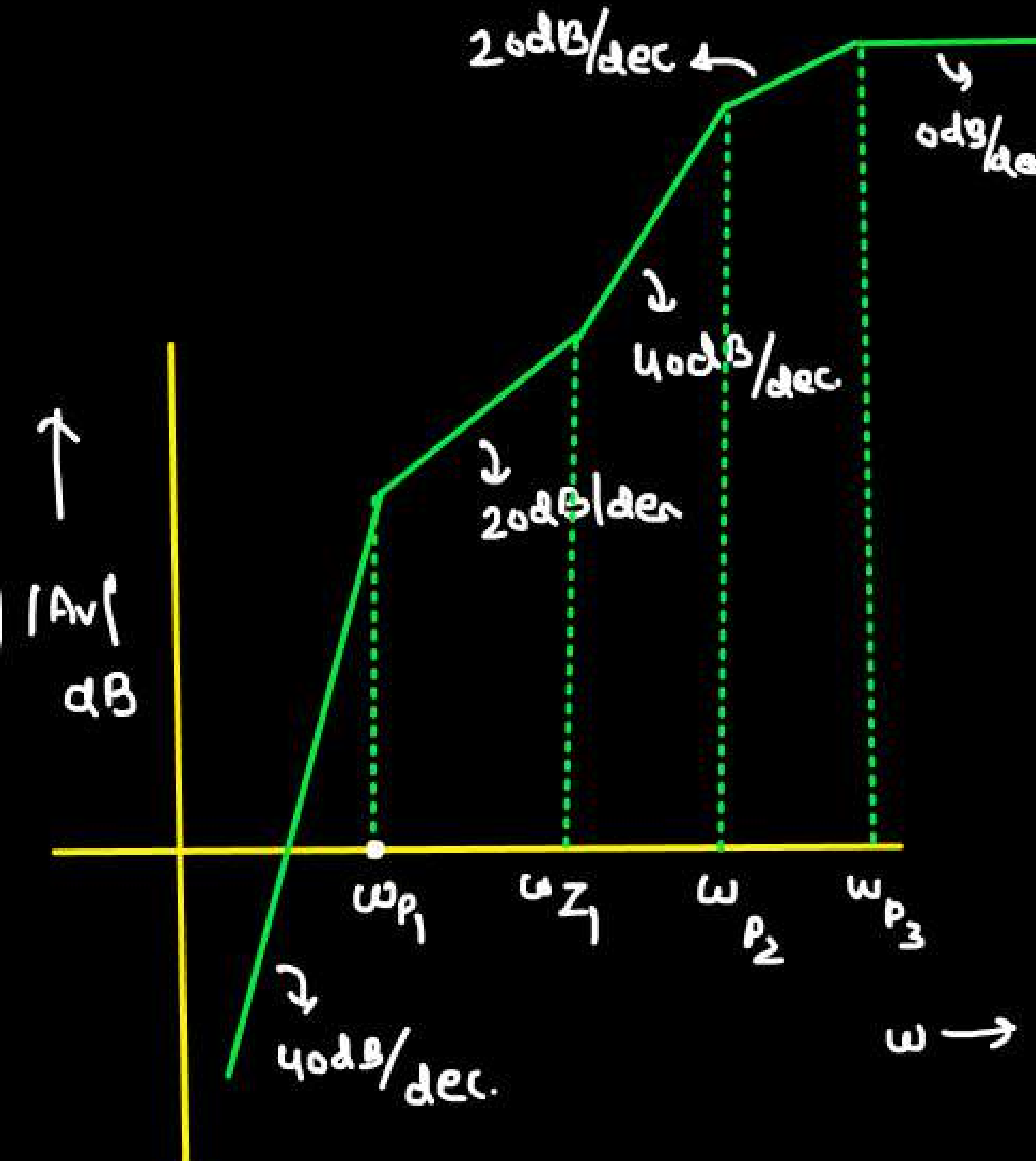
$$\omega_{p_2} = -26.67\ \text{Krad/sec.}$$

10nF :-



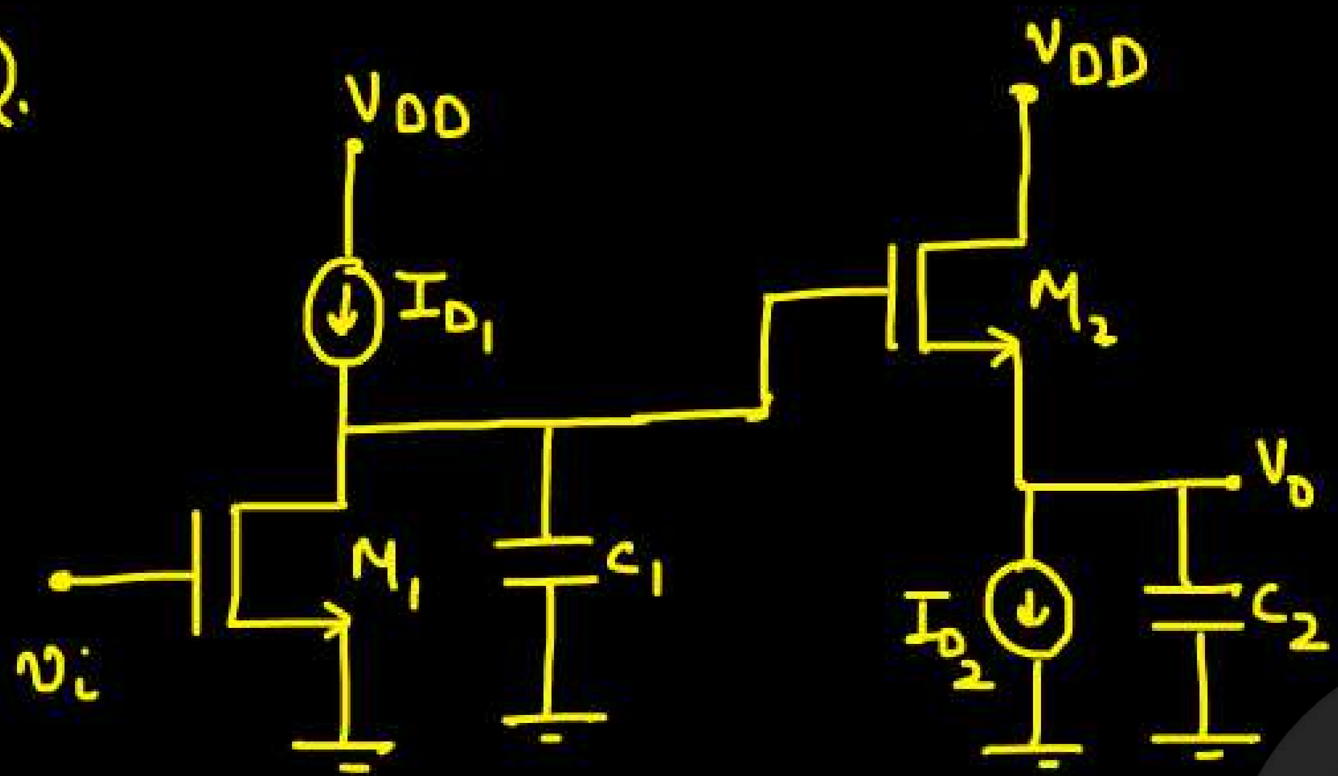
$$\omega_{p_1} = \frac{1}{10n \times 10K} = -10k \text{ rad/sec}$$

$$T(s) = \frac{A s^2 \left(\frac{s}{13.33k} + 1\right)}{\left(\frac{s}{10k}+1\right)\left(\frac{s}{26.67k}+1\right)\left(\frac{s}{36.36k}+1\right)}$$



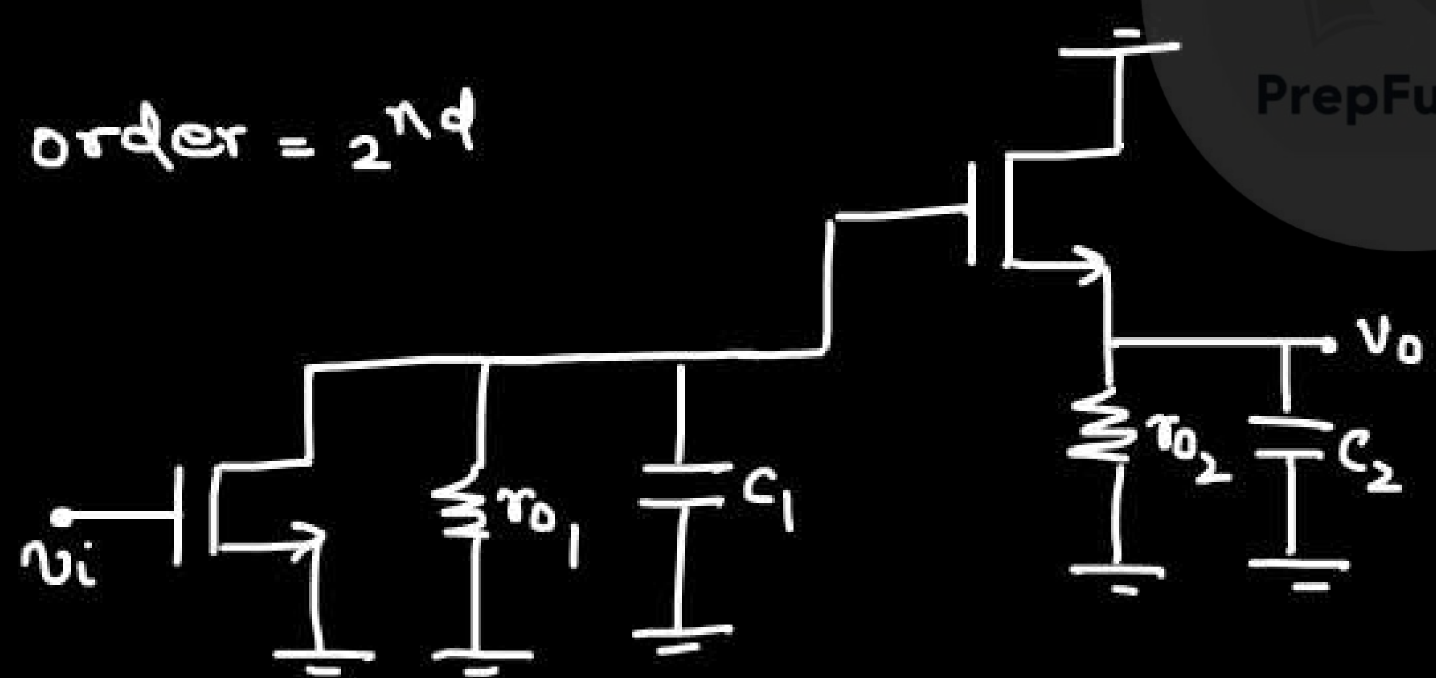
$$\boxed{\text{3-dB cut-off freq.} = 36.36 \text{ k rad/sec.}}$$

Q.



Write down the frequency response intuitively.

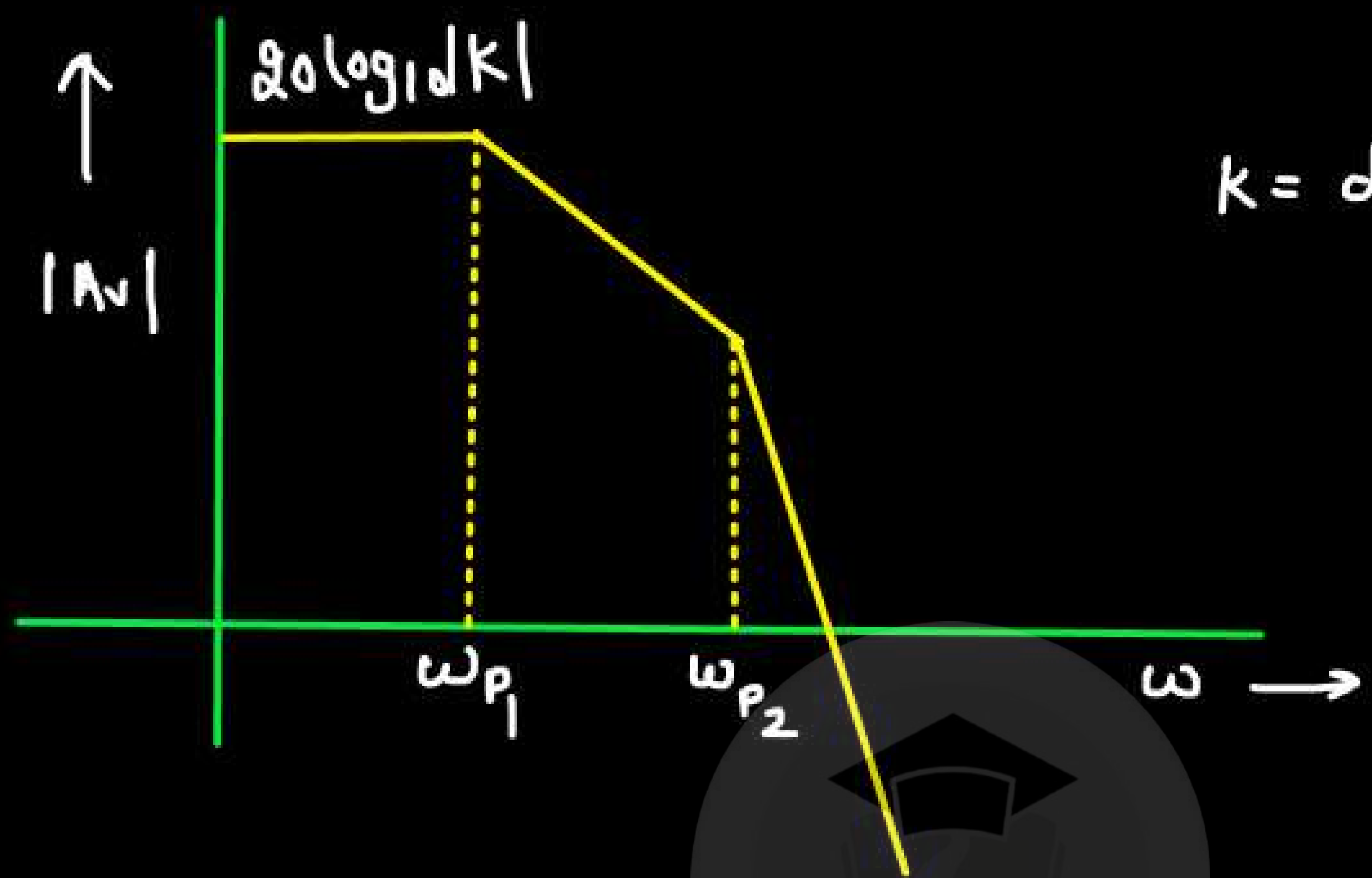
→ order = 2nd



$$\omega_{p_1} \text{ or } \omega_{p_2} = \frac{-1}{r_{o_1} C_1}$$

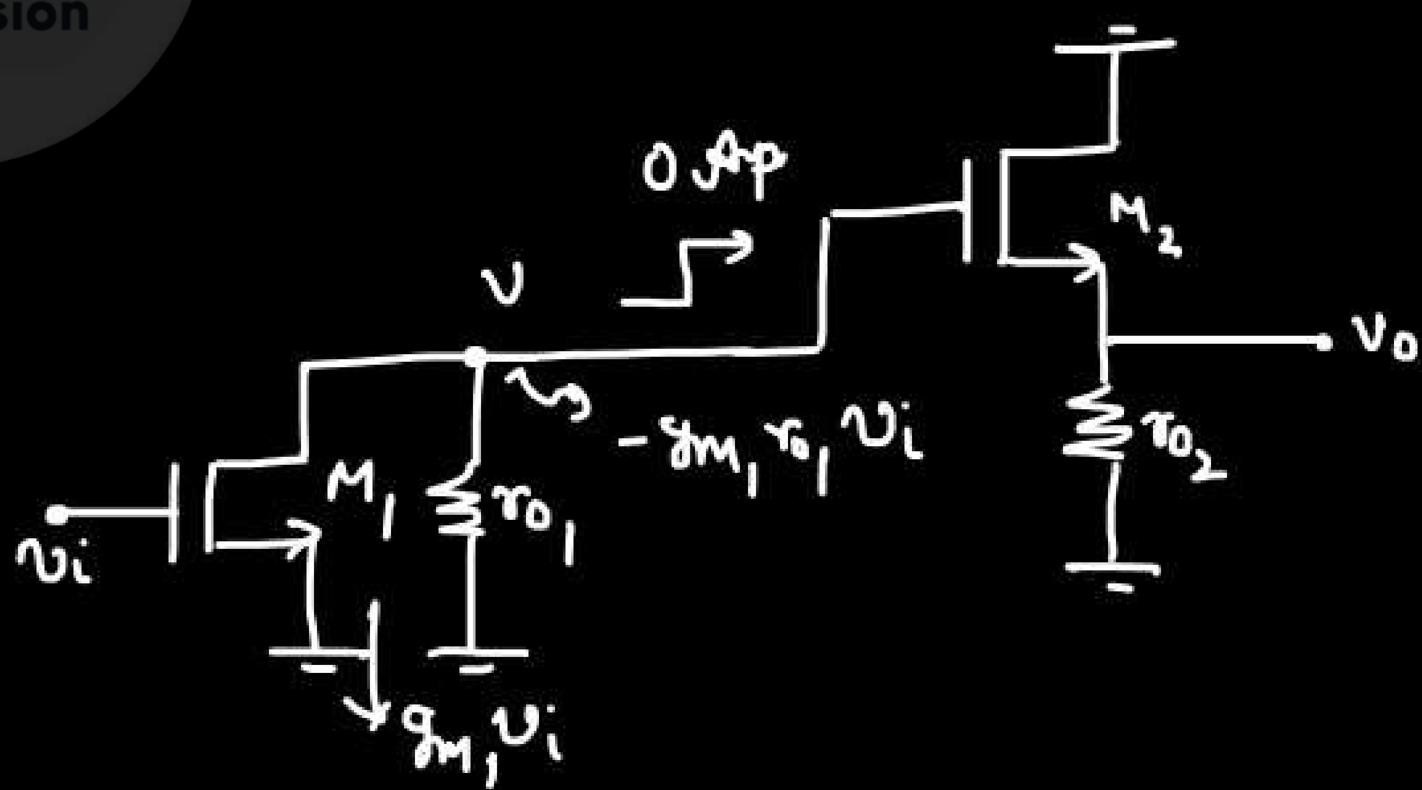
$$\omega_{p_2} \text{ or } \omega_{p_1} = \frac{-1}{C_2\left[\frac{1}{g_{m_2}} \| r_{o_2}\right]}$$

$$\omega_{z_1} = \infty \quad , \quad \omega_{z_2} = \infty$$



K = dc gain

$$\frac{V_0}{v_i} = \frac{-g_{m_2} r_{o_2}}{1+g_{m_2} r_{o_2}} \times g_{m_1} r_{o_1} = K$$

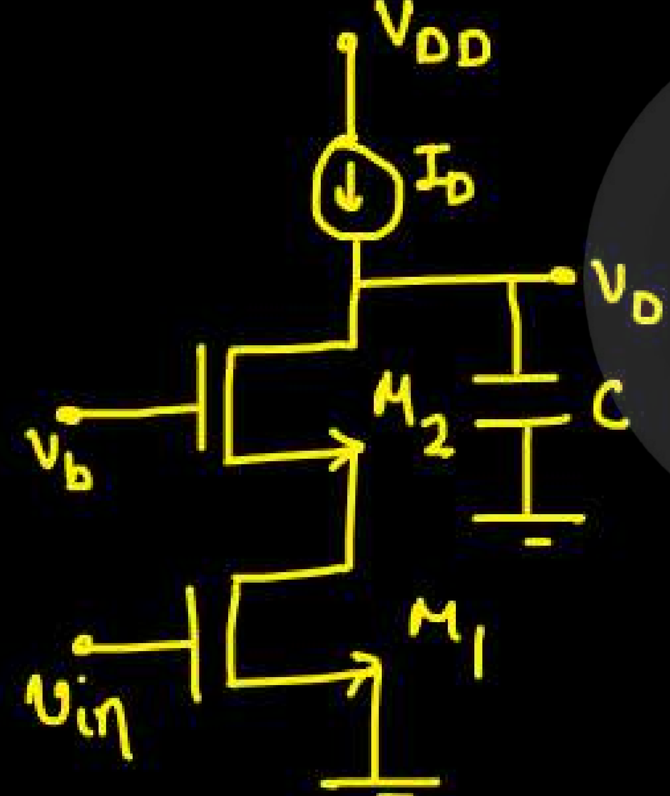


Q. Find (a) DC gain

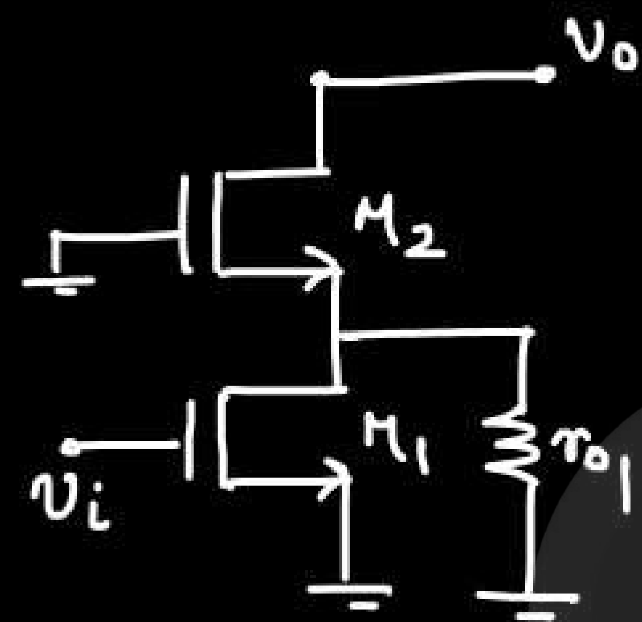
(b) 3-dB Bandwidth ($\omega_{3\text{-dB}}$)

(c) 3-dB Unity gain Bandwidth ($\omega_{u\text{dB}}$)

[Make Necessary Approximations]



(a) Dc gain (Small signal gain):-



$$A_v = -G_m R_{out}$$

$$A_v \approx -g_{m_1} g_{m_2} r_{o_2} r_{o_1}$$

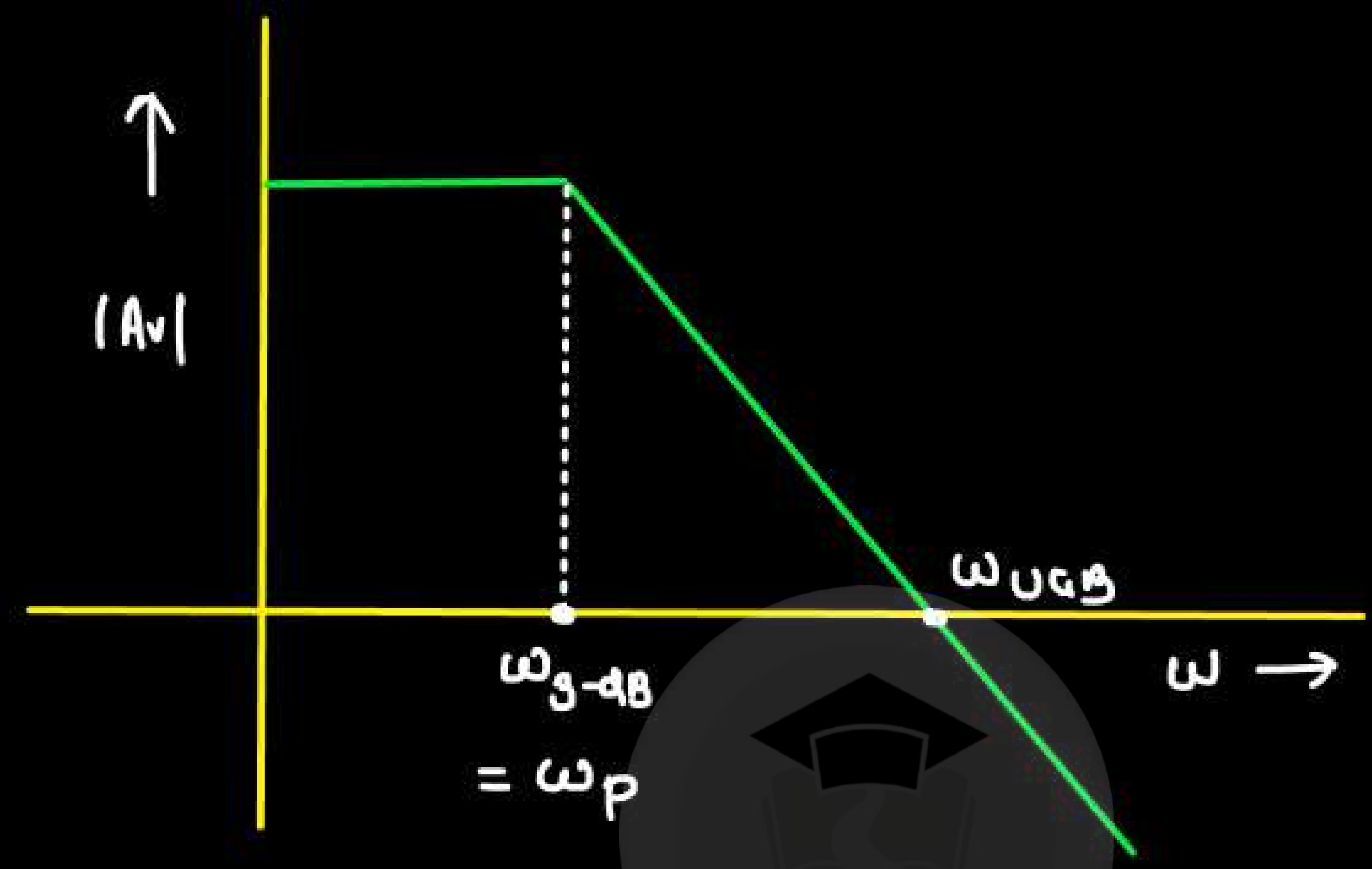
$$R_{out} = g_{m_2} r_{o_2} r_{o_1} + r_{o_2} + r_{o_1}$$

(ii) 1st order:-

$$\omega_z = \infty$$

$$\omega_p = \frac{-1}{C[g_{m_2} r_{o_2} r_{o_1}]}$$

$$\boxed{T(s) = \frac{-g_{m_1} g_{m_2} r_{o_1} r_{o_2}}{1 + sC g_{m_2} r_{o_2} r_{o_1}}}$$



$$3\text{-dB B.W.} = \omega_p = \frac{-1}{C[g_{m_2} r_{o_2} r_{o_1} + r_{o_2} + r_{o_1}]} \approx \frac{-1}{C g_{m_2} r_{o_2} r_{o_1}}$$

<u>Unity gain B.W.</u> (UGB) → For a low Pass filter, the freq. @ which the gain is unity (0 dB).

@ $\omega = \omega_{UGB}$

$$|T(j\omega_{UGB})| = 1$$

$$\frac{g_{m_1} g_{m_2} r_{o_2} r_{o_1}}{\sqrt{1 + \omega_{UGB}^2 C^2 g_{m_2}^2 r_{o_2}^2 r_{o_1}^2}} = 1$$

$$g_{m_1}^2 g_{m_2}^2 r_{o_2}^2 r_{o_1}^2 = \omega_{UGB}^2 C^2 g_{m_2}^2 r_{o_2}^2 r_{o_1}^2$$

$$\boxed{\omega_{UGB} = \frac{g_{m_1}}{C}}$$

For a stable config. →

Gain Bandwidth product is constant.

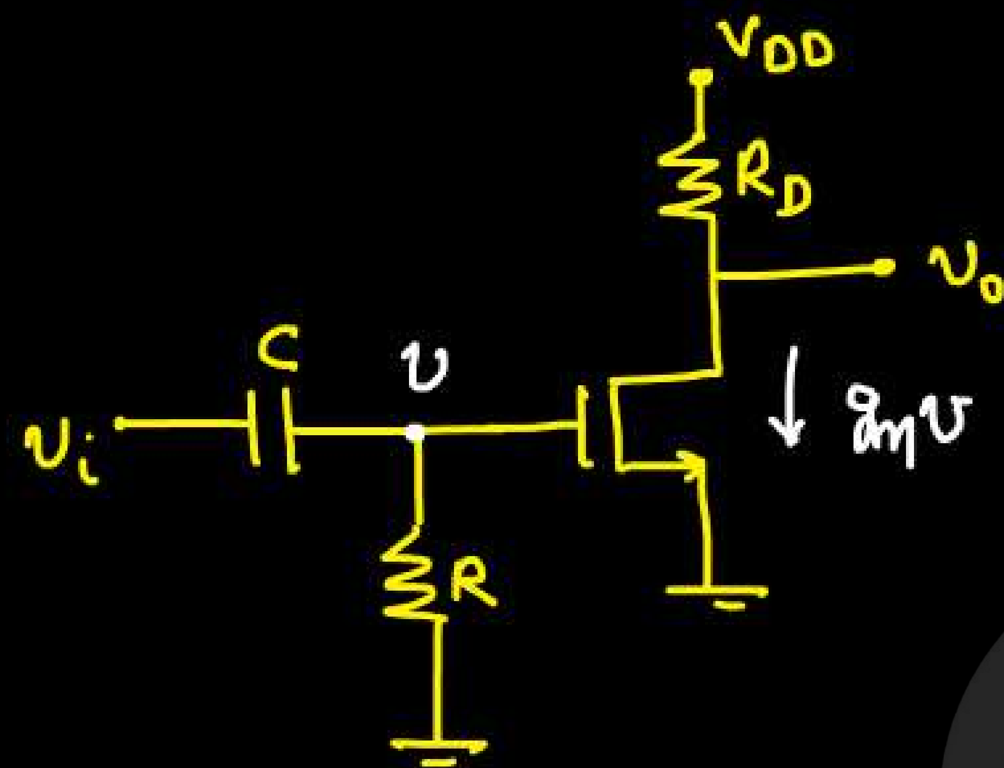
3-dB Bandwidth × DC gain = Unity gain B.W. × 1

$$\boxed{\omega_{UGB} = A_v \times \omega_{3\text{-}dB}}$$

For the given problem,

$$\boxed{\omega_{UGB} = \frac{g_{m_1} g_{m_2} r_{o_2} r_{o_1}}{C\, g_{m_2} r_{o_2} r_{o_1}} = \frac{g_{m_1}}{C}}$$

Q.



Q.(a) Find 3-dB B.W.

(b) Find 3-dB cut-off freq.

(c) Find the freq. @ which the gain is unity.

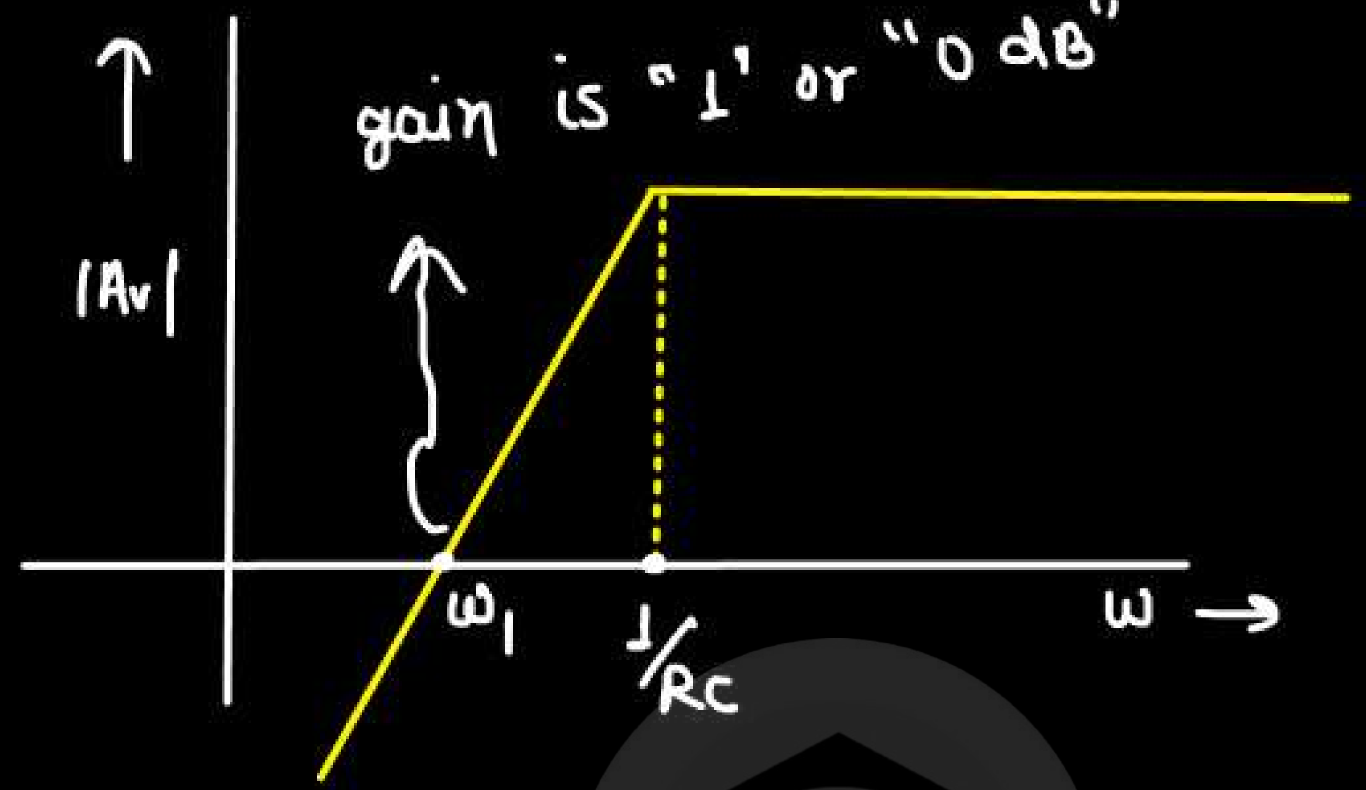
$$v_o = -g_m R_D v \quad \text{—— (1)}$$

$$v = \frac{RCs}{1+RCs} v_i \quad \text{—— (2)}$$

$$\boxed{\frac{v_o}{v_i} = -g_m R_D \left(\frac{RCs}{RCs+1}\right)}$$

$$\omega_z = 0$$

$$\omega_p = \frac{-1}{RC}$$



① 3-dB cut-off freq. = $1/RC = \omega_p$

② 3-dB B.W. = $\infty - \dfrac{1}{RC} = \infty$

$\omega_1 = ?$

@ $\omega = \omega_1$

$$|T(j\omega_1)| = 1$$

$$\frac{g_m R_D \times R C \omega_1}{\sqrt{1+\omega_1^2 R^2 C^2}} = 1$$

$$g_m^2 R_D^2 R^2 C^2 \omega_1^2 = 1 + \omega_1^2 R^2 C^2$$

$$\omega_1^2 \left[g_m^2 R_D^2 R^2 C^2 - R^2 C^2 \right] = 1$$

$$\boxed{\omega_1 = \frac{1}{RC\sqrt{g_m^2 R_D^2 - 1}}}$$

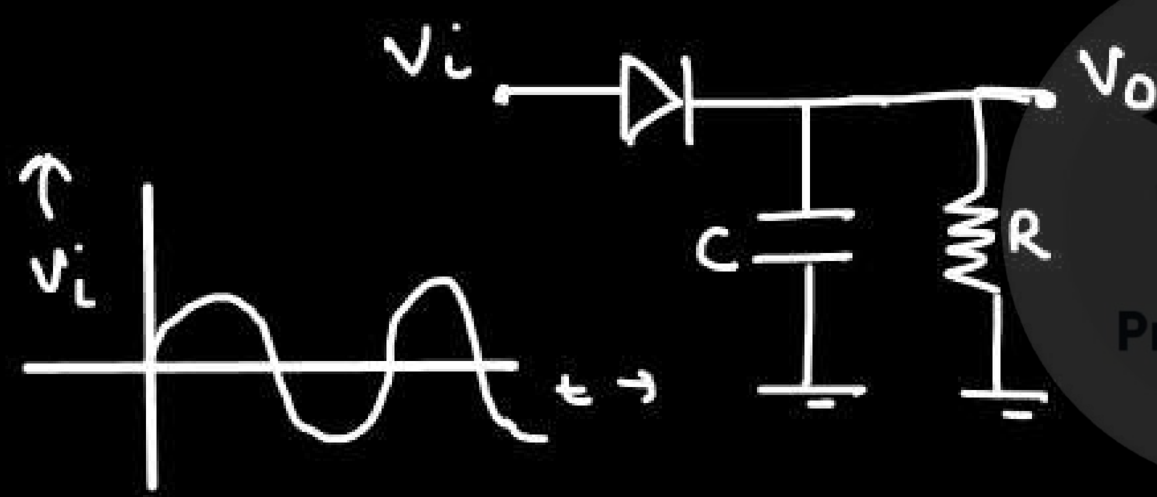
generally $g_m R_D >> 1$

$$\boxed{\omega_1 \approx \frac{1}{RC \times g_m R_D}}$$

Differential Amplifier

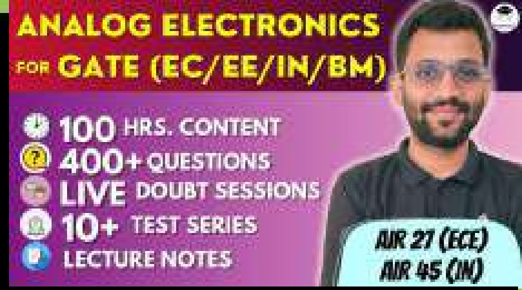
↳ Why do we need differential Amplifier?

* Generally the dc supply we use, have some small ripple.



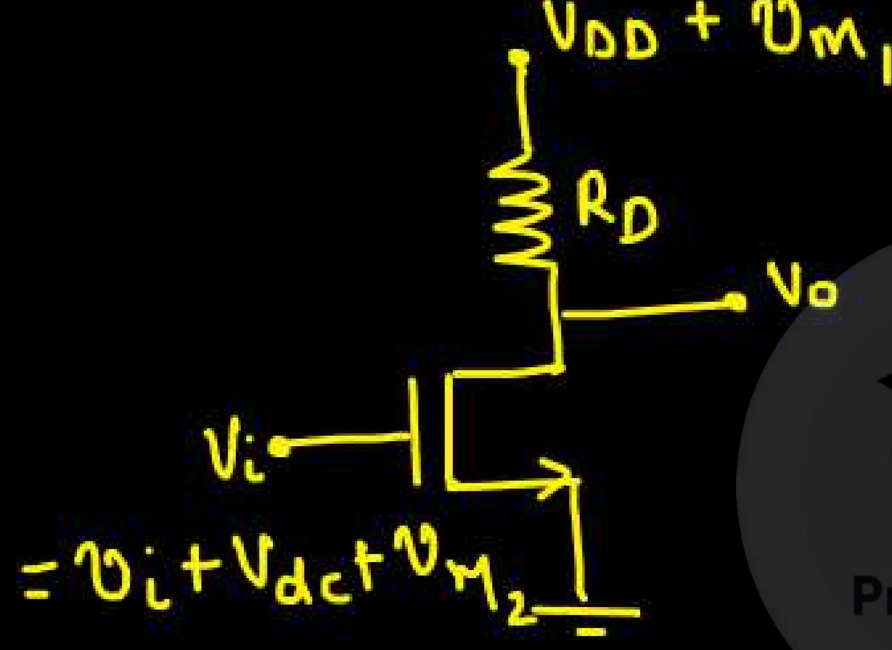
$$\boxed{V_o = \underbrace{V_{dc}}_{\text{dc o/p}} + \underbrace{v_m}_{\text{ripple (small signal noise)}}}$$

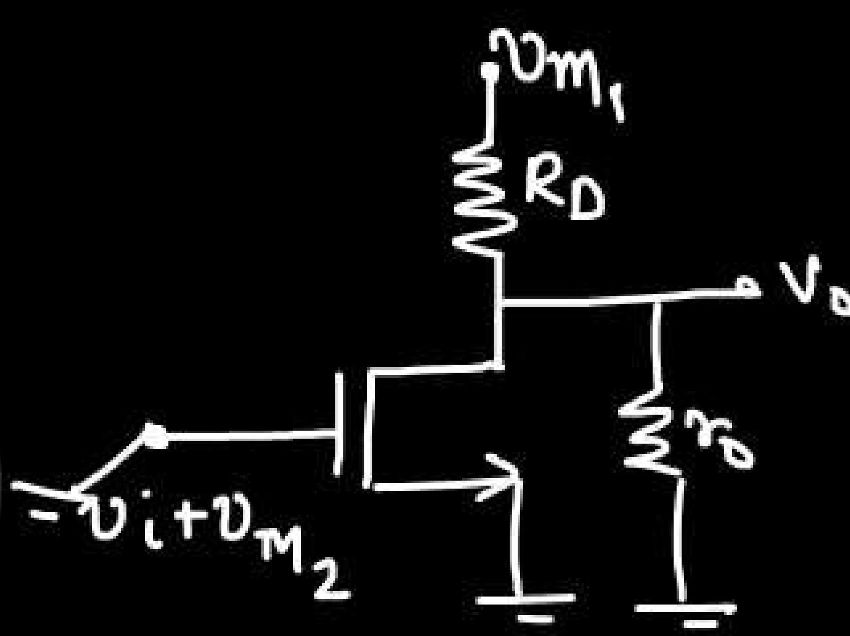
This supply will be fed to the Transistors.



Q. All the supplies have some ripples (v_{m_1}, v_{m_2}).

Find small signal o/p.





$$v_o = -g_m(v_i + v_{m_2})(R_D \| r_o) + \frac{r_o}{r_o + R_D} v_{m_1}$$

$$v_o = -g_m(R_D \| r_o)v_i - g_m(R_D \| r_o)v_{m_2} + \frac{r_o}{r_o + R_D} v_{m_1}$$

$$\boxed{v_0 = \underbrace{-g_m(R_D \| r_o)v_i}_{\text{desired}} \underbrace{- g_m(R_D \| r_o)v_{m_2} + \frac{r_o}{r_o + R_D} v_{m_1}}_{\text{NOISE}}}$$

To eradicate the noise part, we use differential amp.

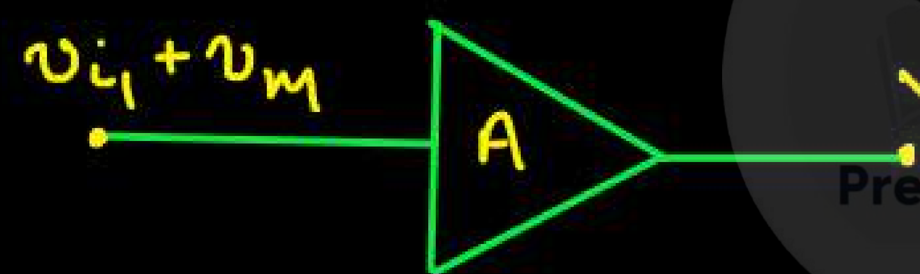
Basic Idea :-

↳ At input, you have "signal + Noise"

↳ At output, you have "signal + Noise"

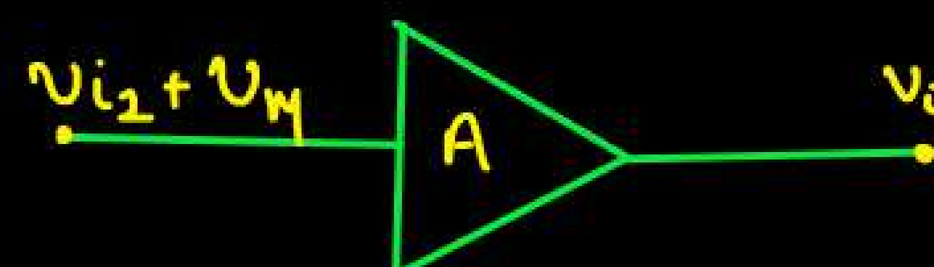
you want Amplified O/P, but no noise ⇒

$$[v_0 = \underline{A} v_i]$$



$$v_{o_1} = A v_{i_1} + A v_n$$

$$V_0 = v_{o_2} - v_{o_1} = A(v_{i_2} - v_{i_1}) + A v_n - A v_n$$



$$v_{o_2} = A v_{i_2} + A v_n$$

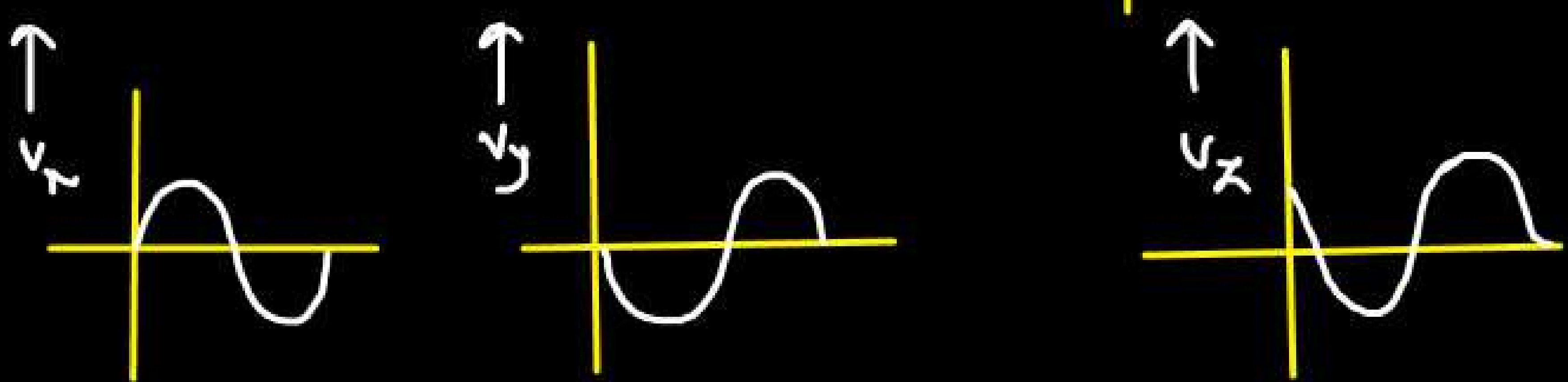
$$\boxed{v_0 = A(v_{i_2} - v_{i_1})}$$

if $v_{i_2} = v_i/2$ and $v_{i_1} = -v_i/2$

$\boxed{v_0 = A v_i}$ ⇒ desired o/p

Here v_{i_2} and v_{i_1} are differential signals.

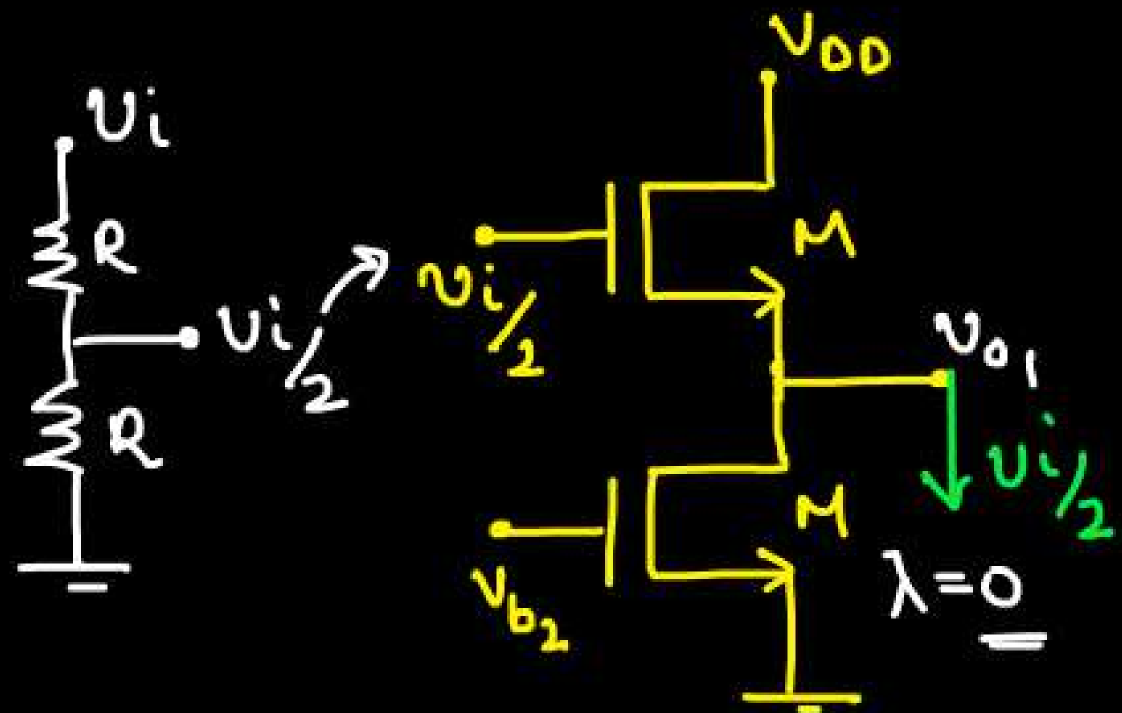
→ Same amplitude
→ Same dc level
→ opposite in phase

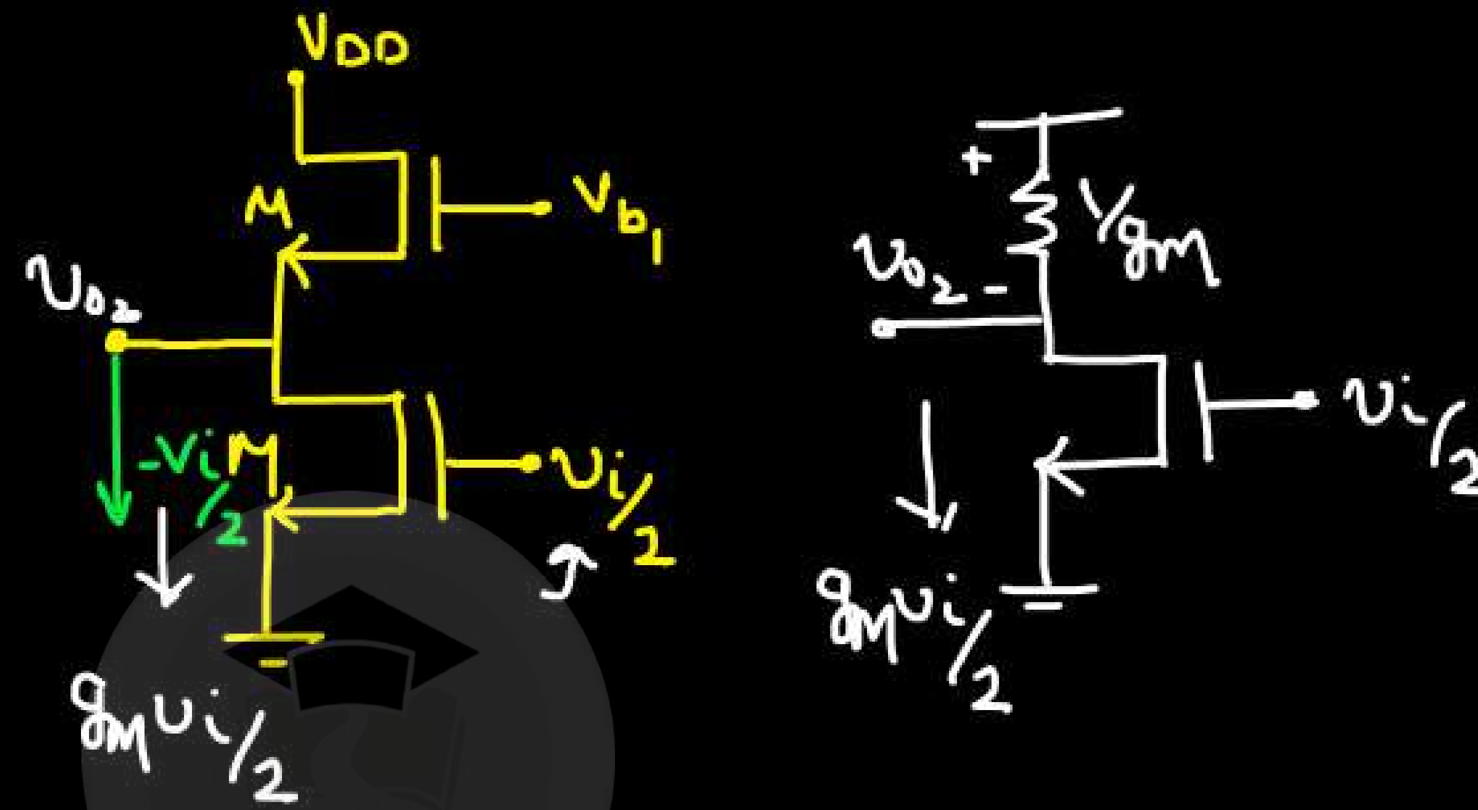


⇒ v_x & v_y are differential signals.

⇒ v_x & v_z are not differential signals.

How to generate differential signal:-





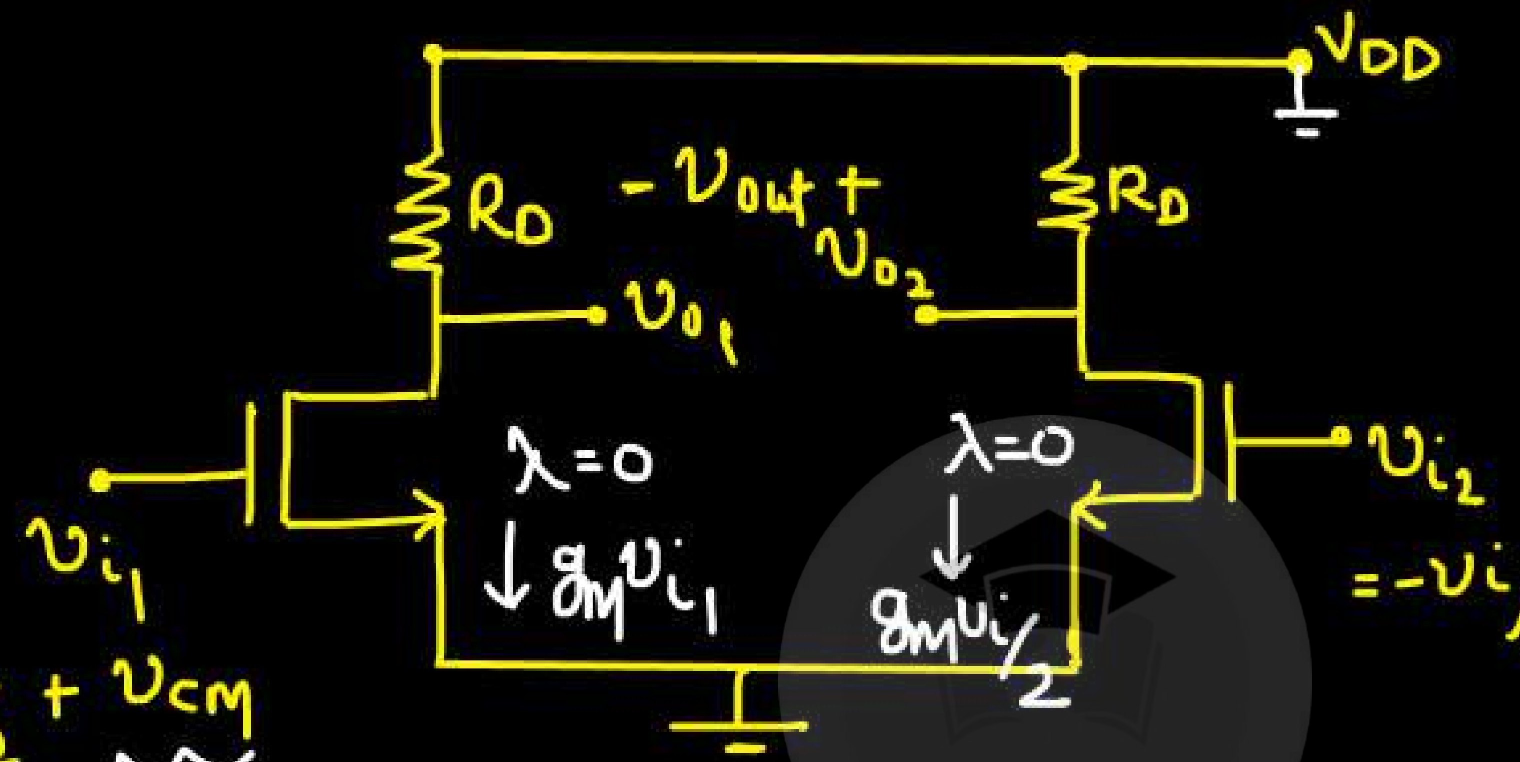
$$g_m\left(\frac{v_i}{2} - v_{o_1}\right) = 0$$

$$\boxed{v_{o_1} = v_i/2}$$

$$v_{o_2} = -g_m v_i/2\left[\frac{1}{g_m}\right]$$

$$\boxed{v_{o_2} = -v_i/2}$$

Differential Amplifier:-



$v_{i_1} = \underbrace{v_i/2}_{\text{small signal i/p}} + \underbrace{v_{cm}}_{\text{small signal Noise}}$

$v_{i_2} = -v_i/2 + v_{cm}$

$$v_{o_1} = -g_m R_D v_{i_1}$$

$$= -g_m R_D \left[v_i/2 + v_{cm}\right]$$

$$\boxed{v_{o_1} = -g_m R_D \frac{v_i}{2} - g_m R_D v_{cm}}$$

$$v_{o_2} = -g_m R_D v_{i_2}$$

$$= -g_m R_D \left[-\frac{v_i}{2} + v_{cm}\right]$$

$$\boxed{v_{o_2} = g_m R_D v_i/2 - g_m R_D v_{cm}}$$

$$v_o = v_{o_2} - v_{o_1}$$

$$= g_m R_D \frac{v_i}{2} - g_m R_D v_{cm} - \left[-g_m R_D \frac{v_i}{2} - g_m R_D v_{cm} \right]$$

$$v_o = g_m R_D v_i$$

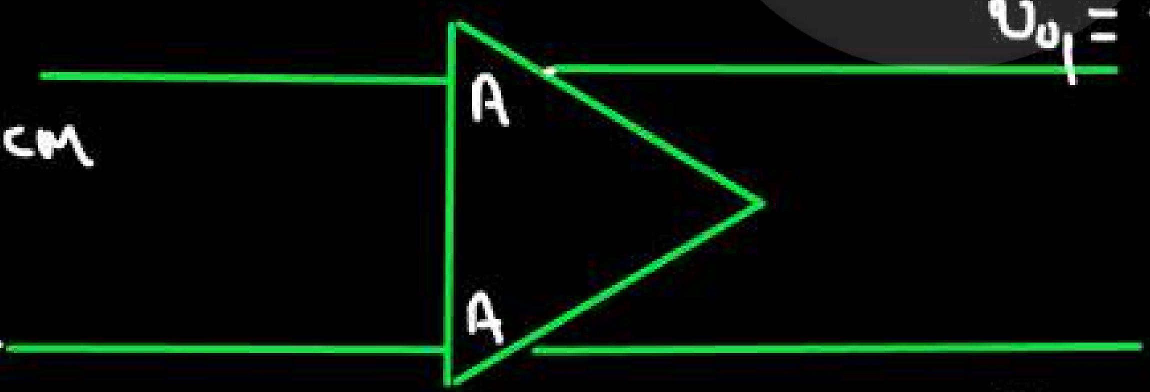
$$\boxed{\frac{v_o}{v_i} = g_m R_D}$$

v_{i_1}

$= v_i/2 + v_{cm}$

v_{i_2}

$= -v_i/2 + v_{cm}$



$v_{o_1} = -g_m R_D v_i/2 - g_m R_D v_{cm}$

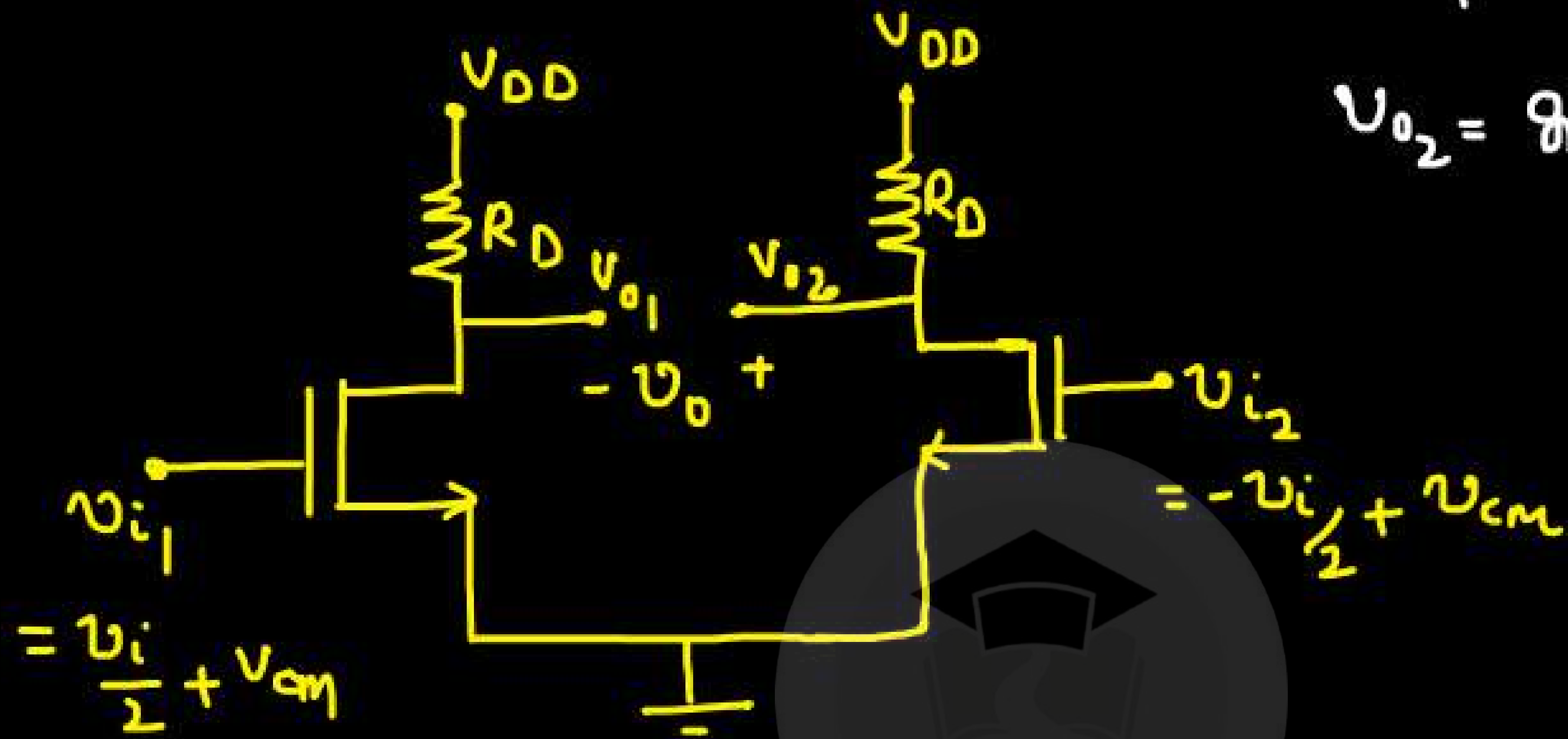
$-$

$$\boxed{v_{out} = v_{o_2} - v_{o_1} = g_m R_D v_i}$$

$+$

$v_{o_2} = g_m R_D v_i/2 - g_m R_D v_{cm}$

Some Common Terms:-



$$v_{o_1} = -g_m R_D \frac{v_i}{2} - g_m R_D v_{cm}$$

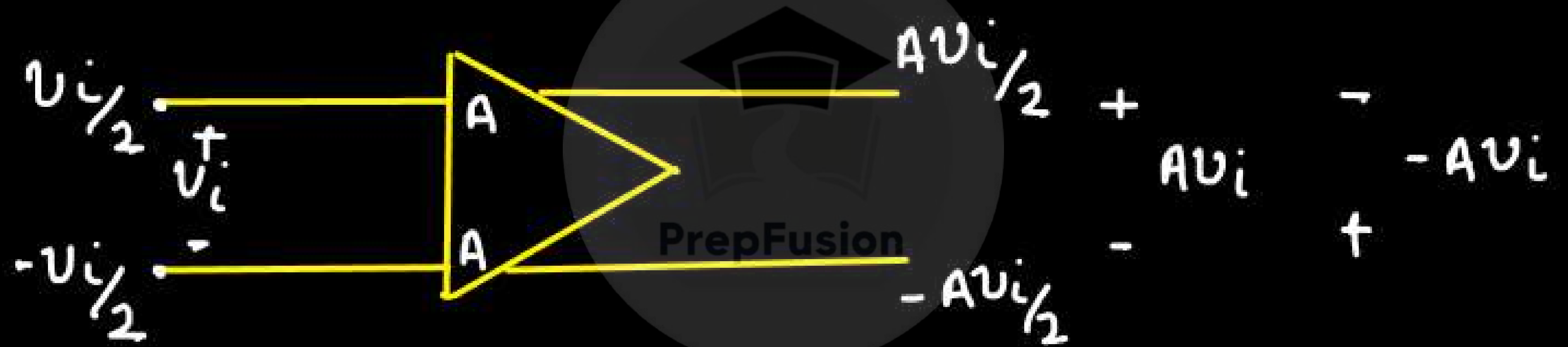
$$v_{o_2} = g_m R_D \frac{v_i}{2} - g_m R_D v_{cm}$$

* differential input $(v_i)_d = v_{i_1} - v_{i_2} = v_i$
* differential output $(v_o)_d = v_{o_2} - v_{o_1} = g_m R_D v_i$
* differential gain $(A_v)_d = \dfrac{(v_o)_d}{(v_o)_i} = g_m R_D$

⇒ HOW TO FIND $\boxed{\text{Differential Gain}}$:-

Put $v_{i_1} = v_i/2$ and $v_{i_2} = -v_i/2$ $\{$if $v_{i_1} - v_{i_2} = v_i\}$

Calculate $v_o = v_{o_2} - v_{o_1}$ OR $v_{o_1} - v_{o_2}$



Here $A = -g_m R_D$

★ Common mode input $(v_i)_{cm} = \dfrac{v_{i_1} + v_{i_2}}{2} = \dfrac{2v_{cm}}{2} = v_{cm}$

★ Common mode output $(v_o)_{cm} = \dfrac{v_{o_1} + v_{o_2}}{2} = \dfrac{-2g_m R_D v_{cm}}{2} = -g_m R_D v_{cm}$

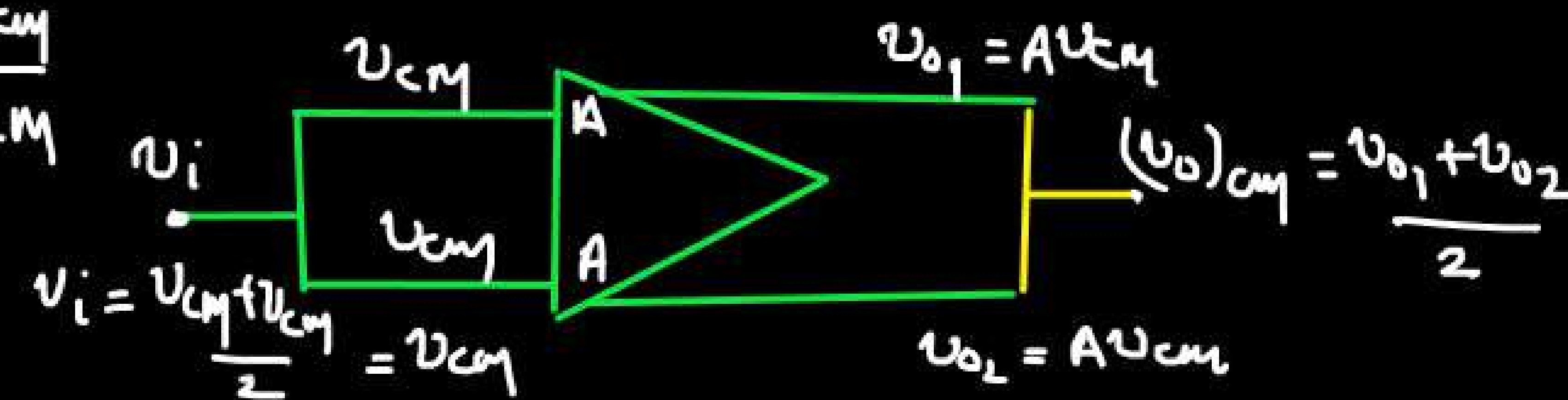
★ Common mode gain $(A_v)_{cm} = \dfrac{(v_o)_{cm}}{(v_i)_{cm}} = -g_m R_D$

HOW TO FIND $\boxed{\text{Common mode gain}}$:-

→ Apply $v_{i_1} = v_{i_2} = v_{cm}$

Find v_{o_1} and v_{o_2} and take average ⇒ $(v_o)_{cm}$

$\text{gain} = \dfrac{(v_o)_{cm}}{v_{cm}}$



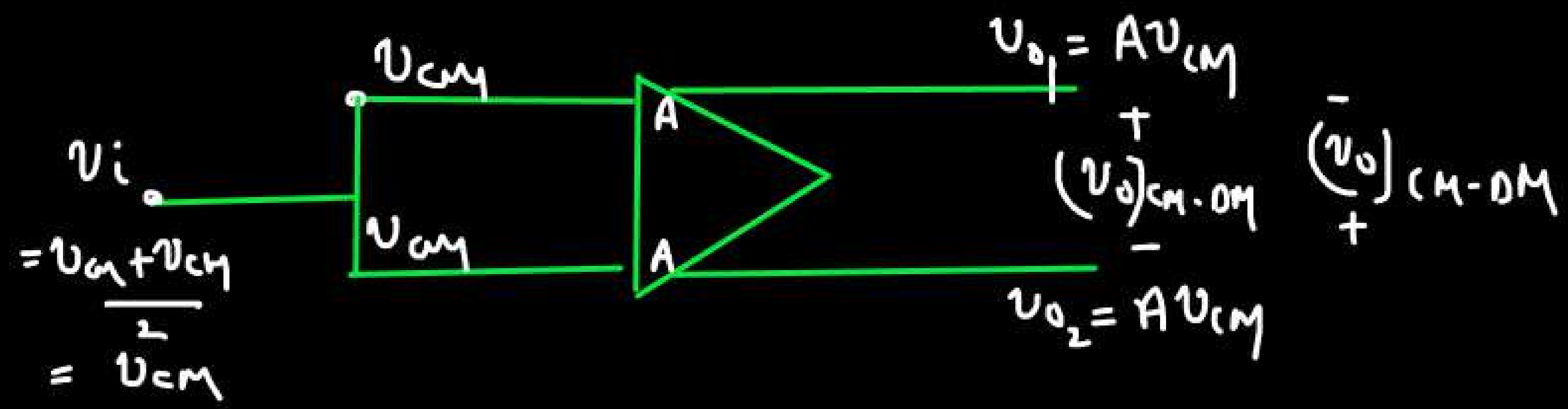
HOW TO FIND $\boxed{\text{Common-Mode Differential gain}}$:-

$$\left[(A)_{CM\text{-}DM} \right]$$

Apply $v_{i_1} = v_{i_2} = v_{CM}$

Find v_{o_1} & v_{o_2} and $(v_o)_{CM\text{-}DM} = v_{o_2} - v_{o_1}$ or $v_{o_1} - v_{o_2}$

$$(A)_{CM\text{-}DM} = \frac{(v_o)_{CM\text{-}DM}}{v_{CM}}$$



Common Mode Rejection Ratio:-

(CMRR)

Shows the ability of rejecting common mode input.

$$\text{CMRR} = \left|\frac{(A)_d}{(A)_{CM\text{-}DM}}\right| = \left|\frac{\text{Differential gain}}{\text{Common-Mode differential gain}}\right|$$

MORE CMRR $\Rightarrow$ Less sensitive to noise

$\text{CMRR} \to \infty \Rightarrow (A)_{CM\text{-}DM} = 0 \Rightarrow$ No noise in the o/p

Q. For the given config (a) and (b). Find

(i) Differential Gain

(ii) Common-Mode Gain

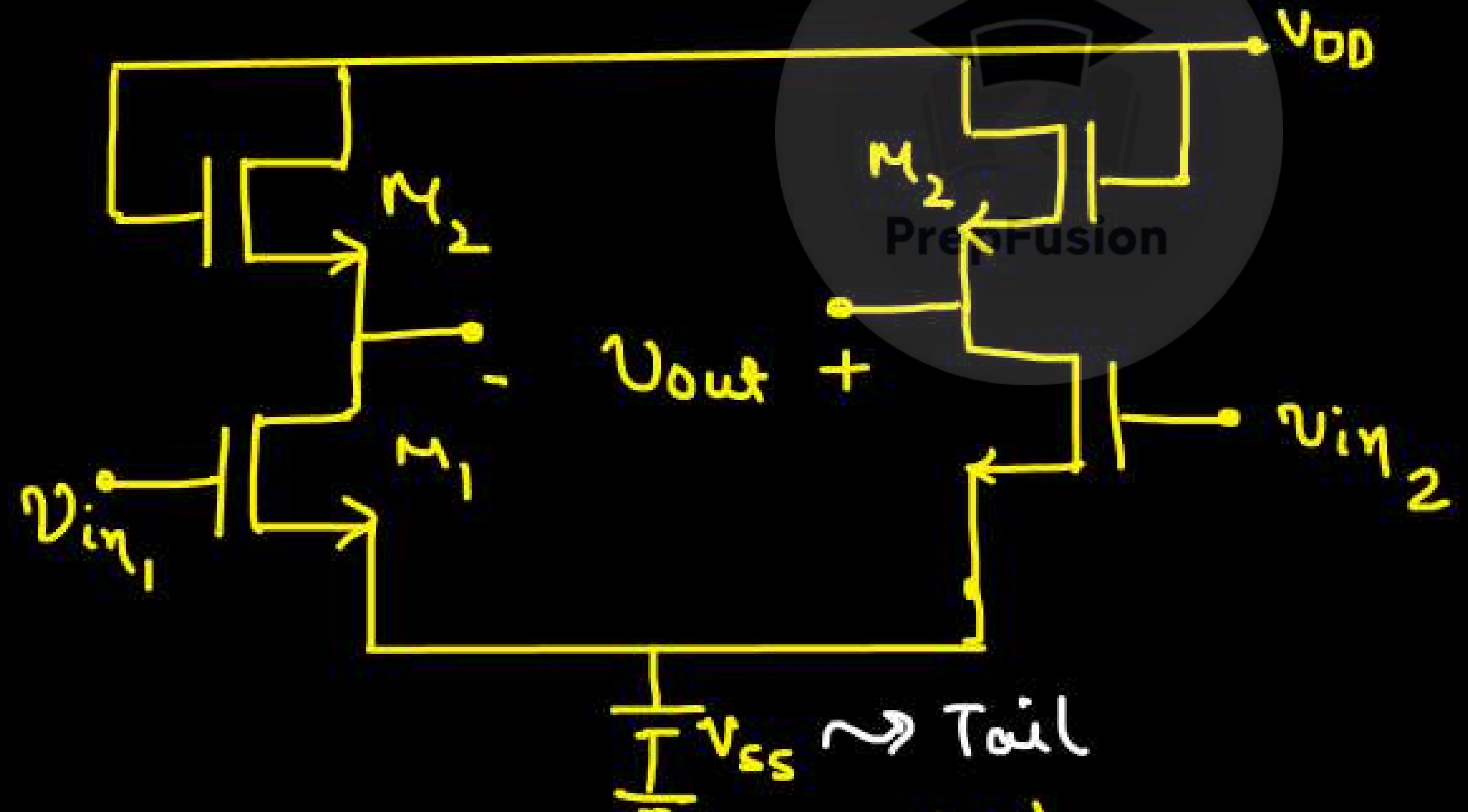
(iii) Common-Mode Differential Gain

(iv) CMRR

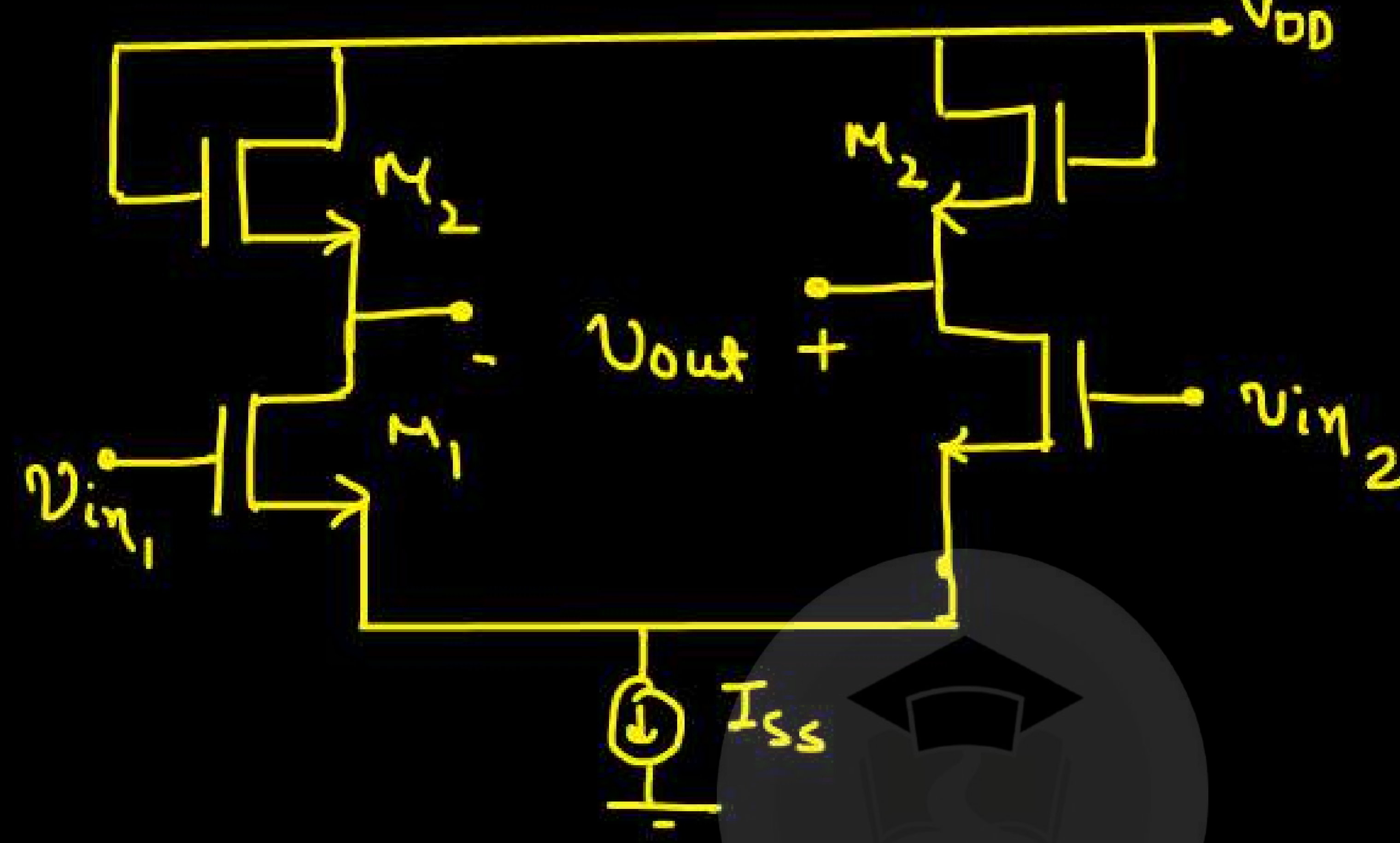
N.B.- $\lambda \neq 0$ for M_2

$\lambda = 0$ for M_1

$v_{in} = v_{in_1} - v_{in_2}$

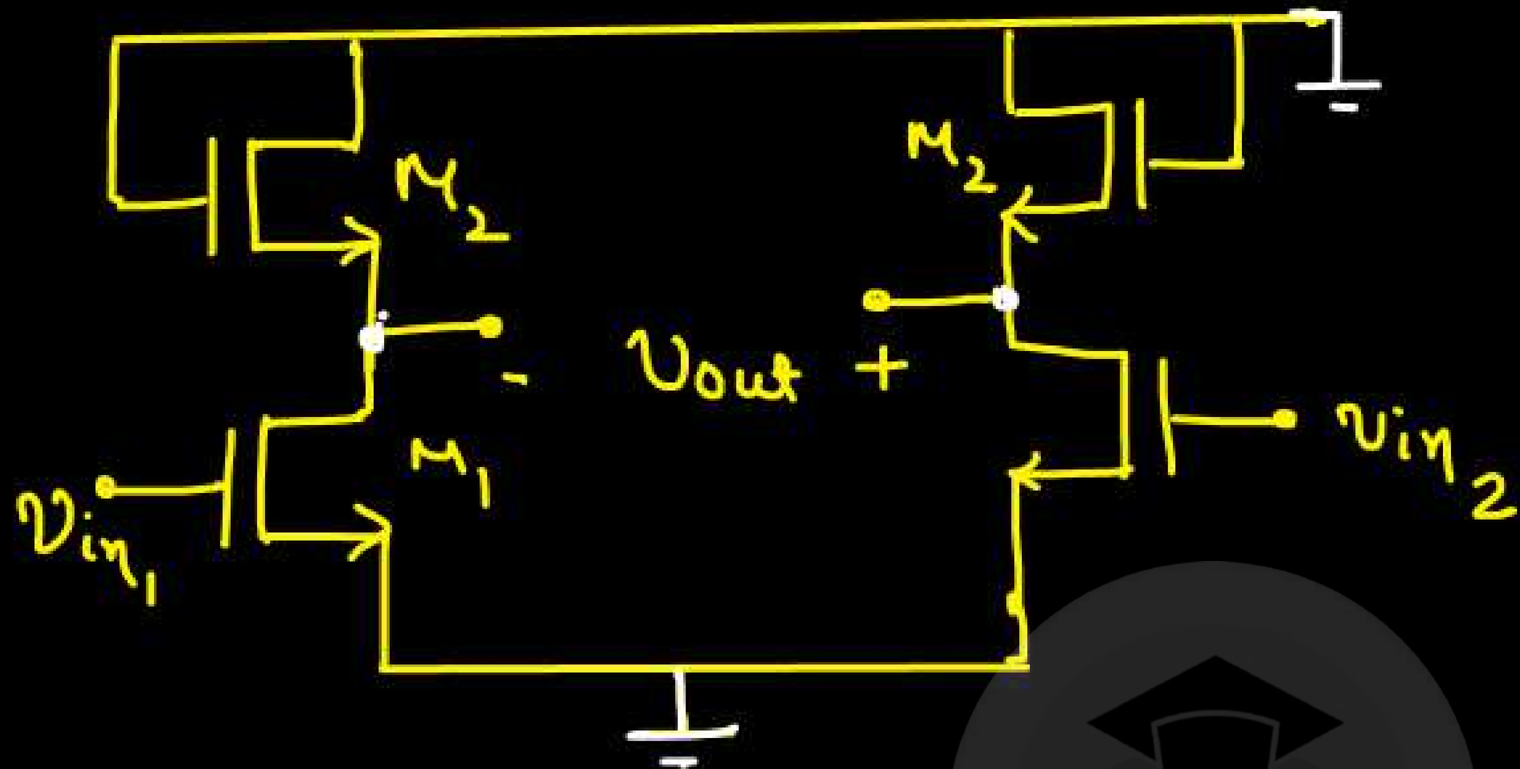


(a)

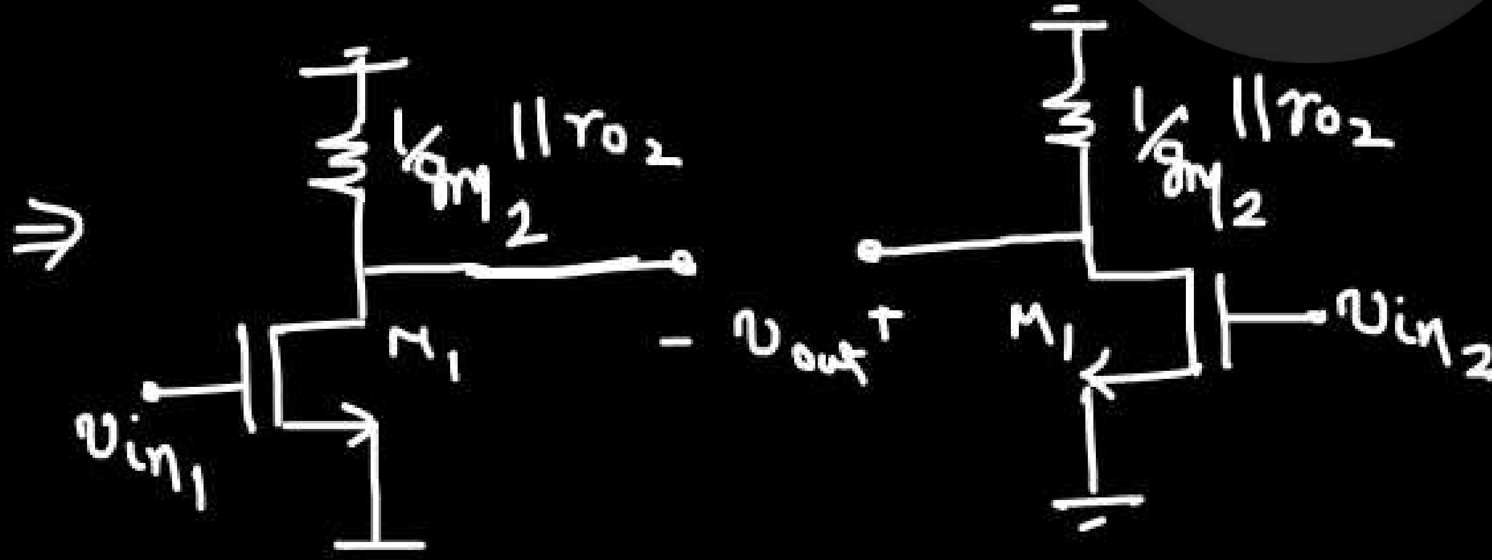


(b)

$V_{in} = V_{in_1} - V_{in_2}$

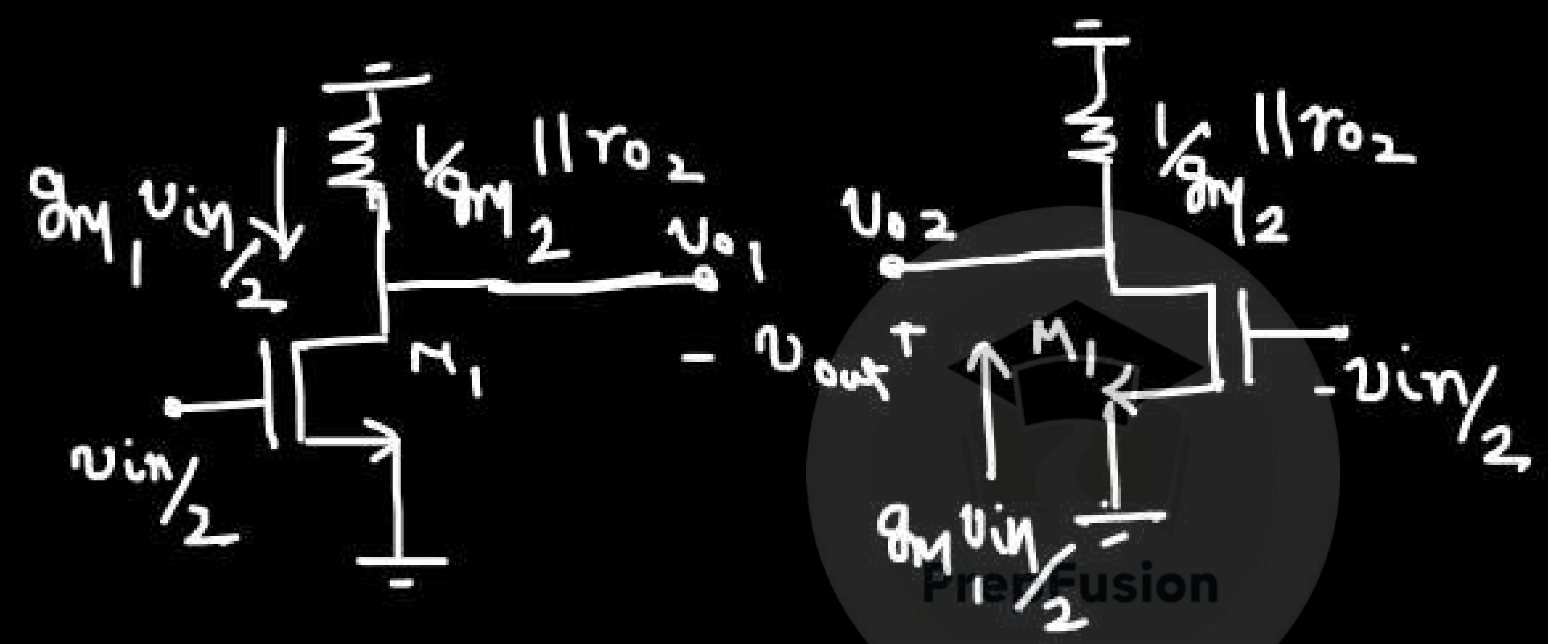

M_2
M_2
$-$ v_{out} $+$
M_1
v_{in_1}
v_{in_2}

(a)


$\Rightarrow$
$1/g_{m_2} \| r_{o_2}$
$1/g_{m_2} \| r_{o_2}$
M_1
M_1
$-$ v_{out} $+$
v_{in_1}
v_{in_2}

(I) Differential gain:-

$$v_{i_1} = \frac{v_{in}}{2} \quad , \quad v_{i_2} = -v_{in}/2 \qquad \left[v_{in_1} - v_{in_2} = v_{in} \right]$$



$$v_{o_1} = -g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{in}/2$$

$$v_{o_2} = g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{in}/2$$

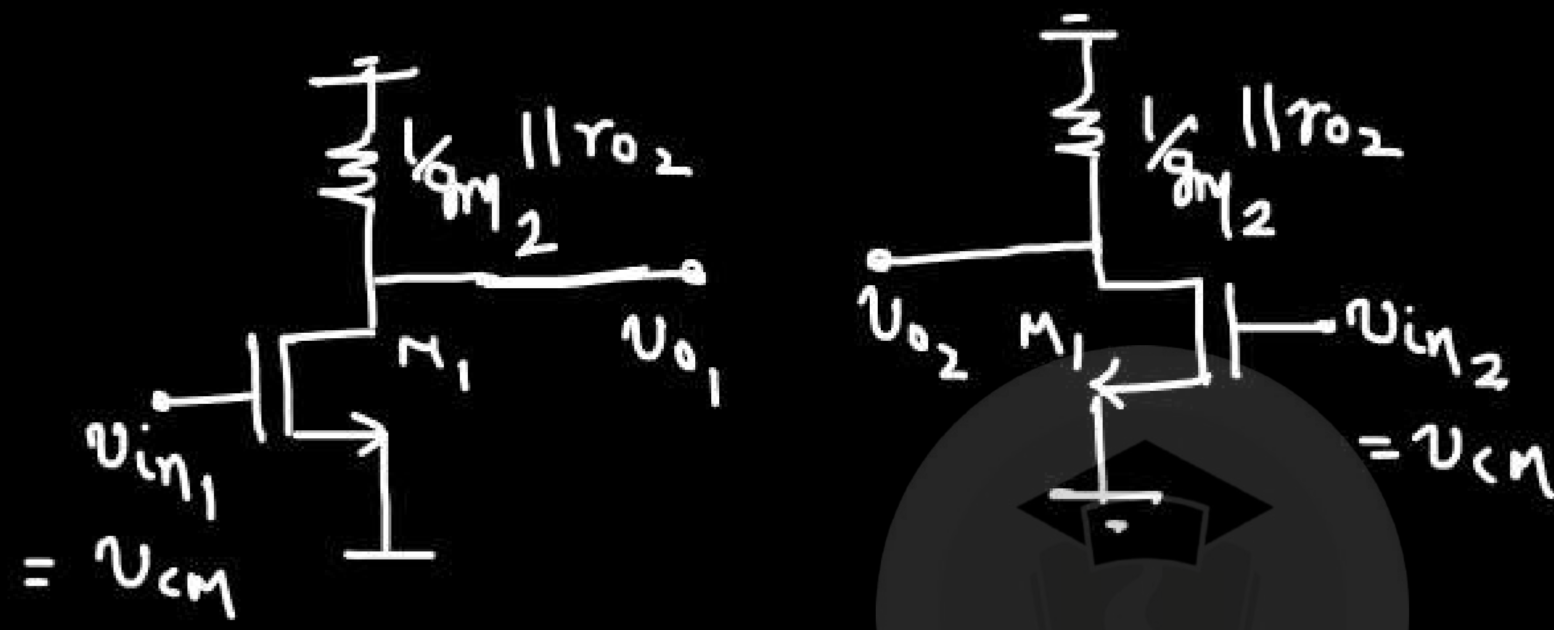
$$\Rightarrow (v_o)_d = g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{in}$$

$$\Rightarrow (v_i)_d = \frac{v_{in}}{2} - \left(-\frac{v_{in}}{2}\right) = v_{in}$$

$$\boxed{(A_v)_d = g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right]} \; \star$$

(II) Common - Mode gain :-

$$v_{i_1} = v_{i_2} = v_{CM}$$



$$v_{o_1} = -g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{CM}$$

$$v_{o_2} = -g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{CM}$$

$$\Rightarrow \quad (v_o)_{CM} = \frac{v_{o_1} + v_{o_2}}{2}$$

$$(v_o)_{CM} = -g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{CM}$$

$$(v_i)_{CM} = \frac{v_{CM} + v_{CM}}{2} = v_{CM}$$

$$\boxed{(A_v)_{CM} = -g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right]}$$

Common Mode Differential gain:-

$$v_{i_1} = v_{i_2} = v_{CM}$$

$$v_{o_1} = -g_{m_1}\left[\frac{1}{g_{m_2}} \parallel r_{o_2}\right] v_{cm}$$

$$v_{o_2} = -g_{m_1}\left[\frac{1}{g_{m_2}} \parallel r_{o_2}\right] v_{cm}$$

$$(v_o)_{CM-DM} = v_{o_2} - v_{o_1} = 0$$

$$(v_i)_{CM-DM} = \frac{v_{cm} + v_{cm}}{2} = v_{CM}$$

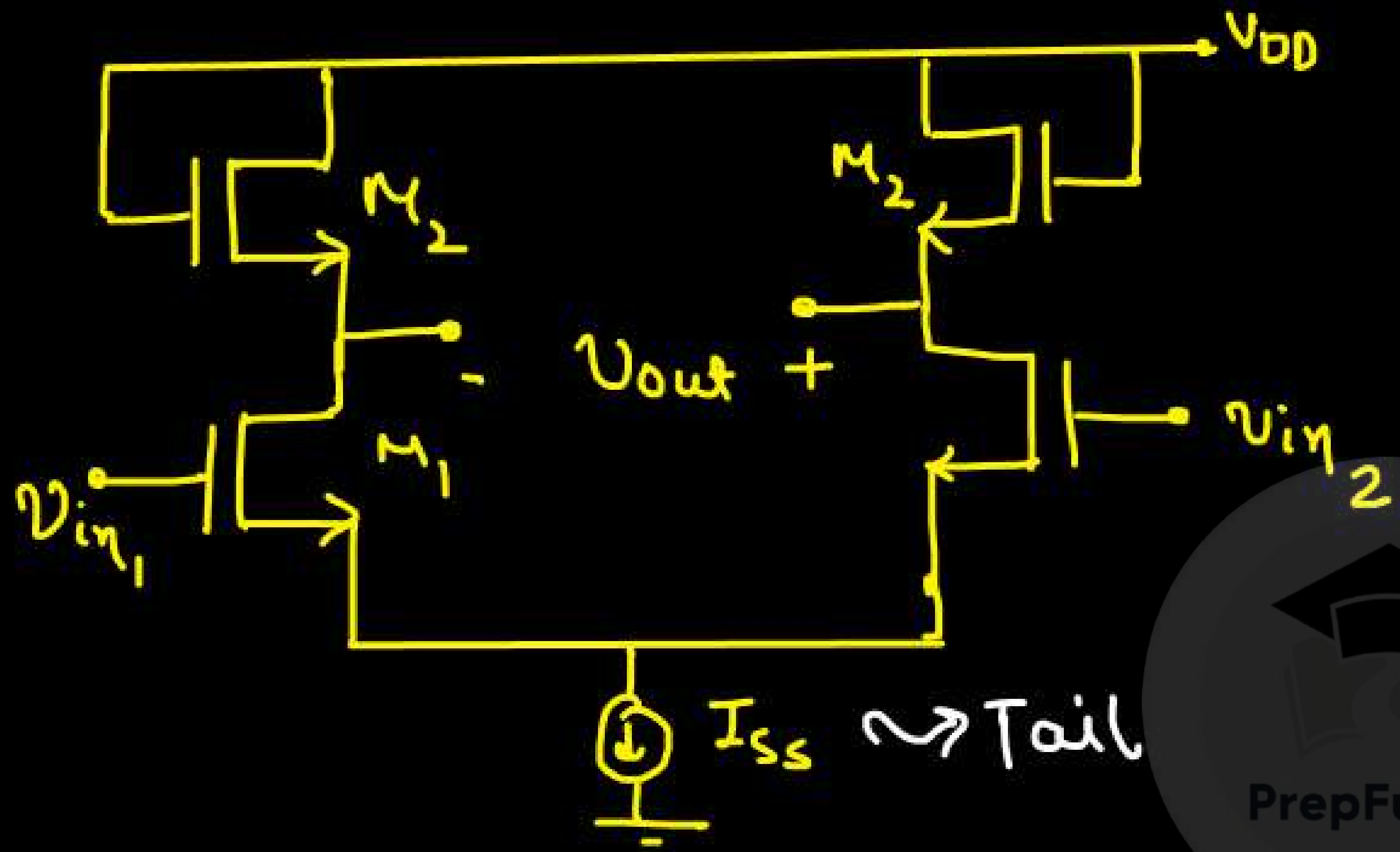
$$\boxed{(A_v)_{CM-DM} = \frac{0}{v_{cM}} = 0}$$

CMRR:-

$$CMRR = \left|\frac{(A)_d}{(A)_{CM-DM}}\right|$$

$$= \left|\frac{(A)_d}{0}\right|$$

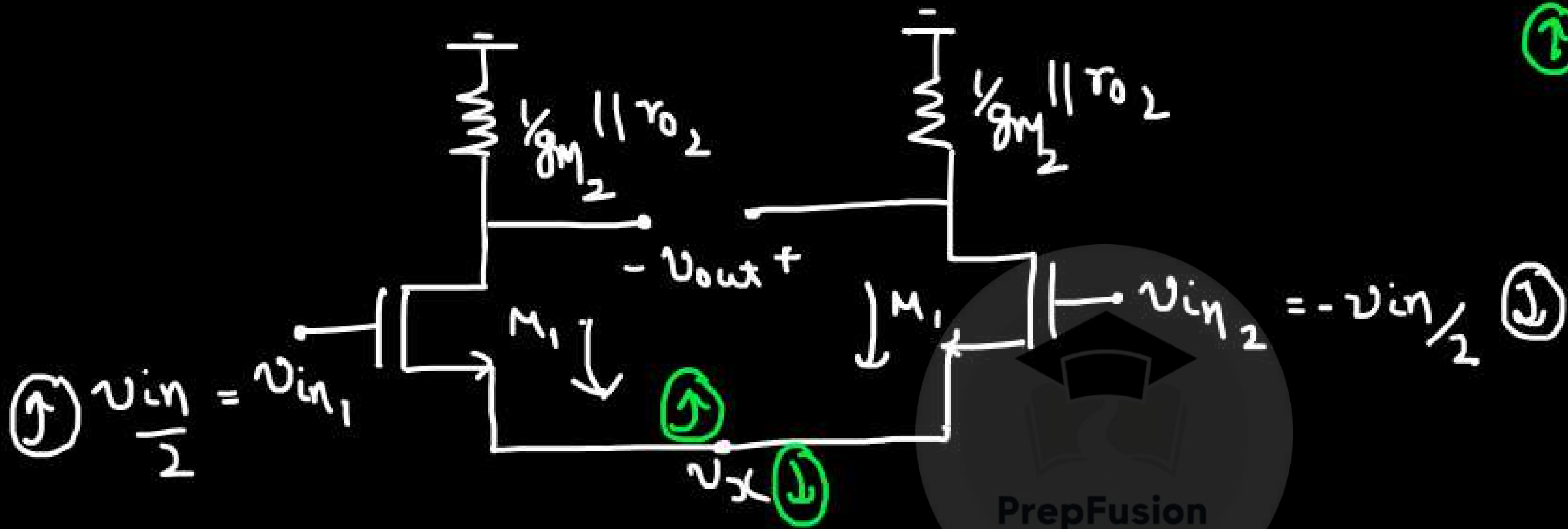
$$\boxed{CMRR = \infty}$$

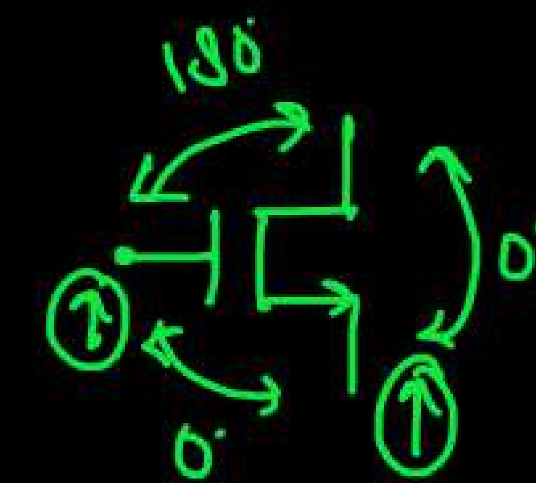


(b)

$$V_{in} = V_{in_1} - V_{in_2}$$

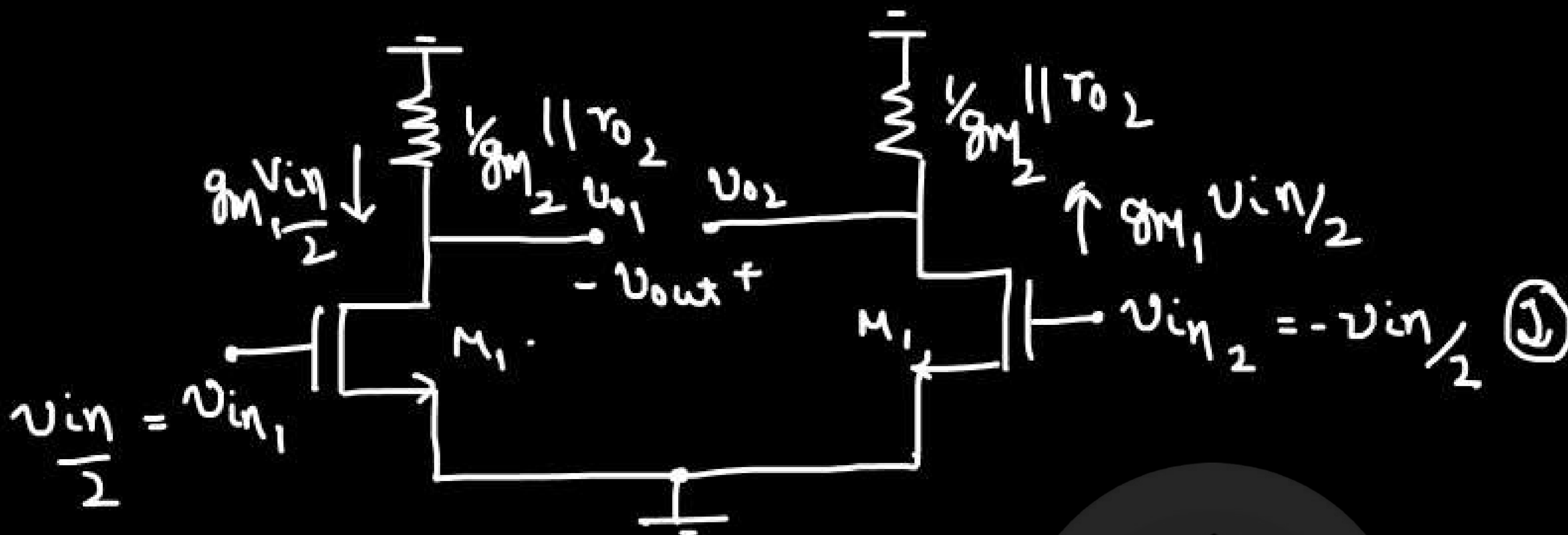
(I) Differential gain :-





$$g_m\left(\frac{v_{in}}{2} - V_x\right) = -\,g_m\left(-\frac{v_{in}}{2} - V_x\right)$$

$$\boxed{V_x = 0}$$



$$v_{o_2} = g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right]\frac{v_{in}}{2}$$

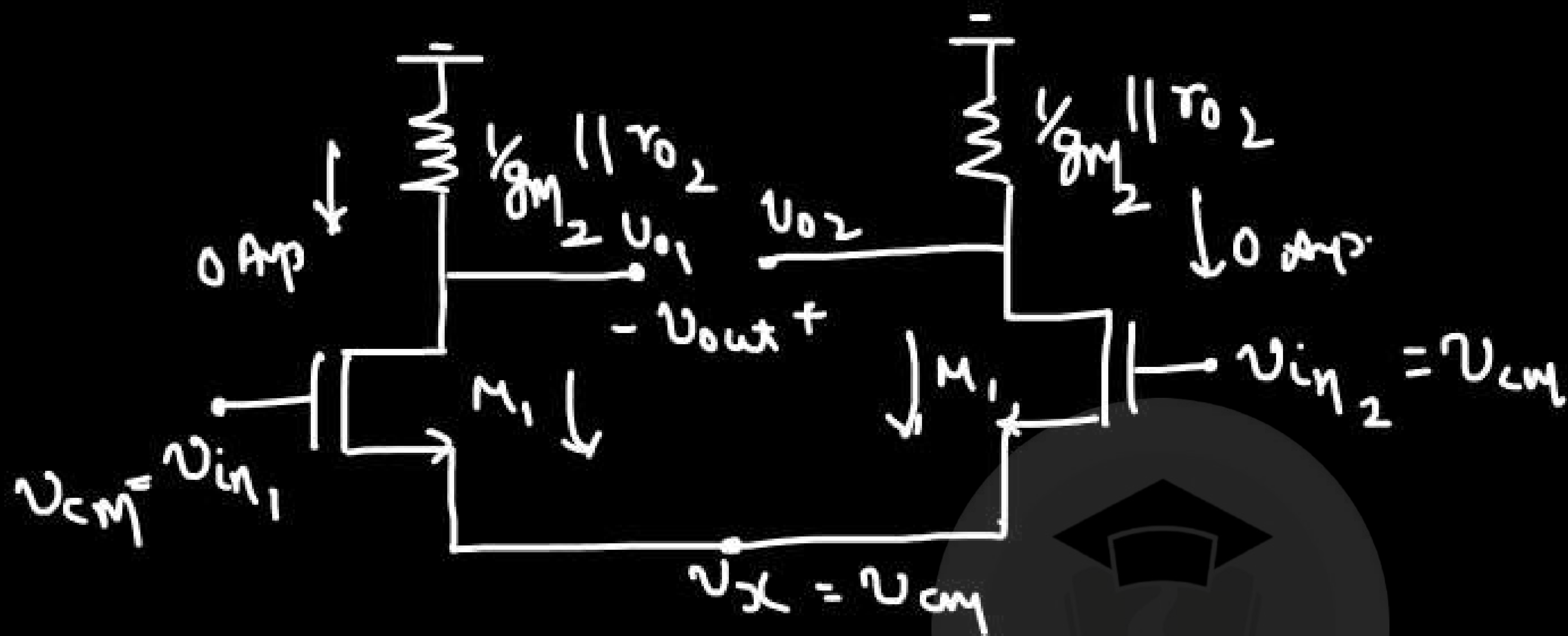
$$v_{o_1} = -g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right]\frac{v_{in}}{2}$$

$$(v_{out})_d = g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right] v_{in}$$

$$(v_{in})_d = v_{in}$$

$$\boxed{A_v = g_{m_1}\left[\frac{1}{g_{m_2}} \| r_{o_2}\right]}$$

(II) Common Mode Gain :-



$$g_{m_1}(v_{cm} - v_x) = -g_{m_1}(v_{cm} - v_x)$$

$$2g_{m_1}(v_{cm} - v_x) = 0$$

$$\boxed{V_x = v_{cm}}$$

$$V_{o_1} = V_{o_2} = 0$$

$$(v_o)_{cm} = \frac{v_{o_1} + v_{o_2}}{2} = 0$$

$$\boxed{(A_v)_{cm} = \frac{0}{v_{cm}} = 0}$$

N.B.:- Common Mode gain shows the amount of noise present in the ckt.
It's good to have as low as common mode gain.

(III) Common-Mode Differential gain :-

$$v_{o_1} = 0$$

$$v_{o_2} = 0$$

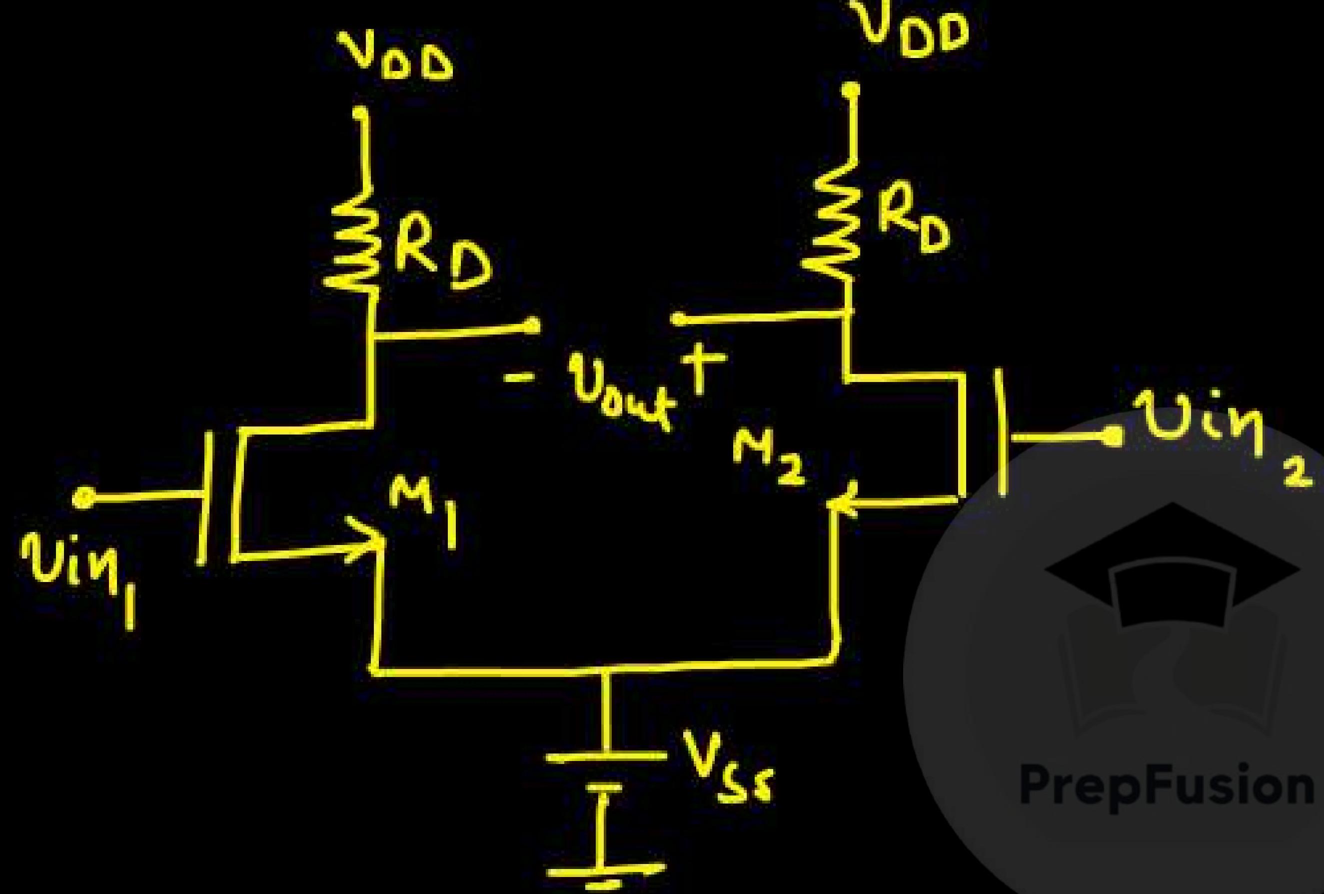
$$(v_o)_{CM-DM} = v_{o_2} - v_{o_1} = 0$$

$$\boxed{(A)_{CM-DM} = 0}$$

N.B.- When there is no Mismatch in Transistors

Voltage source as tail	Current source as tail
① $(A_v)_d = g_{m_1}\left[\frac{1}{g_{m_2}} \parallel r_{o_2}\right]$	① $(A_v)_d = g_{m_1}\left[\frac{1}{g_{m_2}} \parallel r_{o_2}\right] \rightarrow \boxed{\text{Same}}$
② $(A_v)_{CM} = -g_{m_1}\left[\frac{1}{g_{m_2}} \parallel r_{o_2}\right]$	② $(A_v)_{CM} = 0 \rightarrow \boxed{\text{Advantage}}$ ☆
③ $(A_v)_{CM-DM} = 0$	③ $(A_v)_{CM-DM} = 0 \rightarrow \boxed{\text{Same}}$

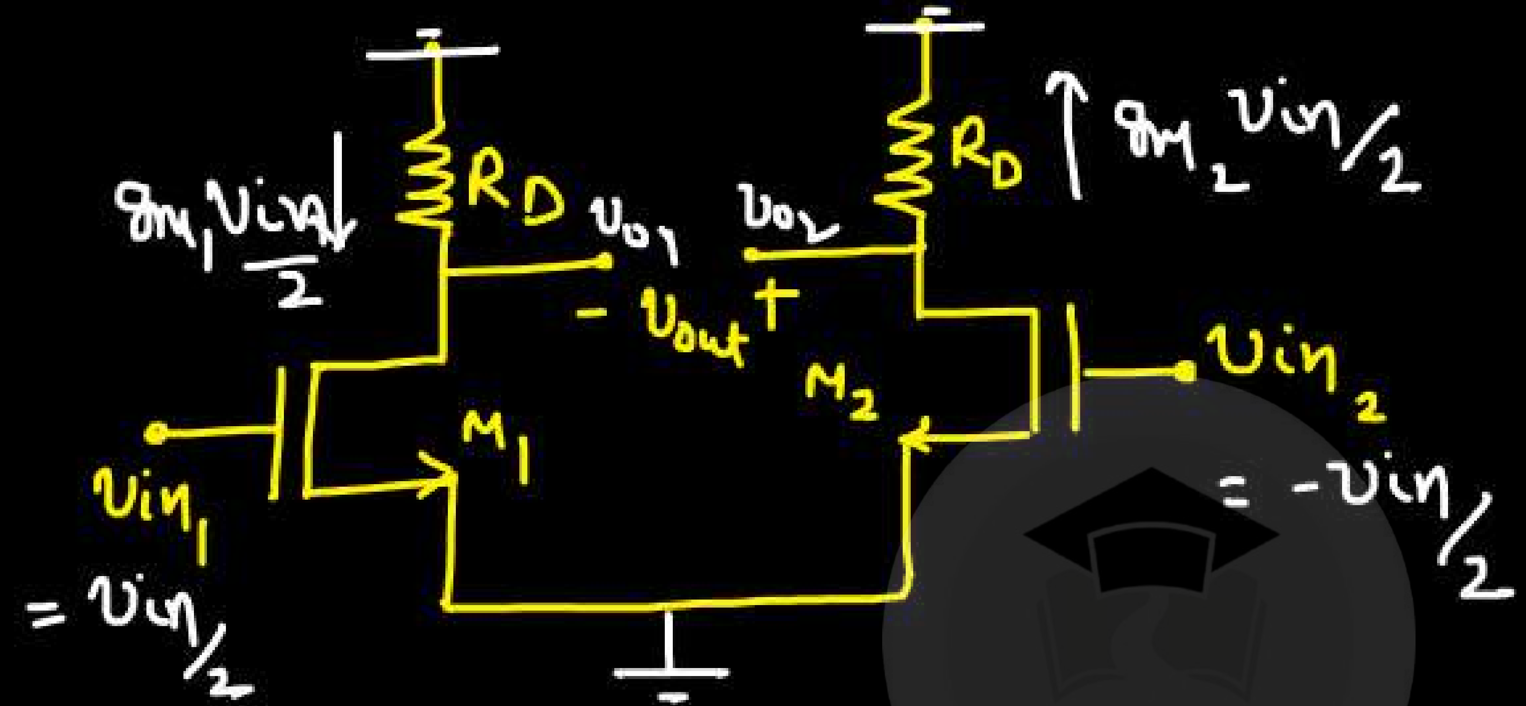
⇒ Finding the same parameters when there is mismatch:-



(a)

$$v_{in} = v_{in_1} - v_{in_2}$$

(a) Differential gain:-



$$v_{o_2} = g_{m_2} R_D v_{in}/2$$

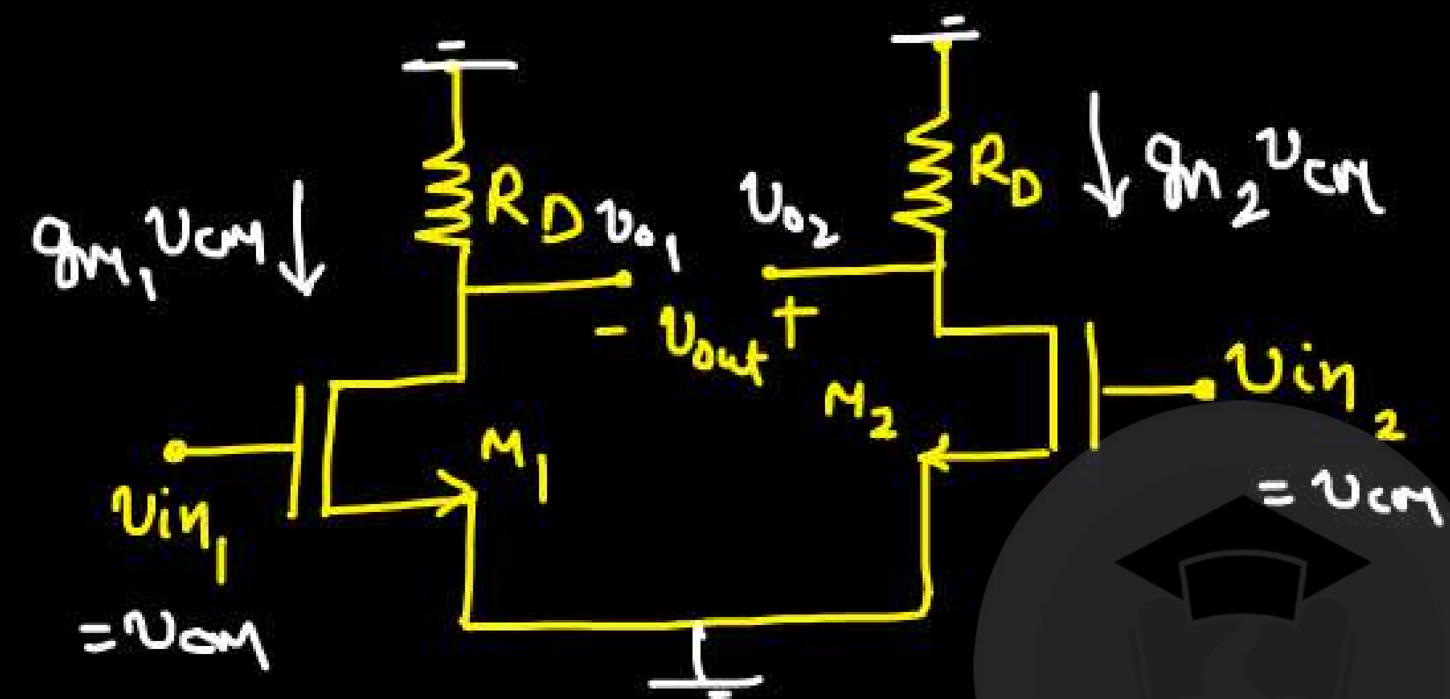
$$v_{o_1} = -g_{m_1} R_D v_{in}/2$$

$$(v_o)_d = v_{o_2} - v_{o_1} = (g_{m_2} + g_{m_1}) R_D v_{in}/2$$

$$(v_i)_d = v_{in}$$

$$\boxed{(A_v)_d = \left(\frac{g_{m_1} + g_{m_2}}{2}\right) R_D}$$

(b) Common - Mode Gain :-



$$v_{o_2} = -g_{m_2} R_D v_{cm}$$

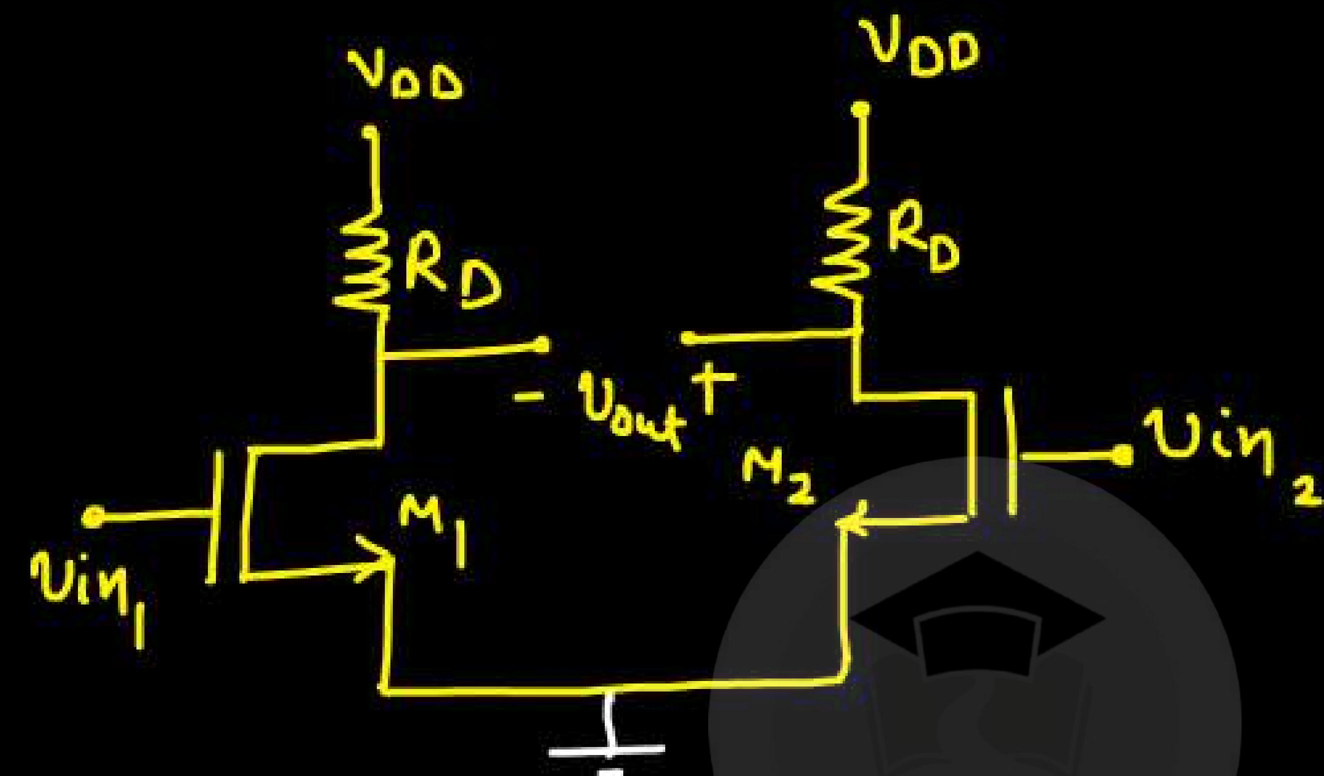
$$v_{o_1} = -g_{m_1} R_D v_{cm}$$

$$(v_o)_{cm} = -\frac{(g_{m_1} + g_{m_2})}{2} R_D v_{cm}$$

$$(v_i)_{cm} = v_{cm}$$

$$\boxed{(A_v)_{cm} = -\frac{(g_{m_1} + g_{m_2})}{2} R_D}$$

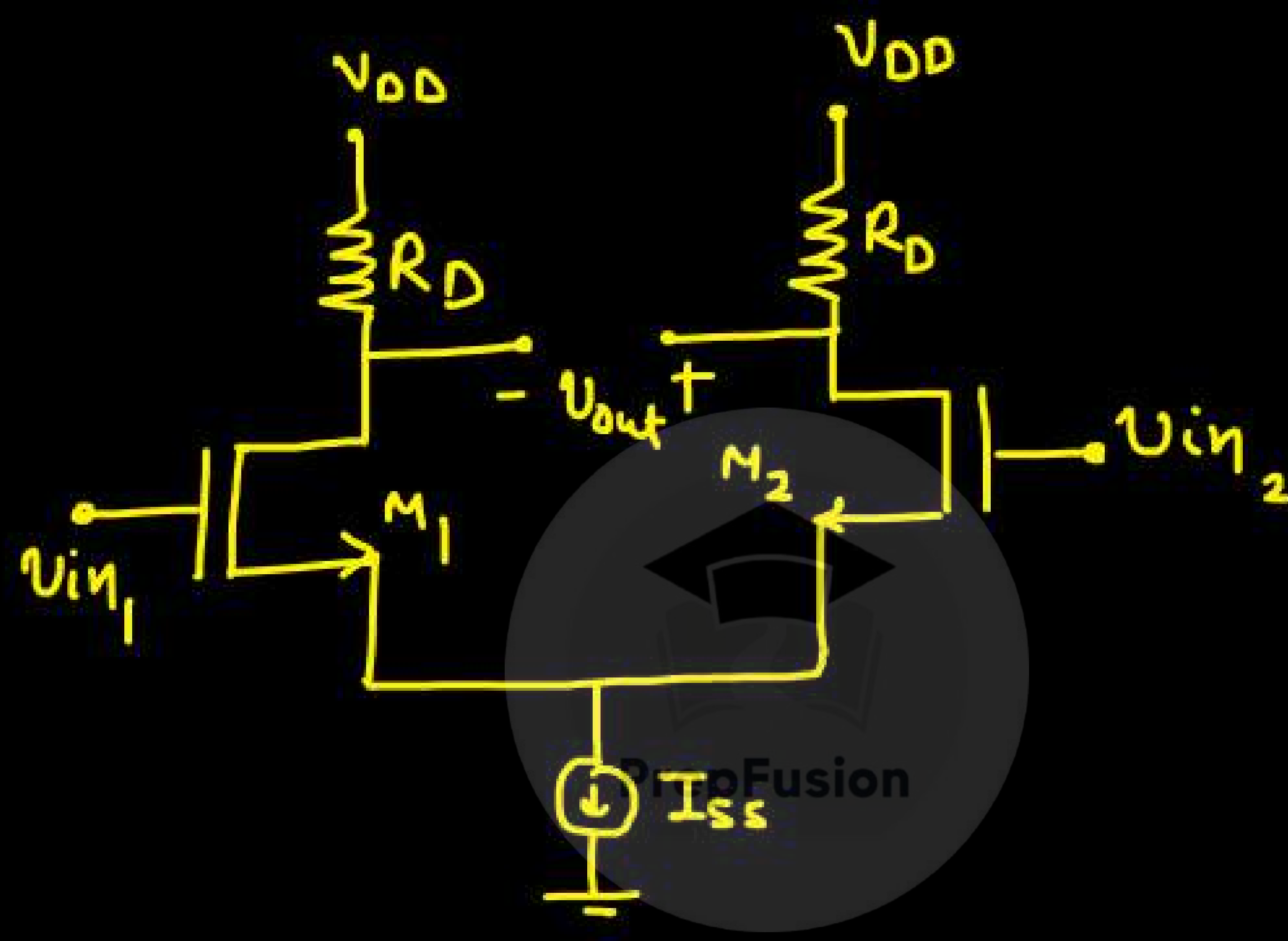
(c) Common Mode Differential Gain :-



$$(v_o)_{CM-DM} = (g_{m_1} - g_{m_2}) R_D v_{cm}$$

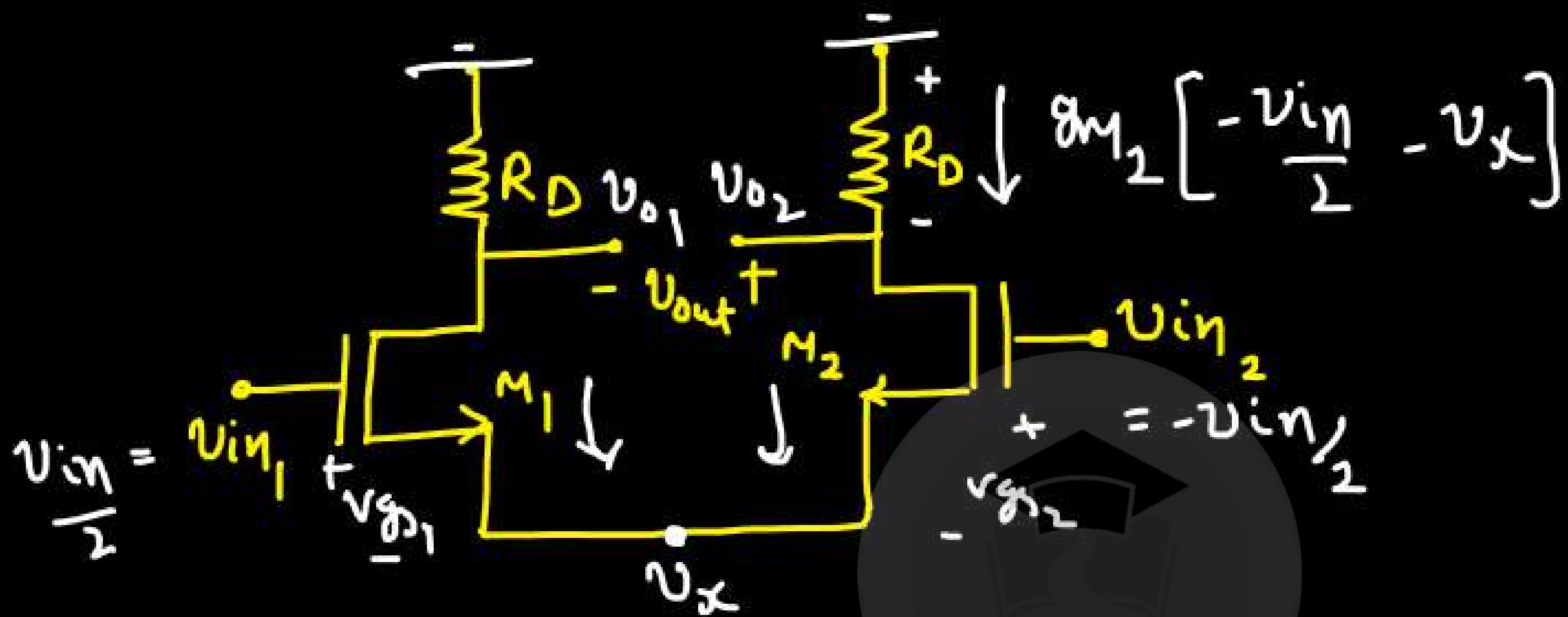
$$(v_i)_{CM} = v_{cm}$$

$$\boxed{(A_v)_{CM-DM} = (g_{m_1} - g_{m_2}) R_D}$$



(b)

(9) Differential Gain :-



$$g_{m_1}\left[\frac{v_{in}}{2} - v_x\right] = -g_{m_2}\left[-\frac{v_{in}}{2} - v_x\right]$$

$$g_{m_1}\frac{v_{in}}{2} - g_{m_1}v_x = g_{m_2}\frac{v_{in}}{2} + g_{m_2}v_x$$

$$\frac{(g_{m_1} - g_{m_2})}{g_{m_2} + g_{m_1}}\frac{v_{in}}{2} = v_x \quad \text{——} \ (1)$$

$$v_{o2} = g_{m2} R_D \left[\frac{v_{in}}{2} + v_x \right]$$

$$v_{o1} = -g_{m1} R_D \left[\frac{v_{in}}{2} - v_x \right]$$

$$(v_o)_d = g_{m2} R_D \left[\frac{v_{in}}{2} + v_x \right] + g_{m1} R_D \left[\frac{v_{in}}{2} - v_x \right]$$

$$(v_o)_d = \frac{\left[g_{m2} + g_{m1} \right]}{2} R_D v_{in} + \left[g_{m2} - g_{m1} \right] R_D v_x$$

$$= \frac{\left[g_{m1} + g_{m2} \right]}{2} R_D v_{in} + \left[g_{m2} - g_{m1} \right] R_D \frac{\left[g_{m1} - g_{m2} \right]}{\left[g_{m2} + g_{m1} \right]} \frac{v_{in}}{2}$$

$$= \frac{\left\{ \left[g_{m1} + g_{m2} \right]^2 R_D - \left[g_{m2} - g_{m1} \right]^2 R_D \right\}}{g_{m1} + g_{m2}} v_{in}/2$$

$$= \frac{[4 g_{m1} g_{m2}]}{g_{m1} + g_{m2}} R_D \frac{v_{in}}{2}$$

$$(v_o)_d = \left[\frac{2 g_{m1} g_{m2}}{g_{m1} + g_{m2}}\right] R_D v_{in}$$

$$(v_i)_d = v_{in}$$

$$\boxed{(A_v)_d = \frac{2 g_{m1} g_{m2}}{g_{m1} + g_{m2}} R_D}$$

Current source as a tail:-

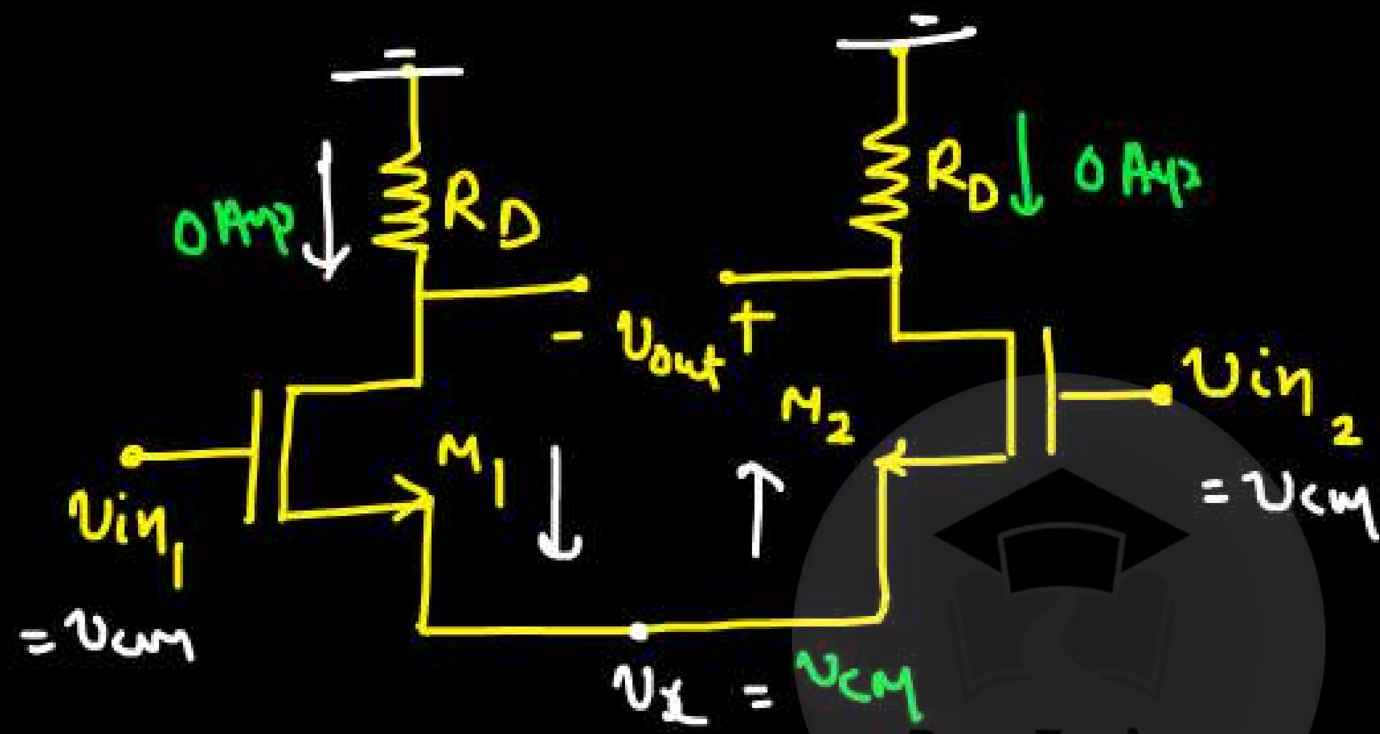
$$(A_v)_{d\,C.S.} = \left(\frac{2 g_{m1} g_{m2}}{g_{m1} + g_{m2}}\right) R_D$$

Voltage source as a tail:-

$$(A_v)_{d\,V.S.} = \left(\frac{g_{m1} + g_{m2}}{2}\right) R_D \rightarrow \text{Advantage}$$

$$\boxed{(A_v)_{d\,V.S.} > (A_v)_{d\,C.S.}}$$ → In case of mismatch

(b) Common mode gain:-



$$g_{m_1}(v_{cm} - v_x) = -g_{m_2}(v_{cm} - v_x)$$

$$(g_{m_1} + g_{m_2})v_{cm} = (g_{m_2} + g_{m_1})v_x$$

$$v_x = v_{cm}$$

$$\boxed{(A_v)_{cm} = 0}$$

$$(A_v)_{cm \to v.s.} = -\frac{(g_{m_1} + g_{m_2})}{2} R_D$$

$$\underbrace{(A_v)_{cm \to c.s.}}_{\downarrow \text{ Advantage}} = 0$$

(c) Common-Mode Differential Gain :-

$$v_{o_1} = v_{o_2} = 0$$

$$\boxed{(A_v)_{CM-DM} = 0}$$

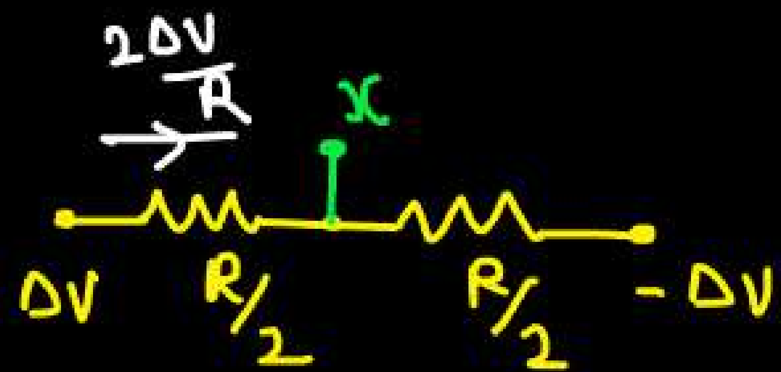
$$(A_v)_{CM-DM \to V.S} = (g_{m_1} - g_{m_2}) R_D$$

$$\underbrace{(A_v)_{CM-DM \to C.S.}}_{\downarrow} = 0$$

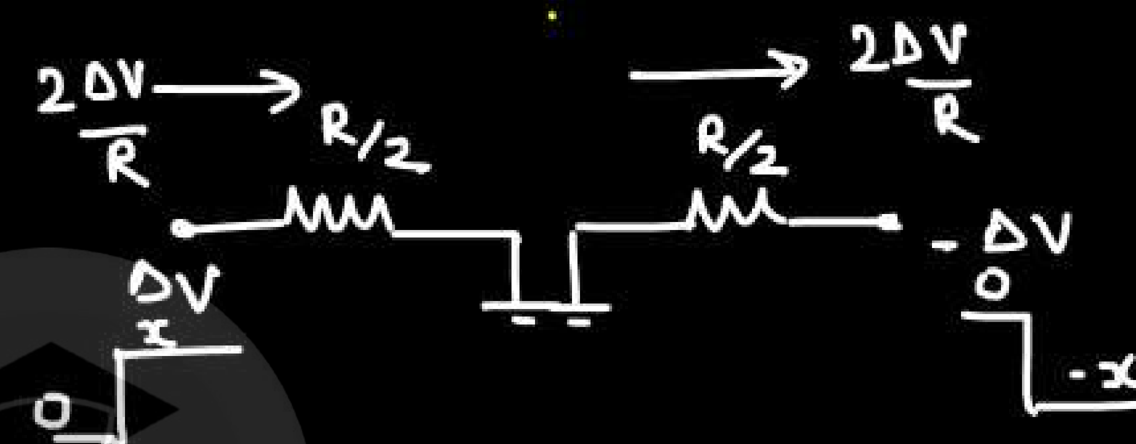
Advantage

★ Some important concepts :-

①



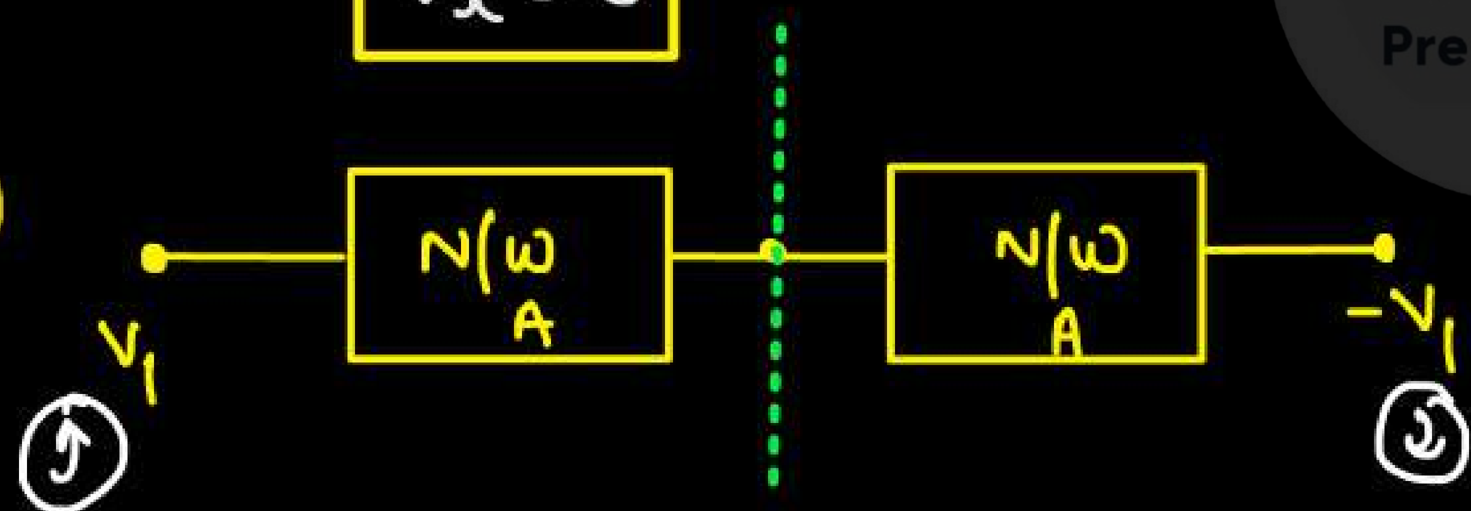
potential @ node x ?



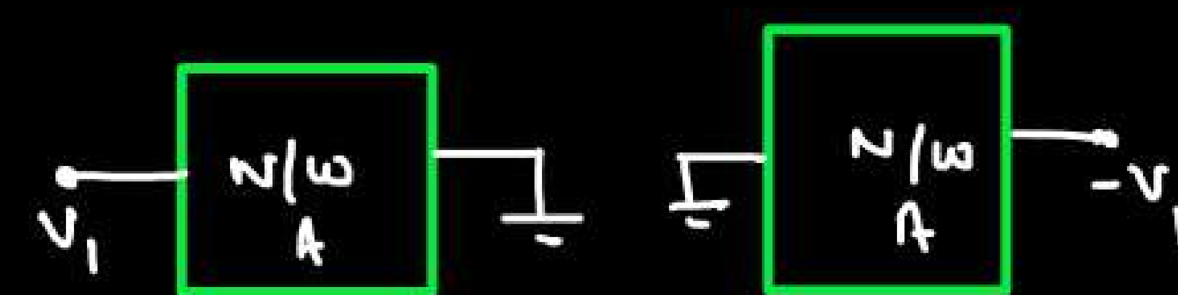
→ $$V_x = \frac{\Delta V (R/2) + (-\Delta V)(R/2)}{R}$$

$$\boxed{V_x = 0}$$

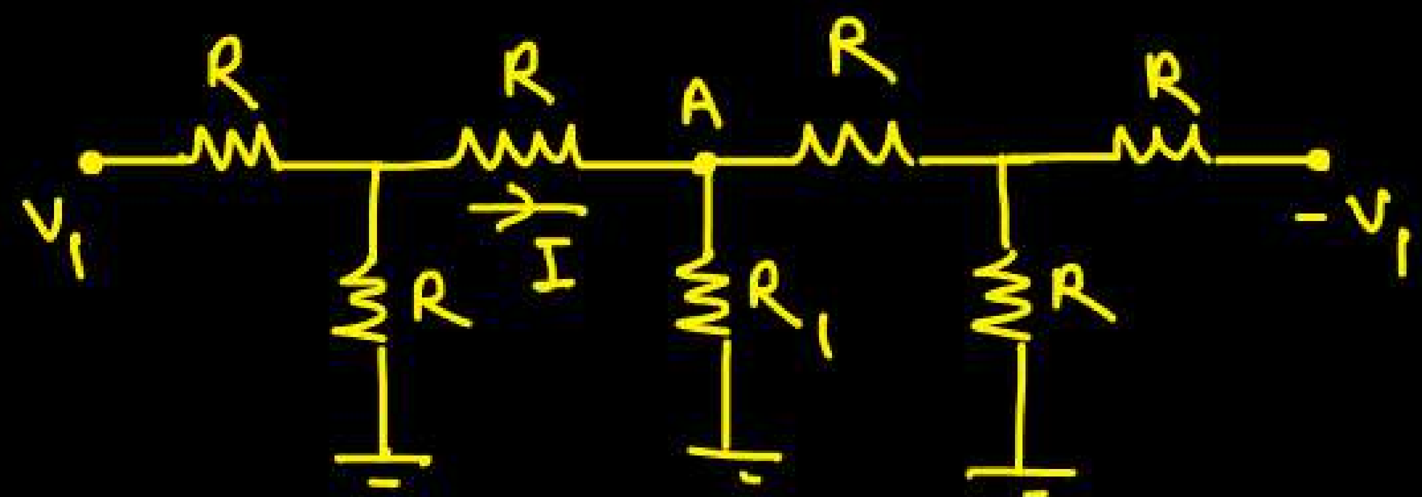
②



≡

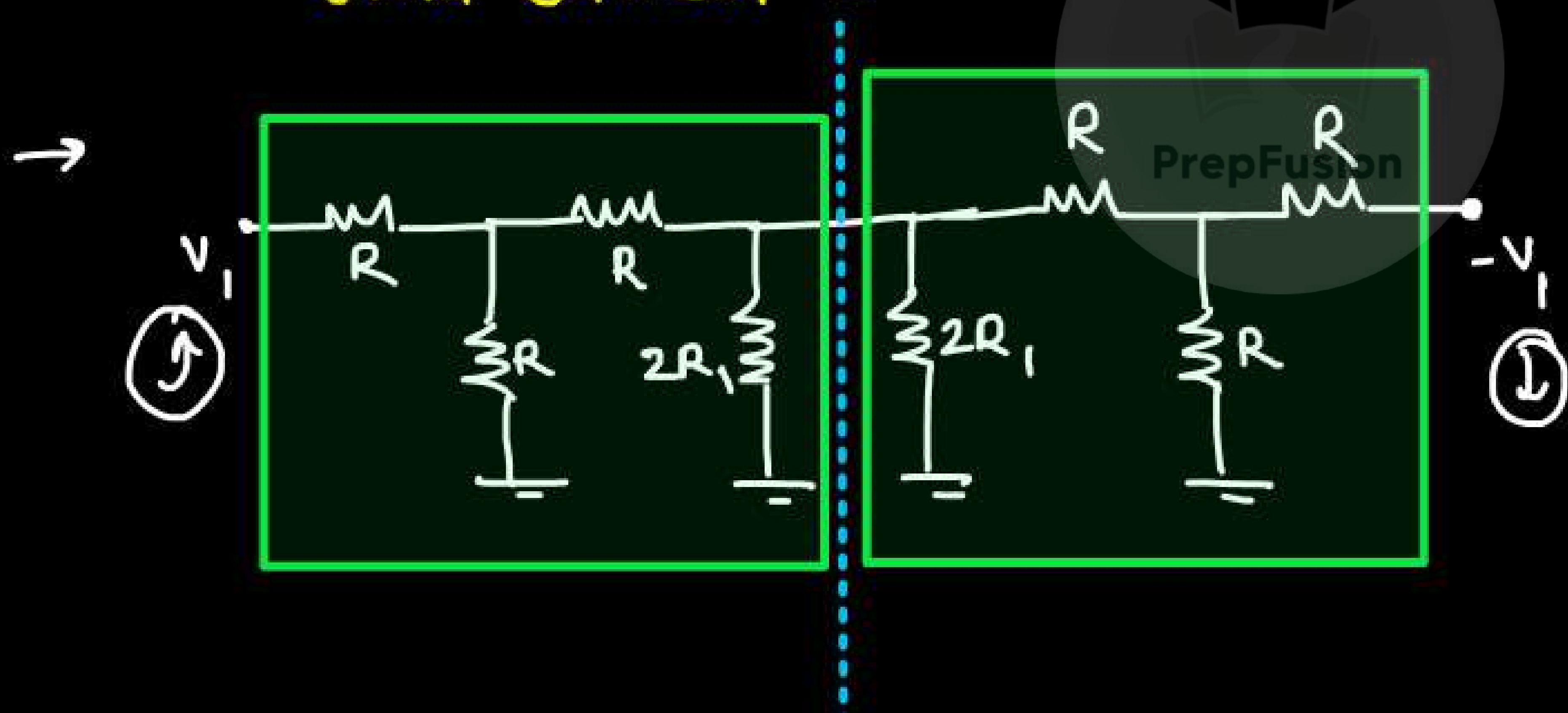


(3)

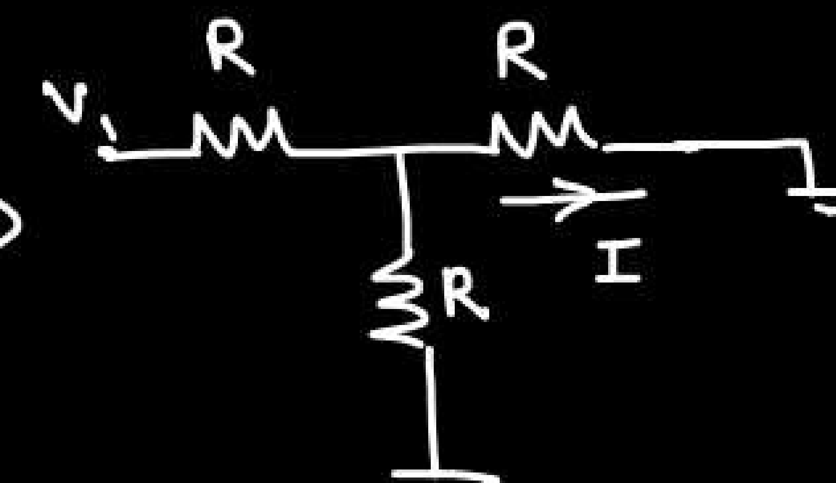


Find the potential @ node A.

Find current I.

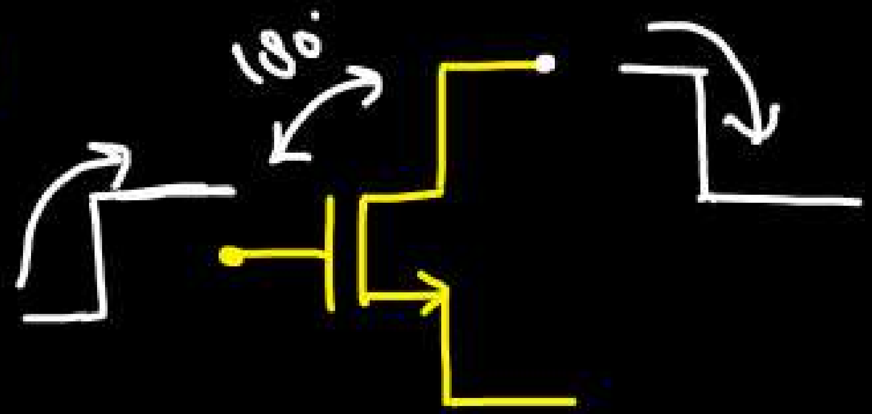


$\Rightarrow$



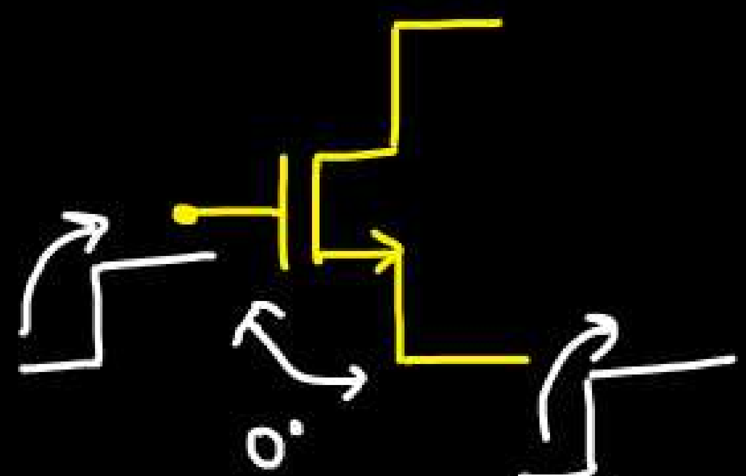
$$\boxed{I = \frac{2V_1}{3R} \times \frac{1}{2} = \frac{V_1}{3R}}$$

4



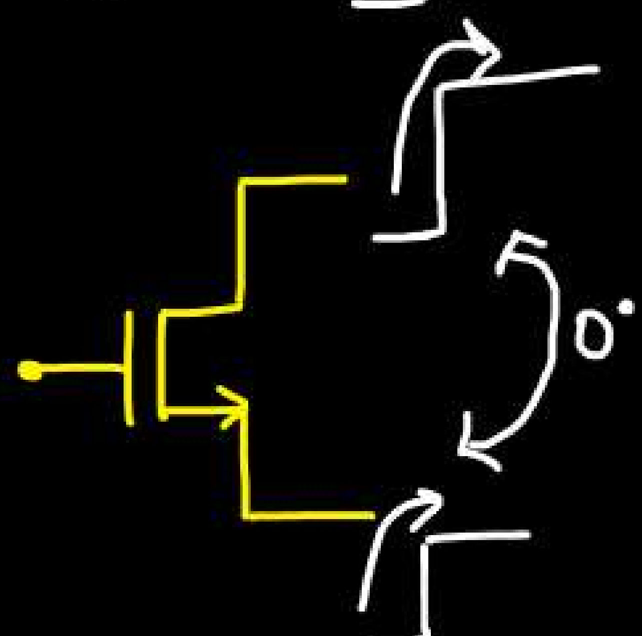
$$A_V = -g_m R_D$$

5



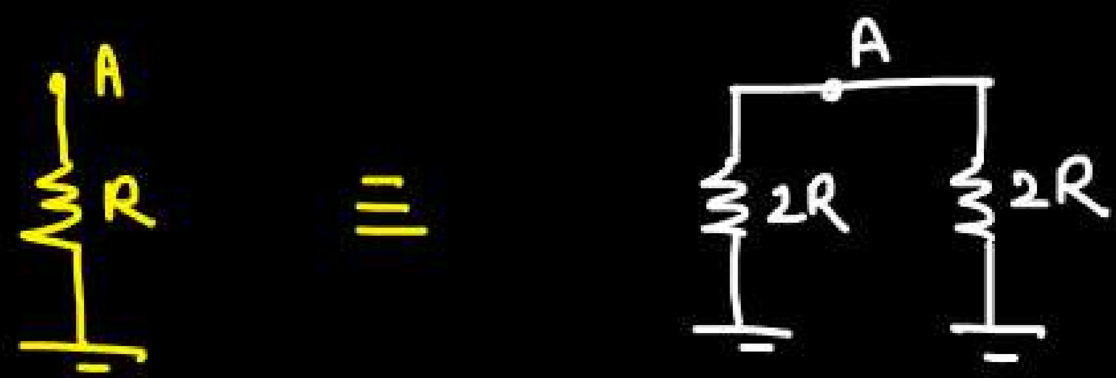
$$A_V = \frac{g_m R_S}{1 + g_m R_S}$$

6

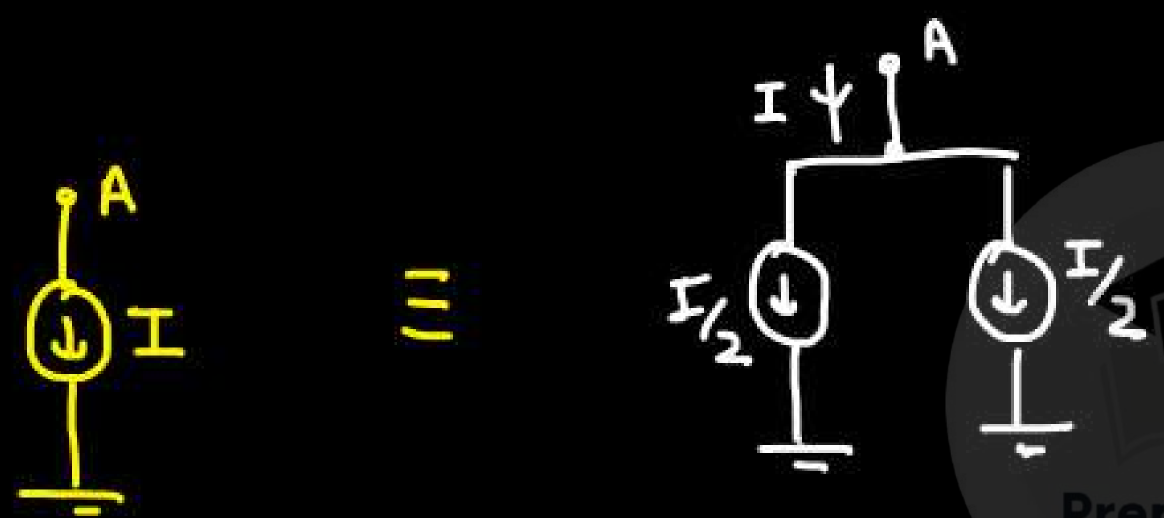


$$A_V = g_m R_D$$

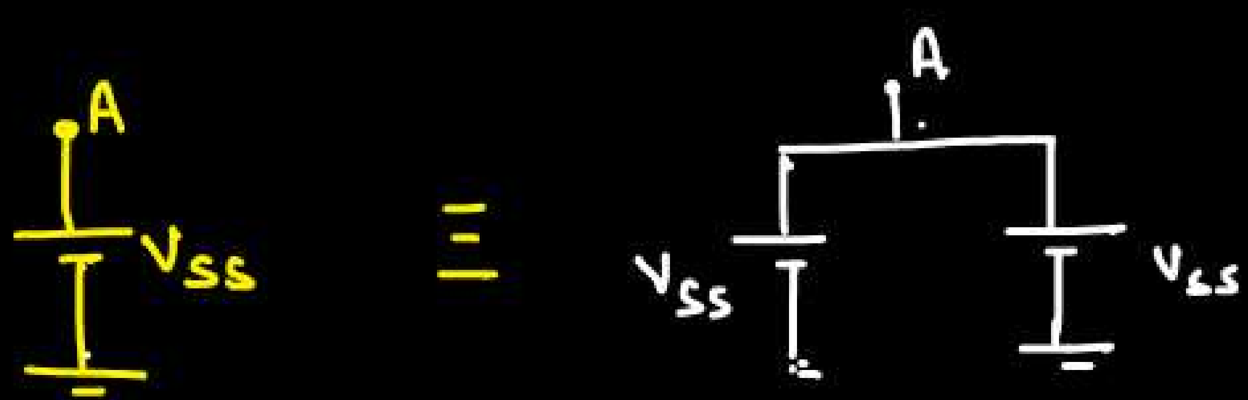
7



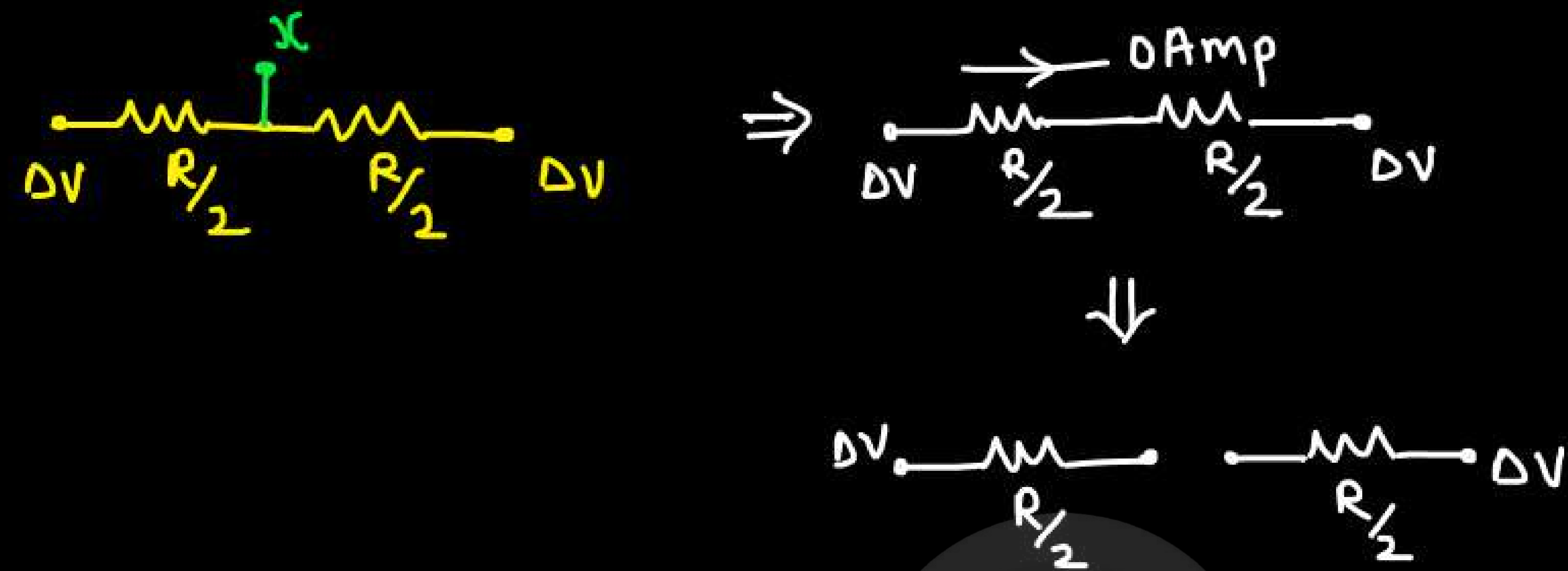
8



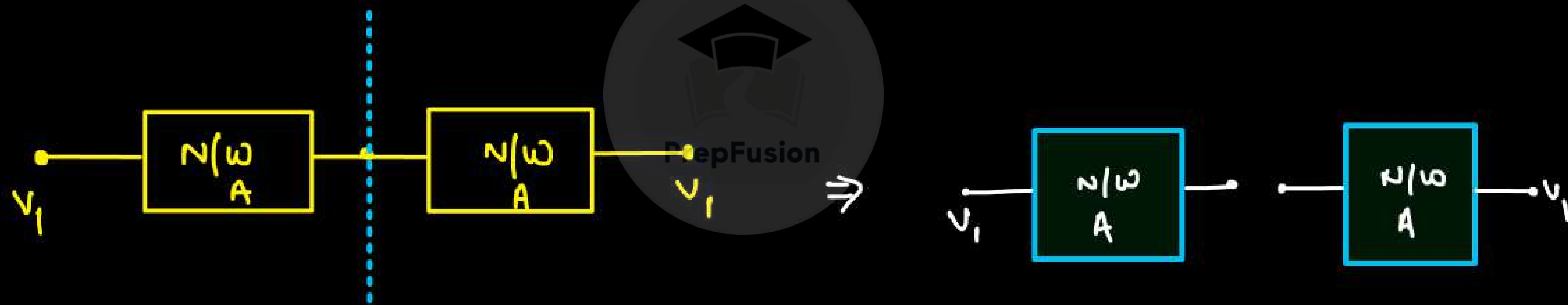
9



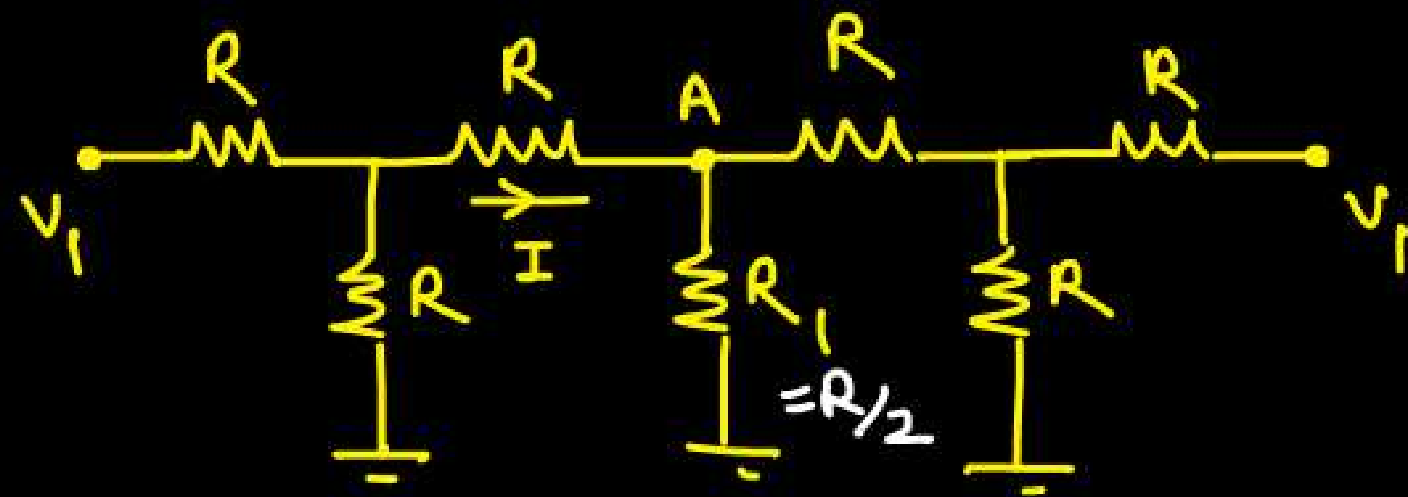
10



11

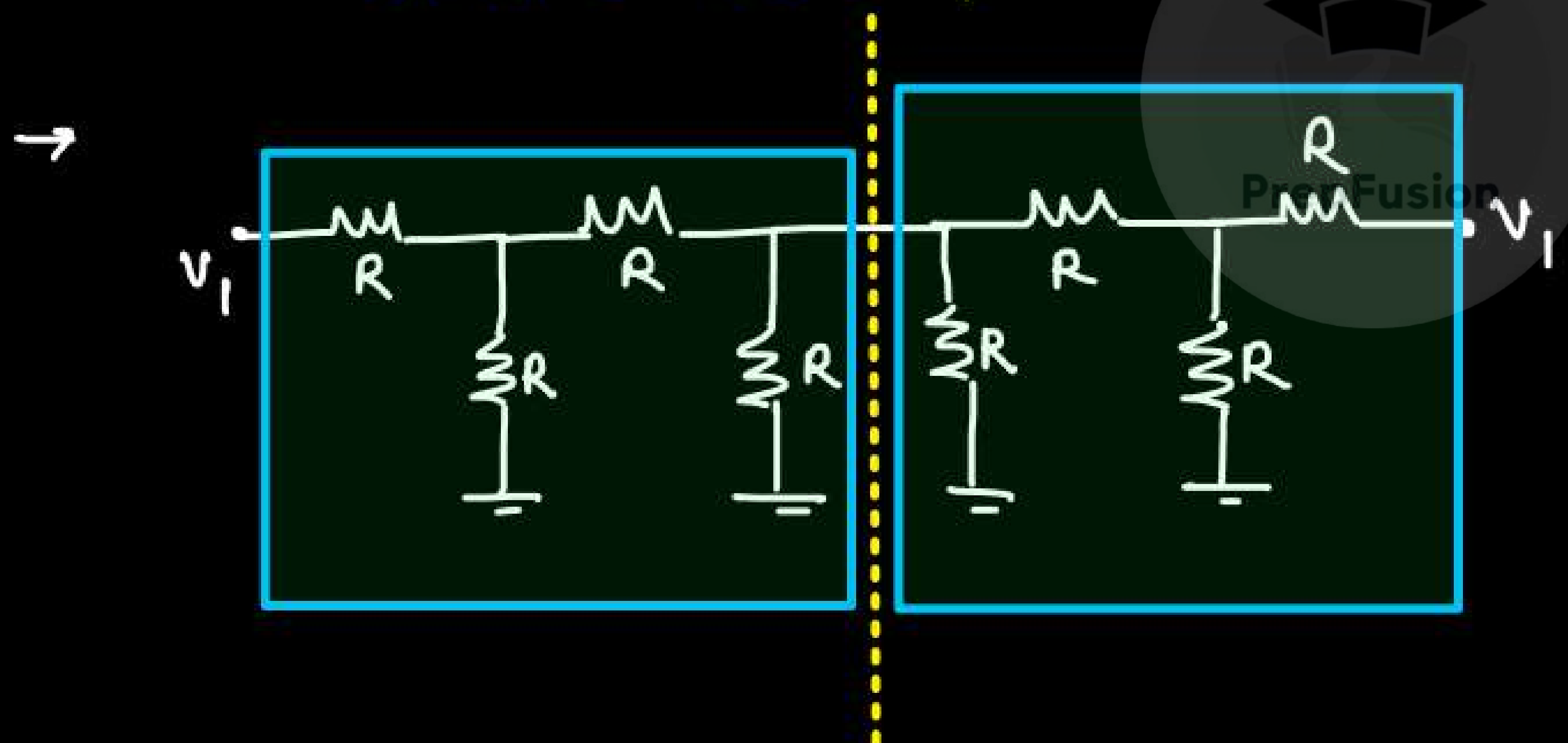


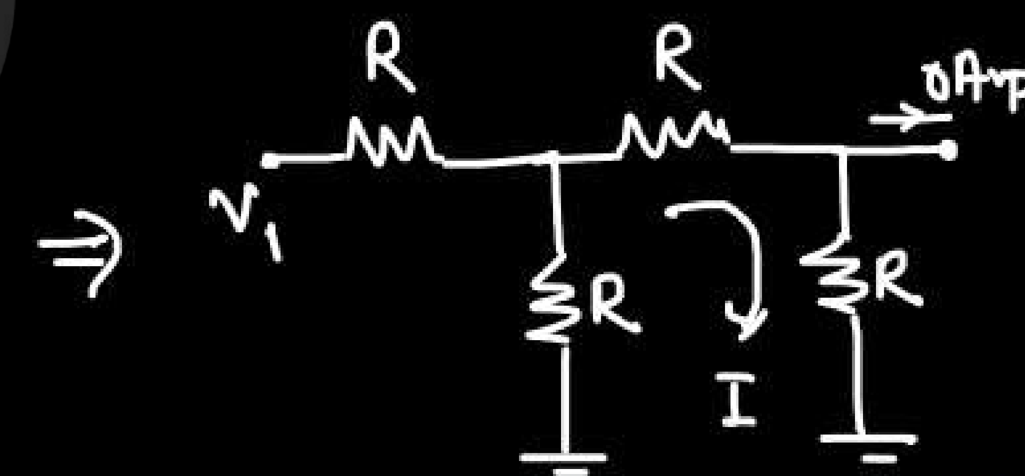
12



$$R_1 = R/2$$

Find current I = ?

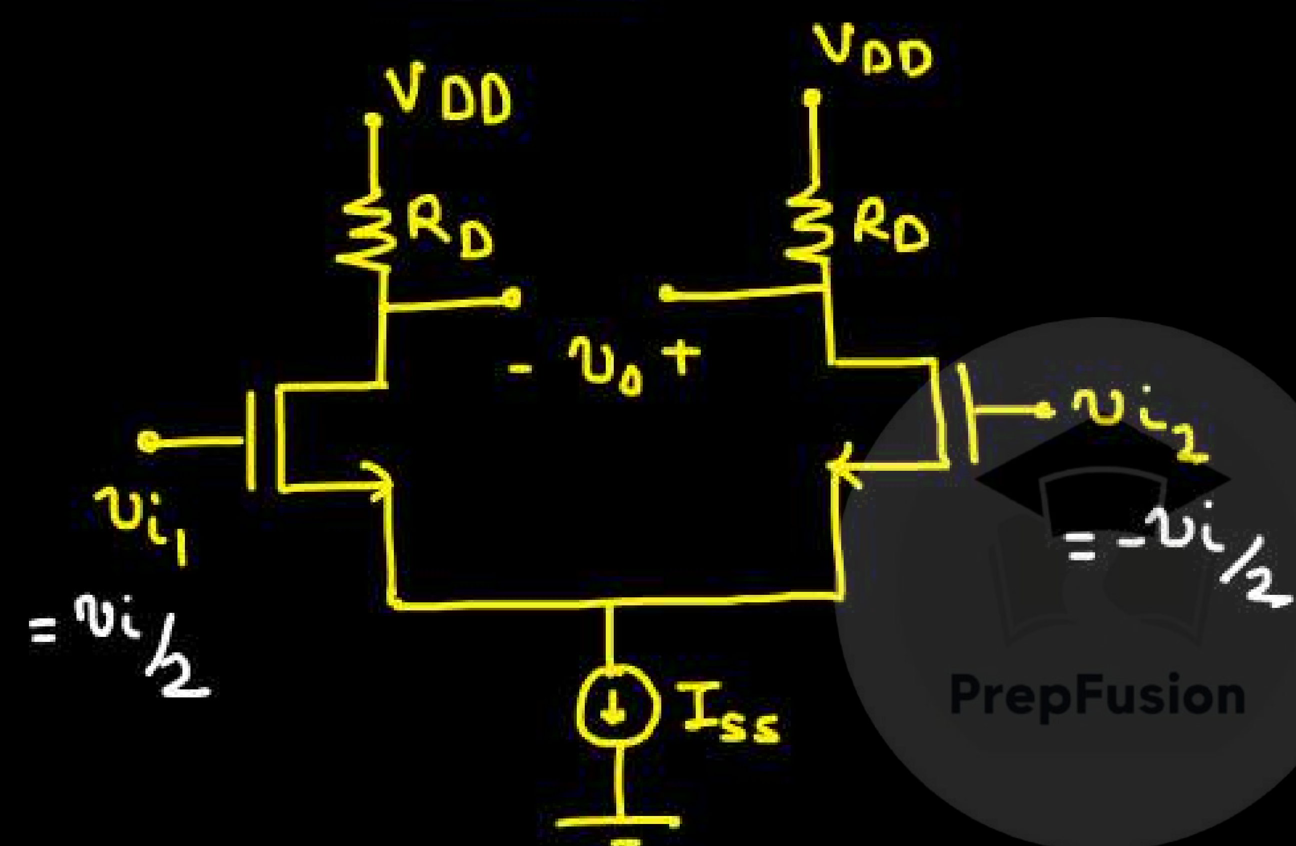




$$\boxed{I = \frac{3V_1}{5R} \times \frac{R}{3R} = \frac{V_1}{5R}}$$

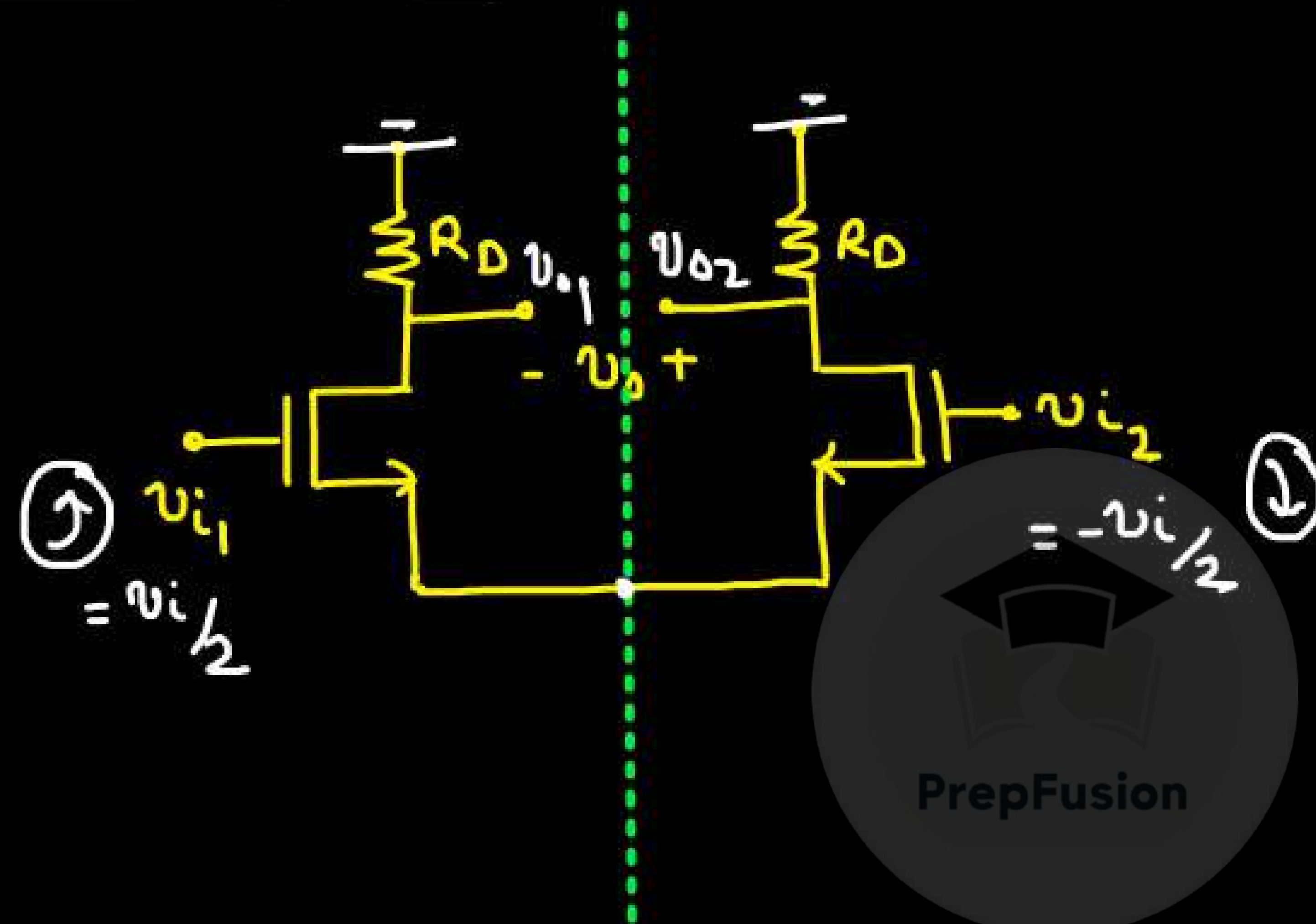
⇒ Concept of Half ckt :-

(a) For Differential Gain :-

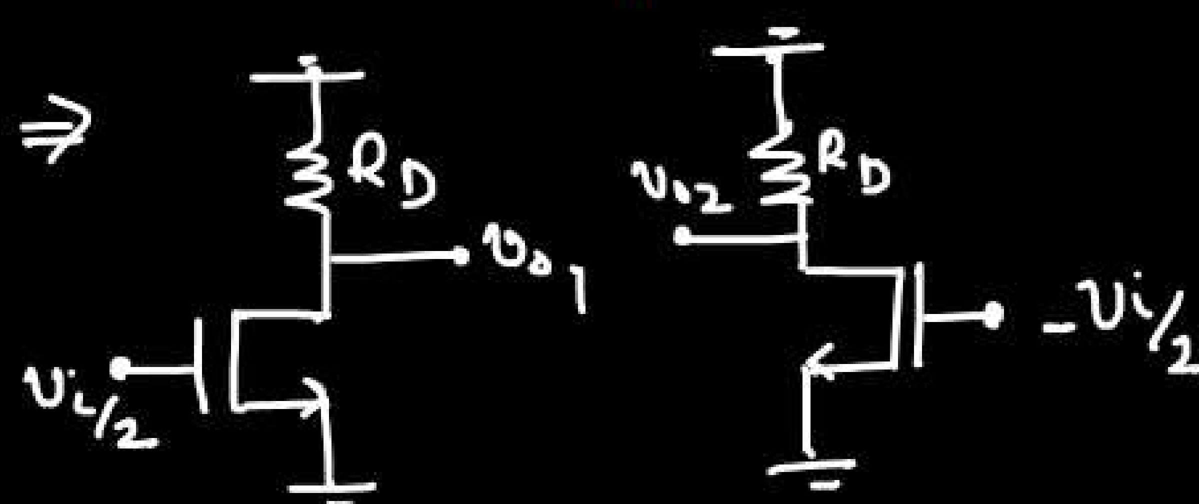


$$v_{i_1} - v_{i_2} = v_{in}$$

Small signal Model :-



⇒



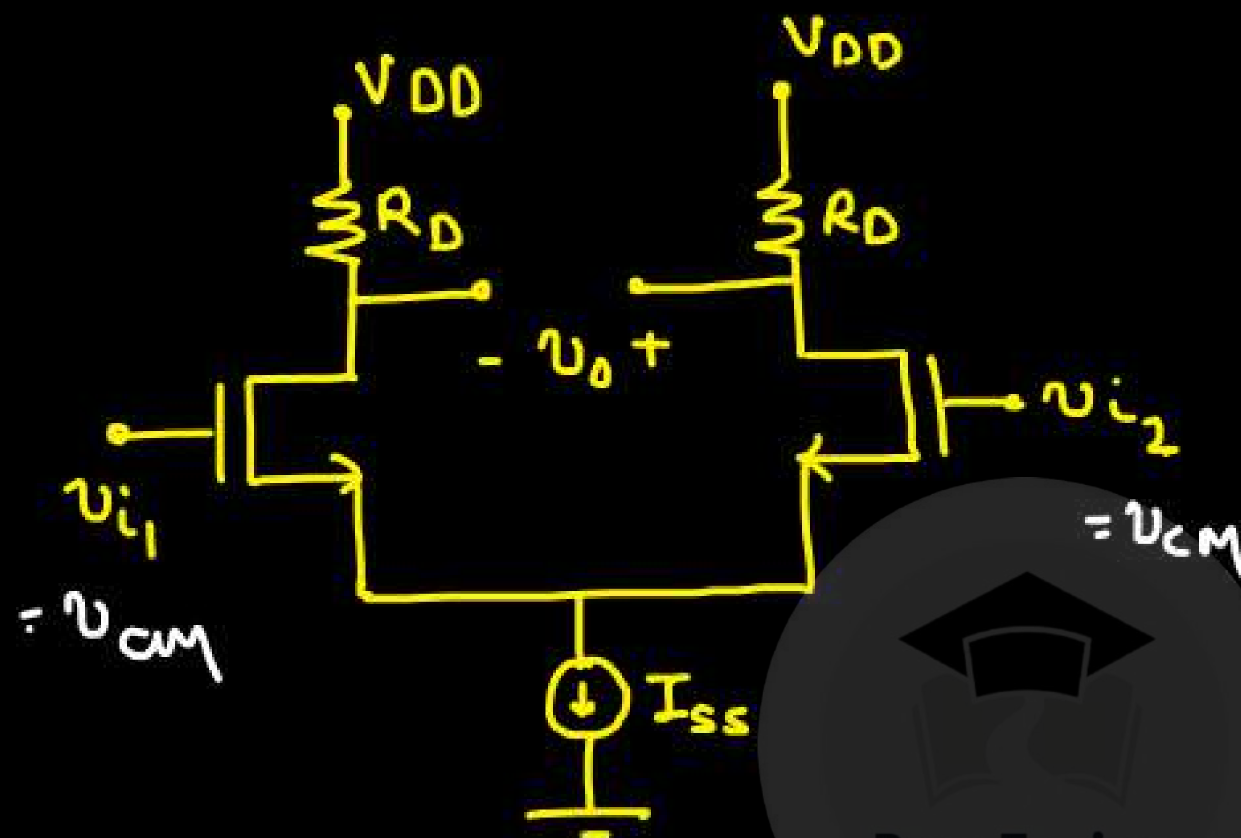
$$v_{o1} = -g_m R_D \, v_i/2$$

$$v_{o2} = g_m R_D \, v_i/2$$

$$v_o = g_m R_D \, v_i$$

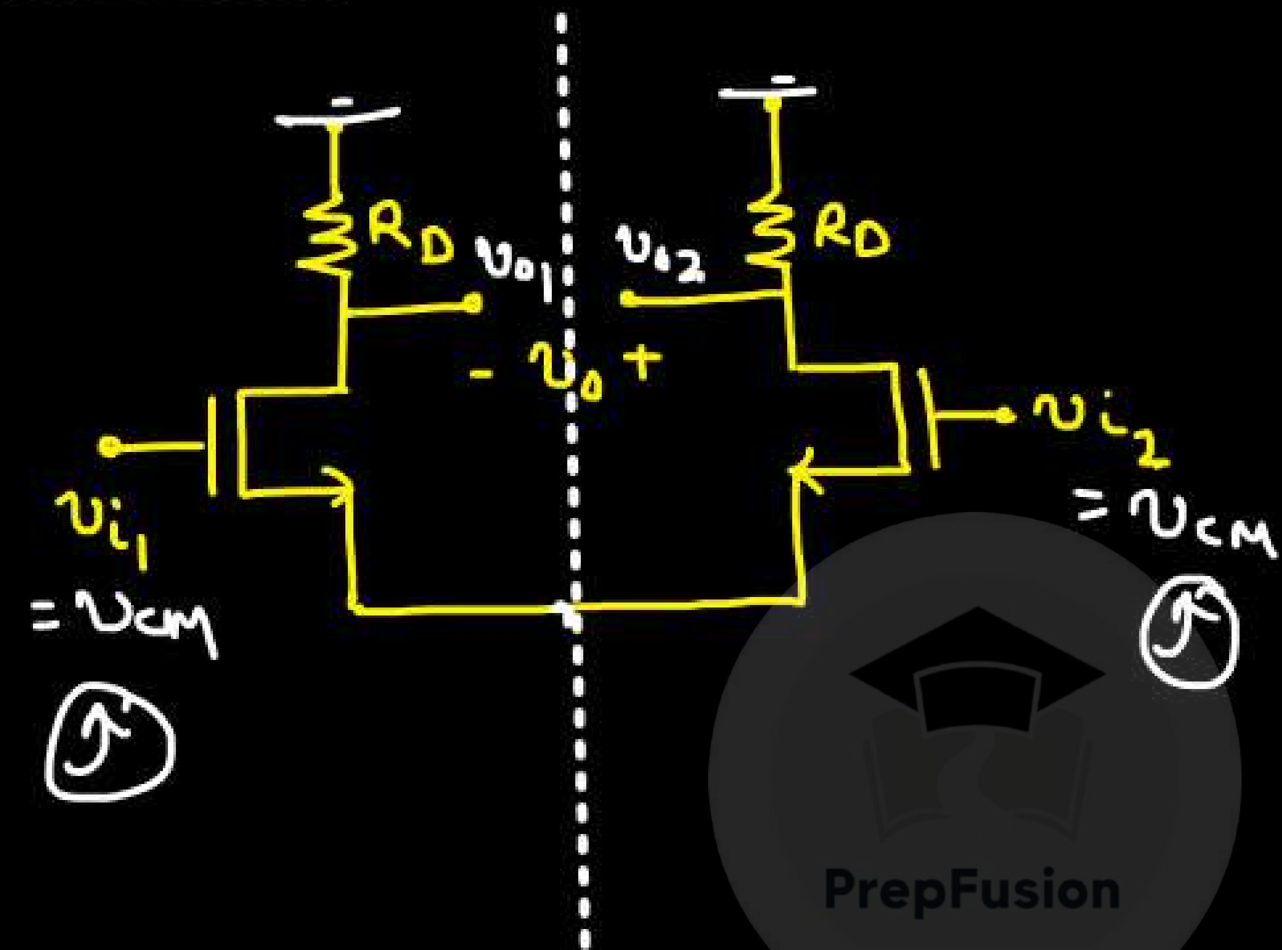
$$\boxed{(A_v)_d = g_m R_D}$$

For common Mode gain :-



$$v_{i_1} - v_{i_2} = v_{in}$$

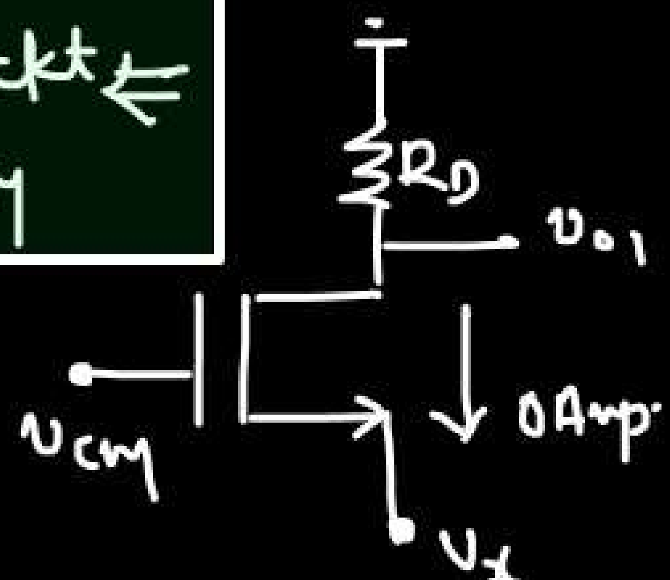
Small Signal Model :-



$$(v_o)_{CM} = \frac{v_{o2} + v_{o1}}{2}$$

$$(v_i)_{CM} = v_{CM}$$

Same Half ckt ⇐ for CM-DM



$$v_{o1} = 0$$

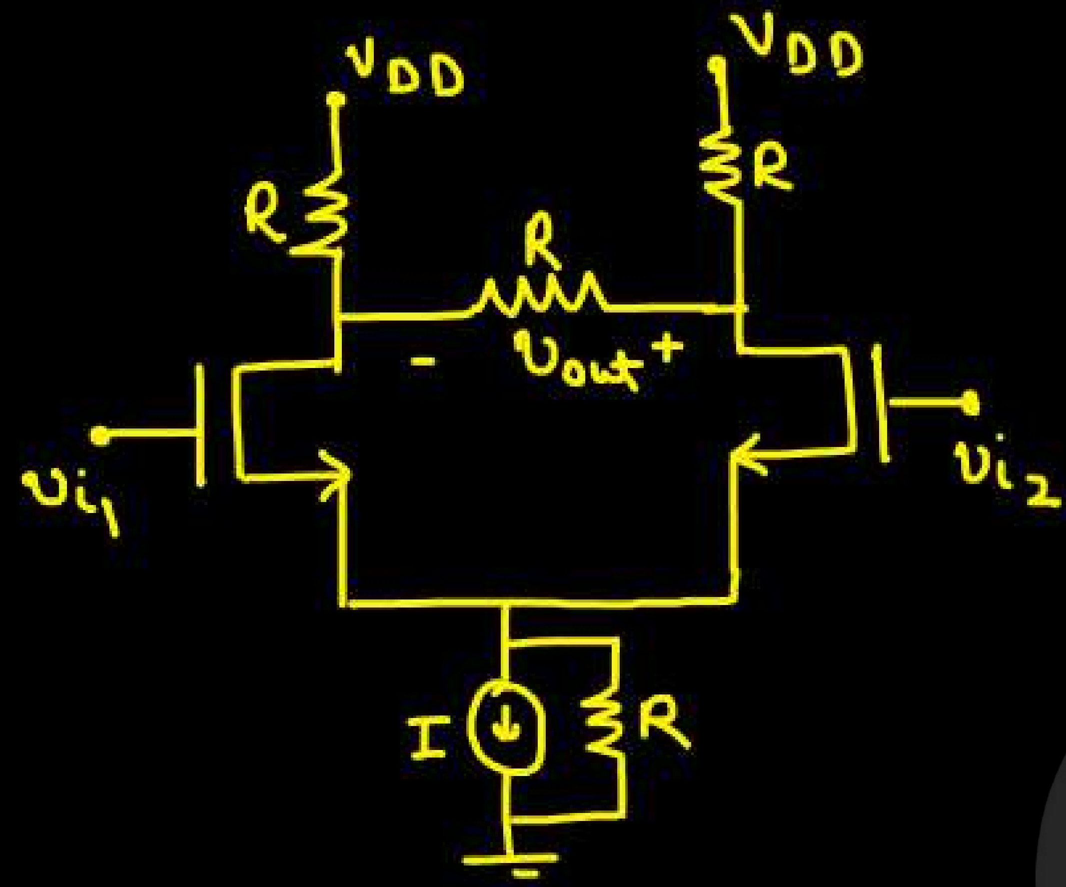
$$v_{o2} = 0$$

$$\boxed{(A_v)_{CM} = 0}$$

$$g_m(v_{CM} - v_x) = 0$$

$$\boxed{v_x = v_{CM}}$$

Q.



Find

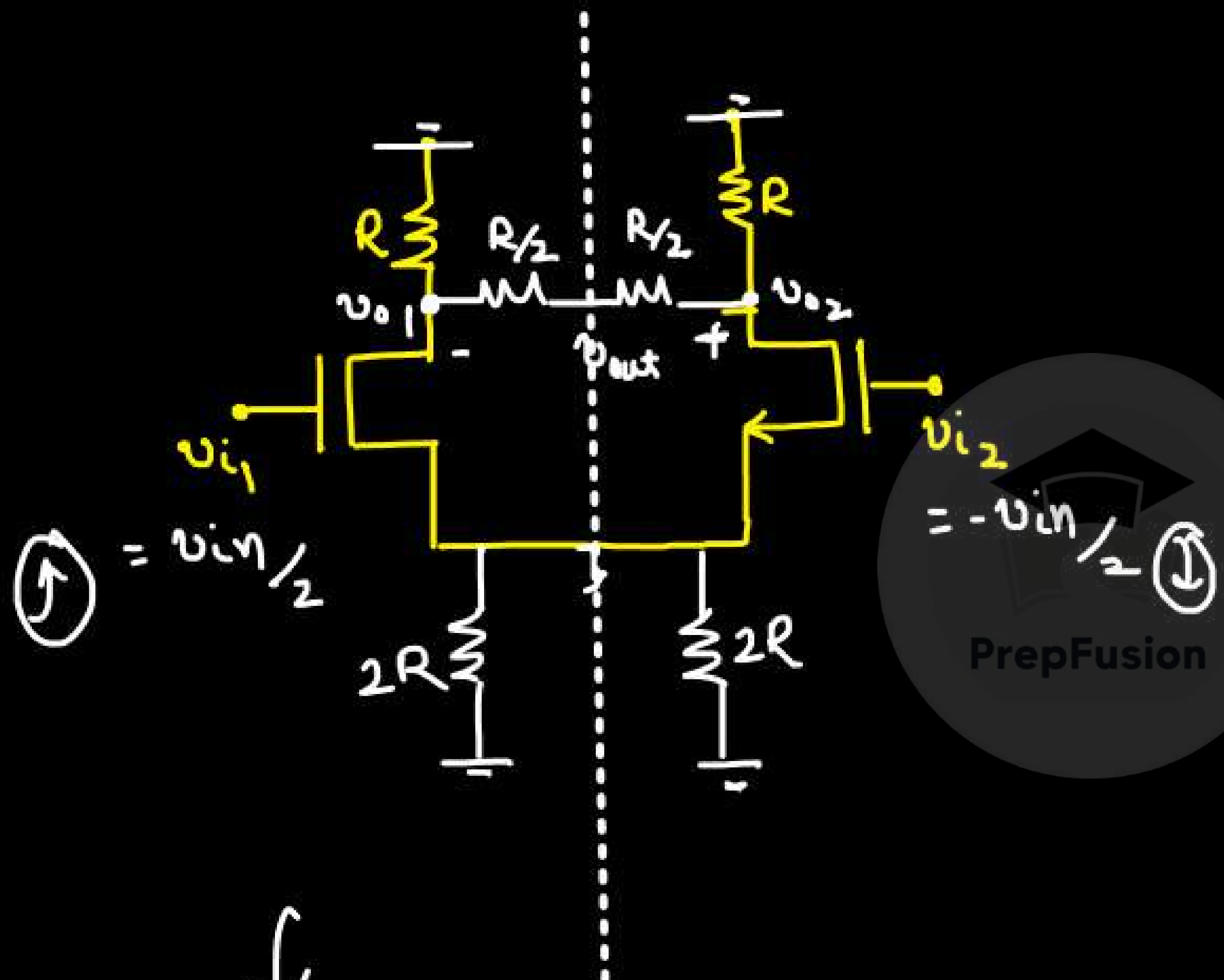
(a) Differential Gain

(b) Common-Mode Gain

(c) Common-Mode Differential Gain

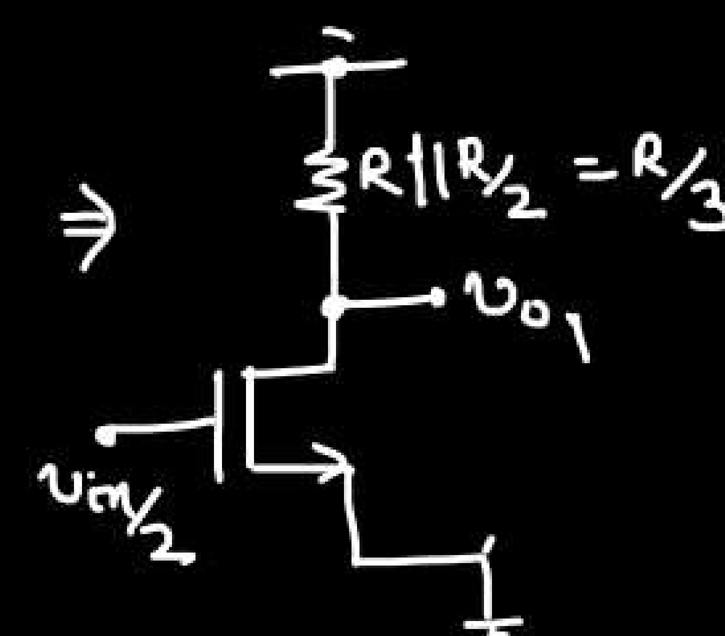
(d) CMRR

(9) Differential gain :-



$$v_{out} = v_{o2} - v_{o1}$$

$\Rightarrow$



$$v_{o1} = -g_m \frac{R}{3} \frac{v_{in}}{2}$$

$$v_{o2} = g_m \frac{R}{3} \frac{v_{in}}{2}$$

$\Leftarrow$

$$(v_o)_d = g_m \frac{R}{3} v_{in}$$

$$(v_i)_d = v_{in}$$

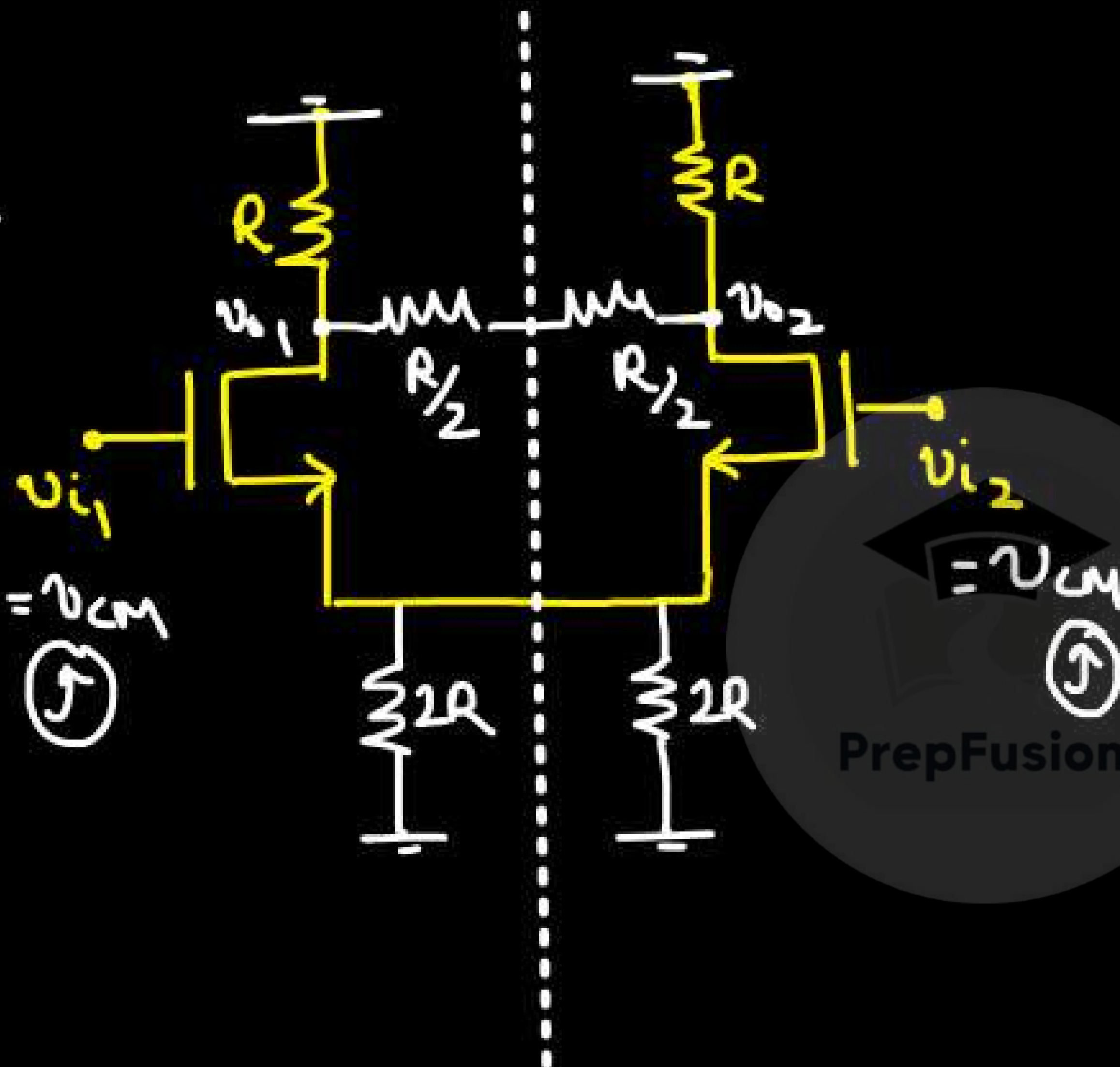
$\Leftarrow$

$$\boxed{A_v = g_m \frac{R}{3}}$$

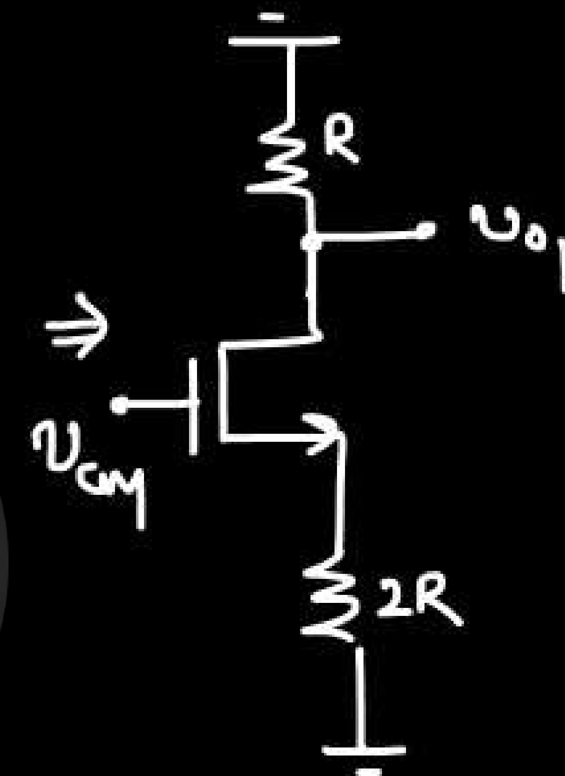
(b) Common Mode gain :-

$$(v_o)_{cm} = \frac{v_{o1} + v_{o2}}{2}$$

$$(v_i)_{cm} = v_{cm}$$



$\Rightarrow$



$$v_{o1} = \frac{-g_m R}{1 + 2g_m R} v_{cm}$$

$$v_{o2} = \frac{-g_m R}{1 + 2g_m R} v_{cm}$$

$$(v_o)_{cm} = \frac{-g_m R}{1 + 2g_m R} v_{cm}$$

$$\boxed{(A_v)_{cm} = \frac{-g_m R}{1 + 2g_m R}}$$

(c) Common Mode Differential Gain :-

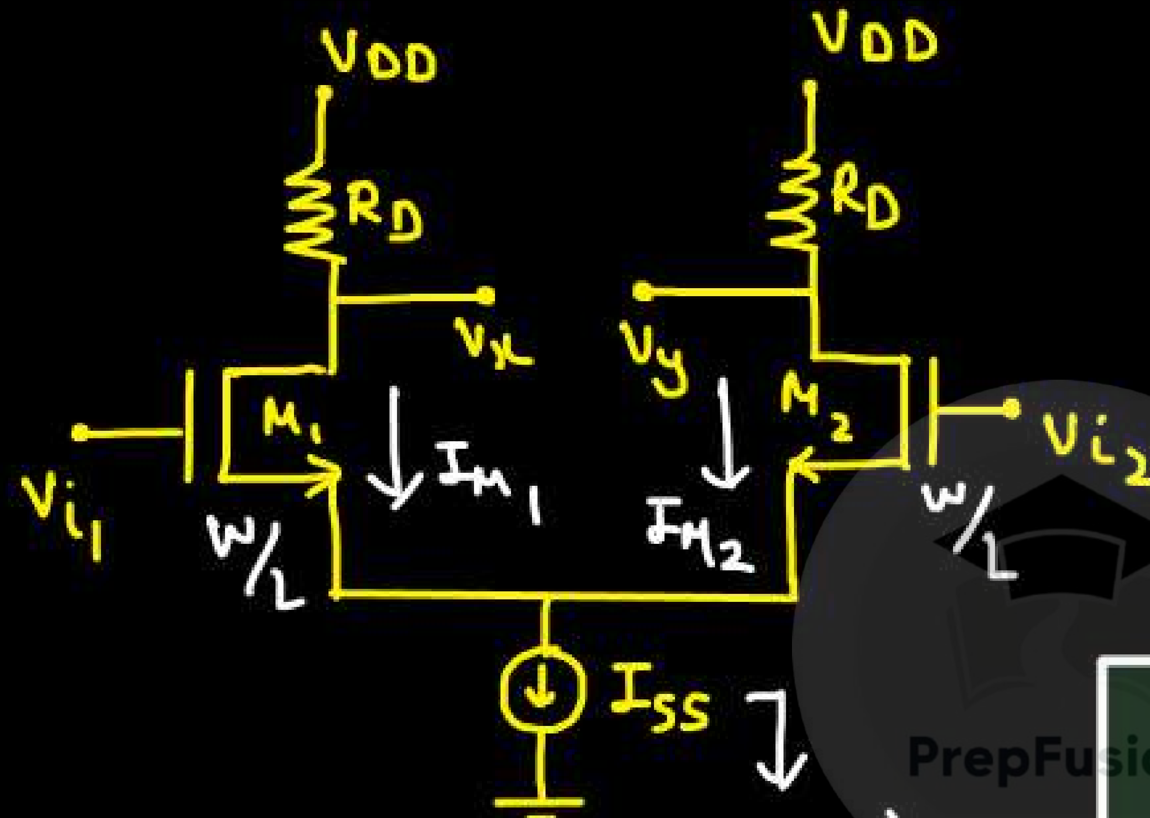
$$(v_o)_{CM-DM} = v_{o_2} - v_{o_1}$$

$$= 0$$

$$\boxed{(A_v)_{CM-DM} = 0}$$

⇒ Large Signal Analysis of differential Amplifier:-

(DC)



↓ const.

$$I_{M_1} + I_{M_2} = I_{SS}$$

$$V_x = V_{DD} - I_{M_1} R_D$$

$$V_y = V_{DD} - I_{M_2} R_D$$

Let

@ some $V_{i_1} = V_a \Rightarrow I_{M_1} = I_{SS}$, $I_{M_2} = 0$ Amp.

$$\boxed{V_x = V_{DD} - I_{SS} R_D}$$

$$V_y = V_{DD}$$

$$\boxed{V_{xy} = -I_{SS} R_D}$$

⇐

if $V_{i_1} \uparrow \Rightarrow I_{M_1} \uparrow \Rightarrow V_x \downarrow$

⇓

$I_{M_2} \downarrow \Rightarrow V_y \uparrow$

⇓

$V_{xy} = V_x - V_y \downarrow$

$$\boxed{\begin{aligned} &\text{if } V_{i_2} \uparrow \Rightarrow I_{M_2} \uparrow \Rightarrow V_y \downarrow \\ &\qquad\qquad \Downarrow \\ &\qquad I_{M_1} \downarrow \Rightarrow V_x \uparrow \\ &\qquad\qquad \Downarrow \\ &\qquad V_{xy} = V_x - V_y \uparrow \end{aligned}}$$

let @ some $V_{i_2} = V_b$

$\Rightarrow$

$I_{M_2} = I_{ss}$

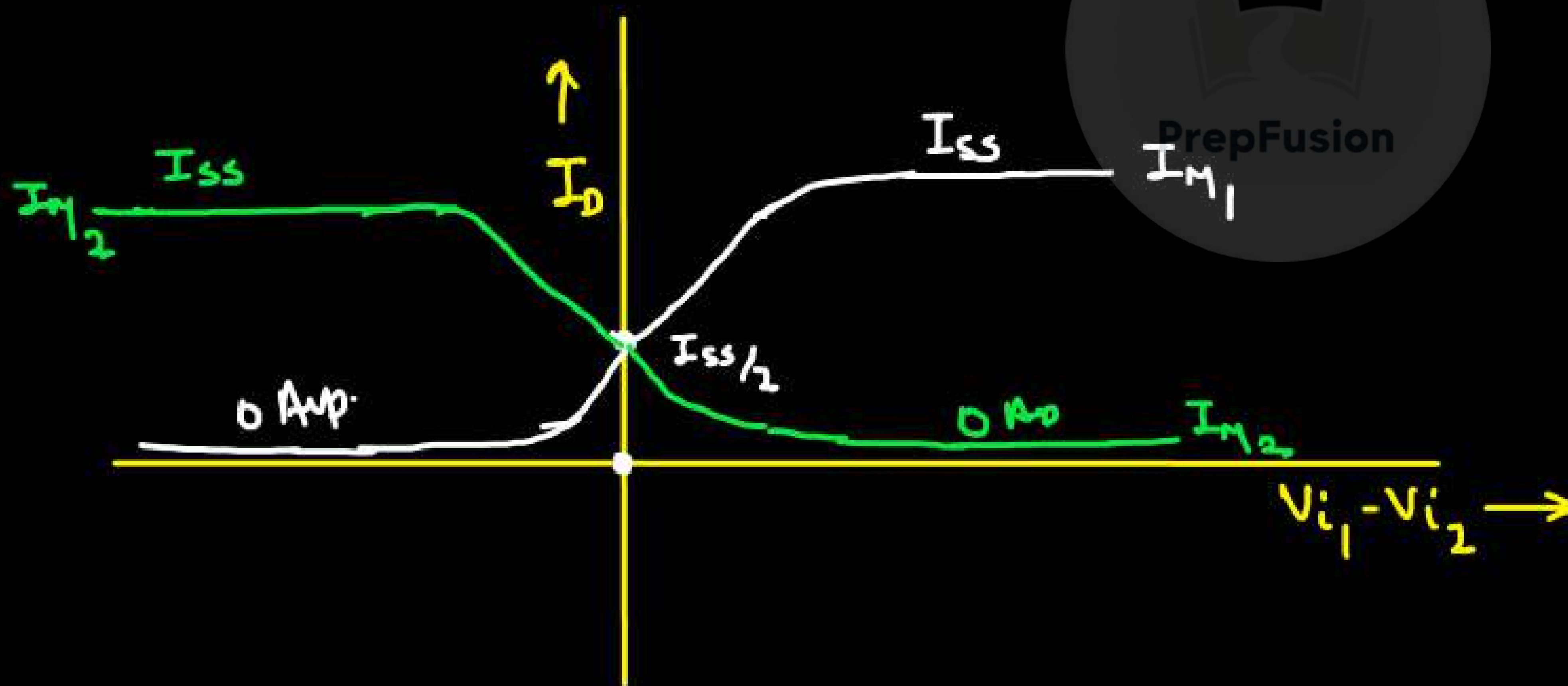
$\Downarrow$

$I_{M_1} = 0 \text{ Amp}$

$$\boxed{V_y = V_{DD} - I_{ss} R_D}$$

$V_x = V_{DD}$

$$\boxed{V_{xy} = I_{ss} R_D}$$

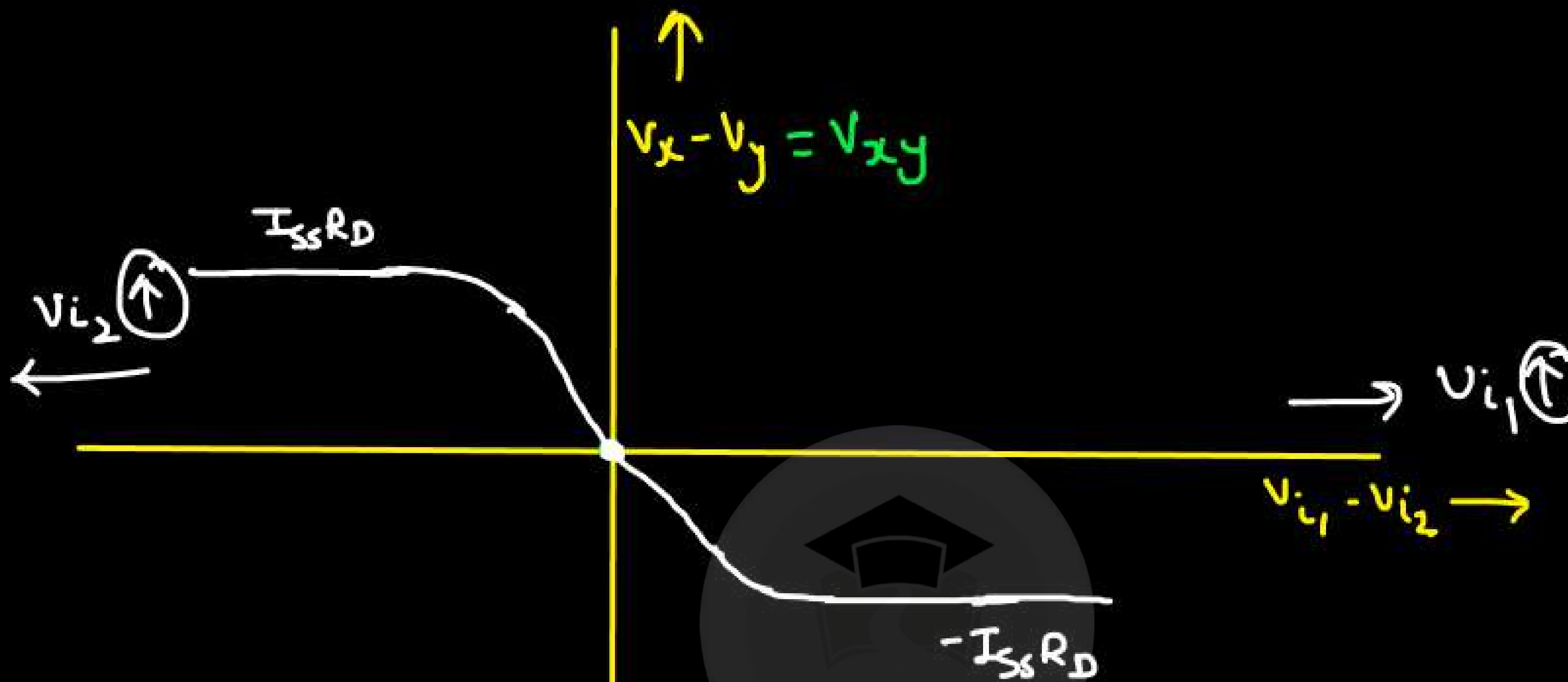


if $V_{i_1} - V_{i_2} > 0$

$\Rightarrow V_{i_1} > V_{i_2}$

if $V_{i_1} - V_{i_2} < 0$

$\Rightarrow V_{i_1} < V_{i_2}$



if $v_{i_1} > v_{i_2} \Rightarrow v_x < v_y \Rightarrow v_{xy} = -ve$

if $v_{i_2} > v_{i_1} \Rightarrow v_x > v_y \Rightarrow v_{xy} = +ve$

When $v_{i_1} - v_{i_2} = 0$

$\Rightarrow v_{i_1} = v_{i_2} \Rightarrow I_{M_1} = I_{M_2} = I_M$

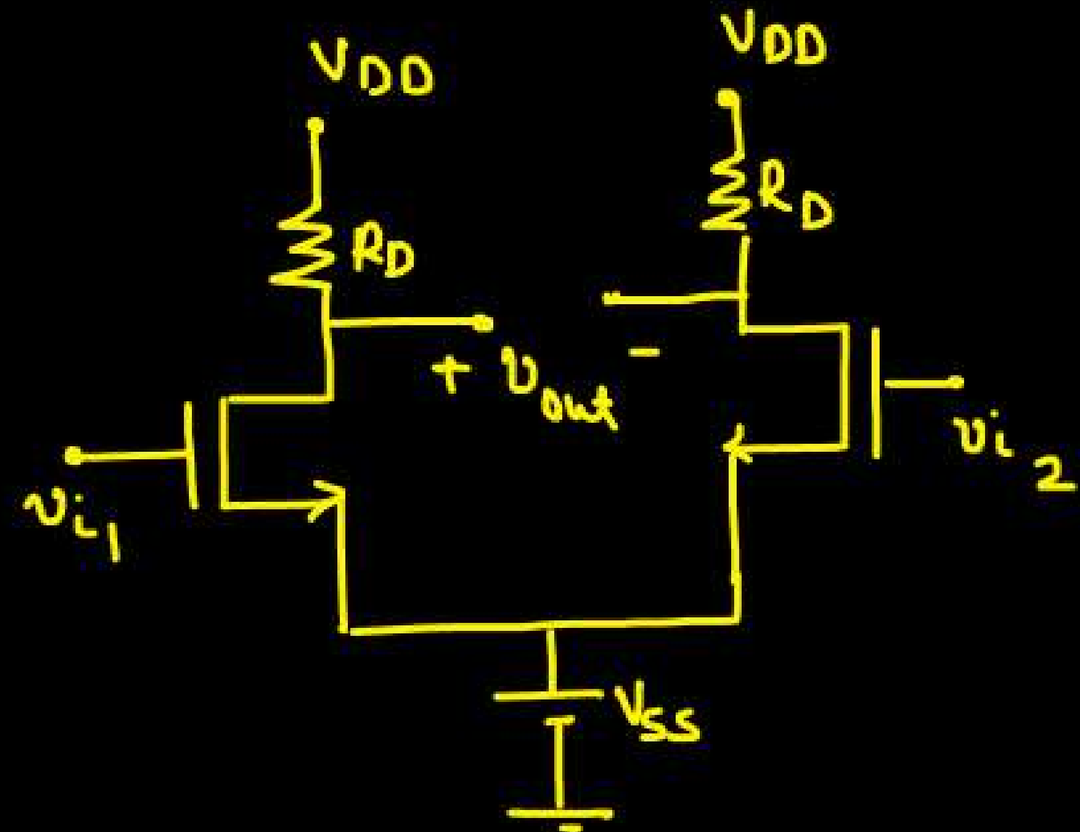
$V_x = V_{DD} - I_M R_D$

$V_y = V_{DD} - I_M R_D$

$V_{xy} = 0$

Assigment - 11

Q.



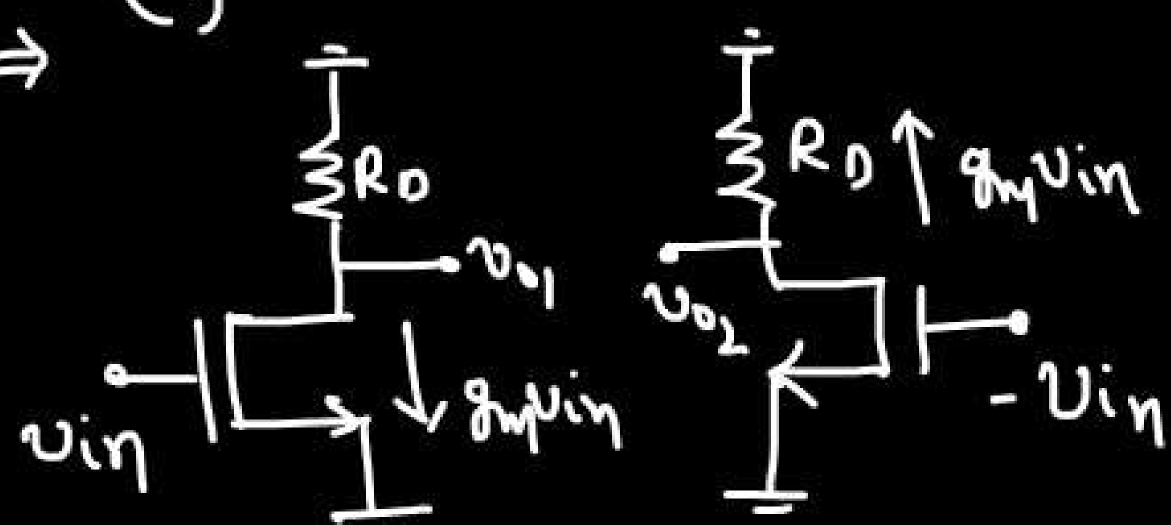
Find

(a) Differential gain

(b) Common-Mode gain

$v_{i_1} - v_{i_2} = 2v_{in}$

⇒ (a)



$v_{o_1} = -g_m R_D v_{in}$

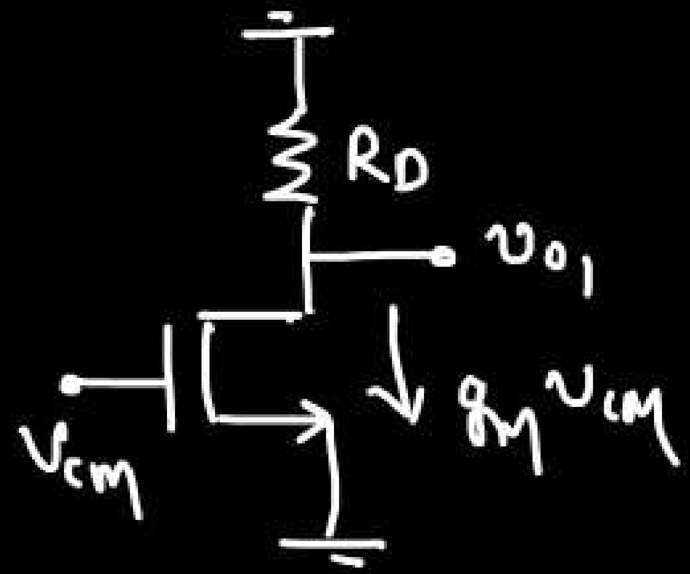
$v_{o_2} = g_m R_D v_{in}$

$(v_o)_d = v_{o_1} - v_{o_2} = -2g_m R_D v_{in}$

$(v_i)_d = 2v_{in}$

$$\boxed{(A_v) = -g_m R_D}$$

(b)



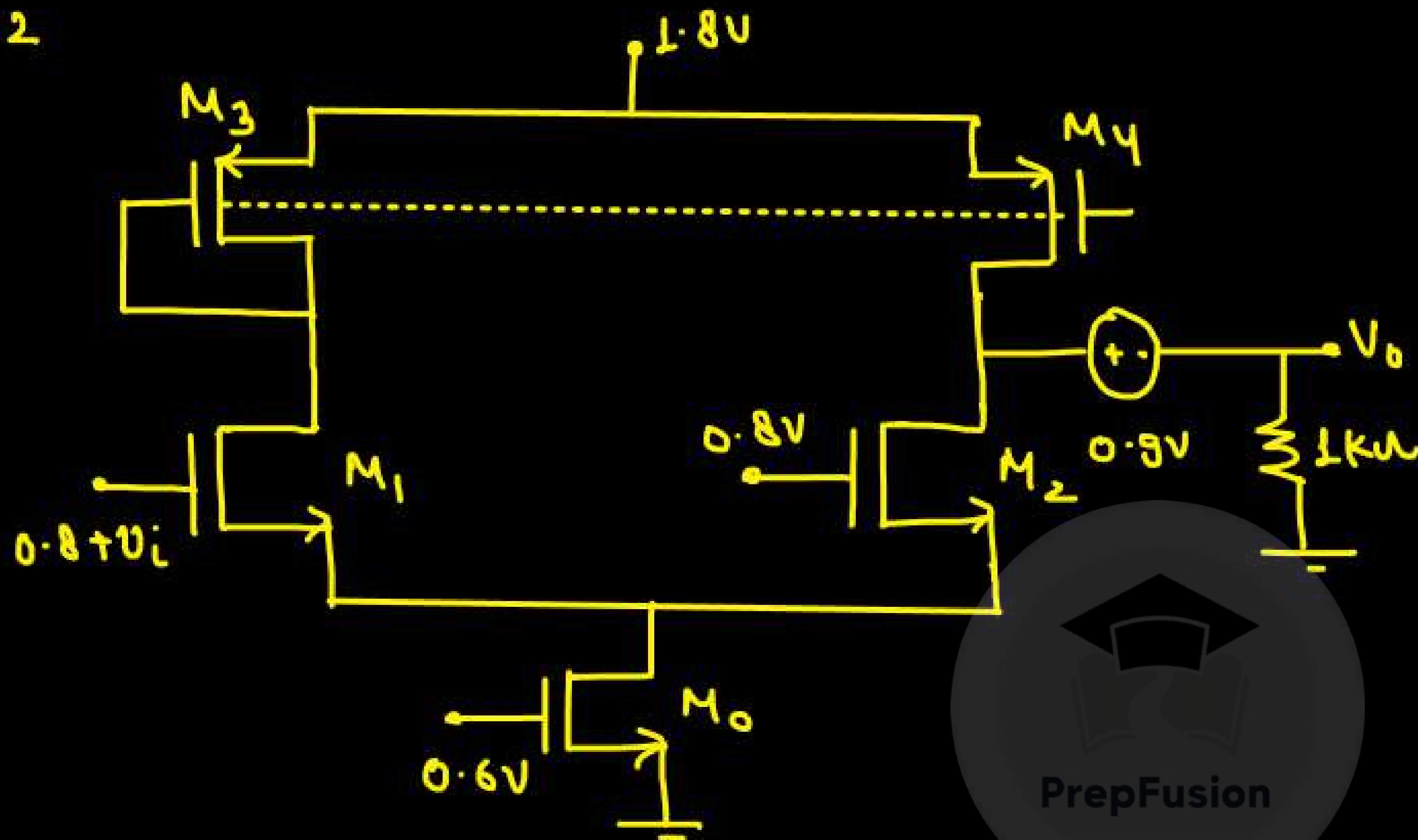
$$v_{o_1} = -g_m R_D v_{cm}$$

$$v_{o_2} = -g_m R_D v_{cm}$$

$$(v_o)_{cm} = -g_m R_D v_{cm}$$

$$\boxed{(A_v)_{cm} = -g_m R_D}$$

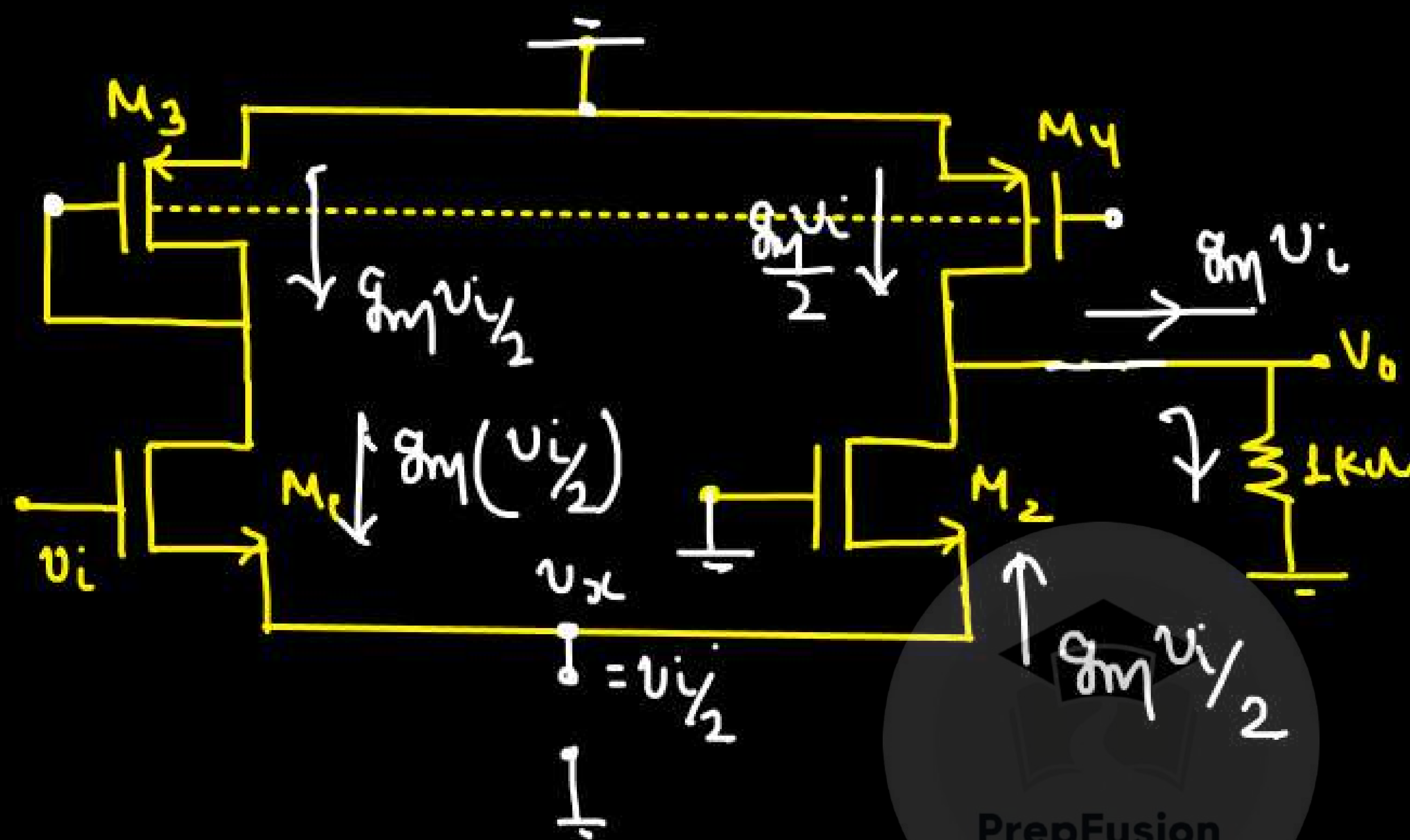
Q. 2



$M_0 - M_4$ all are biased in sat. region.

For all Transistors $g_m = 25\,mS$, $\lambda = 0$

Find small signal voltage gain. $\left(\frac{v_o}{v_i}\right)$



$$g_m(v_i - v_x) = g_m v_x$$

$$\boxed{v_x = v_i/2}$$

For M_3 and M_4

both g_m & v_{gs} are same

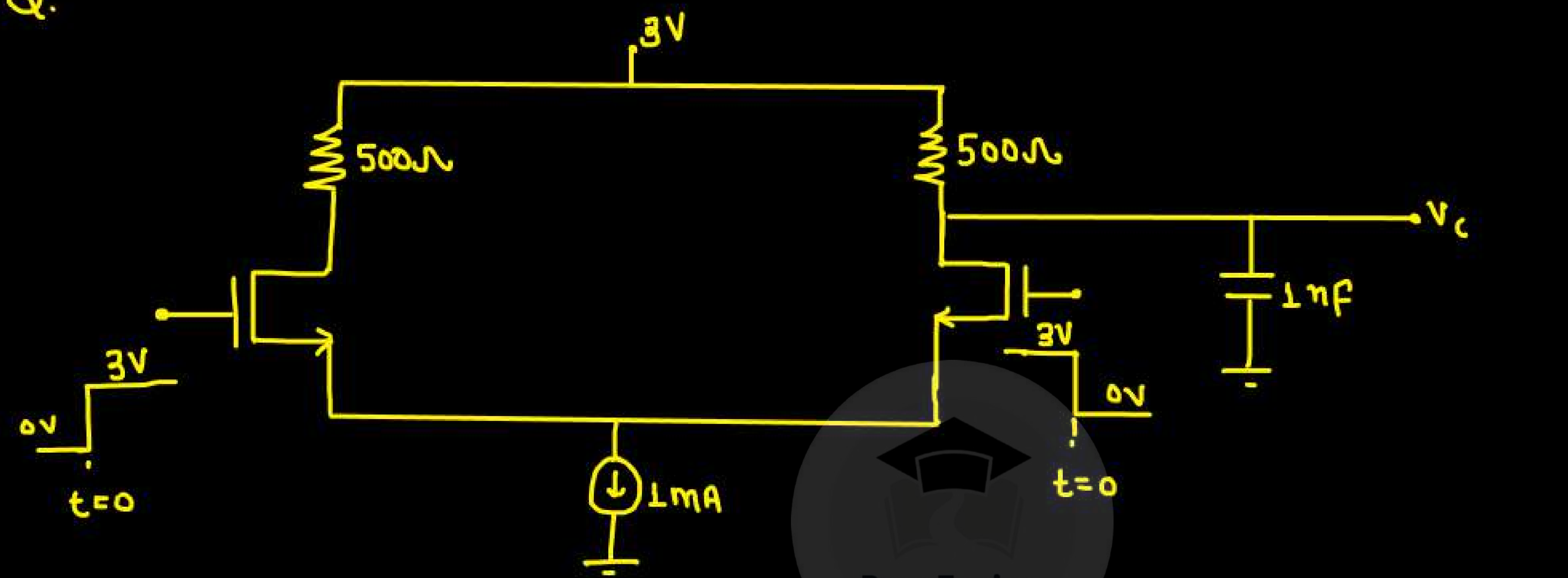
$\Rightarrow (i_d)_{M_3} = (i_d)_{M_4}$

$$v_o = g_m v_i (1k\Omega)$$

$$\frac{v_o}{v_i} = 25m\,(1k)$$

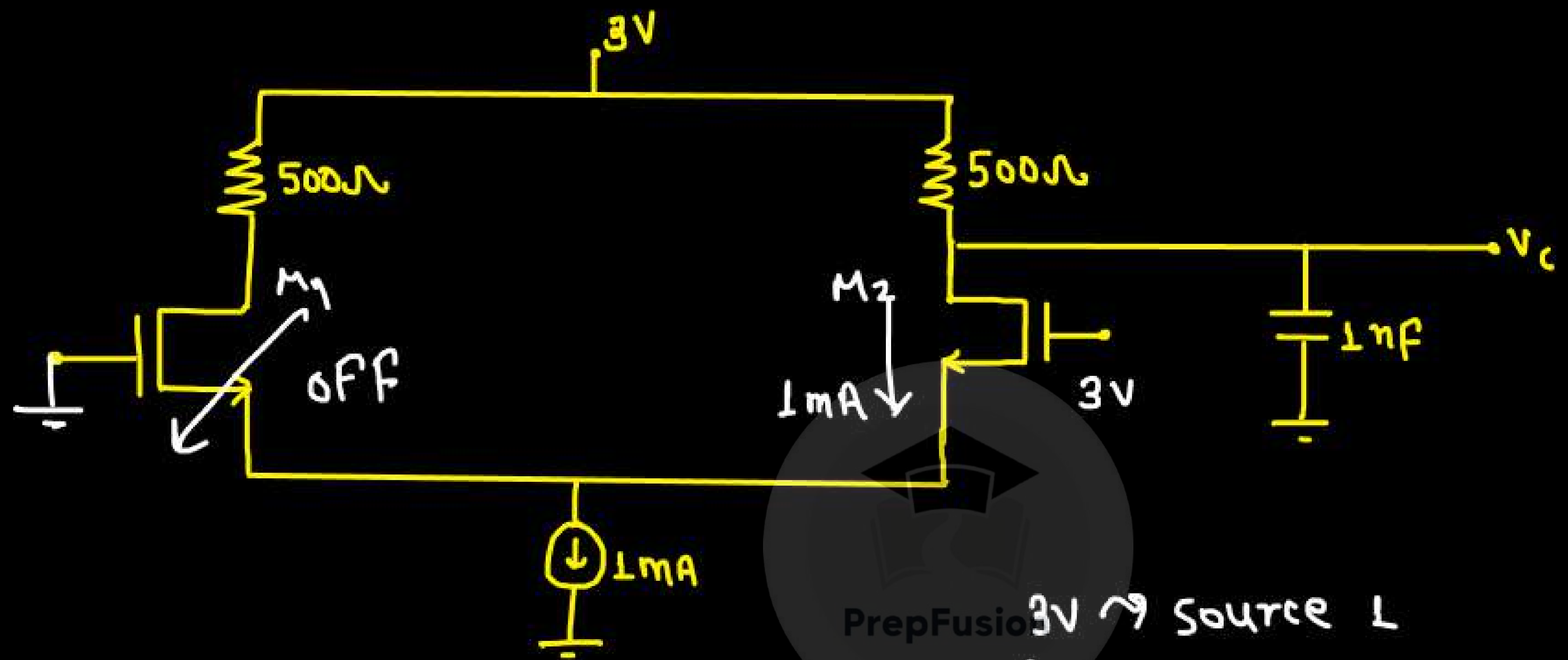
$$\boxed{\frac{v_o}{v_i} = 25\ V/V}$$ ANS

Q.

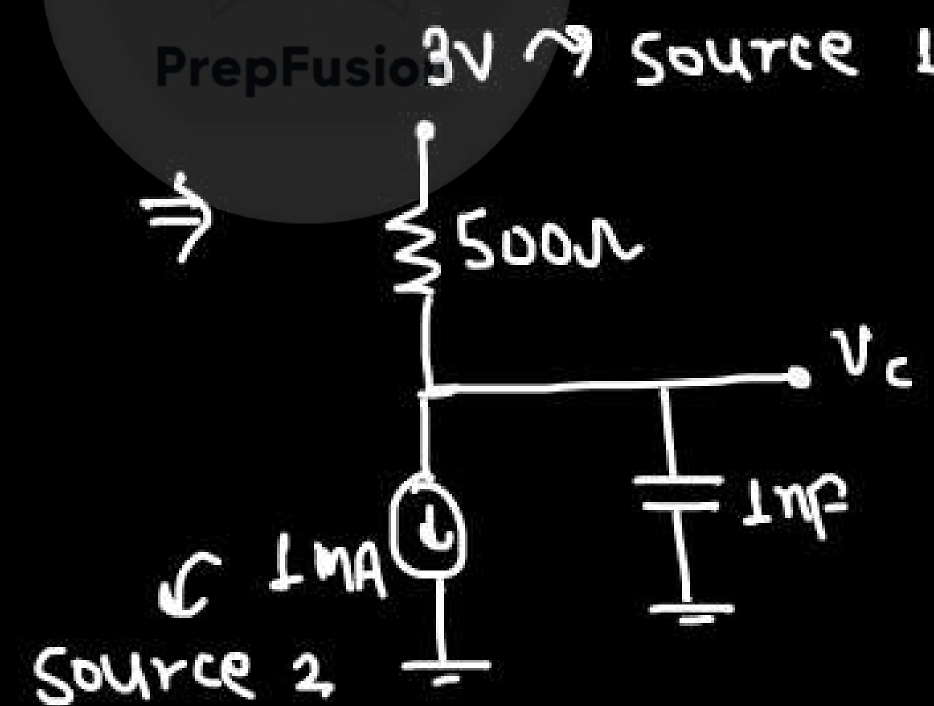


Find the time at which V_c node reaches to 2.9V

For $t<0$:-



⇒

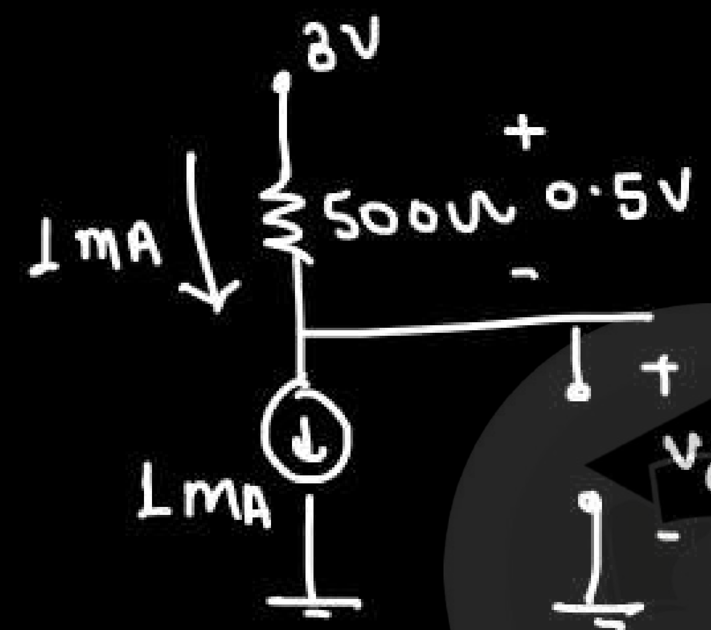


$V_c(-\infty) = 0V$

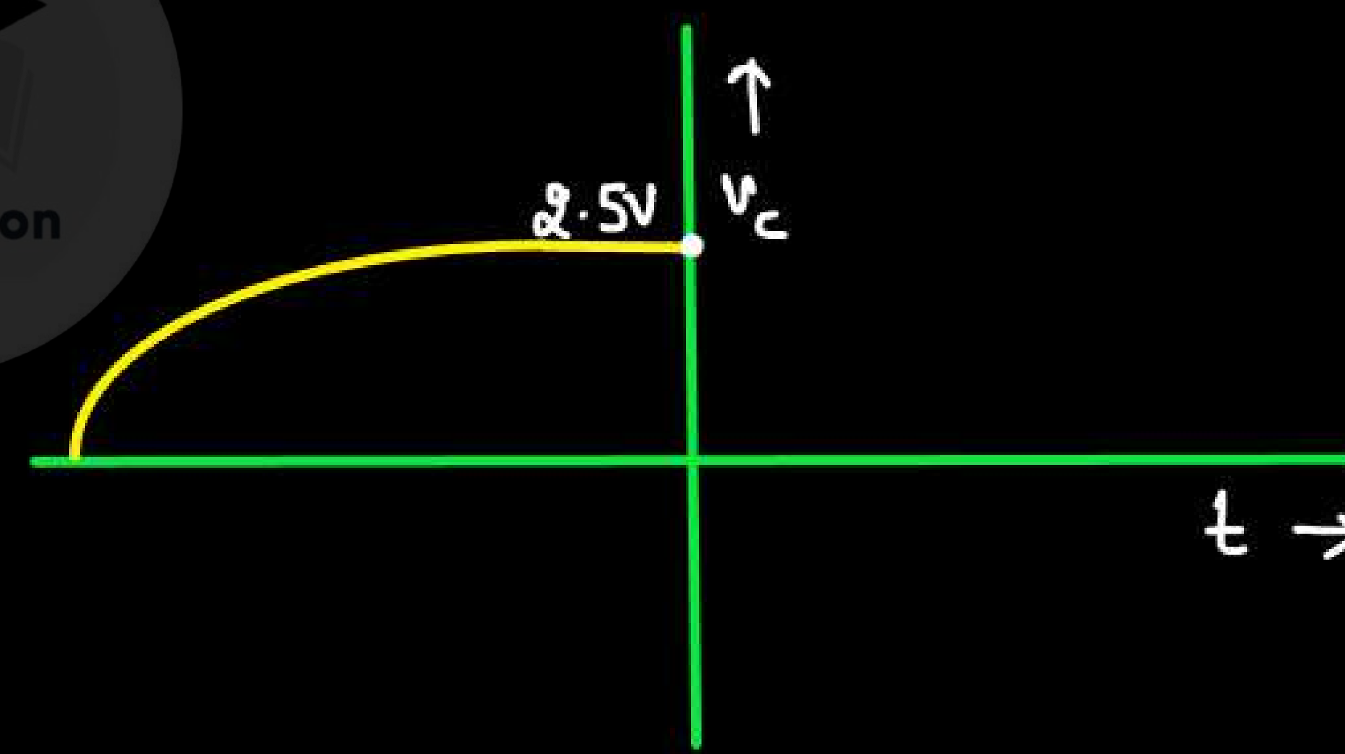
$V_c(0^-) =$

$V_c = 0^-$ (S.S.)

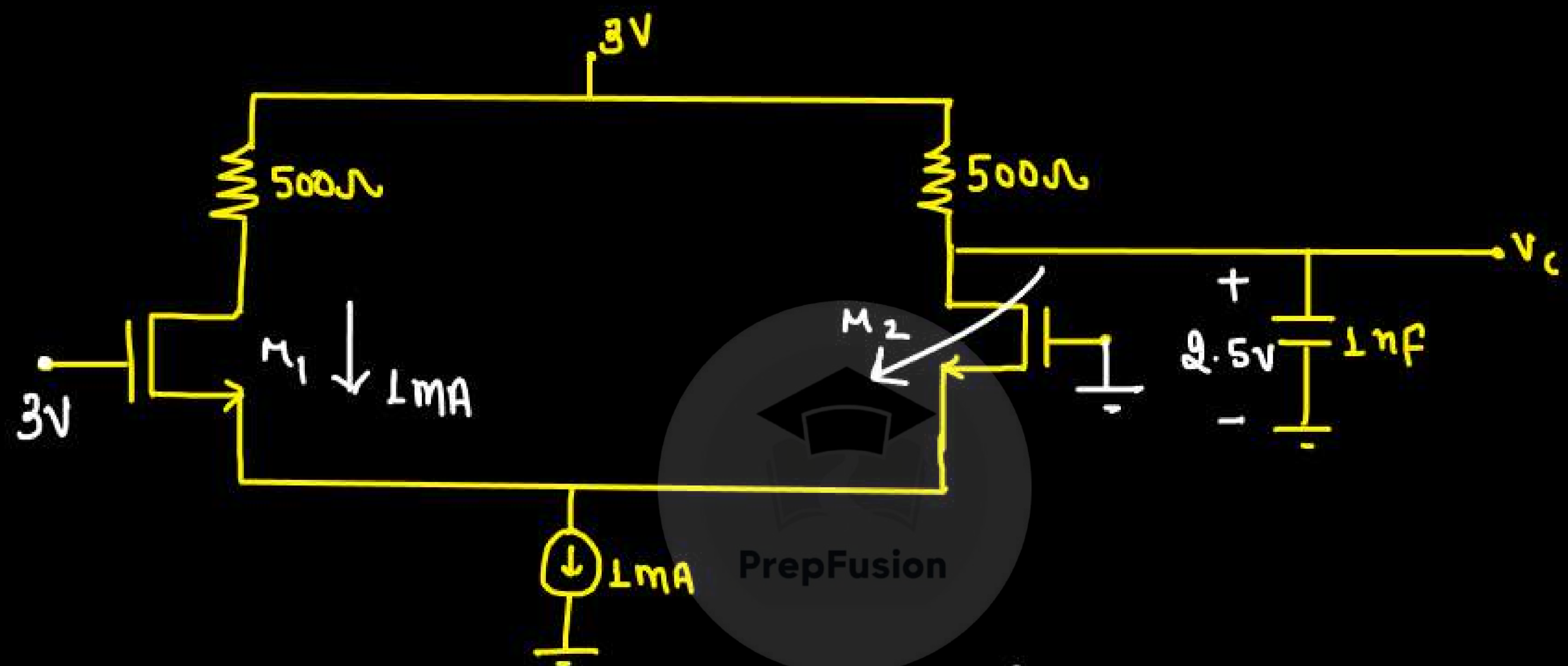
@ S.S. $\Rightarrow$ cap. O.C.



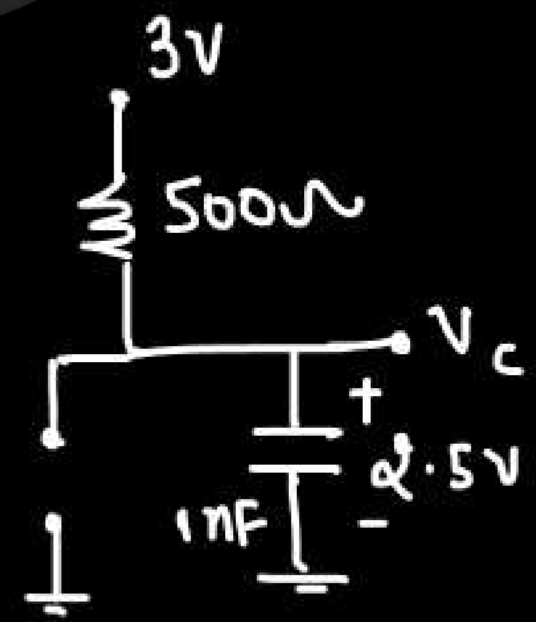
$$\boxed{V_c(0^-) = 2.5\,V}$$

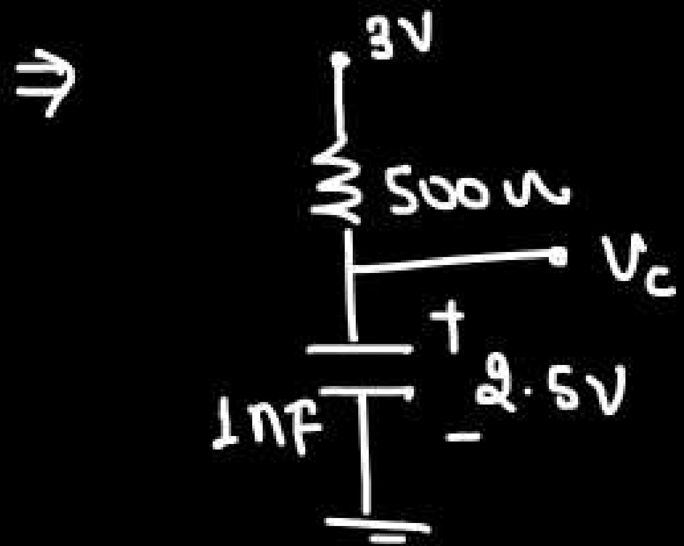


For t > 0



M_2 is off



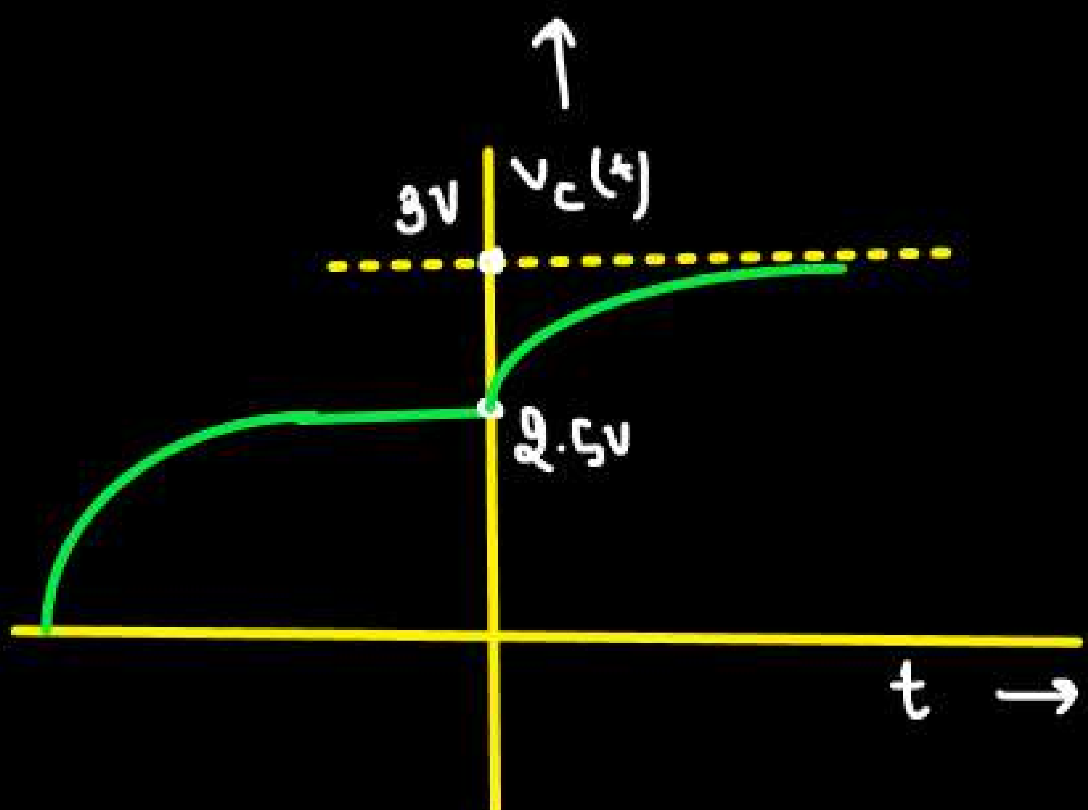


$$v_c(0^+) = 2.5V$$

$$v_c(\infty) = 3V$$

$$\tau = RC = 500 \times 1nF = 0.5\mu sec.$$

$$\boxed{v_c(t) = 3 - 0.5e^{-t/0.5\mu}}$$



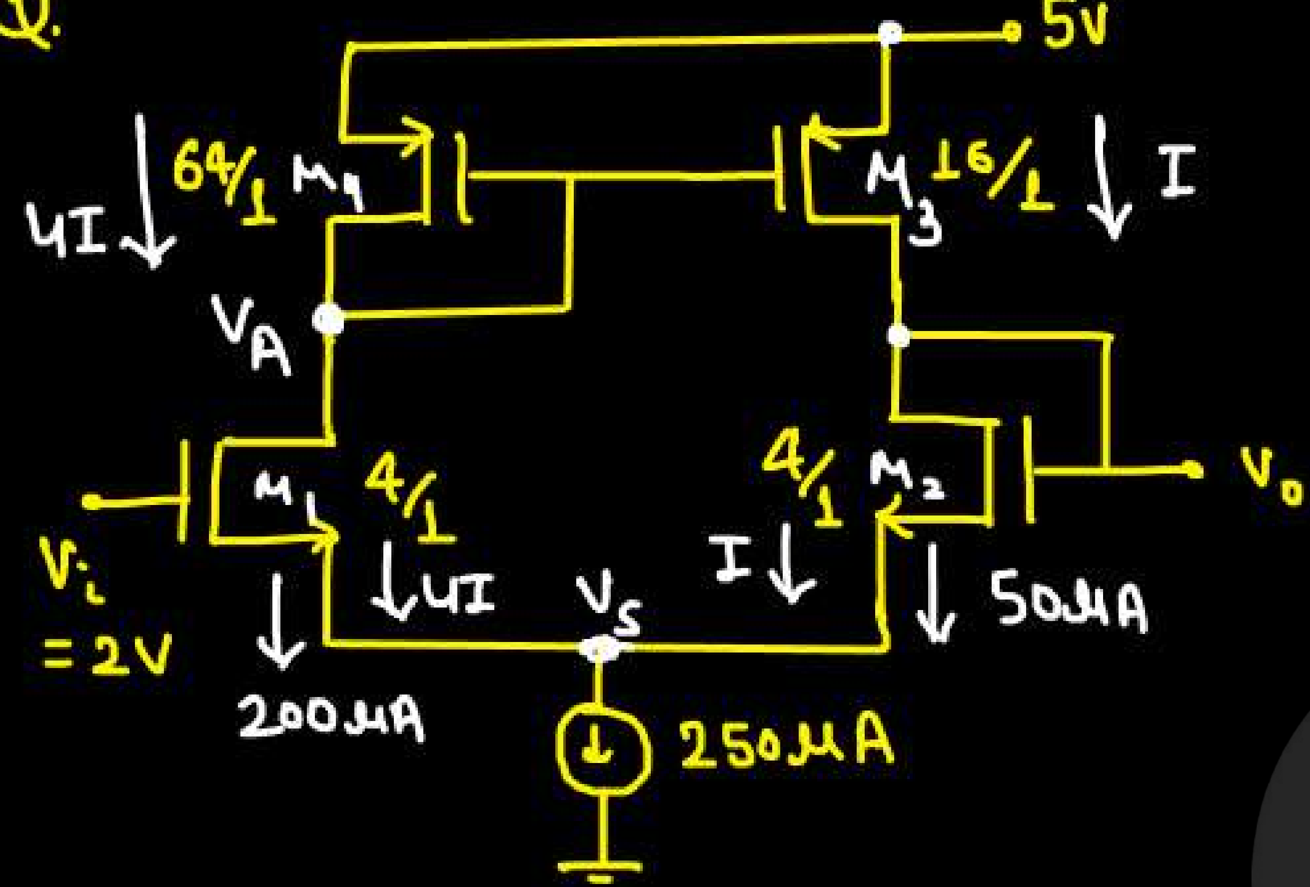
let @ $t = t_1$, $v_c(t_1) = 2.9V$

$$2.9 = 3 - 0.5e^{-t/0.5\mu}$$

$$t_1 = 0.5\ln(5)\ \mu sec.$$

$$\boxed{t_1 = 0.8\mu sec.}$$ ANS.

Q.



$\mu_n C_{ox} = 400\ \mu A/V^2$, $V_{Tn} = 0.5V$

$\mu_p C_{ox} = 100\ \mu A/V^2$, $V_{Tp} = 0.5V$

Find output voltage V_o.

M_4 and M_3 are in current Mirror. [M_3 should be in sat.]

$$\boxed{\text{Assuming } M_3 \text{ to be in sat.}}$$

$\Rightarrow$ M_4 and M_3 are in C.M.

$4I + I = 250\mu$

$$\boxed{I = 50\mu A}$$

Both M_1 and M_2 are having same source potential

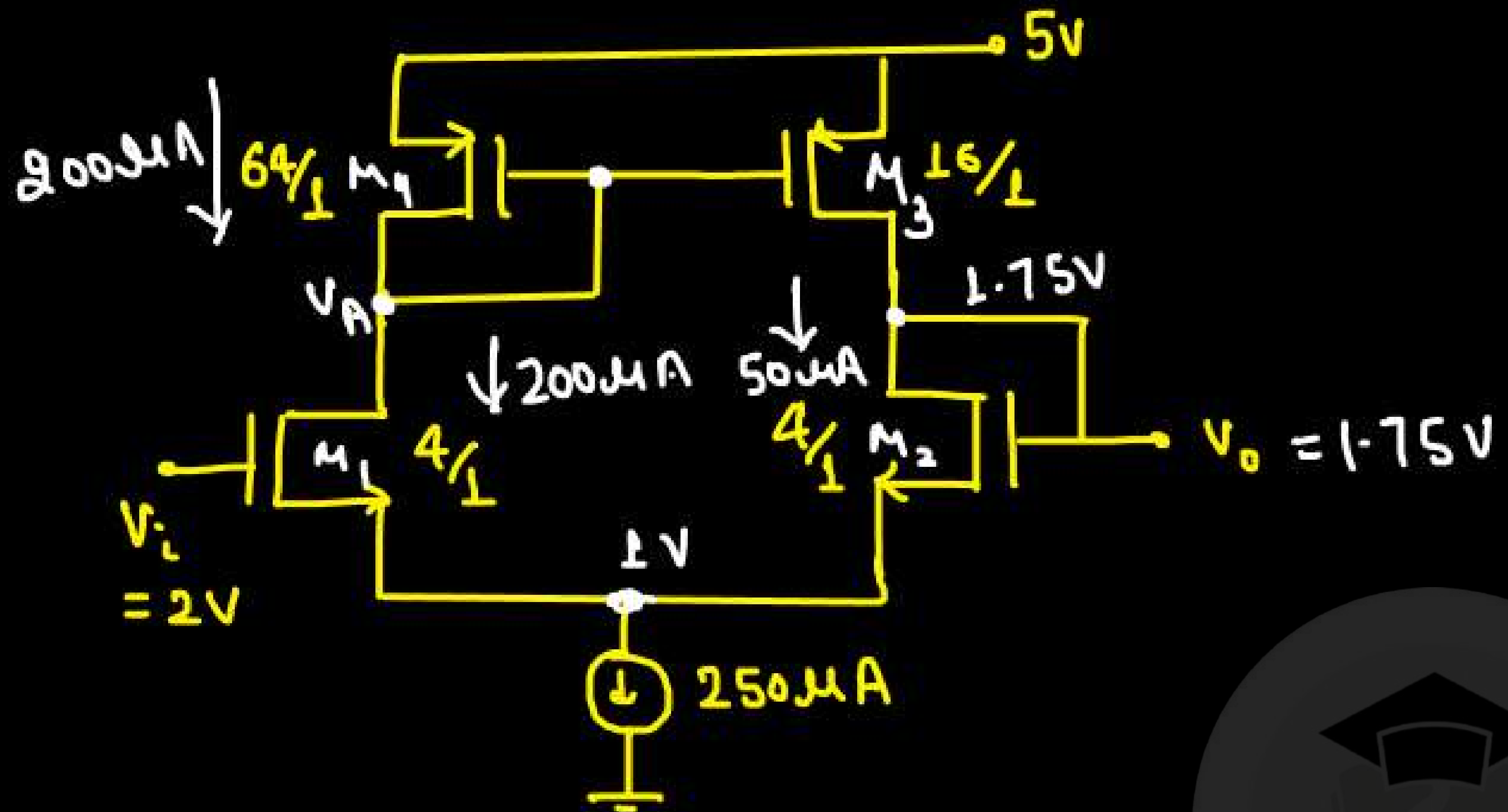
$\boxed{\text{Let, } M_1 \text{ is in saturation}}$

$$I_{M_1} = 200\mu A$$

$$\Rightarrow \quad 200\mu A = \frac{400\mu \times 4}{2}(2 - V_S - 0.5)^2$$

$$0.5 = 1.5 - V_S$$

$$\boxed{V_S = 1V}$$



M_2 is in sat.

$$I_{M_2} = 50\mu A$$

$$\Rightarrow 50\mu = \frac{400\mu \times 4}{2}\left[V_0 - 1 - 0.5\right]^2$$

$\boxed{V_0 = 1.75V}$ ⇒ correct ? ⇒ NOT SURE ⇒ Take care of Assump.

Check:- if M_1 and M_3 are in sat. or NOT.

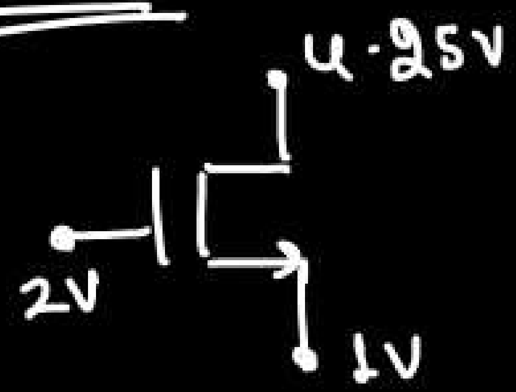
$$I_{M_4} = 200\,\mu A \quad [\text{Sat.}]$$

$$\Rightarrow 200\mu = \frac{100\mu \times 64}{2}\left[5 - V_A - 0.5\right]^2$$

$$0.25 = 4.5 - V_A$$

$$\boxed{V_A = 4.25V}$$

For M_1:-



$V_{DS} = 3.25V$

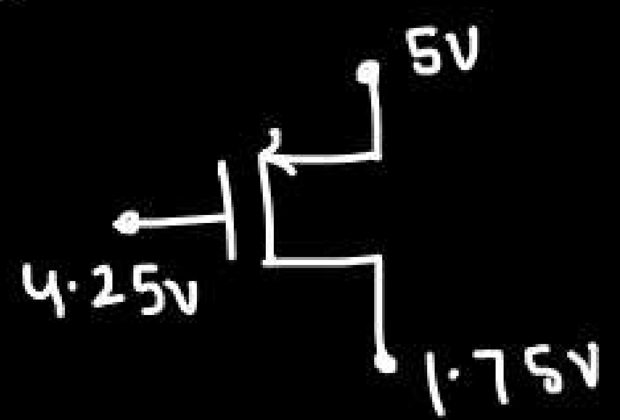
$V_{GS} = 1V$

$V_T = 0.5V$

$V_{OV} = 0.5V$

$\Rightarrow V_{DS} > V_{OV} \Rightarrow M_1$ is in sat $\Rightarrow$ Assumption correct

For M_3:



$V_{SG} = 0.75$

$V_T = 0.5$

$V_{ov} = 0.25$

$V_{SD} = 3.25$

$\Rightarrow V_{SD} > V_{ov} \Rightarrow$ sat. region

$\Downarrow$

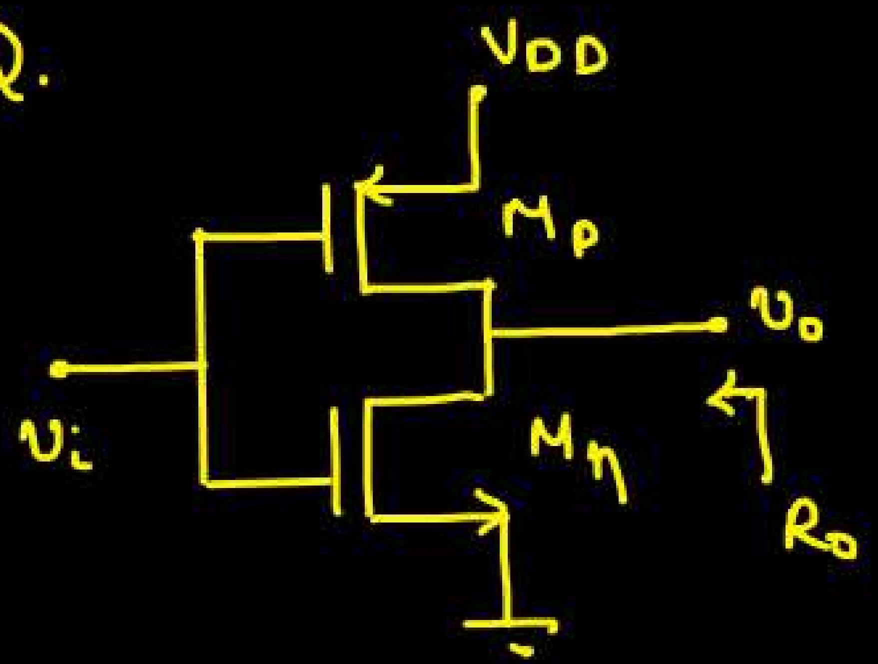
Assumption correct

$\Rightarrow$ all Tr M_1, M_2, M_3 and M_4 are in sat.

$$\boxed{V_0 = 1.75V}$$

Ans.

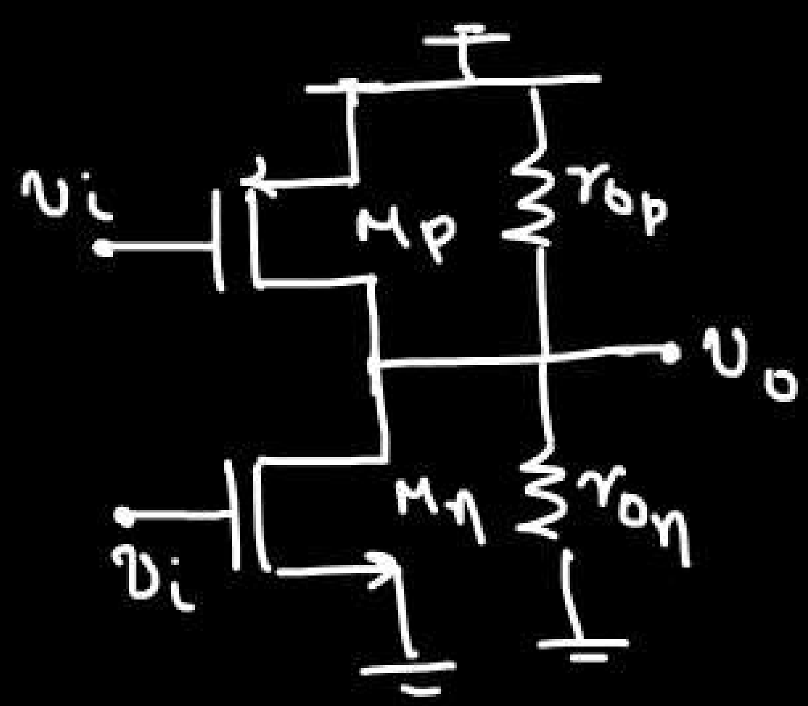
Q.



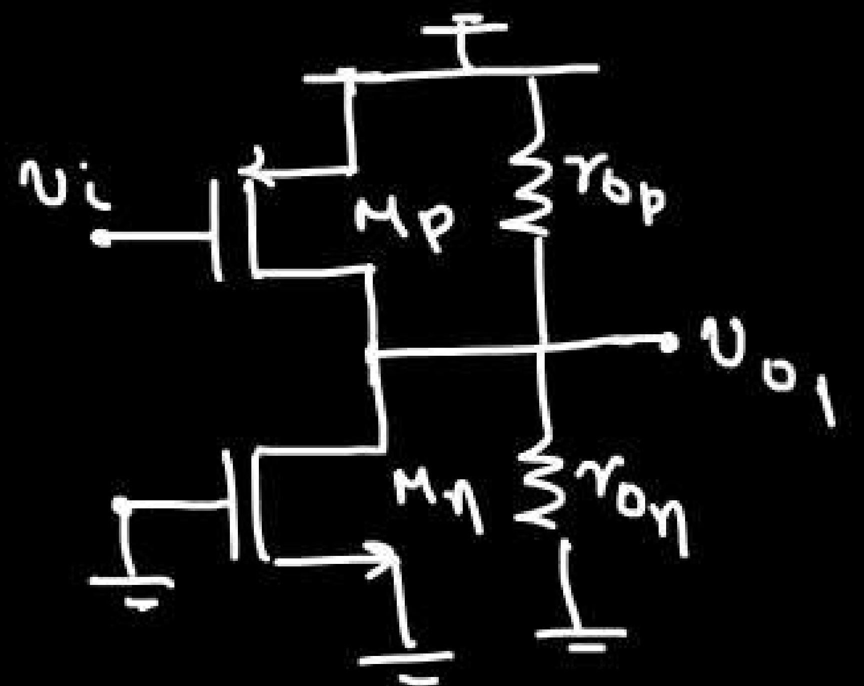
① Find the small signal voltage gain.

② Find small signal o/p resistance.

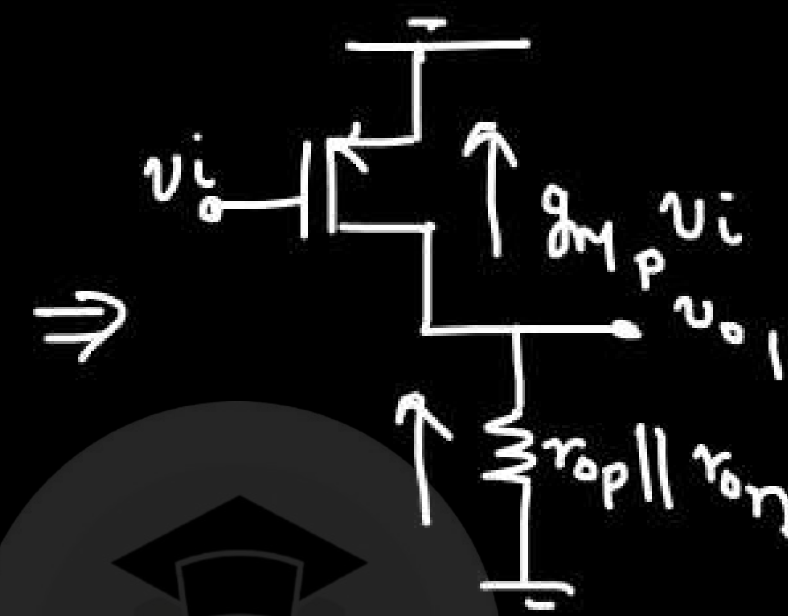
⇒



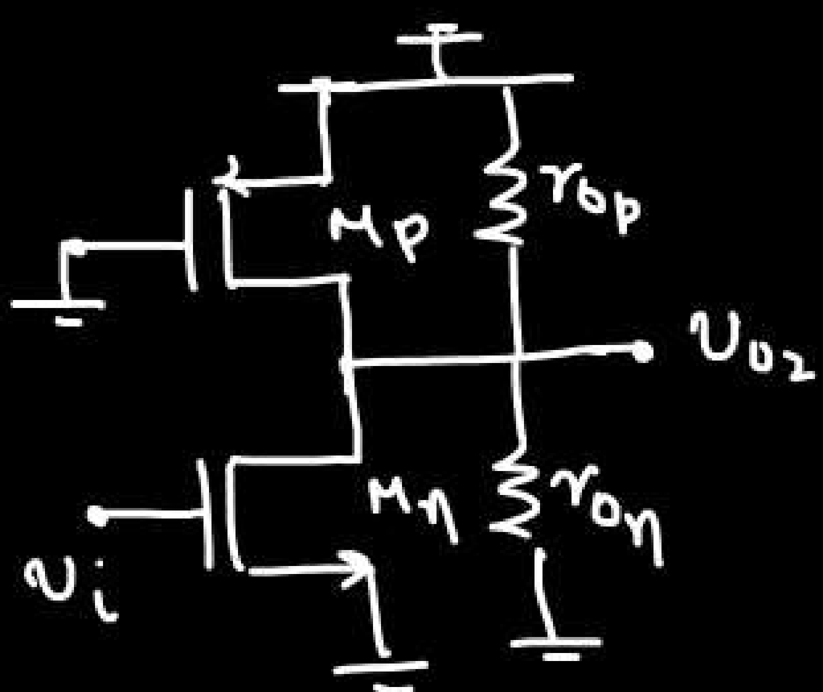
Applying superposition:-



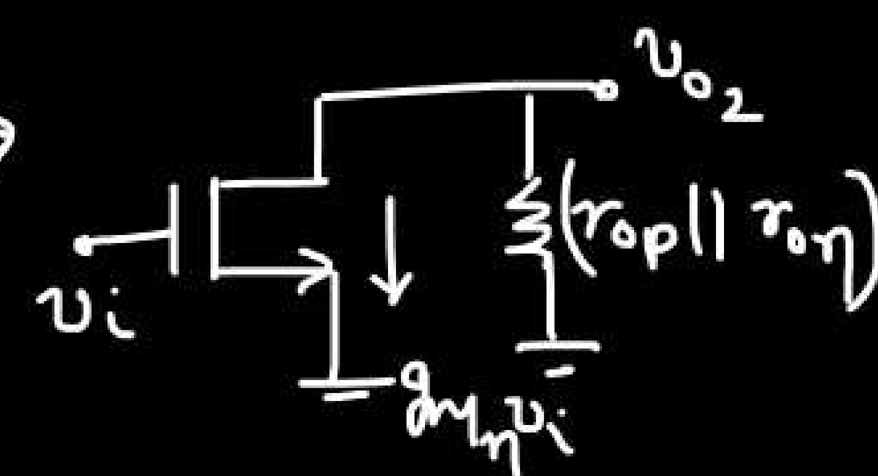
$\Rightarrow$



$$v_{o1} = -g_{mp} (r_{op} \| r_{on}) v_i \quad \text{—} \quad (1)$$



$\Rightarrow$



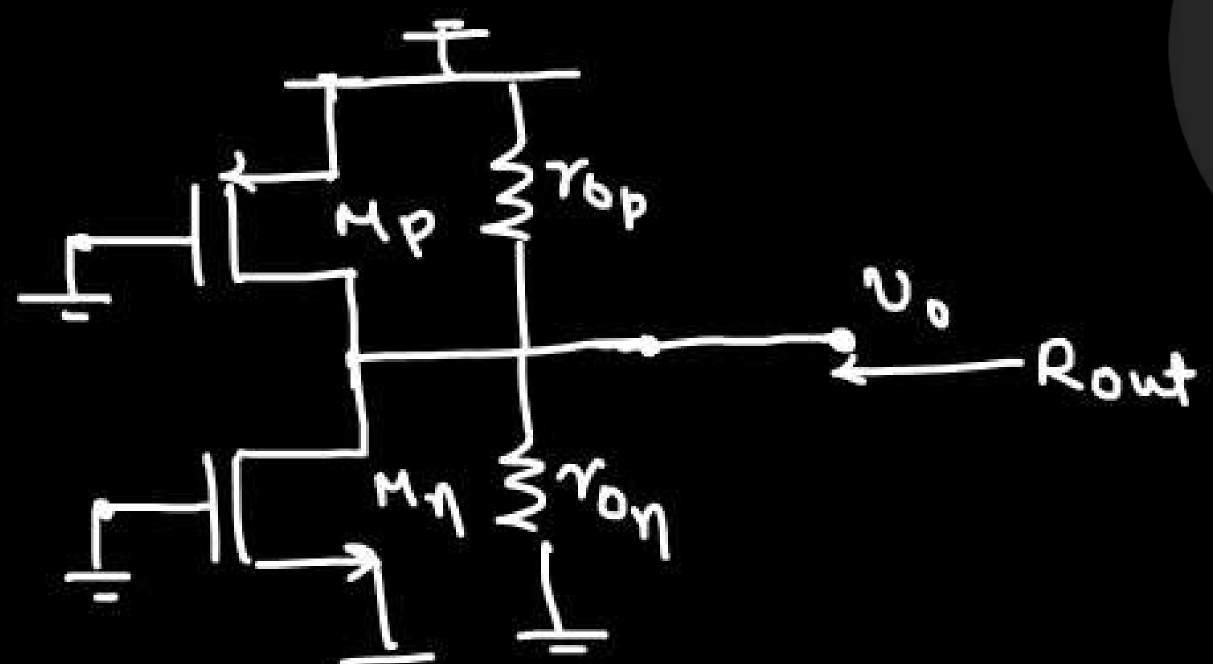
$$v_{o2} = -g_{mn} (r_{op} \| r_{on}) v_{in} \quad \text{—} \quad (2)$$

$$v_o = v_{o1} + v_{o2}$$

$$v_o = -(g_{m_p} + g_{m_n})(r_{op} \| r_{on})\, v_{in}$$

$$\boxed{\frac{v_o}{v_{in}} = -(g_{m_p} + g_{m_n})(r_{op} \| r_{on})}$$ ANS

O/P impedance:-



$$\boxed{R_{out} = r_{op} \| r_{on}}$$

Q. For a n-channel enhancement type MOS,

$$W/L = 10$$

$$\mu_n C_{ox} = 1\,mA/V^2$$

$$V_T = 1V$$

$$V_{GS} = 2 - \sin(2t)\ V$$

$$V_{DS} = 1V$$

max^m value of drain to source current = ?

(a) 40 mA (b) 20 mA

(c) 15 mA (d) 5 mA

→ $V_{GS} = 2 - \sin(2t)\ V \quad \{1 < V_{GS} < 3\}$

$\boxed{V_{DS} = 1V}$

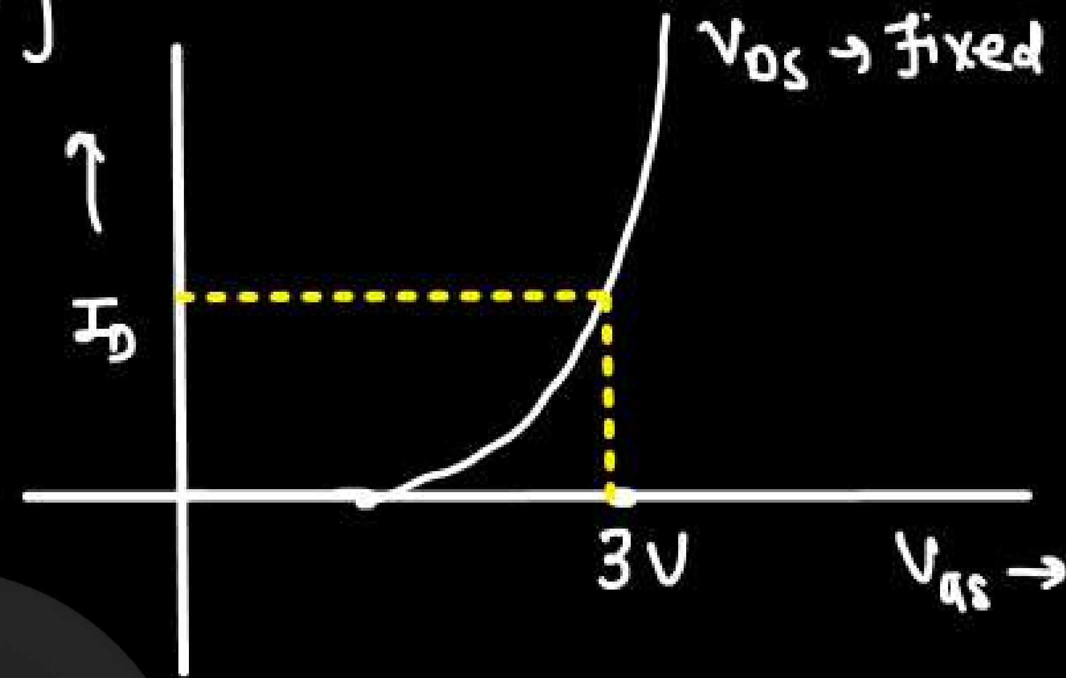
more $V_{GS} \Rightarrow$ more I_D

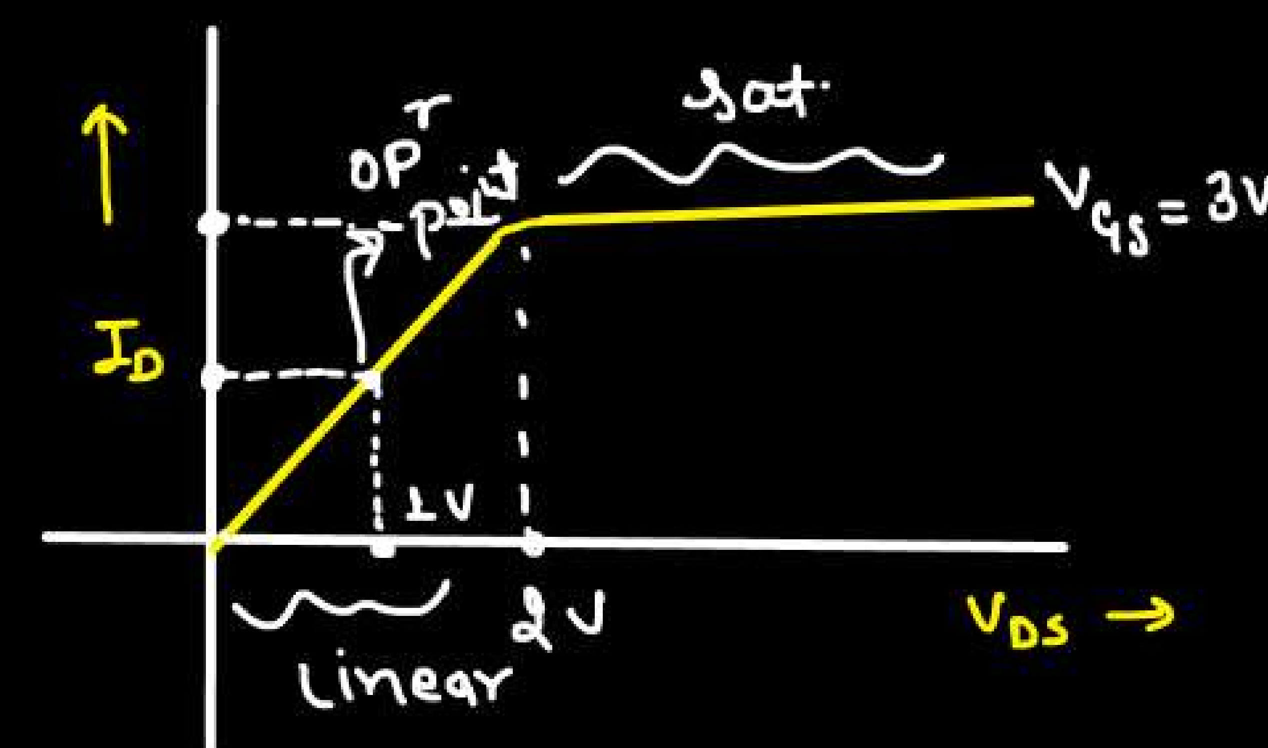
$(I_D)_{max} = ?$

@ $(V_{GS})_{max} \Rightarrow (I_D)_{max}$

$(V_{GS})_{max} = 2 - (-1) = 3V$

$\boxed{(I_D)_{max} = \frac{1m \times 10}{2}(3-1)^2 = 20mA}$ X





$$(V_{GS})_{max} = 3V$$

$$V_{DS} = 1V$$

$$V_T = 1V$$

$$V_{OV} = 3-1 = 2V$$

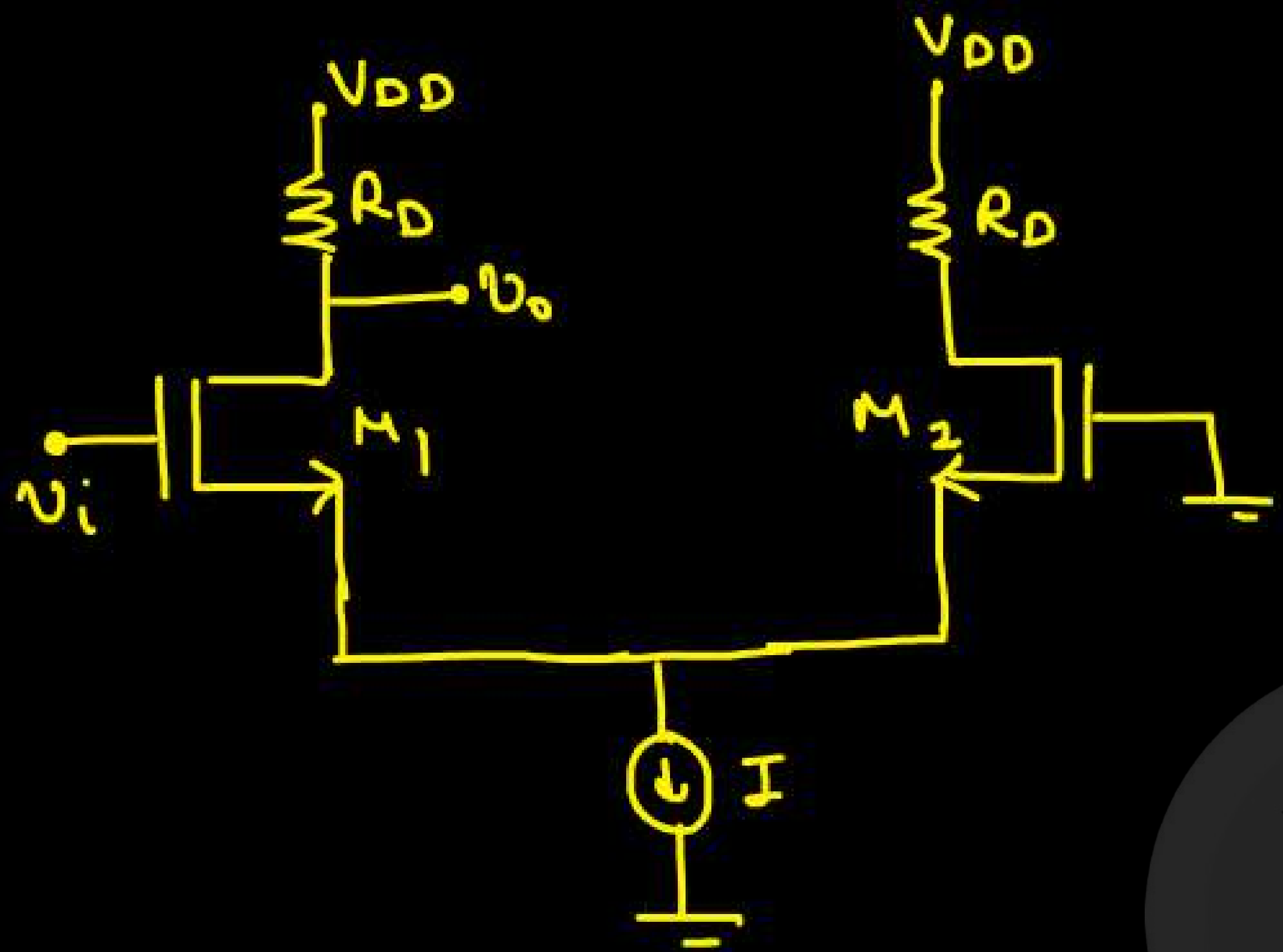
$V_{DS} < V_{OV} \Rightarrow$ MOS is working in linear region for max V_{GS}

$$(I_D)_{max} = 10m\left[(2)(1) - \frac{1^2}{2}\right]$$

$$\boxed{(I_D)_{max} = 15mA}$$

Ans.

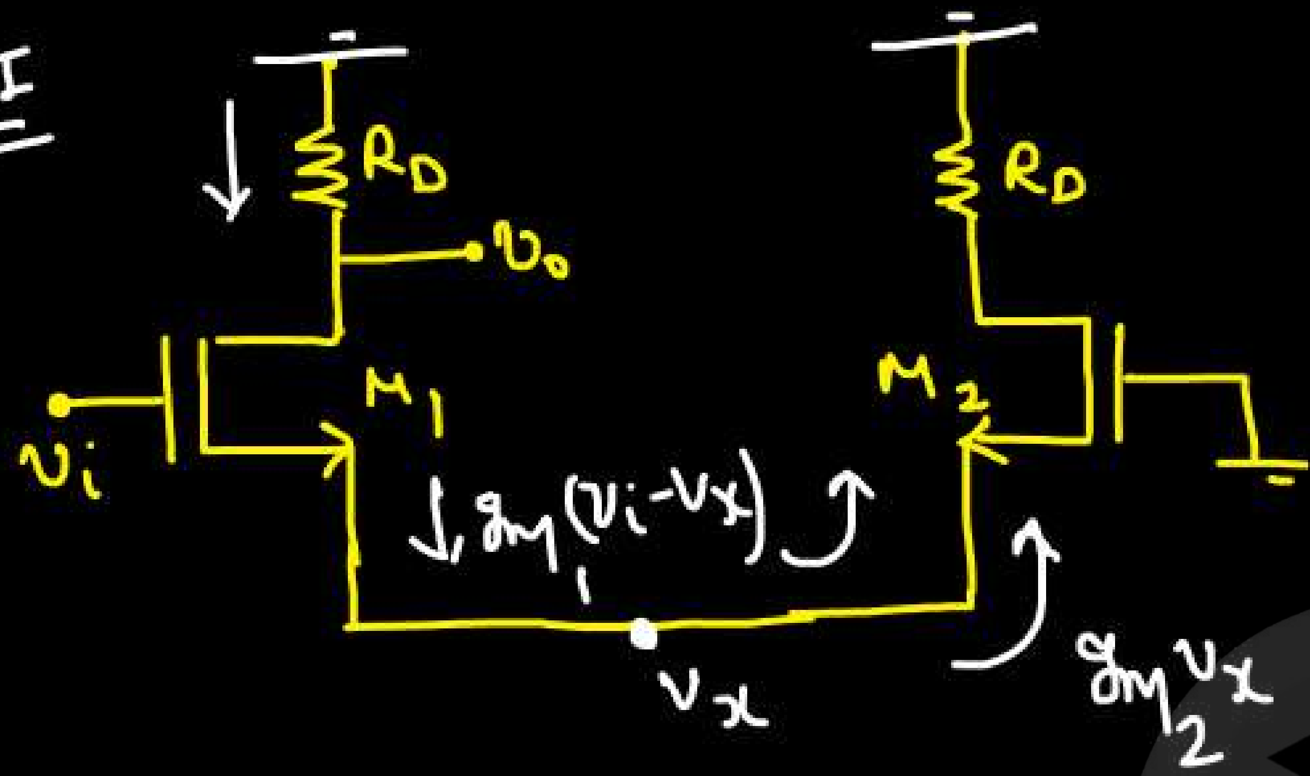
Q.



Take $\lambda = 0$

Find small signal voltage gain $\frac{v_o}{v_i}$.

→ M-I



$$\frac{v_o}{v_i} = ?$$

$$g_{m_1}(v_i - v_x) = g_{m_2} v_x$$

$$\boxed{v_x = \frac{g_{m_1}}{g_{m_1} + g_{m_2}} v_i}$$

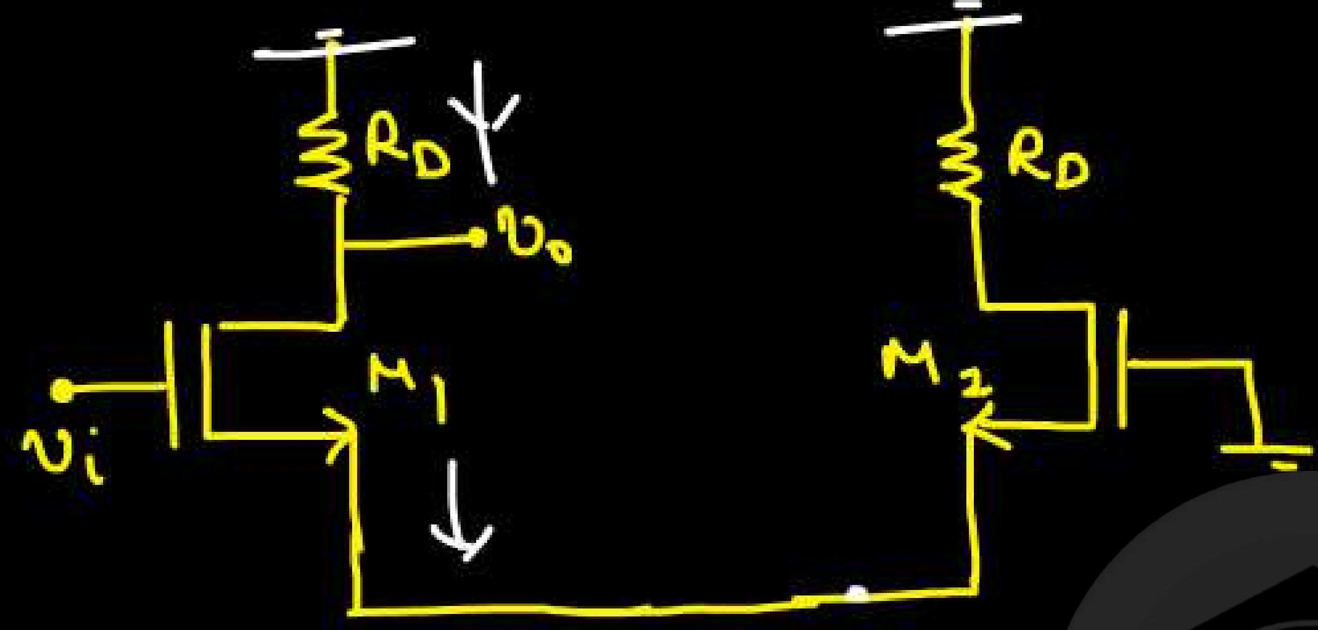
$$v_o = -g_{m_1} R_D (v_i - v_x)$$

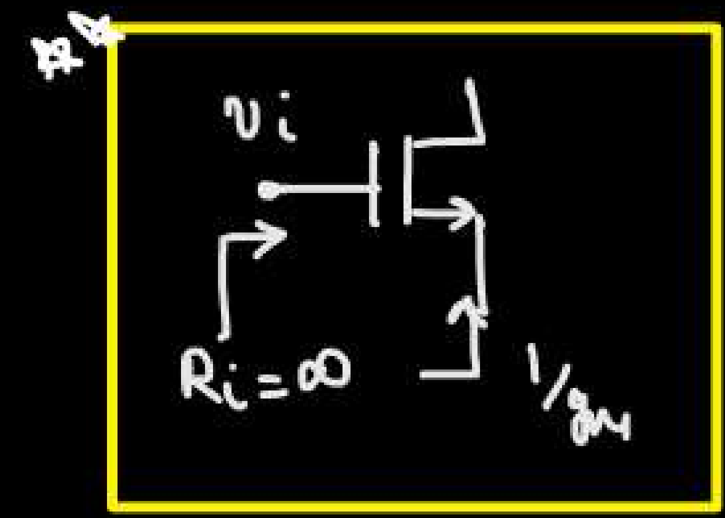
$$v_o = -g_{m_1} R_D \left(v_i - \frac{g_{m_1}}{g_{m_1} + g_{m_2}} v_i \right)$$

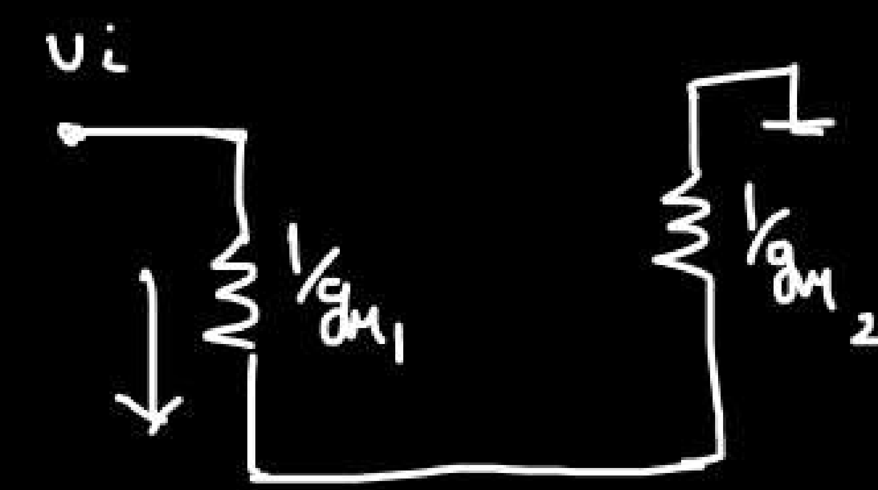
$$v_o = -g_{m_1} R_D \left[\frac{g_{m_2}}{g_{m_1} + g_{m_2}} \right] v_i$$

$$\boxed{\frac{v_o}{v_i} = \frac{-g_{m_1} g_{m_2}}{g_{m_1} + g_{m_2}} R_D}$$

M - II





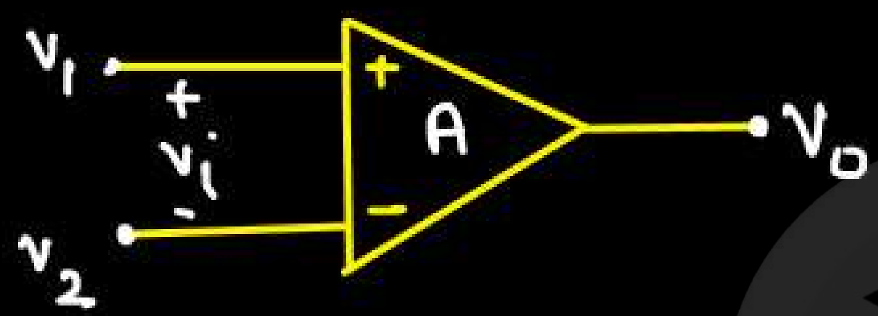


$$-\frac{v_i}{\frac{1}{g_{m_1}}+\frac{1}{g_{m_2}}}R_D = v_o$$

$$\boxed{\frac{v_o}{v_i} = \frac{-g_{m_2}g_{m_1}}{g_{m_2}+g_{m_1}}R_D}$$

⇒ Building 2-stage OP-Amp:-

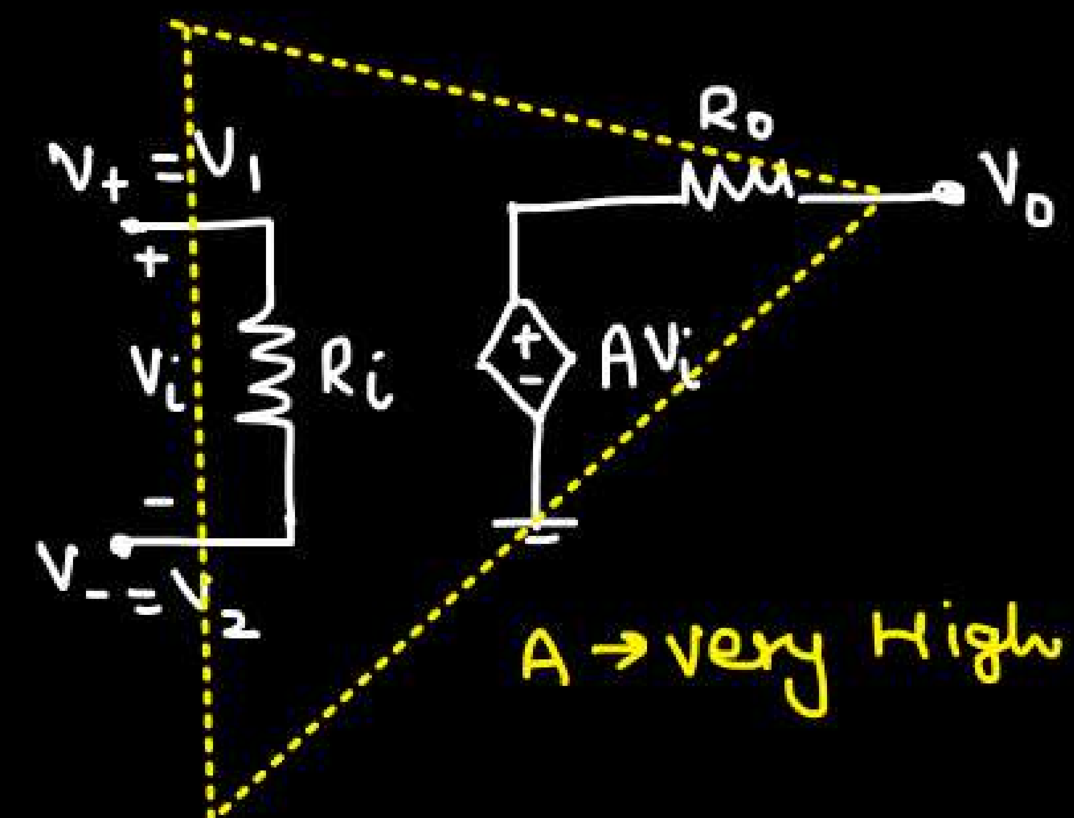
★ **What is OP-Amp?** (operational Amplifier)



$$V_o = A(V_+ - V_-)$$

$$V_o = A(V_1 - V_2)$$

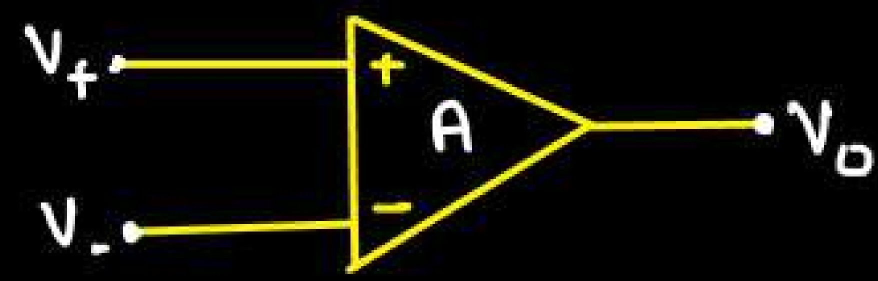
$$\boxed{V_o = \underbrace{A}_{\text{High}} V_i}$$



$A \rightarrow$ very High

$R_i \rightarrow$ very High (∞)

$R_o \rightarrow$ very low (0)



$$V_o = A(V_+ - V_-)$$

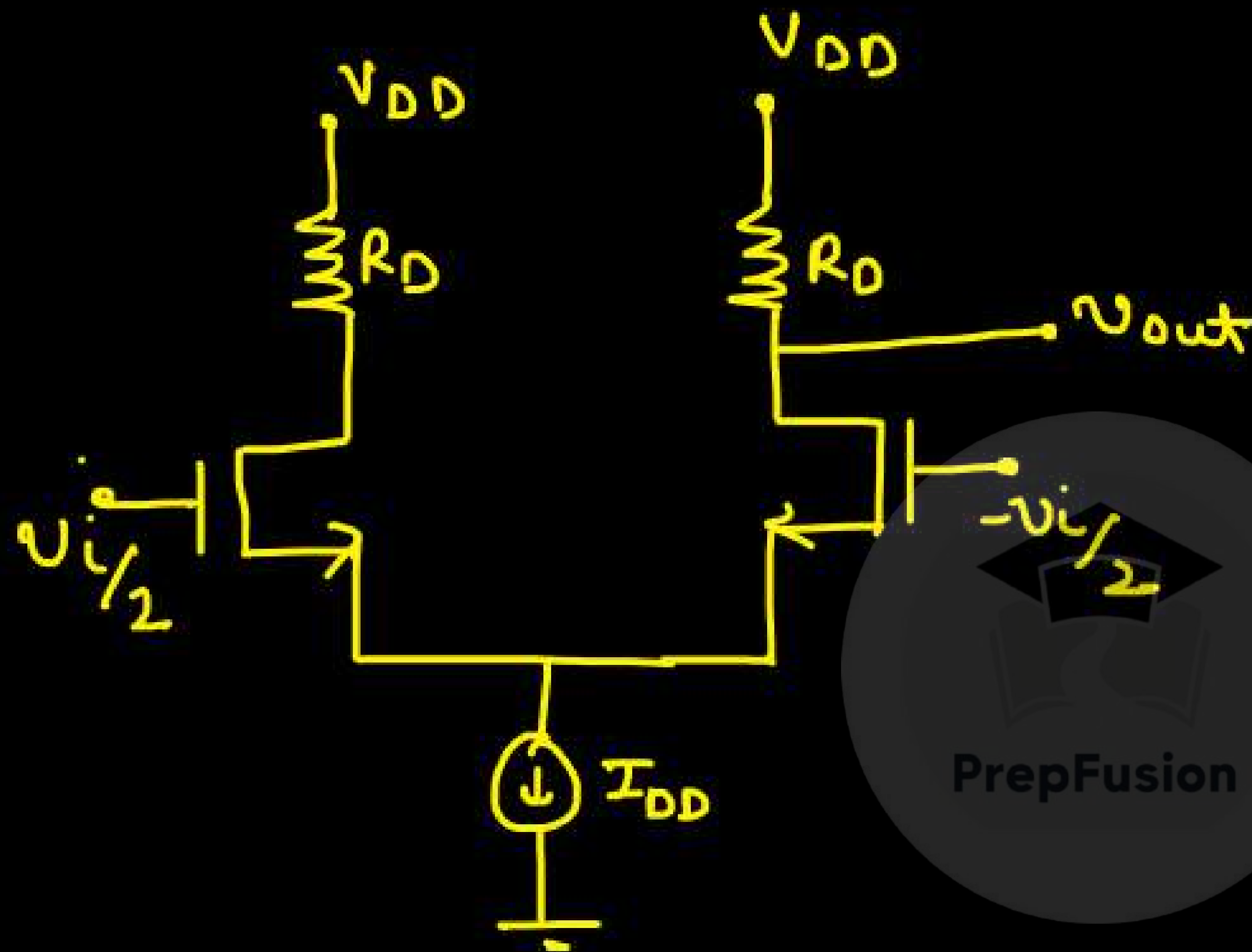
$$\boxed{\begin{array}{l} V_+ \uparrow \Rightarrow V_o \uparrow \\ V_- \uparrow \Rightarrow V_o \downarrow \end{array}}$$

Target :-

Desiging High input impedance, low o/p impedance and a High gain Amplifier.

(double ended i/p, single ended o/p)

⇒ What we have studied?

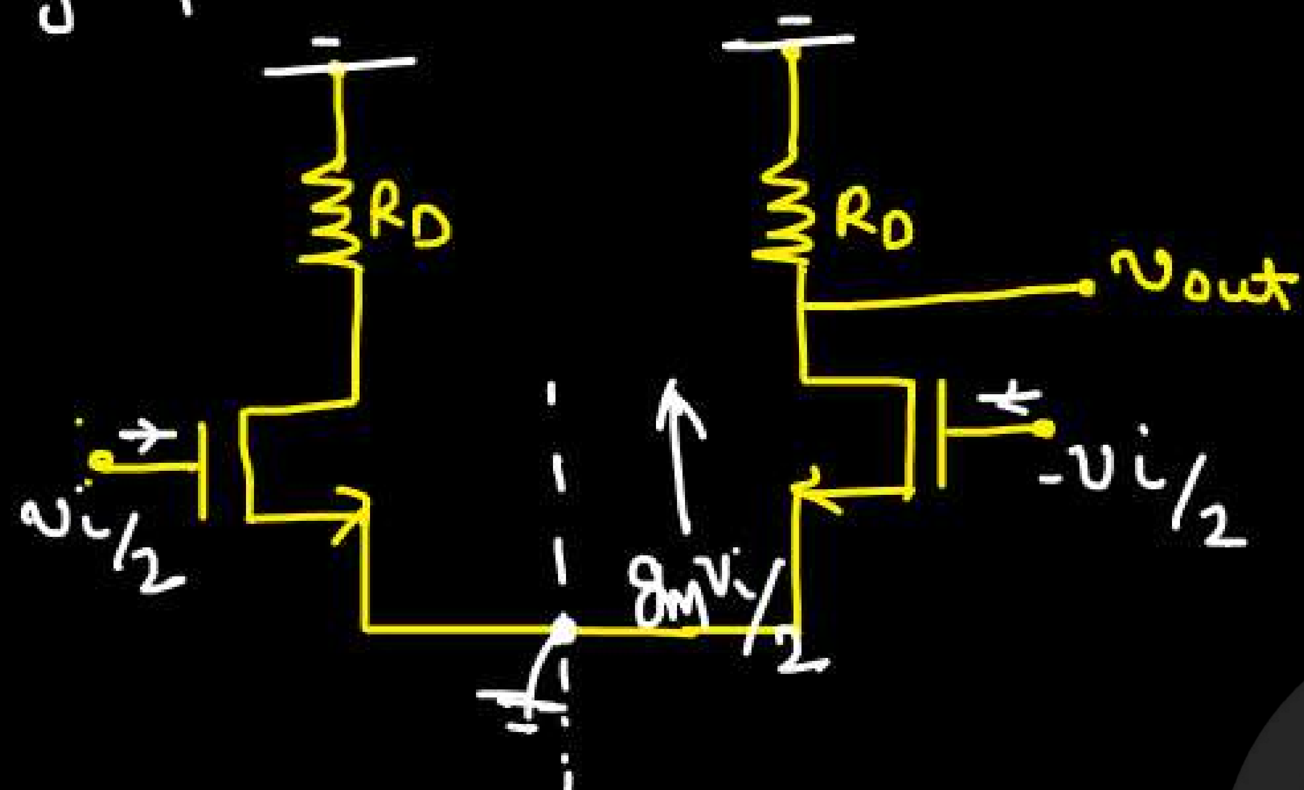


(i) gain = ? = $\frac{v_o}{v_i}$

(ii) i/p impedance = ?

(iii) o/p impedance = ?

(i) gain:-



$$v_0 = \frac{g_m v_i}{2} R_D$$

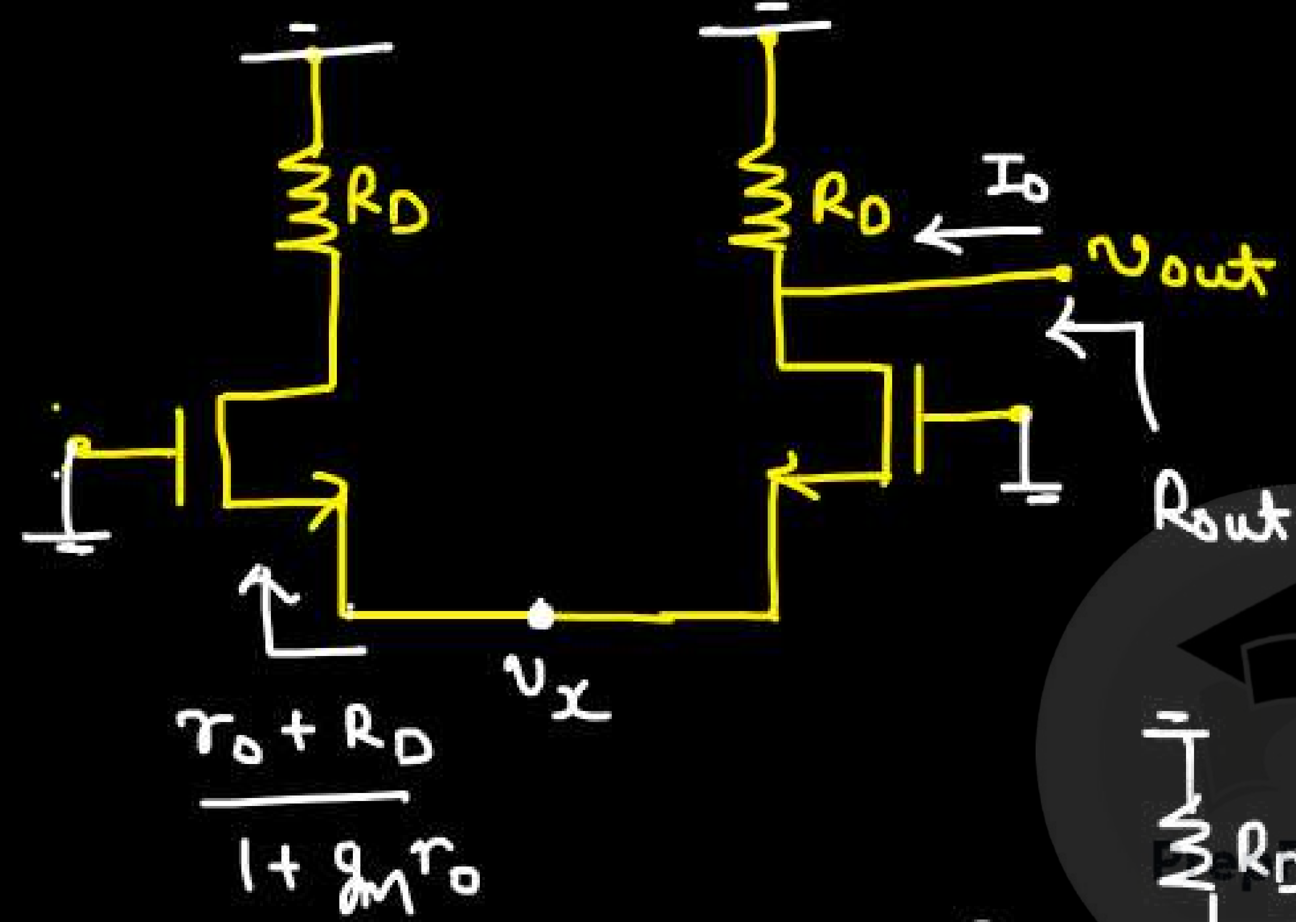
$$\boxed{\frac{v_0}{v_i} = \frac{g_m R_D}{2}}$$ $\Rightarrow$ NOT VERY High (X)

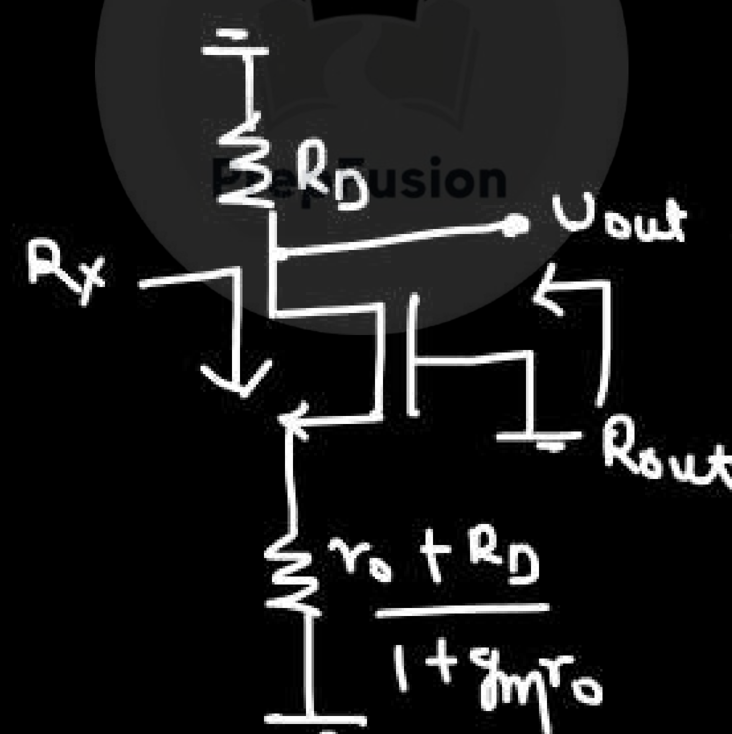
(ii) Input Impedance:-

$$\boxed{\frac{v_i}{I_i} = \frac{v_i}{0} = \infty}$$ $\Rightarrow$ High Input Impedance ($\checkmark$)

(iii) o/p impedance :-

(Let's take $\lambda \neq 0$)





$$R_x = g_m r_o \left(\frac{r_o + R_D}{1 + g_m r_o}\right) + r_o + \left(\frac{r_o + R_D}{1 + g_m r_o}\right)$$

$$= \frac{r_o + R_D}{1 + g_m r_o}\left[1 + g_m r_o\right] + r_o$$

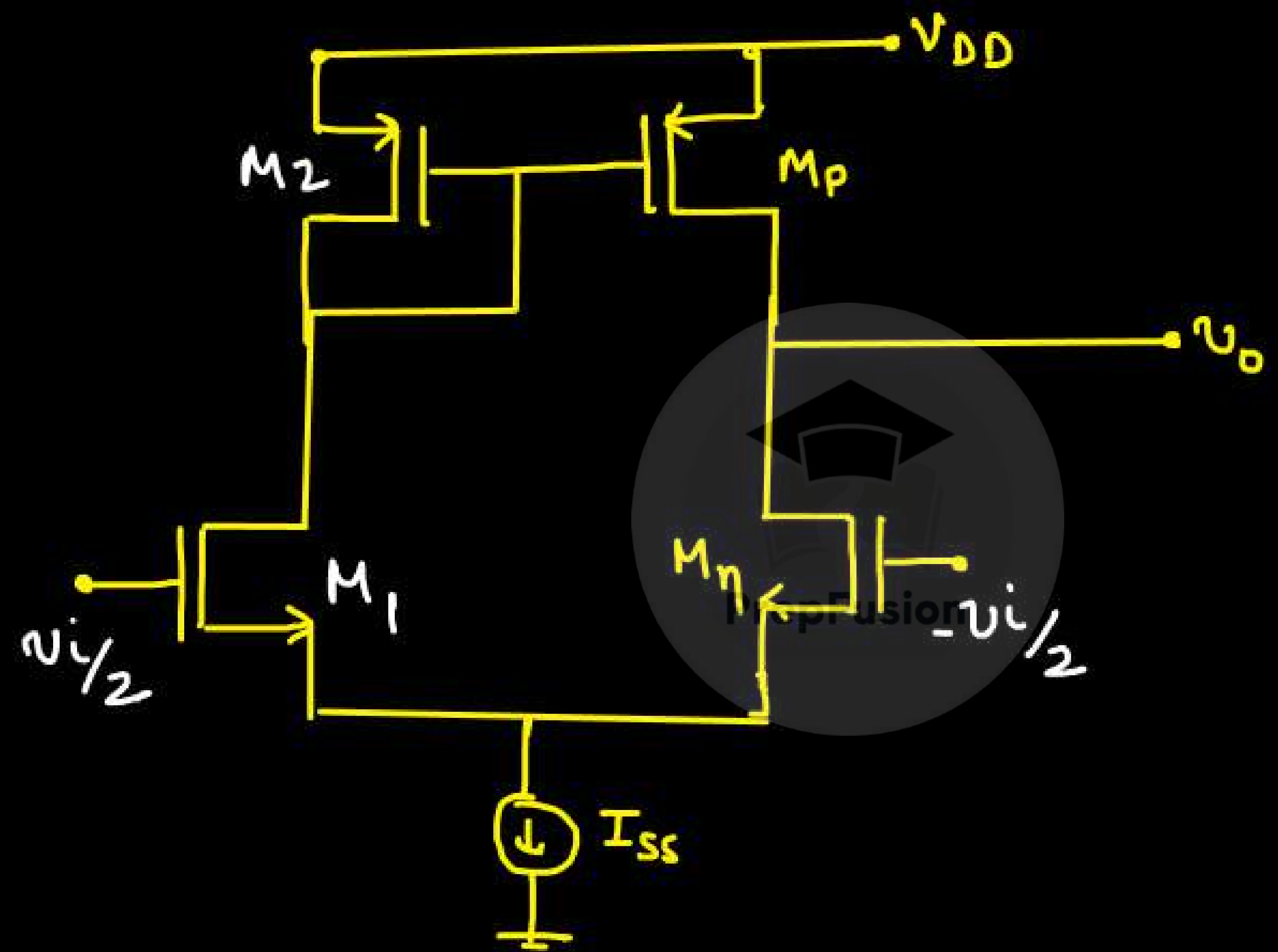
$$\boxed{R_x = 2r_o + R_D}$$

$$R_{out} = R_x \| R_D$$

$$\boxed{R_{out} = (2r_o + R_D) \| R_D}$$

$\approx R_D \Rightarrow$ low (✓)

Differential Amplifier with active load :-

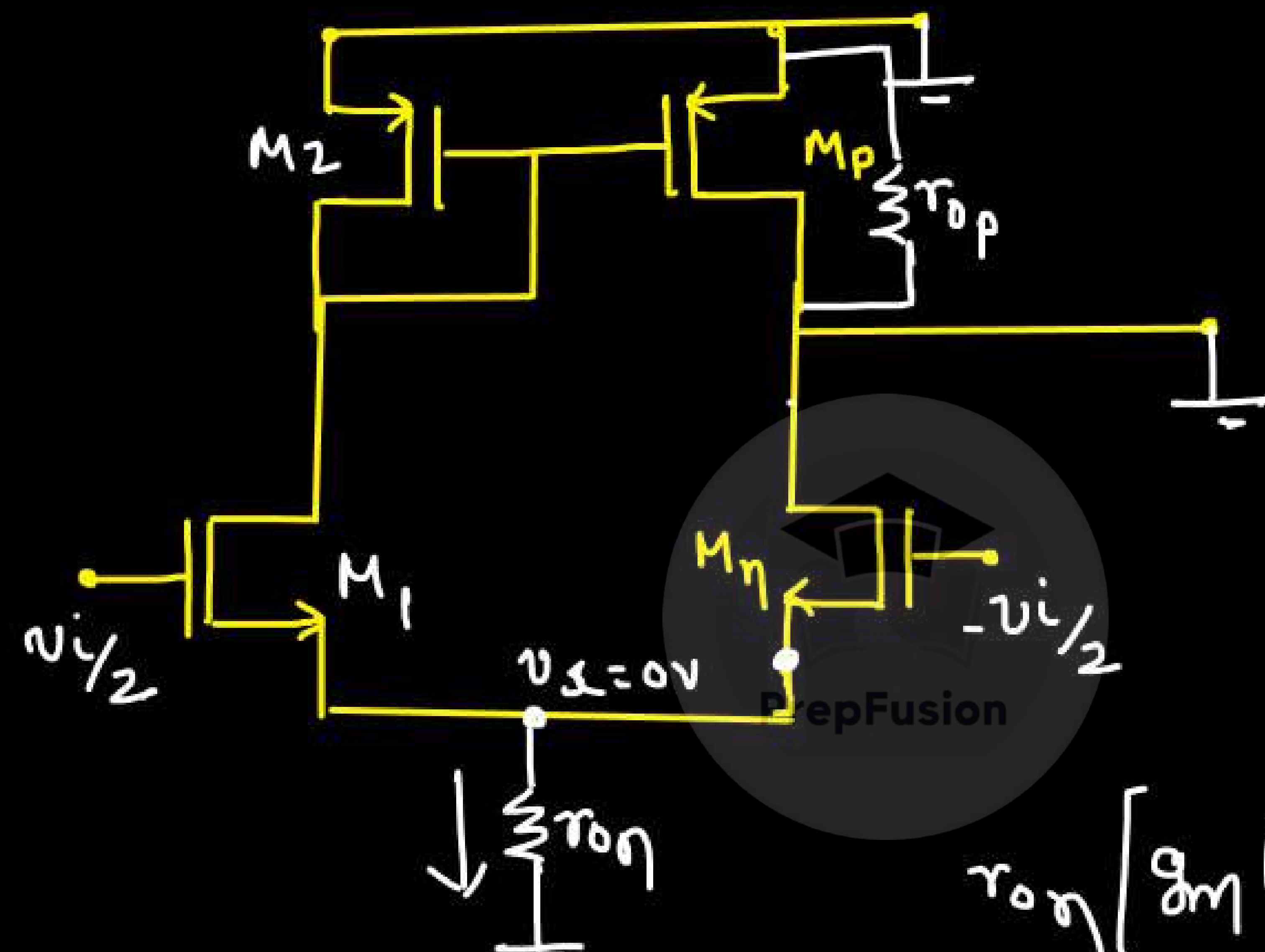


For ease of calculation, we will take $\lambda = 0$ for M_1 & M_2

$\lambda \neq 0$ for M_n & M_p

Voltage Gain:-

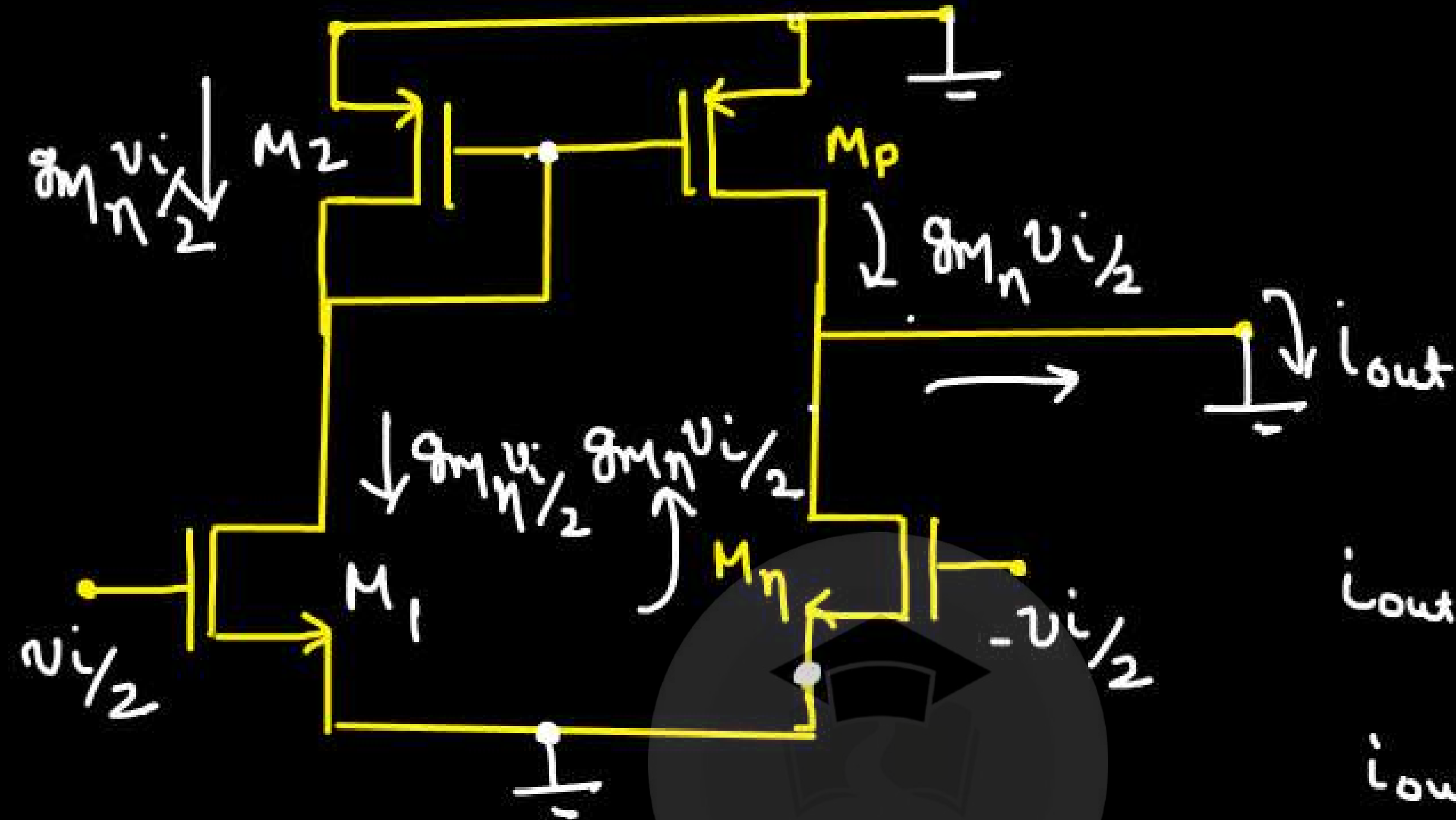
$G_m \rightarrow$



$$r_{on}\left[g_m\left(\frac{v_i}{2} - v_x\right) + g_m\left(\frac{-v_i}{2} - v_x\right)\right] = v_x$$

$$-2g_m r_{on} v_x = v_x$$

$$v_x\left[1 + 2g_m r_{on}\right] = 0 \Rightarrow \boxed{v_x = 0}$$

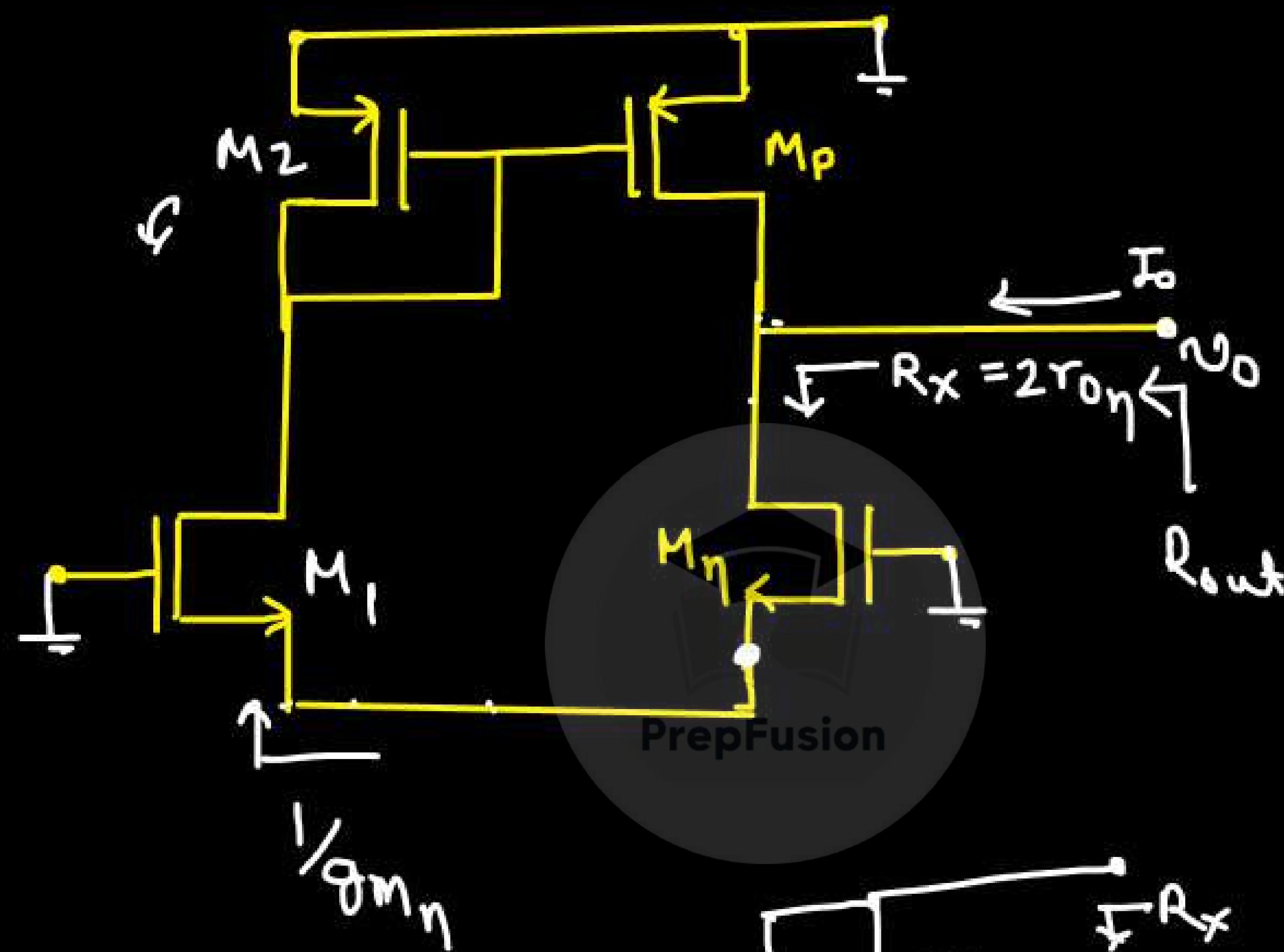


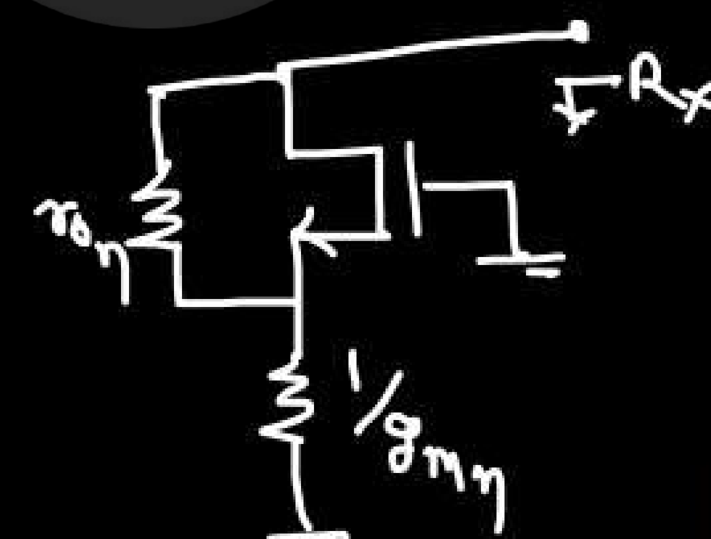
$$i_{out} = g_{m_n} v_i/2 + g_{m_n} v_i/2$$

$$i_{out} = g_{m_n} v_i$$

$$\boxed{G_m = g_{m_n}}$$

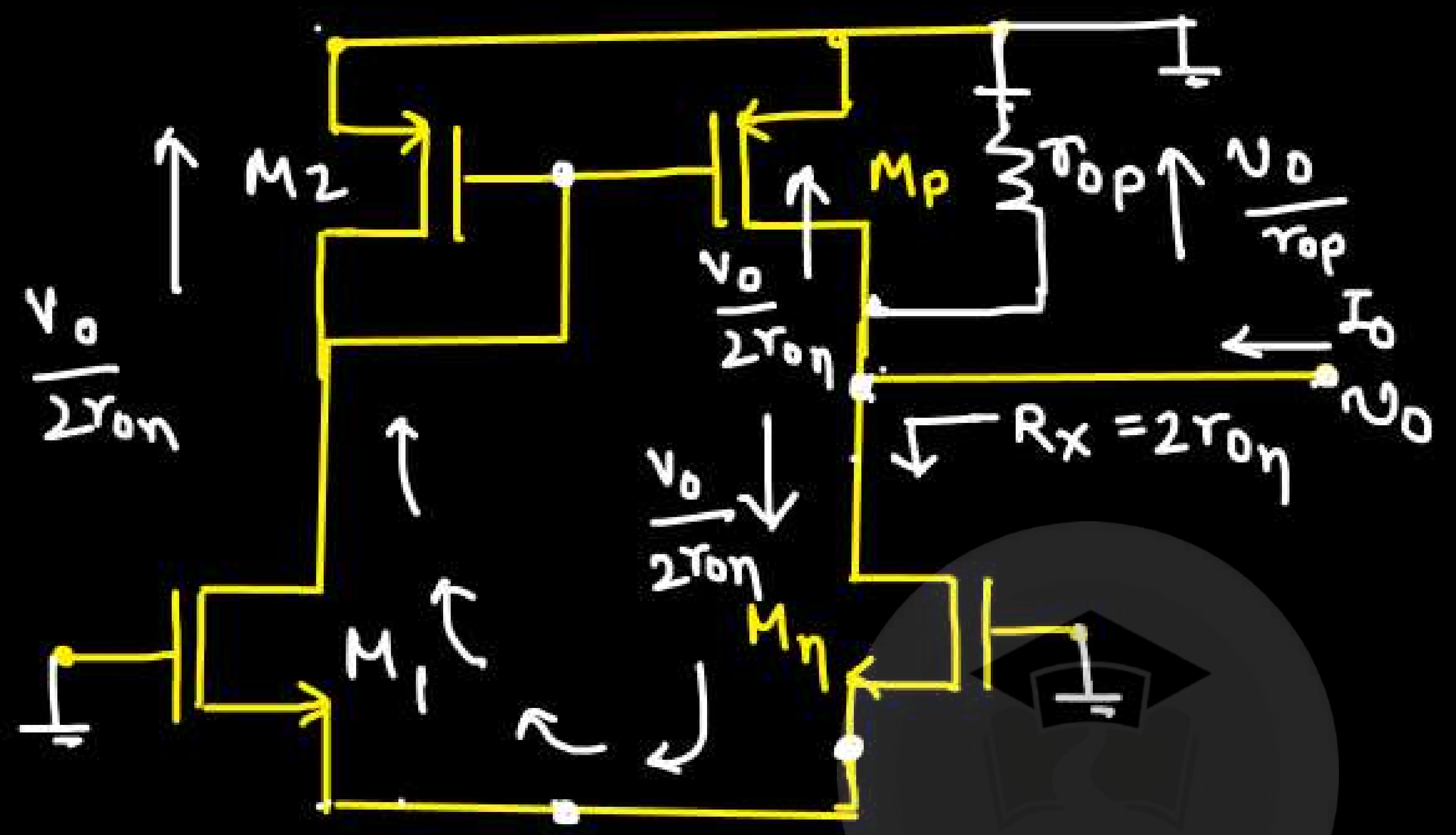
R_{out} :-





$$R_x = g_{m_n} r_{on} \times \frac{1}{g_{m_n}} + r_{on} + \frac{1}{g_{m_n}}$$

$$\boxed{R_x = 2r_{on} + \frac{1}{g_m} \approx 2r_{on}}$$



$$\frac{v_0}{r_{op}} + \frac{v_0}{2r_{on}} + \frac{v_0}{2r_{on}} = I_0 \Rightarrow \frac{v_0}{r_{op}} + \frac{v_0}{r_{on}} = i_0$$

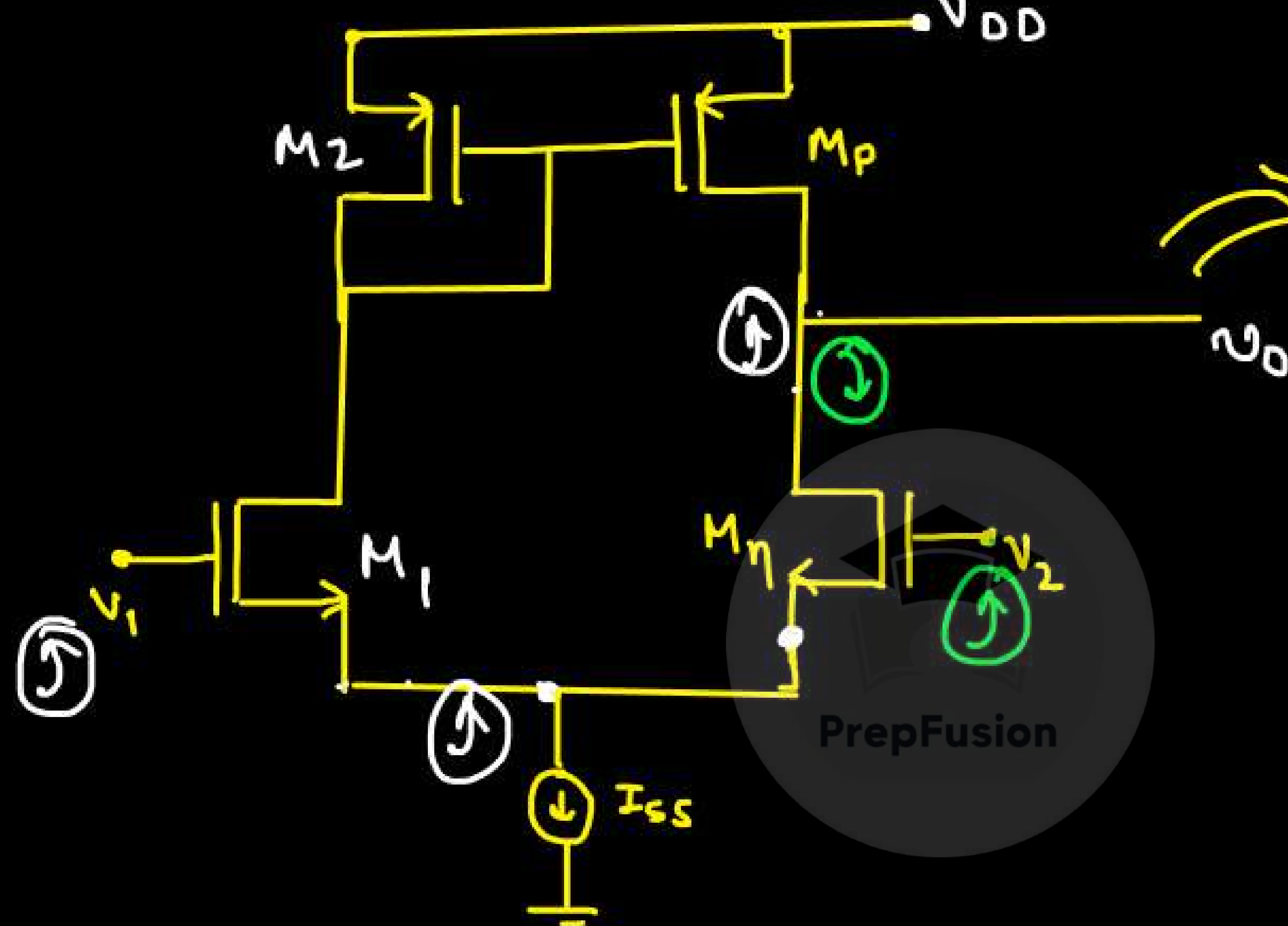
$$\boxed{\frac{v_0}{i_0} = R_{out} = r_{op} \| r_{on}}$$

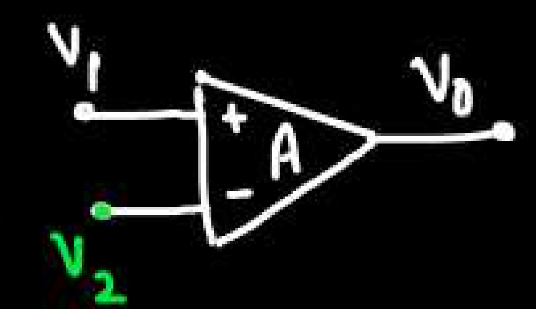
↝ High (NOT Desired)

$$\boxed{A_v = g_{m_n}\left(r_{op} \| r_{on} \right)} \Rightarrow \text{High (desired)}$$

Input impedance $\boxed{R_i = \infty} \Rightarrow$ High (desired)

$\boxed{\text{Matter of concern} \Rightarrow \text{o/p impedance}}$



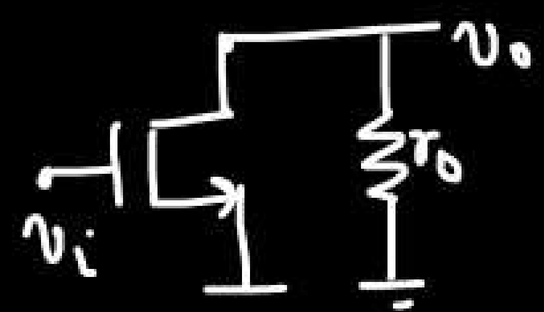


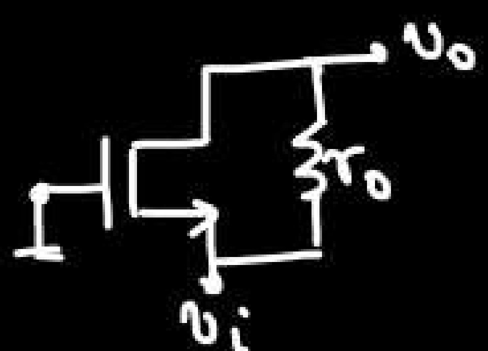
NOT An op-Amp

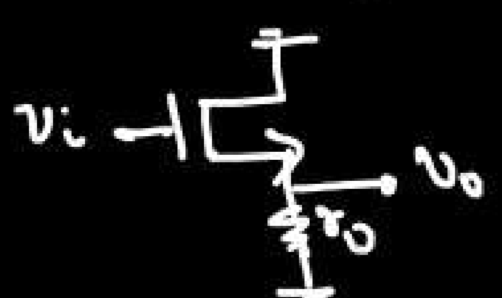
$V_1 \uparrow \Rightarrow v_0 \uparrow \Rightarrow V_1 = V_+$

$V_2 \uparrow \Rightarrow V_0 \downarrow \Rightarrow V_2 = V_-$

	Gain	o/p impedance
① Common Source	$-g_m r_o$	$r_o \rightarrow$ High
② Common Gate	$1 + g_m r_o$	$r_o \rightarrow$ High
③ Common drain	$\dfrac{g_m r_o}{1 + g_m r_o} \approx 1$	$r_o \parallel \dfrac{1}{g_m} \approx \dfrac{1}{g_m} \rightarrow$ low

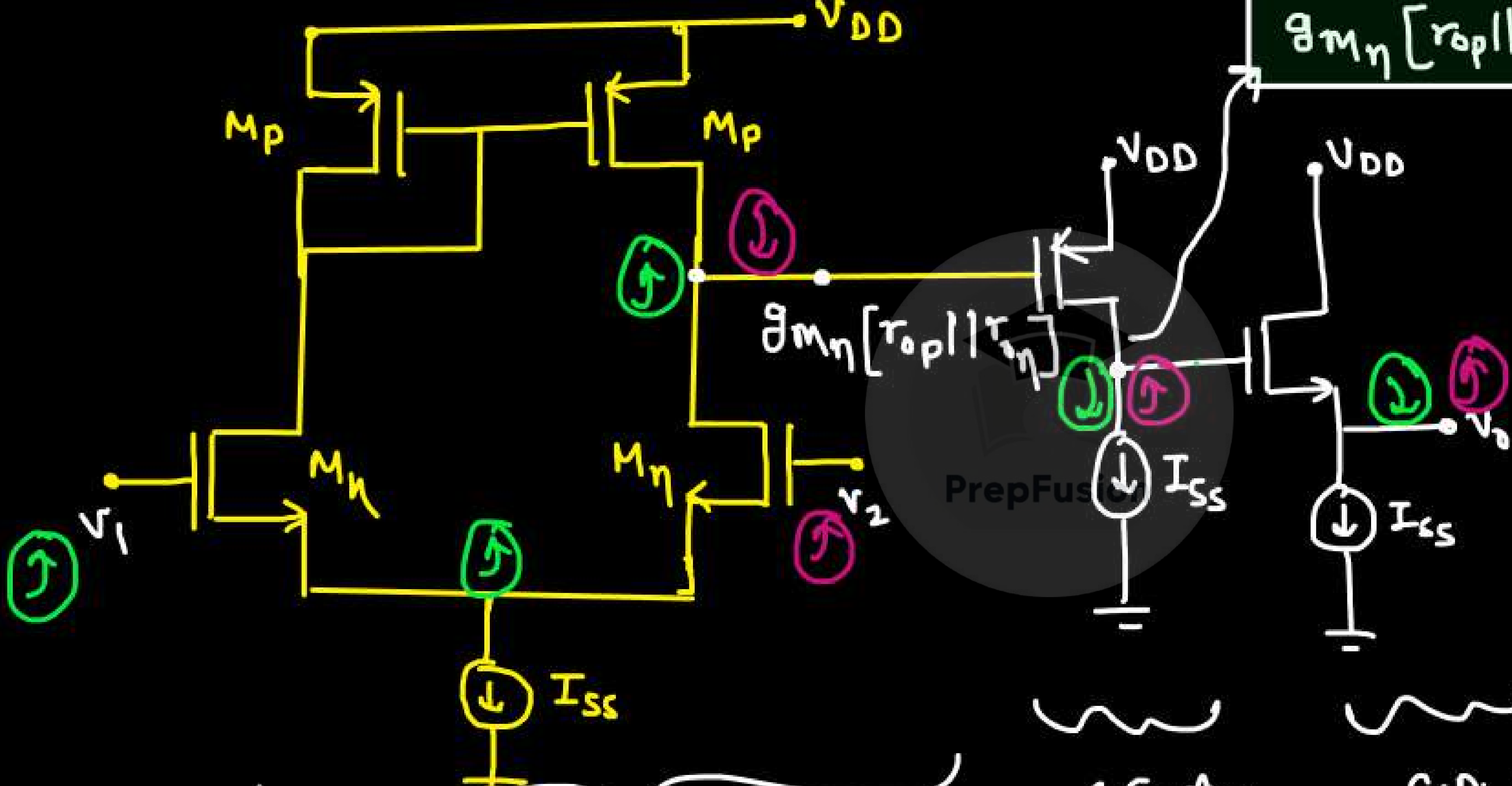






Gain =

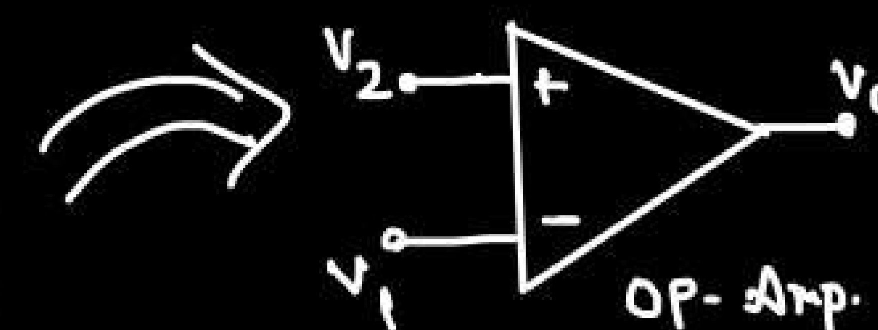
$g_{m_n}[r_{op} \| r_{on}] \times g_{m_p} r_{op}$



Diff. Amp with active load

C.S Amp. (To increase gain)

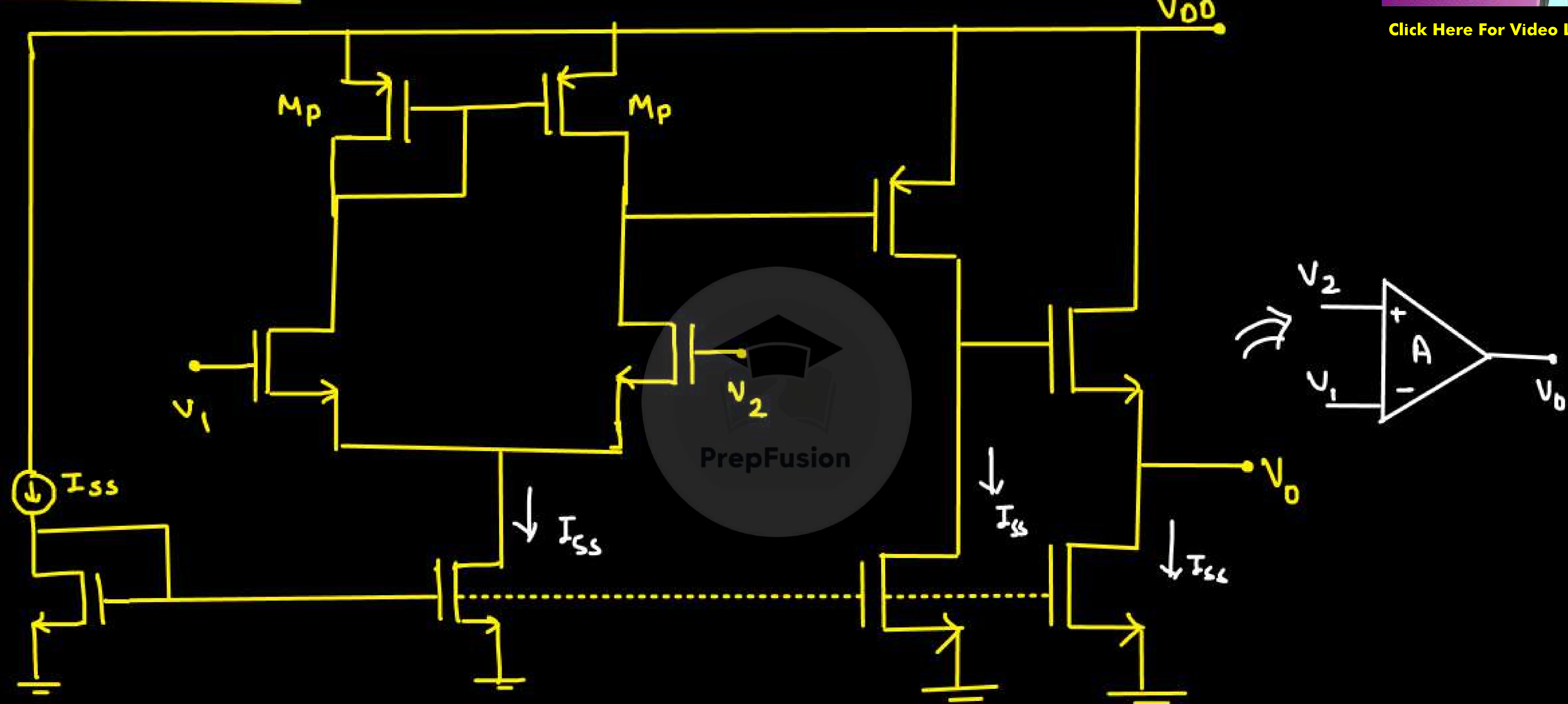
C.D. Amp. (lower o/p impedance)



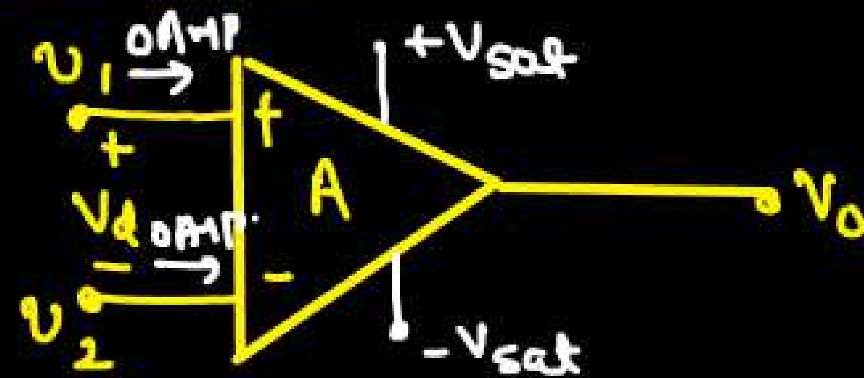
$R_{out} \approx 1/g_{m_n}$ (✓)

$R_{in} = \infty$ (✓)

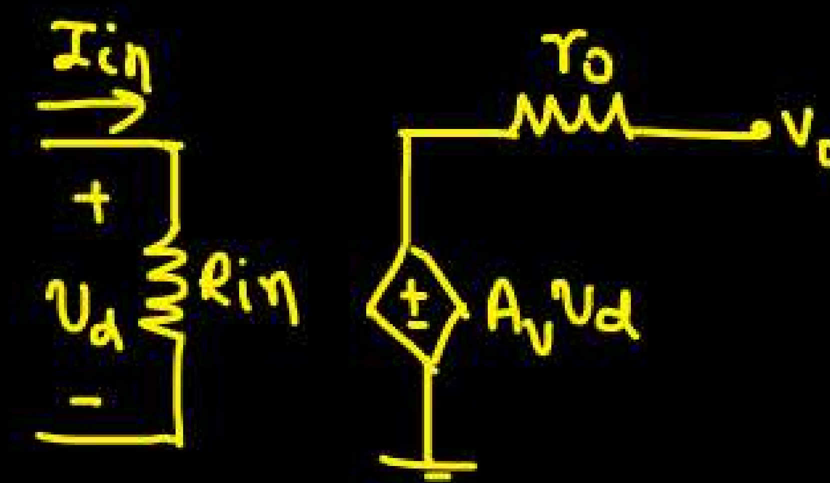
Final design:-



Some Basics of OP-Amp :-



⇒



$V_o = A V_d$

$-V_{sat} < V_o < +V_{sat}$

$-V_{sat} < A V_d < +V_{sat}$

$$\boxed{\frac{-V_{sat}}{A} < V_d < \frac{+V_{sat}}{A}}$$

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

$V_+ = V_1 \uparrow \Rightarrow V_o \uparrow$

$V_- = V_2 \uparrow \Rightarrow V_o \downarrow$

For an ideal op-amp ⇒

$R_{in} = \infty$
$I_{in} = 0$
$r_o = 0$
$A_v = \infty$

CMRR $= \infty$
slew rate $= \infty$

★ For an OP-Amp, O/P can never go above +ve Sat. voltage and can never go below -ve sat. voltage

Let, $A = 10^3\ V/V$; $\pm V_{sat} = \pm 5V$

(i) $V_d = 1\,mV$

$$V_0 = A V_d = 10^3 \times 1\,mV = 1V \ ✓$$

(ii) $V_d = -3\,mV$

$$V_0 = -3m \times 10^3 = -3V \ ✓$$

(iii) $V_d = -5\,mV$

$$V_0 = -5m \times 10^3 = -5V \ ✓$$

(iv) $V_d = 7\,mV$

$$V_0 = 7m \times 10^3 = 7V \ ✗ \Rightarrow 5V \ ✓$$

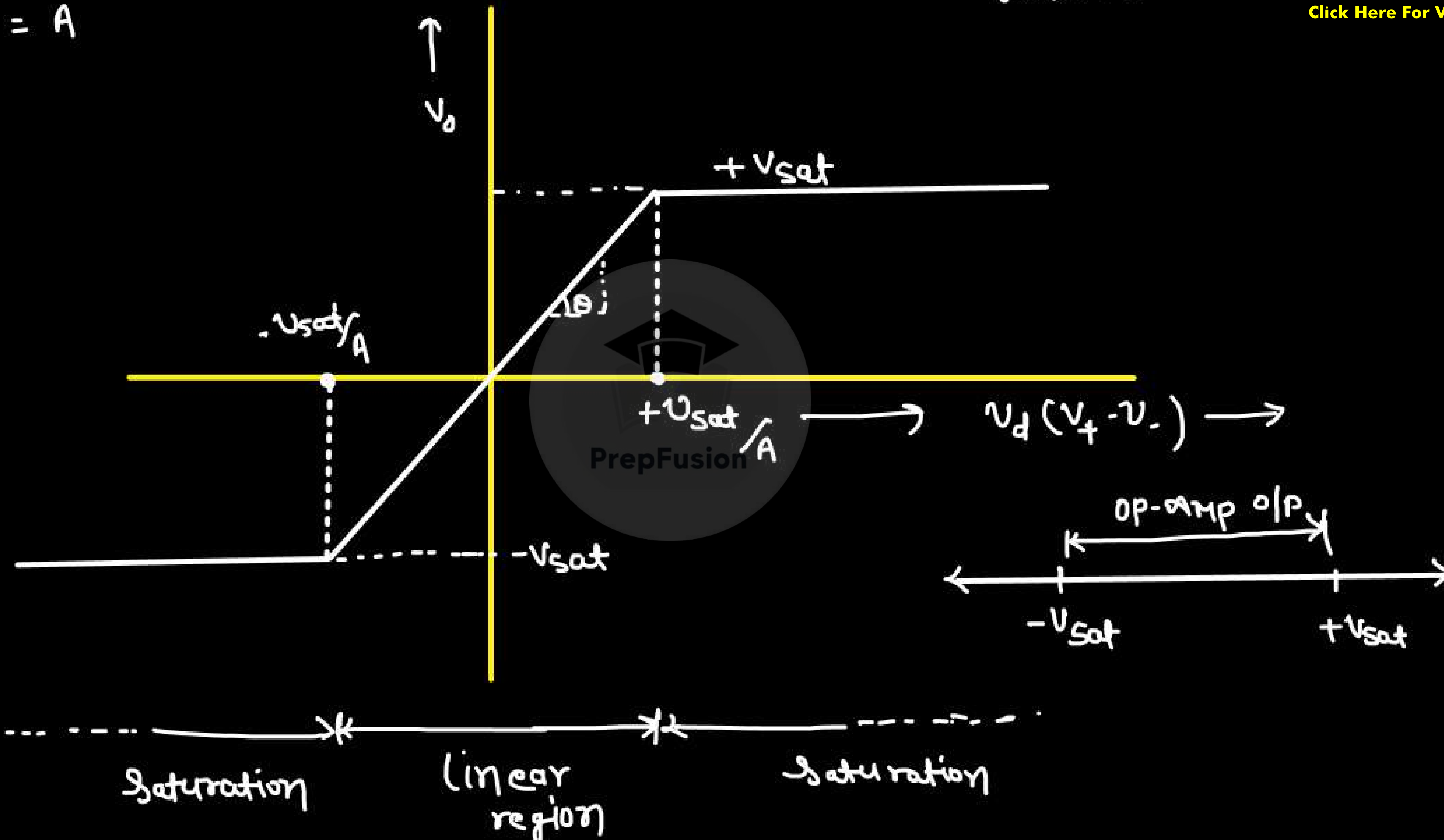
(v) $V_d = -6\,mV$

$$V_0 = -6m \times 10^3$$
$$= -6V \ ✗$$
$$\Rightarrow -5V$$

$$v_0 = A v_d$$

$$\frac{v_0}{v_d} = A$$

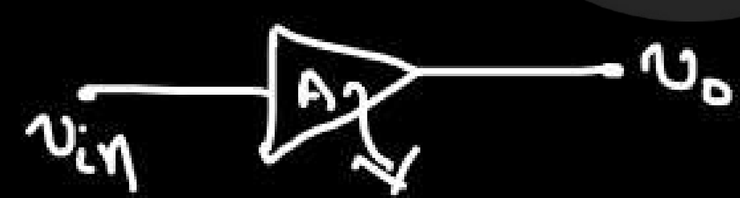
$$\tan\theta = A$$



Feedback :-

Taking a fraction of the o/p of an amplifier and connecting it back to the i/p. This fed-back signal can be connected in a way that it either adds to the normal input or subtracts from it.

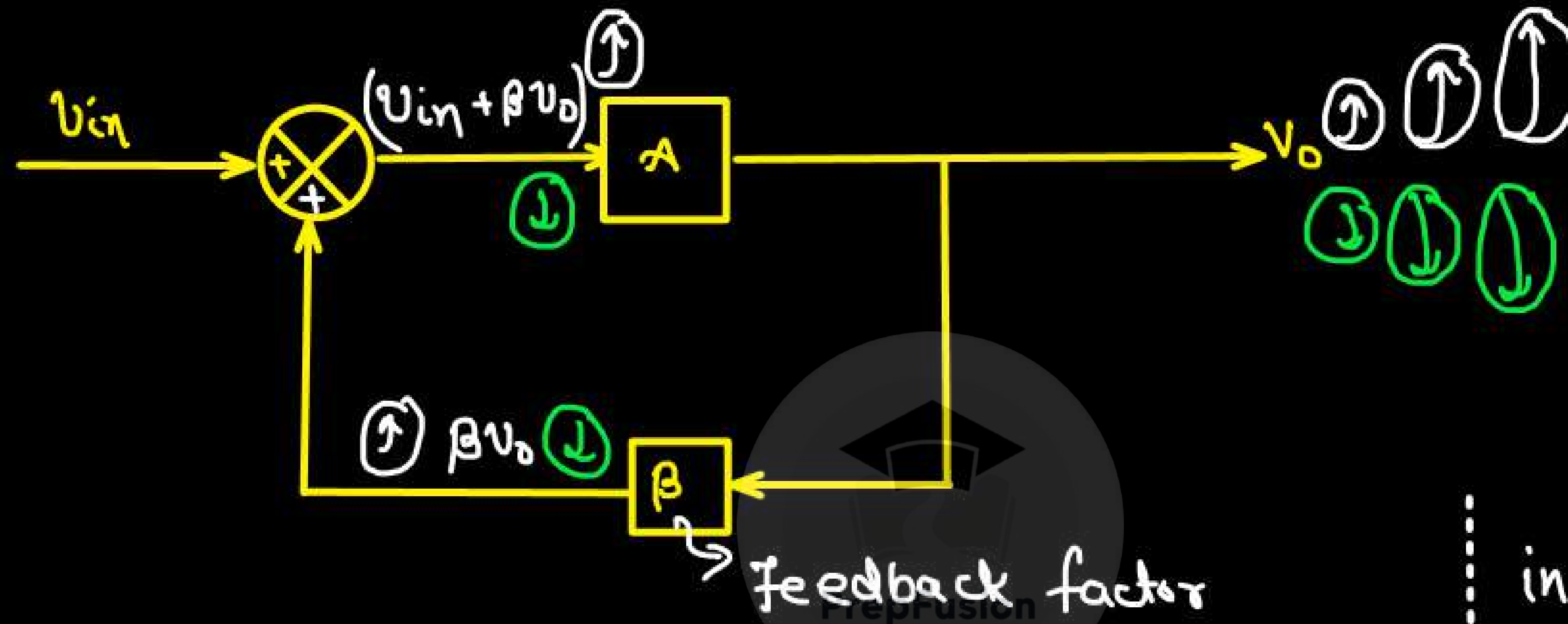
System w/o any feedback :-



open loop gain

$$v_o = A v_{in}$$

① Positive feedback :-



$$v_o = A(v_{in} + \beta v_o)$$

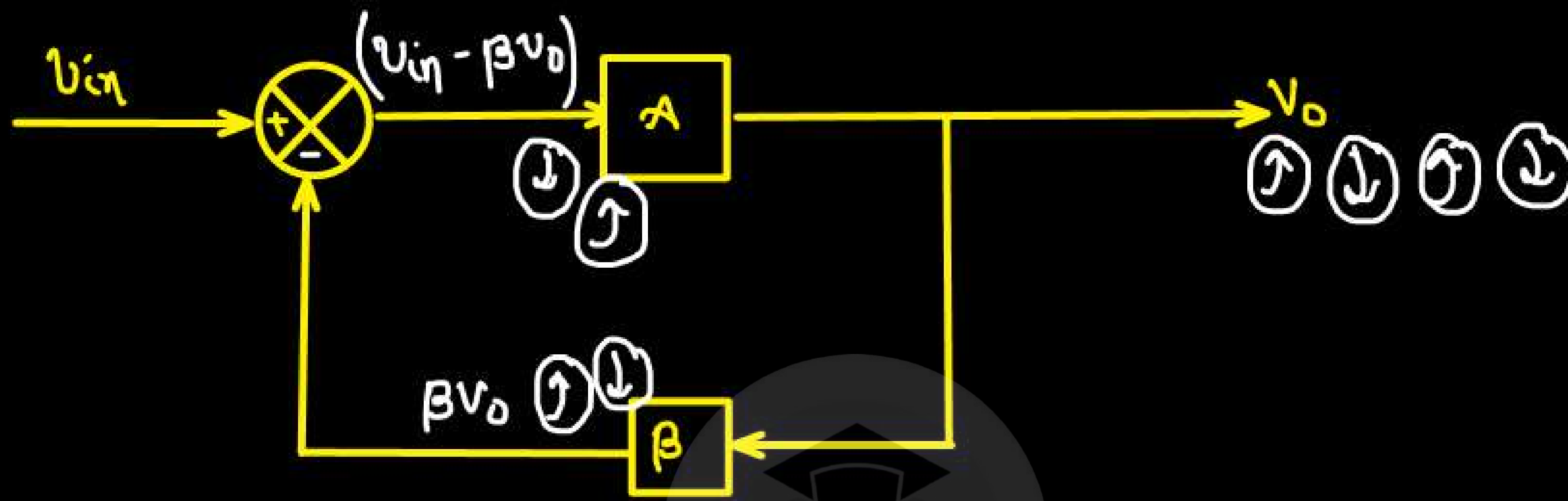
$$v_o - A\beta v_o = A v_{in}$$

$$\boxed{\frac{v_o}{v_{in}} = \frac{A}{1-A\beta}}$$ → Closed loop gain

in positive f/b, if o/p increases, then it keeps on increasing and results in unstable o/p.

Positive f/b s/s are unstable.

② Negative feedback:-



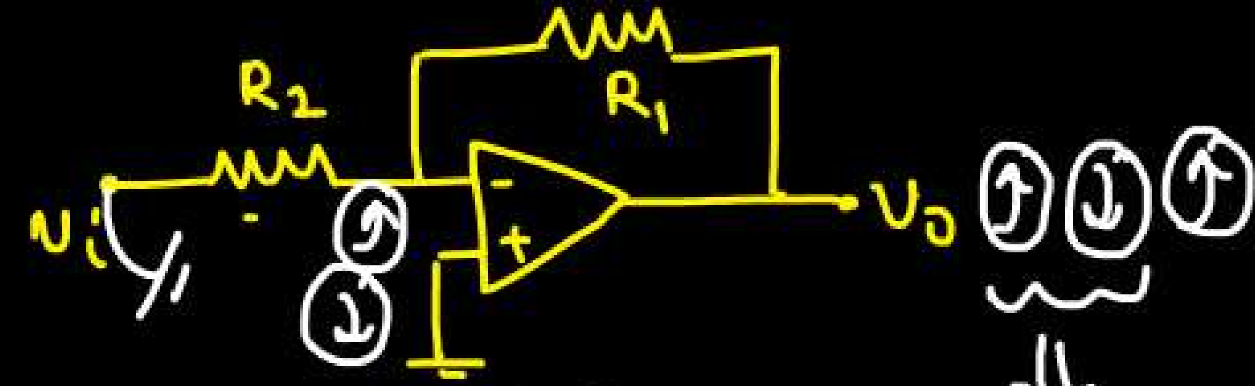
$$(v_{in} - \beta v_0)A = v_0$$

$$\boxed{\frac{v_0}{v_i} = \frac{A}{1+A\beta}}$$ → closed loop gain

in negative f/b, you get a stable o/p.

Eg →

1



(a)

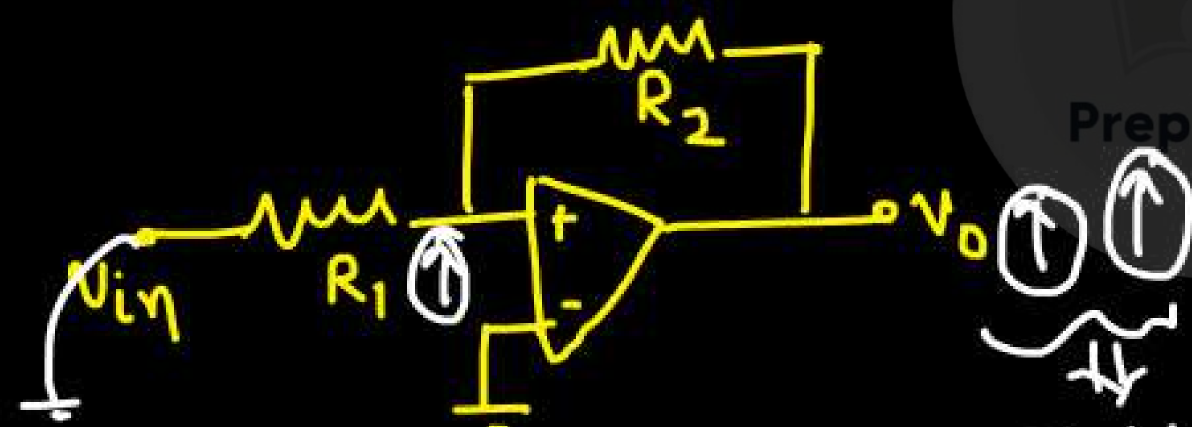
⇓

Negative f/b

$$v_0 = A(v_+ - v_-)$$

when you check the type of f/b, Nullify the i/p

2



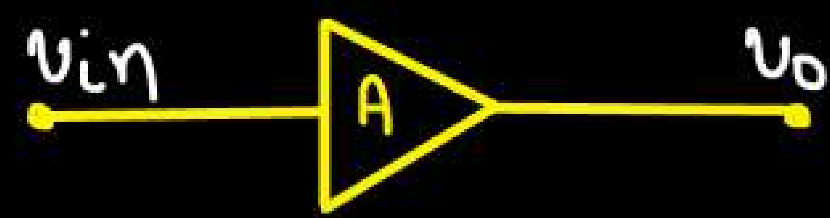
⇓

Positive f/b

$$v_0 = A(v_+ - v_-)$$

★ Advantages of feedback:-

1. Gain stability:-



open-loop

$v_o = A v_{in}$

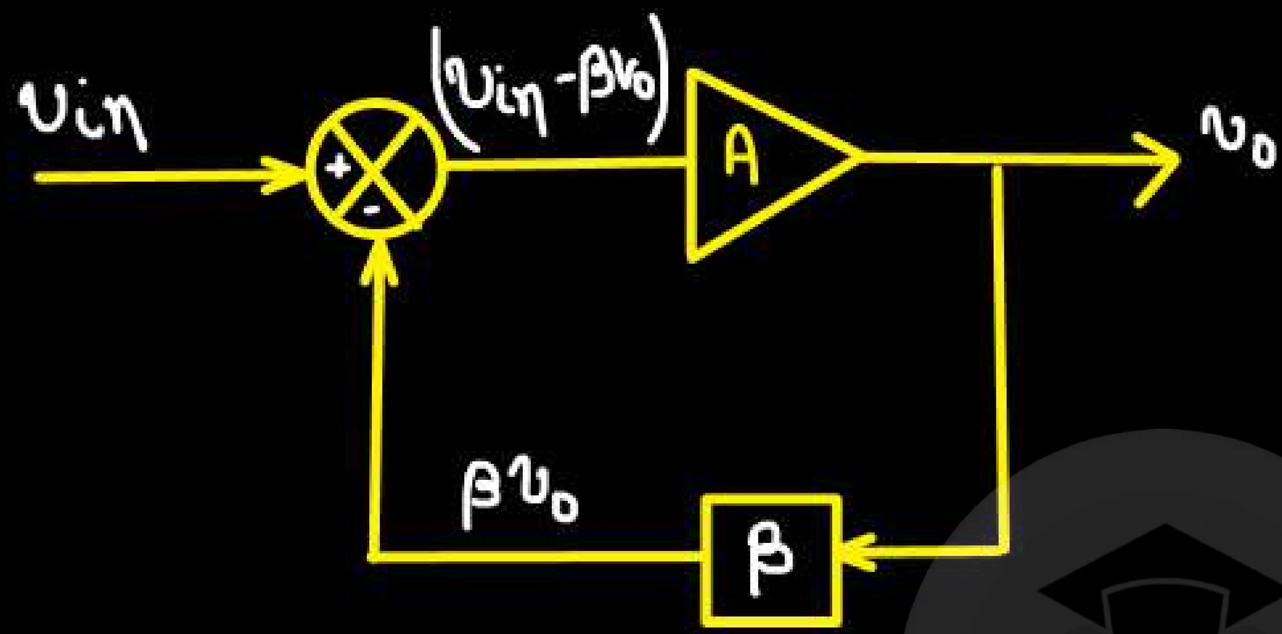
Let's assume, your gain $A = 10^3 \to 10^4$

Let; $v_{in} = 1mV$

$v_o = A v_{in}$

$= 1V \to 10V$

Introducing negative f/b :-



$$v_0 = A(v_{in} - \beta v_0)$$

$$\frac{v_0}{v_{in}} = \frac{A}{1 + A\beta}$$

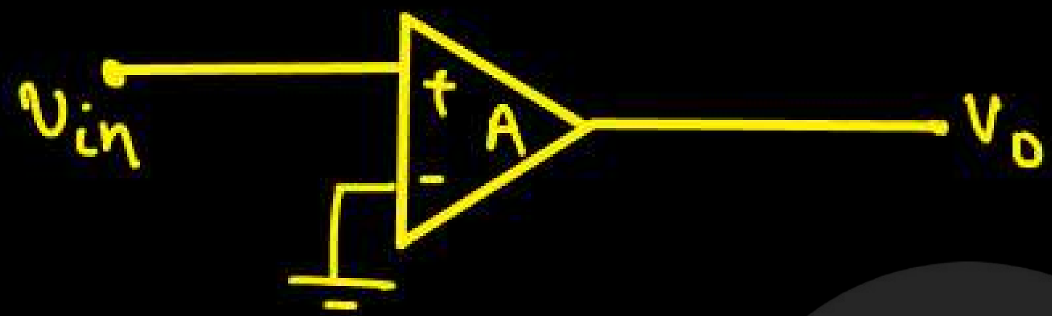
β is designed such that $A\beta >> 1$

$$\boxed{\frac{v_0}{v_{in}} \approx \frac{A}{A\beta} \approx \frac{1}{\beta}} \Rightarrow \text{constant}$$

$\Rightarrow$ Here you are getting a constant gain.

Example:-

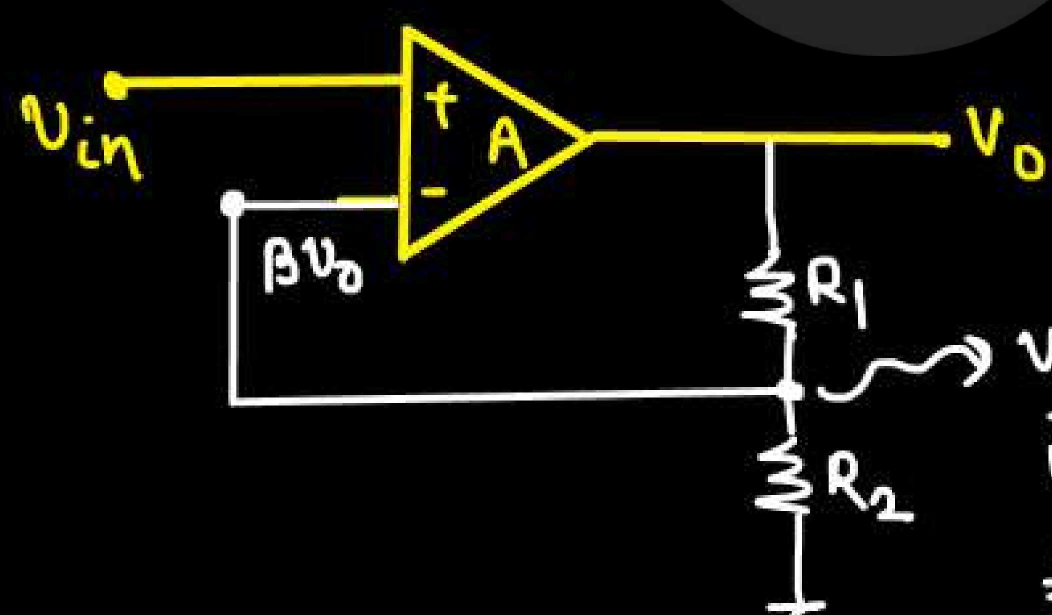
Before f/b:-



$$\boxed{v_0 = A v_{in}}$$

if $A \rightarrow$ variable, then $v_0 \rightarrow$ variable

After f/b:-



$$\frac{V_0 R_2}{R_1+R_2} = \beta V_0$$

$$\Rightarrow \beta = \frac{R_2}{R_1+R_2}$$

$$(v_{in} - \beta v_0) A = v_0$$

$$\frac{v_0}{v_{in}} = \frac{A}{1+A\beta}$$

$$\boxed{\frac{v_0}{v_{in}} \approx \frac{1}{\beta} = 1 + \frac{R_1}{R_2}}$$

$\Rightarrow$ loop gain :-

$$(A_v)_{w/o\ f/b} = A \rightarrow \text{open loop gain}$$

$$(A_v)_{\text{with neg } f/b} = \frac{A}{1-A\beta} \rightarrow \text{closed loop gain}$$

$$\boxed{A\beta = \text{loop gain}}$$

Q. An amplifier is connected in negative f/b. if the percentage change is open loop gain is 10%, then what will be the % change in closed loop gain. loop gain is 99.

→

closed loop gain $A_{CL} = \dfrac{A_{OL}}{1 + A_{OL}\beta}$ — (1)

$$\frac{DA_{OL}}{A_{OL}} \times 100\% = 10\%$$

$$\frac{DA_{OL}}{A_{OL}} = 0.1$$

$$\frac{DA_{CL}}{A_{CL}} = ?$$

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

$$DA_{CL} = \frac{(1 + A_{OL}\beta)\,DA_{OL} - A_{OL}\beta\,DA_{OL}}{(1 + A_{OL}\beta)^2}$$

$\beta \rightarrow$ constant

$$DA_{CL} = \frac{DA_{OL}}{(1 + A_{OL}\beta)^2}$$

$$\frac{DA_{CL}}{A_{CL}} = \frac{DA_{OL}\,(1 + A_{OL}\beta)}{(1 + A_{OL}\beta)^2 \times A_{OL}}$$

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

$$\boxed{\frac{DA_{CL}}{A_{CL}} = \frac{DA_{OL}/A_{OL}}{(1 + A\beta)}}$$

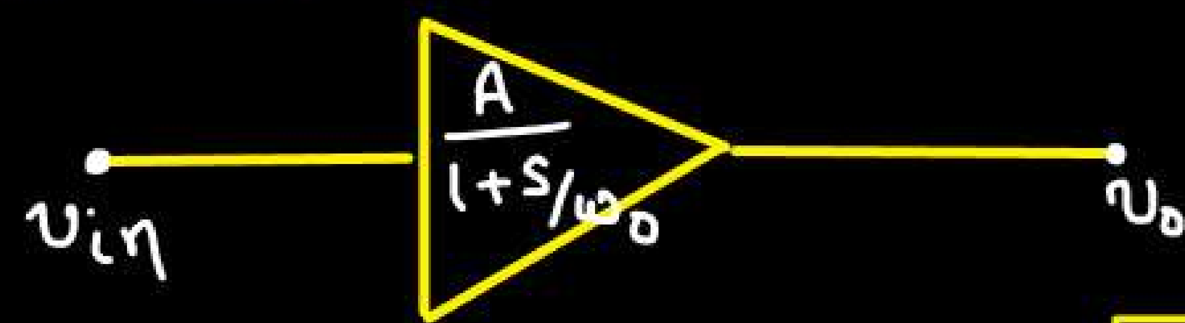
Given $A\beta = 99$

$$\frac{\Delta A_{CL}\%}{A_{CL}} = \frac{\Delta A_{OL}/A_{OL}\%}{1+99}$$

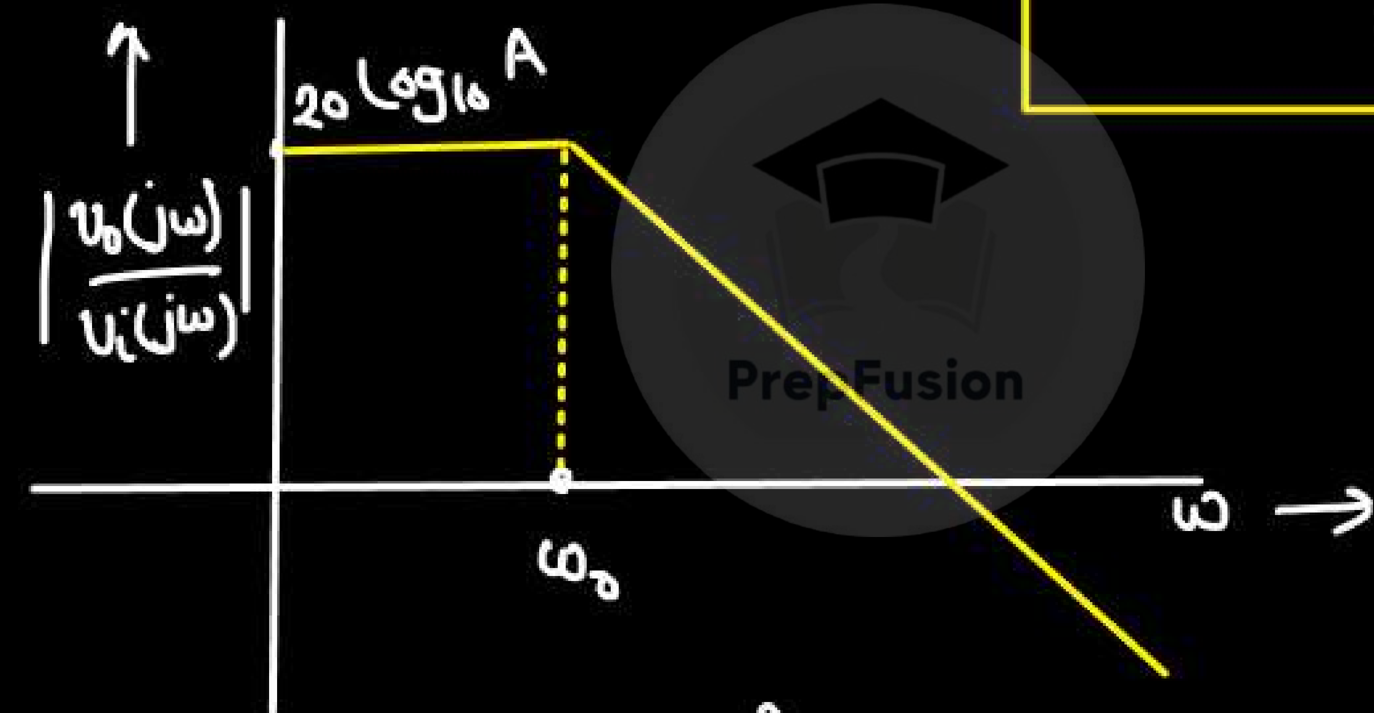
$$= \frac{10\%}{100}$$

$$\boxed{\frac{\Delta A_{CL}}{A_{CL}} = 0.1\%}$$

2. Increase in B.W. -

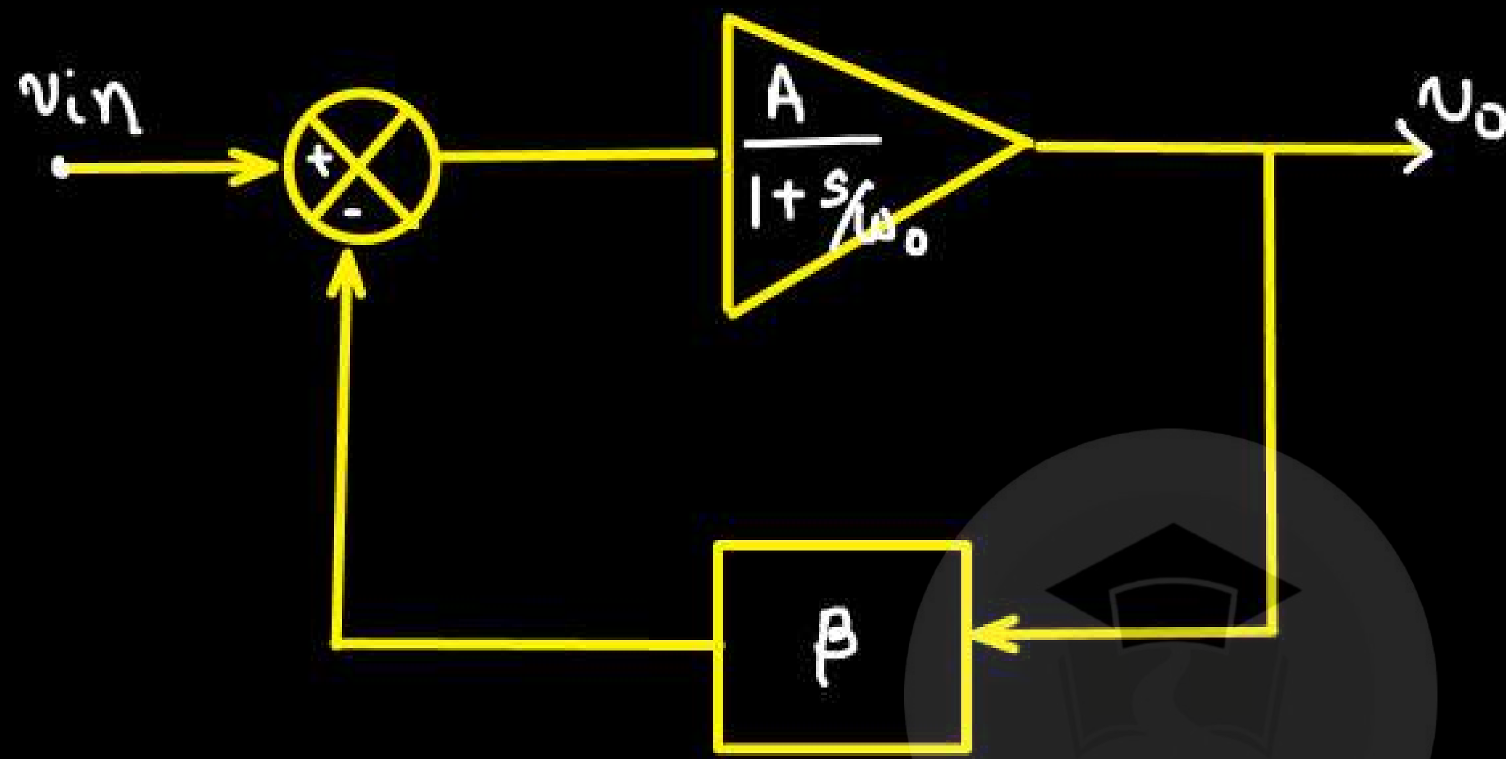


$$\boxed{v_o(s) = \frac{A}{1+S/\omega_0}\, v_i(s)}$$



B.W. = ω_0 {getting a good gain}

Introducing feedback:-



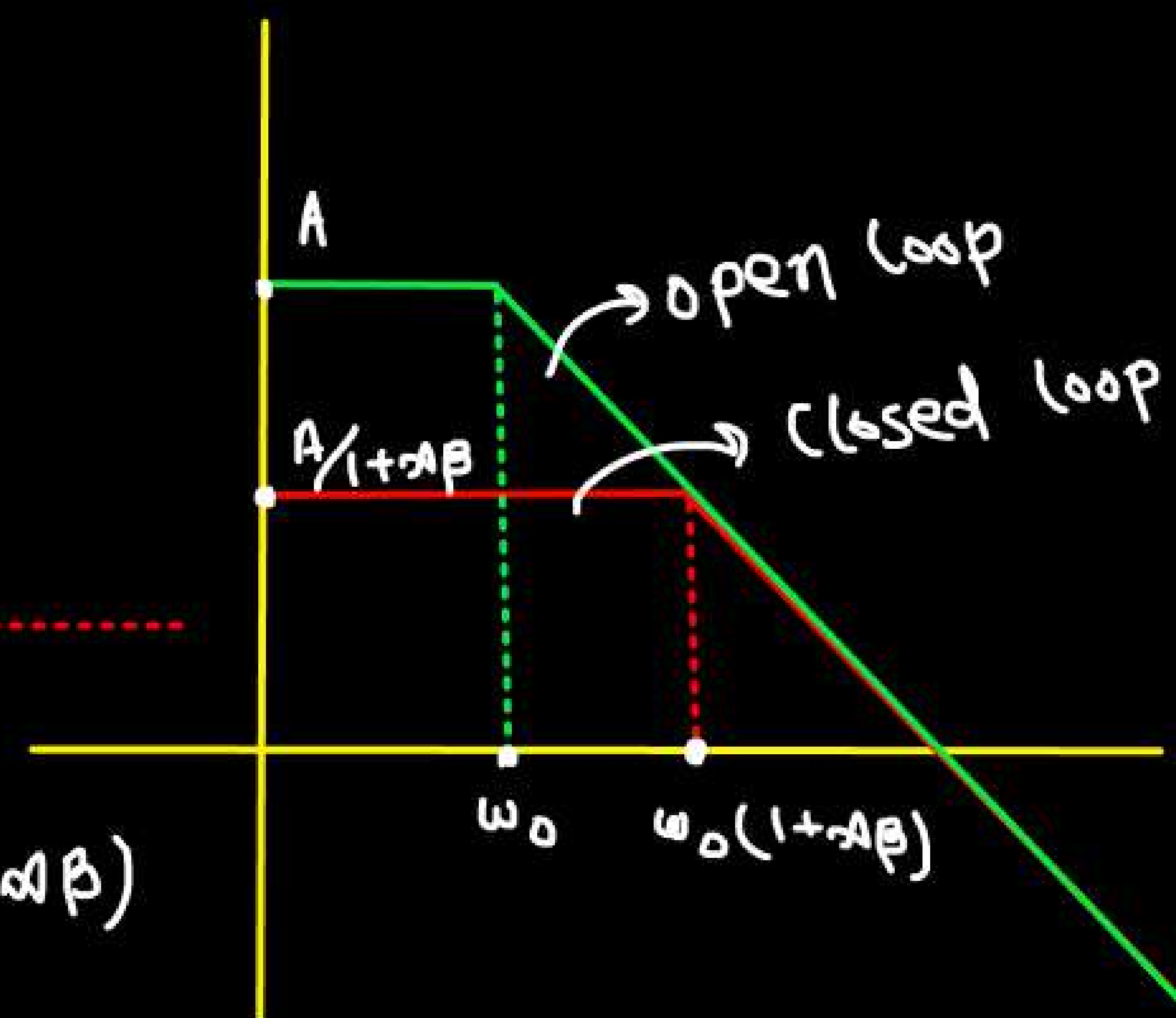
$$\frac{v_0(s)}{v_i(s)} = \frac{\frac{A}{1+s/\omega_0}}{1+\frac{A\beta}{1+s/\omega_0}} = \frac{A}{A\beta+1+s/\omega_0} = \frac{A\omega_0}{s+\omega_0(1+A\beta)}$$

$$\frac{V_o(s)}{V_i(s)} = \frac{A\omega_0}{s + \omega_0(1+A\beta)}$$

$$\boxed{\frac{V_o(s)}{V_i(s)} = \frac{A/1+A\beta}{\frac{s}{\omega_0(1+A\beta)} + 1}}$$

$$\text{dc gain} = \frac{A}{1+A\beta}$$

$$\text{Bandwidth} = \omega_0(1+A\beta)$$



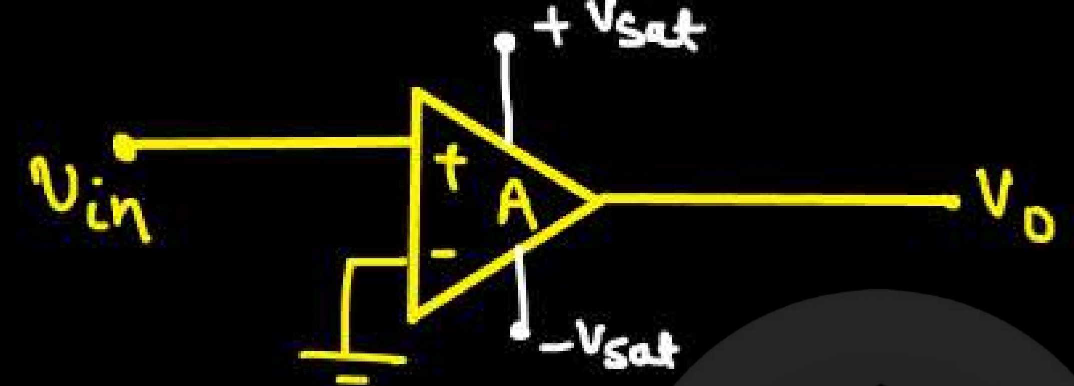
For open loop :- DC gain $= A$, $B.\omega. = \omega_0$

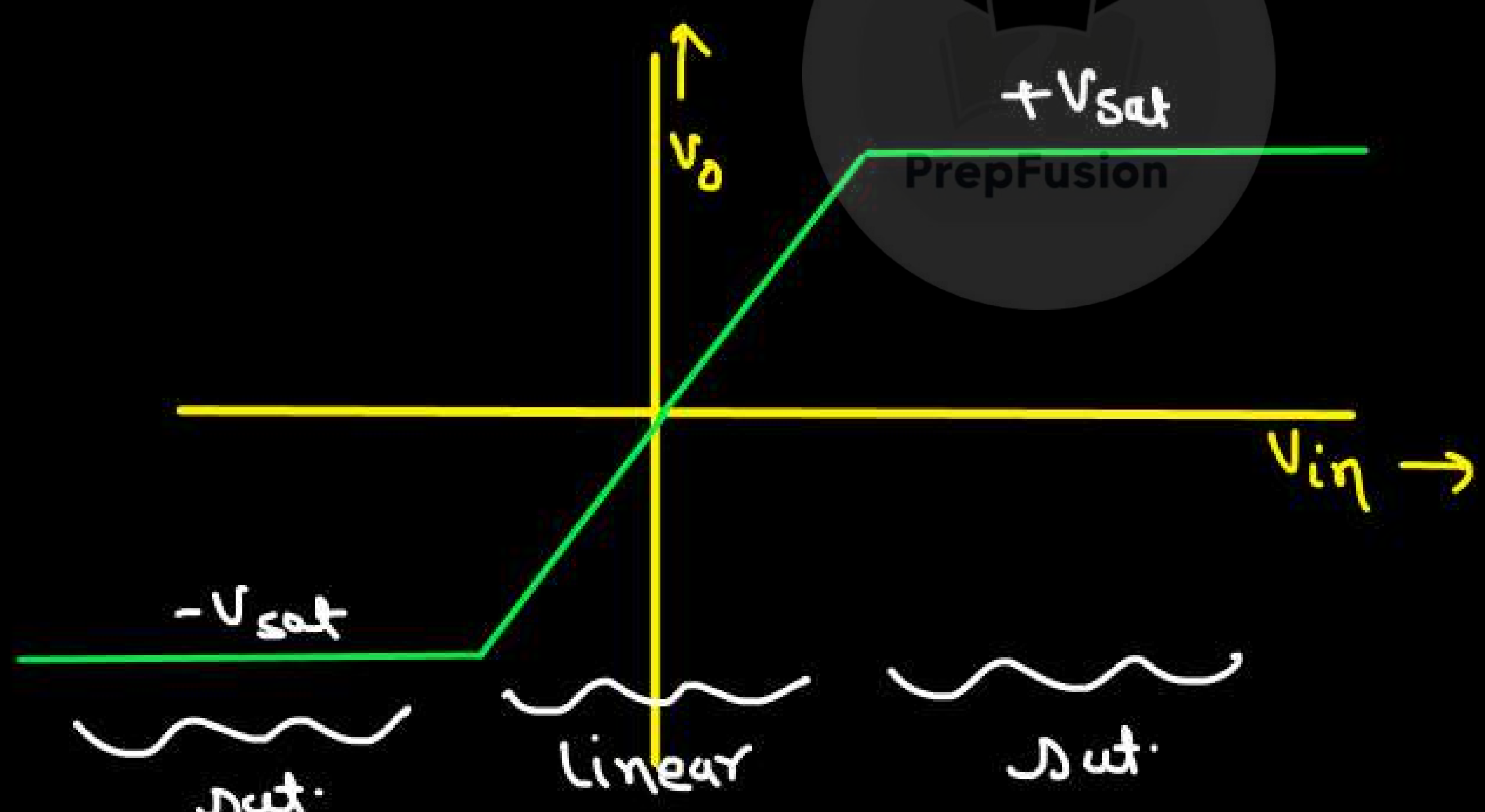
For closed loop :- DC gain $= \frac{A}{1+A\beta}$, $B.\omega. = \omega_0(1+A\beta)$

in both cases $\boxed{G.B.\omega. = A\omega_0}$

(iii) Increase in linearity:-

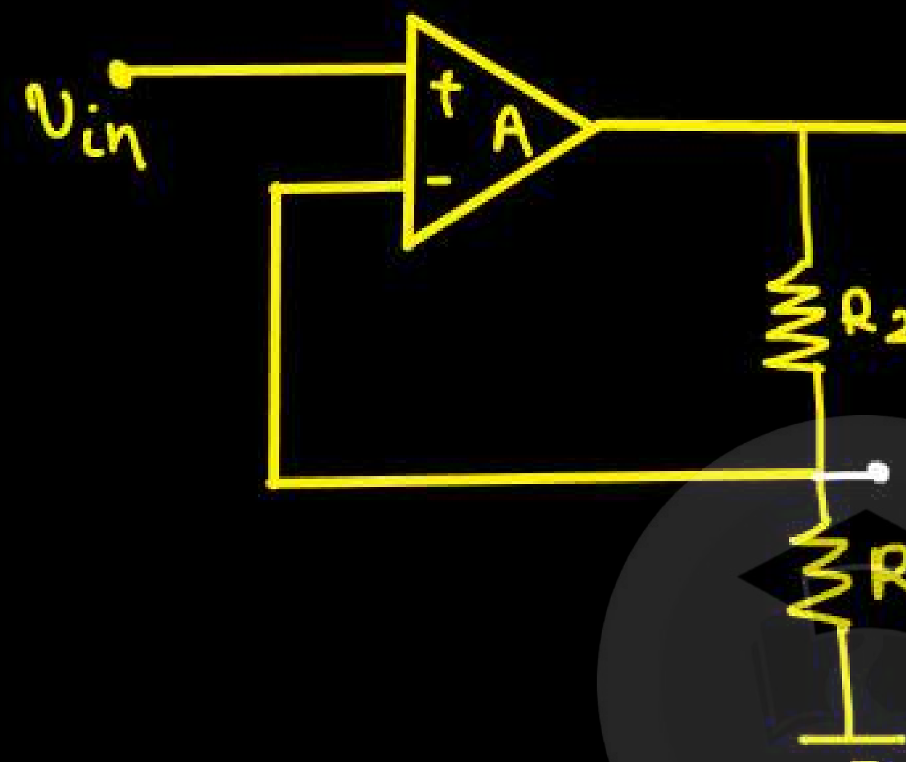
Before f/b:-





linearity ↓

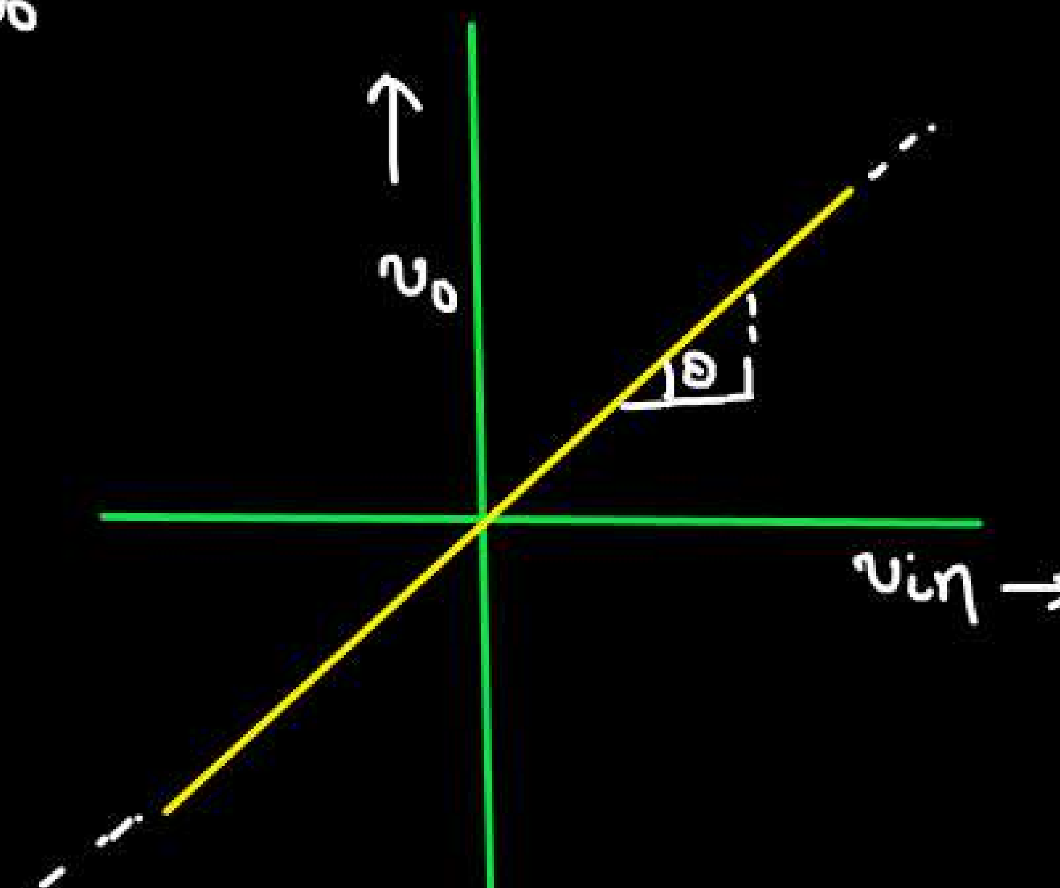
After f/b:-



$$\beta V_0 = \frac{R_1}{R_1+R_2} v_0, \quad \frac{R_1}{R_1+R_2} \rightarrow \beta$$

$$\frac{v_0}{v_{in}} = \frac{A}{1+A\beta} \approx \frac{1}{\beta} = 1+\frac{R_2}{R_1}$$

$$\boxed{v_0 = \left(1+\frac{R_2}{R_1}\right) v_{in}}$$



increased Linearity

⇒ In Negative f/b:-

1. s/s → stable [Gain is constant]
2. Gain → Reduces
3. B.W. → Increases
4. Linearity → Increases
5. Time constant → decreases $\left[B.W. \propto \frac{1}{\tau} \right]$

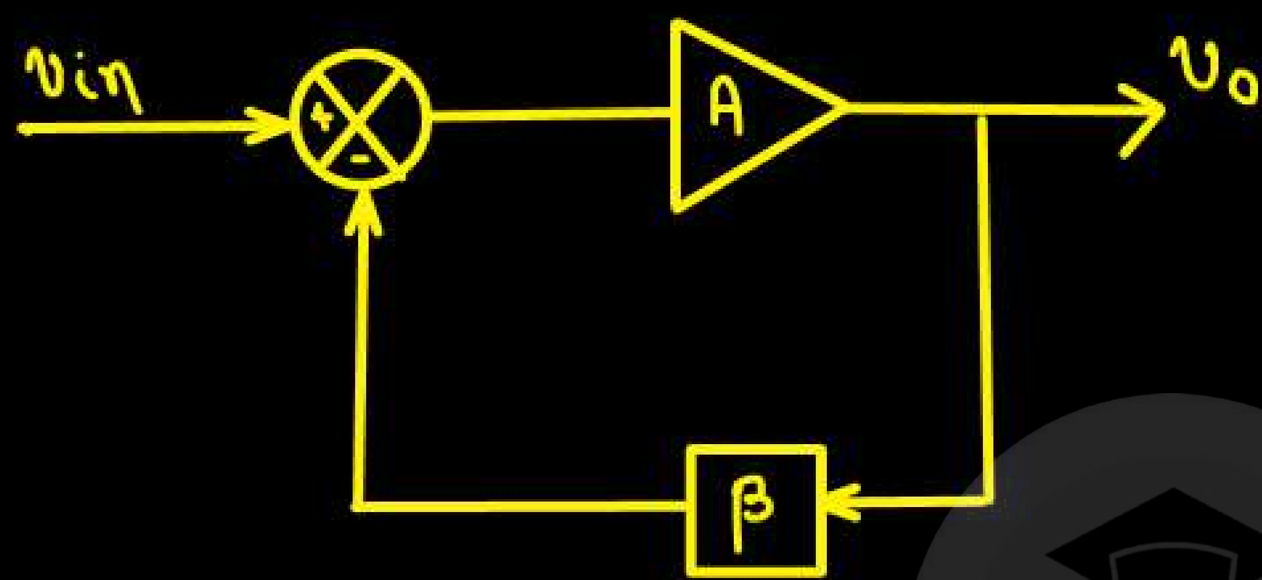
★ open loop gain = A

After f/b:-

(i) Closed loop gain (Neg f/b) = $\dfrac{A}{1+A\beta} = \dfrac{\text{open loop gain}}{1+\text{loop gain}}$

(ii) Closed loop gain (pos f/b) = $\dfrac{A}{1-A\beta} = \dfrac{\text{open loop gain}}{1+\text{loop gain}}$

★ How to find loop gain?

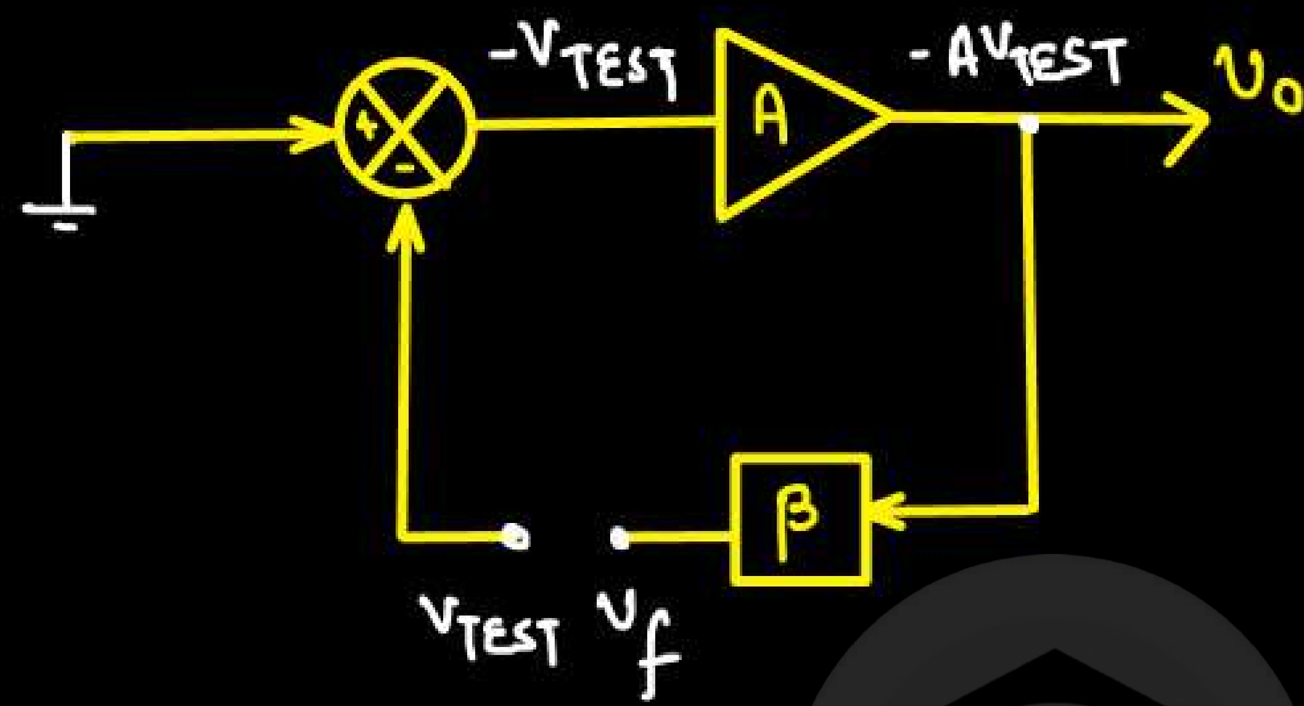


(i) Nullify the i/p.

(ii) Break the loop in feedback path.

(iii) Mark the open end as v_f and v_{TEST}. (V_{TEST} should go towards the input side)

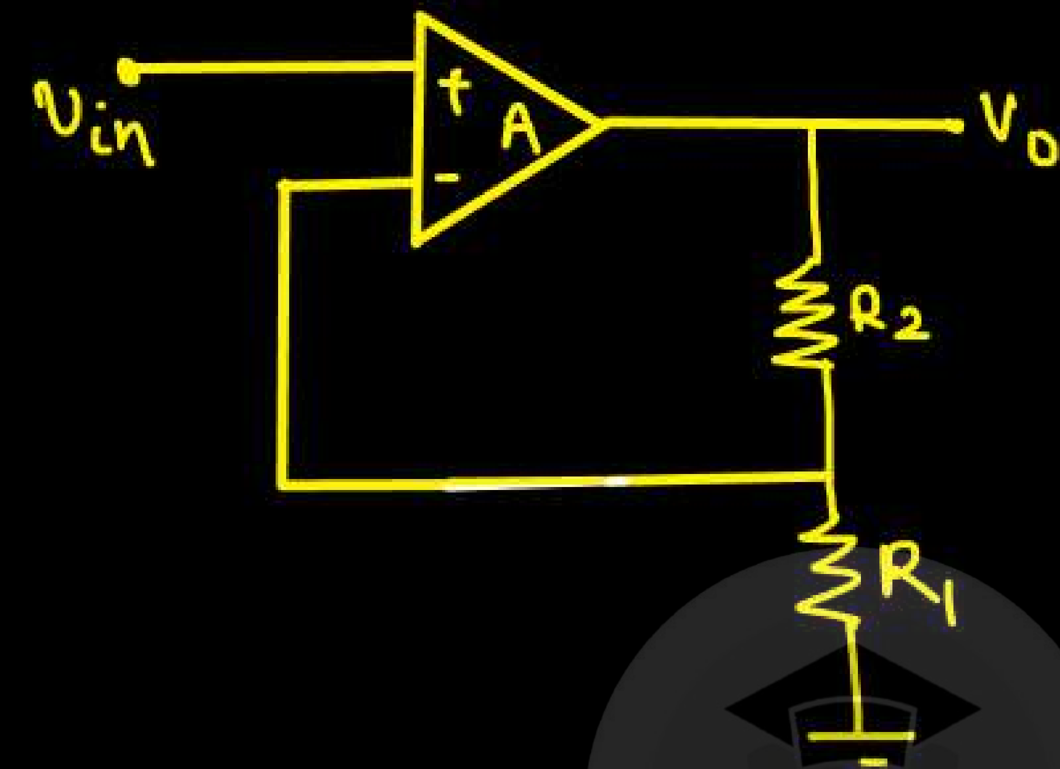
(iv) loop gain $A\beta = -\dfrac{V_f}{V_{TEST}}$



$$v_f = -\beta(A V_{TEST})$$

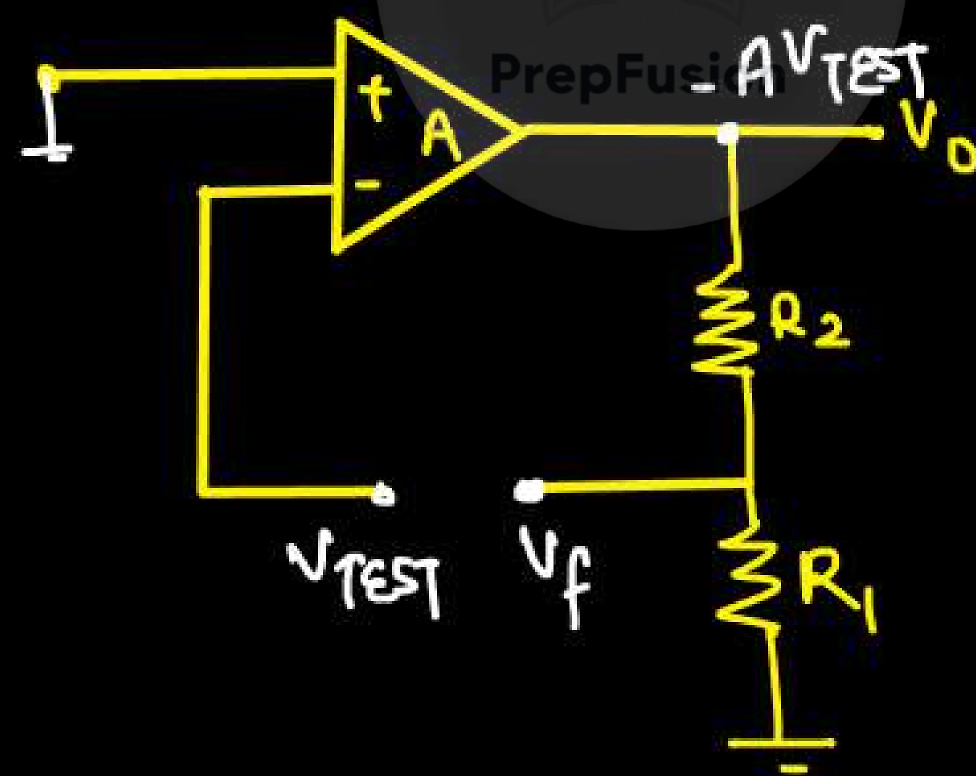
$$\boxed{\frac{-v_f}{V_{TEST}} = A\beta}$$

Example:



loop gain = ?

→



$$-AV_{TEST} \times \frac{R_1}{R_1+R_2} = V_f$$

$$\frac{-V_f}{V_{TEST}} = \boxed{\text{loop gain} = \frac{AR_1}{R_1+R_2}}$$

Types of Amplifiers:-

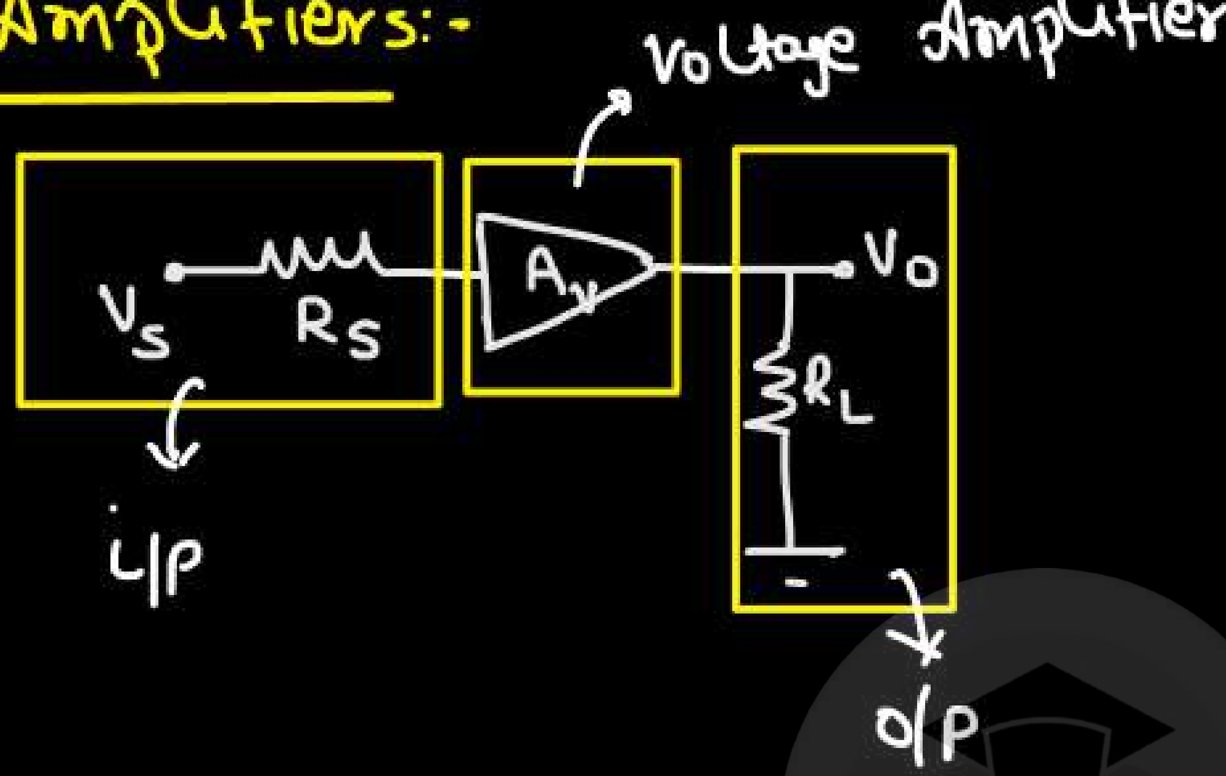
(i) Voltage Amplifiers:-

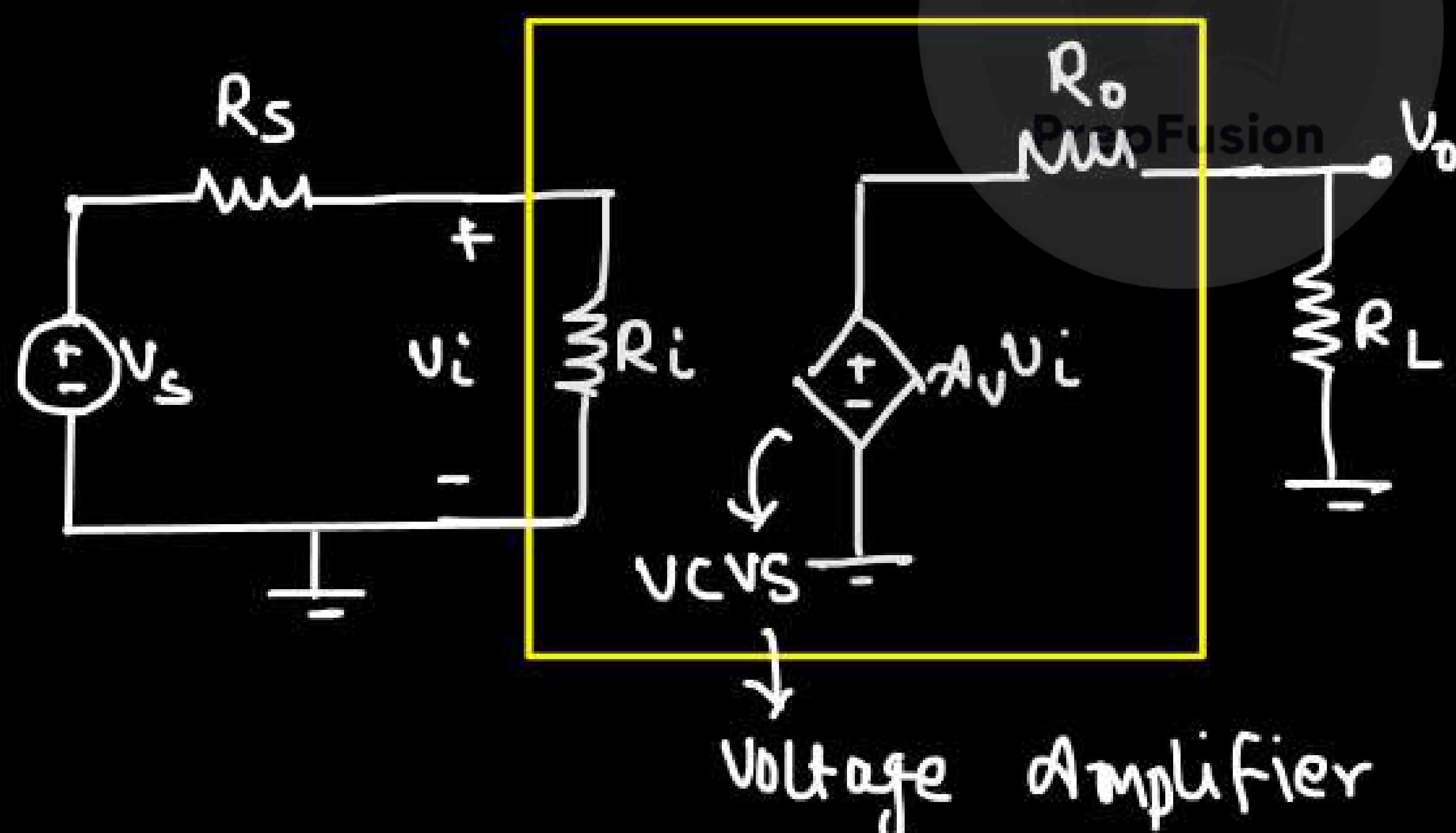
(ii) Transresistance amplifiers:-

(iii) Transconductance Amplifiers:-

(iv) Current Amplifiers:-

(i) Voltage Amplifiers:-





$$v_i = \frac{R_i}{R_i+R_s} V_s$$

$$V_o = \frac{A_v \times v_i \times R_L}{R_L+R_o}$$

$$V_o = A_v\left[\frac{R_i}{R_i+R_s}\right] V_s \times \frac{R_L}{R_L+R_o}$$

$$\boxed{\frac{V_o}{V_s} = A_v \left[\frac{R_i}{R_i + R_s}\right] \left[\frac{R_L}{R_L + R_o}\right]}$$

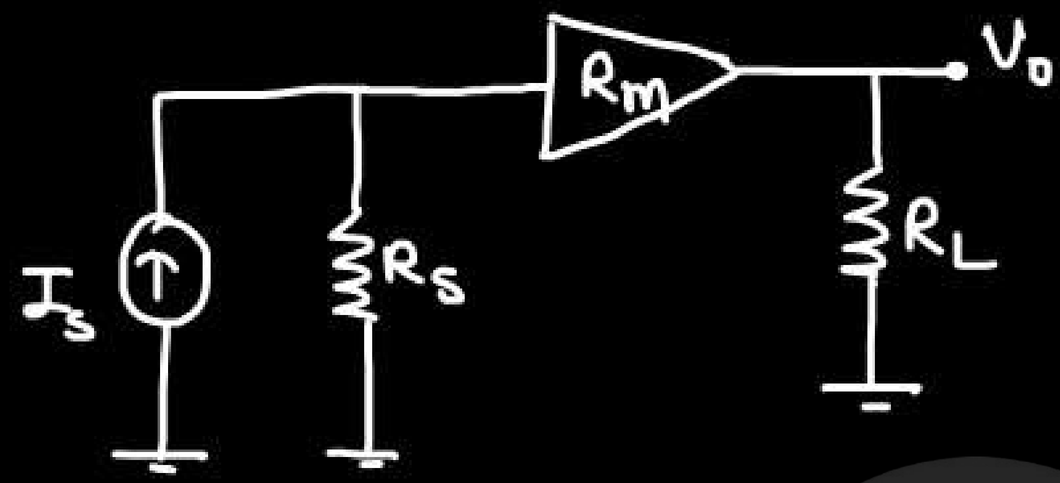
For an ideal voltage amplifier :- $\boxed{\begin{matrix} R_i = \infty \\ R_o = 0 \end{matrix}}$ **
→ High
→ low

if $R_i = \infty$, $R_o = 0$

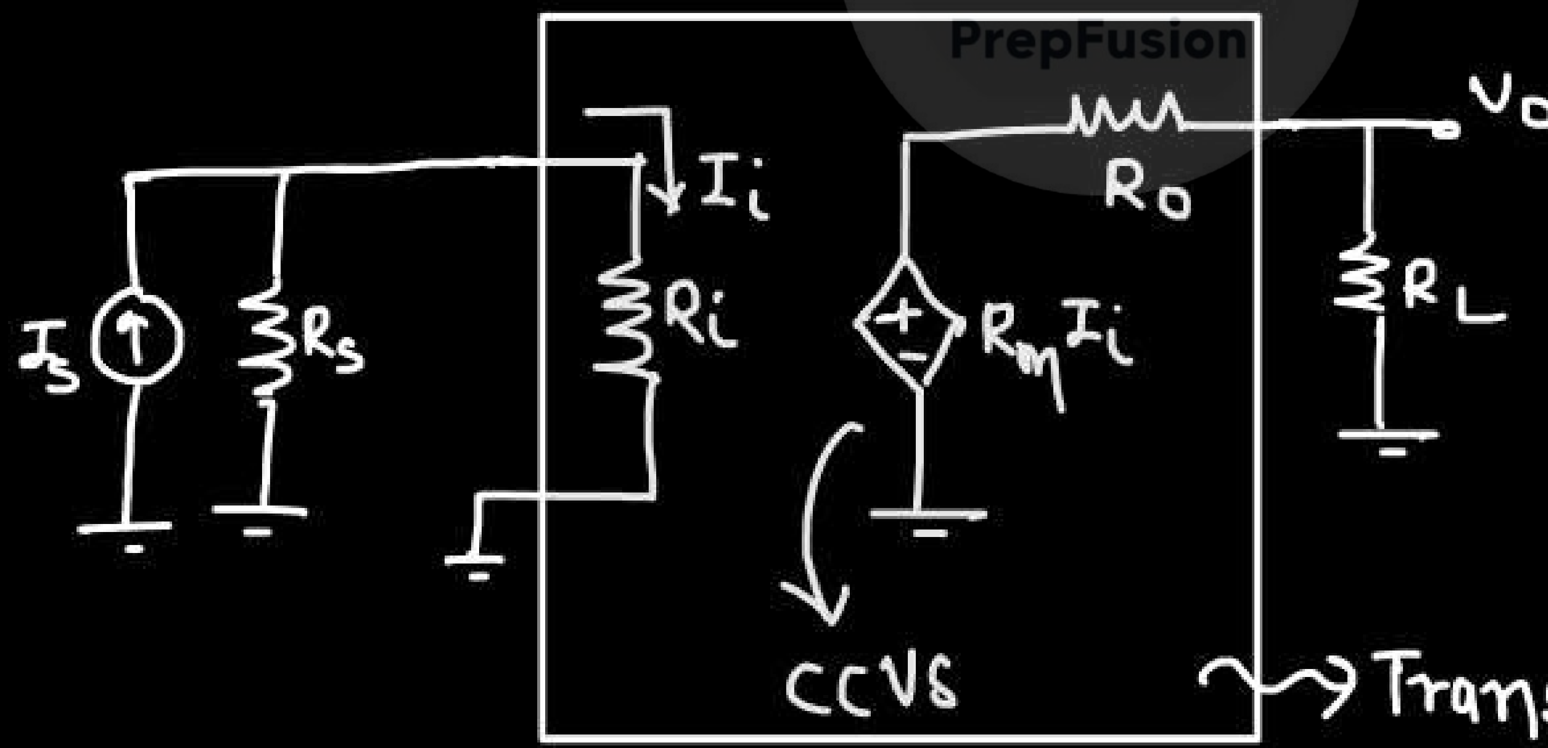
$$\boxed{\frac{V_o}{V_s} = A_v}$$

Unit of $A_v = V/V$

(ii) Trans-resistance Amplifier :-



$$R_m = \frac{\text{Volt}}{\text{Ampere}} = \text{ohm}$$



$$I_i = \frac{R_s}{R_s + R_i} I_s$$

$$V_o = \frac{R_L}{R_L + R_o} \times R_m I_i$$

$$V_o = (R_m)\left(\frac{R_L}{R_L+R_o}\right)\left(\frac{R_s}{R_s+R_i}\right) I_s$$

$$\boxed{\frac{V_o}{I_s} = (R_m)\left(\frac{R_L R_s}{(R_L+R_o)(R_s+R_i)}\right)}$$

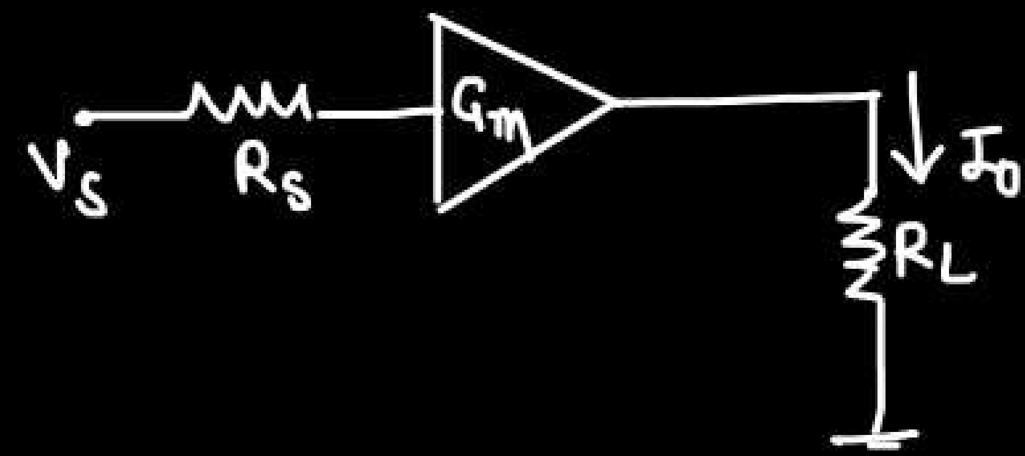
For ideal Transresistance amplifier, $\boxed{\begin{array}{l} R_i = 0\,\Omega \\ R_o = 0\,\Omega \end{array}}$ $\rightarrow$ low, $\rightarrow$ low

if $R_i = 0$ and $R_o = 0$

$$\boxed{\frac{V_o}{I_s} = R_m}$$

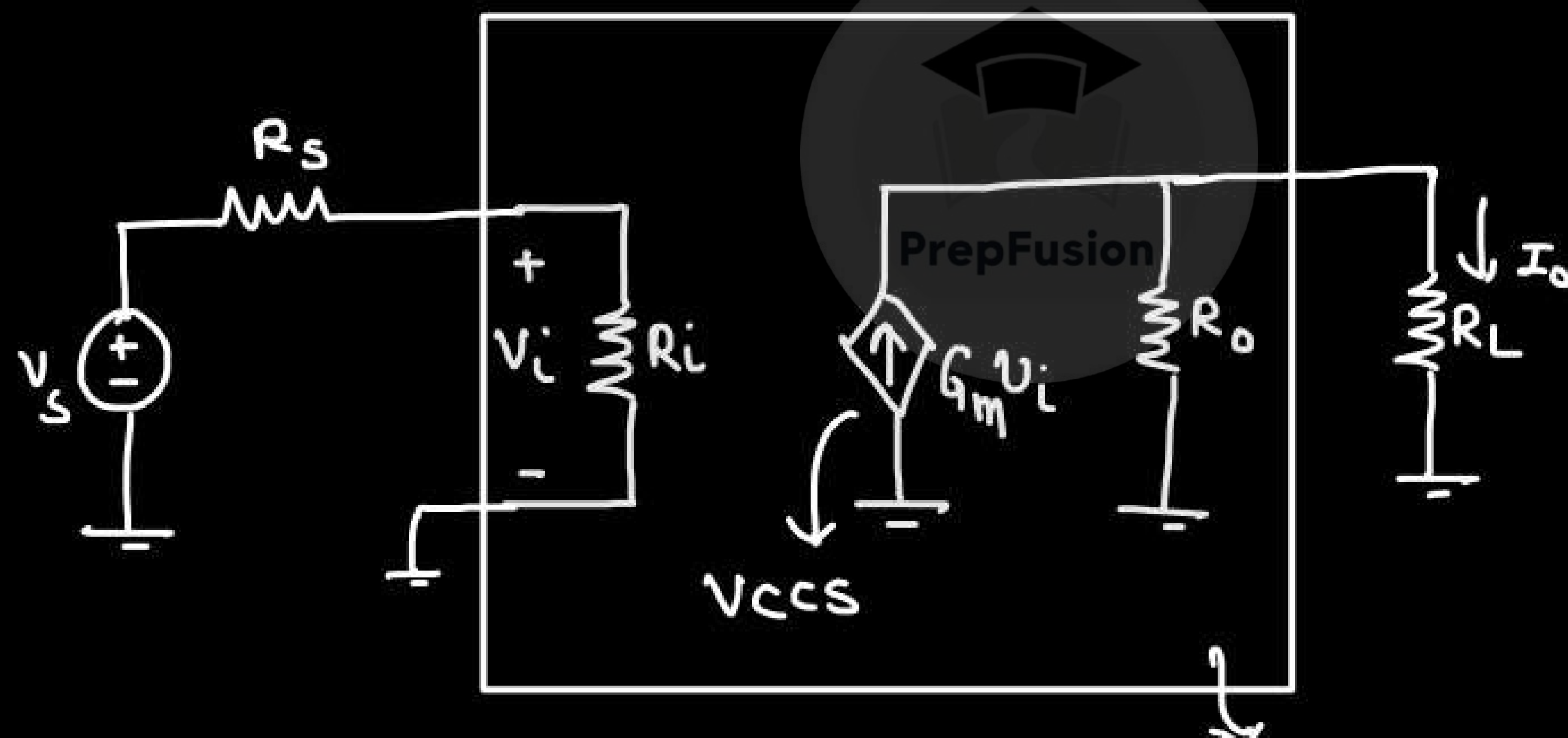
$\boxed{\text{unit of } R_m \rightarrow \text{ohm}}$

(iii) Transconductance Amplifier :-



$$G_m \rightarrow \frac{\text{Current}}{\text{Voltage}} = \frac{A}{V}$$

$$= \text{mho} = S$$



Transconductance Amplifier

$$v_i = \frac{R_i}{R_i + R_s} V_s$$

$$I_o = \frac{R_o}{R_o + R_L} \times G_m v_i$$

$$I_o = (G_m)\left(\frac{R_o}{R_o+R_L}\right)\left(\frac{R_i}{R_i+R_s}\right)V_s$$

$$\boxed{\frac{I_o}{V_s} = G_m\left(\frac{R_o}{R_o+R_L}\right)\left(\frac{R_i}{R_i+R_s}\right)}$$

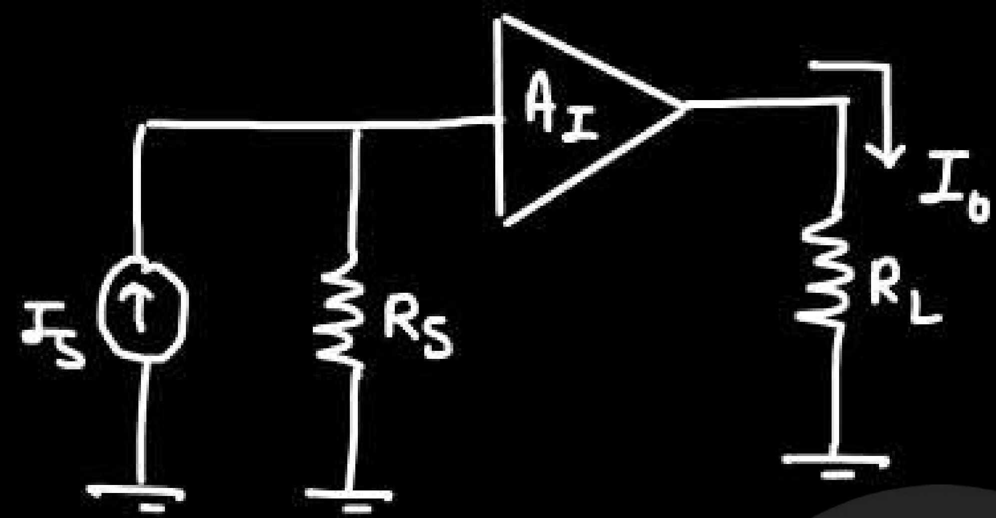
For ideal Transconductance Amplifier ; $\boxed{\begin{array}{l} R_i = \infty \\ R_o = \infty \end{array}}$

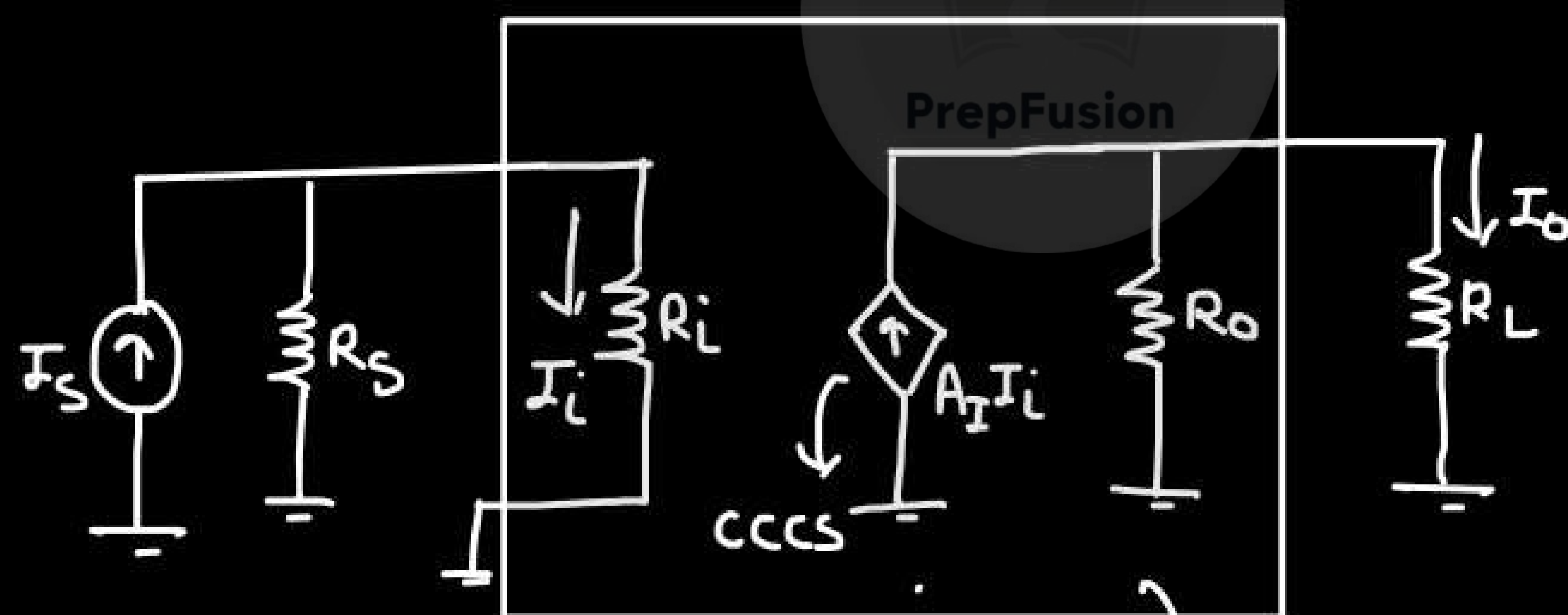
$R_i = \infty$, $R_o = \infty$

$$\boxed{\frac{I_o}{V_s} = G_m}$$

Unit of $G_m \rightarrow$ mho/s

(iv) Current Amplifier :-





$$I_i = \frac{R_S}{R_S + R_i} I_S$$

$$I_o = \frac{R_o}{R_o + R_L} A_I I_i$$

$$I_o = A_I \left(\frac{R_o}{R_o+R_L}\right)\left(\frac{R_s}{R_s+R_i}\right) I_s$$

$$\boxed{\frac{I_o}{I_s} = A_I \left(\frac{R_o}{R_o+R_L}\right)\left(\frac{R_s}{R_s+R_i}\right)}$$

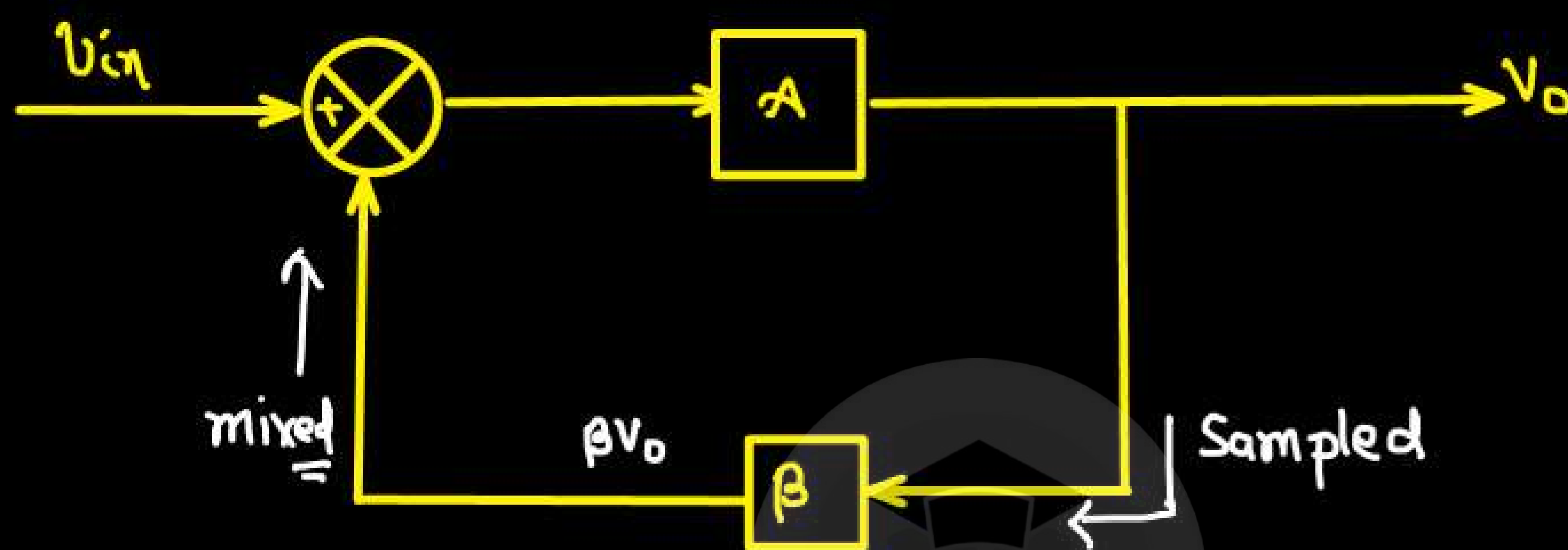
For ideal current Amplifier, $\boxed{\begin{array}{l} R_i = 0 \\ R_o = \infty \end{array}}$

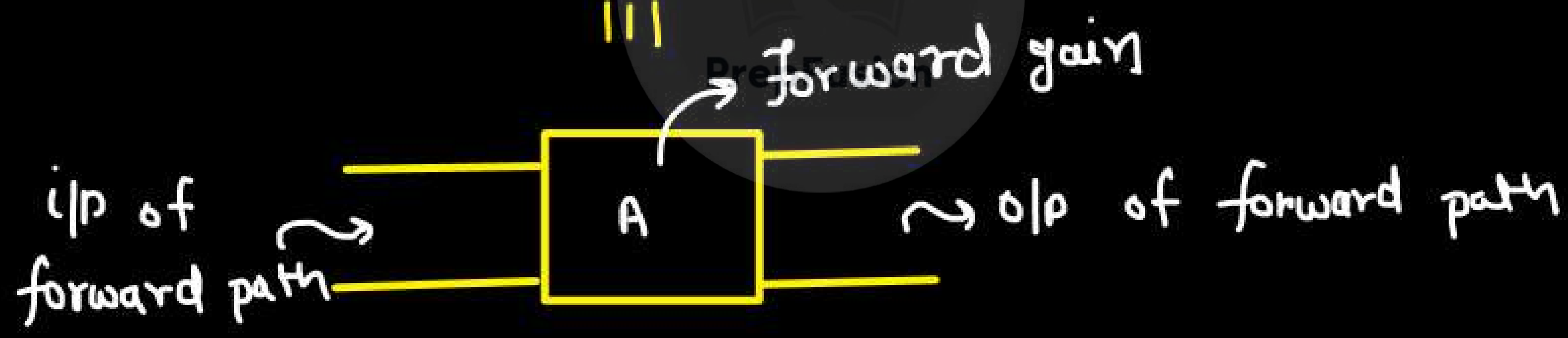
$R_i = 0$, $R_o = \infty$

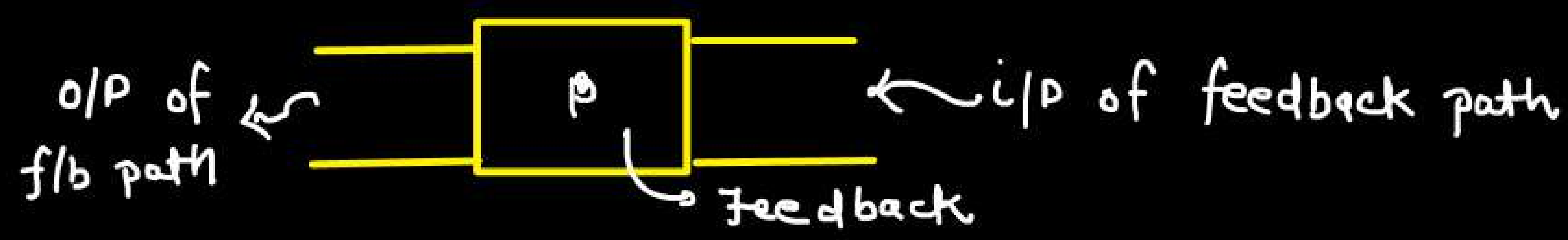
$$\boxed{\frac{I_o}{I_s} = A_I}$$

Type of Amplifier	Input Resistance	Output Resistance
(i) Voltage Amplifier	∞	0
(ii) Transresistance Amp.	0	0
(iii) Transconductance Amp	∞	∞
(iv) Current Amplifier	0	∞

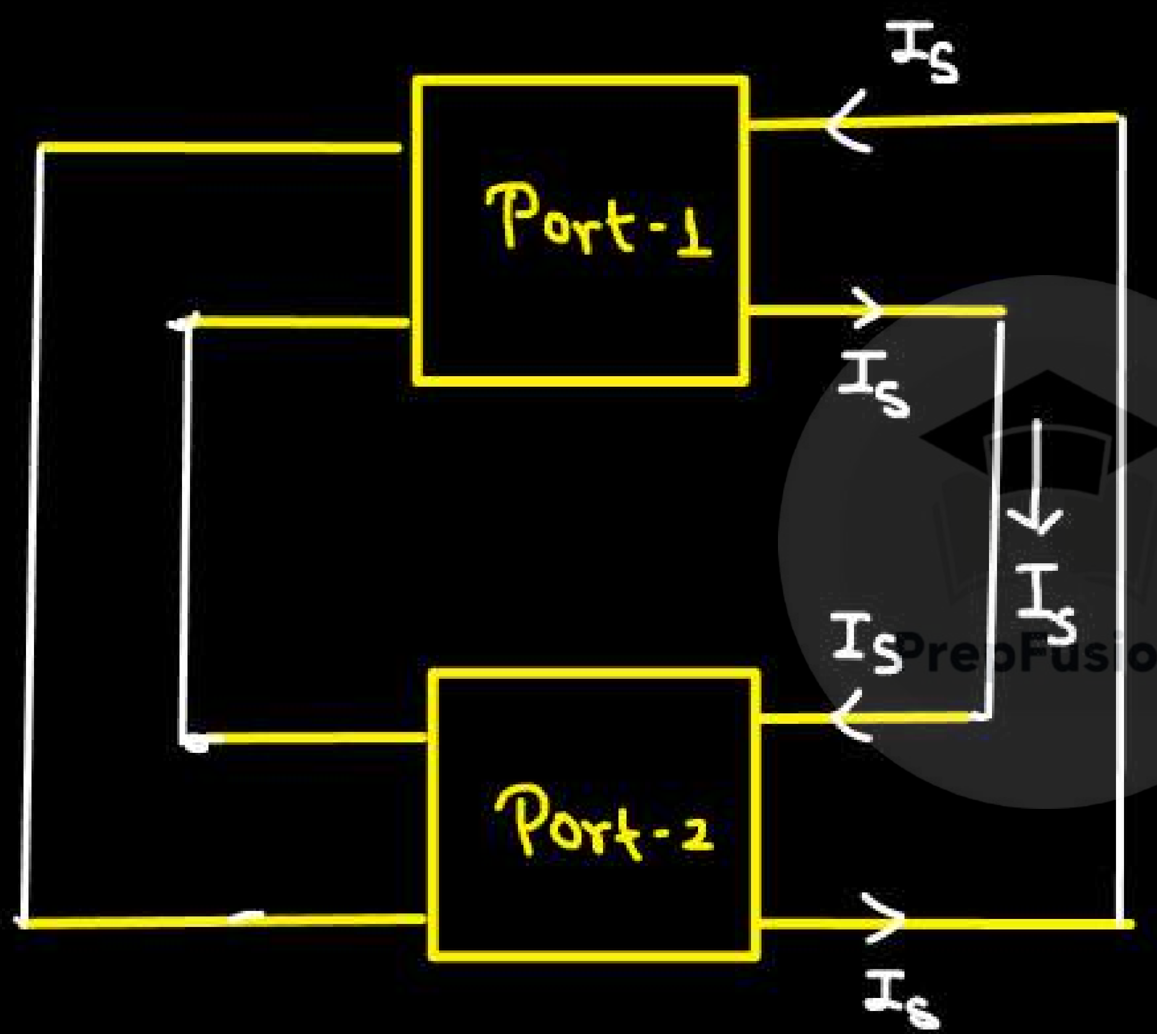
Alternative feedback Model:-

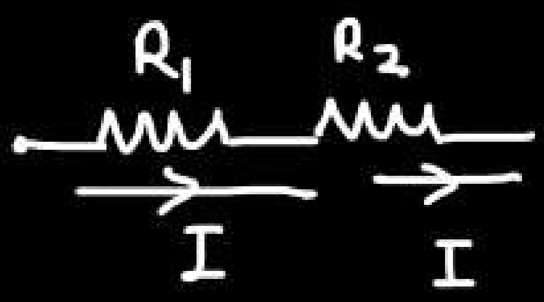






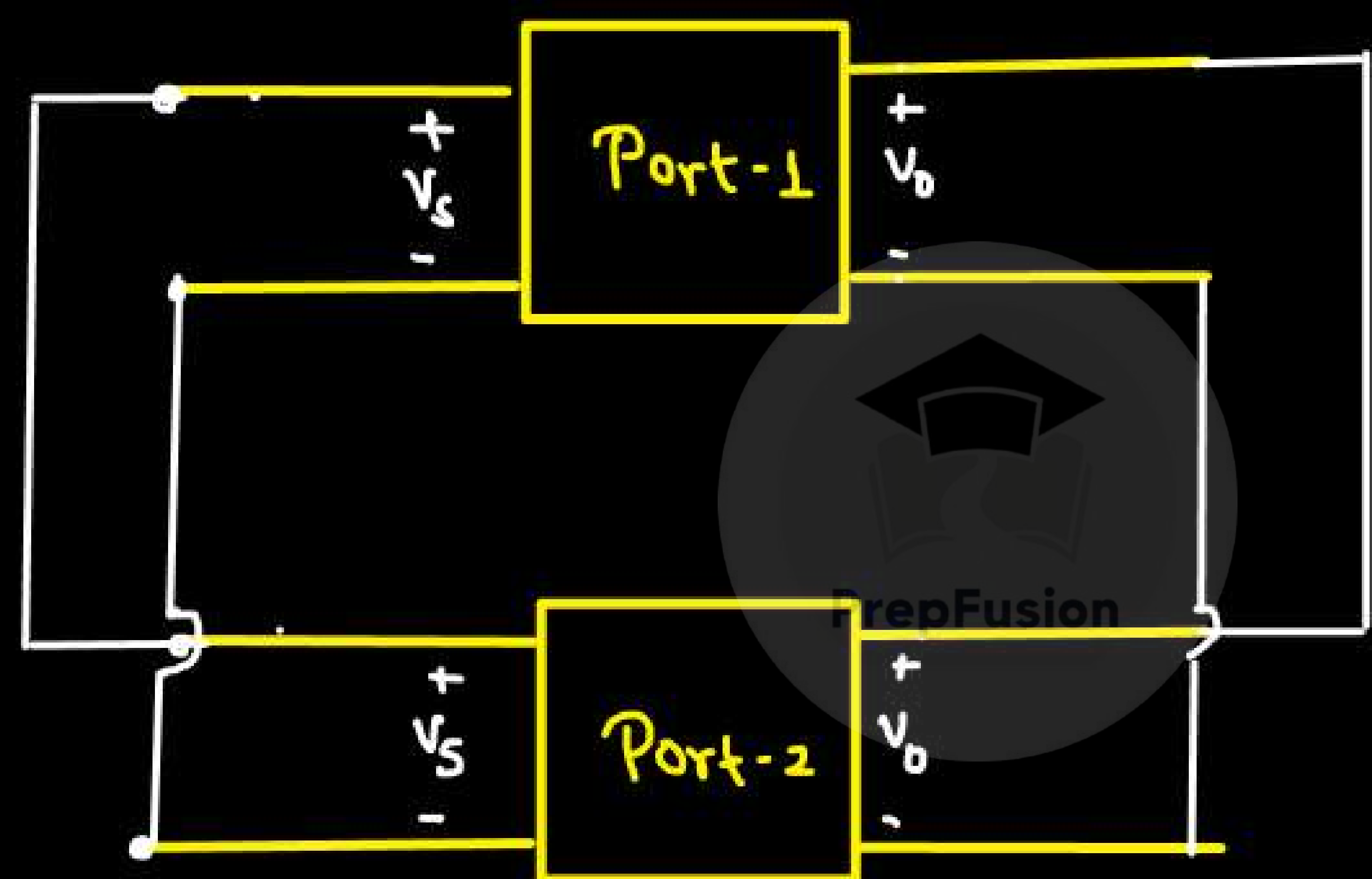
☆ Series Connection of 2- Two port N/w:-

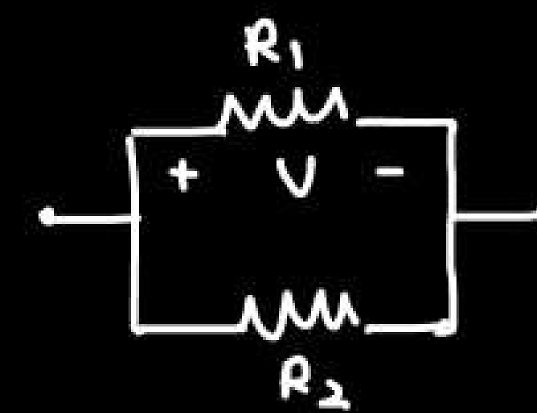




☆ Parallel connection of 2 - Two port N/w :-

(Shunt)

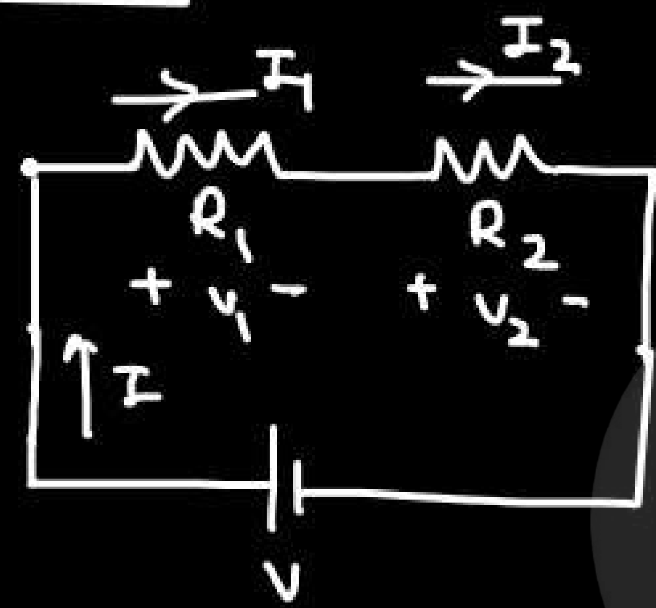




+ V −

★ Important points to remember:-

1. Series Connection:-

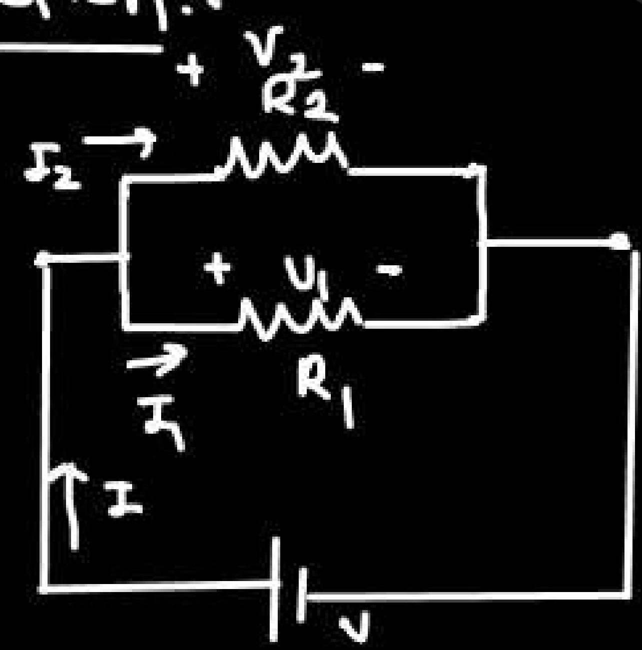


$I = I_1 = I_2 \rightarrow$ current same

$V = V_1 + V_2 \rightarrow$ voltage mixed

$\boxed{\text{series = current sampled, voltage mixed}}$

2. Parallel Connection:-
(Shunt)

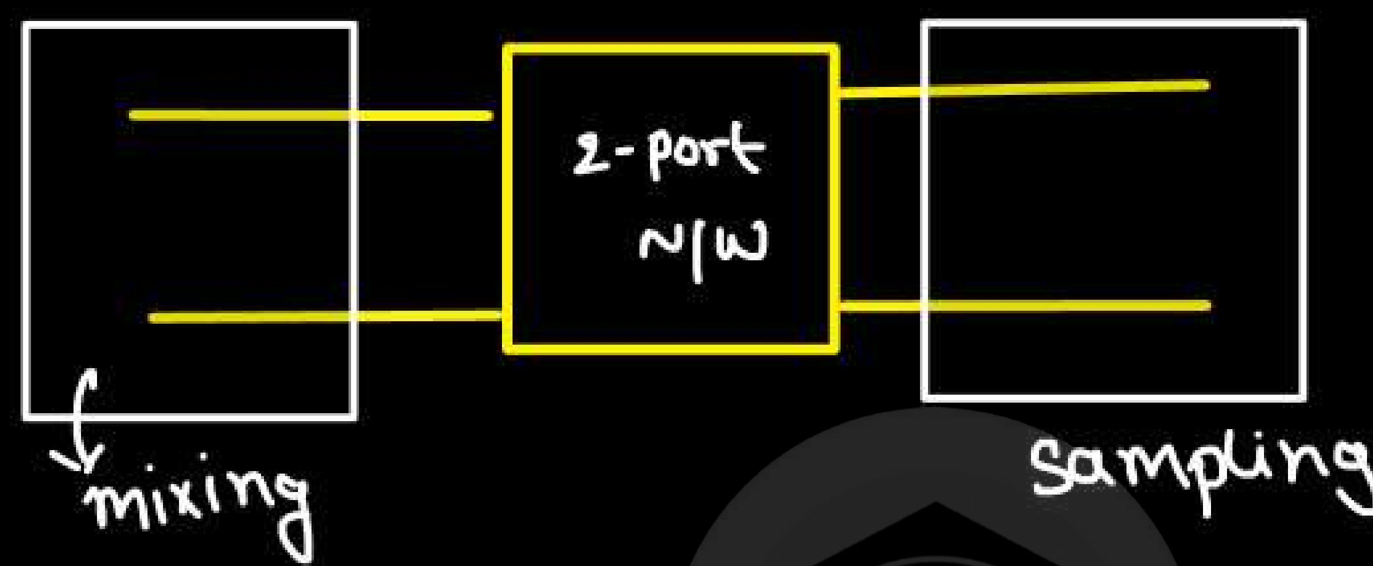


$V = V_1 = V_2 \rightarrow$ voltage same

$I = I_1 + I_2 \rightarrow$ current mixed

$\boxed{\text{Parallel = Voltage sampled, current mixed}}$

For a two port N/W:-



☆ Decode the following:-

1. Voltage Sampling → Shunt connection
2. Current Mixing → Shunt connection
3. Voltage Mixing → Series connection
4. Current Sampling → Series connection

5. Series connection → Current Sampling, Voltage mixing
6. Shunt connection → Voltage Sampling, Current mixing
7. Series connection at input → Voltage mixing
8. Series connection at output → Current sampling
9. Shunt connection at input → current mixing
10. Shunt connection at output → Voltage sampling

Conclusion:-

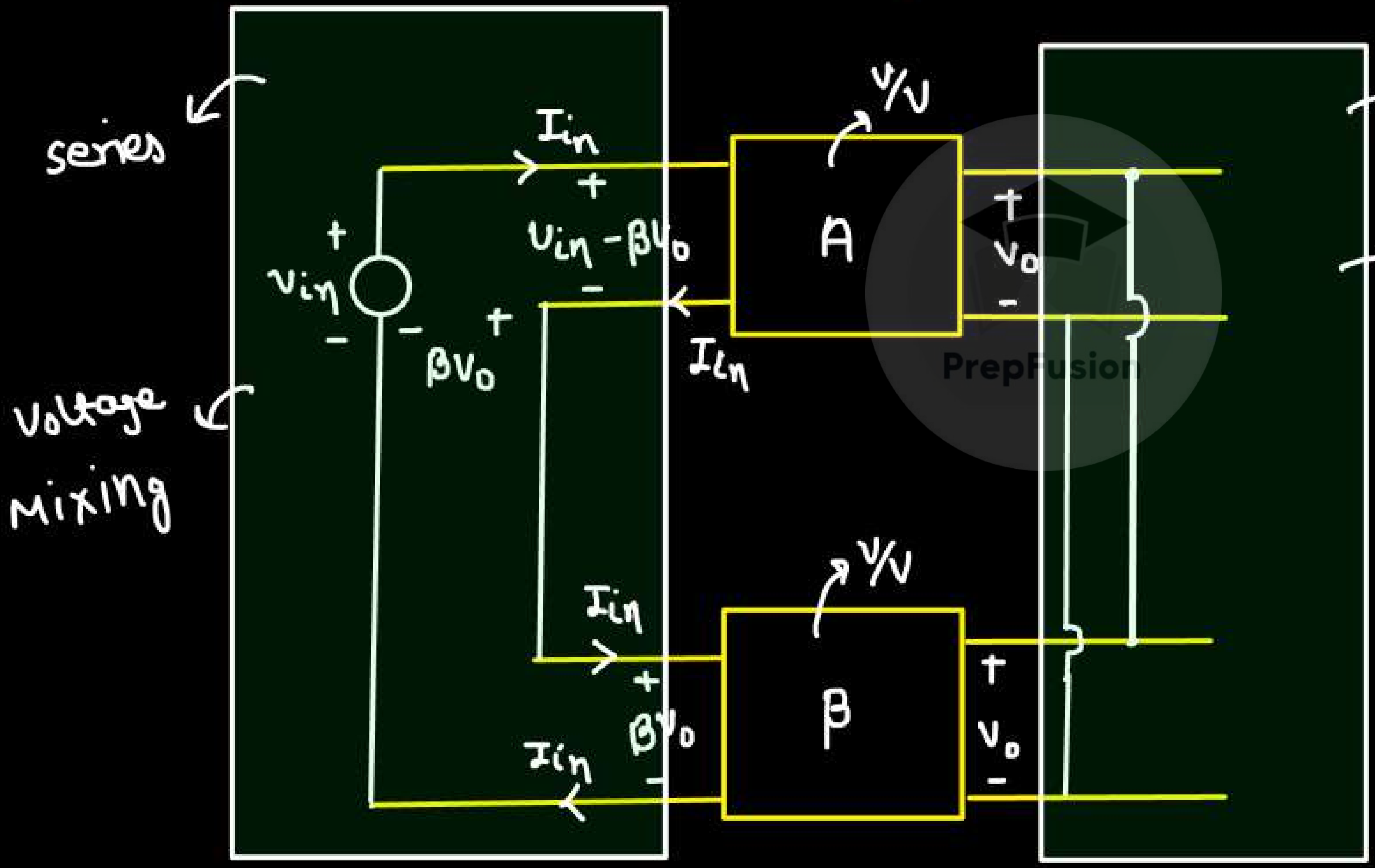
1. i/p → mixing, o/p → sampling
2. Series → Current sampling, Voltage mixing
3. Shunt → Voltage sampling, Current mixing

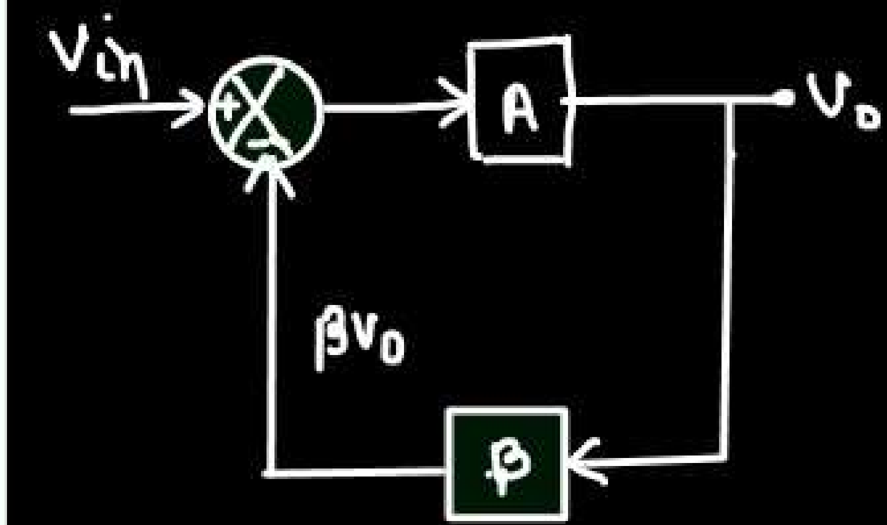
⇒ Feedback Topologies :-

	o/p - i/p	i/p - o/p	o/p - i/p
①	Voltage - Voltage	Series - Shunt	Voltage - Series
②	Voltage - Current	Shunt - Shunt	Current - Shunt
③	Current - Voltage	Series - Series	Voltage - Series
④	Current - Current	Shunt - Series	Current - Series

☆ Voltage - Voltage Feedback Topology :-

(Series - Shunt) ↳ From o/p voltage is sensed and fed back to the i/p





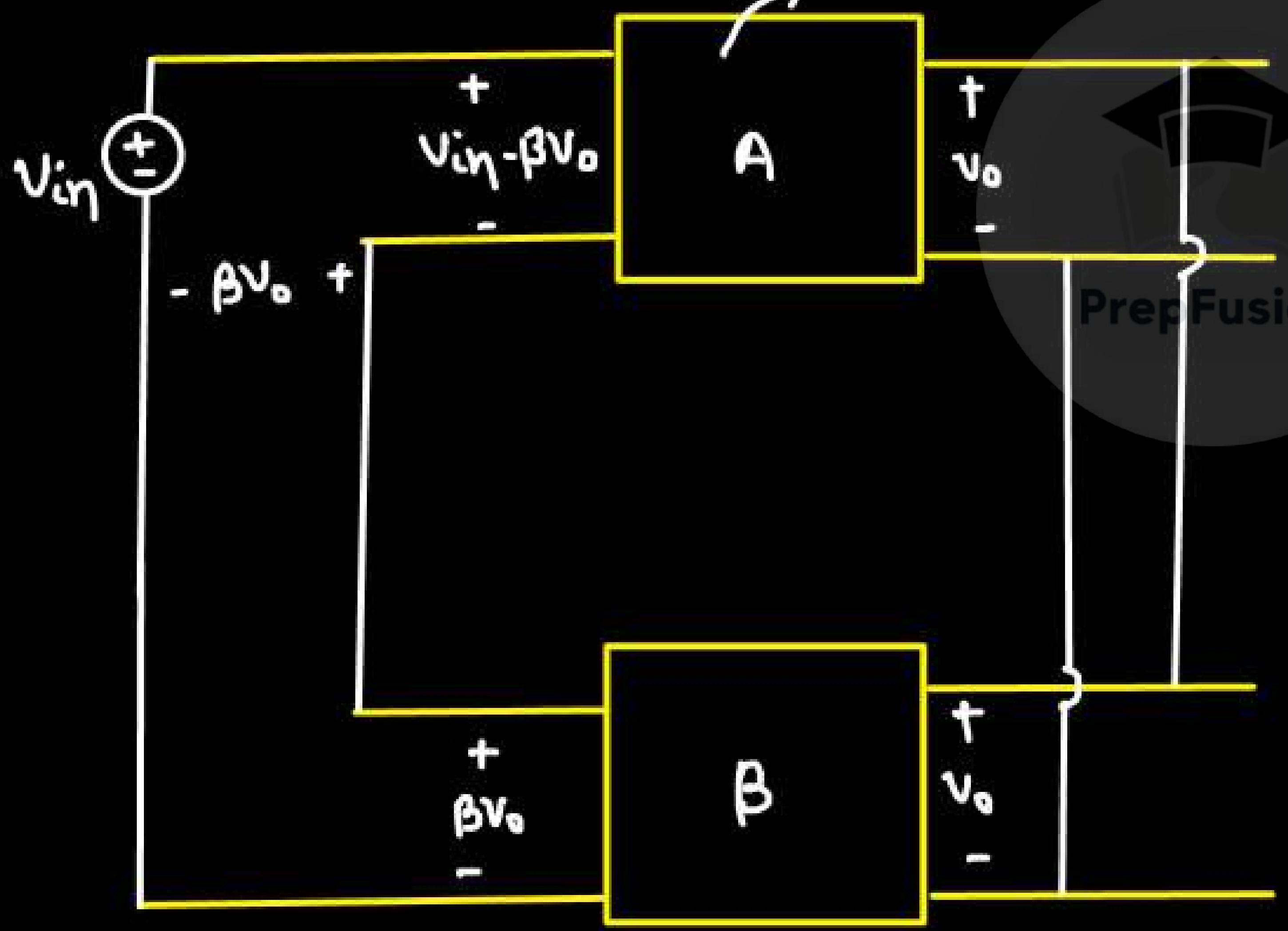
open loop gain = A

open loop input resistance = Rin

open loop output resistance = R_o

① Closed loop Gain :-

Voltage Amplifier

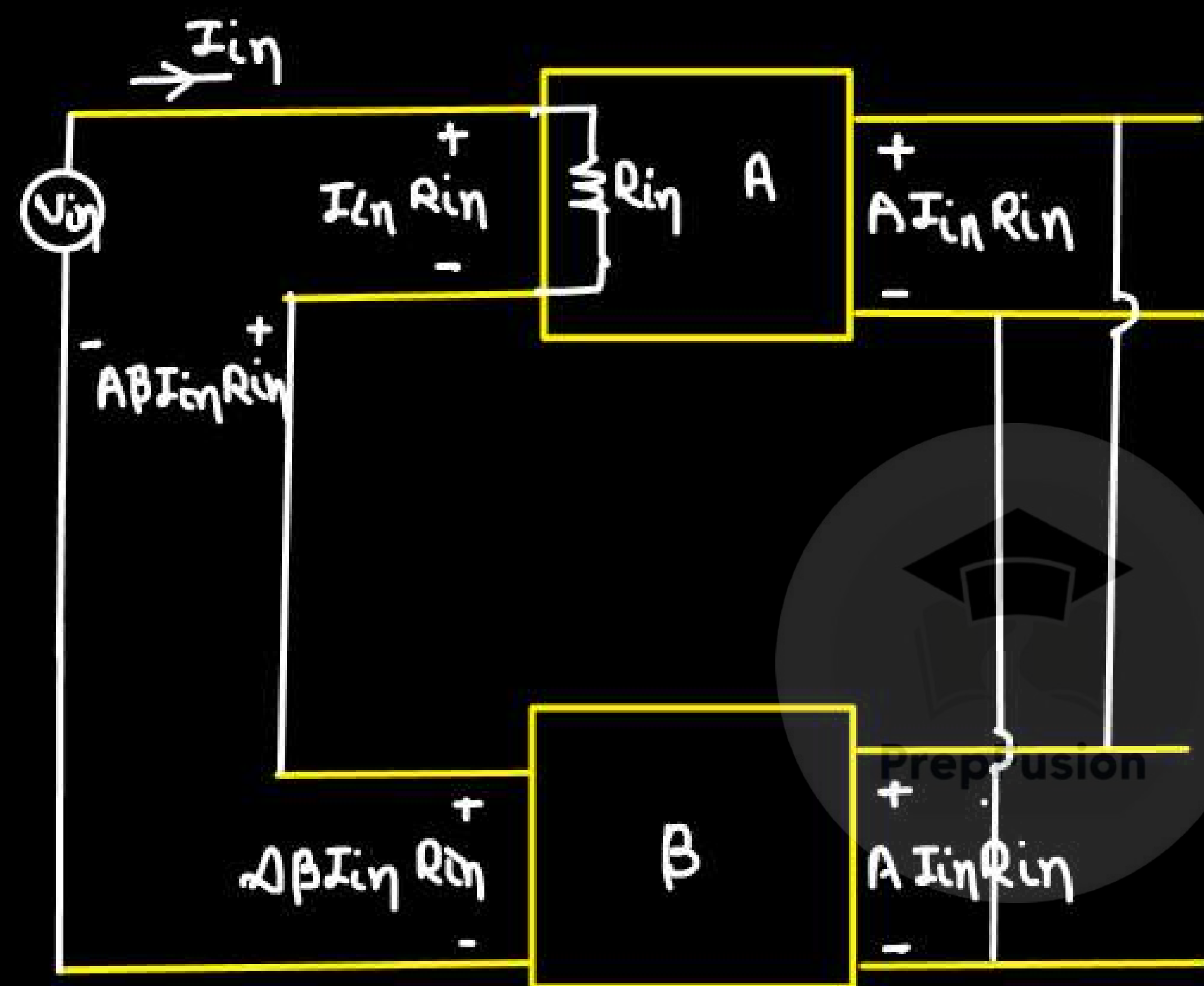


$$CLG = \frac{v_{in}}{v_o} = (A_v)_f$$

$$A(v_{in} - \beta V_o) = V_o$$

$$\boxed{\frac{V_o}{v_{in}} = (A_v)_f = \frac{A}{1+A\beta}}$$

② Closed loop input impedance :-



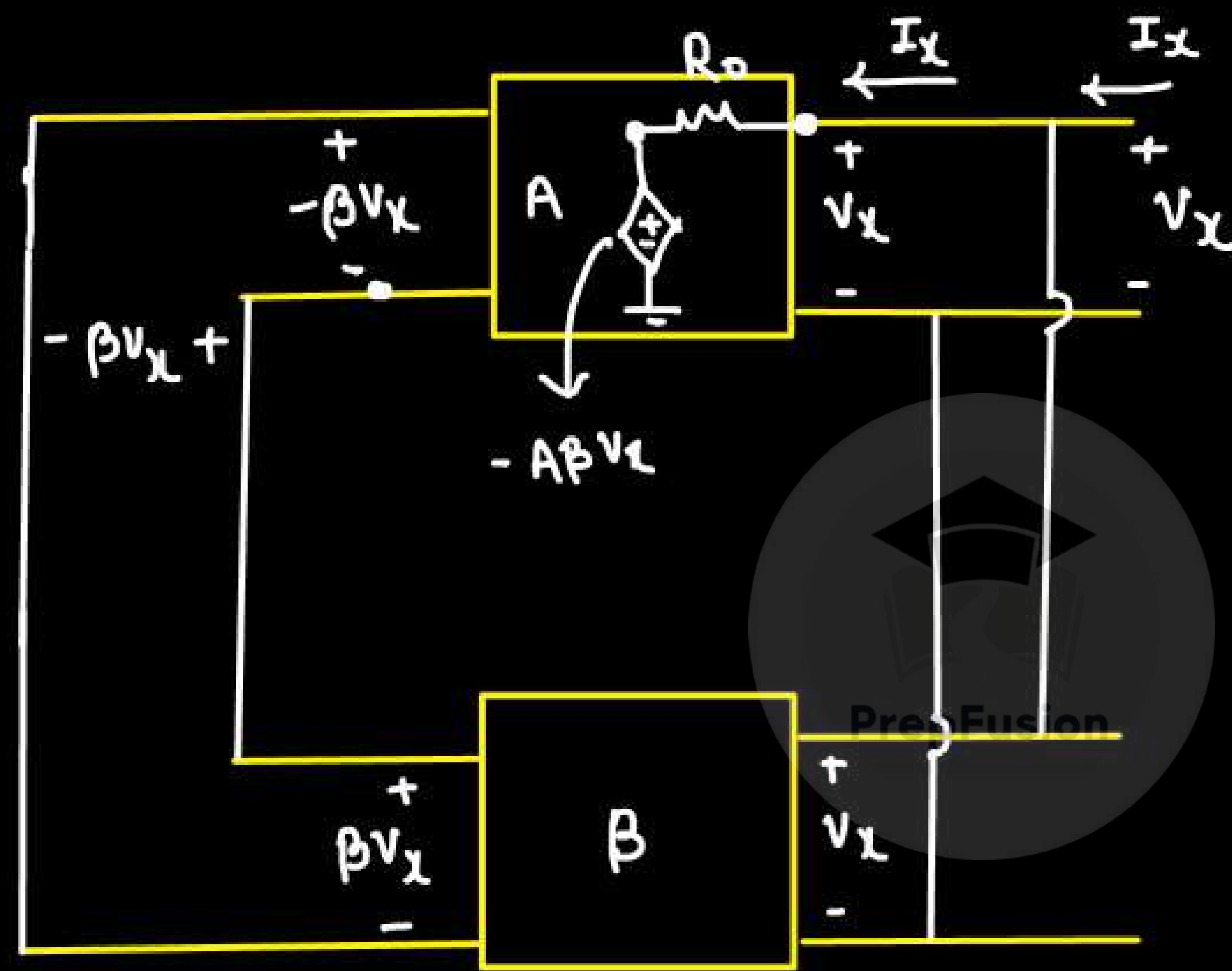
$$(R_{in})_f = \frac{V_{in}}{I_{in}}$$

$$V_{in} = I_{in}R_{in} + A\beta\, I_{in}R_{in}$$

$$\boxed{\frac{V_{in}}{I_{in}} = (R_{in})_f = R_{in}(1 + A\beta)}$$

③ Closed - Loop Output Impedance :-

$$(R_o)_f = \frac{V_x}{I_x}$$



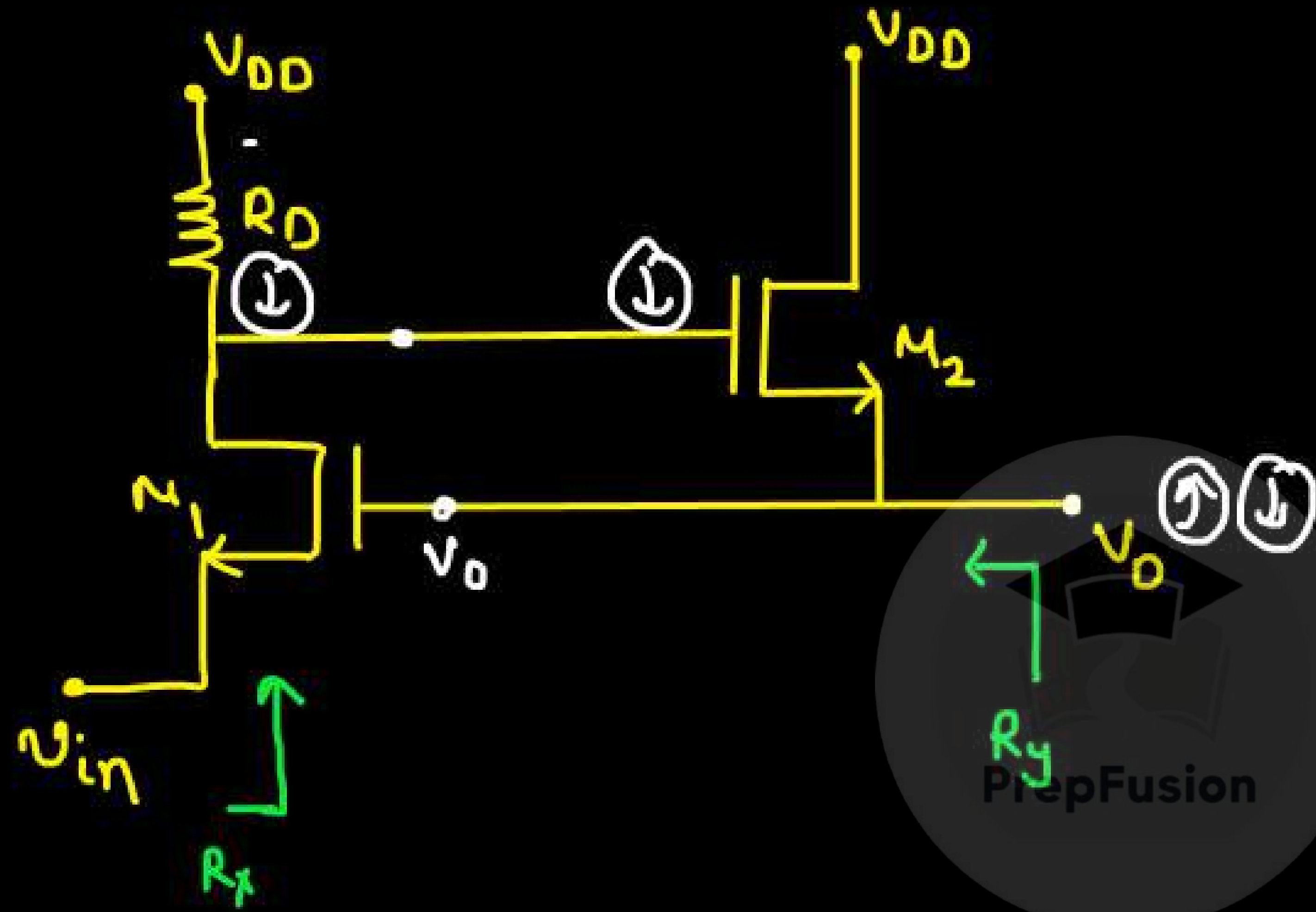
Assumption:-

R_o is very small, so complete I_x will be flowing through R_o. (Not in f/b path)

$$\frac{V_x - (-A\beta V_x)}{R_o} = I_x \Rightarrow \boxed{(R_o)_f = \frac{V_x}{I_x} = \frac{R_o}{1+A\beta}}$$

Example:-

Q.



Take $\lambda = 0$

Find R_x, R_y and $\frac{v_o}{v_i} = ?$

$\Rightarrow$ $\boxed{\text{Negative f/b}}$

Topology → Voltage-voltage f/b

★ Short-cut to find f/b Topology:-

① For sampling, always look at o/p voltage

if there is voltage sampling

$v_f = \beta v_o$, $I_f = G_m v_o$

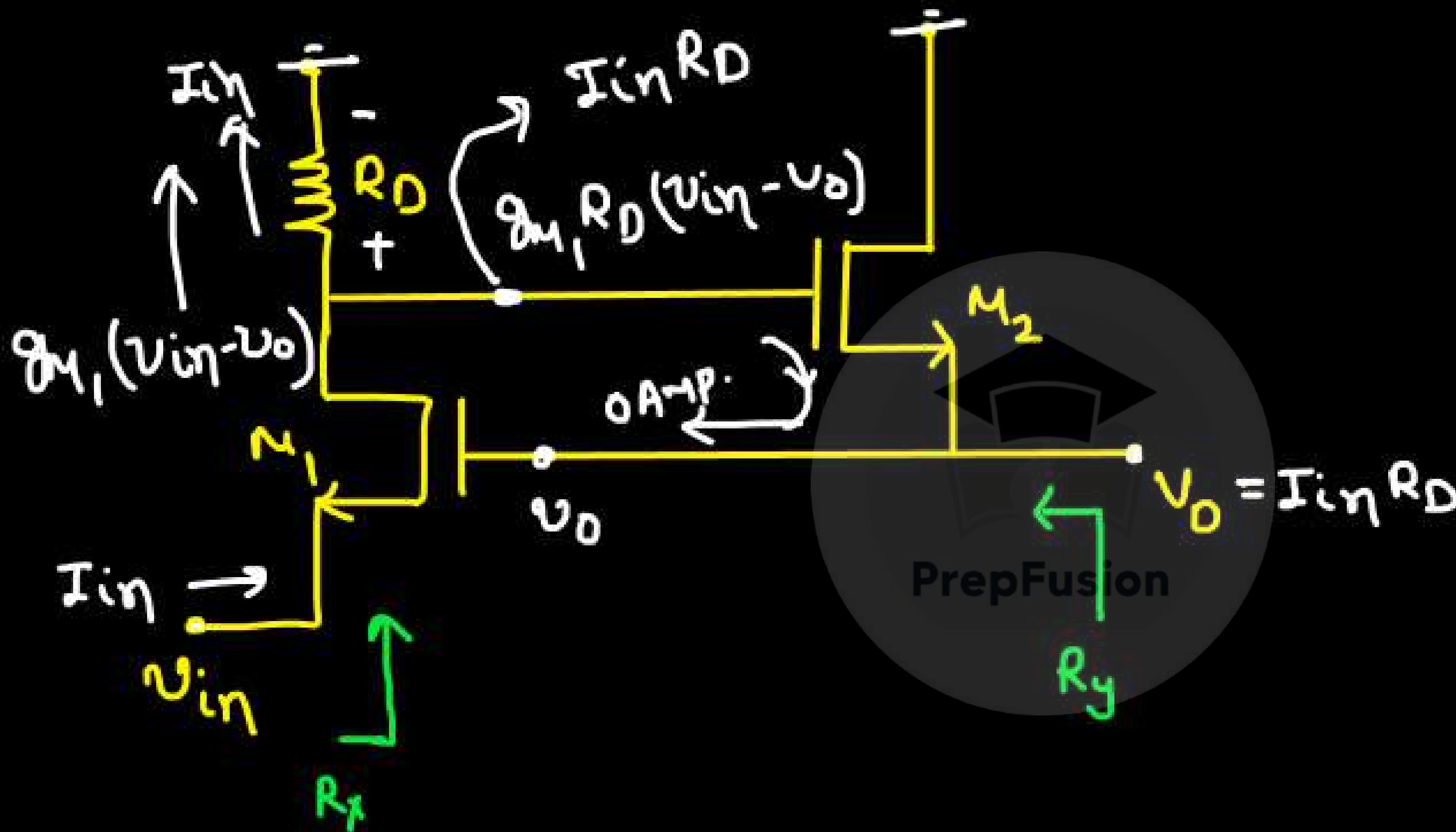
if we put $v_o = 0\,V$ ⇒ There should be no f/b that is coming towards the i/p side.

⇒ if that is so, that means there is voltage sampling

o/w current sampling

② For mixing, always check the i/p current. If current is mixed, then there is current mixing, o/w voltage mixing.

M-I w/o the concept of f/b topology :-



$$g_{m_1} R_D (v_{in} - v_o) = v_o$$

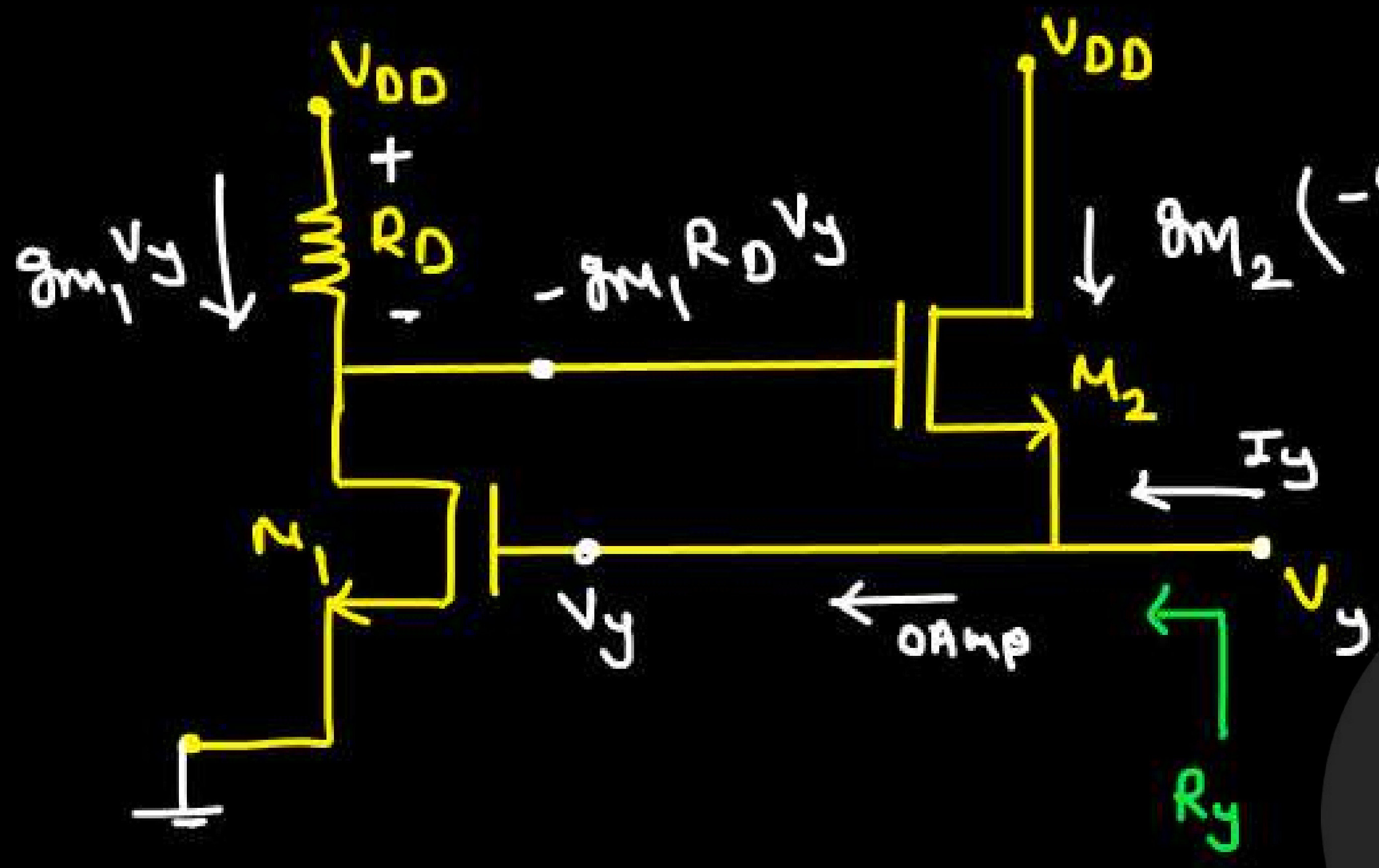
$$\boxed{\frac{v_o}{v_{in}} = \frac{g_m R_D}{1 + g_m R_D}}$$

$$R_x = \frac{v_{in}}{I_{in}}$$

$$g_{m_1}(v_{in} - I_{in} R_D) = I_{in}$$

$$g_{m_1} v_{in} = (g_{m_1} R_D + 1) I_{in}$$

$$\boxed{\frac{v_{in}}{I_{in}} = R_x = \frac{1}{g_{m_1}}(1 + g_{m_1} R_D)}$$

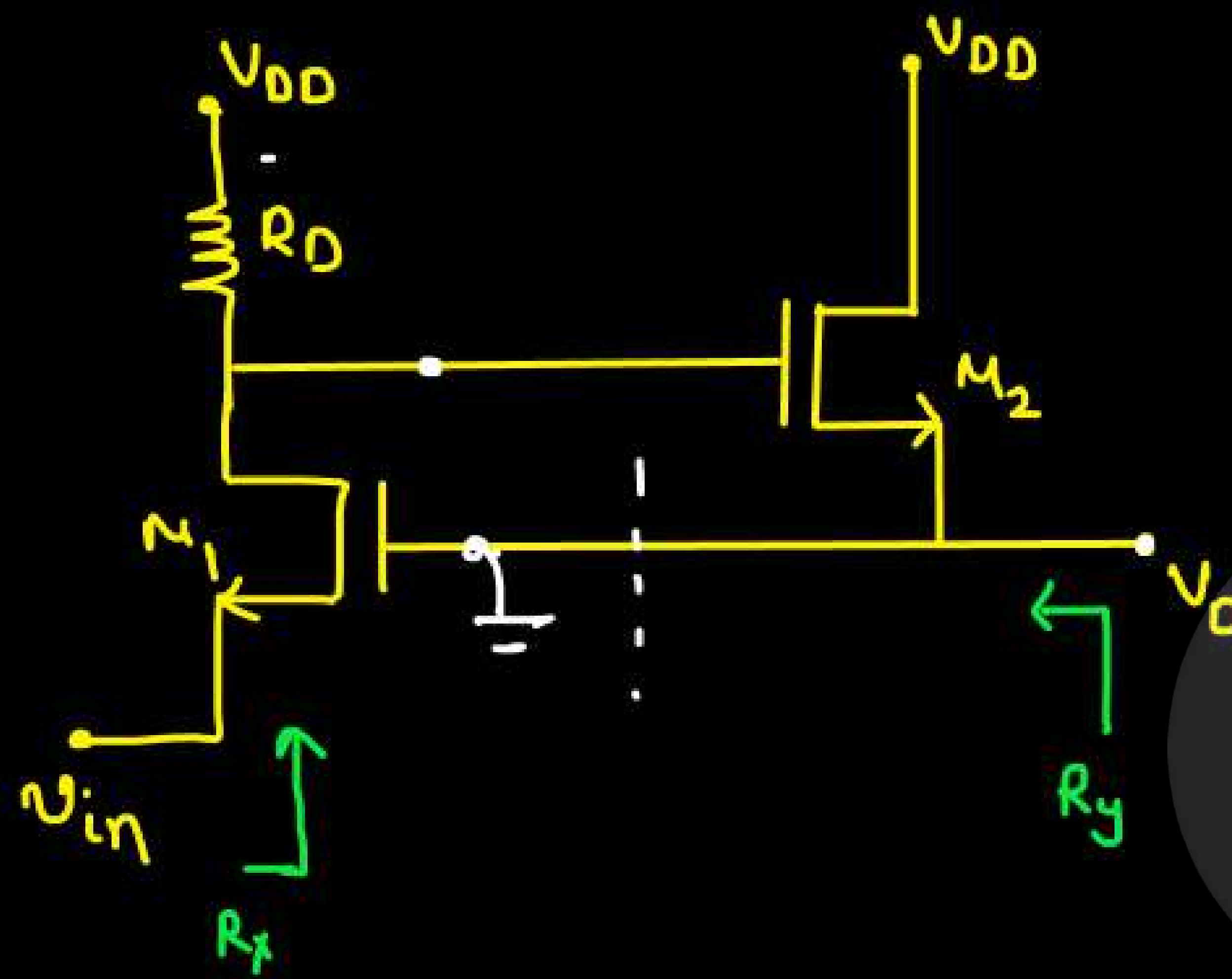


$$-g_{m2}(-g_{m1}R_DV_y - V_y) = I_y$$

$$g_{m2}(g_{m1}R_D + 1)V_y = I_y$$

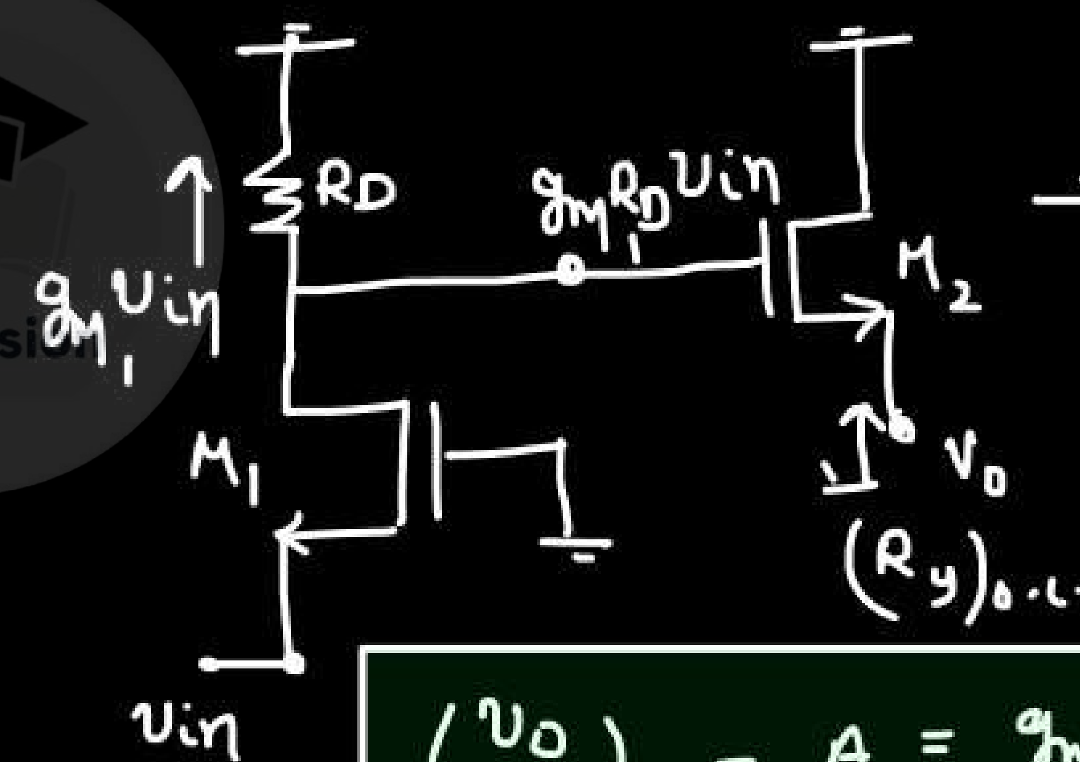
$$\boxed{R_y = \frac{V_y}{I_y} = \frac{1/g_{m2}}{1 + g_{m1}R_D}}$$

★ with the concept of feedback Topology :-

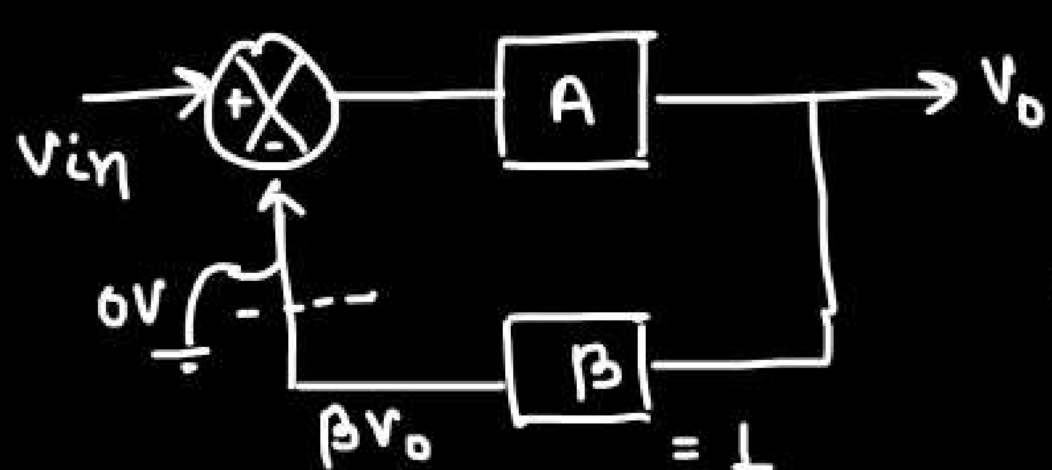


⇒ Voltage - Voltage f/b

★ open loop gain = ? = A



→ open loop



$$\boxed{\left(R_x\right)_{o.L.} = \frac{1}{g_{m_1}}}$$

$$\boxed{\left(\frac{v_o}{v_i}\right)_{o.L.} = A = g_{m_1} R_D}$$

$$\boxed{\beta = 1}$$

$$\boxed{\left(R_y\right)_{o.L.} = 1/g_{m_2}}$$

For voltage - voltage f/b Topology :-
(in case of Neg. f/b)

① Close loop gain $\boxed{(A_v)_f = \dfrac{A}{1+A\beta} = \dfrac{g_{m_1} R_D}{1+g_{m_1} R_D}}$

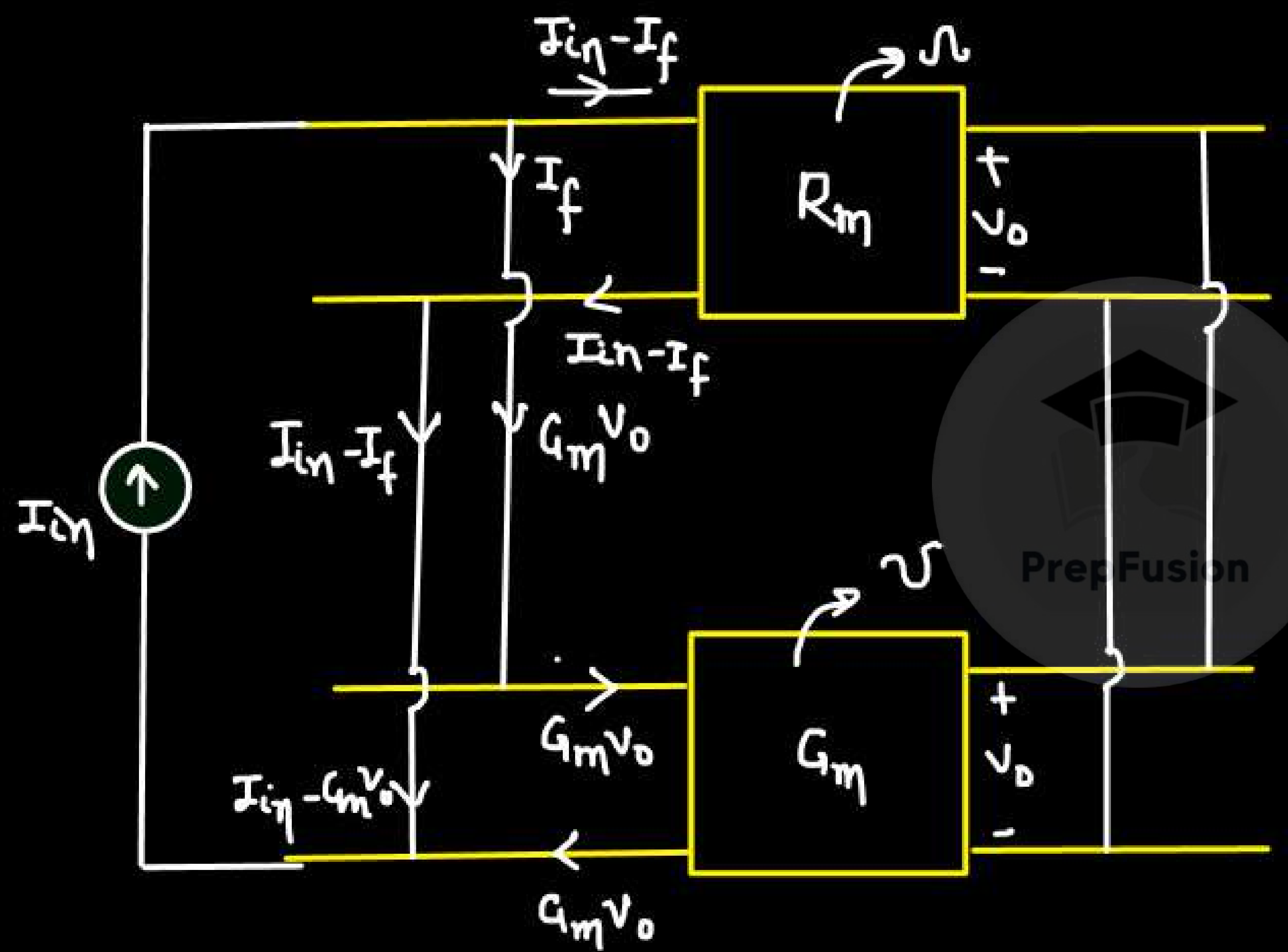
② Close loop input impedance $R_x = (R_x)_{o.l.}(1+A\beta)$

$$\boxed{R_x = \frac{1}{g_{m_1}}(1+g_{m_1} R_D)}$$

③ Closed loop o/p impedance $\boxed{R_y = \dfrac{(R_y)_{o.L.}}{1+A\beta} = \dfrac{1/g_{m_2}}{1+g_{m_1} R_D}}$

★ Voltage - Current f/b :-

(Shunt - Shunt)

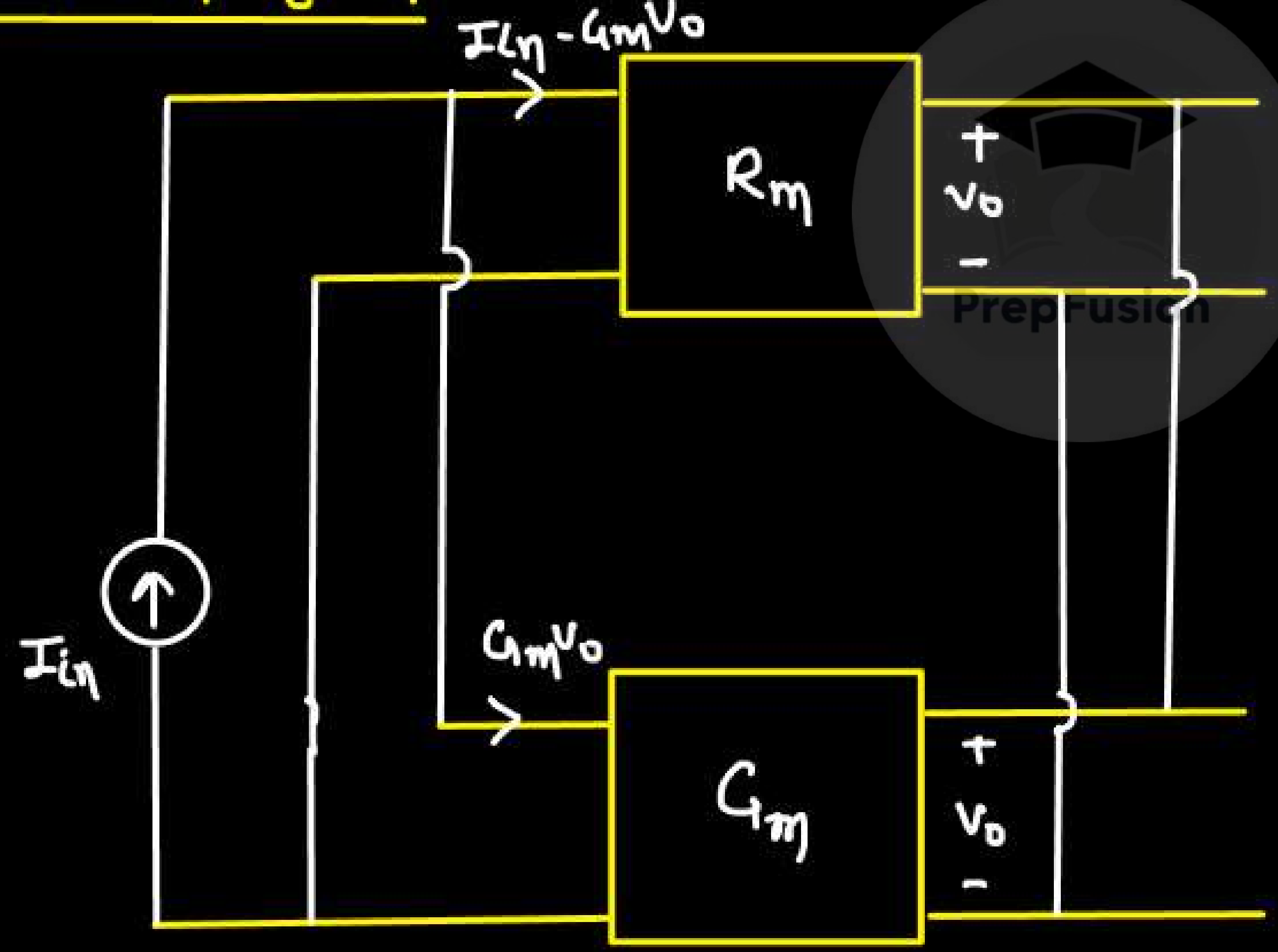


Open loop gain → R_m (Ω)

Open loop input impedance → R_{in}

Open loop output impedance → R_o

① Closed loop gain :-



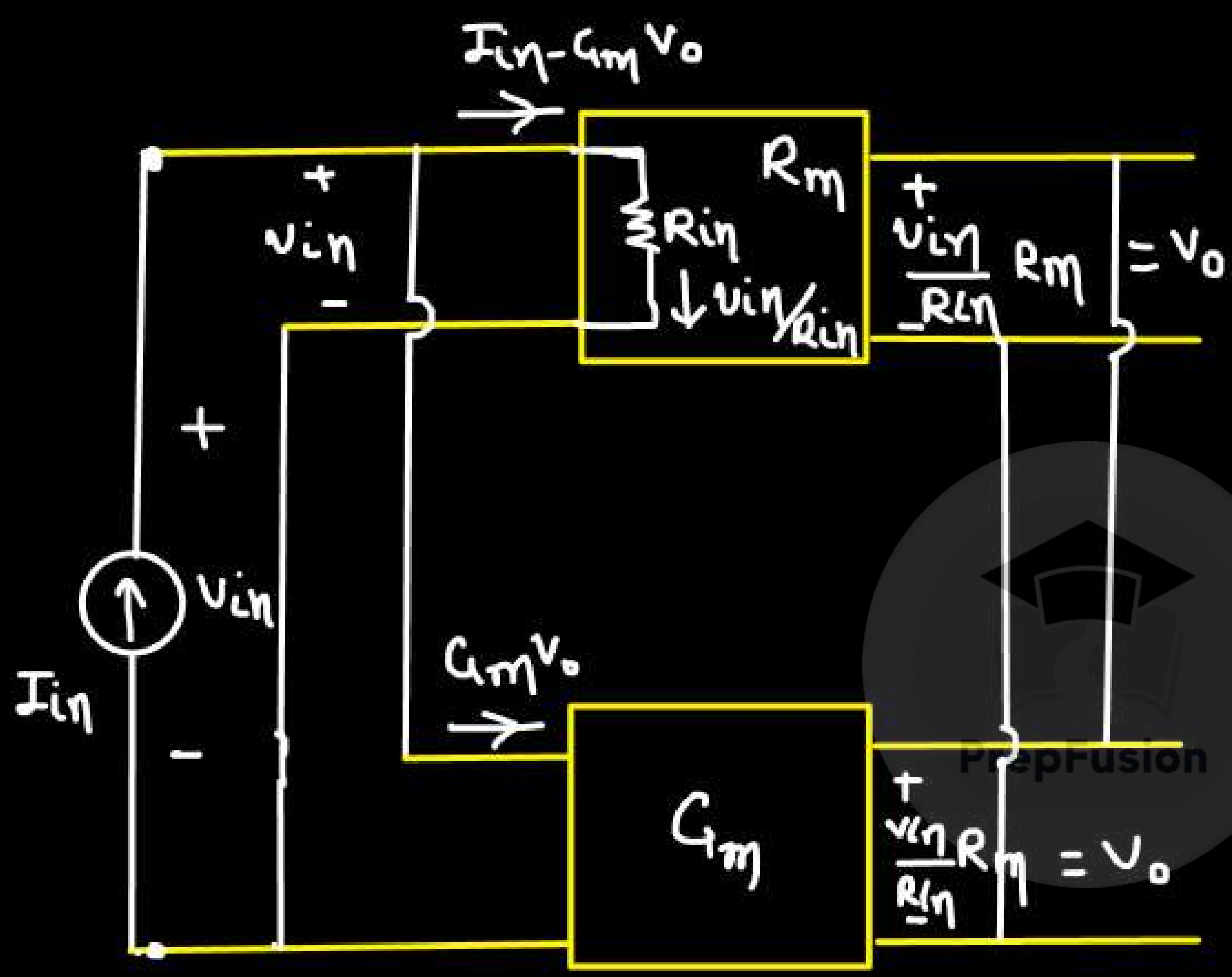
closed loop gain

$$\boxed{(A_R)_f = \frac{V_o}{I_{in}}}$$

$$(I_{in} - G_m V_o) R_m = V_o$$

$$\boxed{\frac{V_o}{I_{in}} = (A_R)_f = \frac{R_m}{1 + G_m R_m}}$$

② Closed loop input Resistance:-



$$(R_{in})_f = \frac{v_{in}}{I_{in}}$$

$$\frac{v_{in}}{R_{in}} = I_{in} - G_m V_o$$

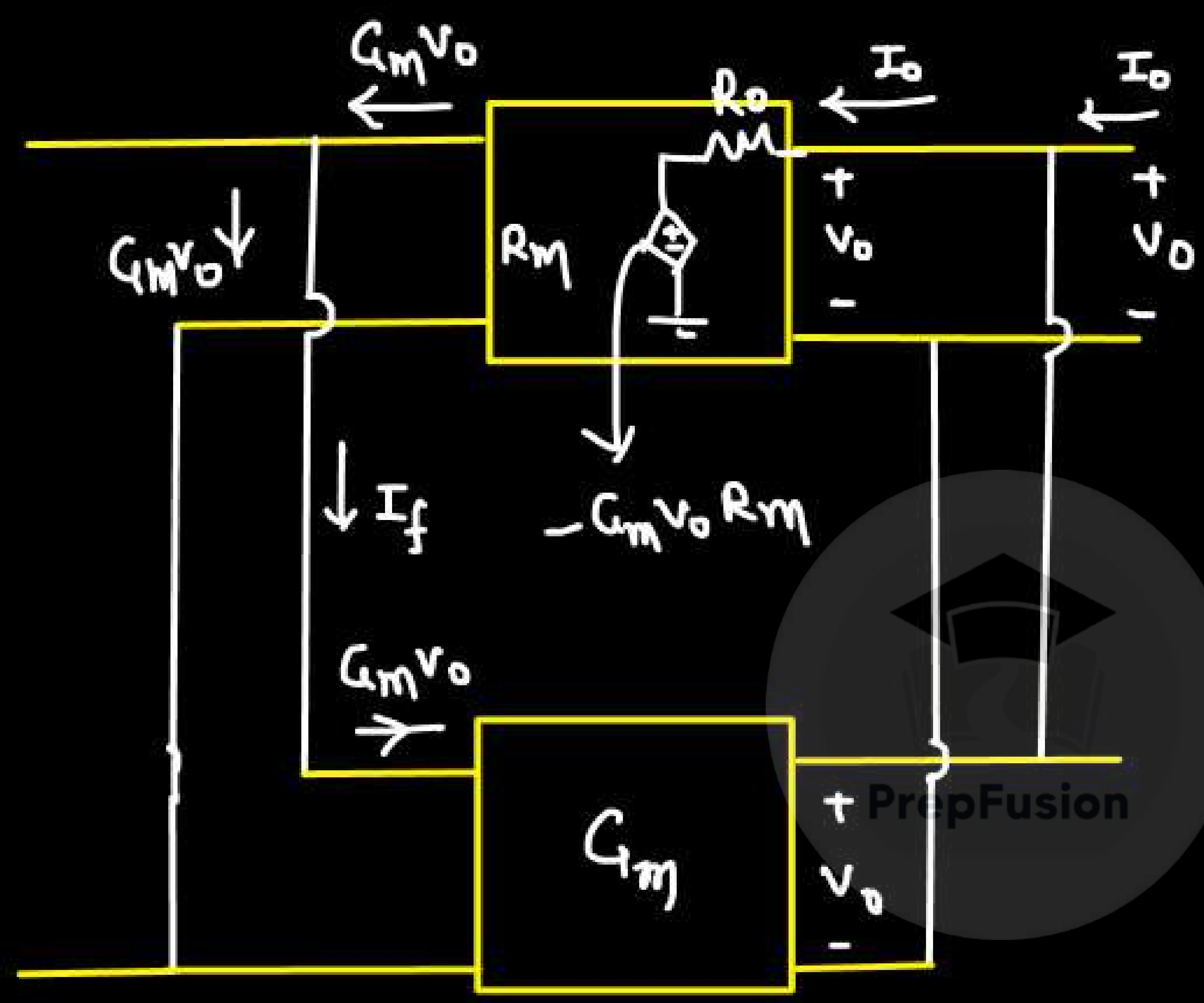
$$\frac{v_{in}}{R_{in}} = I_{in} - \frac{G_m v_{in}}{R_{in}} R_m$$

$$v_{in}[1 + G_m R_m] = R_{in} I_{in}$$

**

$$\boxed{(R_{in})_f = \frac{R_{in}}{1 + G_m R_m}}$$

③ Closed loop Output Impedance:-



$$(R_o)_f = \frac{V_o}{I_o}$$

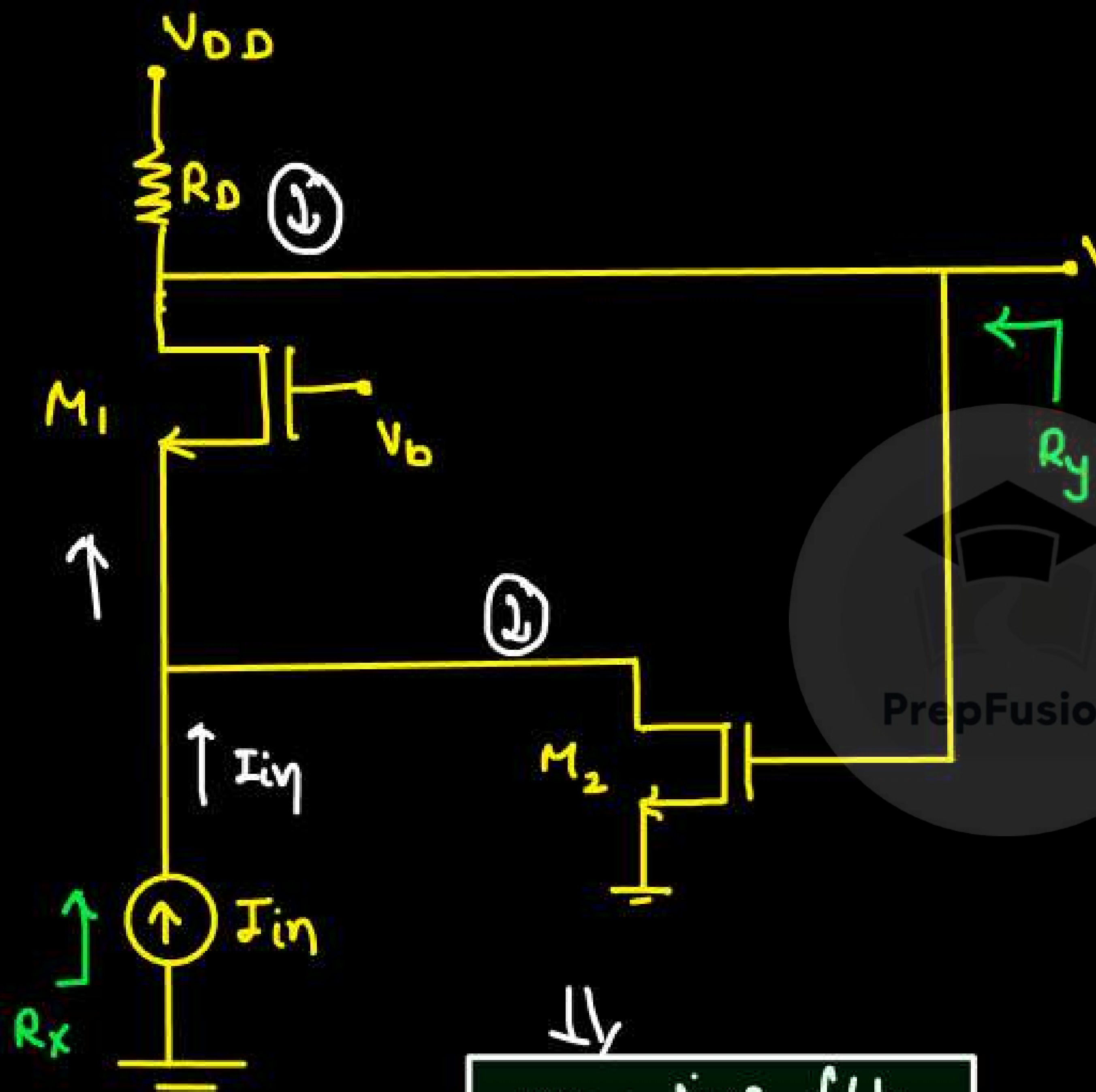
Assumption:-

Complete I_o is flowing through R_o.

$$\frac{V_o + G_m V_o R_m}{R_o} = I_o$$

$$\boxed{\frac{V_o}{I_o} = (R_o)_f = \frac{R_o}{1 + G_m R_m}}$$

Eg:-



Take $\lambda = 0$

① Find $\frac{v_o}{I_{in}}$?

② Find R_x and R_y.

$\Downarrow$

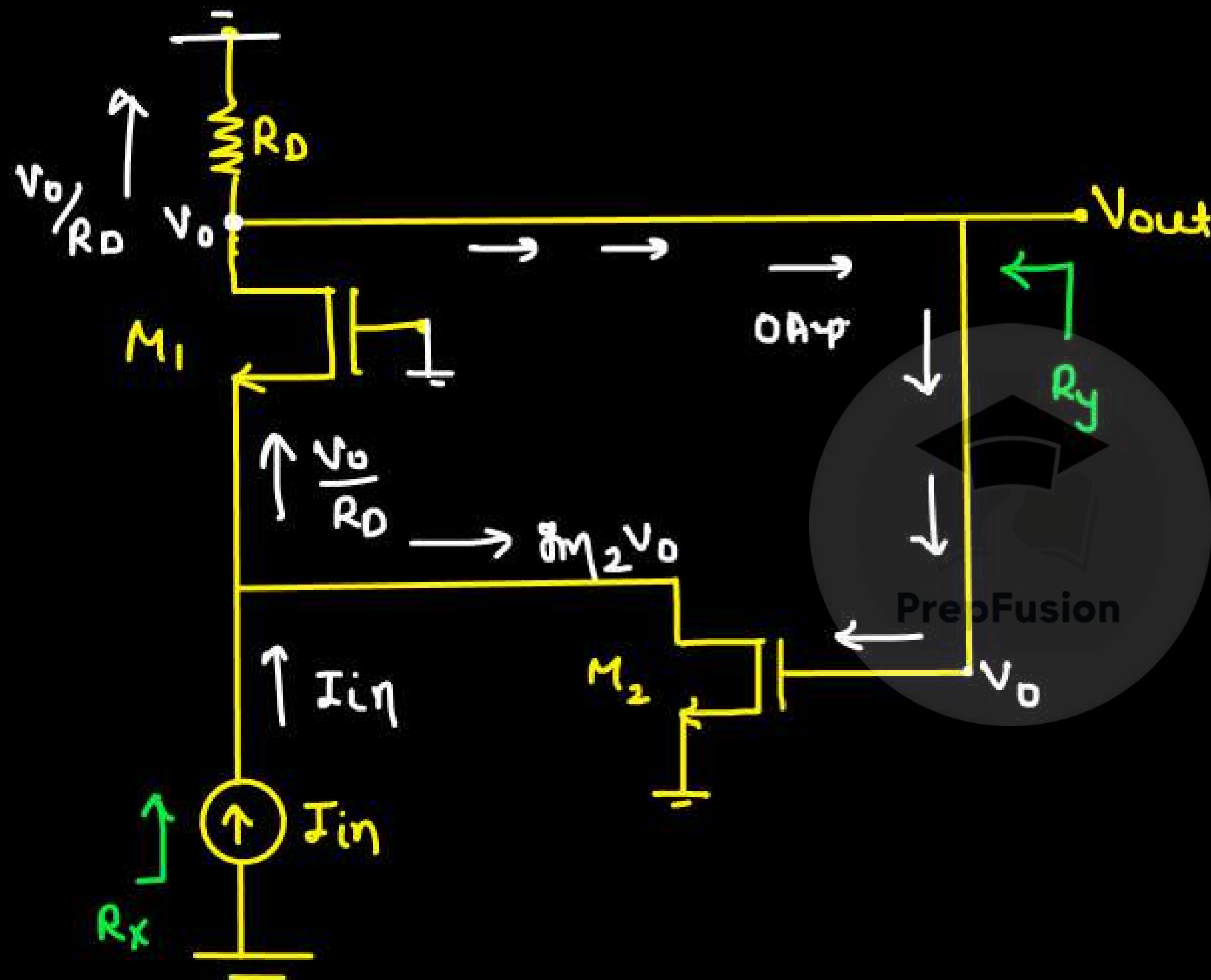
$\boxed{\text{Negative f/b}}$

current mixing

voltage sampling

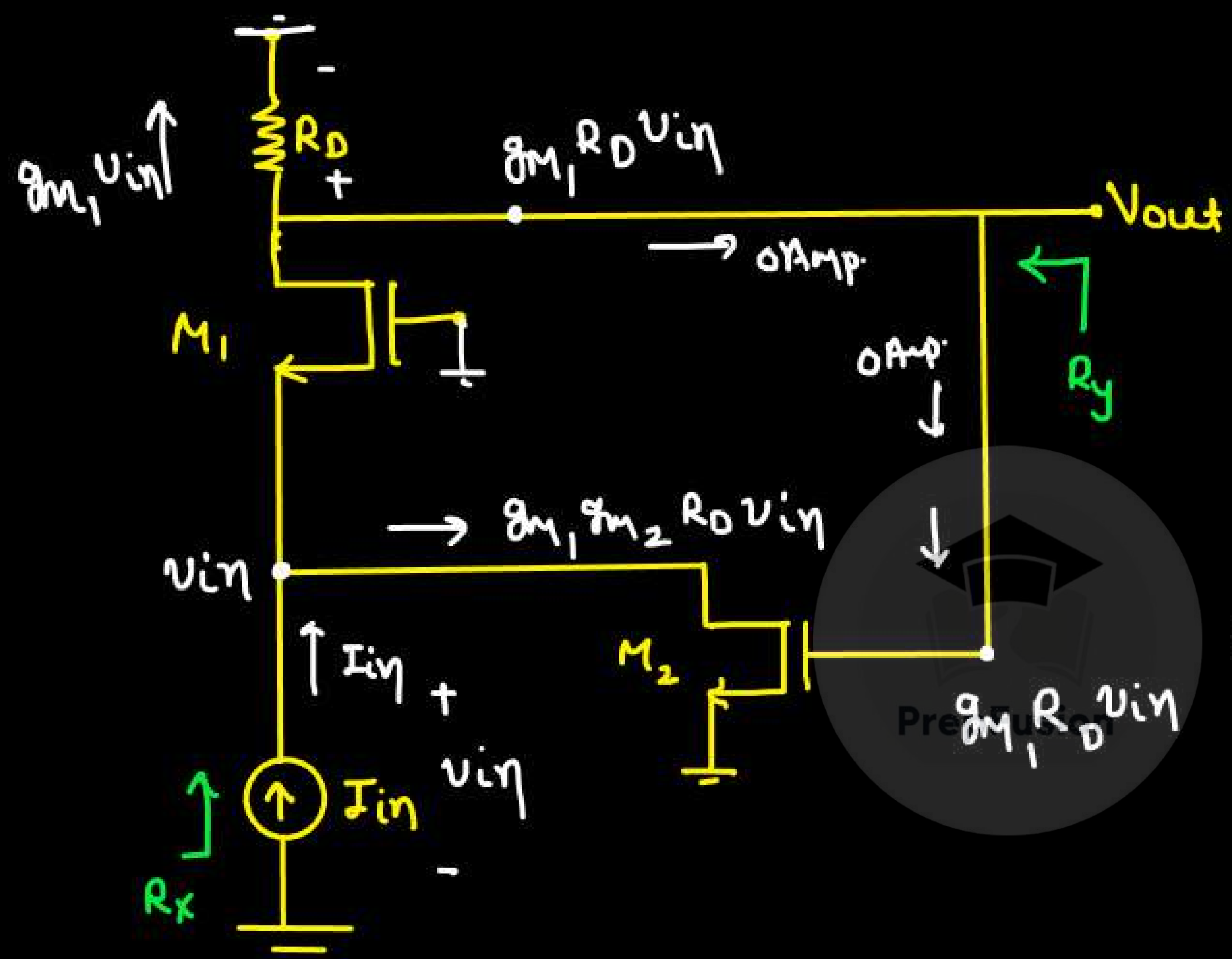
$\Rightarrow$ $\boxed{\text{Voltage Current f/b}}$

M-I w/o using the concept of f/b



(1) $I_{in} = g_{m_2} v_o + \frac{v_o}{R_D}$

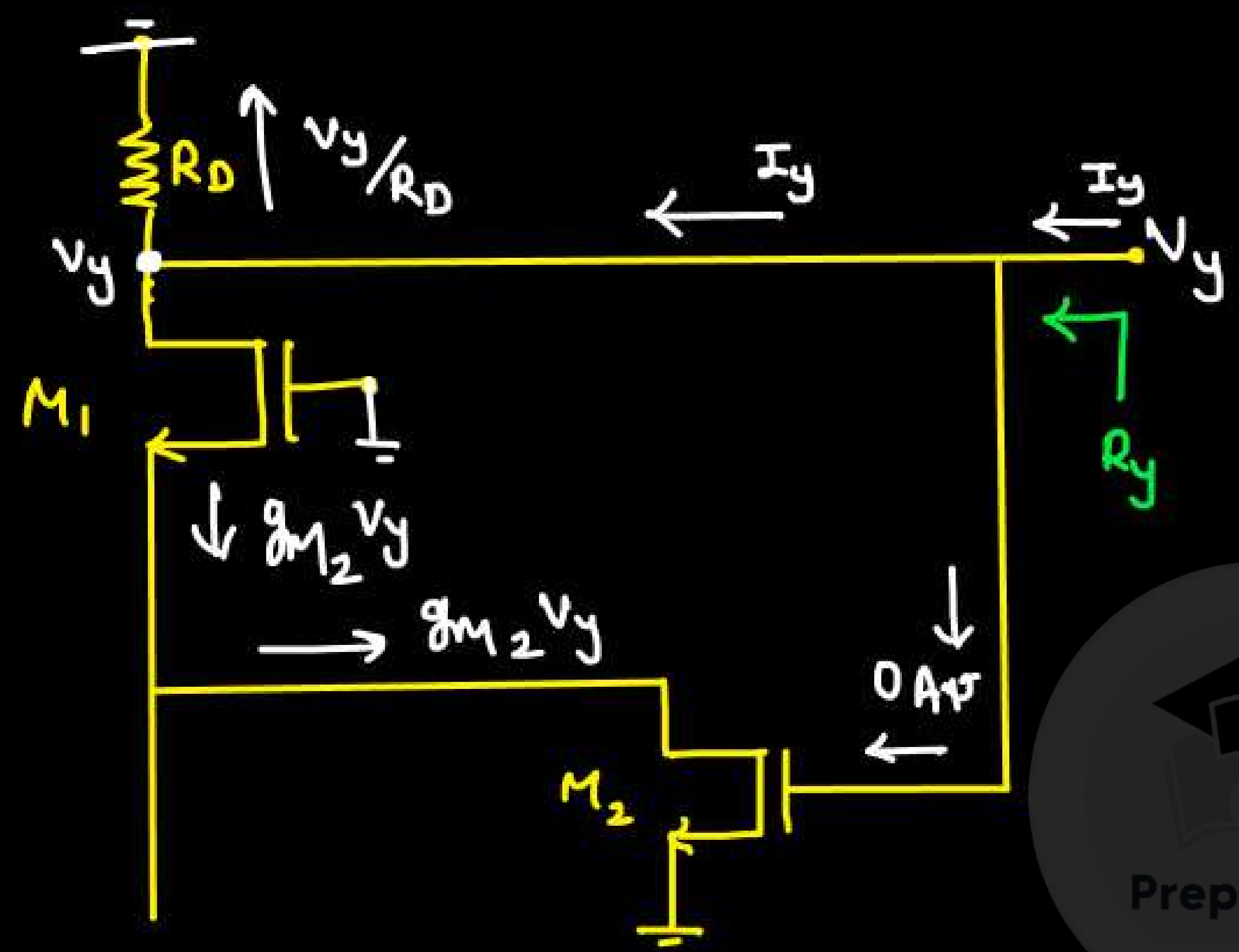
$$\boxed{\frac{V_o}{I_{in}} = \frac{R_D}{g_{m_2} R_D + 1}}$$



$$R_x = \frac{v_{in}}{I_{in}}$$

$$I_{in} = g_{m1} v_{in} + g_{m1} g_{m2} R_D v_{in}$$

$$\boxed{\frac{v_{in}}{I_{in}} = \frac{1/g_{m1}}{1 + g_{m2} R_D}}$$

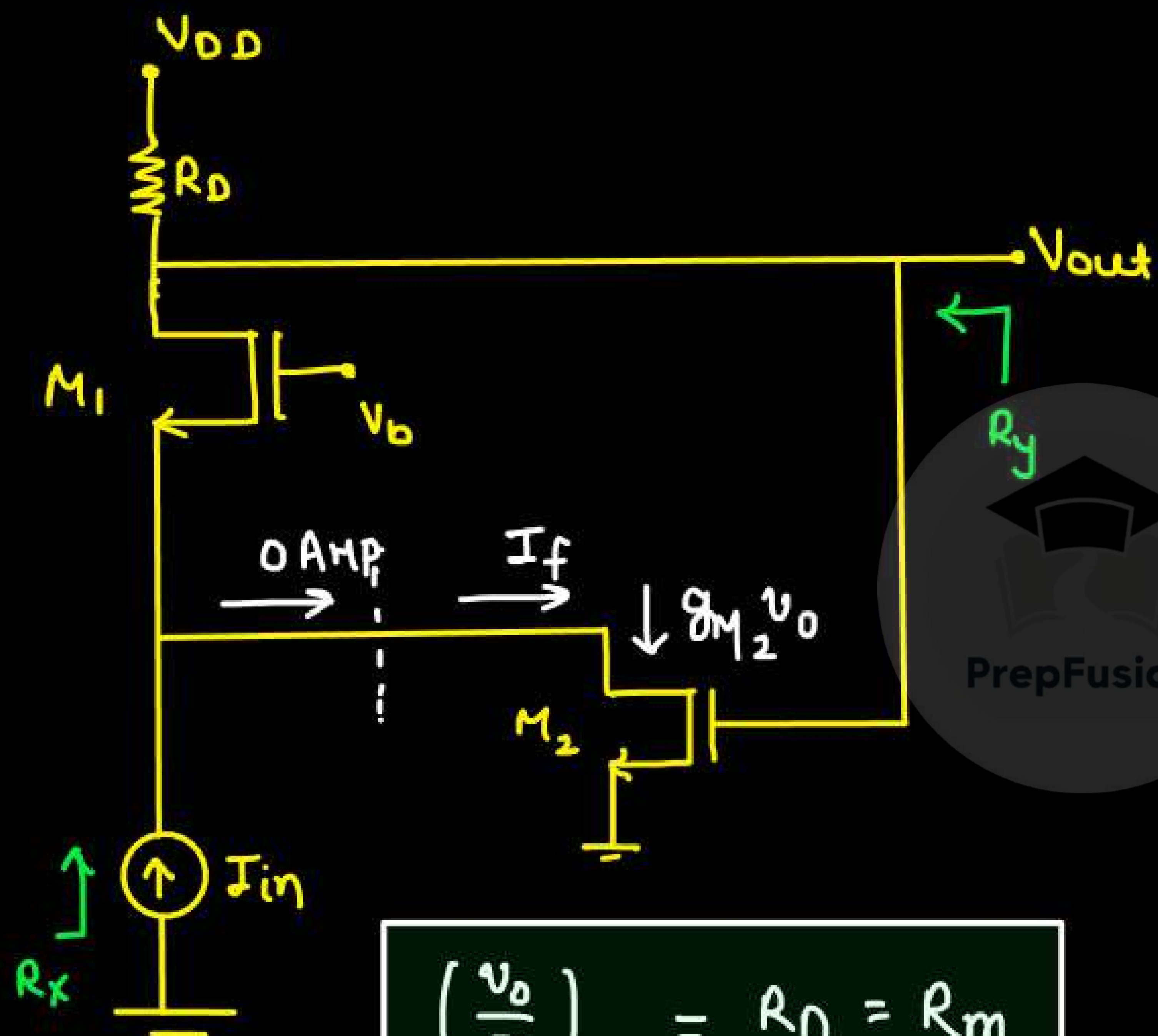


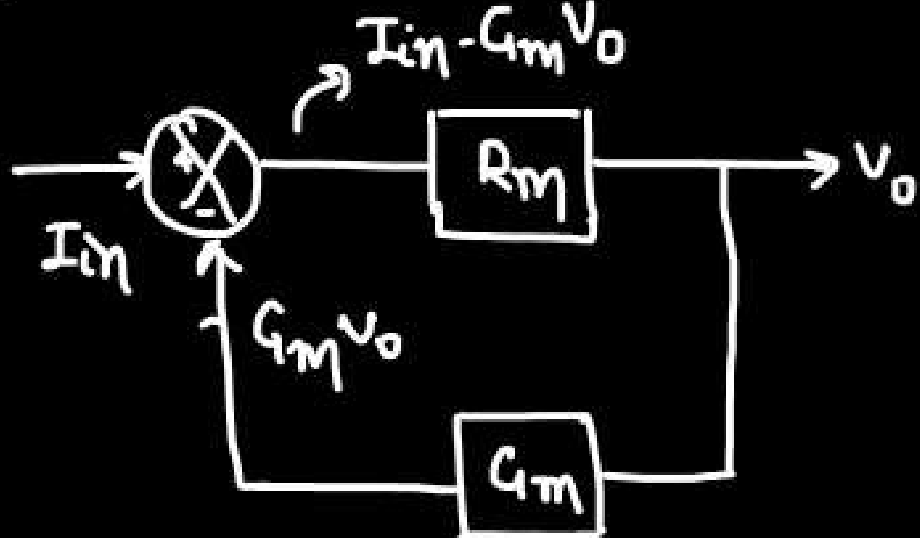
$$I_y = \frac{V_y}{R_D} + g_{m_2} V_y$$

$$\boxed{R_y = R_D \parallel \frac{1}{g_{m_2}}}$$

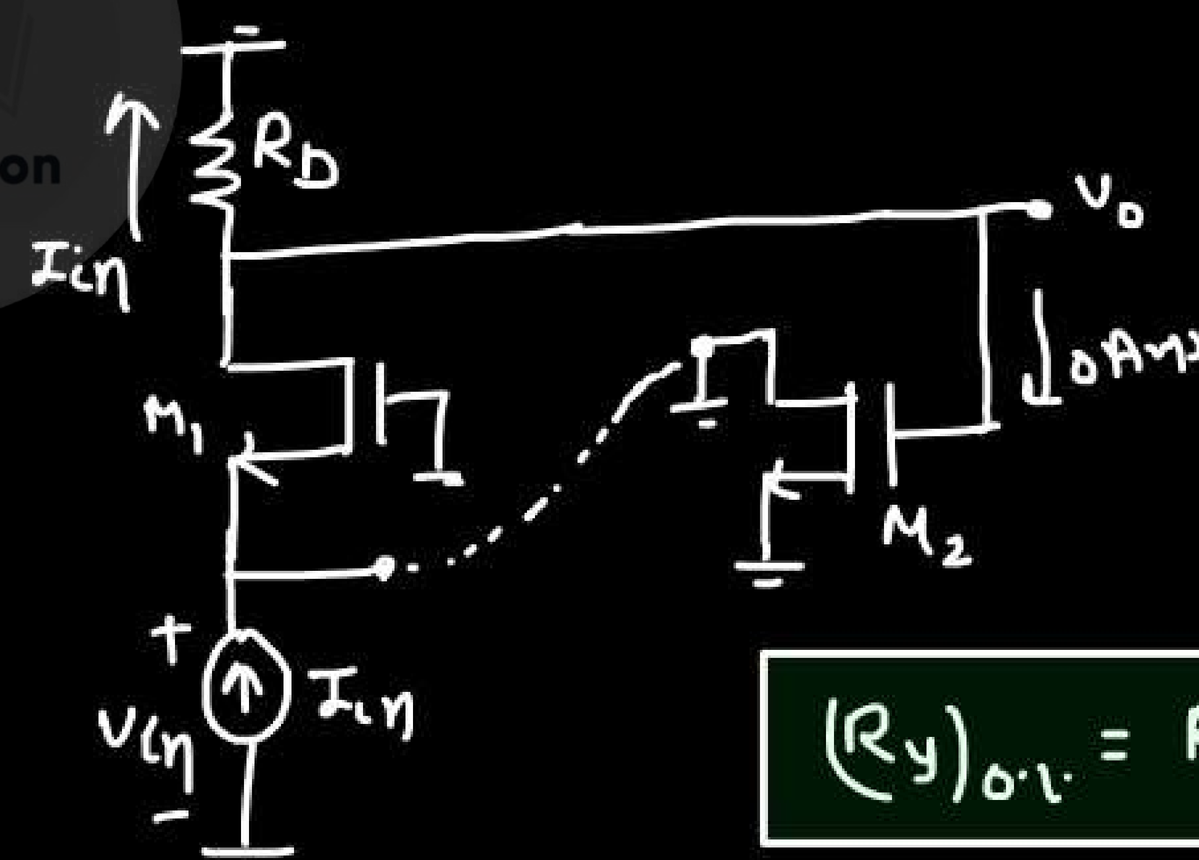
$$\boxed{R_y = \frac{R_D}{1 + g_{m_2} R_D}}$$

M-II with the concept of f/b topology :-





open-loop →



$$\left(\frac{v_o}{I_{in}}\right)_{O.L.} = R_D = R_m$$

$$(R_x)_{O.L.} = 1/g_{m_1}$$

$$(R_y)_{O.L.} = R_D$$

$$I_f = g_{m_2} v_o$$

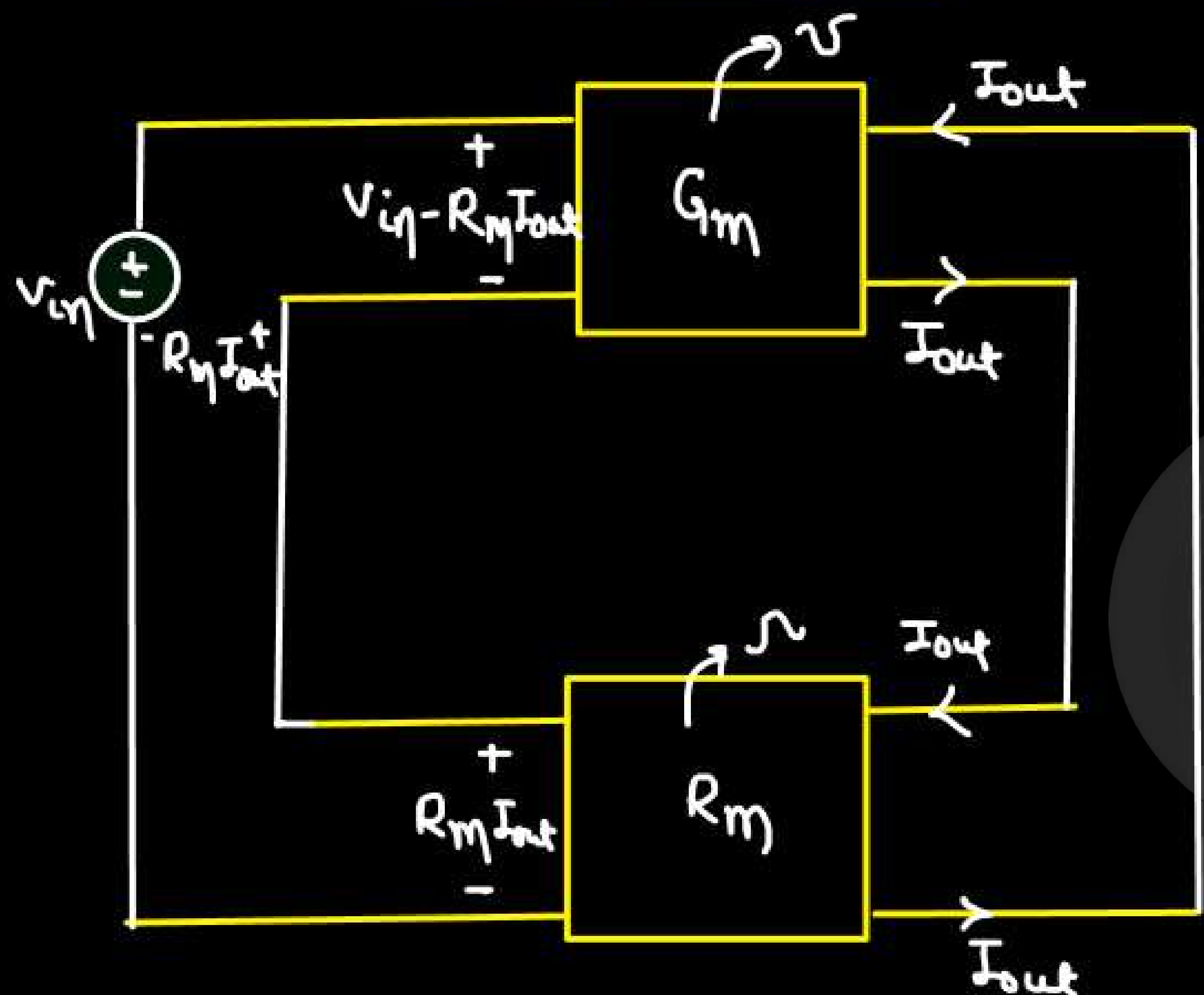
$$\boxed{\frac{I_f}{V_o} = G_m = g_{m_2}}$$

(1) $\boxed{\text{Closed loop gain} = \frac{R_m}{1+G_m R_m} = \frac{R_D}{1+g_{m_2} R_D}}$

(2) closed loop input impedance $\boxed{(R_{in})_f = \frac{1/g_{m_1}}{1+g_{m_2} R_D}}$

(3) $\boxed{(R_o)_f = \frac{R_D}{1+g_{m_2} R_D}}$

★ Current-Voltage feedback :- (series-Series)



open loop gain = G_m

open loop i/p impedance = R_{in}

open loop o/p impedance = R_o

① Closed loop gain = $\boxed{\dfrac{G_m}{1+G_mR_m}}$

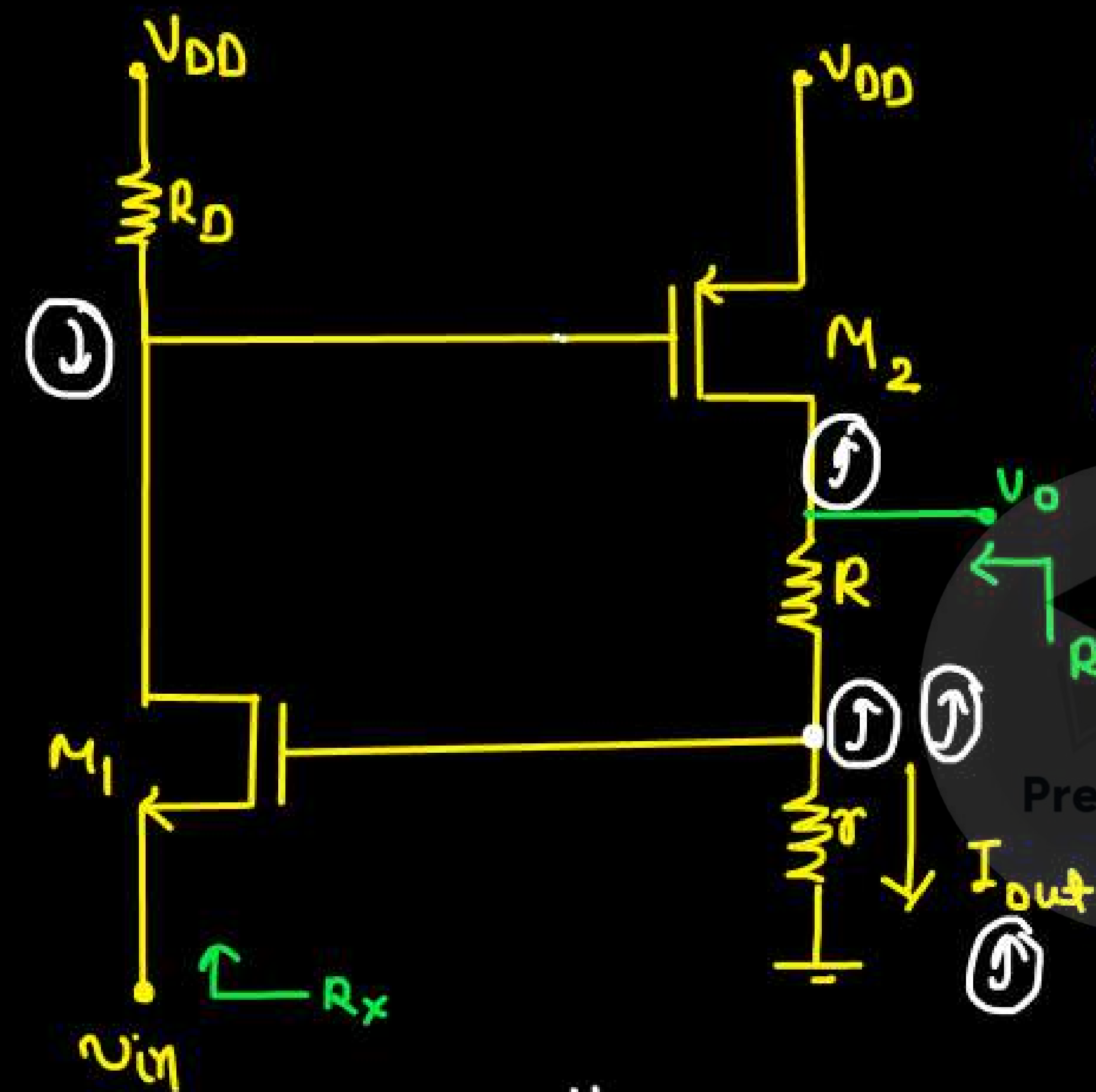
② Closed loop input impedance

$$\boxed{(R_i)_f = R_{in}(1+G_mR_m)}$$

③ Closed loop o/p impedance :-

$$\boxed{(R_o)_f = R_o(1+G_mR_m)}$$

Eg. →



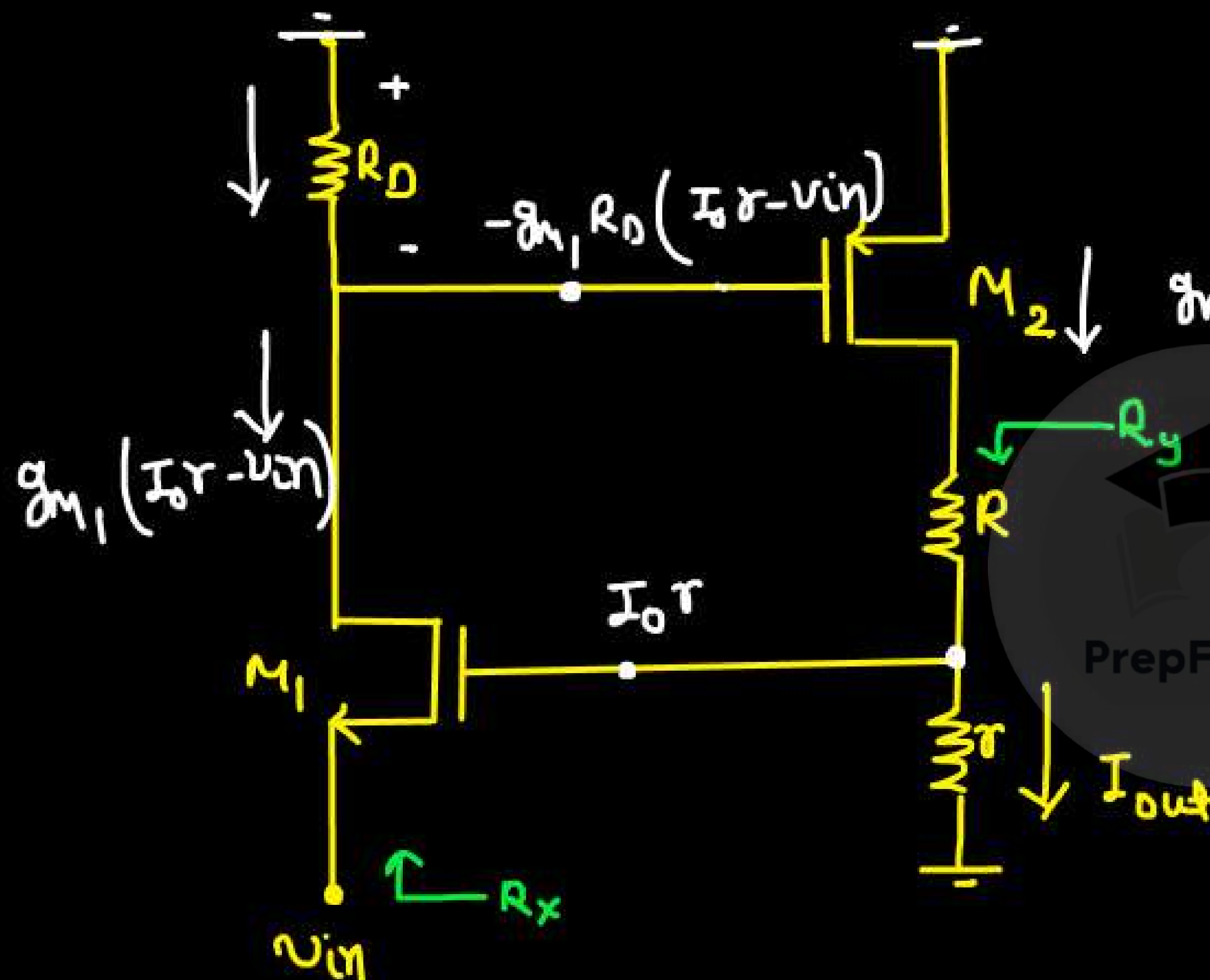
① Find $\frac{I_{out}}{v_{in}}$.

② Find R_x and R_y.

⇓

$\boxed{\text{positive f/b}}$

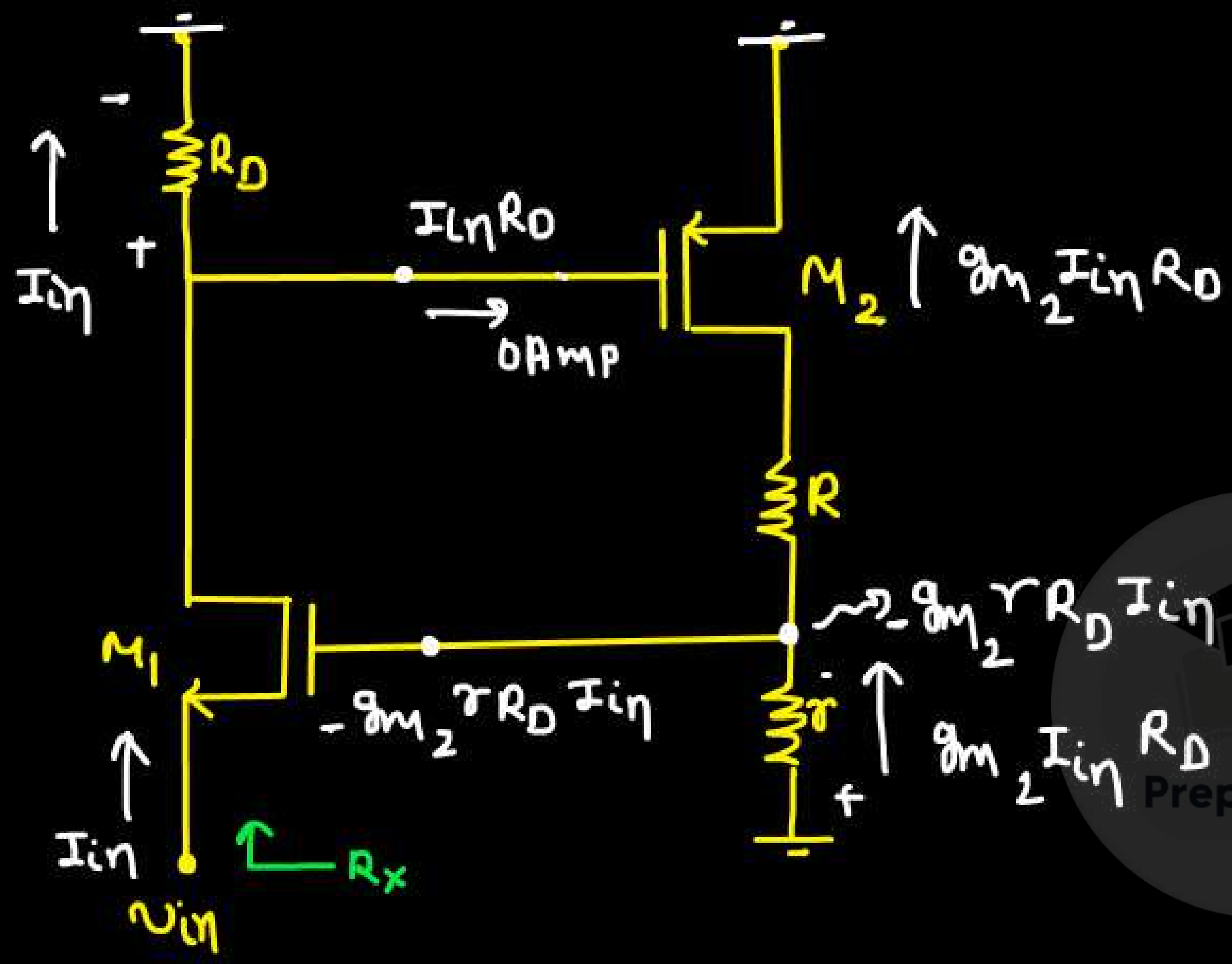
M·I w/o the concept of feedback:-



$$g_{m_2} g_{m_1} R_D (I_o r - v_{in}) = I_o$$

$$g_{m_2} g_{m_1} R_D r I_o - I_o = g_{m_1} g_{m_2} R_D v_{in}$$

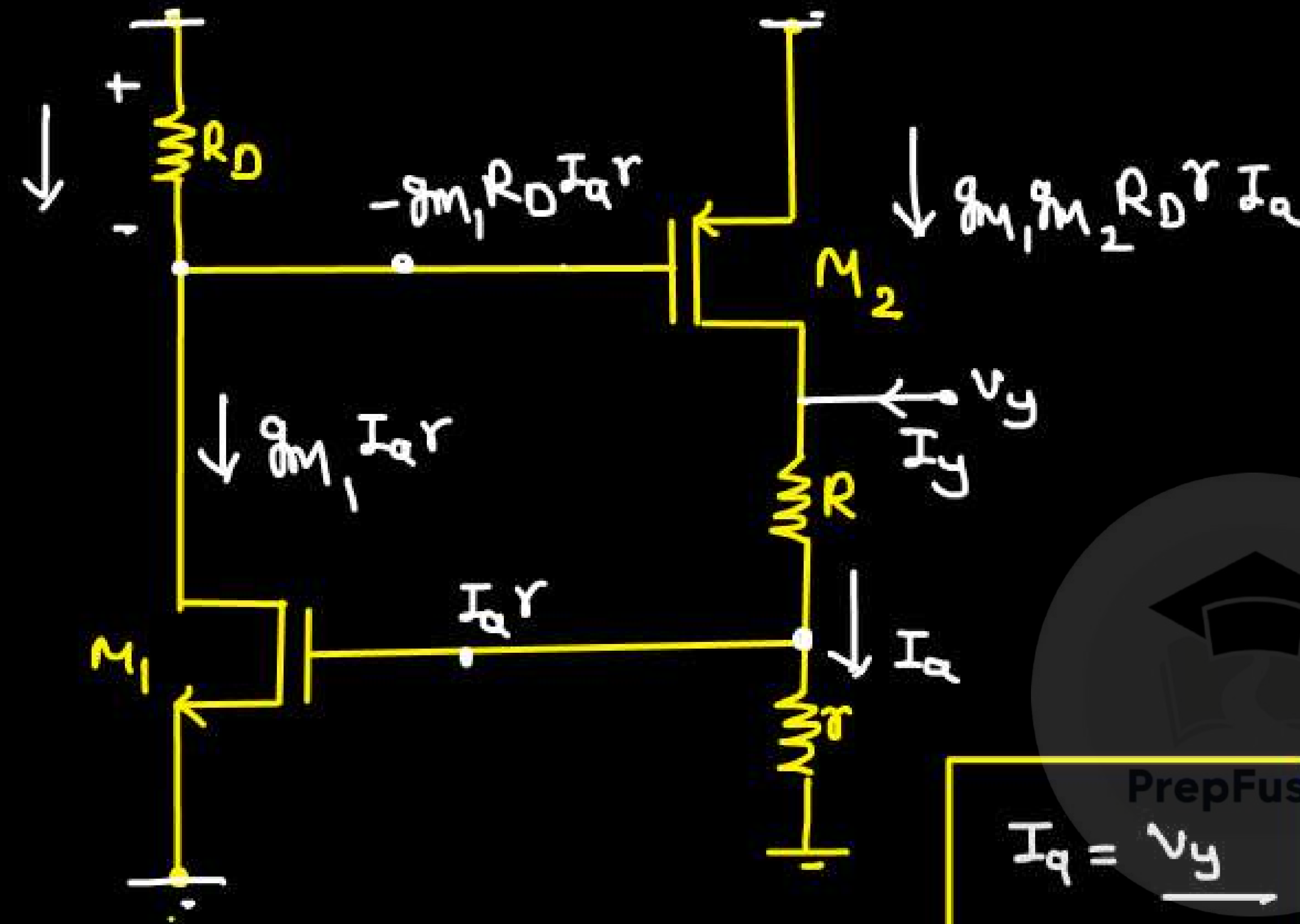
$$\boxed{\frac{I_o}{v_{in}} = \frac{-g_{m_1} g_{m_2} R_D}{1 - g_{m_1} g_{m_2} R_D r}}$$



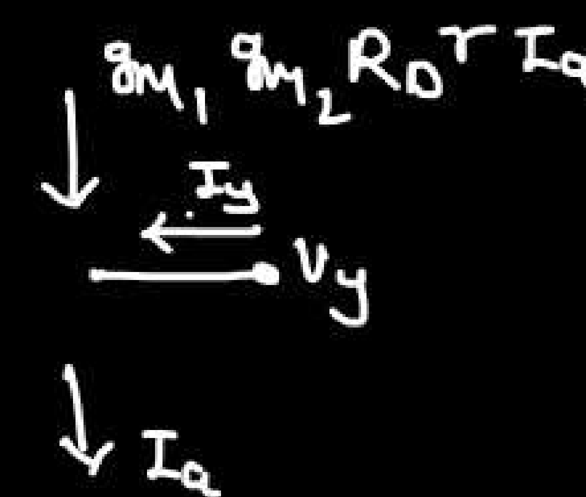
$$g_{m_1}\left(v_{in} + g_{m_2} r R_D I_{in}\right) = I_{in}$$

$$g_{m_1} v_{in} = I_{in}\left[1 - g_{m_1} g_{m_2} r R_D\right]$$

$$\boxed{\frac{v_{in}}{I_{in}} = \left[1 - g_{m_1} g_{m_2} r R_D\right] \frac{1}{g_{m_1}}}$$



$$R_y = \frac{V_y}{I_y}$$



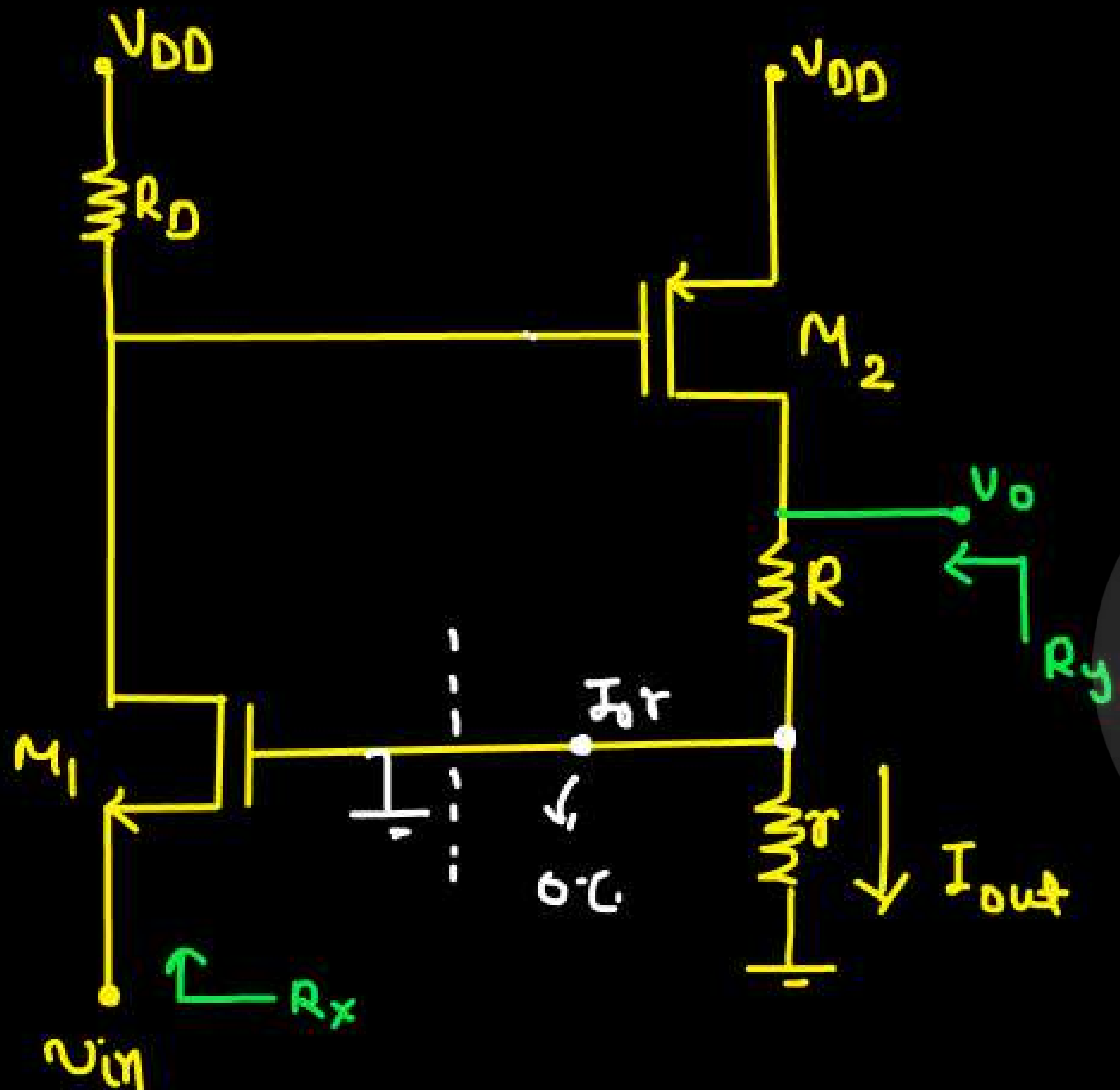
$$I_a = \frac{V_y}{r+R}$$

$$I_y + \frac{g_{m_1} g_{m_2} R_D r V_y}{r+R} = \frac{V_y}{r+R}$$

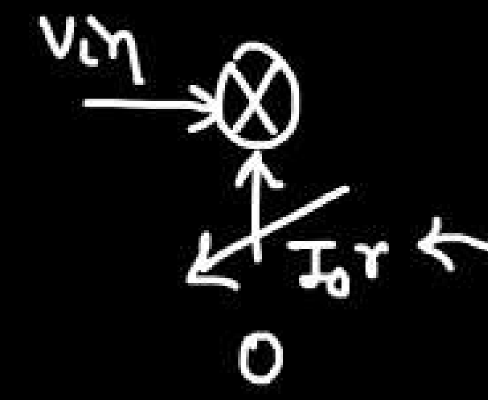
$$I_y = \left(\frac{1 - g_{m_1} g_{m_2} R_D r}{r+R}\right) V_y$$

$$\frac{V_y}{I_y} = R_y = \frac{r+R}{1 - g_{m_1} g_{m_2} R_D r}$$

M-I with the concept of f/b Topology:-

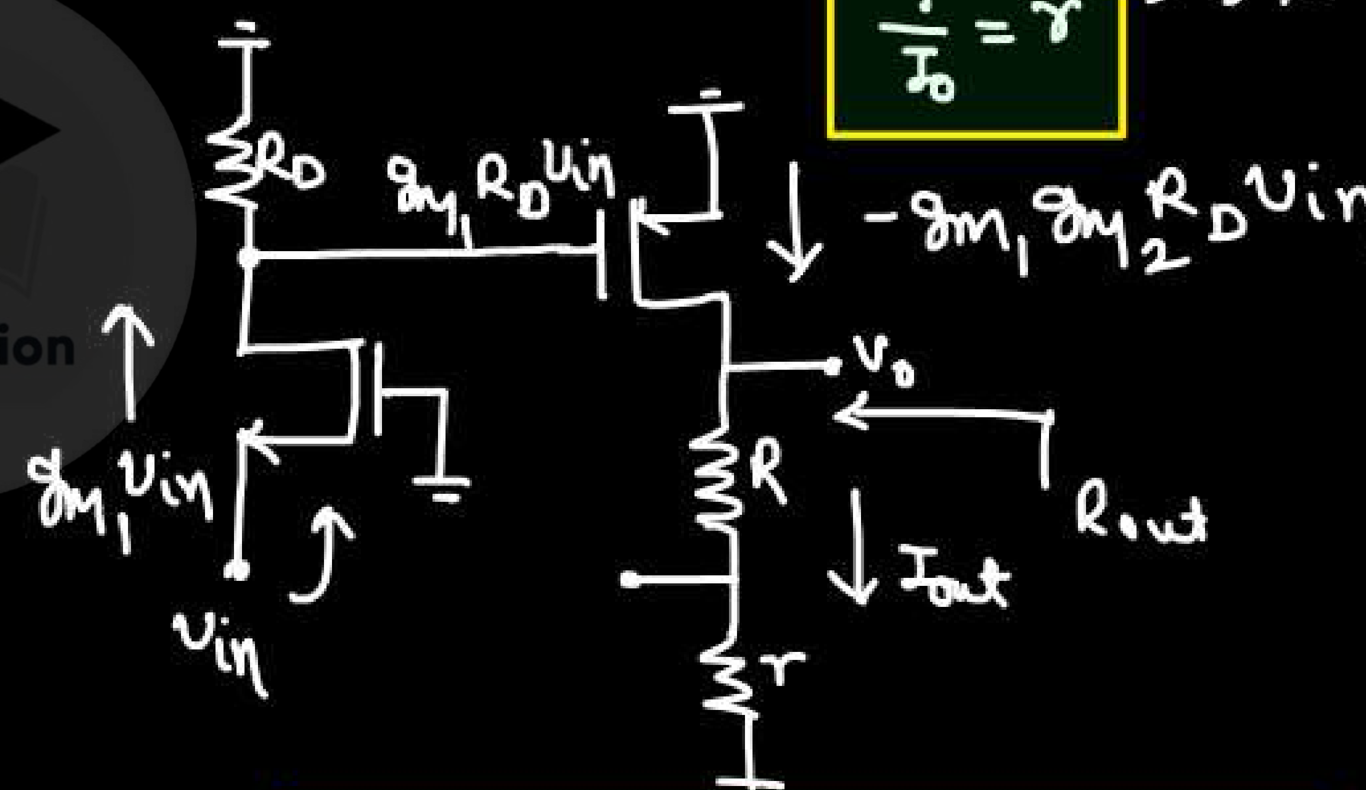


$\Rightarrow$



$v_f = I_o r$

$\boxed{\frac{v_f}{I_o} = r} \rightarrow$ F/b factor



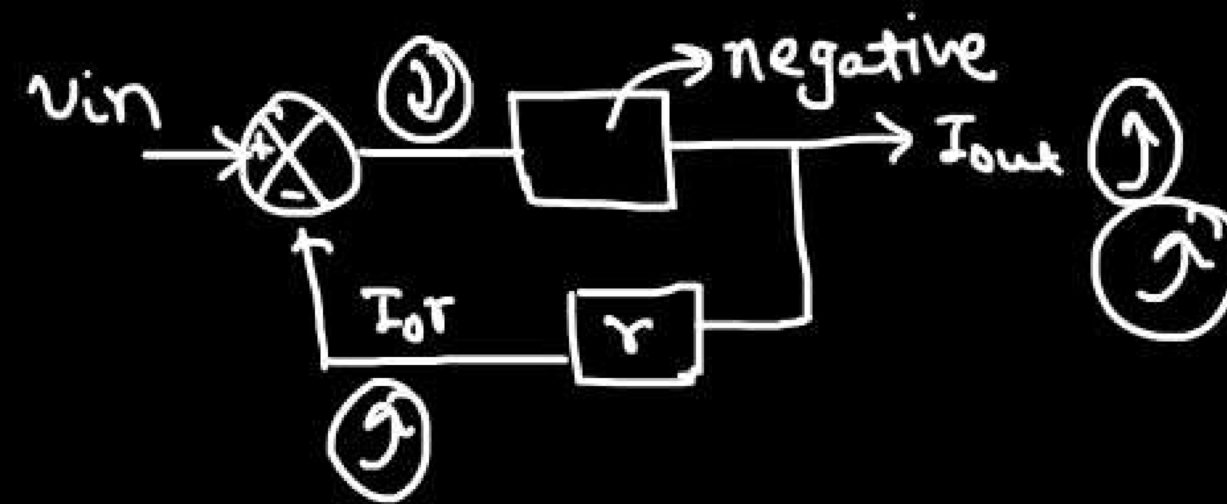
current - voltage f/b

Voltage mixing, current sampling

$$\boxed{\left(\frac{I_{out}}{v_{in}}\right)_{o.L.} = -g_{m1} g_{m2} R_D}$$

$$\boxed{(R_{in})_{O.L.} = \frac{1}{g_{m_1}}}$$

$$\boxed{(R_o)_{O.L.} = R + r}$$

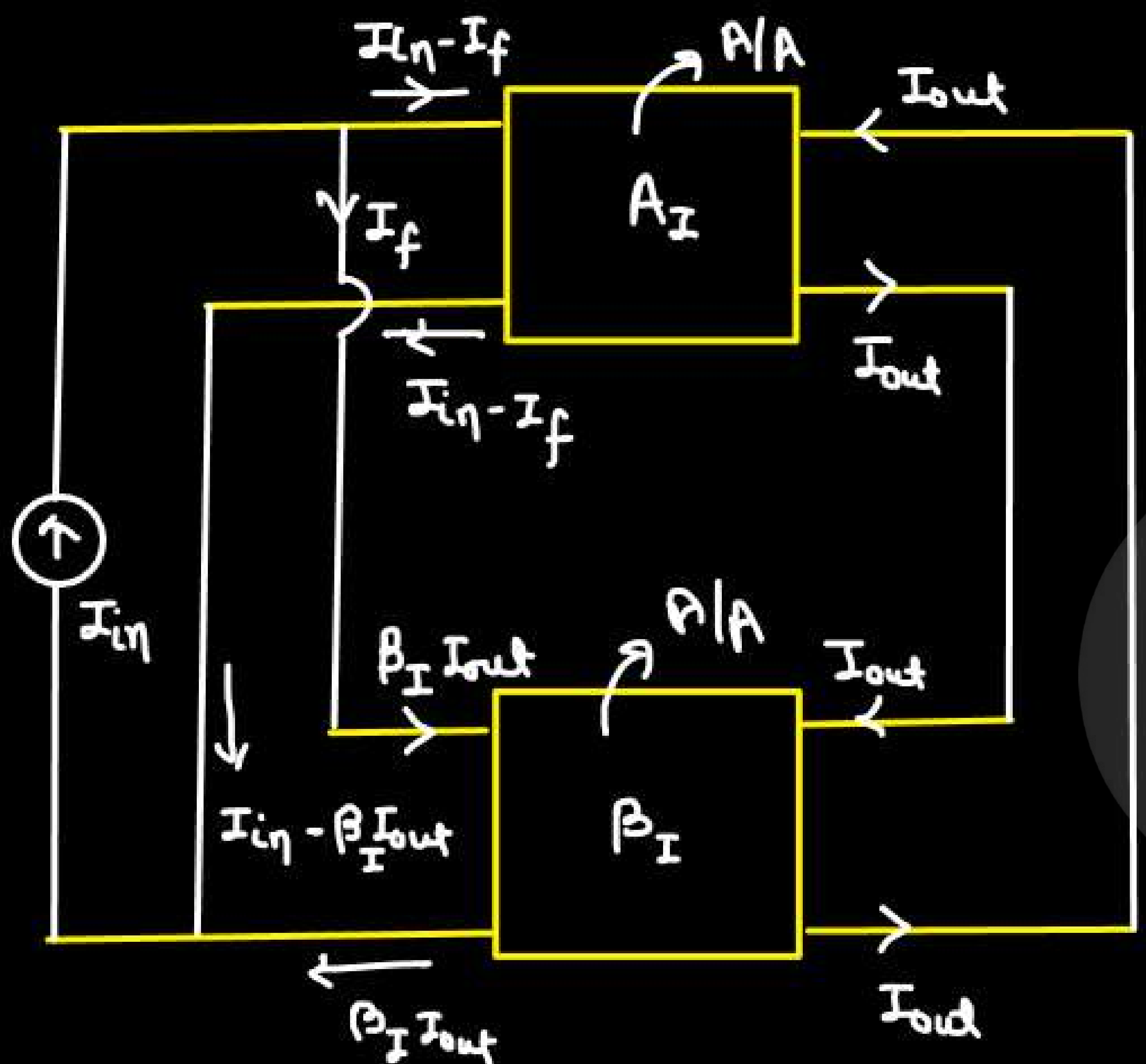


☆ $$\boxed{\text{closed loop gain} = \frac{-g_{m_1} g_{m_2} R_D}{1 - g_{m_1} g_{m_2} R_D r}}$$

☆ $$\boxed{R_x = \frac{1}{g_{m_1}}\left[1 - g_{m_1} g_{m_2} R_D r\right]}$$

★ $$\boxed{R_y = (R + r)\left[1 - g_{m_1} g_{m_2} R_D r\right]}$$

* Current-Current feedback :- (shunt-series)



open loop gain = A_I

open loop i/p impedance = Rin

open loop o/p impedance = R_o

① Closed loop gain = $\dfrac{A_I}{1+A_I\beta_I}$

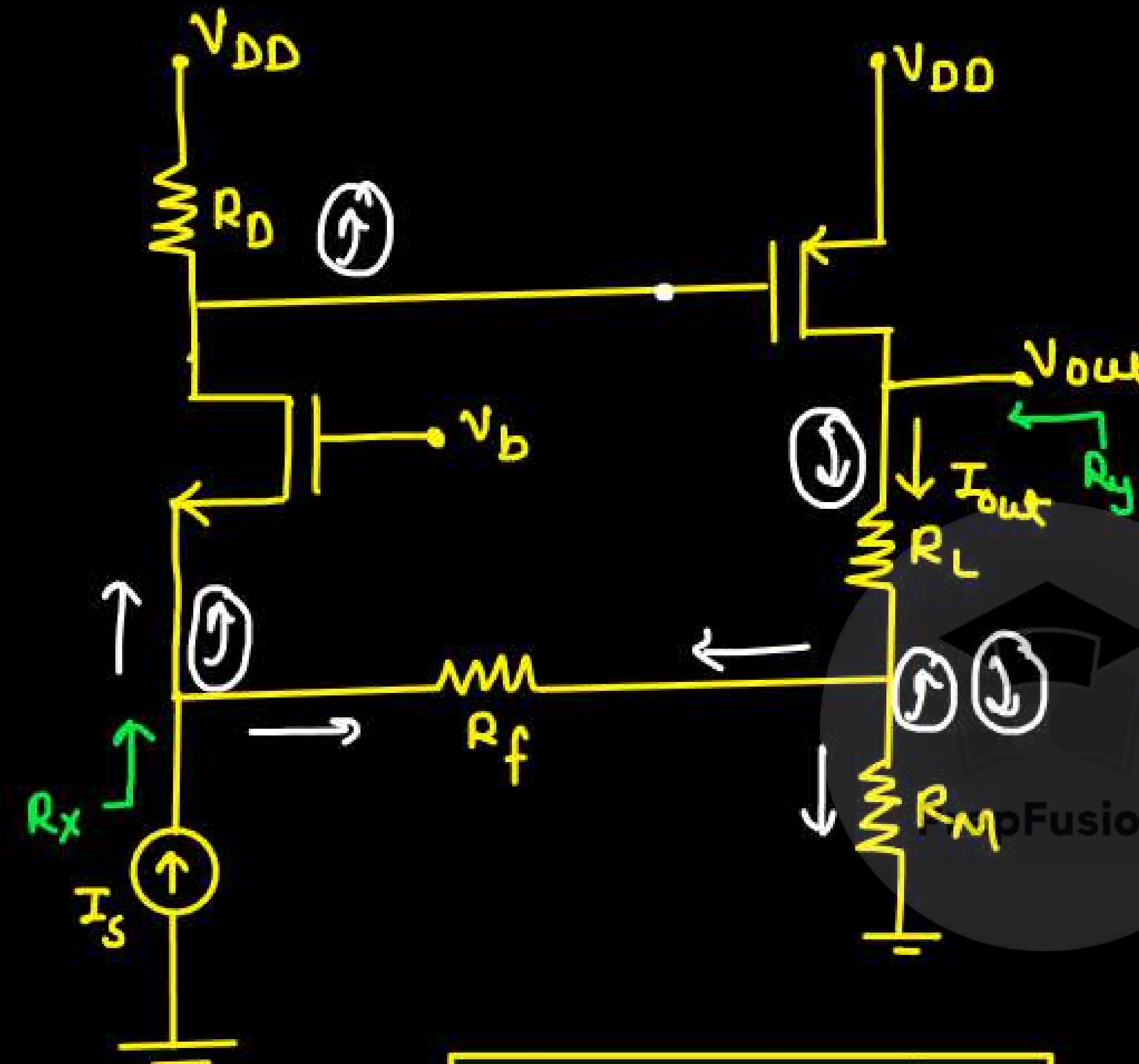
② Closed loop I/P impedance

$= R_{in}/1+A_I\beta_I$

③ Closed loop o/p impedance

$= R_o[1+A_I\beta_I]$

Eg. →



[Make Proper Assumption.]

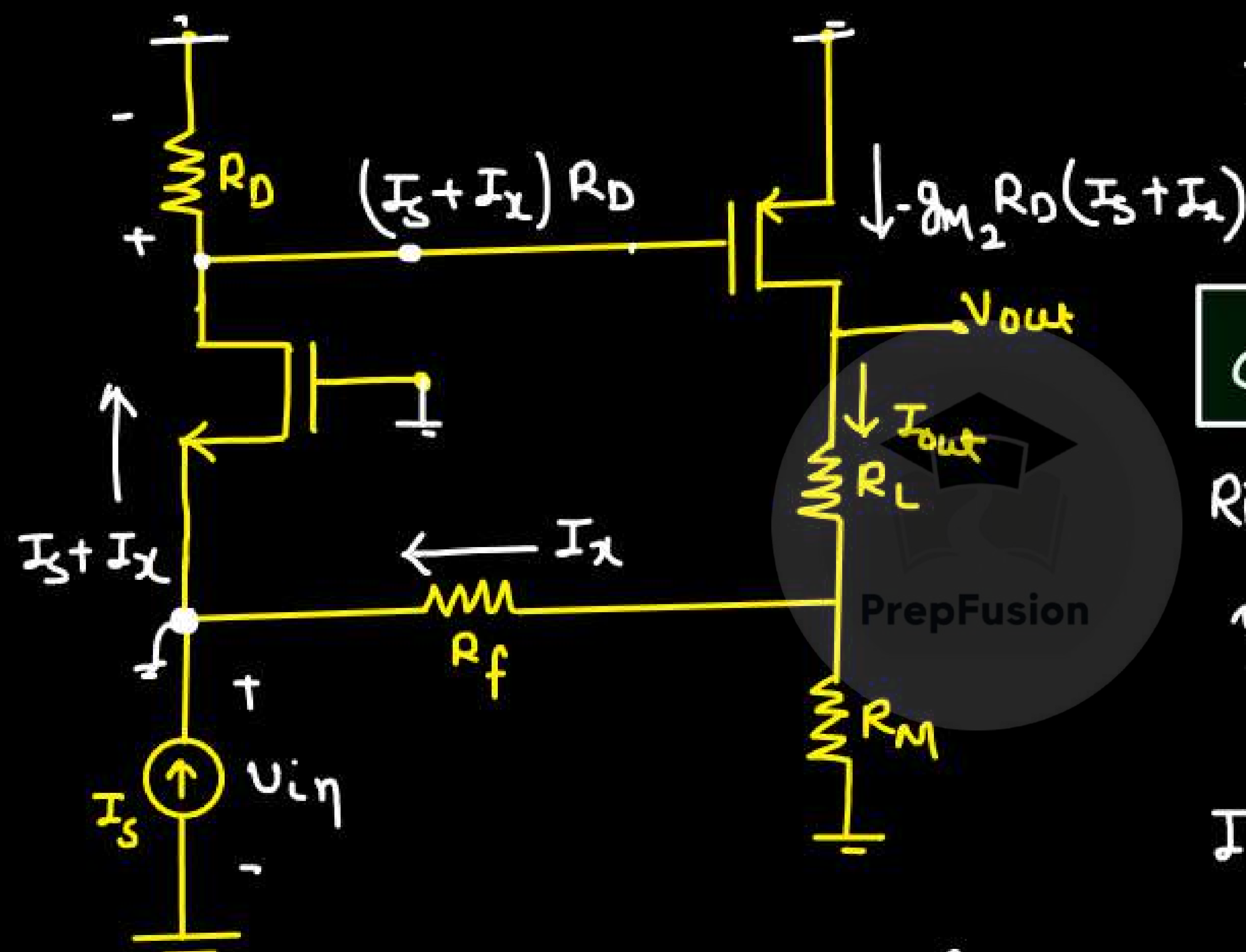
① Find $\frac{I_{out}}{I_s}$.

② Find R_x & R_y.

$\boxed{\Rightarrow \text{Negative f/b}}$

current mixing, current - sampling ⇒ $\boxed{\text{Current - Current f/b Topology}}$

M-I w/o the concept of f/b Topology :-



$$\frac{I_{out}}{I_s} = ?$$

$\boxed{\text{CURRENT - CURRENT f/b}}$

$R_{in} \rightarrow$ very low

$\frac{v_{in}}{I_s} \rightarrow$ very low

I can take, $v_{in} \rightarrow 0$

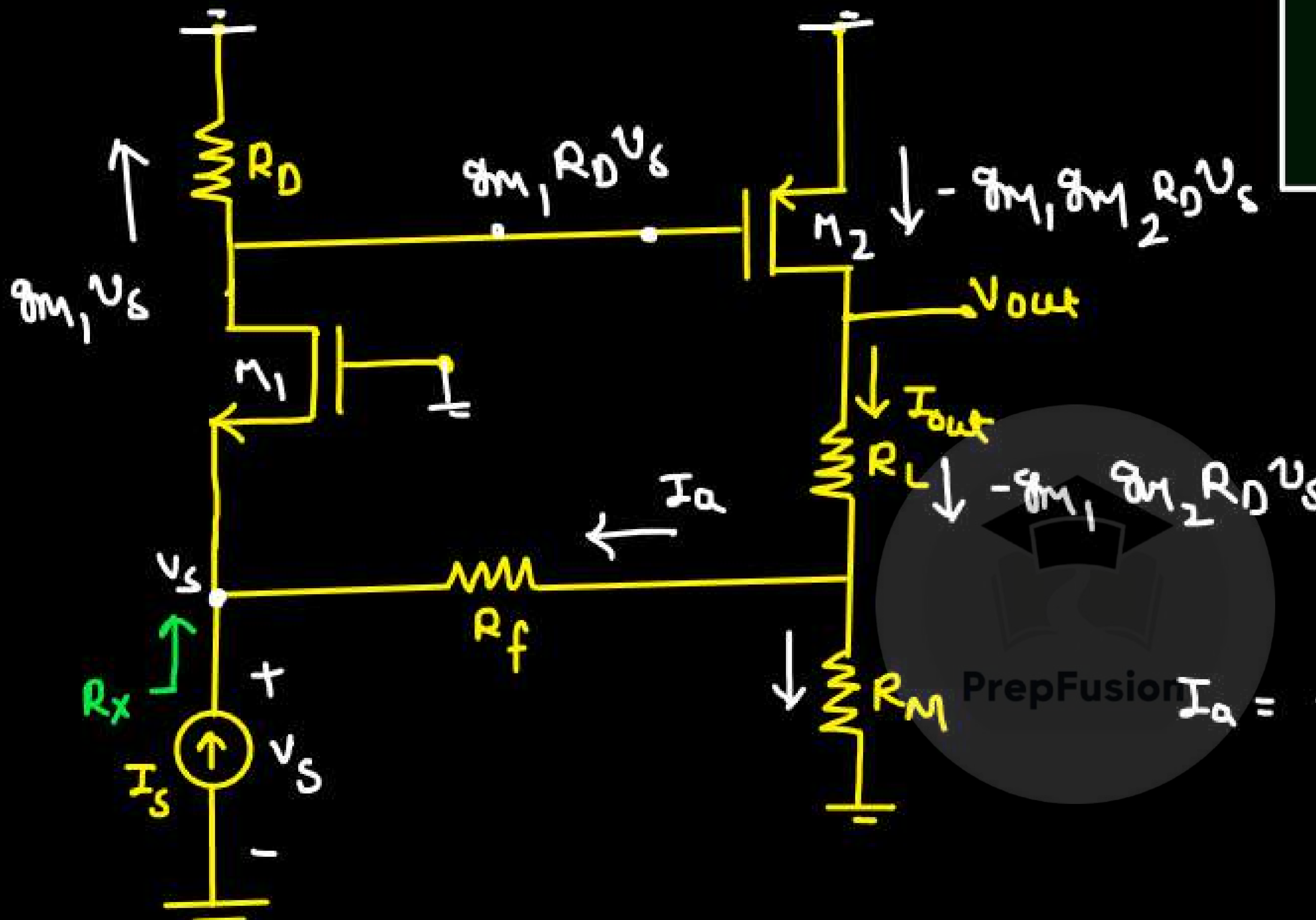
$$I_x = \frac{R_M}{R_M+R_f} I_{out}$$

$$-g_{m_2} R_D \left(I_S + \frac{R_M}{R_M + R_f} I_{out} \right) = I_{out}$$

$$-g_{m_2} R_D I_S = I_{out} \left[1 + \frac{g_{m_2} R_D R_M}{R_M + R_f} \right]$$

$$\boxed{\frac{I_{out}}{I_S} = \frac{-g_{m_2} R_D}{1 + g_{m_2} R_D \left(\frac{R_M}{R_M + R_f} \right)}}$$

$$\boxed{R_x = \frac{V_s}{I_s}}$$



$$I_a = -g_{m1} g_{m2} R_D v_s \times \frac{R_M}{R_M + R_f} \longrightarrow (1)$$

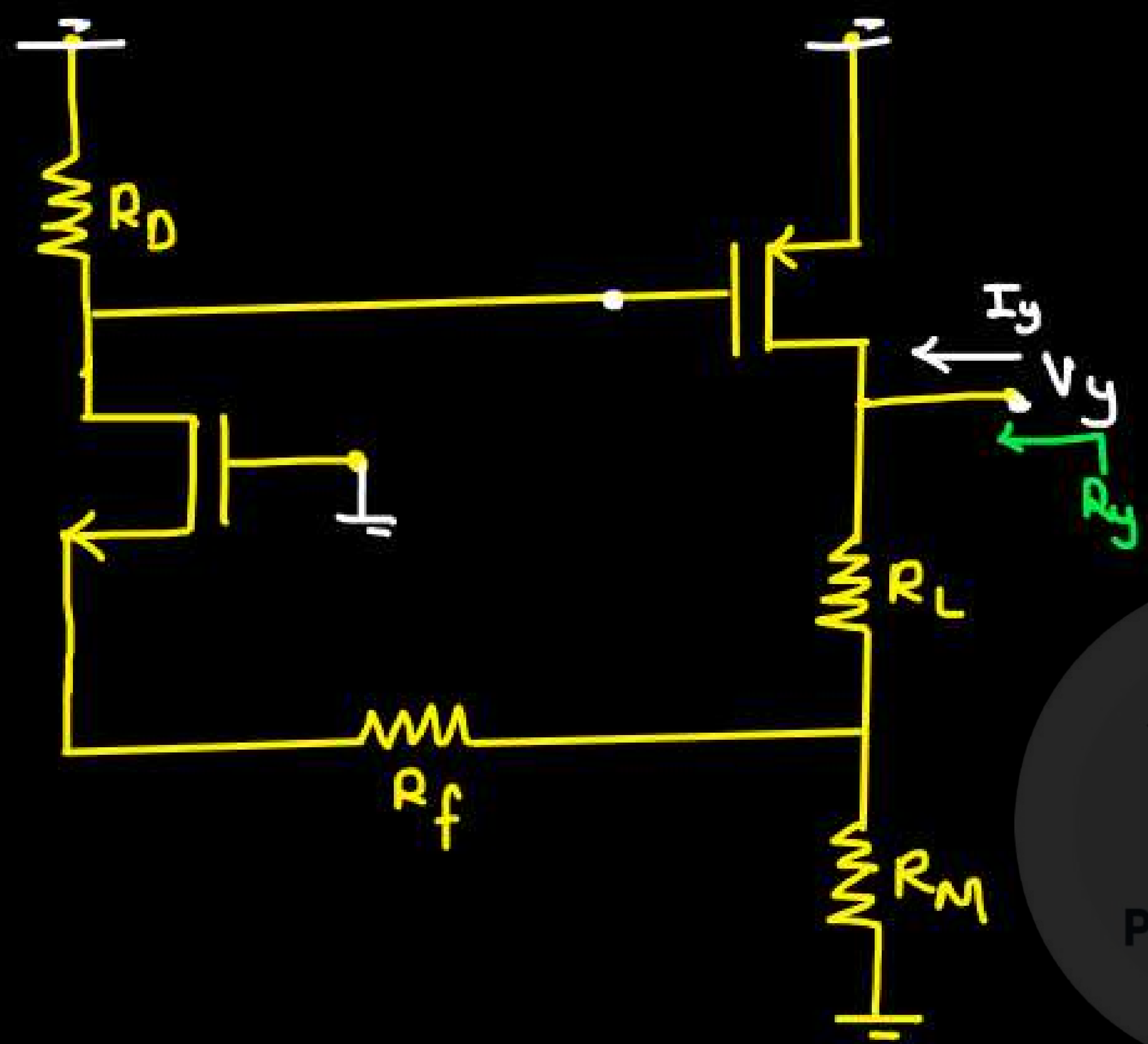
$$\{ v_s \to \text{very small} \}$$

$$I_s + I_a = g_{m1} v_s$$

$$I_s - g_{m1} g_{m2} R_D \left(\frac{R_M}{R_M + R_f} \right) v_s = g_{m1} v_s$$

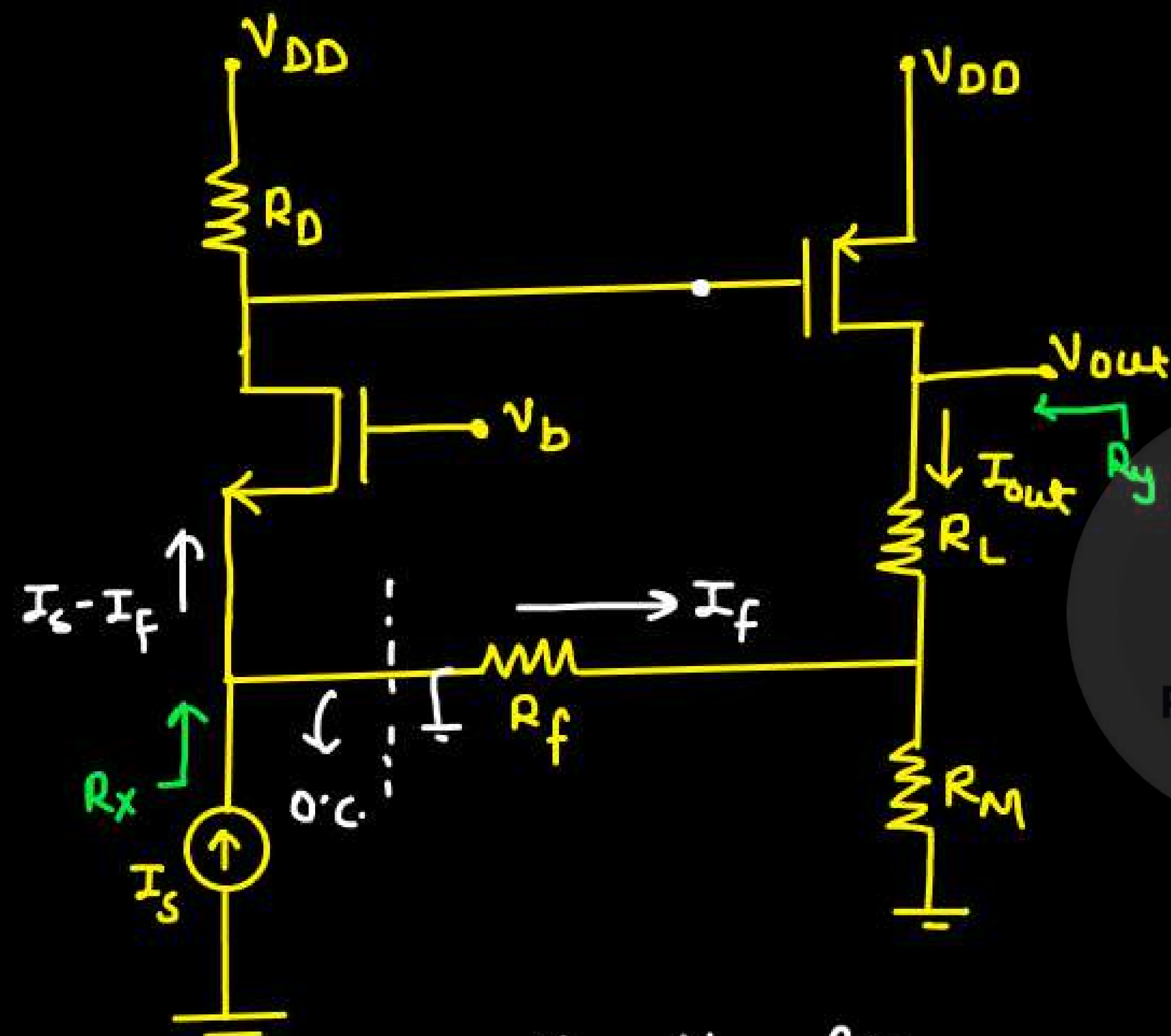
$$I_s = \left[g_{m_1} + g_{m_1} g_{m_2} R_D \left(\frac{R_M}{R_M + R_f} \right) \right] V_s$$

$$\boxed{R_x = \frac{V_s}{I_s} = \frac{1/g_{m_1}}{1 + g_{m_2} R_D \left(\frac{R_M}{R_M + R_f} \right)}}$$

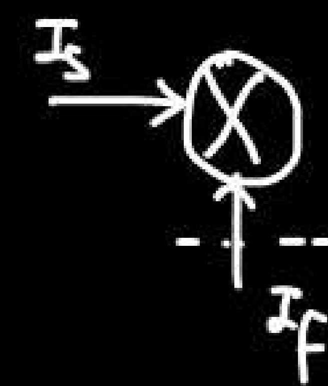


$$\boxed{R_y = \frac{V_y}{I_y}} \rightarrow \text{complex expression}$$

With the concept of f/b Topology:-

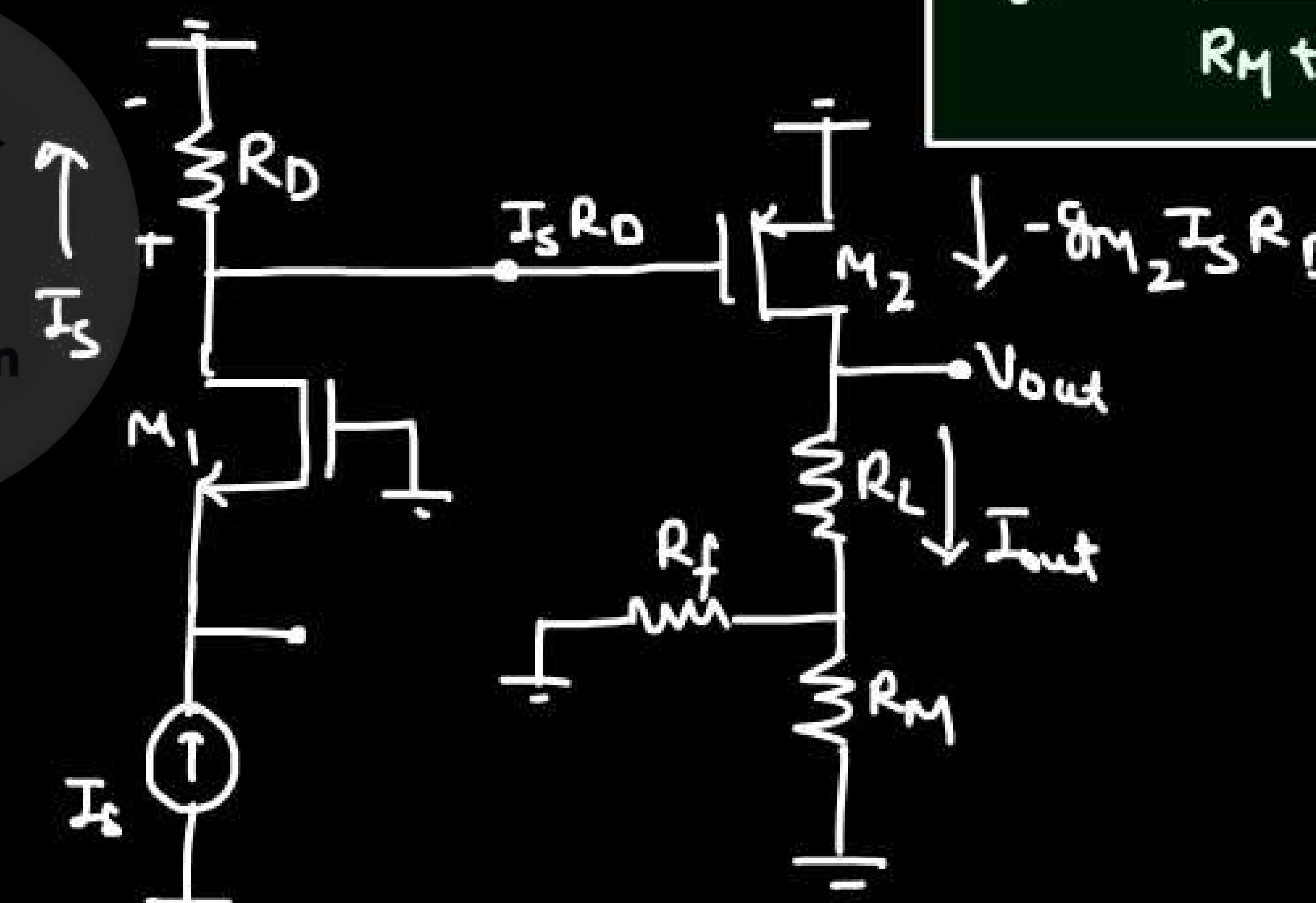


Negative f/b



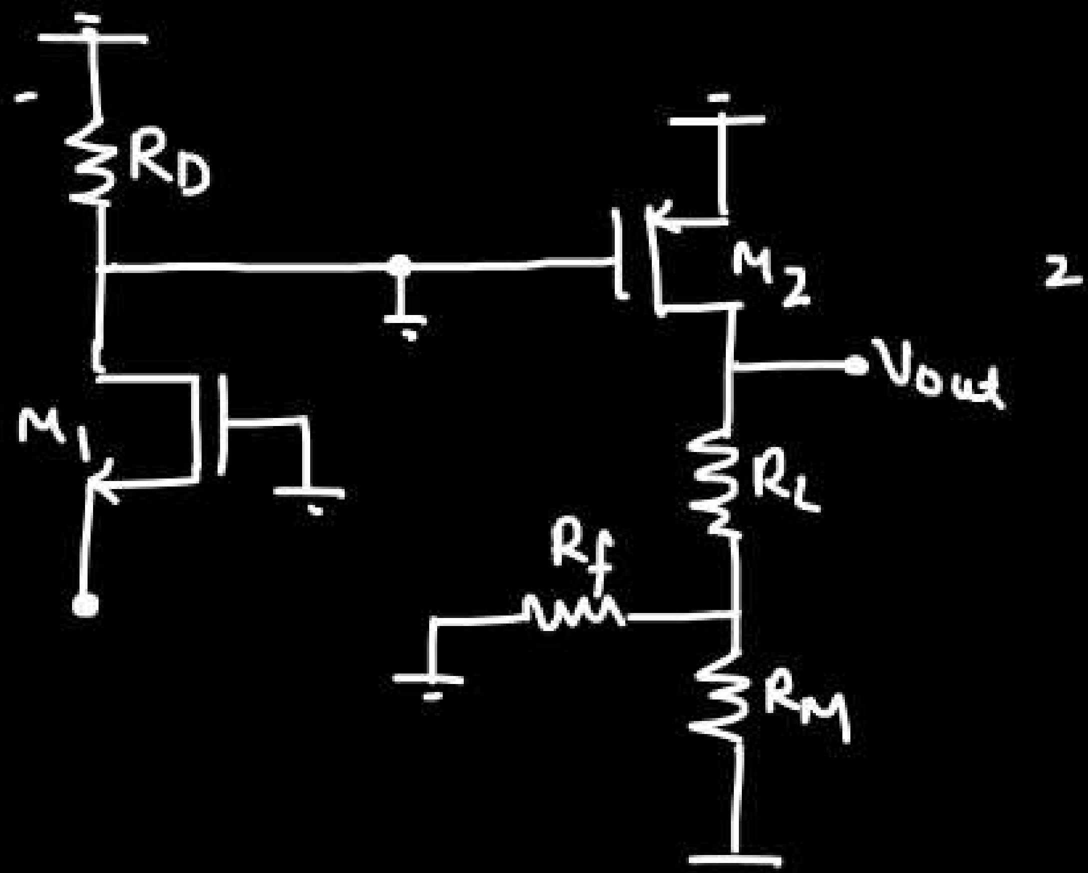
$$I_f = \frac{-R_M}{R_M + R_f} I_{out}$$

$$\boxed{B_I = -\frac{R_M}{R_M + R_f}}$$



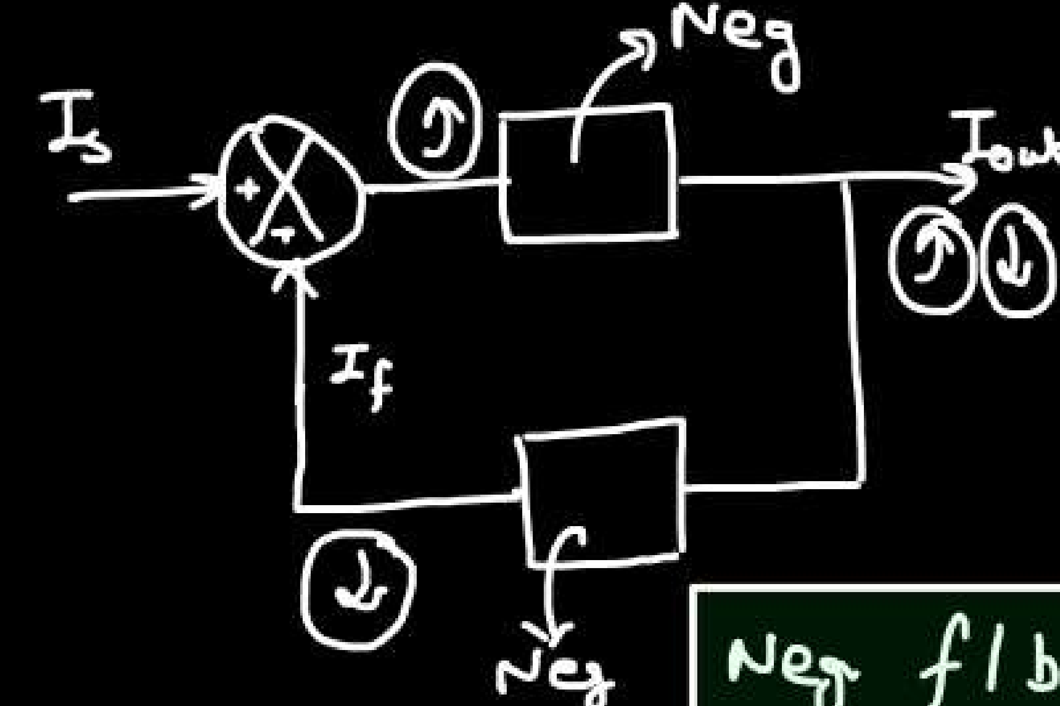
$$\boxed{\left(\frac{I_{out}}{I_s}\right)_{O.L.} = -g_{m_2} R_D}$$

$$I_{out} = -g_{m_2} I_s R_D$$



$$(R_i)_{O.L.} = \frac{1}{g_{m_1}}$$

$$(R_o)_{O.L.} = (R_L + R_M \| R_f)$$



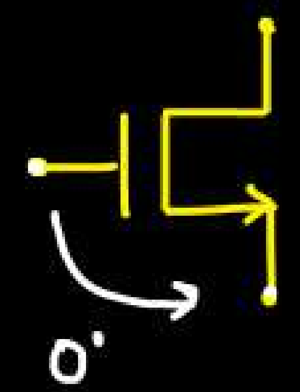
Neg f/b

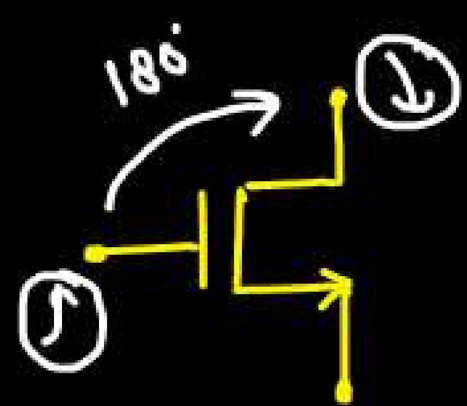
① $$\text{Closed loop gain} = \frac{-g_{m_2} R_D}{1 + g_{m_2} R_D \left(\frac{R_M}{R_M + R_f}\right)}$$

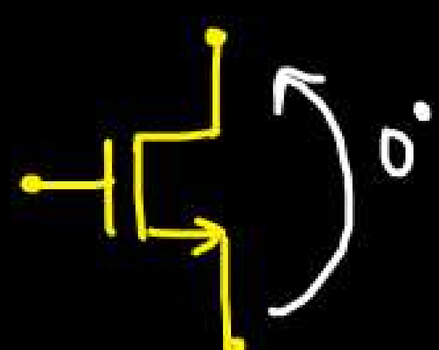
② $$R_x = \frac{1/g_{m_1}}{1 + g_{m_2} R_D \left(R_M / R_M + R_f\right)}$$

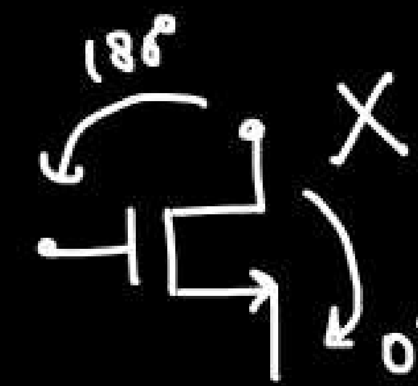
③ $$R_y = (R_L + R_M \| R_f)\left(1 + g_{m_2} R_D \left\{\frac{R_M}{R_M + R_f}\right\}\right)$$

Type of feedback Topology	Forward Gain (open loop)	Feedback Factor (β)	Closed loop Gain	Closed loop Input impedance	Clo[illegible] o/p impedance
1. Voltage - voltage	A_V	β_V	$\frac{A_V}{1+A_V\beta_V}$	$R_{in}(1+A_V\beta_V)$	$R_o/1+A_I\beta_I$
2. Voltage - Current	R_M	G_m	$\frac{R_M}{1+G_M R_M}$	$\frac{R_{in}}{1+G_m R_M}$	$\frac{R_o}{1+G_m R_M}$
3. Current - Voltage	G_m	R_m	$\frac{G_m}{1+R_M G_M}$	$R_{in}(1+G_M R_M)$	$R_o(1+G_m R_M)$
4. Current - Current	A_I	β_I	$\frac{A_I}{1+A_I\beta_I}$	$\frac{R_{in}}{1+A_I\beta_I}$	$R_o(1+A_I\beta_I)$



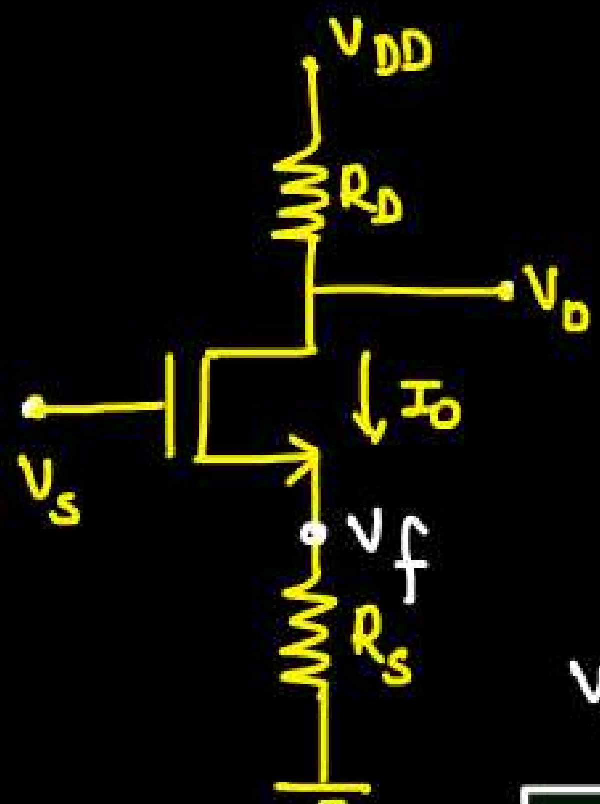






@ drain, you never apply i/p.

Q. Determine the type of feedback and feedback factor.



$V_f = I_o R_s$

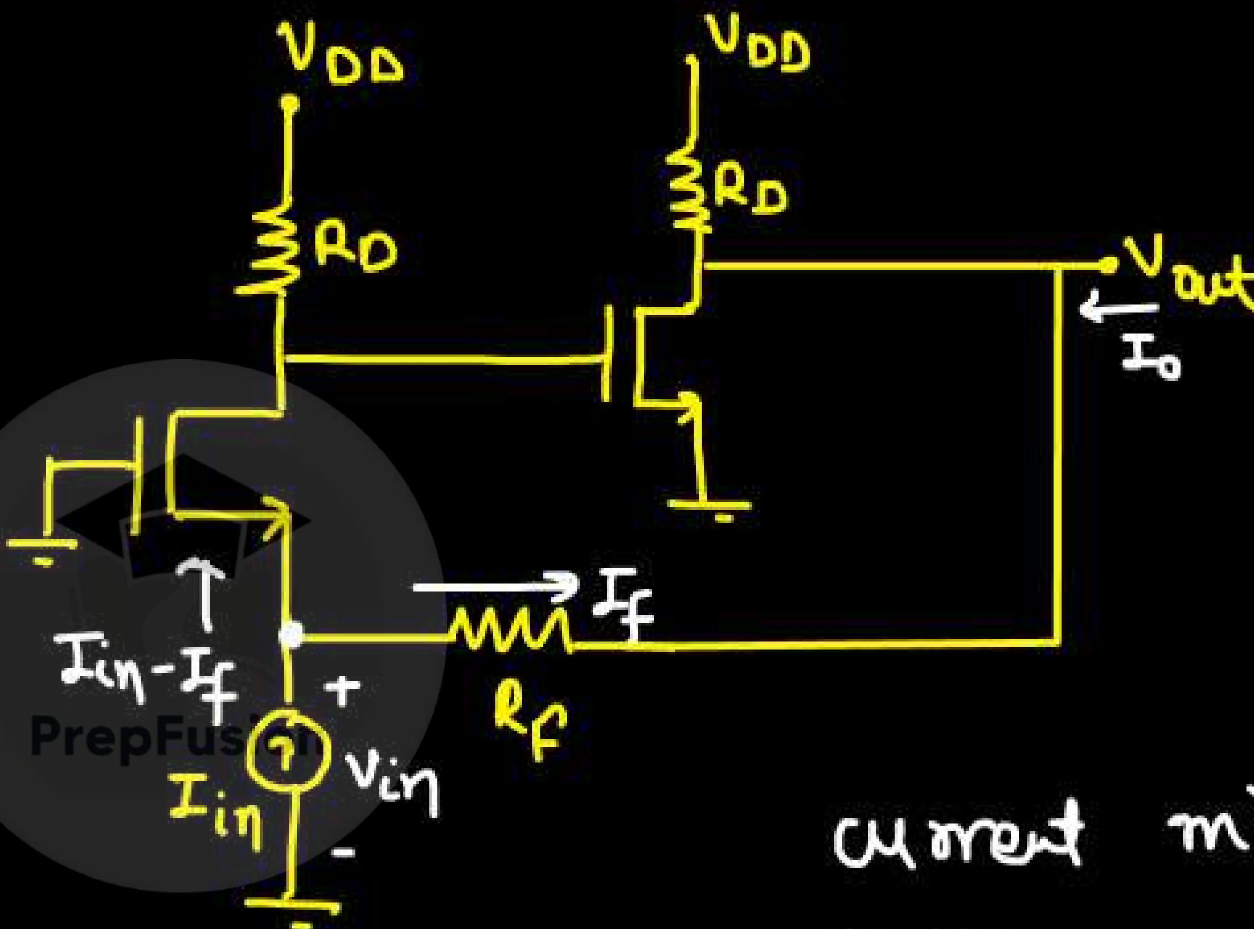
$$\boxed{R_m = \frac{V_f}{I_o} = R_s}$$

(a)

current sampled

voltage mixing

Current - Voltage



(b)

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

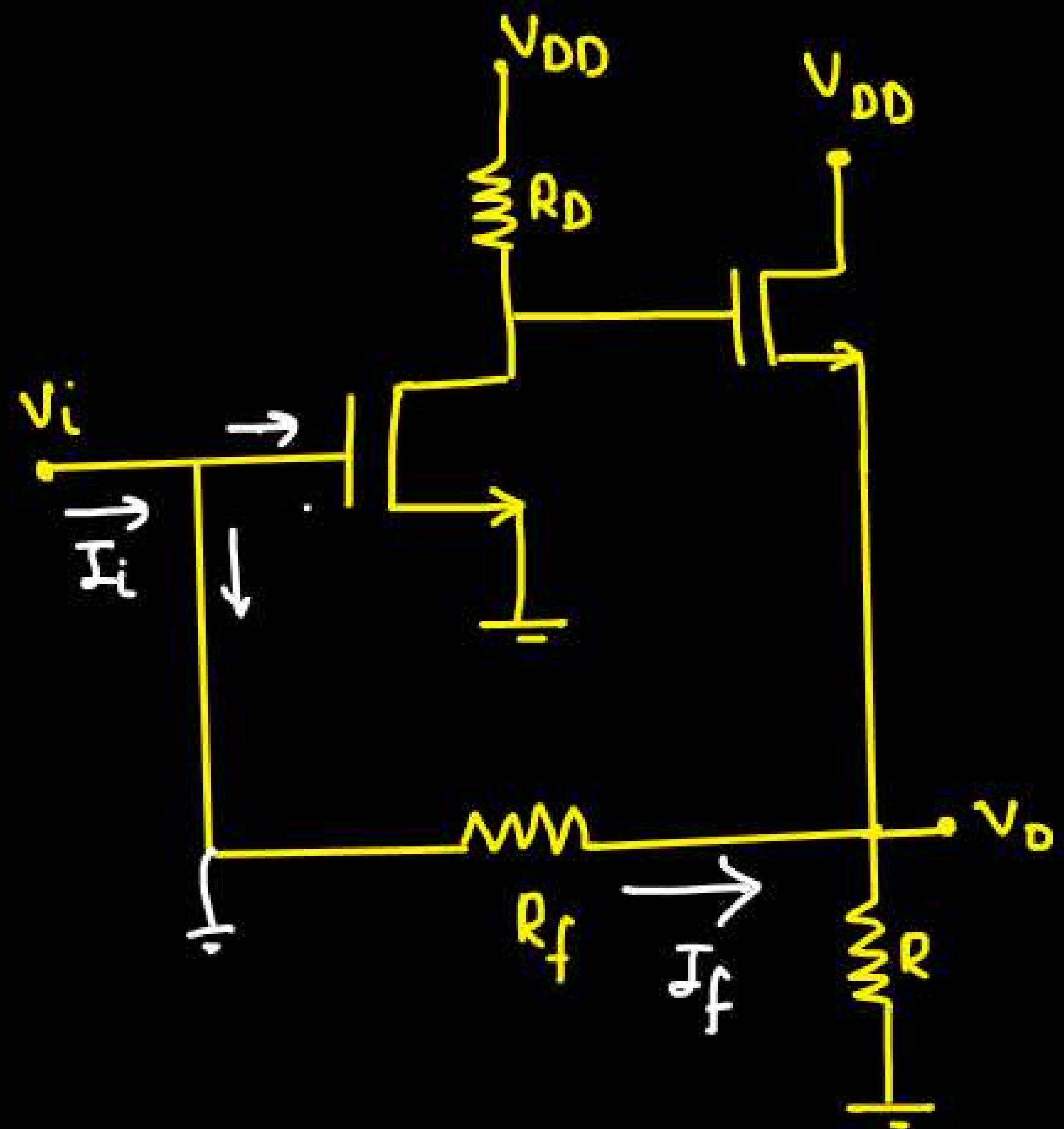
$$\boxed{\frac{I_f}{V_o} = -\frac{1}{R_f}}$$

current mixing

Voltage sampling

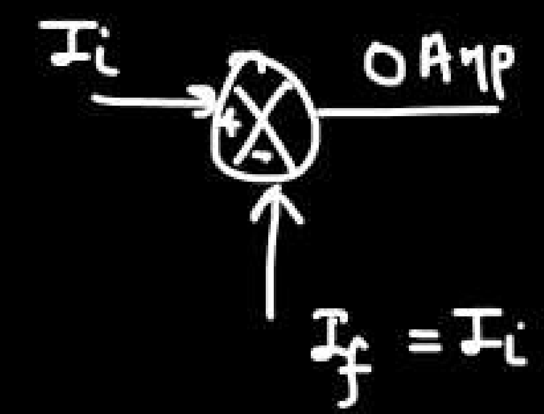
$\Rightarrow$ **Voltage - Current**

$\Leftarrow$ $(R_{in})_f \rightarrow$ low $\Rightarrow V_{in} \rightarrow 0$



(c)

current mixing
voltage sampling



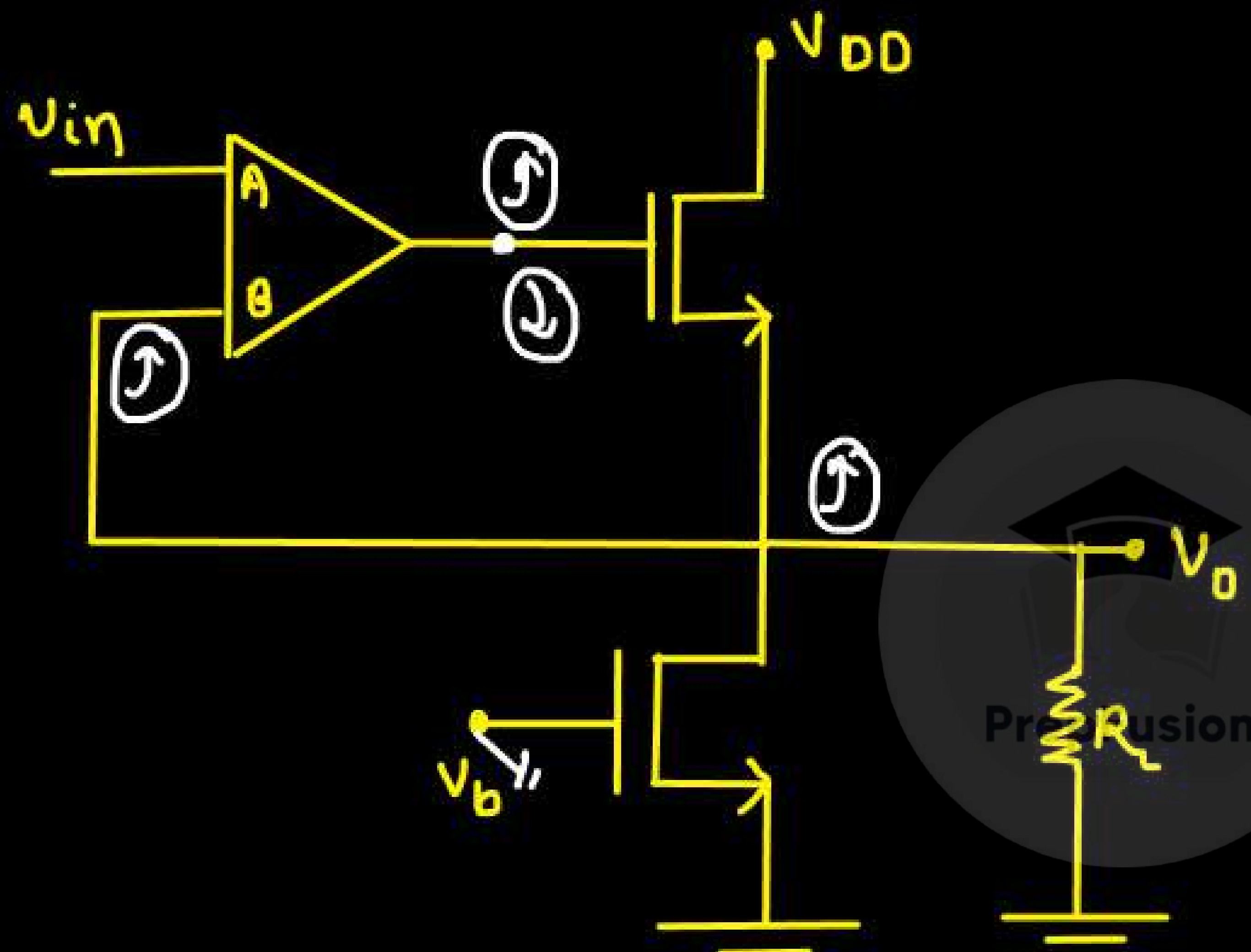
$$I_f = \frac{-V_o}{R_f}$$

$$\boxed{\frac{I_f}{V_o} = \frac{-1}{R_f}}$$

** $\boxed{\text{Voltage - Current}}$

$R_{in} \to \text{low} \Rightarrow V_{in} \to \text{low}$

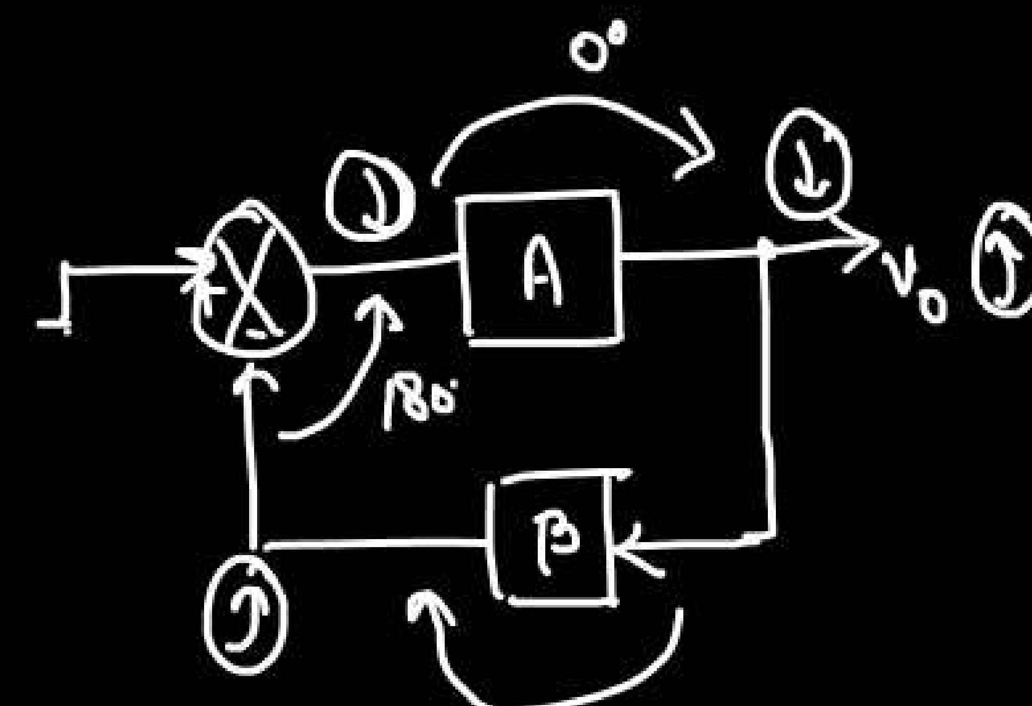
Q. Determine the sign of A and B for Negative f/b.



(a)

$B \rightarrow -ve$

$A \rightarrow +ve$

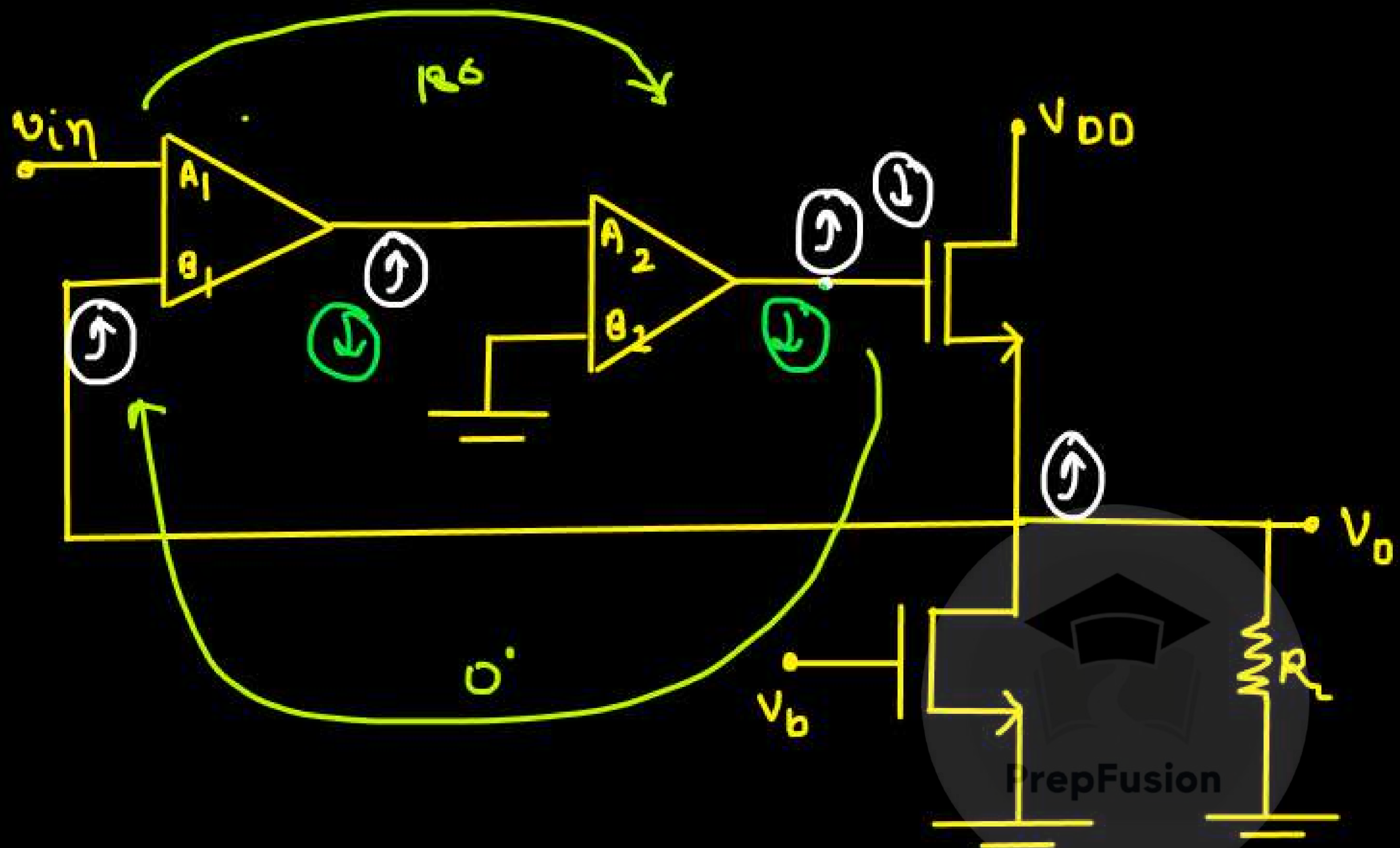


0°

$\Rightarrow \underline{\underline{180^\circ}}$

Neg f/b → 180°, 540° - - $(2n+1)180^\circ$

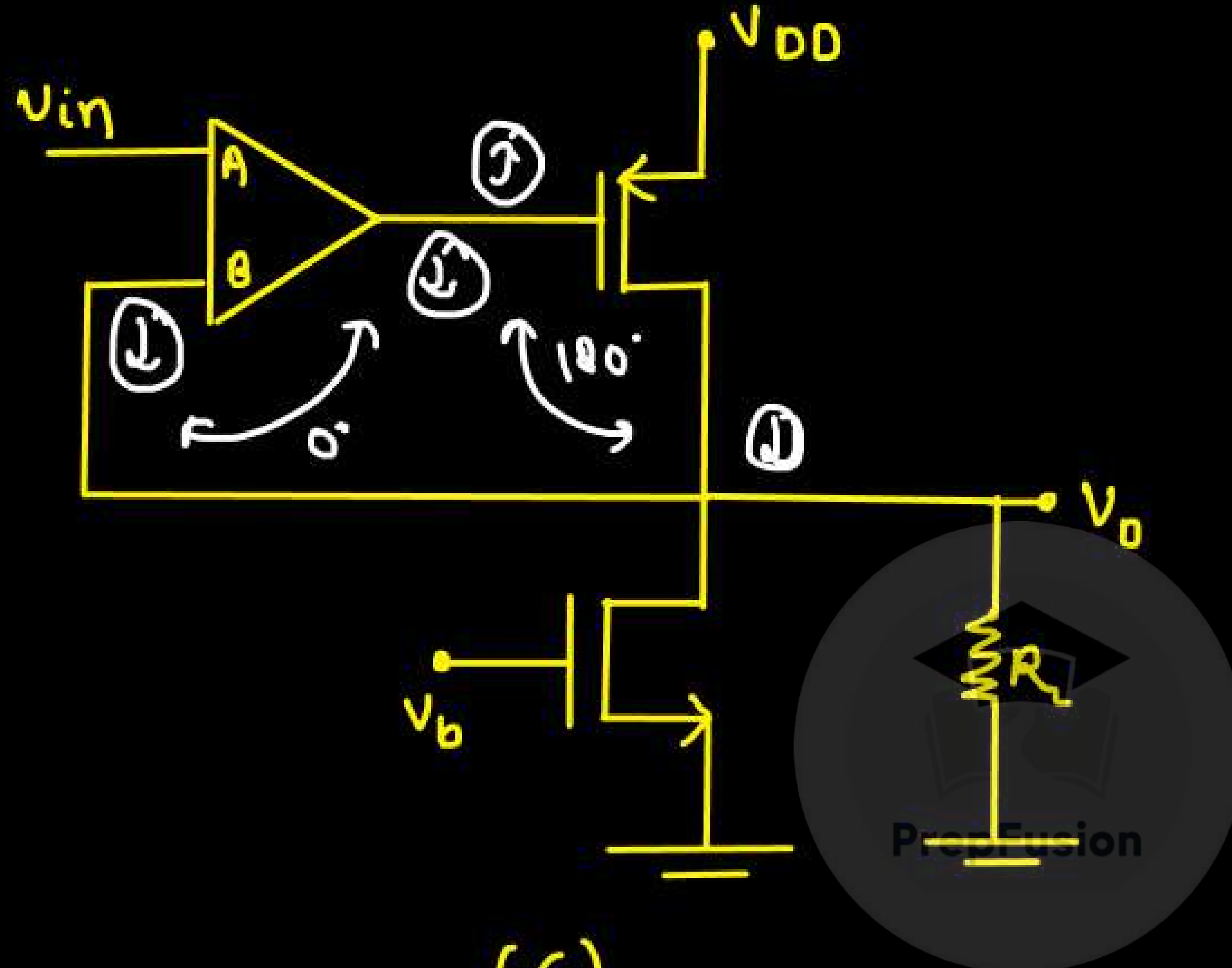
Pos f/b → 0°, 360° - ... $360^\circ n$



(b)

① if $A_1 = -ve$, $B_1 = +ve \Rightarrow A_2 = -ve$, $B_2 = +ve$

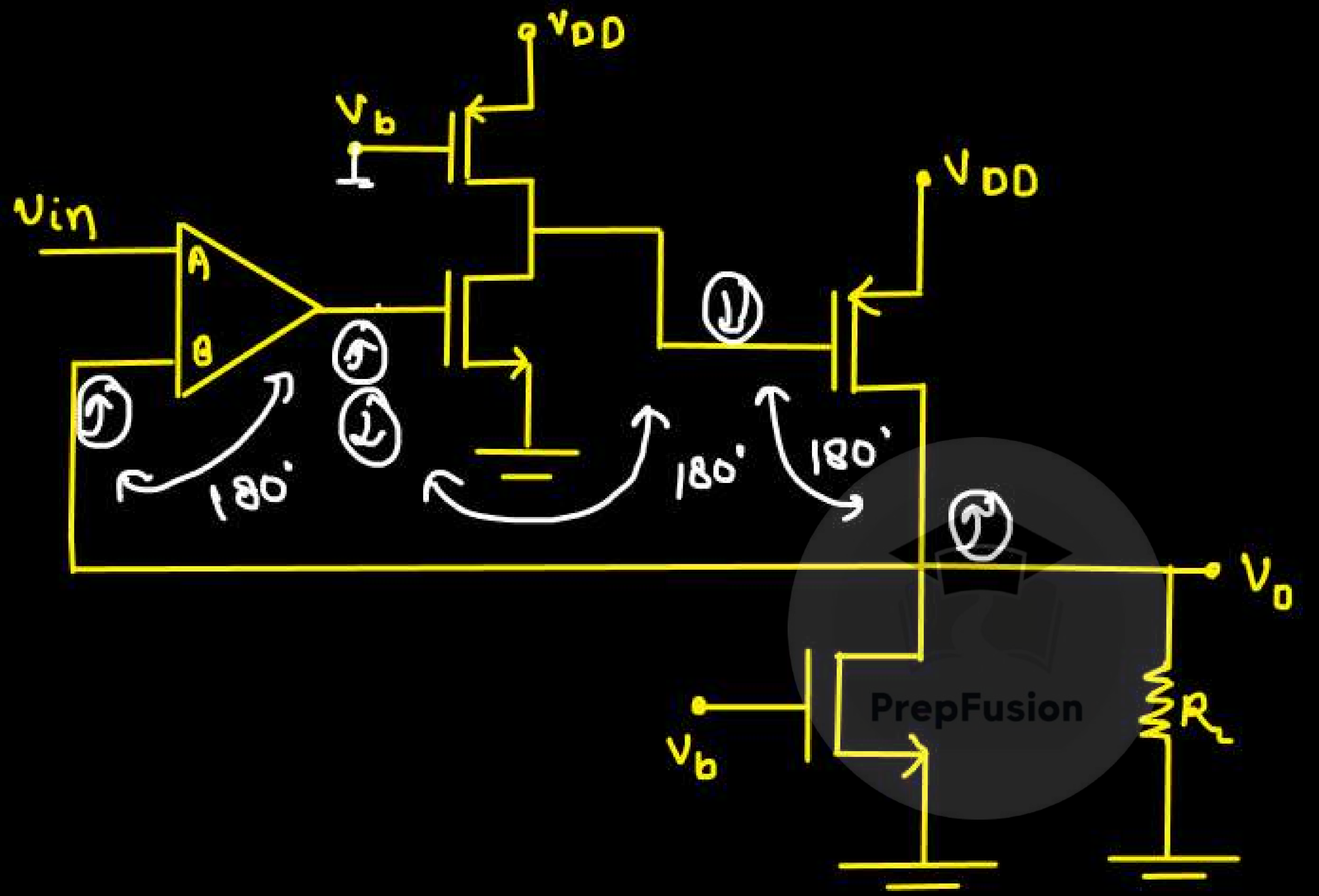
② if $A_1 = +ve$, $B_1 = -ve \Rightarrow A_2 = +ve$, $B_2 = -ve$



(c)

B = +ve

A = -ve

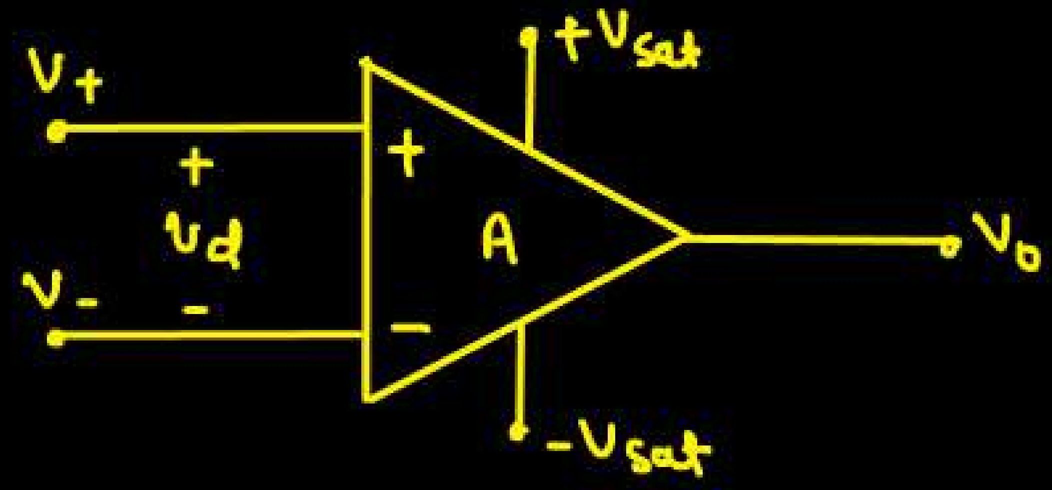


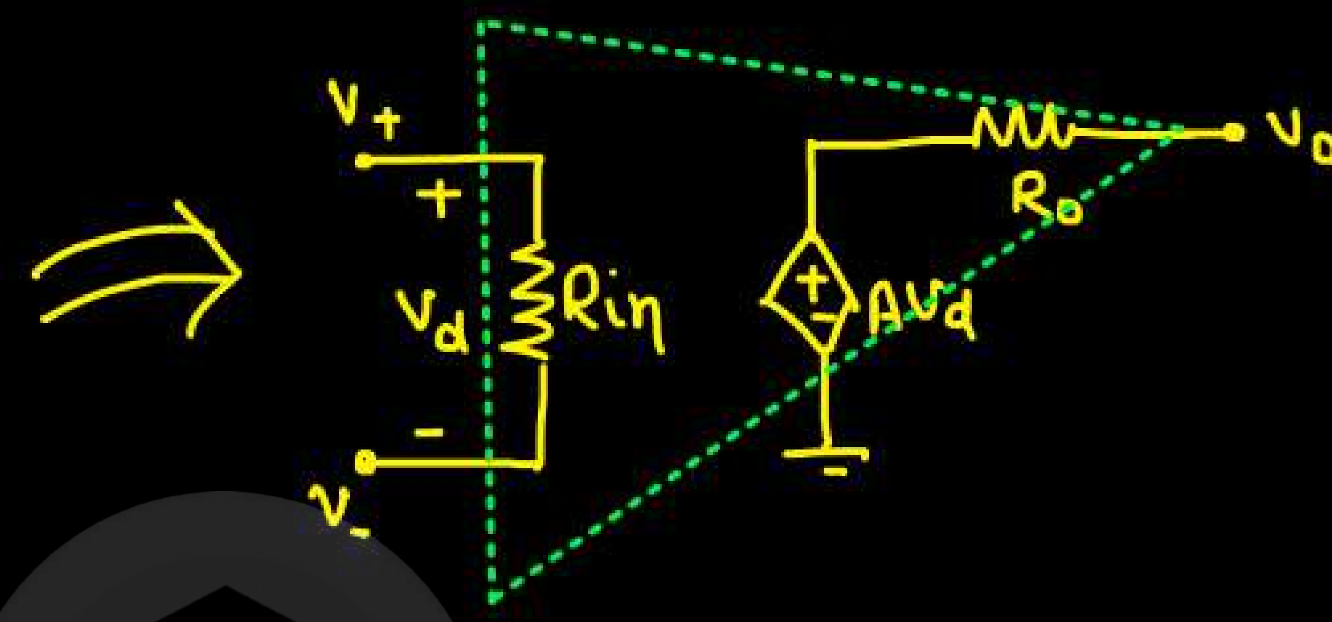
(d)

B = −ve

A = +ve

Introduction to Op-Amp:-





$$\boxed{v_0 = A v_d}$$

$$\boxed{v_0 = A(v_+ - v_-)}$$

$v_+ \uparrow \Rightarrow v_0 \uparrow$

$v_- \uparrow \Rightarrow v_0 \downarrow$

$v_- \rightarrow$ Inverting

$v_+ \rightarrow$ Non-Inverting

$R_{in} \rightarrow$ High
$A \rightarrow$ High
$R_0 \rightarrow$ low

N.B.:- O/P of an op-Amp can't keep on increasing or decreasing. It will saturate @ some point.

Q. Let $\pm V_{sat} = \pm 5V$

Gain of op-Amp $(A) = 10^3\ V/V$

Find output voltage for the given differential voltage (v_d)?

where $v_d = v_+ - v_-$

(a) $v_d = 2mV$

$V_o = A v_d$

$= 10^3 \times 2m$

$\boxed{V_o = 2V}$ ✓

(b) $v_d = 5mV$

$V_o = A v_d$

$= 10^3 \times 5m$

$\boxed{V_o = 5V}$ ✓

(c) $v_d = -3mV$

$V_o = A v_d$

$= 10^3 \times (-3)m$

$\boxed{V_o = -3V}$ ✓

(d) $v_d = -5mV$

$V_o = A v_d$

$= 10^3 \times (-5m)$

$\boxed{V_o = -5V}$ ✓

(e) $v_d = 7\,mV$

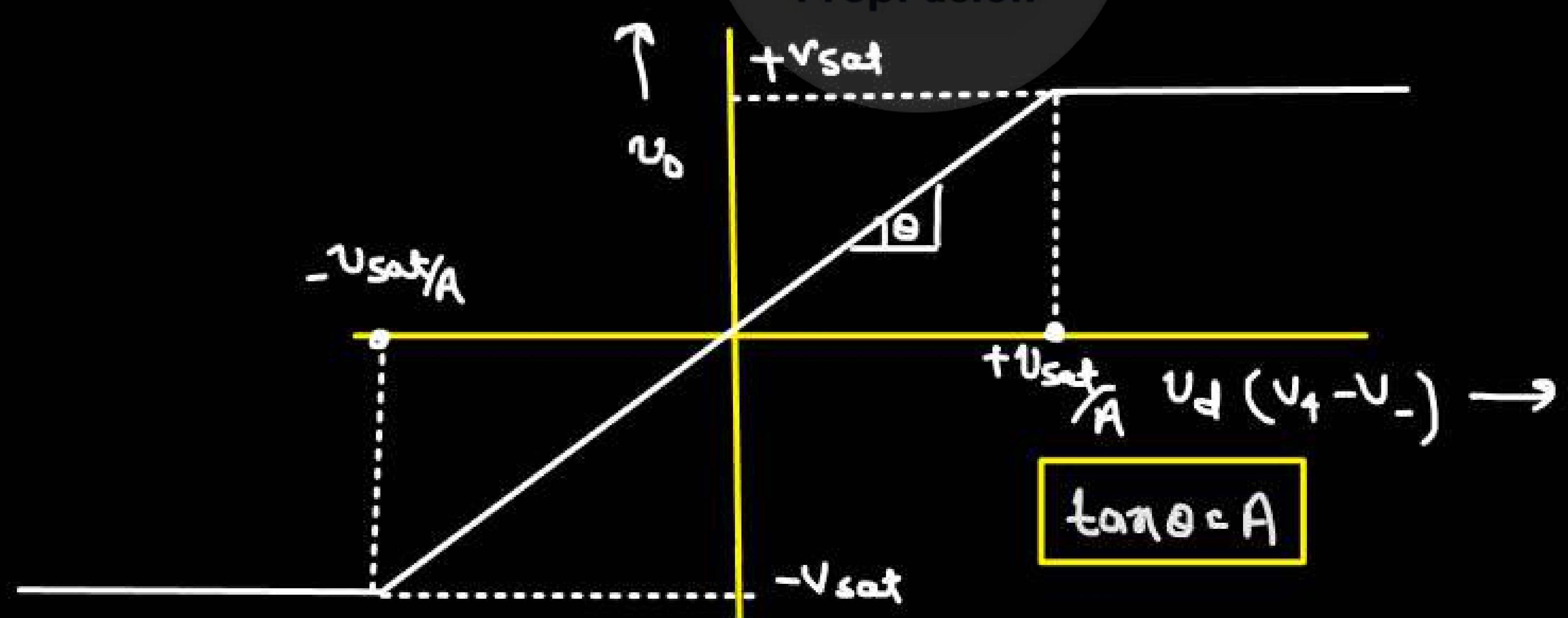
$$v_o = A v_d$$
$$= 10^3 \times 7m$$
$$= 7V \times$$
$$\boxed{v_o = 5V}$$

(f) $v_d = -8\,mV$

$$v_o = A v_d$$
$$= 10^3 \times (-8m)$$
$$v_o = -8V$$
$$\boxed{v_o = -5V}$$

$$\boxed{-v_{sat} \leq v_o \leq v_{sat}}$$

Transfer characteristics :-



$$v_o = A v_d$$

$$\boxed{\tan\theta = A}$$

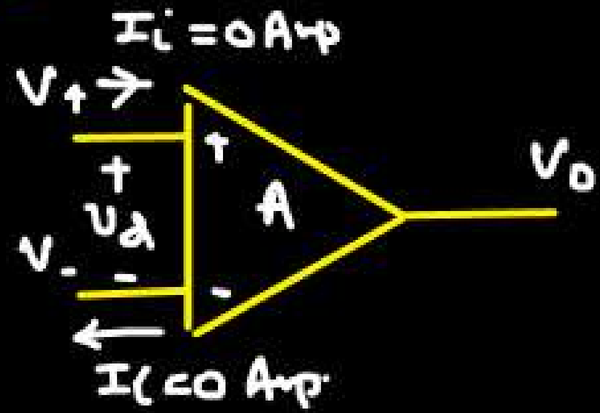
For ideal op-Amp:

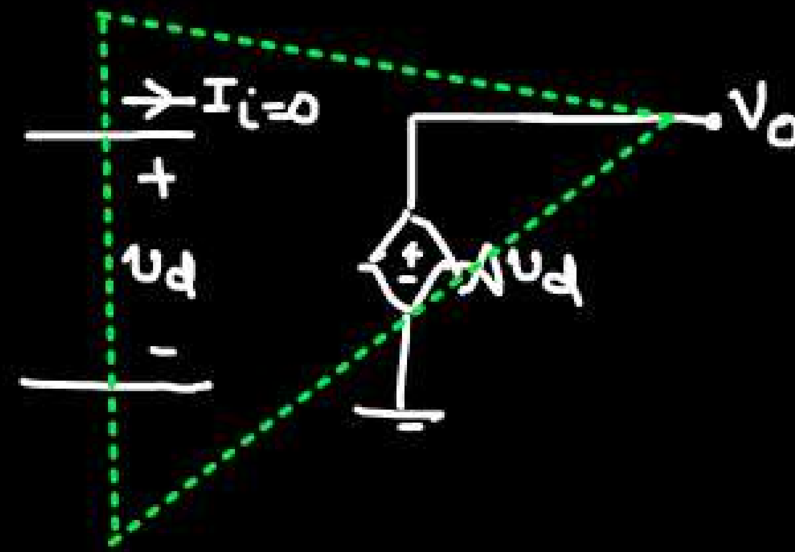
$A = \infty$

$R_{in} = \infty$

$R_o = 0$

$I_i = 0$ Amp





Q. Let gain of op-Amp $A = \infty$, $\pm V_{sat} = \pm 5V$

Find v_o for following differential voltage (v_d) ?

$v_d = v_+ - v_-$

(a) $v_d = 3mV$

$v_o = A v_d$
$= \infty \times 3m$
$= \infty$ X
$\boxed{v_o = +5V}$

(b) $v_d = -2mV$

$v_o = A v_d$
$= \infty (-2m)$
$= -\infty$ X
$\boxed{v_o = -5V}$

(c) $v_d = 7mV$

$v_o = A v_d$
$= \infty (7mV)$
$= \infty$ X
$\boxed{v_o = +5V}$

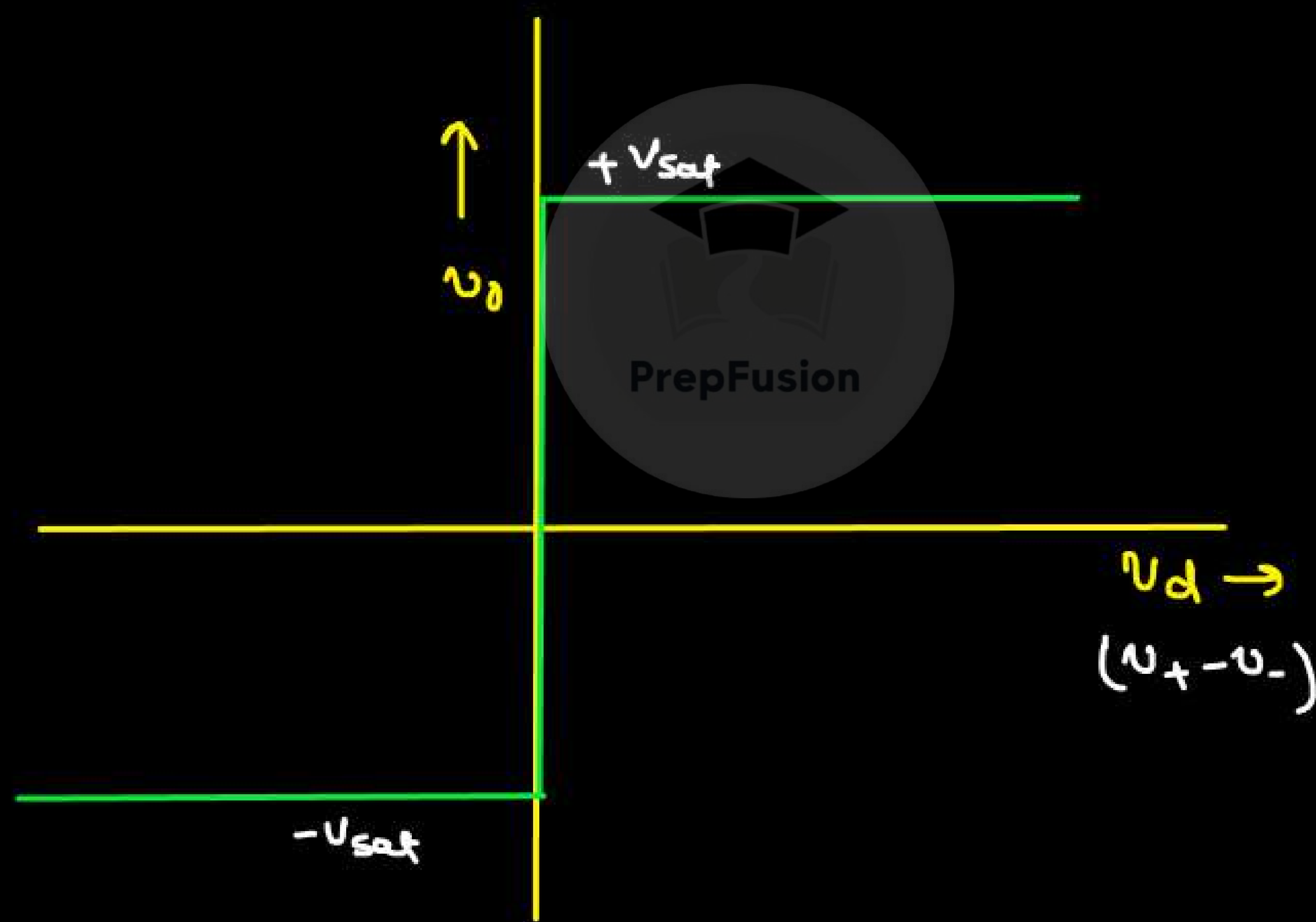
(d) $v_d = -6mV$

$v_o = \infty \times (-6)$
$= -\infty$ X
$\boxed{v_o = -5V}$

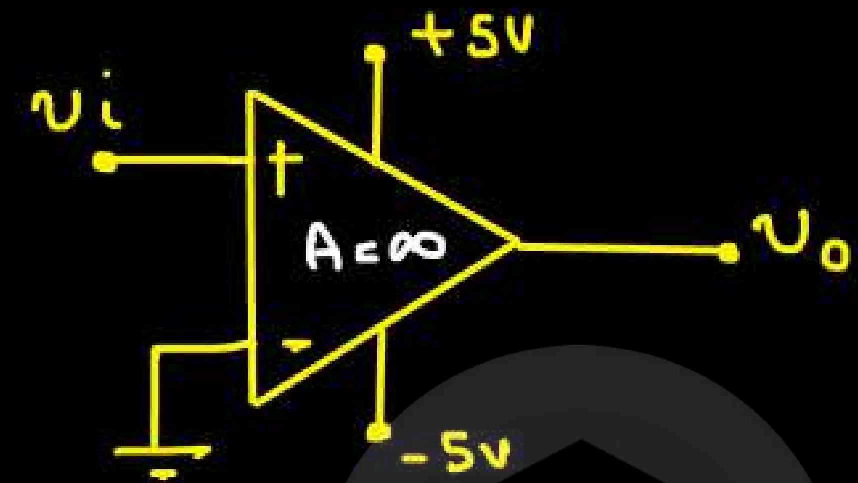
Ideal characteristics of MOS:-

(i) if $v_d > 0 \Rightarrow v_+ > v_- \Rightarrow v_0 = +v_{sat}$

(ii) if $v_d < 0 \Rightarrow v_+ < v_- \Rightarrow v_0 = -v_{sat}$

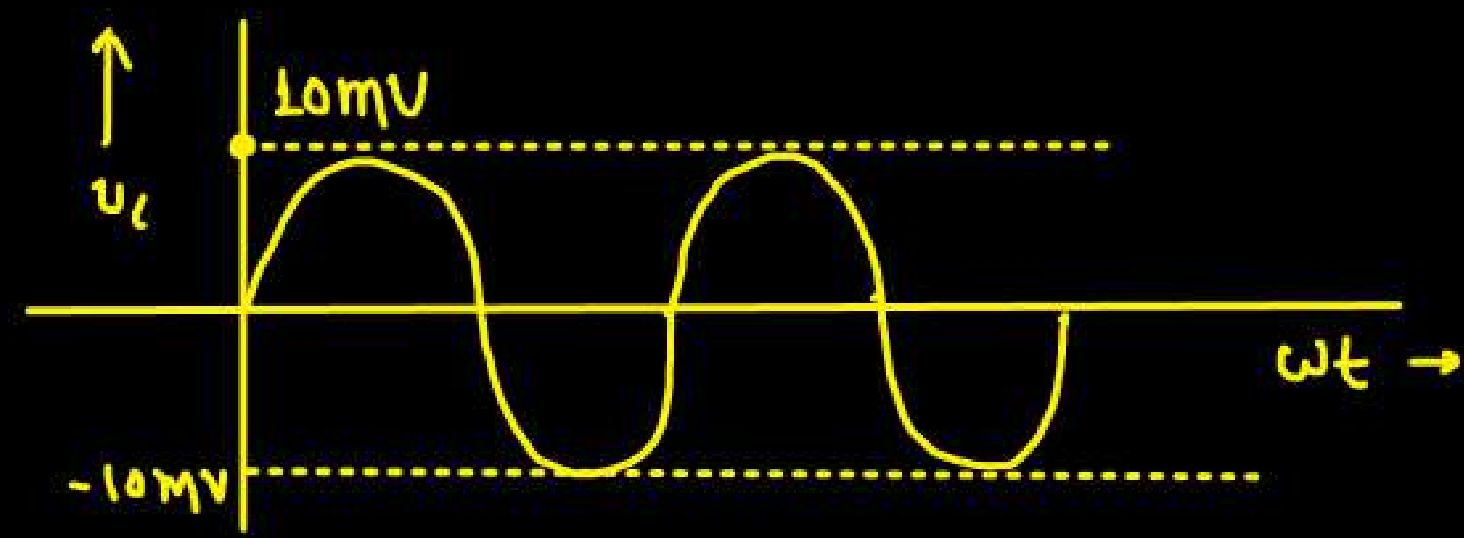


✯ Op-Amp as a Comparator :-



Given op-Amp is ideal.

Find v_o for the given i/p v_i

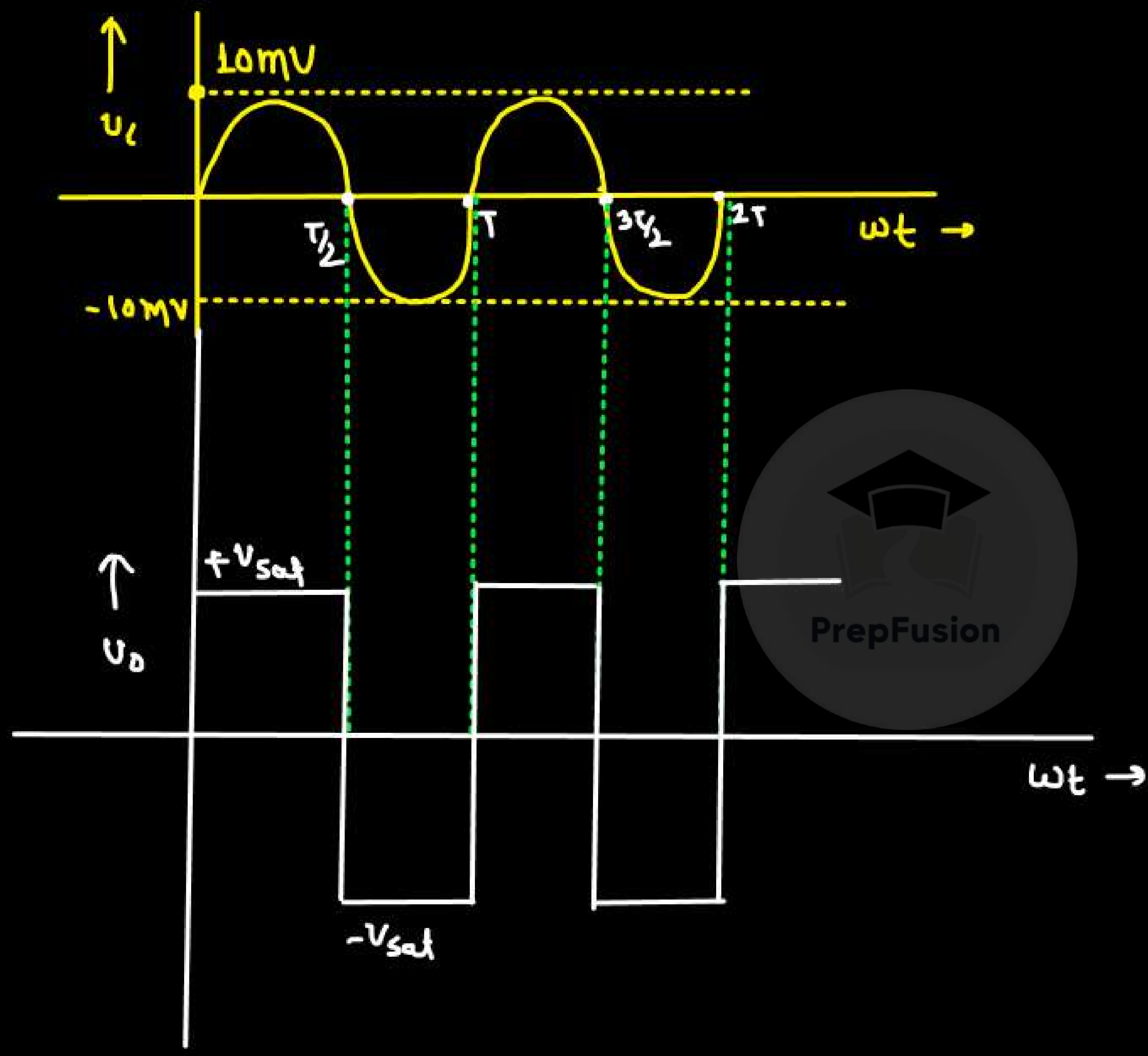


$\Rightarrow$ if $v_+ > v_- \Rightarrow v_o = +V_{sat}$

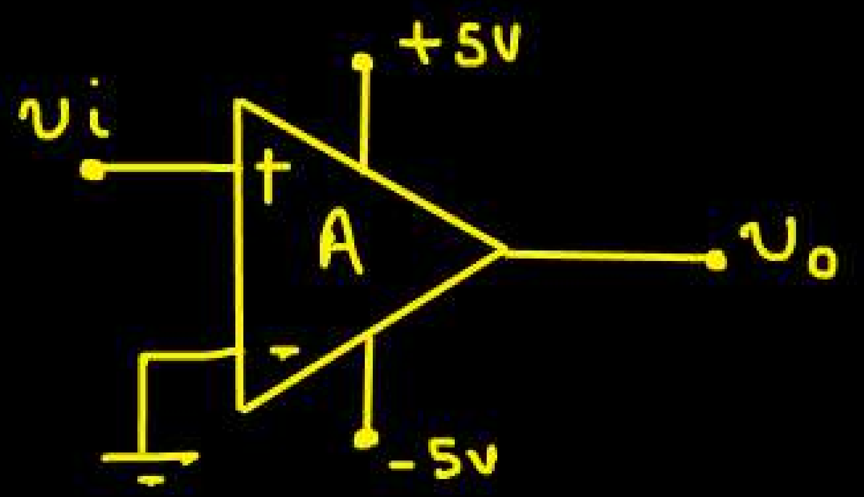
↳ $\boxed{v_i > 0 \Rightarrow v_o = +v_{sat}}$

$\Rightarrow$ if $v_+ < v_- \Rightarrow v_o = -V_{sat}$

$\boxed{v_i < 0 \Rightarrow v_o = -V_{sat}}$

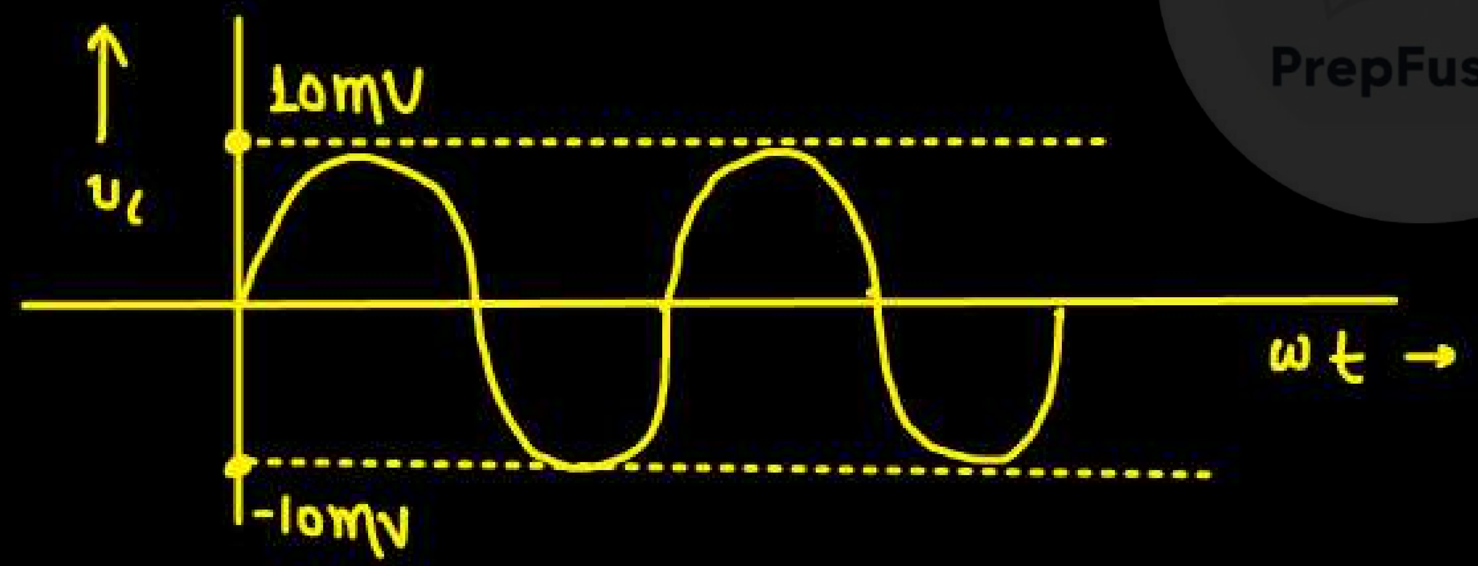

10mV
v_i
$T/2$
T
$3T/2$
2T
ωt →
-10mV
$+V_{sat}$
v_o
ωt →
$-V_{sat}$

Q.



Given op-Amp has a gain $A = 10^3\ V/V$

Find v_o for the given i/p v_i



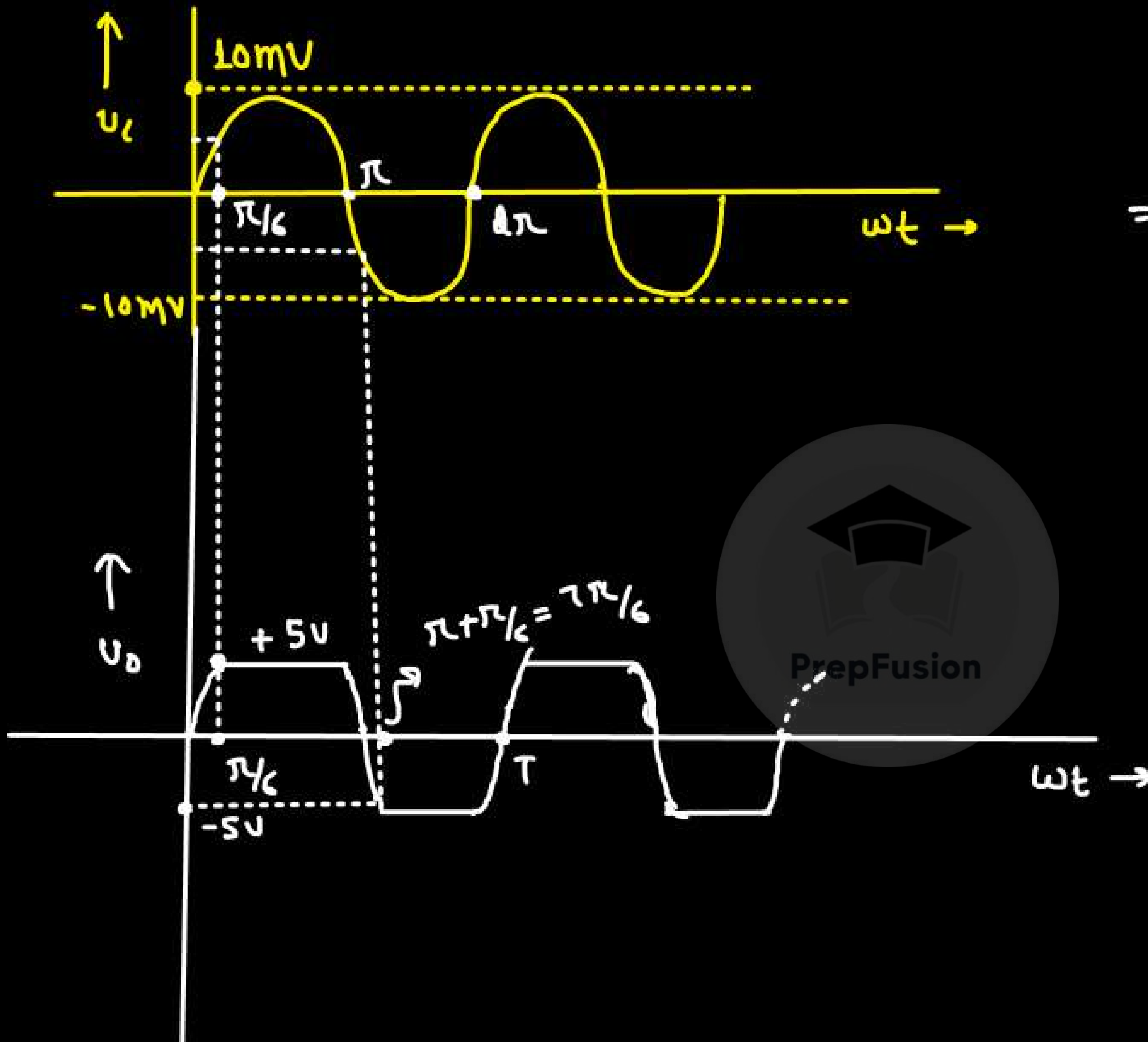
$$v_o = A v_d$$

$$v_o = 10^3 (v_i - 0)$$

$$\boxed{v_o = 10^3 v_i}$$

** $\boxed{+5V < v_o < -5V}$

-10mV

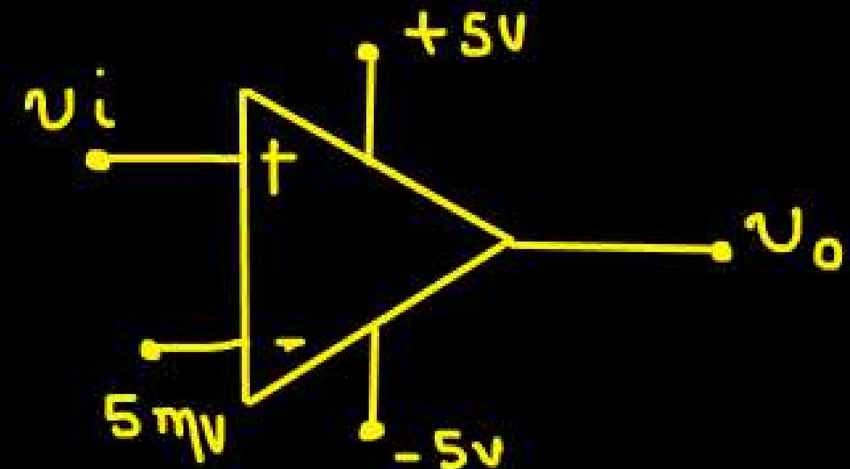


$10mV \sin \omega t$

$= 10mV \times \sin(\pi/6)$

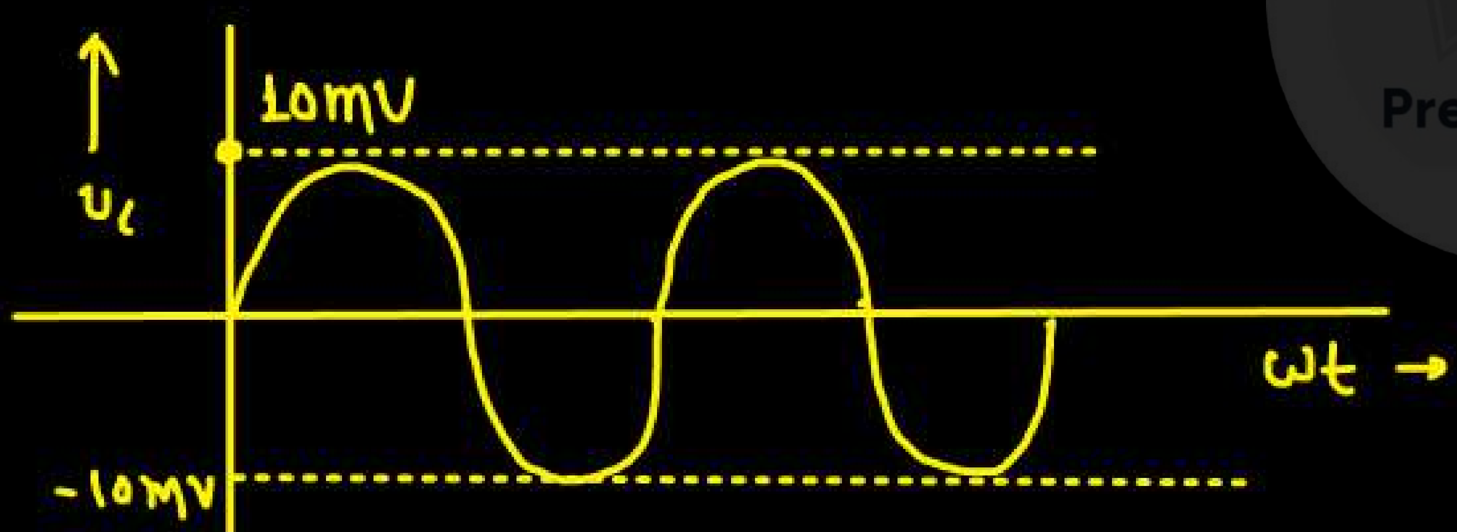
$= 5mV$

Q:



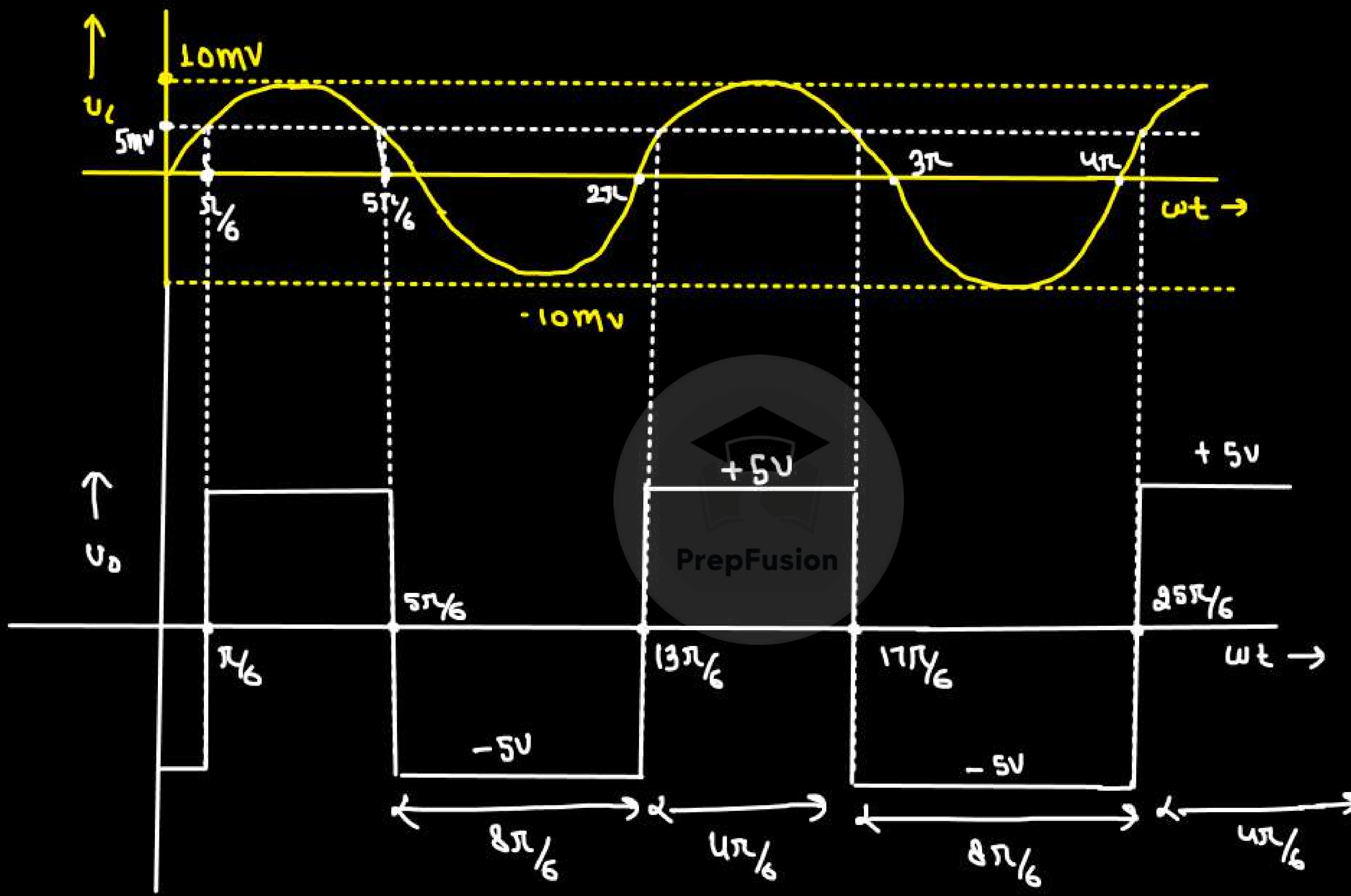
Given op-Amp is ideal.

Find v_o for the given i/p v_i



$$\Rightarrow \boxed{\begin{array}{l} v_i > 5\,mV \Rightarrow v_o = +V_{sat} \\ v_i < 5\,mV \Rightarrow v_o = -V_{sat} \end{array}}$$

Find the avg. value of o/p?


10mV
v_i
5mV
$\pi/6$
$5\pi/6$
2π
3π
4π
$\omega t \rightarrow$
-10mV
v_o
+5V
+5V
$5\pi/6$
$25\pi/6$
$\pi/6$
$13\pi/6$
$17\pi/6$
$\omega t \rightarrow$
-5V
-5V
$8\pi/6$
$4\pi/6$
$8\pi/6$
$4\pi/6$

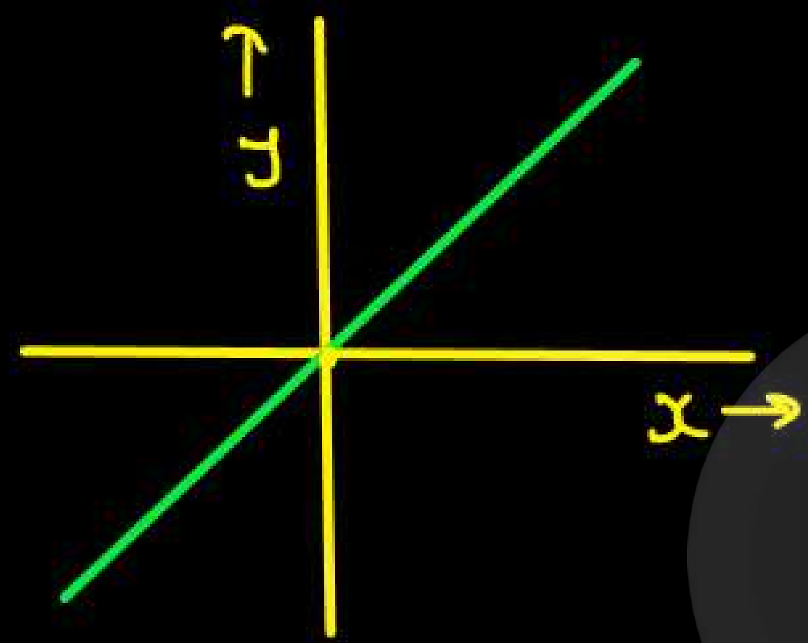
$$(\text{Average})_{o/p} = \frac{\text{Area of a Time period}}{\text{Time period}}$$

$$= \frac{-5 \times \frac{8\pi}{6} + 5 \times \frac{4\pi}{6}}{2\pi}$$

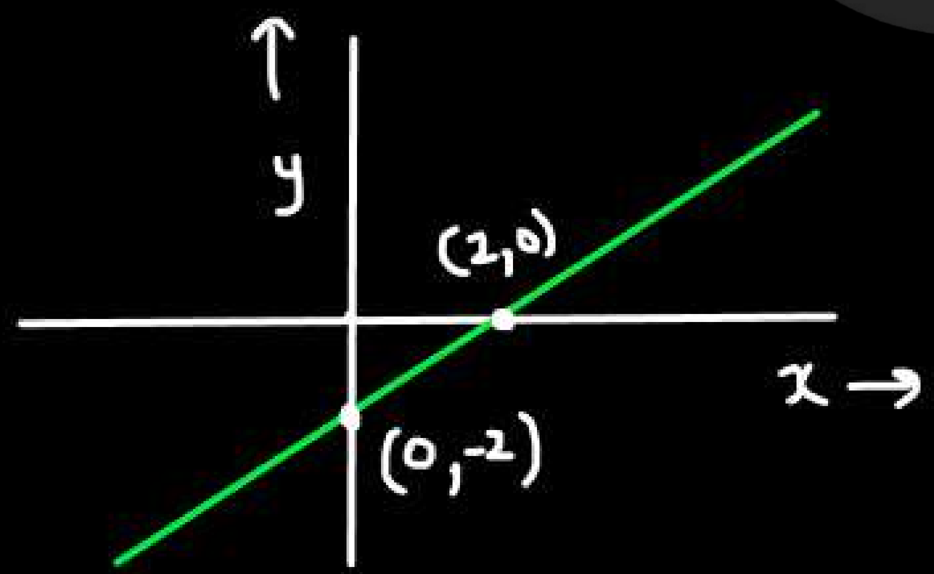
$$\boxed{(\text{Average})_{o/p} = -1.67\,V}$$

Revision:

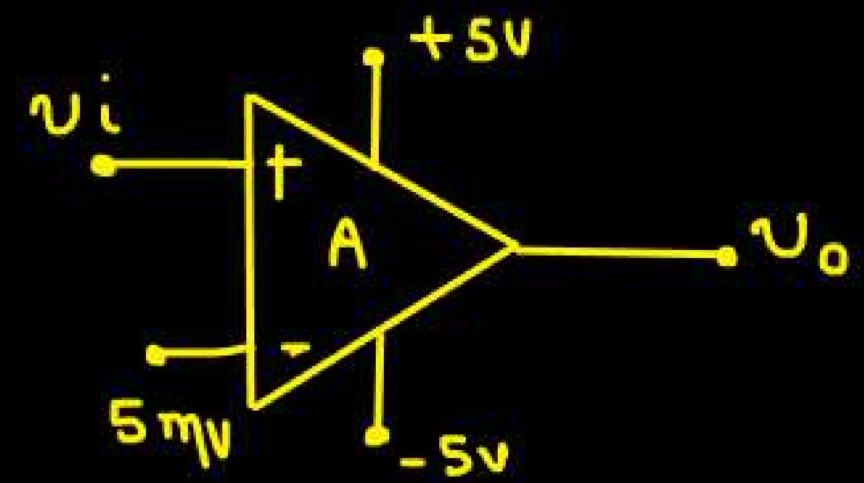
Q. Graph of $y = x$ is given. Plot $y = x - 2$



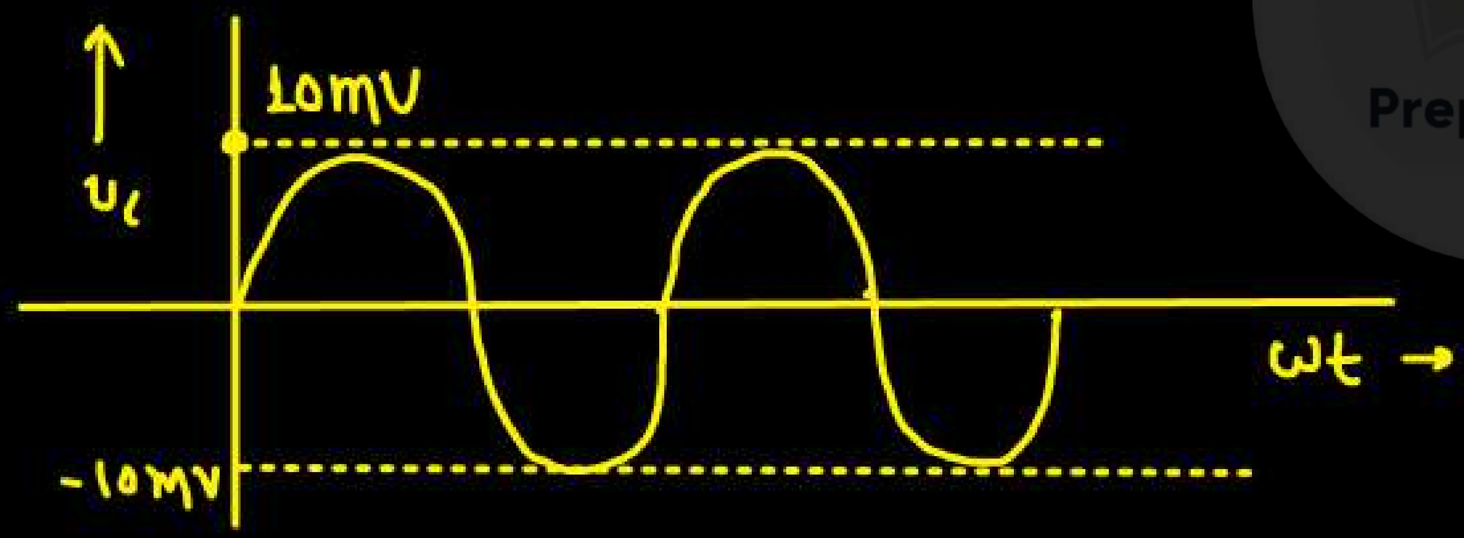
→



Q.



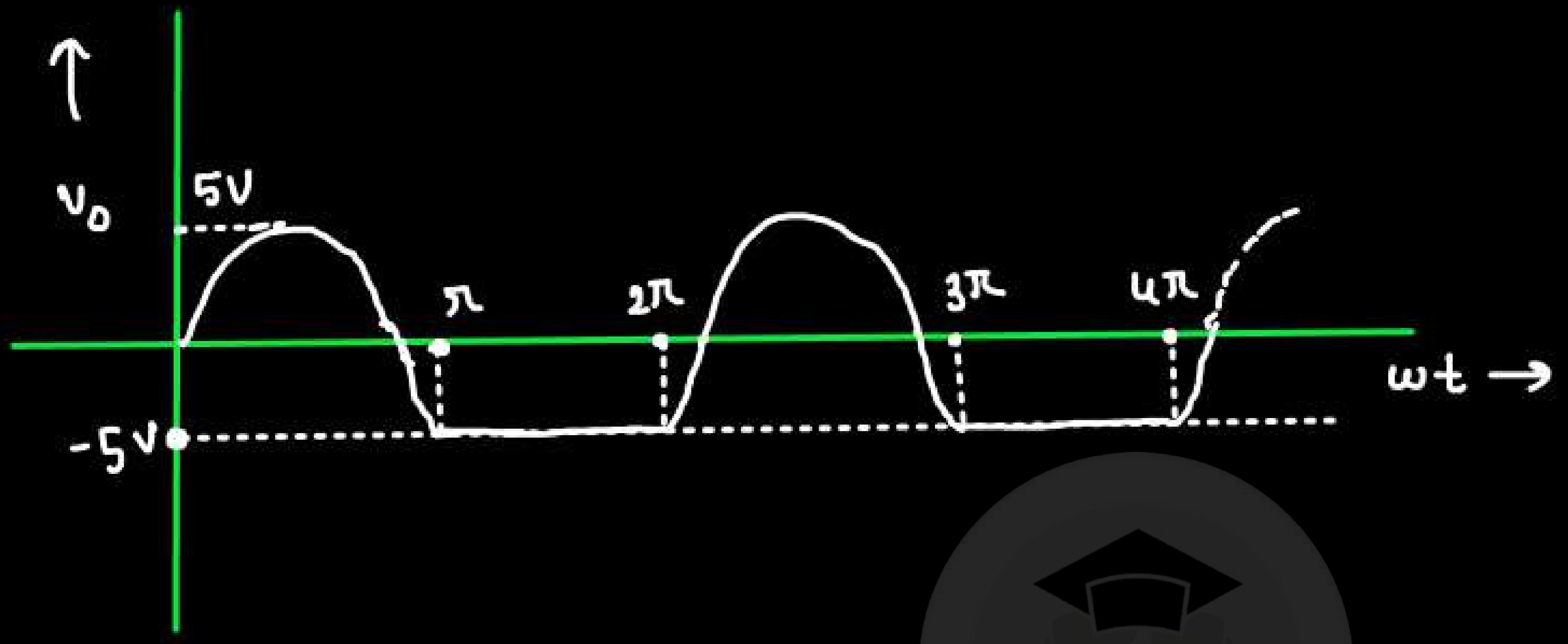
Given op-Amp is having $A = 10^3$ V/V
Find v_o for the given i/p v_i



$$\boxed{v_o = 10^3 (v_i - 5mV)}$$

$$\boxed{-5V \le v_o \le +5V}$$

$v_i = 10mV \sin\omega t$



$$v_0 = 10^3 (v_i - 5mv)$$

$$-5 = 10^3 (10mv \sin \omega t - 5mv)$$

$$-5 = 10 \sin \omega t - 5$$

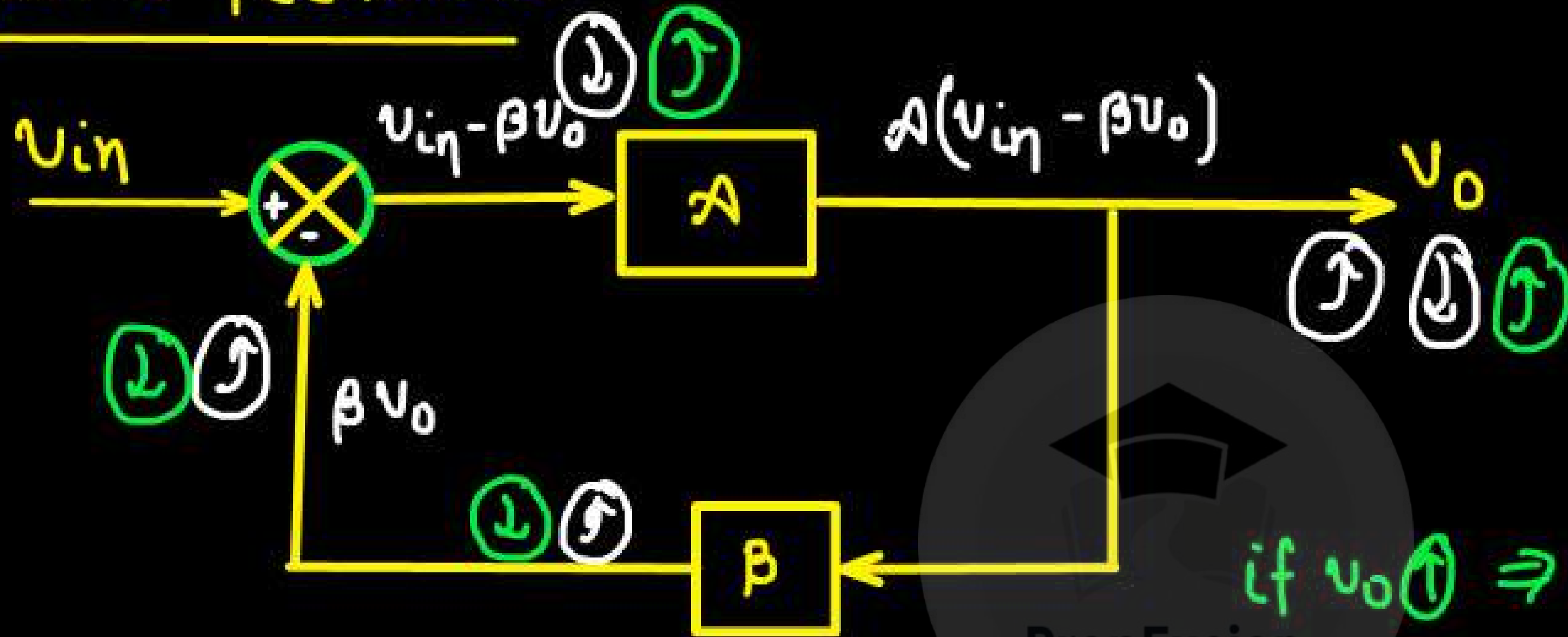
$$10 \sin \omega t = 0$$

$$\omega t = \pi, 2\pi, 3\pi, 4\pi$$

⇒ Basics of feedback :-

Considering A and β to be positive

① Negative feedback :-

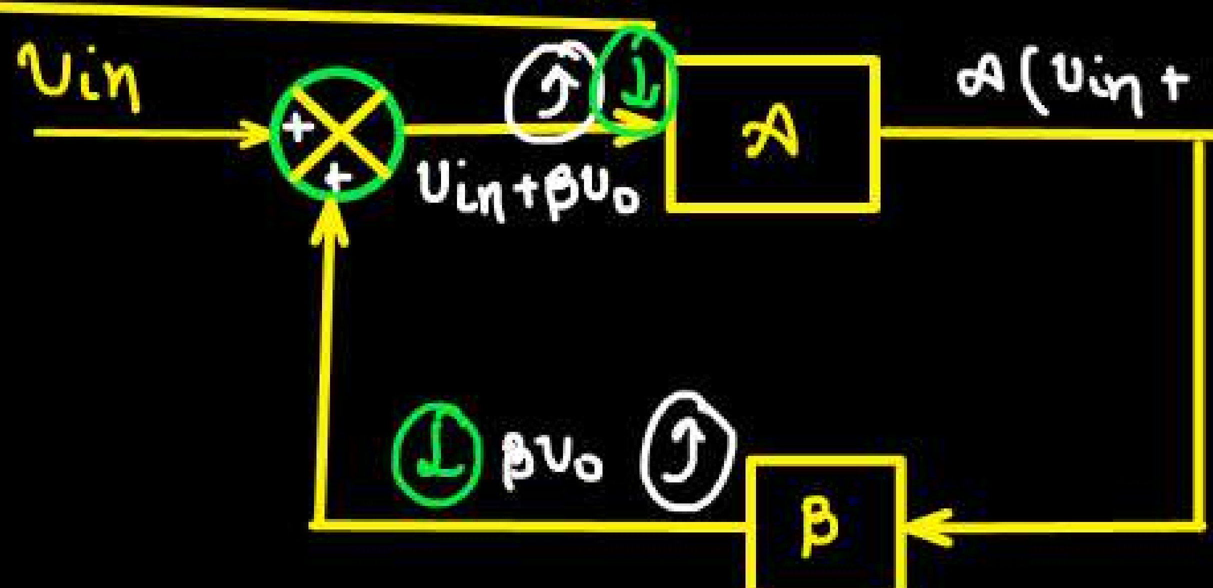


$v_0 = A(v_{in} - \beta v_0)$

$$\boxed{v_0 = \frac{A}{1+A\beta} v_i}$$

if $v_0 \uparrow \Rightarrow v_0 \downarrow \Rightarrow$ Negative f/b system is stable

② Positive feedback :-



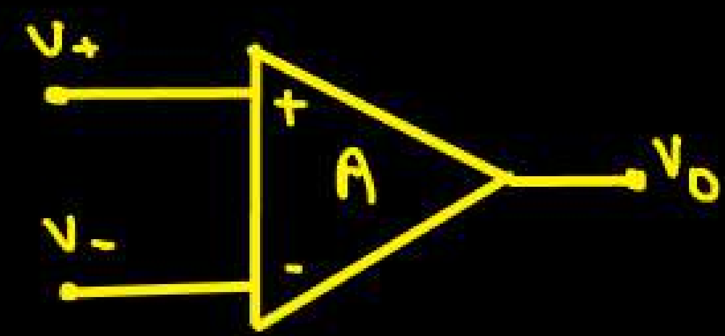
$$\boxed{\frac{v_0}{v_i} = \frac{A}{1-A\beta}}$$

if $v_0 \uparrow \Rightarrow v_0 \uparrow$

OR

$v_0 \downarrow \Rightarrow v_0 \downarrow \Rightarrow$ positive f/b s/s is unstable

⇒ Concept of Virtual Short:-



$$v_0 = A(v_+ - v_-)$$

if $A = \infty$

$$\frac{v_0}{A} = v_+ - v_-$$

$$\boxed{v_+ - v_- = \frac{v_0}{\infty}}$$

For positive f/b, v_0 = unstable

For Negative f/b, v_0 = stable

$$v_+ - v_- = \frac{v_0}{\infty} \rightarrow \text{stable}$$

$$v_+ - v_- = 0$$

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

Concept of virtual short:-

In case of Negative f/b; Inverting terminal (v_-) potential is equal to the potential of Non-inverting terminal (v_+).

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

★ Virtual short is not valid when -

(i) There is a positive feedback.

(ii) Gain A is finite

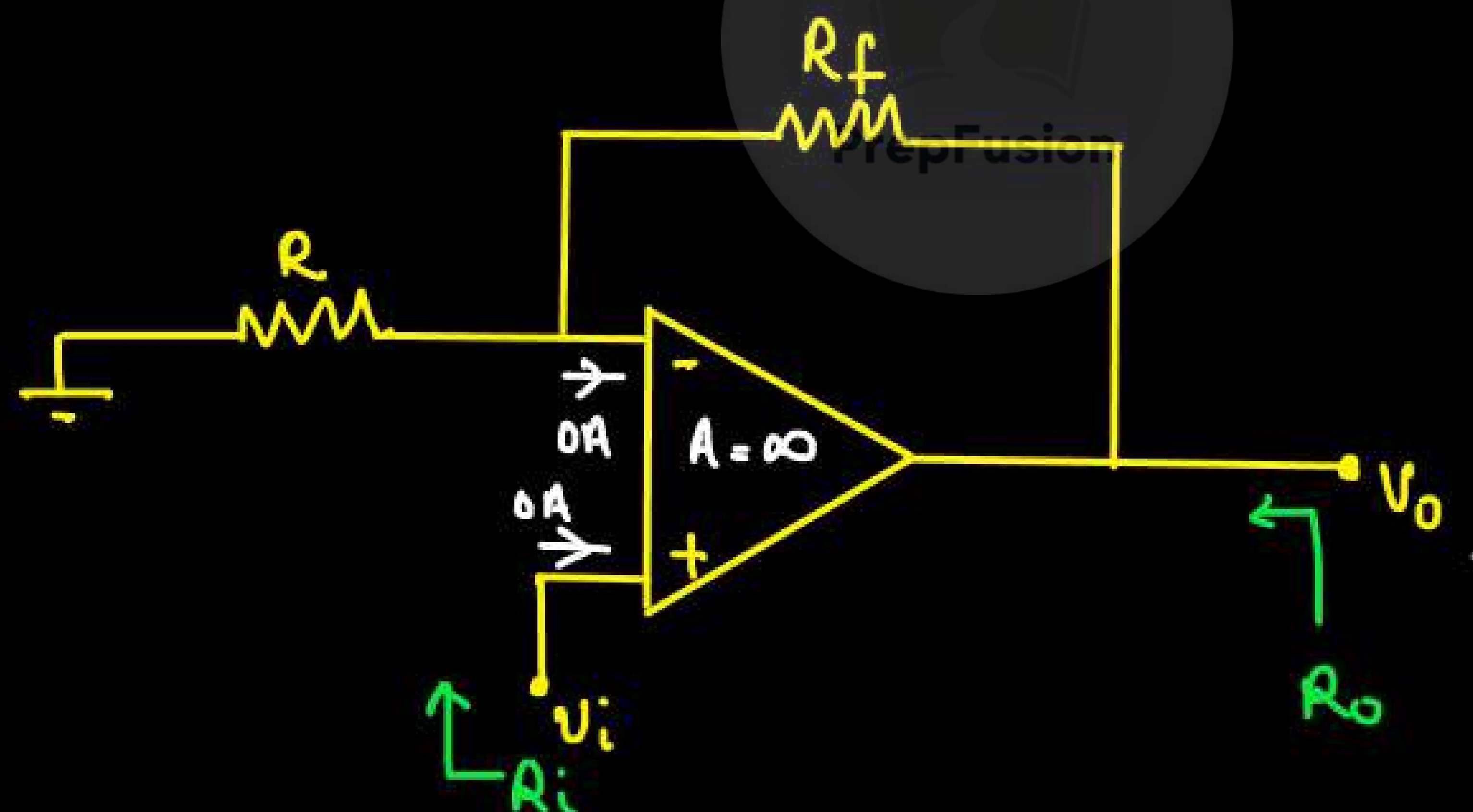
(iii)** When o/p is saturated ($\pm V_{sat}$).

* Different OP-Amp Configurations:

⇒ OP-Amp in Negative feedback:-

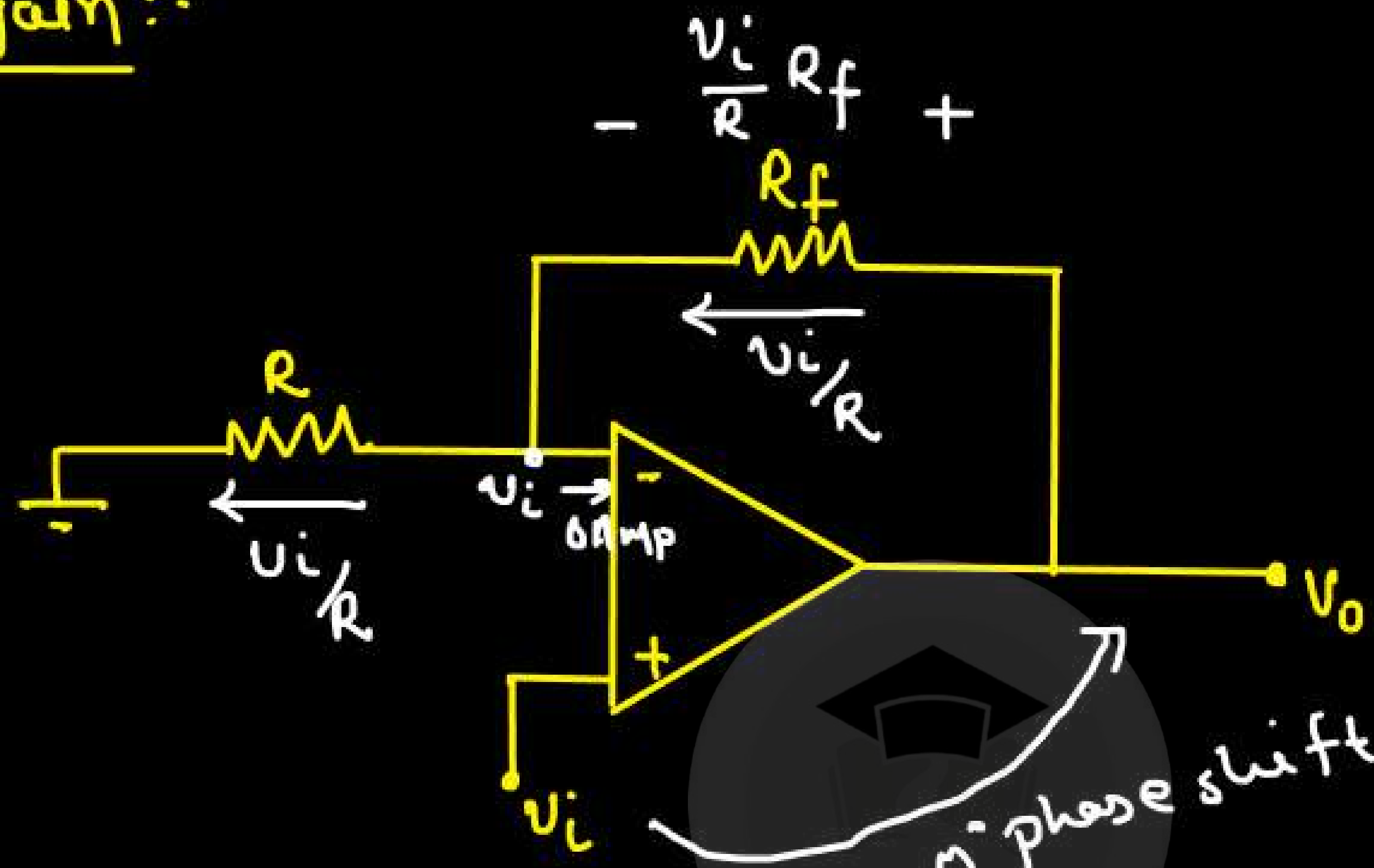
① **Non-inverting Amplifier:-**

↳ i/p is connected to non-inverting (V_+) terminal.



Considering ideal OP-Amp

(a) Voltage gain :-



$$v_0 = v_i + \frac{v_i}{R} R_f$$

$$v_0 = \left[1 + \frac{R_f}{R}\right] v_i$$

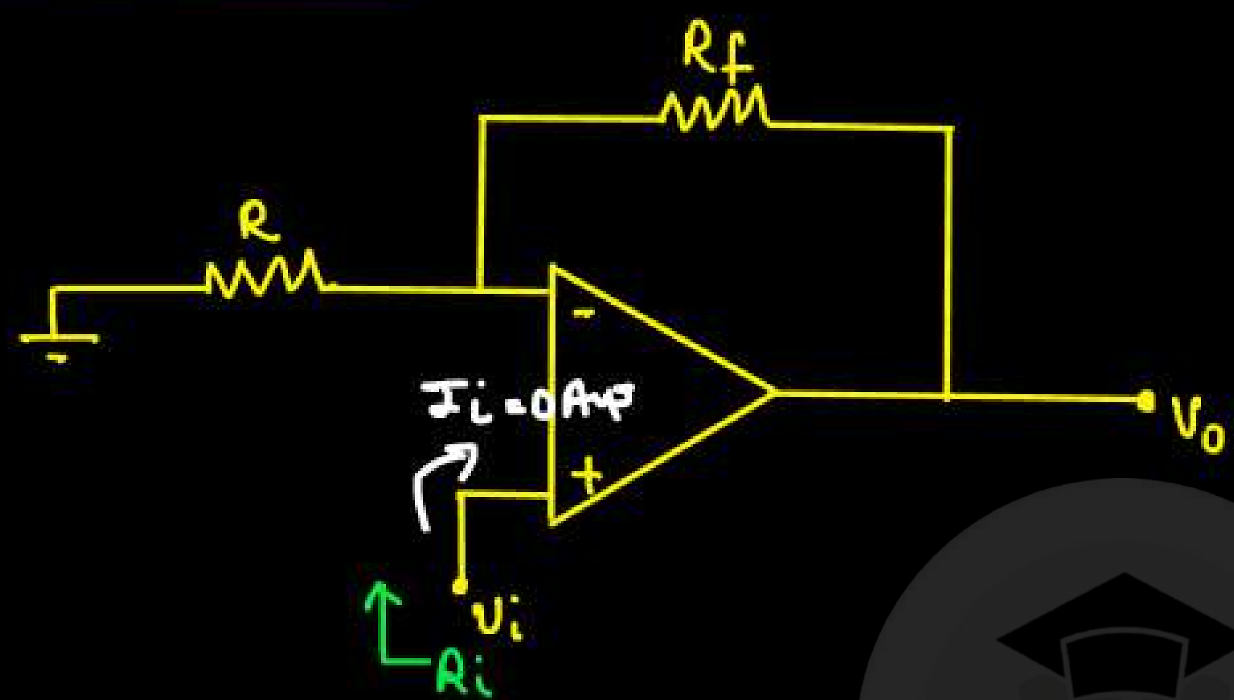
$$\Rightarrow \boxed{\frac{v_0}{v_i} = 1 + \frac{R_f}{R}}$$

$\Downarrow$

Gain of Non inverting Amplifier

R_i'

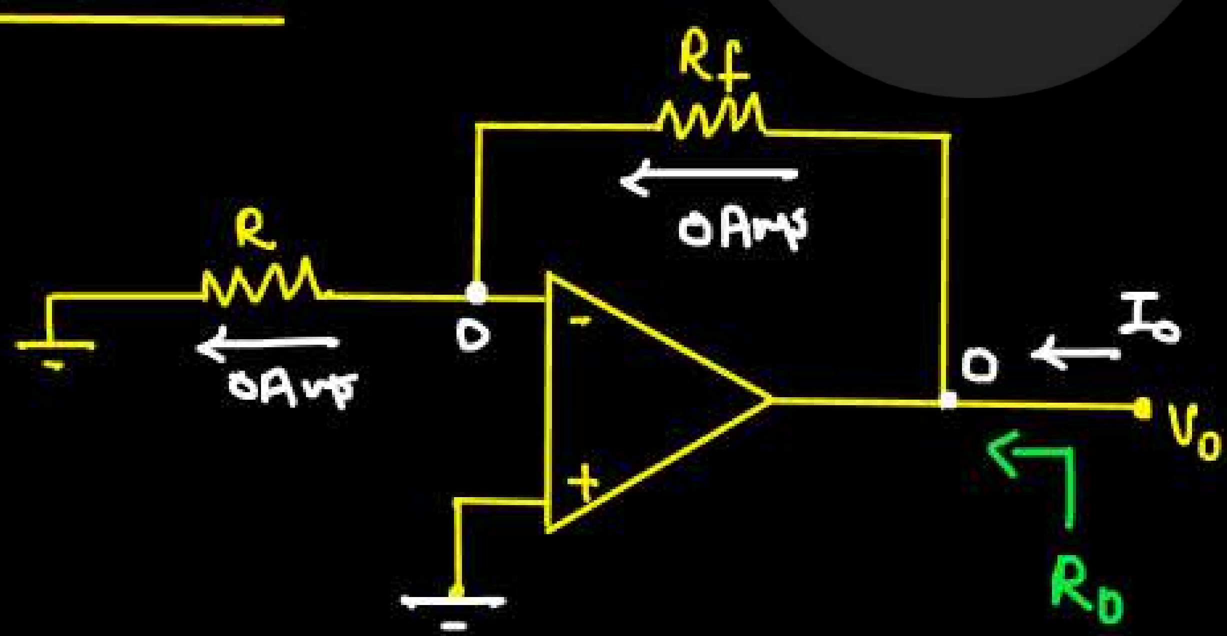
(b) Input Resistance :-



$$R_i = \frac{V_i}{I_i} = \frac{V_i}{0}$$

$$\boxed{R_i = \infty}$$

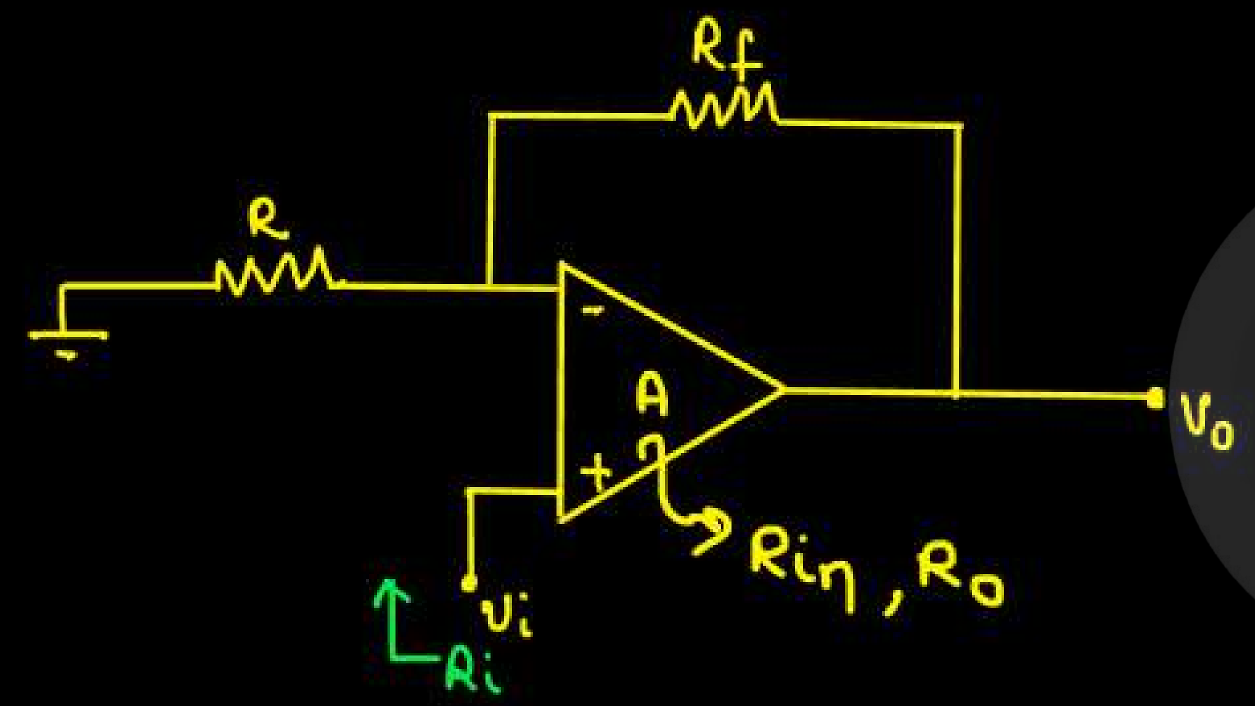
(c) Output Resistance :-

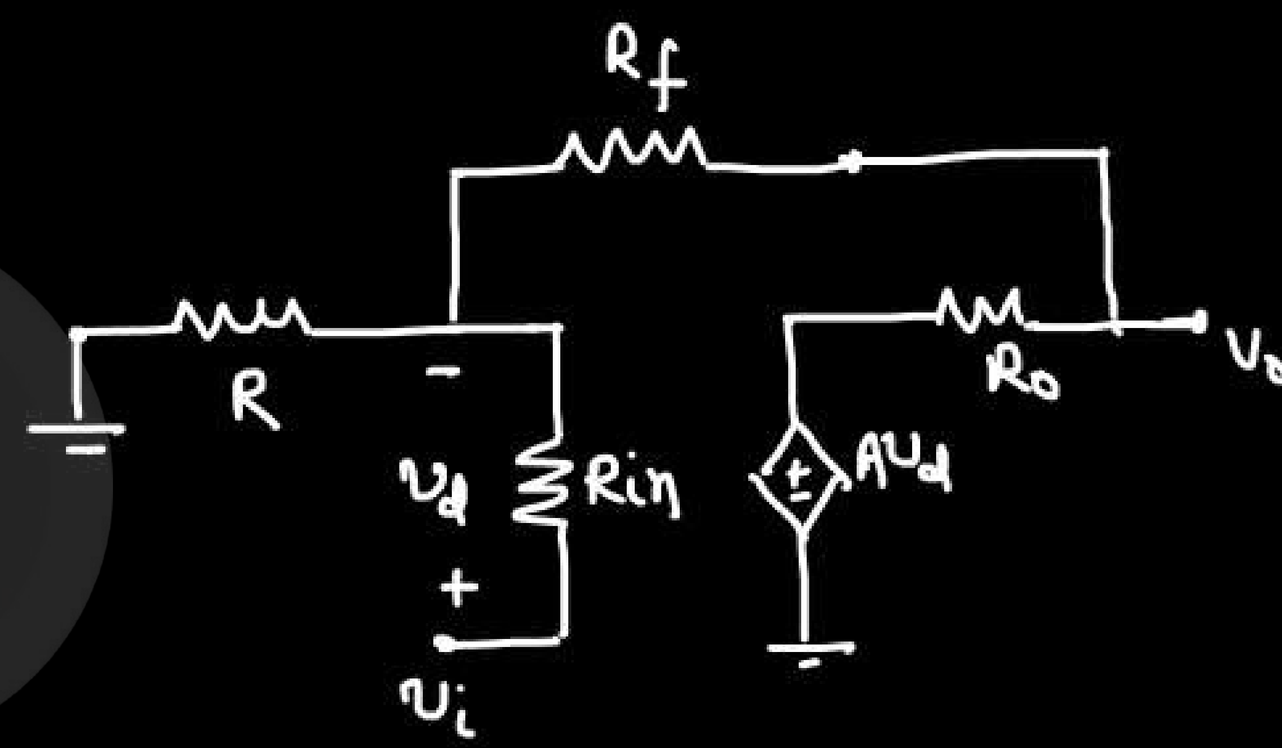


$$R_o = \frac{V_o}{I_o} = \frac{0}{I_o}$$

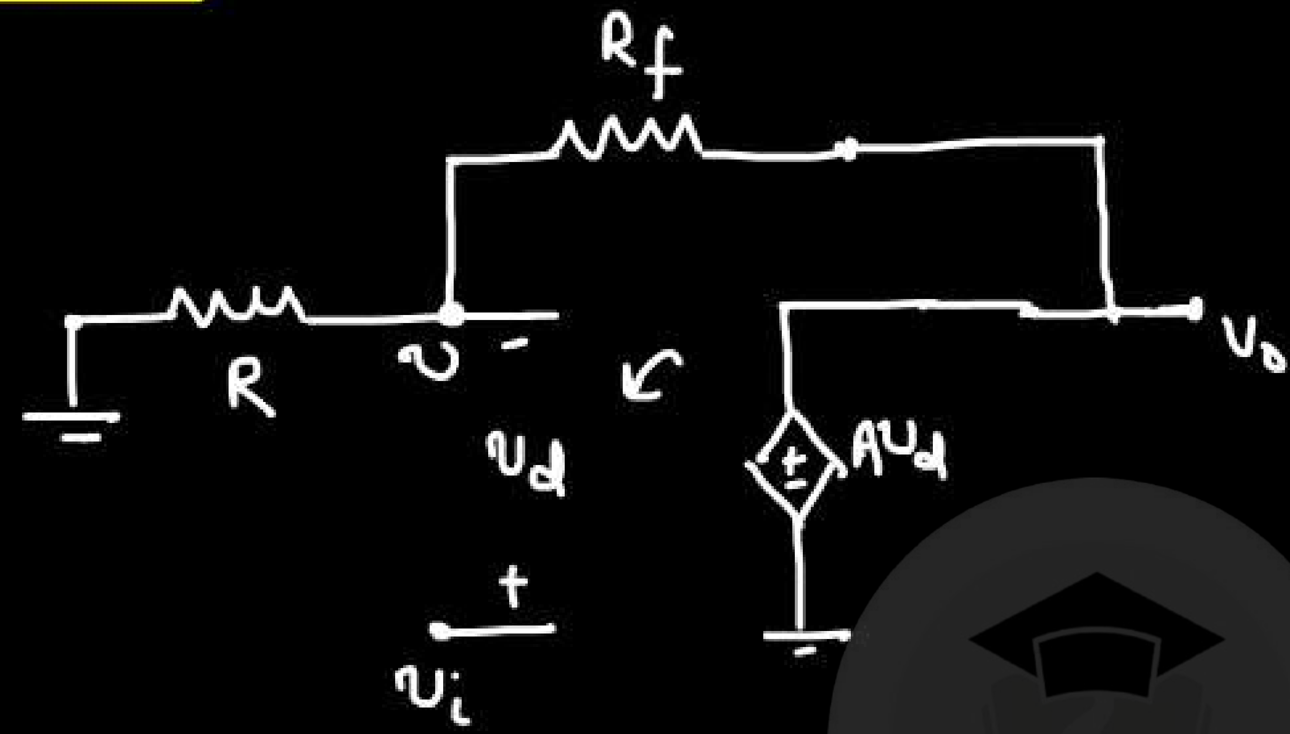
$$\boxed{R_o = 0}$$

* Non-inverting Amplifier considering Non-ideal Op-Amp [R_{in}, A, R_o]





(a) Voltage gain:-



For op-amp →

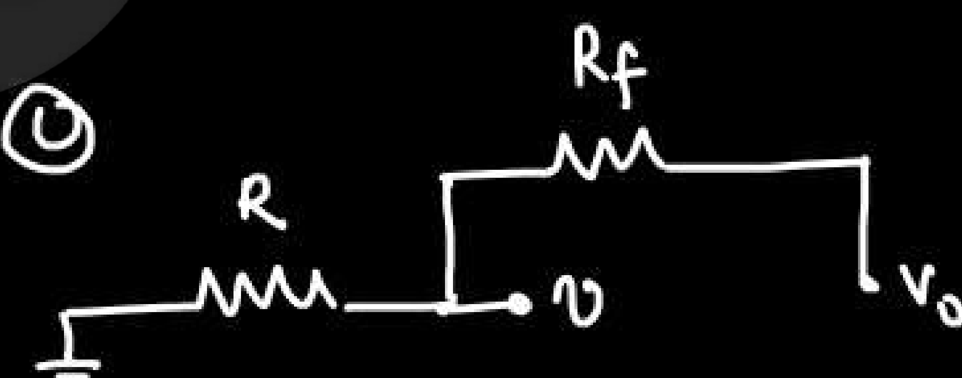
$R_{in} \to$ High

$R_o \to$ low

So, Assuming $R_{in} \to \infty$, $R_o \to 0$

$$v_o = A v_d$$

$$v_o = A[v_i - v] \longrightarrow (1)$$



$$v = \frac{v_o \times R}{R + R_f}$$

$$v = \beta v_o \longrightarrow (2) \quad \text{where } \beta = \frac{R}{R+R_f}$$

By eqⁿ ① and ②

$$v_o = A\left[v_i - \beta v_o\right]$$

$$v_o\left[1 + A\beta\right] = A v_i$$

**

$$\boxed{\frac{v_o}{v_i} = \frac{A}{1 + A\beta}}$$

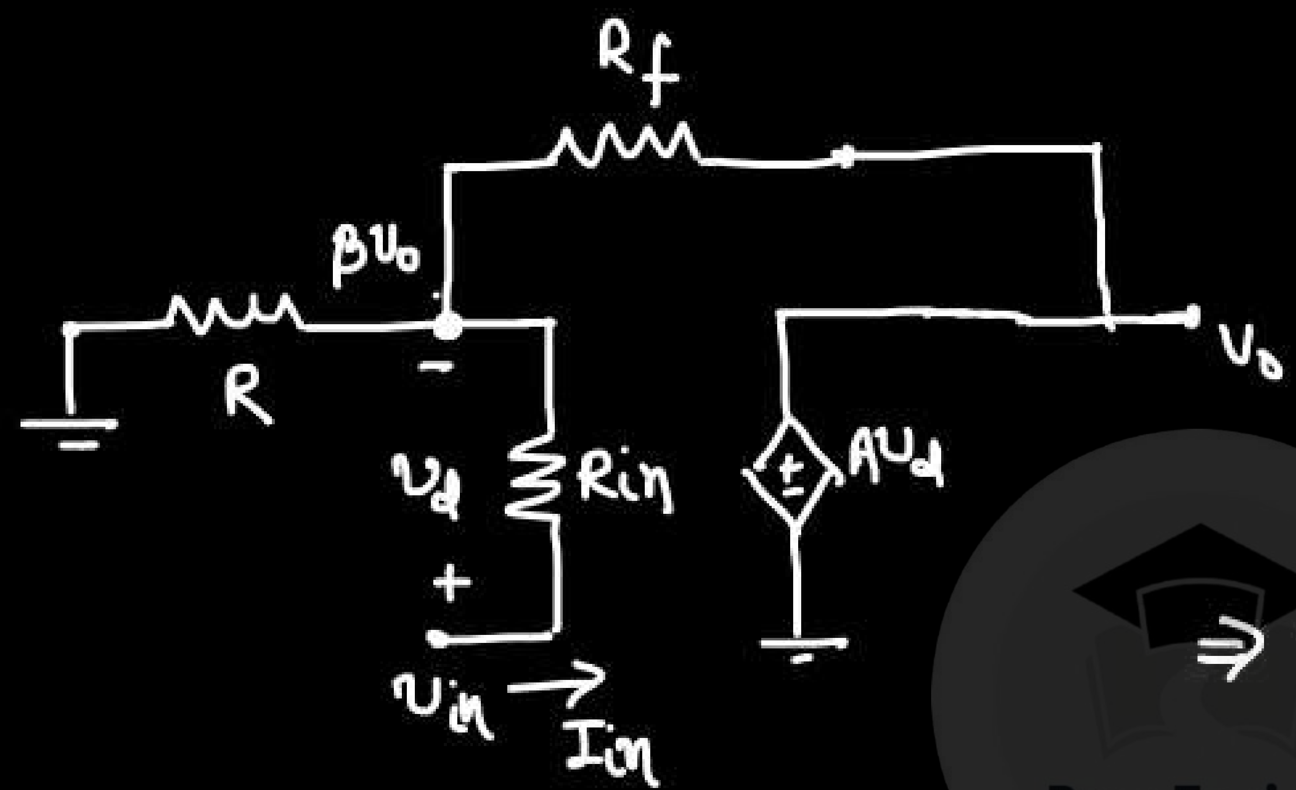
where $\beta = \dfrac{R}{R + R_f}$

if A is very large (∞)

$$\frac{v_o}{v_i} = \frac{A}{A\beta} = \frac{1}{\beta} = \frac{R + R_f}{R} = 1 + \frac{R_f}{R}$$

$$\boxed{\frac{v_o}{v_i} = 1 + \frac{R_f}{R}}$$

(b) Input Resistance :-



$$(R_{in})_f = \frac{v_i}{I_i}$$

$$\boxed{\beta = \frac{R}{R+R_f}}$$

$$\Rightarrow \frac{v_{in} - \beta v_o}{R_{in}} = I_{in}$$

$$v_{in} - \beta v_o = I_{in} R_{in}$$

$$v_{in} - \beta\left(\frac{A}{1+A\beta}\right) v_{in} = I_{in} R_{in}$$

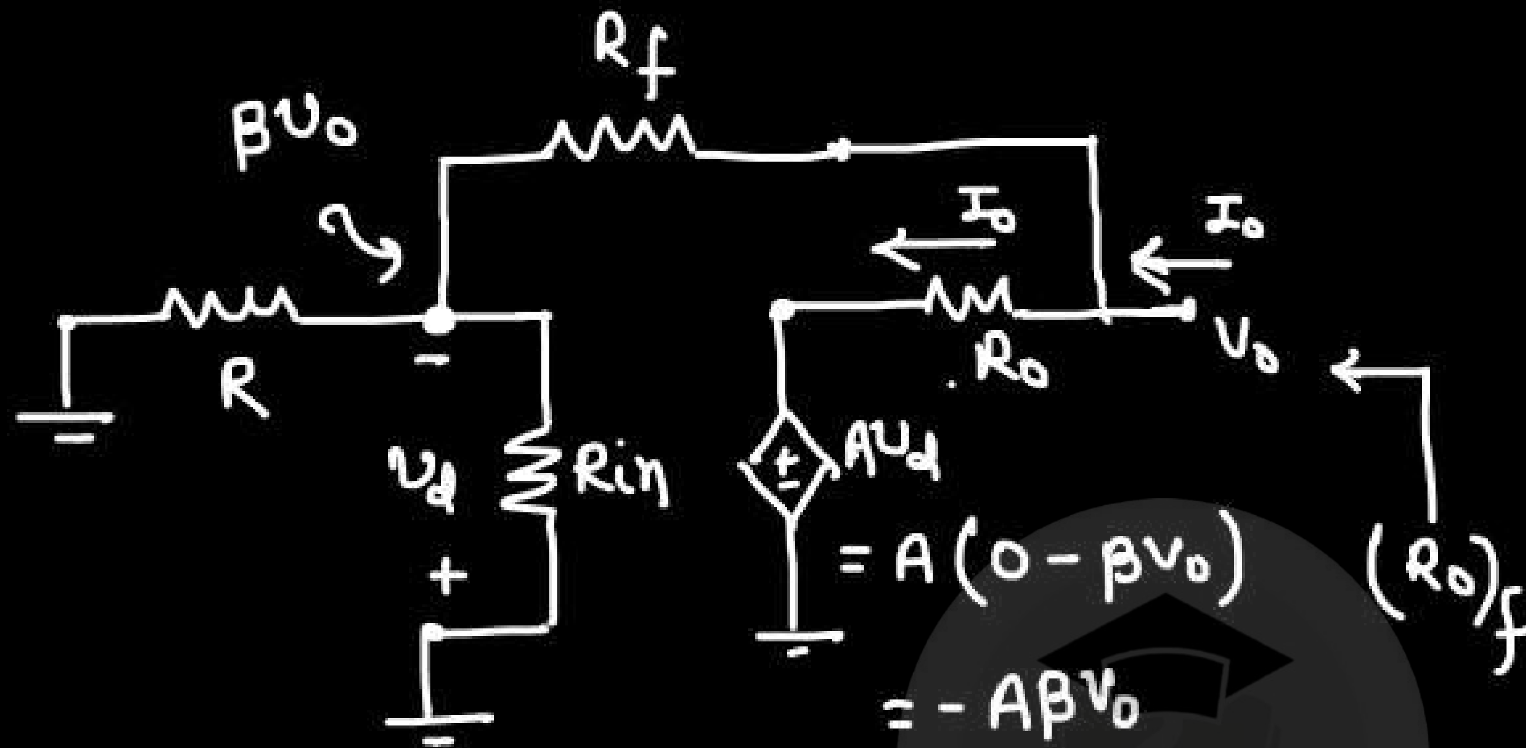
$$v_{in}\left[1 - \frac{A\beta}{1+A\beta}\right] = I_{in} R_{in}$$

$$\boxed{\frac{v_{in}}{I_{in}} = (R_{in})_f = R_{in}[1 + A\beta]}$$

if $A \rightarrow$ very large $\rightarrow \infty$

$$\boxed{(R_{in})_f = \infty}$$

(c) Output Impedance (R_o):-



$$(R_o)_f = \frac{v_o}{I_o}$$

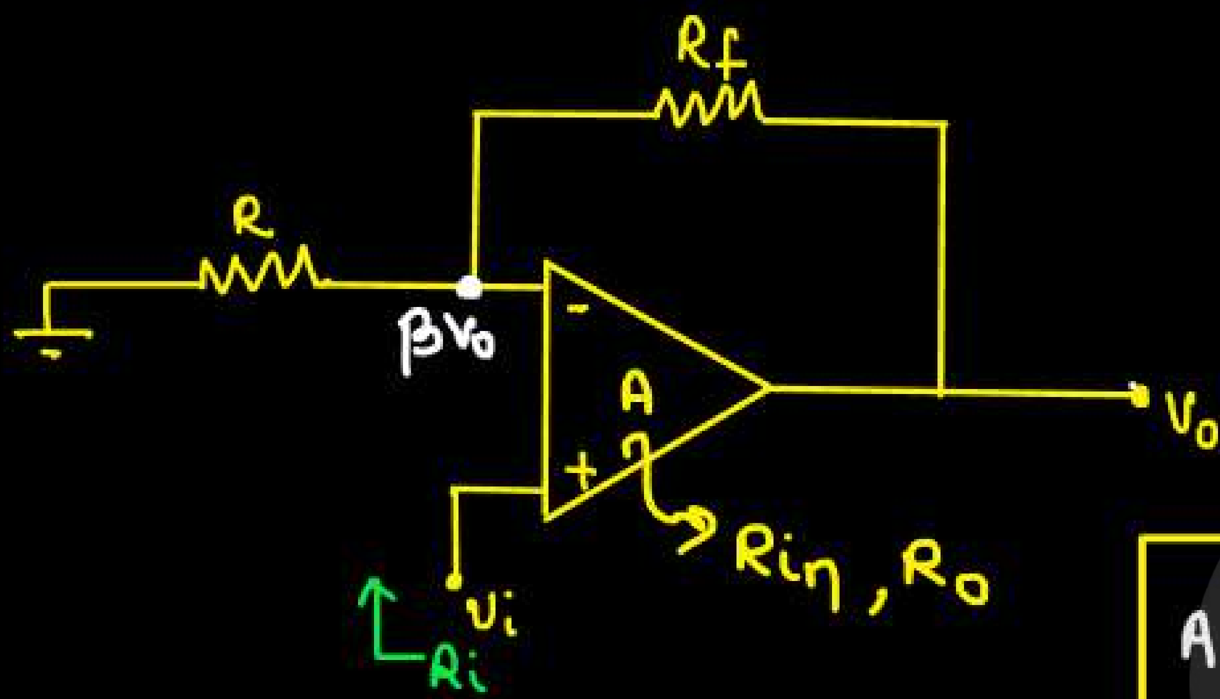
$$\frac{v_o - (-A\beta v_o)}{R_o} = I_o$$

$$\boxed{\frac{v_o}{I_o} = \frac{R_o}{1 + A\beta} = (R_o)_f}$$

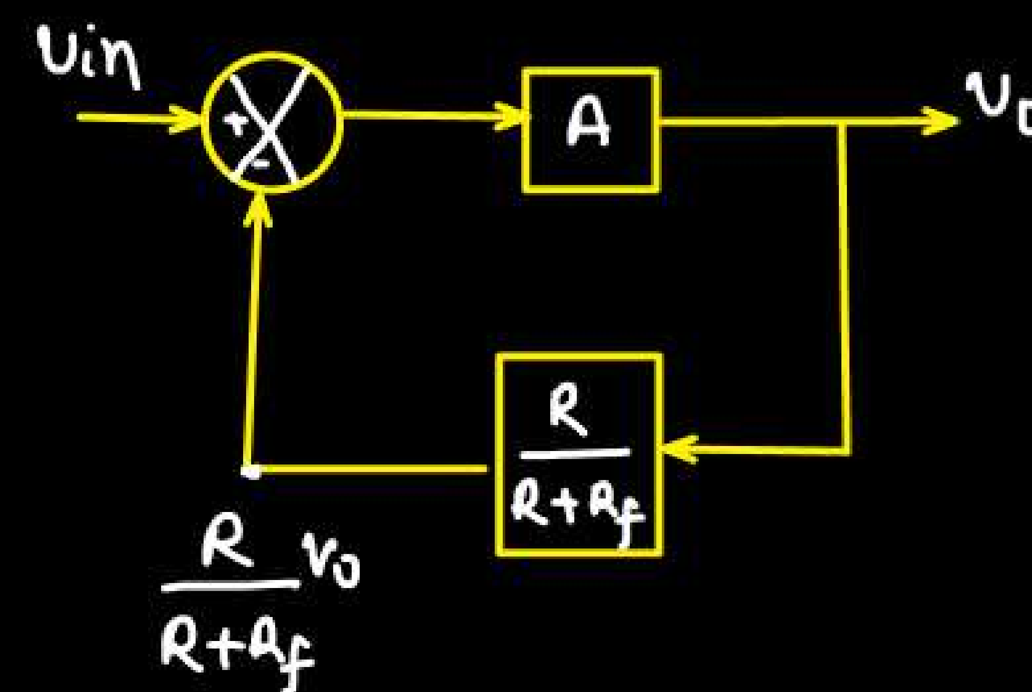
$\Rightarrow$ if $A \to \infty$

$$\boxed{R_{of} = 0\,\Omega}$$

★ Understanding feedback topology in Non-inv. Amp:-



$$\beta = \frac{R}{R+R_f}$$



$$\boxed{A(v_i - \beta v_o) = v_o}$$

Voltage mixing
voltage sampling

⇒ Voltage - voltage f/b Topology

⇒ Voltage Amplifier

$R_{in} \rightarrow$ High , $R_o \rightarrow$ low

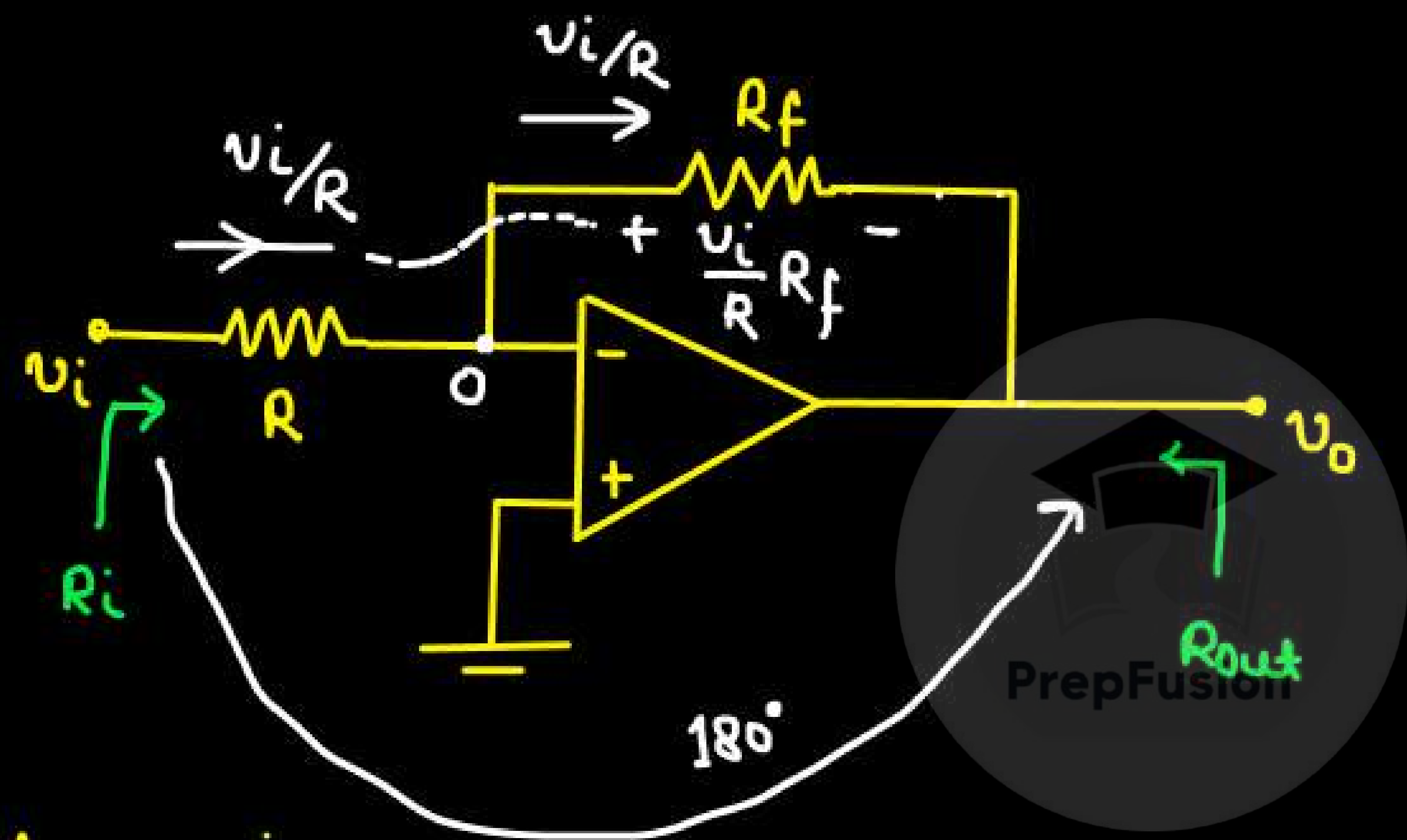
$$\boxed{(A_v)_f = \frac{A}{1+A\beta}}$$

$$\boxed{(R_{in})_f = R_{in}(1+A\beta)}$$

$$\boxed{(R_o)_f = \frac{R_o}{1+A\beta}}$$

(2) Inverting Amplifier :-

↳ i/p is applied at inverting terminal.

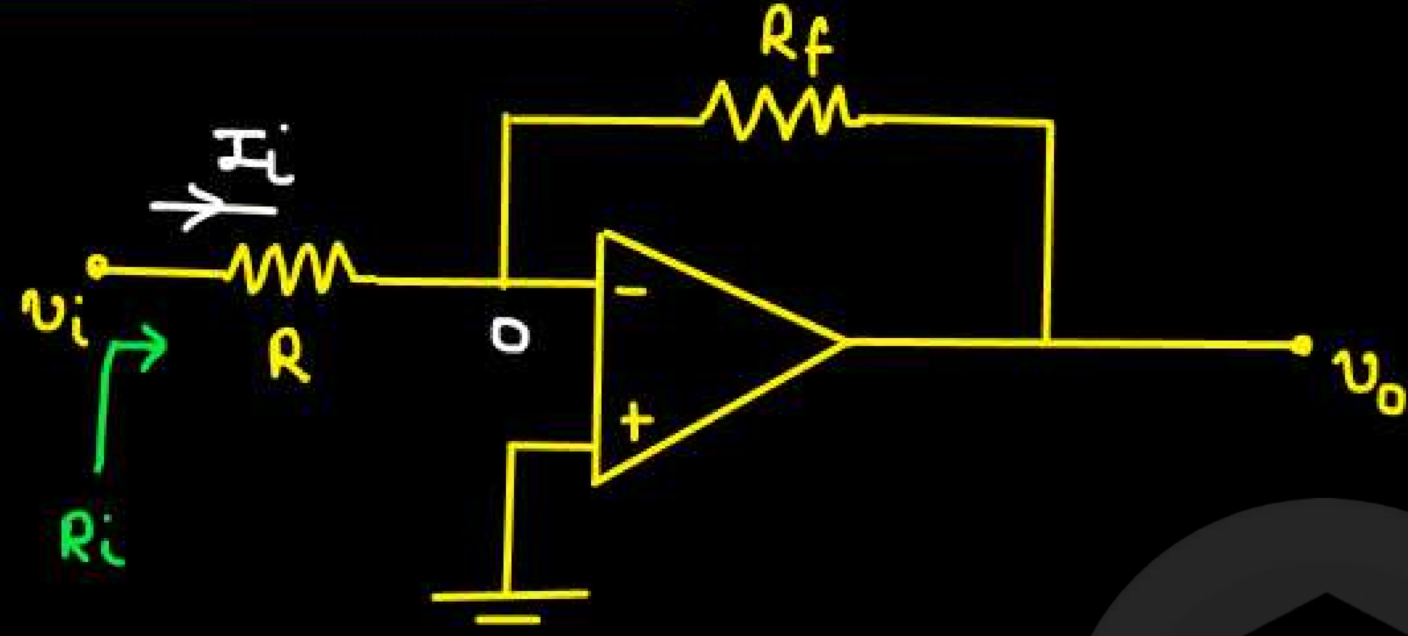


Considering ideal OP-Amp

(a) Voltage gain :-

$$-\frac{v_i}{R} R_f = v_o \Rightarrow \boxed{\frac{v_o}{v_i} = \frac{-R_f}{R}}$$

(b) Input Resistance:-

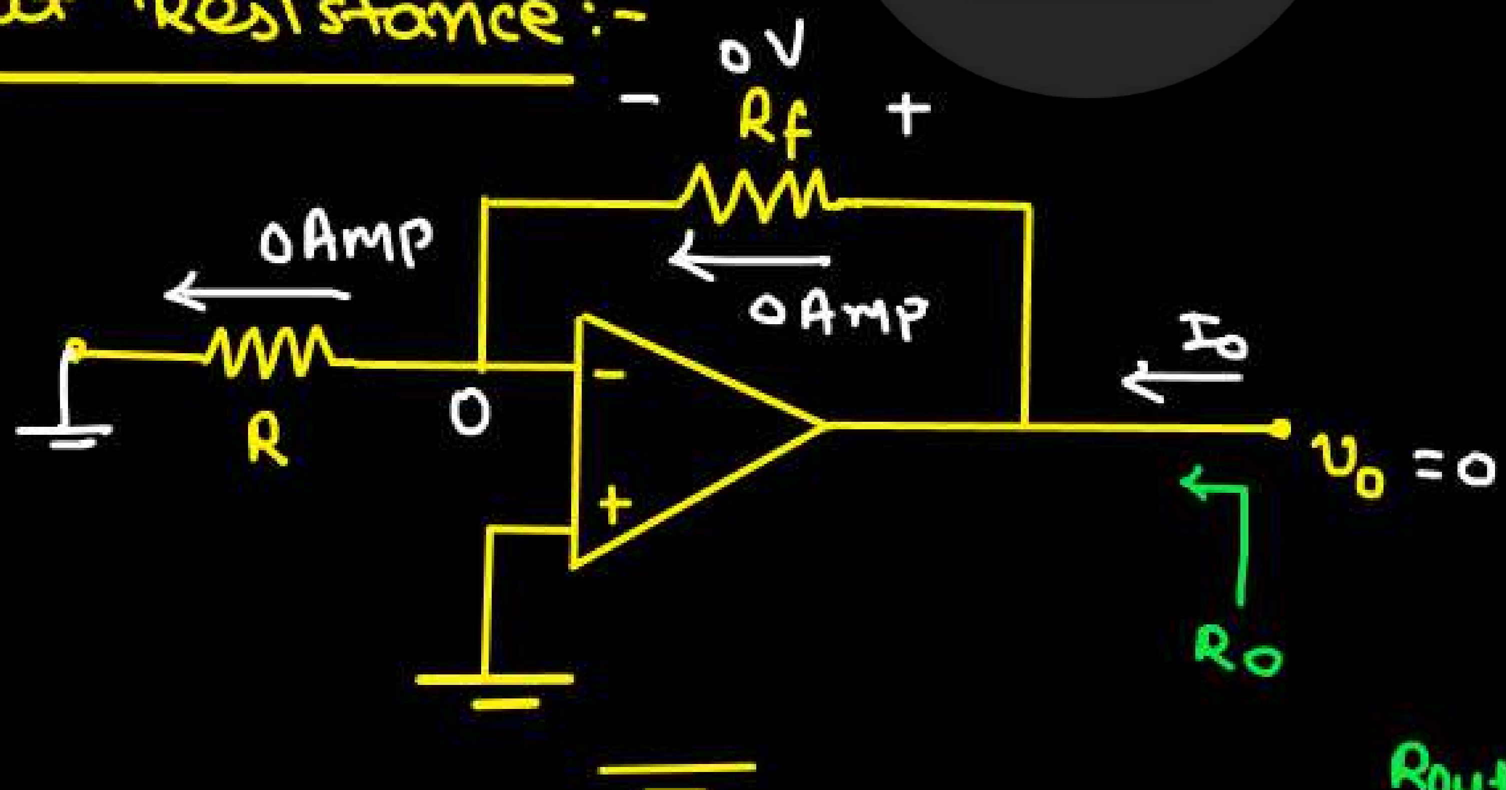


$$\boxed{R_i = \frac{v_i}{I_i}}$$

$$\frac{v_i}{R} = I_i$$

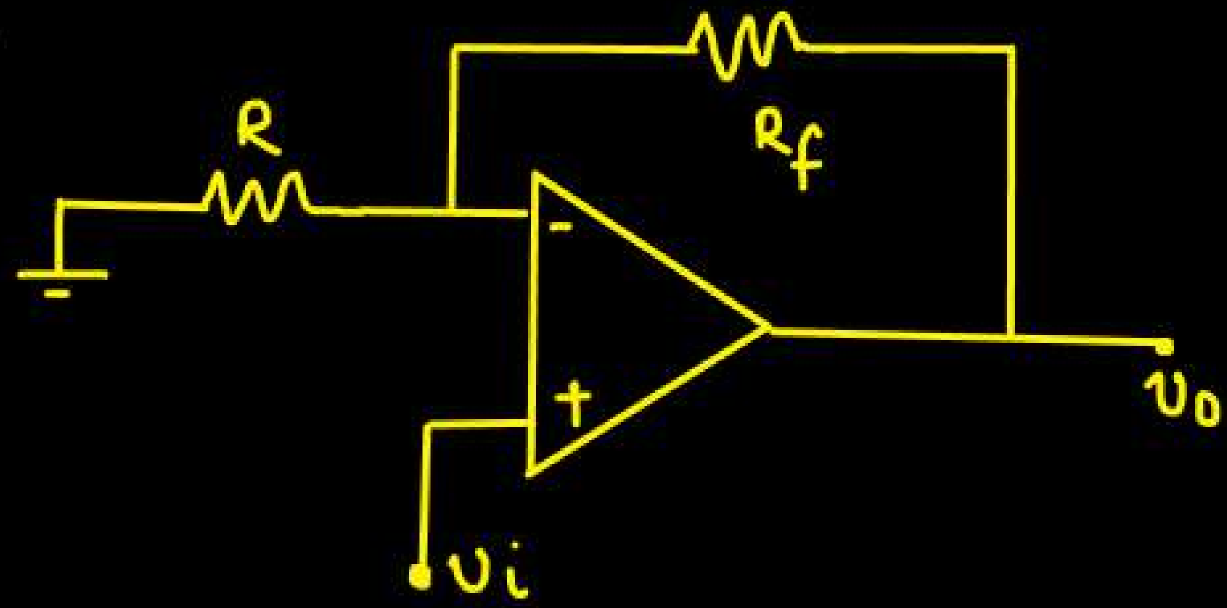
$$\boxed{\frac{v_i}{I_i} = R_i = R}$$

(c) Output Resistance:-

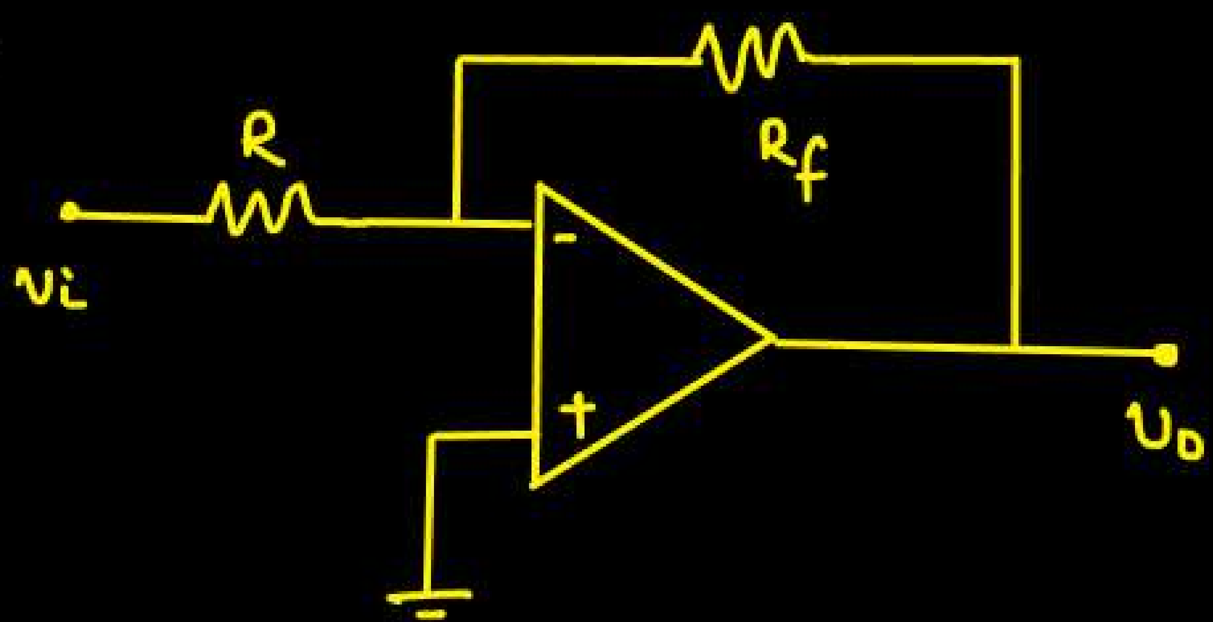


$$R_o = \frac{v_o}{I_o} = \frac{0}{I_o} = 0$$

$$\boxed{R_o = 0\,\Omega}$$

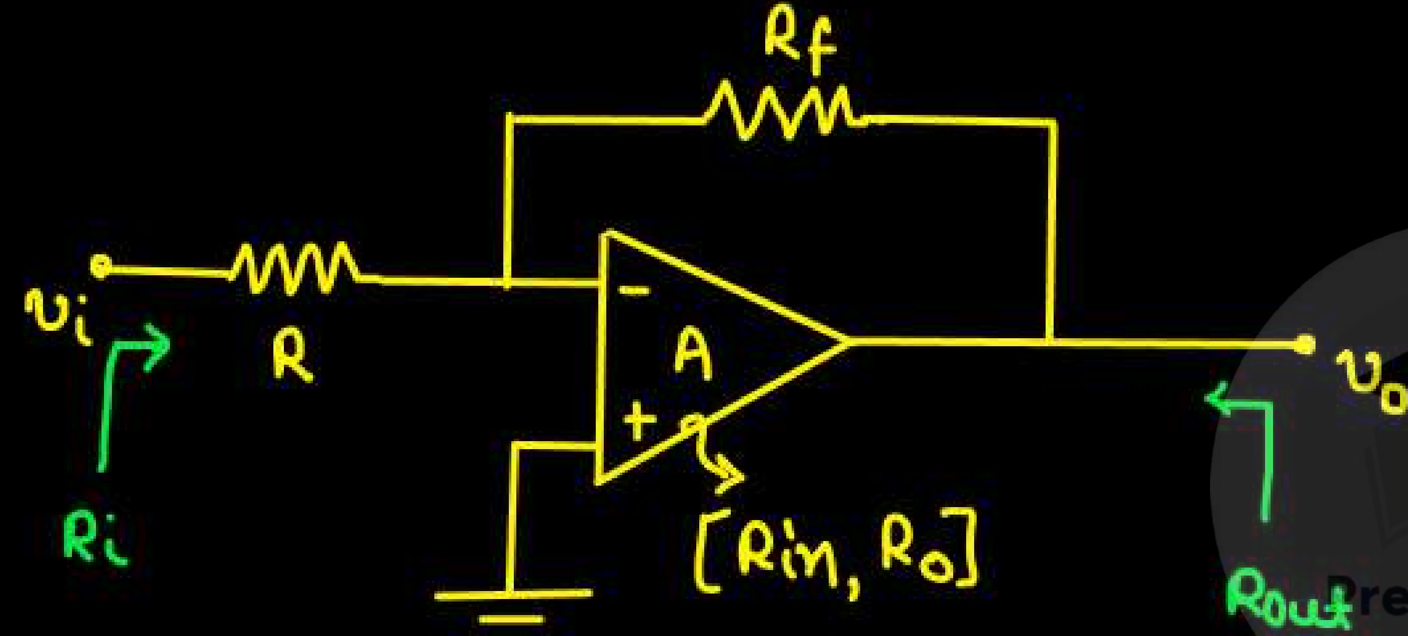


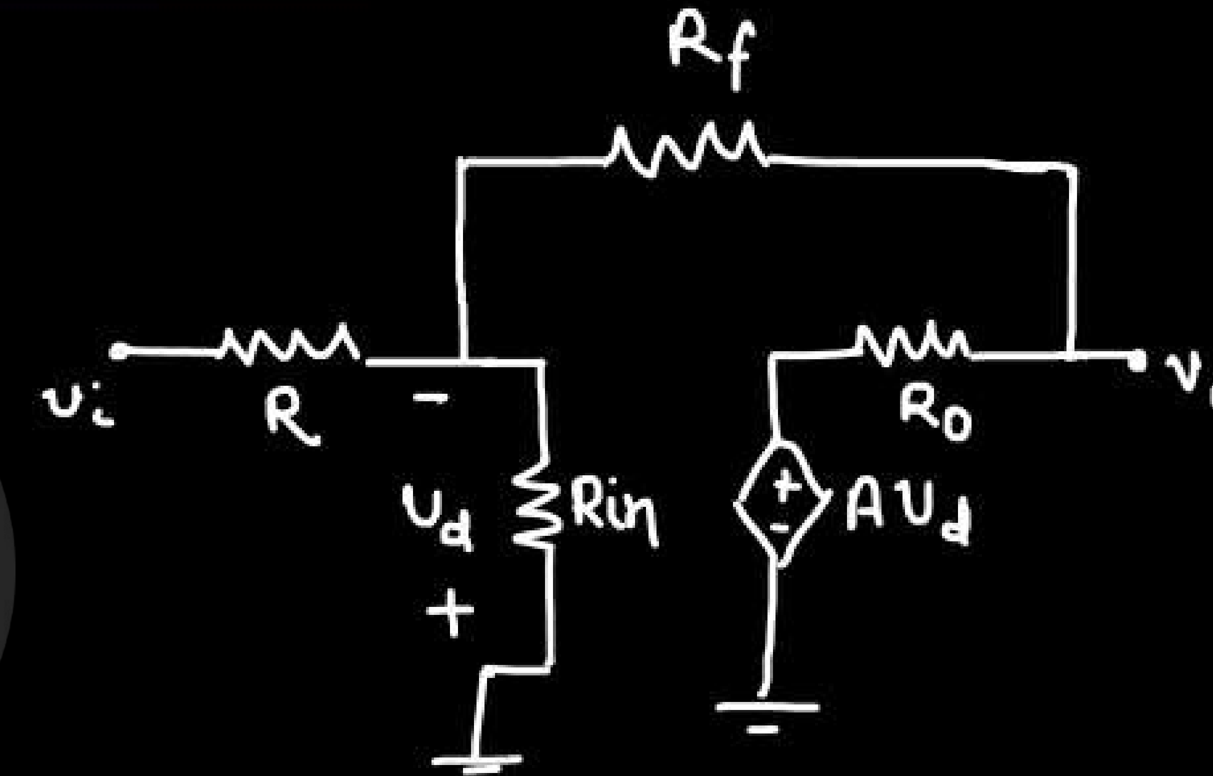
$$\boxed{\frac{v_o}{v_i} = 1 + \frac{R_f}{R}}$$



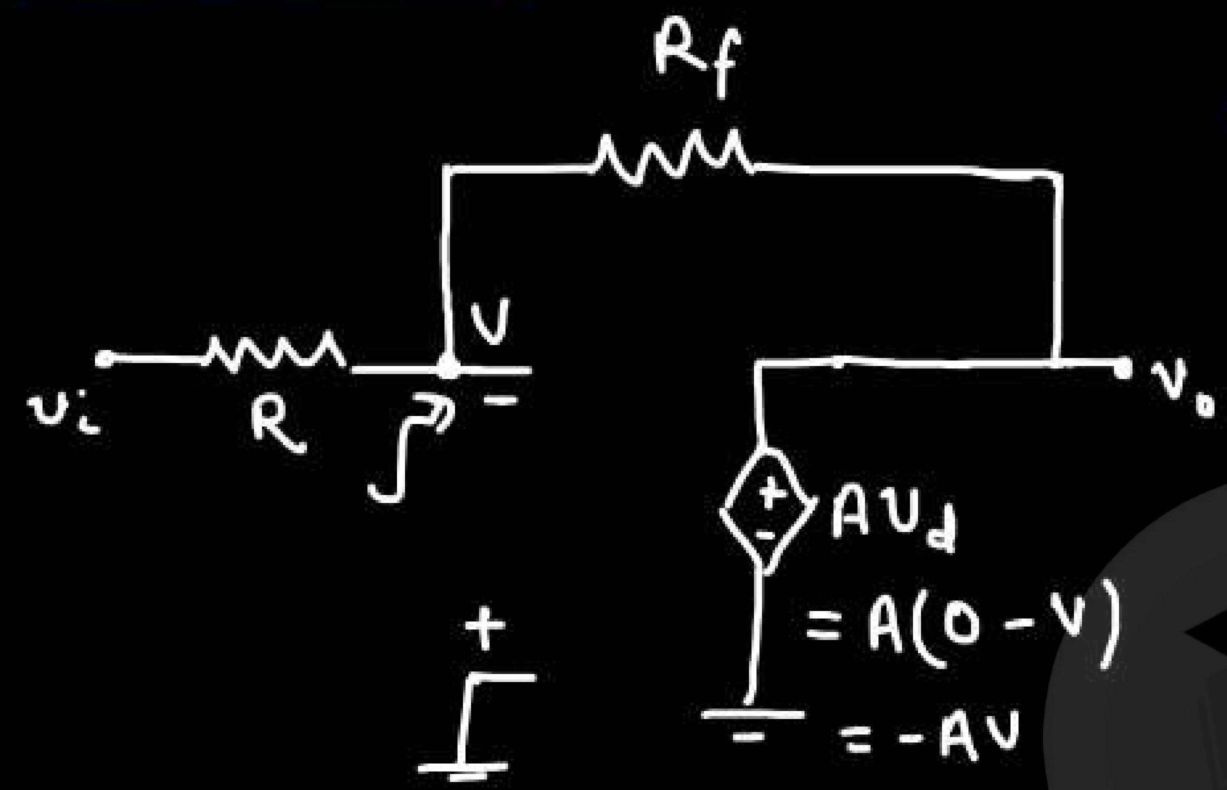
$$\boxed{\frac{v_o}{v_i} = -\frac{R_f}{R}}$$

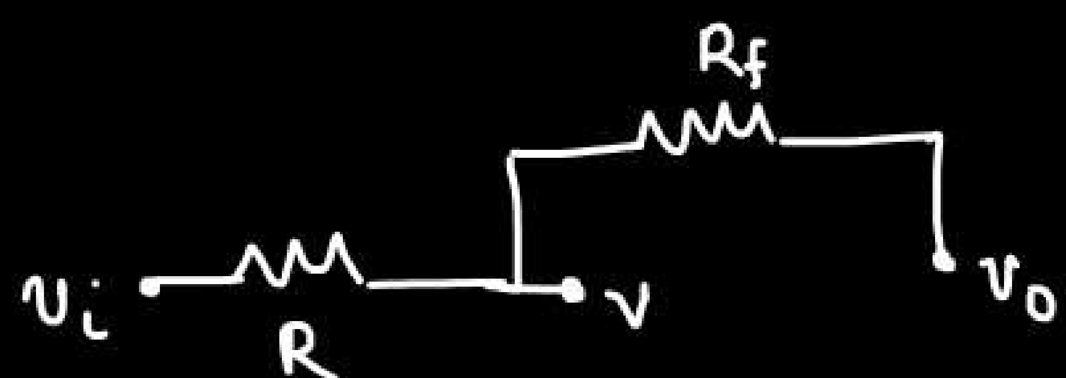
★ Inverting Amplifier considering Non-ideal Op-Amp [R_{in}, A, R_o]





(a) Voltage gain :-





$$\frac{v_i R_f + v_o R}{R + R_f} = V \longrightarrow (1)$$

Let ; $R_i = \infty$

$R_o = 0$

$V_o = -AV$

By eq^n (1)

$$V_o = -A\left[\frac{v_i R_f + V_o R}{R + R_f}\right]$$

$$[R + R_f]v_o = -A R_f v_i - A R v_o$$

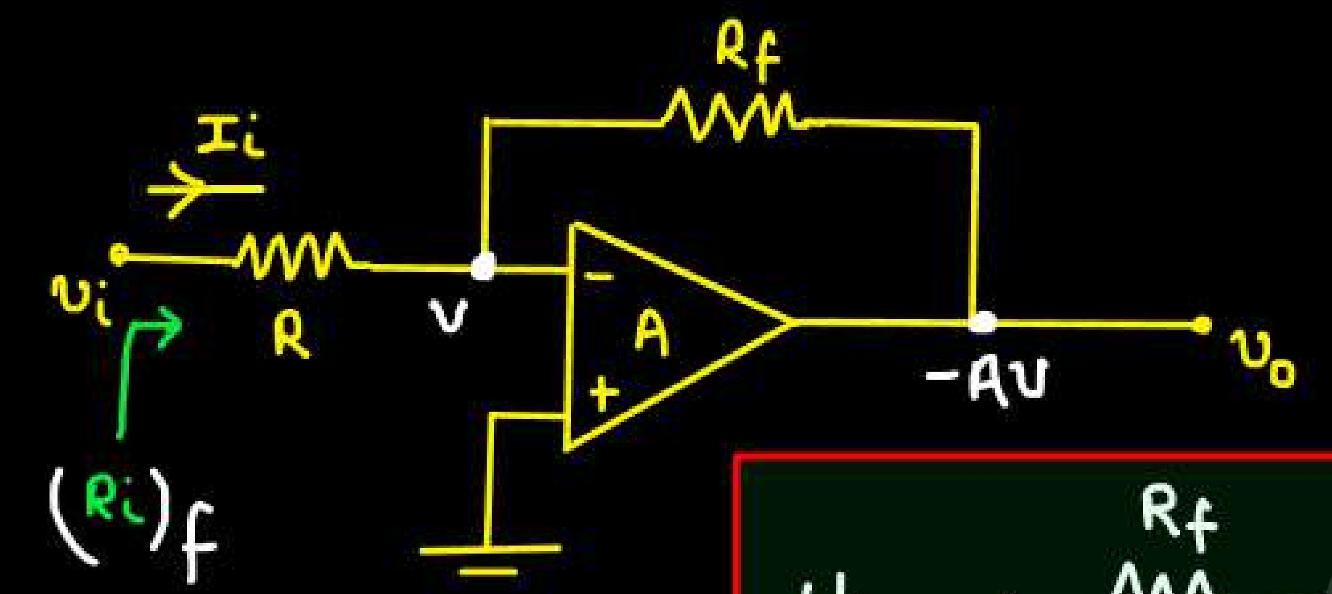
$$v_o[R + R_f + AR] = -A R_f v_i$$

$$\boxed{\frac{v_o}{v_i} = \frac{-A R_f}{R_f + (1+A)R}}$$

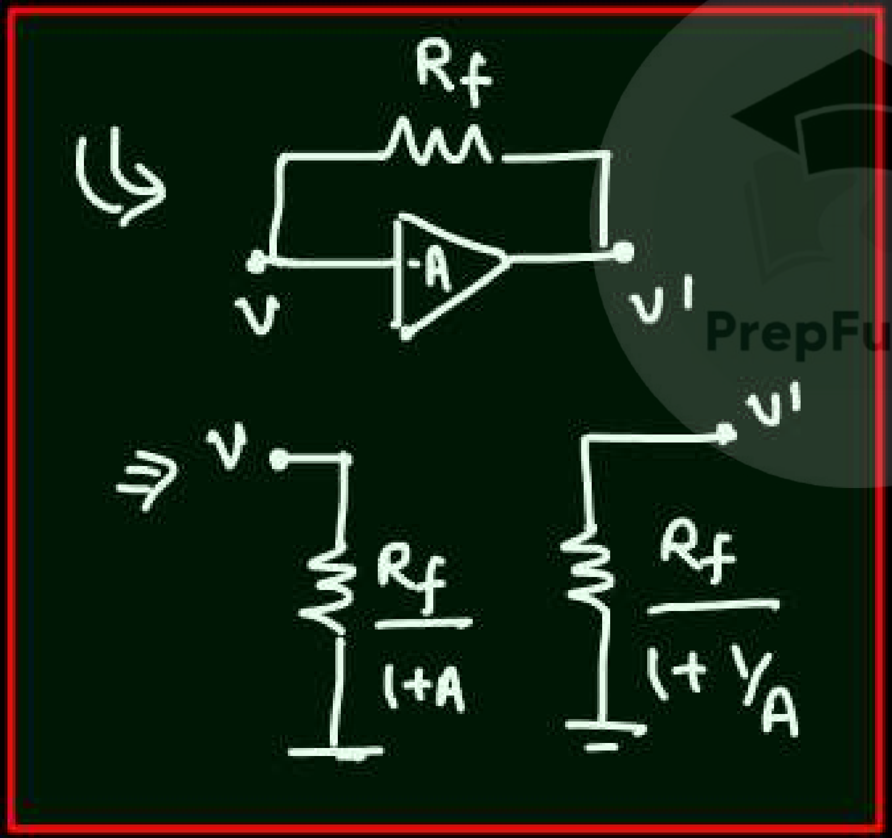
if $A \to \infty$

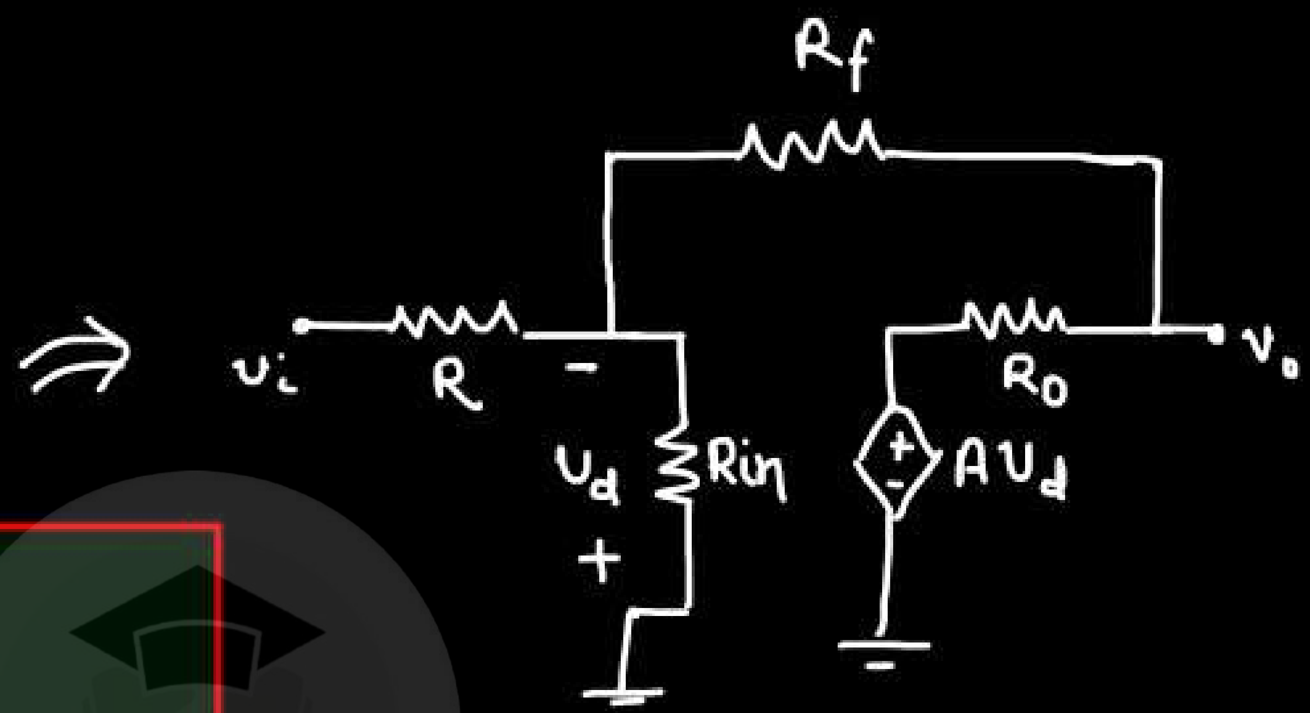
$$\boxed{\frac{v_o}{v_i} = \frac{-A R_f}{AR} = \frac{-R_f}{R}}$$

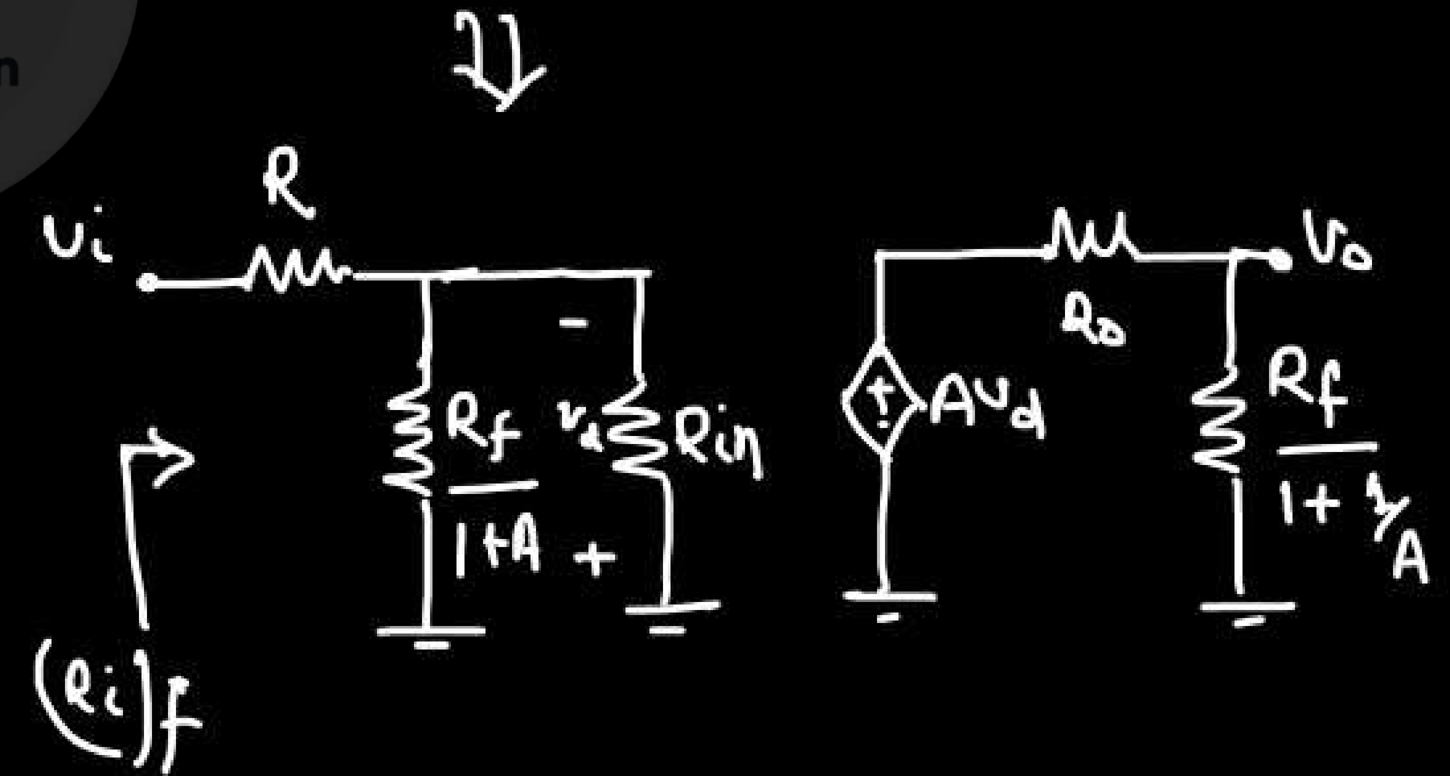
(b) Input Resistance:-



$$\frac{v_i}{I_i} = (R_i)_f$$



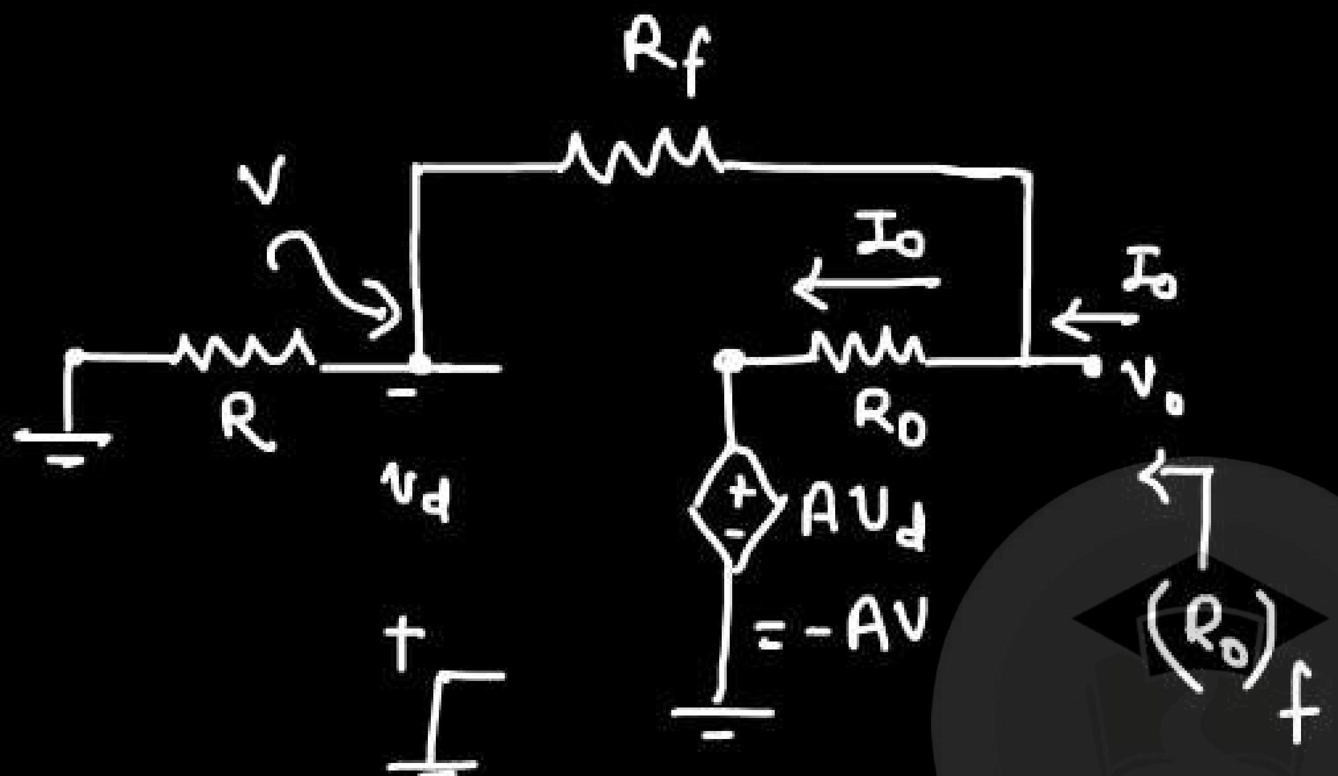




**

$$\Rightarrow \boxed{(R_i)_f = R + \left[\frac{R_f}{1+A} \,||\, R_{in}\right]}$$

(c) Output Resistance :-



$$\boxed{(R_o)_f = \frac{V_o}{I_o}}$$

Assumption:-

R_o is too small, so it takes all the I_o current

$$\frac{V_o - (-AV)}{R_o} = I_o$$

$$V_o + AV = I_o R_o$$

$$V_o + A\left[\frac{R}{R+R_f}\right]V_o = I_o R_o$$

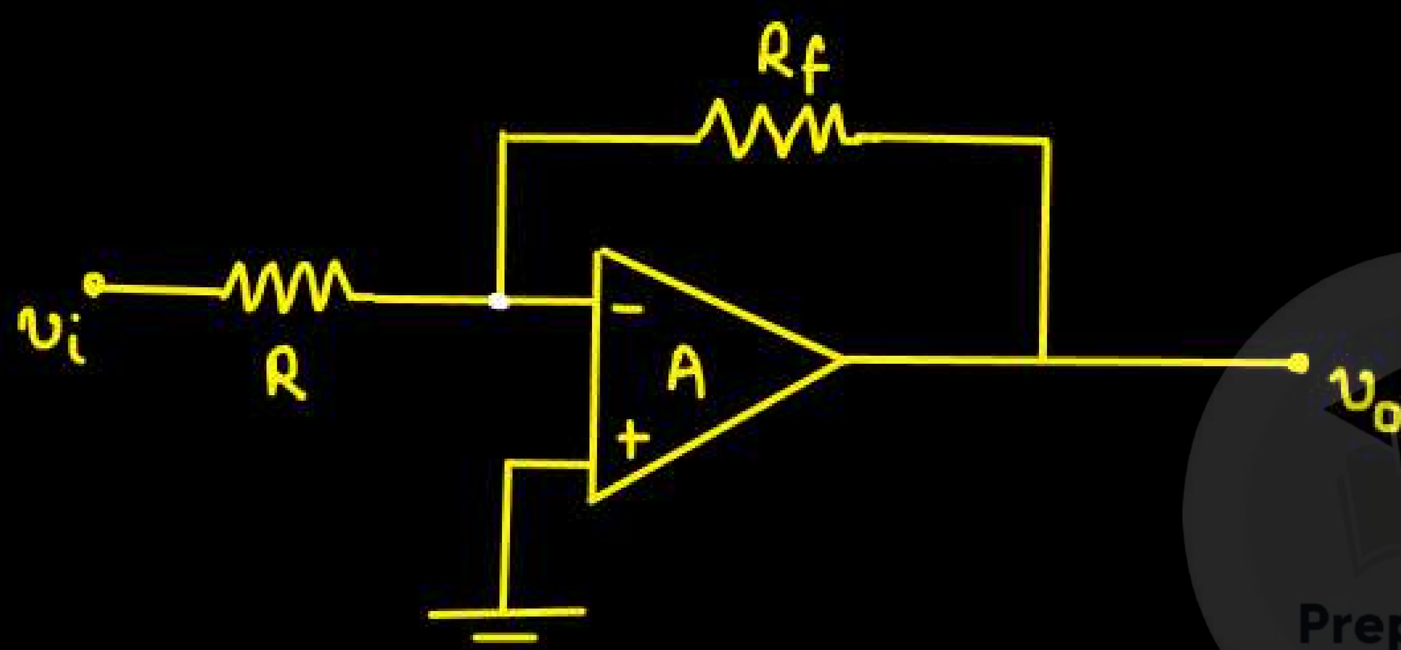
**

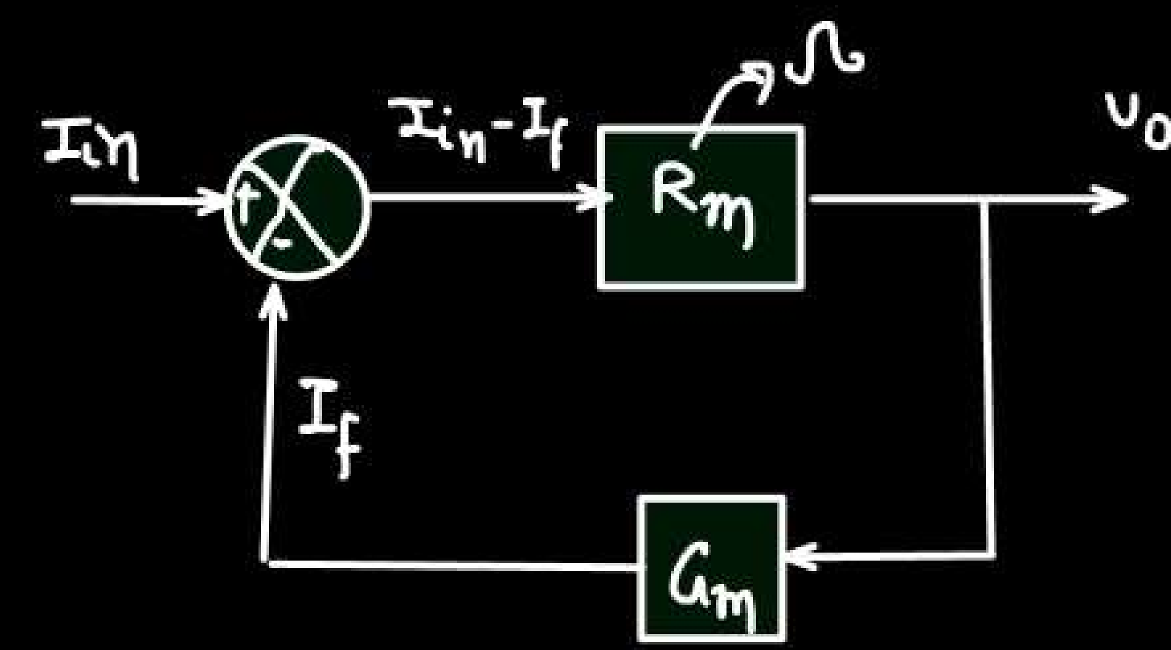
$$\boxed{(R_o)_f = \frac{V_o}{I_o} = \frac{R_o}{1 + \frac{AR}{R+R_f}}}$$

$A \to \infty$

$$\boxed{(R_o)_f = 0}$$

* Understanding Inverting amplifier with the concept of feedback Topology :-





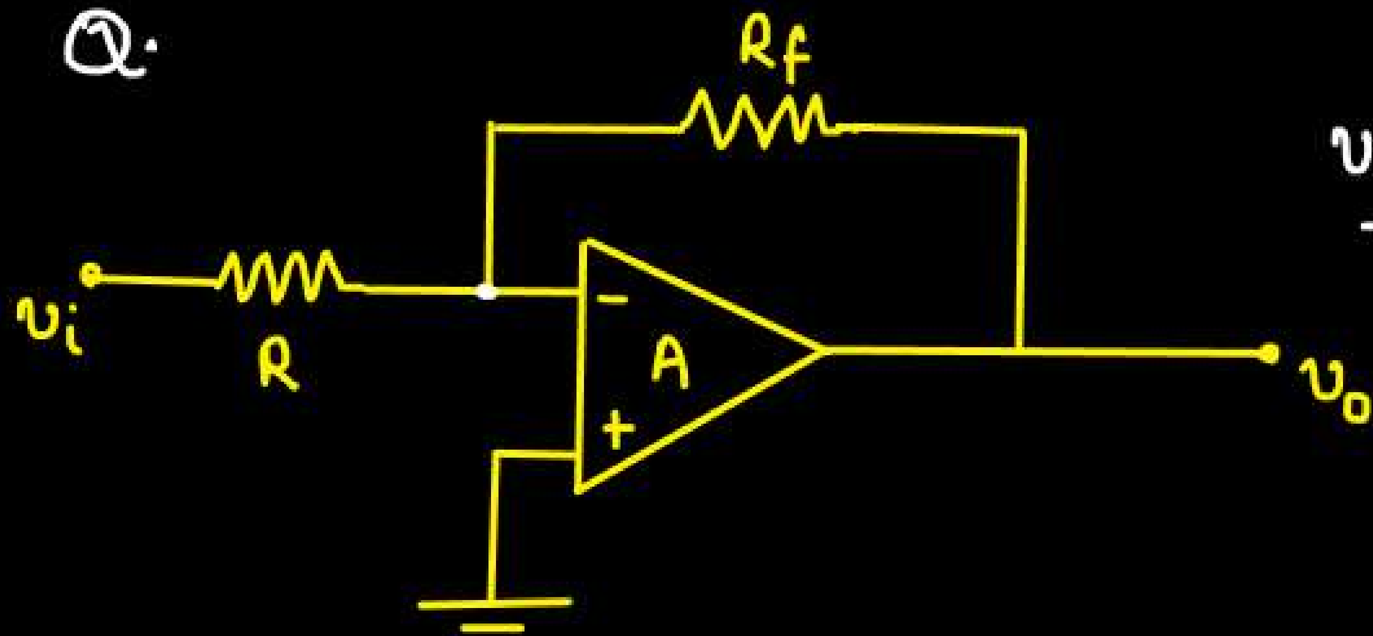
current-mixing
voltage-sampling

<u>Voltage-current f/b Topology</u>

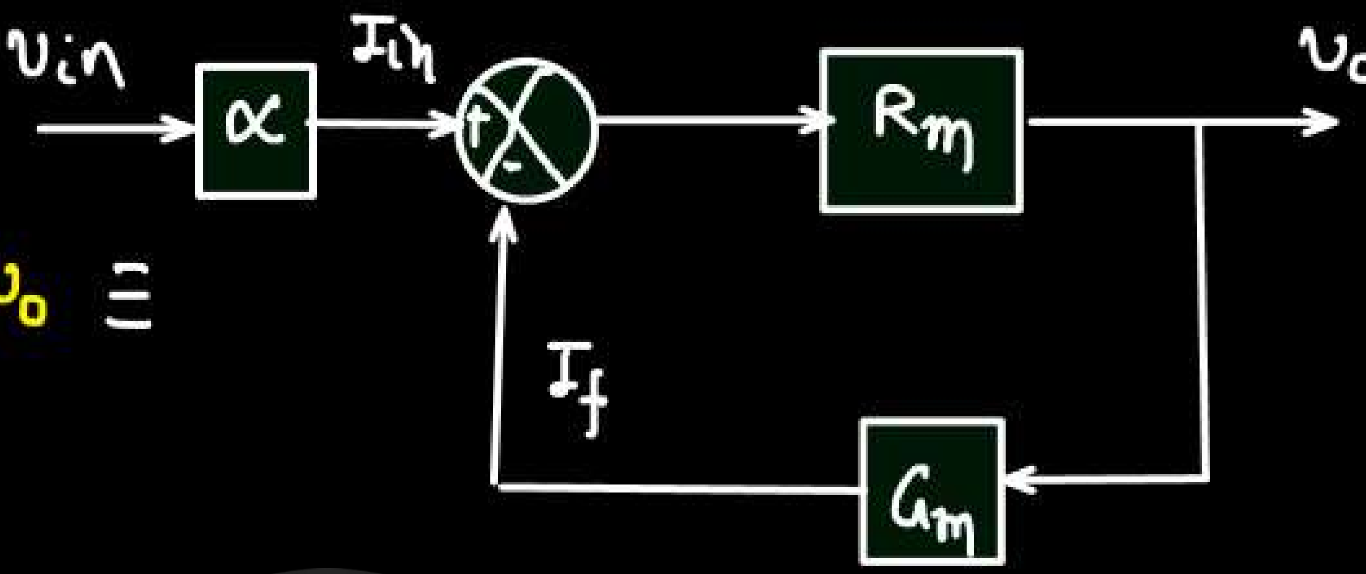
$\Downarrow$

Transresistance amplifier

Q.

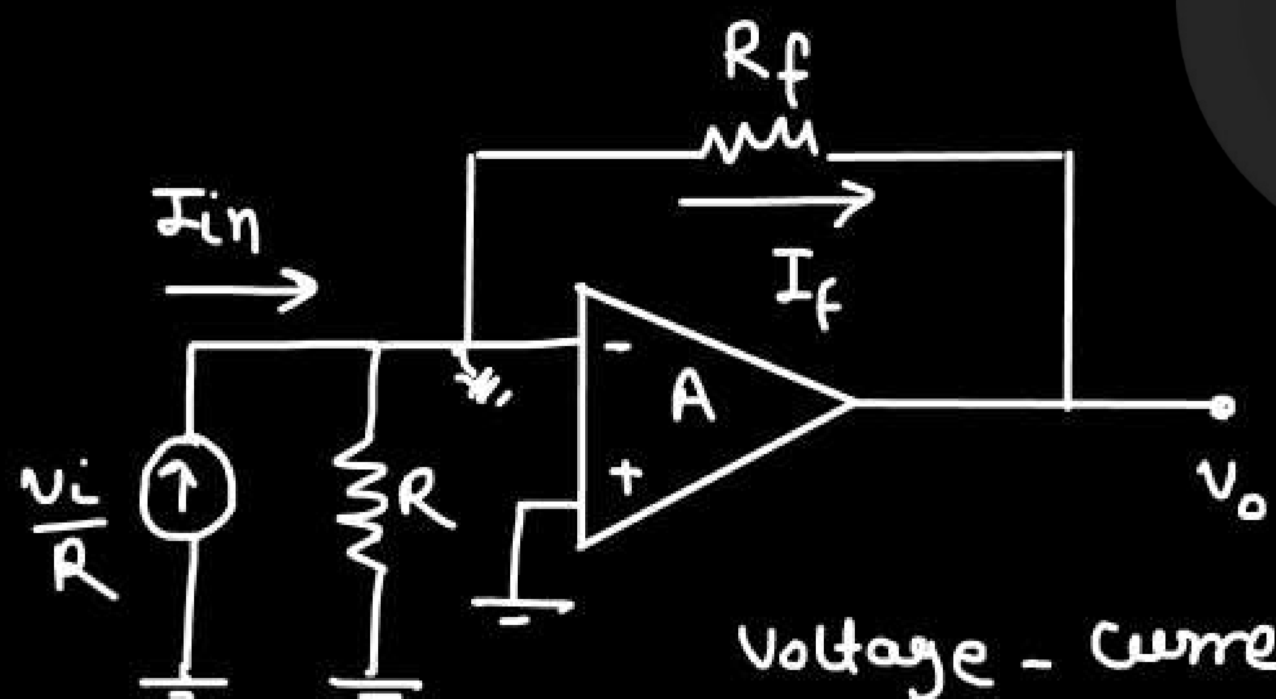


≡



Find α, R_m and G_m ?

⇒



Voltage - current

⇒ $R_i \to$ low , $R_o \to$ low

$$I_f = \frac{-v_o}{R_f}$$

$$G_m = \frac{I_f}{v_o} = -\frac{1}{R_f}$$

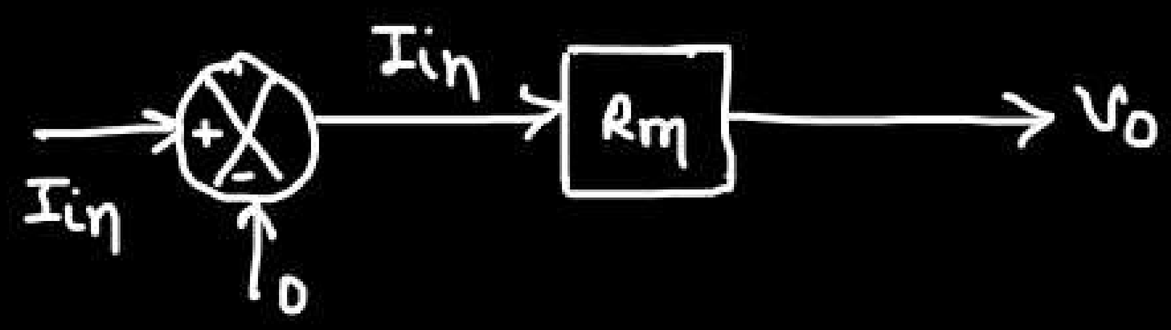
$$\boxed{G_m = \frac{-1}{R_f}}$$

$$\alpha v_{in} = I_{in}$$

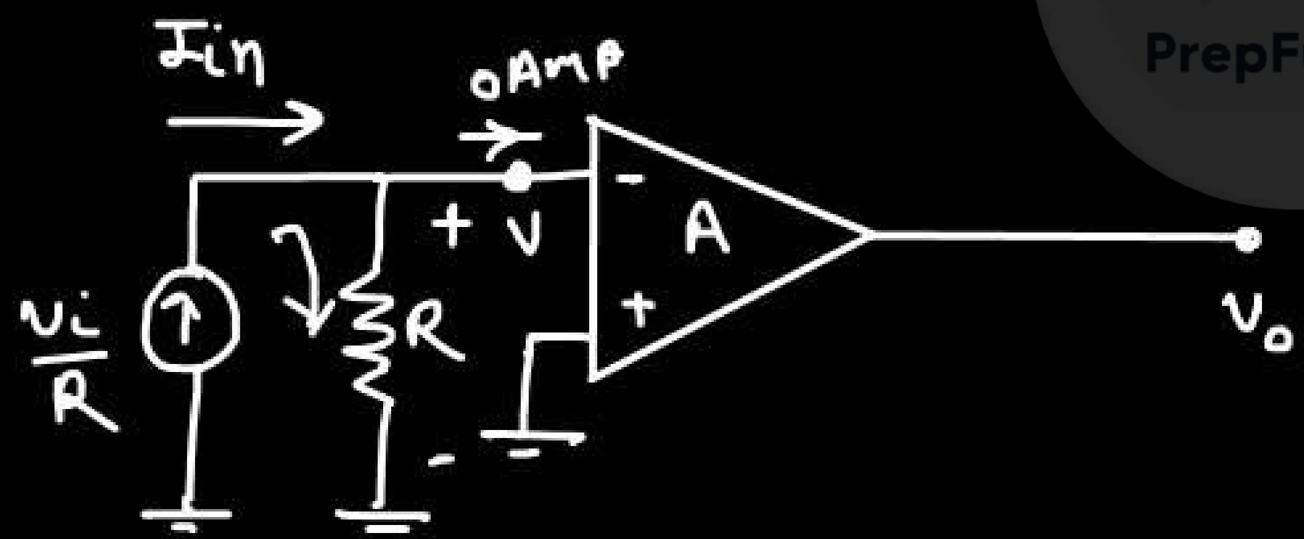
$$I_{in} = \frac{v_{in}}{R}$$

$$\boxed{\alpha = \frac{1}{R}}$$

open loop :-



$$\boxed{I_{in} R_m = V_o}$$

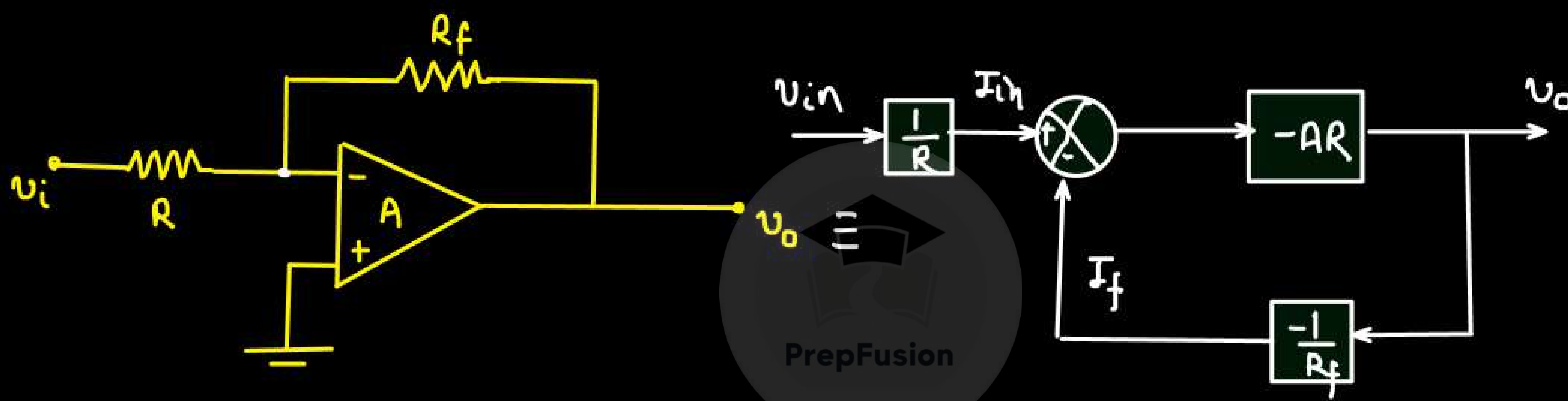


$$V = I_{in} R$$

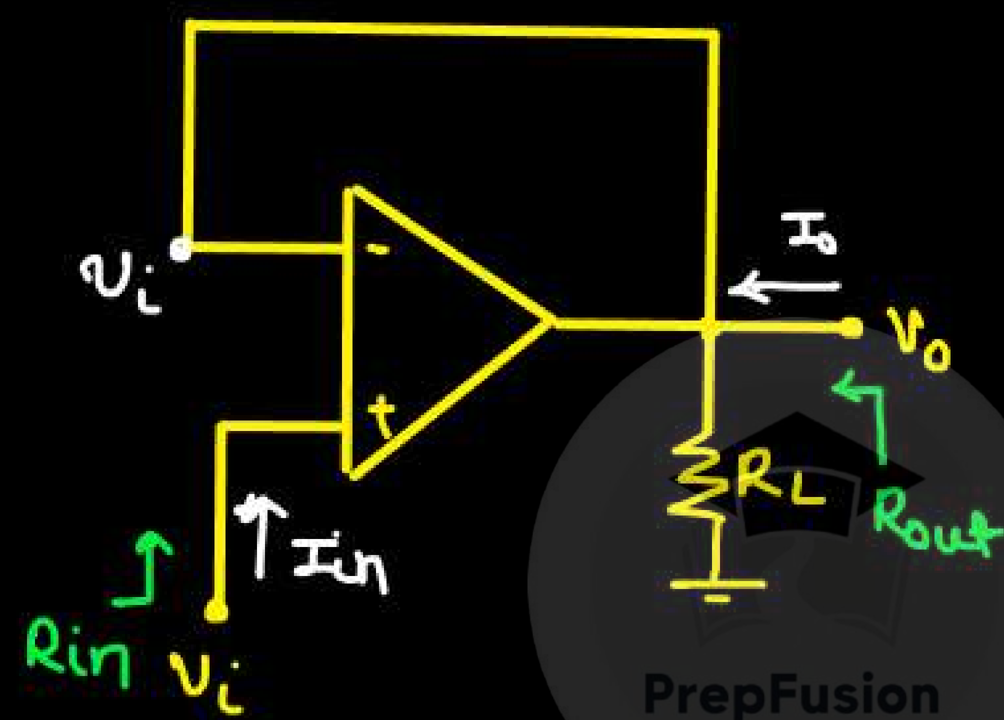
$$V_o = -AV$$

$$V_o = -A[I_{in} R]$$

☆☆
$$\boxed{\frac{V_o}{I_{in}} = -AR = R_m}$$


R_f
v_i
R
$-$
$+$
A
v_o
$\equiv$
v_{in}
$\frac{1}{R}$
I_{in}
$+$
$-$
$-AR$
v_o
I_f
$\frac{-1}{R_f}$

★ Voltage follower using op. amp:-

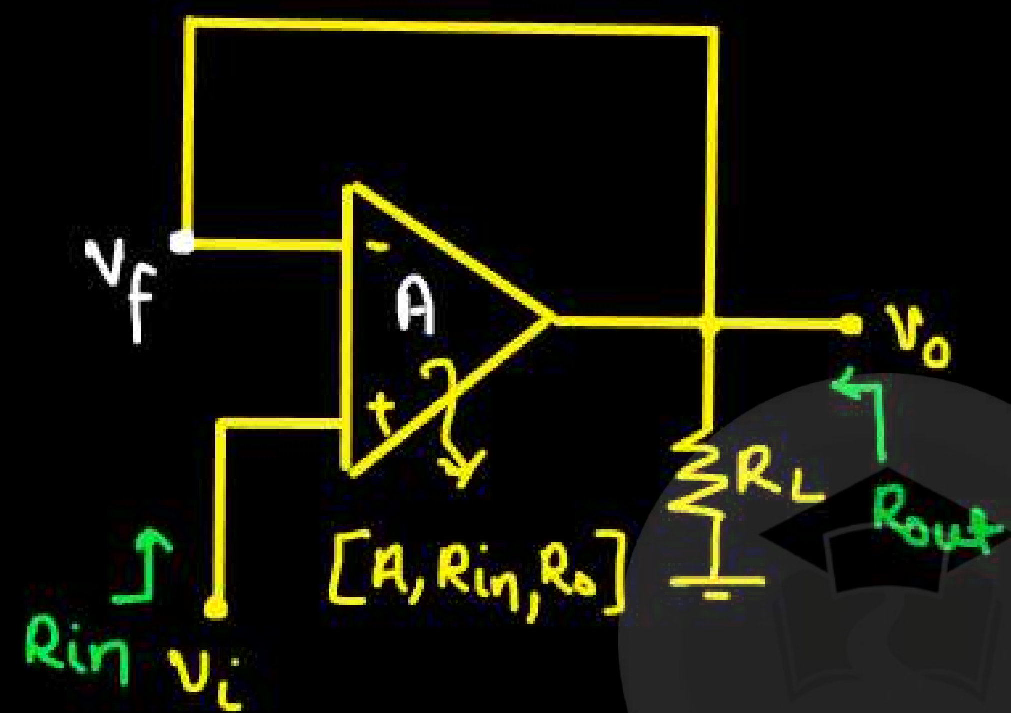


(a) Voltage gain:- $v_o = v_i \Rightarrow \boxed{\frac{v_o}{v_i} = 1} \Rightarrow$ voltage follower

(b) $\boxed{R_{in} = \frac{v_i}{I_i} = \frac{v_i}{0} = \infty}$

(c) $\boxed{R_{out} = \frac{V_o}{I_o} = \frac{0}{I_o} = 0}$

☆ Considering non-ideal Op-Amp:-



Voltage - mixing
Voltage - Sampling

$\Downarrow$

Voltage Amplifier

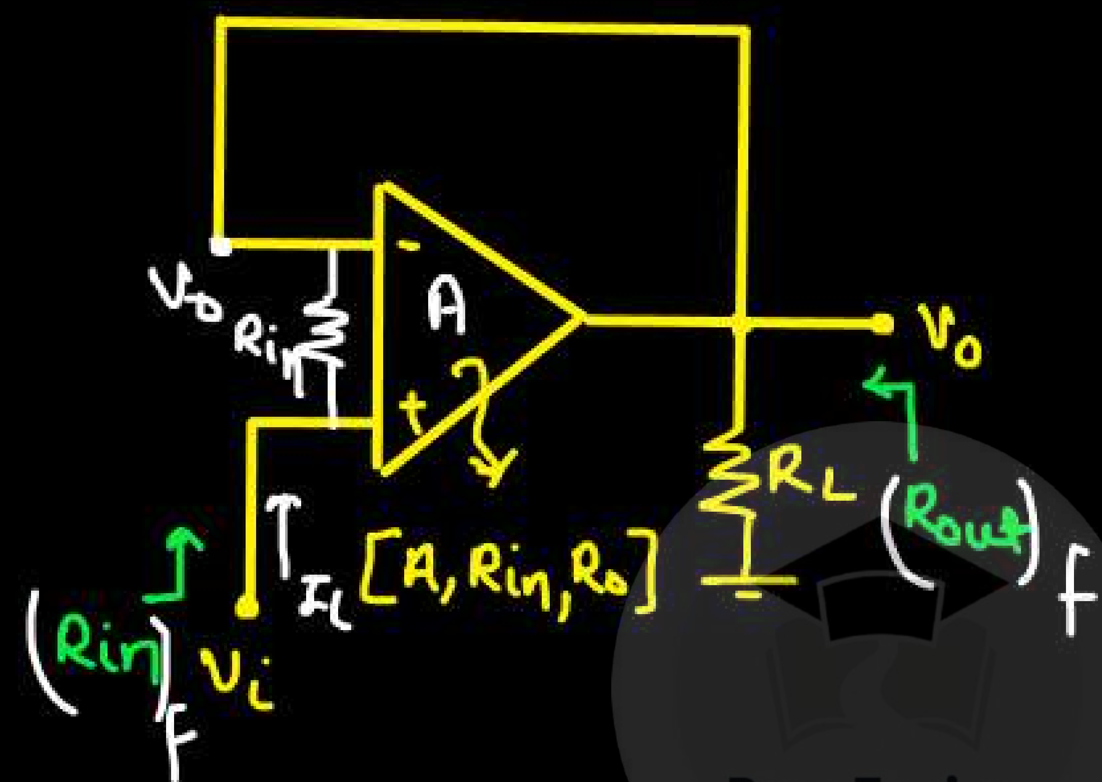
☆ $\boxed{\text{Feedback factor } \beta = 1}$

(a) Voltage gain $= \dfrac{A}{1 + A\beta} = \dfrac{A}{1 + A}$

(b) Input Impedance $= R_{in}(1 + A)$

(c) Output Impedance $= \dfrac{R_o}{1 + A}$

(a) Voltage gain:-

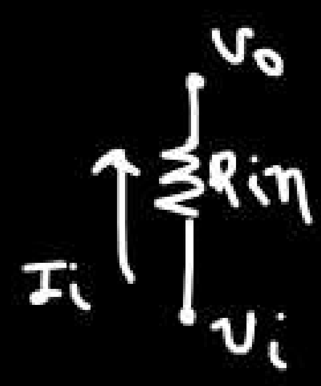


$$V_o = A[V_i - V_o]$$

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

(b) Input Impedance:-

$$(R_{in})_f = \frac{V_i}{I_i}$$

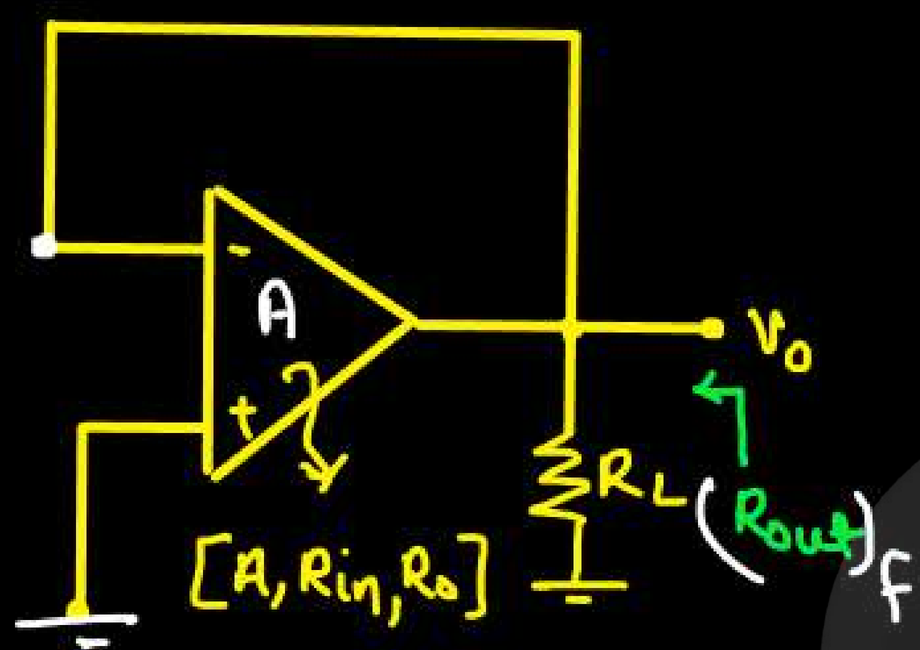


$$V_i - V_o = I_{in} R_{in}$$

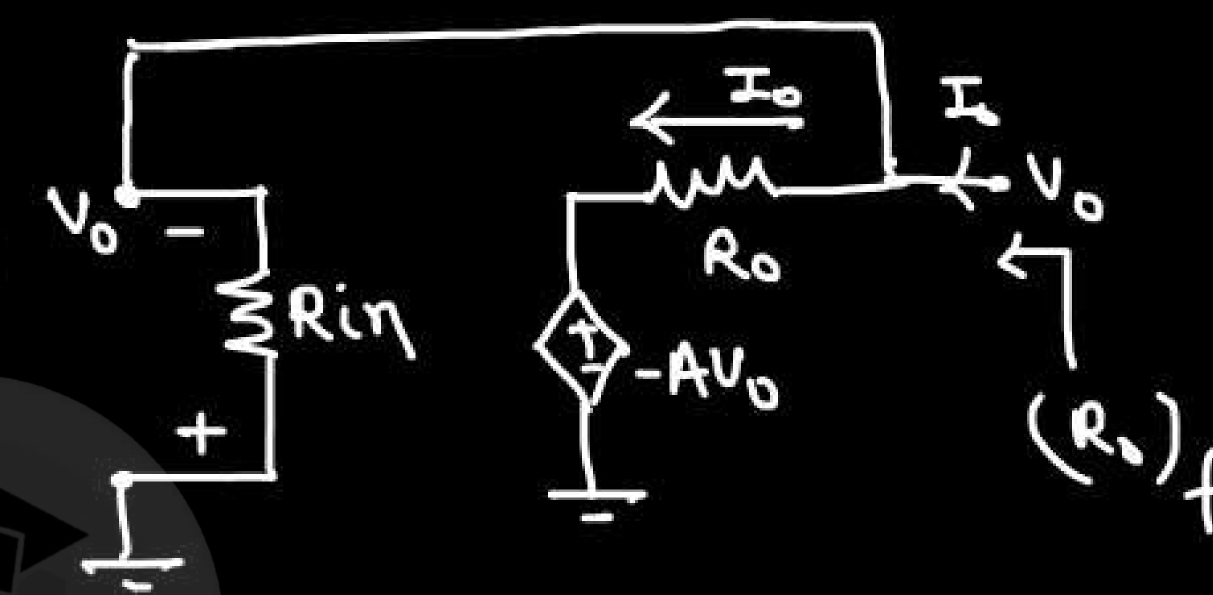
$$V_i - \frac{A}{1+A} V_i = I_{in} R_{in}$$

$$\boxed{(R_{in})_f = R_{in}(1+A)}$$

(c) Output Impedance:-



$\equiv$



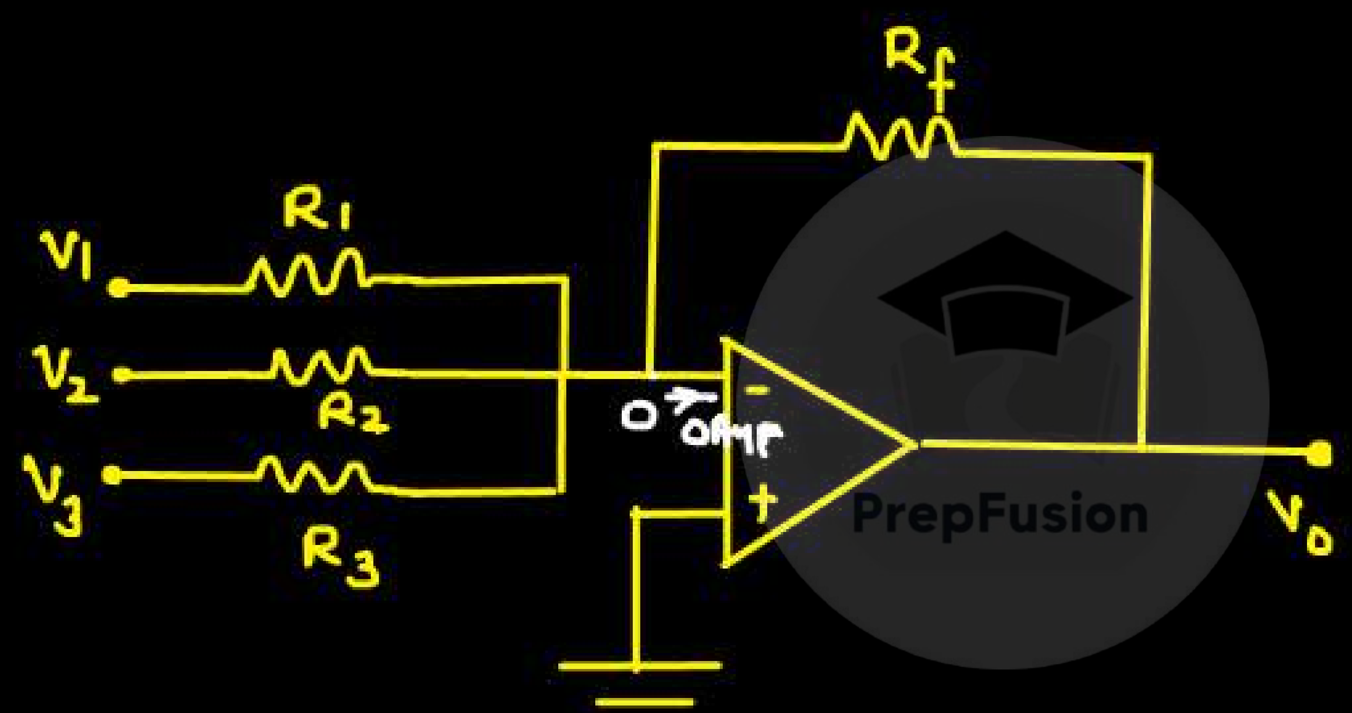
$$\frac{V_o - (-AV_o)}{R_o} = I_o$$

$$\frac{V_o}{I_o} = \frac{R_o}{1+A}$$

$$\boxed{(R_o)_f = \frac{R_o}{1+A}}$$

⇒ OP-Amp Applications:-

① Inverting Adder:-



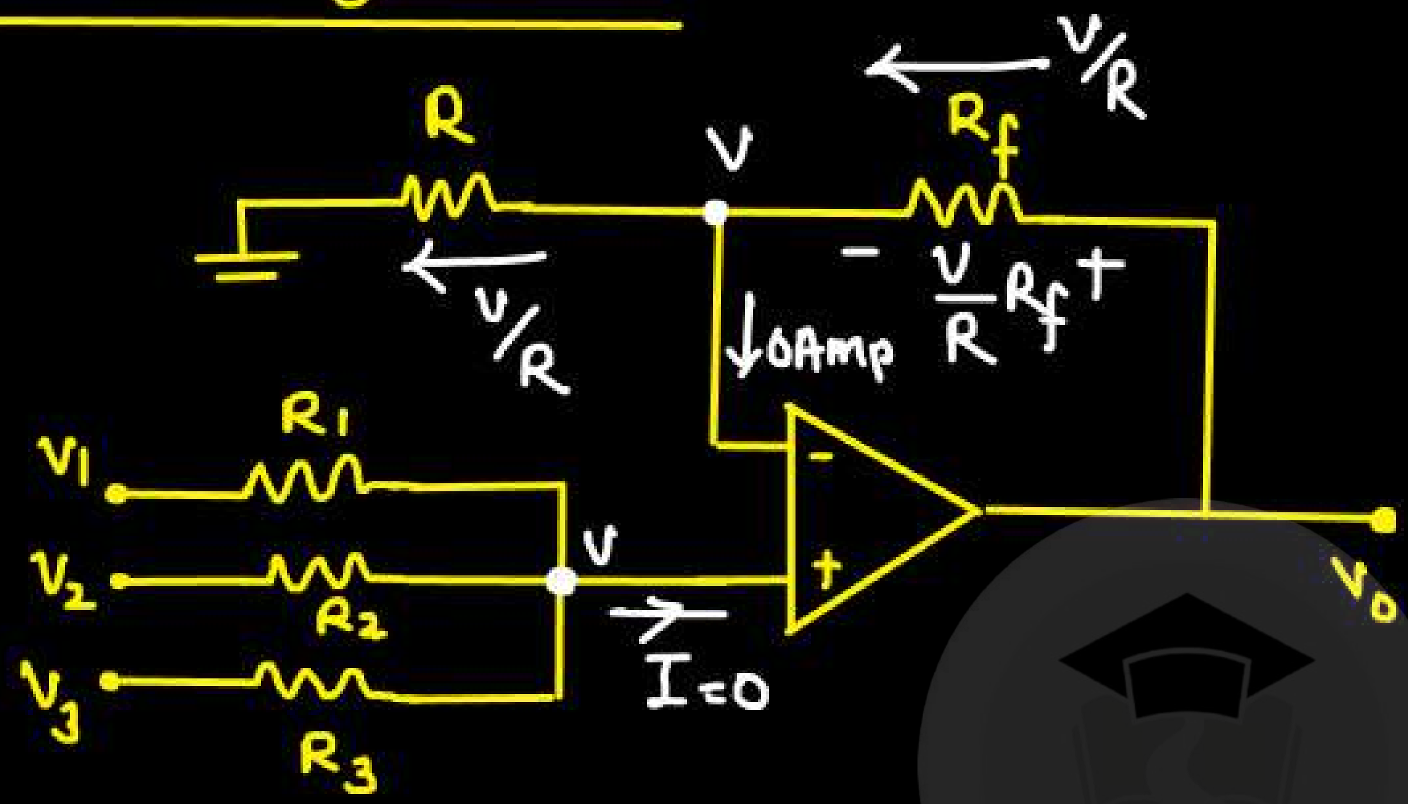
$$\left(\frac{0-V_1}{R_1}\right)+\left(\frac{0-V_2}{R_2}\right)+\left(\frac{0-V_3}{R_3}\right)+\left(\frac{0-V_0}{R_f}\right)=0$$

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

if $R_1 = R_2 = R_3 = R$

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

② Non-inverting Adder:-



Take $\boxed{R_1 = R_2 = R_3 = R}$

$$V_0 = V + \frac{V}{R}R_f$$

$$V_0 = \left(1 + \frac{R_f}{R}\right)V \quad \text{--- } ①$$

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

$$V\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right] = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

Take $R_1 = R_2 = R_3 = R$

$$\frac{3V}{R} = \frac{V_1 + V_2 + V_3}{R}$$

$$V = \frac{V_1+V_2+V_3}{3} \quad \text{—— (2)}$$

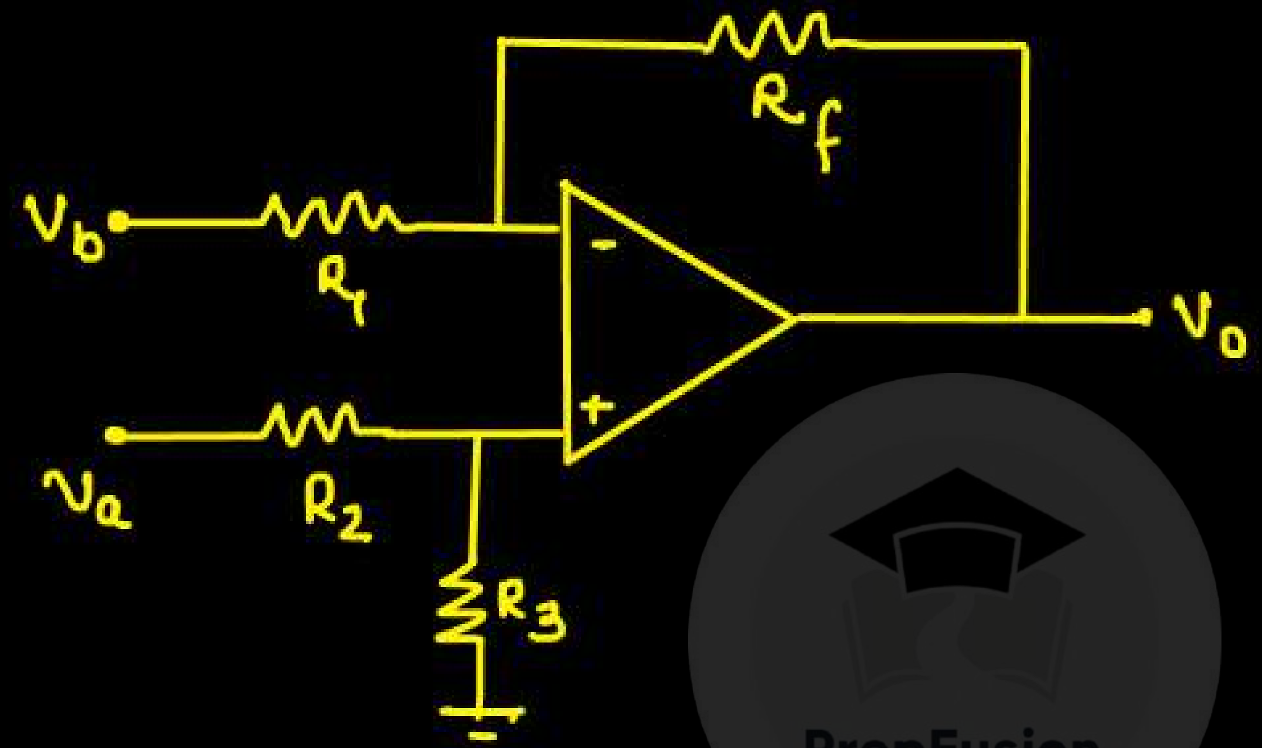
By eq^n (1) and (2)

$$\boxed{V_0 = \left(1+\frac{R_f}{R}\right)\left(\frac{V_1+V_2+V_3}{3}\right)}$$

if $\boxed{R_f = 2R}$

$$\boxed{V_0 = V_1+V_2+V_3}$$

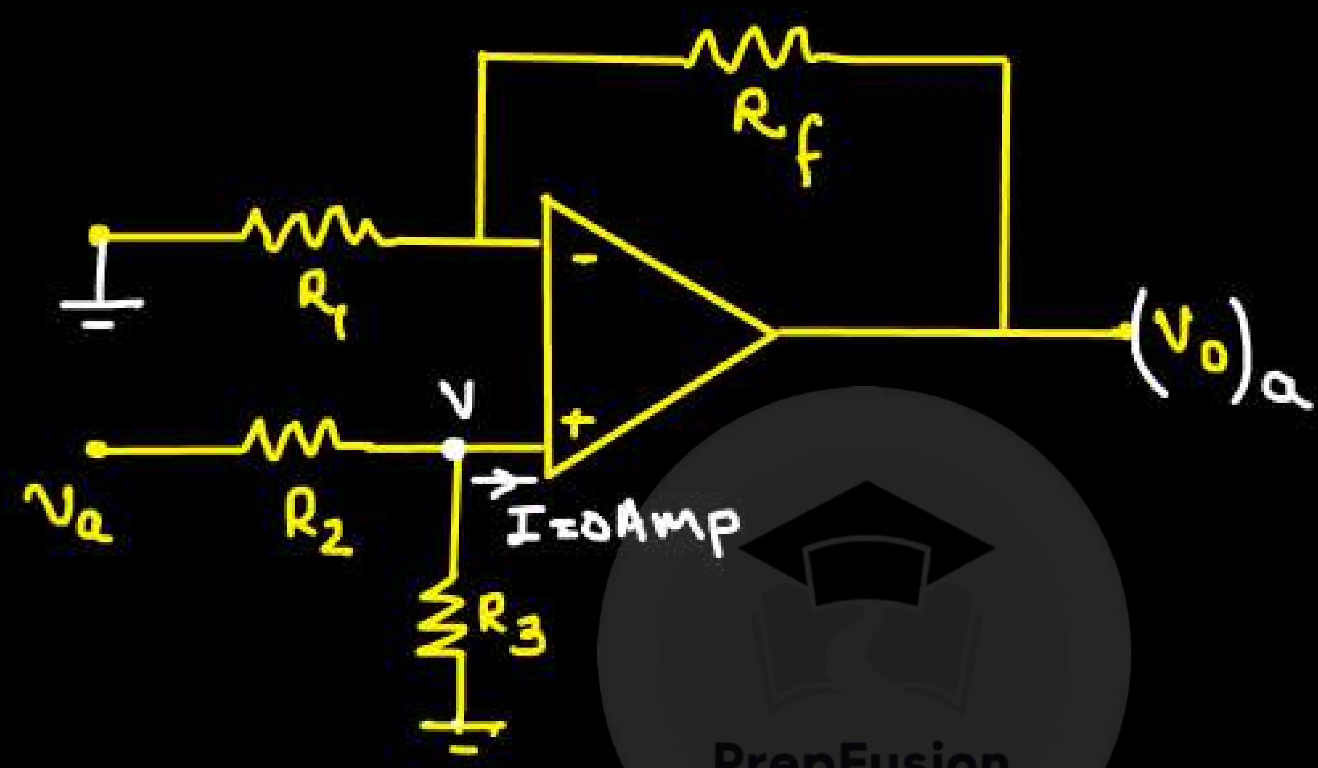
③ Differential Amplifier :-

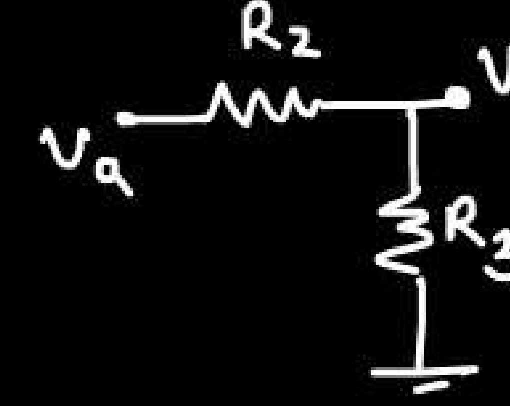


Take $\boxed{\dfrac{R_1}{R_f} = \dfrac{R_2}{R_3}}$

Applying superposition Theorem:-

(i)



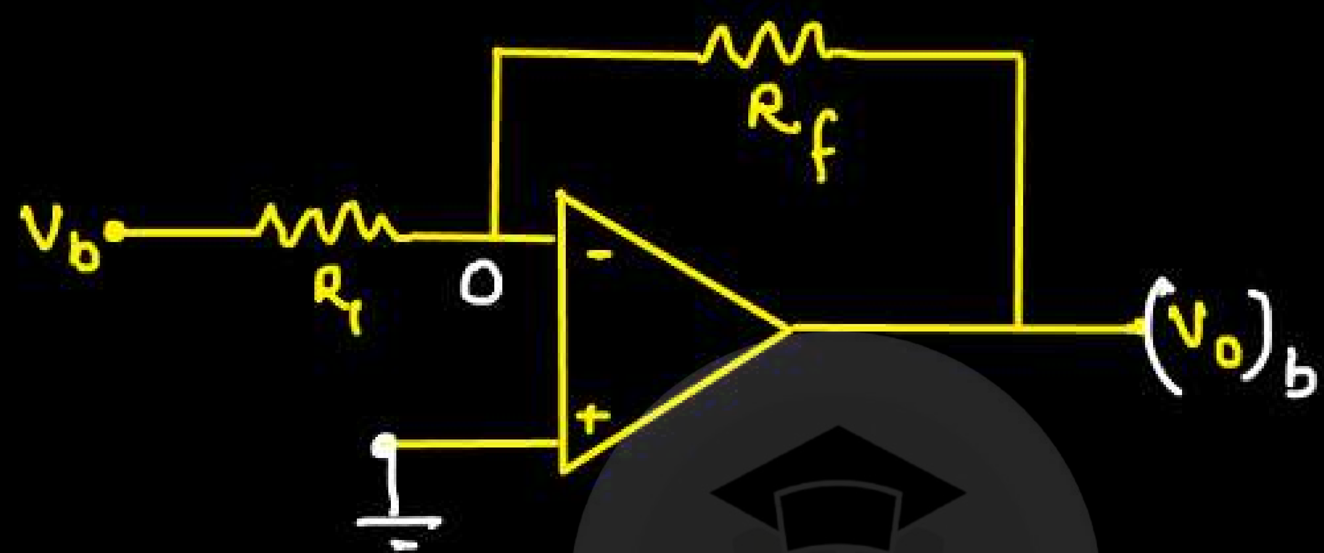


$$V = \frac{R_3}{R_3 + R_2} V_a$$

$$(V_o)_a = \left(1 + \frac{R_f}{R}\right) V \quad \text{— (1)}$$

$$V = \frac{R_3}{R_3 + R_2} V_a \quad \text{— (2)}$$

$$(V_o)_a = \left[1 + \frac{R_f}{R_1}\right]\left[\frac{R_3}{R_3+R_2}\right] v_a \quad \text{—} \; (3)$$



$$(V_o)_b = -\frac{R_f}{R_1} v_b \quad \text{—} \; (4)$$

$$v_o = (v_o)_a + (v_o)_b$$

$$v_o = \left(1 + \frac{R_f}{R_1}\right)\left(\frac{R_3}{R_3+R_2}\right) v_a - \frac{R_f}{R_1} v_b$$

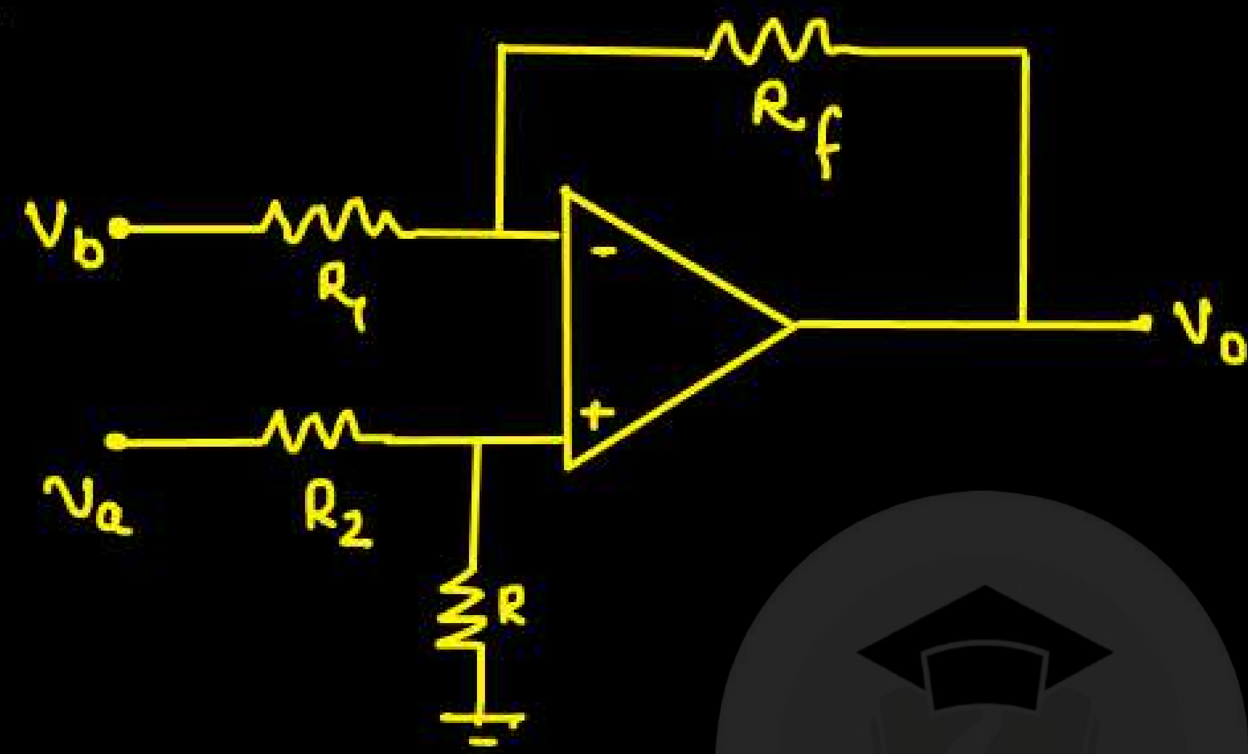
Given $\boxed{\dfrac{R_1}{R_f} = \dfrac{R_2}{R_3}}$

$$V_0 = \left[1 + \frac{R_f}{R_1}\right]\left[\frac{1}{1+\frac{R_2}{R_3}}\right]V_a - \frac{R_f}{R_1}V_b$$

$$= \left[\frac{R_1+R_f}{R_1}\right]\left[\frac{R_f}{R_f+R_1}\right]V_a - \frac{R_f}{R_1}V_b$$

$$\boxed{V_0 = \frac{R_f}{R_1}\left[V_a - V_b\right]}$$

☆ Conclusion:-

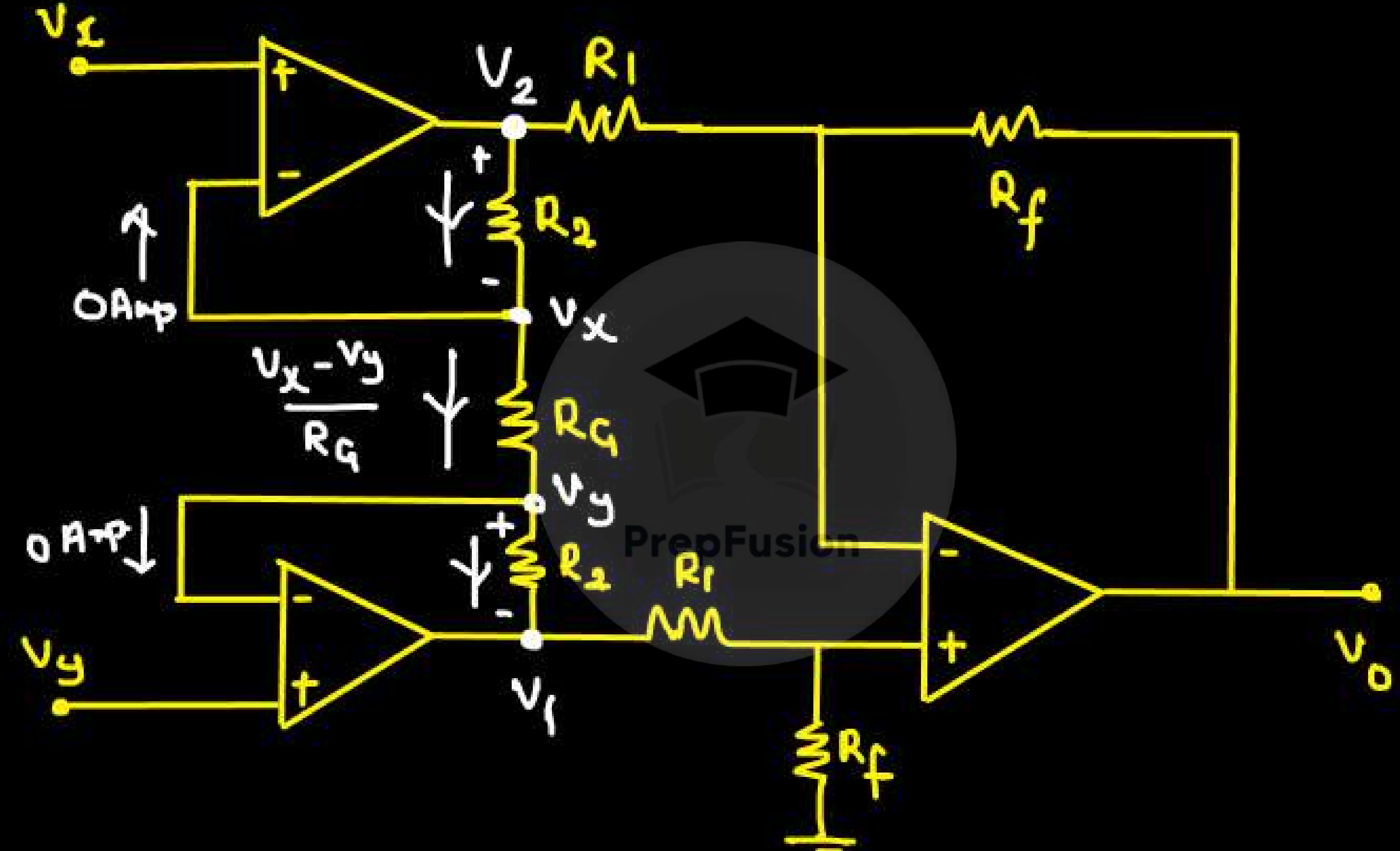


if $\boxed{\dfrac{R_1}{R_f} = \dfrac{R_2}{R_3}}$

$$\boxed{v_o = \frac{R_f}{R_1}\left(v_a - v_b\right)}$$

$$\boxed{v_o \propto (v_a - v_b)}$$

④ Instrumentation Amplifier :-



$$V_o = \frac{R_f}{R_1}(V_1 - V_2) \quad \text{— (1)}$$

$$V_2 = v_x + R_2 \left(\frac{v_x - v_y}{R_G} \right) \quad \text{—} \quad (2)$$

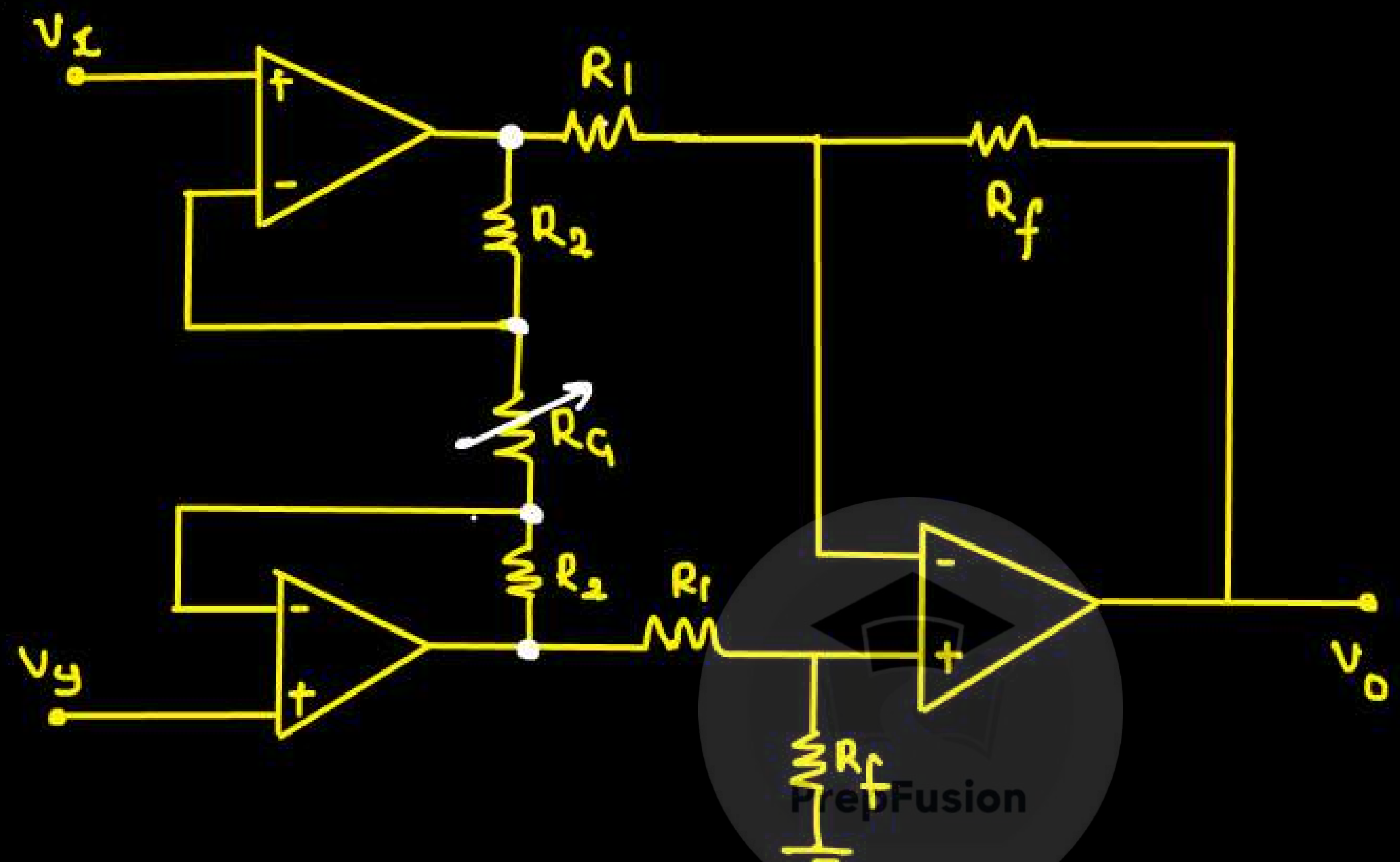
$$V_1 = v_y - R_2 \left(\frac{v_x - v_y}{R_G} \right) \quad \text{—} \quad (3)$$

$$V_o = \frac{R_f}{R_1} \left[v_y - \frac{R_2}{R_G} (v_x - v_y) - v_x - \frac{R_2}{R_G} (v_x - v_y) \right]$$

$$= \frac{R_f}{R_1} \left[(v_y - v_x) + \frac{R_2}{R_G} (v_y - v_x) + \frac{R_2}{R_G} (v_y - v_x) \right]$$

$$\boxed{v_o = \frac{R_f}{R_1} \left[1 + \frac{2R_2}{R_G} \right] (v_y - v_x)}$$

Conclusion:-

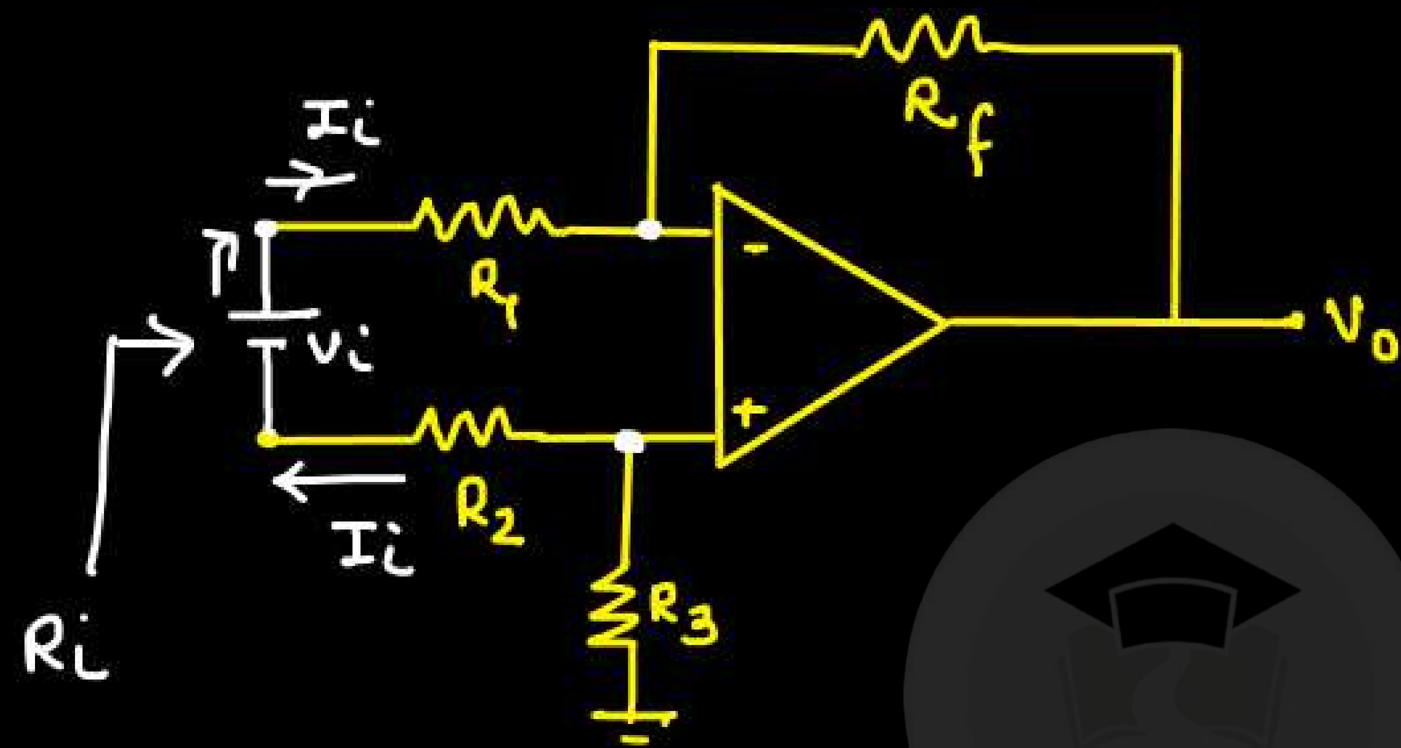


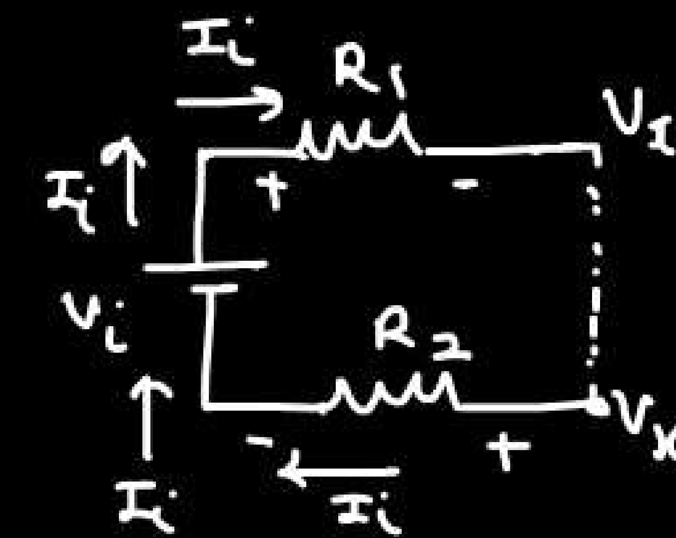
$$\boxed{V_0 = \frac{R_f}{R_1}\left[1 + \frac{2R_2}{R_G}\right]\left[V_y - V_x\right]}$$

$$\boxed{V_0 \propto (V_y - V_x)}$$

↳ I.A. is a kind of differential Amplifier with Higher gain.

★ Input Impedance of differential amplifier:-



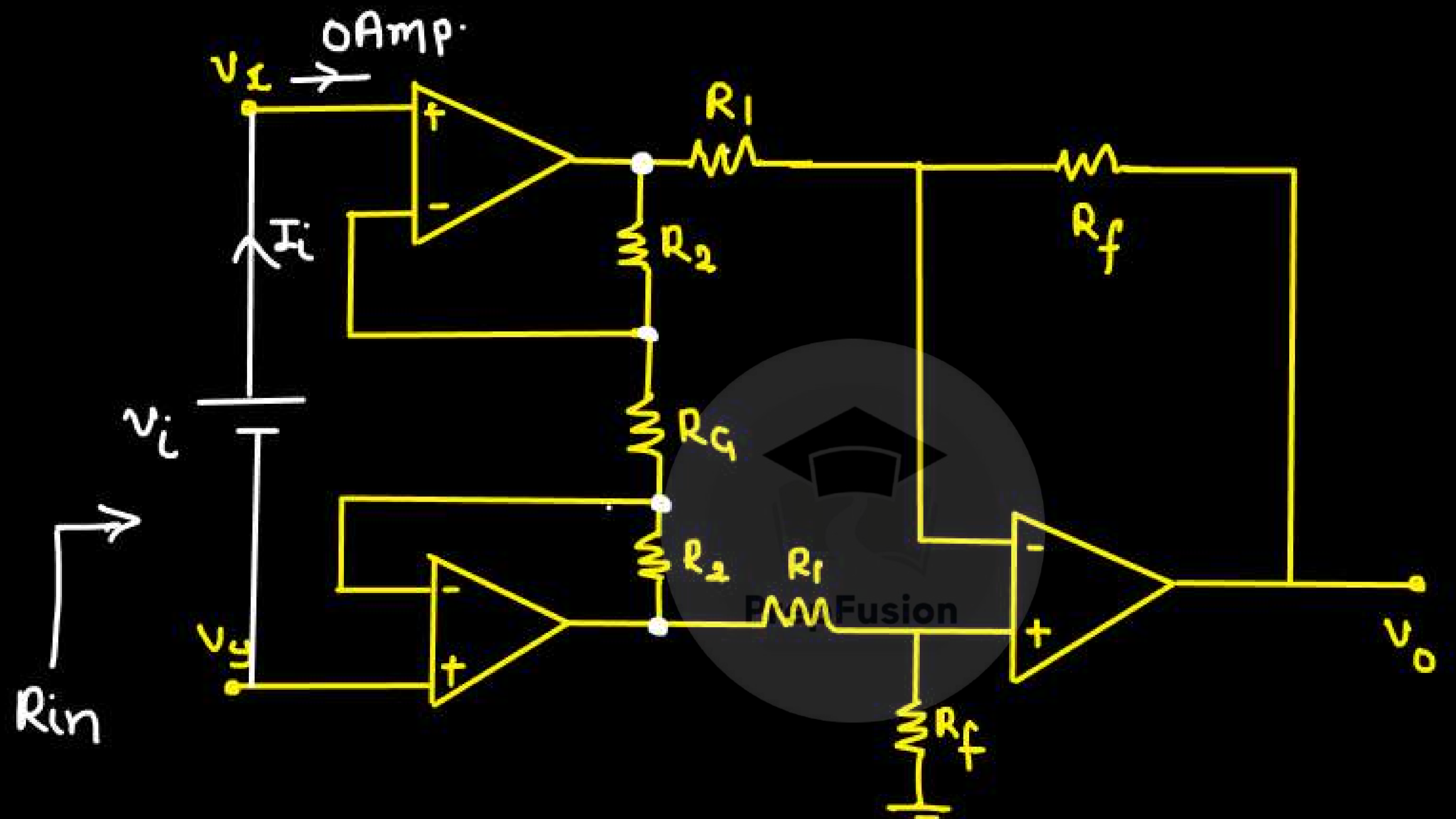


$$\cancel{V_X} - I_i R_2 + v_i - I_i R_1 = \cancel{V_X}$$

$$v_i = I_i (R_1 + R_2)$$

$$\boxed{R_i = R_1 + R_2}$$

Input Impedance of I.A. →



$$\boxed{R_{in} = \frac{V_i}{I_i} = \frac{V_i}{0} = \infty}$$

☆ Advantages of Instrumentation Amplifier:-

① High gain, High CMRR, High i/p impedance

②

$$(\text{Gain})_{I.A.} = \left[1 + \frac{2R_2}{R_G}\right]\left[\frac{R_f}{R}\right]\left[V_+ - V_-\right]$$

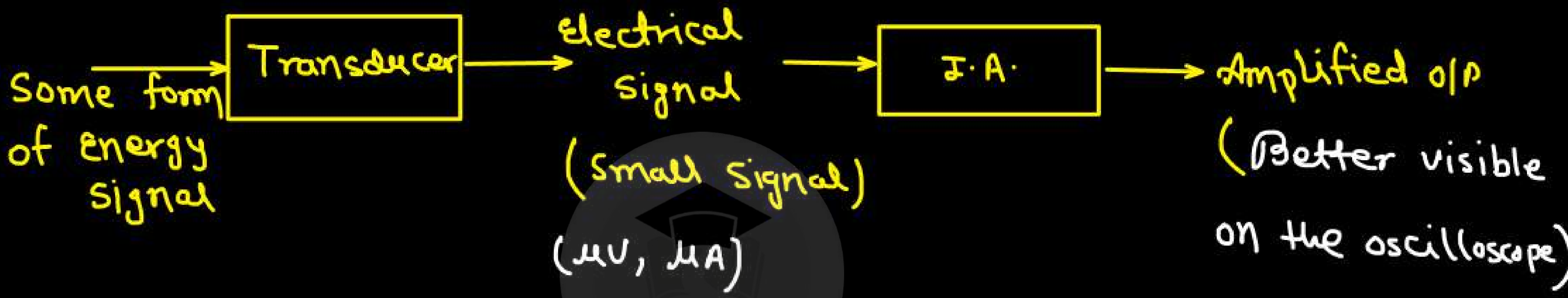
$$(\text{Gain})_{D.A.} = \frac{R_f}{R}\left[V_+ - V_-\right]$$

Advantage of I.A. over D.A.:-

(i) Higher Gain, Higher CMRR, Higher i/p impedance.

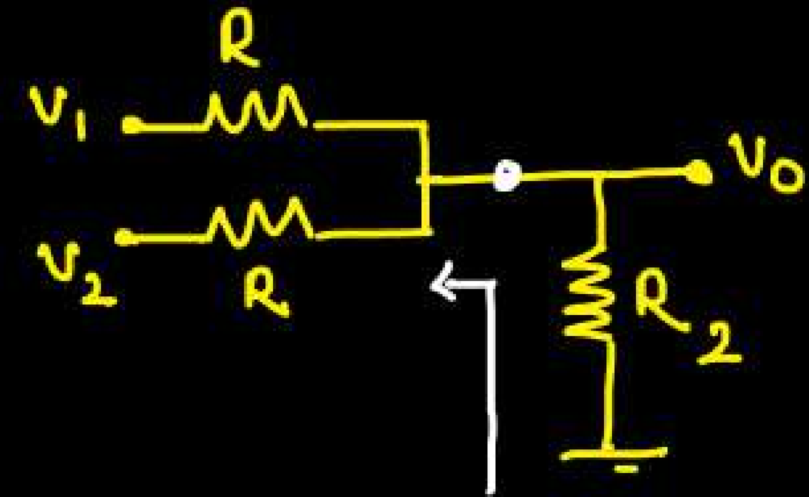
(ii) More control over gain [By changing less resistor values]

✲ Use of Instrumentation Amplifiers:-

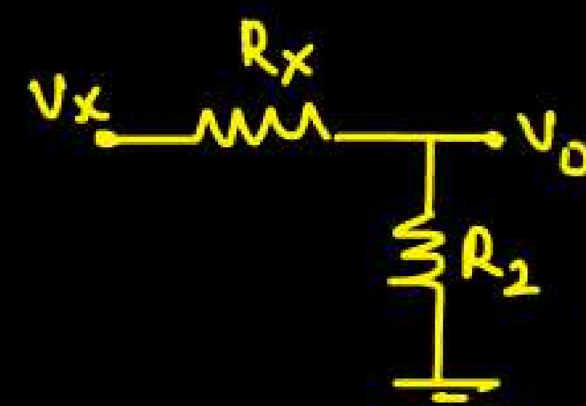


Revision Question:-

Q.

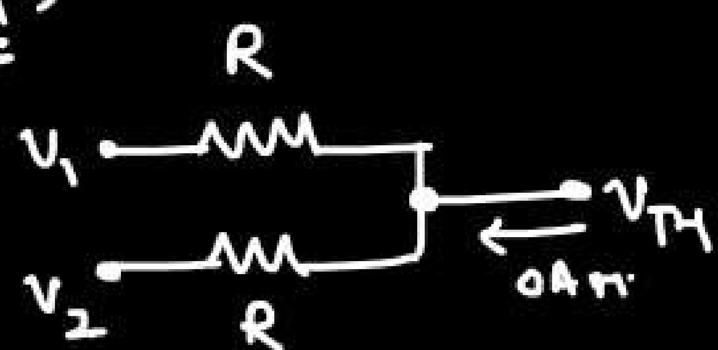


$\equiv$



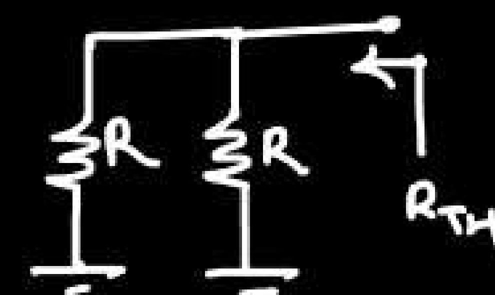
Find V_x and R_x ?

$\rightarrow$ $\underline{\underline{V_{TH}}} \rightarrow$

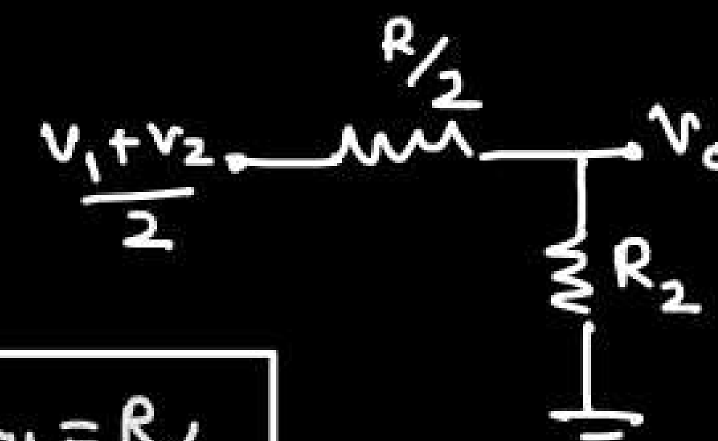


$$V_{TH} = \frac{V_1 R + V_2 R}{R+R} = \frac{V_1 + V_2}{R}$$

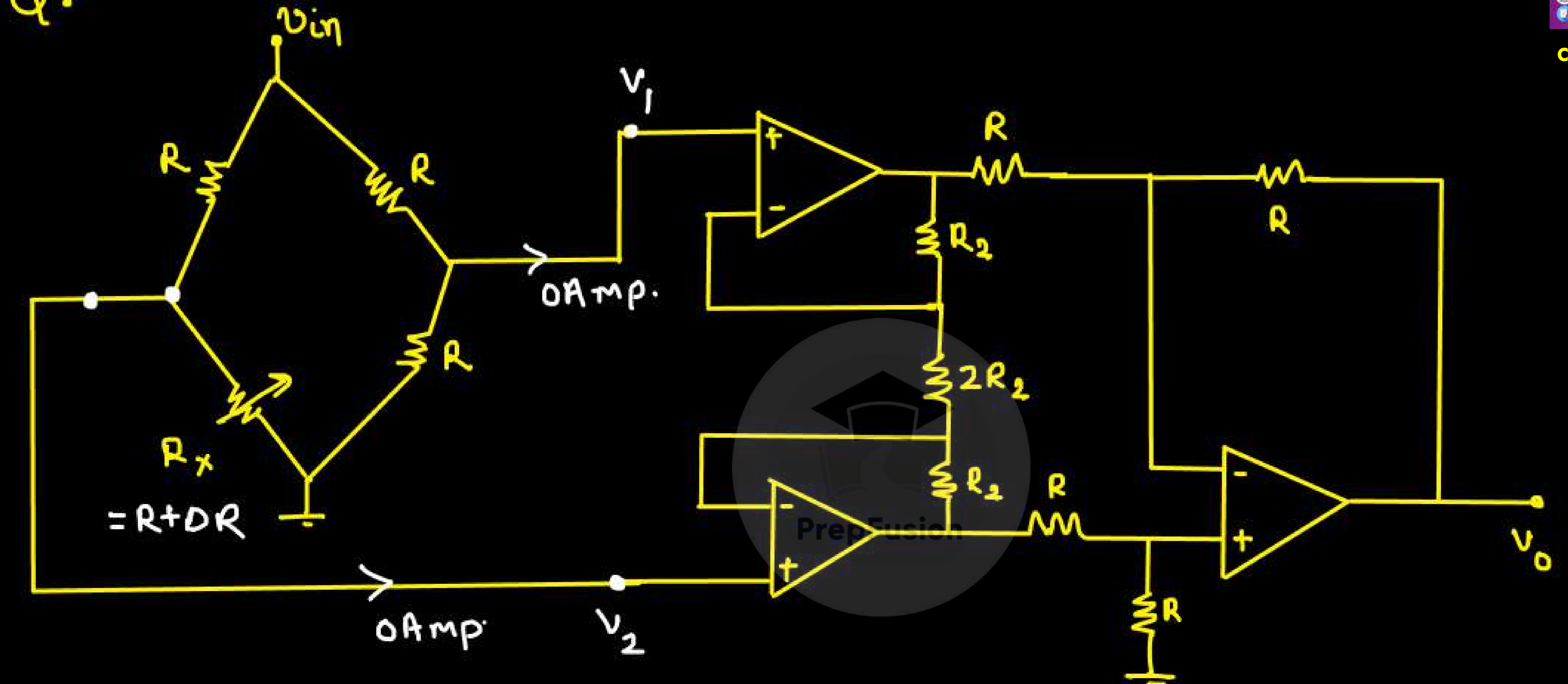
$\underline{\underline{R_{TH}}} \rightarrow$



$$\boxed{R_{TH} = R/2}$$



Q.



Initially $R_x = R$, but because of Temp. changes, the R_x value becomes $R + \Delta R$. Find V_0 voltage in this case.

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

$$\boxed{V_0 = 2\left[V_2 - V_1\right]}$$

when $R_x = R$

$$V_1 = V_2 = \frac{v_{in}}{2} \Rightarrow \boxed{V_0 = 0\,V}$$

when $R_x = R + \Delta R$

$$V_2 = \frac{R + \Delta R}{R + R + \Delta R} v_i = \frac{R + \Delta R}{2R + \Delta R} v_i$$

$$V_1 = \frac{v_i}{2}$$

$$V_0 = 2\left[V_2 - V_1\right]$$

$$= 2\left[\frac{R+\Delta R}{2R+\Delta R}v_i - \frac{v_i}{2}\right]$$

$$= 2\left[\frac{2R+2\Delta R-2R-\Delta R}{2(2R+\Delta R)}\right]v_i$$

$$v_0 = \left[\frac{\Delta R}{2R+\Delta R}\right]v_i$$

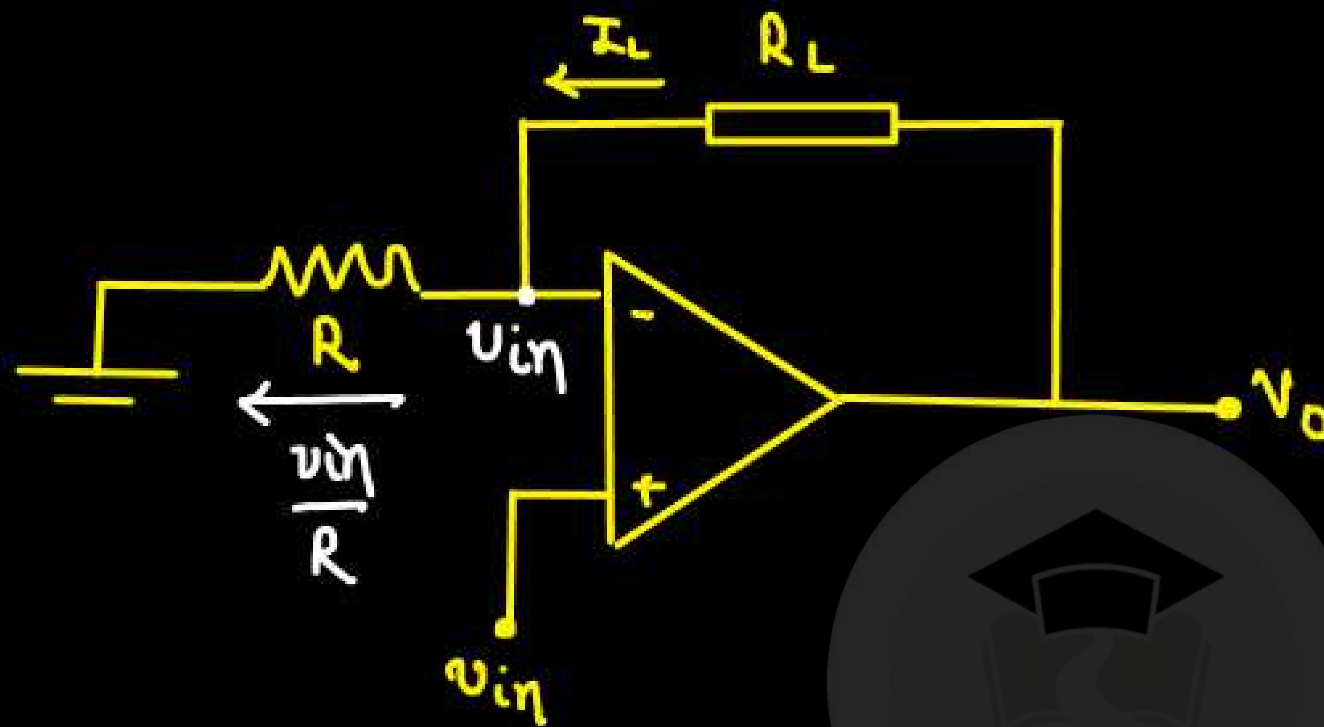
$$2R >>> \Delta R$$

$$v_0 = \frac{\Delta R}{2R}v_i$$

$$\boxed{v_0 \propto \frac{\Delta R}{R}}$$

o/p voltage $\propto$ change in Resistance

(5) Voltage to current converter :-

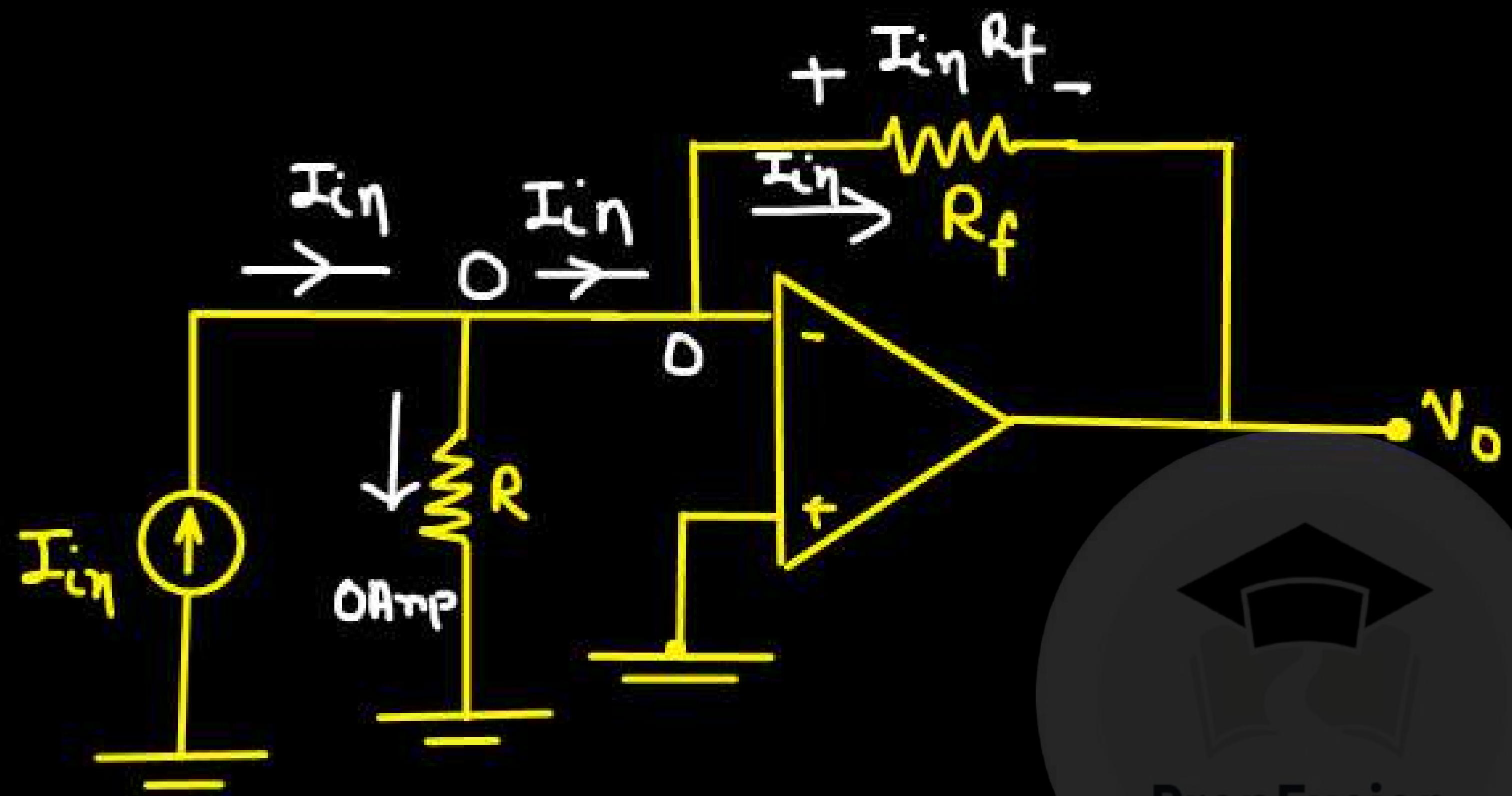


$$\boxed{\frac{v_{in}}{R} = I_L \qquad I_L \propto v_{in}}$$

$$\boxed{I_L \neq f(R_L)}$$

$$\boxed{I_L = f(v_i)}$$

⑥ Current to Voltage Converter :-

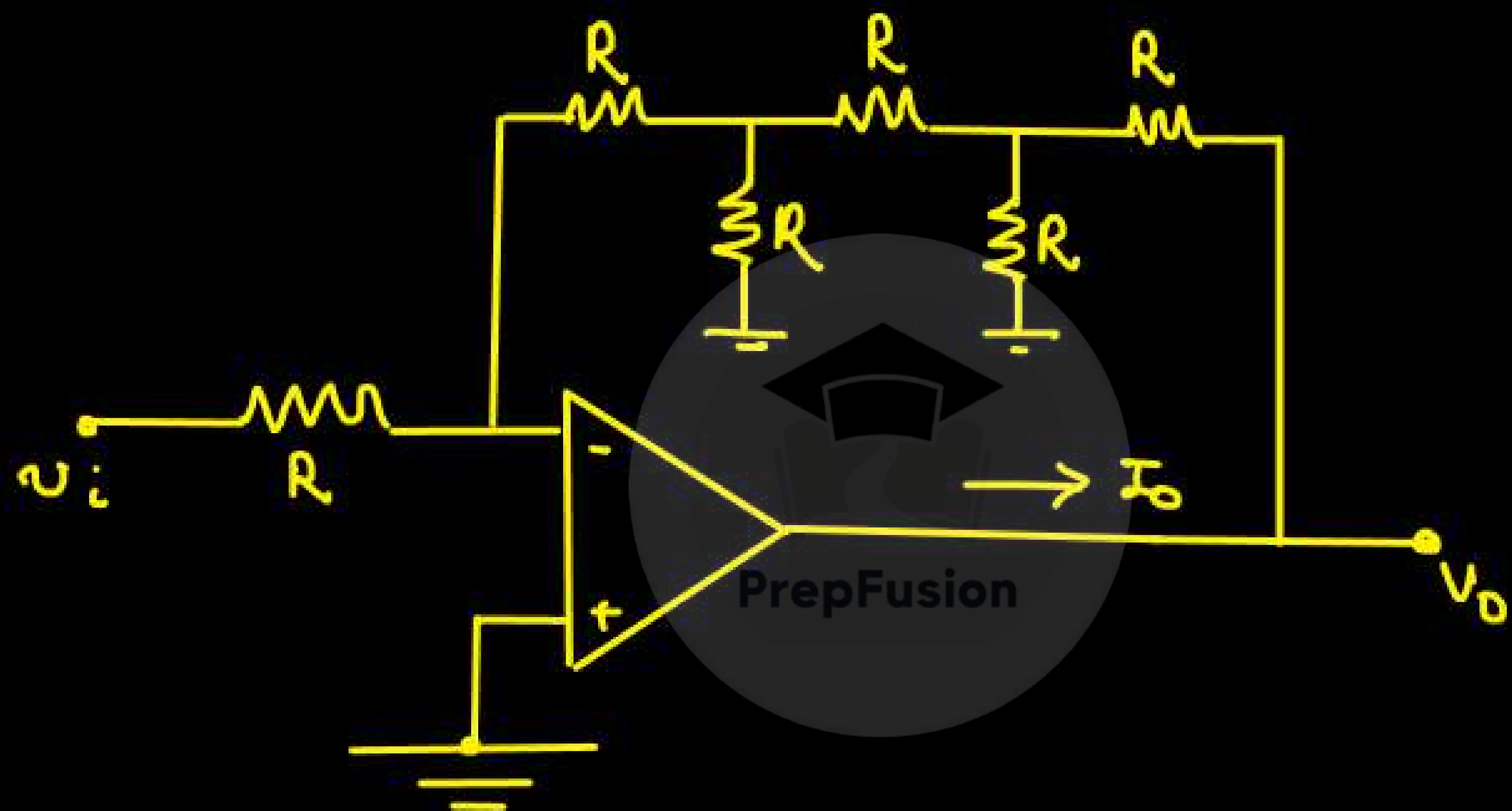


$$\boxed{V_o = -I_{in}R_f}$$

$$\boxed{V_o \propto I_{in}}$$

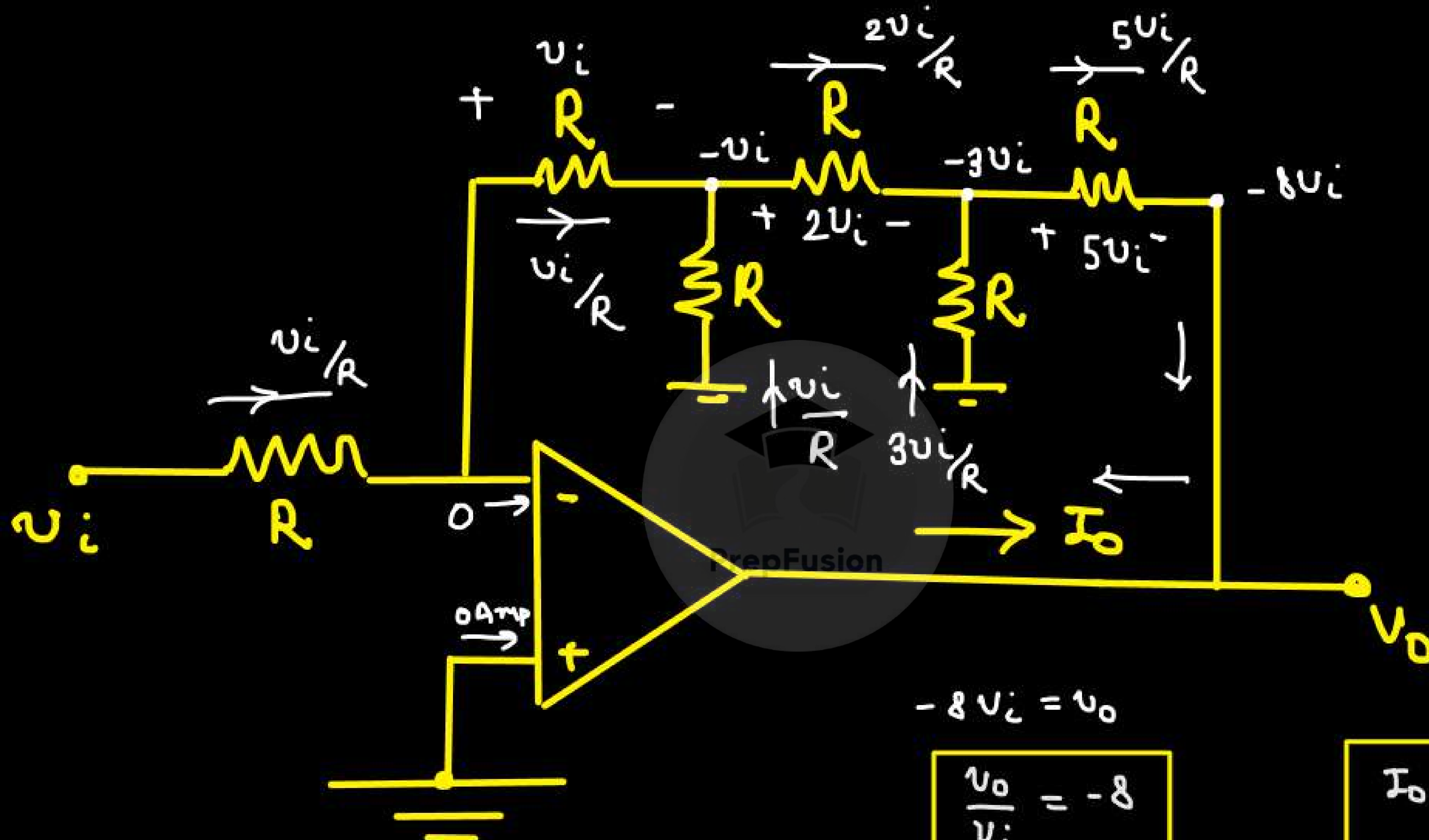
Assignment -12

Q. 1



Find the gain $\frac{v_o}{v_i} = ?$

Find I_o ?

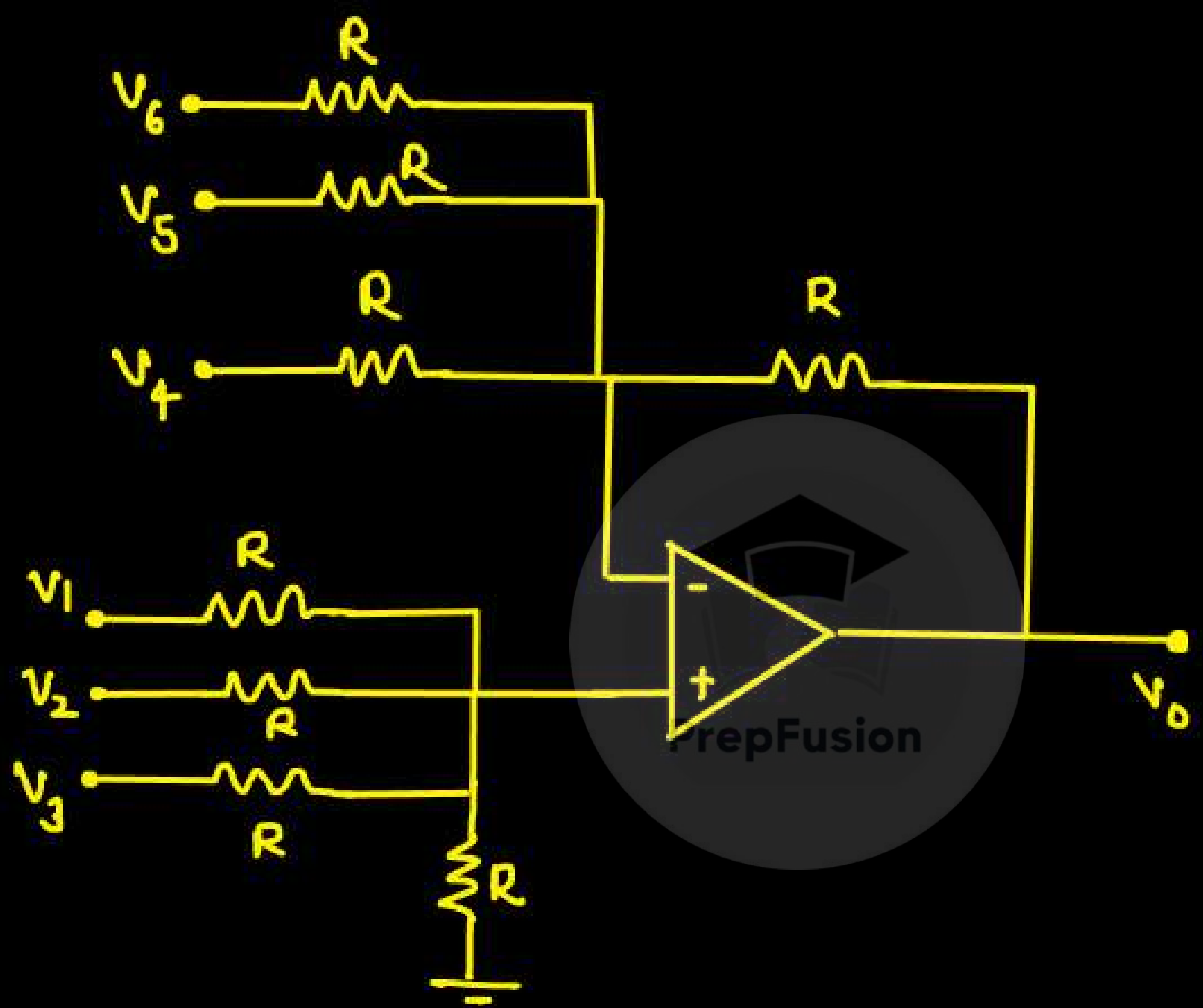


$-8v_i = v_o$

$$\boxed{\frac{v_o}{v_i} = -8}$$

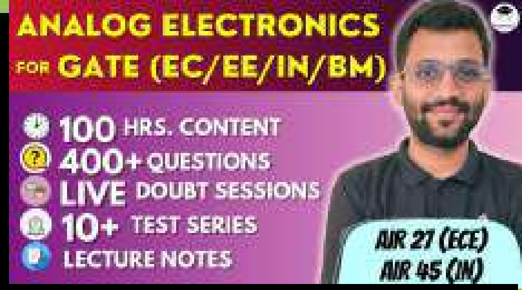
$$\boxed{I_o = -\frac{5v_i}{R}}$$

Q. 2



R
V_6
R
V_5
R
V_4
R
R
V_1
V_2
R
V_3
R
R
V_0
PrepFusion

Find $V_0 = ?$



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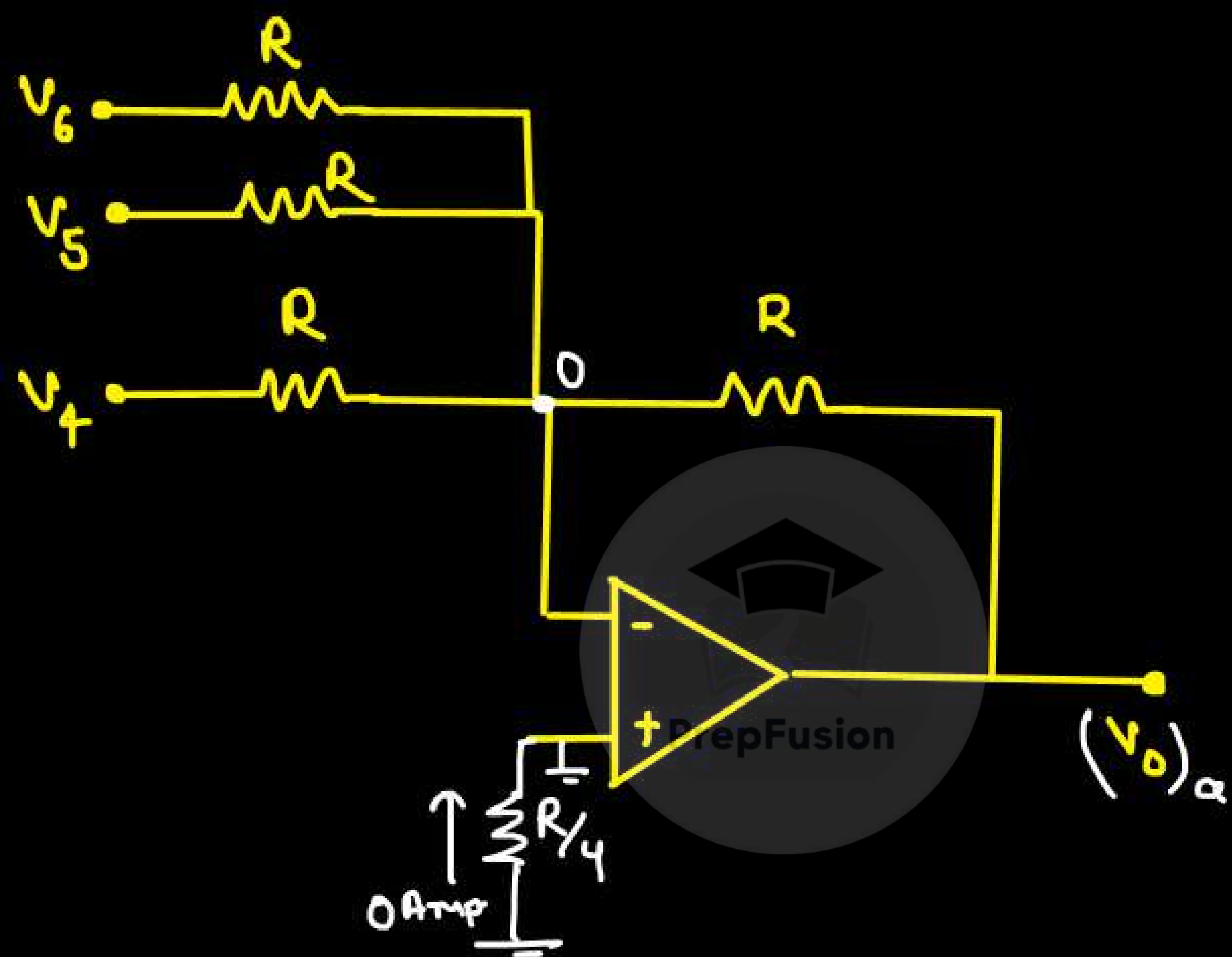
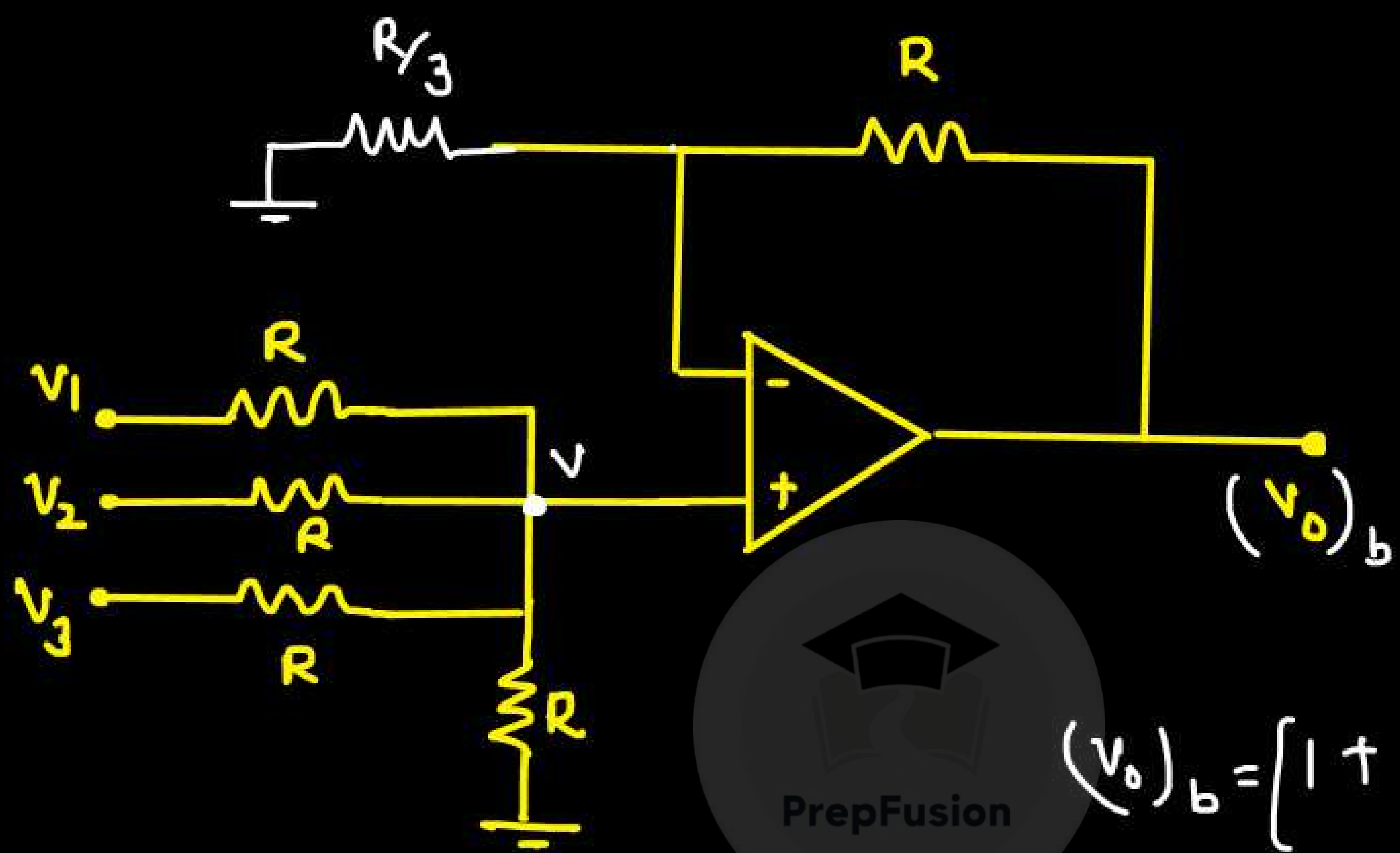
AIR 27 (ECE)
AIR 45 (IN)



$$-\frac{V_6}{R} - \frac{V_5}{R} - \frac{V_4}{R} - \frac{(V_0)_a}{R} = 0$$

$$\boxed{(V_0)_a = -(V_4 + V_5 + V_6)} \quad \text{—} \ (1)$$



$$(V_0)_b = \left[1 + \frac{R}{R/3}\right] V$$

$$(V_0)_b = 4V \quad \text{— } (2)$$

$$\frac{V - V_1}{R} + \frac{V - V_2}{R} + \frac{V - V_3}{R} + \frac{V}{R} = 0$$

$$4V = V_1 + V_2 + V_3 \longrightarrow (3)$$

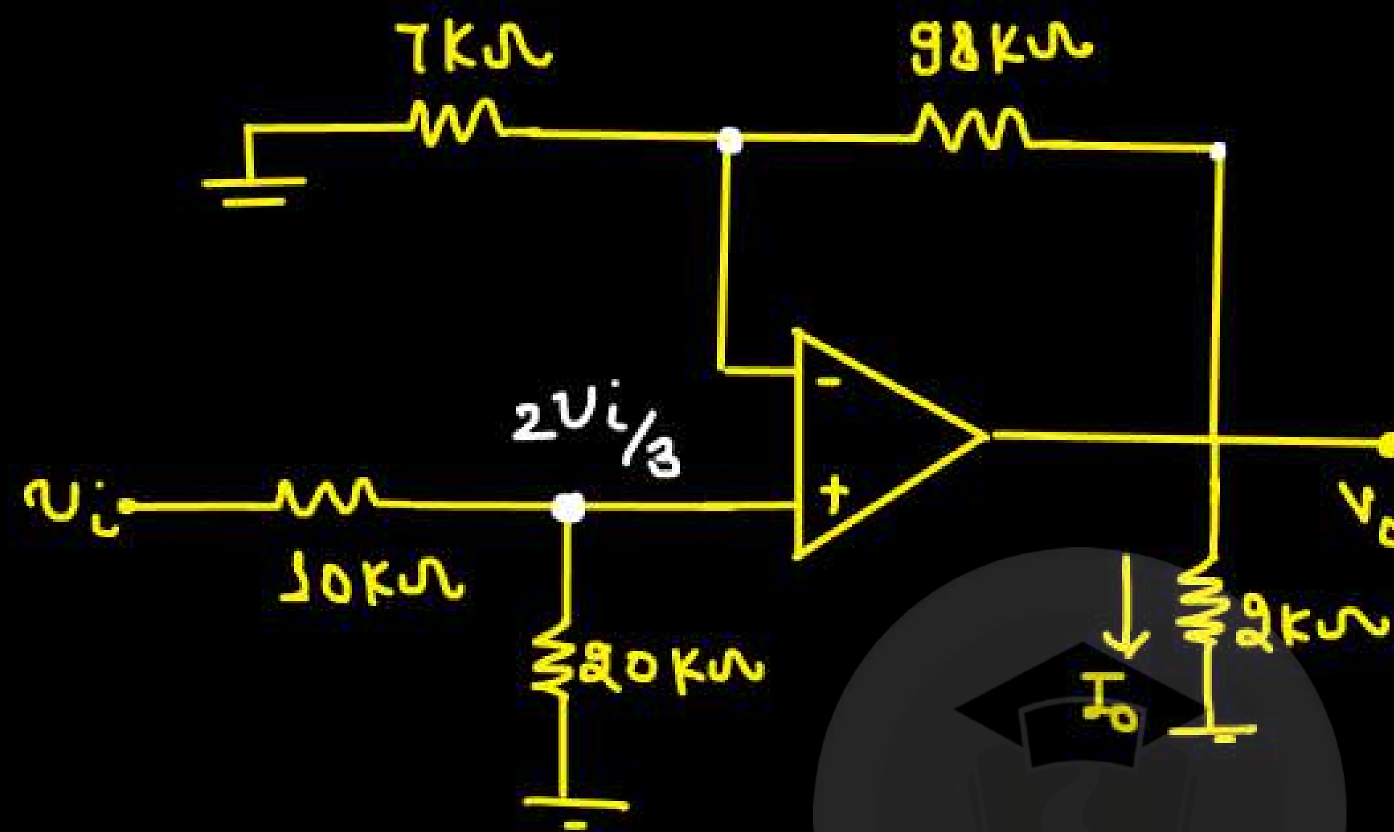
By eq^n (2) and (3)

$$\boxed{(V_0)_b = V_1 + V_2 + V_3}$$

$$V_0 = (V_0)_a + (V_0)_b$$

$$\boxed{V_0 = V_1 + V_2 + V_3 - V_4 - V_5 - V_6}$$

Q.



$$V_o = \left(1 + \frac{98K}{7K}\right) \times \frac{2v_i}{3}$$

$$= 15 \times \frac{2v_i}{3}$$

$$= 10v_i$$

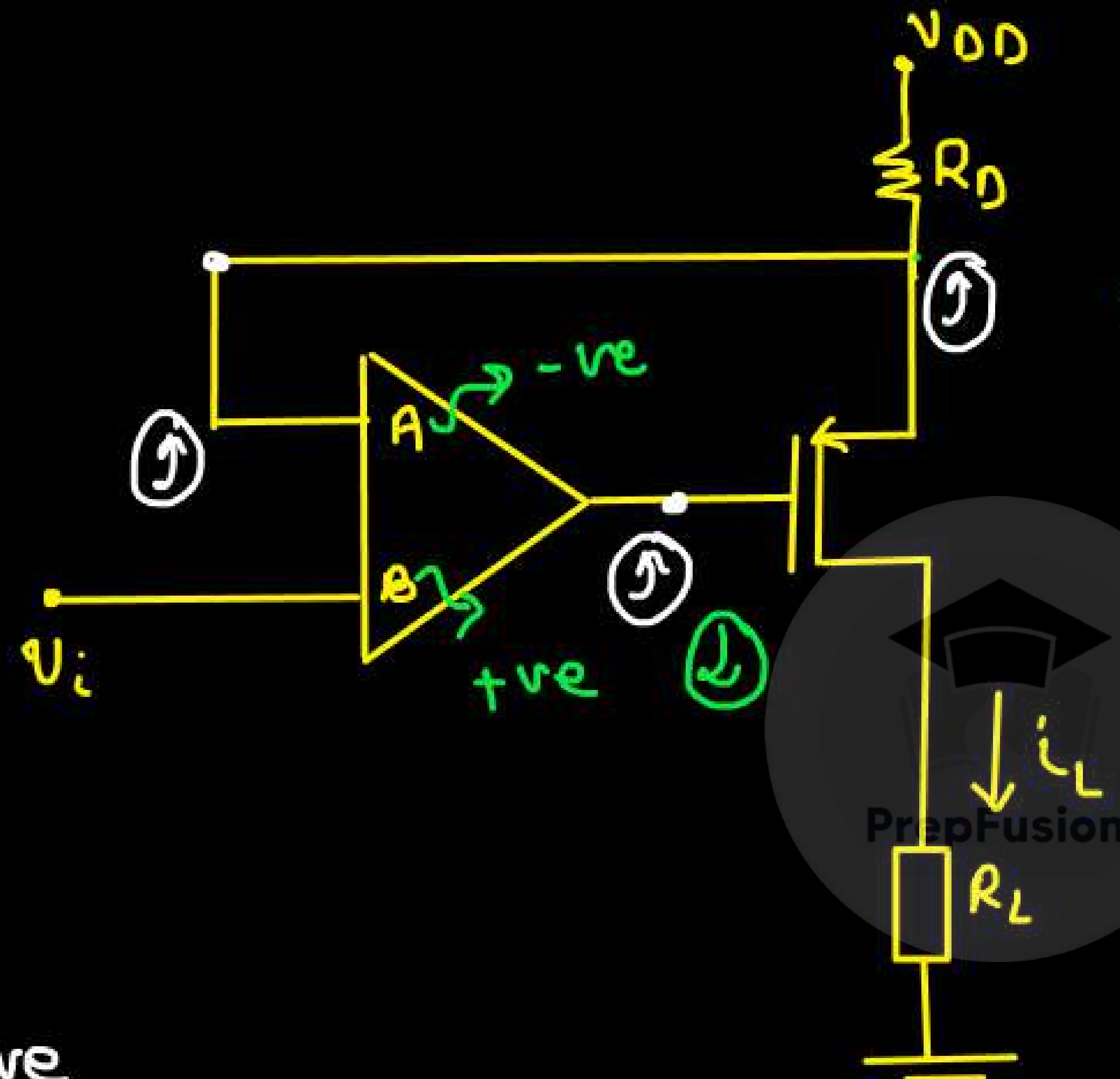
$v_i = 0.5\sin(\omega t)$

Find the max^m Amplitude of I_o?

$$I_o = \frac{V_o}{2k} = \frac{10v_i}{2k} = \frac{5\sin(\omega t)}{2k} = 2.5\sin\omega t \text{ mA}$$

$$\boxed{(I_o)_{max} = 2.5\text{ mA}}$$

Q.

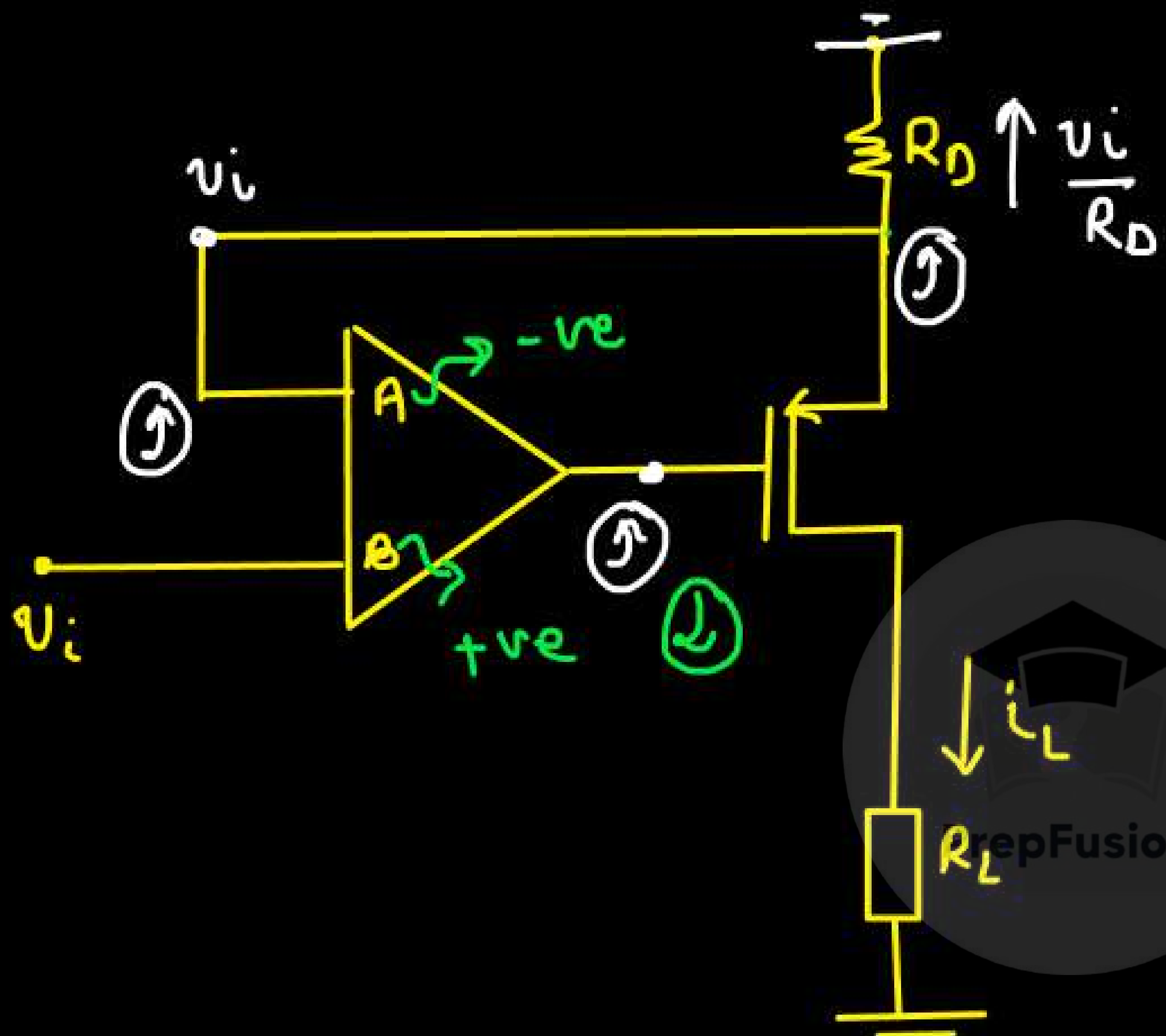


(a) Find the sign of A and B such that op-Amp is working in Negative feedback.

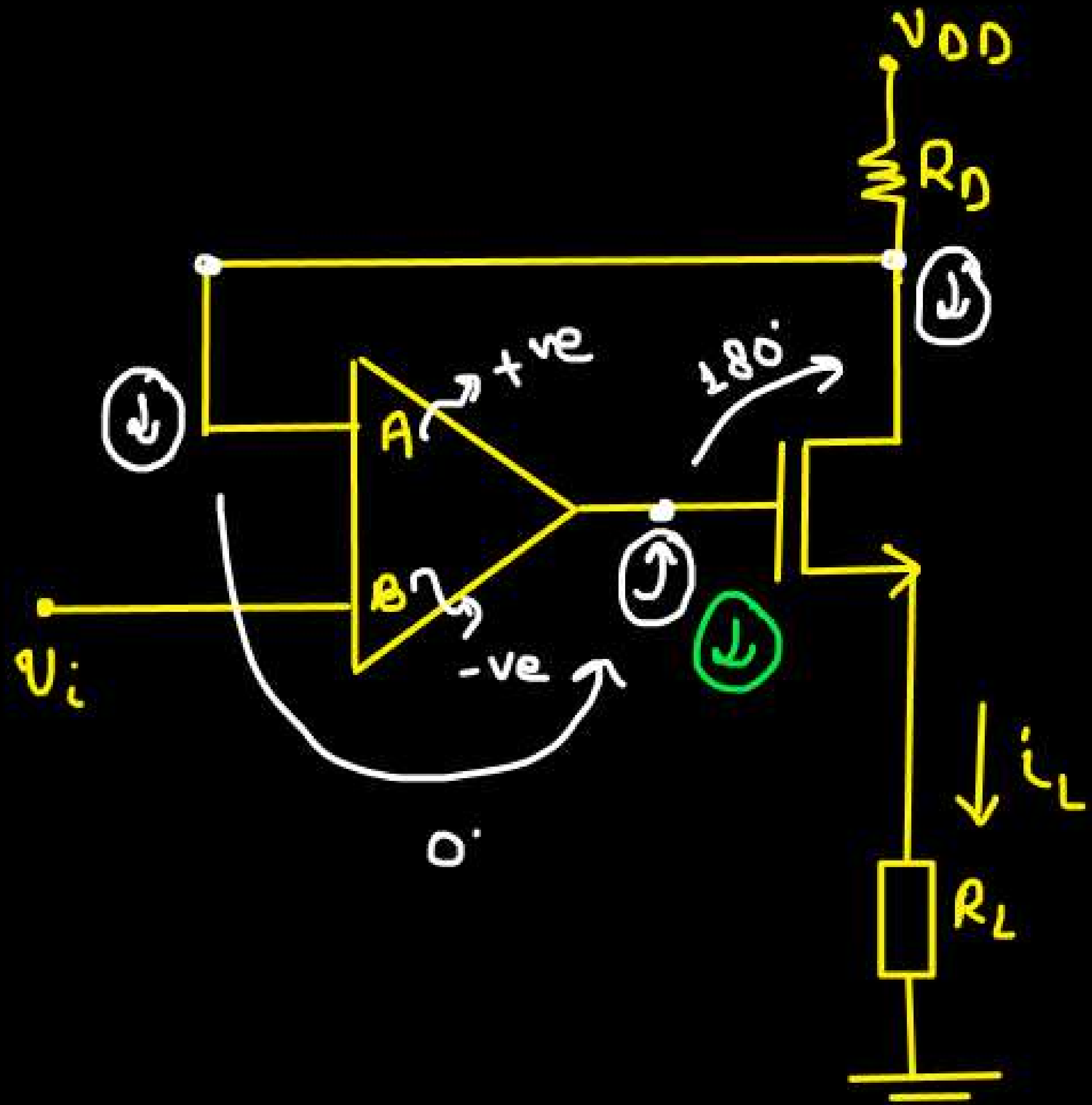
(b) Find small signal current i_L in terms of small signal voltage v_i.

A = −ve

B = +ve



$$\boxed{-\frac{v_i}{R_D} = i_L}$$



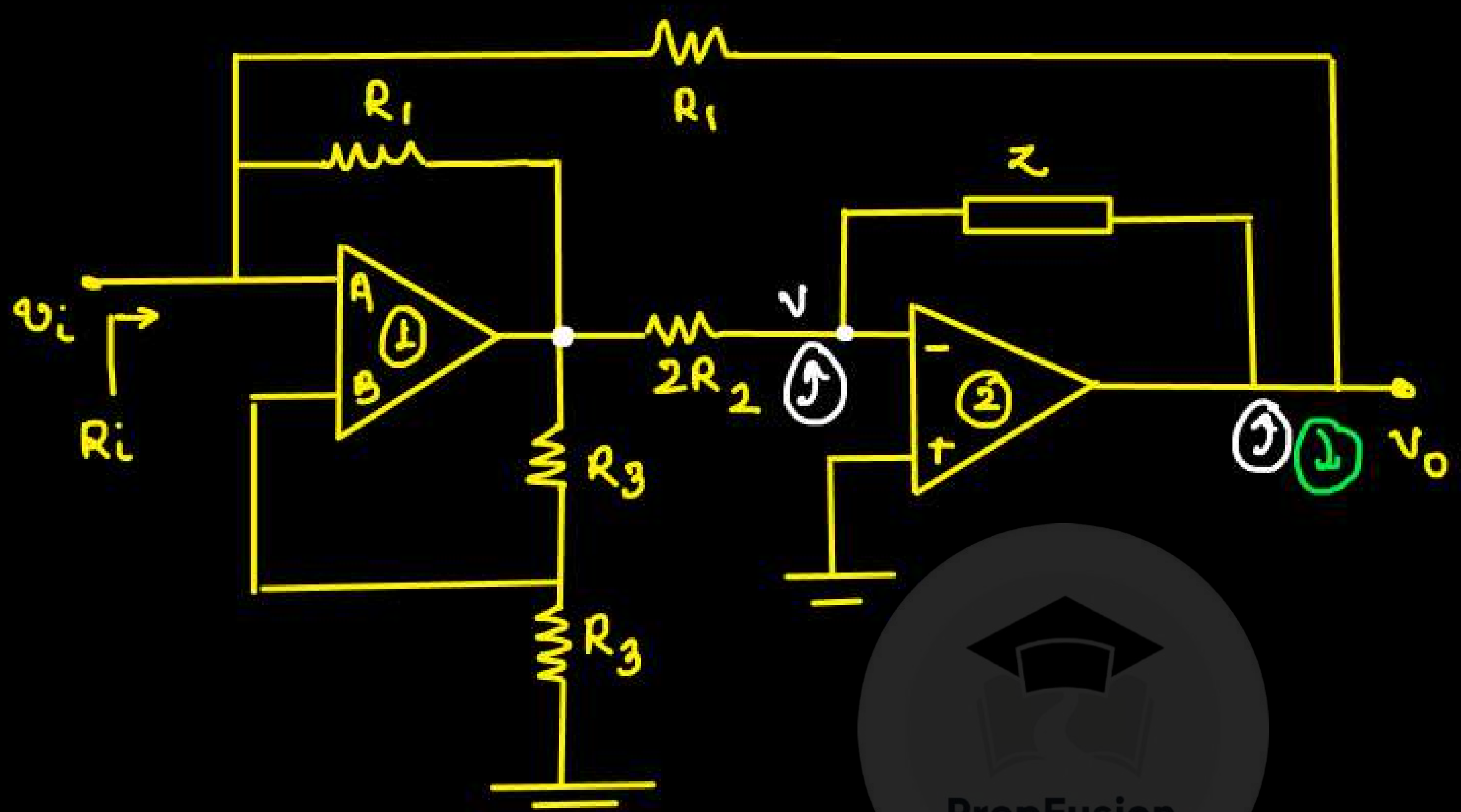
(a) Find the sign of A and B such that op-Amp is working in Negative feedback.

(b) Find small signal current i_L in terms of small signal voltage v_i.

(a) A = +ve, B = -ve

(b) $-\frac{v_i}{R_D} = i_L$

MSQ Q.



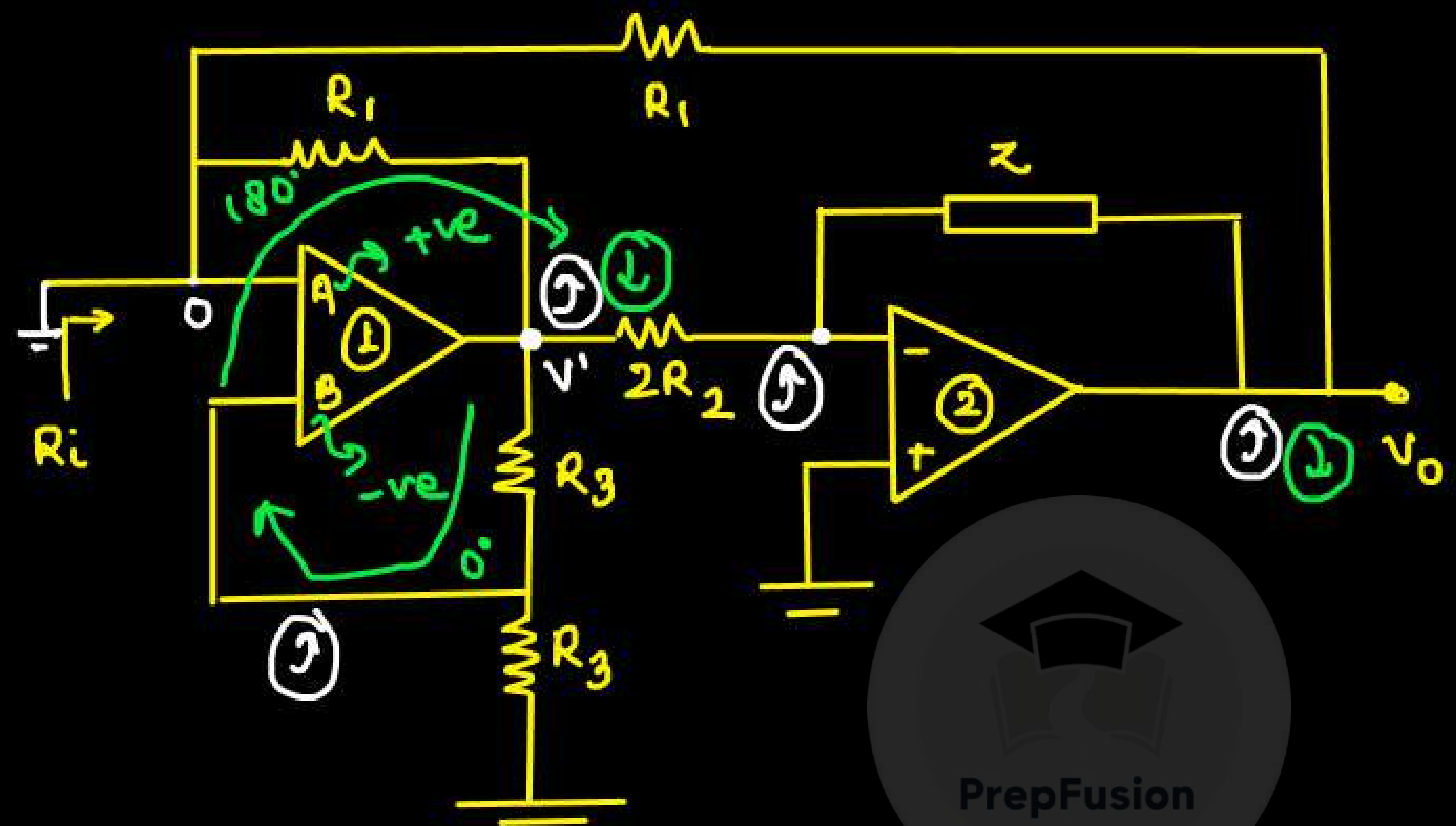
Which of the following is/are correct?

(a) For both of the op-amps to work in Neg. f/b ; A = +ve, B = −ve

(b) For both of the op-amps to work in Neg. f/b ; A = −ve, B = +ve

(c) Considering negative f/b, R_i acts as inductor if Z = inductor

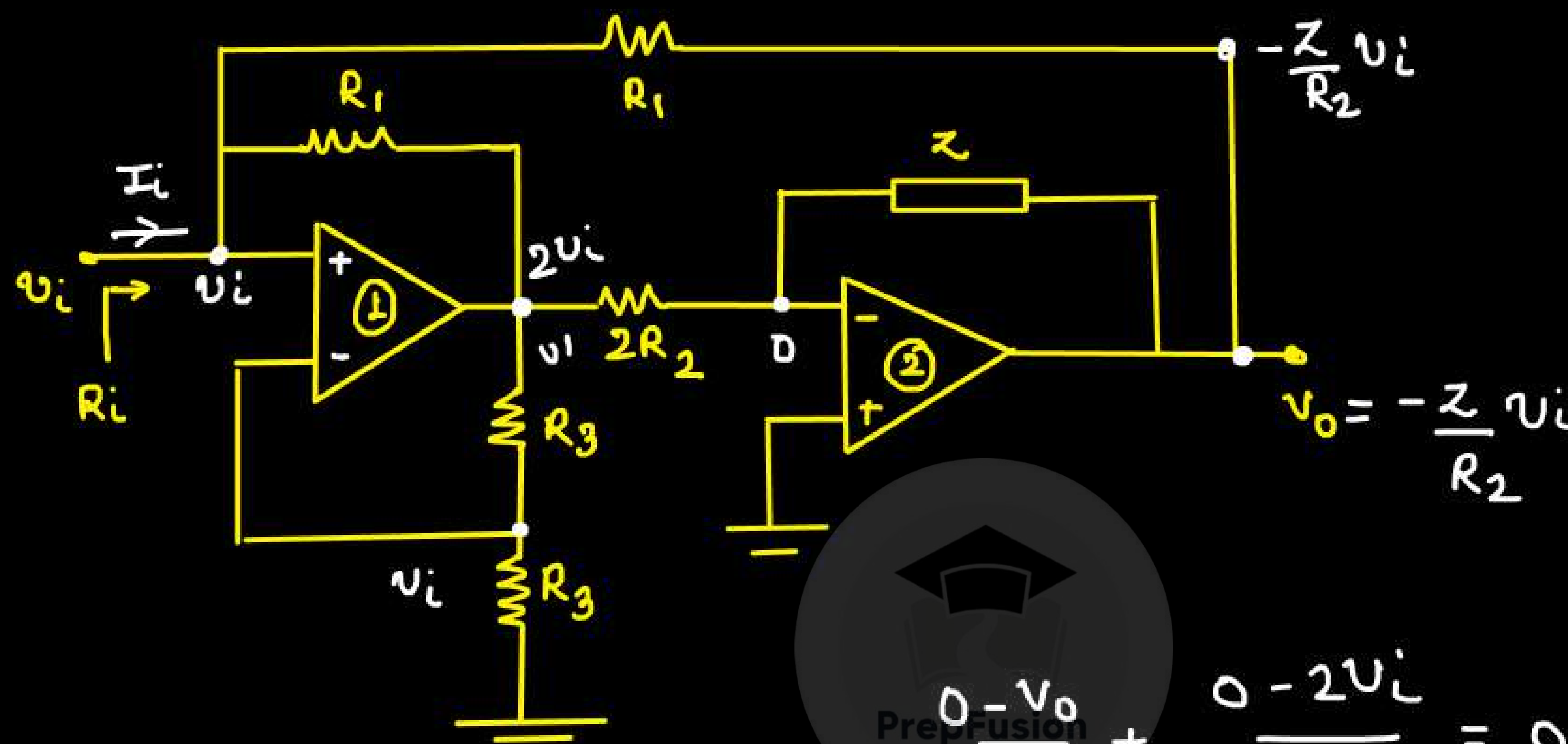
(d) Considering Negative f/b, R_i acts as capacitor if Z = capacitor



Node A → 0

Node B → ↑ {if v' increases}

B = -ve , A = +ve



$$\frac{0 - V_o}{Z} + \frac{0 - 2V_i}{2R_2} = 0$$

$$V_o = -\frac{Z}{R_2} v_i \quad \text{——} \quad (1)$$

$$\frac{v_i - 2V_i}{R_1} + \frac{v_i + \frac{Z}{R_2} v_i}{R_1} = I_i$$

$$-v_i + v_i + \frac{Z}{R_2} v_i = I_i R_1 \Rightarrow \boxed{\frac{v_i}{I_i} = \frac{R_1 R_2}{Z}} \qquad \boxed{R_i = \frac{R_1 R_2}{Z}}$$

$$R_i = \frac{R_1 R_2}{Z}$$

$Z \rightarrow$ Inductor ; $Z = j\omega L$

$$R_i = \frac{R_1 R_2}{j\omega L} = -j\,\frac{R_1 R_2}{\omega L}$$

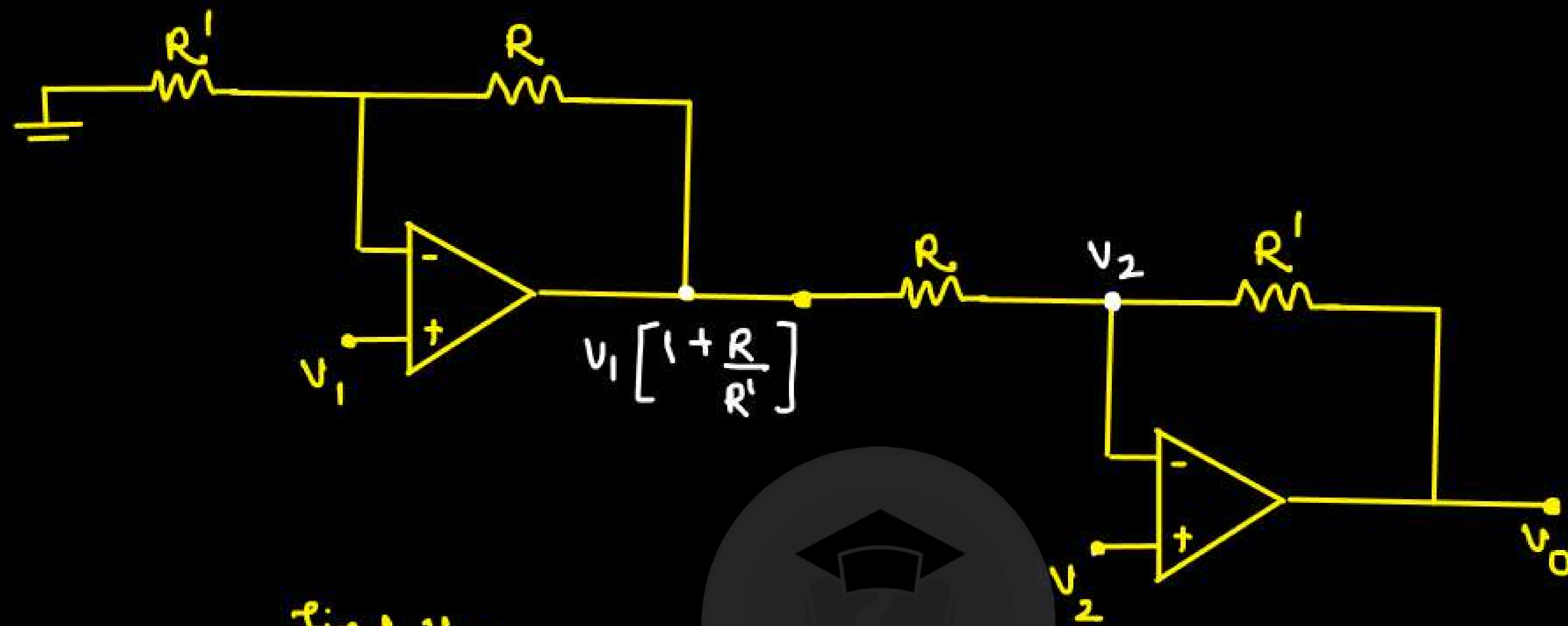
$\boxed{\text{if } Z \rightarrow \text{Inductor} \Rightarrow R_i \rightarrow \text{capacitor}}$

if $Z \rightarrow$ capacitor ; $Z = \frac{1}{j\omega C}$

$$R_i = \frac{R_1 R_2}{\frac{1}{j\omega C}} = j\omega C R_1 R_2 \rightarrow \text{Inductor}$$

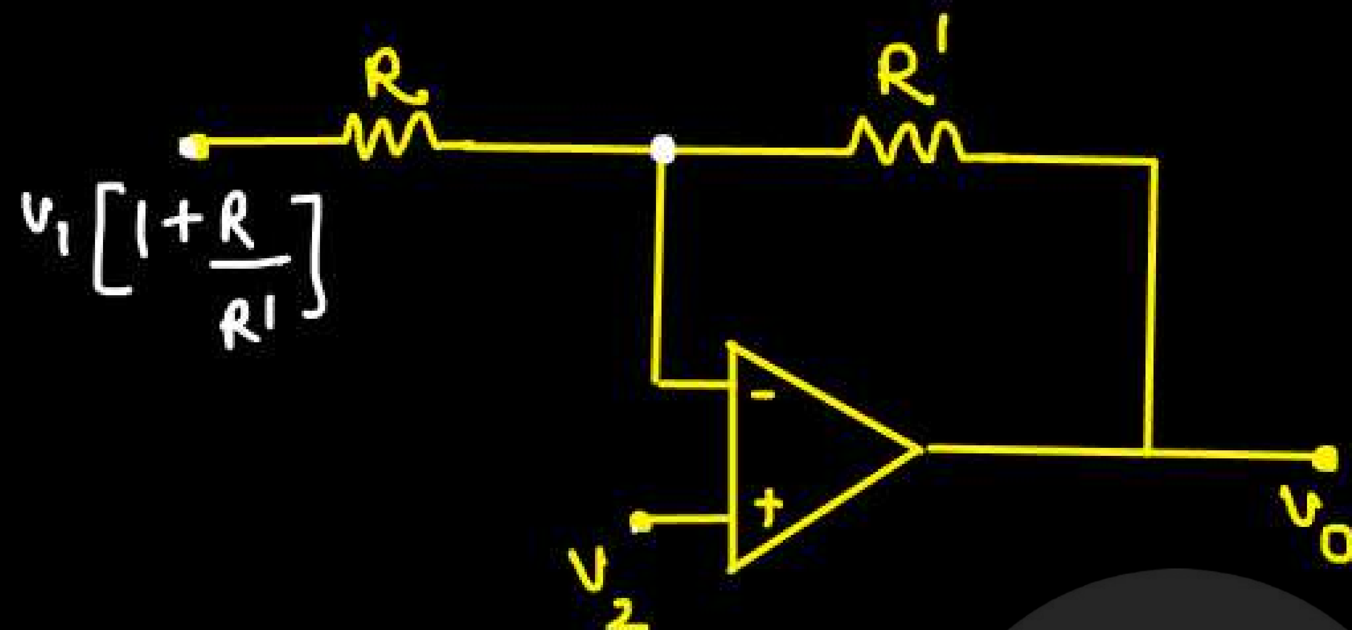
$\boxed{\text{if } Z \rightarrow \text{capacitor} \Rightarrow R_i \rightarrow \text{Inductor}}$

Q.



Find V_0.

→



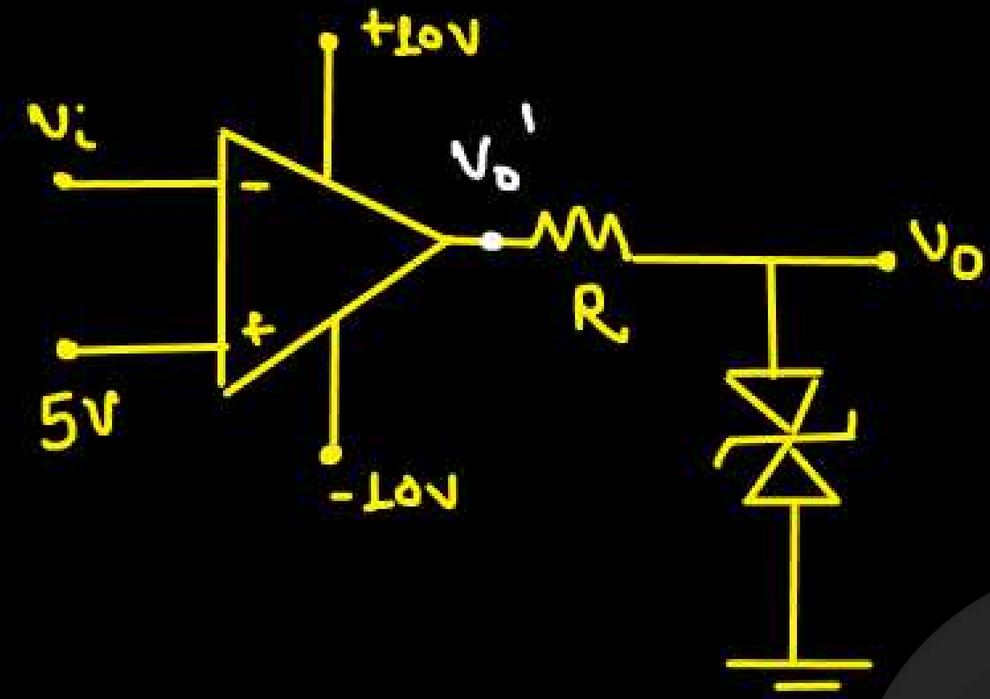
$$V_0 = \left[1 + \frac{R'}{R}\right] v_2 - \frac{R'}{R}\left[1 + \frac{R}{R'}\right] v_1$$

$$= v_2 + \frac{R'}{R} v_2 - \frac{R'}{R} v_1 - v_1$$

$$= (v_2 - v_1) + \frac{R'}{R}(v_2 - v_1)$$

$$\boxed{V_0 = \left(1 + \frac{R'}{R}\right)(v_2 - v_1)}$$

Q.

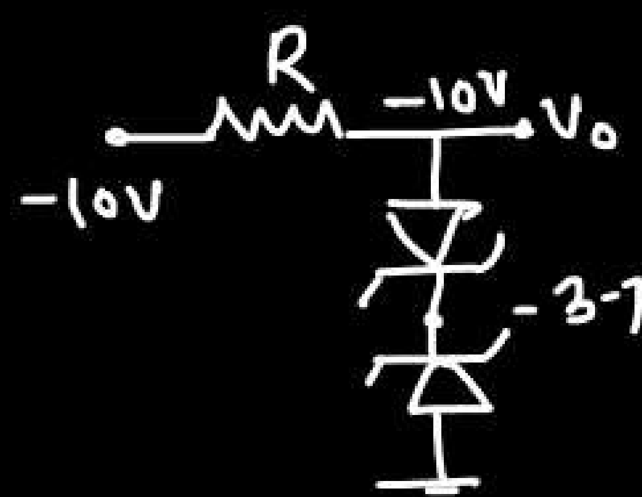


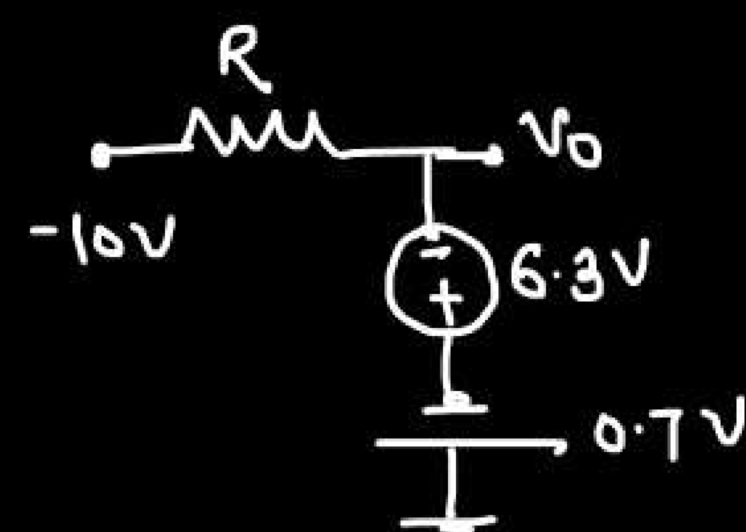
For the zener,

$V_{ON} = 0.7V$, $V_Z = 6.3V$

Draw Transfer characteristics v_o v/s v_i ?

→ $v_i > 5V \Rightarrow v_o' = -10V$

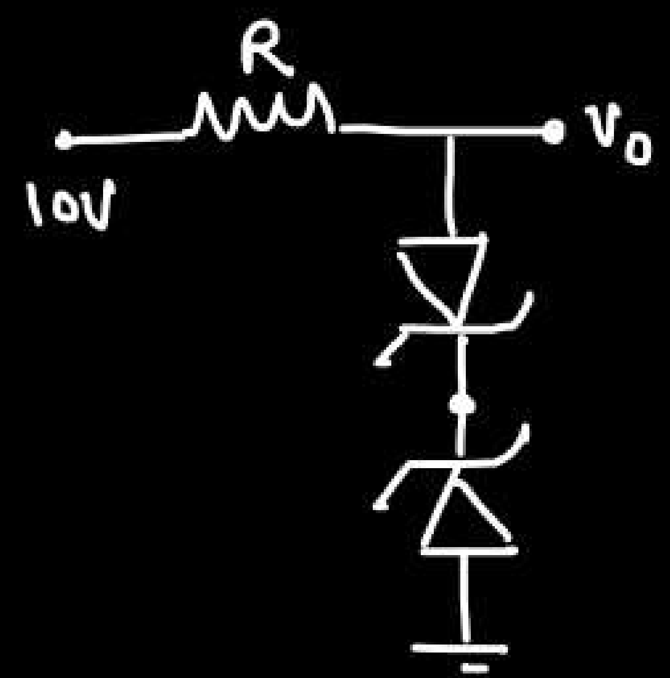




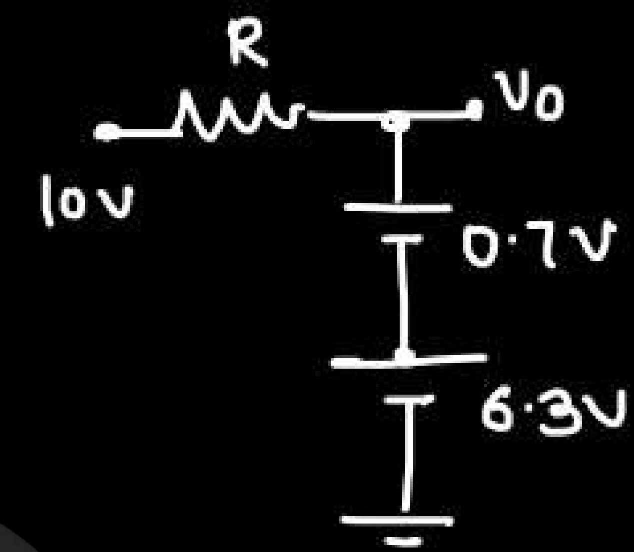
$v_i > 5V$

$\Rightarrow \boxed{v_o = -7V}$

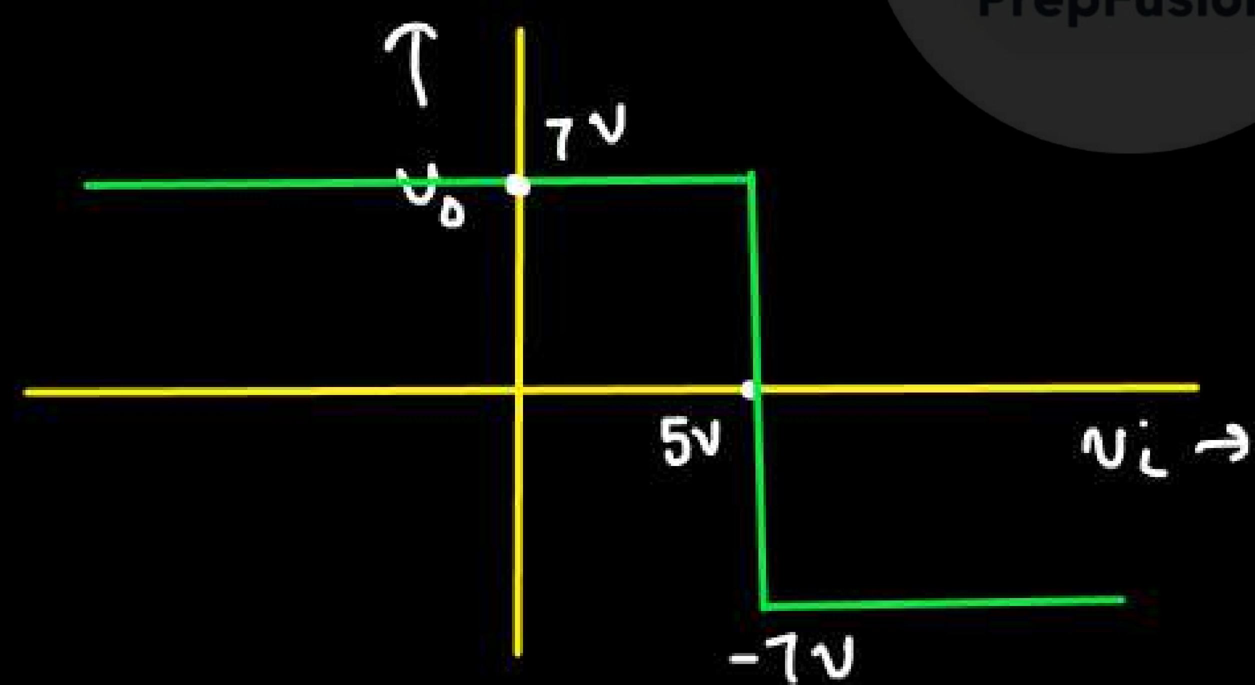
$V_i < 5V \Rightarrow V_0' = +10V$

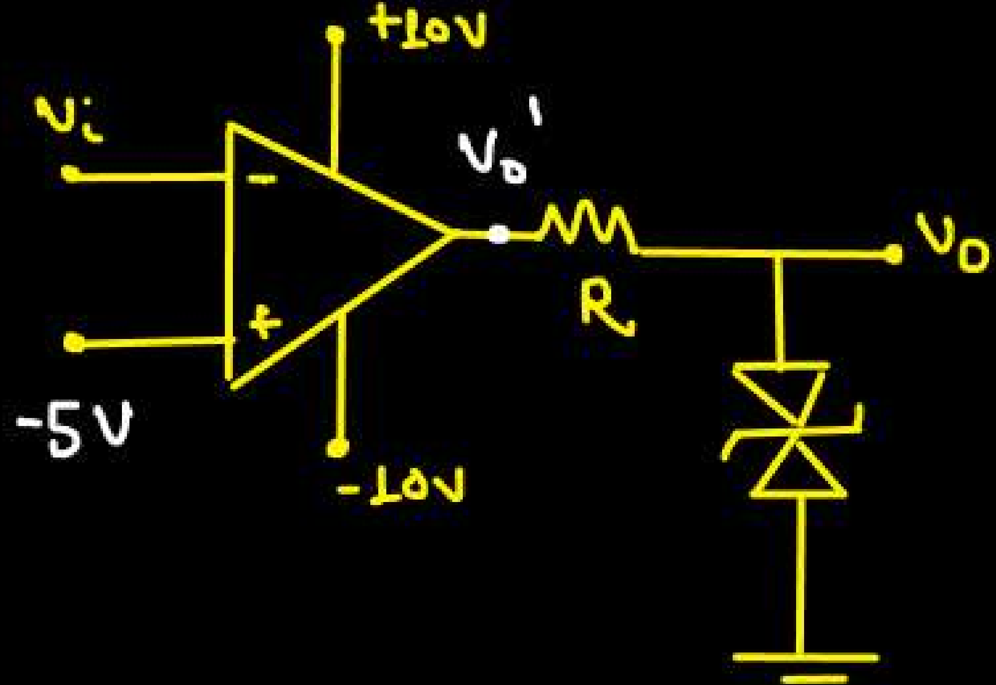


$\Rightarrow$



$\boxed{V_0 = 7V}$





For the zener,

$V_{ON} = 0.7V$, $V_Z = 6.3V$

Draw Transfer characteristics v_o v/s v_i ?

→ $v_i > -5V \Rightarrow v_o' = -10V$

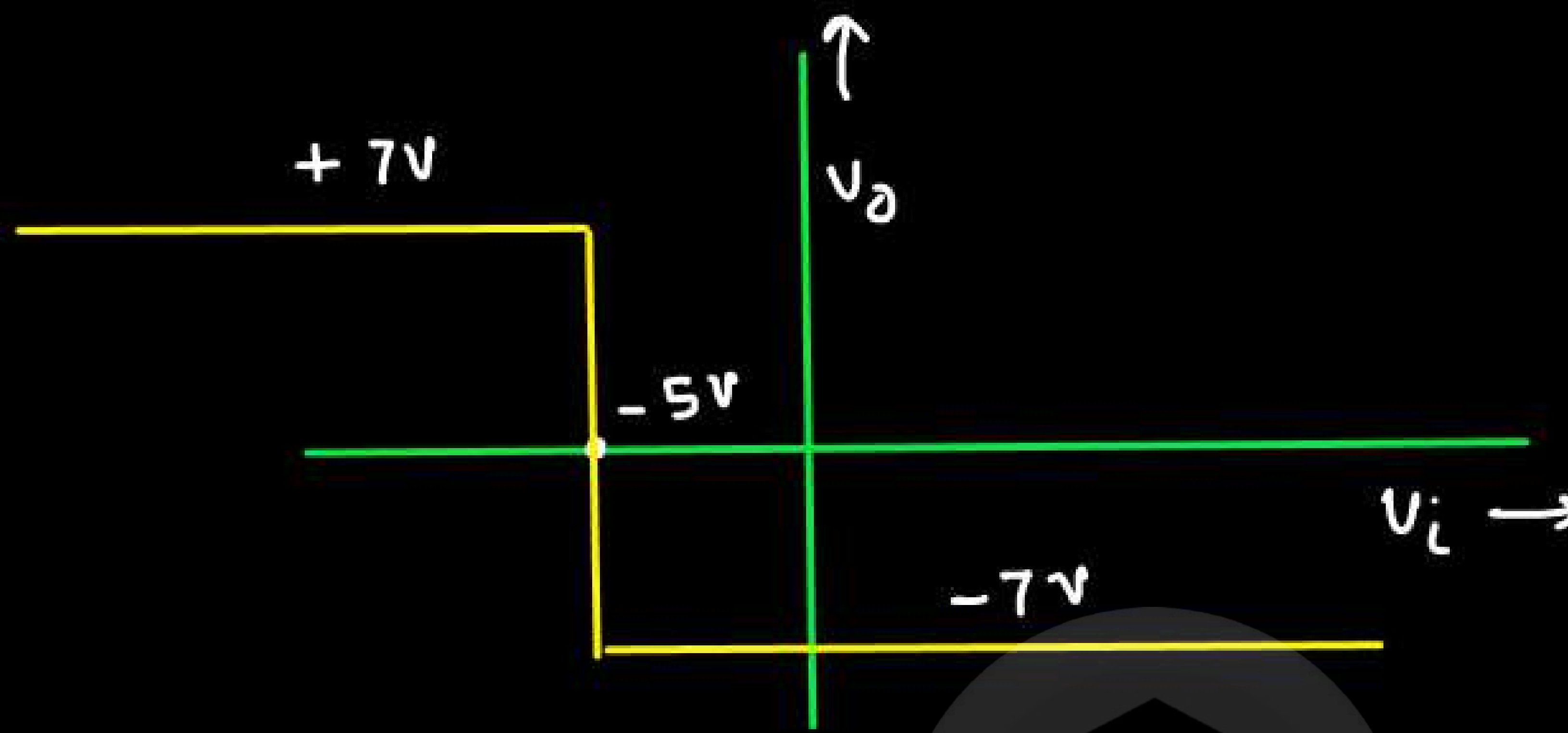
$\Downarrow$

$\boxed{v_o = -7V}$

$v_i < -5V \Rightarrow v_o' = 10V$

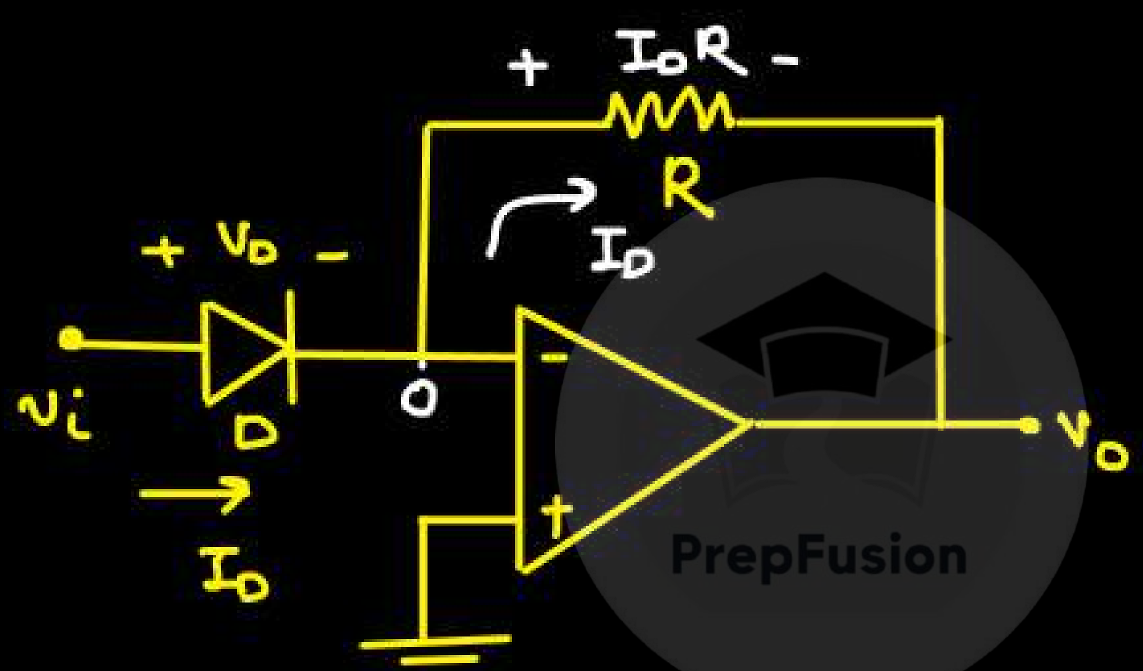
$\Downarrow$

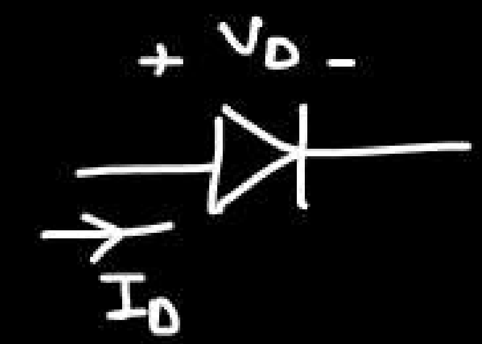
$\boxed{v_o = +7V}$


+ 7V
V_0
- 5V
V_i
-7V

★ Non-Linear Applications of OP-Amp:-

① Anti-log | exponential Amplifiers:-





$\Rightarrow V_D = v_i$

Considering, diode turns on for $V_D > 0$

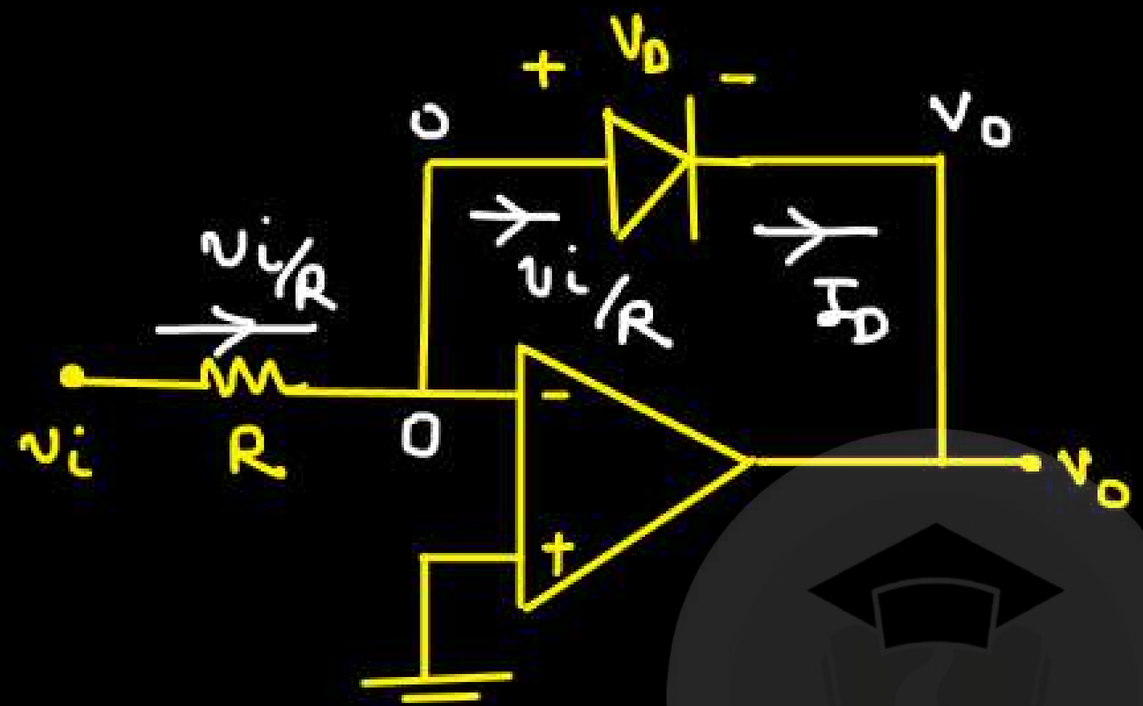
$$I_D = I_s e^{V_D/nV_T}$$

$$V_o = -I_D R$$

$$= -I_s e^{V_D/nV_T} \times R$$

$$\boxed{V_o = -I_s R e^{v_i/nV_T}} \Rightarrow \boxed{V_o \propto e^{v_i/nV_T}}$$

② Logarithmic Amplifier:-



$$V_D = -V_o$$

$$I_D = I_s e^{V_D/nV_T}$$

$$\frac{v_i}{R} = I_s e^{-V_o/nV_T}$$

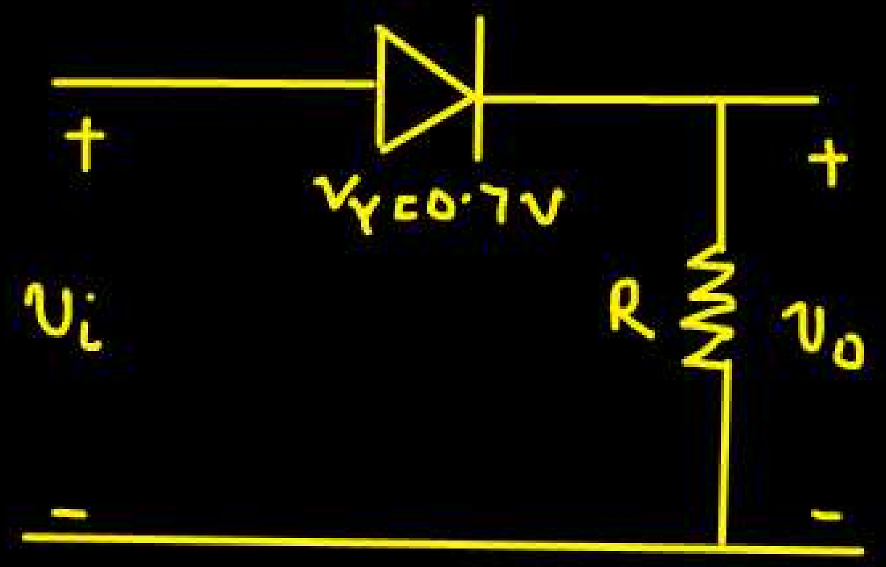
$$\exp\left(-\frac{V_o}{nV_T}\right) = \frac{v_i}{I_s R}$$

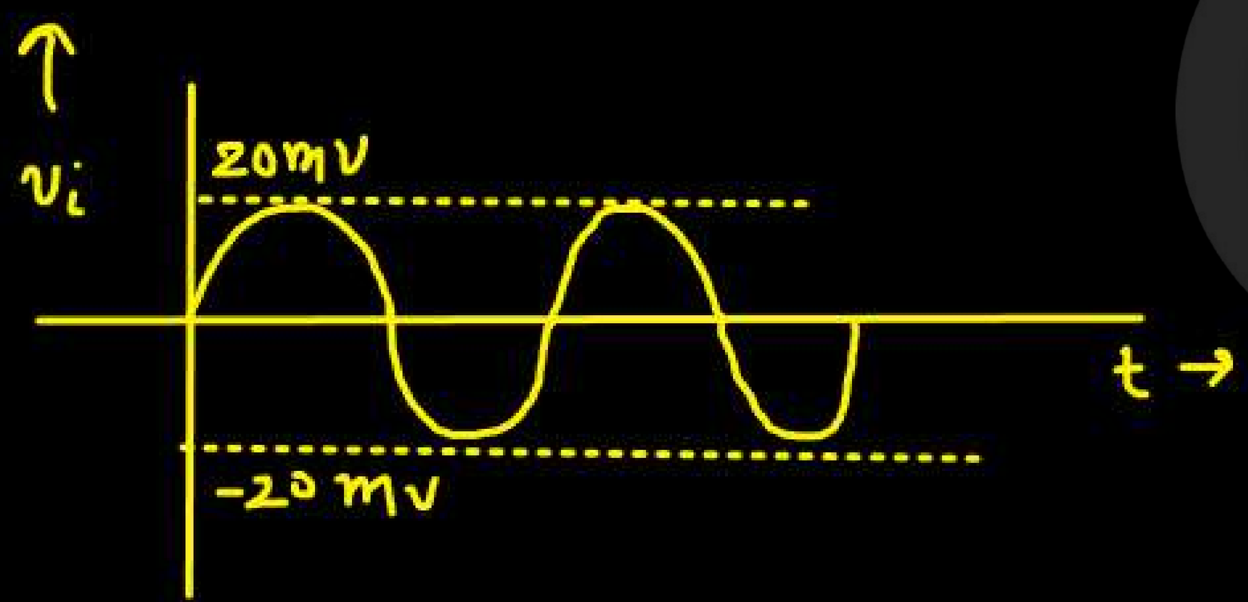
$$\Rightarrow -\frac{V_o}{nV_T} = \ln\left[\frac{v_i}{I_s R}\right]$$

$$\Rightarrow \boxed{v_o = -nV_T \ln\left[\frac{v_i}{I_s R}\right]}$$

$$\boxed{v_o \propto \ln[\alpha v_i]}$$

✪ Half Wave rectifier using diode ($V_\gamma = 0.7V$) :-





$v_i = 20mV \sin\omega t$

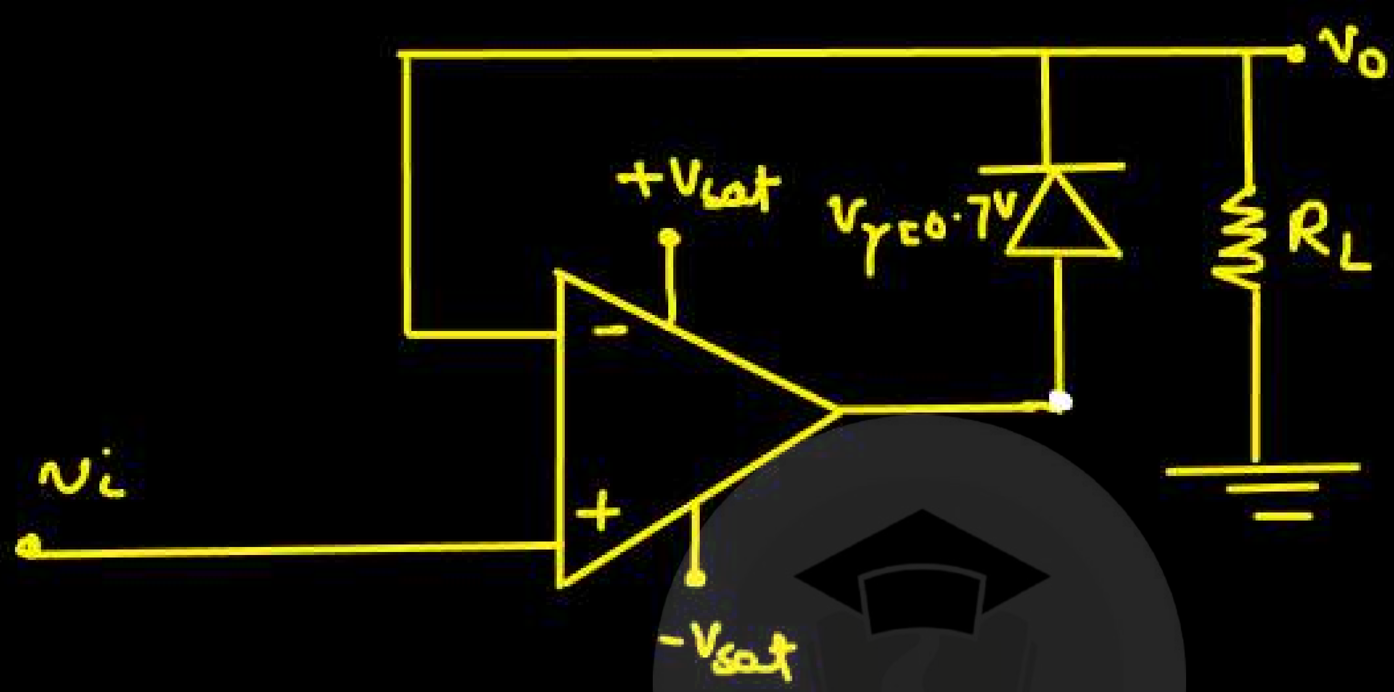
and $V_\gamma = 0.7V$

⇒ diode will never turn on

⇒ $\boxed{V_o = 0V}$

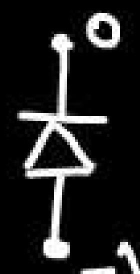
↳ Here, this ckt is not working as HWR because $\boxed{(v_i)_{max} < V_\gamma}$

③ HWR using Precision diode :-

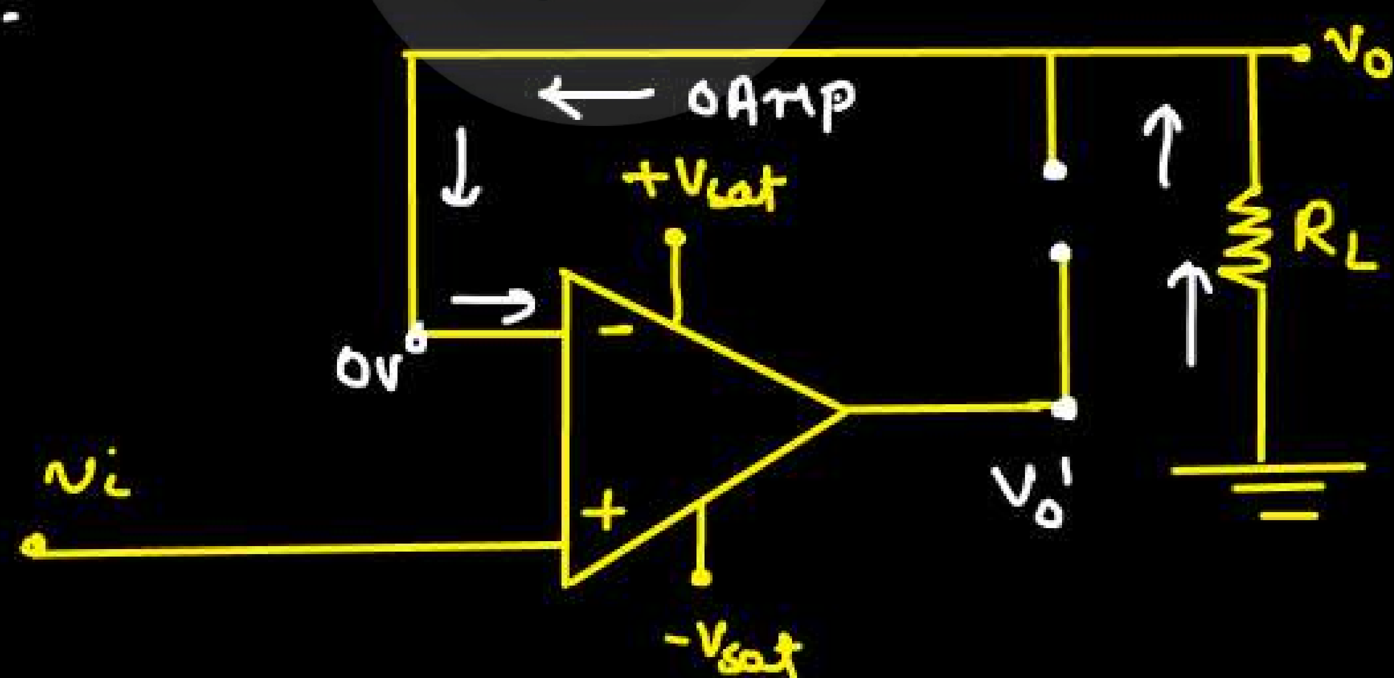


→ Apply O.C. Test :-

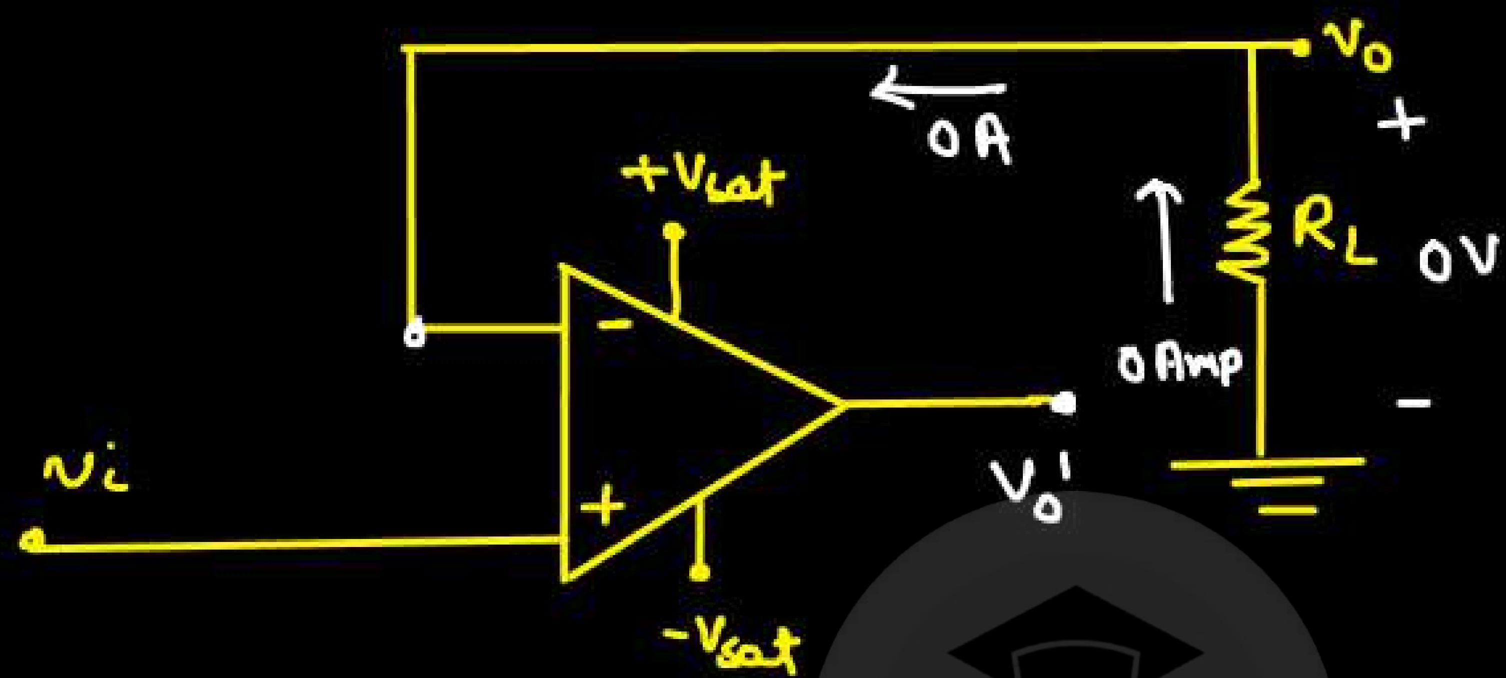
$v_i < 0V \Rightarrow V_0' = -V_{sat}$



$\Rightarrow$ diode is off



if diode is off

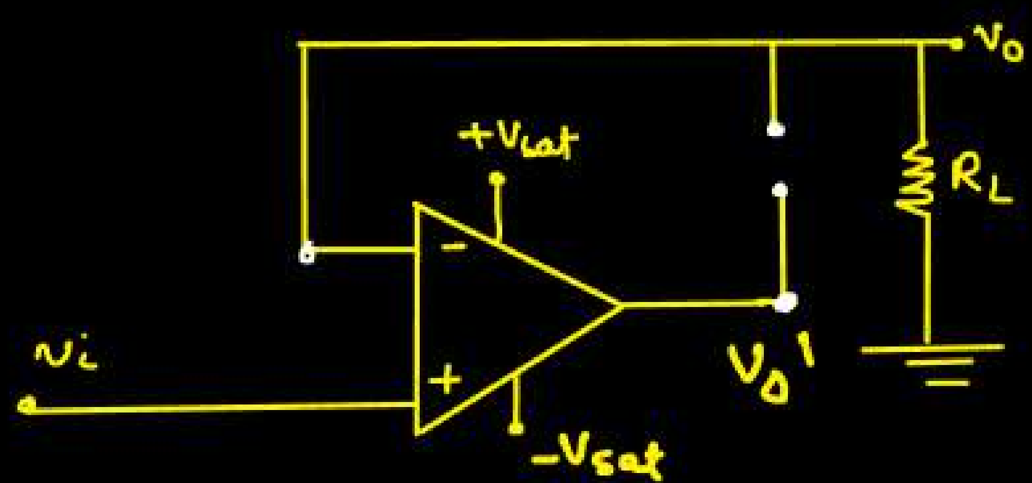


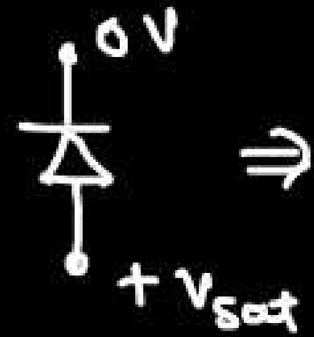
$\Rightarrow$ There is no f/b

$\boxed{V_o = 0V}$ $\{$ for $v_i < 0 \}$

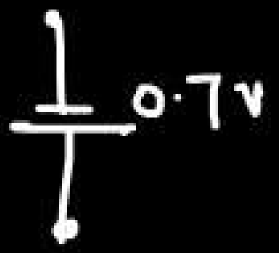
For $v_i > 0$:-

$v_o' = +V_{sat}$

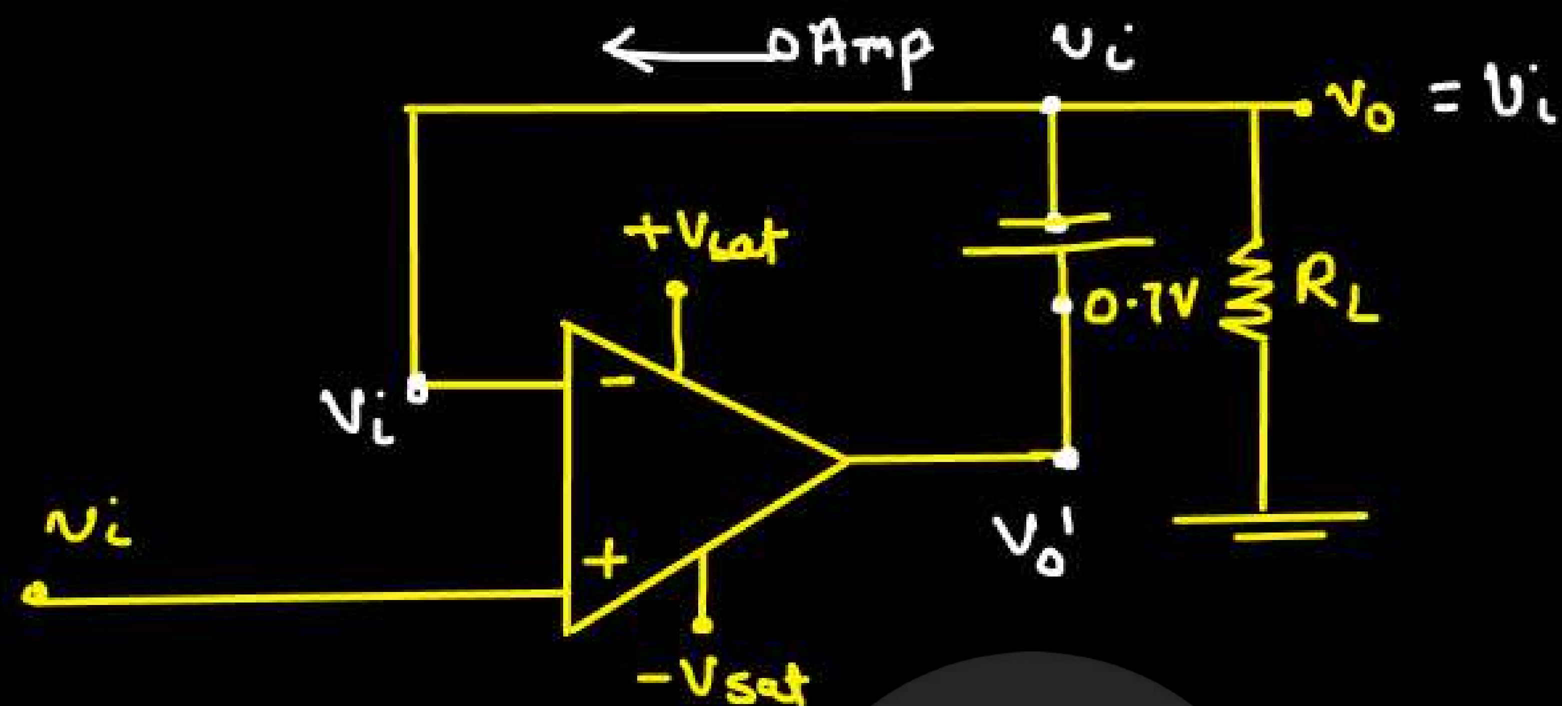




$\Rightarrow$ diode is ON $\Rightarrow$



$-V_{sat}$



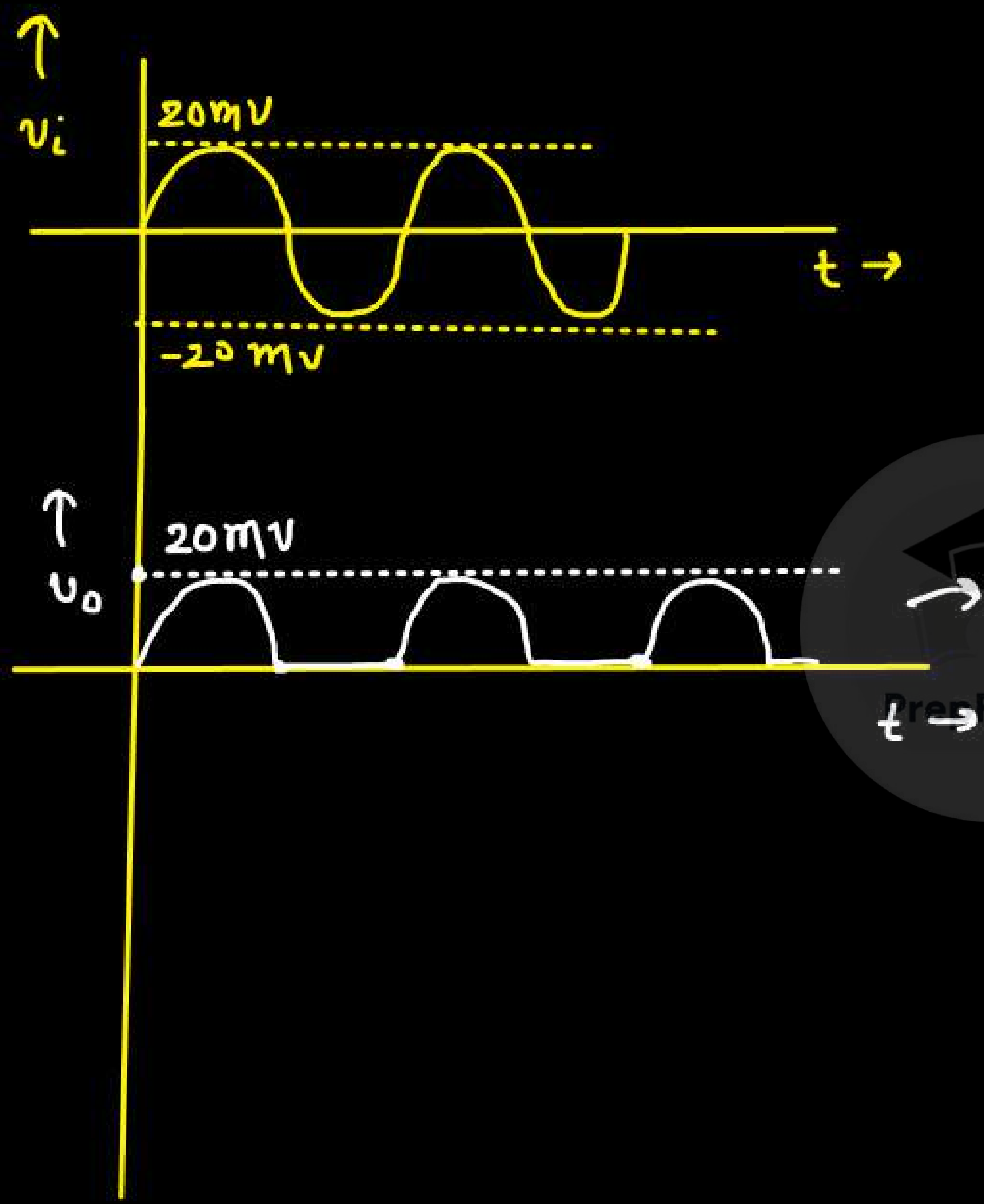
$\Rightarrow$ There is negative present $\Rightarrow$ virtual short is valid

$$\boxed{V_o = v_i}$$

For $v_i > 0 \Rightarrow v_o = v_i$

$v_i < 0 \Rightarrow v_o = 0$

−Vsat



→ Using precision diode

☆ OP-Amp is active element or Passive :-

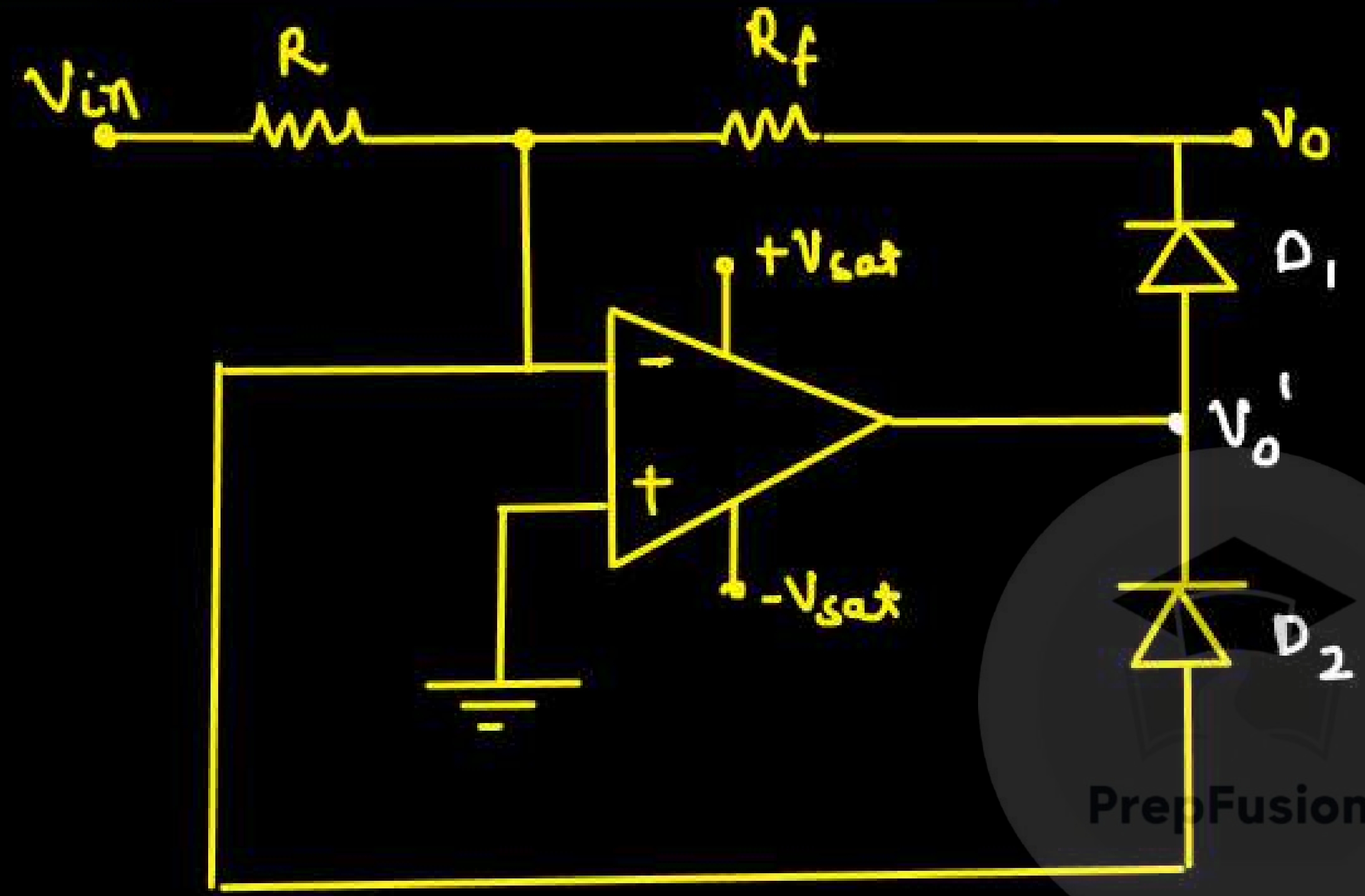
↳ Produces High gain using external supply.

↳ Can delivery the energy.

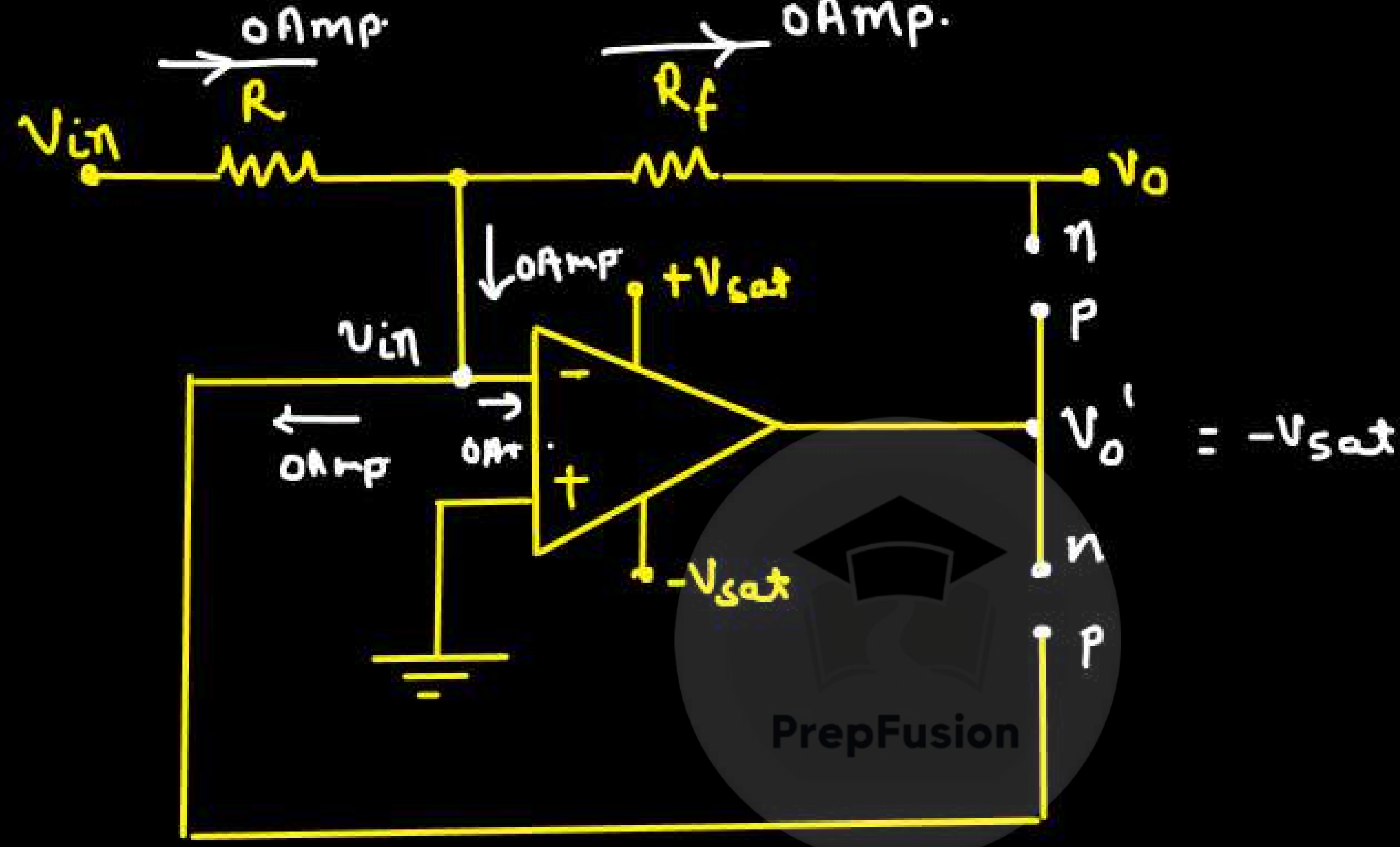
$$\Downarrow$$

Active element

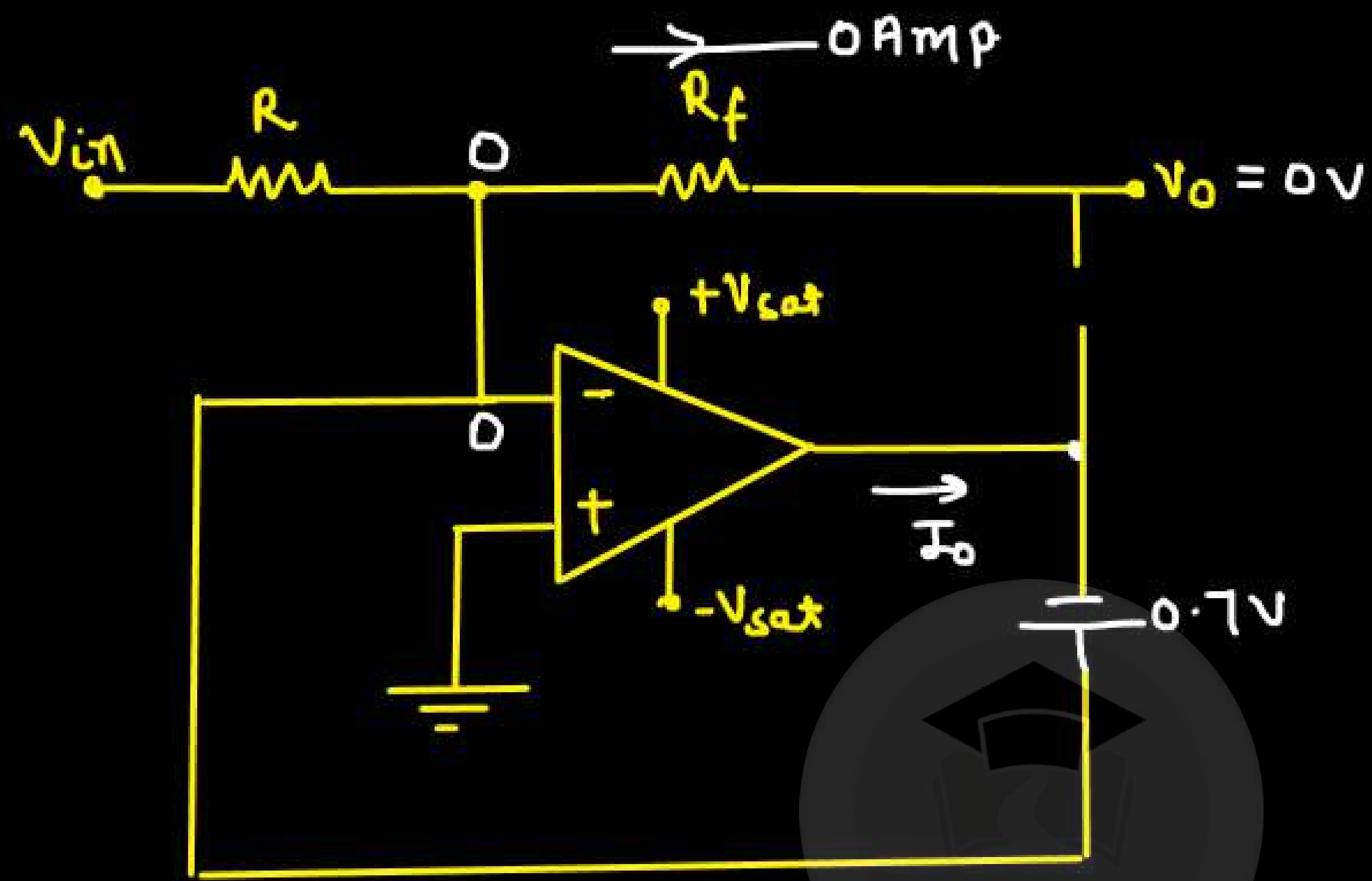
④ Active Half Wave Rectifier:-



Applying O.C. Test :-



① $v_{in} > 0 \Rightarrow V_o' = -V_{sat} \Rightarrow D_2$ Turns ON, D_1 is off

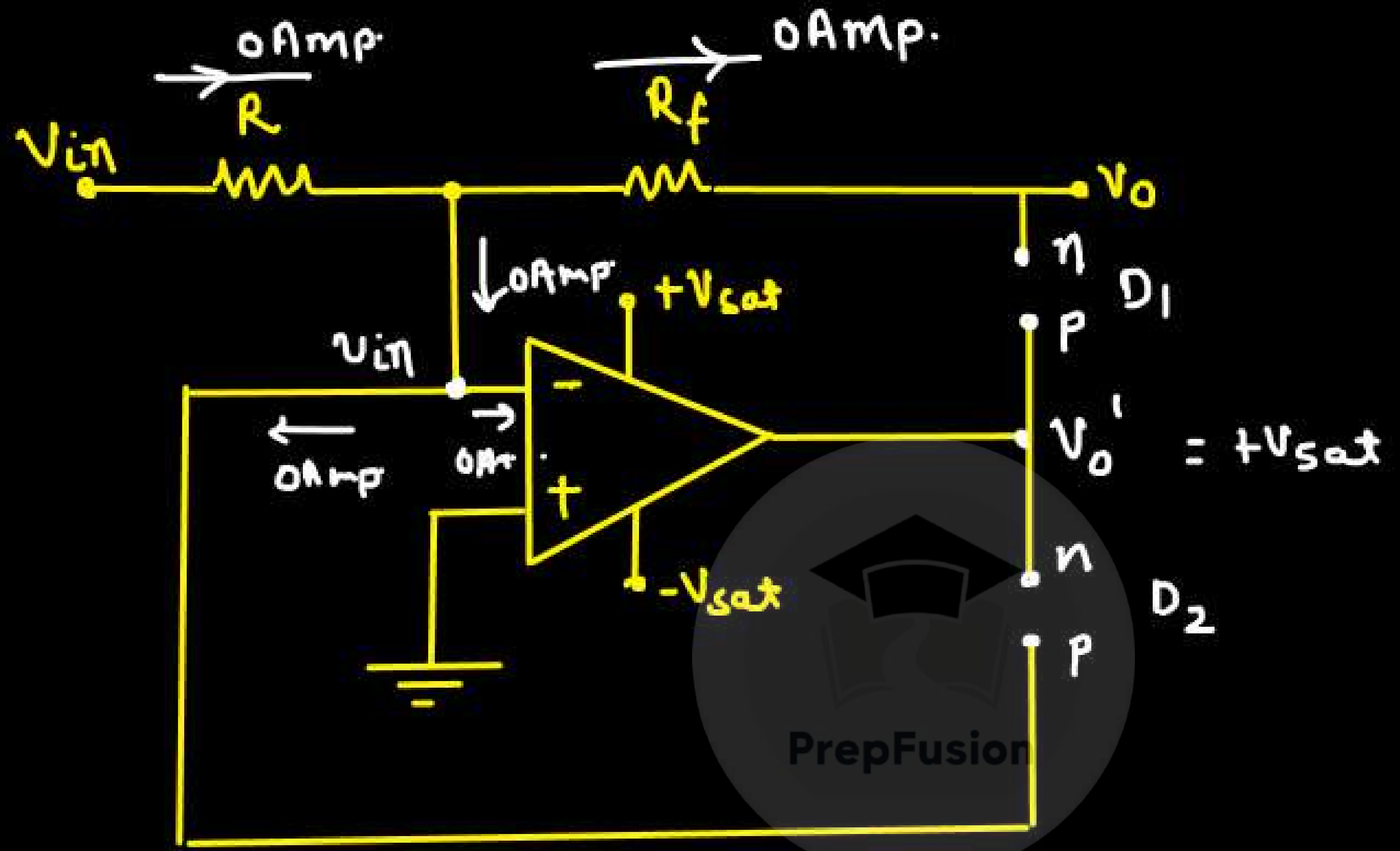


$$I_o = \frac{-v_{in}}{R}$$

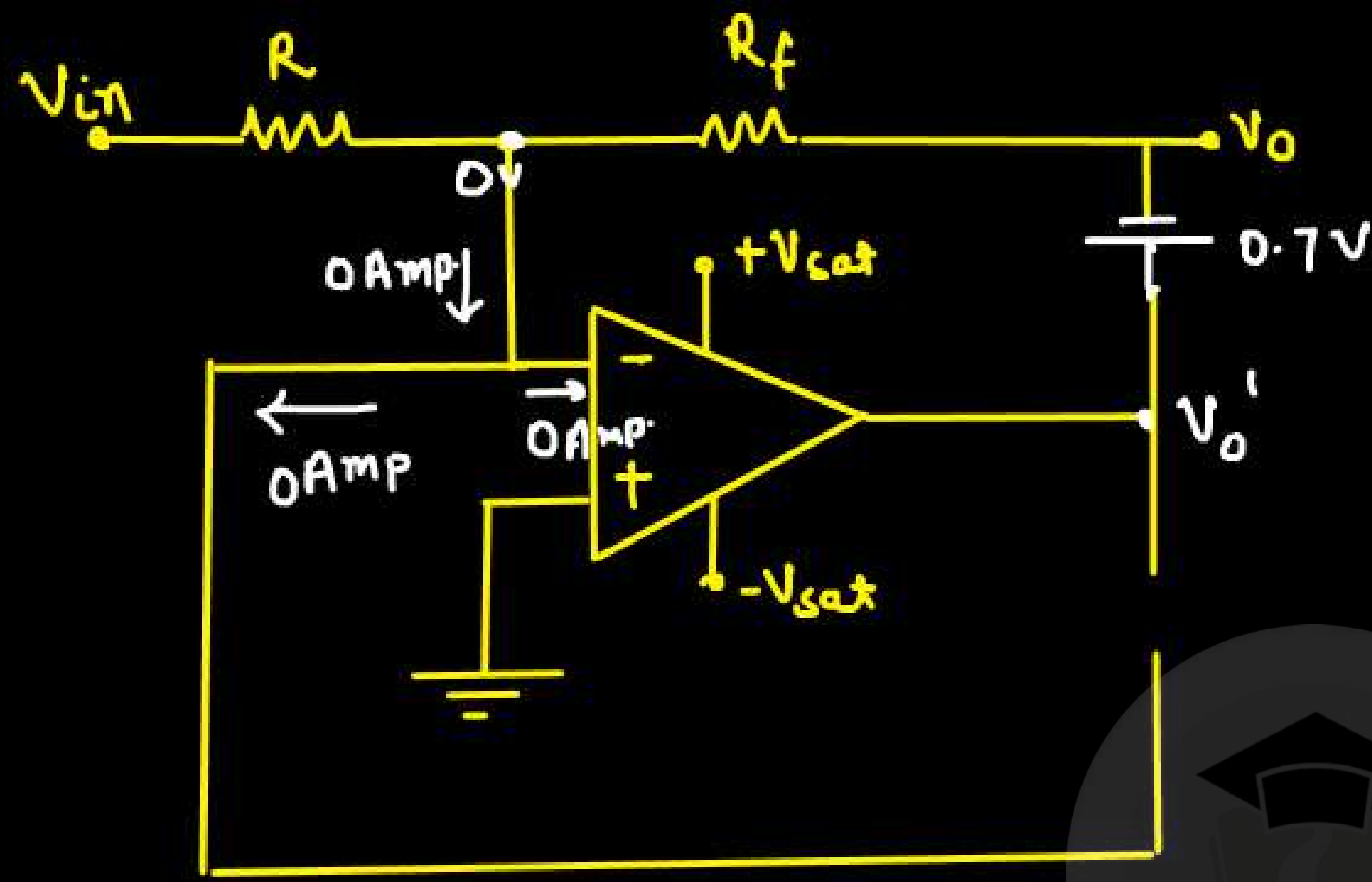
Negative f/b is present

For $v_i > 0 \Rightarrow \boxed{V_o = 0\,V}$

Applying o.c. Test:-



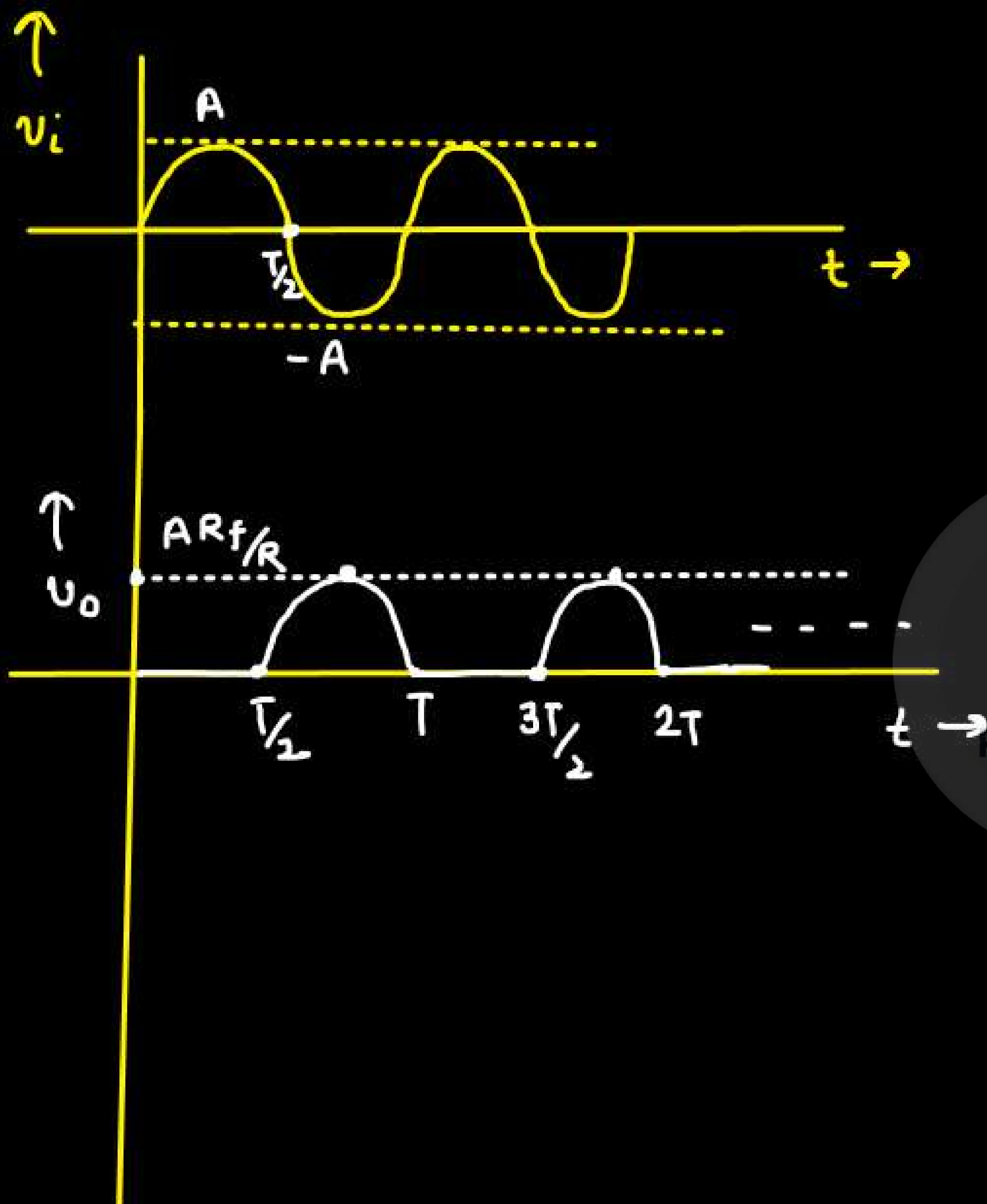
$v_{in} < 0 \Rightarrow V_0' = +V_{sat} \Rightarrow D_1$ turns ON, D_2 is off



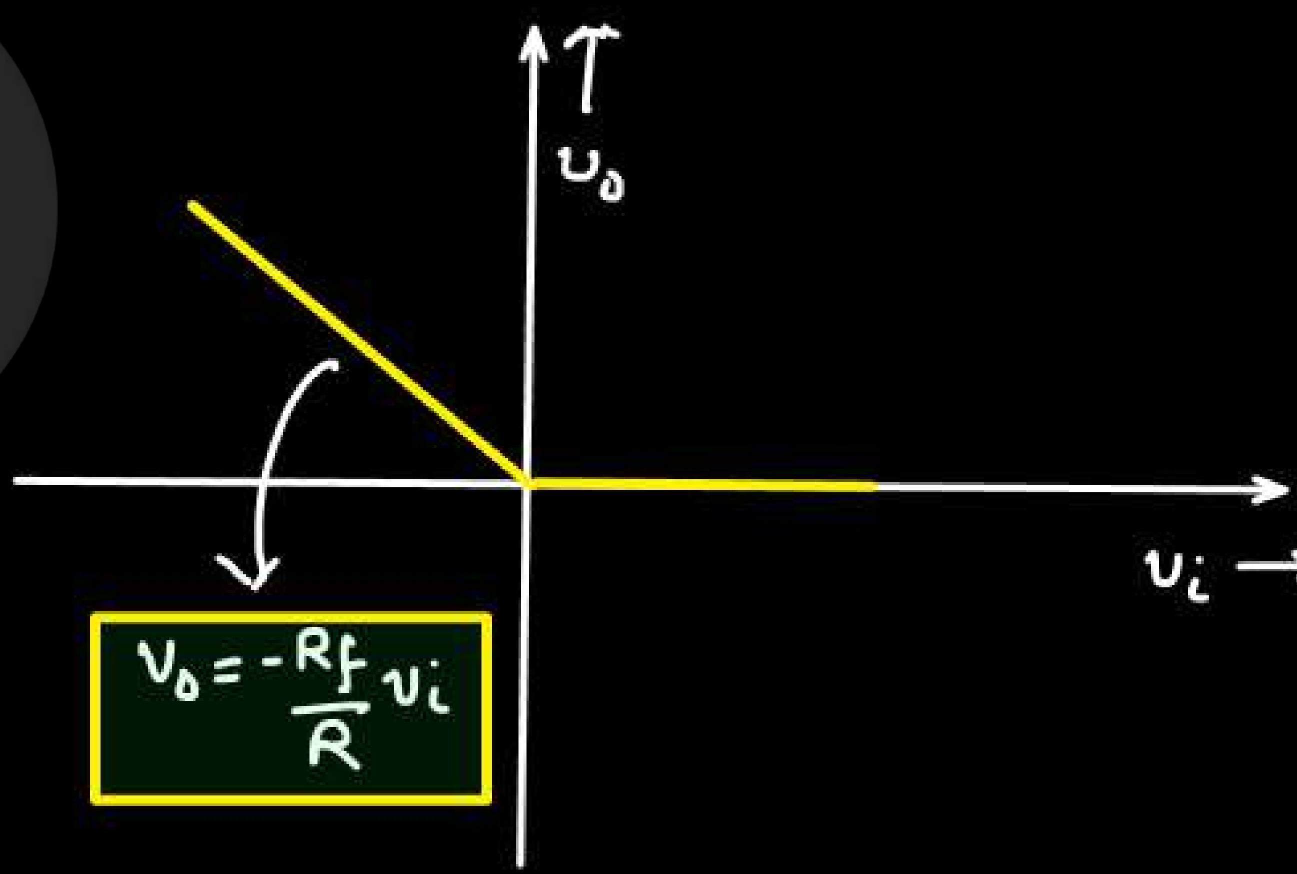
$$\frac{0-v_{in}}{R} + \left(\frac{0-v_o}{R_f}\right) = 0$$

$$\boxed{v_o = -\frac{R_f}{R} v_{in}} \quad \{ v_i < 0 \}$$

$$\boxed{\begin{array}{l} V_i > 0 \Rightarrow V_o = 0V \\ v_i < 0 \Rightarrow v_o = -\dfrac{R_f}{R} v_{in} \end{array}}$$

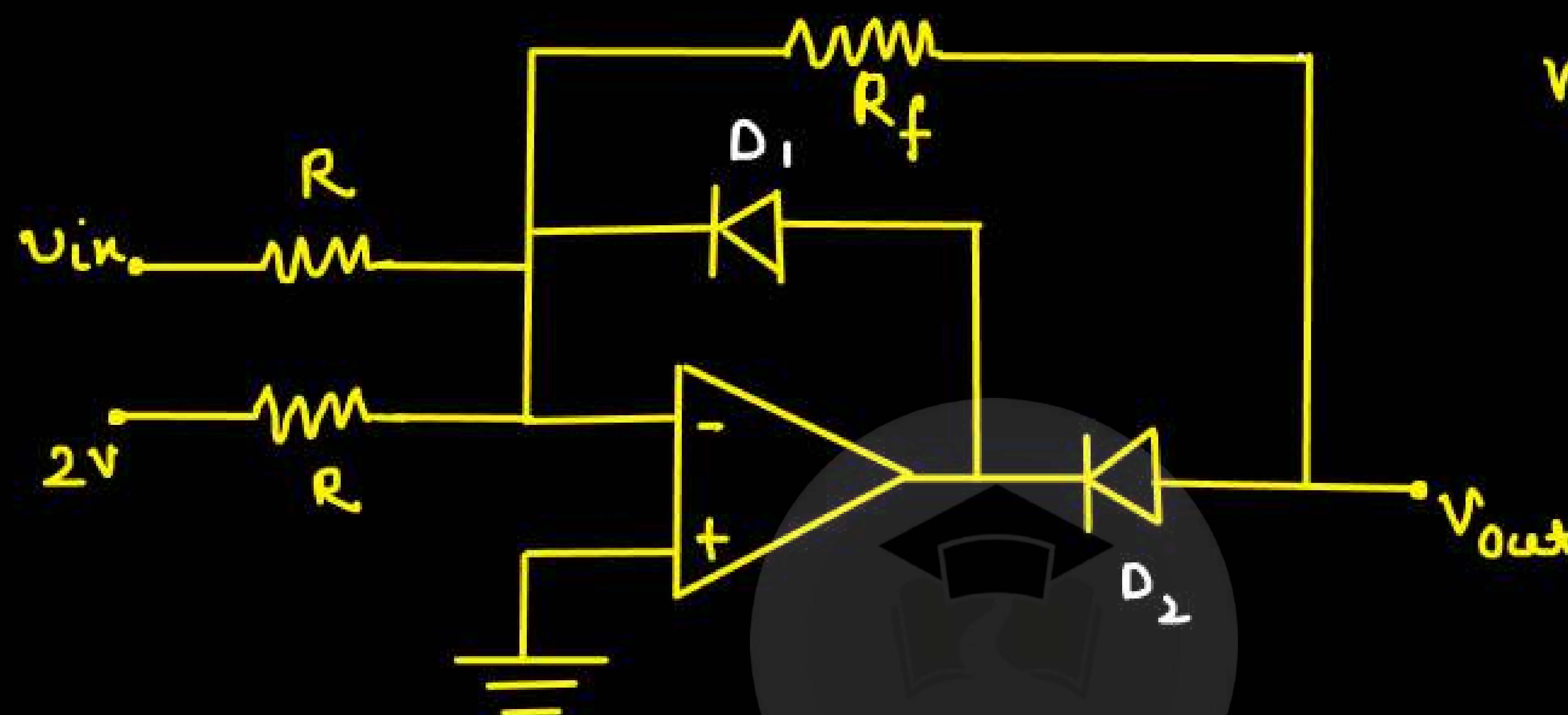


Transfer characteristics:-

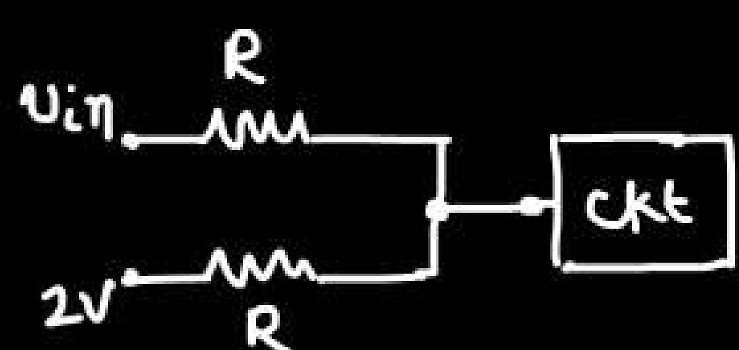


$$\boxed{V_o = -\frac{R_f}{R} v_i}$$

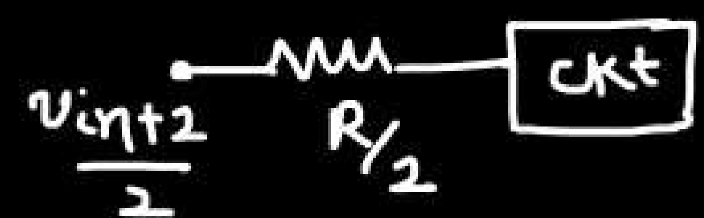
Q. Draw Transfer characteristics?

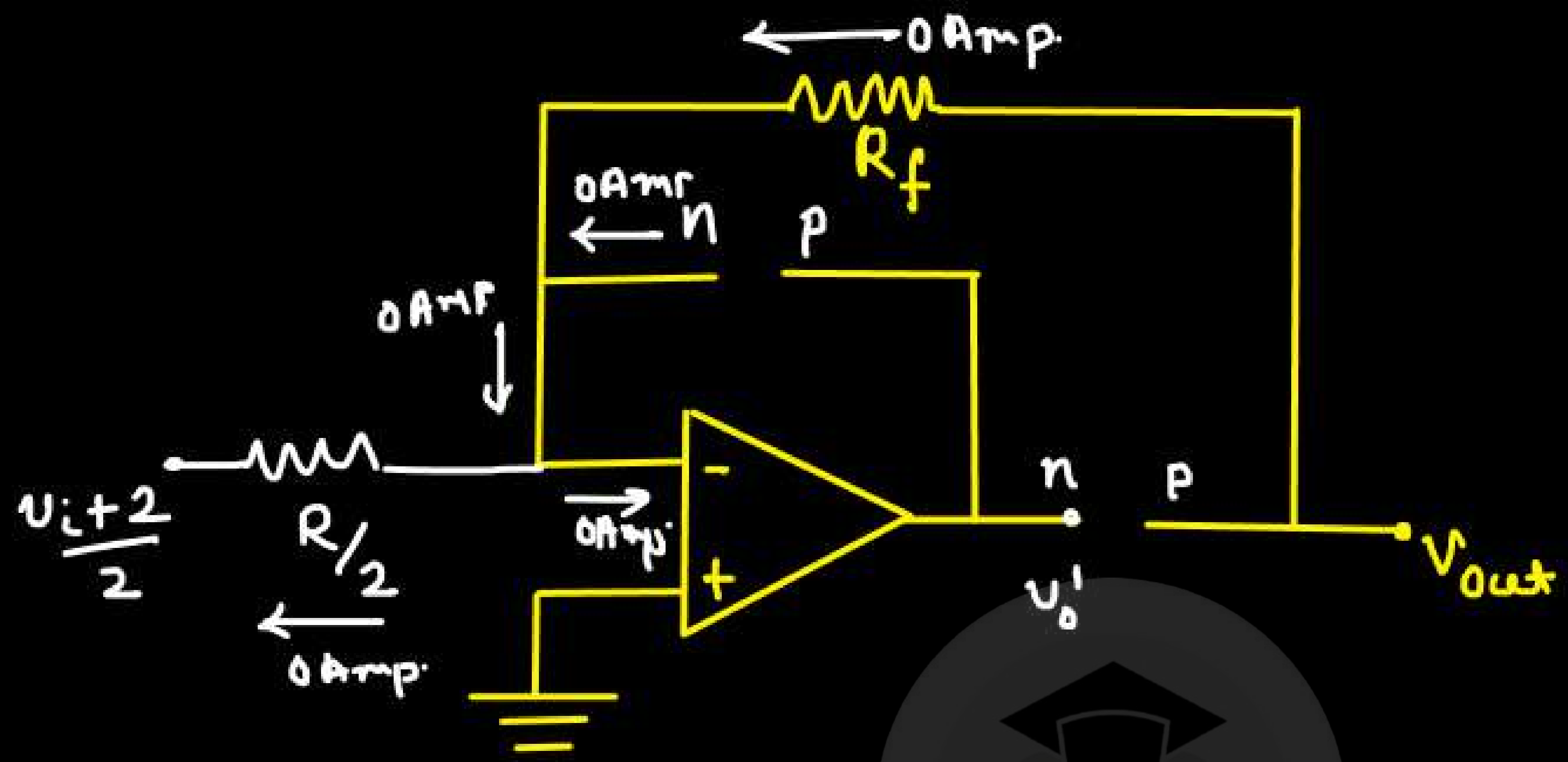


$V_\gamma = 0.7V$



$\equiv$

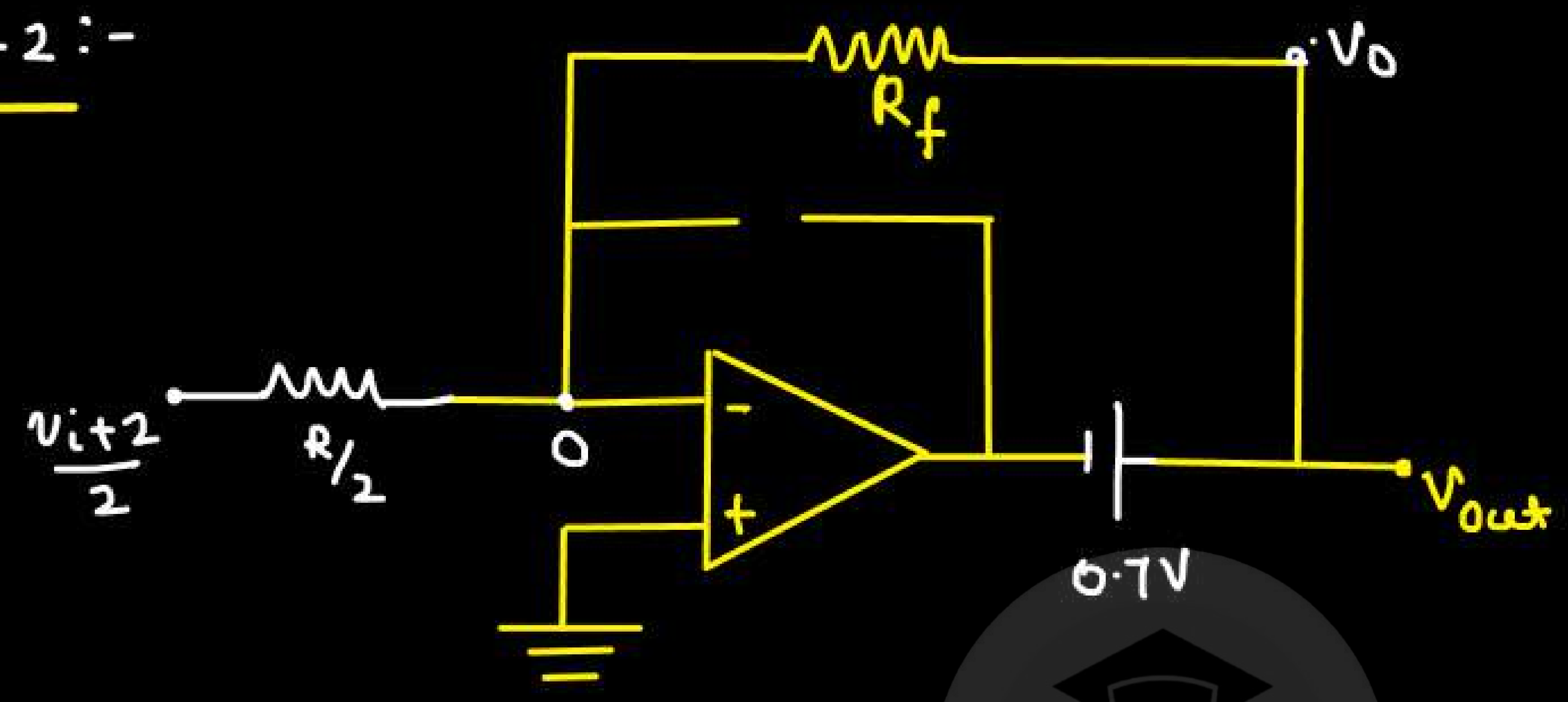




$\frac{v_i+2}{2} > 0 \Rightarrow V_o' = -V_{sat} \Rightarrow D_2$ turns ON , D_1 is OFF

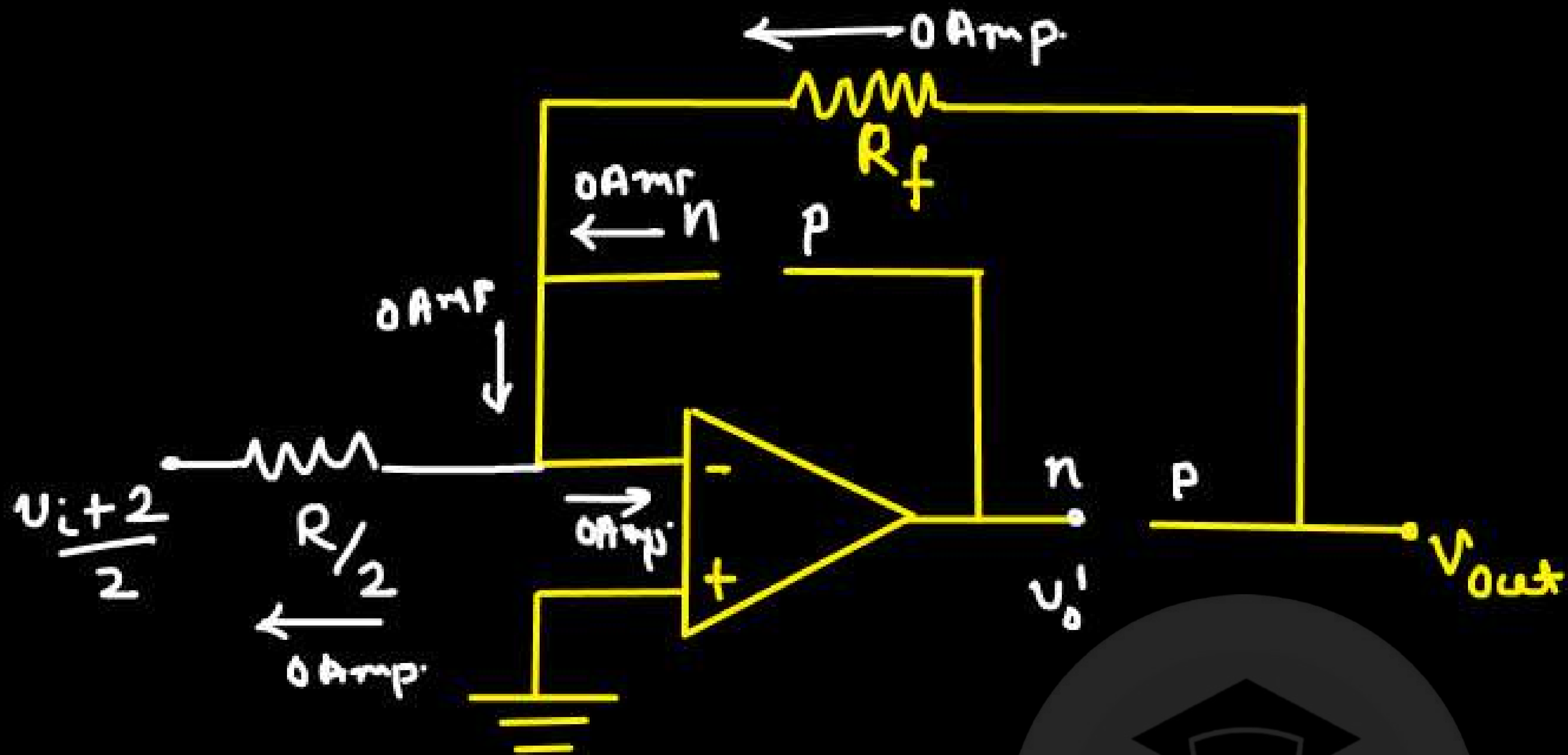
$$\boxed{v_i > -2}$$

$\underline{v_i > -2}$:-



$$v_0 = -\frac{2R_f}{R}\left[\frac{v_i+2}{2}\right]$$

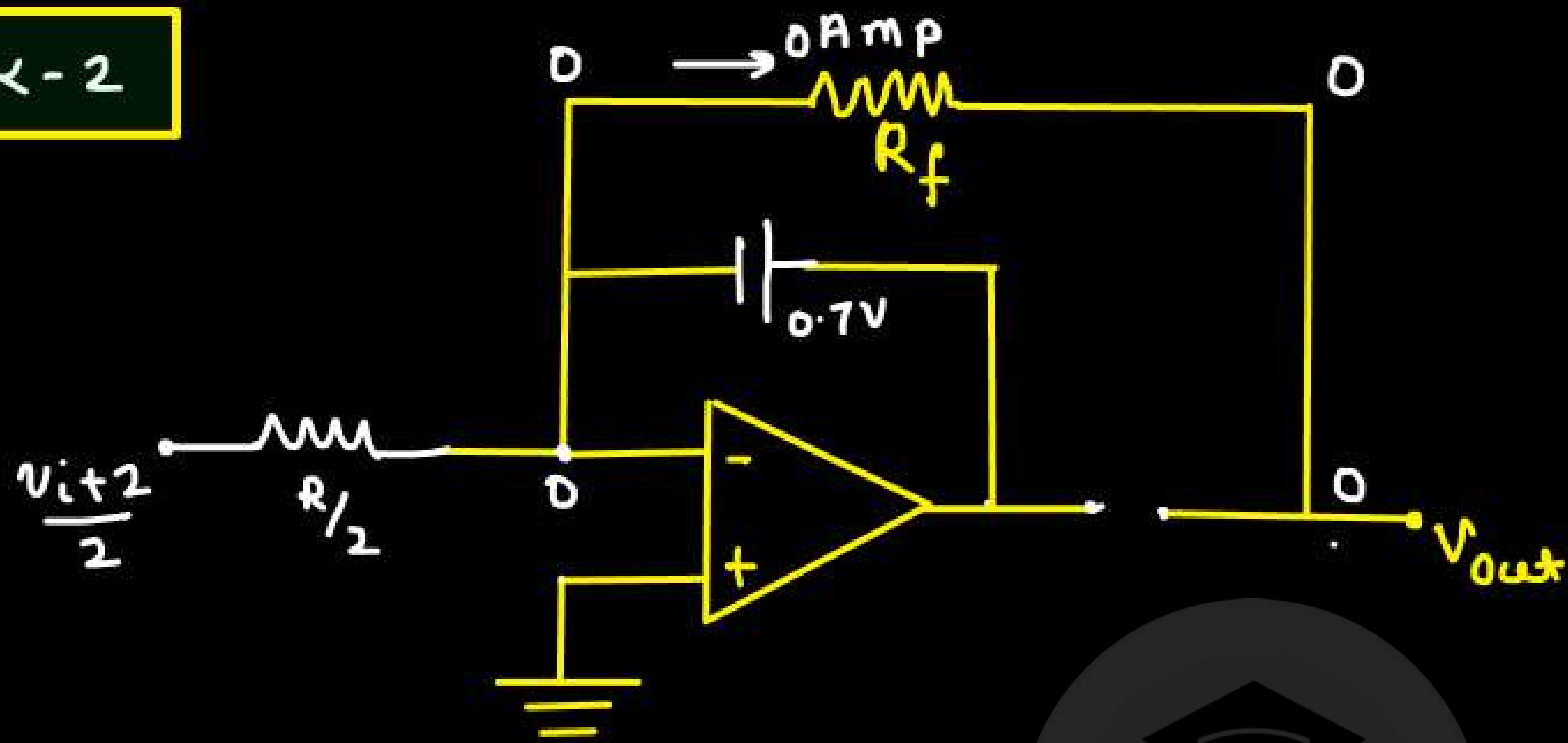
$$\boxed{v_0 = -\frac{R_f}{R}[v_i+2]}$$ $\{v_i > -2\}$



$\frac{v_i+2}{2} < 0 \Rightarrow V_o' = +v_{sat} \Rightarrow D_1$ turns on , D_2 is off

$\boxed{v_i < -2}$

$\boxed{v_i < -2}$

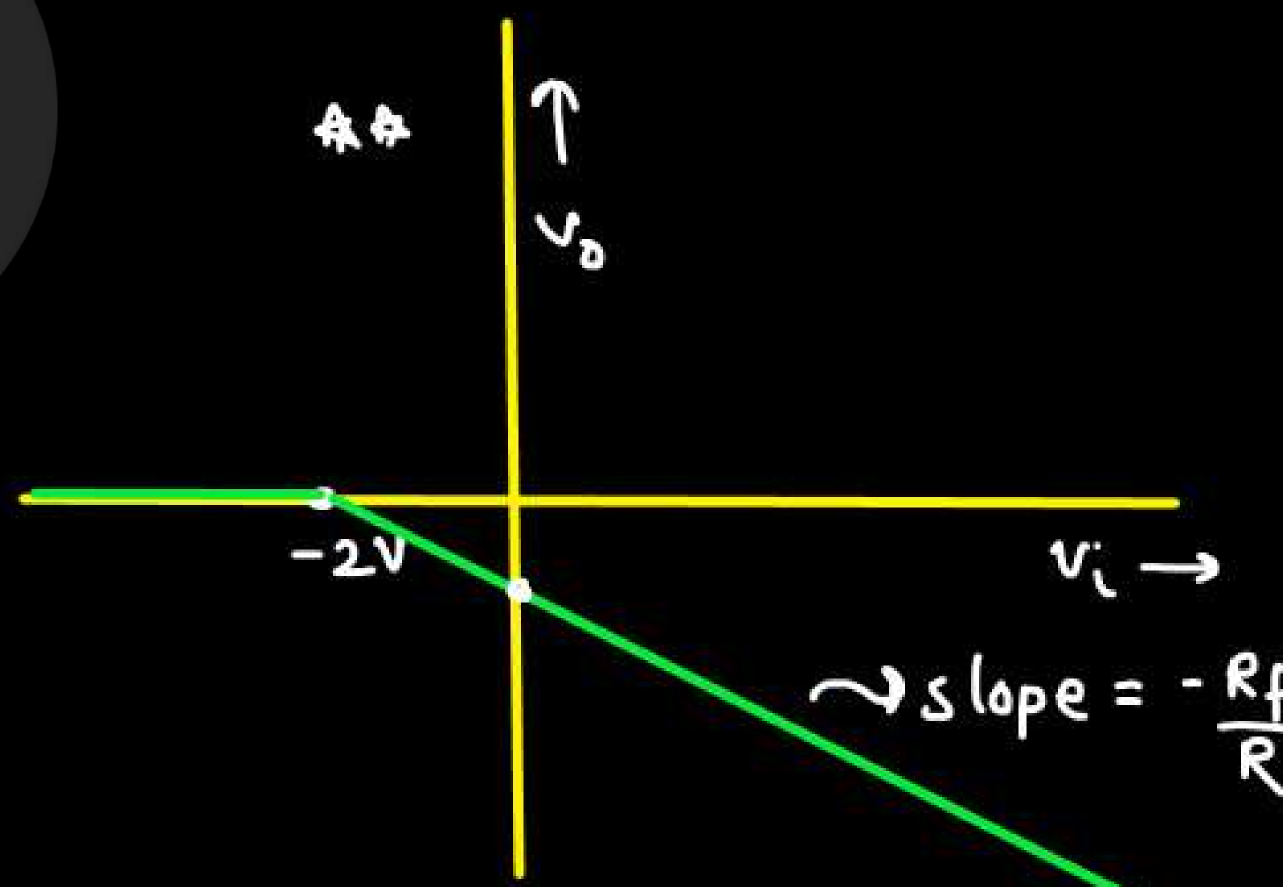


$\boxed{V_0 = 0V}$

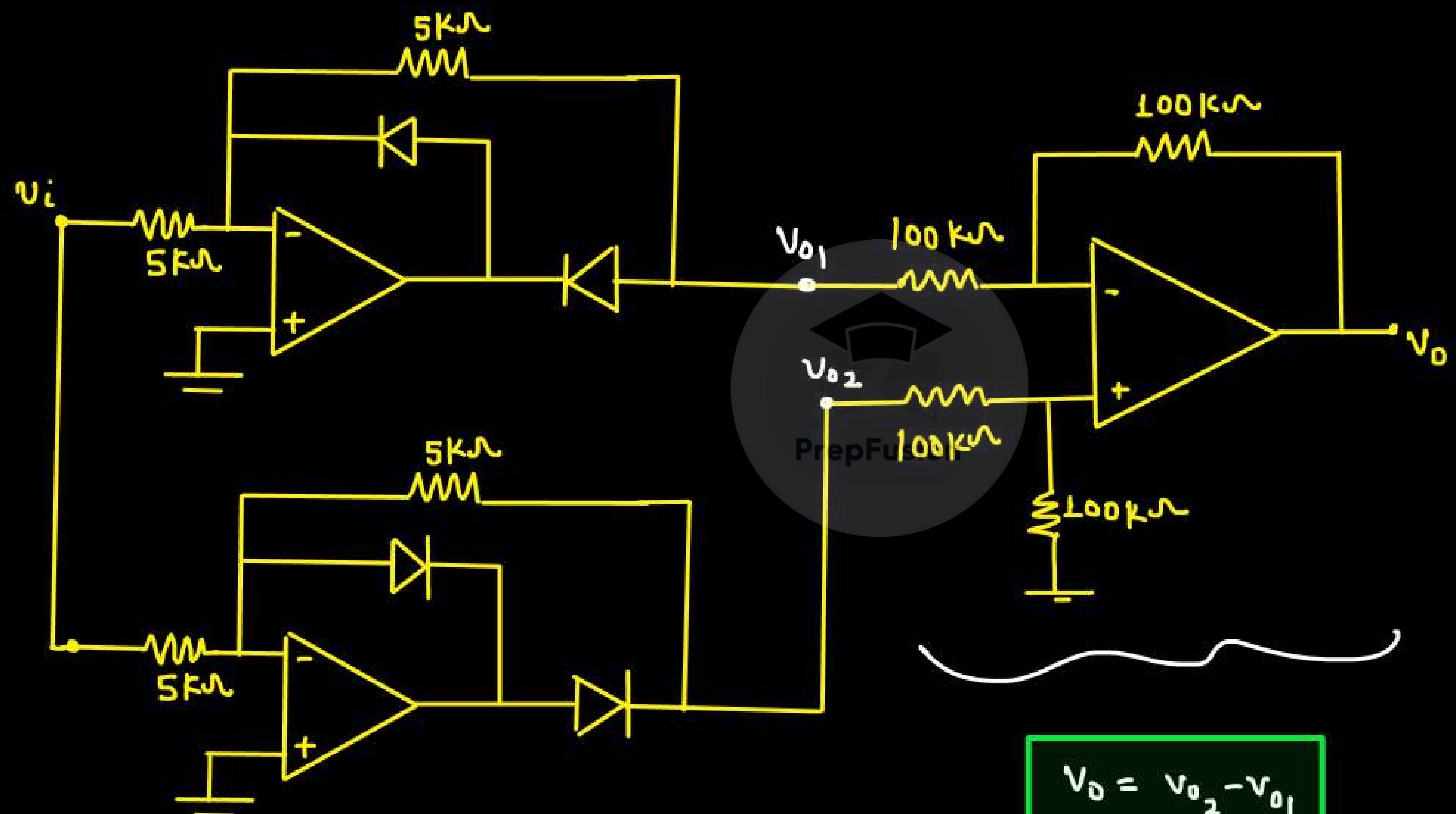
**

$$\boxed{\begin{array}{l} v_i > -2 \Rightarrow V_0 = -\frac{R_f}{R}(v_i+2) \\ v_i < -2 \Rightarrow V_0 = 0V \end{array}}$$

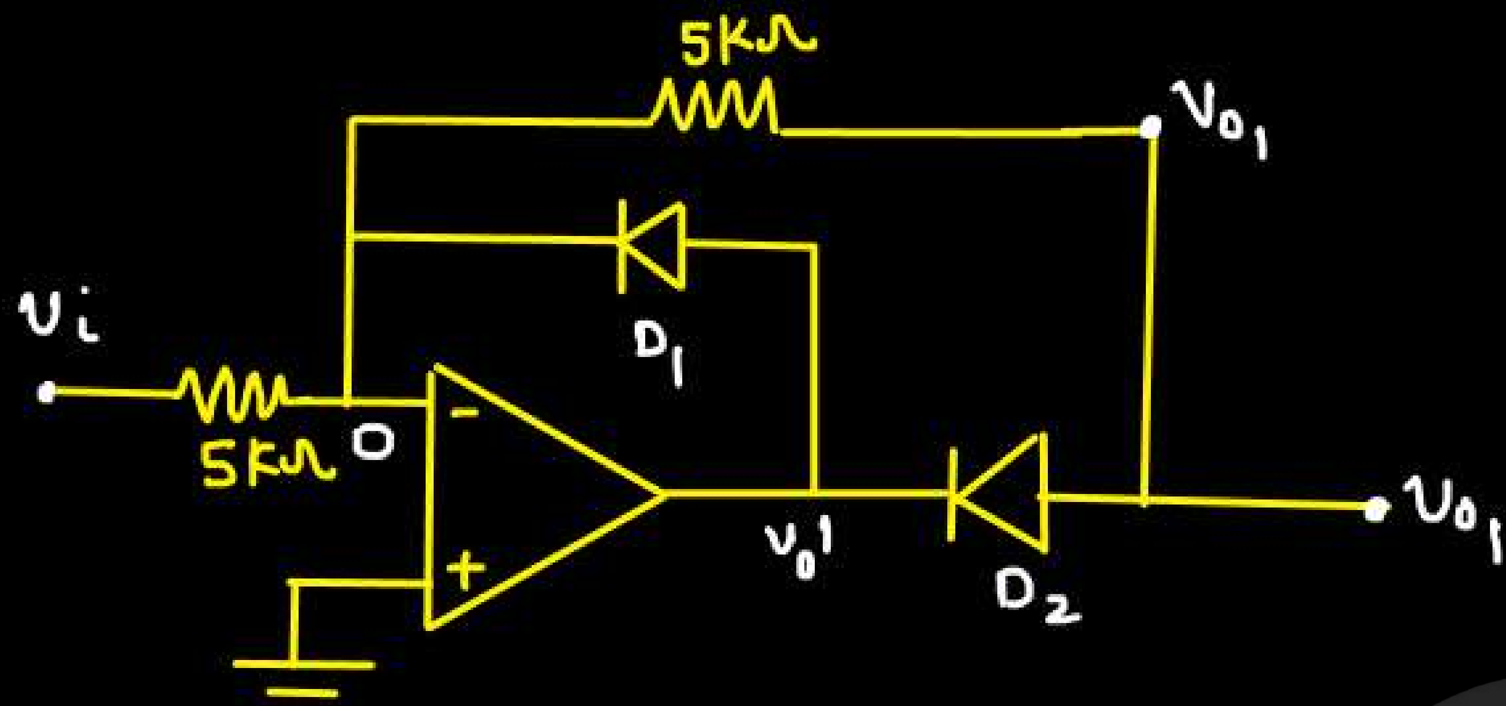
**



⑤ Active Full Wave Rectifier :-



$$\boxed{V_0 = V_{o_2} - V_{o_1}}$$



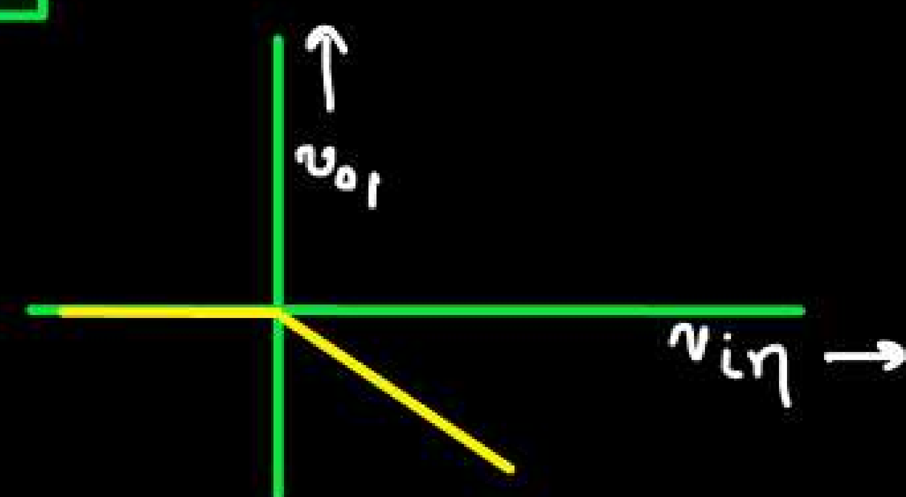
$v_i > 0 \Rightarrow v_o' = -V_{sat} \Rightarrow D_2$ ON , D_1 OFF

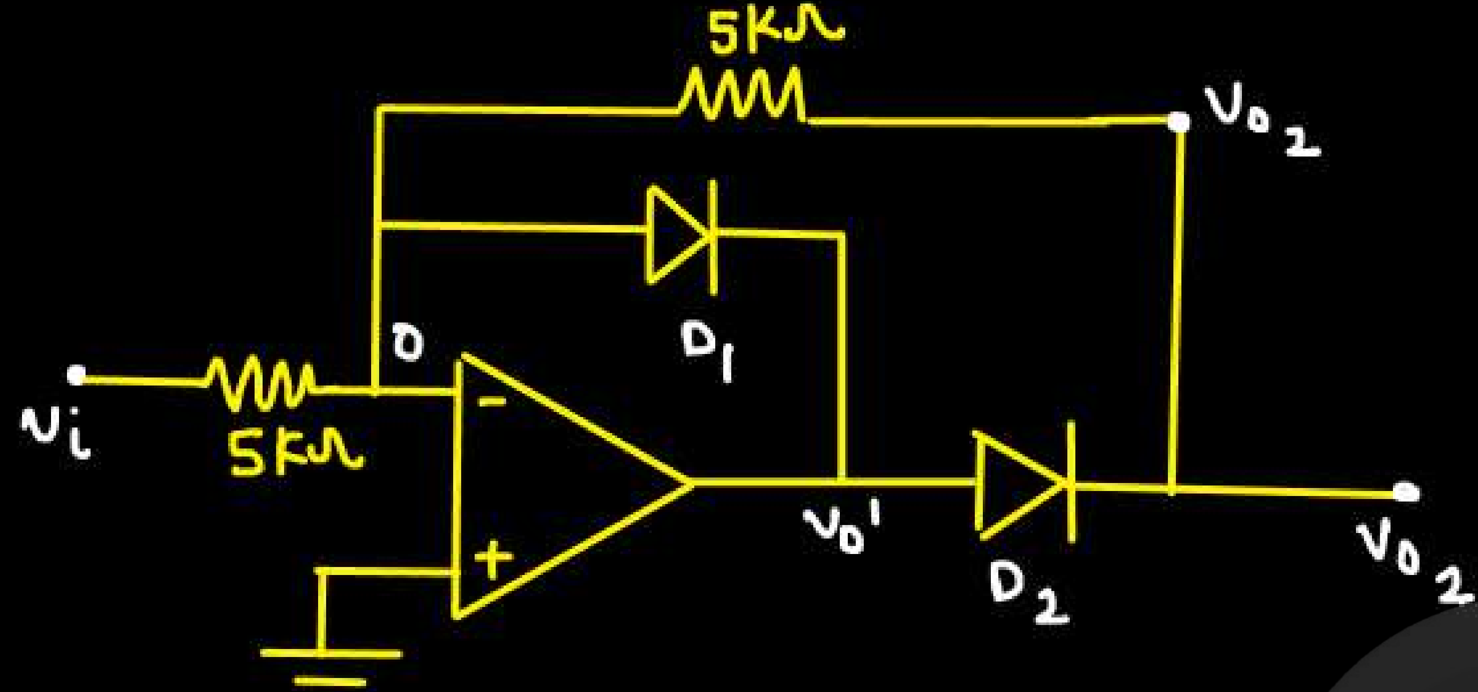
$$v_{o1} = -\frac{5k\Omega}{5k\Omega} v_i$$

$$\boxed{v_i > 0 \Rightarrow v_{o1} = -v_i}$$

$v_i < 0 \Rightarrow v_o' = +V_{sat} \Rightarrow D_1$ ON
D_2 OFF

$$\boxed{v_i < 0 \Rightarrow v_{o1} = 0\,V}$$





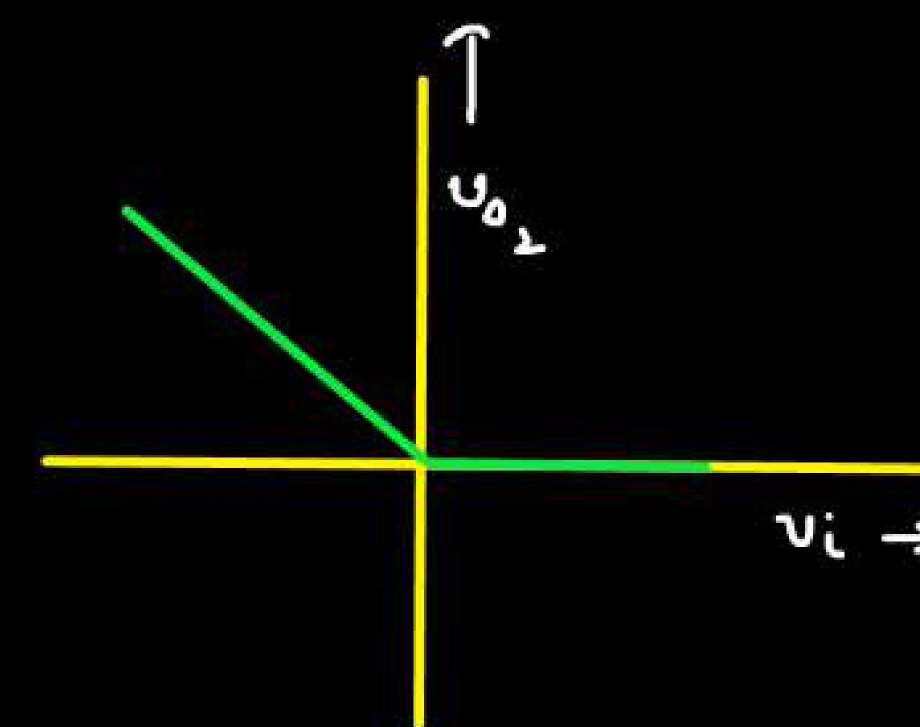
$v_i > 0 \Rightarrow v_o' = -v_{sat} \Rightarrow D_1$ turns ON, D_2 is off

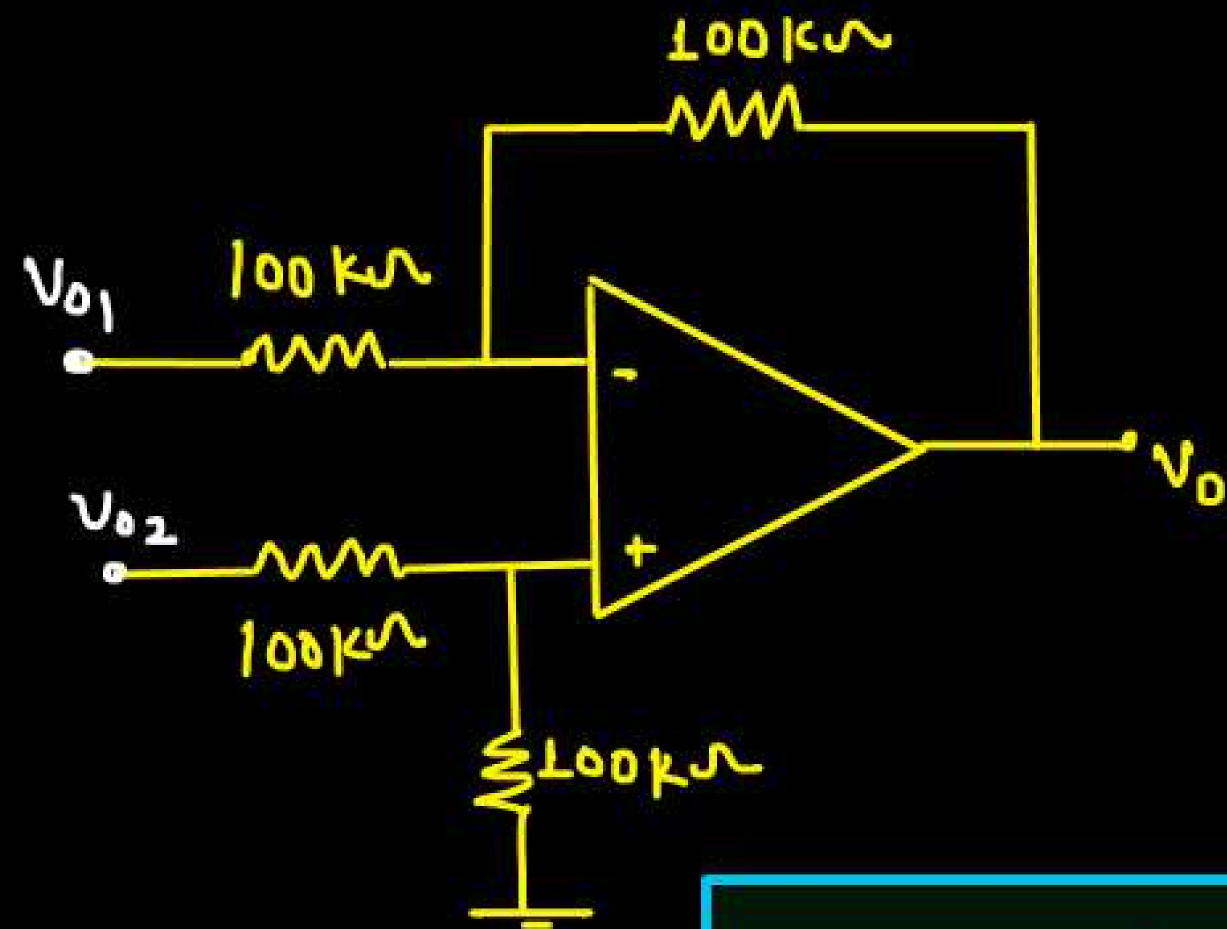
$$\boxed{v_i > 0 \Rightarrow v_{o_2} = 0V}$$

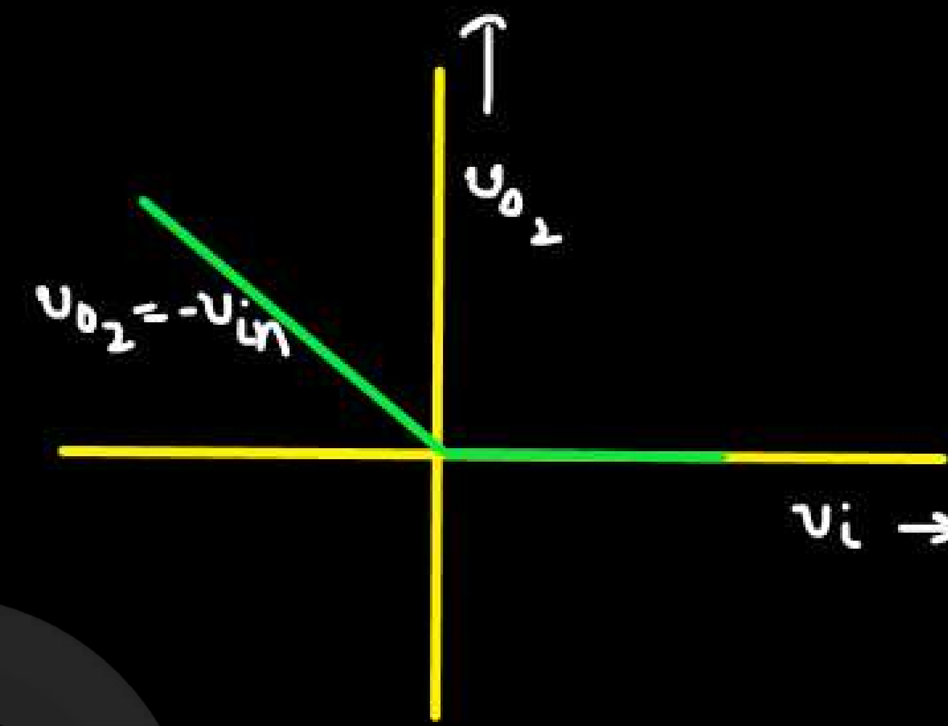
$v_i < 0 \Rightarrow v_o' = +v_{sat} \Rightarrow D_2$ turns ON, D_1 is off

$$v_{o_2} = -\frac{5k\Omega}{5k\Omega} \times v_i$$

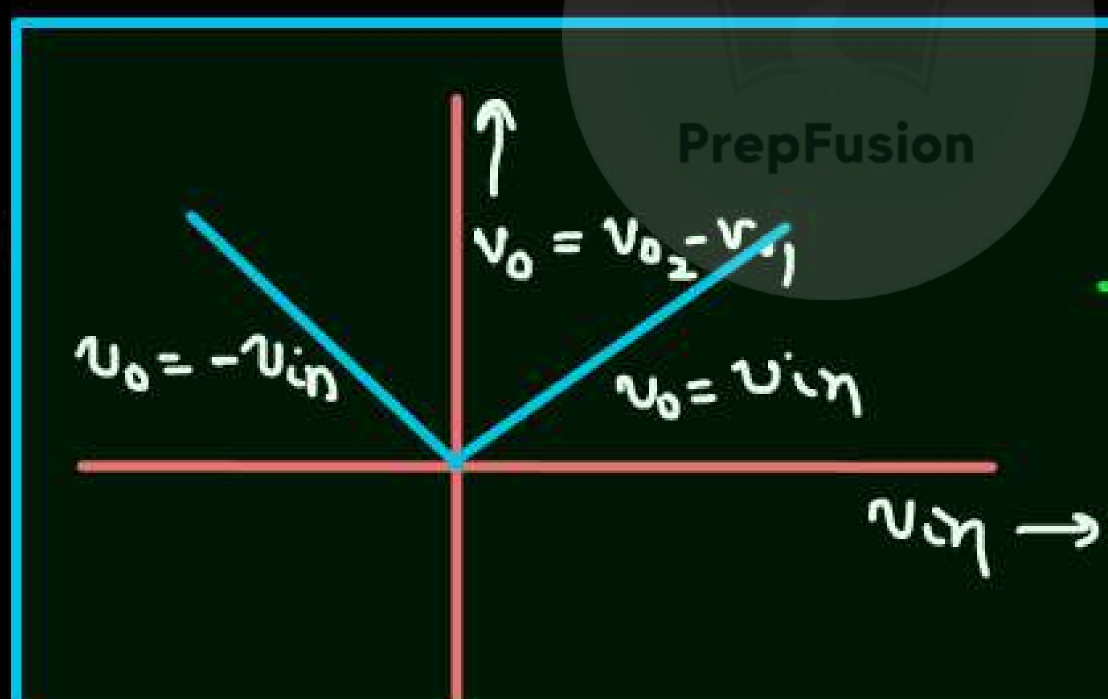
$$\boxed{v_i < 0 \Rightarrow v_{o_2} = -v_i}$$

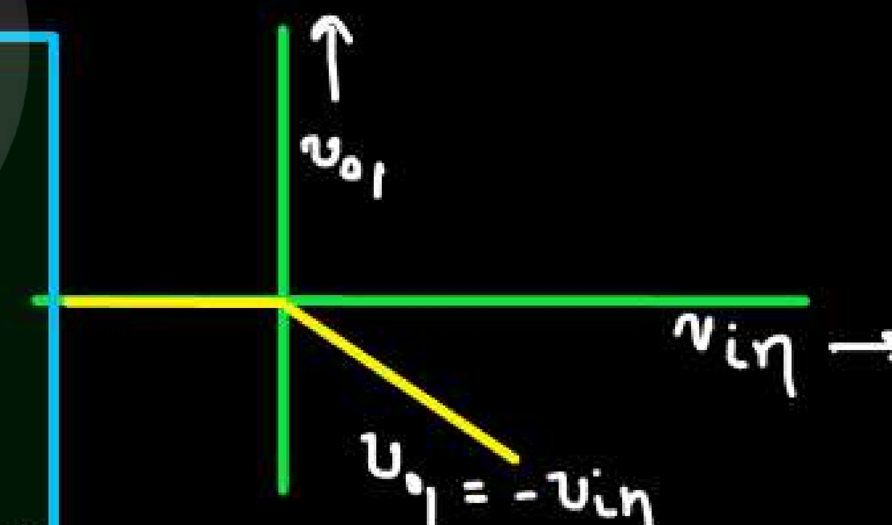






$$V_o = V_{o2} - V_{o1}$$



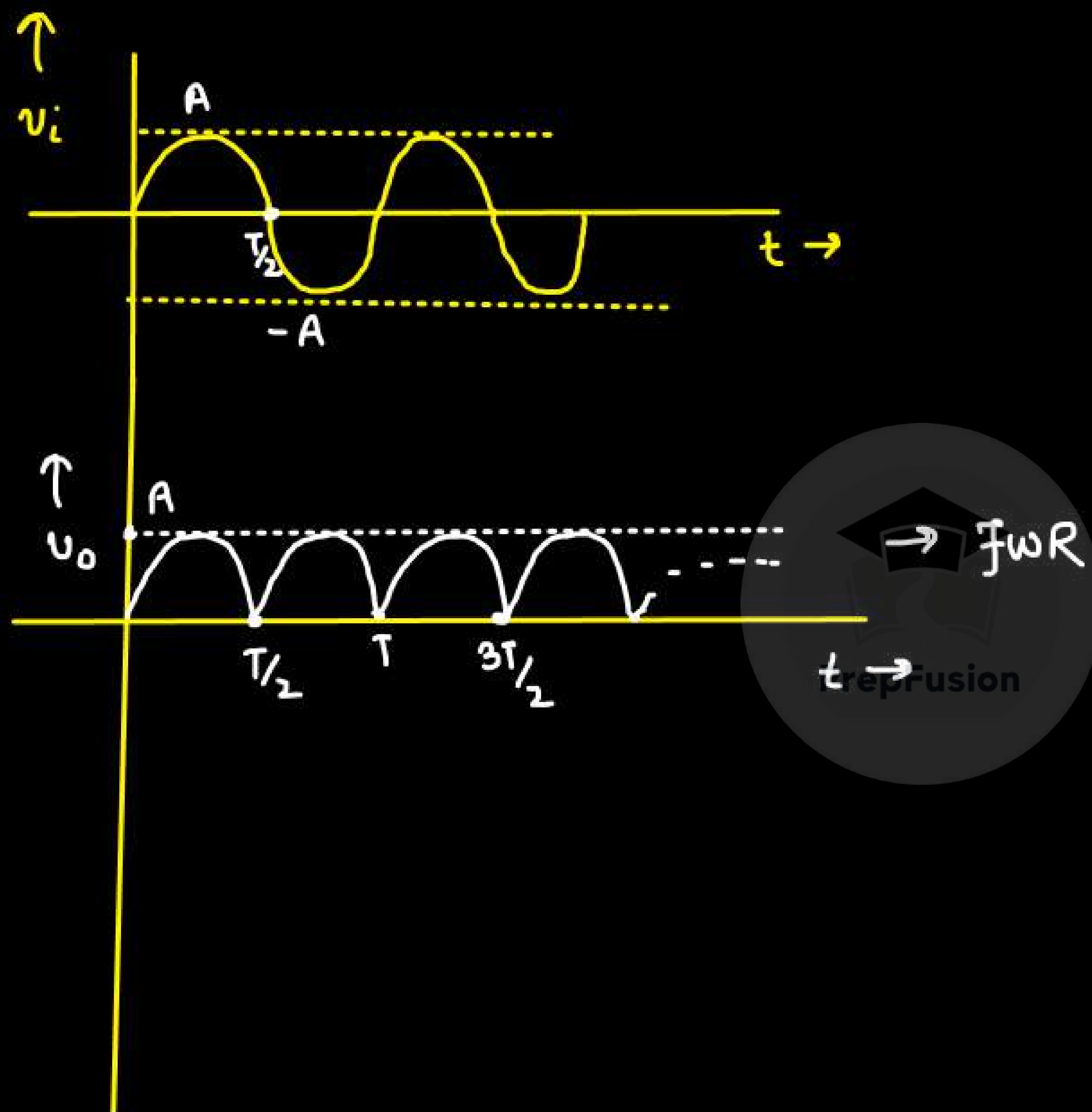


$\underline{v_{in} > 0}$

$$v_o = 0 - (-v_{in})$$
$$= v_{in}$$

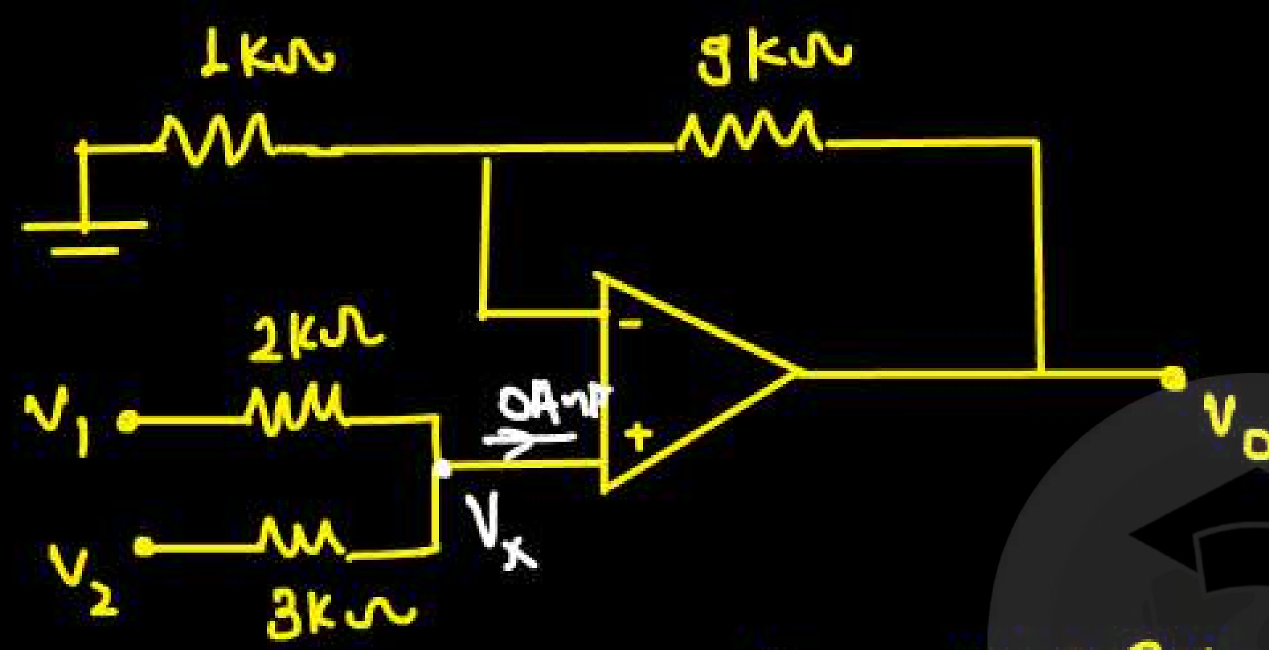
$\underline{v_{in} < 0}$:-

$$v_o = -v_{in} - 0 = -v_{in}$$


v_i
A
T/2
t →
-A
v_o
A
T/2
T
3T/2
t →
→ FWR

Assignment - 13

Q.



$$V_0 = \alpha V_1 + \beta V_2$$

Value of $\alpha + \beta$ is ___ .

$$\Rightarrow V_0 = \left[1 + \frac{9k}{1k}\right] V_x$$

$$V_0 = 10 V_x \quad \text{— (1)}$$

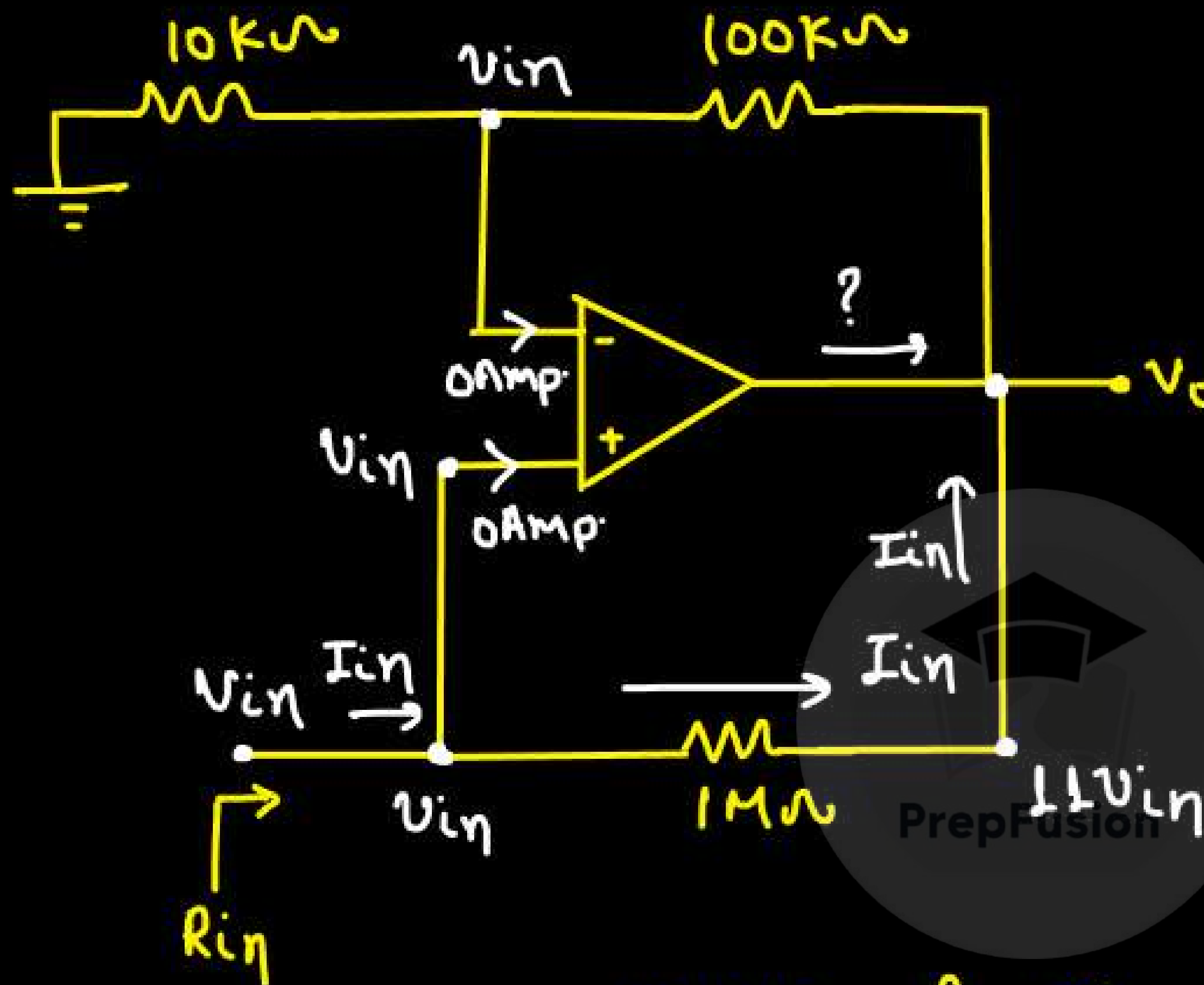
$$V_x = \frac{3V_1 + 2V_2}{5} \quad \text{— (2)}$$

$$V_0 = 10\left[\frac{3V_1 + 2V_2}{5}\right] = 6V_1 + 4V_2$$

$\alpha = 6$, $\beta = 4$

$$\boxed{\alpha + \beta = 10}$$

Q.



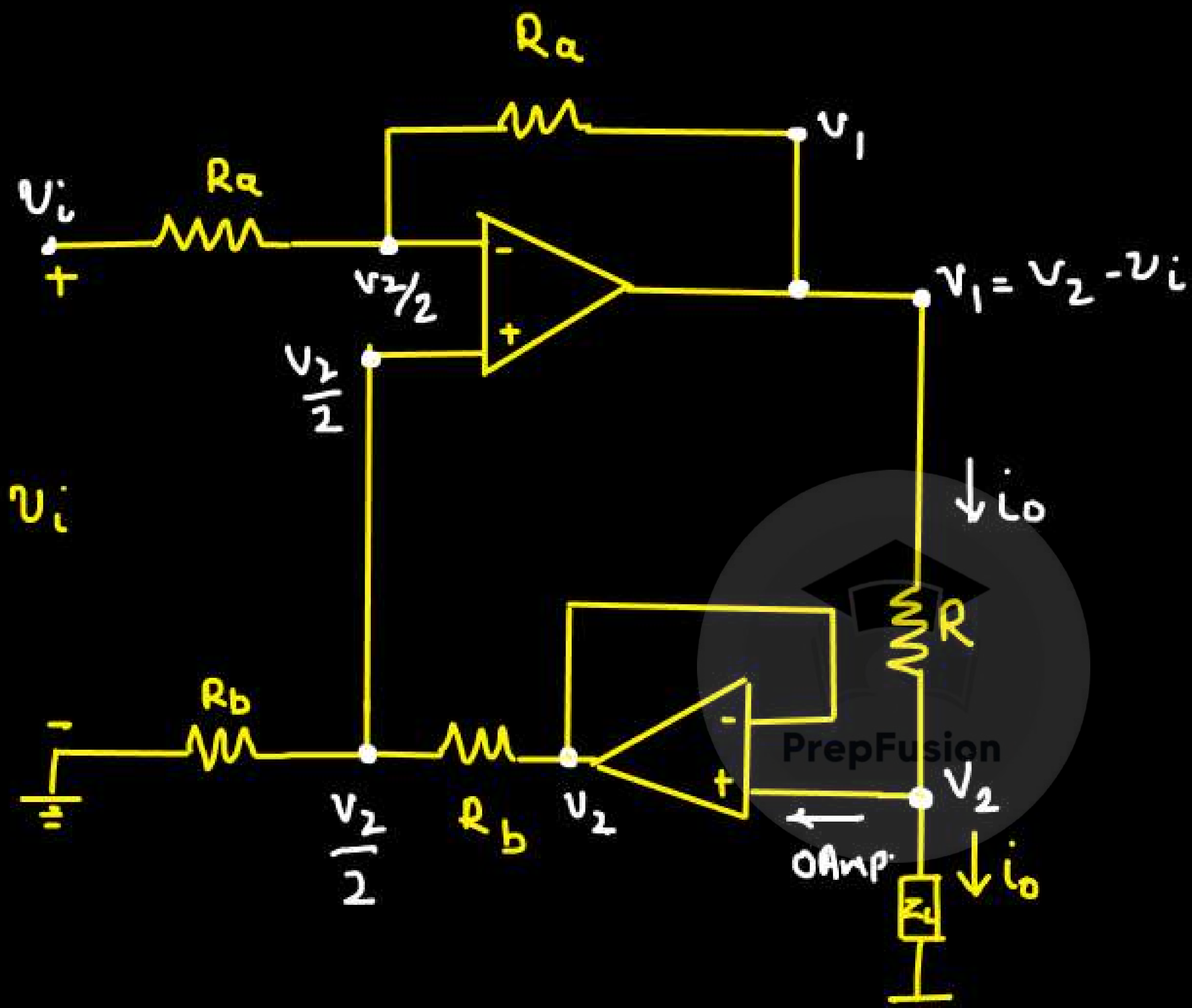
$$V_o = \left[1 + \frac{100}{10}\right] v_{in} = 11 v_{in}$$

$$R_{in} = \frac{v_{in}}{I_{in}}$$

Value of Rin is $\underline{-100}$ kohm.

$$\frac{v_{in} - 11 v_{in}}{1\,M\Omega} = I_{in} \Rightarrow \boxed{R_{in} = \frac{v_{in}}{I_{in}} = -100\,k\Omega}$$

Q.



Find the expression of i_o

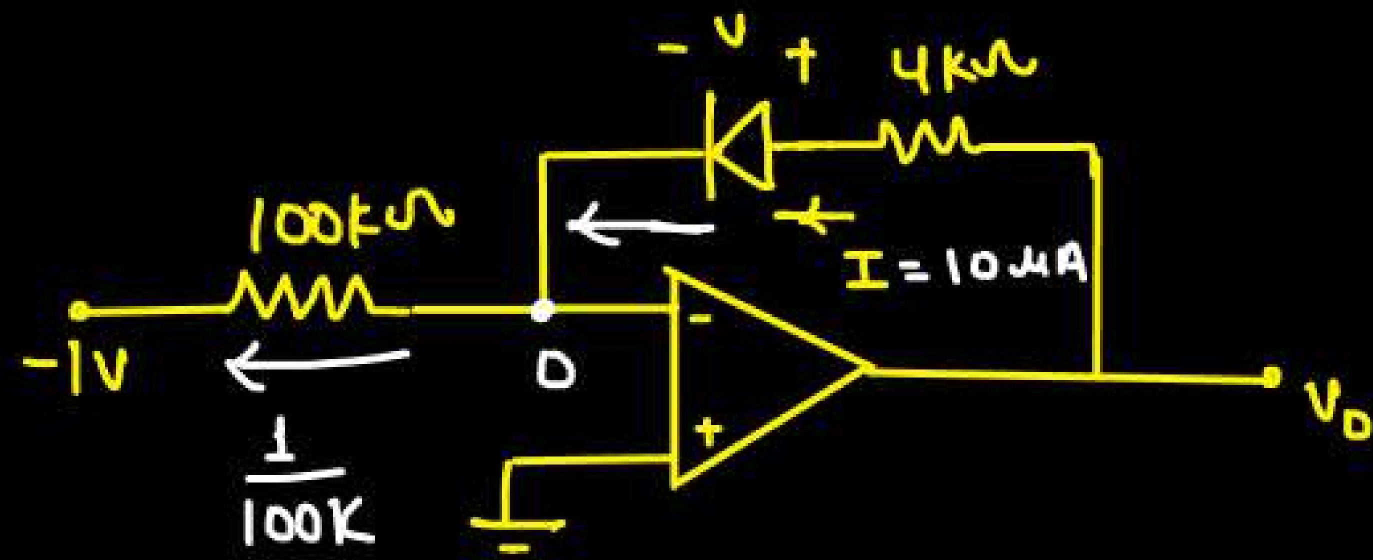
$[\, i_o \neq f(Z_L) \,]$

$$i_o = \frac{v_1 - v_2}{R}$$

$$\boxed{i_o = -\frac{v_i}{R}}$$

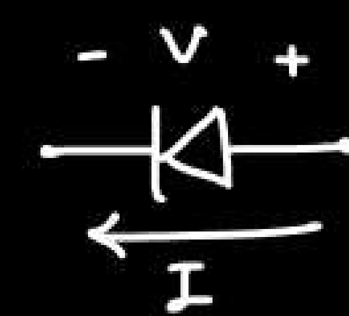
$$\frac{v_i + v_1}{2} = \frac{v_2}{2} \Rightarrow v_1 = v_2 - v_i$$

Q.



$\frac{1}{100K}$

$= 10\mu A$



$I = I_0[e^{V/V_T} - 1]$

For the diode $I = I_0\left[e^{V/V_T} - 1\right]$

$V_T = 25mV$, $I_0 = 1\mu A$

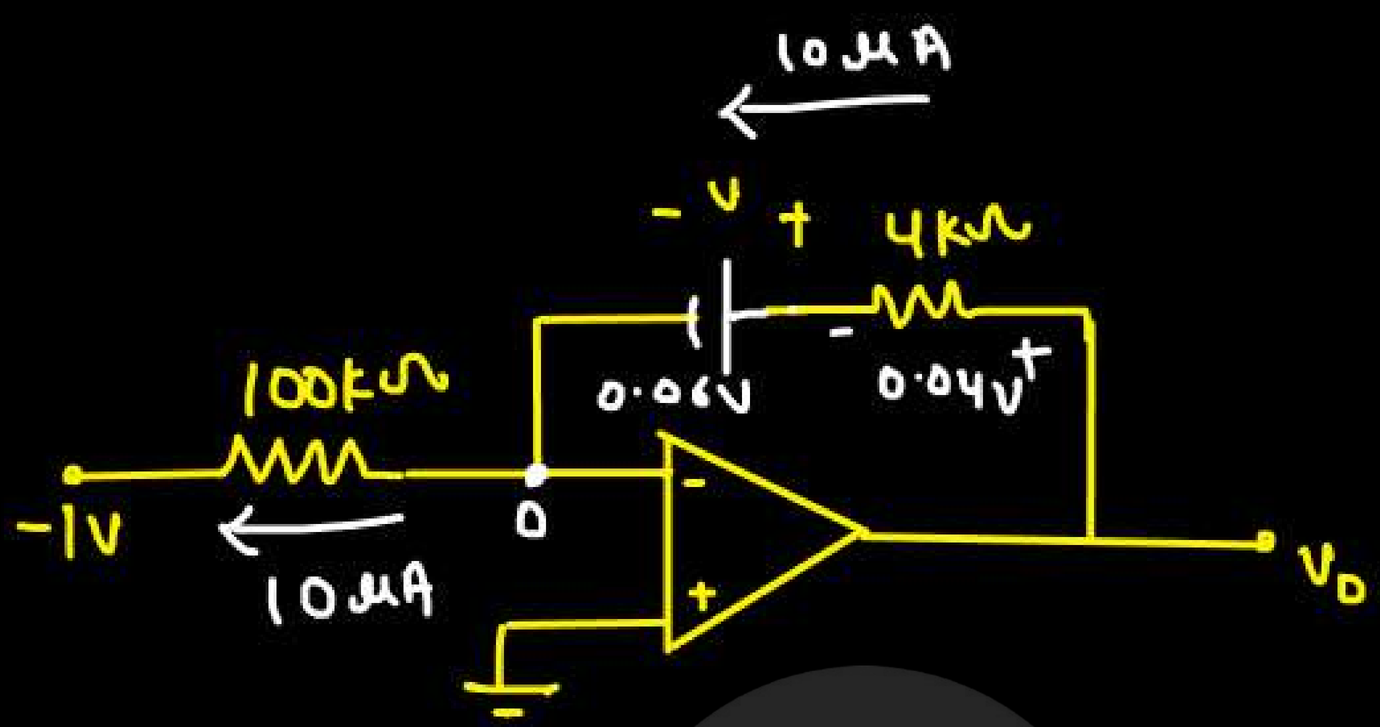
Value of V_0 is ___ mV.

↳

$$I = I_0\left[e^{V/V_T} - 1\right]$$

$$10\mu = 1\mu\left[e^{V/25mV} - 1\right] \Rightarrow V = 0.06V$$

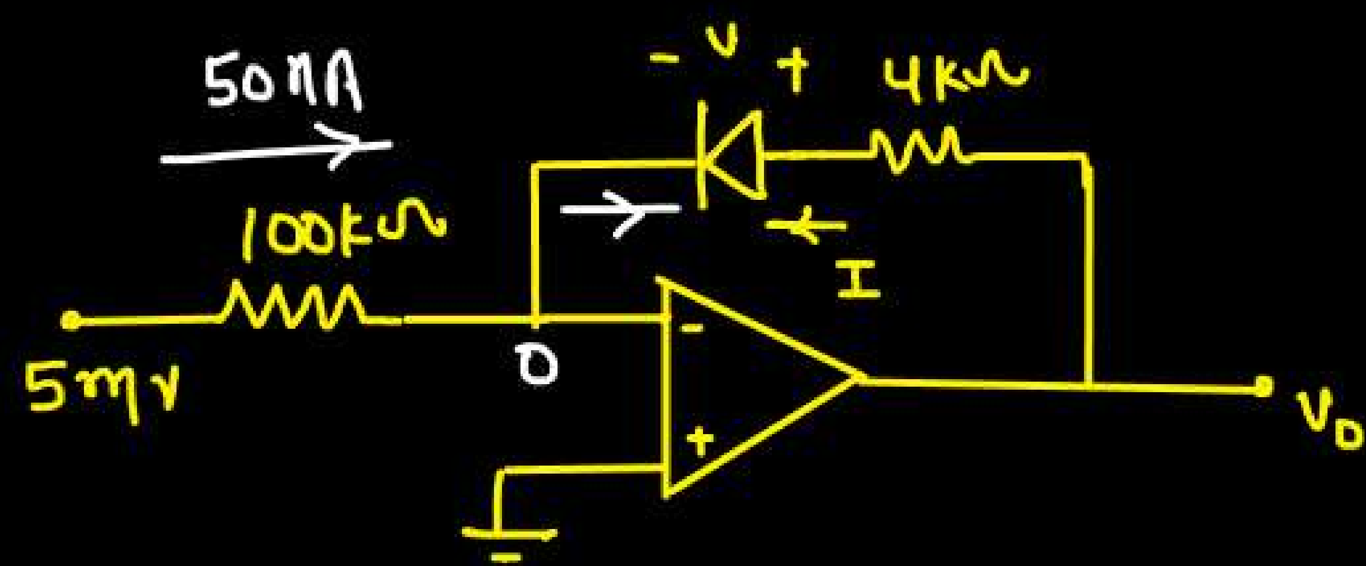
$$V = 25mV \ln(11)$$



$$V_0 = 0 + 0.06 + 0.04$$

$$\boxed{V_0 = 0.1 \text{ Volt}}$$

Q.



For the diode $I = I_0\left[e^{V/V_T} - 1\right]$

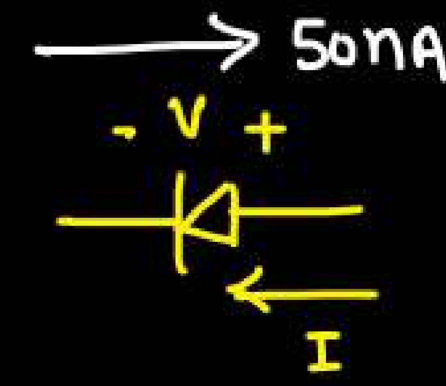
$V_T = 25\,mV$, $I_0 = 1\,\mu A$

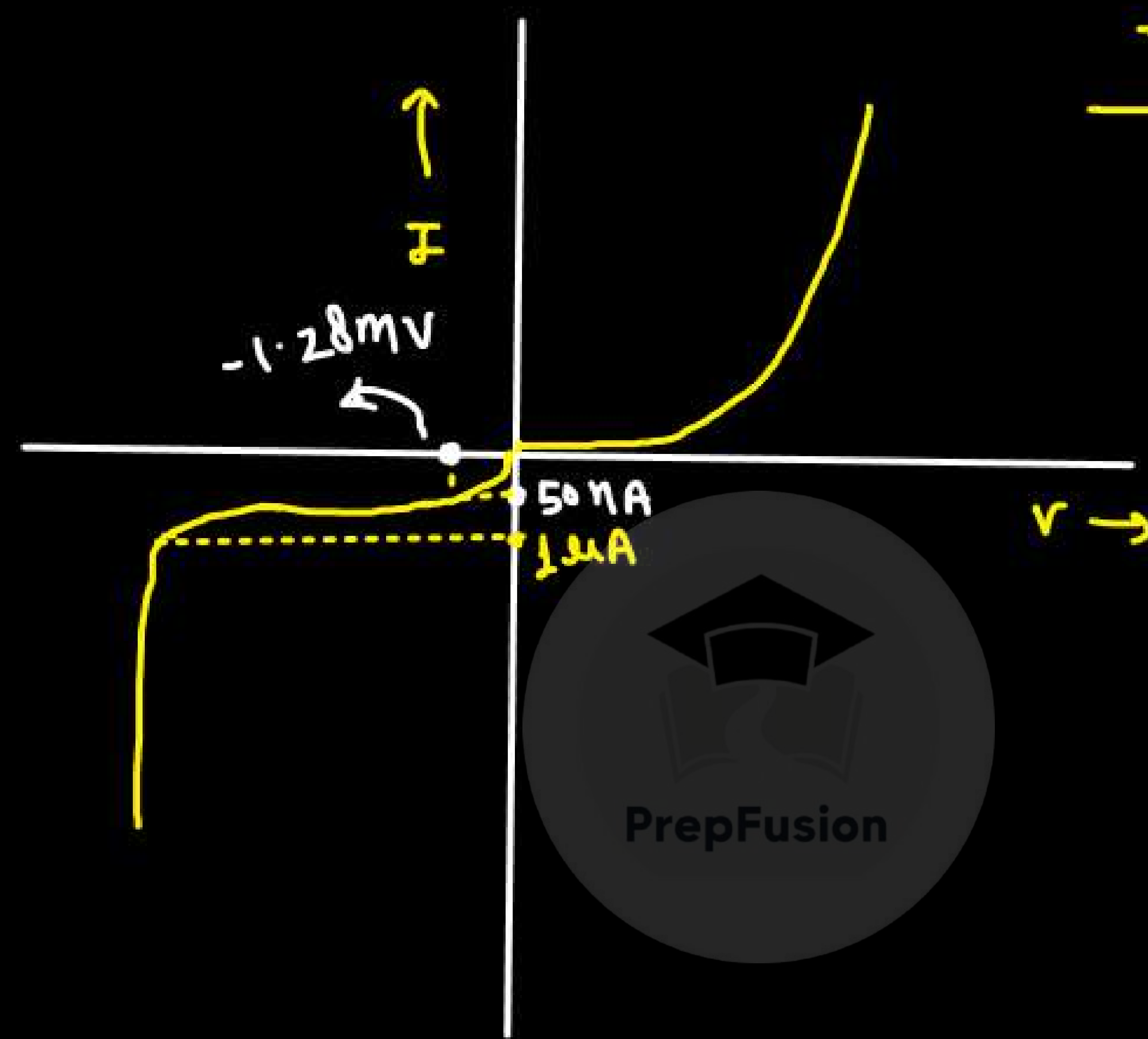
Value of V_0 is ___ mV.

→ Assuming, diode is giving me some finite voltage ⇒ neg f/b is +nt

⇓

virtual short is valid





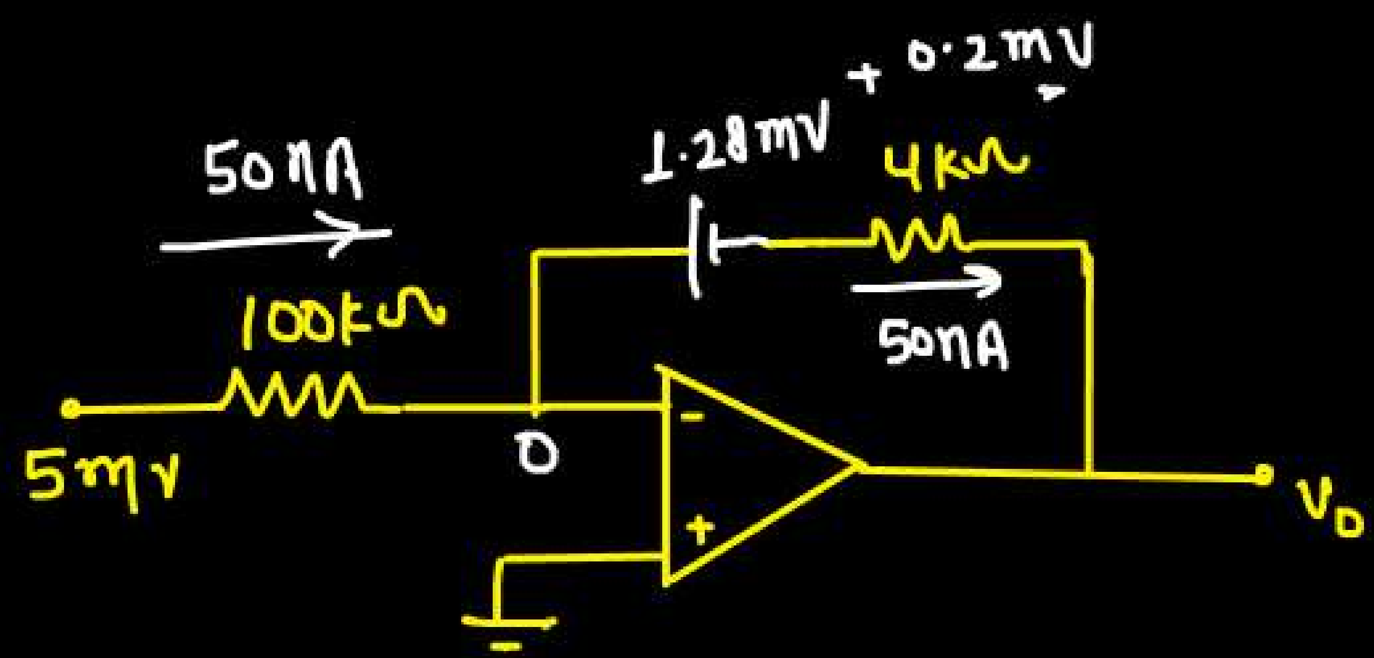
$$I = I_0\left[e^{V/V_T} - 1\right]$$

$$-5\times10^{-8} = 1\times10^{-6}\left[e^{V/25mV} - 1\right]$$

$$-0.05 = e^{V/25mV} - 1$$

$$e^{V/25mV} = 0.95$$

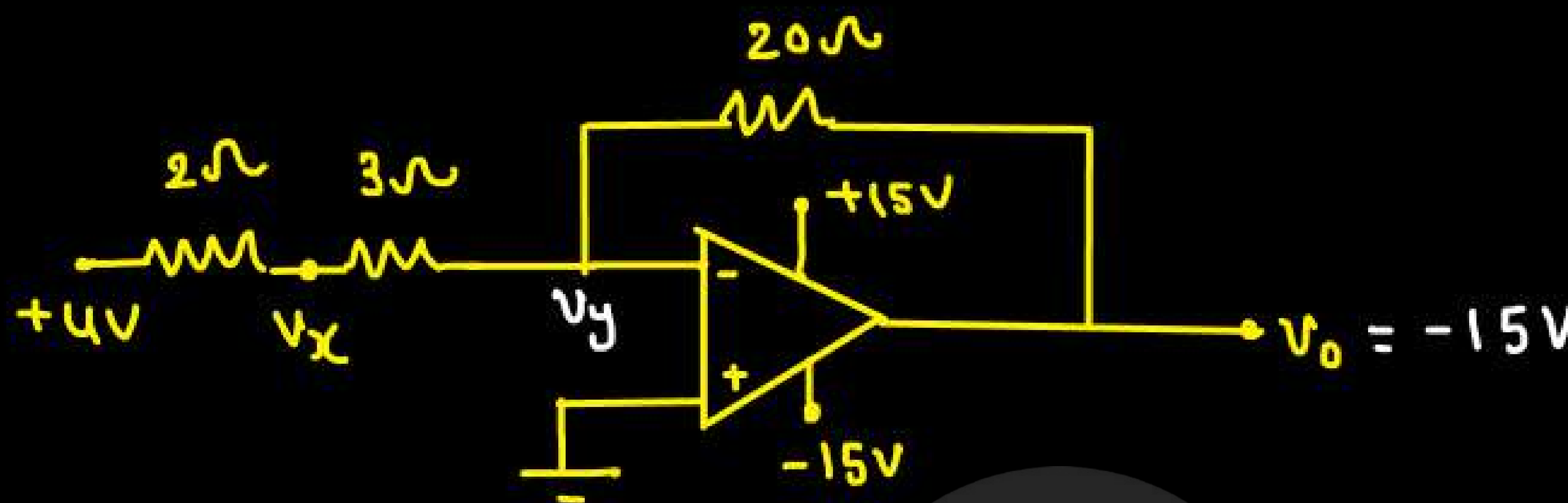
$$\boxed{V = -1.28\,mV}$$



$$V_o = 0 - 1.28\,mV - 0.2\,mV$$

$$\boxed{V_o = -1.48\,mV}$$

Q.



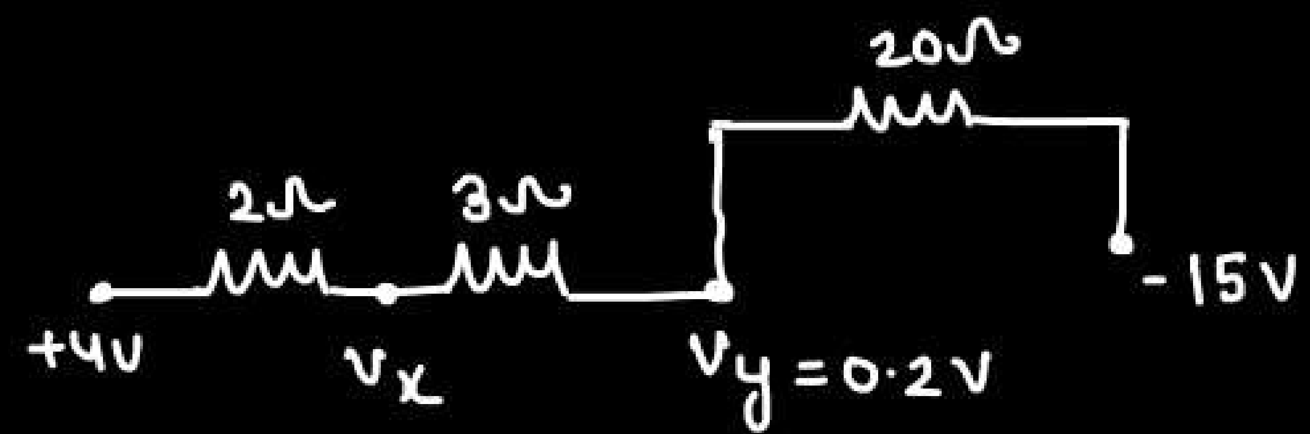
The potential @ node x is ___ ?

→

$$V_0 = \left(\frac{-20}{5}\right)4 = -16V \; \times \Rightarrow \underbrace{-15V}$$

⇓

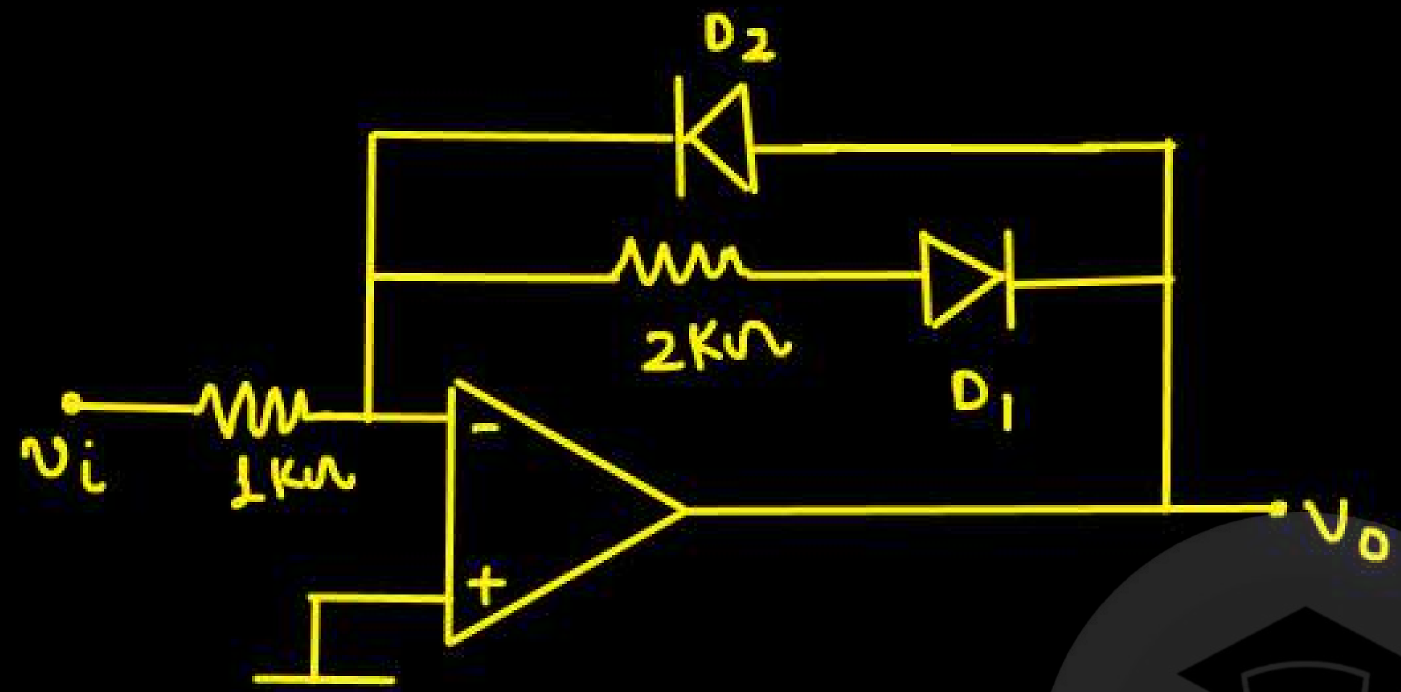
virtual short not valid



$$V_y = \frac{-15(5) + 4(20)}{25} = 0.2\,V$$

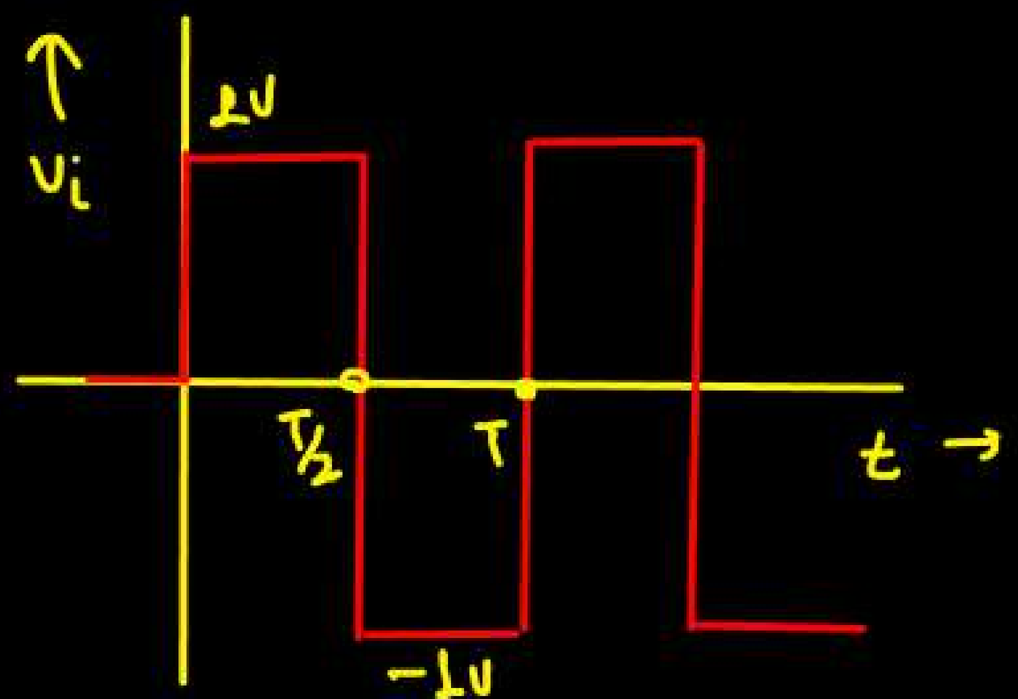
$$\boxed{V_x = \frac{0.2(2) + 4(3)}{5} = \frac{12 + 0.4}{5} = 2.48\,V}$$

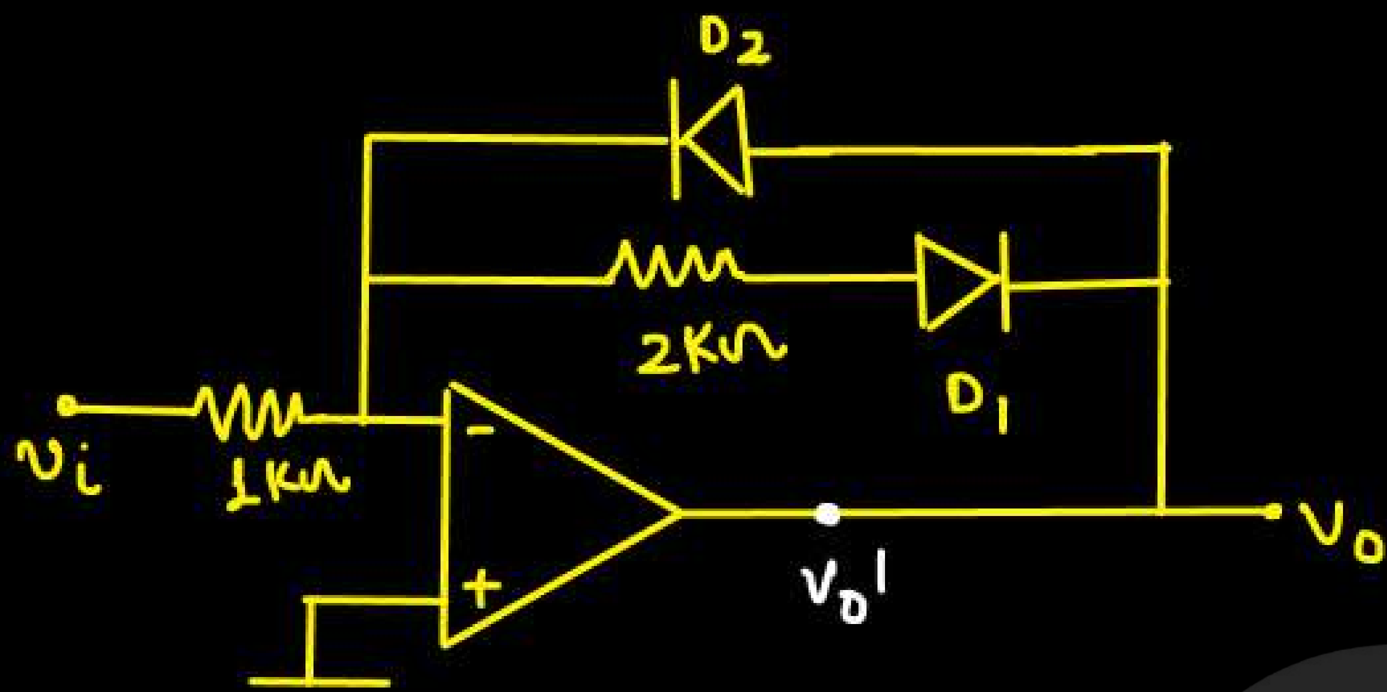
Q.



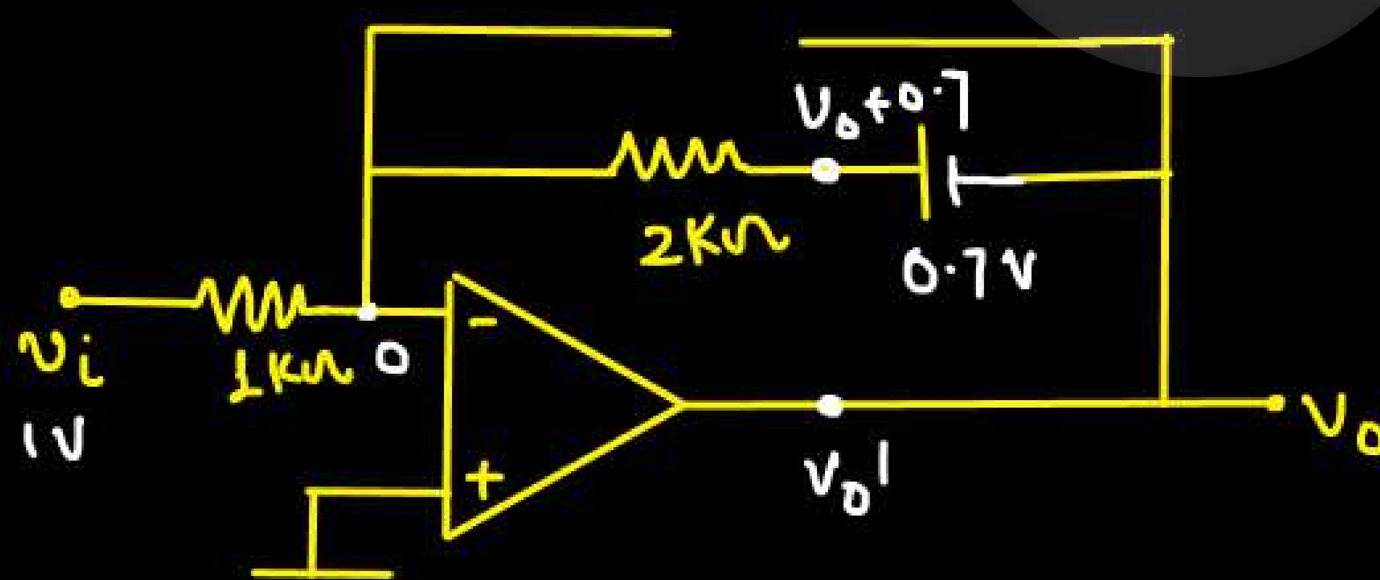
Forward voltage drop for both of the diode is 0.7 V.

Find the avg. value of v_o.





$0 < t < T/2 \Rightarrow v_i = +1V \Rightarrow V_o' = -V_{sat} \Rightarrow D_1$ ON , D_2 OFF



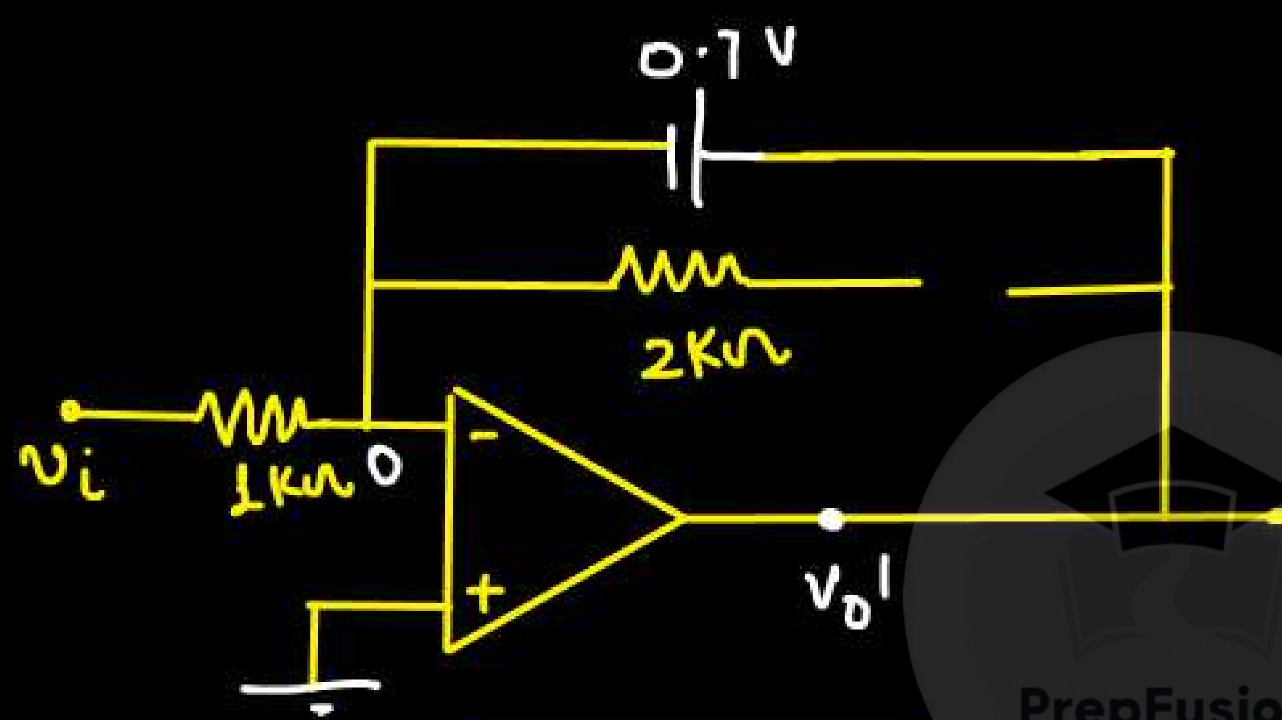
$$\frac{-v_i}{1K} + \left(\frac{0 - v_0 - 0.7}{2K}\right) = 0$$

$$-2v_i - v_0 - 0.7 = 0$$

$$\boxed{v_0 = -2.7V} \quad \left\{0 < t < T/2\right\}$$

$T/2 < t < T$:-

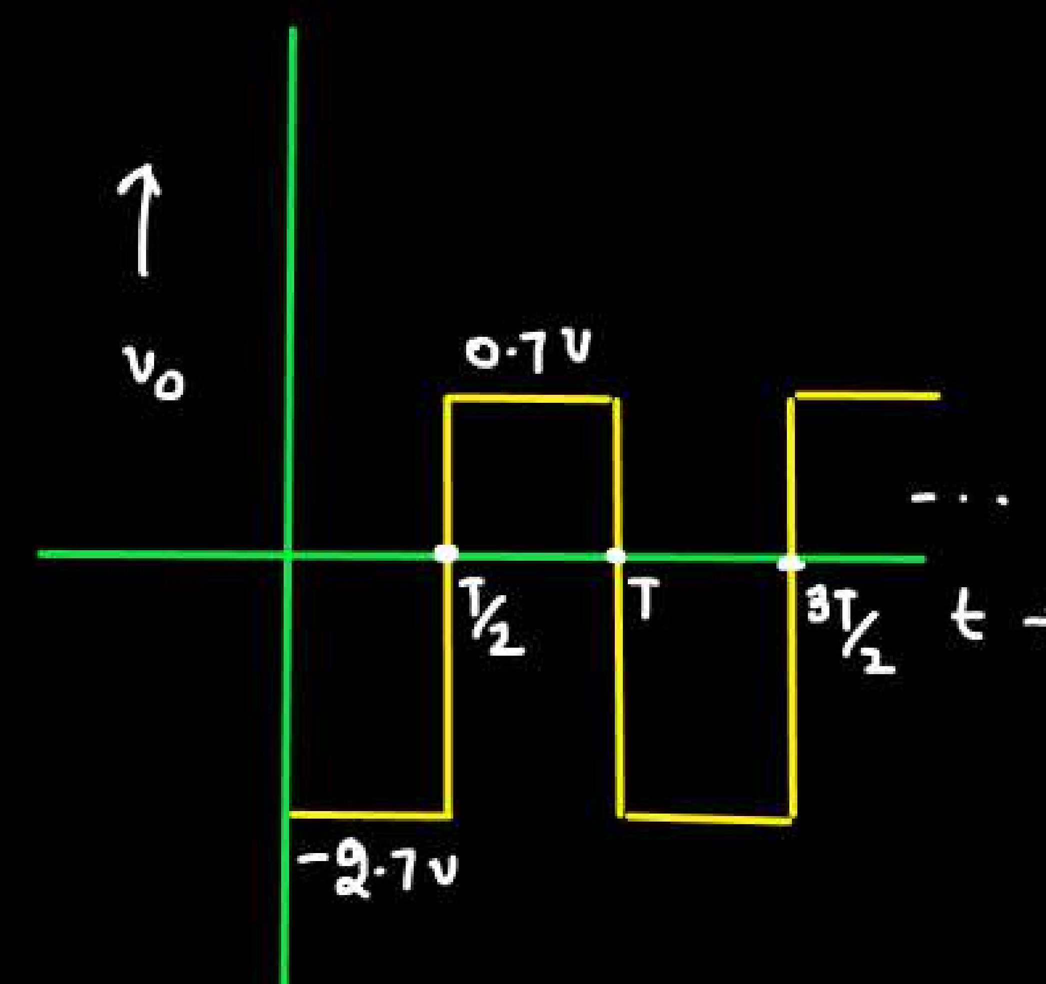
$v_i = -1\,V \Rightarrow v_o' = +v_{sat} \Rightarrow D_2$ ON, D_1 OFF



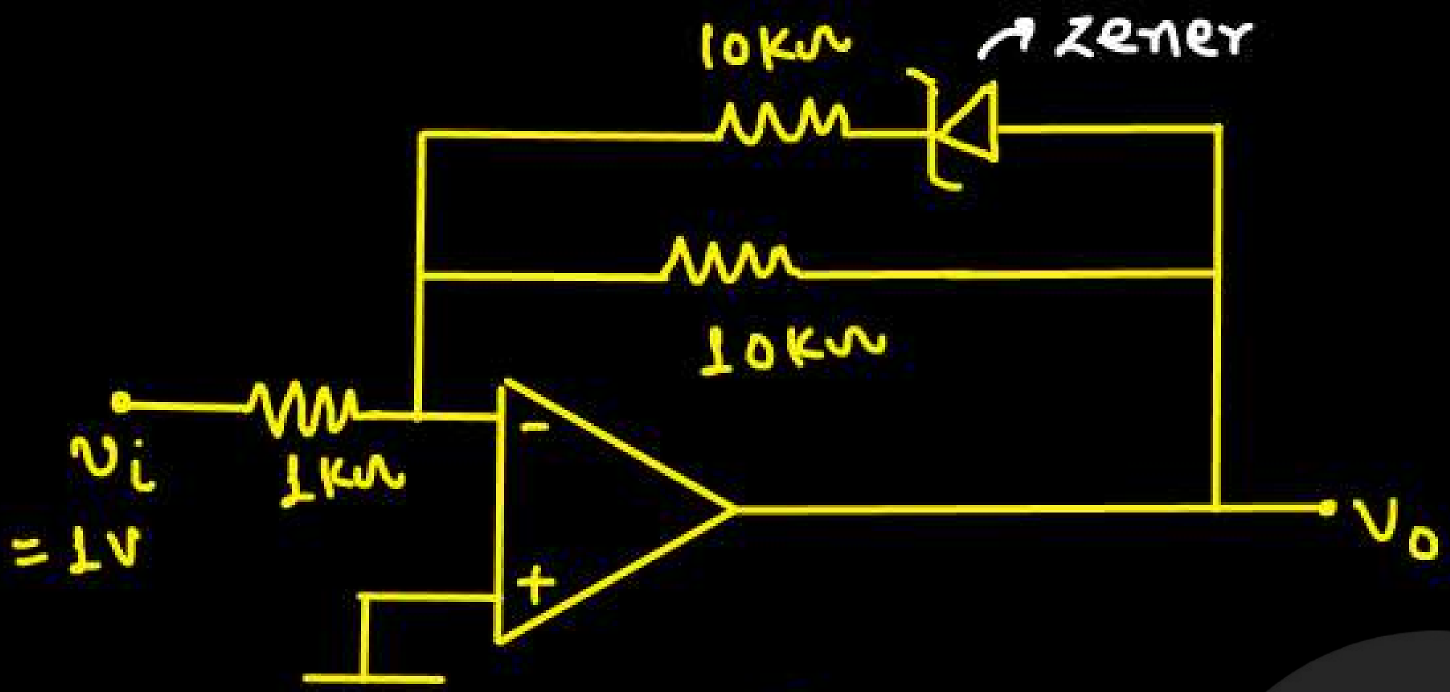
$\boxed{V_o = 0.7\,V}$ $\{T/2 < t < T\}$

$$(V_o)_{avg.} = \frac{(-2.7)\,T/2 + (0.7)\,T/2}{T}$$

$$\boxed{(V_o)_{avg.} = -1\,V}$$



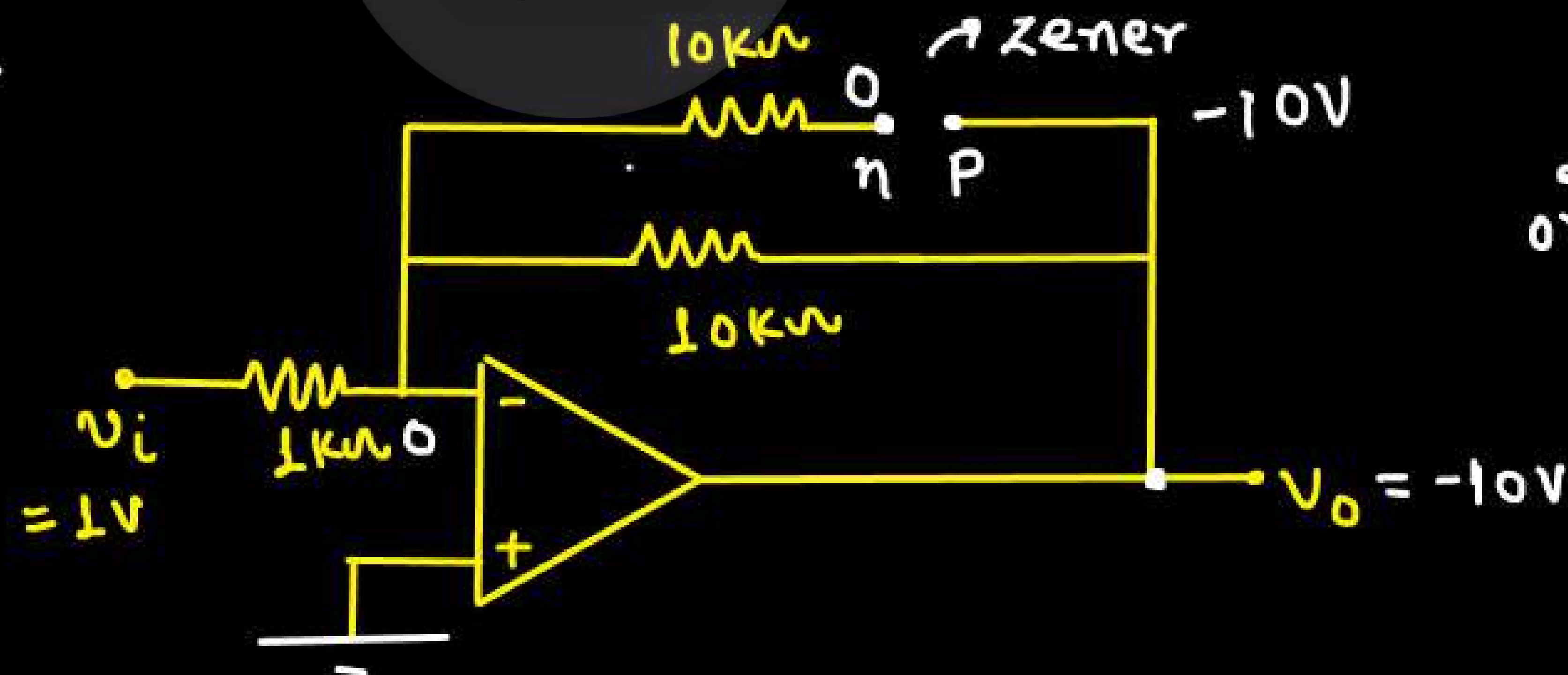
Q.

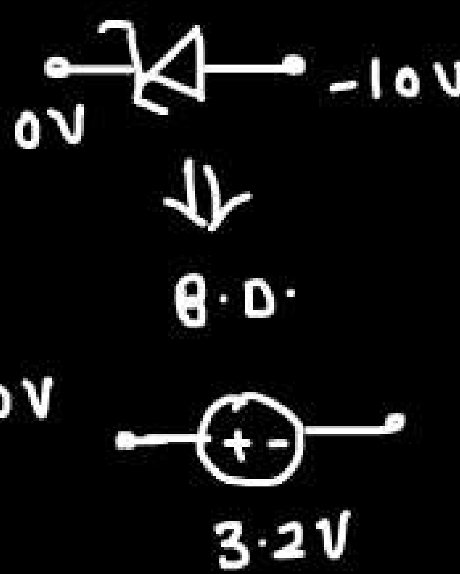


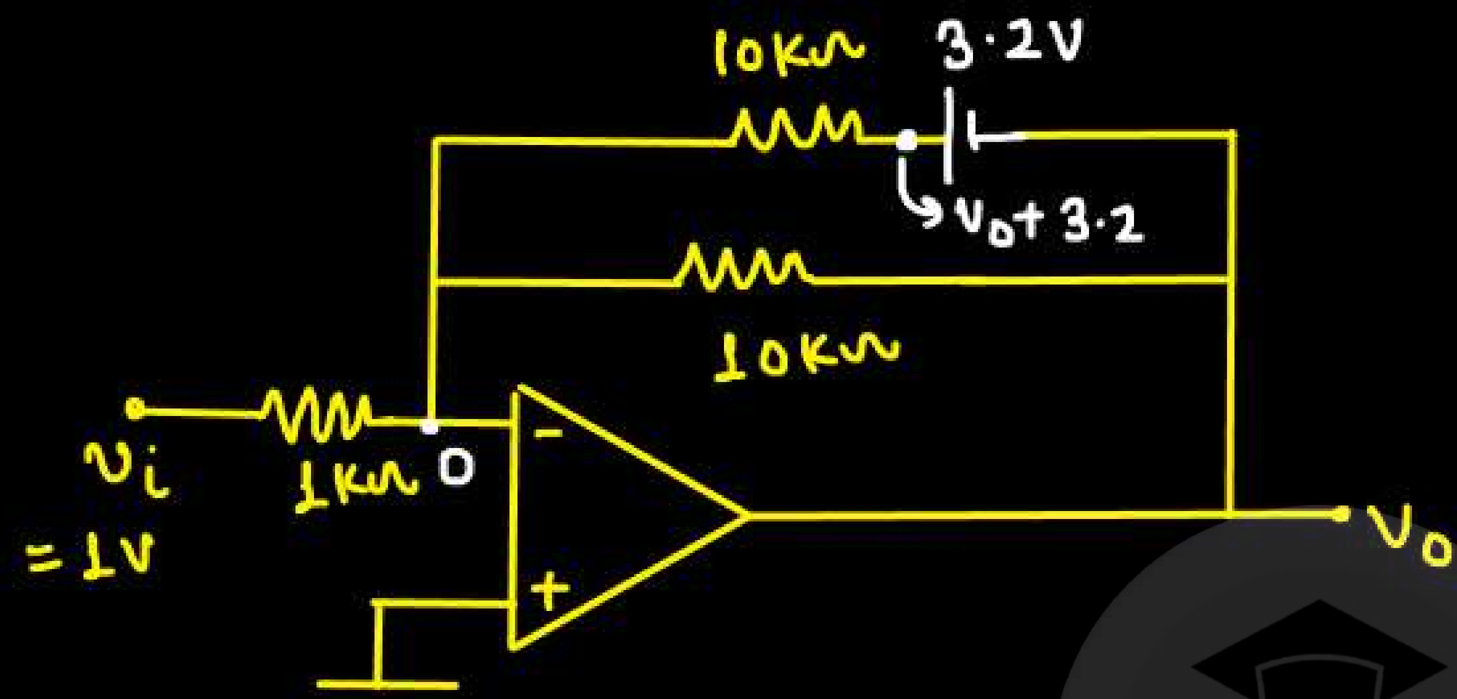
Breakdown voltage of zener diode = 3.2V

Find v_o.

→ Applying O.C. Test :-







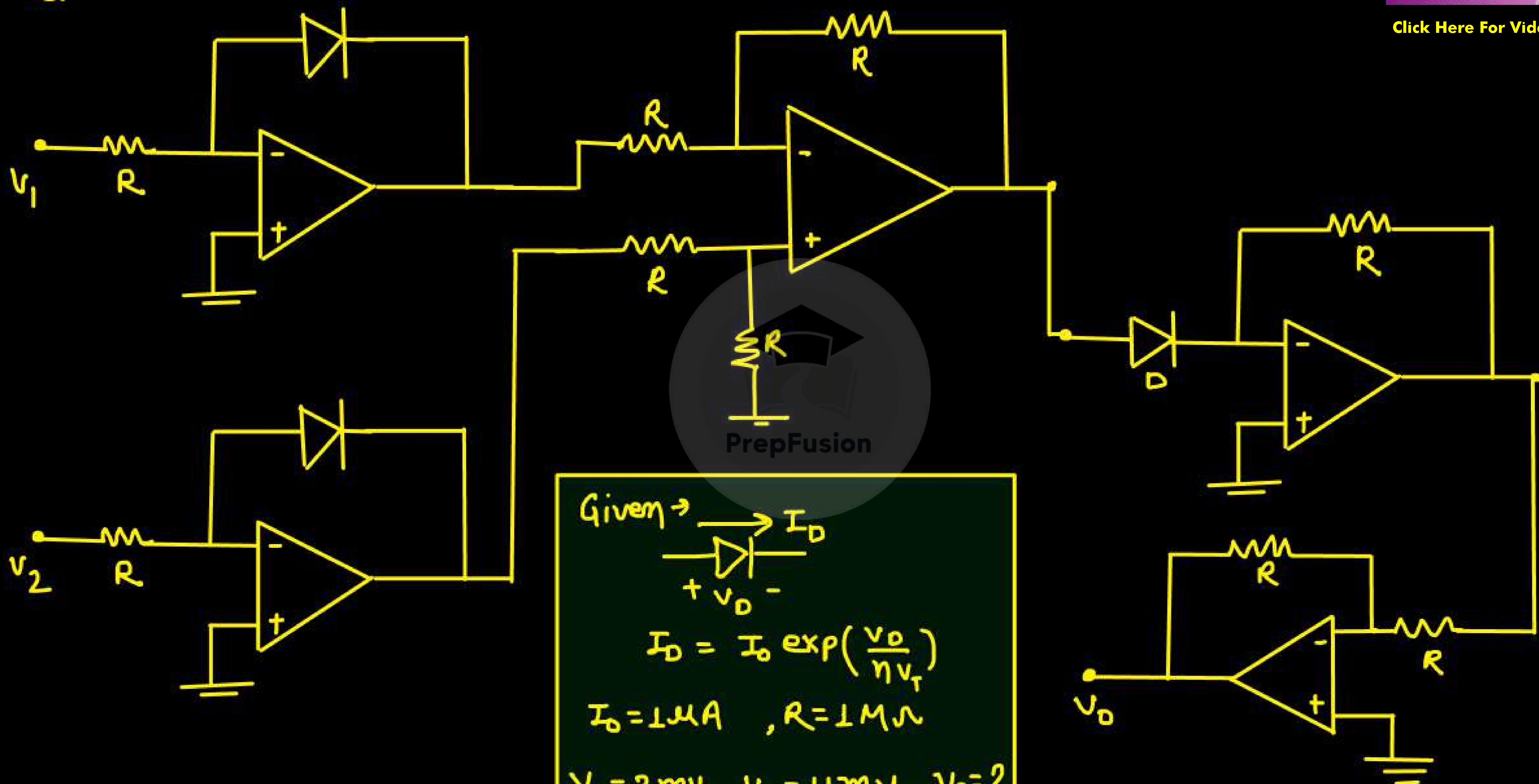
$$\frac{0-1}{1K} + \frac{0-V_o}{10K} + \frac{0-(V_o+3.2)}{10K} = 0$$

$$-10 - V_o - V_o - 3.2 = 0$$

$$2V_o = -13.2$$

$$\boxed{V_o = -6.6\ V}$$

Q.



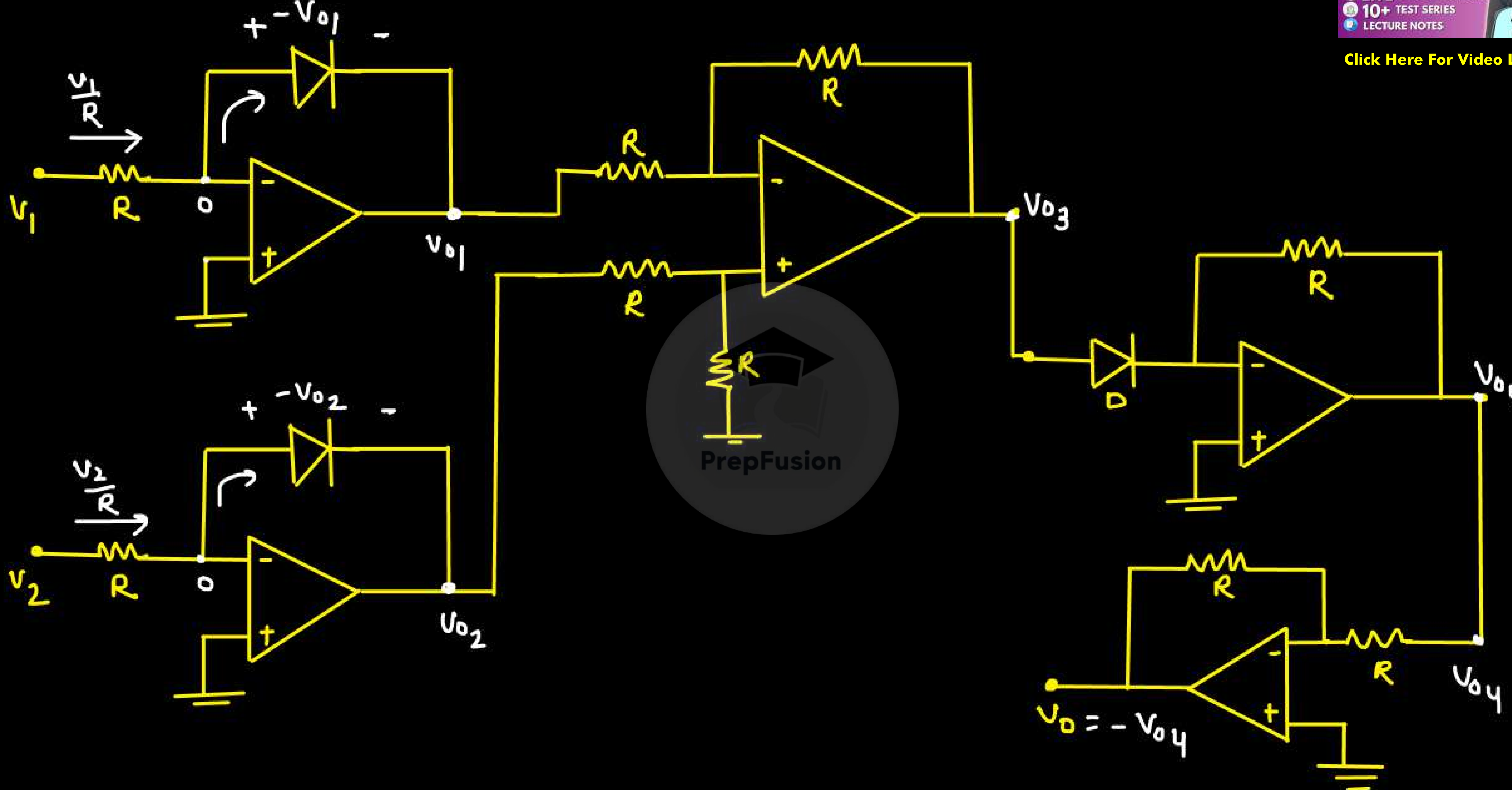
Given → I_D

$+ \; V_D \; -$

$$I_D = I_0 \exp\left(\frac{V_D}{\eta V_T}\right)$$

$I_0 = 1\mu A$, $R = 1M\Omega$

$V_1 = 2mV$, $V_2 = 4mV$, $V_0 = ?$

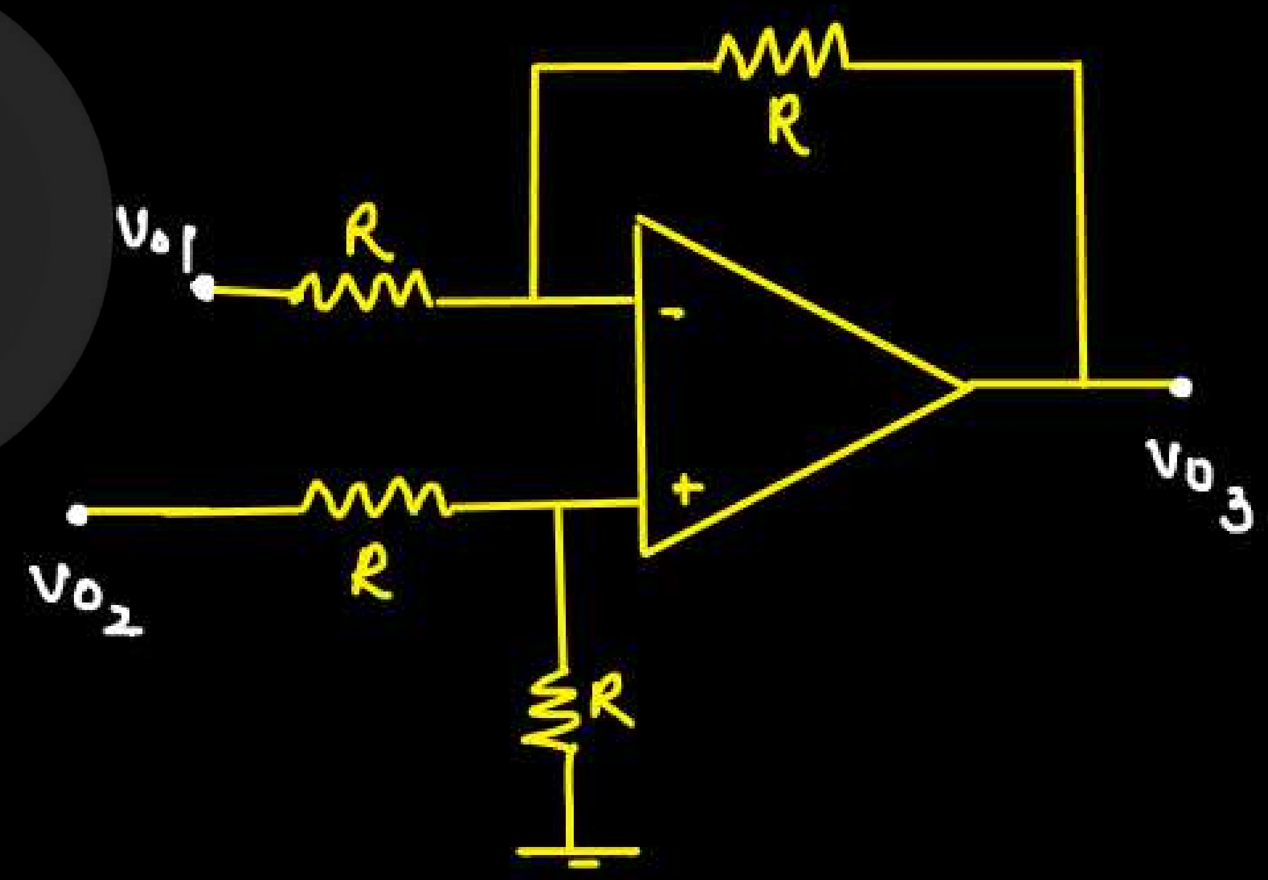


V_1
R
$\frac{V_1}{R}$
0
$+ \; -V_{o1} \; -$
V_{o1}
V_2
R
$\frac{V_2}{R}$
0
$+ \; -V_{o2} \; -$
V_{o2}
R
R
R
R
V_{o3}
D
R
V_{o4}
R
R
V_{o4}
$V_o = -V_{o4}$

$$\frac{v_1}{R} = I_0 \exp\left[-\frac{V_{o1}}{\eta V_T}\right]$$

$$V_{o1} = -\eta V_T \ln\left[\frac{v_1}{I_0 R}\right] \quad \text{—— } 1$$

$$V_{o2} = -\eta V_T \ln\left[\frac{v_2}{I_0 R}\right] \quad \text{—— } 2$$



$$V_{o3} = \frac{R}{R}\left[V_{o2} - V_{o1}\right]$$

$$= -\eta V_T \ln\left(\frac{v_2}{I_0 R}\right) + \eta V_T \ln\left(\frac{v_1}{I_0 R}\right)$$

$$= \eta V_T \left[\ln\left(\frac{v_1}{I_0 R}\right) - \ln\left(\frac{v_2}{I_0 R}\right)\right]$$

$$V_{o3} = \eta V_T \ln\left(\frac{v_1}{I_0 R} \times \frac{I_0 R}{v_2}\right)$$

$$V_{o3} = \eta V_T \ln\left(\frac{v_1}{v_2}\right) \quad \text{— } (3)$$

$$V_{o4} = -I_D R$$

$$V_{o4} = -I_o \exp\left[\frac{V_{o3}}{\eta V_T}\right] R$$

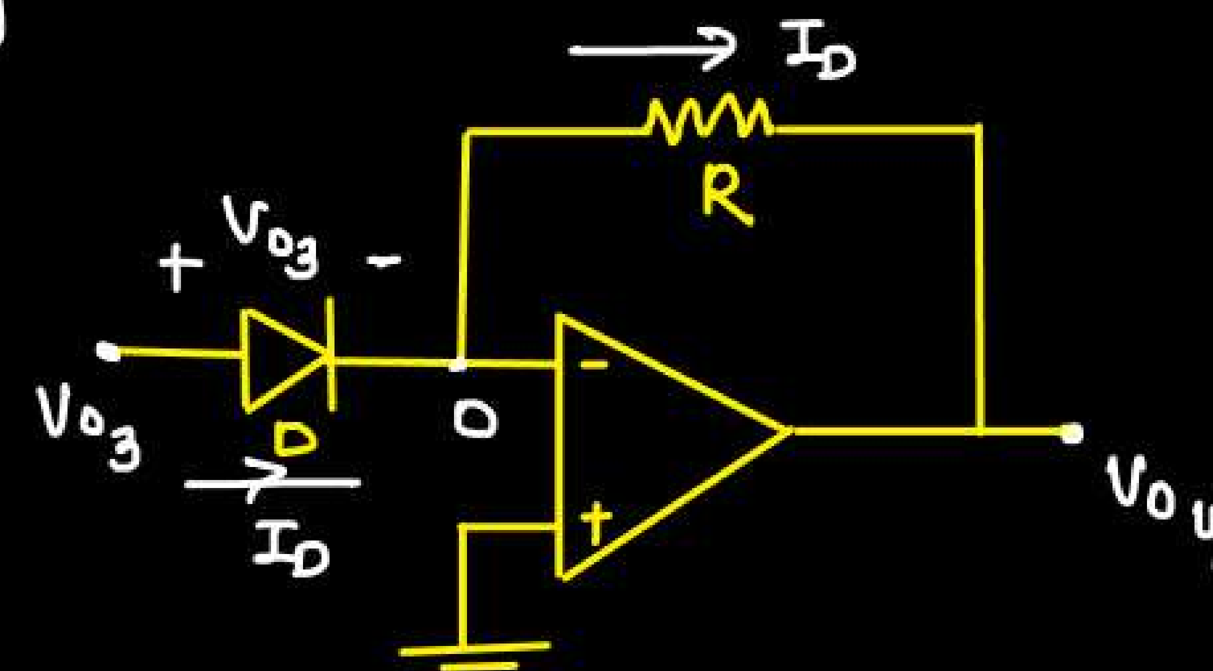
$$V_{o4} = -I_o R \exp\left[\frac{\cancel{\eta V_T} \ln\left(\frac{v_1}{v_2}\right)}{\cancel{\eta V_T}}\right]$$

$$V_{o4} = -I_o R \exp\left[\ln\left(\frac{v_1}{v_2}\right)\right]$$

$$V_{o4} = -I_o R\left(\frac{v_1}{v_2}\right) \quad \text{— } (4)$$

$$V_o = -V_{o4}$$

$$\boxed{V_o = I_o R\left(\frac{v_1}{v_2}\right)}$$



$$V_0 = 1\mu \times 1M \left(\frac{2m}{4m}\right)$$

** $\boxed{V_0 = 0.5V}$

Filters:-

Passes a particular range of frequencies.

(a) LPF

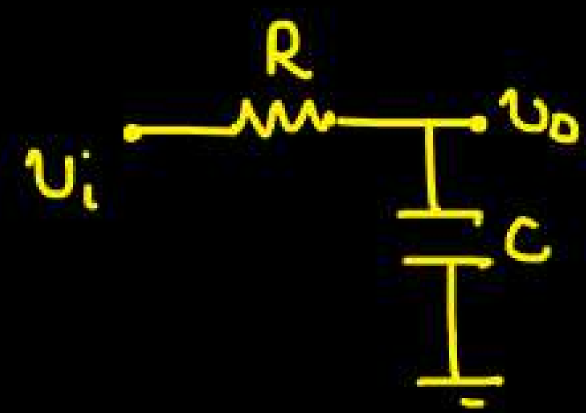
(b) HPF

(c) BPF

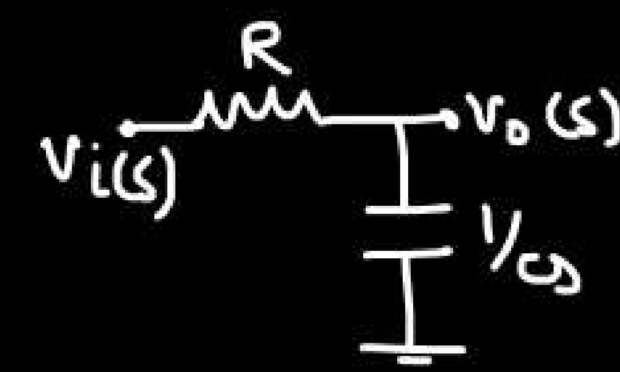
(d) BSF

(e) APF

Passive Filter:-



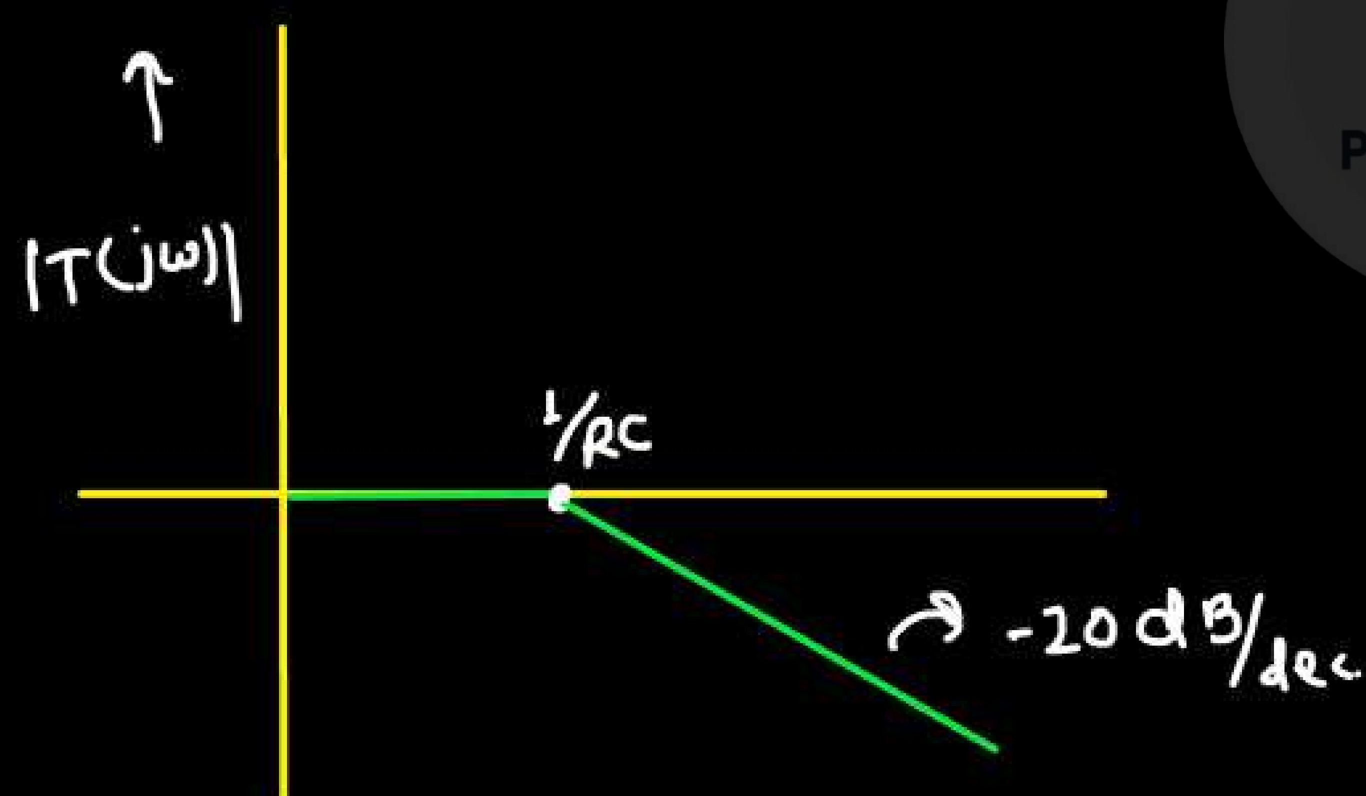
$\Rightarrow$



$$\frac{V_o(s)}{V_i(s)} = \frac{1}{1+RCs}$$

$$\boxed{T(s) = \frac{1}{1+RCs}}$$

$$|T(j0)| = 1 = 0\,dB$$



Unity gain B.W.

$$|T(j\omega)| = \frac{1}{\sqrt{1+\omega^2R^2C^2}}$$

$$|T(j\omega_{UGB})| = 1$$

$$\boxed{\omega_{UGB} = 0 \text{ rad/sec.}}$$

Fixed

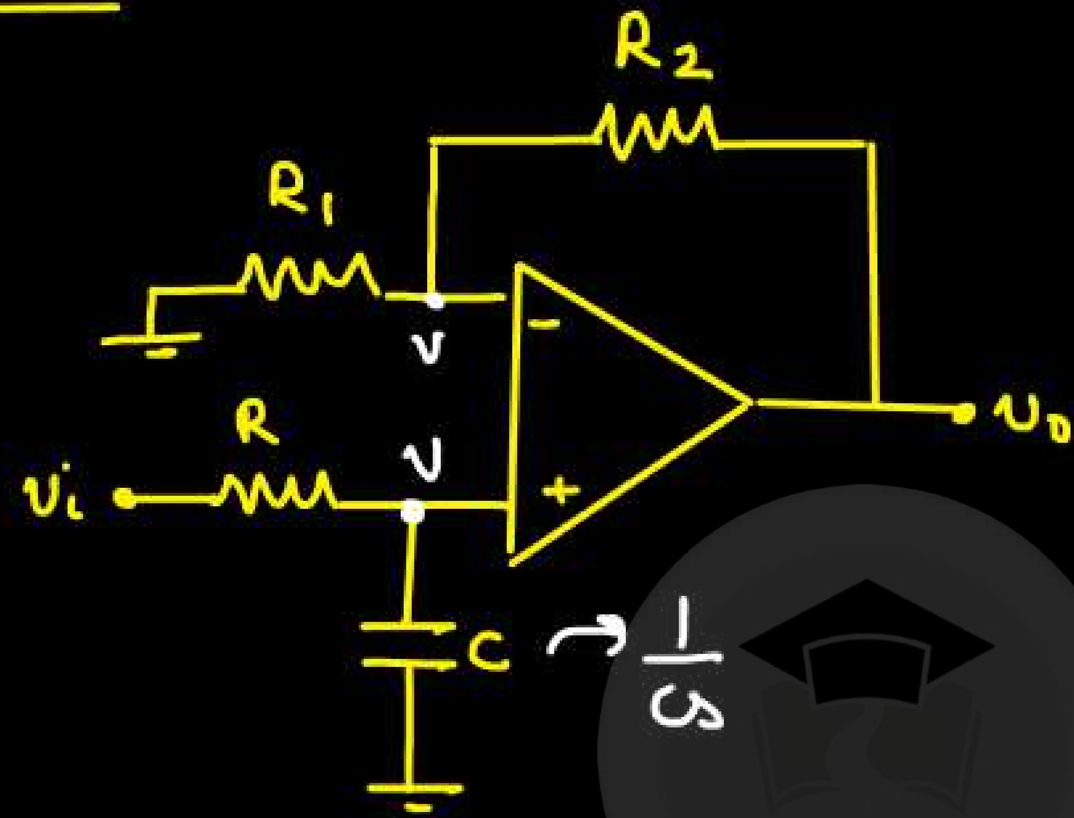
Active Filters:-

- Filters made using active elements like op-amp, Transistors etc.

- Using Active filters, you can adjust the dc gain and unity gain frequency of the filter.

- Using active filters, you can avoid loading effects while cascading.

(1) Low Pass Filter:-



$$V_0(s) = \left(1 + \frac{R_2}{R_1}\right) V(s) \quad \text{--- (1)}$$

$$V(s) = \frac{1}{1+RCs} V_i(s) \quad \text{--- (2)}$$

By eqn (1) and (2)

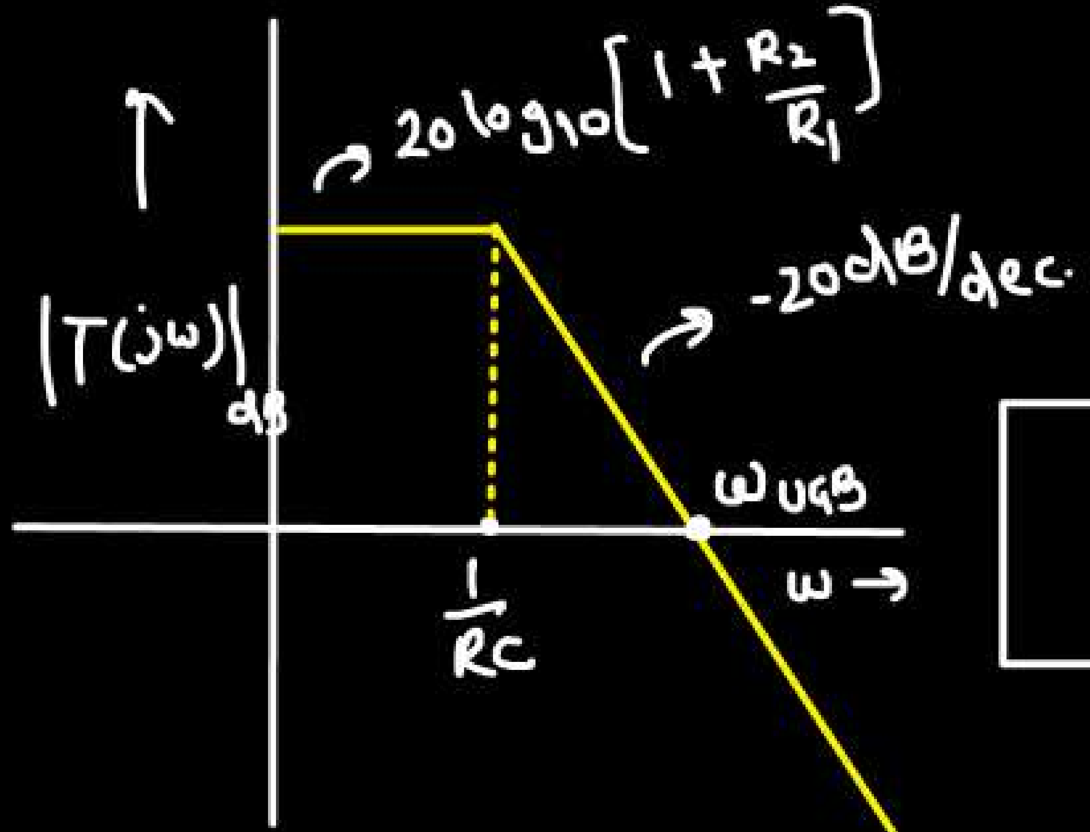
$$\boxed{\frac{V_0(s)}{V_i(s)} = \left(1 + \frac{R_2}{R_1}\right) \times \frac{1}{1+RCs}}$$

$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{\left(1+R_2/R_1\right)}{1+RCs}$$

at $\omega=0$ / dc gain $\boxed{T(j0) = 1+\frac{R_2}{R_1}}$

$\Downarrow$

dc gain is adjustable by controlling R_2 and R_1 values

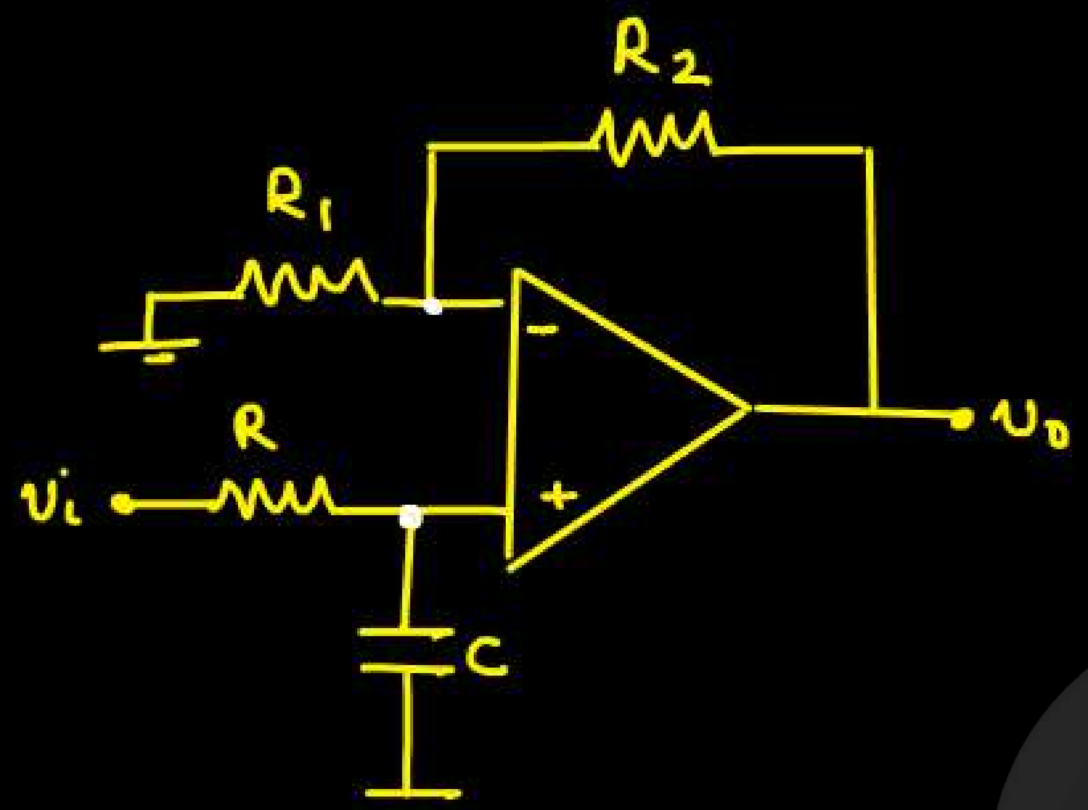


$$\boxed{\omega_{3\text{-}dB} = \frac{1}{RC}}$$

ω_{UGB} = dc gain $\times$ $\omega_{3\text{-}dB}$

$$\boxed{\omega_{UGB} = \left(1+\frac{R_2}{R_1}\right) \times \frac{1}{RC}}$$

Eg:-



$RC = 2$ sec.

$$\frac{R_2}{R_1} = 9$$

Find $\omega_{3\text{-dB}}$, ω_{UGB} and dc gain.

$$T(s) = \frac{10}{2s+1}$$

→ dc gain = 10

→ $\omega_{3\text{-dB}} = 1/2$ rad/sec.

→ $\omega_{UGB} \approx 10 \times \frac{1}{2} = 5$ rad/sec.

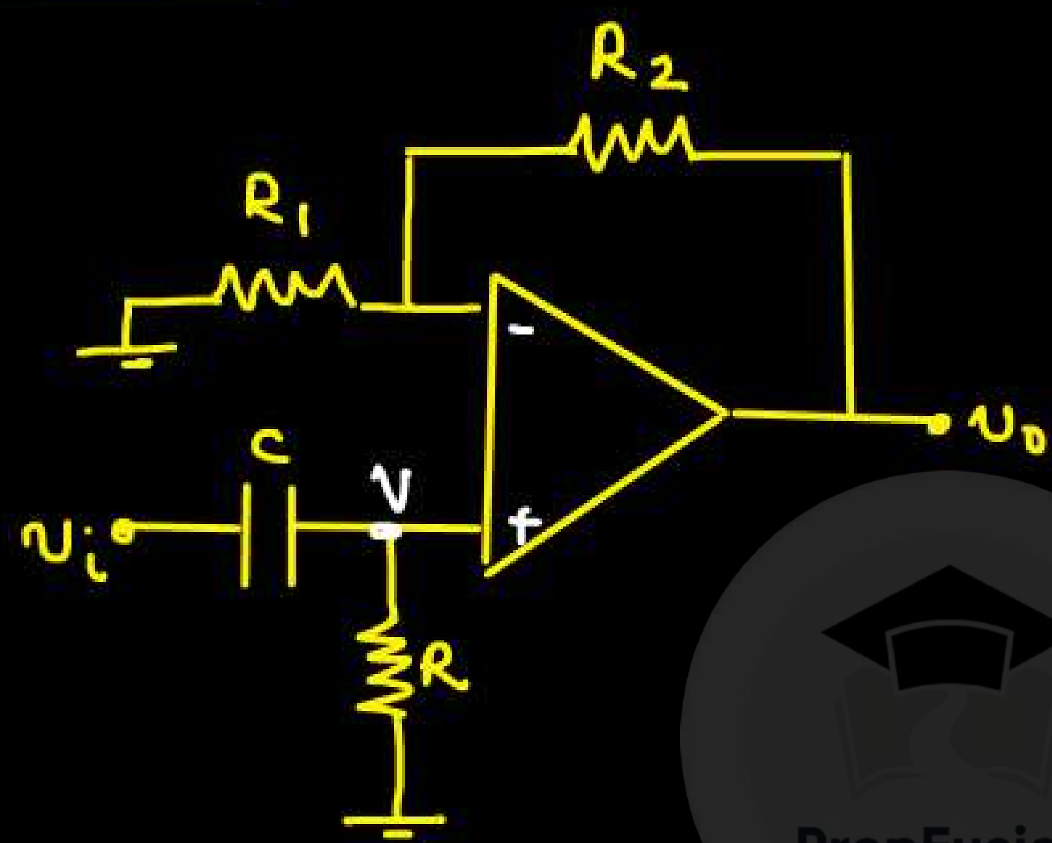
$$|T(j\omega)| = \frac{10}{\sqrt{1+4\omega^2}}$$

$$|T(j\omega_{UGB})| = \frac{10}{\sqrt{1+4\omega_{UGB}^2}} = 1$$

$$\Rightarrow \sqrt{\frac{99}{4}} = \omega_{UGB}$$

$$\boxed{\omega_{UGB} = 4.97 \text{ rad/sec.}}$$

2 High Pass Filter:-



$$v_0(s) = \left(1+\frac{R_2}{R_1}\right) v(s)$$

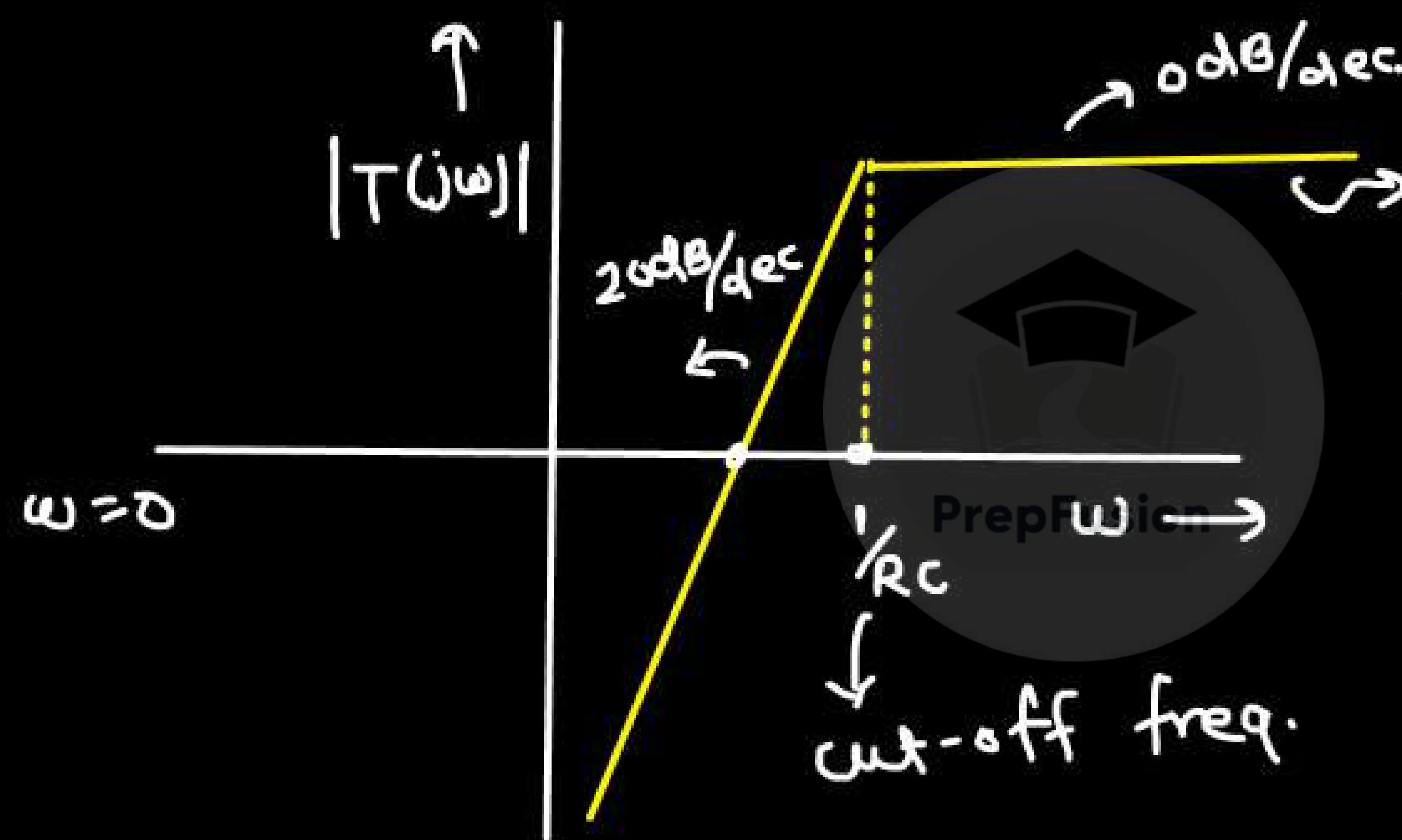
$$v(s) = \frac{R}{R+\frac{1}{Cs}}\, v_i(s) = \frac{RCs}{RCs+1}\, v_i(s)$$

$$\Rightarrow v_0(s) = \left(1+\frac{R_2}{R_1}\right)\left(\frac{RCs}{RCs+1}\right) v_i(s)$$

$$\boxed{T(s) = \frac{V_0(s)}{v_i(s)} = \left(1 + \frac{R_2}{R_1}\right) \times \frac{RCs}{RCs + 1}}$$

$\omega_z = 0$

$\omega_p = \frac{1}{RC}$



$20\log_{10}\left[1 + \frac{R_2}{R_1}\right] dB = |T(j\infty)|$

$\Rightarrow$ H.P.F.

✱ How to check the type of filter without writing Transfer function:-

↳ Put $\omega=0$ and $\omega=\infty$

(i) if at $\omega=0 \Rightarrow V_0 \neq 0$
and $\omega=\infty \Rightarrow V_0=0$
$\Rightarrow$ Passes only low freq. $\Rightarrow$ L.P.F.

(ii) if at $\omega=0 \Rightarrow V_0=0$
and $\omega=\infty \Rightarrow V_0 \neq 0$
$\Rightarrow$ Passes only High freq. $\Rightarrow$ H.P.F.

(iii) if at $\omega=0 \Rightarrow V_0=0$
and $\omega=\infty \Rightarrow V_0=0$
$\Rightarrow$ Passes some range of freq. b/w $\omega=0$ and ∞
$\Rightarrow$ B.P.F.

(iv) if $\omega = 0 \Rightarrow V_0 \neq 0$

$\omega = \infty \Rightarrow V_0 \neq 0$ $\Rightarrow$ $\underbrace{\text{Band reject / All Pass filter}}$

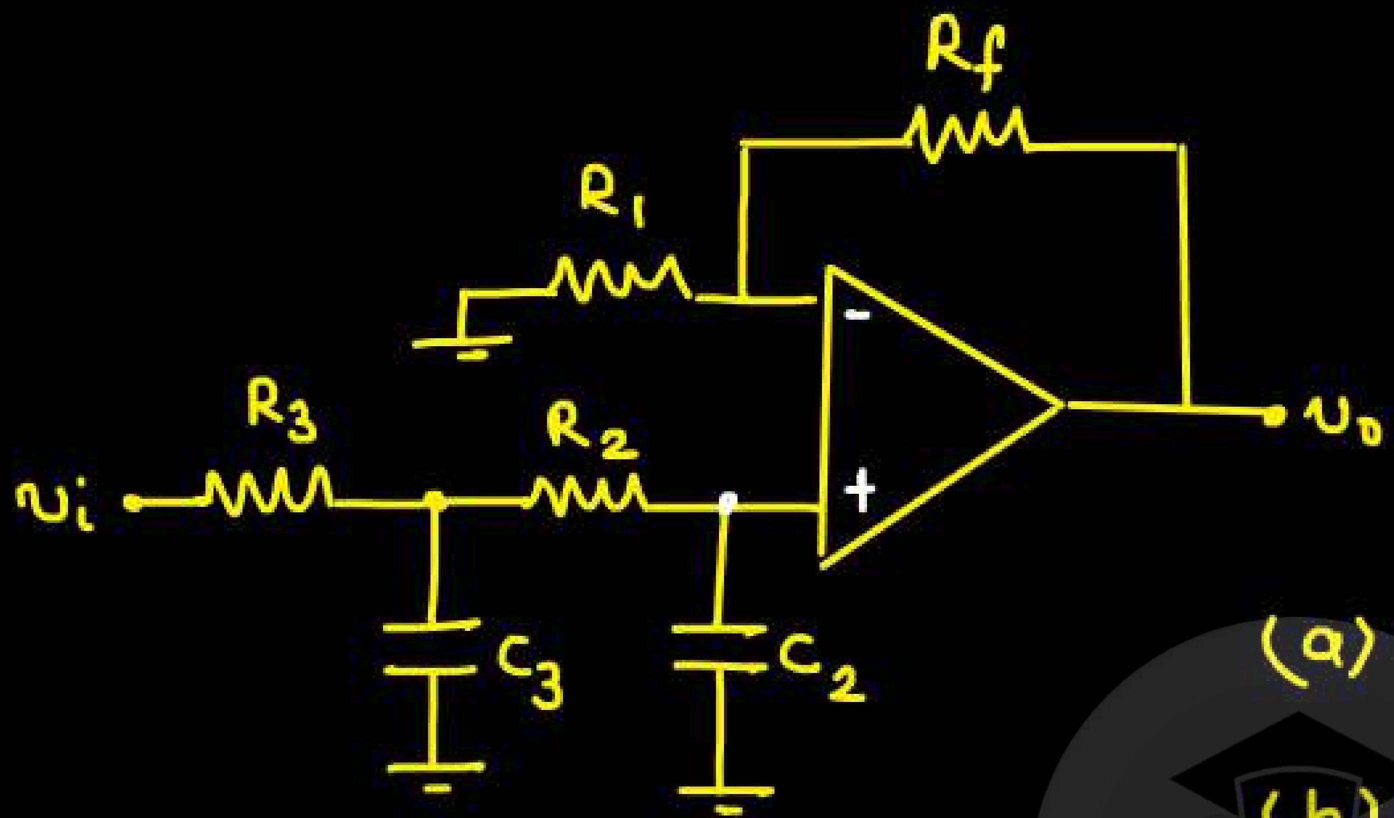
$\Downarrow$

Check Transfer f^n

Pole - zero symmetric about $j\omega$ axis $\rightarrow$ APF

o/w $\rightarrow$ BPF

Q.



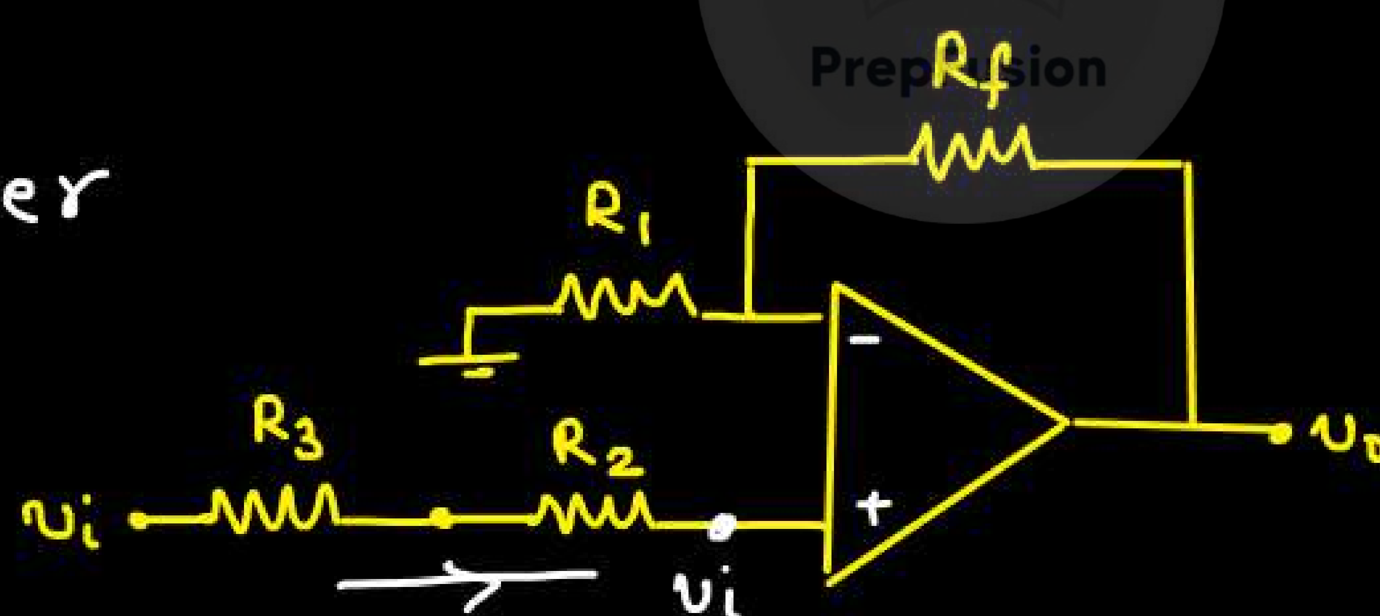
(a) Find the order of the filter.

(b) Find the type of the filter.

(a) 2^{nd} order

(b) $\omega = 0$

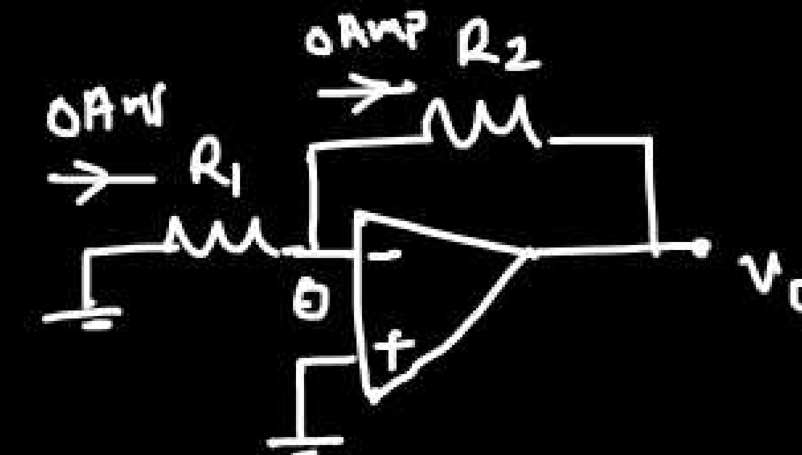
$X_C = \infty$



$$\boxed{v_0(\omega=0) = \left(1 + \frac{R_f}{R_1}\right) v_i}$$

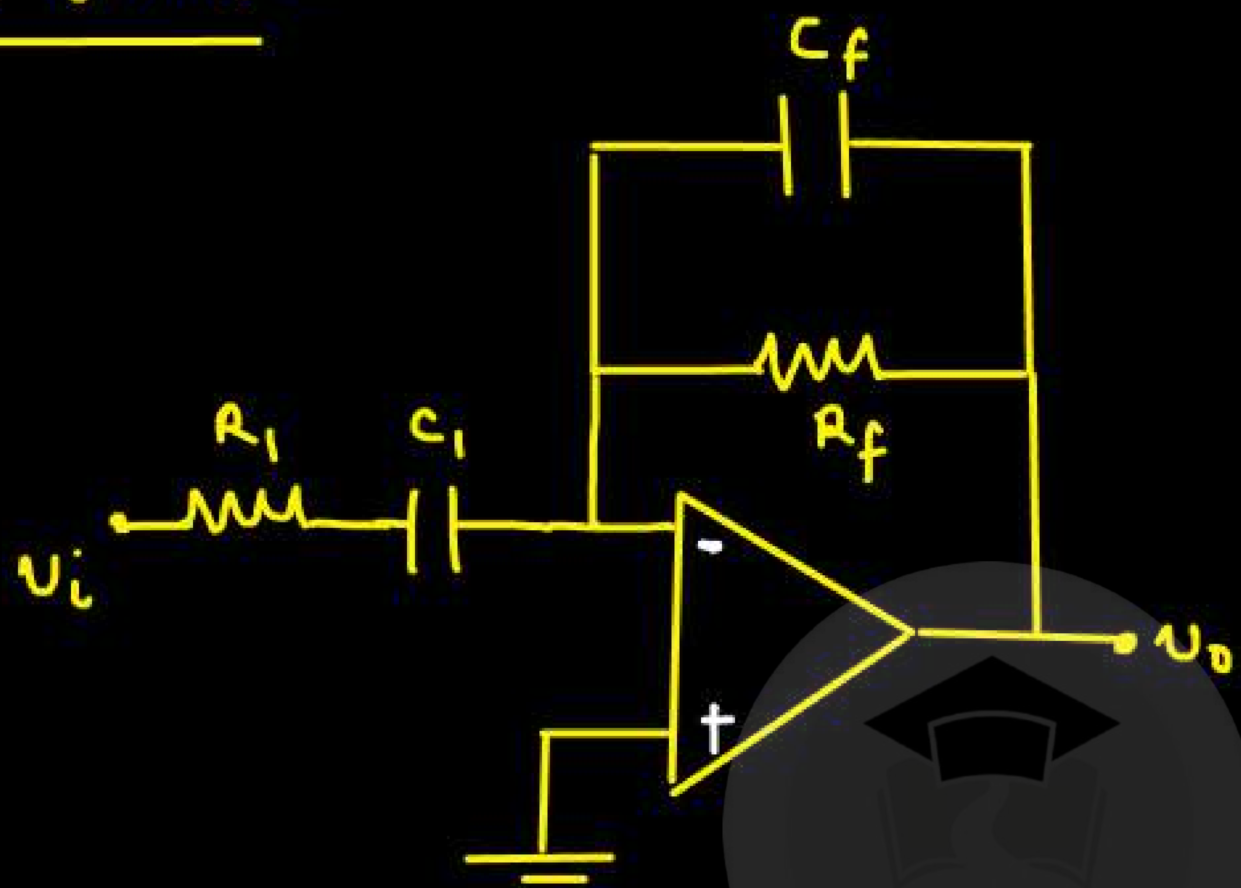
$\Rightarrow$ $\boxed{\text{LPF}}$

$\omega = \infty$

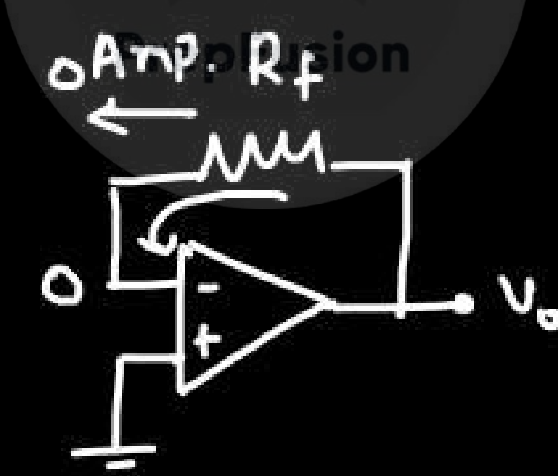


$$\boxed{v_0(\omega=\infty) = 0}$$

③ Band Pass Filter:-



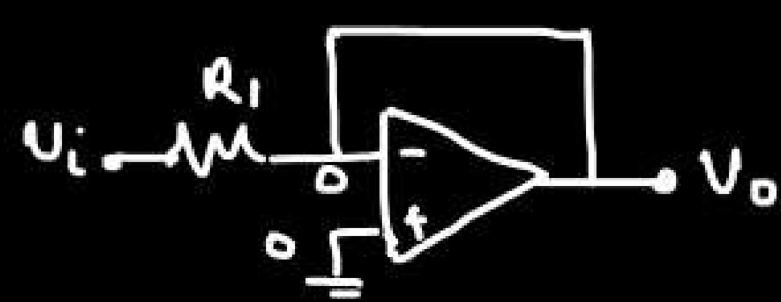
$\omega = 0 \Rightarrow$



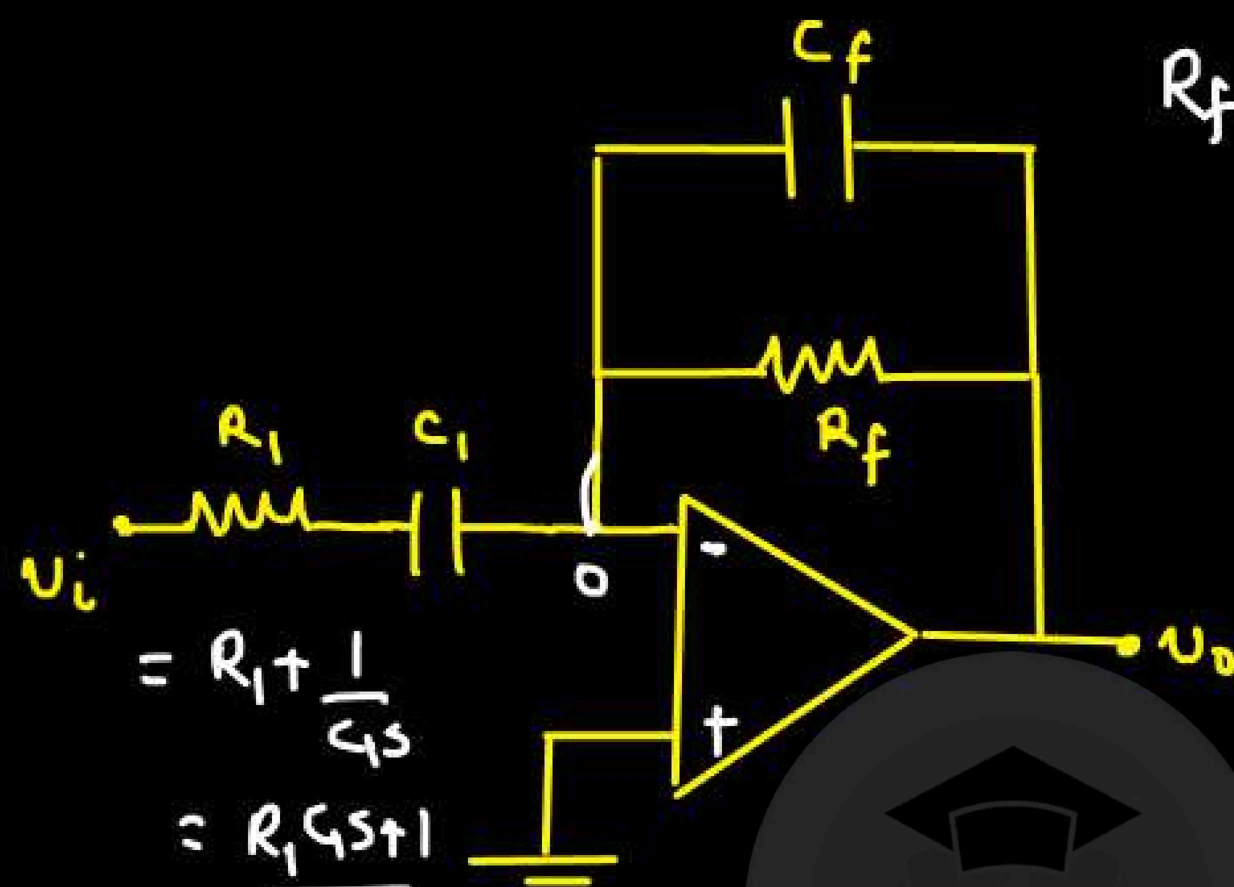
$\Rightarrow \boxed{V_o(\omega=0) = 0\,V}$

$\Rightarrow \boxed{BPF}$

$\omega = \infty \Rightarrow$



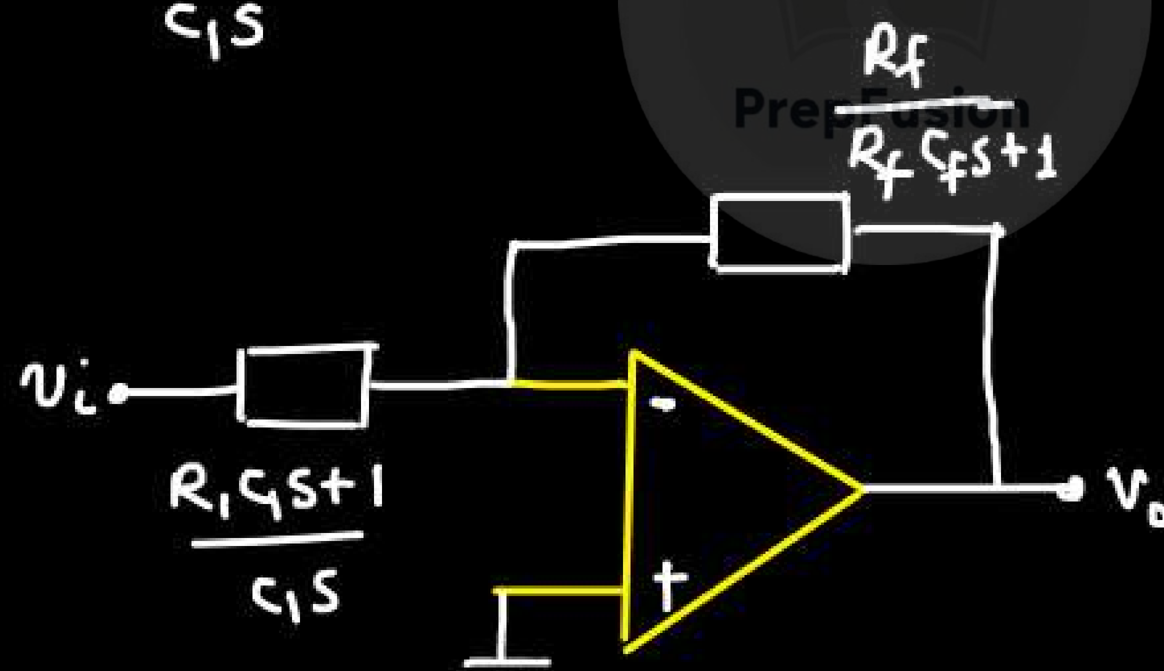
$\boxed{V_o(\omega=\infty) = 0\,V}$



$$R_f \,\|\, \frac{1}{C_f s} = \frac{R_f}{R_f C_f s + 1}$$

$$= R_1 + \frac{1}{C_1 s}$$

$$= \frac{R_1 C_1 s + 1}{C_1 s}$$

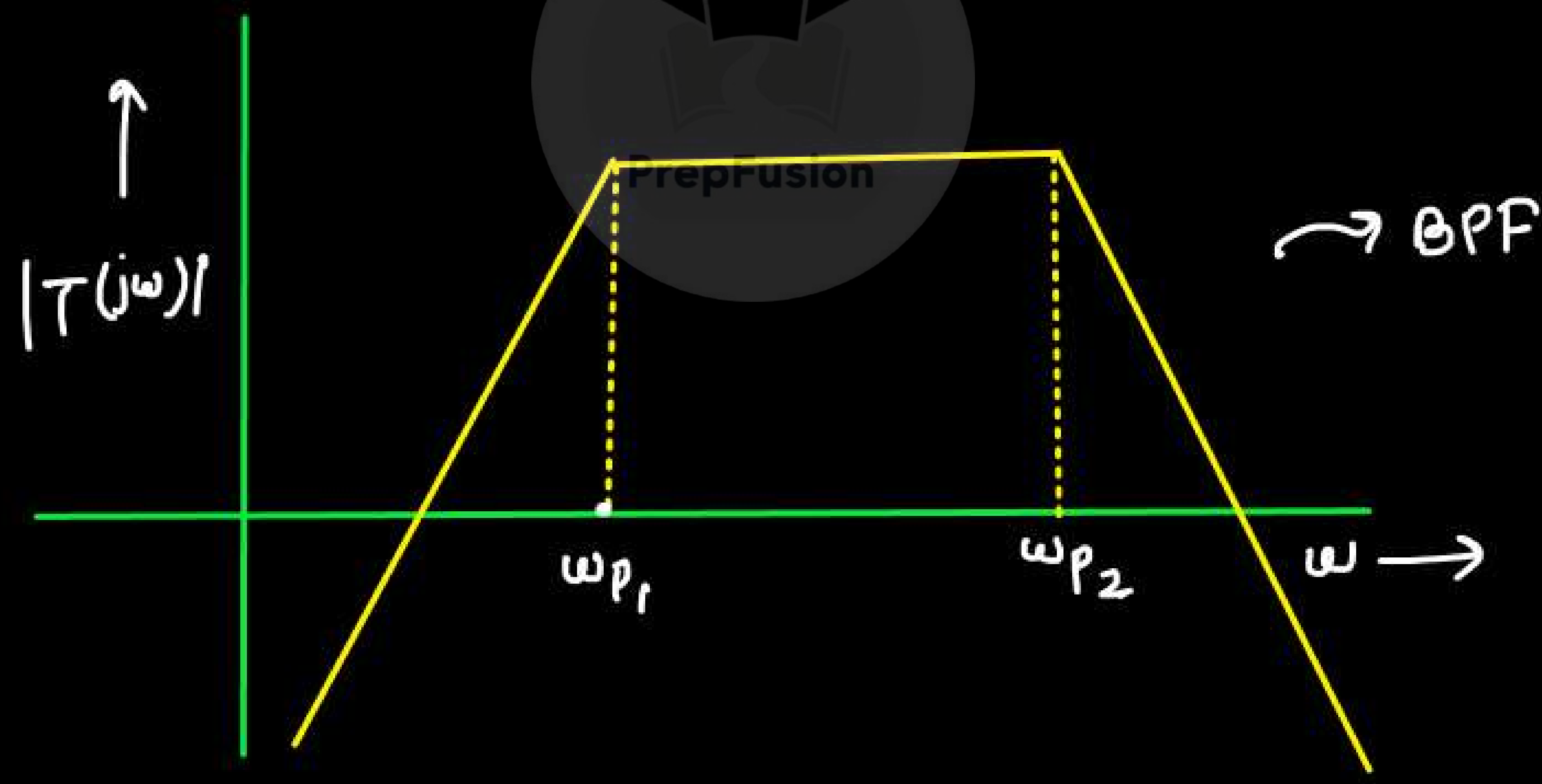


$$\frac{v_o(s)}{v_i(s)} = \frac{\dfrac{-R_f}{R_f C_f s + 1}}{\dfrac{R_1 C_1 s + 1}{C_1 s}}$$

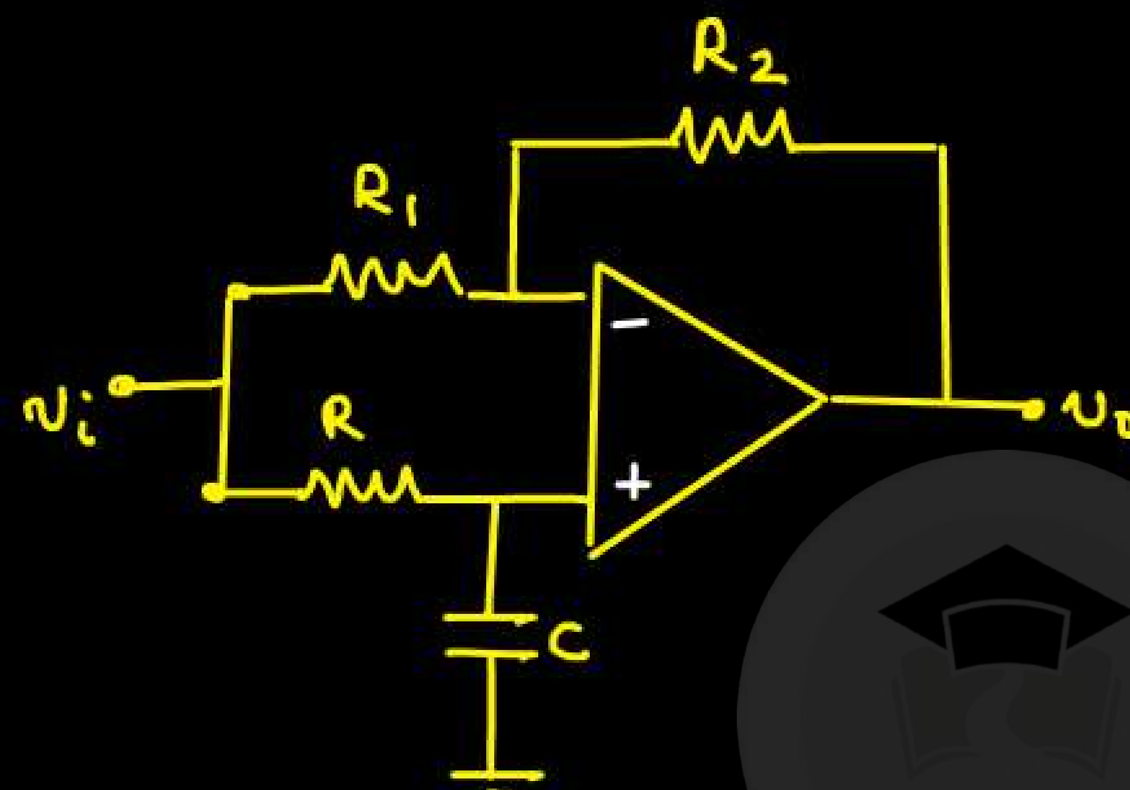
$$\boxed{\frac{v_o(s)}{v_i(s)} = \frac{-R_f C_1 s}{(R_f C_f s + 1)(R_1 C_1 s + 1)}}$$

$\omega_z = 0$

$$\omega_P = \frac{1}{R_f C_f} \qquad \omega_P = \frac{1}{R_1 C_1}$$

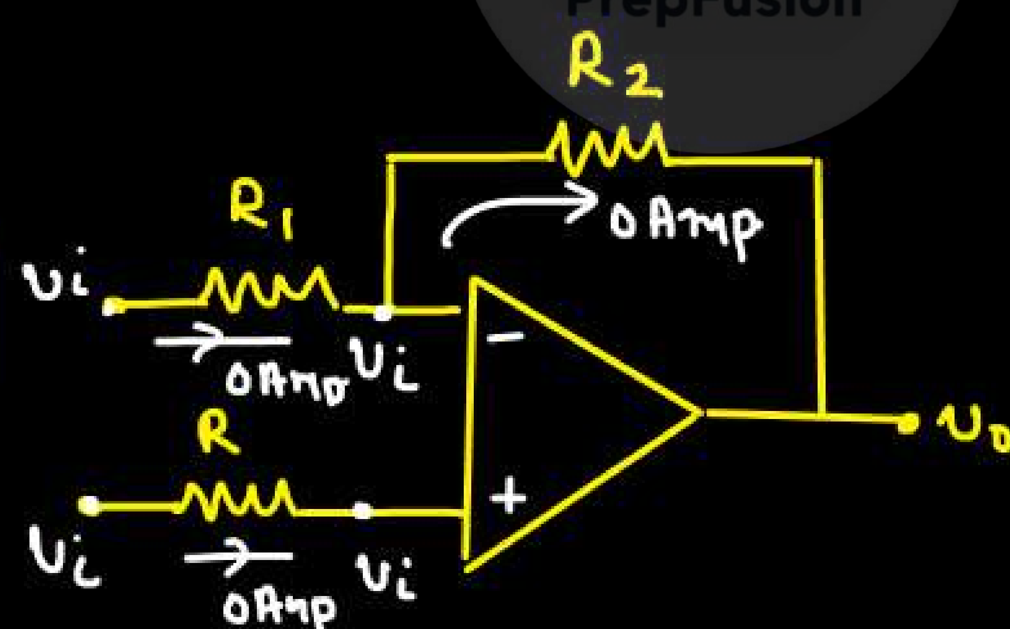


④ All Pass Filter:-

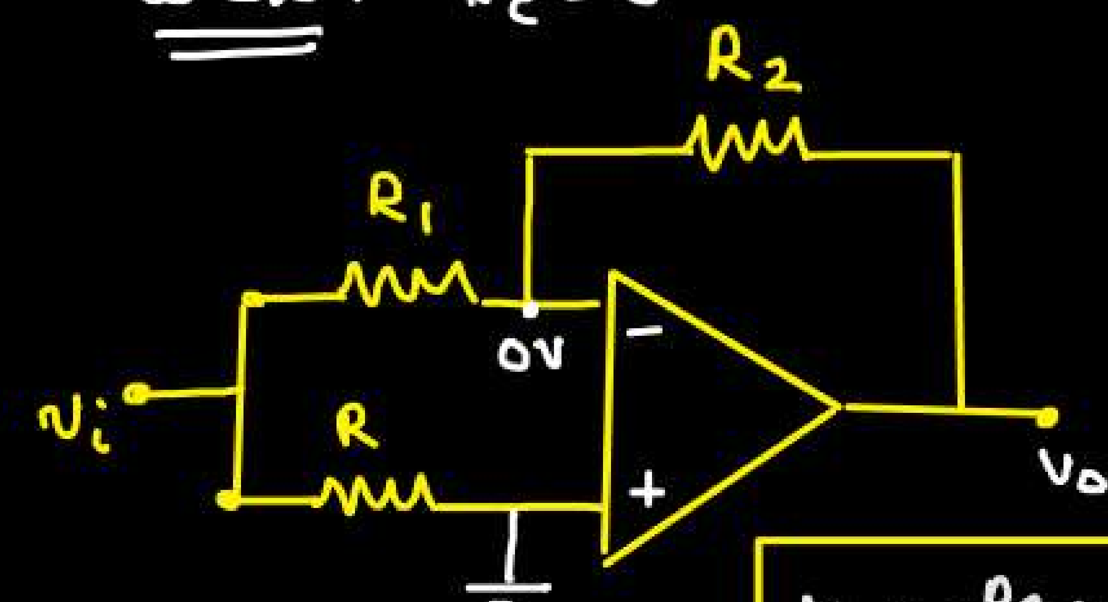


$\omega = 0$:- $X_c = \infty$

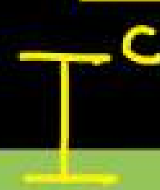
$$\boxed{V_o(\omega = 0) = V_i}$$



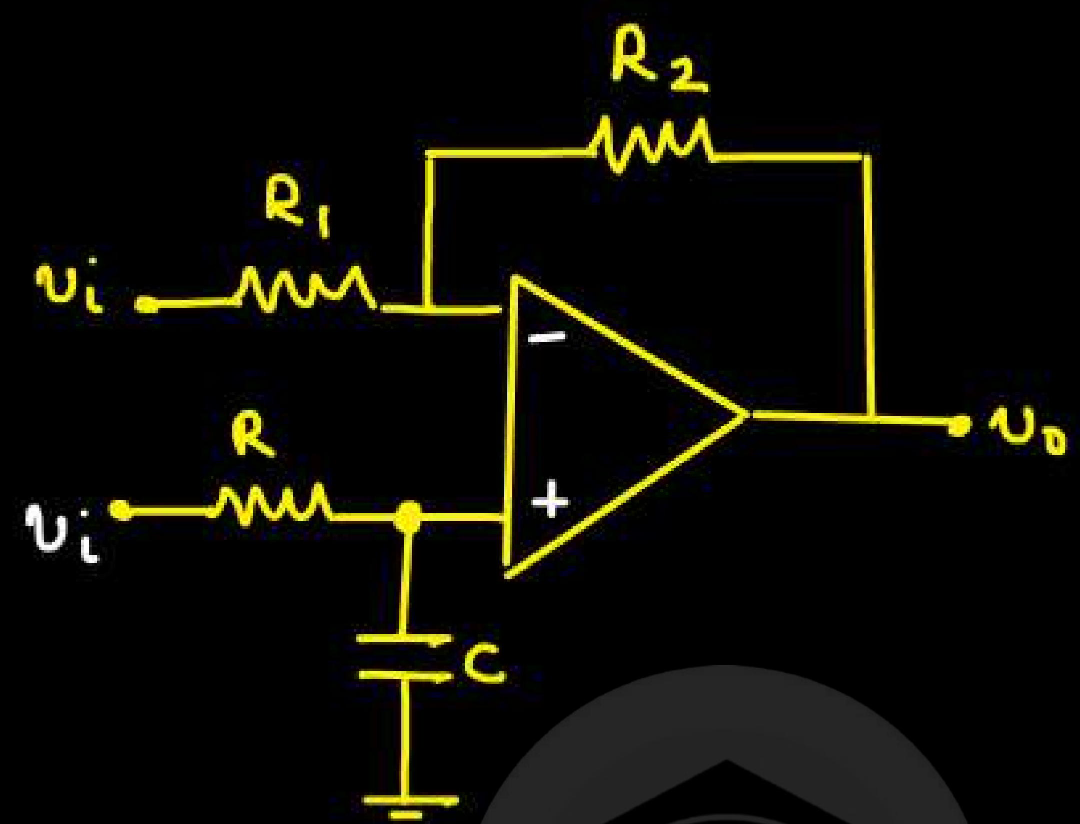
$\omega = \infty$:- $X_c = 0$



$$\boxed{V_o = -\frac{R_2}{R_1} V_i}$$



V_o



$$v_o(s) = \left(1+\frac{R_2}{R_1}\right)\times\frac{1}{RCs+1}v_i(s) - \frac{R_2}{R_1}v_i(s)$$

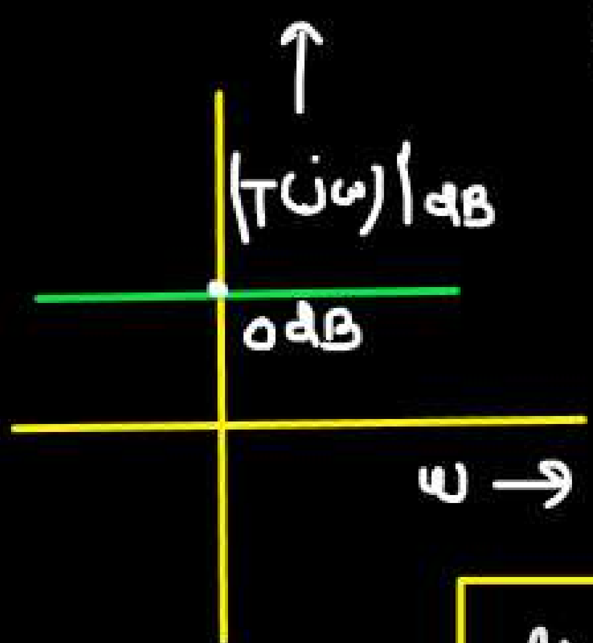
$$= \frac{v_i(s)}{1+RCs} + \frac{R_2}{R_1}v_i(s)\left[\frac{1}{1+RCs}-1\right]$$

$$= \frac{v_i(s)}{1+RCs} + \frac{R_2}{R_1}v_i(s)\left[\frac{-sRC}{1+sRC}\right]$$

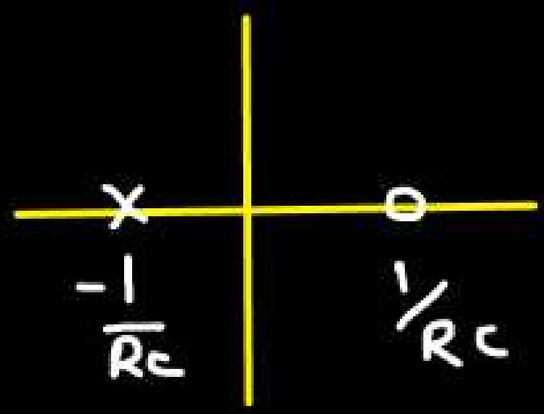
$$\boxed{v_0(s) = \frac{v_i(s)}{1+sRC}\left[1 - \frac{R_2}{R_1}sRC\right]}$$

$$\omega_p = -\frac{1}{RC} \qquad \omega_z = \frac{R_1}{R_2 RC} \rightarrow \text{BSF}$$

But if $R_2/R_1 = 1$



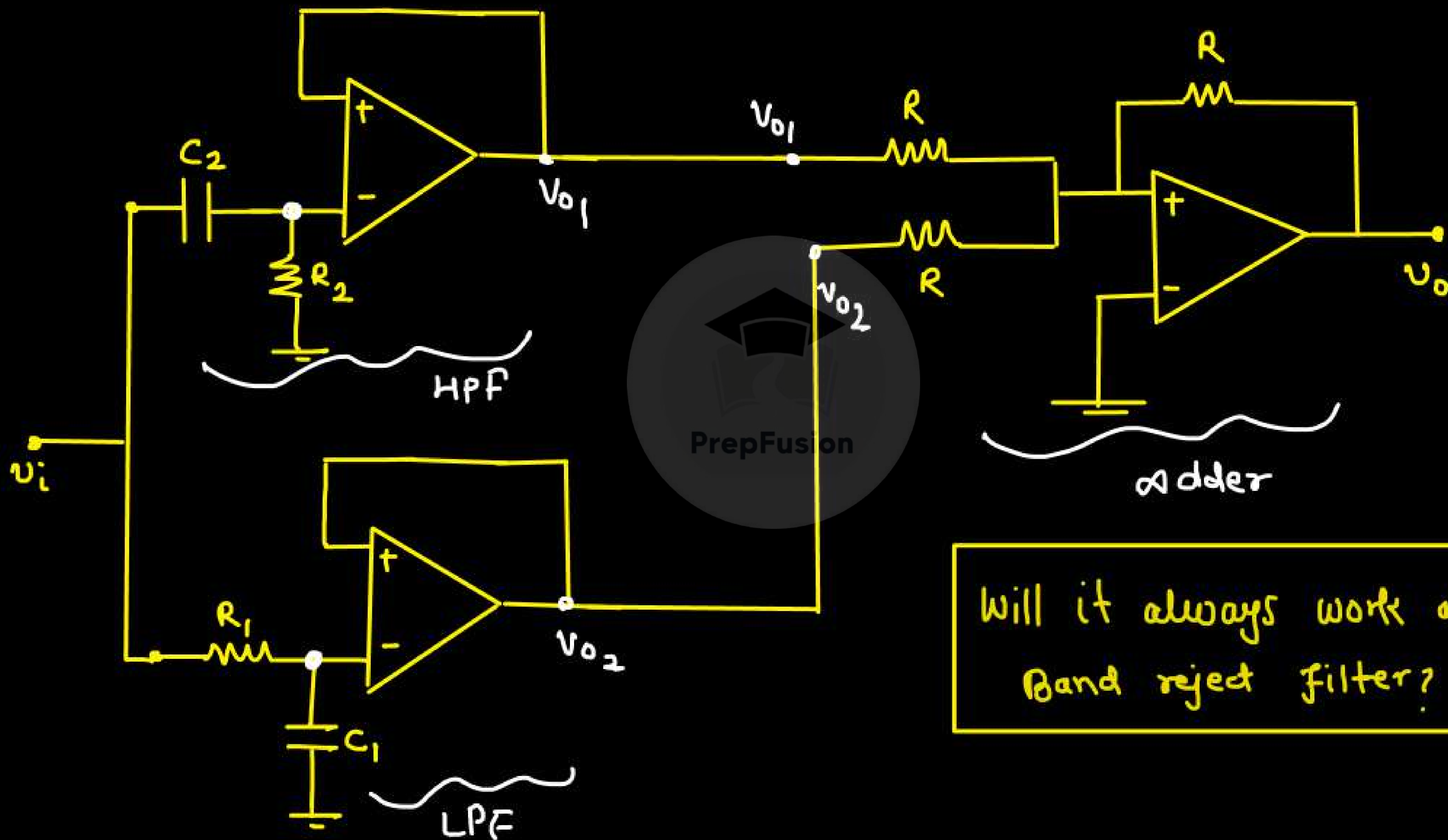
$$\omega_p = -\frac{1}{RC}, \quad \omega_z = \frac{1}{RC} \rightarrow \text{APF}$$



$$\boxed{\frac{v_0(s)}{v_i(s)} = \frac{1-sRC}{1+sRC}}$$

$$|T(j\omega)| = \frac{\sqrt{1+\omega^2R^2C^2}}{\sqrt{1+\omega^2R^2C^2}} = 1$$

⑤ Band Reject Filter :- / Band stop Filter



Will it always work as Band reject Filter?

$$V_{o_1}(s) = \frac{sR_2C_2}{1+sR_2C_2}\, v_i(s)$$

$$V_{o_2}(s) = \frac{1}{1+sR_1C_1}\, v_i(s)$$

$$v_o = -2\left[\frac{v_{o_1}+v_{o_2}}{2}\right]$$

$$= -v_{o_1} - v_{o_2} = -(v_{o_1}+v_{o_2})$$

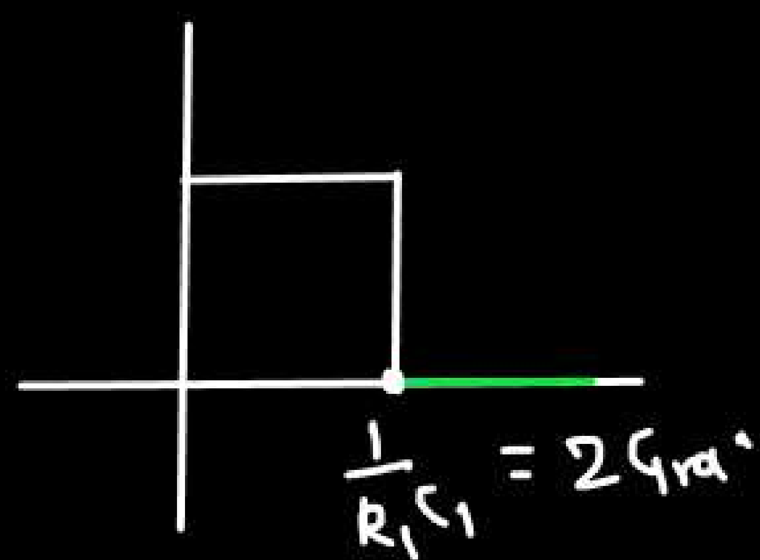
$$v_o = -\left[\frac{1}{1+sR_1C_1} + \frac{sR_2C_2}{1+sR_2C_2}\right] v_i(s)$$

$$\frac{v_o(s)}{v_i(s)} = -\left[\frac{1+sR_2C_2+sR_2C_2+s^2R_1R_2C_1C_2}{(1+sR_1C_1)(1+sR_2C_2)}\right]$$

$$\boxed{\frac{v_o(s)}{v_i(s)} = -\frac{1 + 2sR_2C_2 + s^2R_1R_2C_1C_2}{(1+sR_1C_1)(1+sR_2C_2)}}$$

$\downarrow$

Two poles, Two zeros



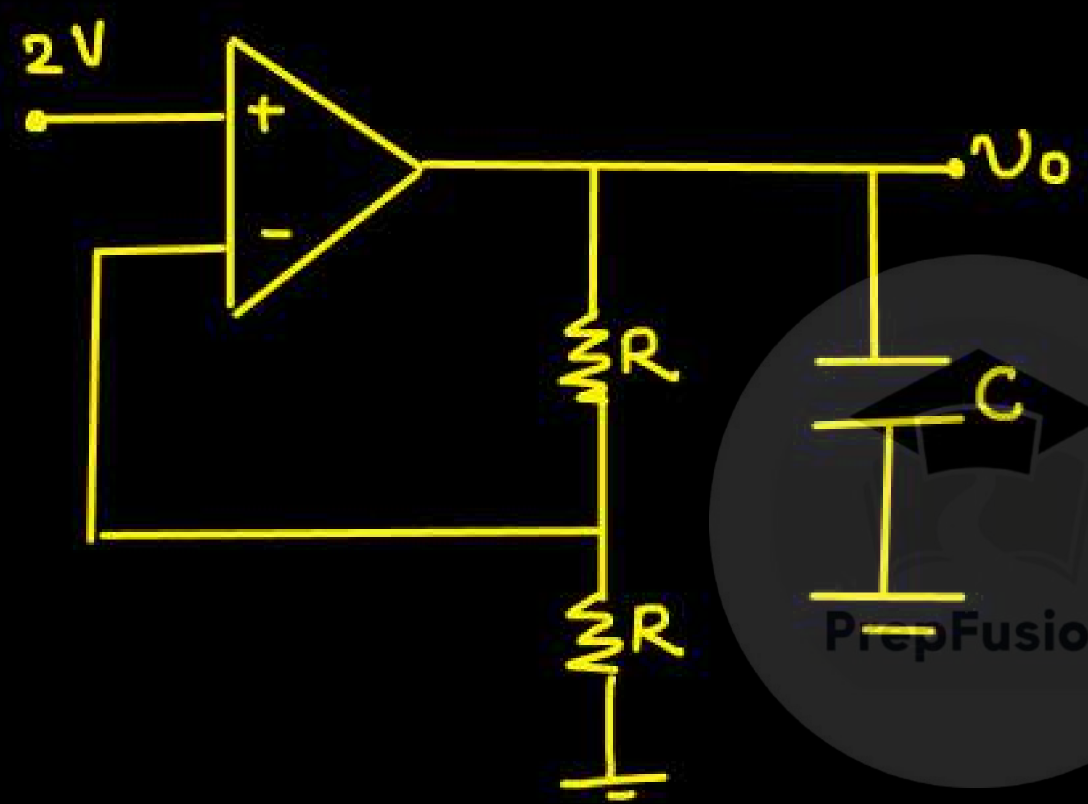
+

if $\frac{1}{R_1C_1} > \frac{1}{R_2C_2} \Rightarrow$ The filter doesn't act as B.S.F.

if $\frac{1}{R_1C_1} < \frac{1}{R_2C_2}$ or $\boxed{R_1C_1 > R_2C_2} \Rightarrow$ The filter acts as B.S.F.

Assignment - 14

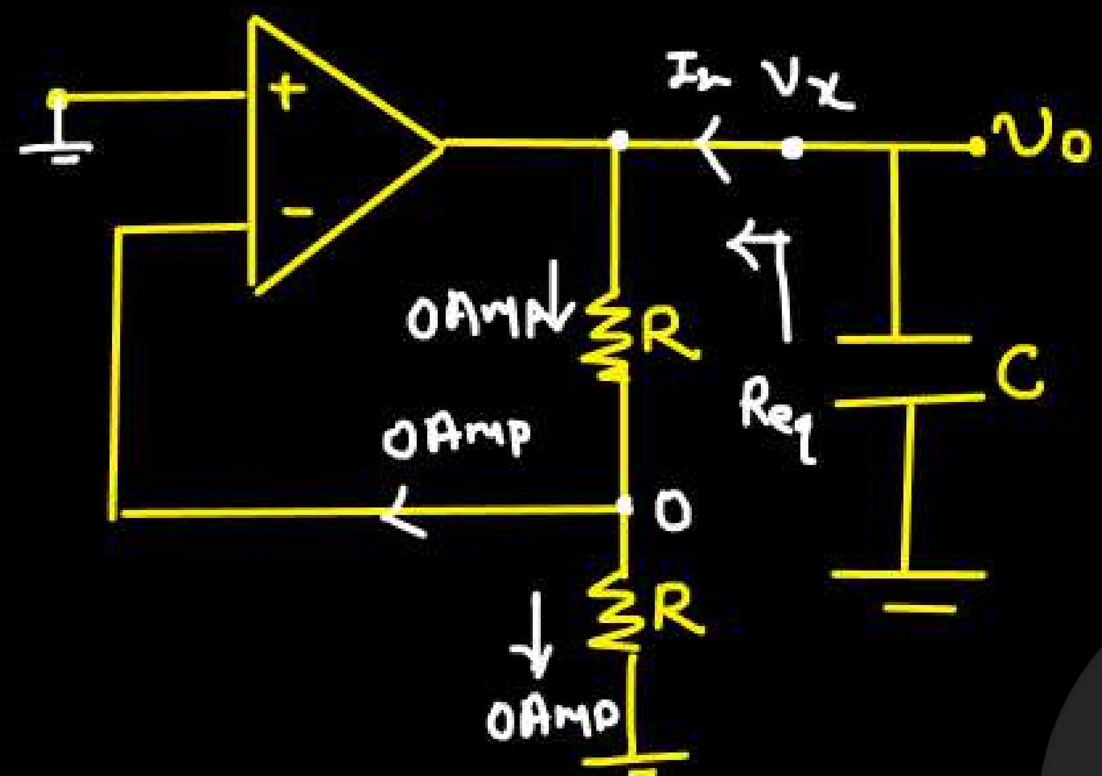
Q. 1



What is the time constant of the ckt?

→

M-I :-

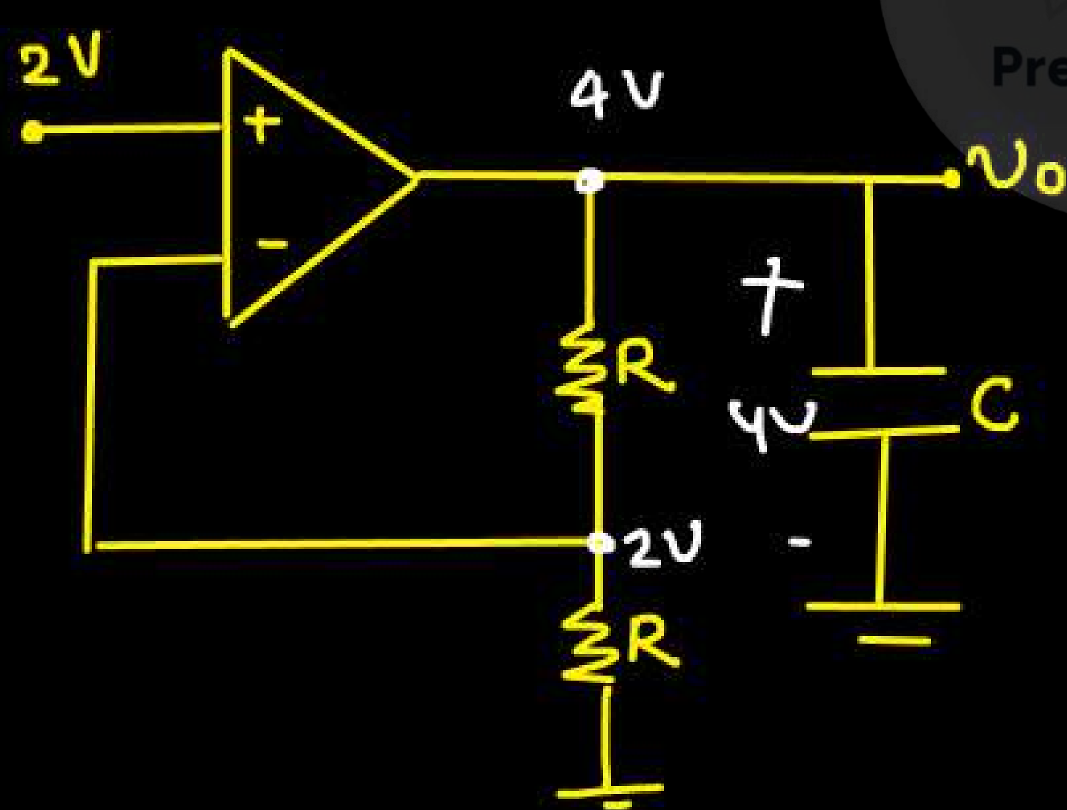


$\tau = R_{eq}\, C$

$R_{eq} = \frac{V_x}{I_x} = \frac{0}{I_x} = 0\,\Omega$

$\boxed{\tau = 0}$

M-II :-

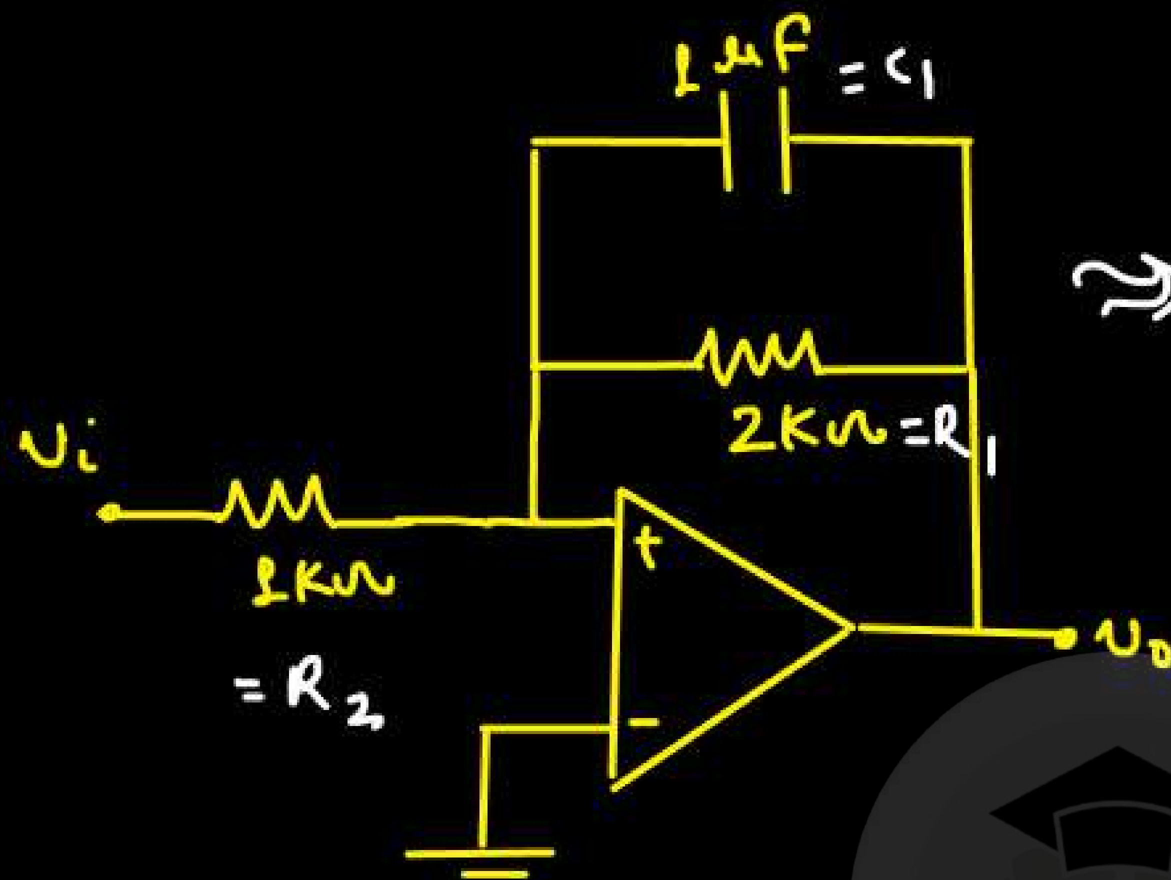


$\boxed{V_0 = 4V}$

$\boxed{\tau = 0}$

$\Rightarrow$ $\boxed{\text{zero order ckt}}$

Q.



$$\Rightarrow R_1 \parallel \frac{1}{C_1 s} = \frac{R_1}{R_1 C_1 s + 1}$$

(a) Find the type of Filter?

(b) DC gain = ?

(c) 3-dB Bandwidth = ?

(d) Unity gain Bandwidth = ? (Approx)

(a) $\omega = 0 \Rightarrow v_o = -2v_i$

$\omega = \infty \Rightarrow v_o = 0$

$\boxed{\Rightarrow \text{L.P.F.}}$

(b) Dc gain (gain @ $\omega = 0$) :-

$$\boxed{\frac{v_o}{v_i} = -2}$$

(c) $$\frac{V_o(s)}{V_i(s)} = -\frac{R_1}{(R_1 C_1 s + 1) R_2}$$

$$\boxed{\omega_{3\text{-dB}} = \frac{1}{R_1 C_1} = \frac{1}{2k \times 1\mu} = 0.5\,k\,\text{rad/sec.}}$$

(d) $$\boxed{\omega_{UGB} \approx |\text{Dc gain}| \times \omega_{3\text{-dB}}}$$

$\approx 2 \times 0.5\,k$ rad/sec

$\approx 1\,k$ rad/sec.

approx

(d) $$\frac{V_o(s)}{V_i(s)} = \frac{-R_1/R_2}{R_1C_1 s + 1} = \frac{-2}{2\times10^{-3}s+1} = T(s)$$

$$|T(j\omega)| = \frac{2}{\sqrt{1+\omega^2\times 4\times10^{-6}}}$$

at $\omega = \omega_{UGB}$

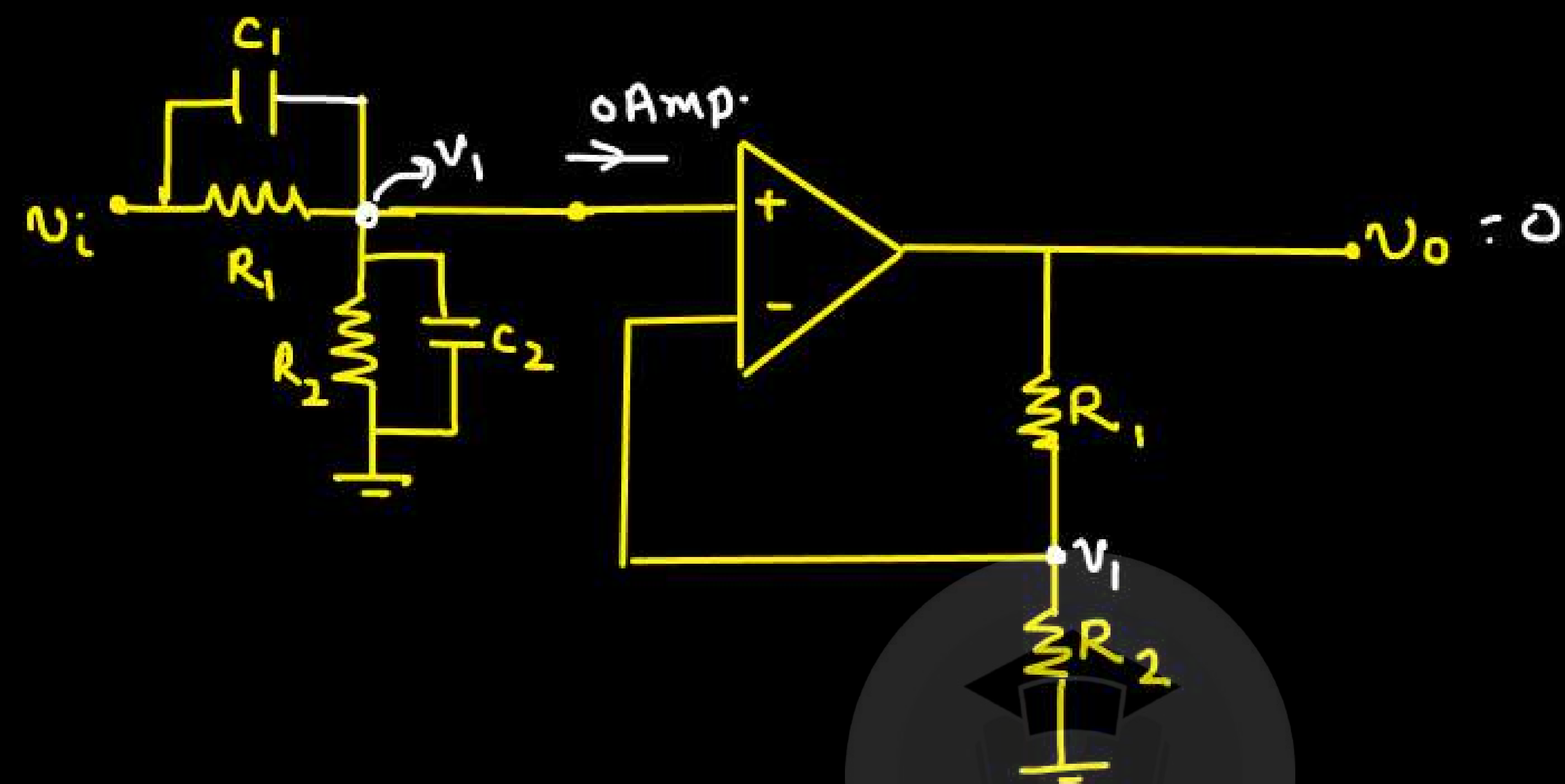
$$|T(j\omega_{UGB})| = 1 = \frac{2}{\sqrt{1+\omega^2\times4\times10^{-6}}}$$

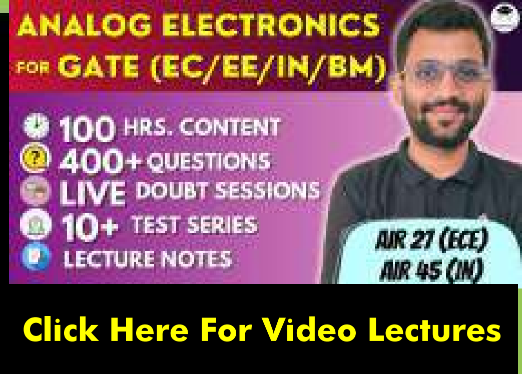
$$\omega^2\times4\times10^{-6} = 3$$

$$\omega_{UGB} = \sqrt{3}/2 \text{ K rad/sec.}$$

$$\boxed{\omega_{UGB} = 0.87 \text{ Krad/sec.}} \rightarrow \text{Exact}$$

Q.





(a) what is the order of the ckt?

(b) What kind of filter is that?

→ (a) 1st order

(b) @ $\omega = 0$

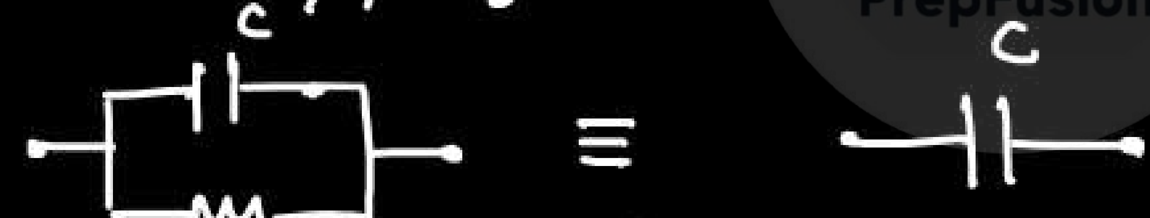
$$V_1 = \frac{R_2}{R_1 + R_2} v_i$$

$$v_o = \left(1 + \frac{R_1}{R_2}\right) \times \frac{R_2}{R_1 + R_2} v_i$$

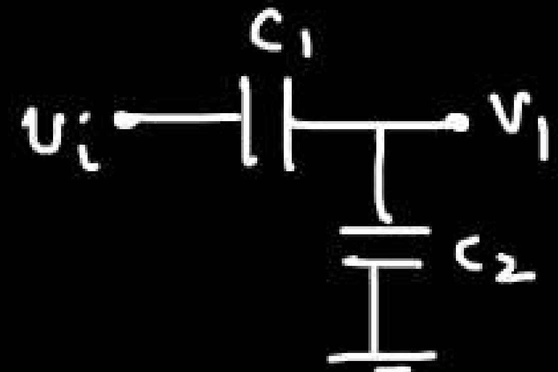
$$\boxed{v_o = v_i}$$

@ $\omega = \infty$

C → very low Z



R is finite Z



$$V_1 = \frac{C_1}{C_1 + C_2} v_i$$

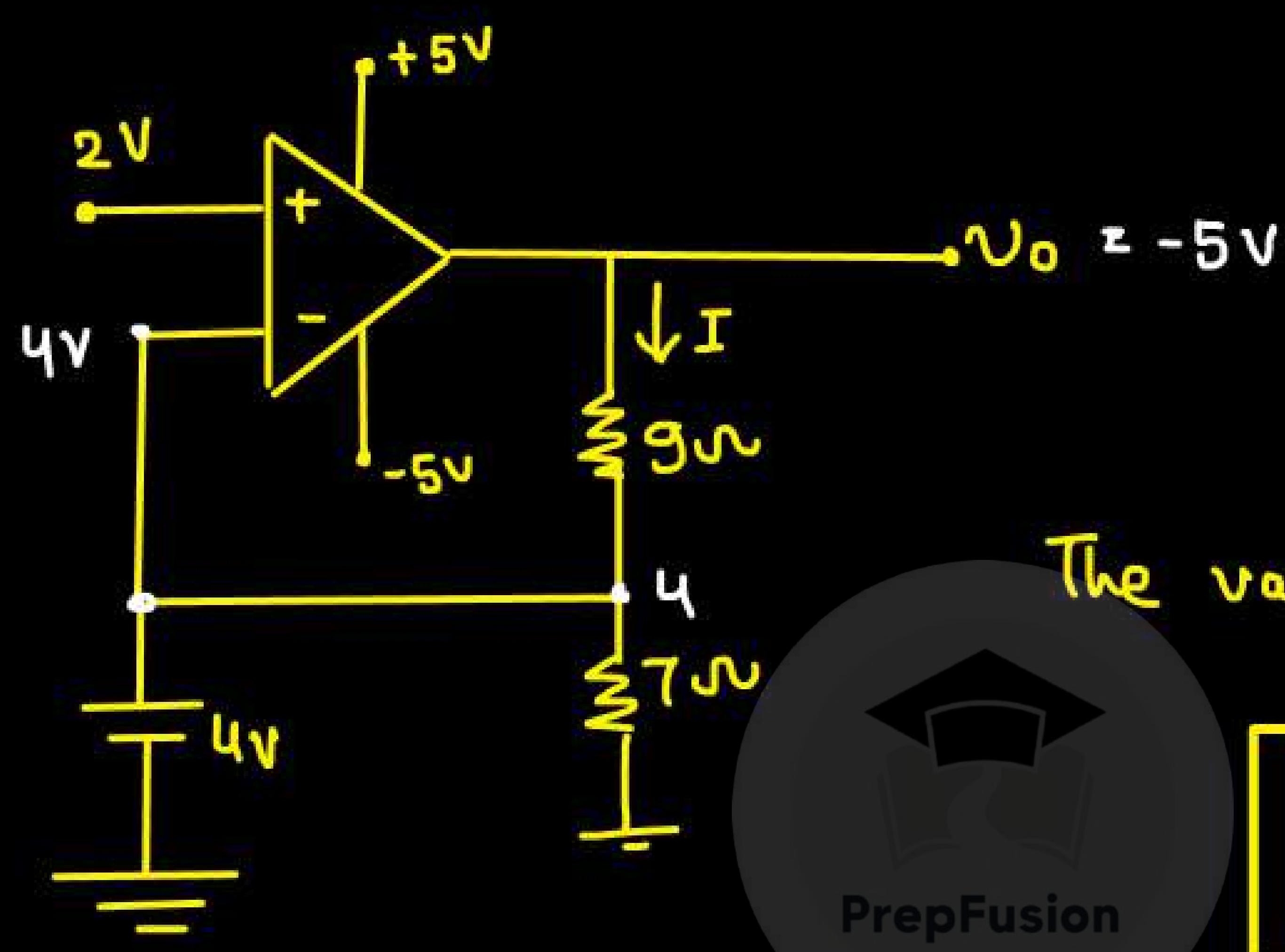
⇒ $\boxed{\text{APF or BSF}}$?

$$\omega_p = \frac{1}{(R_1 \| R_2)(C_1 + C_2)}, \quad \omega_z = \frac{1}{R_1 C_1}$$

⇒ $\boxed{\text{BSF}}$ ✓

$$\boxed{v_o = \left(1 + \frac{R_1}{R_2}\right)\left(\frac{C_1}{C_1 + C_2}\right) v_i}$$

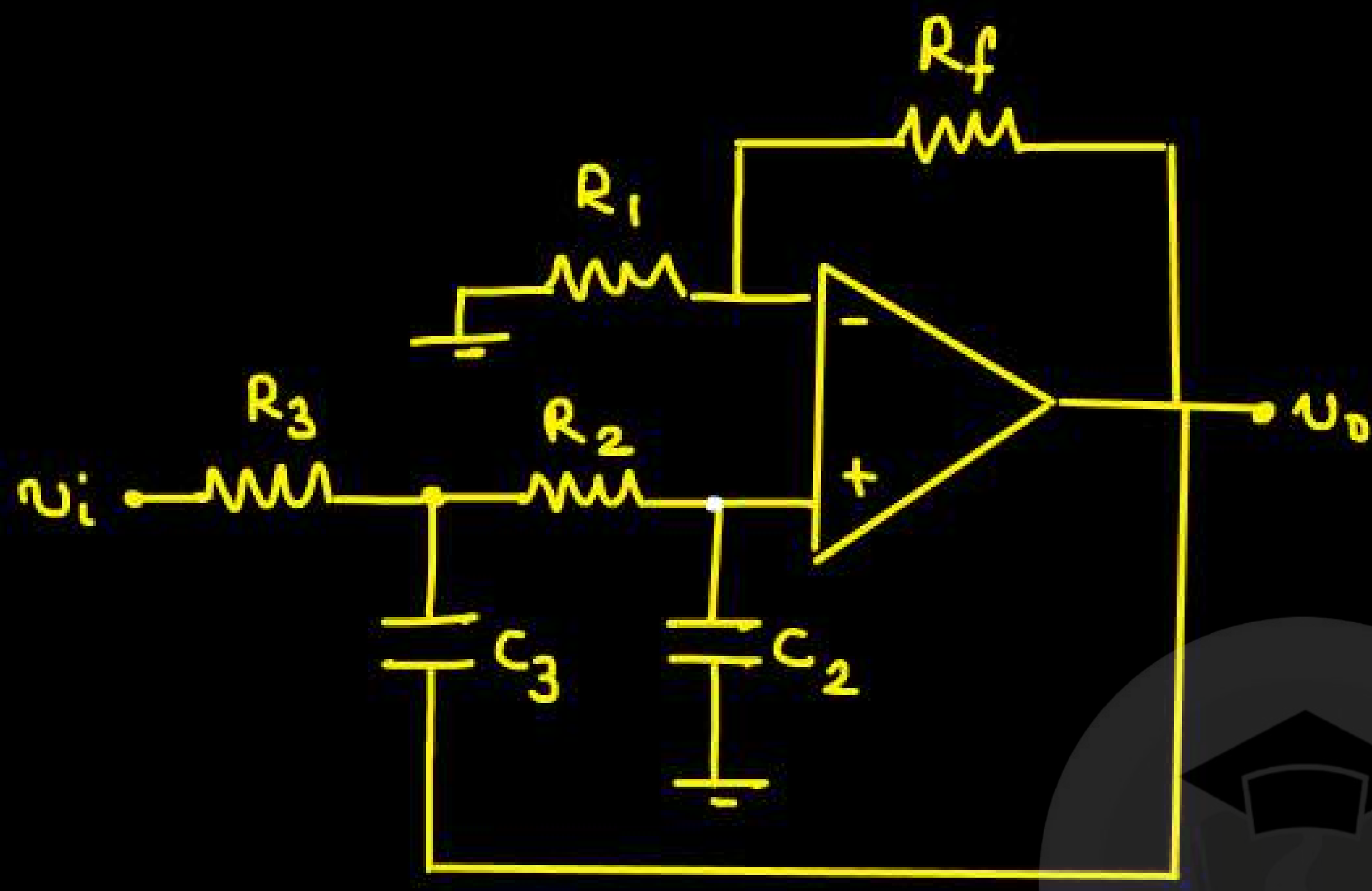
Q.



The value of current I is __ ?

$$\boxed{I = \frac{-5-4}{9} = -1\,\text{Amp}}$$

Q.



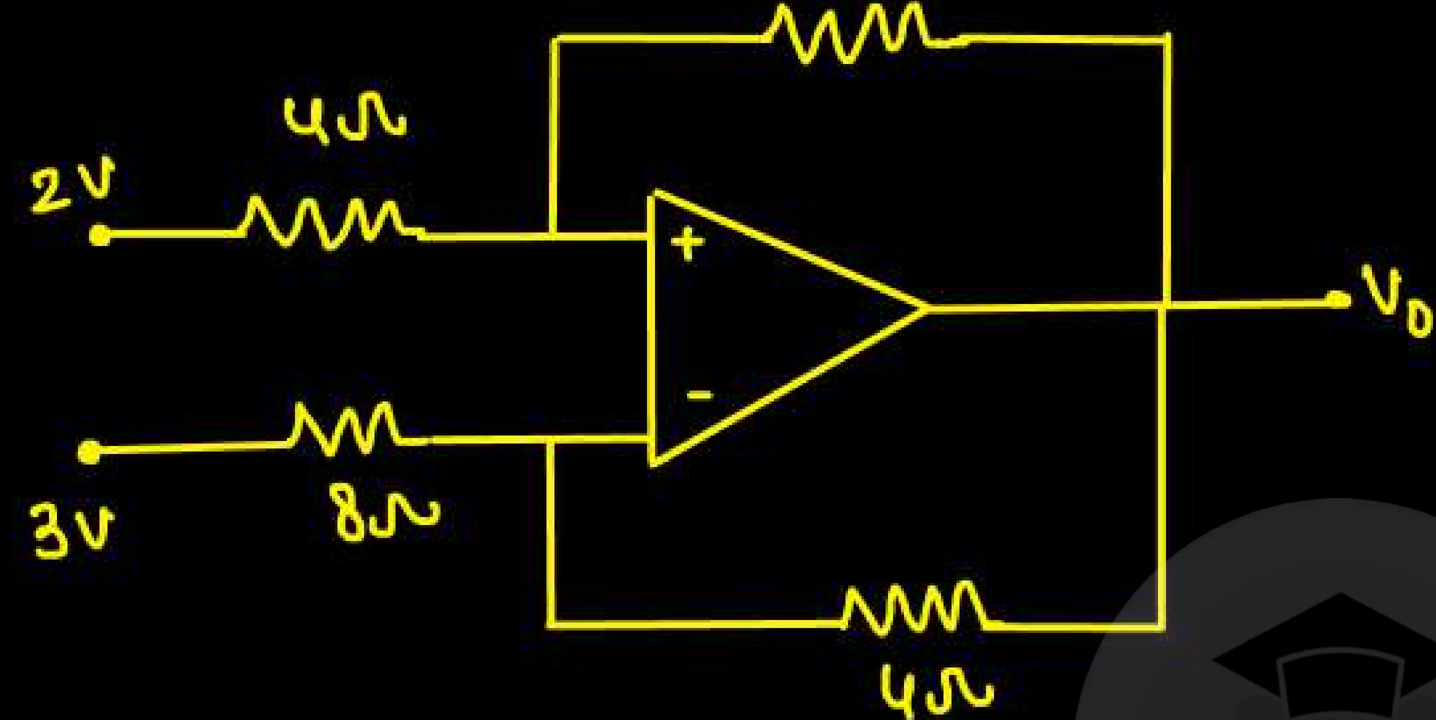
Determine the type of Filter.

$\Rightarrow \quad \omega = 0 \Rightarrow v_o = \left(1 + \frac{R_f}{R_1}\right) v_i$

$\omega = \infty \Rightarrow V_o = 0$

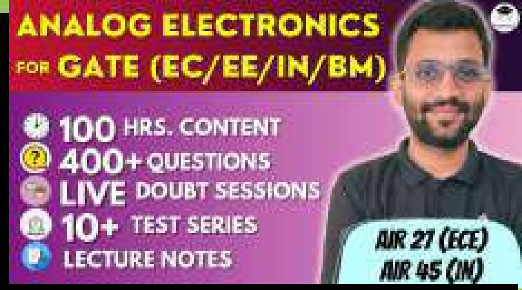
$\Rightarrow \boxed{L.P.F.}$

Q.

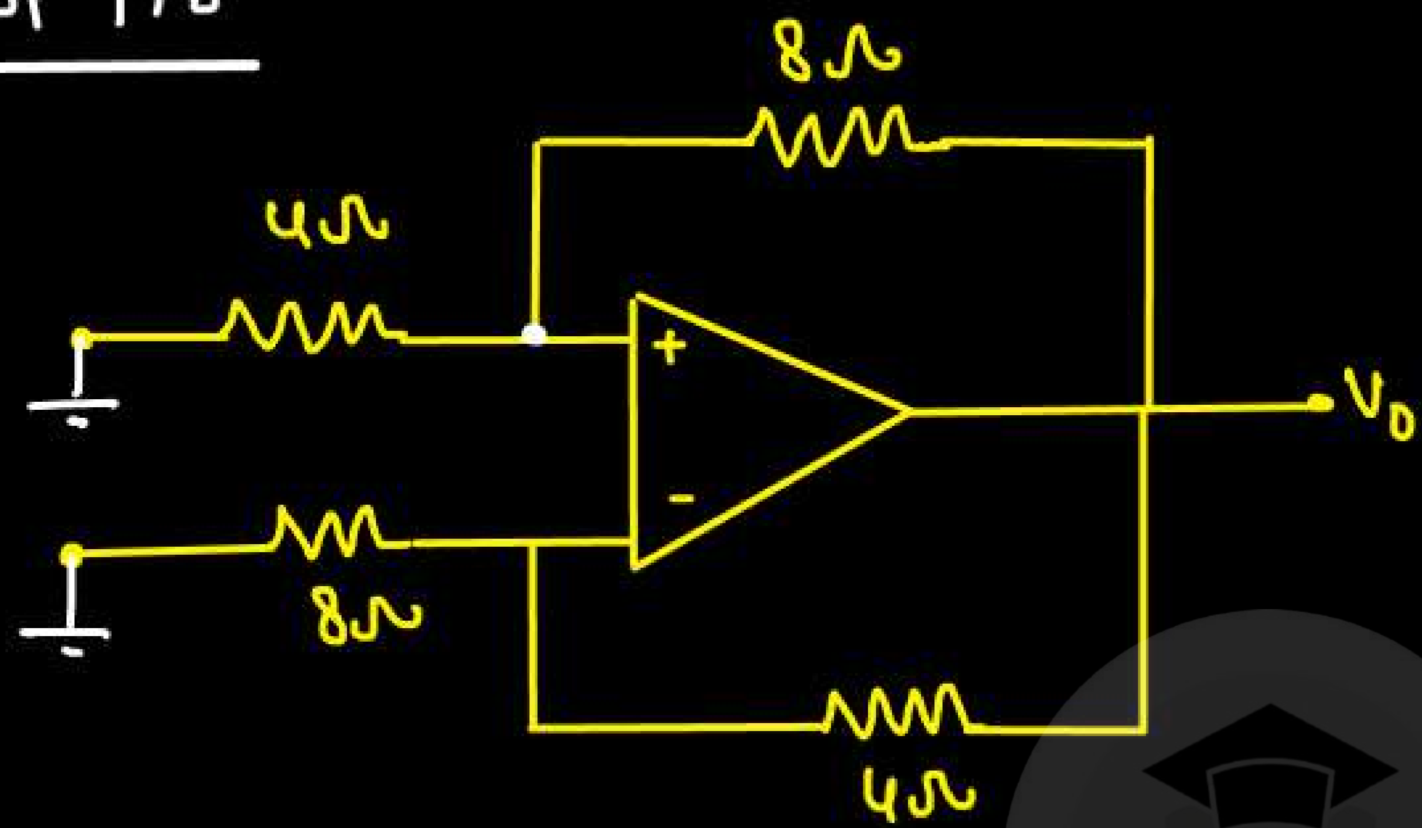


(a) which Feedback is present in the circuit?

(b) Find V_0.



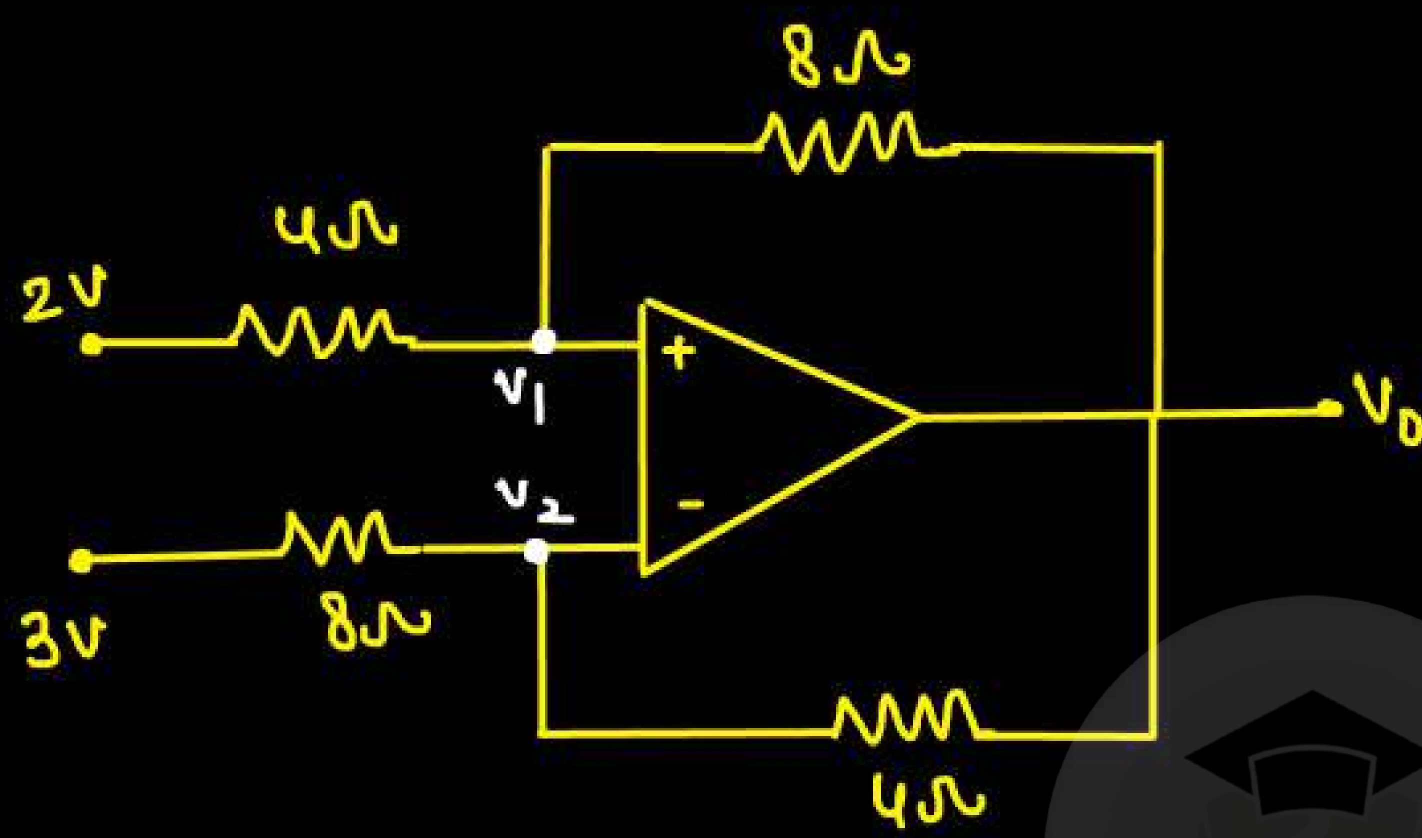
Type of f/b :-



$$v_+ = \frac{4}{12} v_0 = v_0/3$$

$$v_- = \frac{8}{12} v_0 = 2v_0/3 \Rightarrow \text{dominating}$$

$\Rightarrow$ $\boxed{\text{Negative f/b}}$



$$v_1 = v_2$$

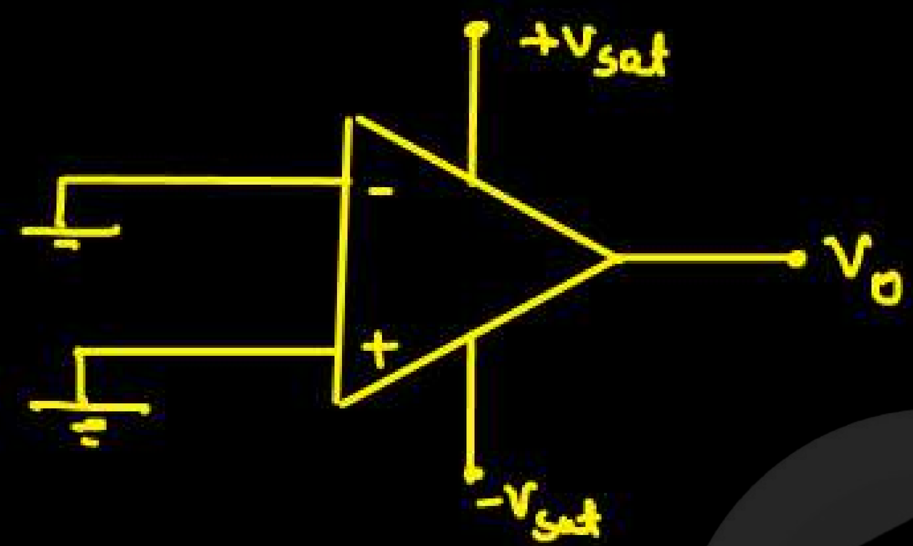
$$\frac{16 + 4v_0}{12} = \frac{8V_0 + 12}{12}$$

$$\boxed{V_0 = 1V}$$

⇒ Parameters of OP-Amp :-

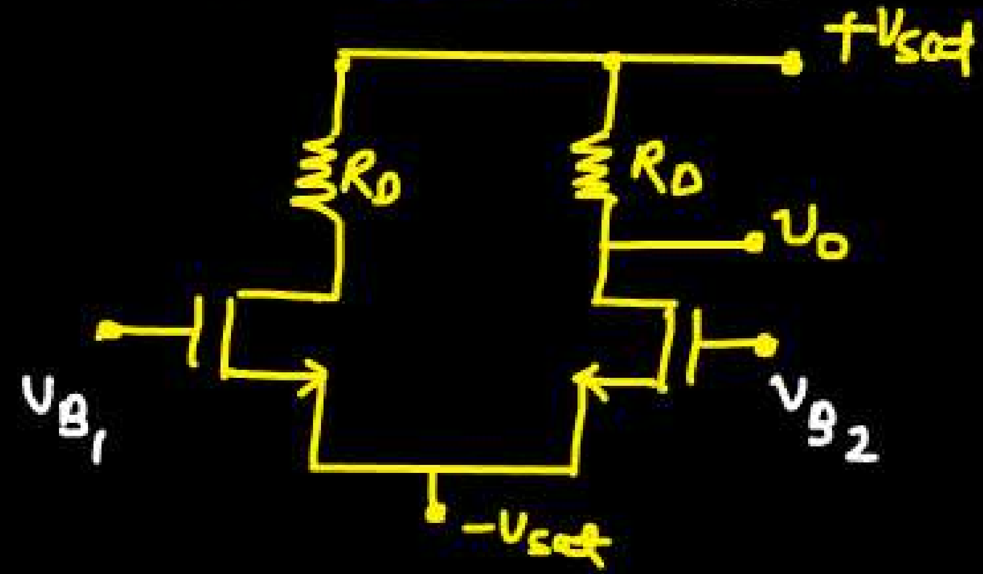
- Input offset Voltage
- Output offset Voltage
- Input offset current
- Input bias current
- CMRR
- Slew Rate
- Frequency Response

1. Input Offset Voltage:-

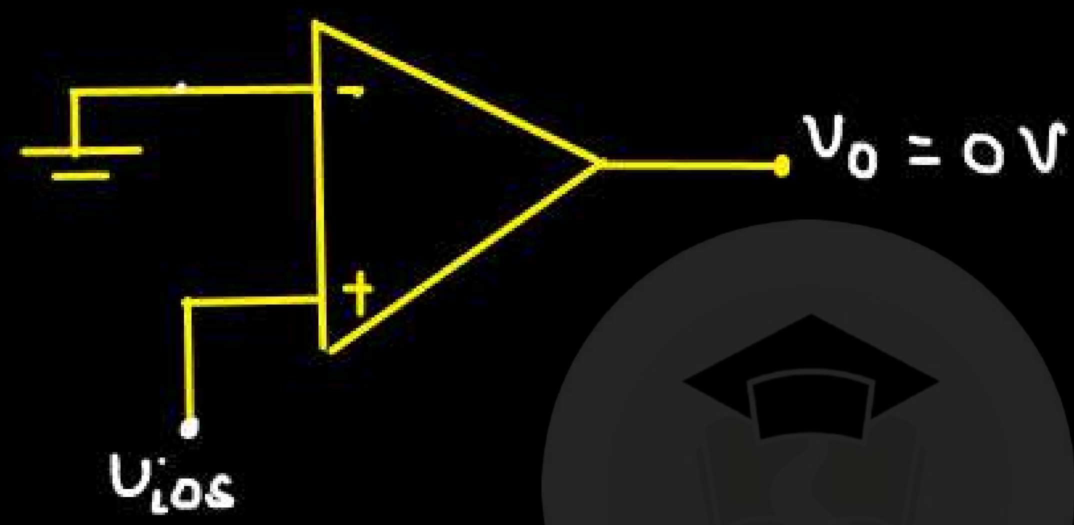


$$(V_o)_{expected} = 0\ V$$

$$(V_o)_{actual} = V_{OO}$$



So, at the input you apply a small offset voltage to make your output zero.

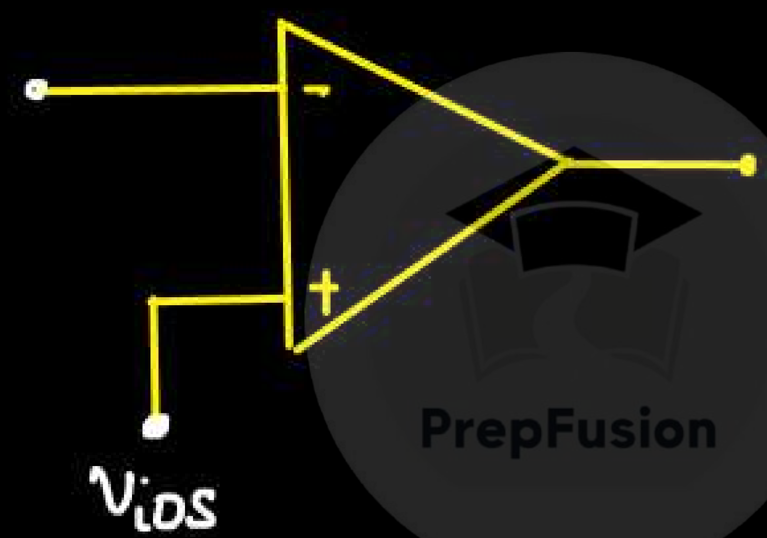


The amount of differential voltage that must be applied b/w two terminals of OP-Amp such that O/P of OP-Amp is zero, is known as input offset voltage.

$$\boxed{\text{Range :- mV to } \mu V}$$

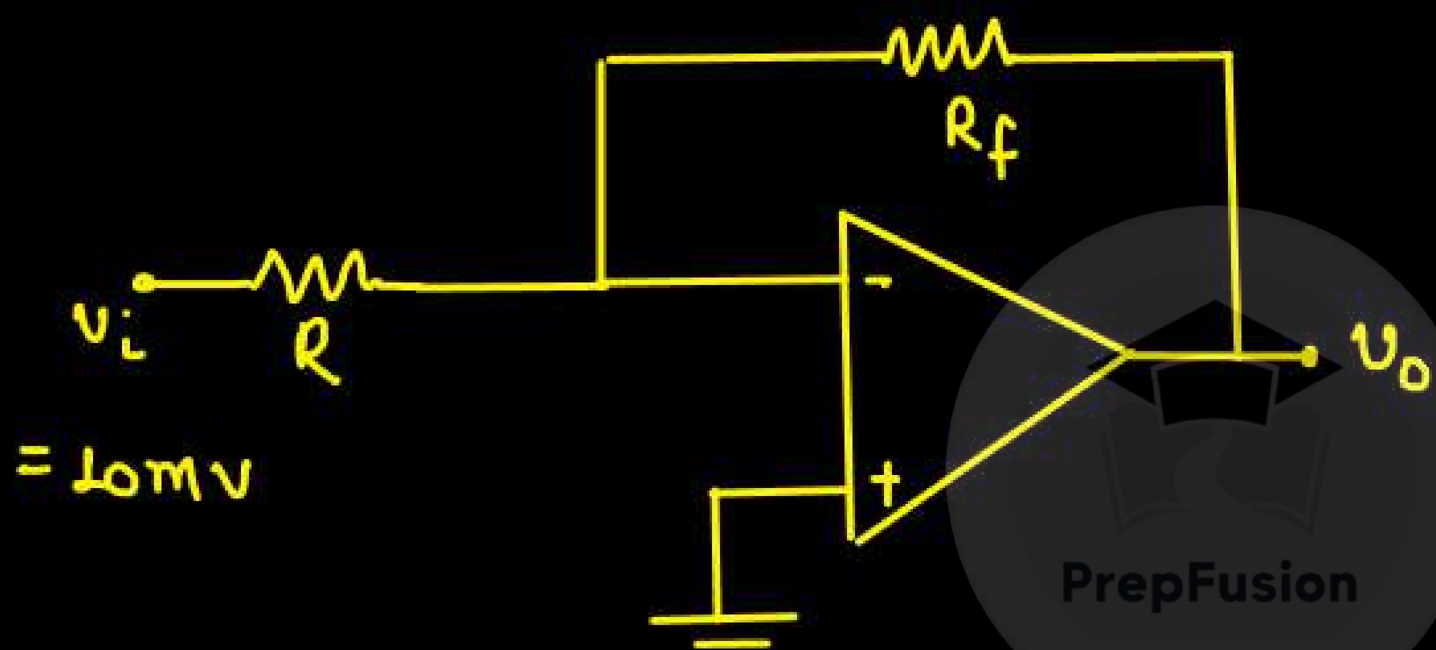
It's tough to predict the polarity of i/p offset voltage.

Generally, offset voltage is shown by a battery @ non-inverting terminal.



⇒ Effect of input offset voltage:-

★ Consider an inverting op-amp with $\frac{R_f}{R} = 100$

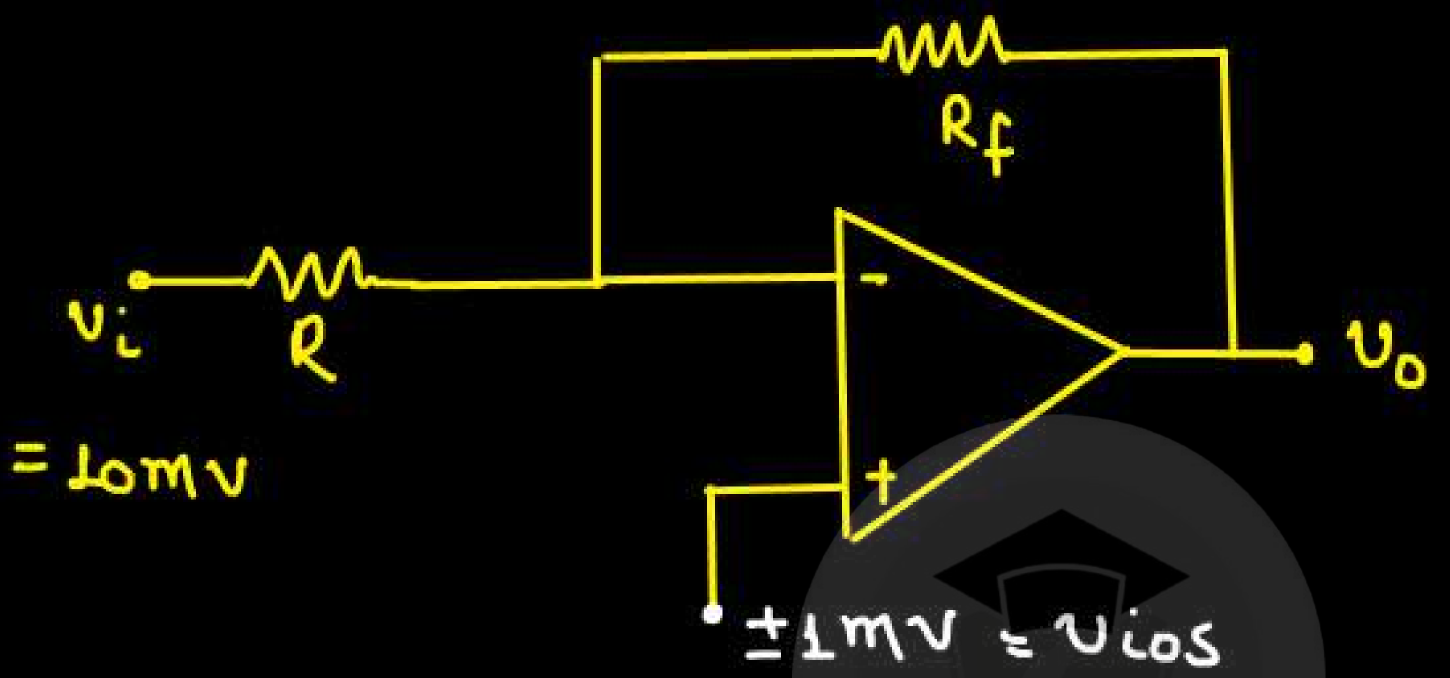


Considering zero offset, $\frac{v_o}{v_i} = \frac{-R_f}{R} = -100$

$$v_o = -100 \times 10mV$$

$$\boxed{v_o = -1V}$$

now, let there is an offset of ±1mV.



$$v_0 = -\frac{R_f}{R} v_i + \left[1 + \frac{R_f}{R}\right] v_{ios}$$

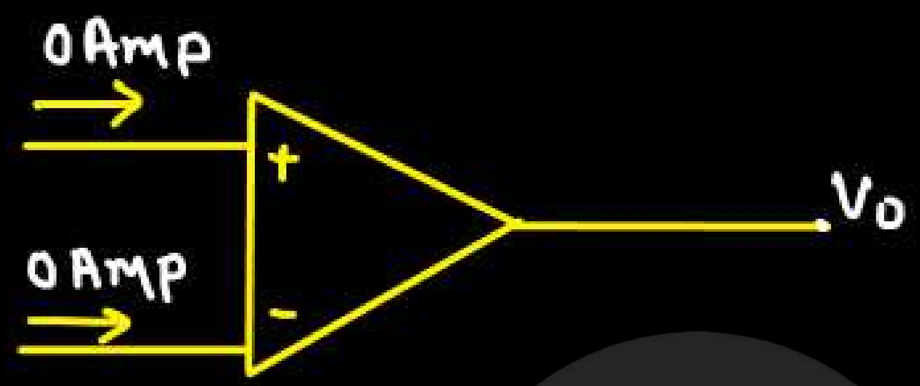
$$= -100 \times 10mV + [1 + 100][\pm 1mV]$$

$$= -1V \pm 0.101\,V$$

$$= -1.101\,V, -0.899\,V$$

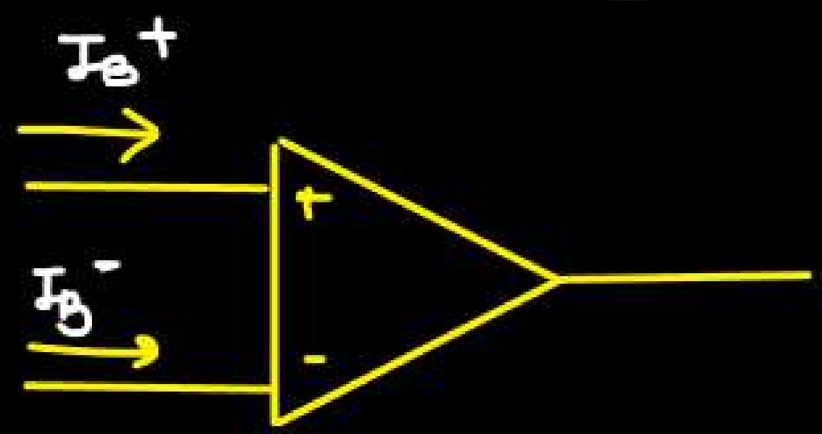
⇒ Input offset current, Input bias current:-

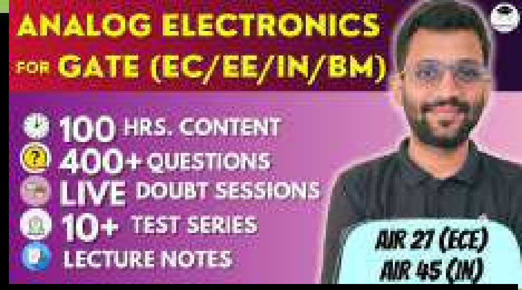
ideally,

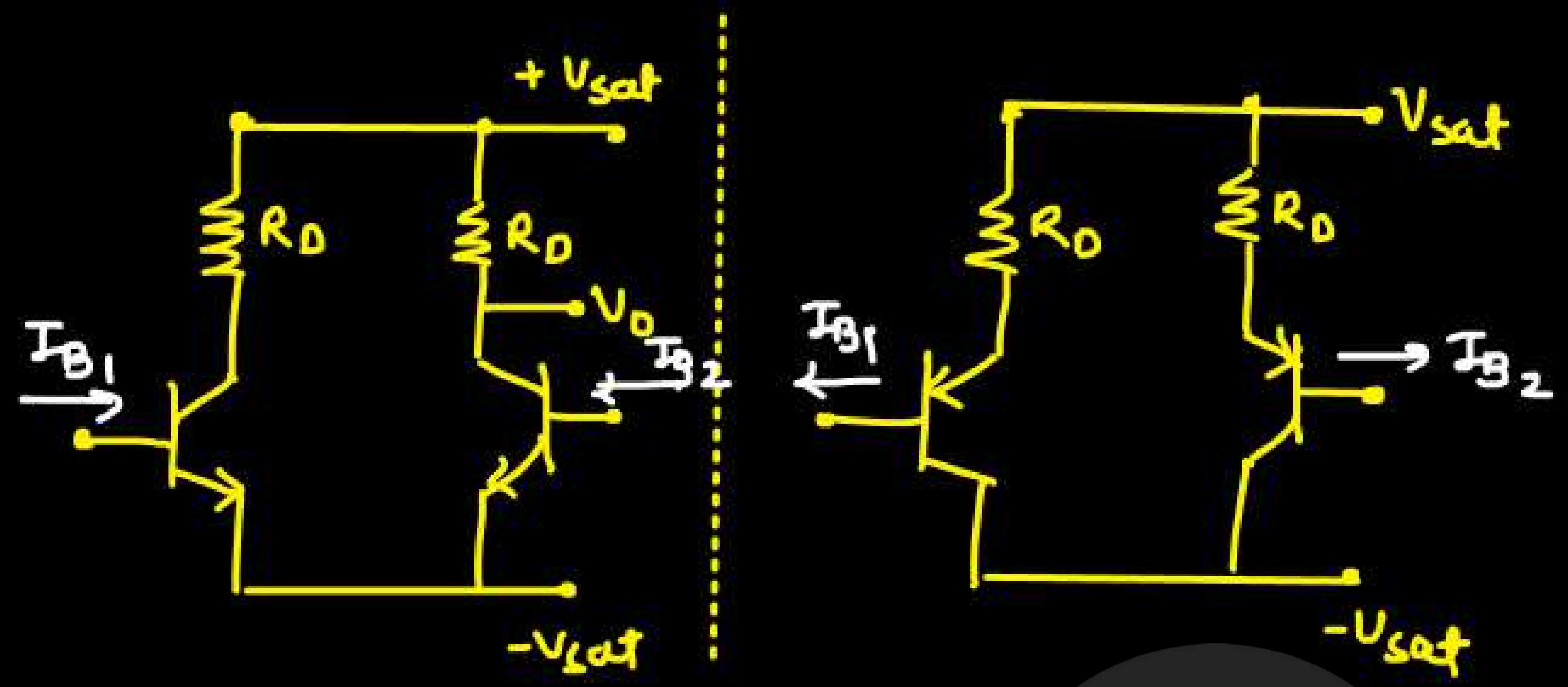


But,

There is some small amount of current that flows through the i/p terminals of the op-amps.







Input bias current :-

$$\boxed{I_B = \frac{I_B^{+} + I_B^{-}}{2}}$$

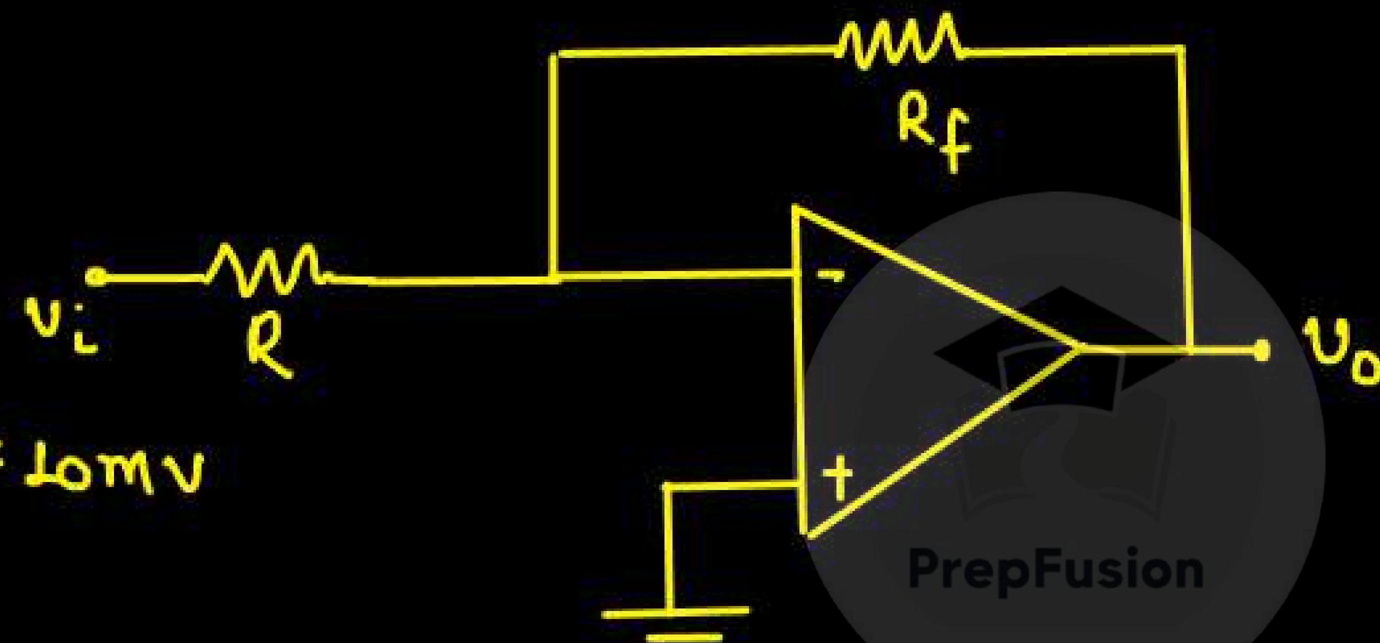
$$\boxed{\text{Range} \rightarrow \mu A \text{ to } nA}$$

Input offset current :-

$$\boxed{I_{ios} = \left| I_B^{+} - I_B^{-} \right|}$$

⇒ Effect of bias current:-

☆ Consider an inverting op-amp with $\frac{R_f}{R} = 100$

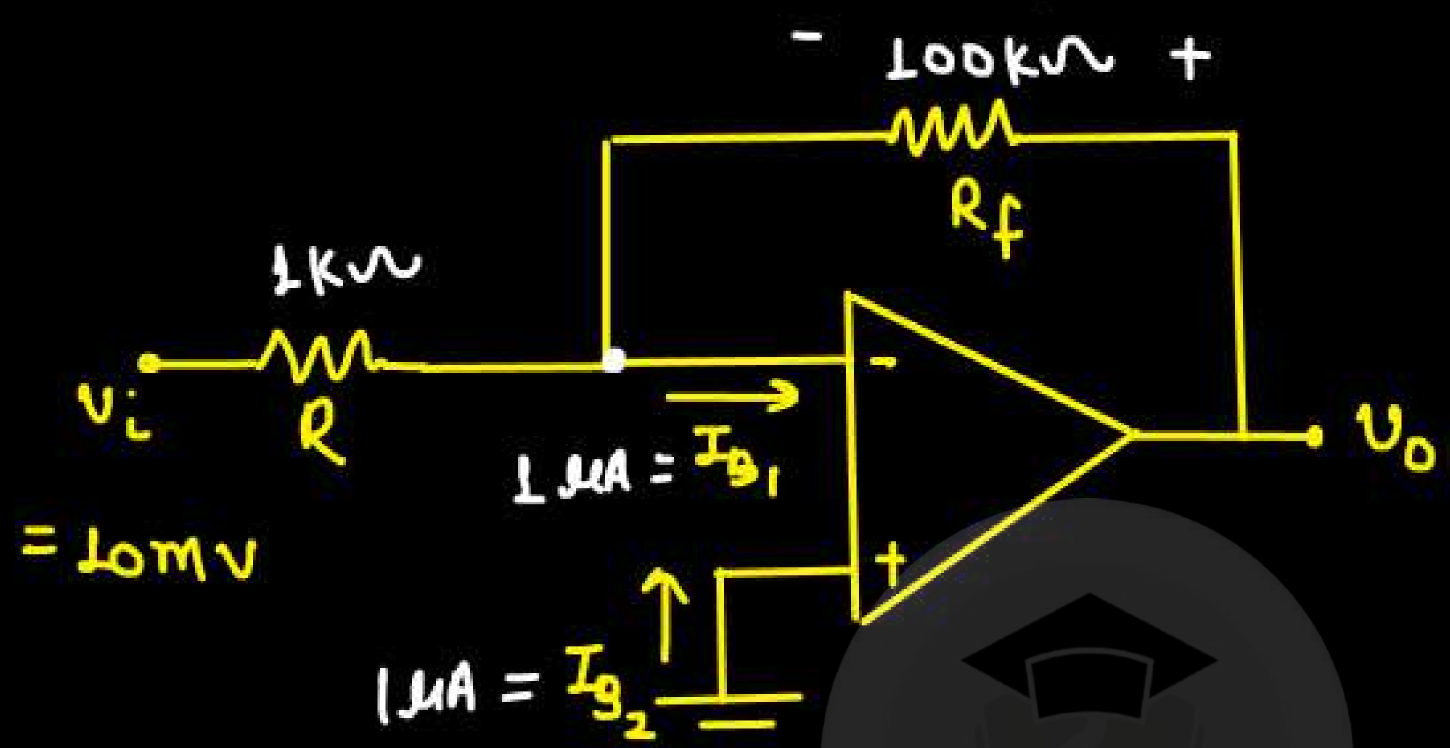


$= 10mV$

Considering zero offset, $\frac{v_o}{v_i} = -\frac{R_f}{R} = -100$

$v_o = -100 \times 10mV = 1V$

Now, Consider bias currents are present as shown.



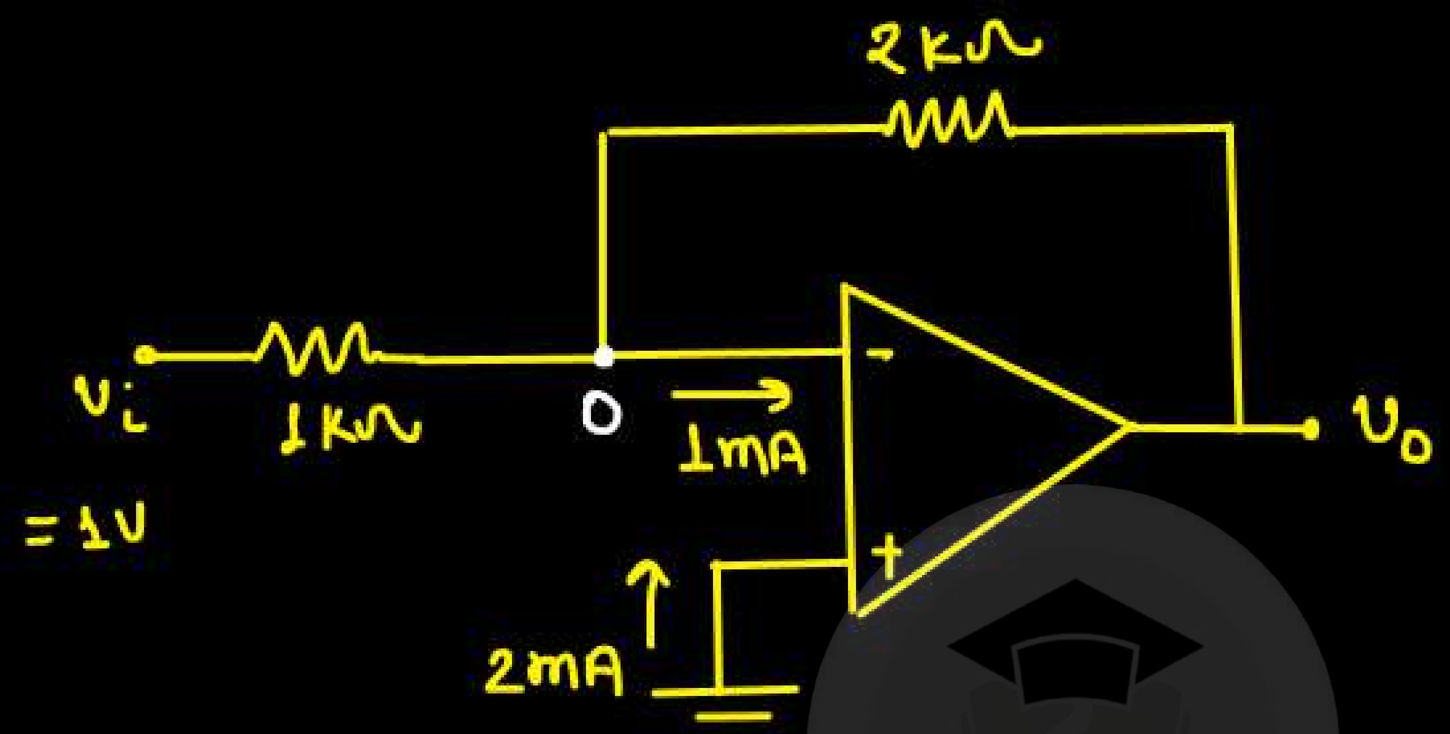
Take $R_f = 100\,k\Omega$, $R = 1k\Omega$, $I_{B_1} = I_{B_2} = 1\mu A$

$$v_o = -\frac{R_f}{R} v_i + I_{B_1} \times R_f$$

$$= -100 \times 10\,mV + [1\mu A] \times 100\,K$$

$$= -1V + 0.1 = -0.9V$$

Q. Find v_o.



→

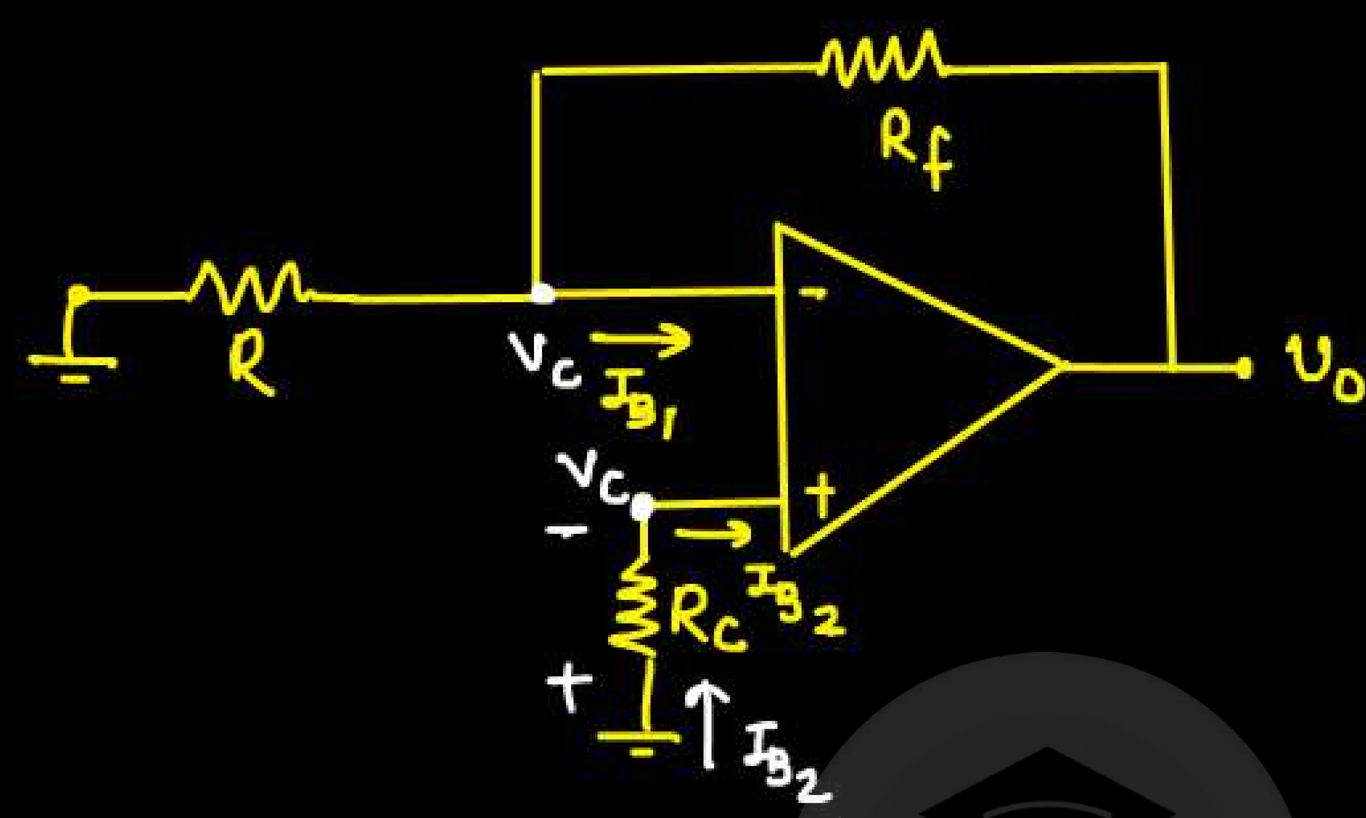
$$\frac{0-1}{1k} + 1mA + \frac{0-v_o}{2k} = 0$$

$$\boxed{V_o = 0\,V}$$

$$V_o = -2 \times 1V + 2k \times 1mA$$

$$\boxed{V_o = 0\,V}$$

Q.



(i) Find o/p voltage V_o.

(ii) if $R_c = R \| R_f$. Find V_o.

→

$$V_c = -I_{B_2} \times R_c \quad \text{—} \quad (1)$$

$$\frac{V_c}{R} + \frac{V_c - V_o}{R_f} + I_{B_1} = 0$$

$$\frac{V_c}{R} + \frac{V_c}{R_f} + I_{B_1} = \frac{V_o}{R_f}$$

$$\boxed{R_f\left[-I_{B_2}R_c\left[\frac{1}{R}+\frac{1}{R_f}\right]+I_{B_1}\right] = V_o}$$

$$\boxed{\text{if } R_c = R \parallel R_f}$$

$$-I_{B_2}\times\left(\frac{RR_f}{R+R_f}\right)\left[\frac{R_f+R}{RR_f}\right]+I_{B_1} = \frac{V_o}{R_f}$$

$$\boxed{V_o = R_f\left(I_{B_1}-I_{B_2}\right)}$$

$$\boxed{V_o = R_f \times I_{ios}}$$

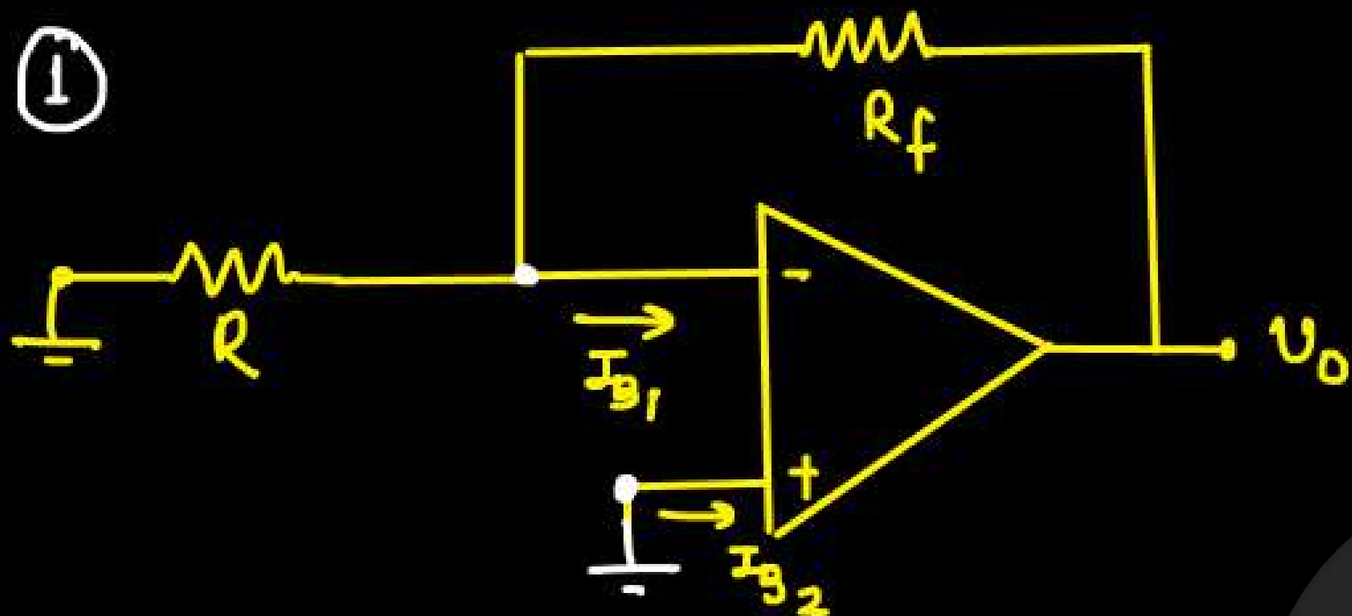
if $I_{B_1} = I_{B_2} = I_B$

$$V_o = (0)R_f$$

$$\boxed{V_o = 0V}$$

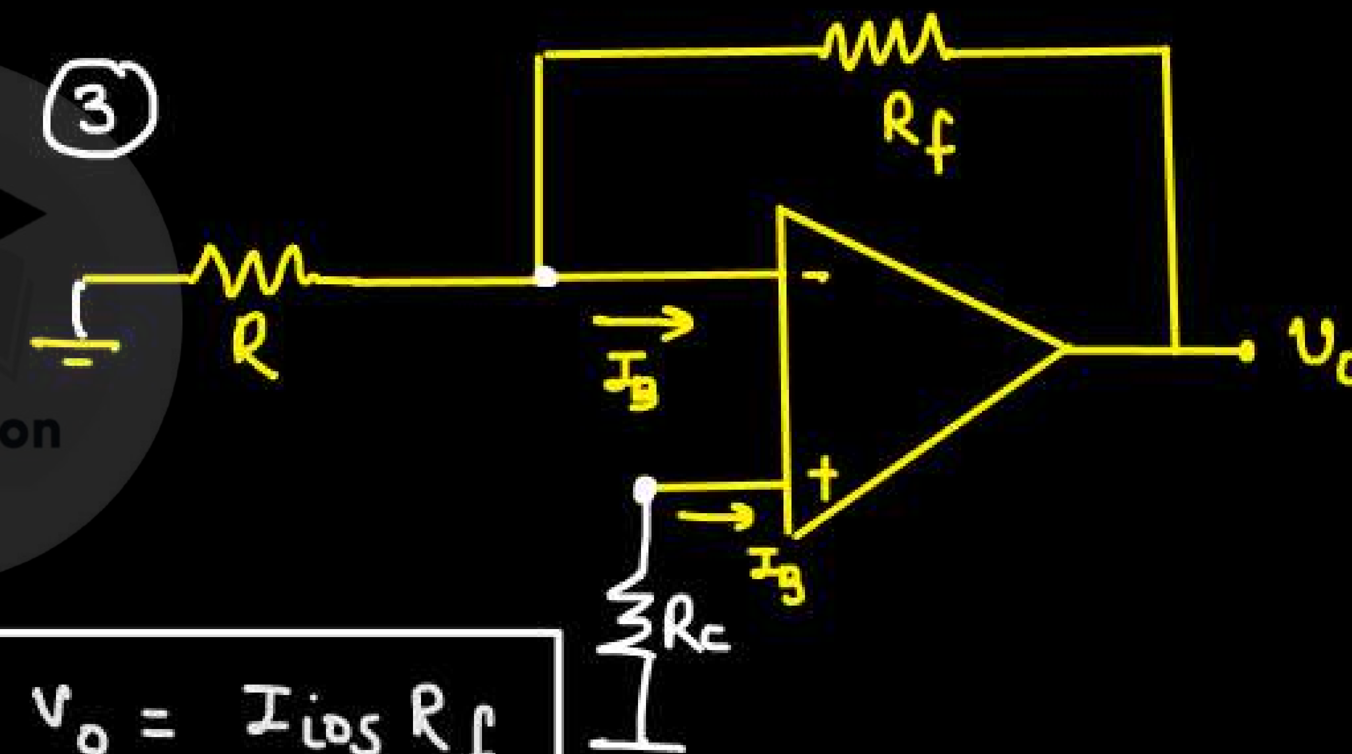
Conclusion:-

①

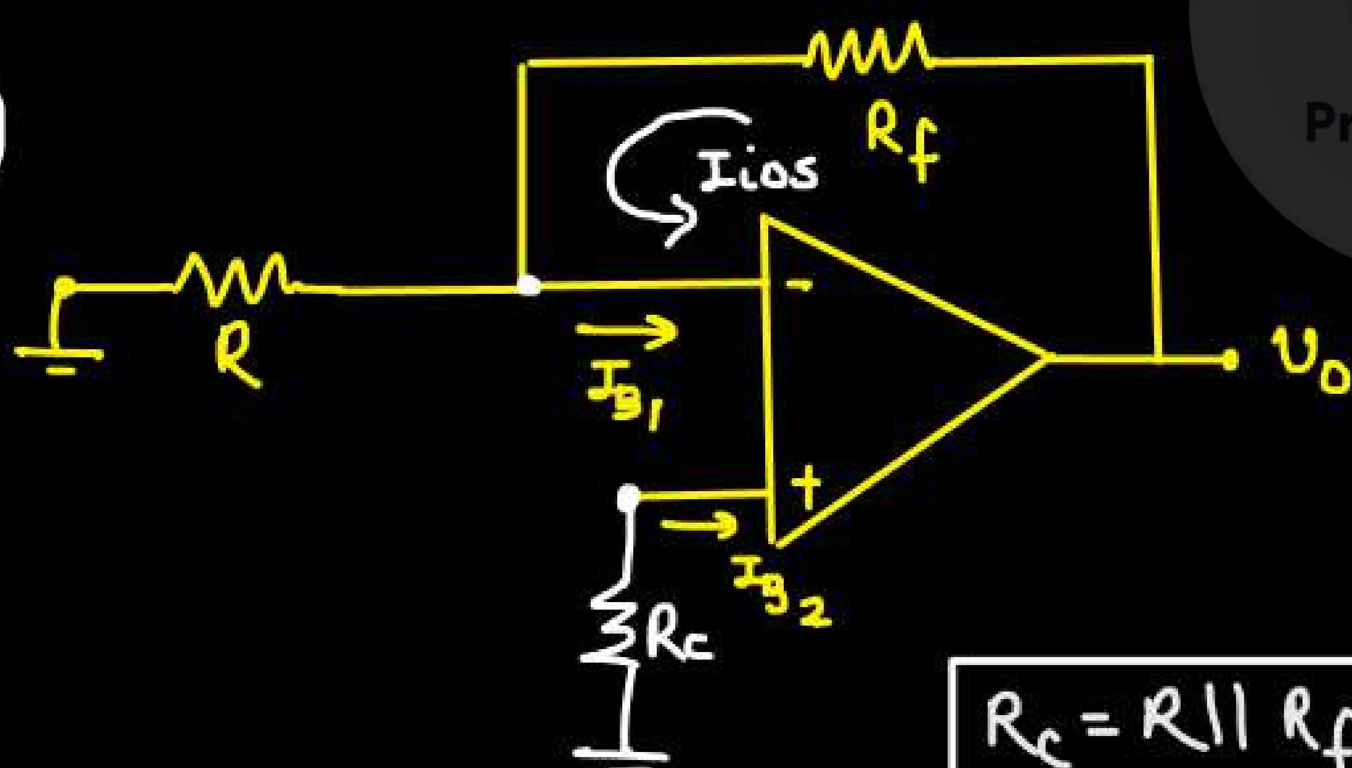


① $\boxed{V_o = I_{B_1} R_f}$

③



②

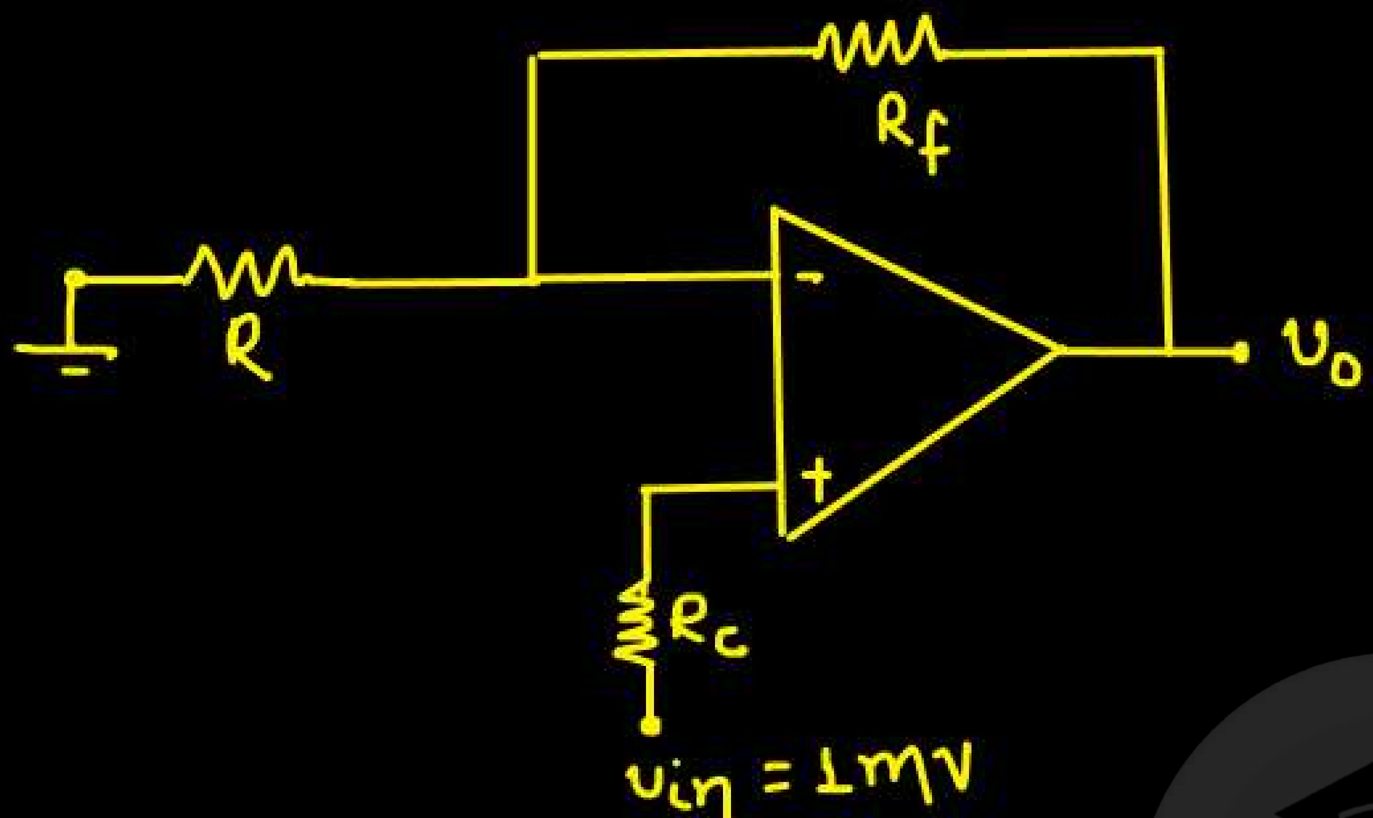


② $\boxed{V_o = I_{os} R_f}$

$\boxed{R_c = R \| R_f}$

③ $\boxed{V_o = 0\,V}$

Q.



$\rightarrow$ $I_{os} = 50nA$

$I_B = 100nA$

For the given config,

$R = 1k\Omega$, $R_f = 9k\Omega$, $R_c = 900\Omega$

input offset voltage = 0.5mV

input offset current = 50nA

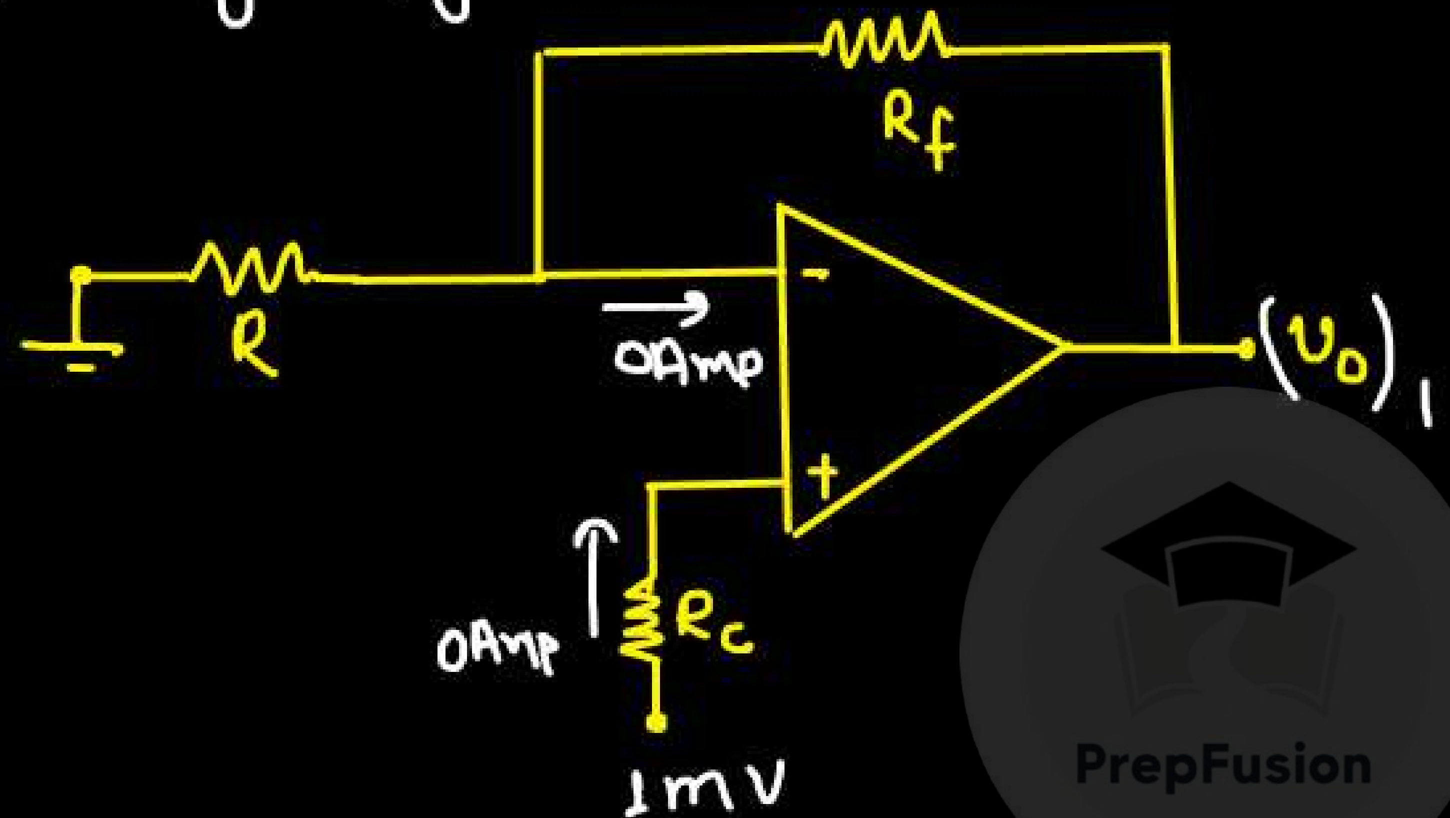
input bias current = 100nA

Find v_0.

$\Rightarrow v_0 =$

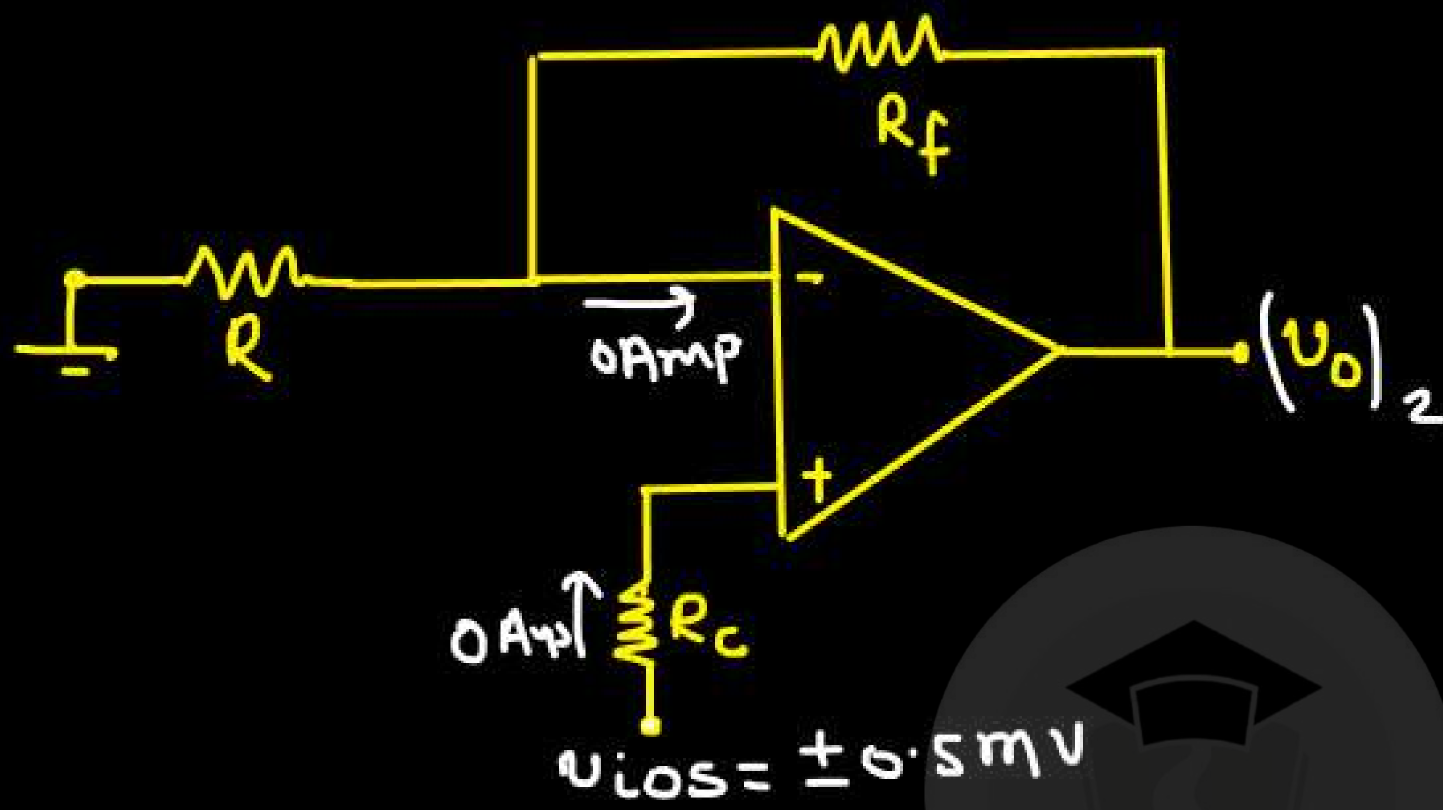
Applying Superposition:-

(i) Considering only v_{in}



$$\boxed{v_{o_1} = \left(1 + \frac{R_f}{R}\right) \times 1\,mV = 10\,mV}$$

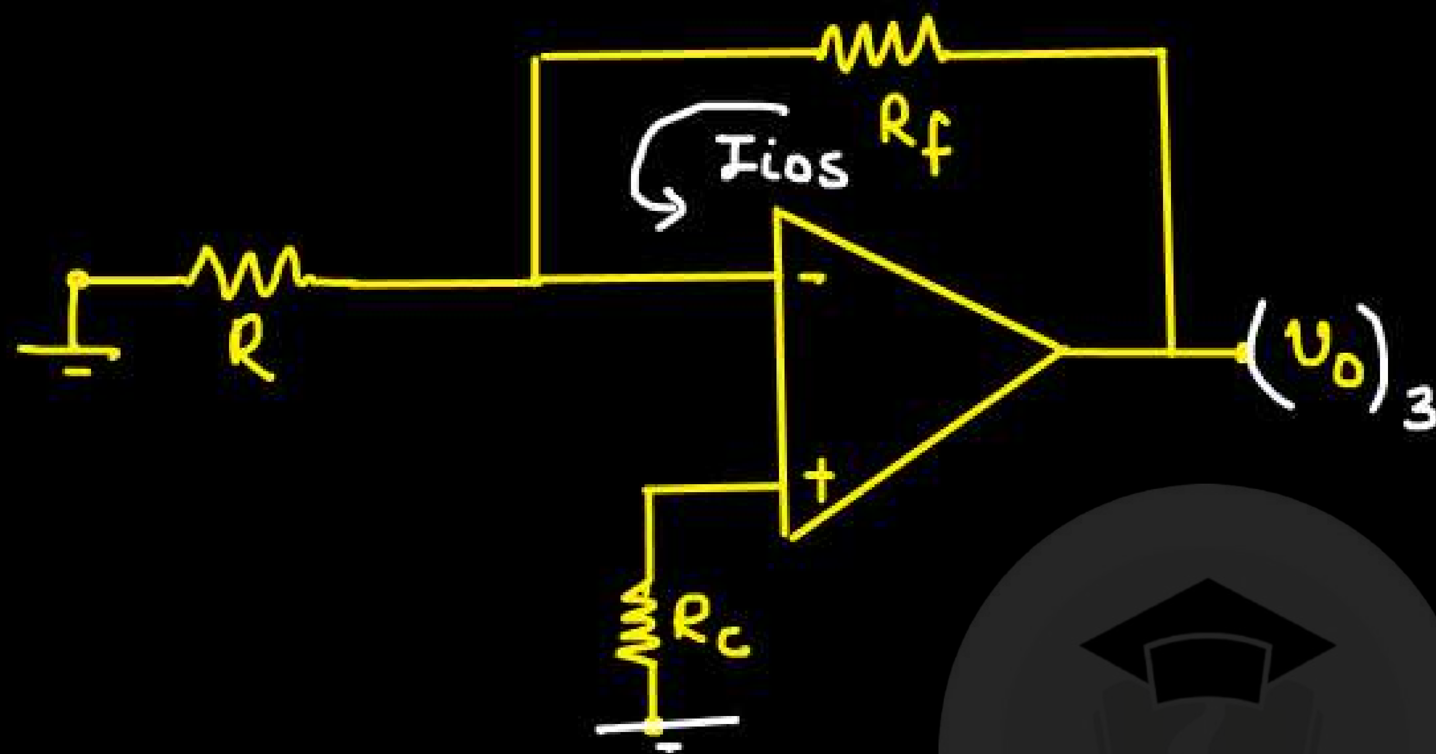
Considering only offset voltage:-



$$v_{o_2} = \left(1 + \frac{R_f}{R}\right) \times (\pm 0.5\,mV)$$

$$\boxed{v_{o_2} = \pm 5\,mV}$$

Considering bias and offset current :-



$$(v_0)_3 = \pm I_{ios} \times R_f$$
$$= \pm 50nA \times 9K$$
$$= \pm 45 \times 10^{-5}\ V$$
$$\boxed{(V_0)_3 = \pm 0.45 mV}$$

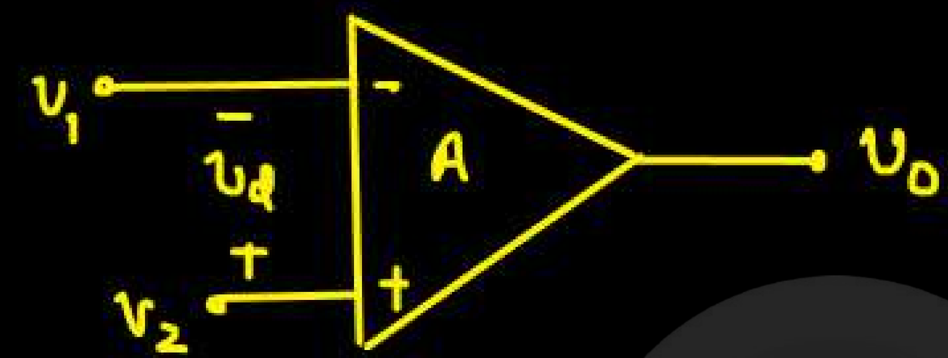
$$\boxed{v_0 = v_{o_1} + v_{o_2} + v_{o_3} = 10mV \pm 5mV \pm 0.45mV}$$

$$\boxed{(v_0)_{max} = 15.45 mV}$$

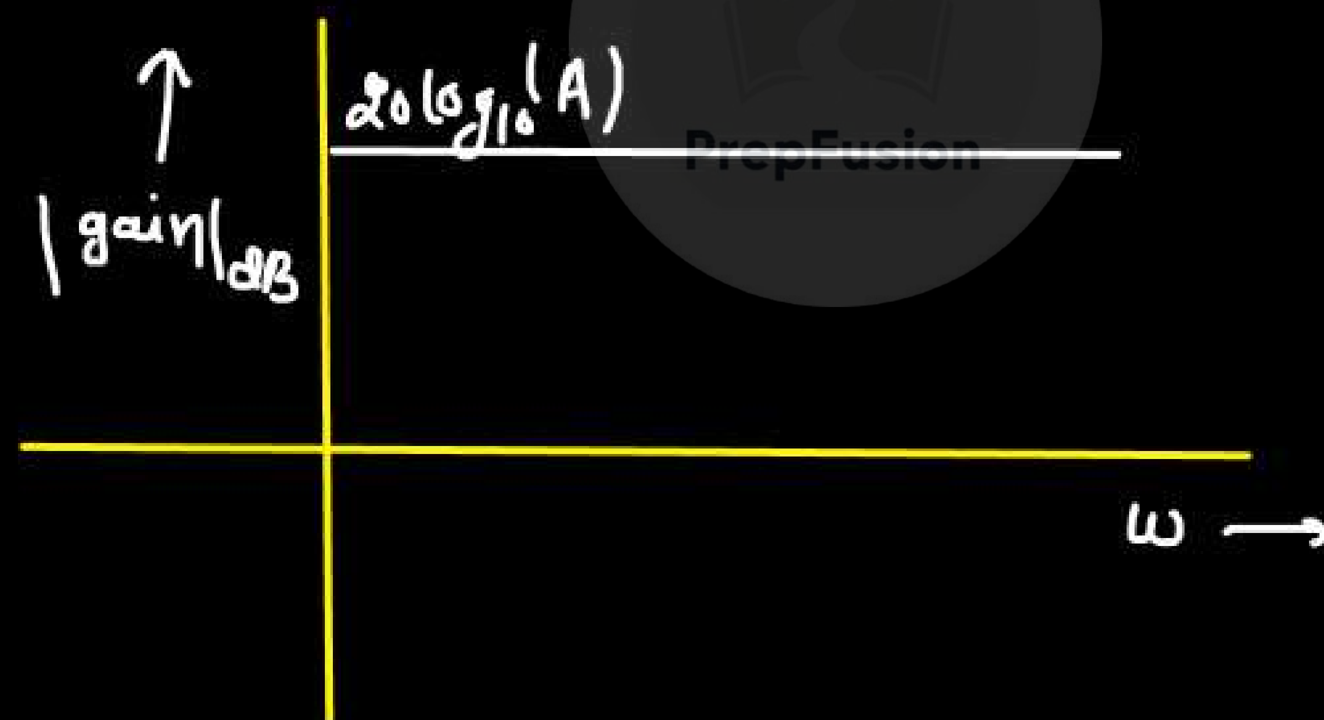
$$\boxed{(v_0)_{min} = 4.55 mV}$$

★ Frequency Response of op-Amp:-

ideally,



$$\boxed{\frac{v_o(s)}{v_d(s)} = A}$$



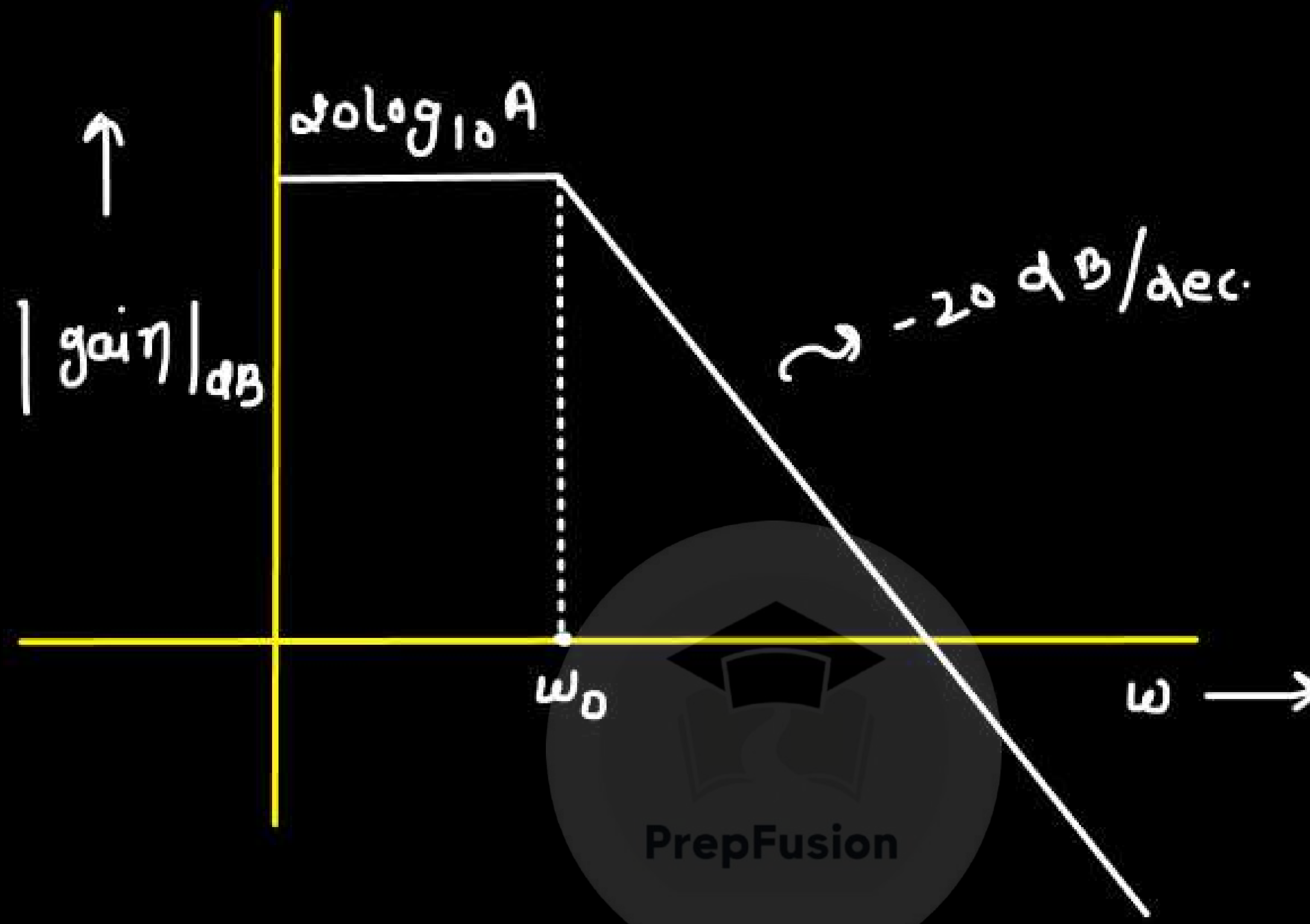
But practically,

The freq. response of op. Amp is same as Low-Pass Filter.

$$v_o(s) = \frac{\frac{1}{Cs}}{\frac{1}{Cs} + r_o} A_v v_d(s)$$

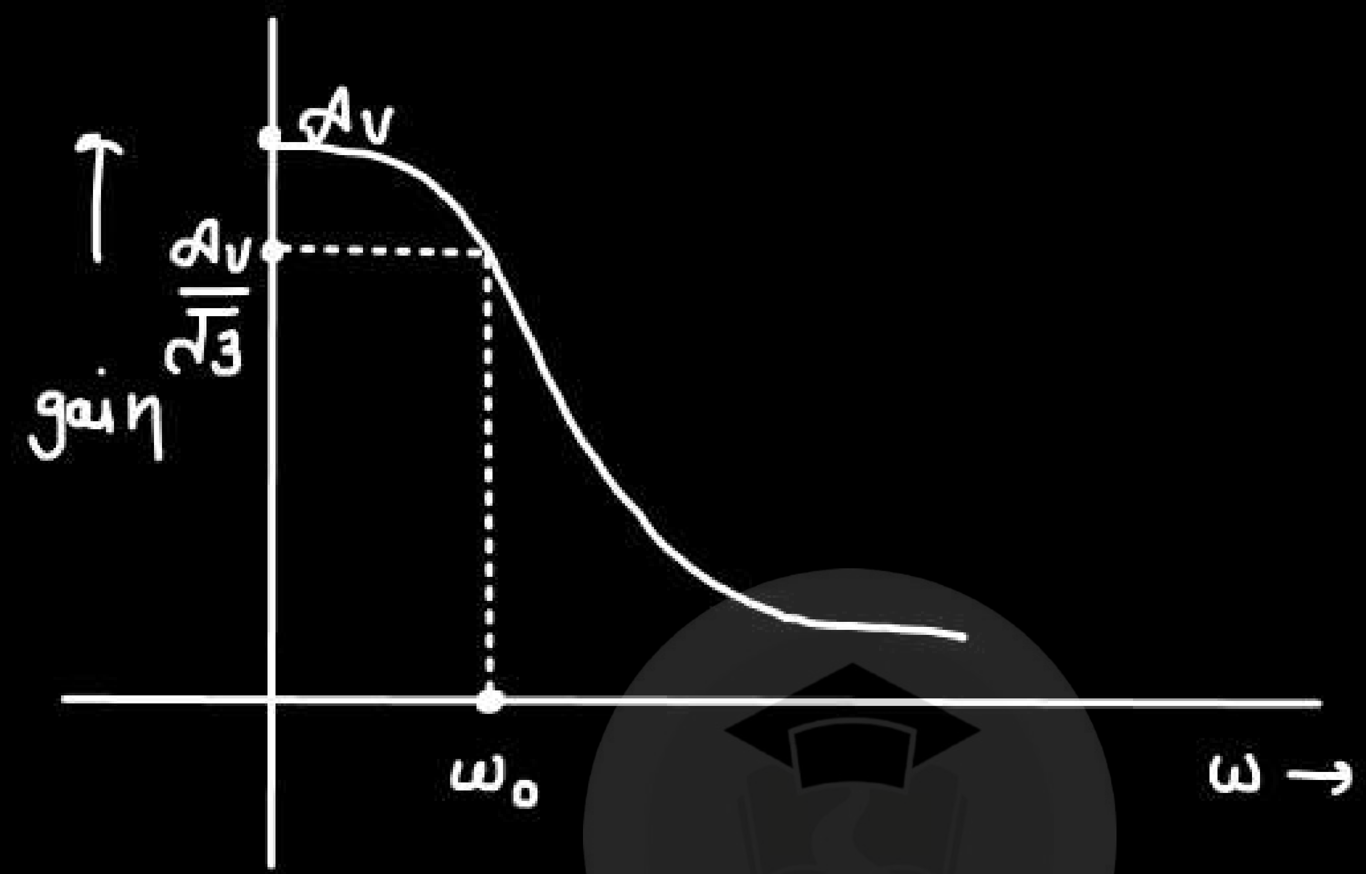
$$v_o(s) = \frac{A_v v_d(s)}{r_o C s + 1}$$

$$\boxed{\frac{v_o(s)}{v_d(s)} = \frac{A_v}{s/\omega_0 + 1}} \quad ; \quad \omega_0 = \frac{1}{r_o C}$$



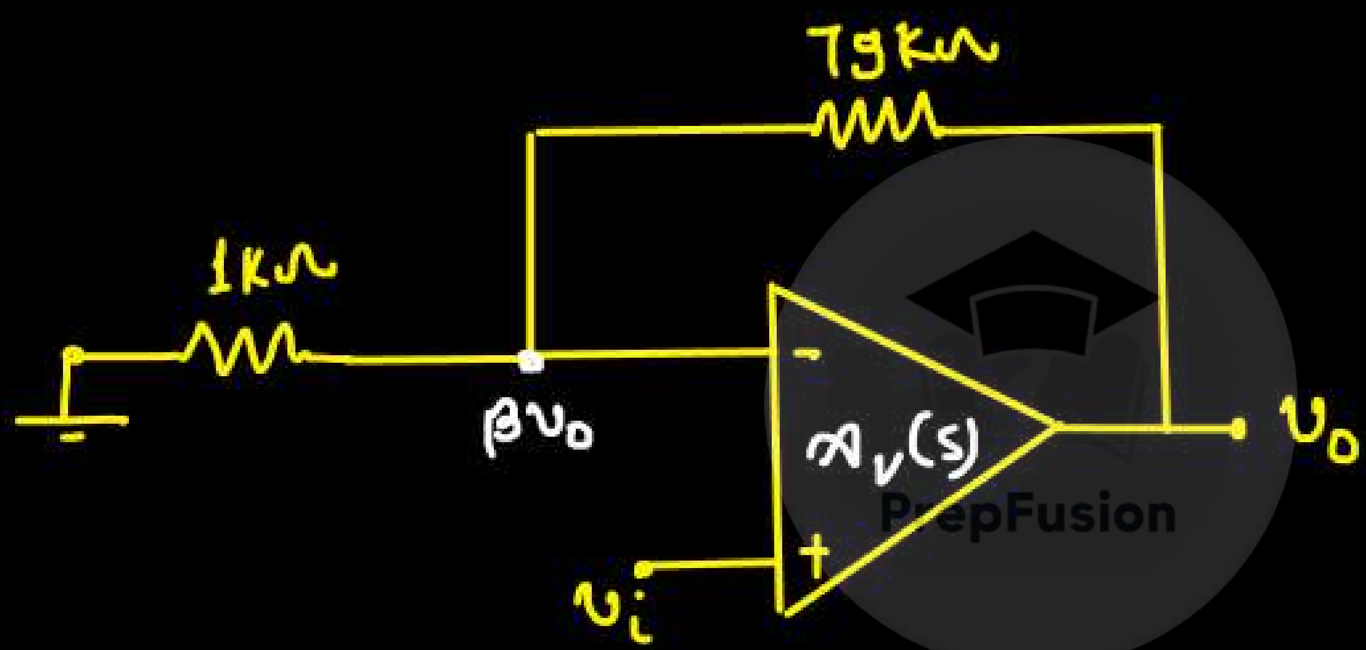
$$\frac{v_o(s)}{v_d(s)} = T(s) = \frac{A_v}{s/\omega_0 + 1}$$

$$|T(j\omega)| = \frac{A_v}{\sqrt{(\omega/\omega_0)^2 + 1}}$$


gain
A_v
$\frac{A_v}{\sqrt{3}}$
ω_0
$\omega \rightarrow$

Q. For the given op-amp, open loop gain is 10^5 V/V and open loop cut-off freq. is 8 Hz.

The voltage gain of amplifier at 15 kHz is ____



→ $A = 10^5$ V/V

$f_0 = 8$ Hz

$\omega_0 = 16\pi$ rad/sec

$$\boxed{A_v(s) = \frac{10^5}{s/\omega_0 + 1}}$$

$\{\omega_0 = 16\pi \text{ rad/sec}\}$

$$A_v(s)\left[v_{in}(s) - \beta v_o(s)\right] = v_o(s)$$

$$\beta = \frac{1k}{1k + 79k} = \frac{1}{80}$$

$$\boxed{\frac{v_o(s)}{v_i(s)} = \frac{A_v(s)}{1 + A_v(s)\,\beta}}$$

$$\frac{v_o(s)}{v_i(s)} = \left[A_v(s)\right]_f = \frac{\dfrac{10^5}{s/\omega_o + 1}}{1 + \dfrac{10^5}{s/\omega_o + 1} \times \dfrac{1}{80}} = \frac{80 \times 10^5}{80\left(s/\omega_o + 1\right) + 10^5}$$

$$\left[A_v(j\omega)\right]_f = \frac{80 \times 10^5}{80\left[\dfrac{j\omega}{\omega_o} + 1\right] + 10^5}$$

$$[A_v(jf)]_f = \frac{80\times 10^5}{80\left[\frac{jf}{f_0}+1\right]+10^5}$$

$$[A_v(j15KHz)]_f = \frac{80\times 10^5}{80\left[\frac{j15\times 10^3}{8}+1\right]+10^5}$$

$$|A_v(j15KHz)_f| = \left|\frac{80\times 10^5}{j15\times 10^4+80+10^5}\right|$$

$$= \frac{80\times 10^5}{\sqrt{(80+10^5)^2+(15\times 10^4)^2}} = \boxed{44.36\ V/V}$$

Ans.

M - II :-

$$(A_v)_f = \frac{10^5}{1+10^5 \times \frac{1}{80}} \approx 80$$

$$(f_o)_f = f\,(1+A\beta) = 8\left[1+\frac{10^5}{80}\right] \approx 10\,kHz$$

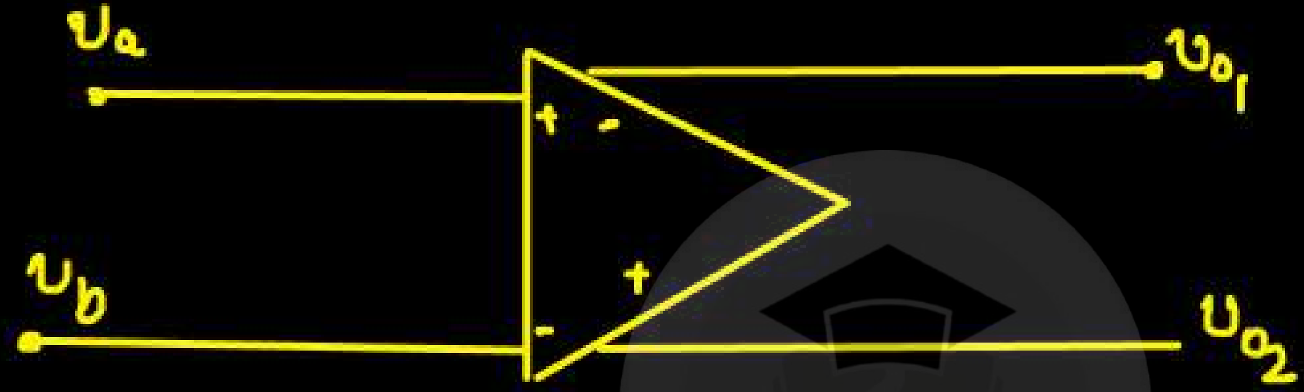
$$\left[A_v(jf)\right]_f = \frac{80}{\frac{jf}{10k}+1}$$

$$\left[A_v(j15K)\right]_f = \frac{80}{\frac{j15k}{10k}+1} = \frac{80}{j1.5+1} =$$

$$\boxed{\text{gain at } 15kHz = \frac{80}{\sqrt{(1.5)^2+1}} = 44.37\ V/V}$$

(4) CMRR (Common Mode Rejection Ratio) :-

For Differential Amplifier :-



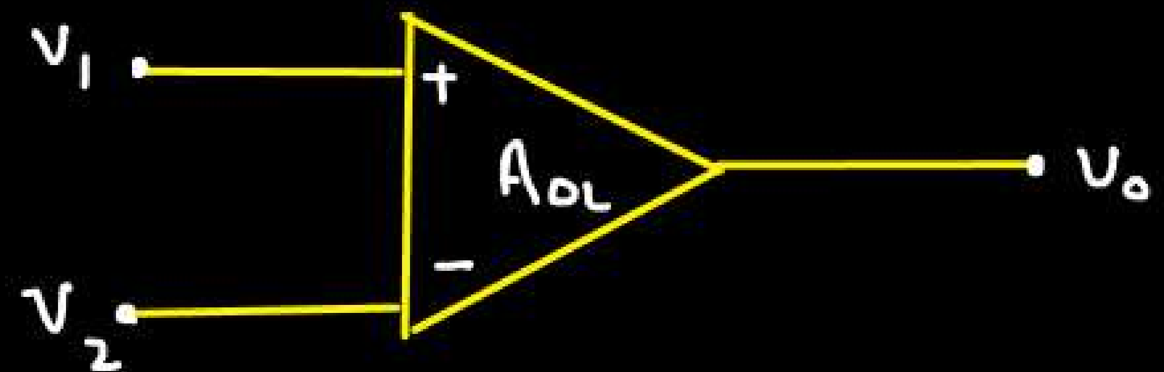
Differential gain $(A_d) = \dfrac{v_{o2} - v_{o1}}{v_{in}}$ $\quad \left\{ v_a = \dfrac{v_{in}}{2},\ v_b = -\dfrac{v_{in}}{2} \right\}$

Common Mode Differential Gain $(A_{cm\text{-}dm}) = \dfrac{v_{o2} - v_{o1}}{v_{cm}}$ $\quad \left\{ v_a = v_b = v_{cm} \right\}$

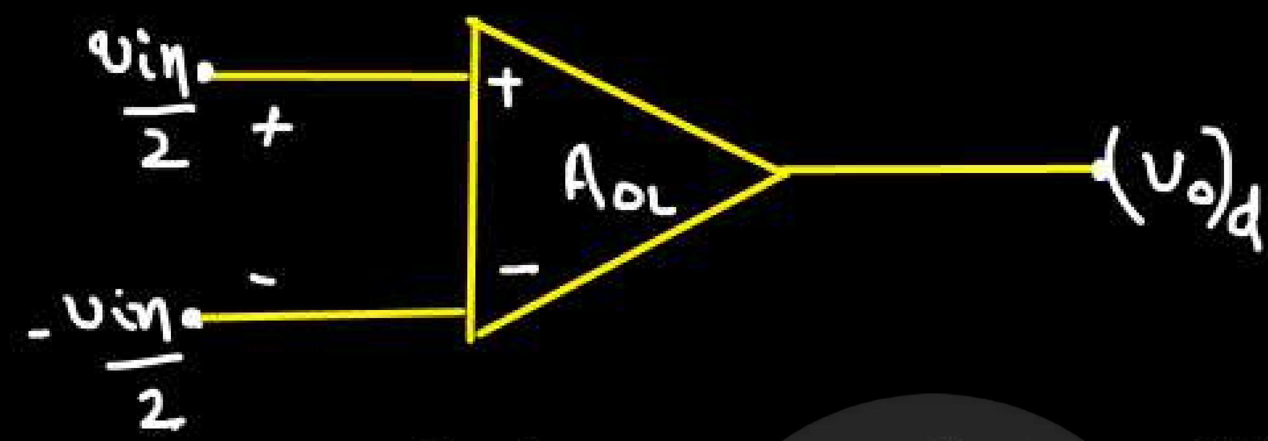
$$\text{CMRR} = \left| \frac{\text{Differential Gain}}{\text{Common Mode Differential Gain}} \right|$$

For Op-Amp:-

$$\text{CMRR} = \left| \frac{\text{Differential Gain}}{\text{Common Mode Gain}} \right|$$



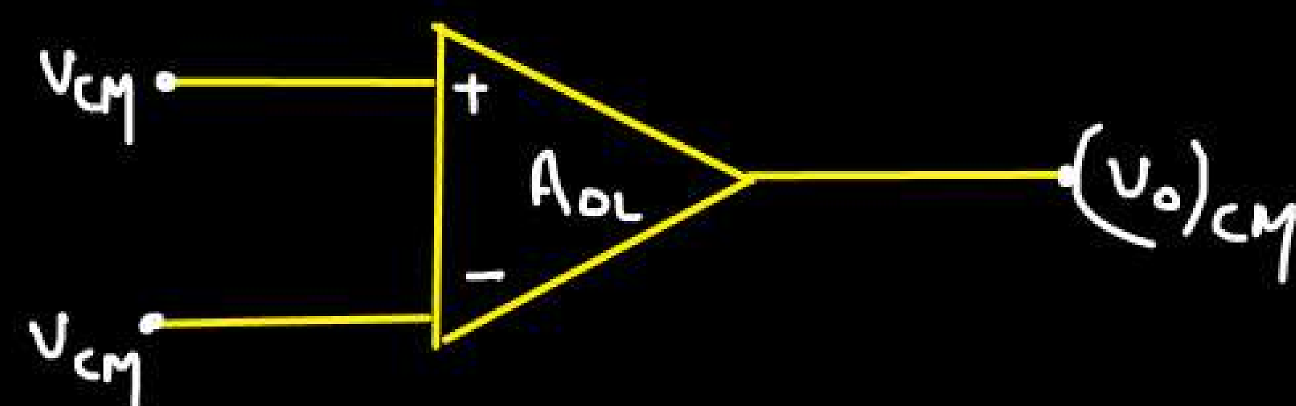
Differential Gain:-



$$(v_o)_d = A_{OL}\left[\frac{v_{in}}{2} + \frac{v_{in}}{2}\right] = A_{OL} v_{in}$$

$$\Rightarrow \boxed{\text{differential gain } A_d = \frac{(v_o)_d}{v_{in}} = A_{OL}}$$

Common Mode Gain:-



$$(v_o)_{CM} = A_{OL}(v_{CM} - v_{CM})$$

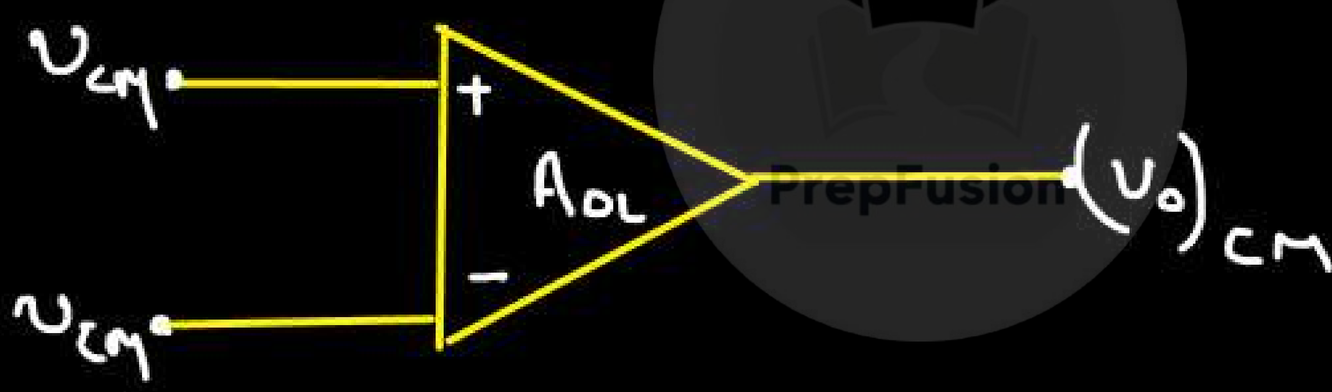
$$\Rightarrow (v_o)_{CM} = 0$$

$$(A_v)_{CM} = \frac{(v_o)_{CM}}{v_{CM}} = 0$$

$$CMRR = \frac{A_d}{A_c} = \frac{A_{OL}}{0} = \infty$$

For an ideally op-amp $\boxed{CMRR = \infty}$

But, Practically

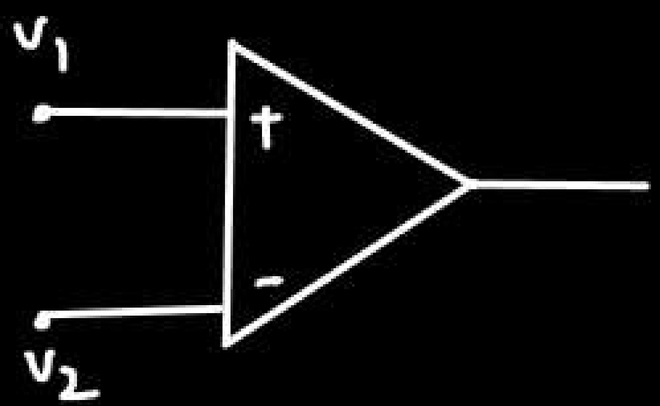


$$\boxed{CMRR = \left|\frac{A_d}{A_c}\right|}$$

Common Mode Gain is by $\boxed{(A)_{CM} = \frac{(v_o)_{cM}}{v_{cM}}}$

So, Generally o/p of op-amp can be expressed as

$$\boxed{v_o = A_d v_d + A_{cm} v_{cm}}$$



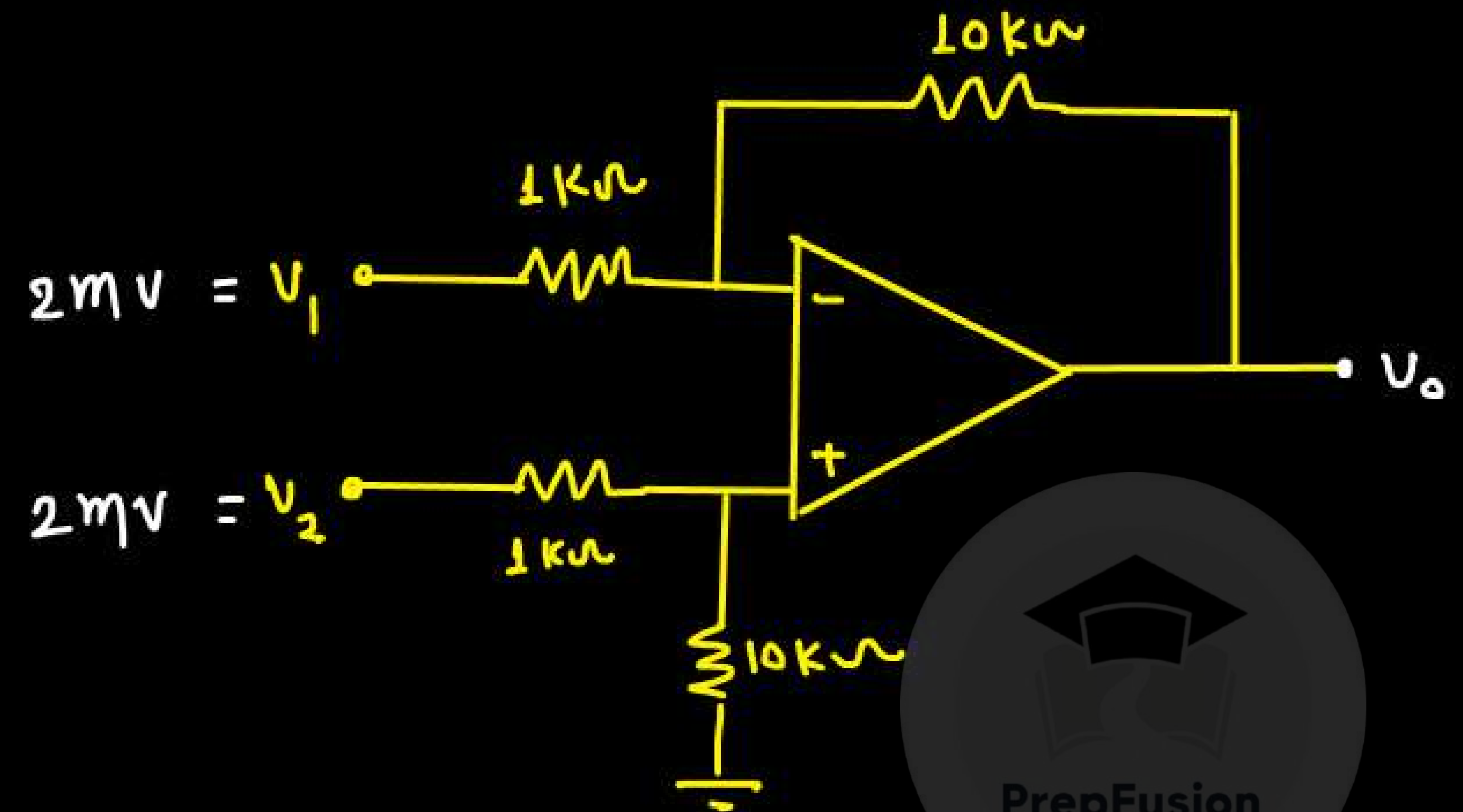
v_o = (differential gain × differential input)
+
(common mode gain × common mode input)

$$\boxed{v_o = A_d (V_1 - V_2) + A_{cm}\left(\frac{V_1 + V_2}{2}\right)}$$

$$\boxed{CMRR = \left|\frac{A_d}{A_{cm}}\right|}$$

↳ Generally CMRR is defined for open-loop config. of op-amp but when we use op-amp as differential amplifier, we take the same CMRR value for closed loop as well.

Q.



$v_{id} = v_2 - v_1 = 5mV$

$V_{CM} = 2mV$ (Common Mode Signal)

CMRR of the op-Amp = 90 dB

Find Common Mode output voltage = ?

2

if $\boxed{\text{OP- Amp was ideal:-}}$

$$(v_0)_{cm} = \frac{10k}{1k}(v_{CM} - v_{CM}) = 0$$

But op- Amp is having CMRR = 90dB

$$20\log_{10}(CMRR)_{deci} = 90$$

$$\boxed{CMRR = 31622.78} = \frac{A_d}{A_c}$$

Differential Gain $(A_d) = ?$

Differential o/p $= 10(V_2 - V_1) = 10 \times 5mV = 50mV$

Differential i/p $= V_2 - V_1 = 5mV$

Differential Gain $(A_d) = \frac{50mV}{5mV} = \underline{10}$

$$\frac{A_d}{A_c} = 31622.78$$

$$\frac{10}{A_c} = 31622.78$$

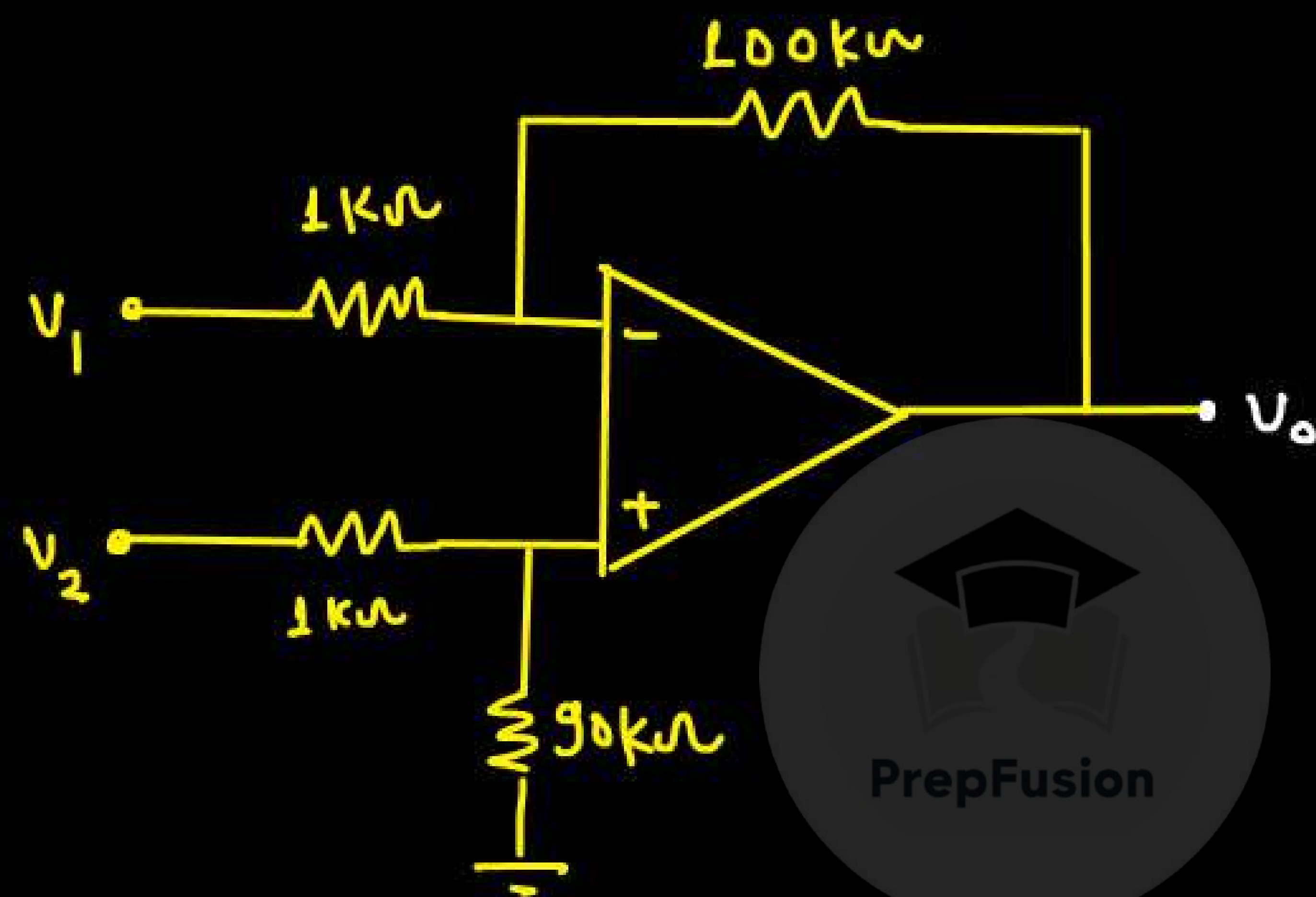
$$\boxed{A_c = 3.16 \times 10^{-4}} \Rightarrow \text{common Mode gain}$$

$$\frac{(v_o)_{cm}}{(v_i)_{cm}} = 3.16 \times 10^{-4}$$

$$(v_o)_{cm} = 3.16 \times 10^{-4} \times 2 \times 10^{-3}$$

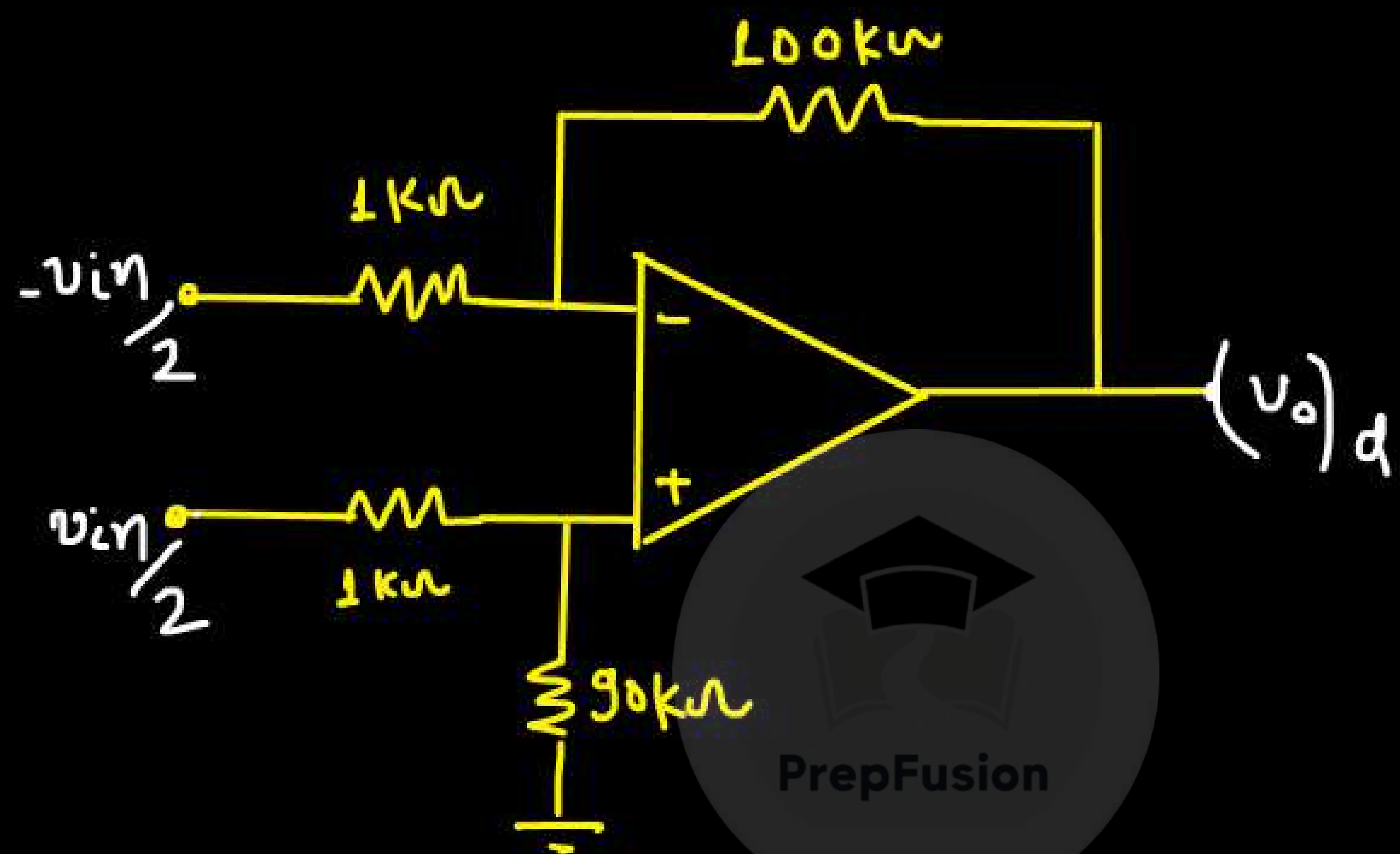
$$\boxed{(v_o)_{cm} = 0.632\,\mu V}$$ ANS.

Q. The given OP-Amp is ideal. (CMRR $= \infty$)



Find CMRR of the differential amplifier shown:-

→ Differential Gain (A_d):-

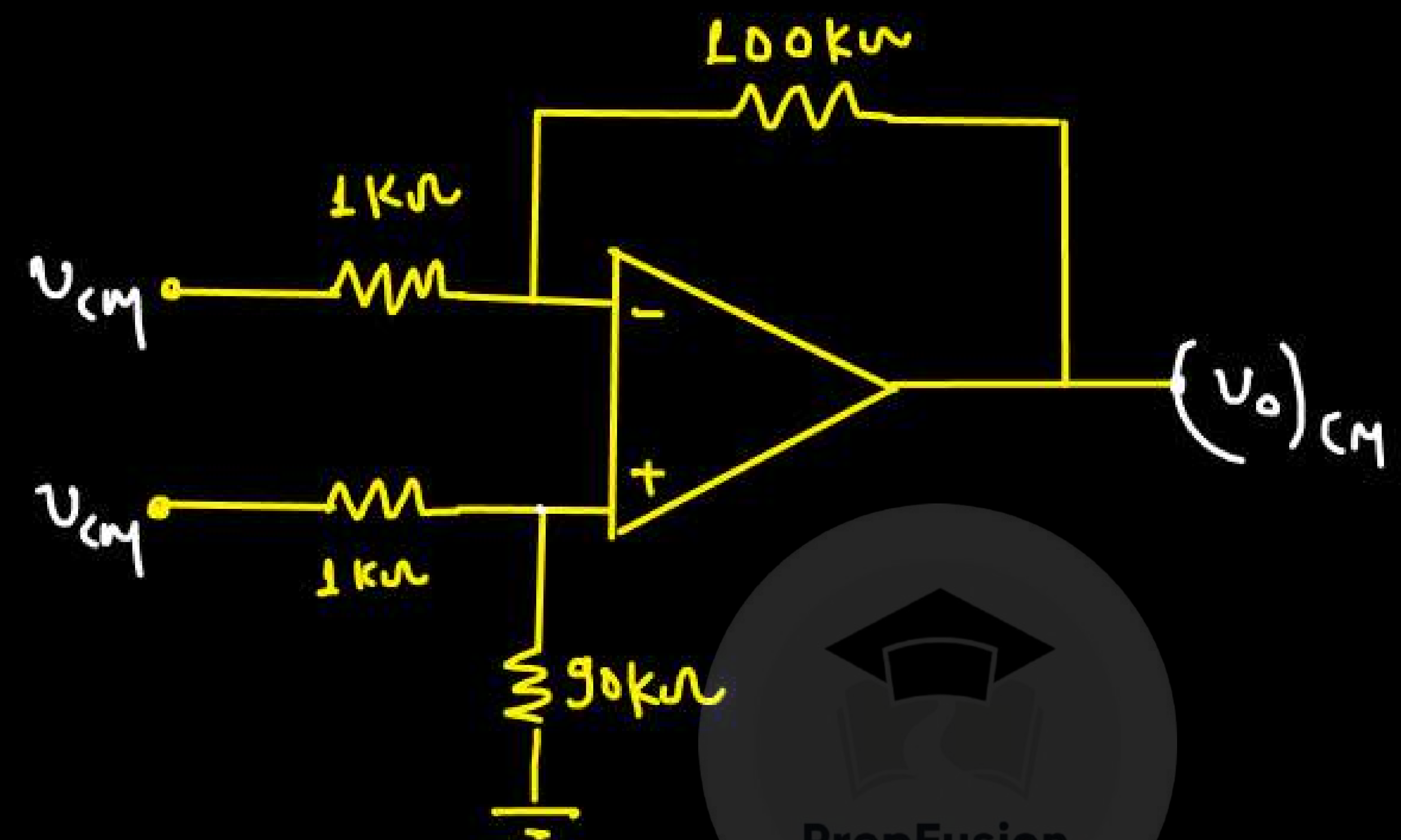


$$(v_0)_d = \frac{90}{91} \times \frac{v_{in}}{2} \times \left[1 + \frac{100}{1}\right] + \left(-\frac{100}{1}\right)\left(-\frac{v_{in}}{2}\right)$$

$$(v_0)_d = \left[\frac{90}{91} \times 101 + 100\right] \frac{v_{in}}{2}$$

$$\boxed{(A_v)_d = \frac{(v_0)_d}{v_{in}} = 99.94\ V/V}$$

Common Mode Gain:-



$$(v_o)_{CM} = \frac{90}{91} \times (1 + 100) v_{CM} + (-100) v_{CM}$$

$$(v_o)_{CM} = -0.109 \times v_{CM}$$

$$(A)_{CM} = (v_o)_{CM} / v_{CM} = -0.109$$

$$\boxed{A_{CM} = -0.109}$$

$$\boxed{CMRR = \left|\frac{A_d}{A_c}\right| = \left|\frac{99.94}{-0.109}\right| = 909.45}$$

$$= 20\log_{10} 909.45$$

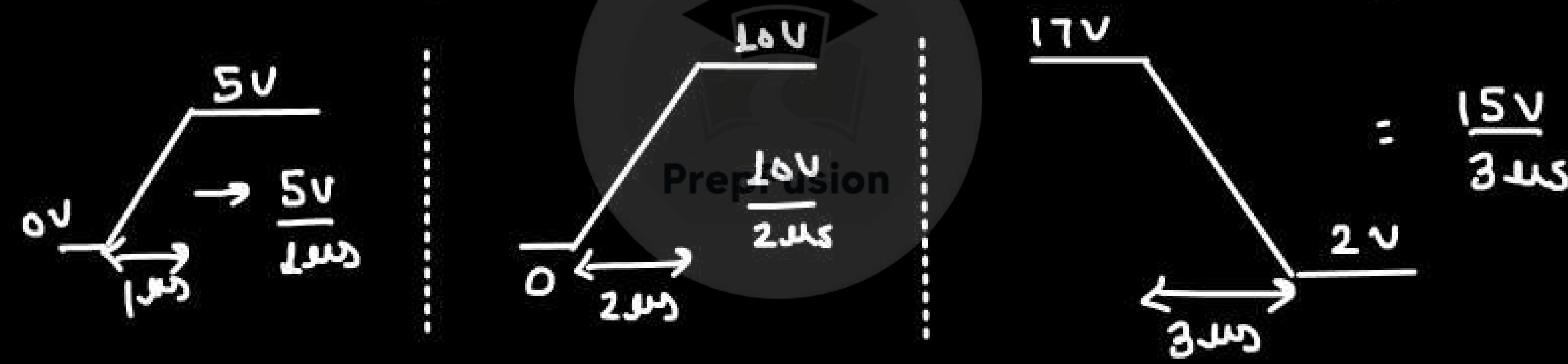
$$= 59.17\ dB$$

(5) Slew Rate:-

Max^m rate of change of o/p voltage.

Let slew rate = $5V/\mu s$

⇒ It would take $1\mu s$ time for the o/p to gain or lose 5V.

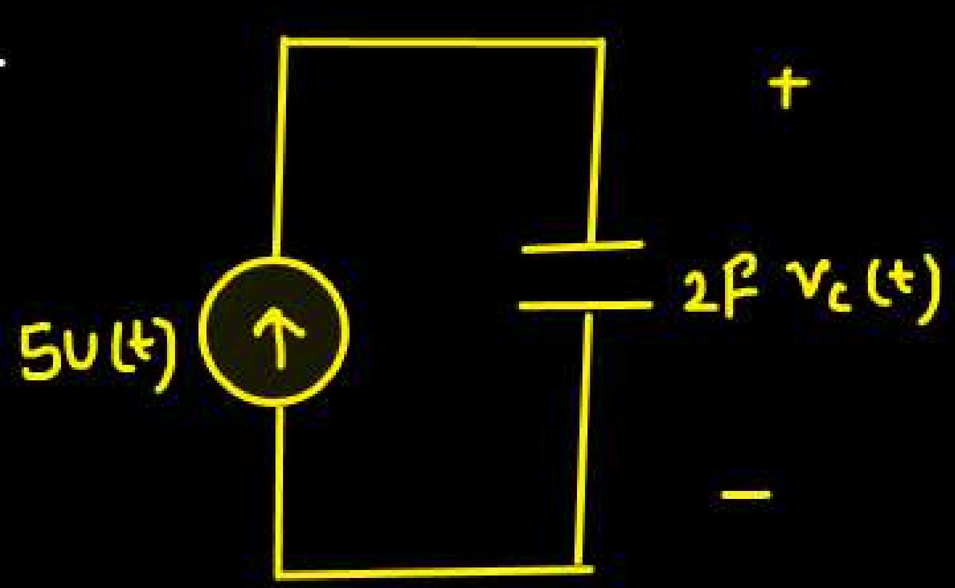


Generally, Slew Rate is defined as:-

$$\boxed{S.R. = \frac{dv_o}{dt}}$$

For Op-Amp SR unit → $V/\mu s$

Q.



Find slew rate considering output to be $v_c(t)$.

→ M-I

$$S.R. = \frac{dv_c(t)}{dt} = ?$$

$$I(t) = \frac{C\,dv_c(t)}{dt}$$

$$\Rightarrow \frac{dv_c(t)}{dt} = \frac{I(t)}{C} = \frac{5U(t)}{C}$$

$$\Rightarrow \boxed{SR = \frac{5}{2} = 2.5\,V/sec.}$$

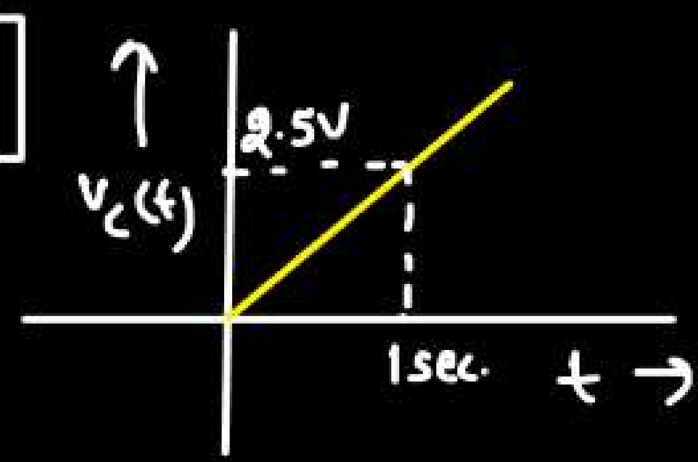
M-II :-

$$v_c(t) = \frac{1}{C}\int_0^t I(t)\cdot dt$$

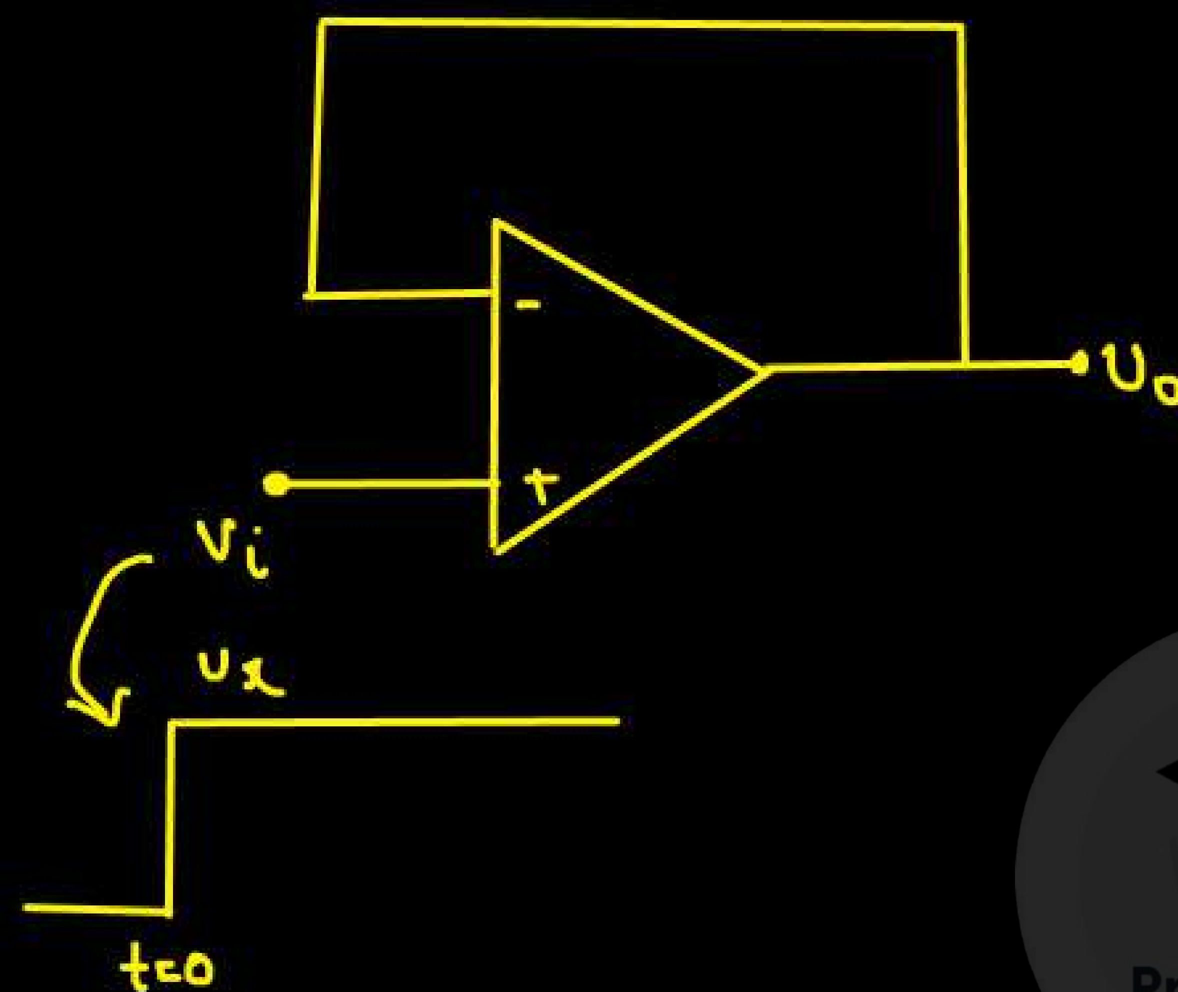
$$= \frac{1}{2}\,5t\,U(t)$$

$$\boxed{v_c(t) = 2.5t\,U(t)}$$

$$SR = 2.5\,V/sec.$$



Q.

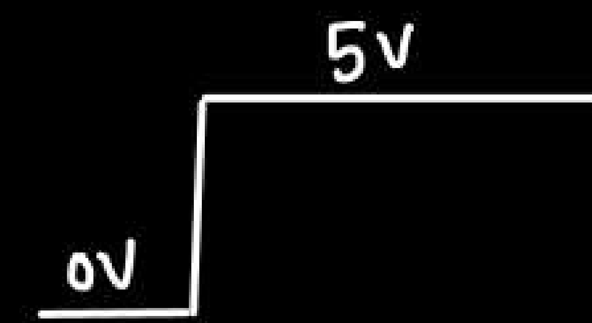


Take slew rate = ∞ [ideal op. Amp]

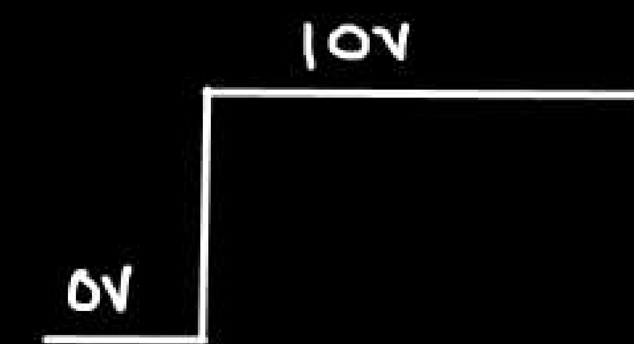
Draw v_o for (a) $v_x = 5V$ (b) $v_x = 10V$

$$S.R. = \infty \, V/\mu s = \frac{V}{0 \, \mu s}$$

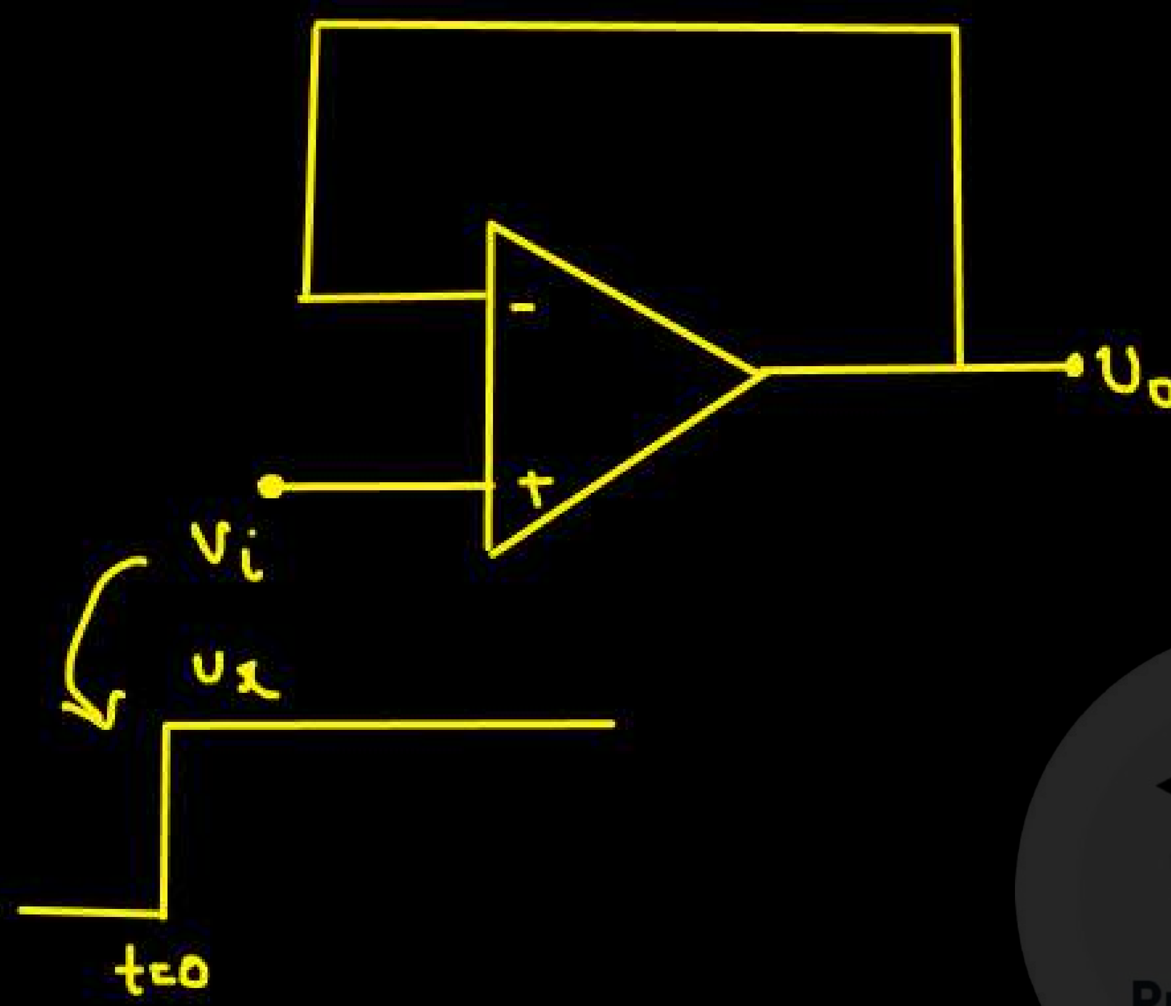
(a)



(b)



Q.



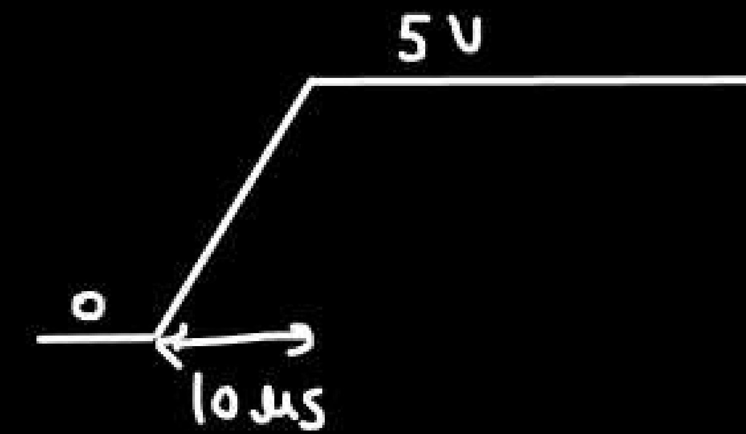
Take slew rate = $0.5V/\mu s$

Draw v_o for (a) $v_x = 5V$ (b) $v_x = 10V$

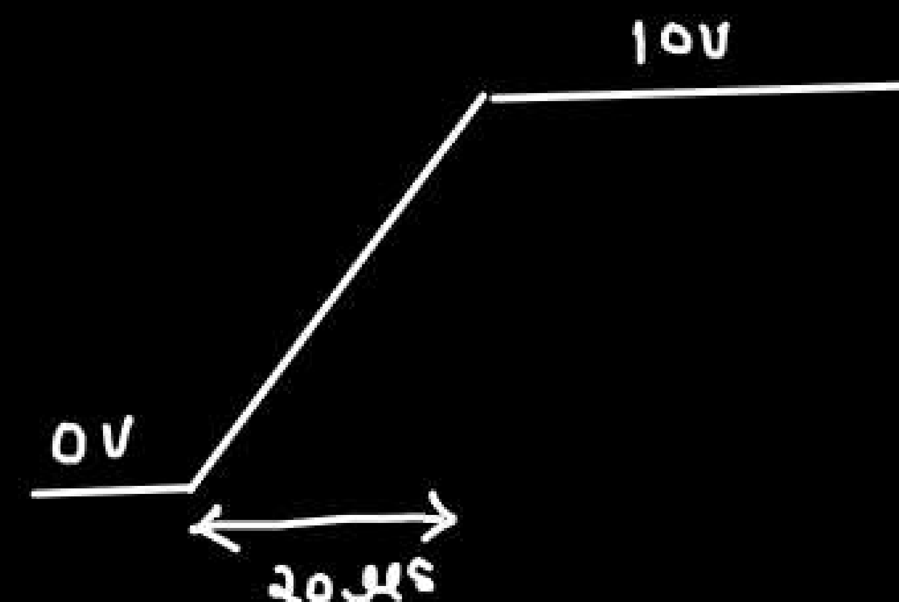
S.R. = $0.5V/\mu s$

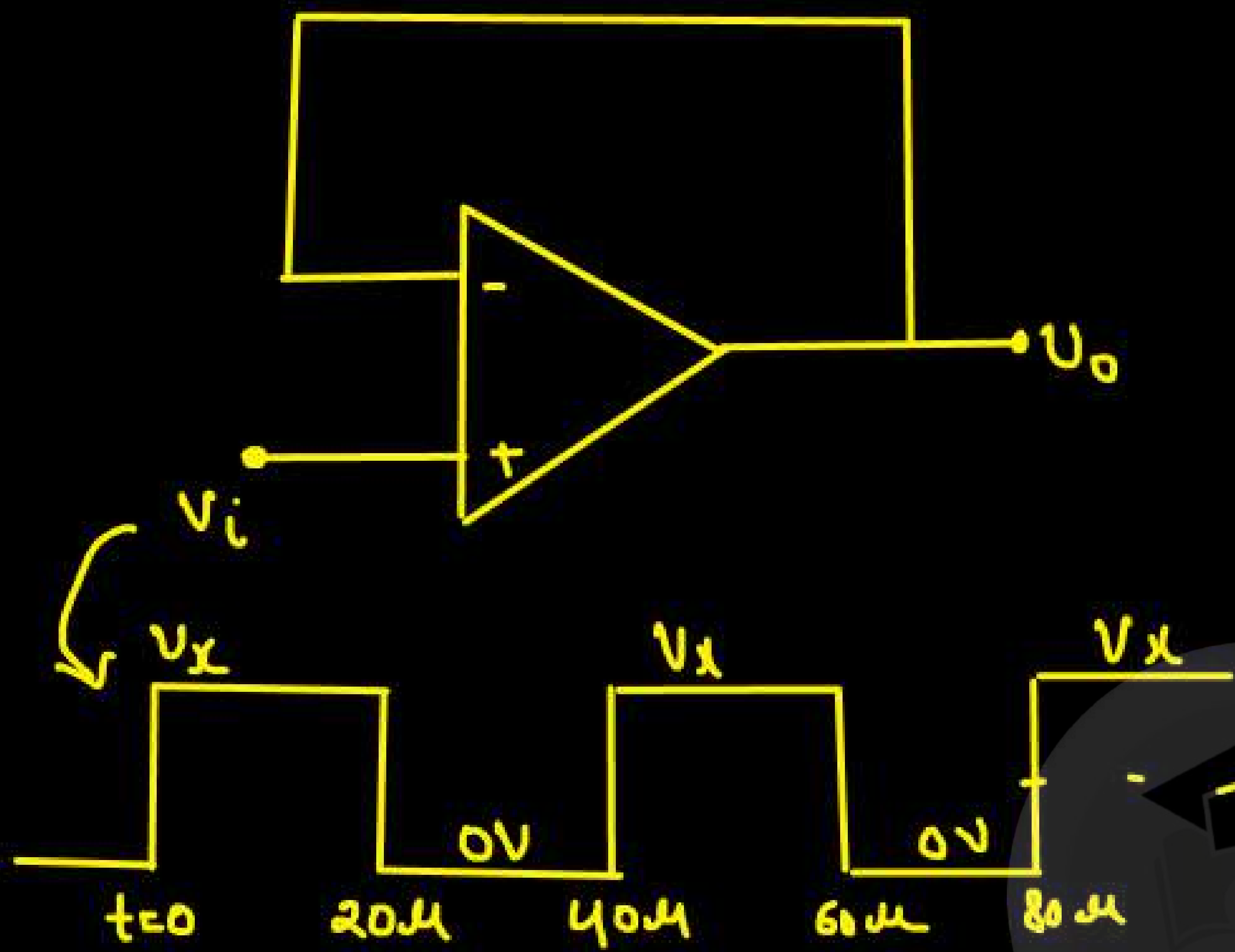
$v_o = v_i$

(a)



(b)





Take slew rate = $0.5\ V/\mu s$

Draw v_o for (a) $V_x = 5V$ (b) $V_x = 10V$ (c) $V_x = 20V$

→

$S.R. = 0.5\ V/\mu s$

$1\mu s \rightarrow 0.5V$

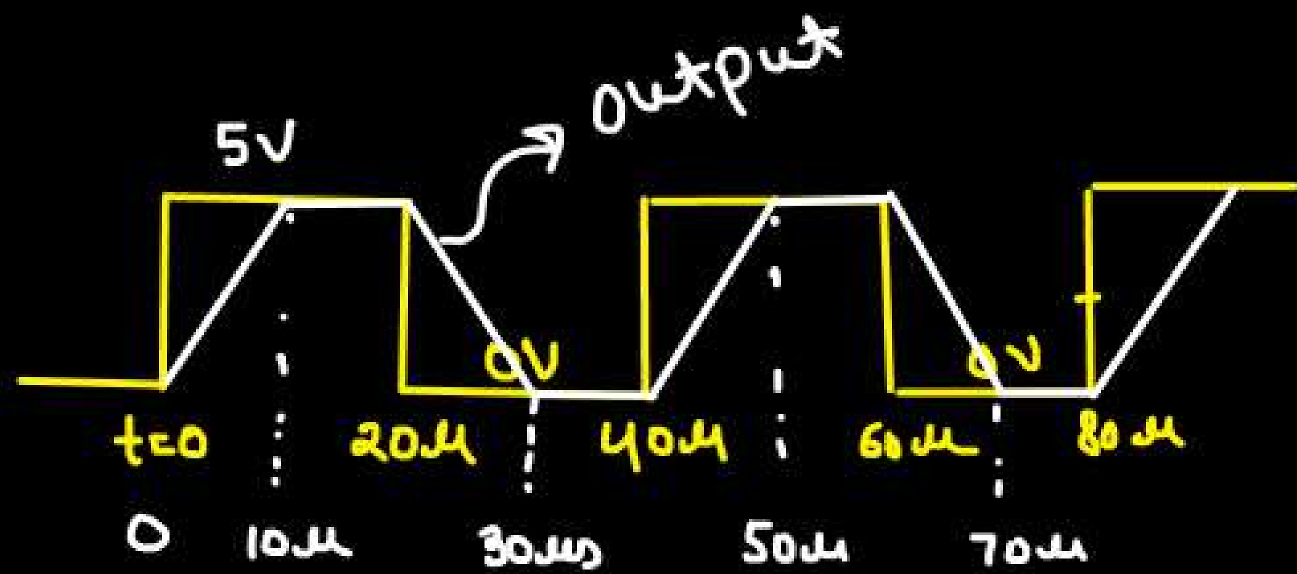
$40\mu s = 20V$

$20\mu s = 10V$

$10\mu s \rightarrow 5V$

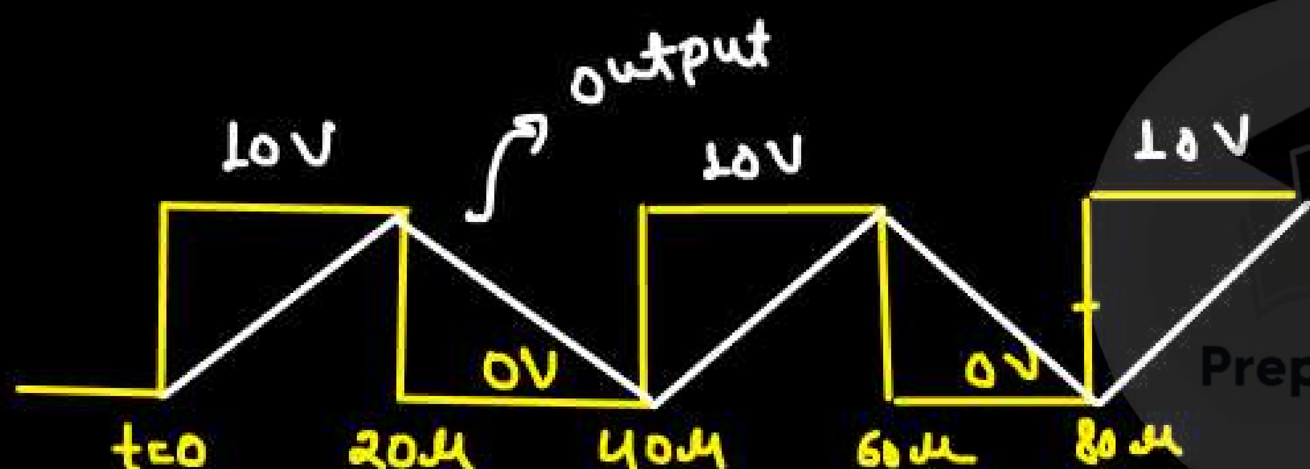
$\boxed{v_o = v_i}$

(a)



→ Trapezoidal

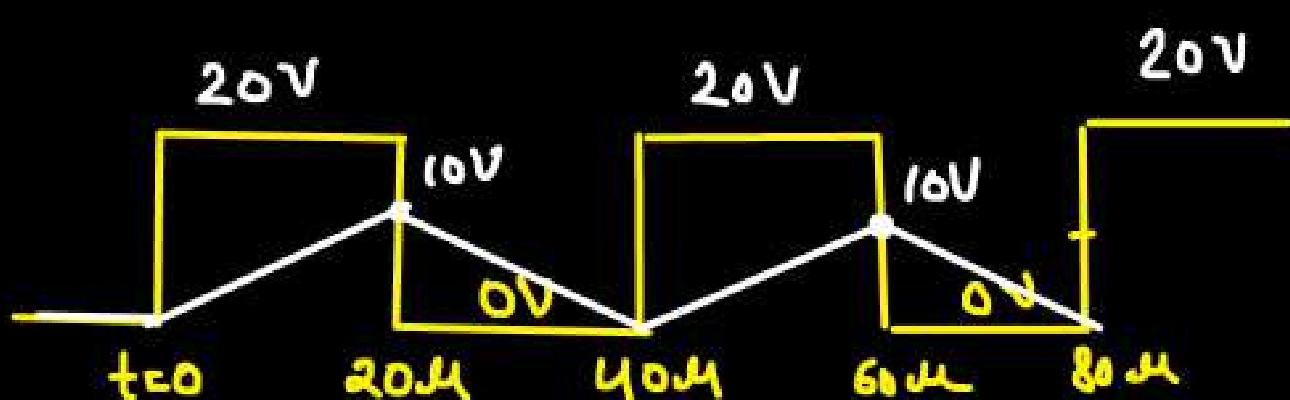
(b)



→ Triangular

$0.5V/\mu sec.$

(c)



→ Triangular

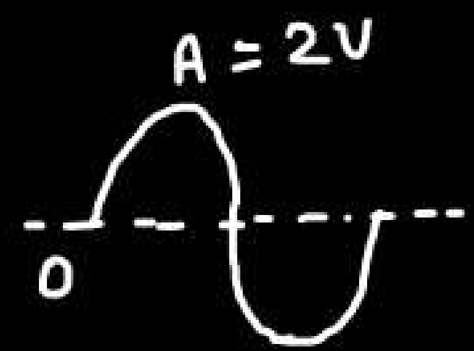
$2V/\mu sec. \rightarrow 10\mu$

★ In case of Sinusoid i/p :-

For distortionless o/p :-

$$\boxed{\left|\frac{dv_o}{dt}\right|_{max} \leq SR}$$

Remember



$$v_o(t) = A_m \sin\omega_m t$$

$$\frac{dv_o(t)}{dt} = A_m \omega_m \sin\omega_m t$$

$$\left|\frac{dv_o(t)}{dt}\right| = A_m \omega_m$$

$$A_m \times 2\pi f_m < SR$$

$$f_m < \frac{SR}{2\pi A_m}$$

$$\boxed{(f_m)_{max} = \frac{SR}{2\pi A_m}}$$

Power Bandwidth

Q. For OP-Amp, Slew rate = $2V/\mu s$

Peak output = 12 V

Maximum allowable freq. of i/p = ?

OR

Power Bandwidth = ?

→

$SR = 2V/\mu sec.$

$$\frac{dv_0}{dt} = A_m \omega_m \sin \omega t$$

$$\left|\frac{dv_0}{dt}\right|_{max} = A_m \times 2\pi f_m$$

$$= 12 \times 2\pi f_m$$

$$12 \times 2\pi f_m < 2V/\mu s$$

$$(f_m)_{max} = \frac{2 \times 10^6}{12 \times 2\pi}$$

$$\boxed{(f_m)_{max} = 26.52 KHz}$$

Q. OP-AMP $SR = 5V/\mu s$

Find out largest sine wave output voltage possible at a freq. of 1 MHz

→

$$\left|\frac{dV_o}{dt}\right|_{max} \leq SR$$

$$A_m \omega_m \leq SR$$

$$A_m \times 2\pi \times 1 \times 10^6 \leq 5 \times 10^6 \, V/sec$$

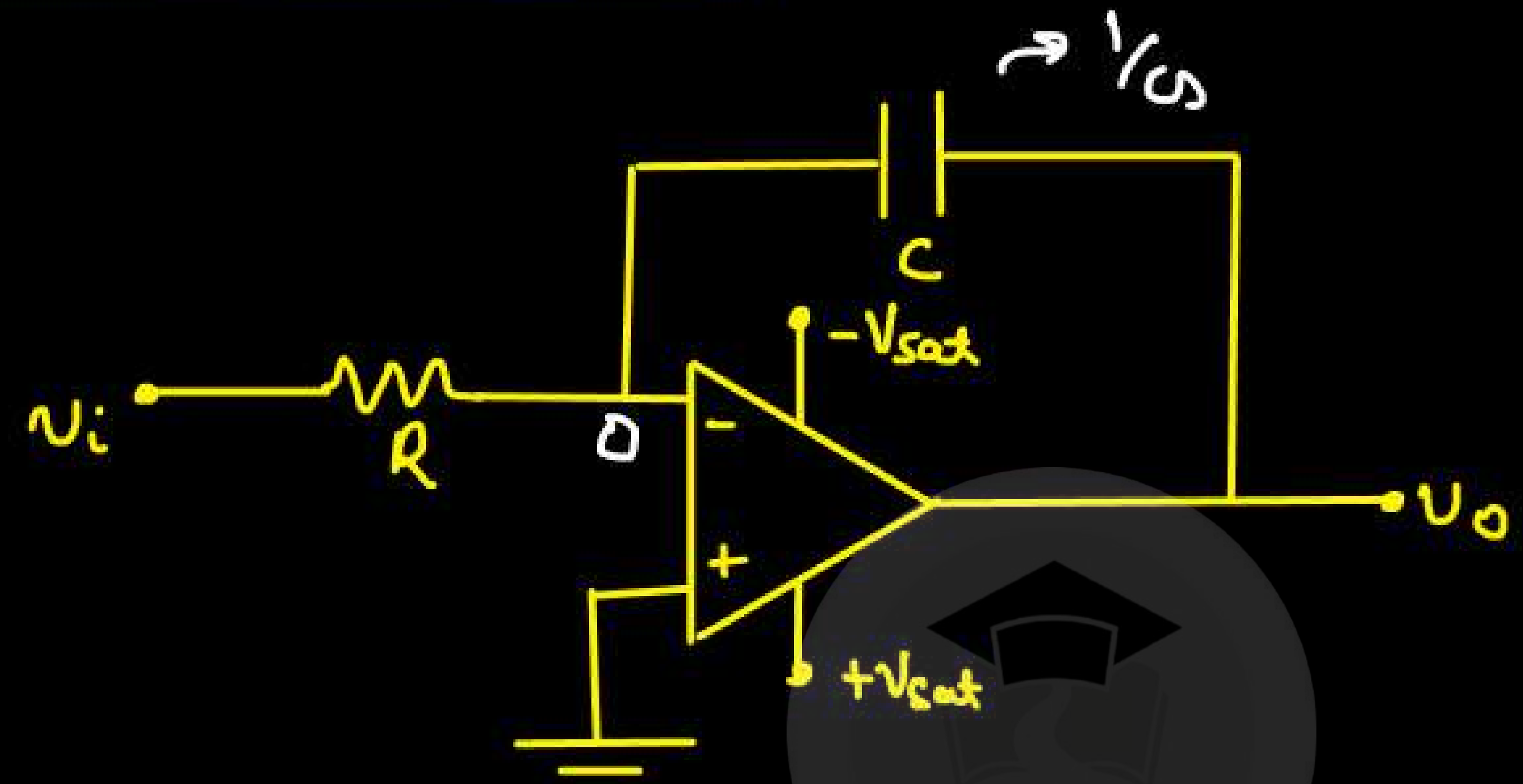
$$A_m \leq \frac{5}{2\pi}$$

$$A_m \leq 0.79V$$

$$\boxed{(A_m)_{max} = 0.79V}$$

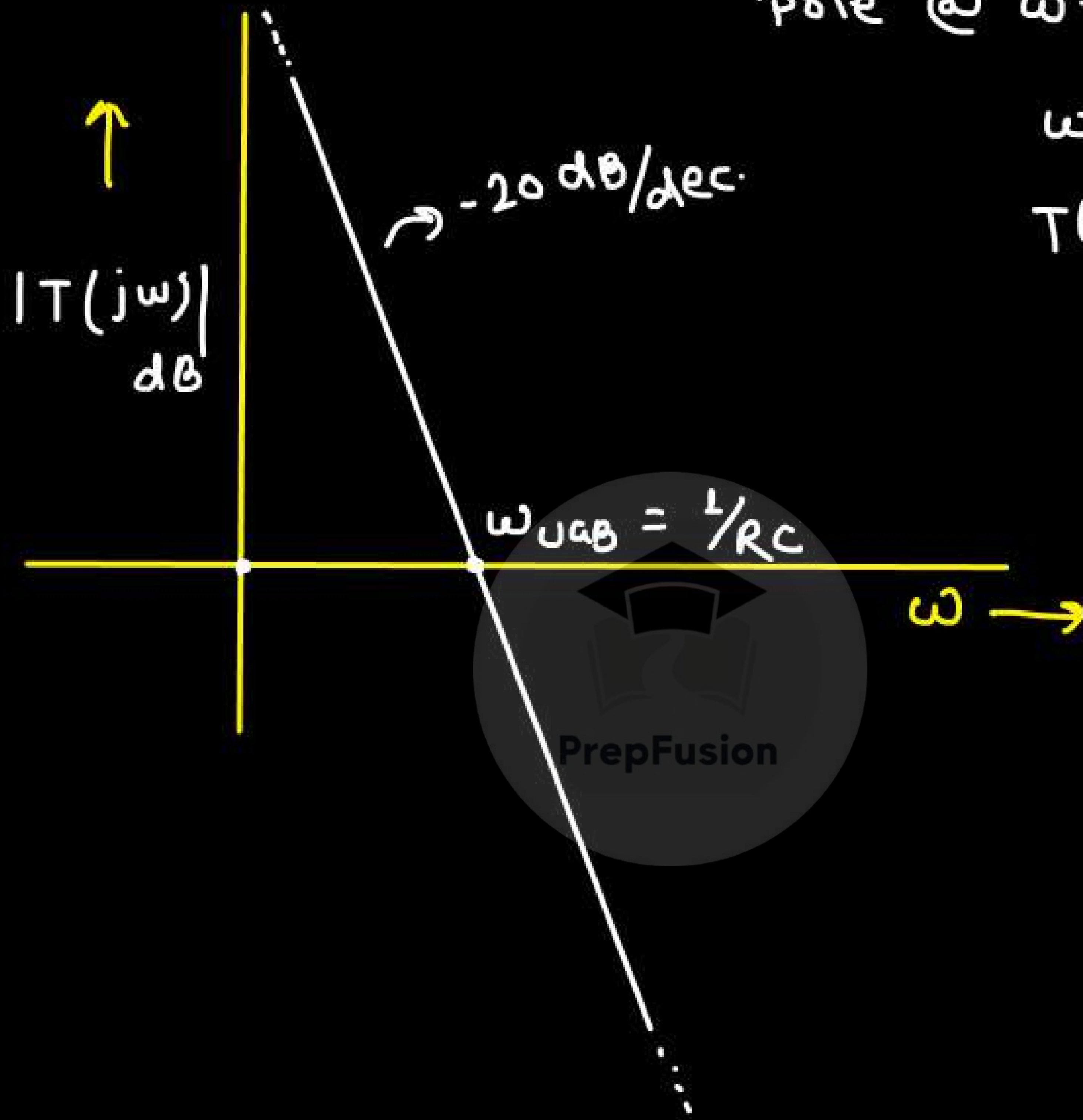
Parameter	Ideal op-amp	Practically
① offset Voltage	0	mV to μV
② Bias Current	0	μA to fA
③ offset Current	0	nA to fA
④ Bandwidth	∞	1 MHz (IC-741)
⑤ CMRR	∞	100 dB
⑥ slew rate	∞	Some V/μs

⇒ Integrator Using OP-Amp:-



$$\boxed{\frac{v_o(s)}{v_i(s)} = \frac{-1}{sCR}} = T(s)$$

$$v_o(s) = \frac{-1}{sRC}\, v_i(s) \Rightarrow \boxed{v_o(t) = \frac{-1}{RC}\int_{-\infty}^{t} v_i(t)\cdot dt}$$



Pole @ $\omega = 0$

$\omega = \infty$

$$T(j\infty) = \frac{1}{\infty} = 0$$

$$= 20\log_{10}(0)$$

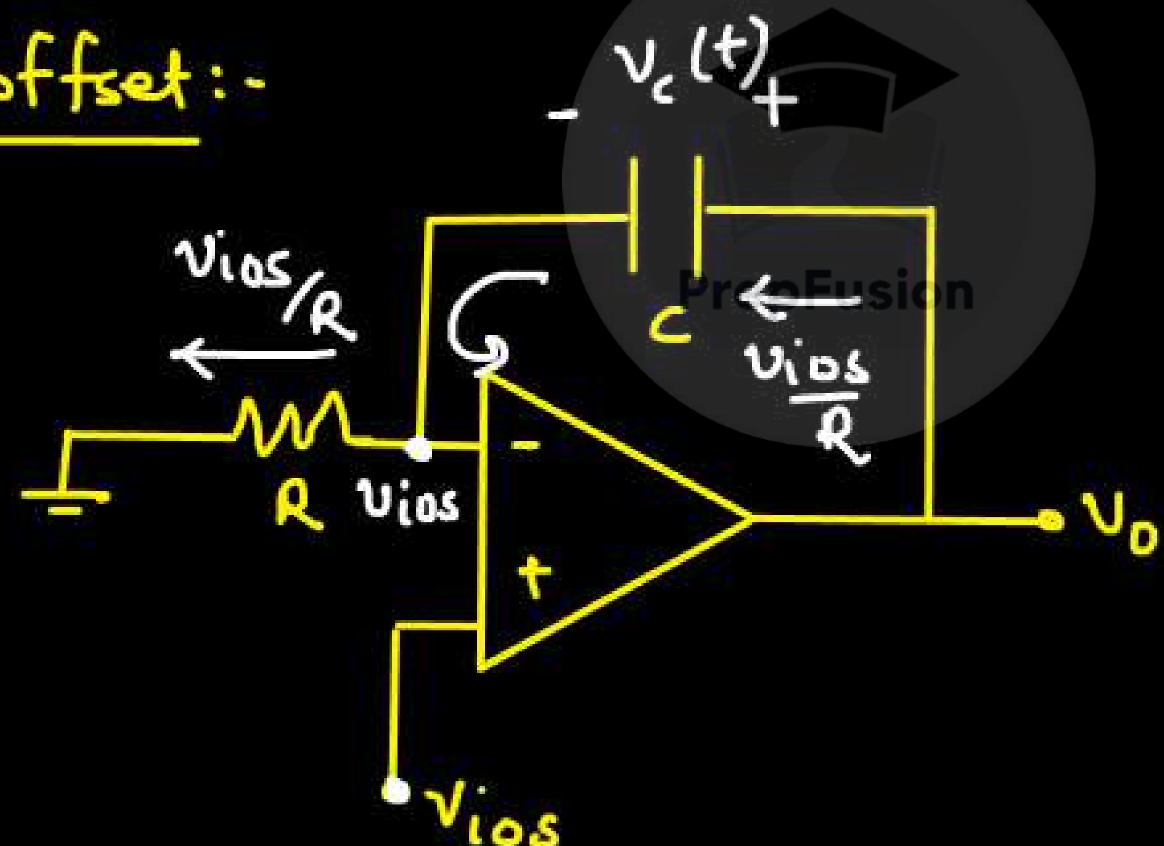
$$= -\infty$$

Drawbacks:-

(a) Acts as open loop config. at low freq. (Saturated O/P).

(b) Very low Bandwidth. The gain keeps on decreasing with increase in freq.

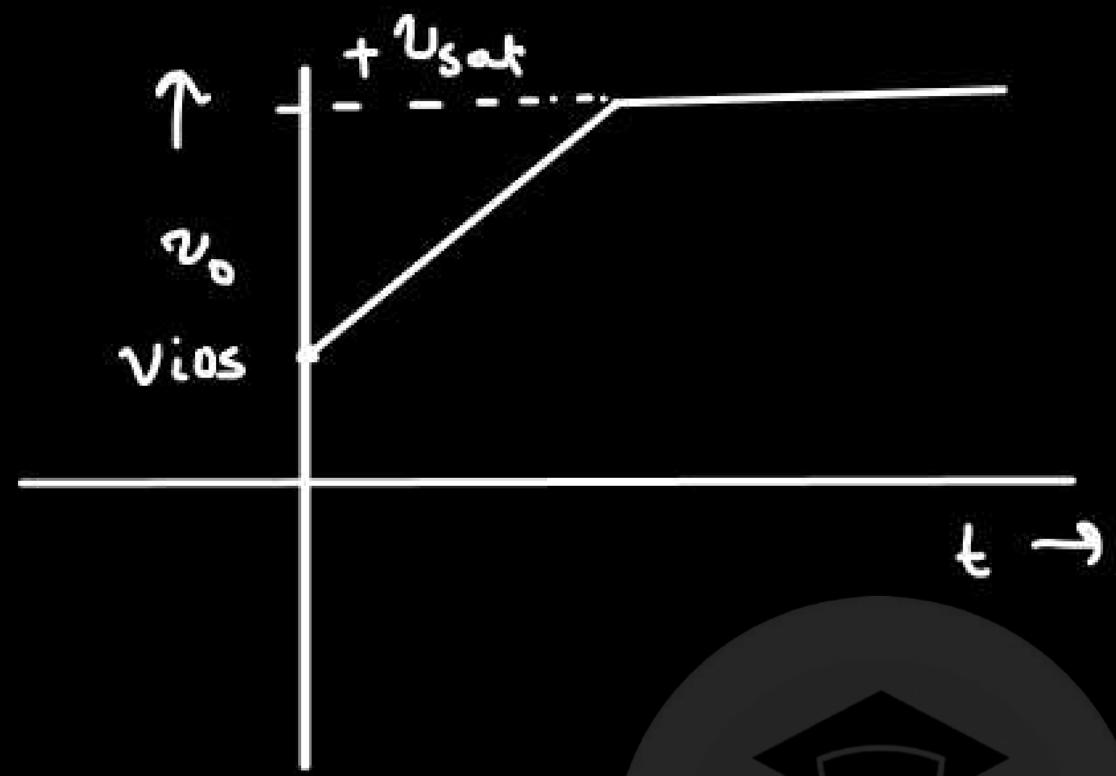
(c) Effect of offset:-



$$v_0 = v_{ios} + v_c(t)$$

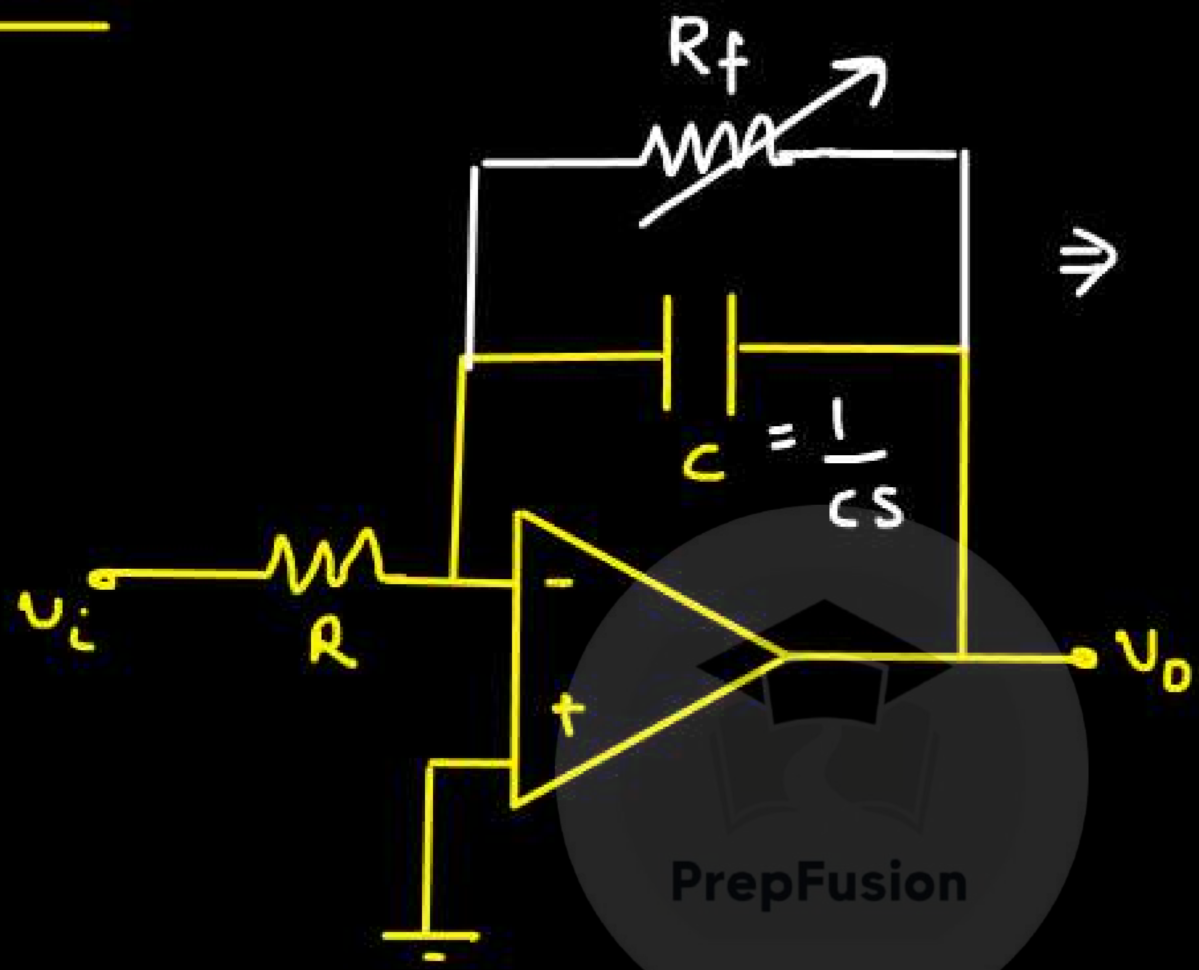
$$= v_{ios} + \frac{1}{C}\int_{-\infty}^{t} \frac{v_{ios}}{R}\,dt$$

$$v_0(t) = v_{ios} + \frac{v_{ios}}{RC}\,t$$



without even applying the i/p, o/p is saturated.

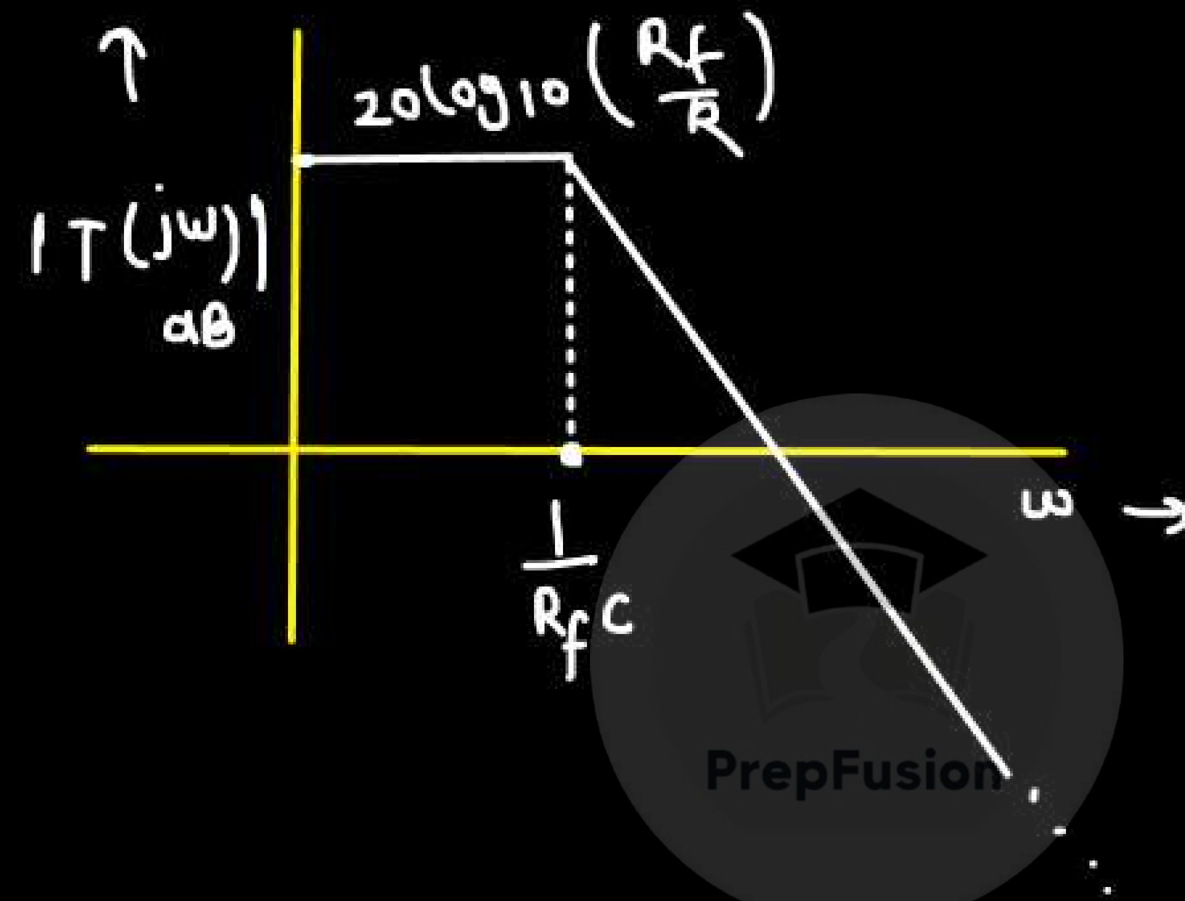
Practical Integrator :-



$$\Rightarrow \frac{R_f}{R_f c s + 1}$$

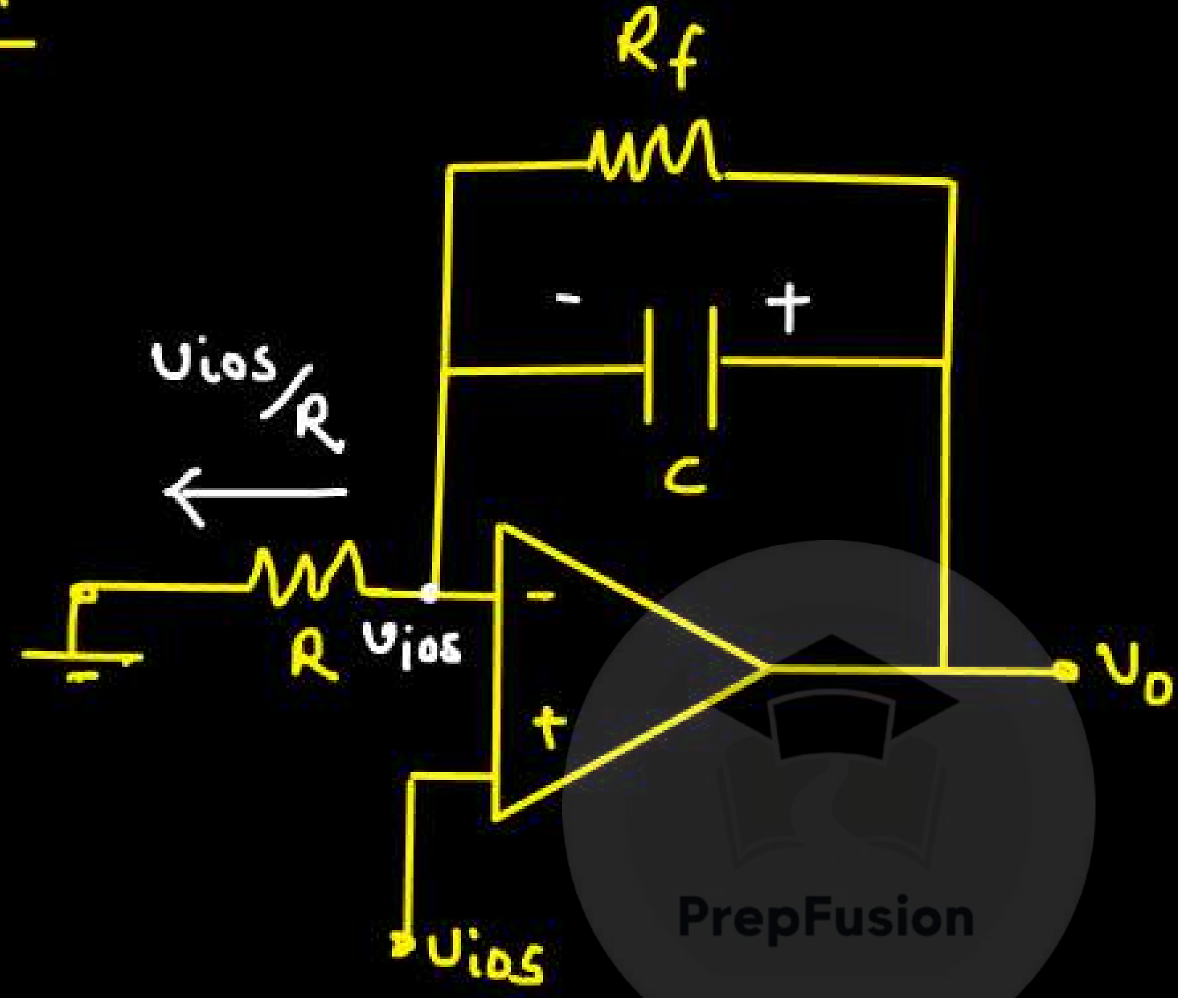
$$\boxed{\frac{v_o(s)}{v_i(s)} = \frac{-R_f/R}{R_f c s + 1}} = T(s)$$

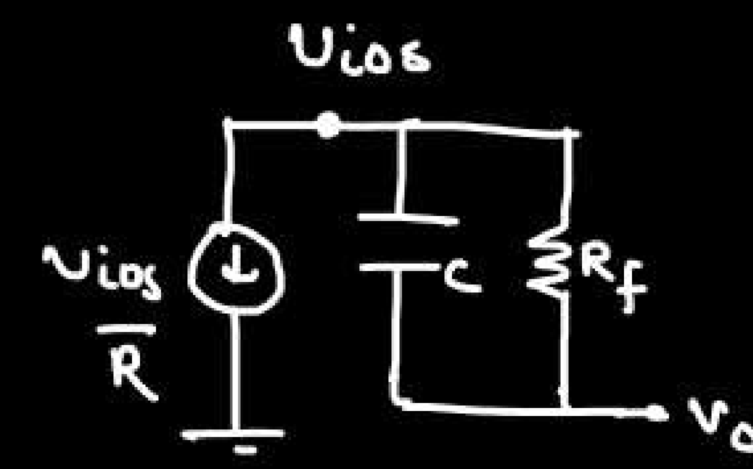
$$\omega_p = \frac{1}{R_f C}$$



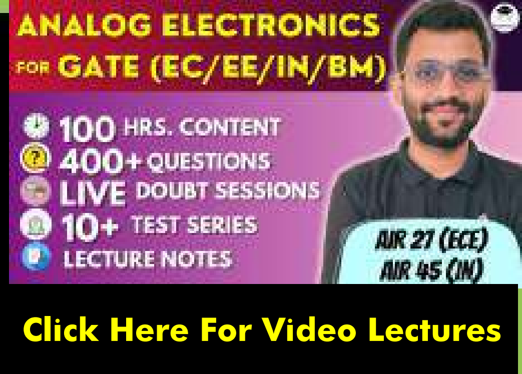
$20\log_{10}\left(\frac{R_f}{R}\right)$
$|T(j\omega)|_{dB}$
$\frac{1}{R_f C}$
ω
PrepFusion

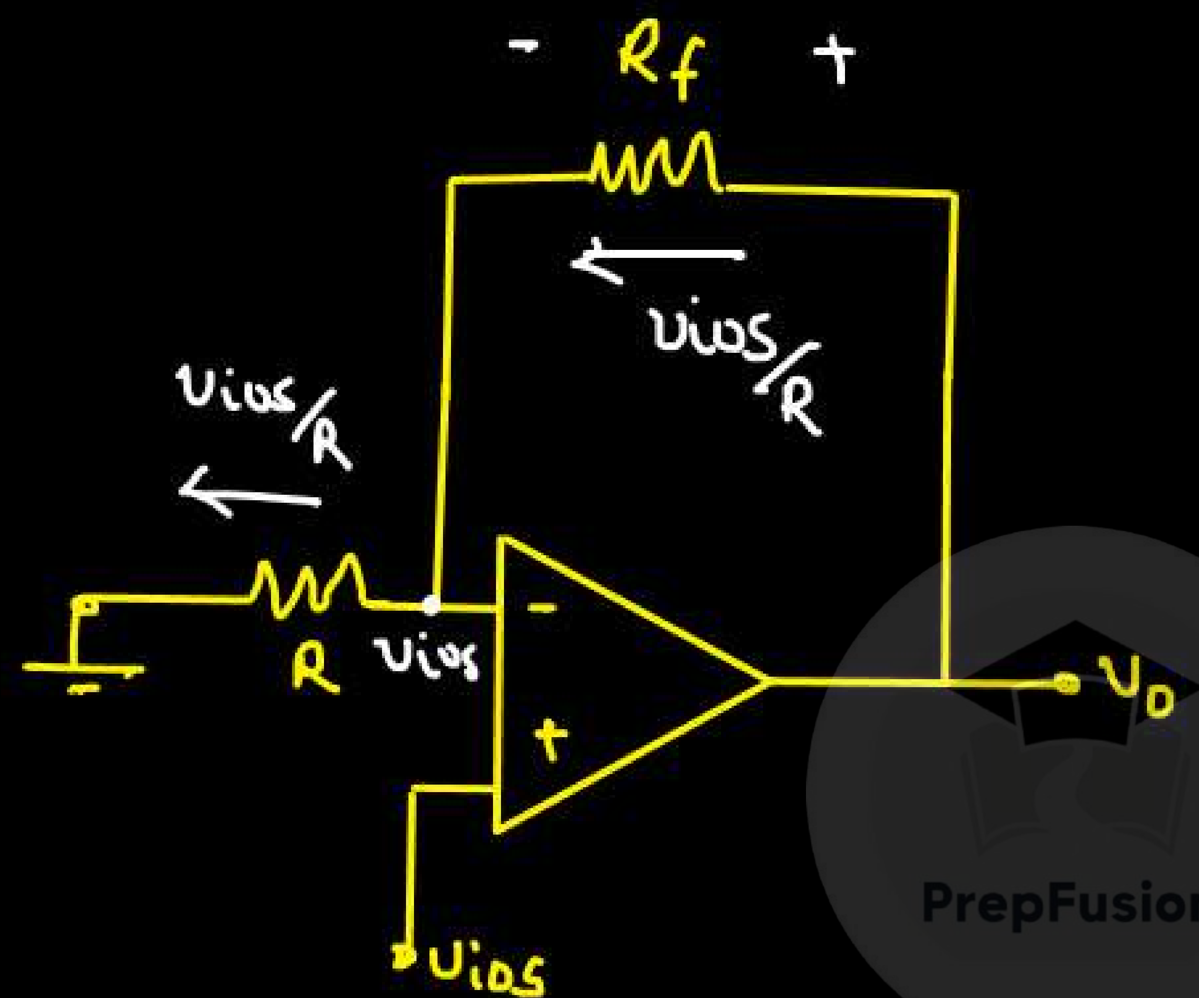
Effect of Offset:-





$$v_o(t=0^+) = v_{ios}$$

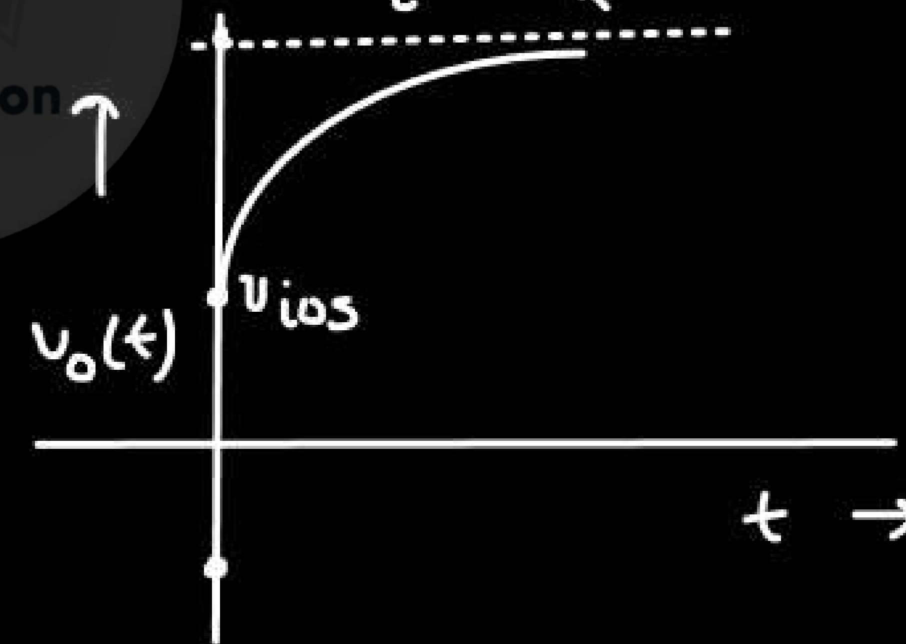




$$v_o(t=\infty) = v_{ios} + \frac{v_{ios}}{R} \times R_f$$

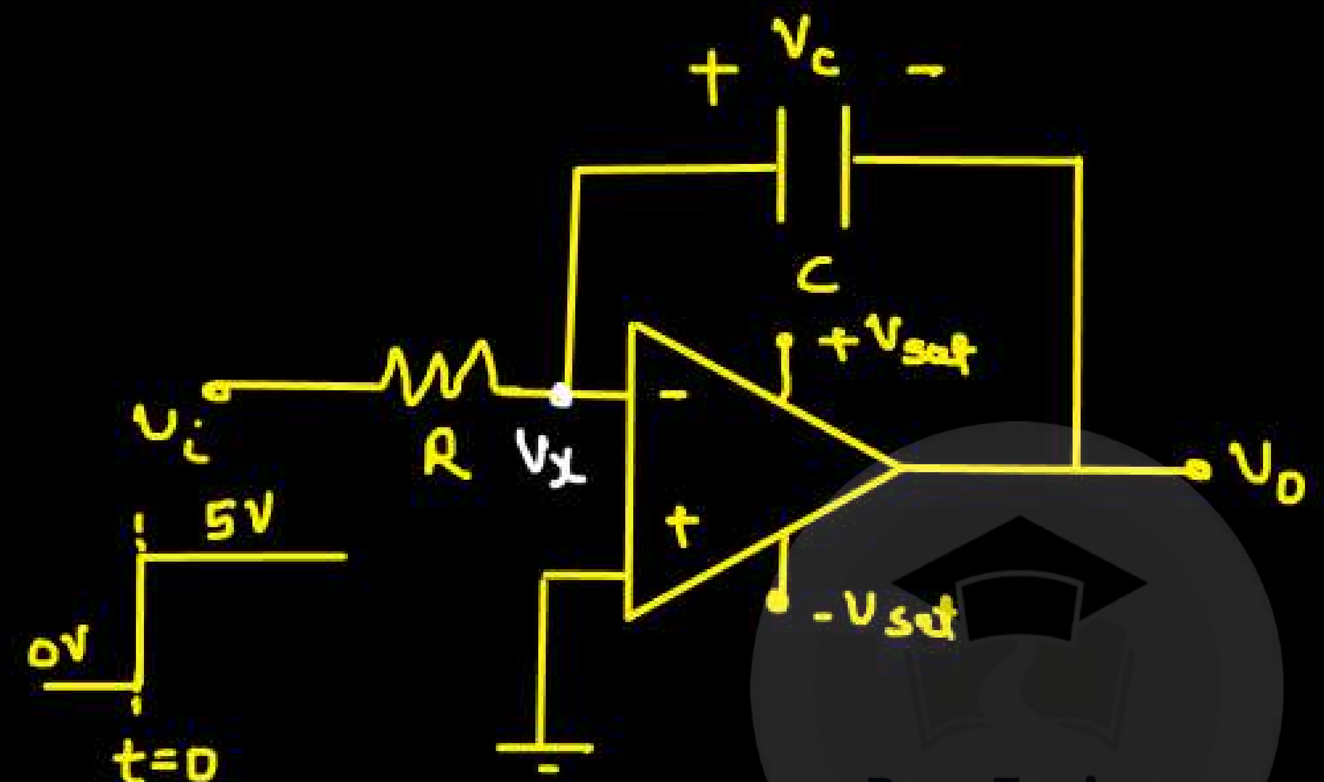
$$v_o(t=\infty) = v_{ios}\left[1+\frac{R_f}{R}\right]$$

$$v_{ios}\left[1+R_f/R\right] \leq v_{sat}$$

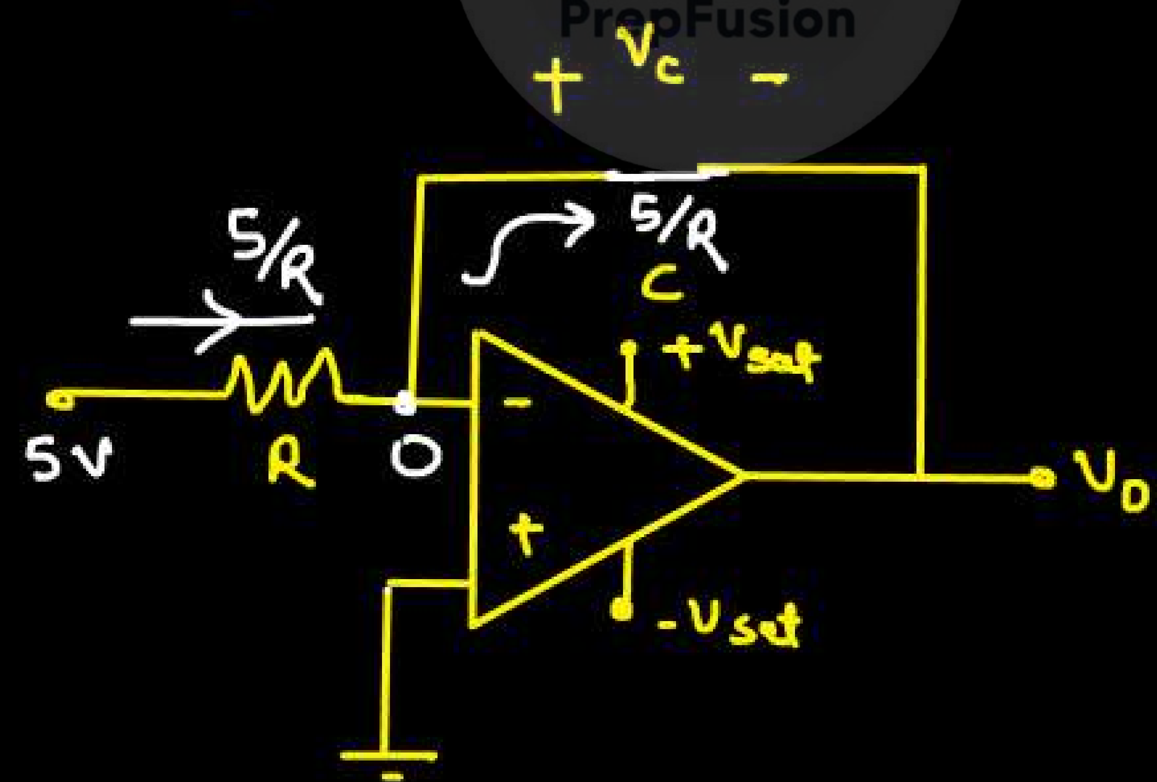


★ Ideal Integrator with different inputs:-

(a)



at $t = 0^+$



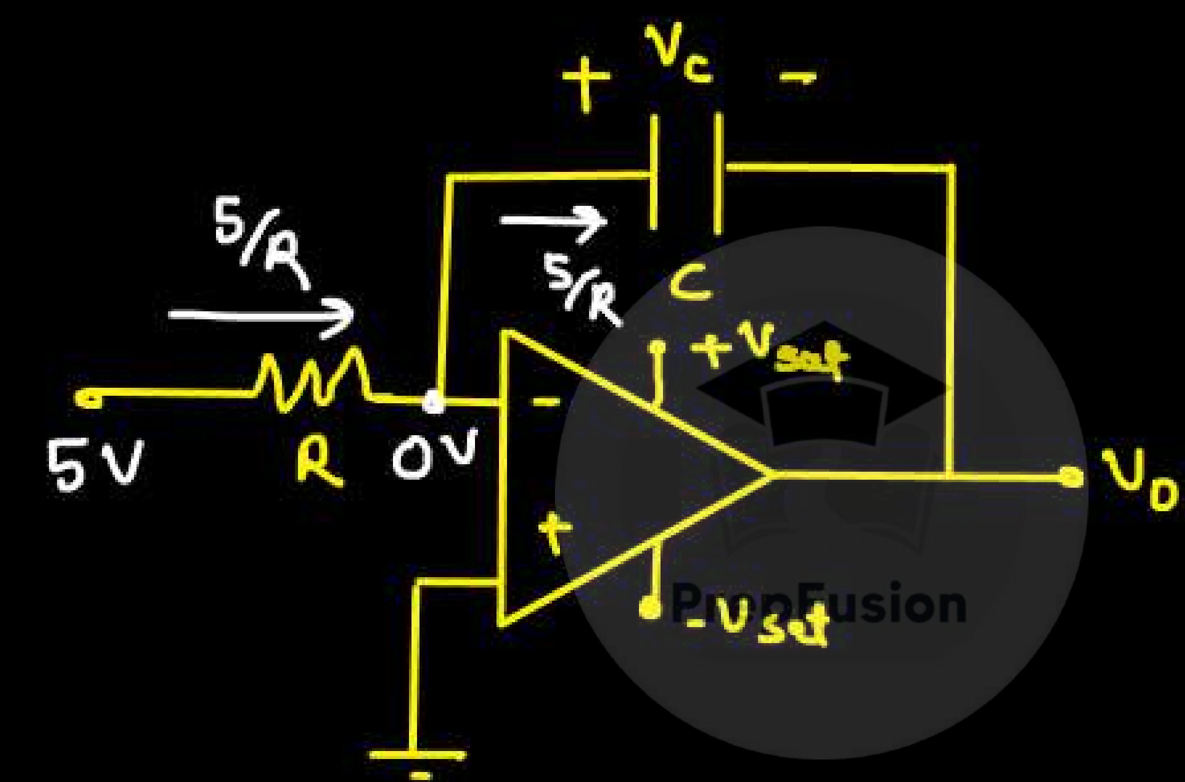
$v_x(t=0^+) = 0$

$v_c(t=0^+) = 0$

$v_o(t=0^+) = 0$

constant $5/R$ current is flowing through cap.

So, cap. would charge linearly



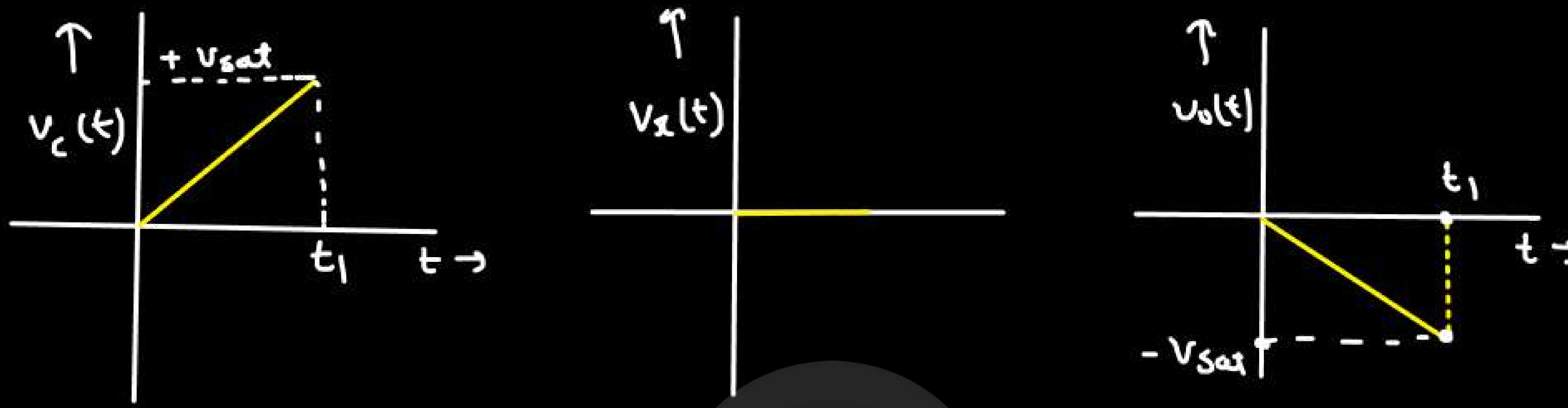
$$v_c(t) = \frac{1}{C}\int_0^t \frac{5}{R}\cdot dt$$

$$\boxed{v_c(t) = \frac{5t}{RC}}$$

$$\boxed{V_x(t) = 0}$$

$$\boxed{v_o(t) = -\frac{5t}{RC}}$$

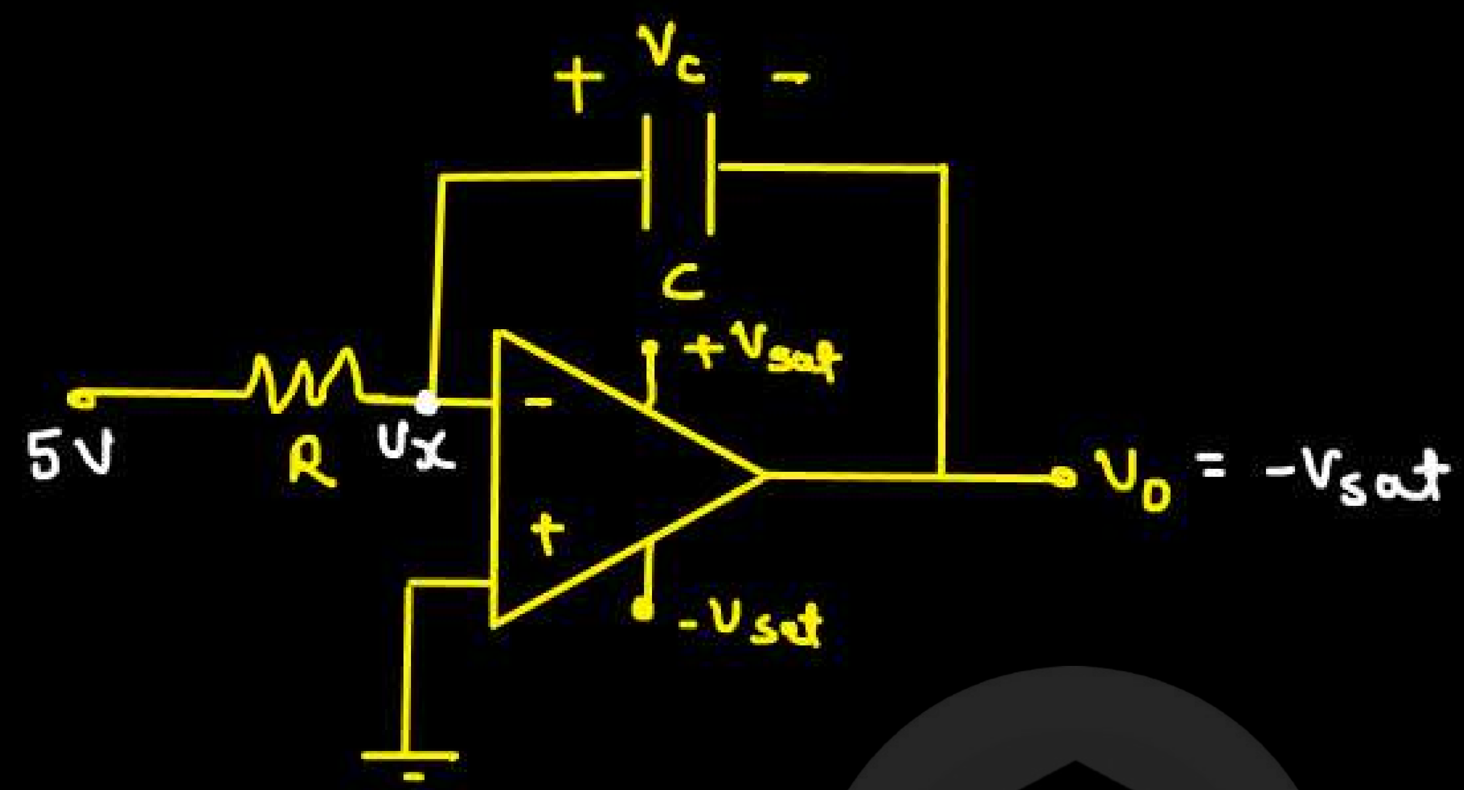
$$\boxed{v_o(t) = -v_c(t)}$$



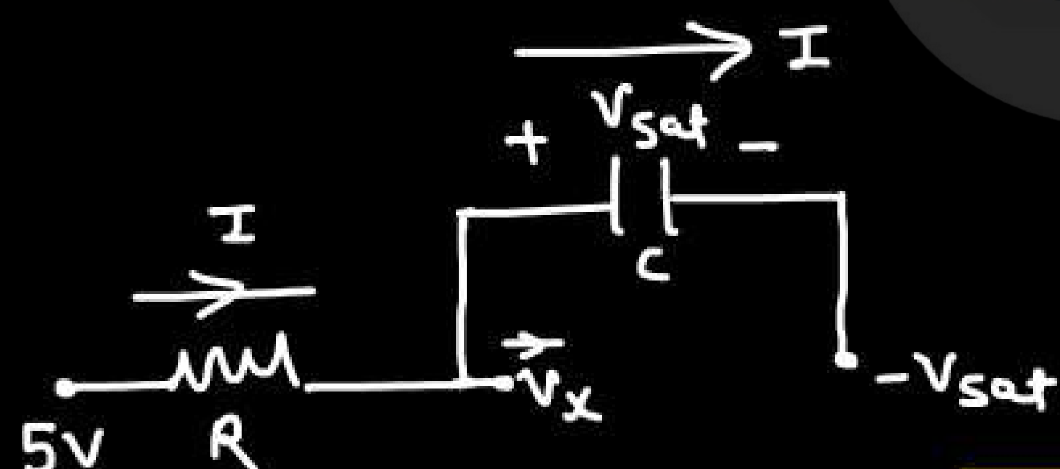
Here, $v_0(t)$ is continously decreasing

but the minimum value it can get is $-V_{sat}$

Let @ $t = t_1$ $\quad v_0(t_1) = -V_{sat}$



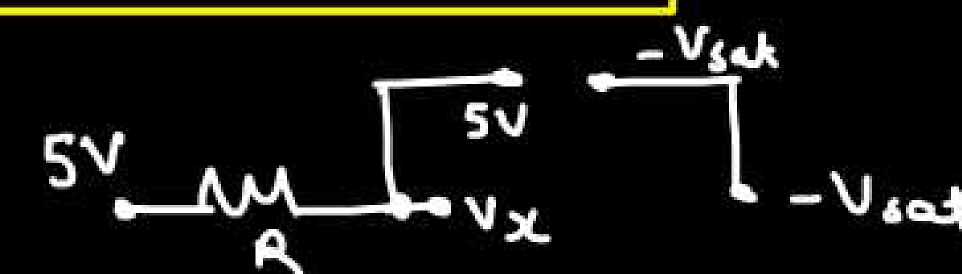
now $\boxed{v_x(t>t_1) \neq 0V}$ { O/P is saturated ⇒ Virtual short NOT valid }

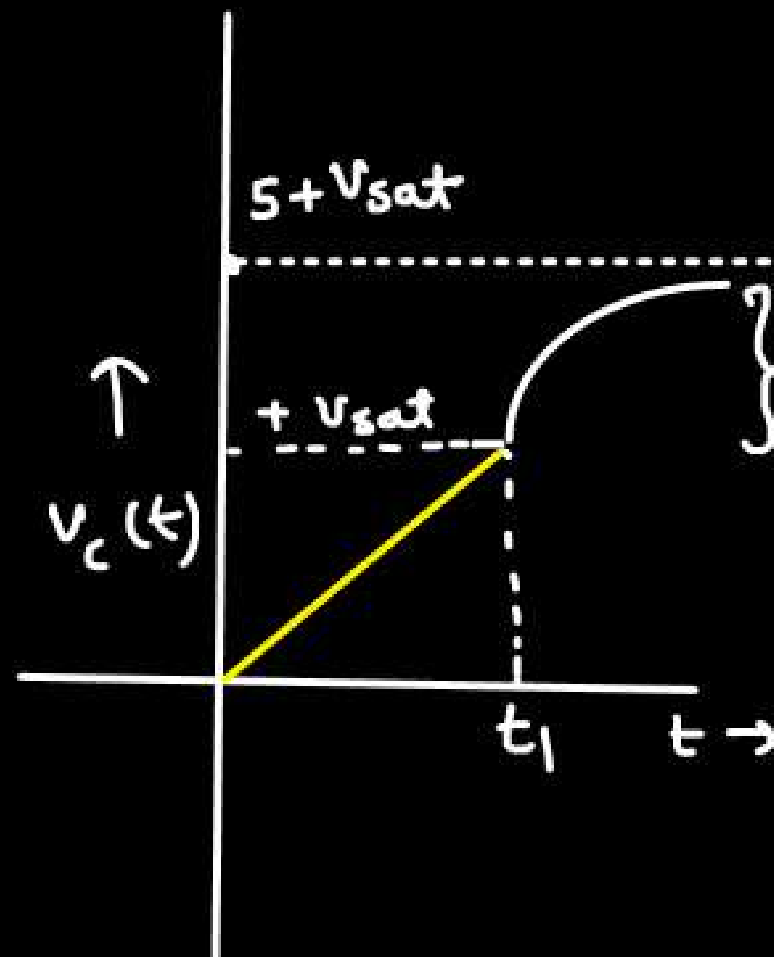


$$\boxed{\begin{aligned} v_x(t=t_1) &= 0V \\ v_x(t=\infty) &= 5V \end{aligned}}$$

$$\boxed{v_0(t=t_1) = -V_{sat} = v_0(t=\infty)}$$

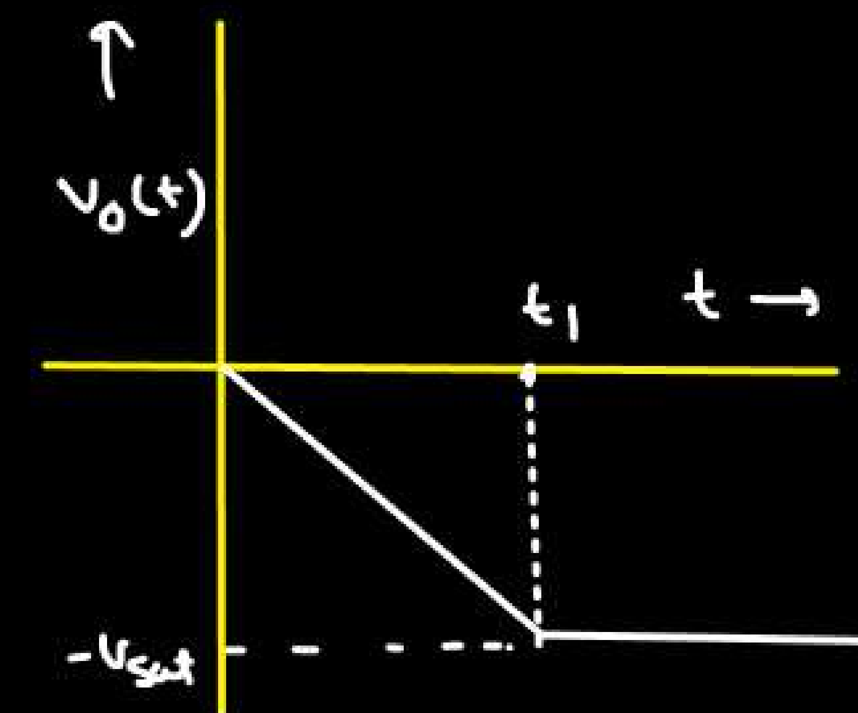
$$\boxed{\begin{aligned} v_c(t=t_1) &= +V_{sat} \\ v_c(t=\infty) &= 5+V_{sat} \end{aligned}}$$

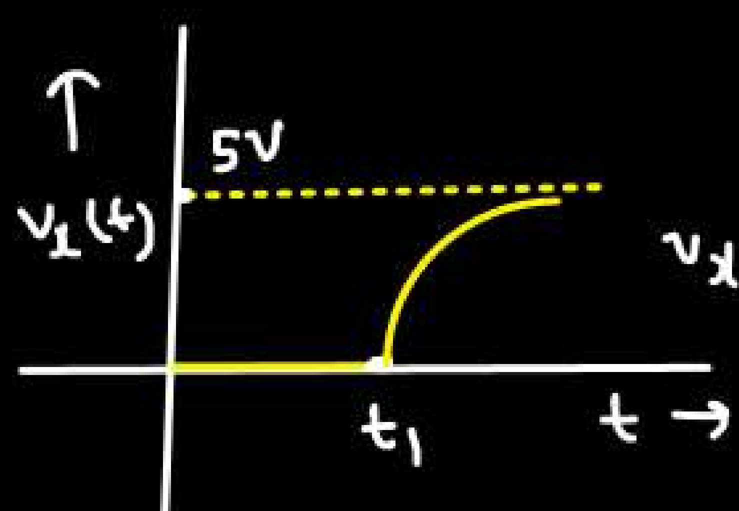




$$\Rightarrow v_c(t) = \left[(5+V_{sat}) - 5e^{-(t-t_1)/RC}\right]u(t-t_1)$$

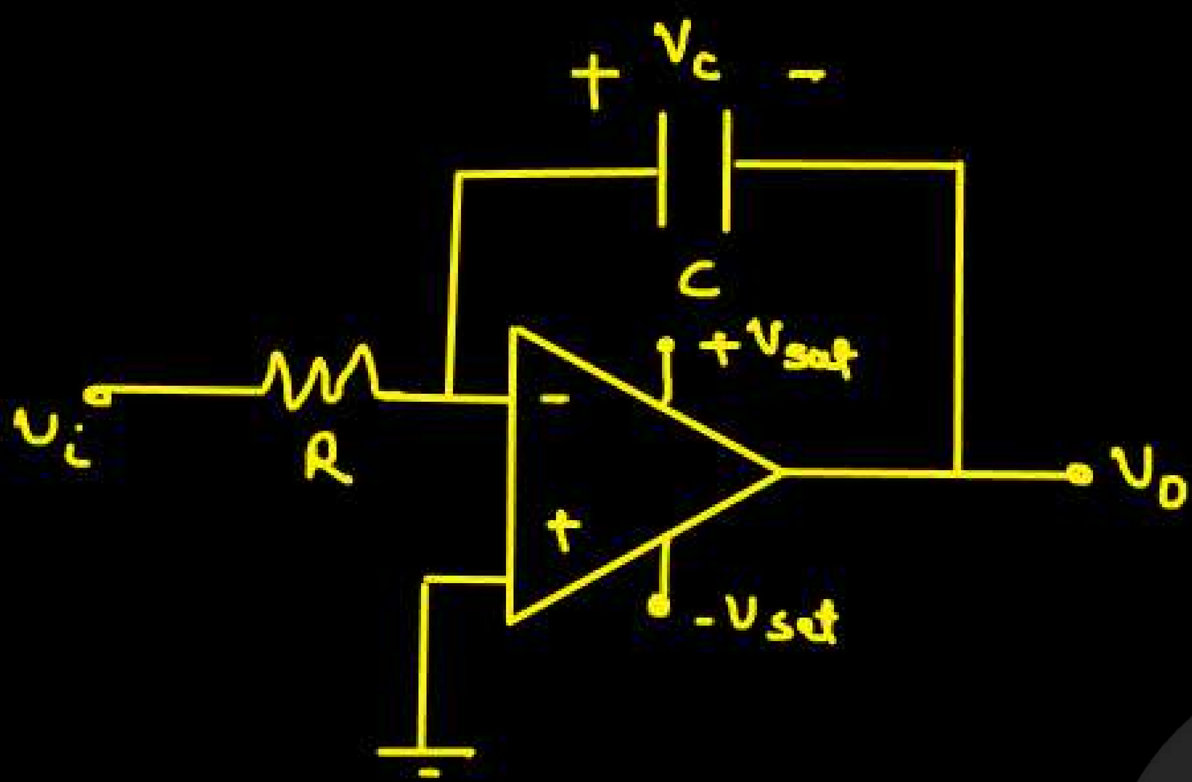
$$\{t > t_1\}$$





$$v_x(t) = 5\left[1 - e^{-(t-t_1)/RC}\right]u(t-t_1)$$

(b)



now, $T < t < 3T/2$

$v_i = 5V$

$$v_c(t) = \frac{5T}{2RC} + \frac{5}{RC}(t-T)$$

$$v_c(3T/2) = \frac{5T}{RC} \quad , \quad V_o(3T/2) = -\frac{5T}{RC}$$

$0 < t < T/2$:-

$v_i = 5V$

$$V_o(t) = -\frac{5t}{RC}$$

$$V_o(T/2) = \frac{-5T}{2RC}$$

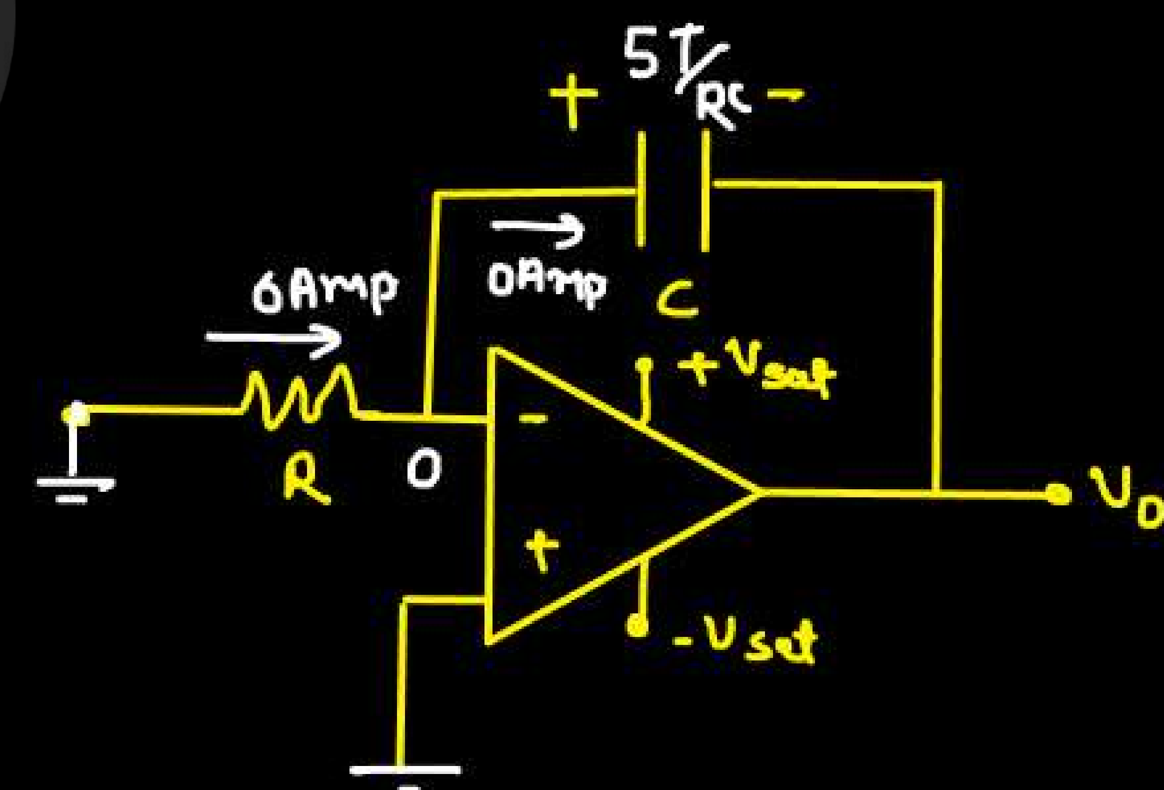
$$V_c(T/2) = \frac{5T}{2RC}$$

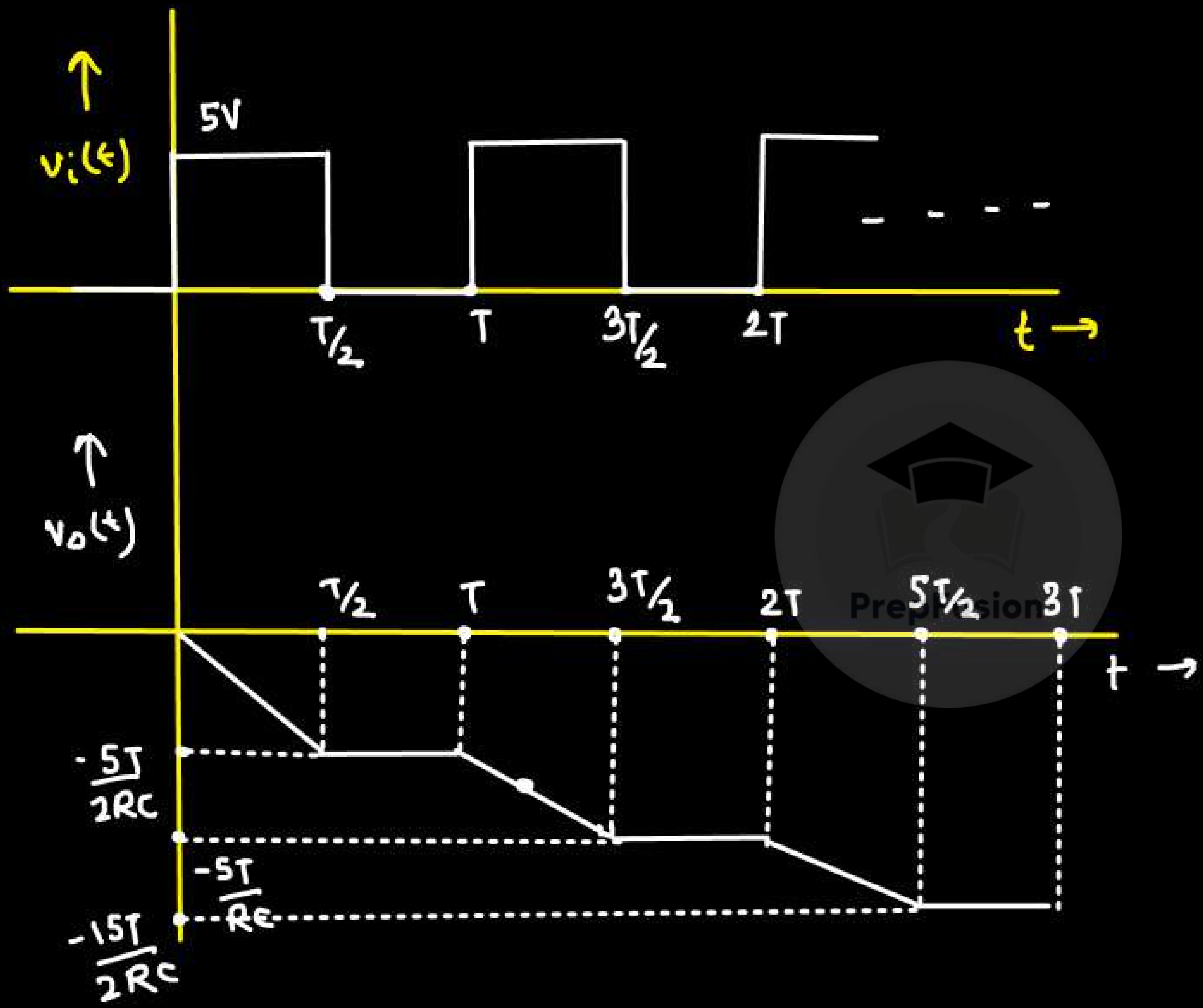
now, $T/2 < t < T$

$v_i = 0V$

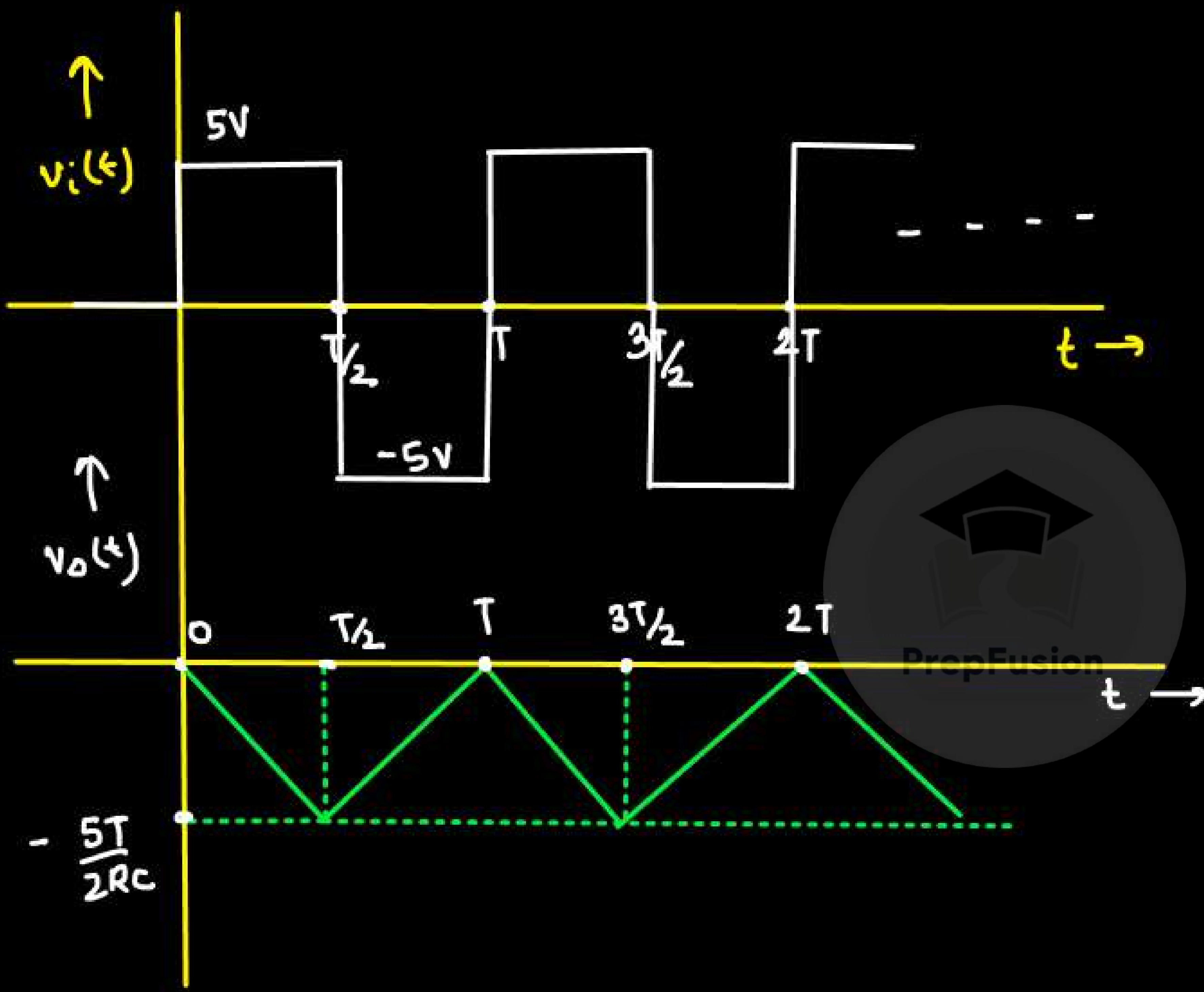
$$V_c(T/2 < t < T) = \frac{5T}{2RC}$$

$$v_o(T/2 < t < T) = -\frac{5T}{2RC}$$



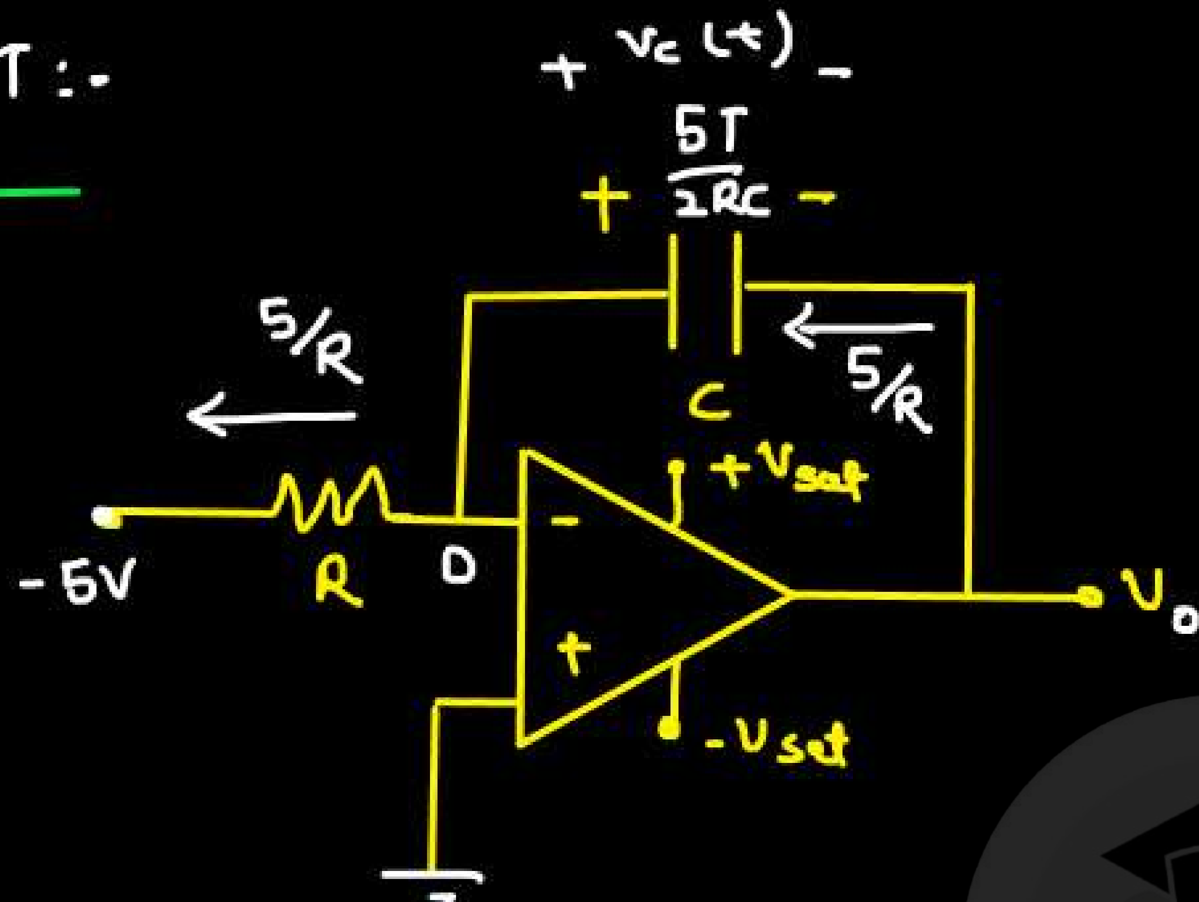


considering o/p doesn't saturate in time window T/2.



considering o/p doesn't saturate in time window $T/2$.

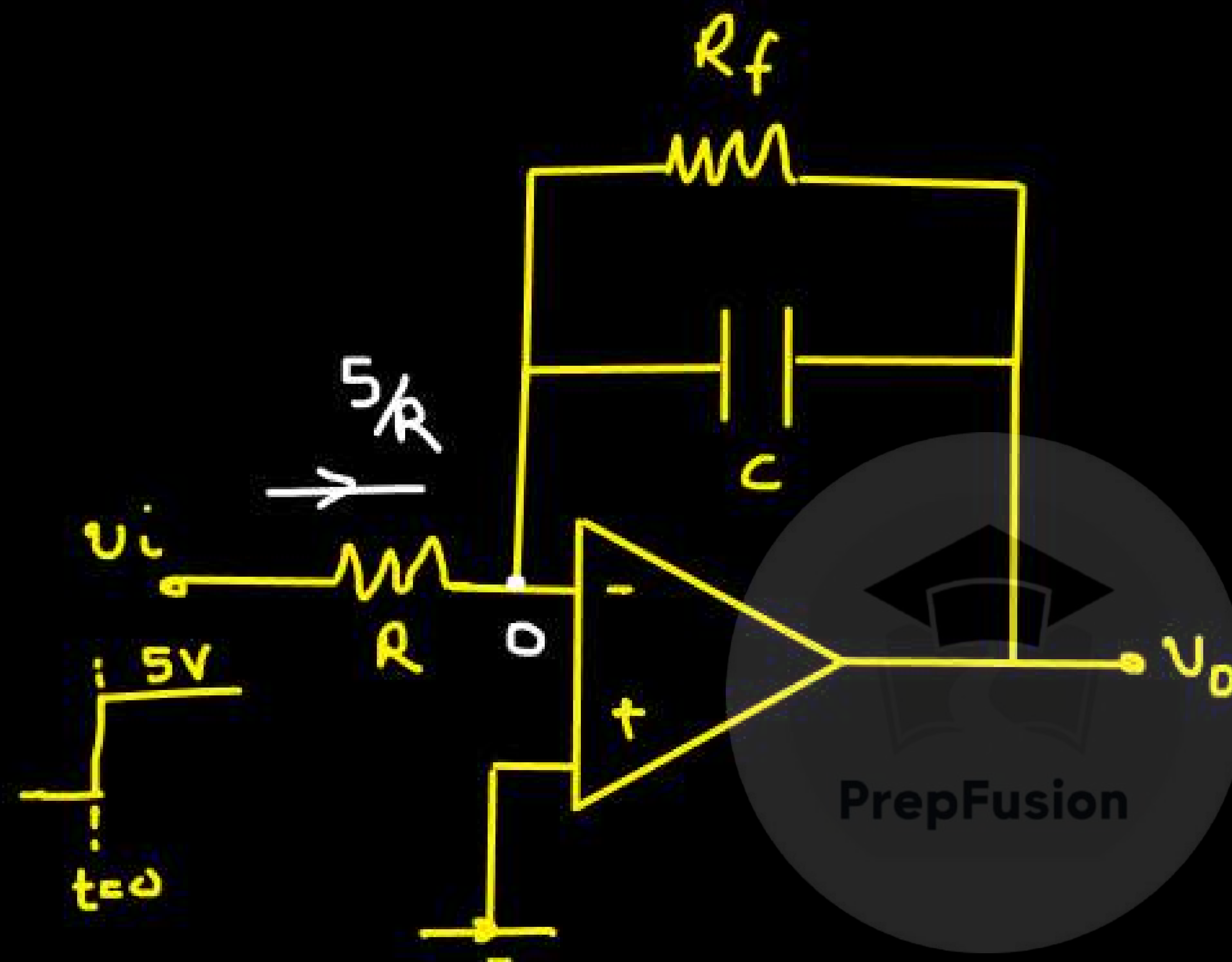
$\frac{T}{2} < t < T$:-



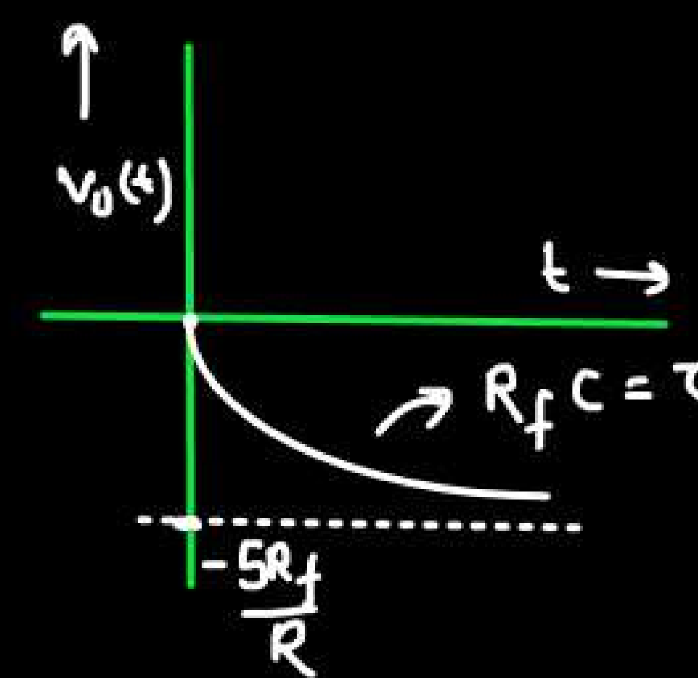
$$v_c(t) = \frac{5T}{2RC} - \frac{5}{RC}\left(t - \frac{T}{2}\right)$$

$$v_c(T) = \frac{5T}{2RC} - \frac{5T}{2RC} = 0$$

Q. Draw o/p waveform for the given i/p.



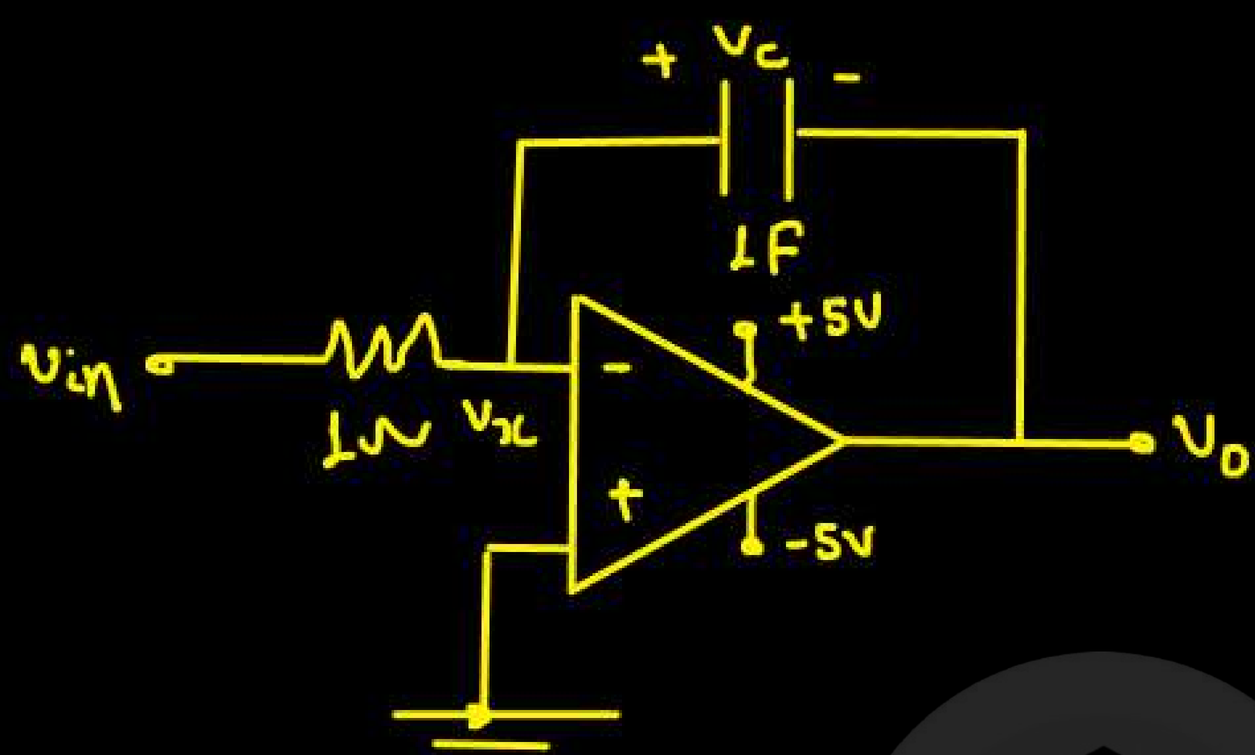
Considering op. amp has very High Saturation voltage.



$@\ t = 0^+ \Rightarrow$ cap. s.c. $\Rightarrow v_0(t=0) = 0V$

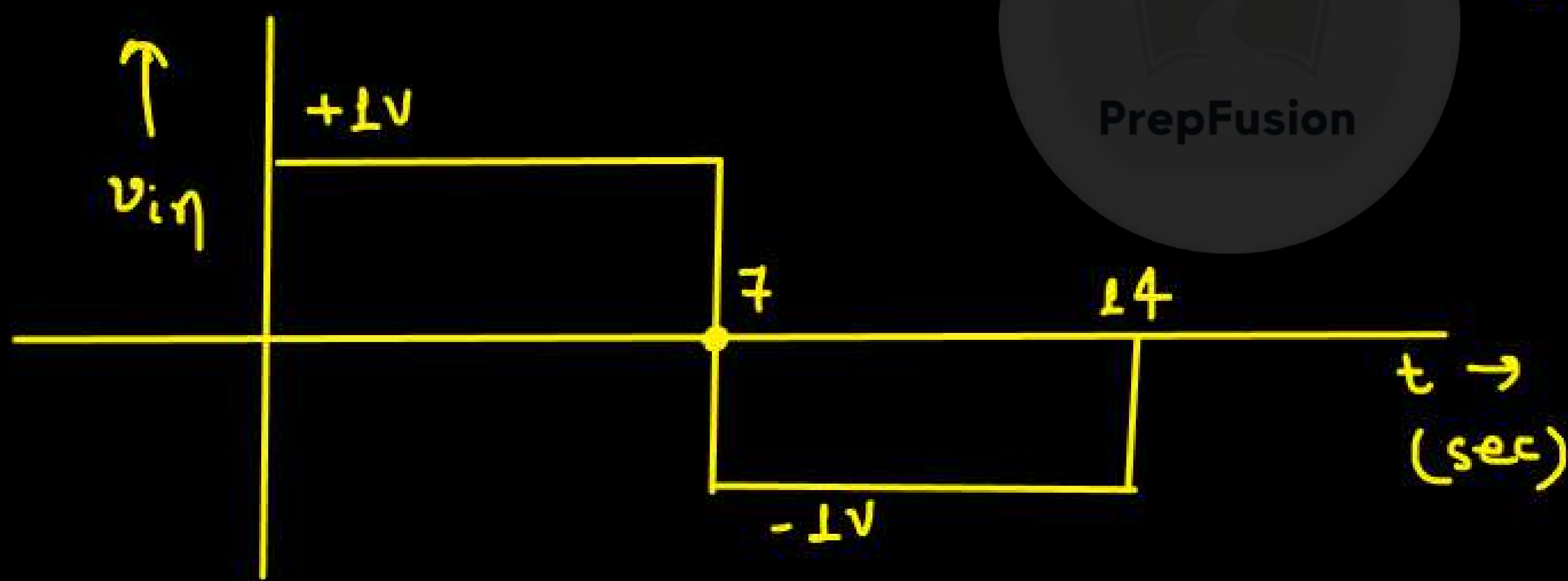
$t = \infty \Rightarrow$ cap. o.c. $\Rightarrow v_0(t=\infty) = -\frac{5R_f}{R}$

Q.

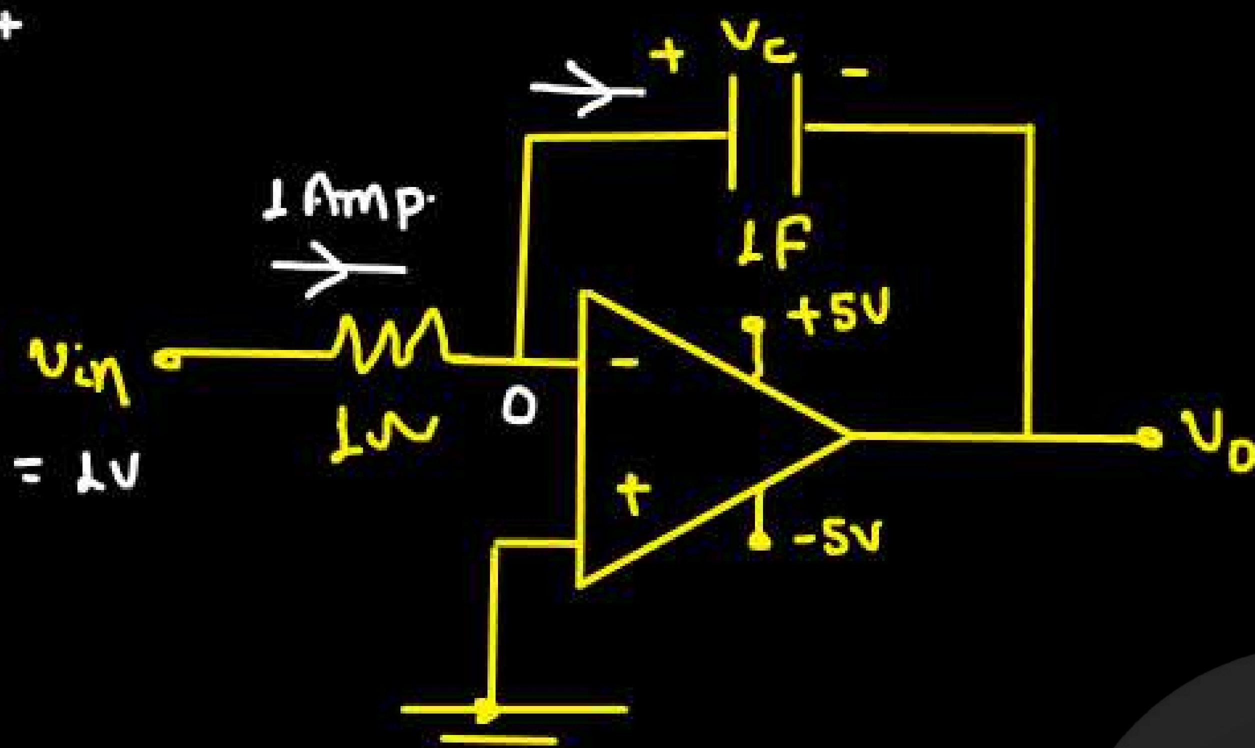


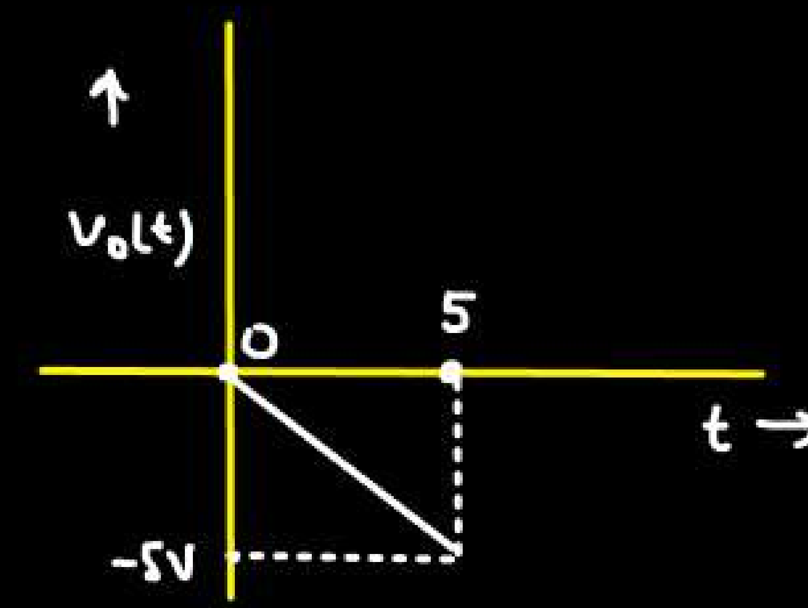
Draw v_c, v_x and v_o waveform.

Find v_o value at $t = 10$ sec.



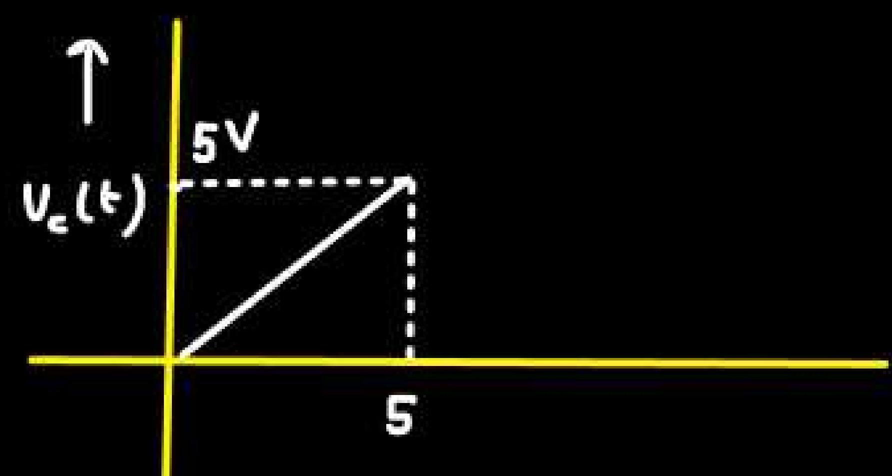
@ $t = 0^+$

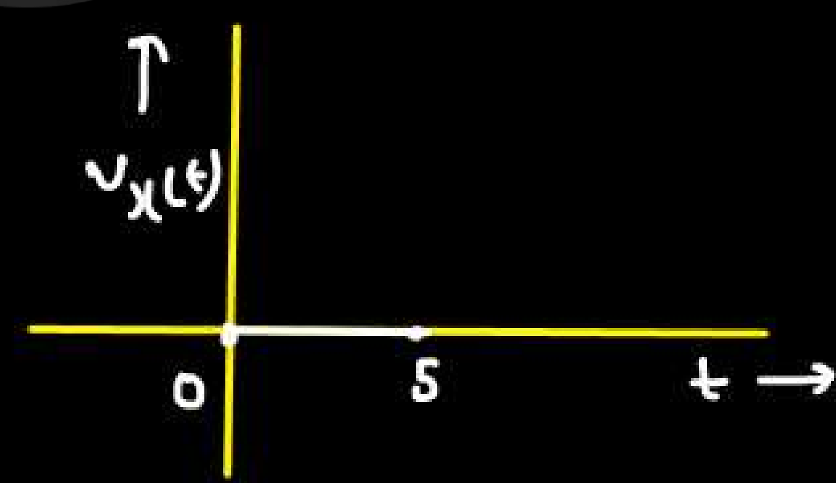




$$V_c(t) = \frac{1}{C}\int_0^t i(t)\cdot dt = \frac{1}{1}\int_0^t 1\cdot dt = t \text{ volt}$$

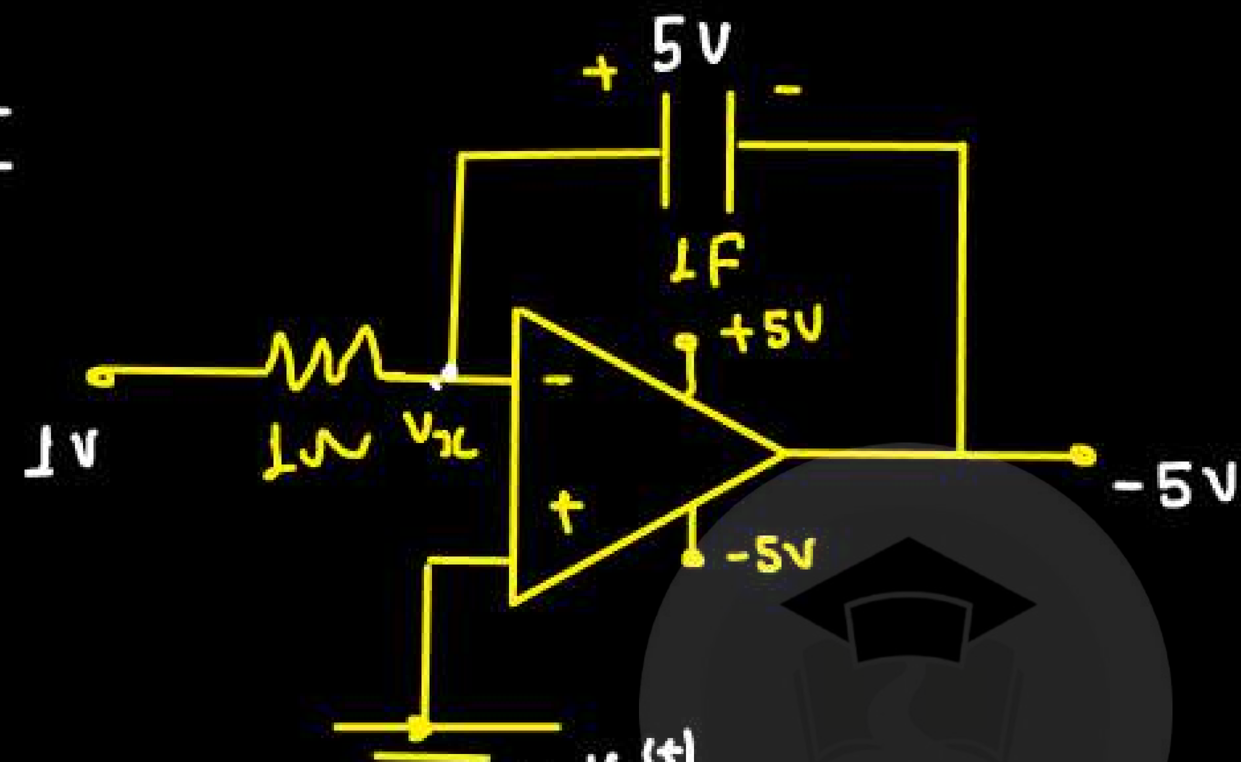
$$V_o(t) = -V_c(t)$$

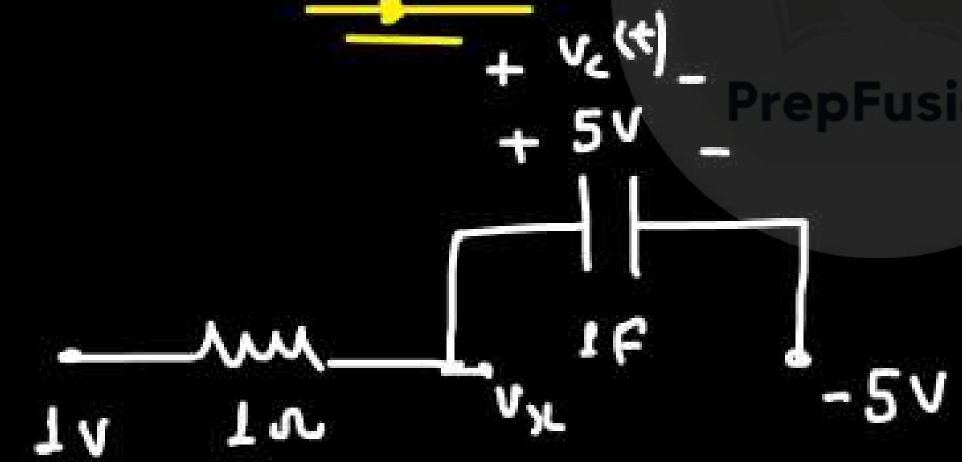




@ t = 5 sec, o/p saturates ⇒ virtual short NOT valid

5 sec < t < 7 sec.-





$V_x(5\,sec) = 0V$

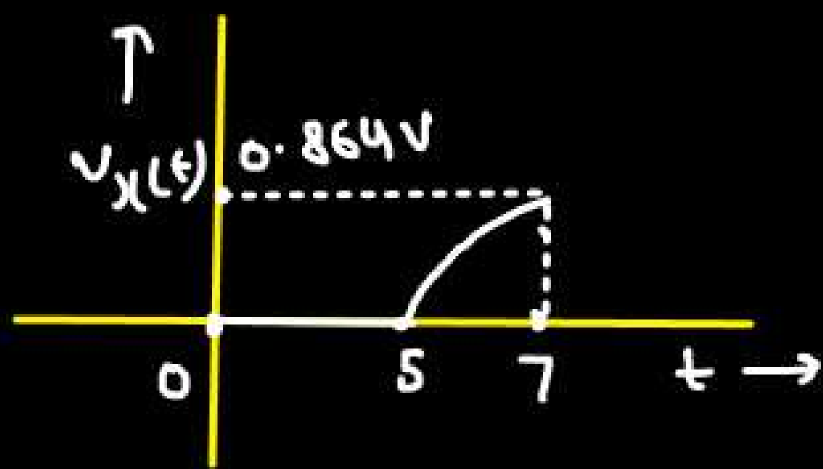
$V_x(\infty) = 1V$

$$\boxed{V_x(t) = \left[1 - e^{-(t-5)/1}\right] u(t-5)}$$

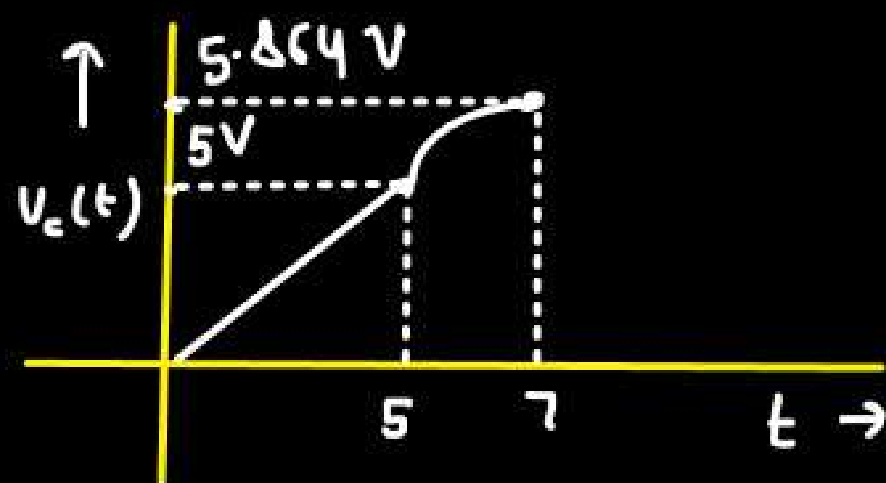
$$\boxed{V_c(t) = \left[6 - e^{-(t-5)}\right] u(t-5)}$$

$V_c(5\,sec) = 5V$

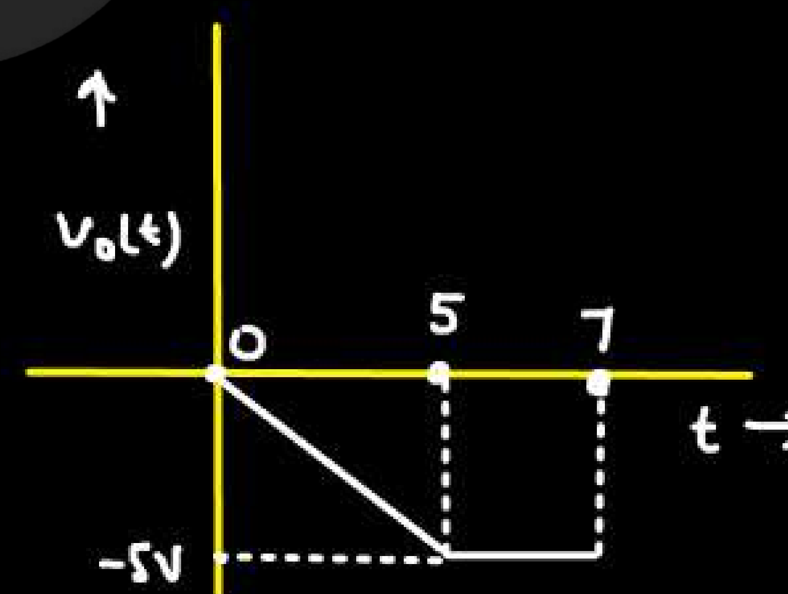
$V_c(\infty) = 6V$



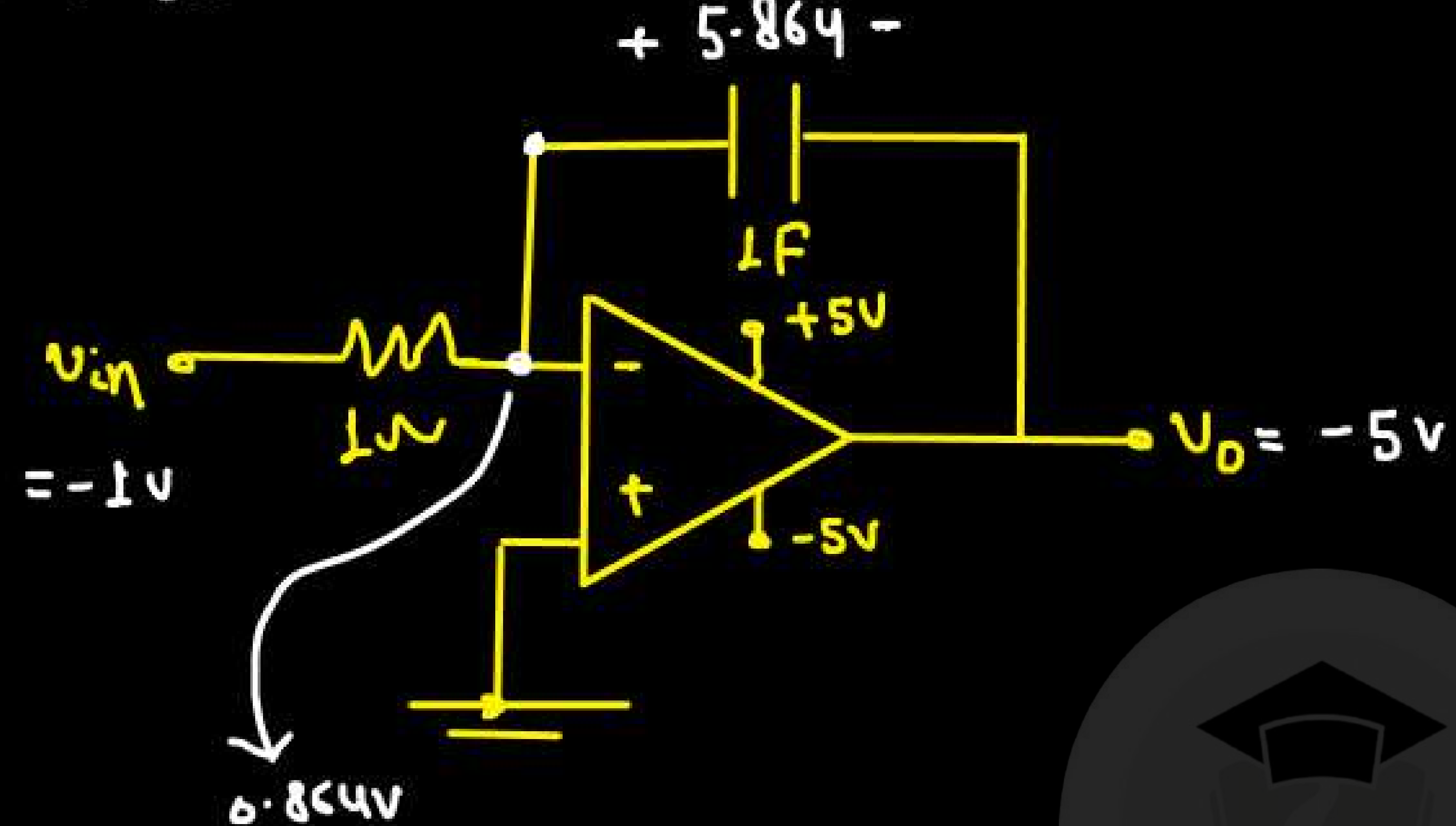
$$V_x(7\,\text{sec.}) = 1 - e^{-2/1}$$
$$= 0.864\,V$$



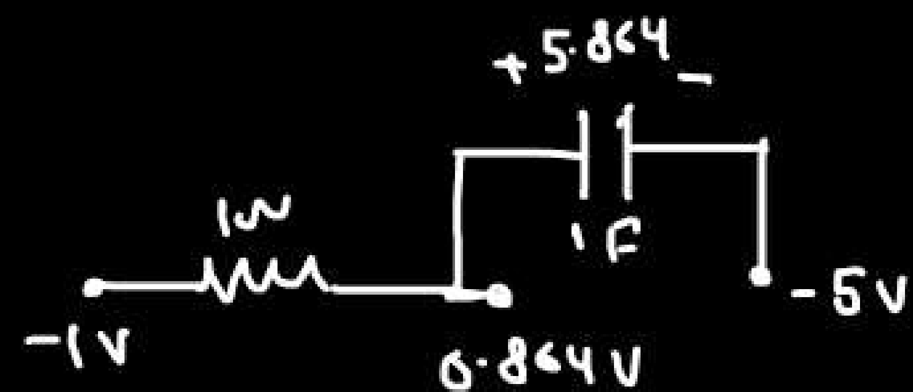
$$V_c(7\,\text{sec.}) = 6 - e^{-2}$$
$$= 5.864\,V$$



at $t = 7^+$ sec.



o/p is still saturated ⇒ concept of virtual short is not valid



$V_x(t=7^+) = 0.864V$

$V_x(t=\infty) = -1V$

$V_c(t=7^+) = 5.864V$, $V_c(t=\infty) = 4V$

$$v_x(t) = \left[-1 + 1.864\, e^{-(t-7)}\right] u(t-7)$$

$$v_c(t) = \left[4 + 1.864\, e^{-(t-7)}\right] u(t-7)$$

at $t = t_1$; $v_x(t_1) = 0$

$$-1 + 1.864\, e^{-(t_1-7)} = 0$$

$$\boxed{t_1 = 7.62\,\text{sec}}$$

$v_x(7.62\,\text{sec}) = 0\,V$

$v_c(7.62\,\text{sec}) = 5\,V$

$\Rightarrow$ if v_x node go below 0V, then cap. voltage changes instantenously which is not possible. so, v_x node stays @ 0V