BE 23-11-14 → A.IC

(OP-AMP)
(Operational Amplifier)

→ Designed to perform Mathematical operation & hence the name operational amplifier.

→ OP-amp is an Integrated circuit or a semiconductor chip fabricated under very large integration method by using planer technology.

→ A voltage controlled device.

FET, OP-Amp, vaccum tubes → voltage controlled
BJT - current controlled device.

→ Linear analog IC, (Linear → we can apply super-position principle)

→ Low power device.

→ Negligible Internal power consumption.

→ The 1st Internal stage in the Op-Amp is emitter coupled diff Amplifier
The last stage is BUFFER.

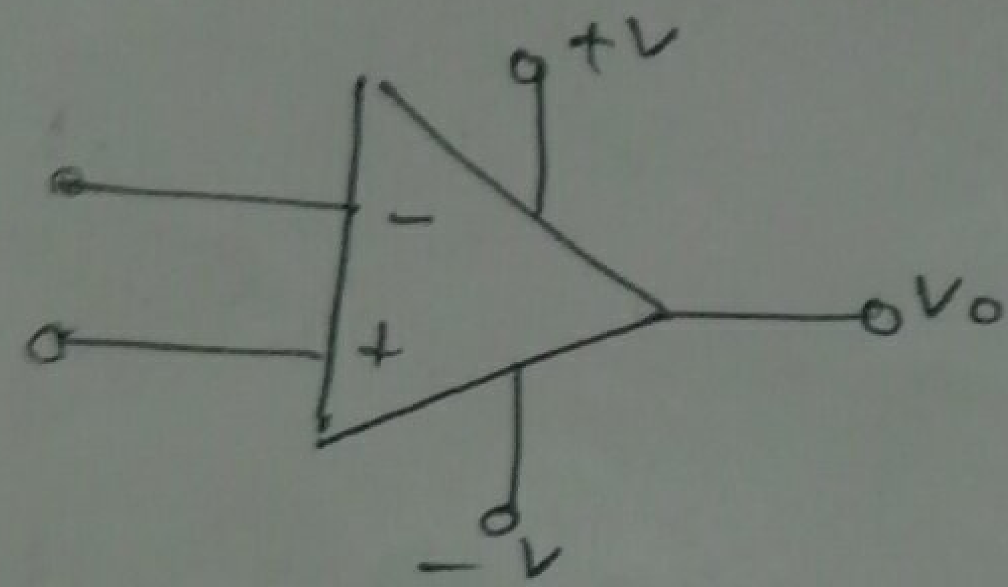
→ Input signal can be dc. signal, sine wave or any types of Ac signals.

- Popularly used. Op-Amp is IC-741

- for IC-741 max^m supply is ±15V

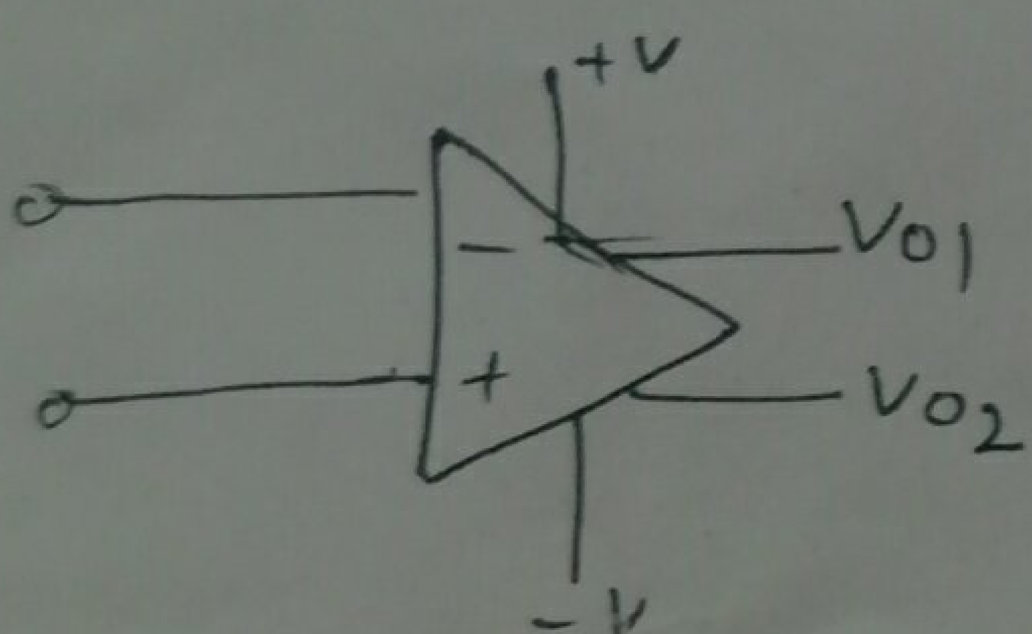
- operated with dual supply

- In single ended op-Amp no. of output terminal is one.



Single Ended. 2

- In double op-Amp no. of output terminals 2, provi complementary output.



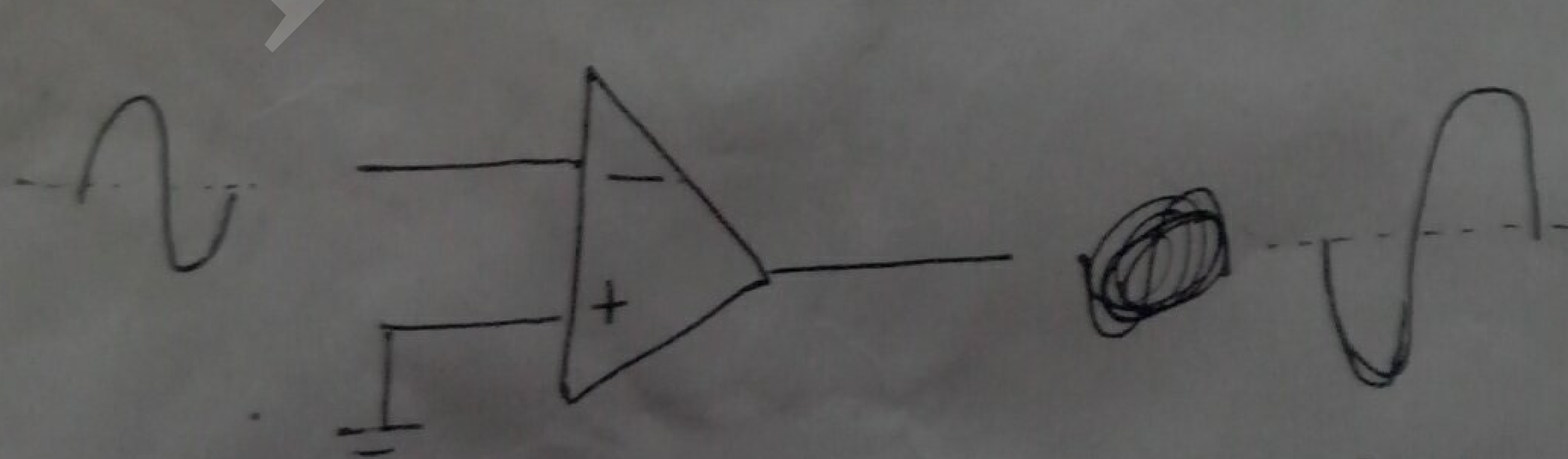
Double Ended

Disadvantage

(1) very sensitive to Humidity
(2) Sensitive to voltage fluctuation, it can be overcome by using Regulated supply.
(3). Sensitive to high temperature.

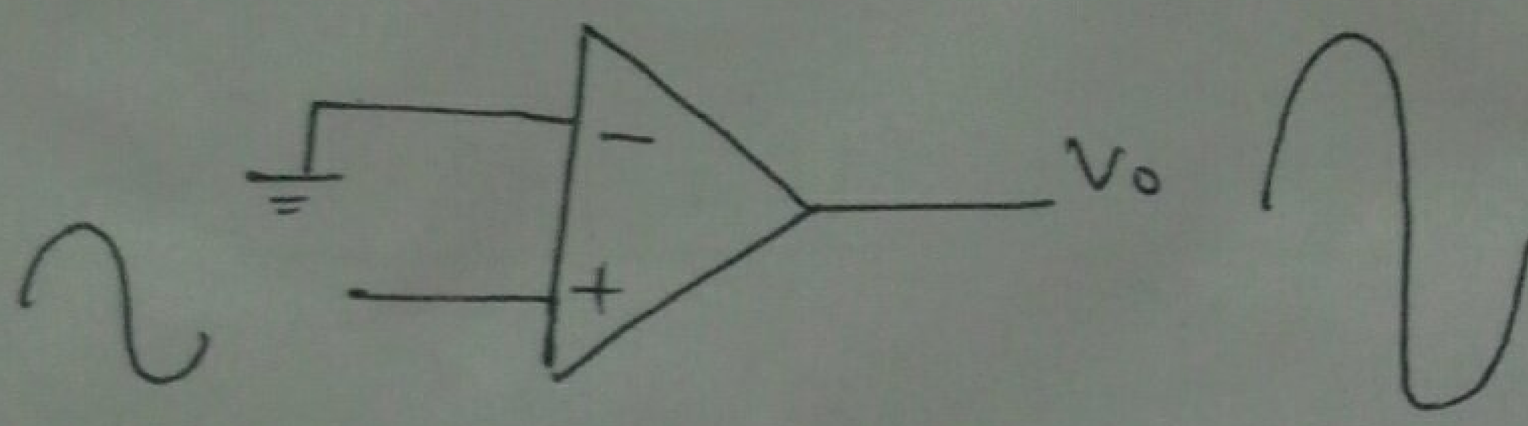
OPERATING MODE:-

(i) Inverting mode:-



Here output signal will be 180° out of phase with I/P, & hence may have high amplitude due to gain of ~~out put~~ op-Amp.

(2). **Non Inverting Mode :-**



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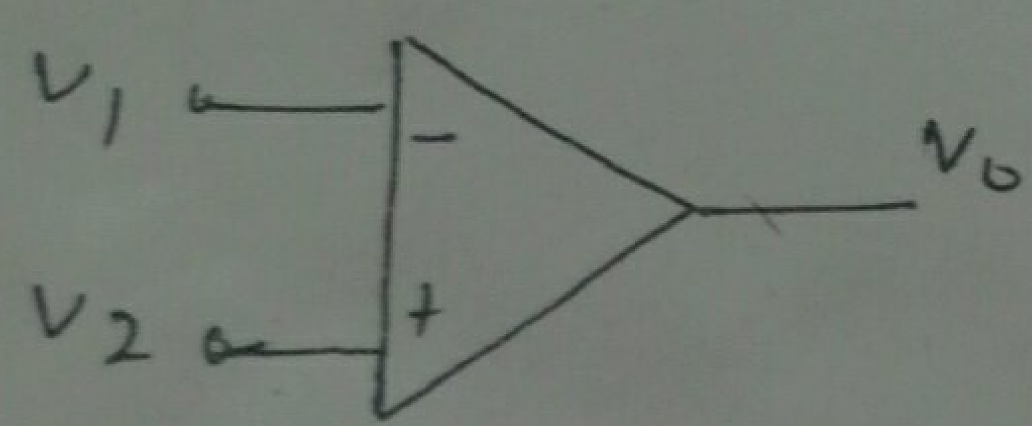
(3). **Differential mode :-**



[Used in designing of Diff^n. ampl^r. & Substractor ckts.]

Op-Amp are generally available in any one of the three following packages.

1. O/P. dual in line package.
2. TO-05 case
3. Flat-Package.

Properties.

	Prop.	Ideal Op-Amp.	Practical Op Amp.
(1)	R_i	∞	10^6 or $1 M\Omega$
(2).	R_o	0	10 to 100 Ω
(3).	gain $A = \frac{V_o}{V_i}$	$-\infty$	-10^6 ; $\lvert A \rvert = 10^6$ −ve sign shows 180° phase shift
(4).	B.W.	∞	$10^6 Hz$ or $1 MHz$ (Max).
(5).	CMRR	∞	10^6 or 120 dB
(6).	slew Rate	∞	80 V/µsec.
(7)	Offset voltage	0	negligible
(8).	off-set current	0	negligible.

Input Resistance in accending order

$\boxed{BJT \rightarrow \text{op-Amp} - JFET - MOSFET}$

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→ In Practical op-Amp. Gain bandwidth product is constant

→ Max$^{m.}$ Bandwidth occure when gain is minimum that is gain = 1

→ The unity Gain Bandwidth product of the op-Amp is 10^6

→ The open loop Gain of the op-Amp is very large & therefore stability is less and to compensate this i.e gain is redu... by applying small amount of (−)ve feedback.

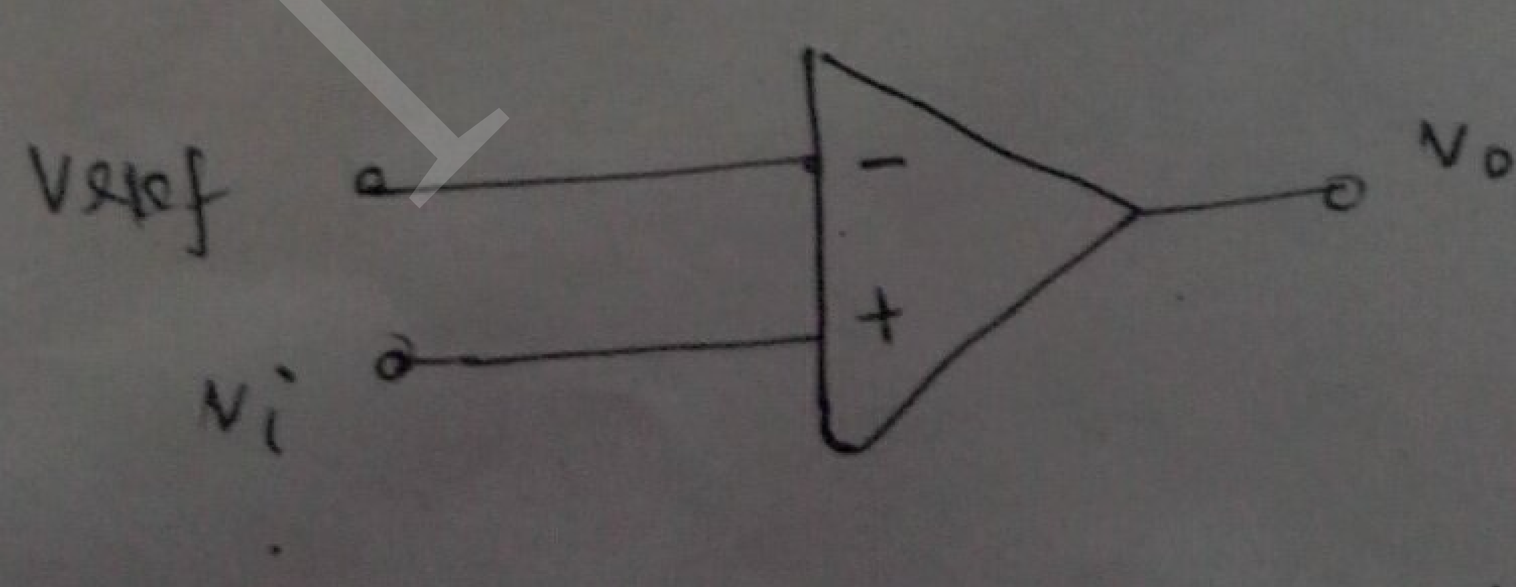
→ closed loop gain is always less than open loop Gain.

Op-amps are generally operated in closed loop (with (−)ve feedback)

⇒ Under open loop condition op-Amp can be used as Comparator

COMPARATOR CKT

①

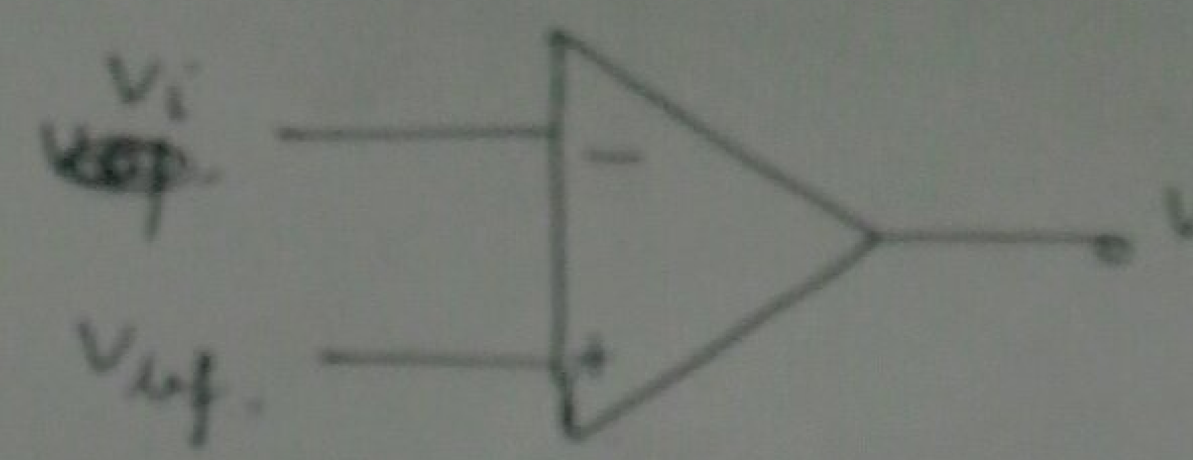


$V_o = 1$ when $V_i > V_{ref}$

$V_o = 0$ when $V_i \leq V_{ref}$

When I/p signal is applied to the non inverting terminal, The output of comparator is logically 1 only when $V_i > V_{ref}$.

(2).

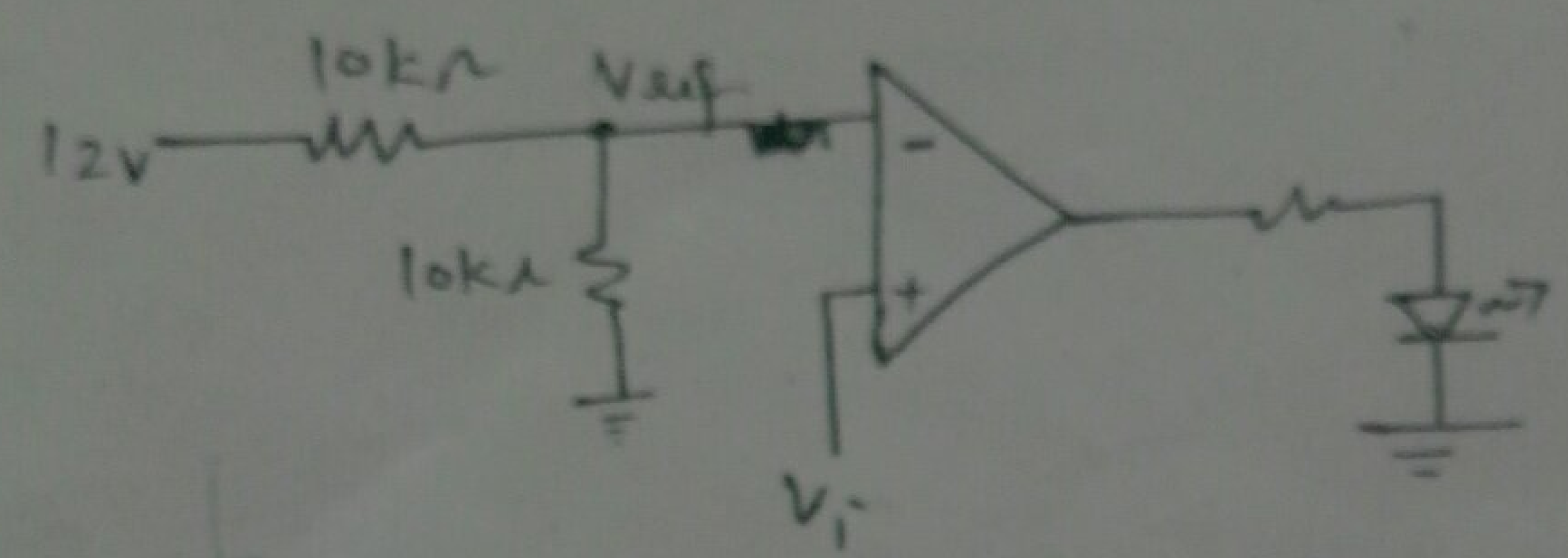


$V_o = 1$ when $V_i < V_{ref}$

$V_o = 0$ when $V_i > V_{ref}$.

When inverting signal is applied to inverting terminal, the output of the comparator is high only when $V_i < V_{ref}$.

Ex.



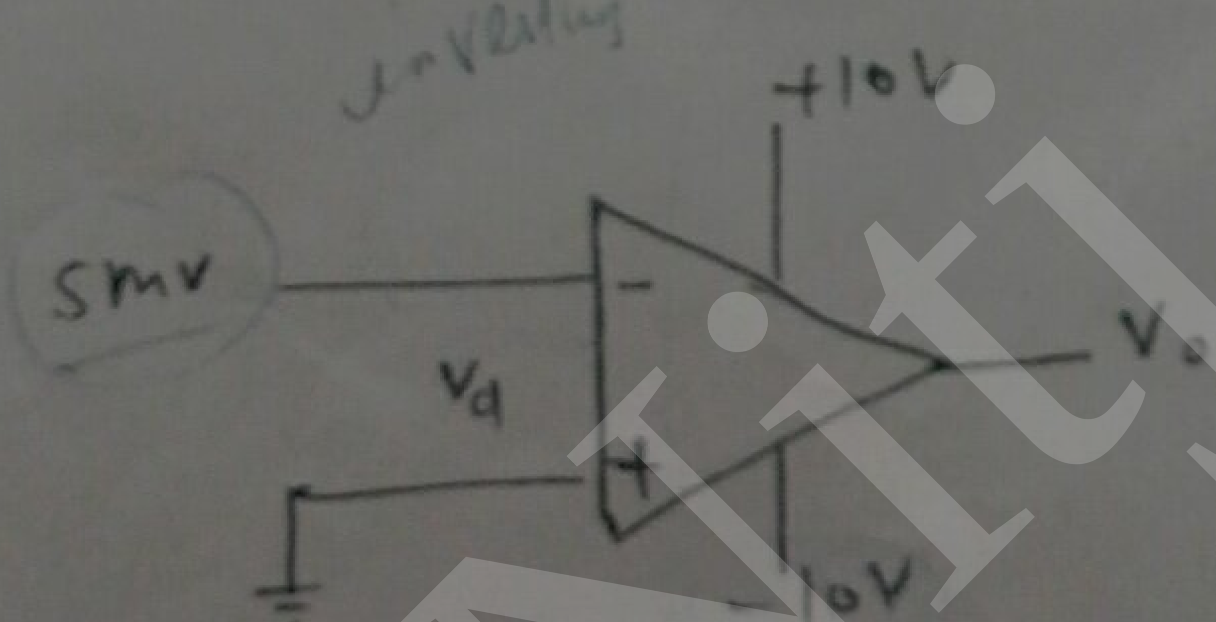
The LED will ON only when $V_i = ?$

$V_i > 6V$

$$V_{ref} = \frac{10K}{20K} \times 12 = 6V$$

Note:- O/P voltage of a practical Op-Amp can not be exceed it's bias voltage.

⇒

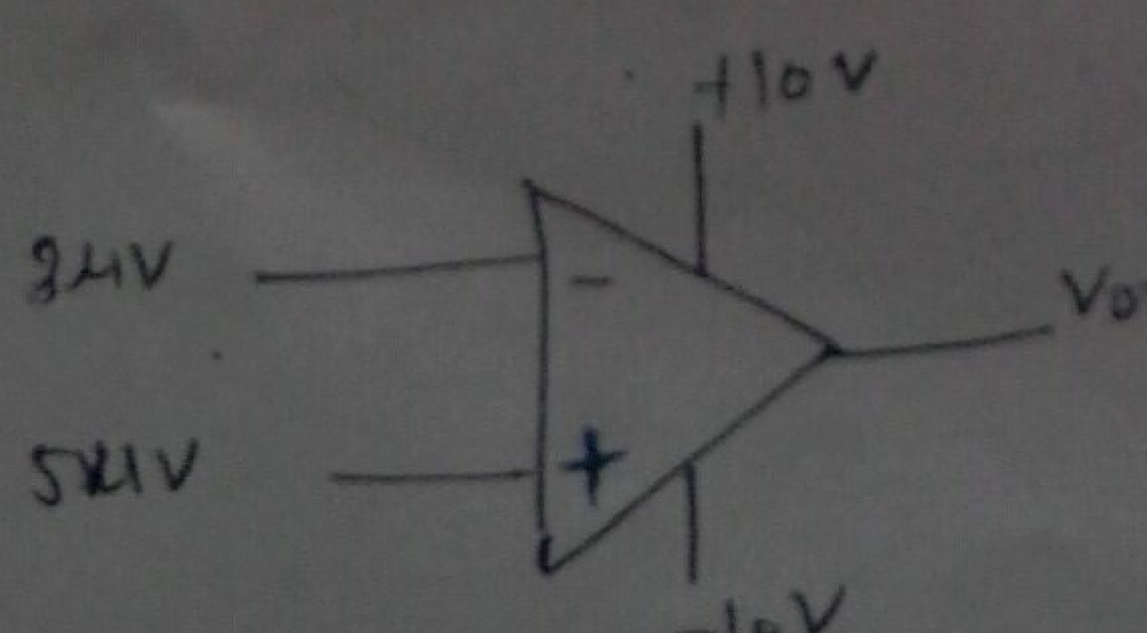


$|A_{OL}| = 10^6$

$$V_o = A_{OL}(V^+ - V^-) = 10^6(0 - 5\times10^{-3})$$
$$= -5000V$$

but V_o can not exceed -10

hence $V_o = -10V$

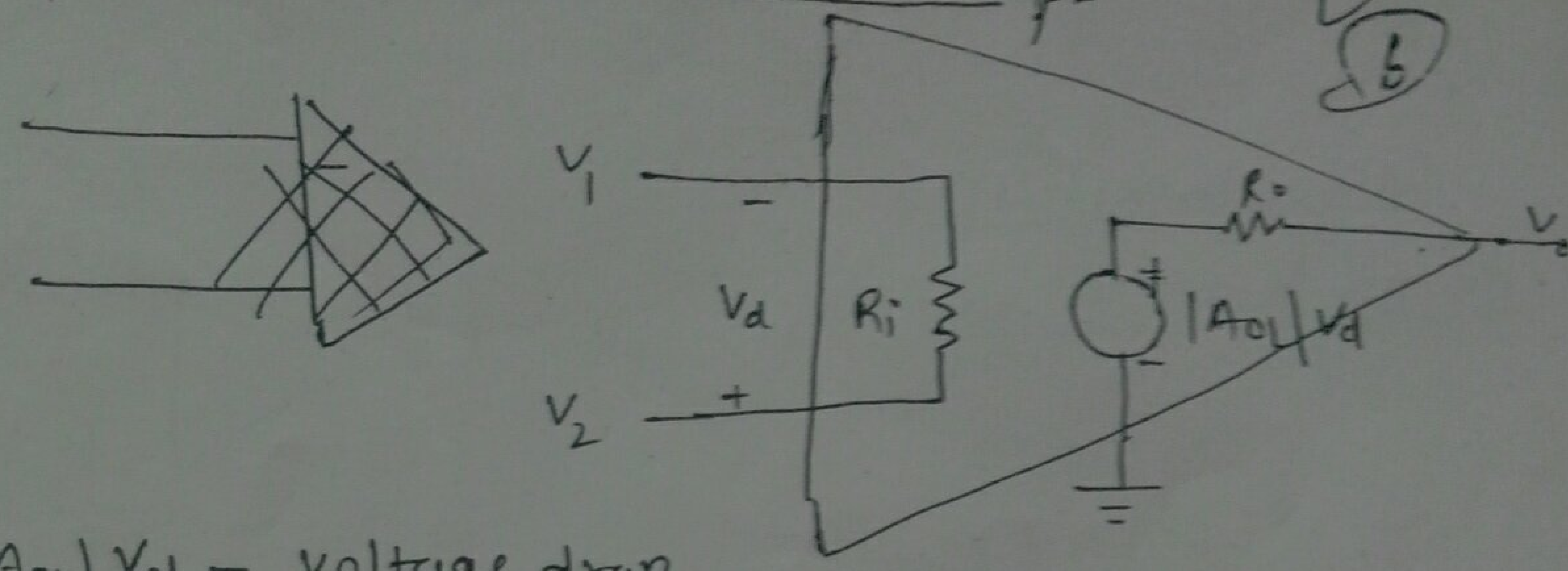


$|A_{OL}| = 10^6$

$$V_o = 10^6(V^+ - V^-)$$
$$= 10^6(5\mu V - 3\mu V) = 10^6 \times 2\times10^{-6} V$$

$$V_o = 2V$$

Equivalent circuit of Practical Op-Amp-

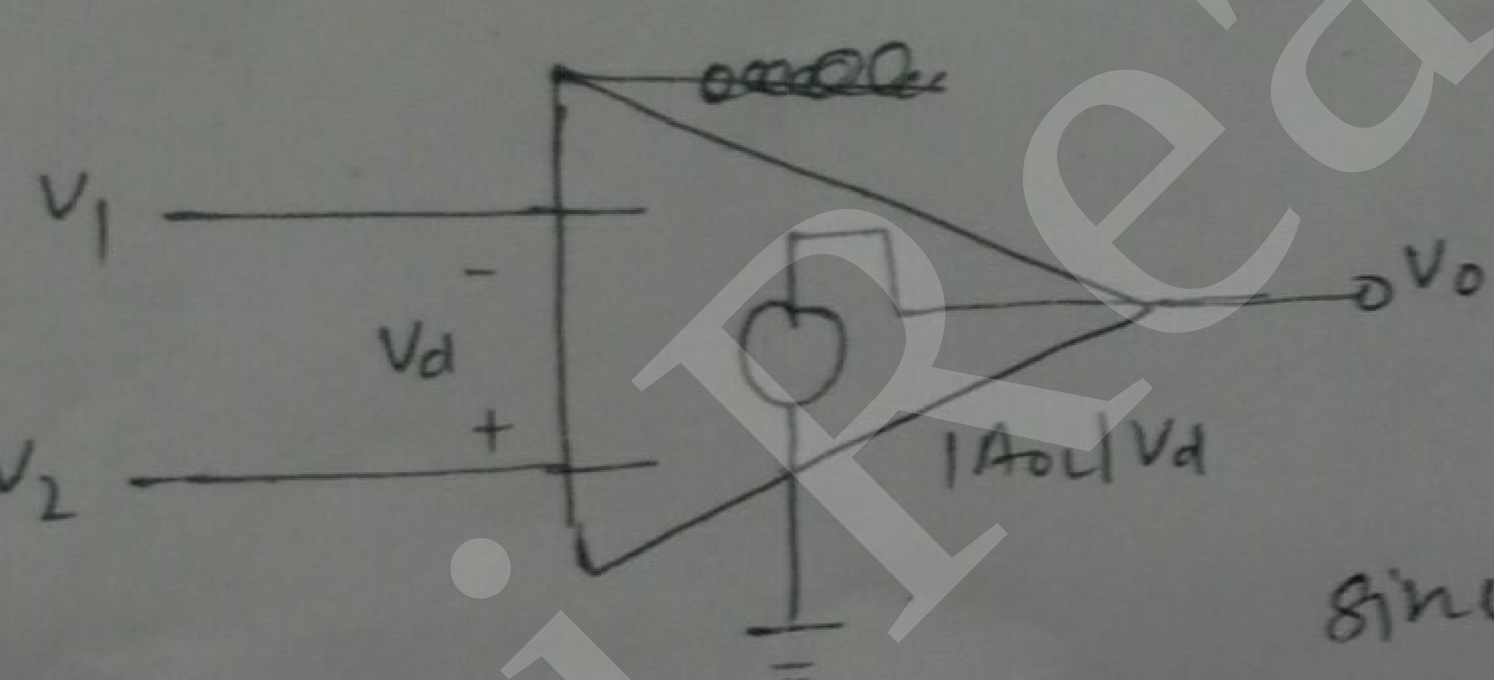


$V_o = |A_{OL}| V_d$ – voltage drop across R_o

But R_o is very less in practical op-Amp (negligible voltage drop across R_o)

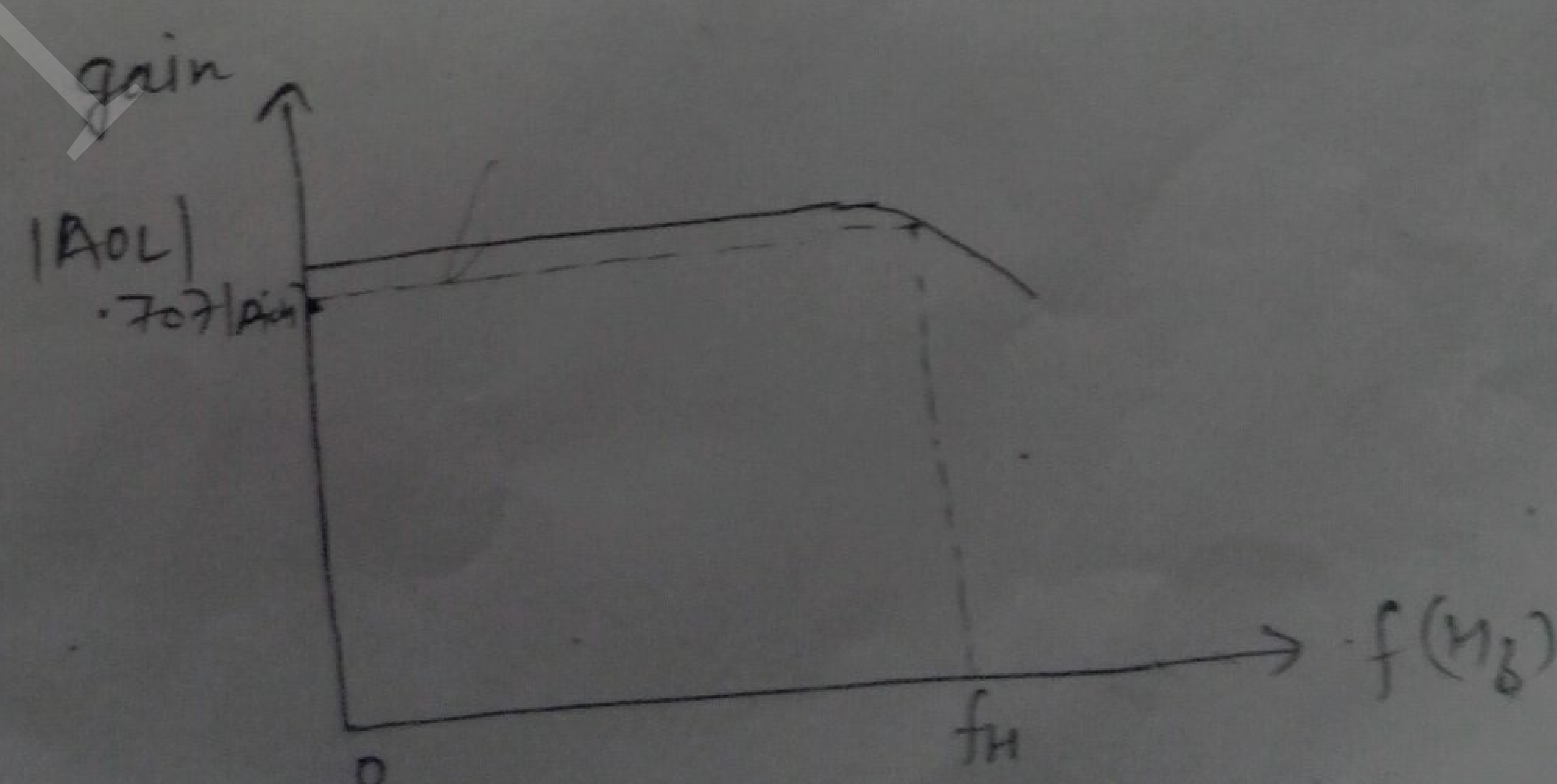
$V_o = |A_{OL}| V_d$

Equivalent circuit of Ideal Op-Amp-



since $R_i = \infty$
$R_o = 0$

Frequency Response of Practical Op-Amp-



This means

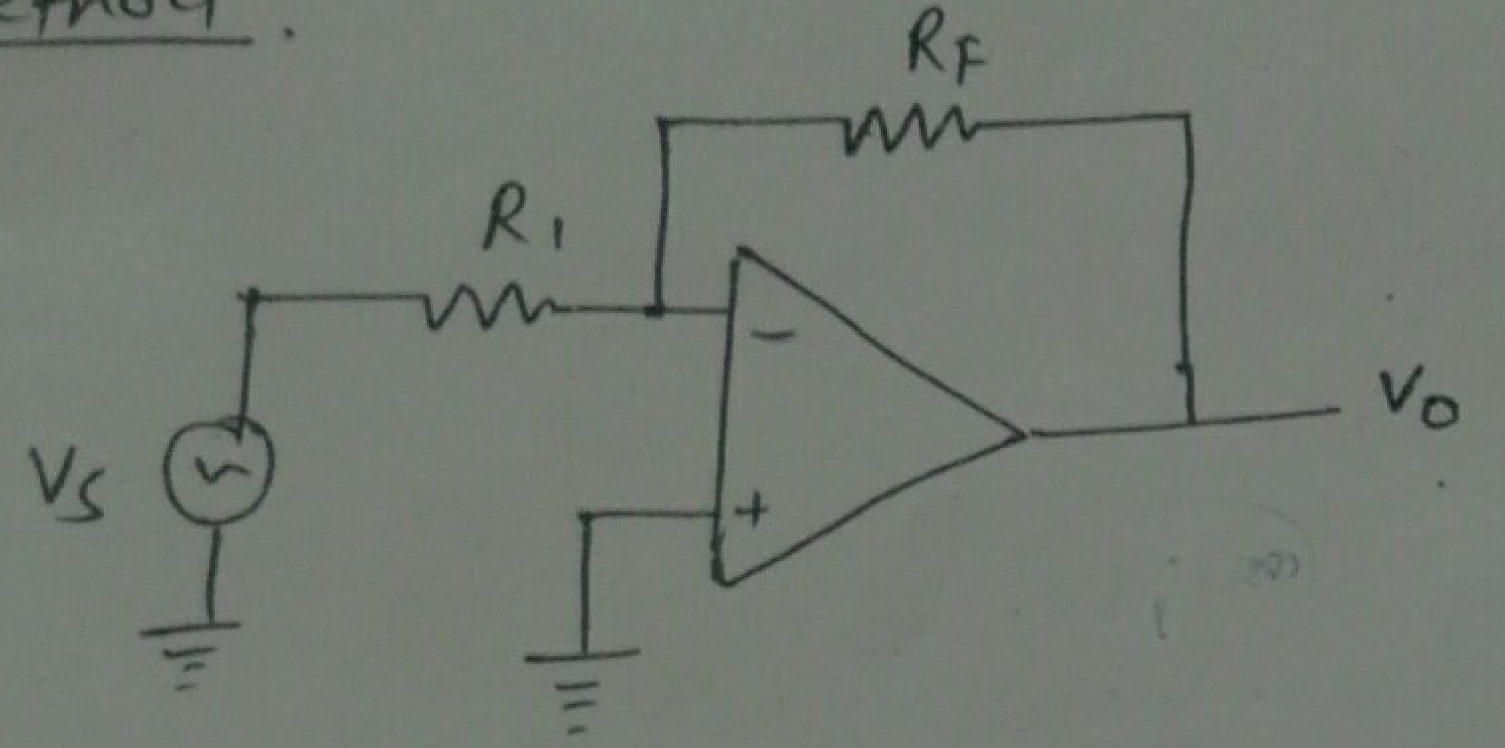
It can also process D.C signal

since $f_L = 0$ so $B.W = F_H - 0$

$B.W = f_H$

Vertual Short or vertual ground: 7

1st Method.

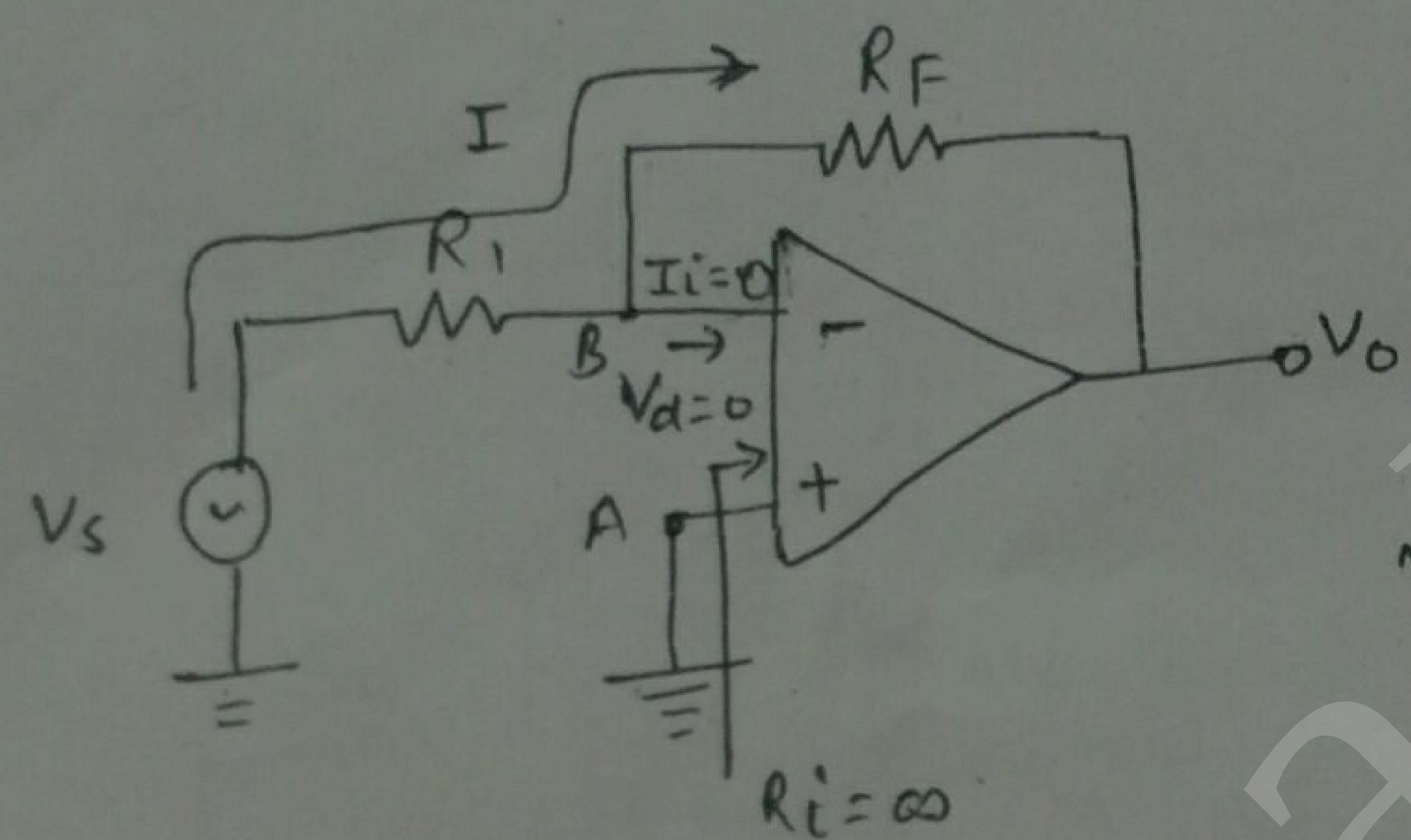


vertual short exist only in Ideal op-amp.

$$\frac{V_o}{V_d} = A$$

if $A \to \infty$ (for Ideal)
$V_d \to 0$

IInd Method.



$$V_d = V^+ - V^-$$

$$0 = V^+ - V^-$$

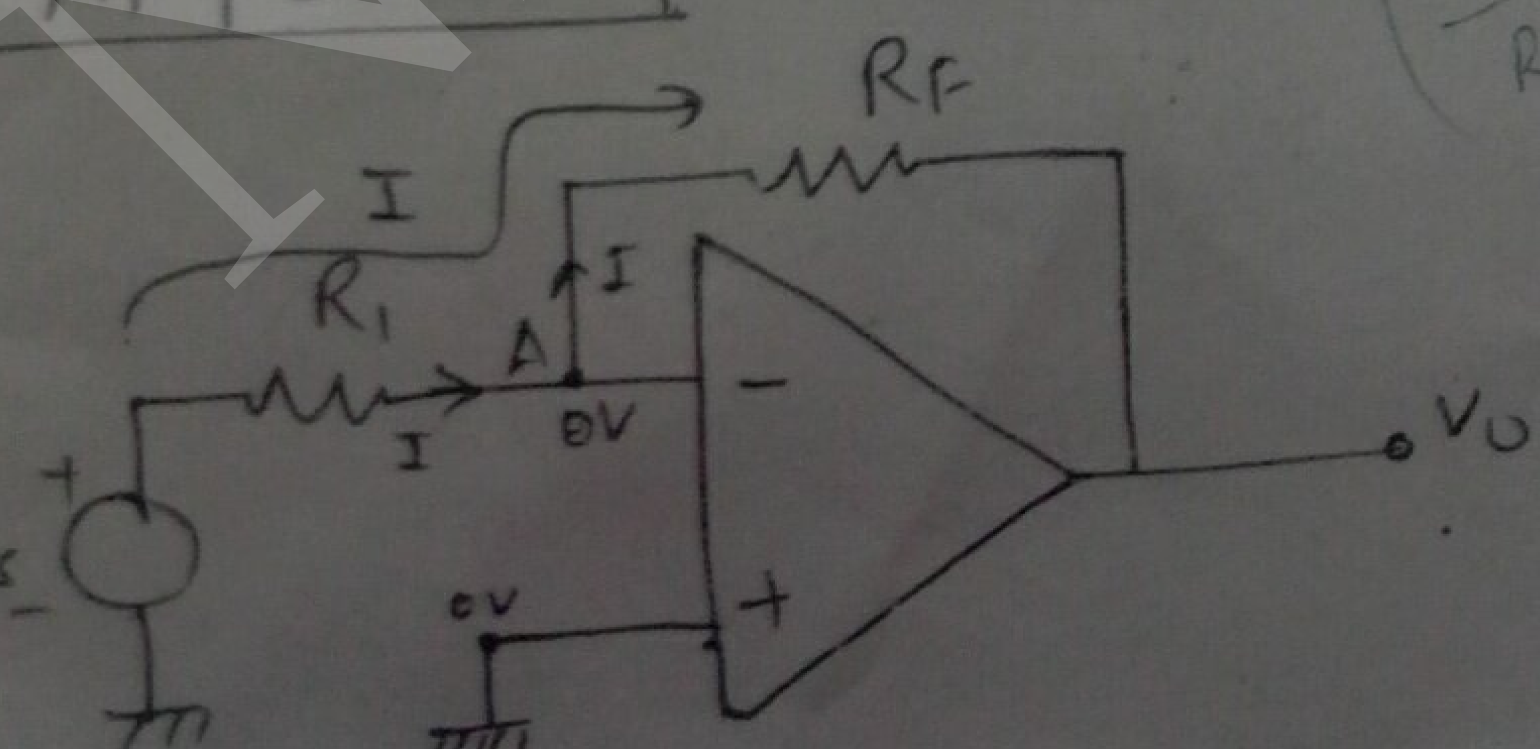
$$V^+ = V^-$$

$$V_A = V_B$$

$$I = \frac{V_S - V_B}{R_1}$$

Node A & B are equipotential. No current passing at the i/p terminal of op-Amp.

INVERTING AMPLIFIER:-



$$\frac{V_s - 0}{R_1} - \frac{V_o - 0}{R_f}$$

$$I = I$$

$$\frac{V_s - 0}{R_1} = \frac{0 - V_o}{R_f}$$

$$\frac{V_o}{V_s} = -\frac{R_f}{R_1}$$

KCL at node A

$$\frac{V_S - 0}{R_1} = \frac{0 - V_O}{R_F}$$

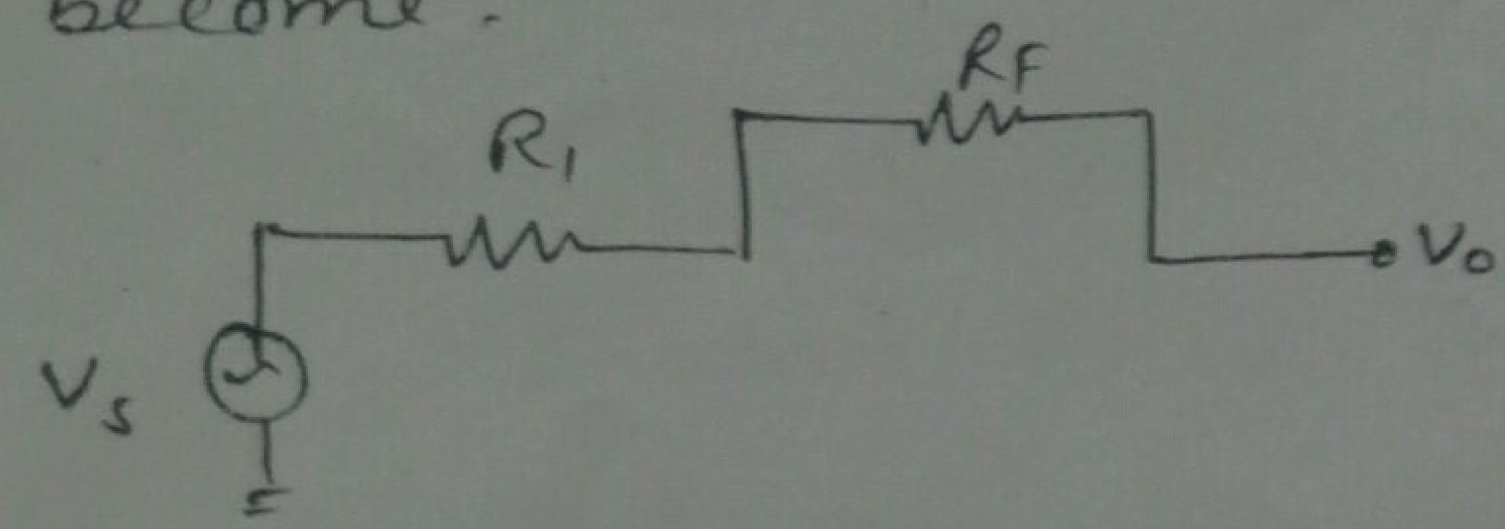
{Since $\frac{V_O}{V_S}$ = gain(A)}

$$\frac{V_O}{V_S} = -\frac{R_F}{R_1}$$

-ve sign shows 180° phase shift

$$\boxed{A = -R_F/R_1}$$

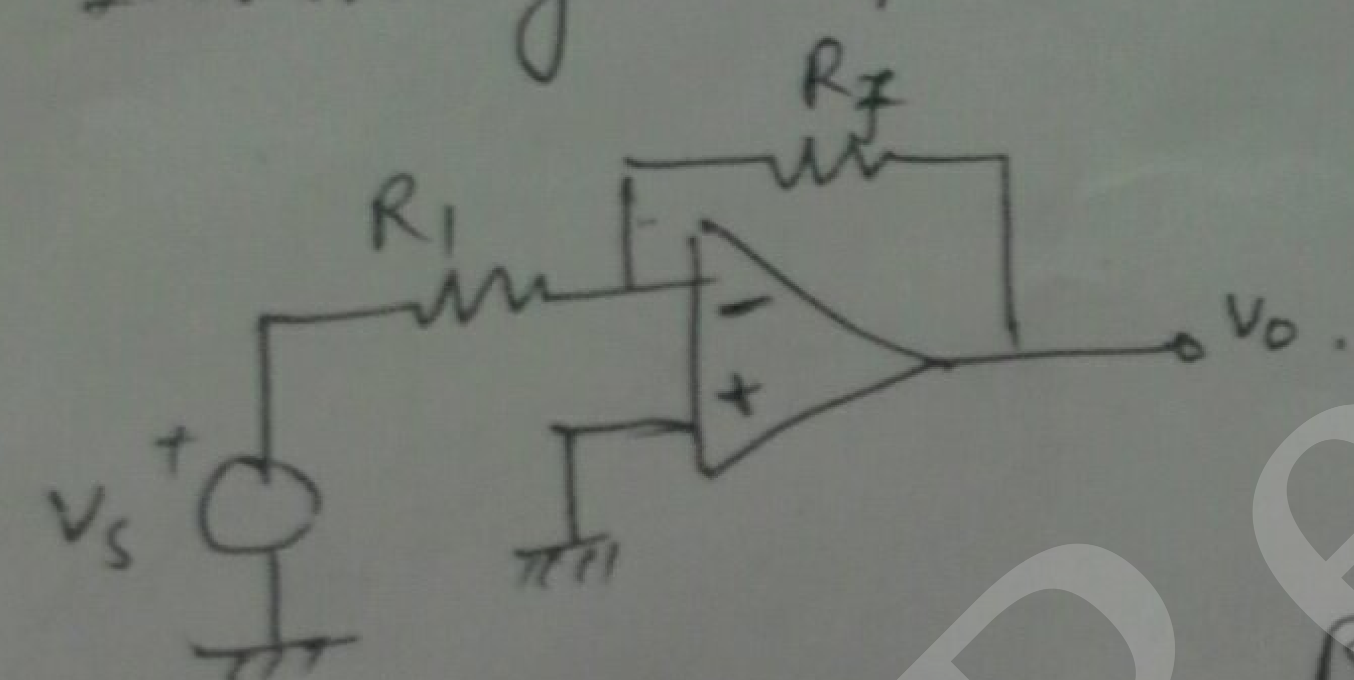
According to Eqn. of gain, gain is independent of Op-Amp Parameter, but if we Remove Op-Amp then ckt become.



& Resistive ckt can never provide gain. so it means Op-Amp is indirectly Responding.

Inverter ckt OR phase shifter.

It is Inverting Amplifier with unity gain.



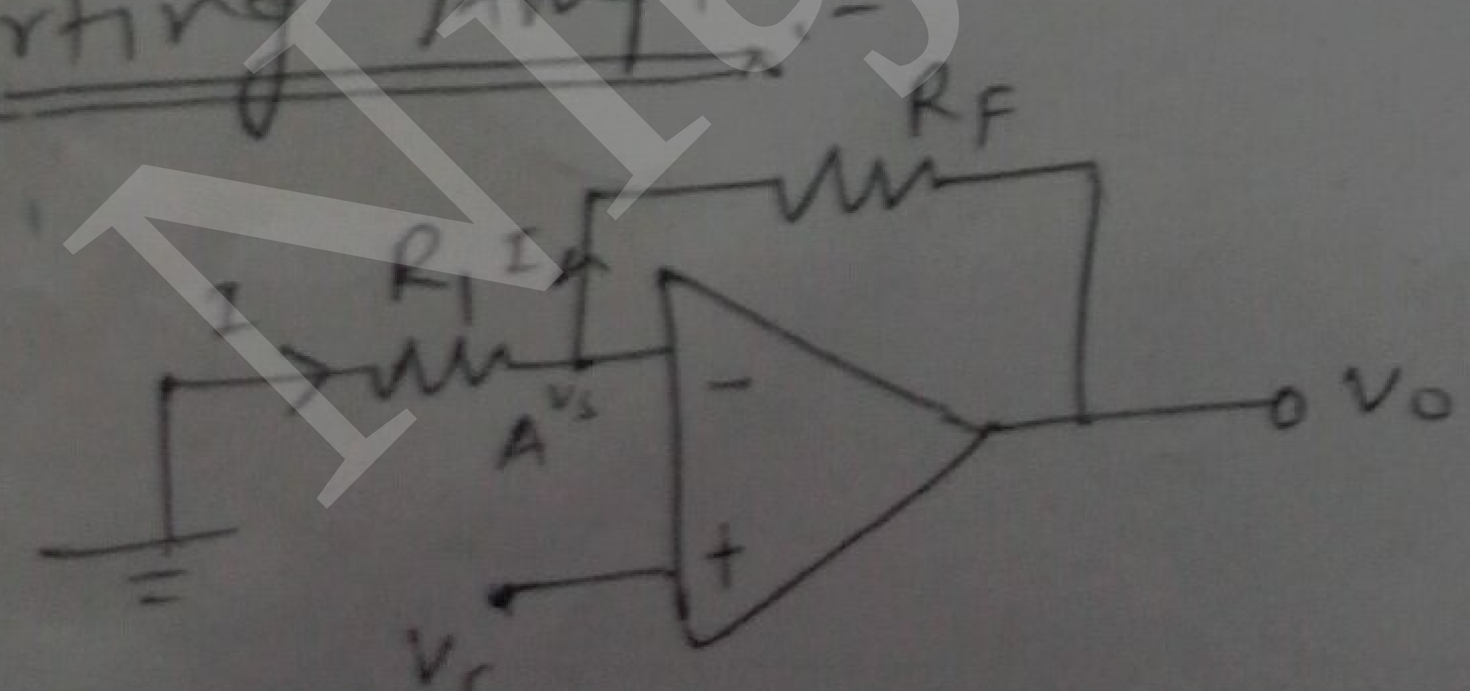
$A = -\frac{R_f}{R_1}$

for unity gain

$\frac{R_f}{R_1} = 1$ OR $R_f = R_1$

$\frac{V_o}{V_s} = -1$ OR $\boxed{V_o = -V_s}$

NON-Inverting Ampr.



$\frac{0 - V_s}{R_1} = \frac{V_s - V_o}{R_f}$

$\frac{-V_s}{R_1} = \frac{V_s - V_o}{R_f}$

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

KCl at node A

$\frac{0 - V_s}{R_1} = \frac{V_s - V_o}{R_F}$

$\frac{-V_s}{R_1} = \frac{V_s}{R_F} - \frac{V_o}{R_F}$

$\frac{V_o}{R_F} = \frac{V_s}{R_F} + \frac{V_s}{R_1}$

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

$\frac{V_o}{V_s} = 1 + \frac{R_F}{R_1}$

OR $\boxed{A = 1 + \frac{R_F}{R_1}}$

Voltage Follower

It is Non-inverting Ampl^r. with unity gain & 0 phase shift.

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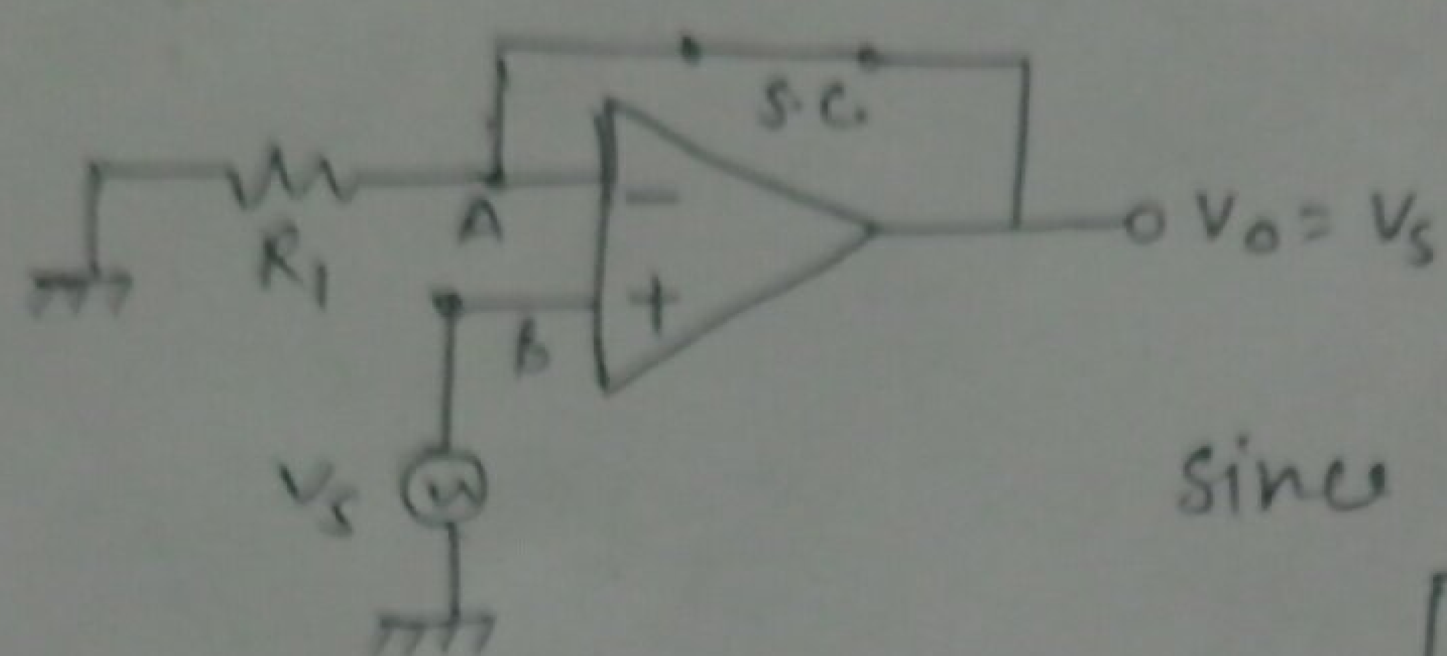
$$A = 1 + \frac{R_F}{R_1} = 1 \Rightarrow R_F = 0$$

If $R_F = 0$ then $1 + \frac{0}{R_1} = 1$



$$V_0 = \left(1 + \frac{R_F}{R_1}\right) V_A$$

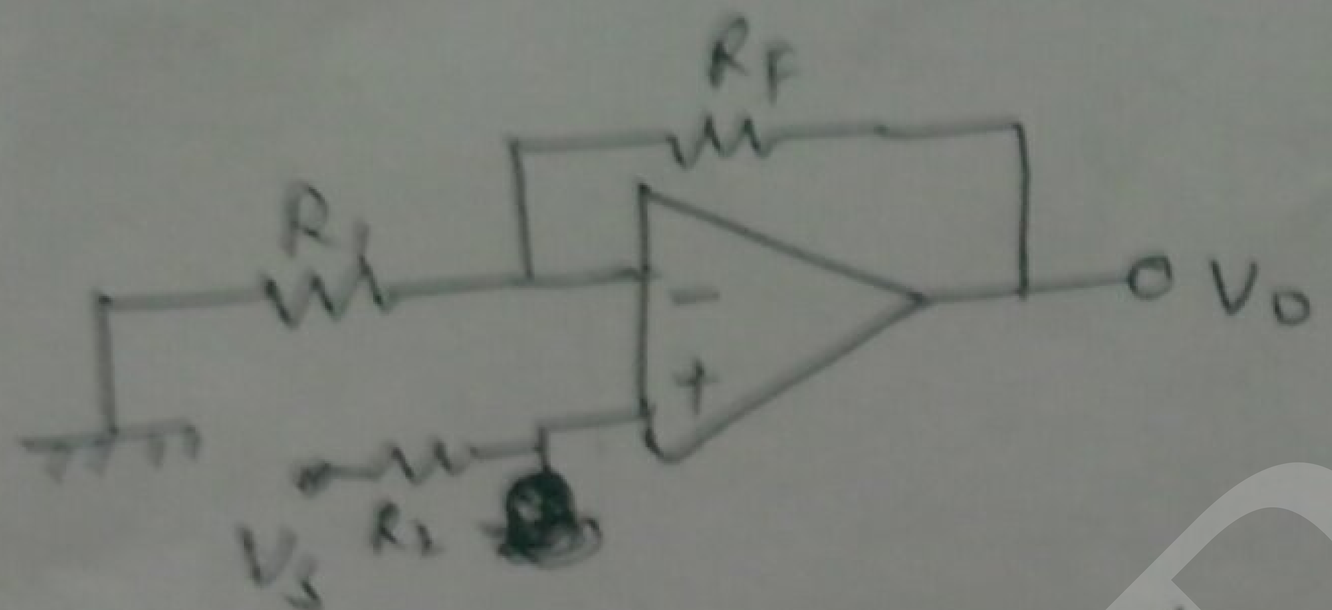
$$V_0 = V_A$$

since $V_A = V_B = V_S$

$$\boxed{V_0 = V_S}$$

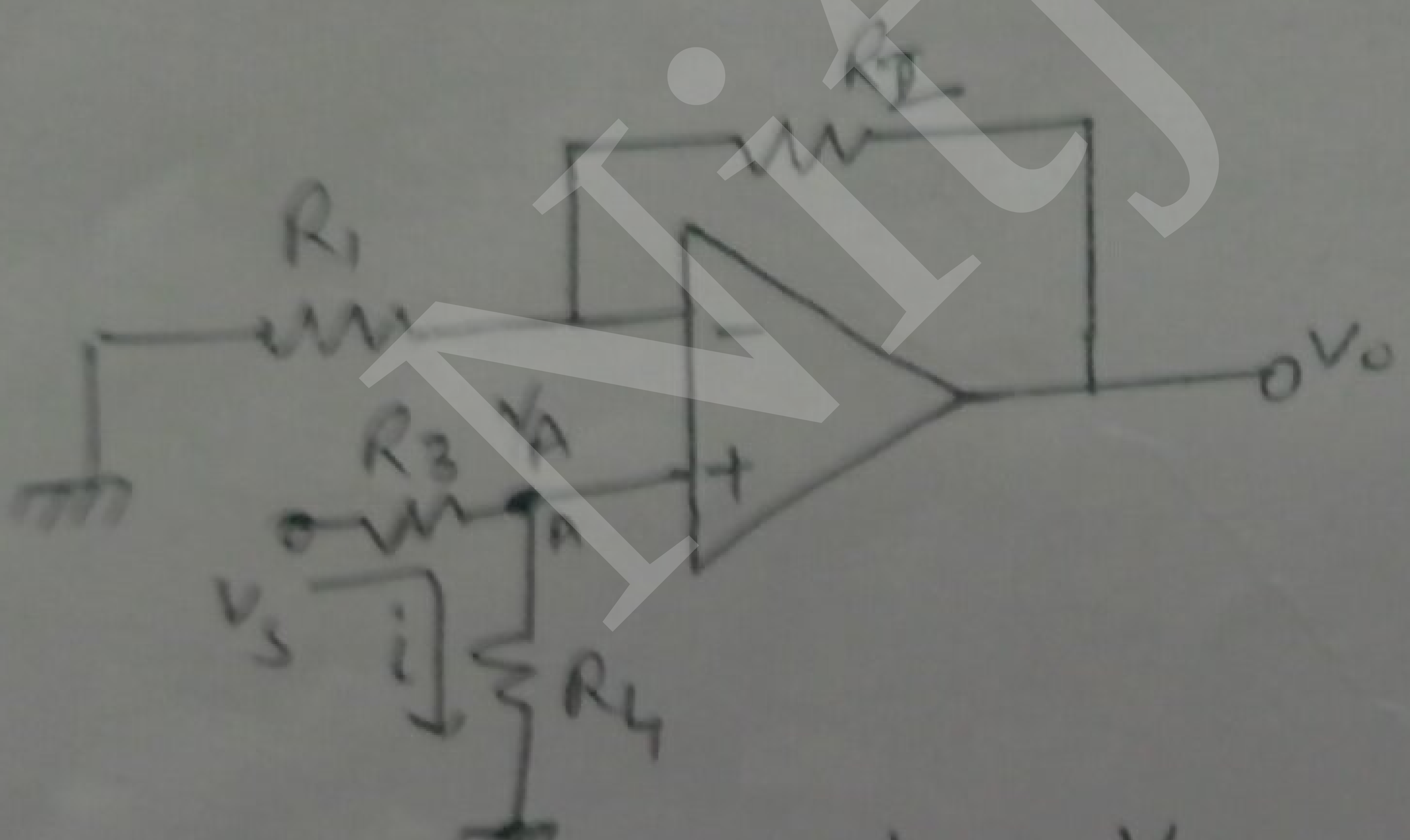
o/p. voltage is reflection of i/p voltage.

⇒



Here $V^+ = V_S$ (since no current flow through R_2).

⇒



$$V^+ = V_A$$

$$V_A = \left(\frac{R_4}{R_3 + R_4}\right) V_s$$ (since current flow through R_3, R_4 to ground)

Differential Ampl^r

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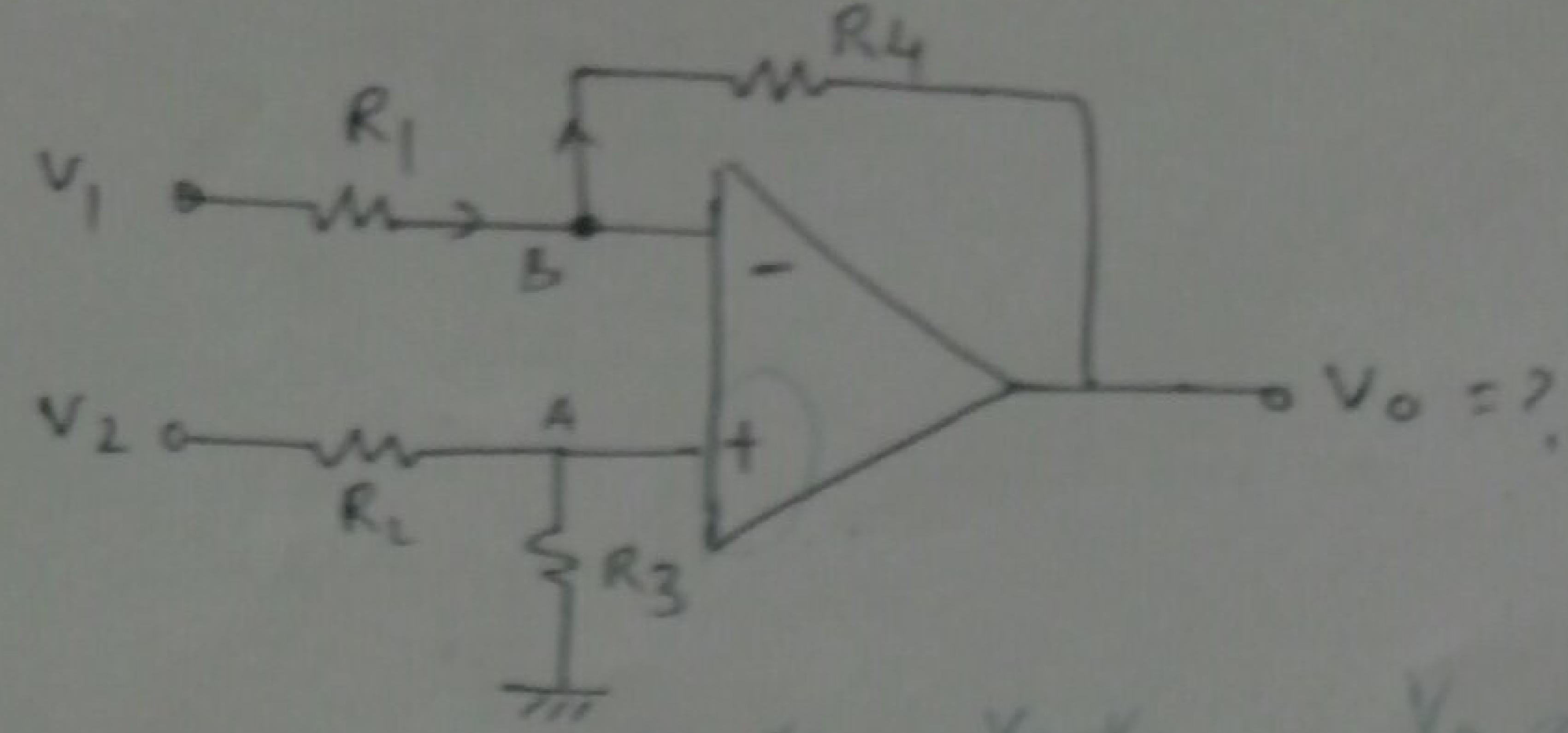

$$V_A = \left(\frac{R_3}{R_2+R_3}\right)V_2 = V_B$$

KCl at B.

$$\frac{V_1 - V_B}{R_1} = \frac{V_B - V_0}{R_4}$$

$$\frac{R_4}{R_1}(V_1 - V_B) = V_B - V_0$$

$$V_0 = V_B - \frac{R_4}{R_1}V_1 + \frac{R_4}{R_1}V_B$$

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

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

gain of Non inverting i/p V_2

gain of Inverting I/P (V_1)

$$\boxed{V_0 = \frac{R_3}{R_1}\left[\frac{R_1+R_4}{R_2+R_3}\right]V_2 - \frac{R_4}{R_1}V_1}$$

Approximated method apply linear or superposition law.

$$V_0(-) = -\frac{R_4}{R_1}V_1$$

$$V_0(+) = \left(1+\frac{R_4}{R_1}\right)V_A \quad \text{while } V_A = \left(\frac{R_3}{R_2+R_3}\right)V_2$$

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

$$V_0 = V_0(-) + V_0(+)$$

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

Note:- if $R_1 = R_2 = R_3 = R_4$ (In the above ckt)

$$V_0 = -V_1 + V_2 \Rightarrow \boxed{V_2 - V_1 = V_0}$$

Then the circuit is called SUBTRACTOR

SUBTRACTOR

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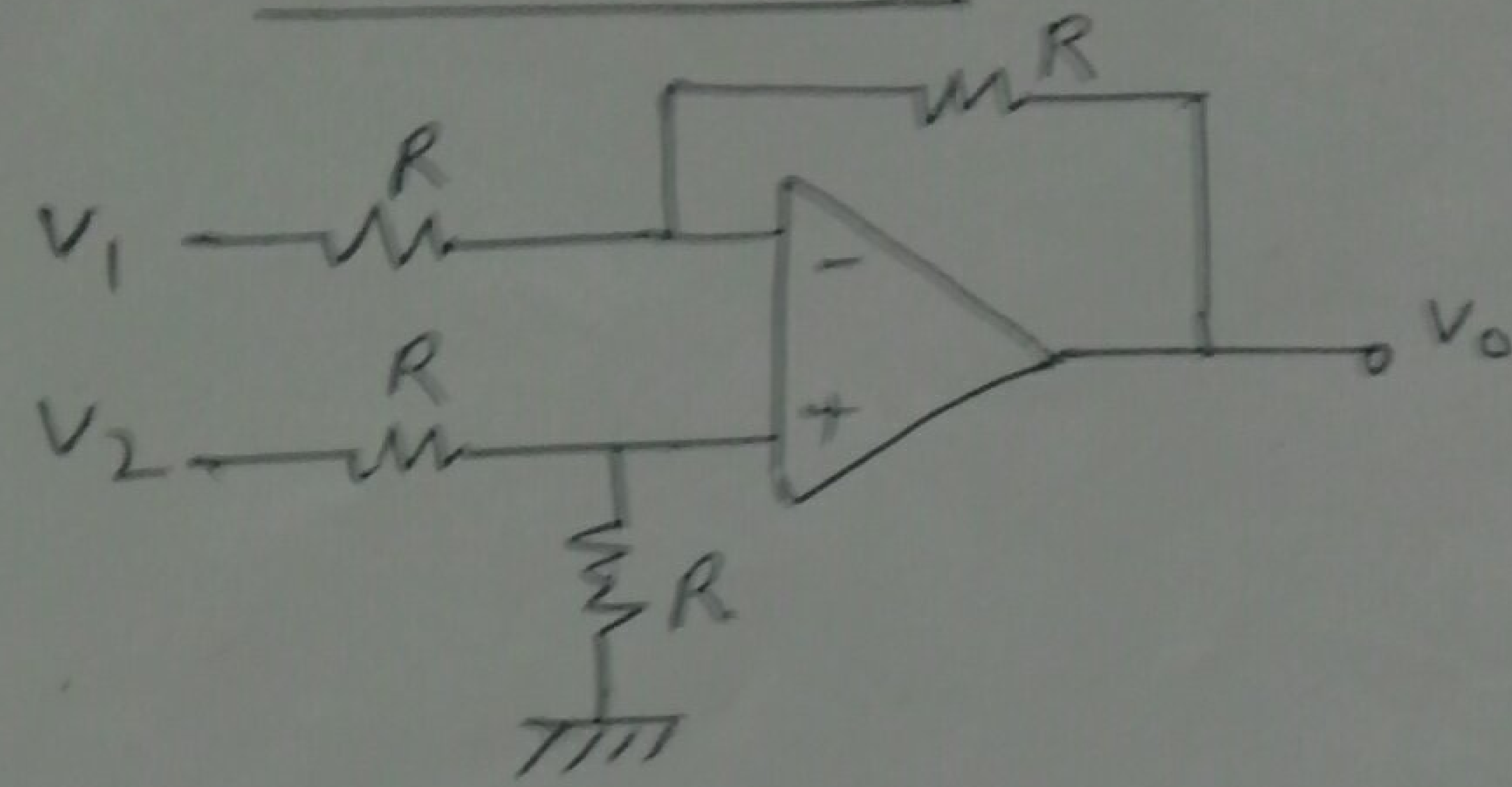

Subtractor is modification of differential Ampl^r with identical Resistances.

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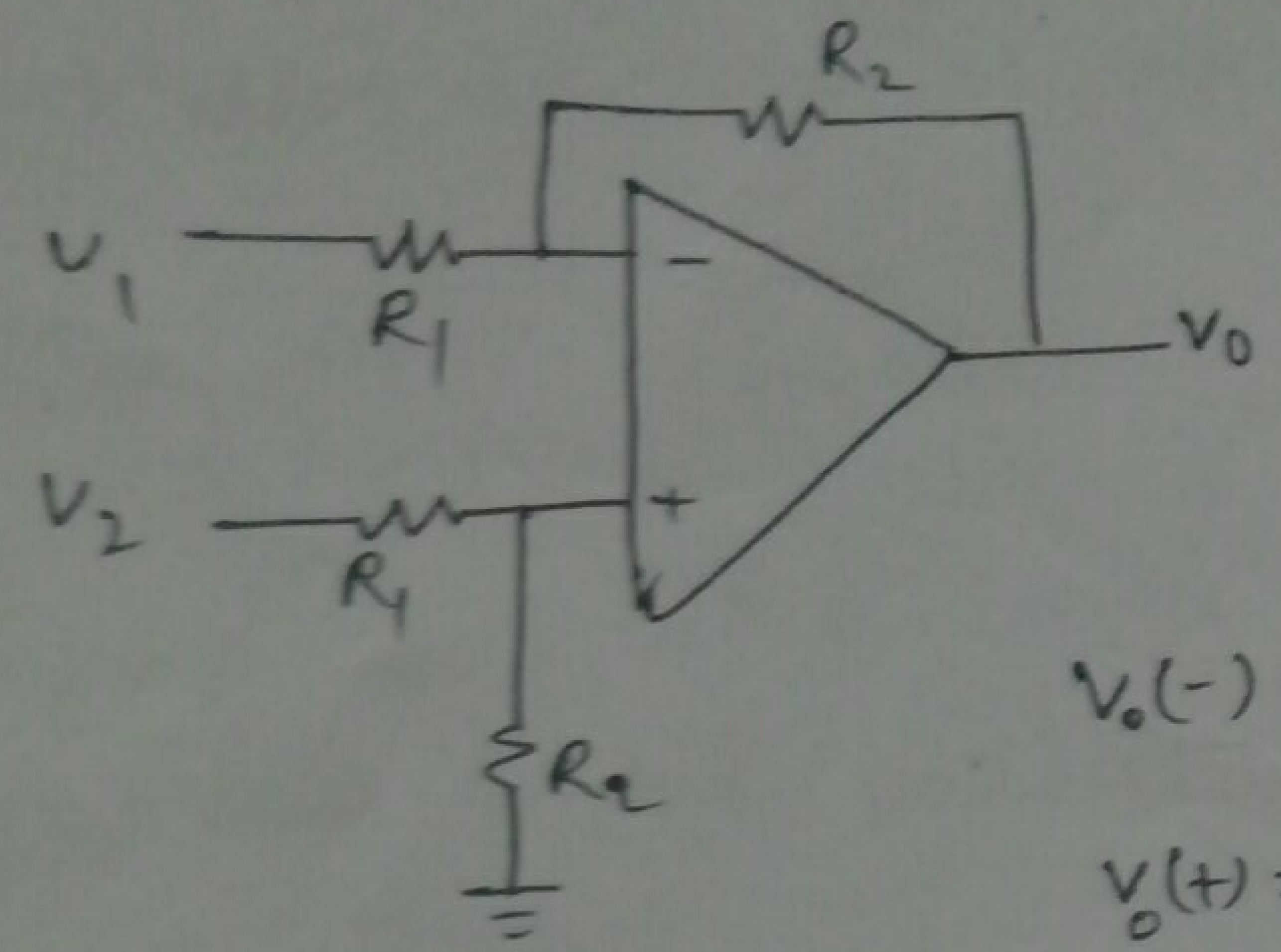
Que find v_0 for given ckt.



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

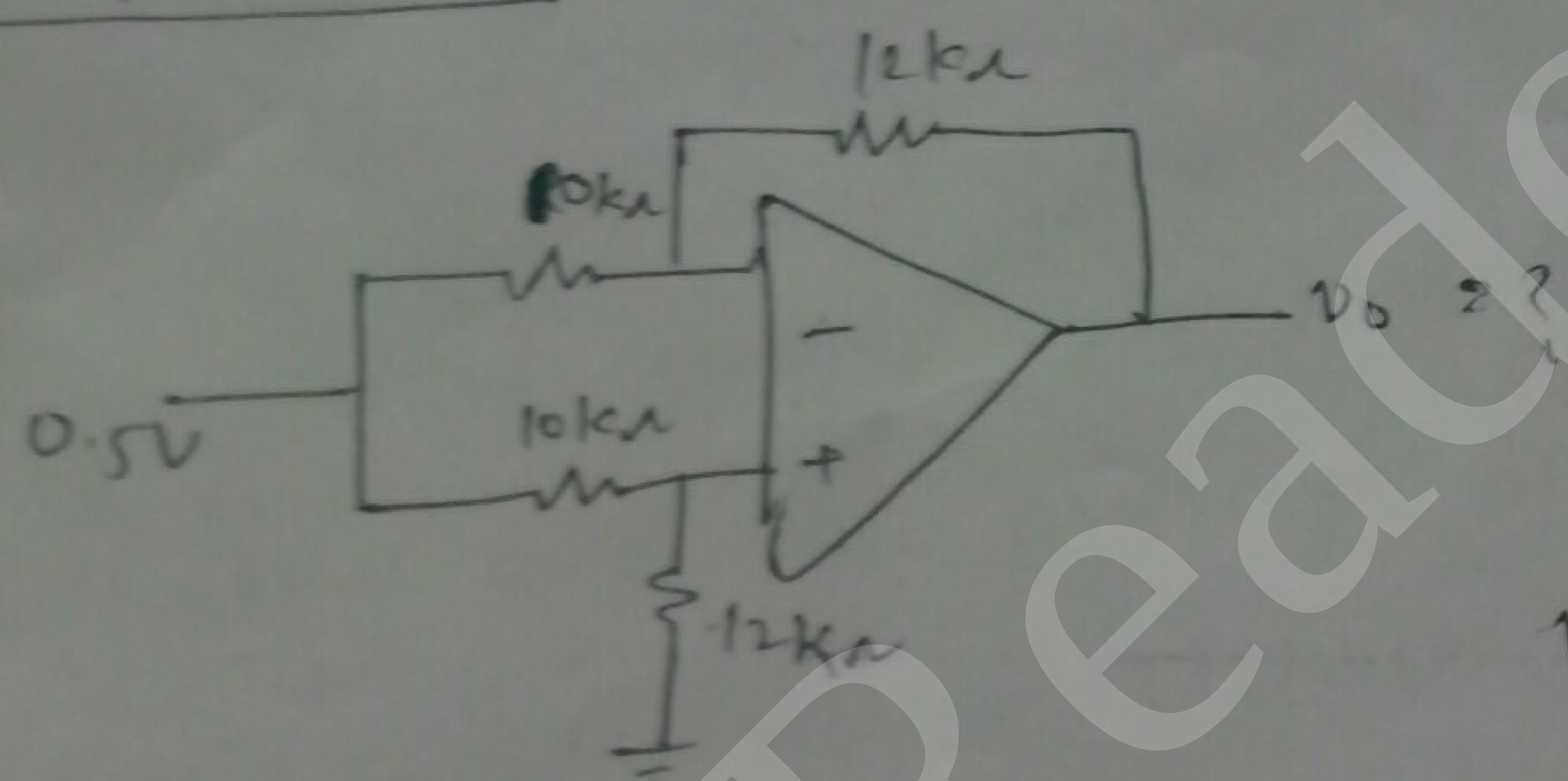
$$V_0(+) = \left(1+\frac{R_2}{R_1}\right)\left(\frac{R_2}{R_1+R_2}\right)V_2$$

$$V_0(+) = \frac{\cancel{(R_1+R_2)}}{R_1} \times \frac{R_2}{\cancel{(R_1+R_2)}}V_2 = \frac{R_2}{R_1}V_2$$

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

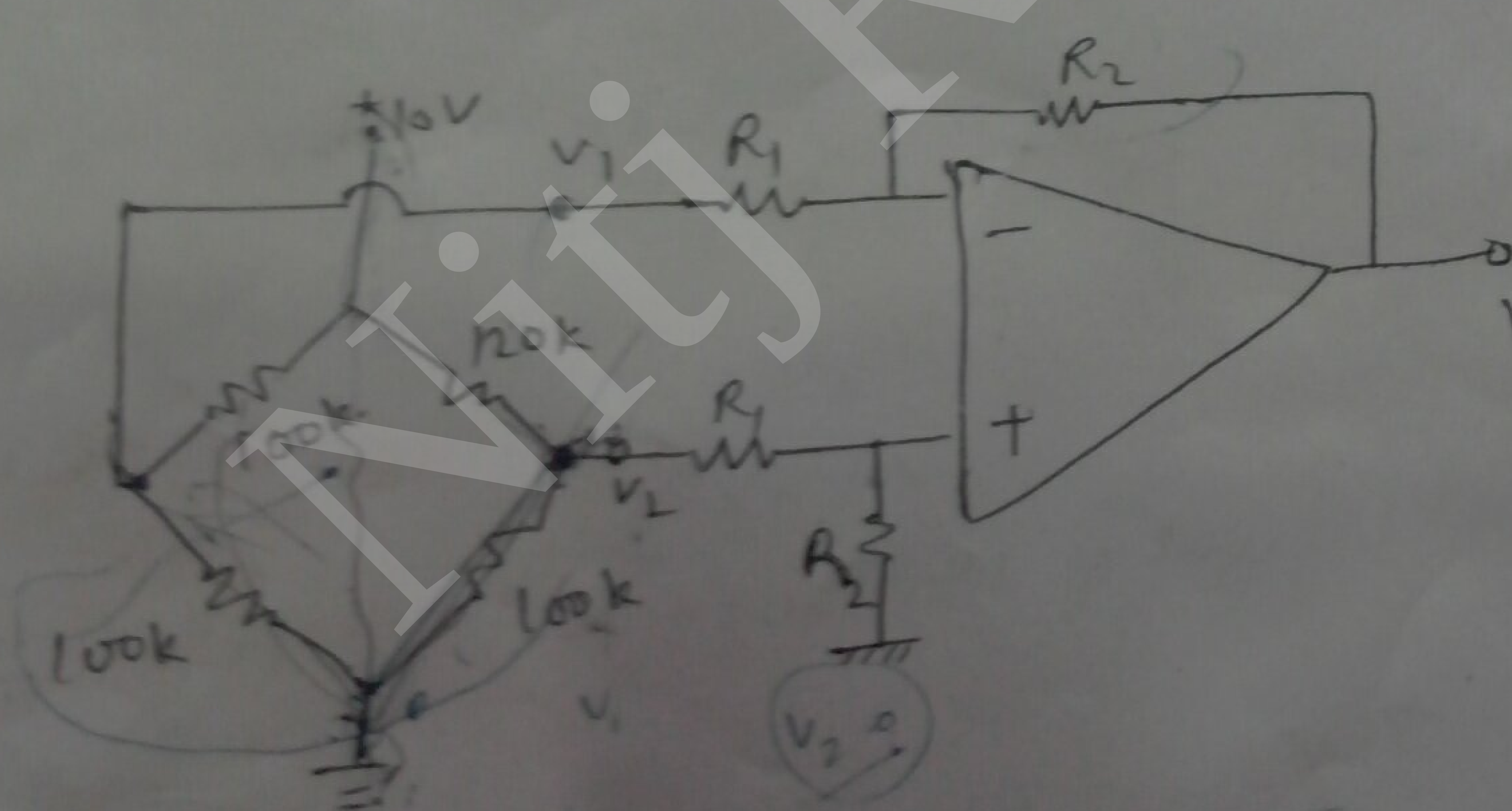
$$\boxed{V_0 = \frac{R_2}{R_1}(V_2 - V_1)}$$

Que



$V_0 = 0$

Que



$V_0 = ?$

$$V_1 = \left(\frac{100k}{200k}\right) \times 10$$

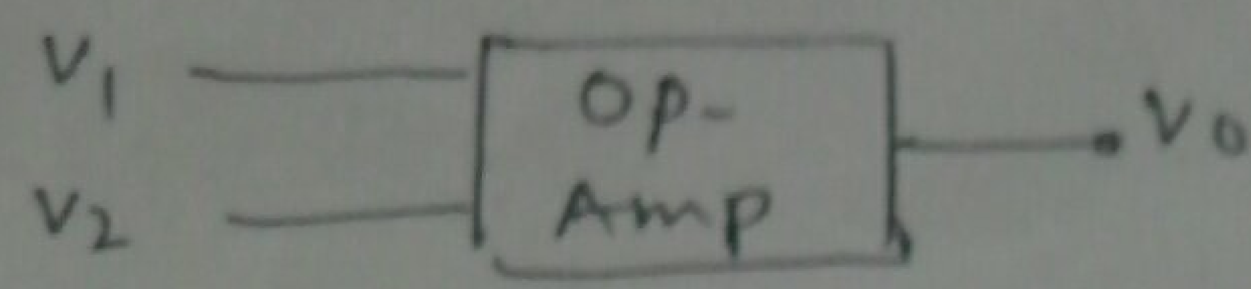
$$V_2 = \left(\frac{100k}{220k}\right) \times 10V$$

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

$$V_0 = \frac{R_2}{R_1}\left(\frac{100k}{220k} - \frac{100k}{200k}\right)10$$

CMMR (Common mode Rejection Ratio)

Consider Block diagram of an op-Amp.



In Ideal op-amp output voltage depends only on the difference of the input voltages & if $V_1 = V_2$, then V_0 reduce to zero

Ideal opAmp.

V_0 is function of $(V_1 - V_2)$

if $V_1 = V_2$

$V_0 = 0$

In a practical op-Amp output voltage is a function of the difference and the average of the two voltage hence if $V_1 = V_2$, V_0 never reduce to zero.

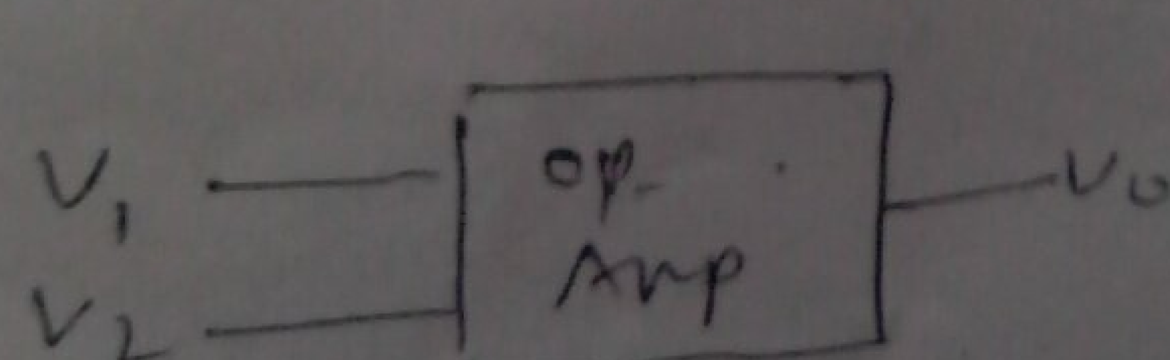
In practical op-Amp.

V_0 is function of $(V_1 - V_2) + \frac{V_1 + V_2}{2}$

if $V_1 = V_2$

$V_0 \neq 0$

By applying superposition principle to the practical op-Amp.



$$V_0 = A_1 V_1 + A_2 V_2 \quad \text{---} (1)$$

A_1 - gain for I/p V_1, when $V_2 = 0$

A_2 = gain for I/p V_2, when $V_1 = 0$

Diffⁿ. I/p signal $V_d = V_1 - V_2$ — ②

common mode signal voltage

$$V_c = \frac{V_1 + V_2}{2} \quad \text{— ③}$$

Solving Eqⁿ. ② & ③

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

$$V_2 = V_c - \frac{V_d}{2}$$

$V_d = V_1 - V_2$

add $2V_c = V_1 + V_2$

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

sub. $-V_2 = \frac{V_d - 2V_c}{2}$

Substituting V_1 & V_2 in eqⁿ No ①

$$V_0 = A_1\left(V_c + \frac{V_d}{2}\right) + A_2\left(V_c - \frac{V_d}{2}\right)$$

$$= A_1 V_c + A_1\frac{V_d}{2} + A_2 V_c - A_2\frac{V_d}{2}$$

$$V_0 = V_c\left[A_1 + A_2\right] + \frac{V_d}{2}\left[A_1 - A_2\right]$$

$$\boxed{V_0 = |A_c| \cdot V_c + |A_d| \cdot V_d}$$

$$\left\{ \begin{aligned} A_d &= \tfrac{1}{2}(A_1 - A_2) \\ A_c &= A_1 + A_2 \end{aligned} \right\}$$

Eqⁿ. For output voltage of practical op-Amp.

$\boxed{A_c = A_1 + A_2}$ → Common mode gain

$\boxed{A_d = \frac{A_1 - A_2}{2}}$ → Differential mode gain

CMRR is denoted by ρ & is defined as the Ratio of differential mode gain to the common mode gain taken in magnitude.

$$\boxed{CMRR = \rho = \left|\frac{A_d}{A_c}\right|}$$

For Ideal op-Amp. Common mode gain $A_c = 0$ so for Ideal op-Amp $CMRR = \infty$

For better performance CMRR must be larger. For op-Amp CMRR is called the Figure of merit (FOM). (13)

For ideal op-Amp

$$\boxed{FOM = \infty}$$

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CMRR can be expressed in dB. as

$$\rho = 20\log\left|\frac{A_d}{A_c}\right| = 20\log A_d - 20\log A_c$$

CMRR can also be defined as the ability of the op-Amp to reject the common mode signal.

For Practical op-Amp CMRR is 100 or 120 dB. maximum.

Qus: Practical op-Amp $A_c = 10\,dB$, $A_d = 60\,dB$, CMRR = ?

$$CMRR = 60 - 10 = 50\,dB$$

Qus A practical op-Amp having $A_d = 100$, $A_c = -0.1$ is operated with I/p voltages $1050\,\mu V$ & $950\,\mu V$. Calculate CMRR, & V_o?

$$CMRR = 60\,dB$$

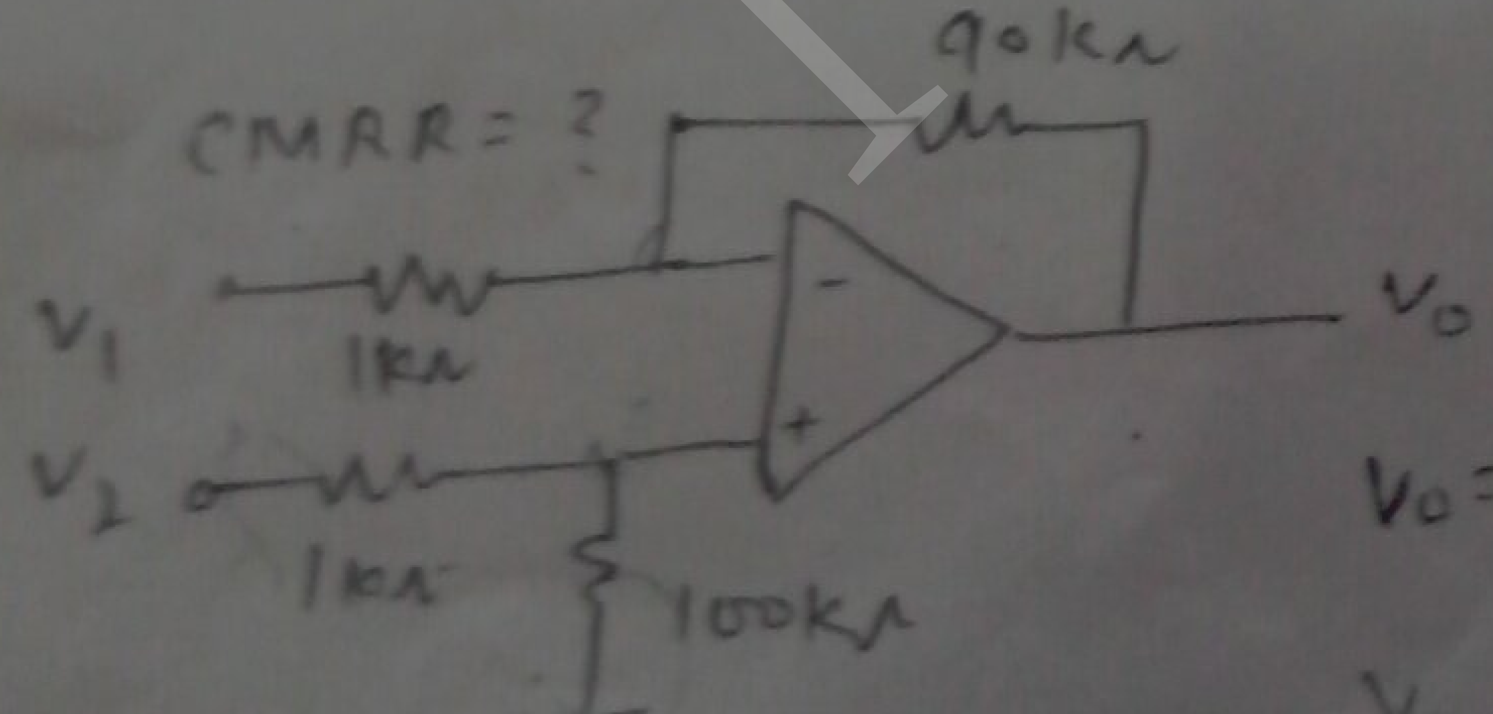
$$V_d = V_1 - V_2 = 1050 - 950 = 100\,\mu V$$

$$V_c = \frac{V_1 + V_2}{2} = \frac{1050 + 950}{2} = 1000\,\mu V$$

$$V_o = |A_d|V_d + |A_c|V_c = 100 \times 100\,\mu V + 0.1 \times 1000\,\mu V$$

$$\boxed{V_o = 10.1\,mV}$$

Qus CMRR = ?



Sol^n CMRR $= \left|\frac{A_d}{A_c}\right|$, $A_C = A_1 + A_2$, $A_d = \frac{A_1 - A_2}{2}$

$$V_o = -\frac{90}{1} V_1 + \left(1 + \frac{90}{1}\right)\frac{100}{(100+1)} V_2$$

$$V_o = -90 V_1 + (91) \times \frac{100}{101} V_2$$

$$V_o = -90 V_1 + 90.09 V_2 \quad \text{—(I)}$$

comparing with standard Eq^n $V_o = A_1 V_1 + A_2 V_2$ —(II)

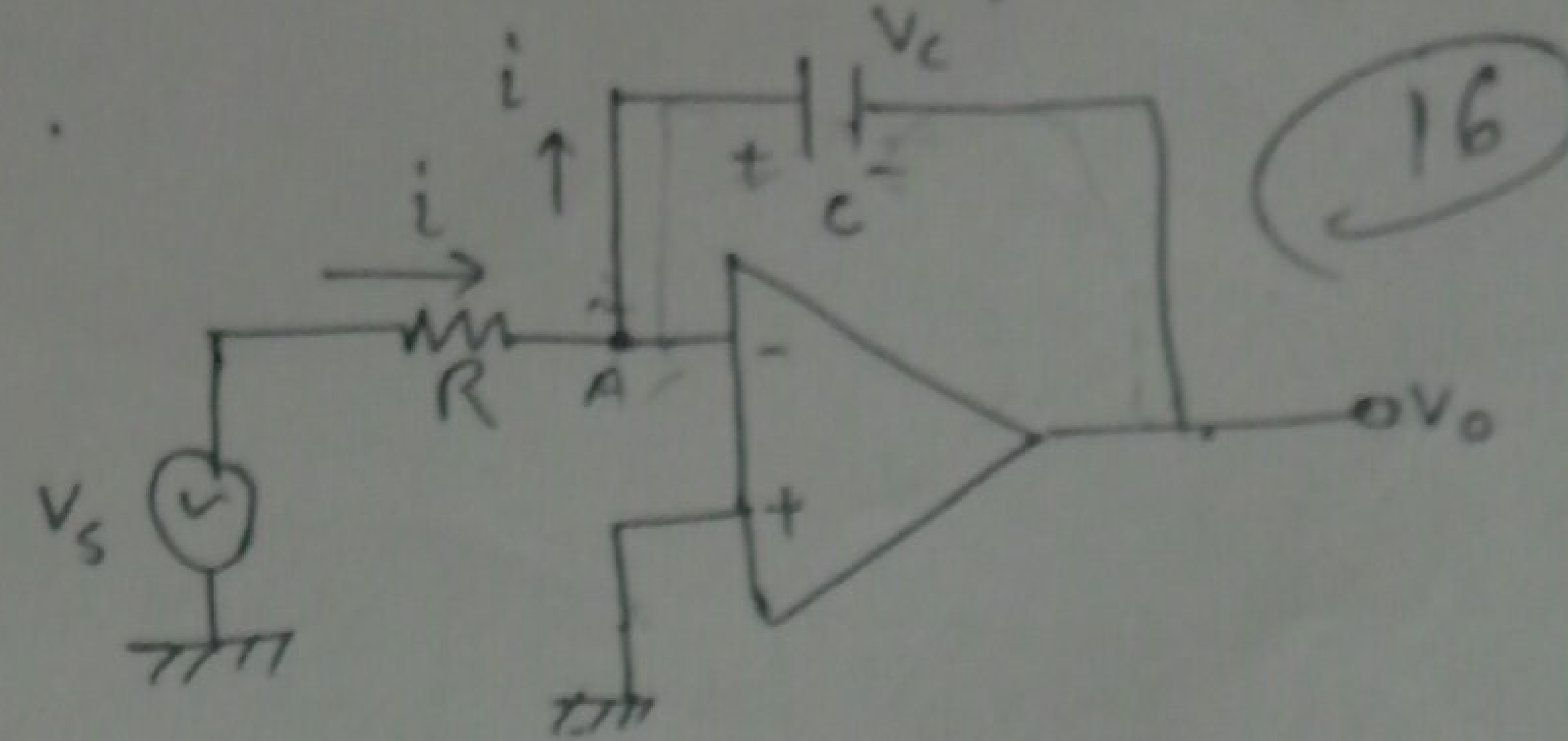
$A_1 = -90$, $A_2 = 90.09$ then $A_c = A_1 + A_2 = .09$

$$A_d = \frac{A_1 - A_2}{2} = -\frac{180.09}{2} = -90.045$$

$$CMRR = \frac{|A_d|}{|A_c|} = \boxed{1000.5}$$

OP-AMP INTEGRATOR

For an Integrator feedback is capacitor & series component is Resistance.



KCL at node A $i = \frac{V_s}{R}$

$v_c + v_0 = 0$

$$V_0 = -V_C$$

$$= -\frac{1}{C}\int i\,dt$$

$$V_0 = -\frac{1}{C}\int \frac{V_s}{R}\,dt$$

$$V_0 = -\frac{1}{RC}\int V_s\,dt$$

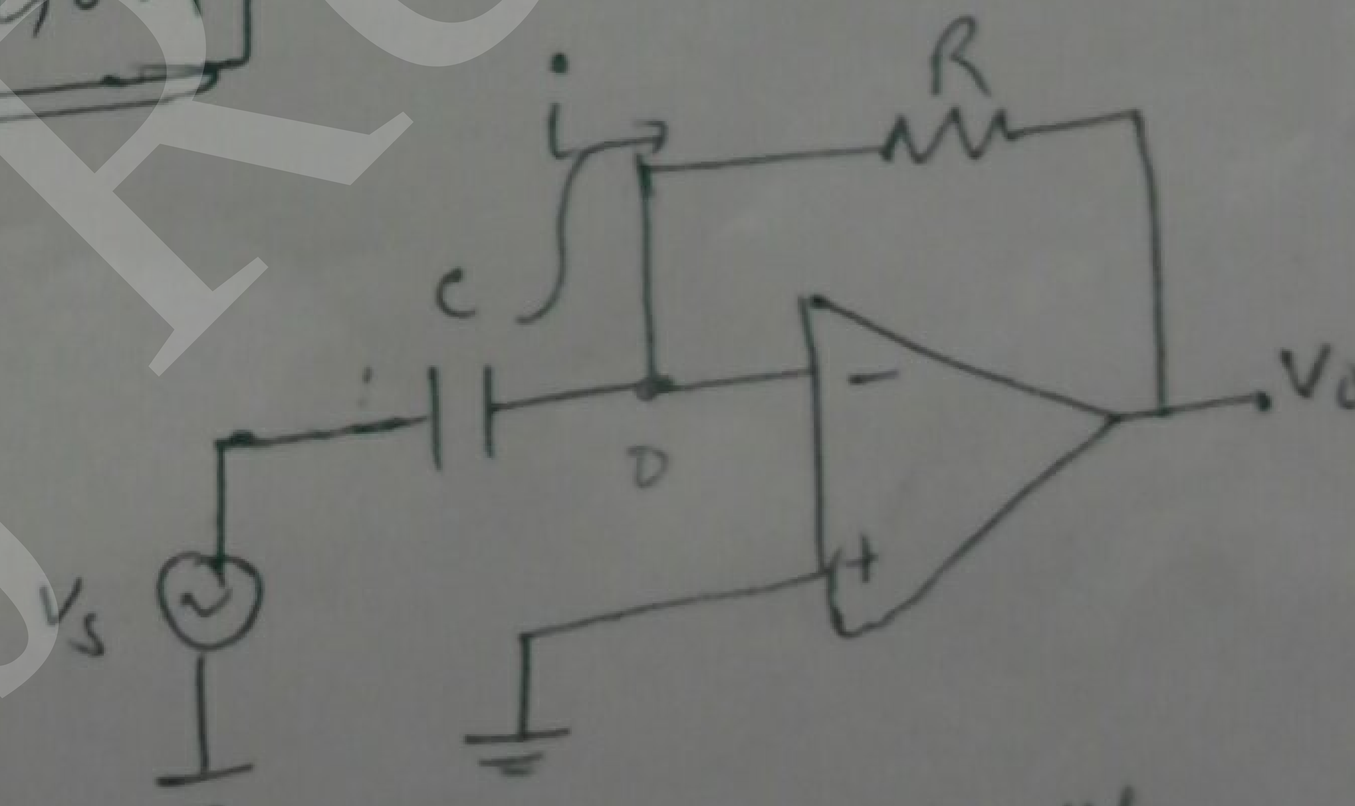
$$\boxed{V_0 = -\frac{1}{\tau}\int V_s\,dt}$$

$v_c = \frac{1}{C}\int i\,dt$

Voltage across capacitor.

$\boxed{\tau = RC = \text{Time Constant}}$

OP-Amp Differentiation



Current through Capacitor

$$i_c = C\frac{dV_s}{dt}$$

$$i_c R + V_0 = 0$$

$$V_0 = -i_c R$$

$$V_0 = -C\frac{dV_s}{dt}R$$

$$V_0 = -RC\frac{dV_s}{dt}$$

$$\boxed{V_0 = -\tau\frac{dV_s}{dt}}$$

$-i_c R - 0 = V_0$

$0 - V_0 = i_c R$

$V_0 = -i_c R$

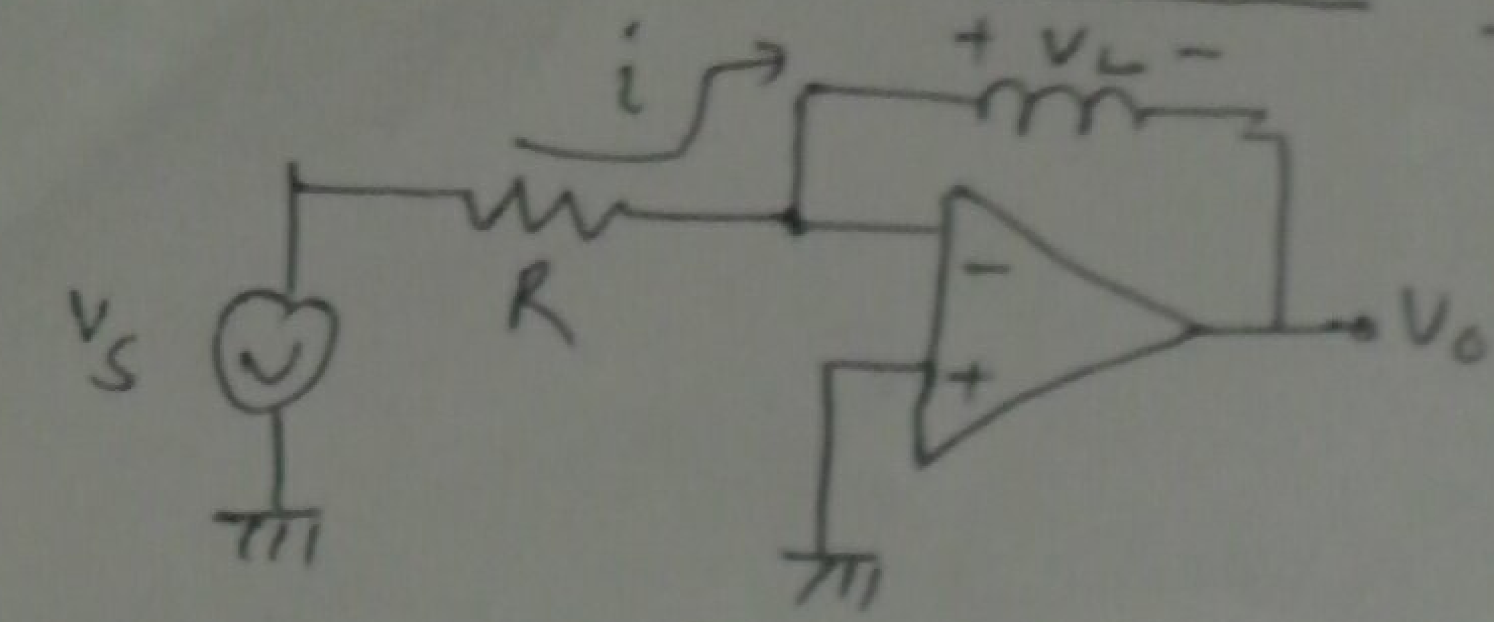
$V_0 = -CR\frac{dV_s}{dt}$

$-RC\left(\frac{dv_c}{dt}\right)$

$V_0 = -\tau\frac{dV_s}{dt}$

(17)

Op-Amp Differentiator with an Inductor



$V_L = L\dfrac{di}{dt}$

$i = \dfrac{V_s}{R}$, $V_o = -V_L$

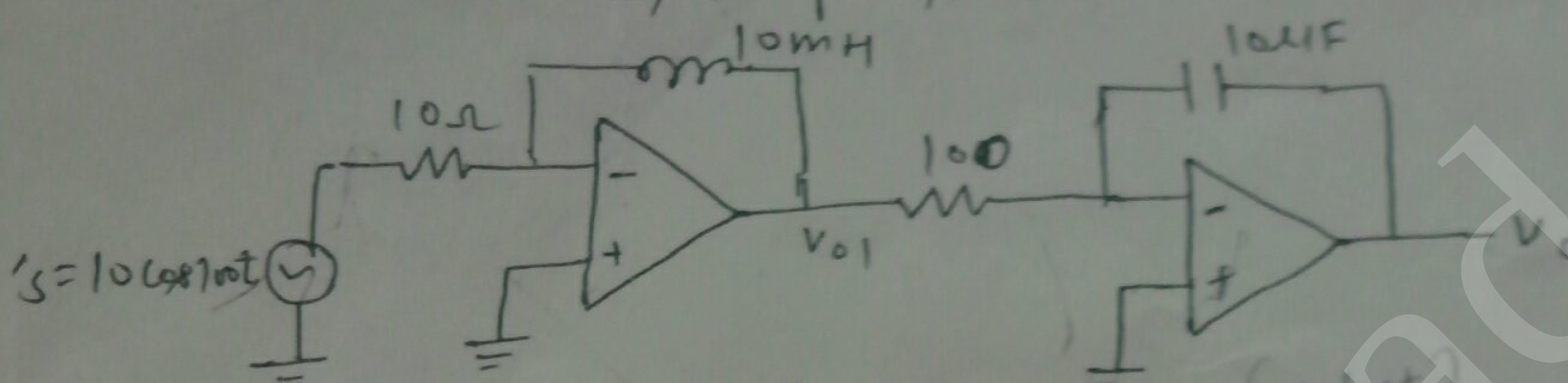
$V_o = -L\dfrac{d}{dt}\left(\dfrac{V_s}{R}\right)$

$\boxed{V_o = -\tau\dfrac{dV_s}{dt}} \leftarrow \boxed{V_o = \dfrac{-L}{R}\dfrac{dV_s}{dt}}$

$q = CV$

$\tau = L/R$ Time constant in R-L Network.

Ques. Ideal Op-Amp. find V_o



$V_o = -\dfrac{L}{R}\dfrac{d}{dt}$

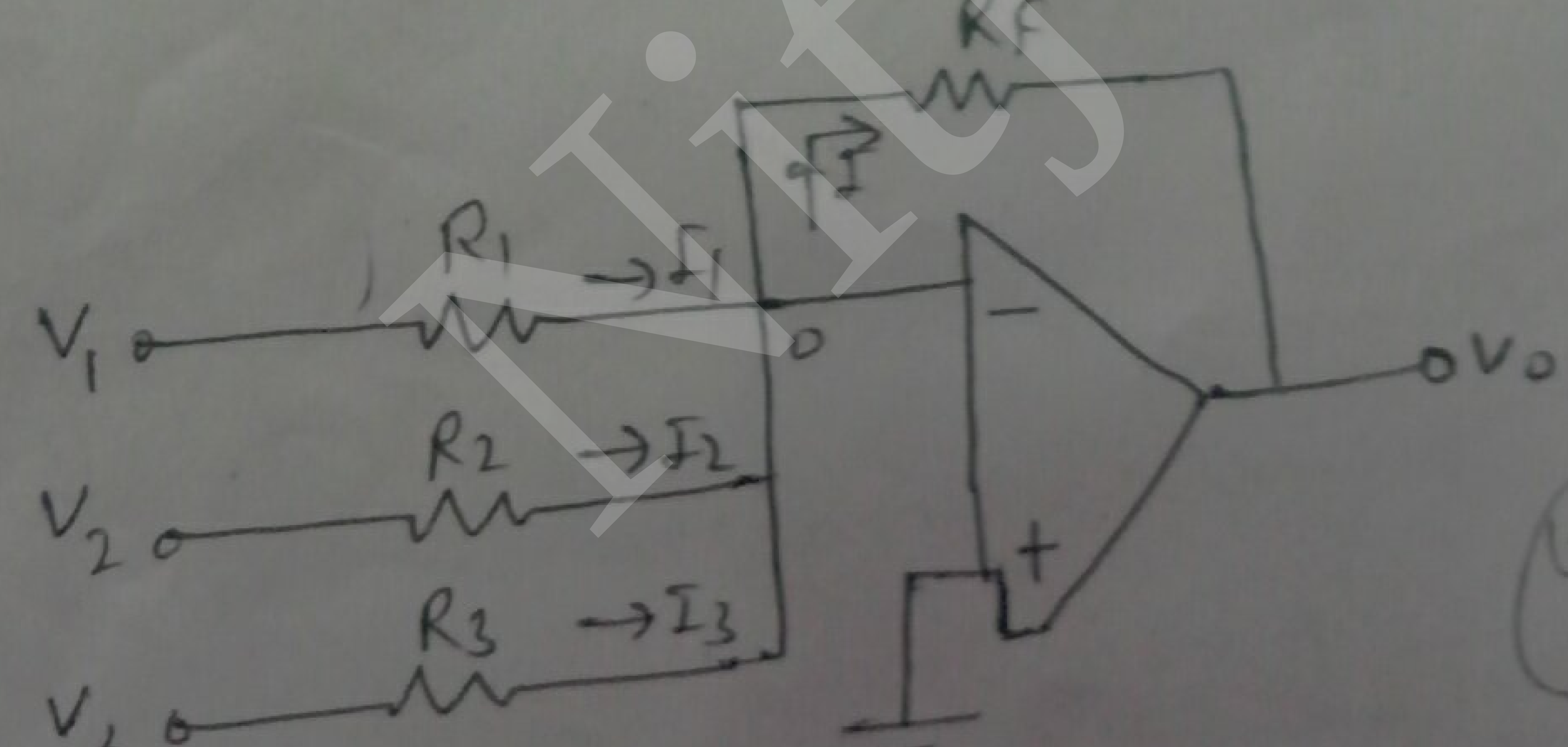
$V_o = -\dfrac{10mH}{10}\dfrac{d}{dt}(10\cos 100t)$

Ans. $V_o = V_s$.

INVERTING SUMMER

also called adder.

$V_o = -\tau\dfrac{dv}{dt}$



$V_o = V_s$

KCL $\quad \dfrac{V_1 - 0}{R} + \dfrac{V_2 - 0}{R_2} + \dfrac{V_3 - 0}{R_3} = \dfrac{0 - V_o}{R_F}$

$$V_o = -\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]R_F$$

OR

$$V_o = A_1V_1 + A_2V_2 + A_3V_3$$

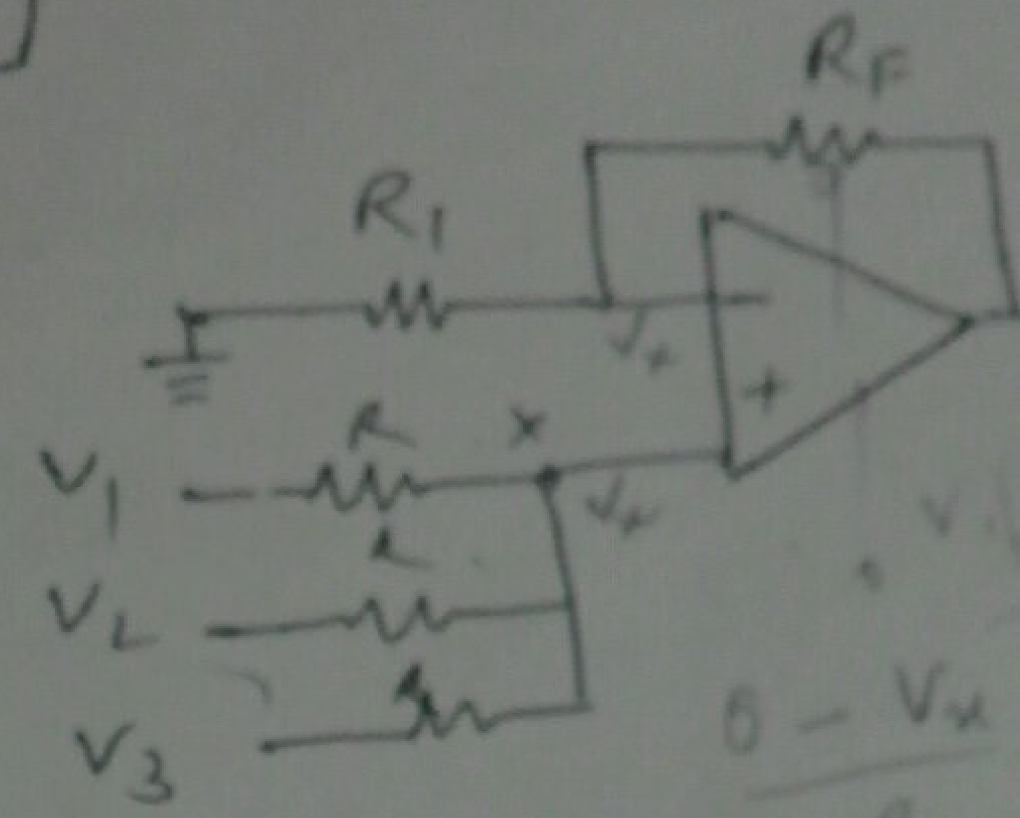
If $R_1 = R_2 = R_3 = R_f$

(18)

$$V_0 = -(V_1 + V_2 + V_3) \rightarrow \text{Inverting Summer}$$

Non Inverting Summer

(18)



By applying superposition principle.

$$V_0 = \left(1 + \frac{R_F}{R_1}\right) V_x$$

let $V_x = V_{x1} + V_{x2} + V_{x3}$

let V_2 & V_3 are grounded then

$$V_{x1} = \frac{V_1 (R/2)}{R + R/2} = \frac{V_1}{3}$$

Let V_1 & V_3 are grounded

$$V_{x2} = \frac{V_2 (R/2)}{R + R/2} = \frac{V_2}{3}$$

Let V_1 & V_2 are grounded

$$V_{x3} = \frac{V_3 (R/2)}{R + R/2} = \frac{V_3}{3}$$

$$V_x = \frac{V_1}{3} + \frac{V_2}{3} + \frac{V_3}{3} = \frac{1}{3}(V_1 + V_2 + V_3)$$

$$V_0 = \left(1 + \frac{R_F}{R_1}\right) \frac{1}{3} (V_1 + V_2 + V_3)$$

Slew Rate (SR) or S_R.

It is defined as the maximum rate at which the amplifier output can be changed in volt/µsec.

$$SR = \frac{\Delta V_0}{\Delta t} \Big| \frac{\text{Volt}}{\mu\text{sec}}$$

for Ideal $SR = \infty$

$$SR = \frac{\Delta V_0}{\Delta V_i} \times \frac{\Delta V_i}{\Delta t}$$

$$\boxed{SR = |A_{CL}| \frac{\Delta V_i}{\Delta t}}$$

Slew Rate is also associated with the max^m operating input signal frequency as

$$f \le \frac{S.R}{2\pi K} \text{ Hz}$$

$$\omega < \frac{SR}{}$$

$K = |A_{CL}| \Delta V_i$