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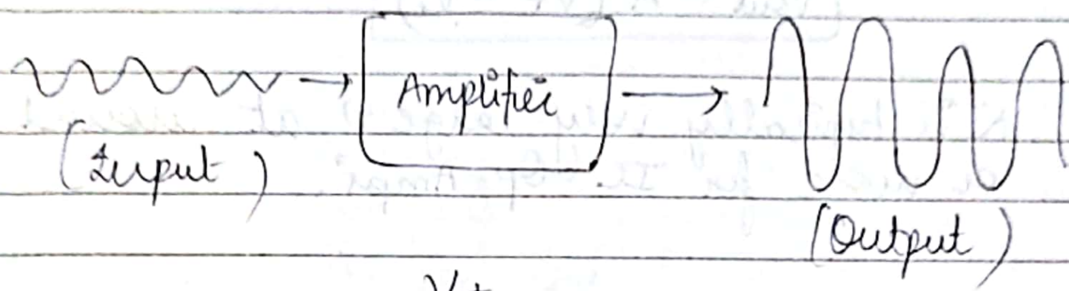
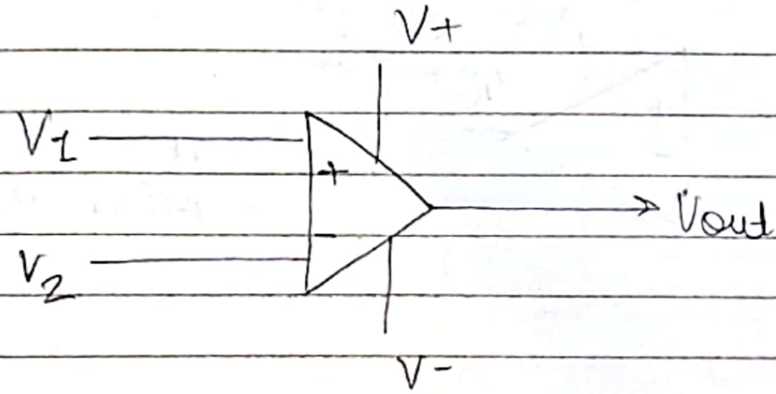
OPAMP : Operational Amplifier

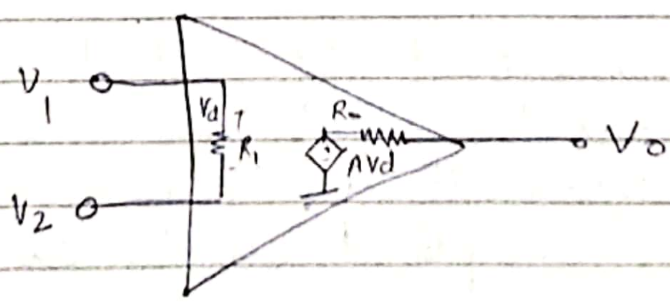




OPAMP diagram

$V_1 \rightarrow$ Non-inverting terminal
$V_2 \rightarrow$ Inverting input.

Opamp: It is an active circuit element designed to perform mathematical operations of addition, subtraction, multiplication, division, differentiation, integration etc.

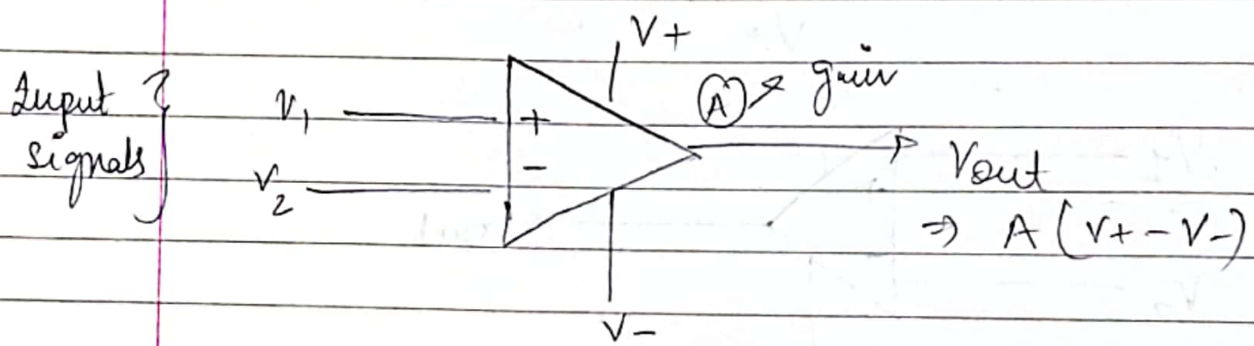


→ An opamp amplifies the difference of the inputs V_+ & V_- (known as differential input voltage)

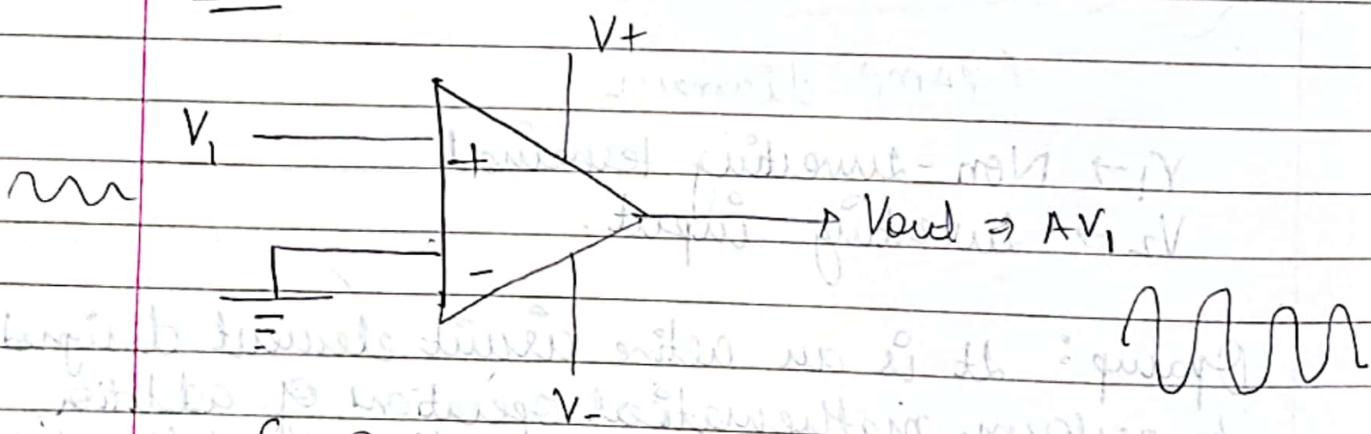
→ This is eqⁿ for an open loop gain amplifier:

$$\boxed{V_{out} = A(V_+ - V_-)}$$

→ K is typically very large → at around 10,000 or more for IC Op-Amps.

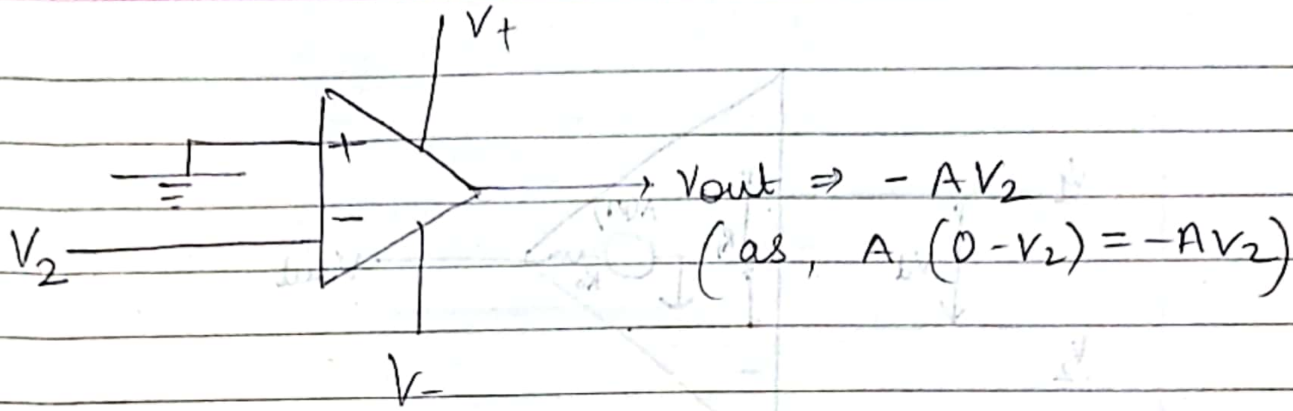


Now,



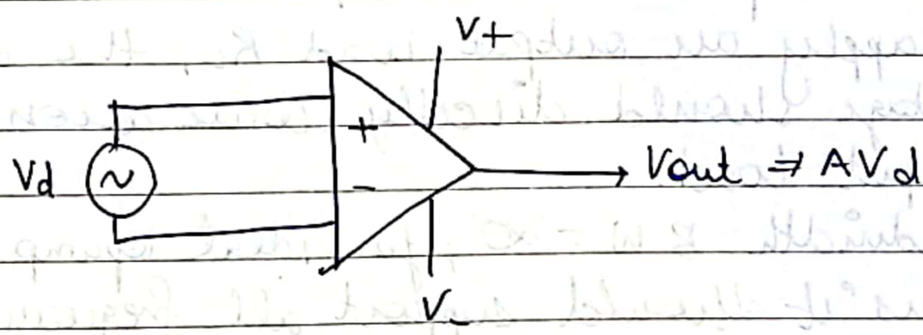
(A is the open loop gain of the operation amplifier)

→ Here phase of the output voltage is same as the input voltage so when we apply voltage at non-inverting terminal the output is amplified in the same phase.

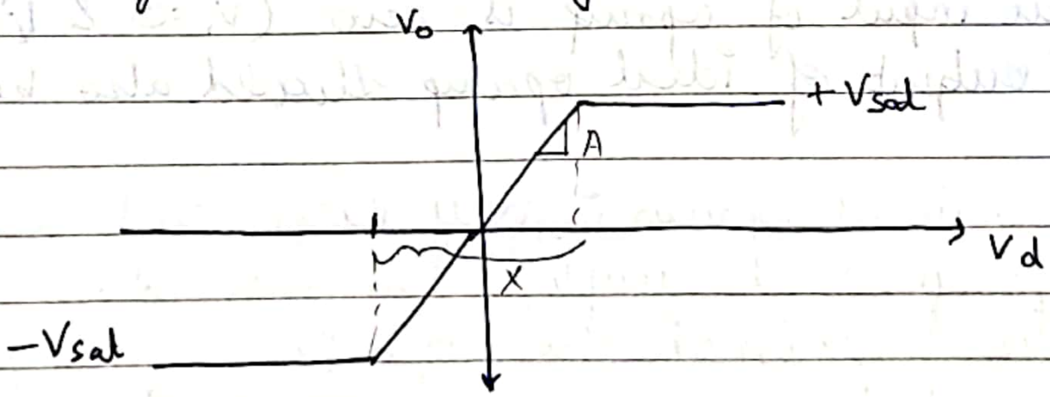


→ So output has a 180° phase diff with the input terminal, and thus the terminal on which voltage is applied is called the inverting terminal.

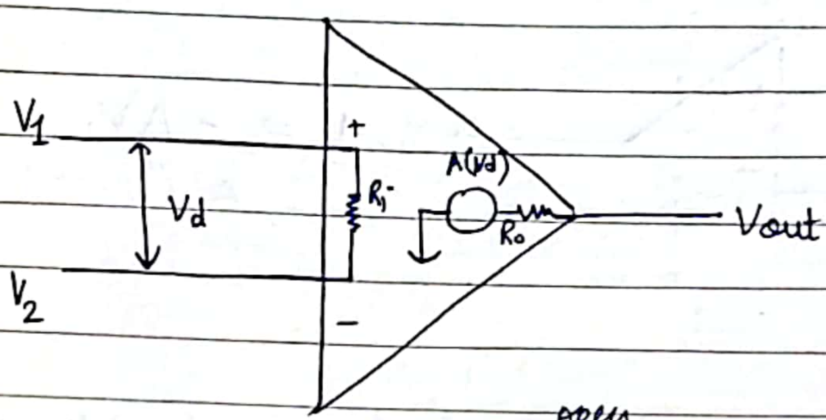
So,



Voltage transfer curve of OP-AMP:



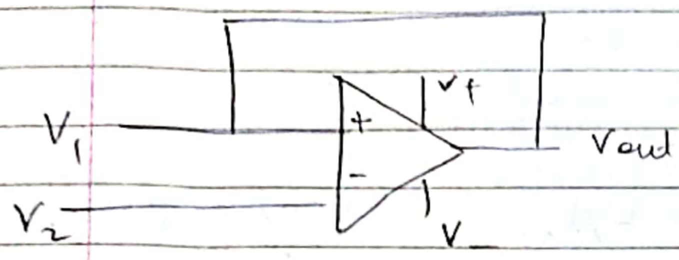
→ After some time the voltage gets saturated which means ones voltage crosses some particular value the output voltage remains constant.



- Ideal Opamp has infinite open loop gain ($A=\infty$)
- Input impedence $R_i = \infty$, so that whatever input is applied at the input terminals gets directly applied to the opamp.
- Output impedence $R_o = 0$, so that whenever we apply an output Load R_L, the output voltage should directly come across the output load.
- Bandwidth $BW = \infty$, for ideal opamp, which means it should support all frequencies starting from 0 to ∞.
- When input of opamp is zero ($V_1 = 0$ & $V_2 = 0$) the output of ideal opamp should also be 0.

- The gain of opamp is very large, so to use an ~~an~~ opamp as an amplifier we should use it in the x region in the graph on previous page. ~~To use But on using opamp in linear config,~~ ~~this~~ But on using opamp in open-loop config, this LINEAR range is very small. So to use it as an amplifier we have to control the gain of the amplifier and we can do so but applying feedback from output to input side.

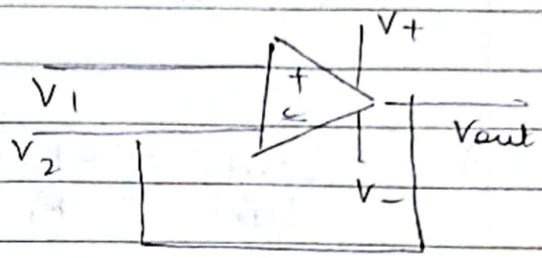
Two ways to apply feedback,



(1)

Positive feedback

→ This leads to unstability so can't be used.

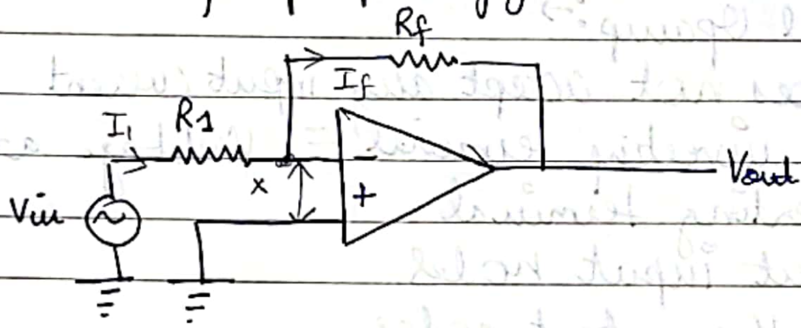


(2)

Negative feedback

→ This is used

Inverting Opamp Config:



According to concept of virtual ground,

$V^+ = 0 \quad V^- \simeq 0$

$V^+ \simeq V^-$

(There's virtual short between V^+ & V^-)

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

Since the input impedance of Opamp is infinite, no current will enter inside it

$\therefore \; I_1 = I_f$

$$\frac{V_{in} - V_x}{R_1} = \frac{V_x - V_o}{R_f}$$

$(V_x = 0)$

$$\frac{V_{in}}{R_1} = -\frac{V_{out}}{R_f}$$

$$\therefore \boxed{V_{out} = \frac{-R_f}{R_1} V_{in}}$$

$$\Rightarrow \boxed{\frac{V_{out}}{V_{in}} = \frac{-R_f}{R_1} = -A_{CL}} \rightarrow \text{(closed loop) gain}$$

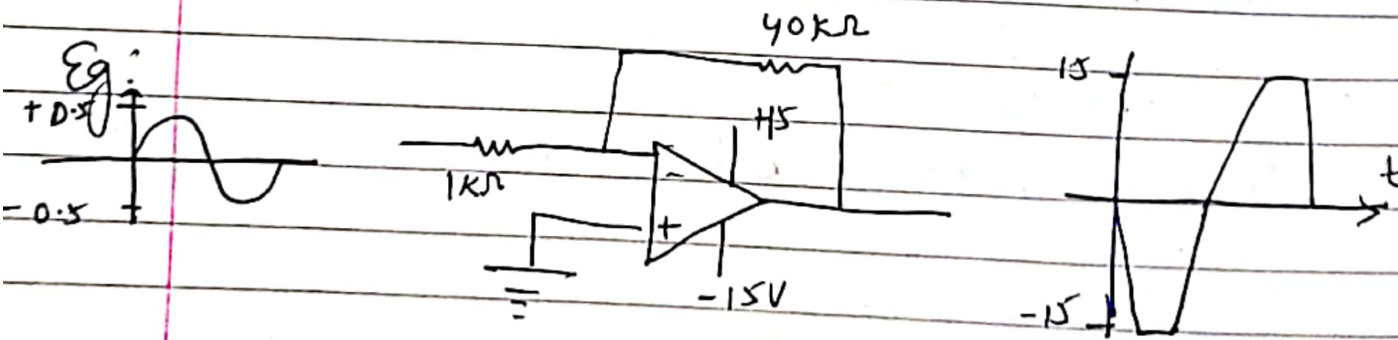
(So by controlling the value of R_f & R_1 we can control the gain of Opamp)

→ The (-ve) sign indicates the output voltage is 180° out of phase w.r.t the input voltage

For an ideal Opamp:→

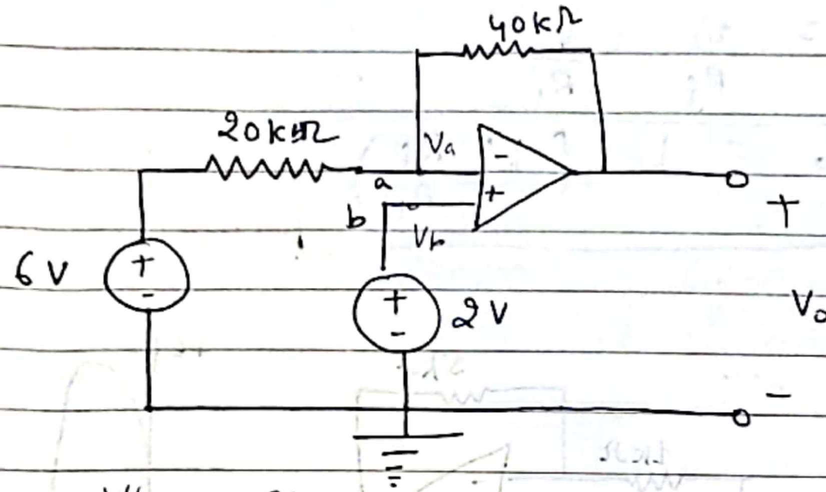
→ Op-amp does not accept any input current
→ Voltage at inverting terminal = Voltage at non-inverting terminal
→ Apply KCL at input nodes
→ No KCL at the output nodes

Eg:



$$\text{Voltage gain } A_{CL} = -\frac{R_f}{R_i} = -\frac{40}{1} = -40$$

Q.



$V_b = 2V$

$V_b = V_a = 2V$ (for ideal Op-amp)

$$\frac{6 - V_a}{\cancel{20}} = \frac{V_a - V_o}{\cancel{40}\,2}$$

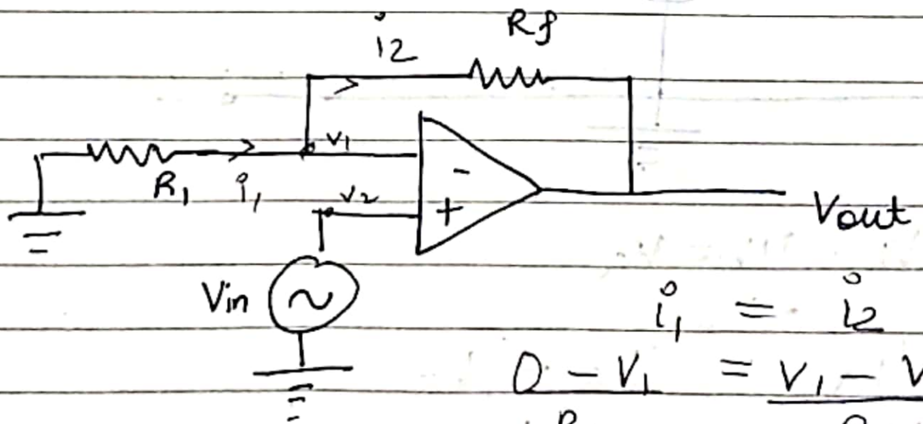
$$4 \times 2 = 2 - V_o$$

$$8 = 2 - V_o$$

$$V_o = -6V$$

(If $V_b = 0$, then $V_o = -12V$)

Non-inverting Op-Amp:-



$$i_1 = i_2$$

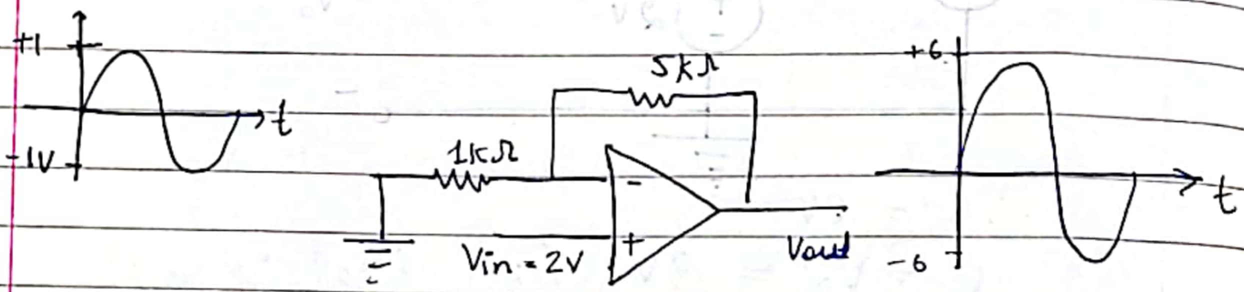
$$\frac{0 - V_1}{R_1} = \frac{V_1 - V_o}{R_f}$$

$$-\frac{V_1}{R_1} = \frac{V_1}{R_f} - \frac{V_o}{R_f}$$

$$\frac{V_o}{R_f} = \frac{V_1}{R_f} + \frac{V_1}{R_1}$$

$$\boxed{V_o = V_1\left(1 + \frac{R_f}{R_1}\right)}$$

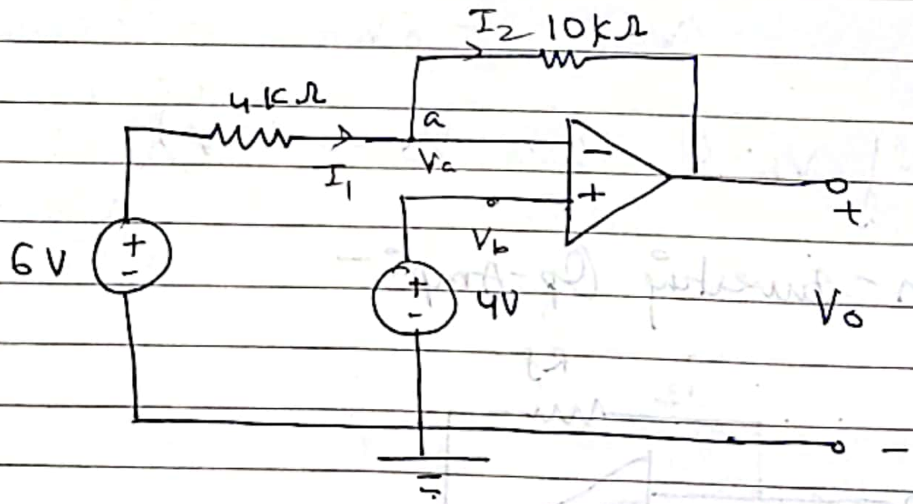
Eg:



Voltage gain, $A_{CL} = 1 + \frac{R_f}{R_1} = 1 + \frac{5}{1} = 6$

$\therefore V_o = 6V_{in} = 6 \times 2 = 12\,V$

Q.



$V_b = 4V = V_a$

$I_1 = I_2$

$$\frac{6 - V_a}{4} = \frac{V_a - V_o}{10}$$

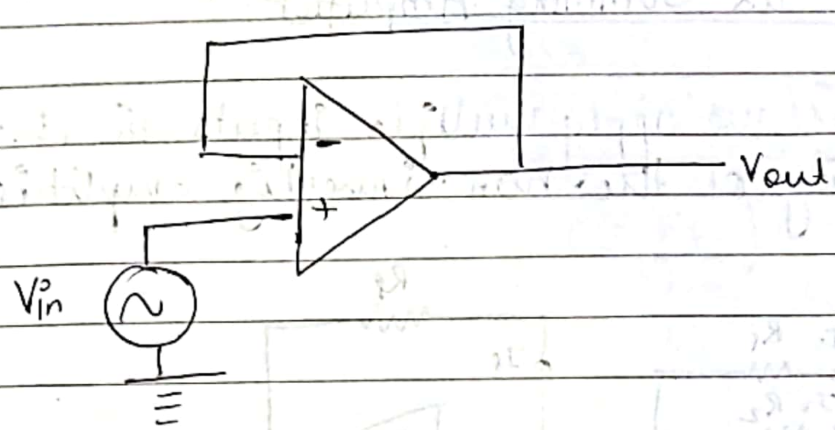
$$\frac{6-4}{\cancel{4}\,2} = \frac{4 - V_o}{\cancel{10}\,5}$$

$5 = 4 - V_o$

$$\boxed{V_o = -1V}$$

OPAMP as a Buffer

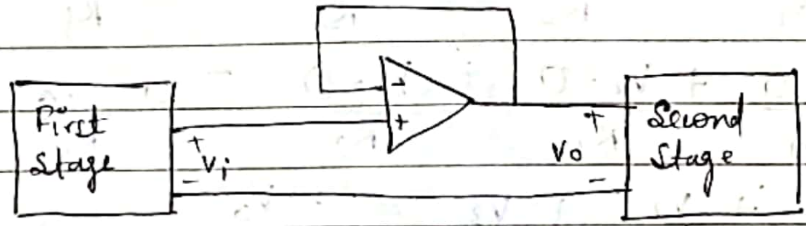
If in a non-inverting Op-amp configuration, $R_f = 0$, $R_1 = \infty$, the circuit is →



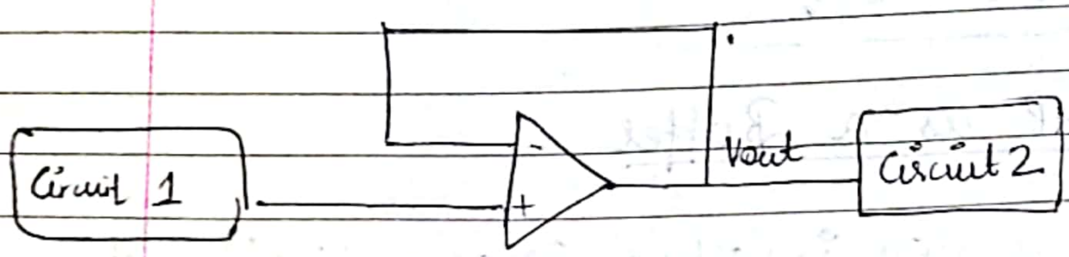
Due to feedback, $V^- = V+$

$V_- = V_{in} = V_{out}$

In this the output voltage follows the input voltage an so it is called the voltage follower circuit.

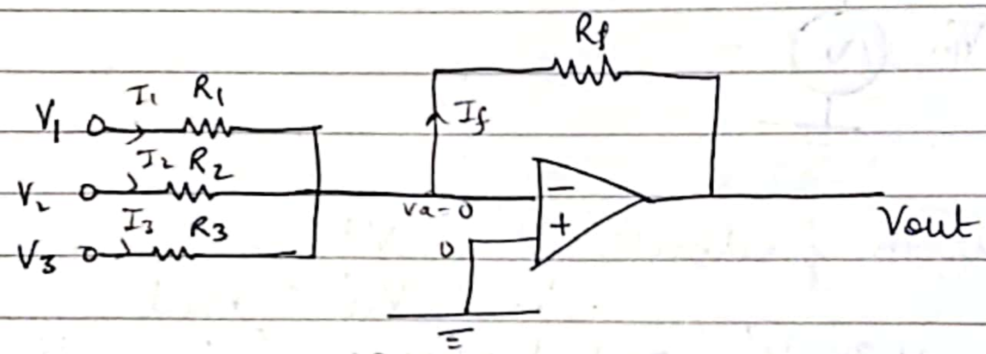


Using buffer circuit we can isolate two different circuits and ensure that whatever voltage is appearing at the output of one circuit will appear at the input of other circuit. It is useful when ~~we do not~~ have low input impedence in one circuit (USED FOR IMPEDENCE MATCHING)



OPAMP as Summing Amplifier:

→ In this we apply multiple inputs in the inverting or the non-inverting amplifier.



Applying KCL,

$$I_1 + I_2 + I_3 = I_f$$

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

$$\frac{V_1 - 0}{R_1} + \frac{V_2 - 0}{R_2} + \frac{V_3 - 0}{R_3} = \frac{0 - V_o}{R_f}$$

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

$$\boxed{V_{out} = -R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]}$$

If we assume; $R_1 = R_2 = R_3 = R$

$$V_{out} = -\frac{R_f}{R}\left[V_1 + V_2 + V_3\right]$$

POPU

Page No.:
Date: / /

Also, if $R_f = R$

$$\boxed{V_o = -[V_1 + V_2 + V_3]}$$

So like this opamp acts as an adder, and we can add multiple input voltages.

⇒ Now if $\frac{R_f}{R_1} \neq \frac{R_f}{R_2} \neq \frac{R_f}{R_3}$

$$\boxed{V_{out} = -[AV_1 + BV_2 + CV_3]}$$ (Scaling operation)

$$\left(A = \frac{R_f}{R_1},\ B = \frac{R_f}{R_2},\ C = \frac{R_f}{R_3}\right)$$

⇒ Now if $R_1 = R_2 = R_3 = R$
and, $\frac{R_f}{R} = \frac{1}{n} = 1/3$

$$\therefore V_{out} = -\frac{R_f}{R}[V_1 + V_2 + V_3]$$

$$\boxed{V_{out} = -\frac{1}{3}[V_1 + V_2 + V_3]}$$ (Averaging operation)

Uses of Summing amplifier:

→ Summing, averaging, Scaling;
→ Providing DC offset
→ Digital to Analog converter
→ Audio mixer

→ All the individual voltage sources are isolated w.r.t each other which is because of the concept of virtual ground. If we consider individual voltage sources at a time, the other voltage sources would be acting

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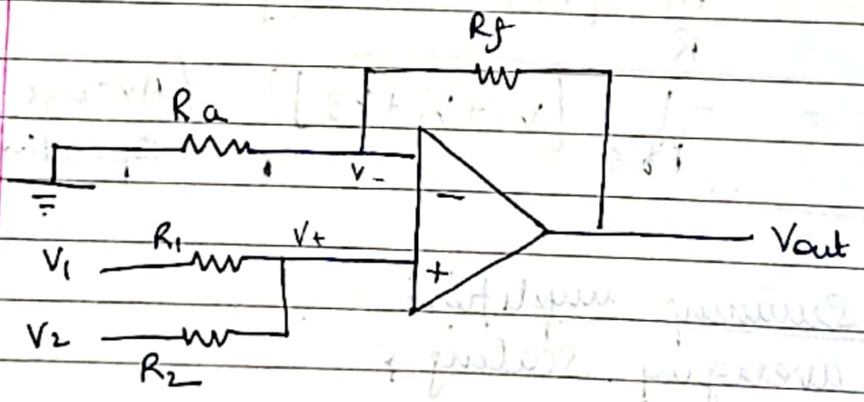
POPU
Page No.:
Date:

as short circuit at that time. So if we consider V_1 acting alone, V_2 & V_3 will act as short circuit or we can say they are ground potential and because of virtual ground a node is also at ground potential. So we can say effectively R_2 & R_3 will not exist in the circuit. And the effective impedence seen by V_1 is R_1. So there is not interference b/w diff voltage sources. This is biggest advantage of this op-amp.

→ To get a positive output we can connect it to another inverting op-amp with a unity gain.

NON-INVERTING SUMMING AMPLIFIER



To find voltage at V+, we apply superposition theorem.

→ First we consider $V_2 = 0$ (ground)

$$V_1^+ = \frac{R_2}{R_1+R_2} \times V_1$$

→ Now we consider $V_1 = 0$ (ground)

$$V_2^+ = \frac{R_1}{R_1+R_2} \times V_2$$

$$V^+ = V_1^+ + V_2^+$$
$$= \frac{R_2 V_1}{R_1+R_2} + \frac{R_1}{R_1+R_2} V_2$$
$$\Rightarrow \cancel{(V_1 + V_2) \quad R}$$

Now we know, $V_{out} = \left(1 + \frac{R_f}{R_a}\right) V_+$

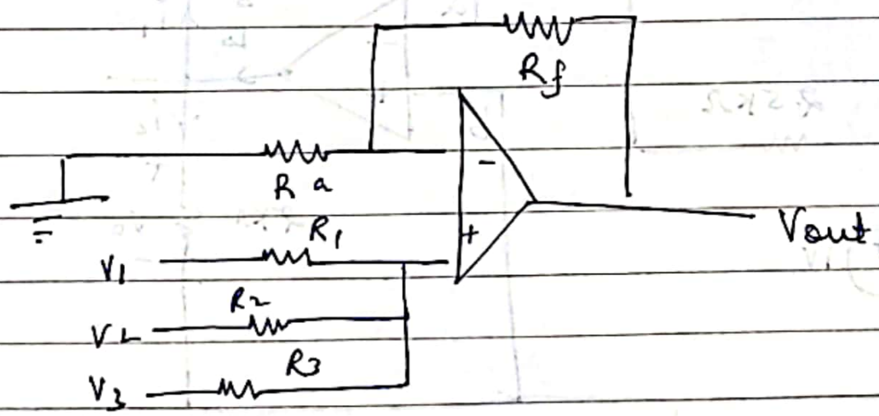
$$\boxed{V_{out} = \left(1 + \frac{R_f}{R_a}\right)\left[\frac{R_2 V_1}{R_1+R_2} + \frac{R_1}{R_1+R_2} V_2\right]}$$

Assuming, $R_1 = R_2 = R$

$$V_{out} = \left(1 + \frac{R_f}{R_a}\right)\left(\frac{V_1 + V_2}{2}\right)$$

If $R_f = R_a$,

$\therefore V_{out} = V_1 + V_2$



$$V_1^+ = \frac{(R_2 \| R_3)}{R_1 + (R_2 \| R_3)} \times V_1 \qquad V_2^+ = \frac{(R_1 \| R_3)}{R_2 + (R_1 \| R_3)} V_2$$

$$V_3^+ = \frac{(R_2 \| R_1)}{R_3 + (R_2 \| R_1)} \times V_3$$

$$V^+ = V_1^+ + V_2^+ + V_3^+$$

Assuming, $R_1 = R_2 = R_3 = R$

$$V_1^+ = \frac{V_1}{3}, \quad V_2^+ = \frac{V_2}{3}, \quad V_3^+ = \frac{V_3}{3}$$

$$V^+ = \frac{V_1 + V_2 + V_3}{3}$$

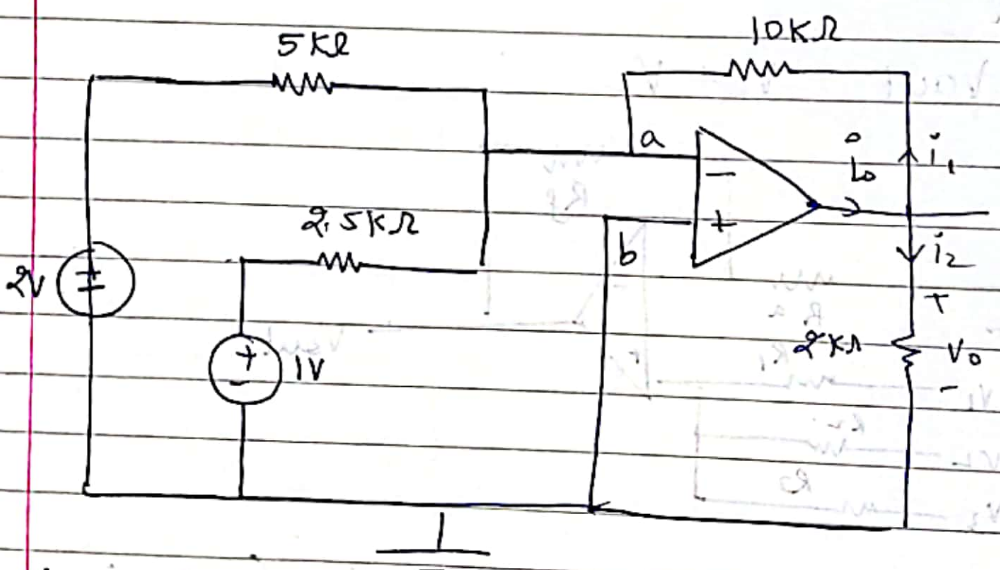
$$V_{out} = \left(1 + \frac{R_f}{R_a}\right) V^+$$

$$= \left(1 + \frac{R_f}{R_a}\right)\left(\frac{V_1 + V_2 + V_3}{3}\right)$$

$$\left(\text{If } 1 + \frac{R_f}{R_a} = 3\right)$$

$$V_{out} = V_1 + V_2 + V_3$$

Q.



$$V_a = V_b = 0$$

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

$$= -10\left(\frac{2}{5} + \frac{1}{2.5}\right)$$

$$= -4 - 4 = -8V$$

$$i_o = i_1 + i_2$$

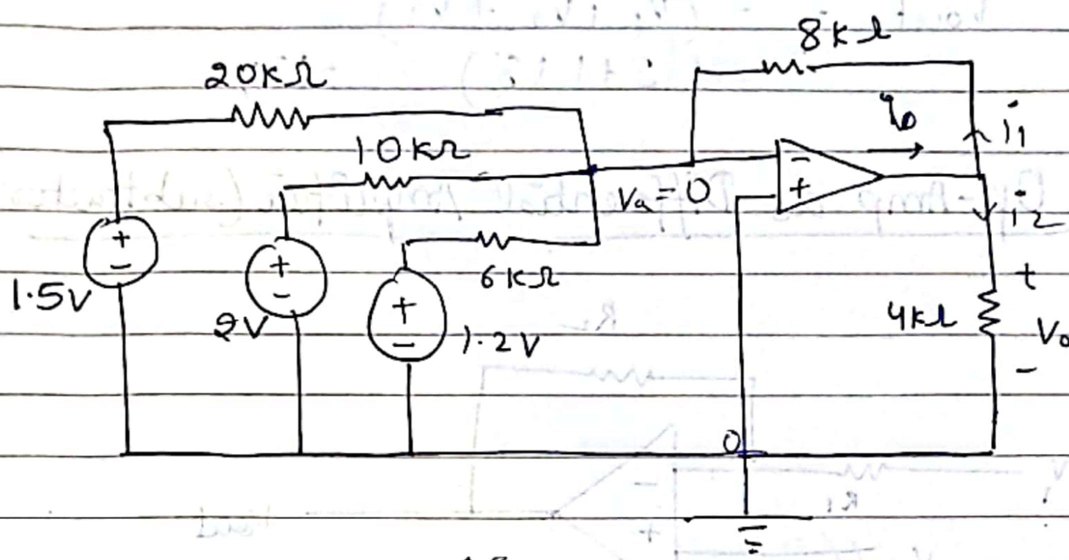
POPU

Page No.:
Date: / /

$$i_o = \frac{V_o - 0}{10} + \frac{V_o - 0}{2}$$

$$= -0.8 - 4 = -4.8\,mA$$

Q.



$$V_o = -8\left(\frac{\cancel{1.5}^{0.3}}{\cancel{20}_4} + \frac{2}{\cancel{10}_5} + \frac{1.2}{\cancel{6}_5}\right)$$

$$= -\frac{\cancel{8}^2 \times 0.3}{\cancel{4}} - \frac{8}{5} - \frac{8}{5}$$

$$= -0.6 - 1.6 - 1.6$$

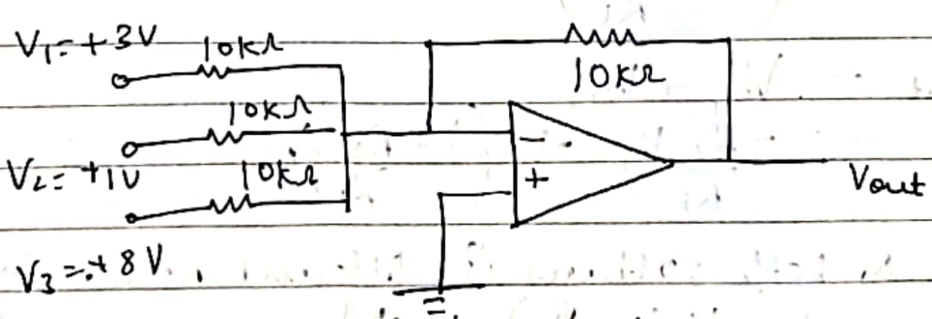
$$= -3.8V$$

$$i_o = i_1 + i_2$$

$$= \frac{V_o - 0}{8} + \frac{V_o - 0}{4} = \frac{-3.8}{8} - \frac{3.8}{4}$$

$$= -3.8\left(\frac{3}{8}\right) = -1.425\,mA$$

Q.

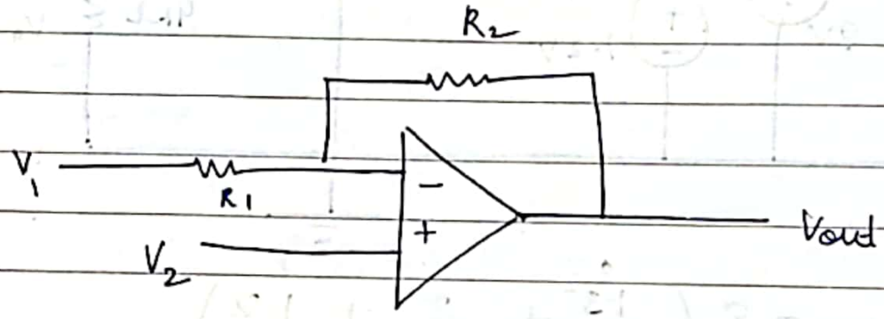


$$V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

$$R_f = R_1 = R_2 = R_3 = 10k\Omega$$

$$V_{out} = -(V_1 + V_2 + V_3)$$
$$= -(3+1+8) = -12V$$

Op-Amp as Differential Amplifier (Subtractor)



This config is combination of inverting & non-inverting configs. Now if we assume ~~by superposition~~, first $V_2 = 0$, it is inverting config, and if we assume $V_1 = 0$, then it is non-inverting configuration.

To get Vout we use superposition principle →

- When $V_2 = 0$

$$V_{o_1} = -\frac{R_2}{R_1}V_1$$

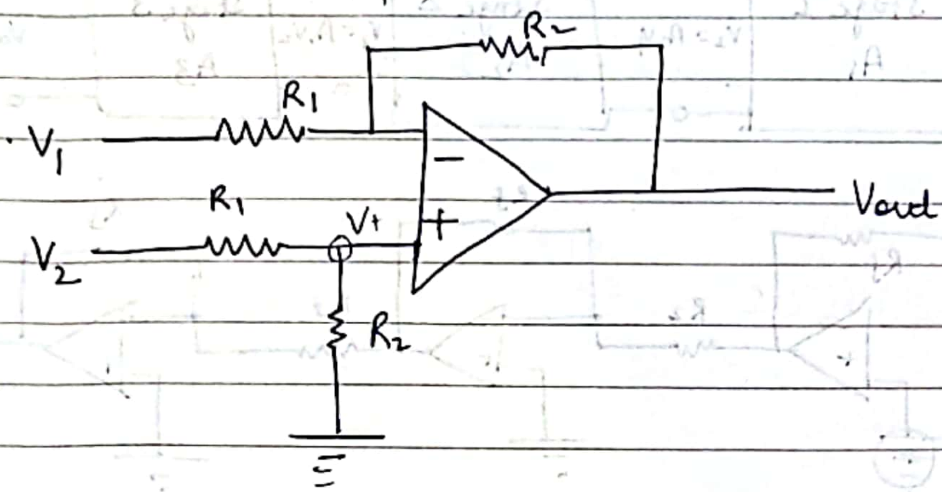
- When $V_1 = 0$

$$V_{o_2} = \left(1 + \frac{R_2}{R_1}\right)V_2$$

$$\therefore V_{out} = V_{o_1} + V_{o_2}$$
$$= -\frac{R_2}{R_1}V_1 + \left(1 + \frac{R_2}{R_1}\right)V_2$$

(Gain to both voltages is different here. So to get $K(V_2 - V_1)$ we have to convert

$1+\frac{R_2}{R_1}$ to $\frac{R_2}{R_1}$)



$$V^+ = \frac{R_2}{R_1+R_2} V_2$$

$$V_{out} = \left(1+\frac{R_2}{R_1}\right)V^+ - \left(\frac{R_2}{R_1}\right)V_1$$

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

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

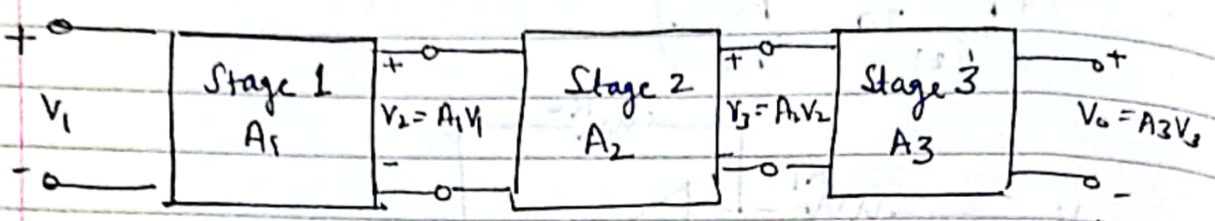
$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1)$$

If $R_2 = R_1 = R$

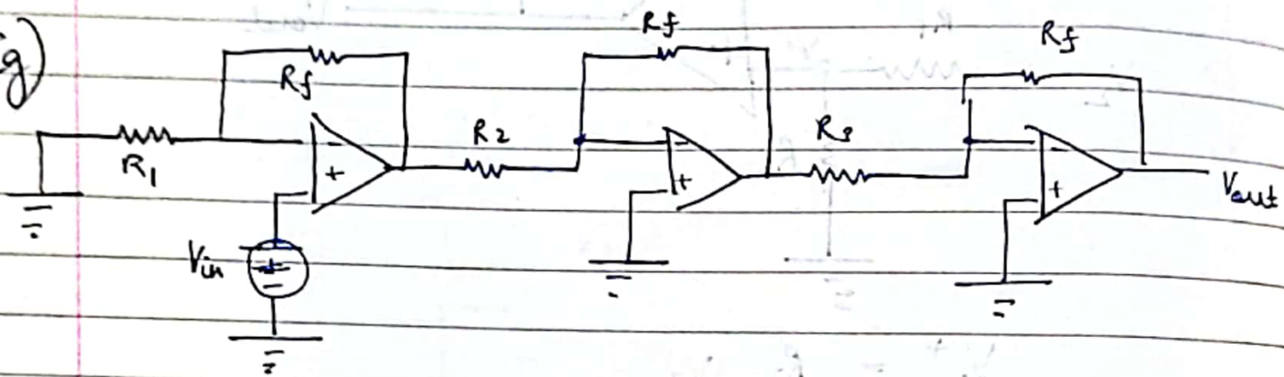
$$\boxed{V_0 = V_2 - V_1}$$

∴ when all resistances are same output voltage is the differnce of V_2 and V_1.

MULTISTAGE OP-AMP CIRCUITS



Eg)

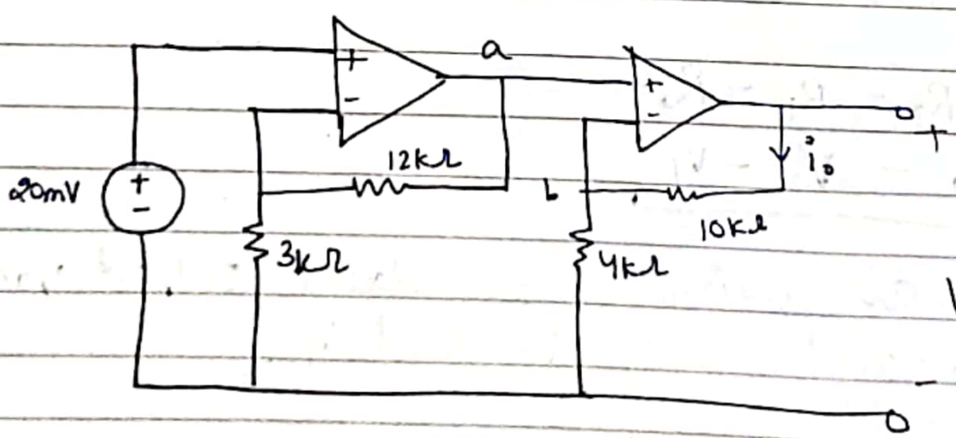


The Overall voltage gain A of this circuit is given by :

$$A = A_1 A_2 A_3$$

where A_1 = Voltage gain of 1^{st} ~~output~~ stage $= 1 + R_f / R_1$
A_2 = Voltage gain of 2^{nd} ~~output~~ stage $= -R_f / R_2$
A_3 = Voltage gain of 3^{rd} stage $= -R_f / R_3$

Q)



At the output of 1^{st} Op-amp →

$$V_o = \left(1 + \frac{12}{3}\right)(20) = 100\,mV$$

Output of 2^{nd} Op-amp →

POPU

Page No.:
Date: / /

$$V_o = \left(1+\frac{10}{4}\right)V_o = (1+2.5)100 = 350\,mV$$

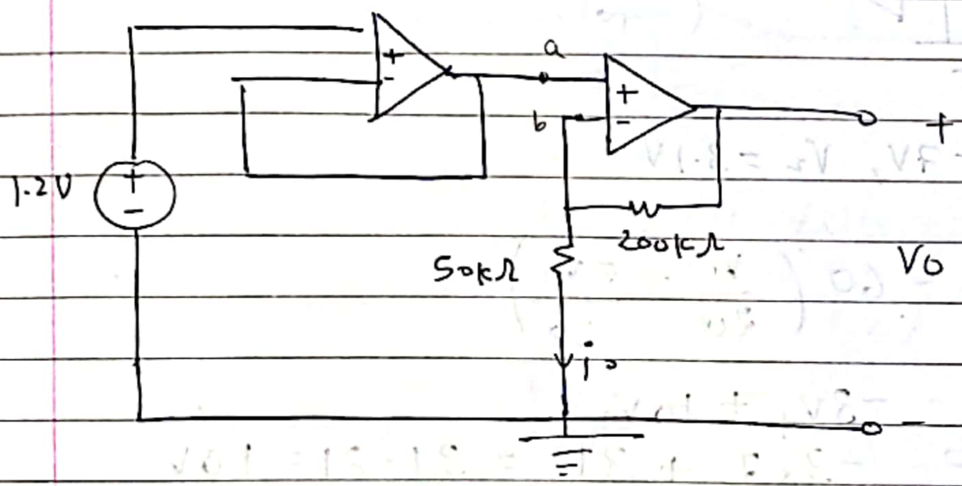
i_o is current through $10k\Omega$ resistor,

$$i_o = \frac{V_o - V_b}{10}\ mA$$

$$V_a = V_b = 100\,mV$$

$$i_o = \frac{(350-100)\times 10^{-3}}{10\times 10^{3}} = 25\,\mu A$$

Q.



Output of first Opamp ⇒ 1.2V

Output of 2nd: $V_o = \left(1 + \frac{200k\Omega}{50k\Omega}\right) 1.2$

$$= (1+4)\,1.2 = 6V$$

$$V_a = V_b = 1.2V$$

$$i_o = \frac{V_b - 0}{50k\Omega} = \frac{1.2}{50k\Omega} = 24\,\mu A$$

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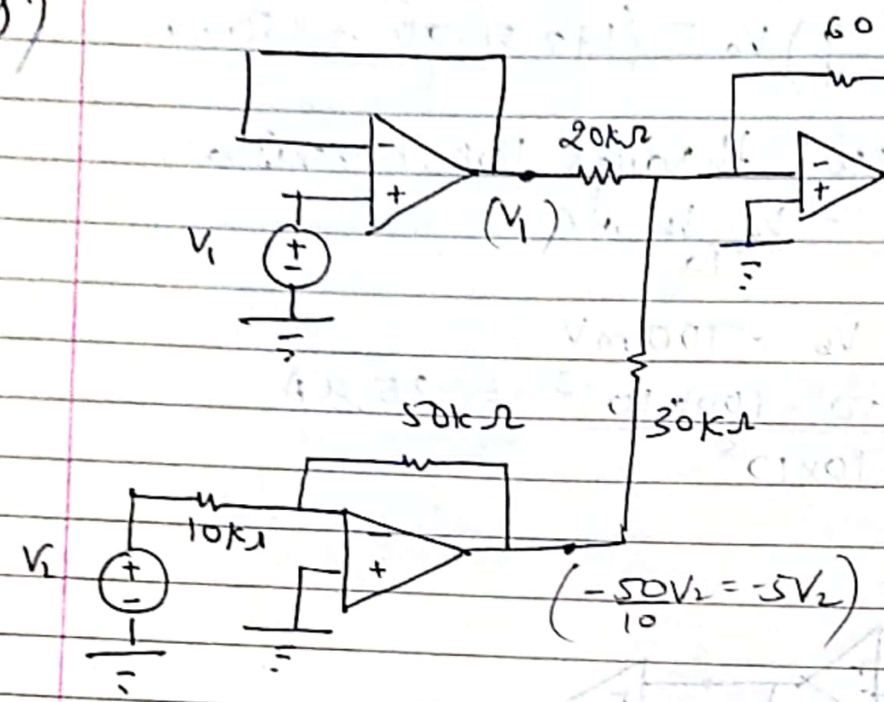


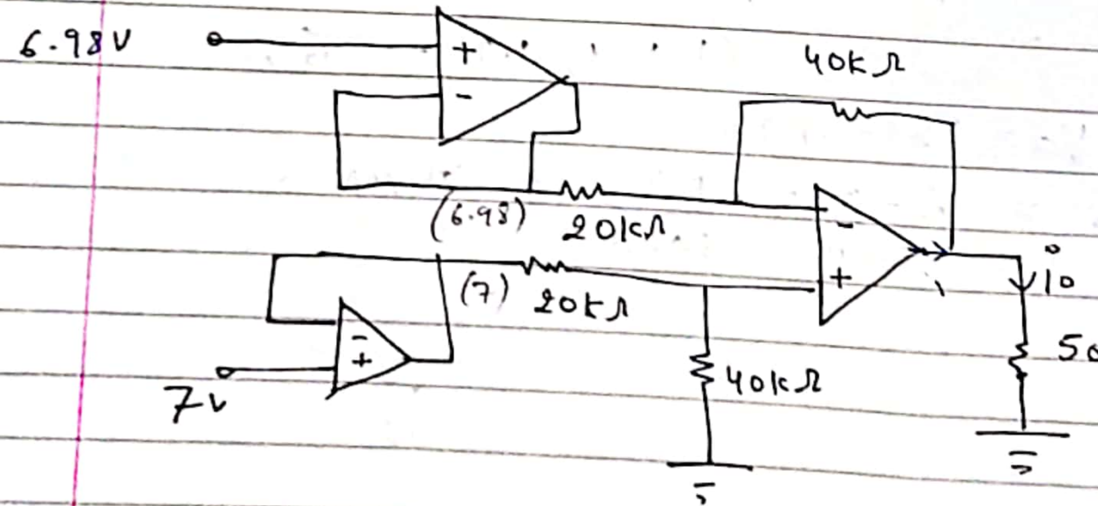
$V_1 = 7V, \; V_2 = 3.1V$

$$V_o = -60\left(\frac{V_1}{20} - \frac{5V_2}{30}\right)$$

$$= -3V_1 + 10V_2$$

$$= -3\times 7 + 31 = 31 - 21 = 10V$$

9)

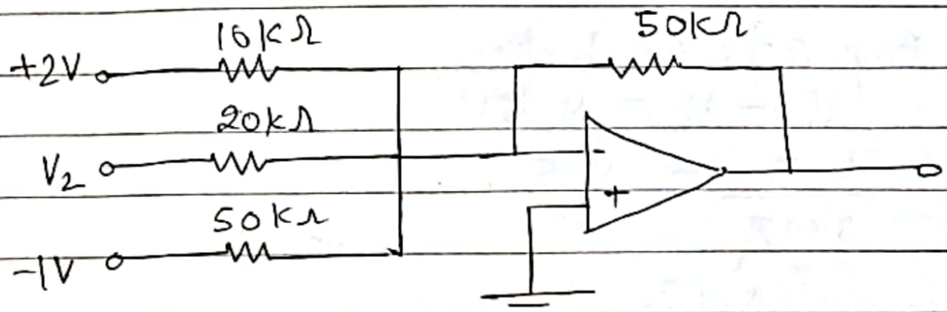


$$V_o = +\frac{R_2}{R_1}(V_2 - V_1) = +\frac{\cancel{40}^{2}}{\cancel{20}}(7 - 6.98)$$

$$V_o = +2 \times 0.02$$
$$= +0.04V$$

$$i_o = \frac{V_o - 0}{50k\Omega} = \frac{+0.04}{50k\Omega} =$$

Q. Determine V_2 to make $V_o = -16.5V$



This Op-amp acts as a summer,

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

$$-16.5 = -50k\left(\frac{2}{10k} + \frac{V_2}{20k} - \frac{1}{50k}\right)$$

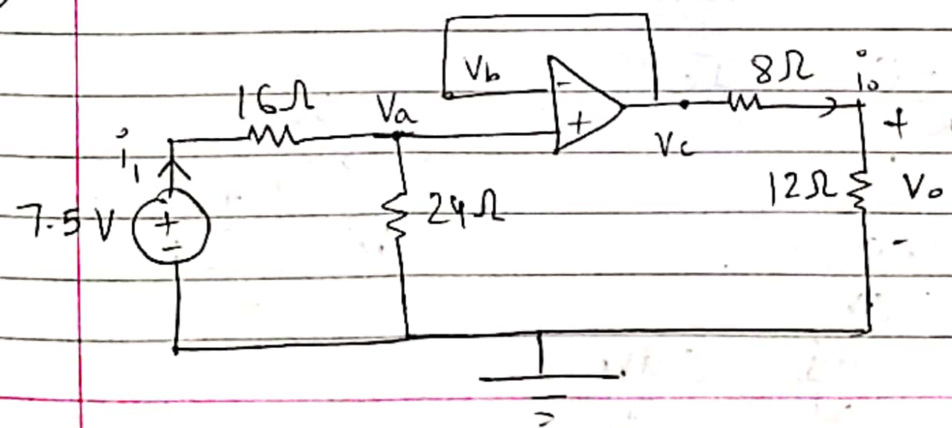
$$-16.5 = -5 \times 2 - 5/_2 \times V_2 + 1$$

$$-16.5 = -10 - 2.5V_2 + 1$$

$$-7.5 = -2.5\,V_2$$

$$\boxed{V_2 = 3 \text{ Volt}}$$

Q Determine V_o:



$$i_1 = \frac{7.5}{16+24} = \frac{7.5}{40}\ A$$

$$V_a = 7.5 - 16 \times i_1$$
$$= 7.5 - \cancel{16}^{4} \times \frac{7.5}{\cancel{40}_{10}}$$
$$= 7.5(1-0.4) = 7.5 \times 0.6 = 4.5V$$

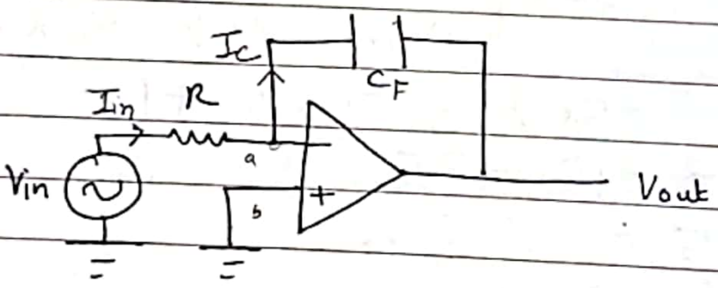
Op-Amp acts as buffer,

$$V_a = V_b = V_c = 4.5V$$

$$i_o = \frac{4.5}{8+12} = \frac{4.5}{20}\ A$$

$$V_o = i_o \times 12$$
$$= 12 \times \frac{4.5}{20} = 2.7V$$

Opamp As Integrator

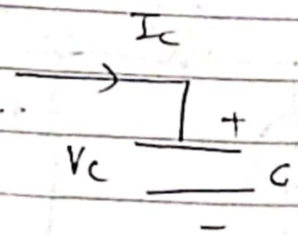


$$V_a = V_b = 0$$

Applying KCL,

$$I_{in} = I_c$$

$$\frac{V_{in} - 0}{R} = I_c$$



In Capacitor,

$$Q = CV$$

$$i_c = \frac{dq}{dt} = C\frac{dV_c}{dt}$$

$$\therefore \frac{V_{in}}{R} = C_F \frac{dV_c}{dt}$$

$$\frac{V_{in}}{R} = C_F \frac{d}{dt}\left[0 - V_{out}\right]$$

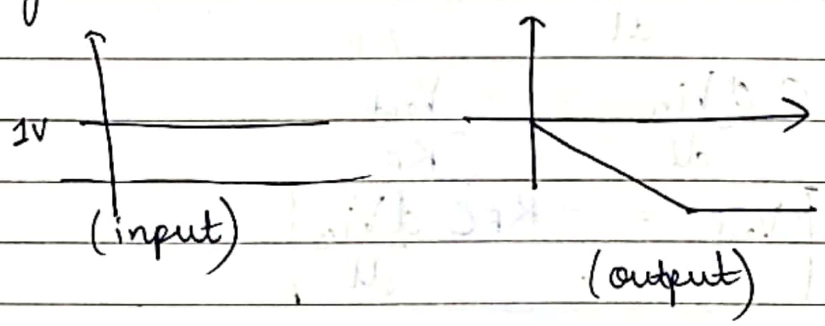
$$\frac{V_{in}}{R} = -C_F \frac{dV_o}{dt}$$

$$\frac{dV_{out}}{dt} = -\frac{V_{in}(t)}{RC_F}$$

$$\boxed{V_{out}(t) = -\frac{1}{RC_F}\int V_{in}(t)\,dt}$$

$RC_F \rightarrow$ integration time of integrator

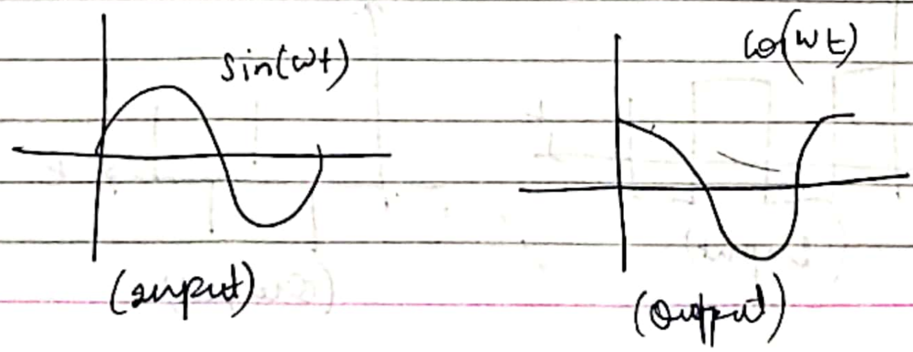
Eg :



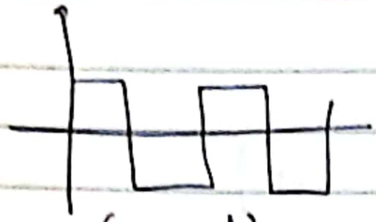
(After some time output voltage will saturate as it cannot go beyond saturation voltage)

→ The rate at which output voltage reaches the saturation voltage depends on R & CF. By changing their values, we can change slope of output signal.

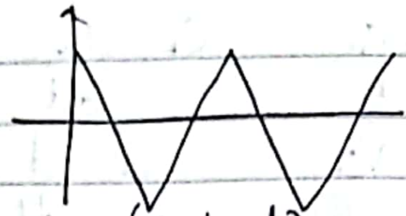
Eg :



Eg:

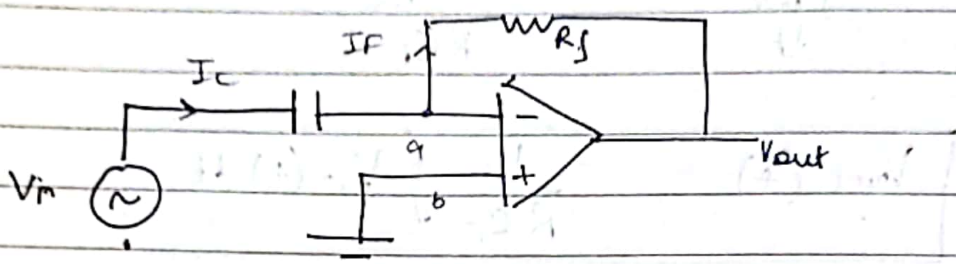


(input)



(Output)

Opamp as Differentiator



$V_a = V_b = 0$

Applying KCL,

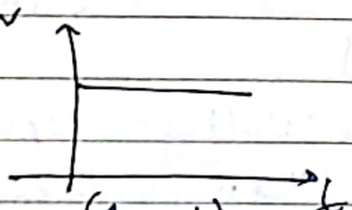
$$I_c = I_F$$

$$C\frac{dV_c}{dt} = \frac{0 - V_{out}}{R_F} \quad (V_c = V_{in})$$

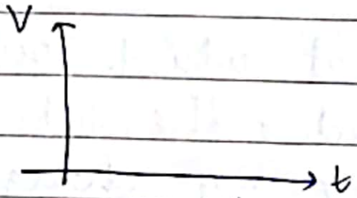
$$C\frac{dV_{in}}{dt} = \frac{-V_{out}}{R_F}$$

$$\boxed{V_{out} = -R_F C \frac{dV_{in}}{dt}}$$

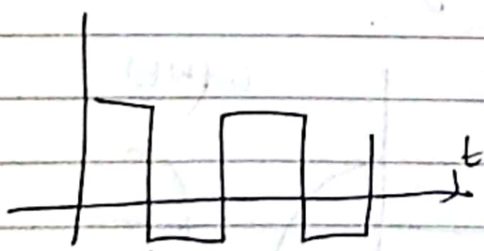
Eg:



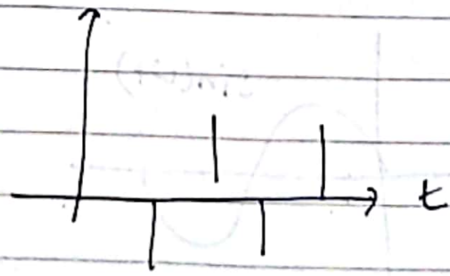
(Input)



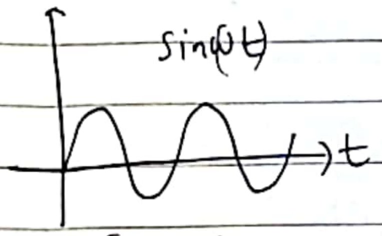
(Output)



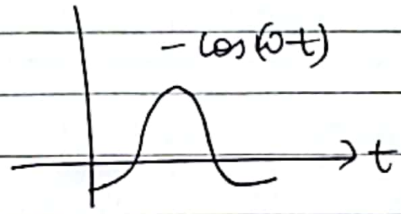
(Input)



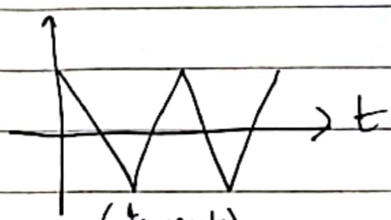
(Output)



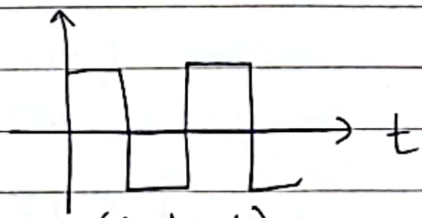
[Input]



(Output)



(Input)



(Output)