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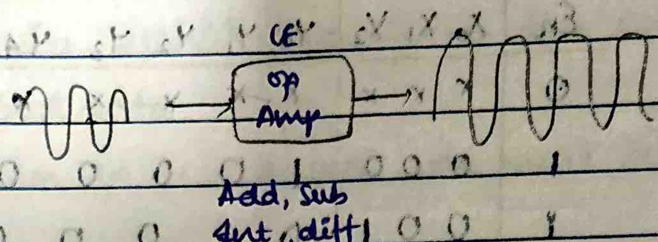
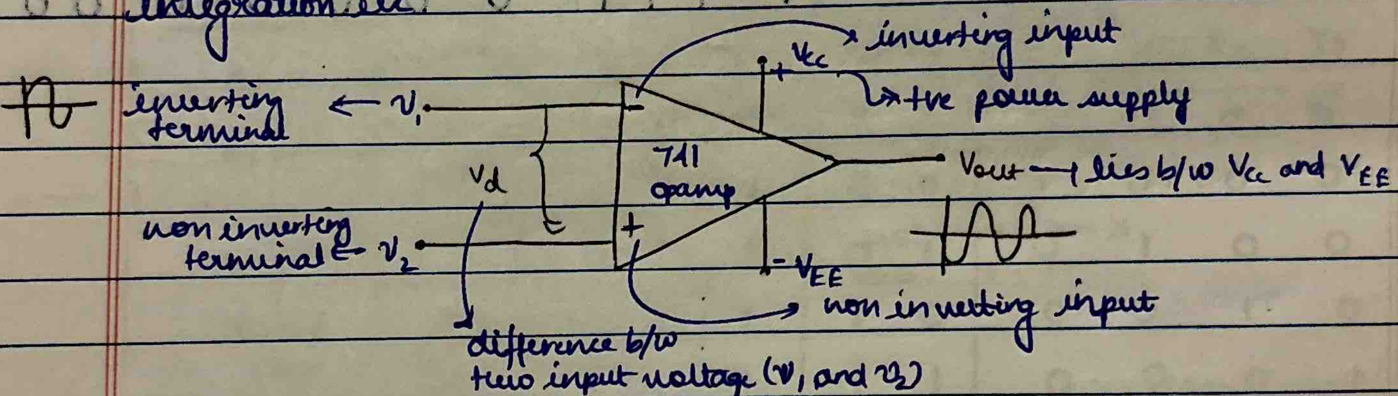
UNIT 3: OPERATIONAL AMPLIFIER



An operational amplifier is a multistage cascaded DC coupled amplifier with an extremely (very) high gain.

It's behaviour can be controlled by adding a suitable feedback (negative) → stabilisation, gain control etc

OPAmps are mainly used for performing mathematical operations such as addition, subtraction, differentiation, integration etc.



CASE 1: Supplying the input signal/voltage to v_1 ; v_2 → grounded

$$\boxed{v_{out} = \underbrace{A}_{10^5 - 10^6} v_{in}}$$

$$v_d = v_2 - v_1$$

$$v_{out} = A(\cancel{v_2}^{0} - v_1)$$

$$= A(-v_1) = -Av_1$$ → phase shift takes place

CASE 2: Give input to the 2nd terminal v_2 and find the output voltage
v_1 → grounded.

$$v_{out} = Av_{in}$$

$$v_d = v_2 - \cancel{v_1}$$

$$\boxed{v_{out} = A(v_2)}$$

PROPERTIES OF IDEAL OPAMP:

(1) Input impedance is infinite
(2) Output impedance is 0
(3) voltage gain is infinity
(4) Bandwidth → ∞.
(5) when equal voltages are applied to both the inputs of opamp, then the output voltage is 0.
(6) Characteristics of an opamp do not change with temperature.
(7) CMRR = Common mode rejection ratio = ∞
(8) Slew rate = ∞
(9)

TYPICAL SPECIFICATIONS OF GENERAL PURPOSE OPAMP

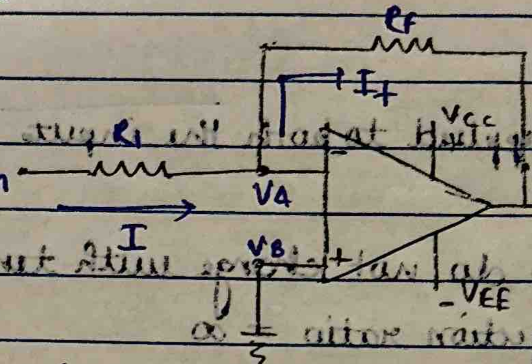
PARAMETER	SYMBOL	IDEAL VALUE	TYPICAL VALUE
(1) voltage gain	A	∞	2×10^5
(2) output impedance	Z_o	0	75Ω
(3) input impedance	Z_i	∞	2MΩ
(4) CMRR		∞	90dB
(5) Slew rate	S_r	∞	0.5V/μs
(6) Bandwidth	BW	∞	1MHz
(7) PSRR (Power supply rejection ratio)	PSRR	0	30 V/V

APPLICATION OF OPAMP:

(1) Inverting operational amplifier
(2) Non inverting operational amplifier
(3) Summing amplifier (summer)
(4) Voltage follower
(5) Integrator
(6) Differentiator
(7) Instrumentation amplifier

(8) Schmidt trigger

(1) Inverting opamp



(eg) $A = 10^5$; $v_{out} = 10V$

$$v_{out} = A v_{in}$$

$$v_{in} = \frac{10}{10^5} = 10^{-4} = 100\mu V$$

$$v_{in} = v_2 - v_1 = 100\mu V$$ → very small value cannot be measured so taken as 0

$$v_2 - v_1 = 0$$

$$\boxed{v_2 = v_1} \Rightarrow \boxed{v^+ = v^-}$$ → virtual ground

Since input impedance $= \infty$ → no current flows through the opamp
so whatever current will flow, will flow through R_f
due to virtual ground ⇒ $v_B = v_A$

$$I = I_f$$ ↗ since current flows through R_f only

$$KVL \Rightarrow \frac{V_{in} - \cancel{V_A}^{0}}{R_1} = \frac{\cancel{V_A}^{0} - V_{out}}{R_f}$$

$$A_v \Rightarrow \frac{v_{out}}{v_{in}} = -\frac{R_f}{R_1}$$ → 180° phase shift

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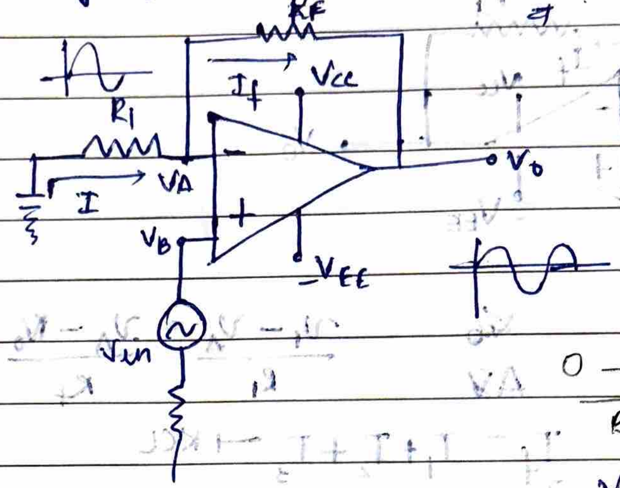
Non inverting operational amplifier → Vin → positive terminal



$$\frac{0 - V_A}{R_1} =$$

$$\frac{V_{in} - V_B}{R_F}$$

Virtual short : $V_A = V_B$

$V_B = V_{in}$ — ①

From KCL, (part A)

$I = I_f$

Applying KVL:

$$\frac{V_A - 0}{R_1} = I, \quad \frac{V_0 - V_A}{R_f} = I_f$$

$$\frac{V_A}{R_1} = \frac{V_0 - V_A}{R_f}$$

$V_A = V_{in}$

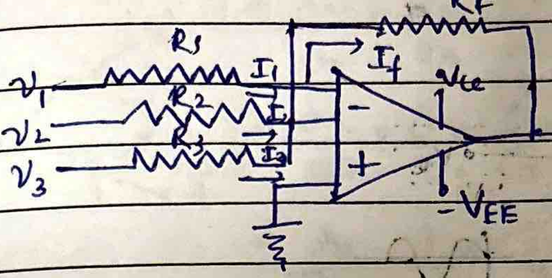
$$\frac{V_{in}}{R_1} = \frac{V_0 - V_{in}}{R_f}$$

$$\frac{R_F}{R_1} = \frac{V_0}{V_{in}} - \frac{\cancel{V_{in}}}{\cancel{V_{in}}}$$

$$\frac{R_F}{R_1} = \frac{V_0}{V_{in}} - 1$$

$$A_V = \frac{V_0}{V_{in}} = \frac{R_F}{R_1} + 1$$

Summing amplifier / summer: $\rightarrow$ inverted summing amplifier



$$\frac{v_1 - v_A}{R_1} = \frac{v_A - V_0}{R_f}$$

$I_f = I_1 + I_2 + I_3 \rightarrow$ KCL

$$\Rightarrow \frac{v_A - v_0}{R_F} = \frac{v_1 - v_A}{R_1} + \frac{v_2 - v_A}{R_2} + \frac{v_3 - v_A}{R_3} \rightarrow \text{KVL}$$

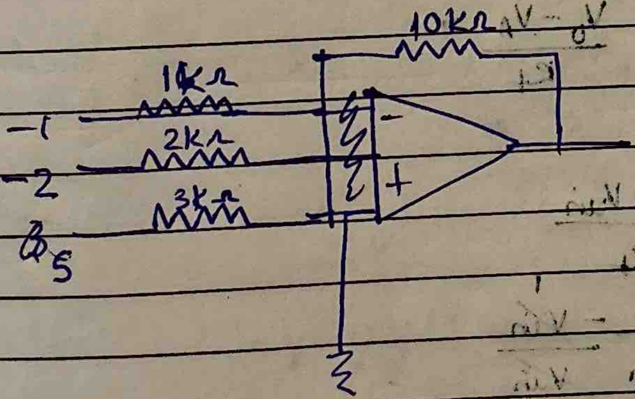
$$\Rightarrow -\frac{v_0}{R_F} = \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}$$

$$v_0 = -R_F\left[\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}\right]$$

Assume, $R_1 = R_2 = R_3 = 1k\Omega$

$$V_0 = -R_f\,[v_1 + v_2 + v_3]$$

(Q)



$$V_0 = -10\times10^3\left[\frac{-1}{1\times10^3} - \frac{2}{2\times10^3} + \frac{5}{3\times10^3}\right]$$

$V_0 = 10/3\ V.$

(Q)

$$v_0 = -25\times10^3\left[\frac{1}{1\times10^3} - \frac{2}{2\times10^3} + \frac{3}{3\times10^3}\right] = -25\times10^3\left[\frac{6 -}{6\times10^3}\right]$$

$$\frac{-25\times10^3}{10^3}$$

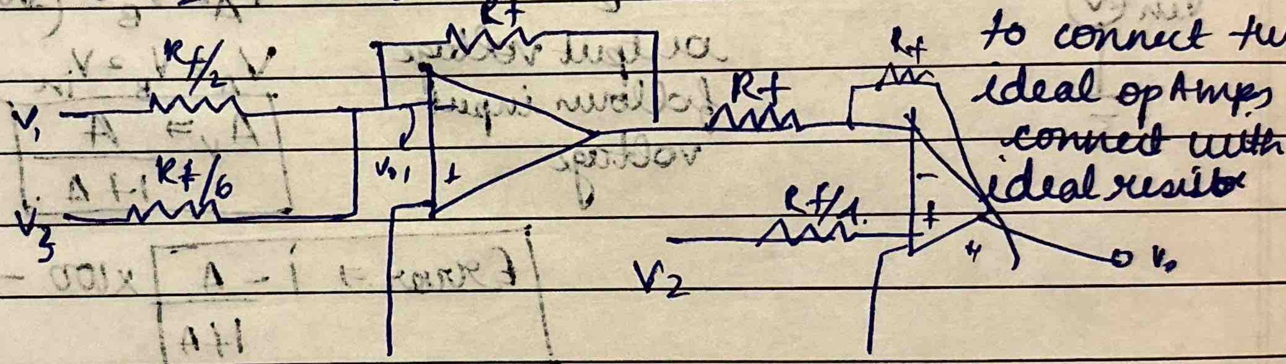
$$v_0 = -15\times10^3\left[\frac{-25}{20\times10^3} + \frac{30}{2\times10^3}\right]$$

$$= -15\times10^3\left[\frac{-25+30}{20\times10^3}\right] = \frac{-15\times5}{20} =$$

(Q) A summer circuit using two ideal opAmps and calculate the different resistor values to obtain $V_0 = 2V_1 - 4V_2 + 6V_3$; V_1, V_2, V_3 → +ve input voltages.

(A)
$$V_0 = -\left[\frac{R_f}{R_1}\cdot V_1 + \frac{R_f}{R_2}\cdot V_2 + \frac{R_f}{R_3}\cdot V_3\right]$$

$\frac{R_f}{R_1} = 2$; $\frac{R_f}{R_2} = 4$; $\frac{R_f}{R_3} = 6$ → resistance ratio cannot be negative



to connect two ideal opAmps connect with ideal resistor

$V_{01} = -2V_1 - 6V_3$

$V_0 = -4V_2 + 2V_1 + 6V_3$

Assumption: Assume $R_f = 10K\Omega$

$R_1 = 5K\Omega$; $R_2 = 2.5K\Omega$; $R_3 = 1.66K\Omega$

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(b) $V_0 = V_1 + 3V_2 + 5V_3 - 7V_4 - 9V_5 - 11V_6$.

$$V_0 = -\left[\frac{R_f}{R_1}\cdot V_1 + \frac{R_f}{R_2}\cdot V_2 + \frac{R_f}{R_3}\cdot V_3 + \frac{R_f}{R_4}V_4 + \frac{R_f}{R_5}\cdot V_5 + \frac{R_f}{R_6}\cdot V_6\right]$$

$$\Rightarrow \frac{R_f}{R_1} = 1;\ \frac{R_f}{R_2} = 3;\ \frac{R_f}{R_3} = 5;\ \frac{R_f}{R_4} = 7;\ \frac{R_f}{R_5} = 9;\ \frac{R_f}{R_6} = 11$$

$V_{01} = -V_1 - 3V_2 - 5V_3$.

$V_0 = V_1 + 3V_2 + 5V_3 - 7V_4 - 9V_5 - 11V_6$.

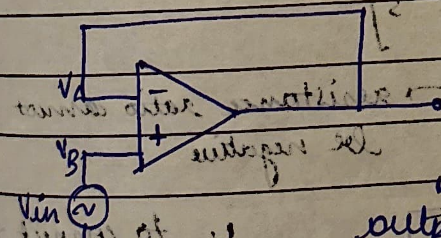
Assume, $R_f = 10k\Omega$

$R_1 = \frac{R_f}{V_1} = \frac{10}{1} = 10k\Omega$ $\quad R_3 = 10/5 = 2k\Omega$

$R_2 = 10/3 = 3.33k\Omega$ $\quad R_4 = 10/7 = 1.4k\Omega$

$R_5 = 10/9 = 1.1k\Omega$ $\quad R_6 = 10/11 = 0.909\,k\Omega$

Voltage follower



$\beta = 1$ — 100% negative feedback

$A_f = \frac{A_v}{1 + A_v\beta} = \frac{A_v}{1 + A_v} \approx 1$ [3]

$V_A = V_B =$ (virtual short)

output voltage follows input voltage

$V_A = V_B = V_{in}$

$$\boxed{A_v = \frac{A}{1+A}}$$

$$\boxed{\text{Error} = 1 - \frac{A}{1+A}} \times 100 \rightarrow \text{for percentage value}$$

(Q) determine the gain of the voltage follower if the $A_v = 1000$, also calculate the error in the gain from that of the voltage follower with that of an ideal opAmp.

(A) $A_f = \frac{A}{1+A\beta} = \frac{A}{1+A} = \frac{1000}{1001}$

$1 - \frac{1000}{1001} = \frac{0001}{1001}$

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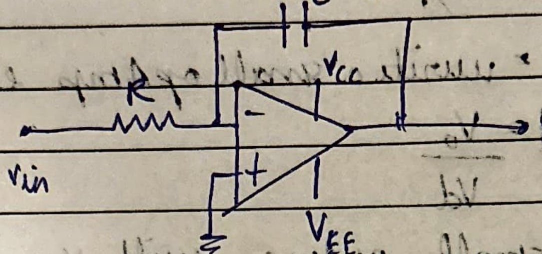
$I = C \cdot \frac{dV}{dt}$

Integrator (OpAmp as integrator):



$\Rightarrow V_A = V_B = 0$ → virtual ground

$I = I_f$

$\frac{V_{in} - \cancel{V_A}}{R} = C \cdot \frac{d(\cancel{V_A} - V_o)}{dt}$

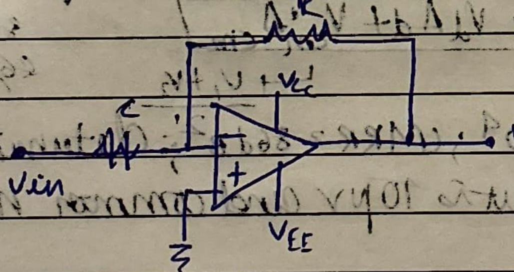
$\Rightarrow \frac{V_{in}}{R} = C \cdot \frac{d(-V_o)}{dt}$

$\frac{V_{in}}{CR} = \frac{d(V_o)}{dt}$

Apply $\int$ on bs;

$V_o = -\frac{1}{RC} \int V_o\,dt.$

Differentiator (OpAmp as differentiator)



$\Rightarrow V_A = V_B = 0$ → virtual ground

$I = I_f$

$\Rightarrow C \cdot \frac{d(V_{in} - V_A)}{dt} = \frac{V_A - V_o}{R}$

$= C \cdot \frac{d(V_{in})}{dt} = \frac{-V_o}{R}$

$\frac{d(V_{in})}{dt} = \frac{-V_o}{RC}$

$V_{in} = \int \frac{V_o \cdot dt}{RC}$

$$\boxed{V_o = -\frac{RC \cdot d(V_{in})}{dt}}$$

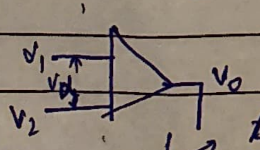
$\cancel{V_{in} = \frac{1}{RC}\int V_o}.$

CMRR (common mode rejection ratio)

It is the ratio of ~~common~~ differential gain to the common mode gain.

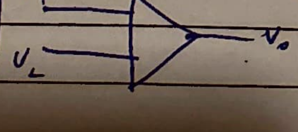
$CMRR = \frac{A_d}{A_{cm}}$ — differential gain of OpAmp giving unequal voltages

A_d



$A_d = 20\log(V_o/V_d)$

A_{cm}



Practical case

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

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$$\text{CMRR in dB} = 20 \log\left(\frac{A_d}{A_c}\right),$$

differential gain (A_d) = write a small opAmp with V_1 and V_2 a

and $V_d = V_2 - V_1$; $A_d = \frac{V_o}{V_d}$

(A_c) → write a small opAmp, with V_1 and V_2 and

$V_1 = V_2$; $V_o = 0$] → ideal condition

∴ gain will be 0 → CMRR → infinity.

∴ Practically, in order to find common mode gain, we generally take output voltage as average of input voltages and then find the CMRR

∴ The net output voltage of an opAmp due to differential and common mode gain

$$\boxed{V_o = V_d A_d + \underbrace{V_{cm}}_{\frac{V_1+V_2}{2}} A_{cm}}$$

$86 = 20 \log_{10}\left(\frac{A_d}{}\right)$

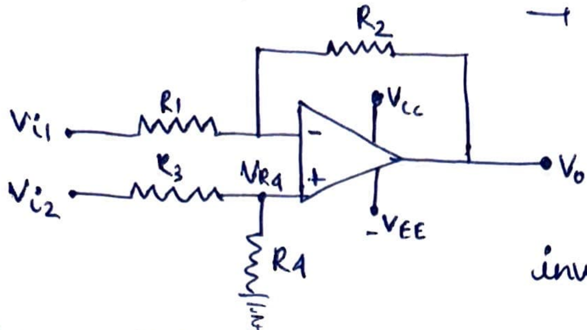
$86/20$ 10

(Q) An opAmp has $A_d = 2 \times 10^4$; CMRR = 86 dB ; determine the output if the differential input is 10 μV and common mode input = 10 mV.

(A) $\cancel{86} = \cancel{10 \times 10^{-56}}$ $\quad \text{CMRR} = \frac{A_d}{A_c}$ $\quad (A_d)\,\text{dB}^2$

Ans = 0.021 V

Operational Amplifiers
Communication systems



Difference Amplifiers

→ it amplifies the difference between the two input voltages. The circuit shown is a combination of both inverting and non inverting amplifiers

Resistors R_1, R_2 and opamp, constitute the inverting amplifier for the input voltage V_{i1}.

It is seen that, the drop across the resistance $R_4 (V_{R4}) \Rightarrow \frac{V_{i2} \times R_4}{R_3 + R_4}$ → using voltage divider rule

CASE 1:

When $V_{i2} = 0$

$$V_{o1} = (\text{Gain})_{\substack{\text{inverting} \\ \text{amplifier}}} \times V_{i1}$$

$$= -R_2/R_1 \cdot V_{i1} \quad \text{—— (1)}$$

CASE 2:

When $V_{i1} = 0$

$$V_{o2} = (\text{Gain})_{\substack{\text{non inverting} \\ \text{amplifier}}} \times V_{R4}$$

$$= \left(1 + R_2/R_1\right) \times V_{R4} = \left(1 + R_2/R_1\right) \times \frac{V_{i2} \times R_4}{R_3 + R_4} \quad \text{—— (2)}$$

Assume $R_3 = R_1$ and $R_2 = R_4$

$$V_{o2} = R_2/R_1 \times V_{i2} \quad \text{—— (3)}$$

The net output voltage is $\boxed{V_o = V_{o1} + V_{o2}}$

$$V_o = -R_2/R_1 \cdot V_{i1} + R_2/R_1 \cdot V_{i2}$$

$$V_o = R_2/R_1 \left[V_{i2} - V_{i1}\right]$$

Condition considering common mode voltages.

$V_{i1} = V_{i2} = V$
$V_o = 0$
→ ideal condition

Substituting this condition in eq (2), we get

$$V_{o2} = \left(1 + R_2/R_1\right) \times \frac{V_{R4}}{R_3 + R_4} ; \quad V_{o1} = -R_2/R_1 \cdot V$$

$$V_o = \underbrace{-R_2/R_1 \cdot V}_{\text{inverting}} + \underbrace{\left[\left(1 + R_2/R_1\right)\left(\frac{R_4}{R_3 + R_4}\right)\right]}_{\text{noninverting}} \cdot V$$

$0 \Rightarrow -\frac{R_2}{R_1}V + \left(1+\frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3+R_4}\right)\cdot V$

$\Rightarrow \frac{R_2}{\cancel{R_1}} = \left(\frac{R_1+R_2}{\cancel{R_1}}\right)\left(\frac{R_4}{R_3+R_4}\right)$

$\Rightarrow R_2 = \frac{(R_1+R_2)(R_4)}{R_3+R_4}$

$\Rightarrow \frac{R_2}{R_1+R_2} = \frac{R_4}{R_3+R_4}$

$\Rightarrow \cancel{1}+\frac{R_2}{R_1} = \cancel{1}+\frac{R_4}{R_3}$

$\Rightarrow \boxed{R_2/R_1 = R_4/R_3}$

(Q) Find the output voltage for the given difference amplifier

$V_{i1}=6V;\ V_{i2}=6V;\ R_1=5K;\ R_2=5K;\ R_3=2K;\ R_4=4K;$

(A) $V_o = R_2/R_1\,[V_{i2}-V_{i1}]$

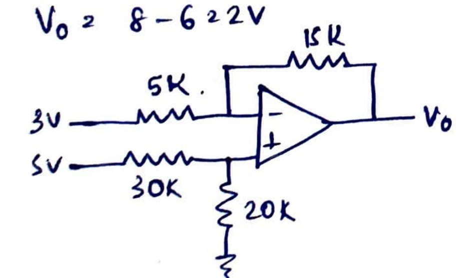
$\Rightarrow 5K/5K\,[6-6]=0.$

$V_{o1} = -\cancel{5}/\cancel{5}\times 6 = -6V$

$V_{o2} = (1+1) = 8V.$

$V_o = 8-6=2V$

(Q)



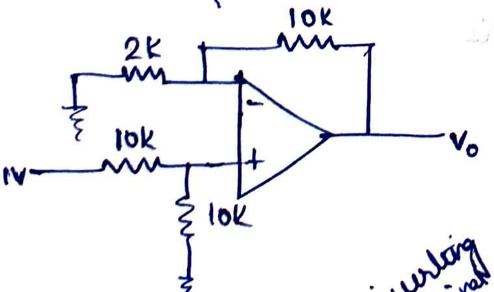
$V_{o1} = -\cancel{15}^{3}/\cancel{5}\times 3 = -9V$

$V_{o2} = \cancel{15}^{3}/\cancel{5}\times 5 = 15V$

$V_o = V_{o2}+V_{o1}$

$= 15-9 = 6V.$

(Q)

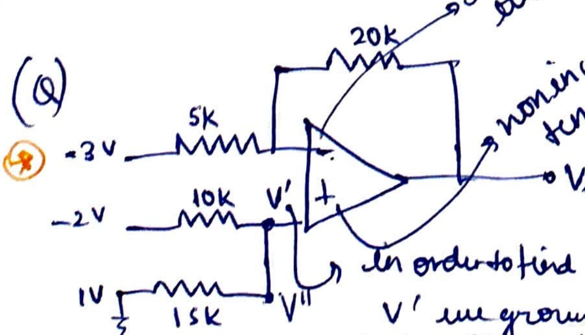


$V_{o1} = 10/2\,[0] = 0$

$V_{o2} = 10/2\,(1) = 5V$

$V_o = V_{o1}+V_{o2} = 5V$

(Q)



inverting terminal

non inverting terminal

In order to find V' we ground the rest of the resistances

$V_{o1} = -\cancel{20}^{4}/\cancel{5}\,[-3] = +12V$

$V_{o2} = \left(1+\cancel{20}^{4}/\cancel{5}\right)\left(\frac{-2\times 15K}{10K+15K}\right)$

$\Rightarrow (5)\left(\frac{-30K}{25K}\right)$ $V' = -6K$

$$V'' = \left(\frac{1 \times 10k}{10k + 15k}\right)$$

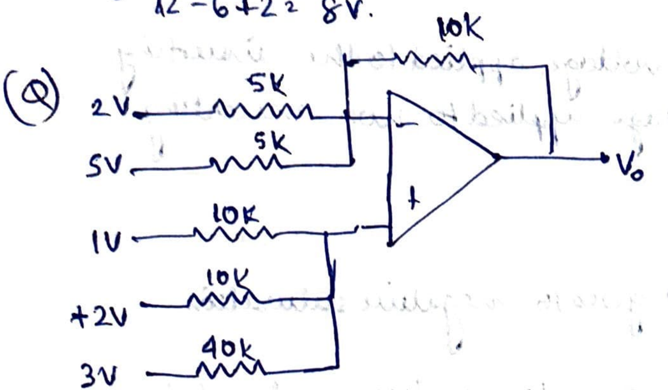
$$V_{O3} = \left(1 + 20/5\right) \times V''$$

$$= \left(1 + 20/5\right) \cdot \left(\frac{10k}{10k + 15k}\right) = 5 \times \frac{10k}{25k} = 2V$$

$$V_O = V_{O1} + V_{O2} + V_{O3}$$

$$= 12 - 6 + 2 = 8V.$$

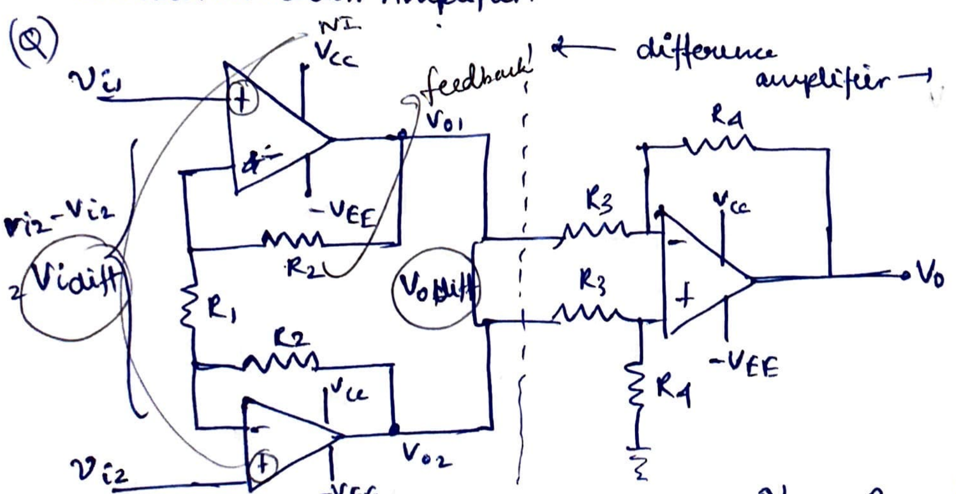
(Q)



Step 1 : Apply summer.

Instrumentation Amplifier.

(Q)



← ~~Instrument~~ ter connected NI Amplifier →

difference amplifier → low input impedance

$$V_{O1} = \left(1 + R_2/R_1\right) \cdot v_{i1} \quad \text{——} \; ①$$

$$V_{O2} = \left(1 + R_2/R_1\right) \cdot v_{i2} \quad \text{——} \; ②$$

$$V_{Odiff} = \left(1 + R_2/R_1\right)\left(v_{i2} - v_{i1}\right)$$

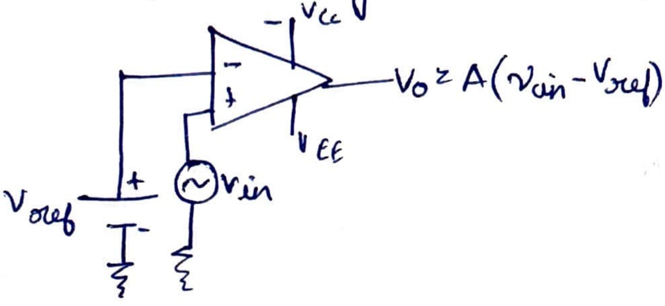
$$V_o = R_4/R_3 \left[V_{Odiff}\right]$$

$$\boxed{= R_4/R_3 \left[1 + R_2/R_1\right] \underbrace{\left(v_{i2} - v_{i1}\right)}_{V_{O2} - V_{O1}}}$$

$$A_V = \underbrace{R_4/R_3 \left[1 + R_2/R_1\right]}_{\text{gain}}$$

Comparator:

It compares the magnitude of two input voltages.



Here V_{ref} represents the constant reference voltage applied to the inverting terminal, (v_{in}) represents the variable voltage applied to non inverting terminal. $V_d = V_{in} - V_{ref}$

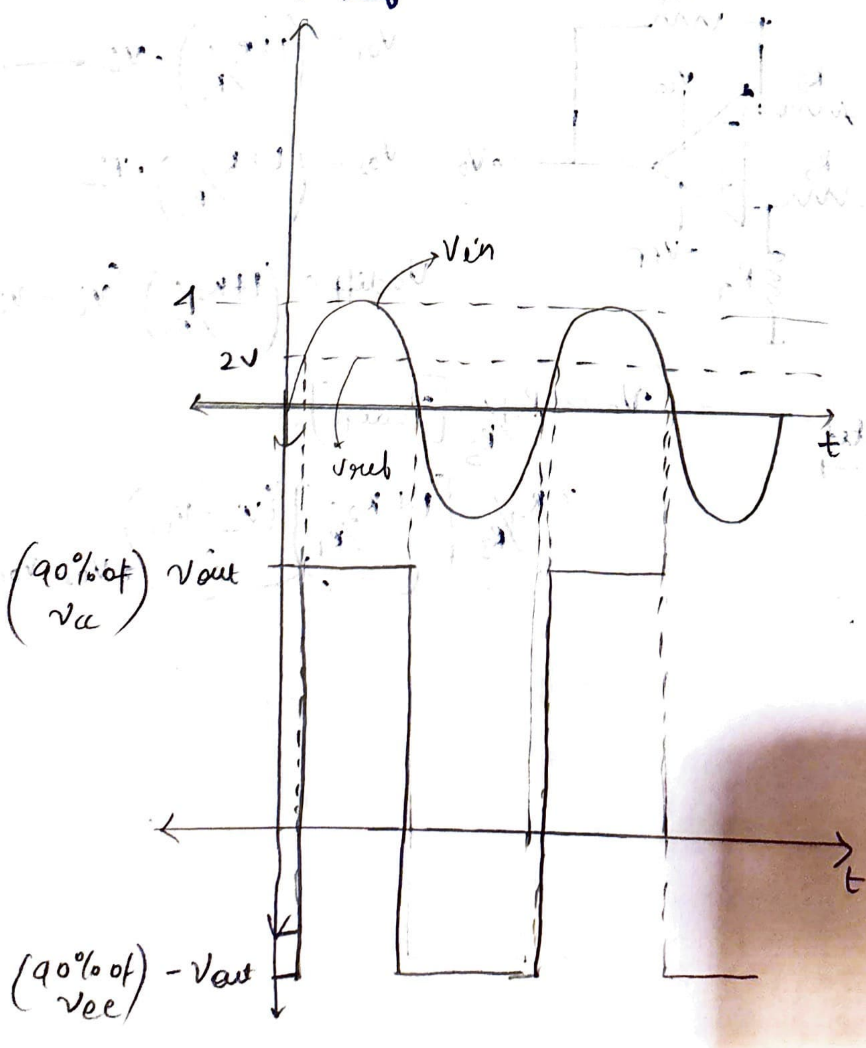
Condition for comparator:

(1) $v_i < V_{ref} \rightarrow$ the V_d is negative ; $v_o \rightarrow$ goes to negative saturation.

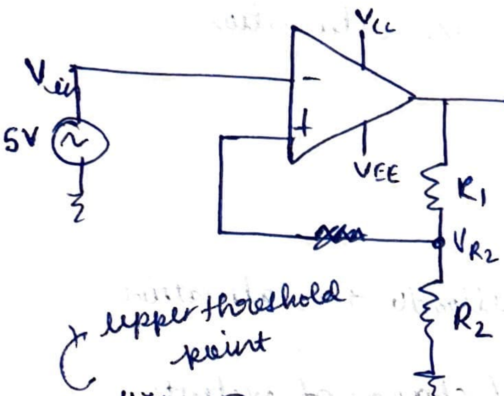
(2) $v_i > V_{ref} \rightarrow$ then v_d is positive ; $v_o \rightarrow$ goes to positive saturation

(3) $v_i = V_{ref} \rightarrow v_d = 0$. ; $v_o \rightarrow 0$.

(Q) $v_{in} = 4\sin\omega t$; $V_{ref} = 2V$

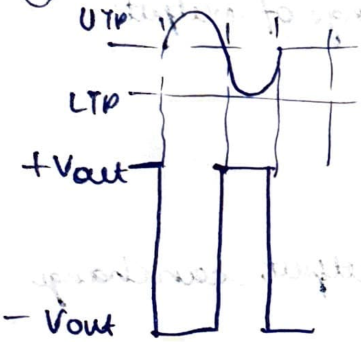


Schmidt trigger. ↗ no feedback → feedback was always given to negative, now given to positive



↗ upper threshold point

It is a fast operating voltage level detector.
Extension of comparator
When the input voltage arrives at a level determined by the circuit, the output voltage switches rapidly between maximum positive level and maximum negative level



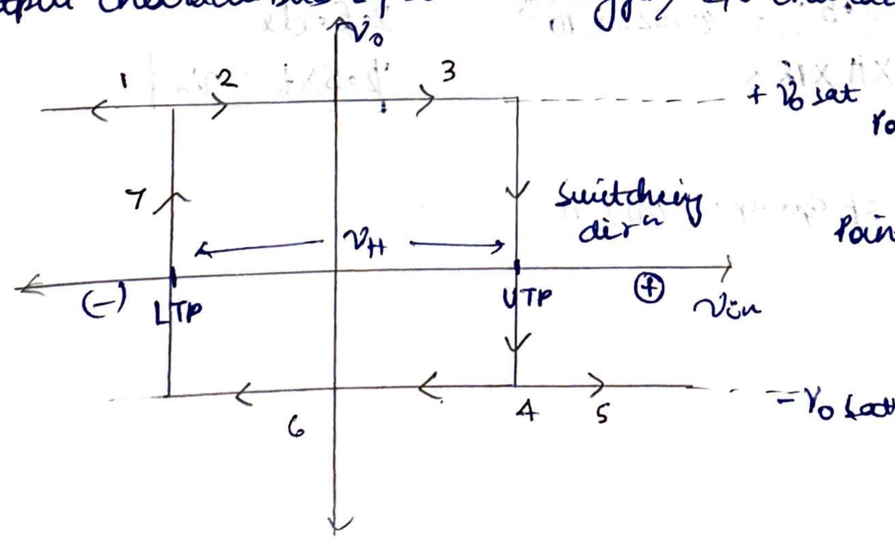
$$v_{R2} = \frac{V_o \cdot R_2}{R_1 + R_2}$$

The input voltage V_i is applied to inverting terminal of the opamp and the feedback goes to non inverting input.
The waveform shows that output switches rapidly from positive saturation to negative saturation only when input exceeds a certain positive ~~p~~ level. (upper trigger point)
The output voltage switches from low to high when the input goes below a negative trigger point (LTP).
The expression for UTP and LTP are:

$$v_{R_2} = UTP = \frac{V_o \cdot R_2}{R_1 + R_2} = \frac{V_{CC} \times R_2}{R_1 + R_2}$$

$$LTP = \frac{-V_o \times R_2}{R_1 + R_2} = \left(\frac{-V_{EE} \times R_2}{R_1 + R_2}\right)$$

Hysteris (V_H) = UTP − LTP
Input Output Characteristic of schmidt trigger / I/O charactristics / Transfer characteristics



Point ① → V_i < LTP, V_o → +ve saturation
Point ② → ① through ② and ③
V_i <> LTP, V_i = LTP,
V_o → +ve saturation

③ ③ → ④ → $v_{in} = UTP$; V_o → ~~-ve saturat~~ switches from +ve saturation to -ve saturation

④ $v_{in} > UTP$ → V_o → +ve saturation (Point ⑧)

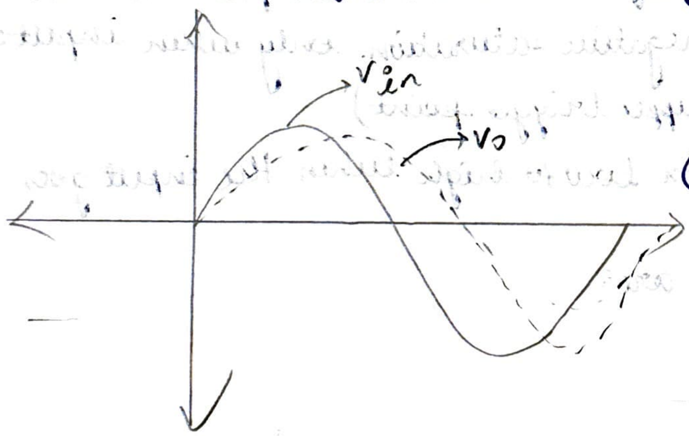
⑤ $v_{in} < UTP$; $v_{in} = UTP$ → V_o → -ve saturation

⑥ $v_{in} = LTP$; V_o → switches from -ve saturation to +ve saturation

Slew rate (SR) → defined as maximum rate of change of output voltage.

$$SR = \left.\frac{\partial V_o}{\partial t}\right|_{max} = V/\mu s.$$

Slew rate is a measure of how fast the opamp output can change in response to changes in the input signal.



$f_{max} = \frac{SR}{2\pi V_m}$ → peak amplitude

f_{max} = max^m frequency deviation w.r.t input voltage

(Q) The output signal of an opamp with a slew rate of 2.5 V/μs has a peak to peak value of 18V. Find the max^m frequency deviation w.r.t to the output voltage.

(A) $f_{max} = \frac{2.5}{2 \times \pi \times 18 \times 10} = 0.022 \times 10^6$

2.5·dt

$\boxed{2.5 \times t = V_o}$

Pin configuration of opamp. (741) IC.