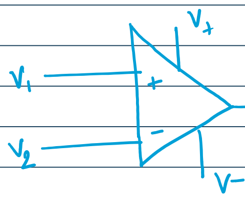
op amps yt

24 December 2024 09:09 AM

(A) → gain

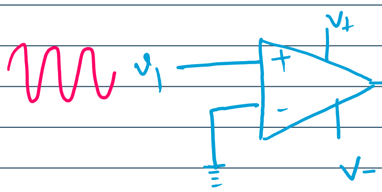
non-inverting input

inverting input



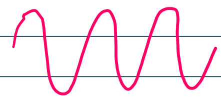
$V_{out} = A(V_1 - V_2)$

NI



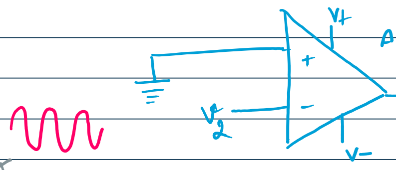
(A) → open loop gain

$V_{out} = \underline{A} V_1$



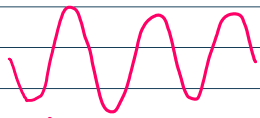
amplified 'A' times w/ same phase

I

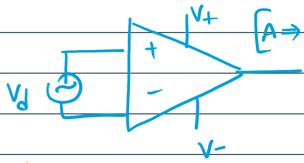


$V_{out} = -A V_2$

$0 - V_2$
$= -V_2$



o/p is inverted.



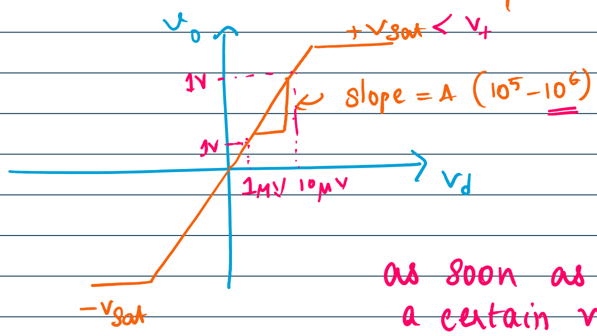
$[A \Rightarrow 10^5 - 10^6]$

$V_{out} = A V_d$

1mV

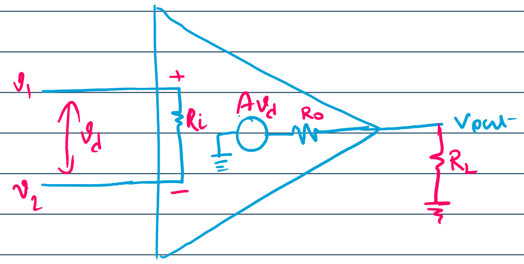
$= 1mV \times 10^5$
$= 100V$

{o/p voltage lies b/w the biasing voltages}



as soon as i/p voltage goes beyond a certain value, the o/p will be get saturated to the ⊕ saturation voltage.

Similarly, as soon as i/p voltages goes beyond some threshold value, at the o/p you will get ⊖ saturation voltage.



Ideally,

(MΩ) $R_i = \infty$

(Ω) $R_o = 0$

(10^5–10^6) $BW = \infty$ (should support all frequencies)

$A = \infty$

if $v_i = 0$, $v_o = 0$

→ Slew rate – how fast op amp is able reach its final value

$SR = \frac{dV_o}{dt}$ rate of change of o/p voltage per unit time.

Ideally, $SR = \infty$ [unit: V/μs]

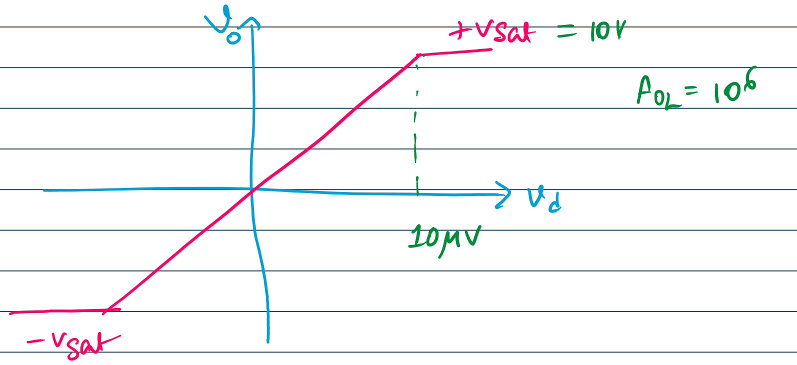
→ Common Mode Rejection Ratio: How well the op amp is able to reject the common i/p voltages that are being applied to both i/ps and how well it is able to amplify the diff. b/w the two voltages.

$CMRR = \frac{A_d}{A_c}$ Ratio of differential voltage gain to common mode voltage gain.

Ideally, $CMRR = \infty$

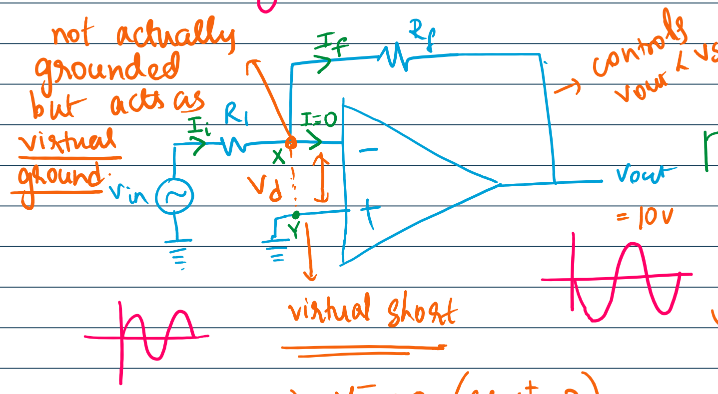
OP AMP 741

R_i	2 MΩ
R_o	75 Ω
A	10^5
Offset voltage	1 mV
SR	0.5 V/μs
CMRR	70–90 dB



$A_{OL} = 10^6$

C1: Inverting Op Amp



$A_{OL} = 10^6$, $V_{out} = 10V$

$\boxed{V_{out} = A V_d}$

$10 = 10^6 \, v_d$

$V_d = 10 \mu V$

$v_d = v^+ - v^- = 10\mu V$ → very less (neg.)

$\Rightarrow v^- = 0$ (as $v^+ = 0$) grounded

$v^+ - v^- \approx 0V$

$\Rightarrow v^+ = v^-$

$R_{in} = \infty \Rightarrow I = 0$

→ $I_i = I_f$

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

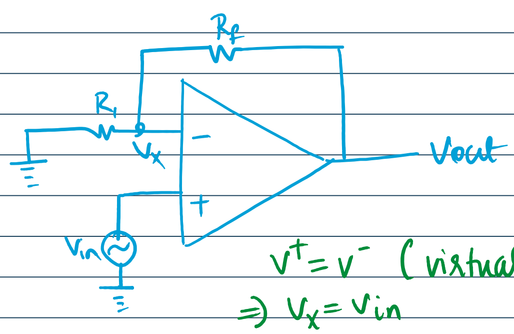
[$V_x = 0$ as Y is grounded] by virtual ground concept.

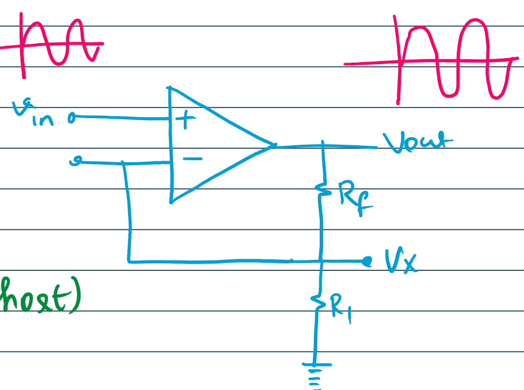
$$\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_f}$$

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

$$\boxed{A_{CL} = \frac{-R_f}{R_1}}$$

C2: Non-inverting Op Amp





$v^+ = v^-$ (virtual short)

$\Rightarrow V_x = V_{in}$

$$V_x = \frac{R_1}{R_1 + R_f} \times V_{out}$$

$$\left\{\begin{array}{l} A_{CL} = A_f \text{ (w/ feedback)} \\ A_{OL} = A \text{ (w/o feedback)} \end{array}\right\}$$

$$V_x = \frac{R_1}{R_1+R_f} \times V_{out}$$

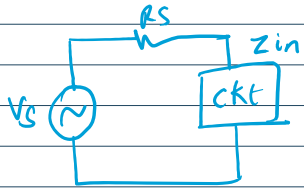
$$V_{in} = \frac{R_1}{R_1+R_f} \times V_{out}$$

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

$$\boxed{A_{CL} = 1 + \frac{R_f}{R_1}}$$

Avantages of NIOA over IOA.

NIOA	IOA
Same phase	180° phase shift.
$Z_{in} = \frac{V_{in}}{I_{in}}$, $I_{in} = 0$	$Z_{in} = \frac{V_{in}}{I_{in}}$, $I_{in} = \frac{V_{in}}{R_1}$
$\Rightarrow Z_{in} = \infty$.	$\Rightarrow Z_{in} = R_1$

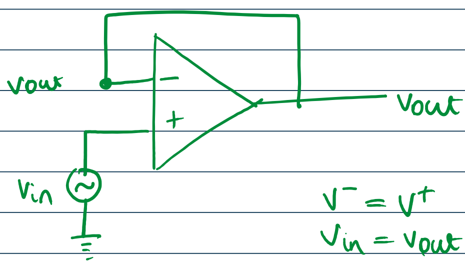


$Z_{in} = R_s$

$V = \frac{R_{in}}{R_{in}+R_s} \times V_S = \frac{V_S}{2}$.

$\Rightarrow Z_{in} \uparrow\uparrow\uparrow$.

Op Amp as a Buffer → Z_i of Buffer is very high !!



$R_f = 0$

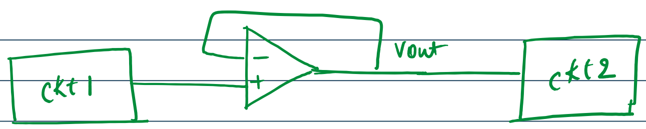
$R_1 = \infty$

$V^- = V^+$

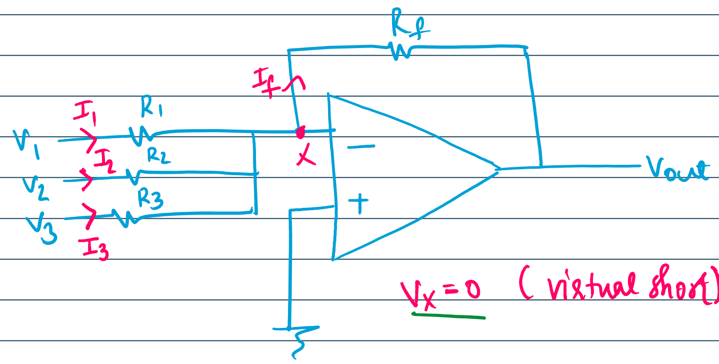
$V_{in} = V_{out}$ } virtual short.

Voltage follower circuit

→ can isolate 2 diff circuits.



Inverting Summing Amplifier:



$\underline{V_x = 0}$ (virtual short)

$$I_1 + I_2 + I_3 = I_f$$

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

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

$$\boxed{V_{out} = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}\right)}$$

→ if $R_1 = R_2 = R_3 = R$

$$v_{out} = -\frac{R_f}{R}(v_1 + v_2 + v_3)$$

if $R_f = R$,

$$v_{out} = -(V_1 + V_2 + V_3)$$

→ if $R_1 \neq R_2 \neq R_3$, $\frac{R_f}{R_1} \neq \frac{R_f}{R_2} \neq \frac{R_f}{R_3}$

$$V_{out} = -[Av_1 + Bv_2 + Cv_3]$$

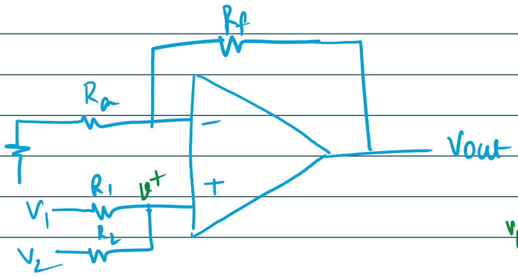
Can be used for → summing, scaling, Averaging

providing DC offset

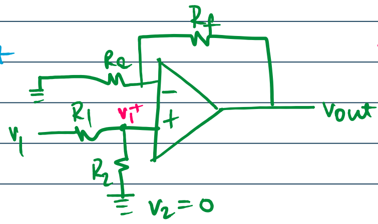
Digital to analog converter

Audio mixer.

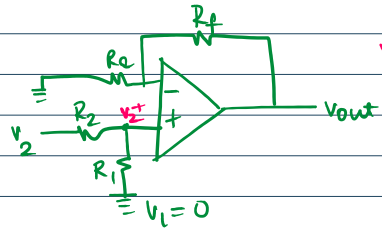
Non - Inverting Summing Amplifier



Superposition Theorem:



$$v_1^+ = \frac{R_2}{R_1+R_2} \times V_1$$



$$v_2^+ = \frac{R_1}{R_1+R_2} \times V_2$$

$$v^+ = v_1^+ + v_2^+$$

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

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

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

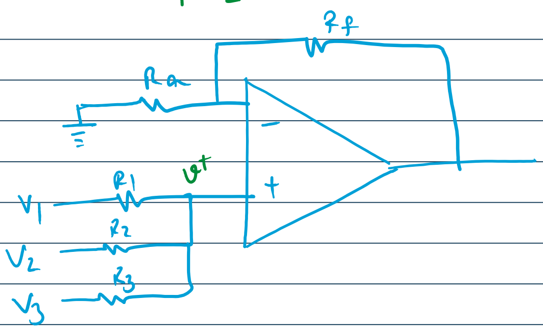
$$V_{out} = \left(1 + \frac{R_f}{R_a}\right)\left(\frac{R_2}{R_1+R_2} V_1 + \frac{R_1}{R_1+R_2} V_2\right)$$

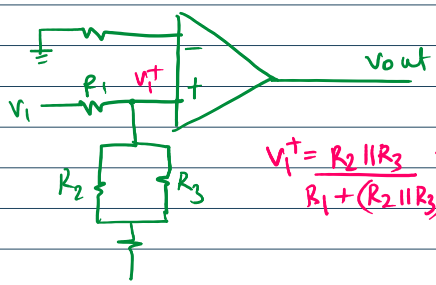
if $R_1 = R_2$,

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

if $R_f = R_a$

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





$$v_1^+ = \frac{R_2 \parallel R_3}{R_1 + (R_2 \parallel R_3)} \times V_1$$

$$v^+ = v_1^+ + v_2^+ + v_3^+$$

Similarly $v_2^+ = \frac{R_1 \parallel R_3}{R_2 + (R_1 \parallel R_3)} \times V_2$

$$v_3^+ = \frac{R_1 \parallel R_2}{R_3 + (R_1 \parallel R_2)} \times V_3$$

if $R_1 = R_2 = R_3$, $v_1^+ = \frac{V_1}{3}$, $v_2^+ = \frac{V_2}{3}$, $v_3^+ = \frac{V_3}{3}$

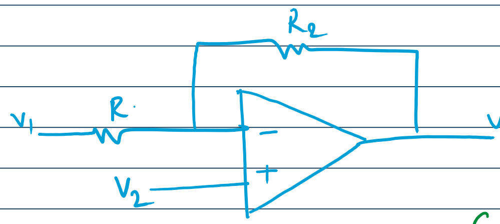
$$v^+ = \frac{V_1+V_2+V_3}{3}$$

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

if $1 + \frac{R_f}{R_a} = 3$, $V_{out} = \underline{\underline{V_1+V_2+V_3}}$

Differential Amplifier

Differential Amplifier



$V_{out} = k(V_2 - V_1)$

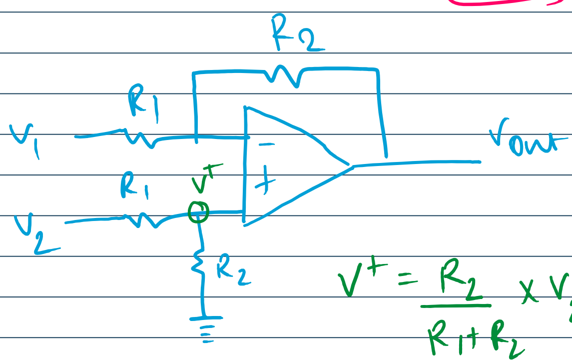
AHelp !!

$$\begin{cases} V_{o1} = \left(\frac{-R_2}{R_1}\right)V_1 & \text{if } V_1 \Rightarrow \sim,\ V_2 \Rightarrow GND \\ V_{o2} = \left(1 + \frac{R_2}{R_1}\right)V_2 & \text{if } V_1 \Rightarrow GND,\ V_2 \Rightarrow \sim \end{cases}$$

$$V_{out} = V_{o1} + V_{o2}$$
$$= \left(\frac{-R_2}{R_1}\right)V_1 + \left(1 + \frac{R_2}{R_1}\right)V_2$$

$\times \left(\frac{R_2}{R_1+R_2}\right)$

this gives $\frac{R_2}{R_1}$ as 'K'



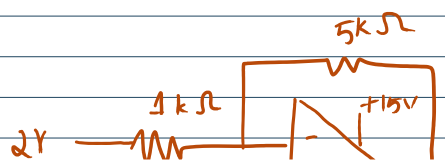
$$V^+ = \frac{R_2}{R_1+R_2} \times V_2$$

$$V_{o2} = \left(1 + \frac{R_2}{R_1}\right)V^+$$
$$= \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_2}{R_1+R_2}\right)V_2$$
$$= \frac{R_2}{R_1}V_2$$

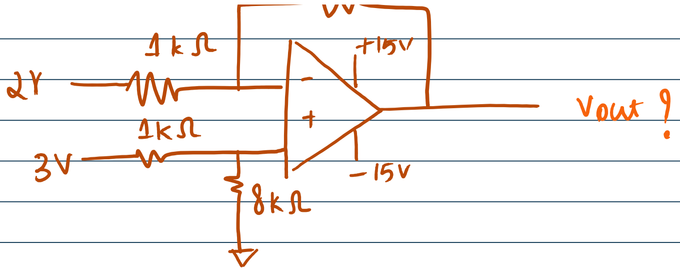
$$V_{out} = V_{o1} + V_{o2}$$
$$= \left(\frac{-R_2}{R_1}\right)V_1 + \left(\frac{R_2}{R_1}\right)V_2$$

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

eg



$V_1 = 2V$



$V_1 = 2V$
$V_2 = 3V$
$R_1 = 1k\Omega$
$R_2 = 5k\Omega$
$R_3 = 8k\Omega$

$$V_{out} = V_{01} + V_{02}$$
$$= \left(\frac{-R_2}{R_1}\right) V_1 + \left(1 + \frac{R_2}{R_1}\right) V^+$$

$$\left[V^+ = \frac{R_3}{R_1 + R_3} \times V_2 \right]$$

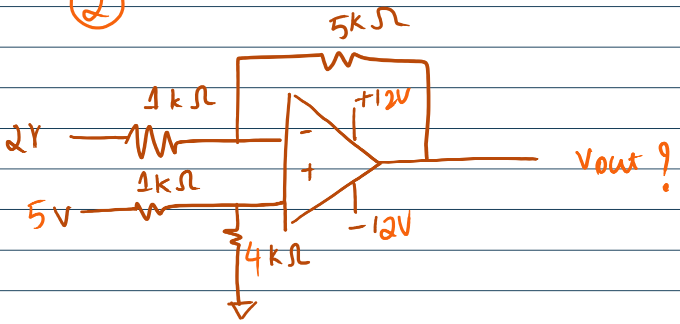
$$= \frac{-5k}{1k} \times 2 + \left(1 + \frac{5k}{1k}\right)\left(\frac{8k}{1k+8k} \times 3\right)$$

$$= -10 + 16$$

$$\underline{\underline{V_{out} = 6\,V}}$$

→ lies b/w $\underbrace{-15V \text{ to } +15V}_{\text{biasing voltages.}}$

(2)

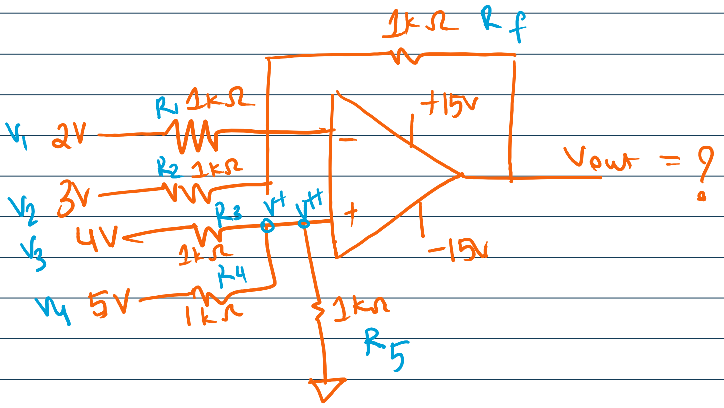


$V_{out} = 14V$ ✗

but +12 is max so

$V_{out} = 12V$

(3)



$$V_{01} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

$$= -\frac{1K}{1K}(2+3) \quad \{R_1 = R_2\}$$

$$V_{01} = -5V$$

let $R_3 = R_4 = R$

$$V_{02} = \left(1 + \frac{R_f}{R_{11}}\right) V^{++}$$

here, $R_3 \| R_4$

$$V_{02} = \left(1 + \frac{1k}{0.5k}\right) 3$$

$$V_{02} = 9V$$

$$V_{out} = V_{01} + V_{02}$$
$$= -5 + 9$$
$$V_{out} = 4V$$

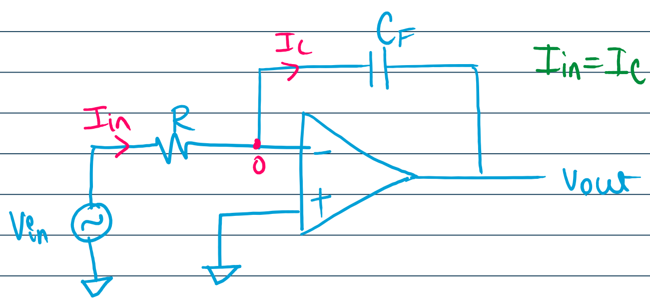
$$V^{++} = \frac{R_5}{R_5 + R_{11}} \times V^{+}$$

$$R_{11} = \frac{R \times R}{R + R} = \frac{R}{2}$$
$$R_{11} = 0.5k\Omega$$

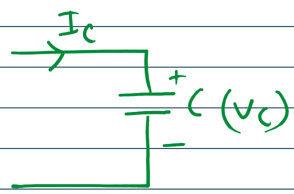
$$V^{+} = \frac{R_4 \times V_3}{R_3 + R_4} + \frac{R_3}{R_3 + R_4} \times V_4$$
$$= \frac{R}{R+R} \times V_3 + \frac{R}{R+R} V_4$$
$$= \frac{4}{2} + \frac{5}{2}$$
$$= 2 + 2.5$$
$$V^{+} = 4.5$$

$$V^{++} = \frac{1k}{1k + 0.5k} \times 4.5$$
$$= 3V$$

Op Amp Integrator



$I_{in} = I_C$.



$$Q = CV$$

$$I_C = \frac{dQ}{dt}$$

$$I_C = C \frac{dV_C}{dt}$$

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

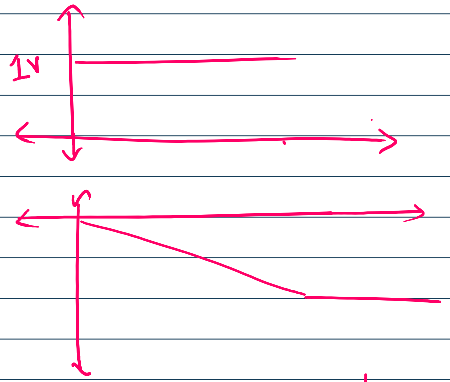
$$\frac{V_{in}}{R} = C_F \frac{dV_C}{dt} \qquad \boxed{V_C = 0 - V_{out}}$$

$$\frac{V_{in}}{R} = C_F \frac{d(0 - V_{out})}{dt}$$

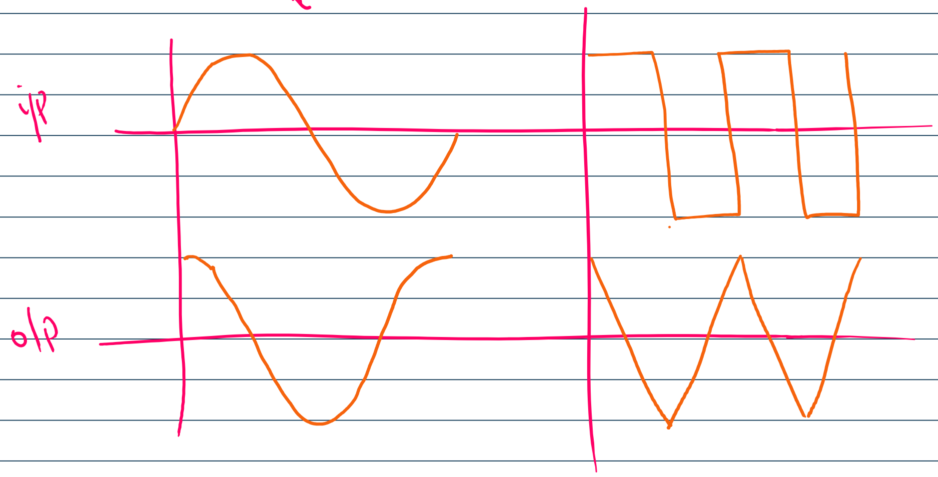
$$\frac{V_{in}}{R} = -C_F \frac{dV_{out}}{dt}$$

$$\frac{dV_{out}}{dt} = \frac{-1}{RC_F} \times V_{in}(t)$$

$$V_{out} = \frac{-1}{RC_F} \int V_{in}(t)\, dt + V_{out}(0^+)$$



By changing R & C_F we can change the slope of o/p signal



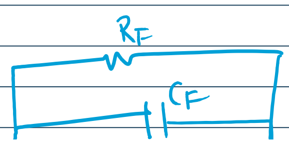
$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

$$V_{out} = \frac{-X_C}{R} \times V_{in}$$

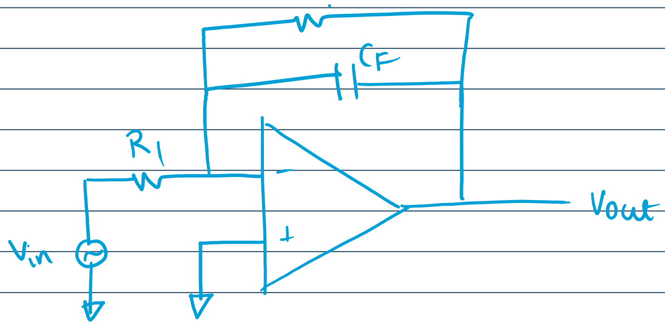
$$A_v = \frac{-X_C}{R} = \frac{1}{2\pi \times R C \times f}$$

Frequency response of Ideal Integrator.

Practical Integrator using Op Amps.

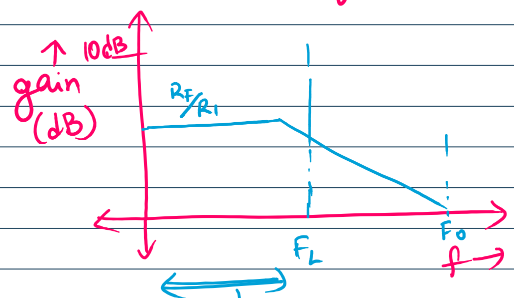


$A_v = -R_F$



$A_V = -\frac{R_F}{R_1}$

Frequency response of Practical Integrator



$F_L = \frac{1}{2\pi R_F C_F}$

$F_0 = \frac{1}{2\pi R C_F}$

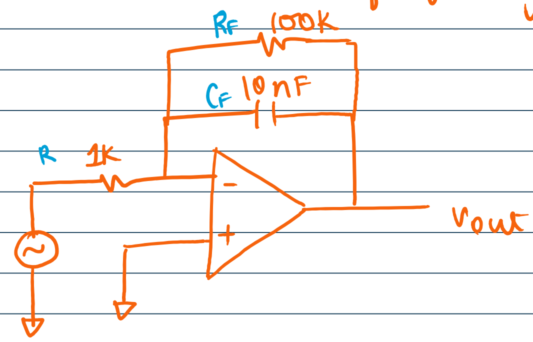
If $f < F_L \Rightarrow$ Inverting OpAmp.

for it to act as integrator op amp,

$\boxed{f > F_L}$ ✗

$f_S > 10 f_L$ for proper integrator

eg: ① find lower frequency limit of integration for the circuit.



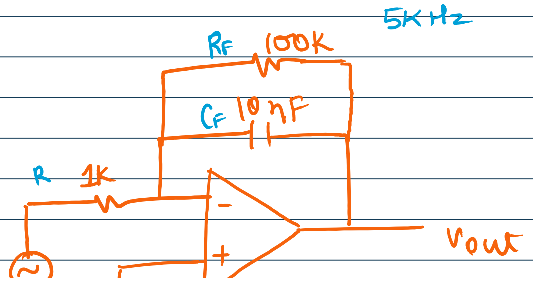
$F_L = \frac{1}{2\pi R_F C_F}$

$= \frac{1}{2(3.14)(100k)(10n)}$

$F_L = 159\ Hz$

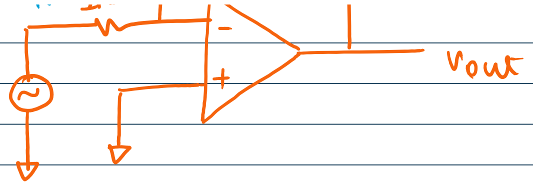
i/p signal must be $> 159Hz$ for integration
and $> 1590Hz$ for proper integration
$(10 \times F_L)$

② $V_{in} = \sin(2\pi \times \underbrace{5000}_{5KHz} t)$



$F_L = \frac{1}{2\pi R_F C_F}$

$= \frac{1}{2(3.14)(100k)(10n)}$



$$2(3.14)(100k)(10n)$$

$F_L = 159\ Hz$

$F_S = 10F_L = 1.59\ kHz$

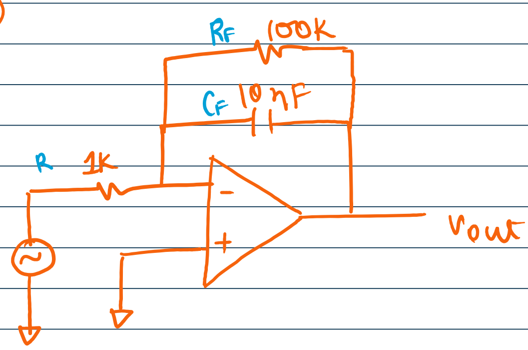
$$V_{out} = \frac{-1}{RC_F}\int v_{in}(t)\,dt$$

$$= \frac{-1}{(1K)(10n)}\int \sin(2\pi \times 5000t)\,dt$$

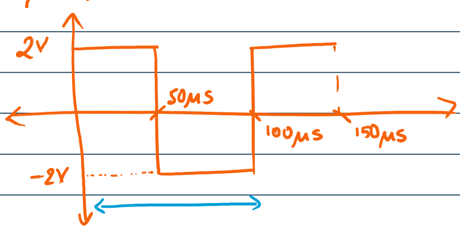
$$= \frac{-10^5}{2\pi \times 5000}\ -\cos(2\pi \times 5000t)$$

$$V_{out} = 3.18\ \cos(2\pi \times 5000t)$$

3



i/p signal =>



$T = 100\mu s$

$F = 10\ kHz$

$F_L = 195\ Hz$

$F_S = 1.59\ kHz$

$v_1(t) = 2V \quad ; \quad 0 < t < 50$

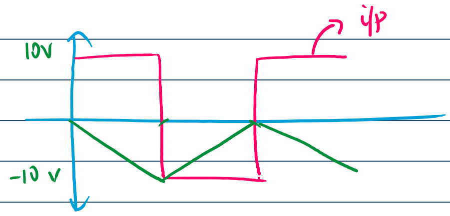
$v_2(t) = -2V \quad ; \quad 50 < t < 100$

$$V_{01} = \frac{-1}{RC_F}\int v_1(t)\,dt \qquad V_{02} = \frac{-1}{RC_F}\int v_2(t)\,dt$$

$$= -10^5 \int_0^{50\mu s} 2\,dt \qquad = -10^5 \int_{50\mu s}^{100\mu s} -2\,dt$$

$$= -10^5 \times 2 \times 50\mu \qquad = -10^5 \times -2\ (100\mu - 50\mu)$$

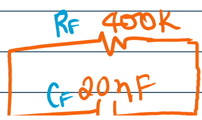
$$V_{01} = -10V \qquad V_{02} = +10V$$



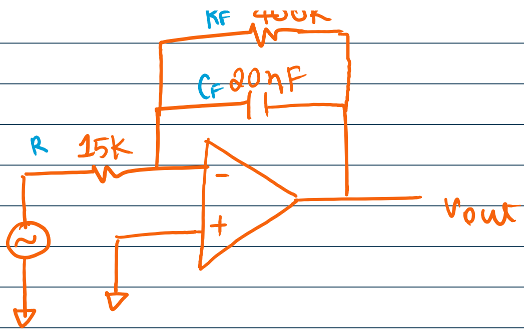
$\boxed{\text{WRONG O/P !!}}$

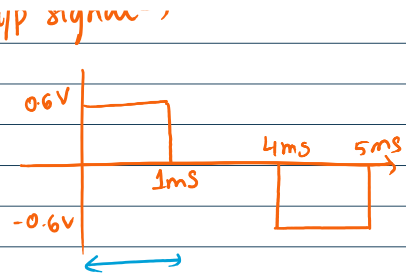
$-10^5\ \ 2 \times 50\mu$

4



i/p signal =>





$$F_L = \frac{1}{2\pi R_F C_F}$$

$$= \frac{1}{2(3.14)(400k)(20n)}$$

$$F_L = 19.89\ Hz$$

DOUBT

$$F_8 = 198.9\ Hz$$
$$= 0.199\ kHz$$

$$V_{01} = \frac{-1}{RC_F}\int_0^{1ms} 0.6\,dt$$

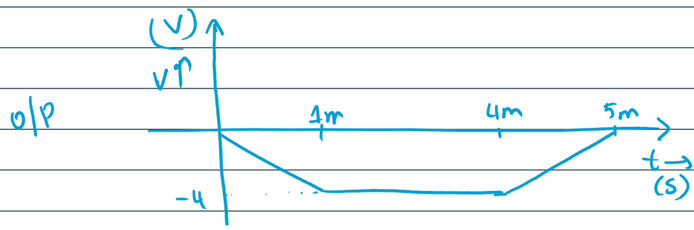
$$= \frac{-1}{(15k)(20n)} \times 0.6\,(1m - 0)$$

$$V_{01} = -4V$$

$$V_{02} = \frac{-1}{RC_F}\int_{4m}^{5m} -0.6\,dt$$

$$= \frac{-1}{(15k)(20n)} \times -0.6\,(5m - 4m)$$

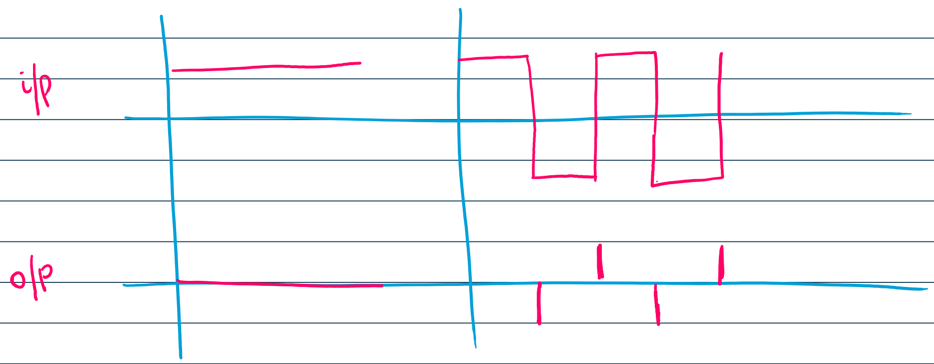
$$V_{02} = +4V$$

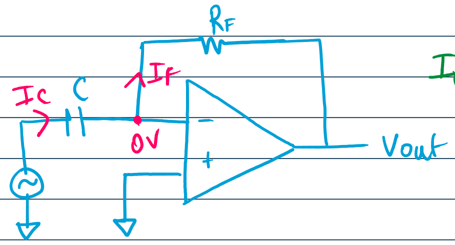


Differentiator Op Amps

82 37 60
2hrs

$V_{in}(t)$ — Differentiator — $V_{out} = \frac{dv_{in}}{dt}$





$I_C = I_F$

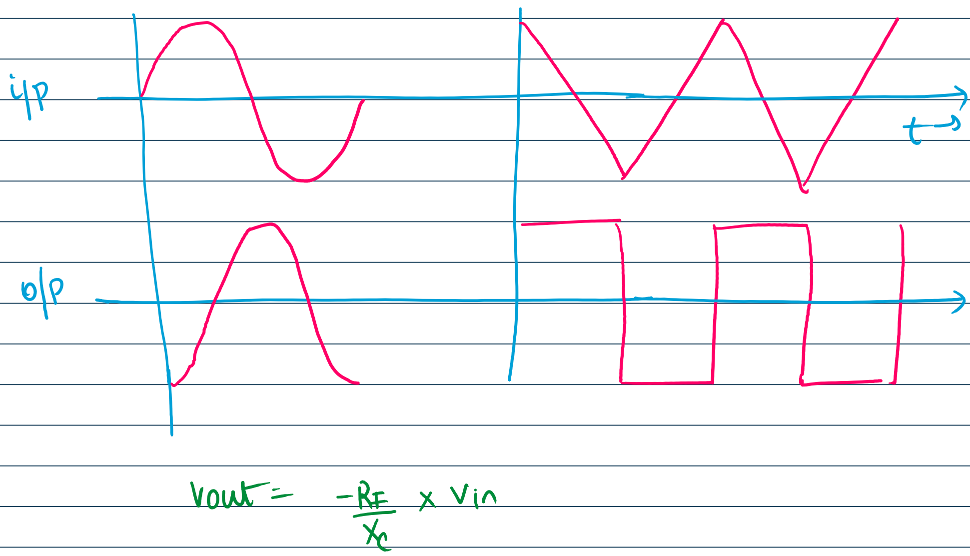
Applying KCL

$I_C = I_F$

$$C\frac{dV_c}{dt} = \frac{0 - V_{out}}{R_F}$$

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

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

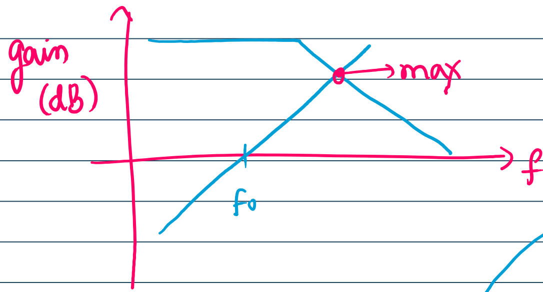


$$V_{out} = \frac{-R_F}{X_c} \times V_{in}$$

$$A = \frac{-R_F}{X_c}$$

$$A = -R_F \times 2\pi f C$$

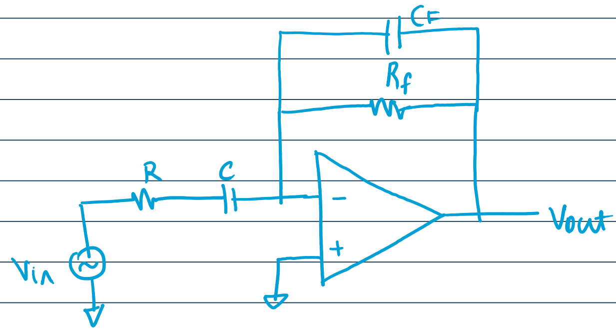
freq. response



$$F_0 = \frac{1}{2\pi R_F C}$$

Hey pilagada yendiro pilagada.
Hey managada

Practical Differentiator:



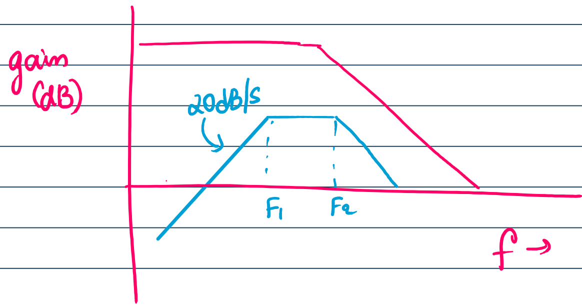
$$F_1 = \frac{1}{2\pi R C}$$

$$F_2 = \frac{1}{2\pi R_F C_F}$$

$F_2 > F_1$

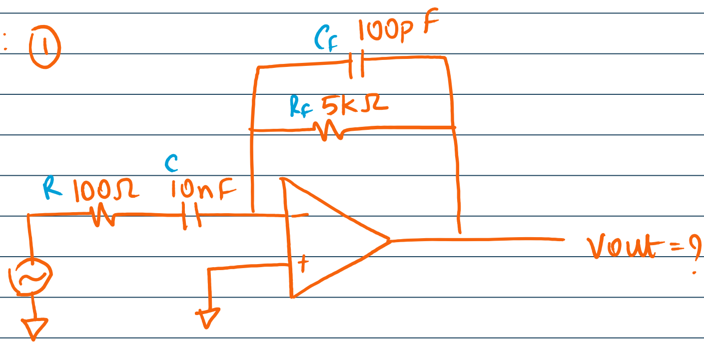
$Z_{in} = \sqrt{R^2 + C^2}$

$Z_{in} > R$



$$F_8 = \frac{F_1}{10}$$

eg : 1



$$F_1 = \frac{1}{2\pi R C}$$

$$F_1 = \frac{1}{2(3.14)(100)(10n)}$$

$F_1 = 159.2\ kHz$

$$F_2 = \frac{1}{2\pi R_F C_F}$$

$$= \frac{1}{2(3.14)(5k)(100p)}$$

$F_2 = 318.3\ kHz$

$$F_1 = \frac{1}{2(3.14)(100)(10n)} \qquad F_2 = \frac{1}{2(3.14)(5k)(100p)}$$

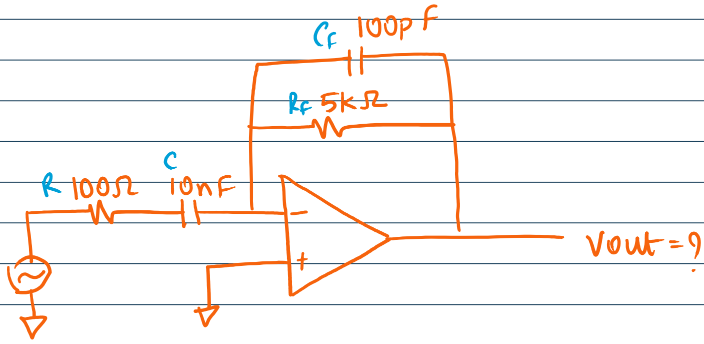
$F_1 = 159.2\ kHz$ $\qquad$ $F_2 = 318.3\ kHz$

$$F_1 < F_2$$

$$f_s < F_1$$

$F_s = \frac{F_1}{10}$ → for proper differentiator.

(2) $v_{in}(t) = 2\sin(2\pi \times 3000t)$



$f_1 = 159.2\ kHz$ $\qquad$ $F_s < \frac{159.2}{10}$

$f_s = 3\ kHz$

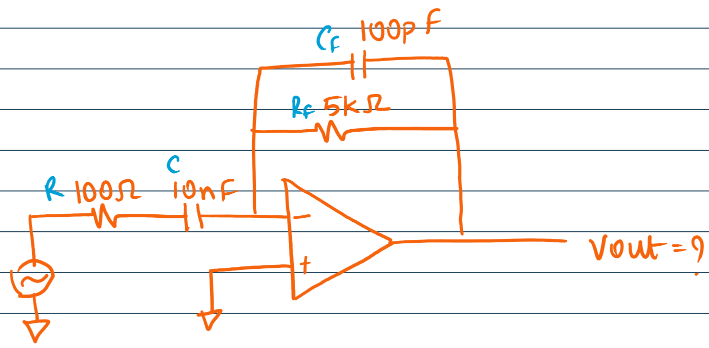
$$V_{out} = -R_f C \frac{dv_{in}}{dt}$$

$$= -5k \times 10n \times \frac{d}{dt}(\sin(2\pi \times 3000t))$$

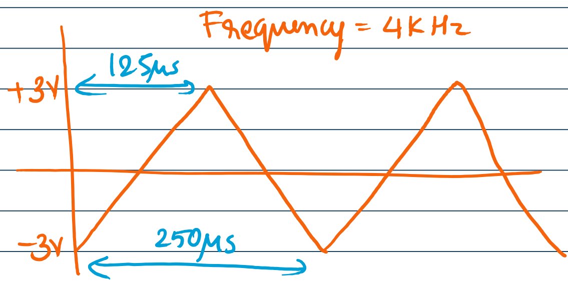
$$= -5 \times 10^{-4} \times 2\pi \times 3000 \times \cos(2\pi \times 3000t)$$

$$= -1.885 \times \cos(2\pi \times 3000t)$$

(3)



i/p signal ⇒



$f_1 = 159.2\ kHz$ $\qquad$ $T = \frac{1}{f} = \frac{1}{4k} = 250\mu s$

$f_1 = 159.2\,kHz$

$f_s = 4\,kHz$

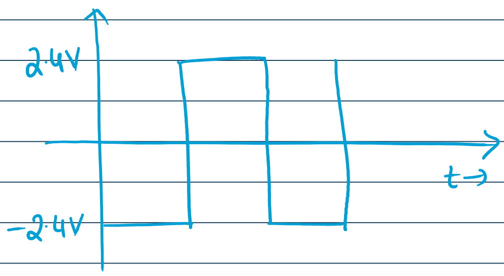
$T = \frac{1}{f} = \frac{1}{4K} = 250\mu s$

$Slope = \frac{6}{125\mu} = 48000\ V/s$

$V_{out} = -R_f C \frac{dv_{in}}{dt}$

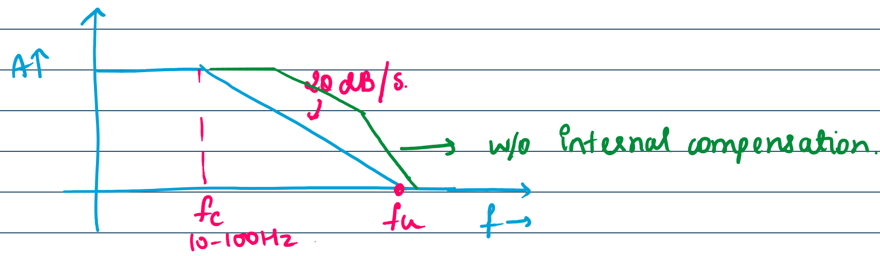
$= -(5K)(10n)(48000)$

$V_{out} = -2.4V$ (for first $125\mu s$)



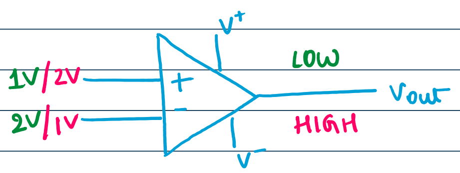
Gain Bandwidth Product.

Frequency Response



Later...

Comparator



if $V(+>-) \Rightarrow$ HIGH

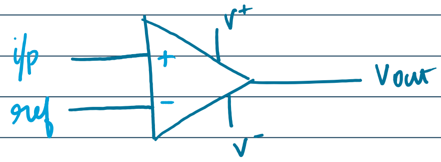
else $\Rightarrow$ LOW

$V_o = A_{OL} \times V_{id}$ $(V_2 - V_1 = V_{id})$

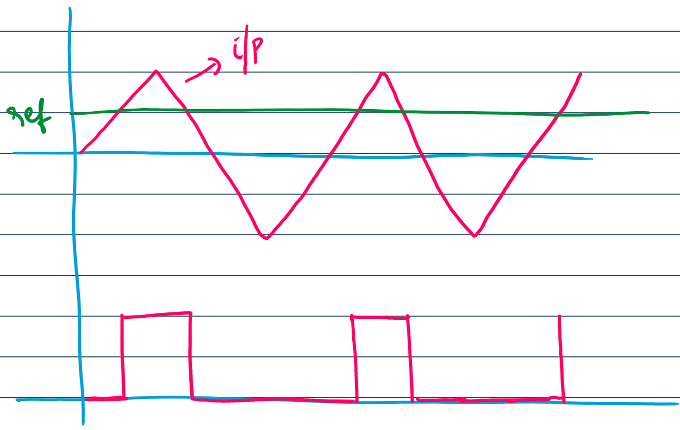
$V_o = +V_{sat}$; $V^+ > V^-$

$V_o = -V_{sat}$; $V^+ < V^-$

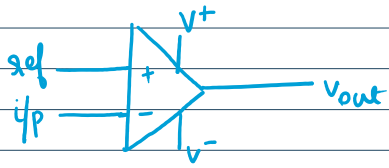
Comparator	Op Amps
→ have low propagation delay and fast rise and fall time	→ designed for linear applications



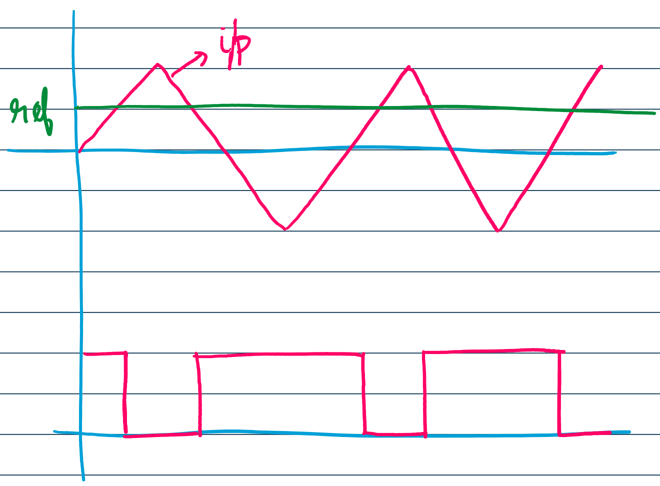
Non-inverting comparator

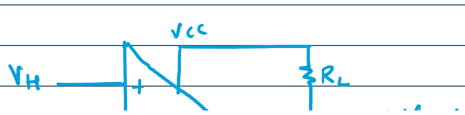


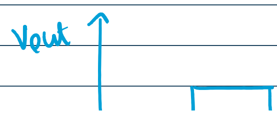
Non-inverting → o/p ↑ only when i/p > ref.

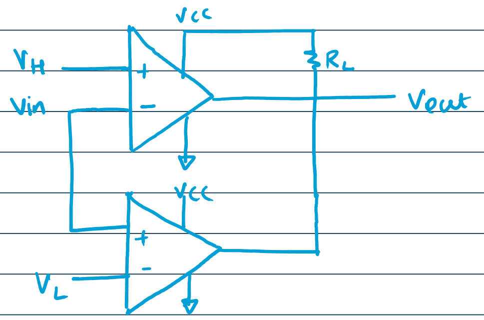


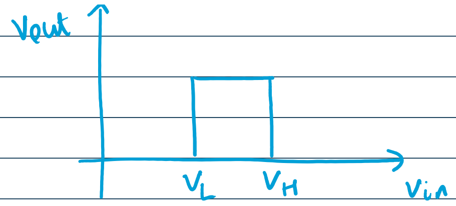
Inverting comparator.







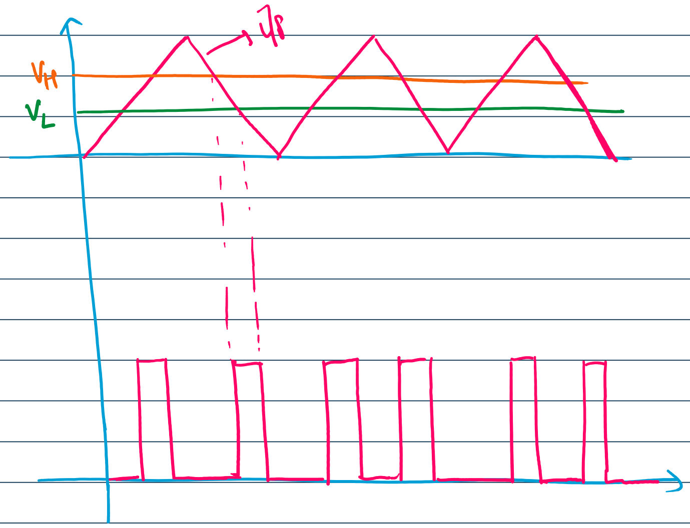


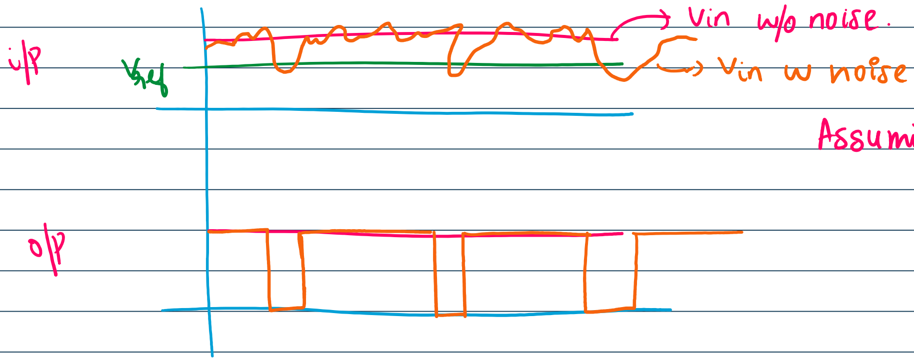


$V_{in} < V_L \Rightarrow$ LOW
$V_H > V_{in} > V_L \Rightarrow$ HIGH
$V_{in} > V_H \Rightarrow$ LOW

0 → 1st comparator.
1 → 2nd comparator
1
1
0

Window comparator



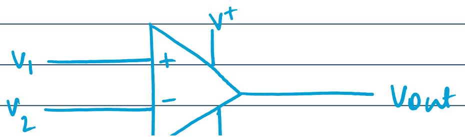


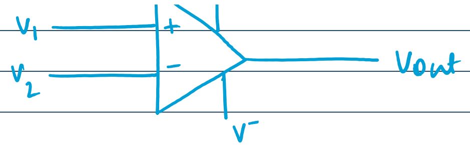
Assuming Non-inverting comparator.

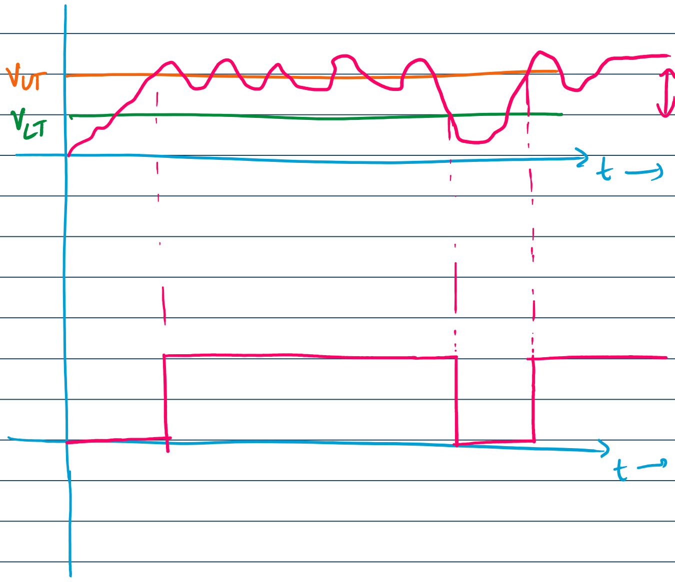
To make comparators immune to noise,

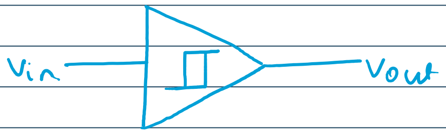
+ve feedback is provided to this comparator ckts.
⇒ schmitt trigger

Schmitt Trigger.





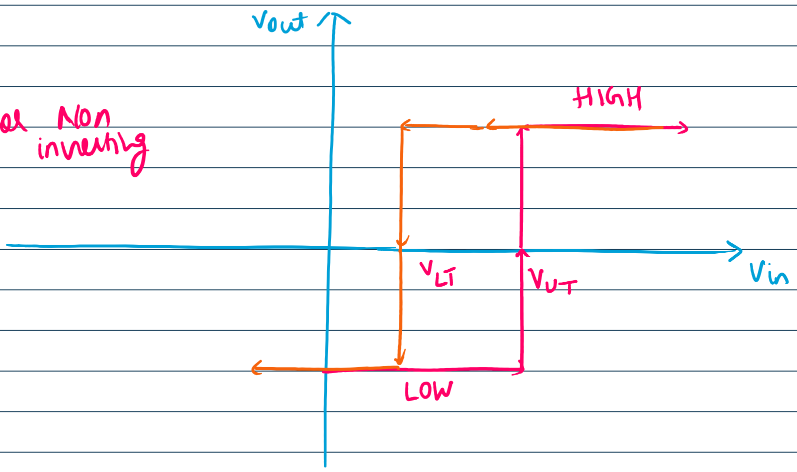




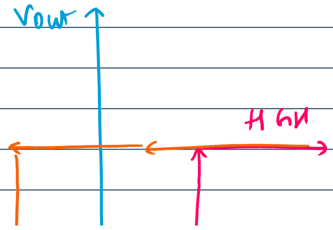
upper threshold voltage ⟶ LOW to HIGH
lower threshold voltage ⟶ HIGH to LOW

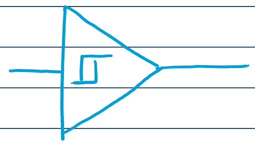
Transfer Characteristics of Schmitt Trigger.

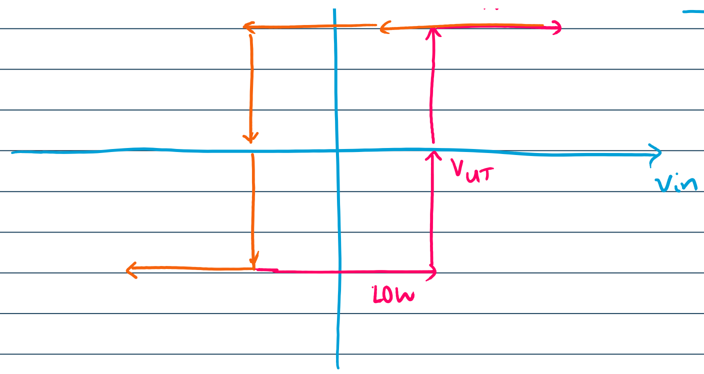
for Non inverting

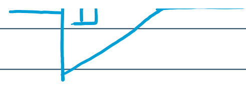


if V_H, V_L equal with opp polarity

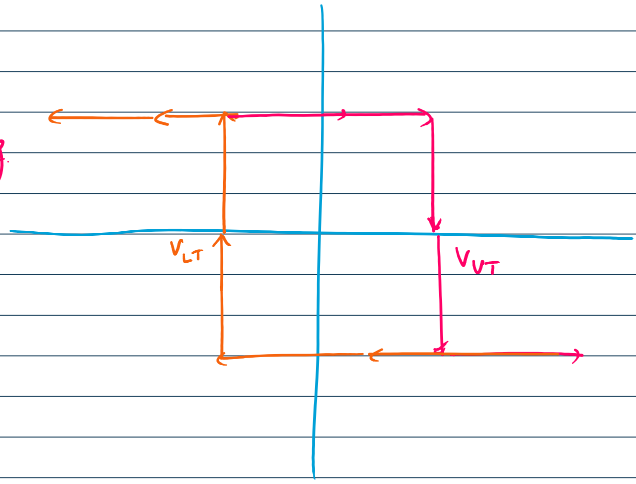


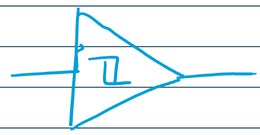




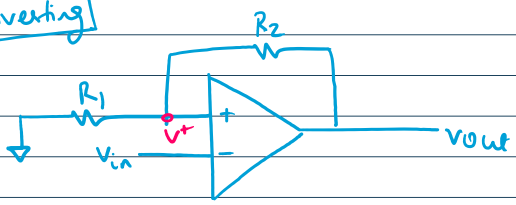


for inverting





Inverting



KCL,

$$\frac{V^+ - 0}{R_1} + \frac{V^+ - V_{out}}{R_2} = 0$$

Vin > V⁺ ⟹ o/p LOW

Vin < V⁺ ⟹ HIGH

$$\frac{V^+}{R_1} + \frac{V^+}{R_2} - \frac{V_{out}}{R_2} = 0$$

$$V^+ \frac{R_1 + R_2}{R_1 R_2} = \frac{V_{out}}{R_2}$$

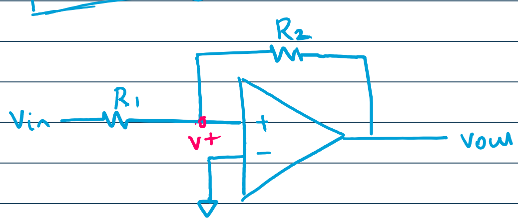
$$V^+ = \frac{R_1}{R_1 + R_2} \times V_{out}$$

→ $V_1 = \boxed{V_{UT} = \frac{R_1}{R_1 + R_2} \times V_H}$ [when $V_{in} < V^+$]

$V_2 = \boxed{V_{LT} = \frac{R_1}{R_1 + R_2} \times V_L}$ [when $V_{in} > V^+$]

→ Hysteresis : $V_{UT} - V_{LT}$

Non-inverting



KCL;

$$\frac{V^+ - V_{in}}{R_1} + \frac{V^+ - V_{out}}{R_2} = 0$$

$$\frac{V^+}{R_1} + \frac{V^+}{R_2} = \frac{V_{in}}{R_1} + \frac{V_{out}}{R_2}$$

$$V^+ = R_2 \times V_{in} + R_L \times V_{out}$$

$$\frac{V^{\cdot}}{R_1} + \frac{V^{\cdot}}{R_2} = \frac{V_{in}}{R_1} + \frac{V_{out}}{R_2}$$

$$V^{+} = \frac{R_2}{R_1+R_2} \times V_{in} + \frac{R_1}{R_1+R_2} \times V_{out}$$

$\rightarrow$ $V^{+} < 0 \Rightarrow V_{out} = LOW$ $\rightarrow$ $V^{+} > 0 \Rightarrow V_{out} = HIGH$

$$V_1 = \frac{R_2}{R_1+R_2} \times V_{in} + \frac{R_1}{R_1+R_2} \times V_L \qquad V_2 = \frac{R_2}{R_1+R_2} \times V_{in} + \frac{R_1}{R_1+R_2} \times V_H$$

if $V_1 > 0 \Rightarrow V_{out} = HIGH$ if $V_2 < 0 \Rightarrow V_{out} = LOW$

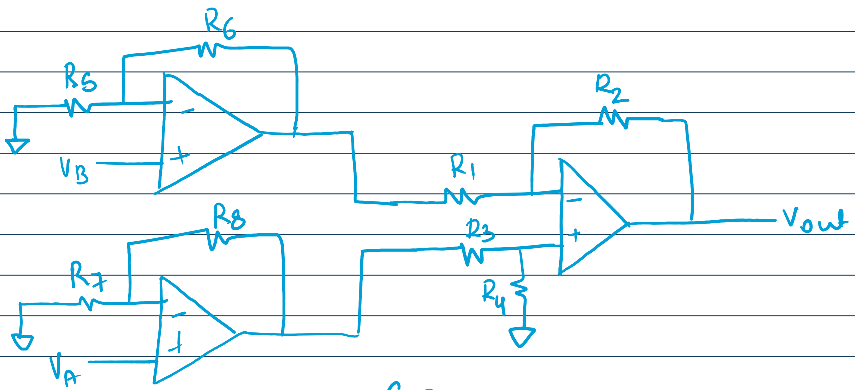
So

$$\frac{R_2}{R_1+R_2} \times V_{in} > \frac{-R_1}{R_1+R_2} \times V_L \qquad \frac{R_2}{R_1+R_2} \times V_{in} < \frac{-R_1}{R_1+R_2} \times V_H$$

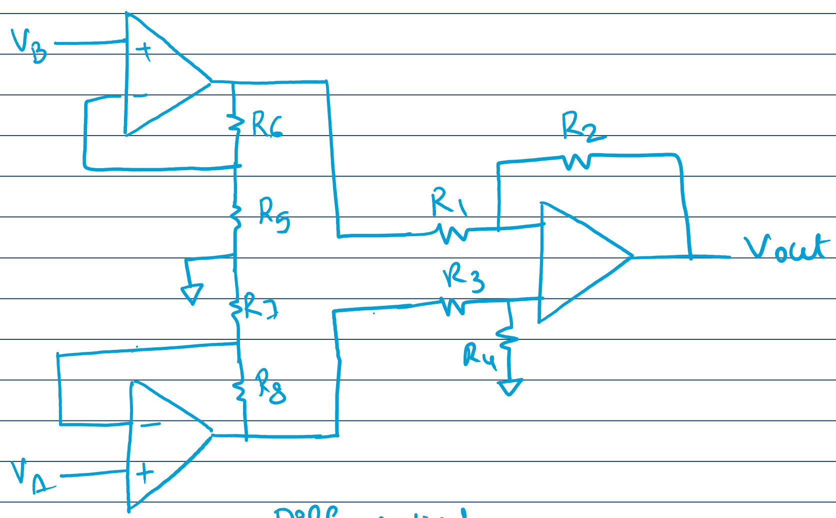
$$V_{in} > \frac{-R_1}{R_2} \times V_L \qquad V_{in} < \frac{-R_1}{R_2} \times V_H$$

$$\boxed{V_{UT} = \frac{-R_1}{R_2} \times V_L} \qquad \boxed{V_{LT} = \frac{-R_1}{R_2} \times V_H}$$

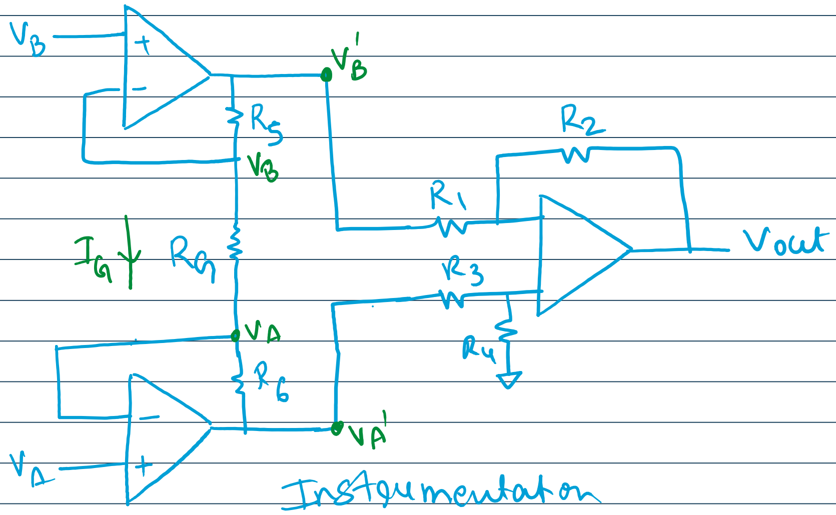
Instrumentation op-Amps.



(OR)



Differential.



Instrumentation

$$V_0 = \left(1 + \frac{2R_5}{R_G}\right)\left(\frac{R_2}{R_1}\right) \times (V_A - V_B)$$

$$R_5 = R_6 \quad \& \quad \frac{R_4}{R_3} = \frac{R_2}{R_1}$$

$$\Rightarrow \quad V_0 = \frac{R_2}{R_1}(V_A' - V_B')$$

$$I_G = \frac{V_B - V_A}{R_G}$$

$$V_B' - V_A' = I_G(R_5 + R_G + R_6)$$

$$V_B' - V_A' = I_G(2R_5 + R_G)$$

$$= (V_B - V_A)\left(1 + \frac{2R_5}{R_G}\right)$$

$$V_A' - V_B' = (V_A - V_B)\left(1 + \frac{2R_5}{R_G}\right)$$

$$V_0 = \left(\frac{R_2}{R_1}\right)\left(1 + \frac{2R_5}{R_G}\right)(V_A - V_B)$$