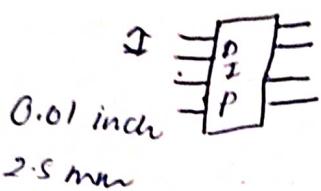


## EC352 Linear Integrated Circuit

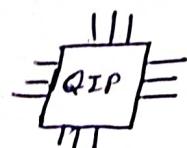
IC - (Integrated Circuit): it is a collection of components like resistor, capacitor, and transistor to perform a certain task which are stuffed into small space.

∴ IC's are in form of packages

DIP (Dual In-line Package)



QIP (Quad In-line Package)



Based on Connection on breadboard or PCB

Through (PTH) In-line

PCB or Breadboard

Surface Mount (SMT)

PCB

# SSI       L - 10 components  
Small scale

\* If size is small then it will be difficult to repair & replace.

# MSI       L - 100

Medium scale

A VLSI       L - 1000

Very large scale integration

Notes:

- \* IC's are a keystone of modern electronics
- \* the IC's are heart and brain of most electronic circuits

\* IC's are a little block chips found all over Embedded Electronics.

\* definition: is a collection of electronic components like resist, transistor all stuffed into a tiny chip and connected together to achieve a specific task or common goal.

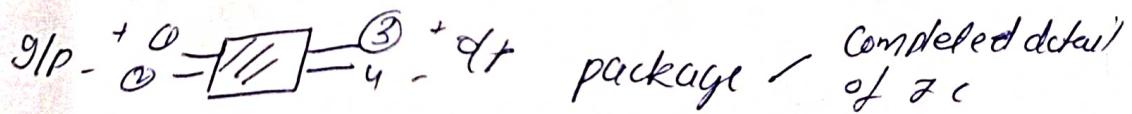
### \* Inside of IC

\* IC is a complex layering of semiconductor waffer or copper and other material which interconnect to form transistors resistor or other components in a circuit.

→ the cut and formed combination of these waffers is called die

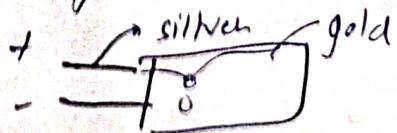
→ the IC itself is tiny, the waffers of s.c ~~are~~ and layers of copper consist of very thin

→ IC package, the package is ~~what~~ encapsulate the IC die and spread it out into a device we can more easily connect to



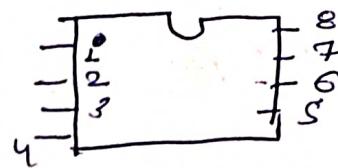
→ Each outer connection on the edge is connected via a tiny piece of gold wire to a pad or pin on the package

→ The pin's are silver which are used to connect to other parts of circuit



## Packages Types

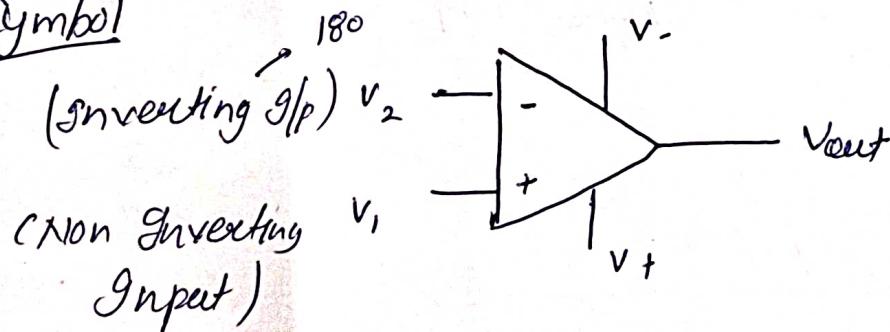
- Each package has unique dimension, mounting types, and pin comb.
- Pin no. + indicated by dot or notch



## Operational Amplifier (OPAMP) IC 741

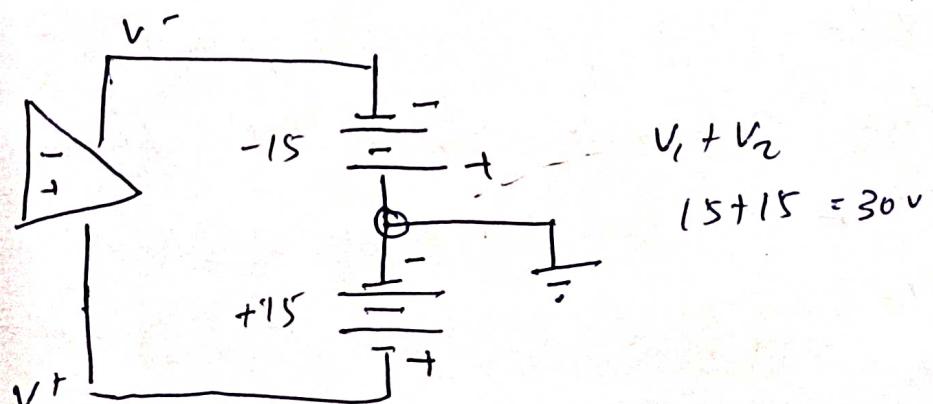
- \* Basically a high gain direct coupled differential amplifier which can amplify both AC & DC signals
- \* It has multi stage amplifier circuit, many no of amplifier circuit are interconnected to get high gain in complicated manner.
- \* It has many number of transistors and resistors
- \* Used as Amplifier, Adder, Subtraction, Integration, Differentiation

### Symbol



→ We have to use 2 power supply

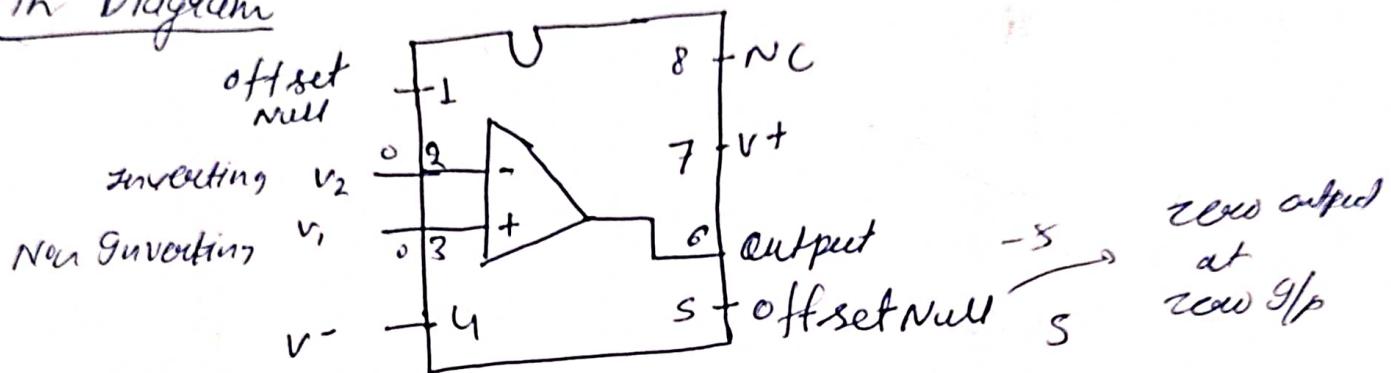
$$\text{AV} = \frac{V_{out}}{V_{in}}$$



## 741

- DIP
- Flat package
- Single, Dual, Quad

### # Pin Diagram



### # Manufacturers

1. fairchild  
Company Name MA 741
2. National Semiconductor LM 741
3. Burr - Brown BB 741
4. Signetics SE 741

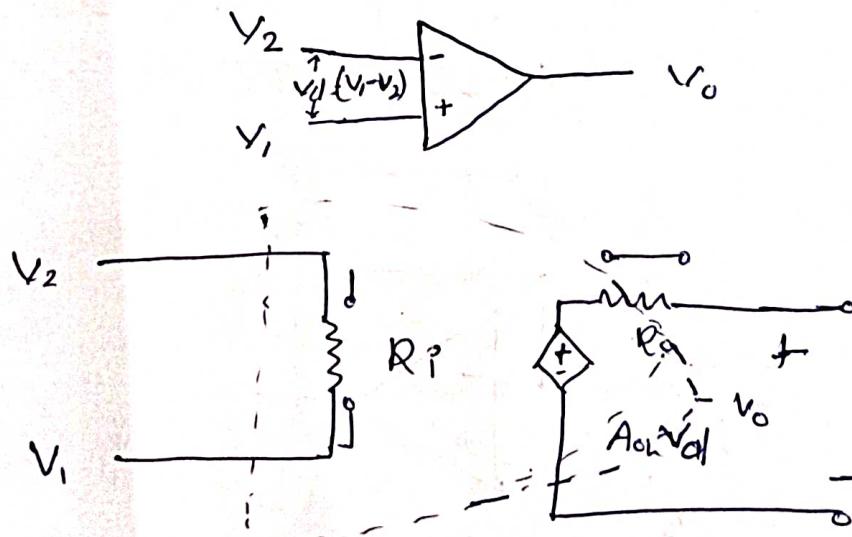
### # Different type of 741

- 741 - military grade opamp (-55°C to 100°C)
- 741C - commercial opamp (0 to 70°C)
- 741A - improved version of 741
- 741E - improved version of 741C } High electrical specification
- 741S -

- immediately react  $\rightarrow V_o = V_i$  (5)
- 741 S - high ~~slew~~ slew rate with 741L
- 741 SC - 741C with high slew rate.

## Characteristics of Ideal Op-Amp

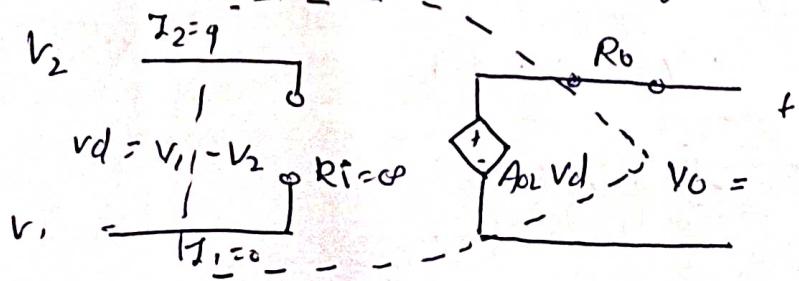
1. Input impedance / resistance ( $R_i = \infty$ )
2. Output impedance / resistance ( $R_o = 0$ )
3. Bandwidth ( $BW = \infty$ )
4. Common mode rejection ratio ( $CMRR = \infty$ )
5. Slew rate =  $\infty$
- 6\*. Open loop gain ( $A_{OL}$ ) =  $\infty$



$A_{OL}$  - open loop gain

To derive

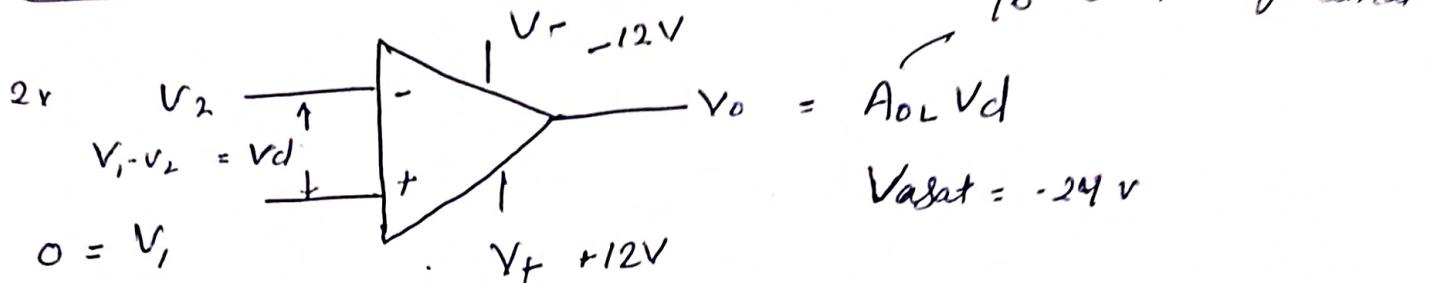
Equivalent circuit diagram of Ideal opamp



(6)

- When Op-Amp Connected in negative feedback  $g_m = 0$
- $V_f$  and gain decided by external component
- Virtual Ground for Negative feedback circuit

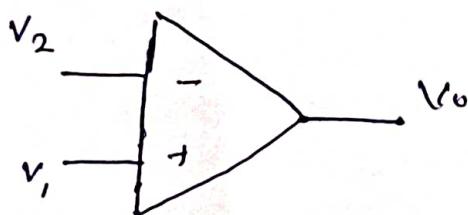
### # open loop Configuration



Active device - require power to work (Additional to  $S_p$ )

↳ In open loop configuration it act as switcher or Comparator circuit.

### Open loop



$$V_o = A_{OL} V_d$$

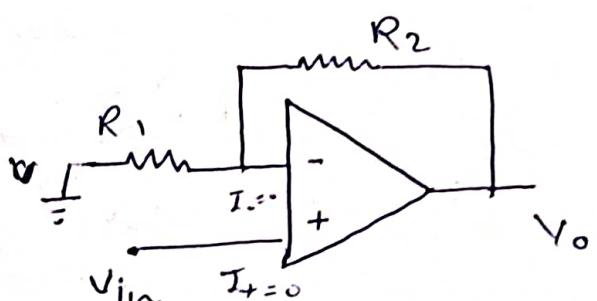
$$V_d = V_i - V_2$$

$$\text{If } V_i > V_2 \quad V_o = +V_{sat} (+ve)$$

$$\text{If } V_2 > V_i \quad V_o = -V_{sat} (-ve)$$

### Closed loop

Negative feedback +  $P+V$  feed



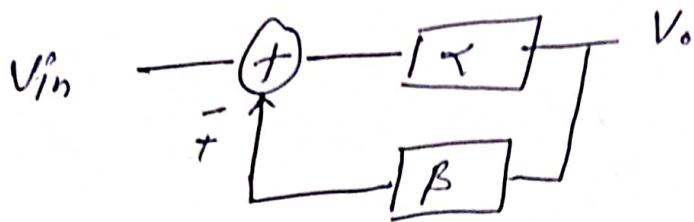
in Negative feedback

$V_{in}$

①  $V_d$  must be  $\approx 0$

②  $+I_+ + I_- = 0$

(7)



$$V_o = \frac{\alpha}{1 + \alpha B} \frac{A_{OL}}{1 + A_{OL}\beta}$$

$$V_o = \frac{\alpha}{1 - \alpha B} \rightarrow \frac{A_{OL}}{1 - A_{OL}B}$$

↓

$\alpha B = 1$   
 $\theta = 360 \text{ or } 0$

Finite

Infinite

Barkhausen Criteria

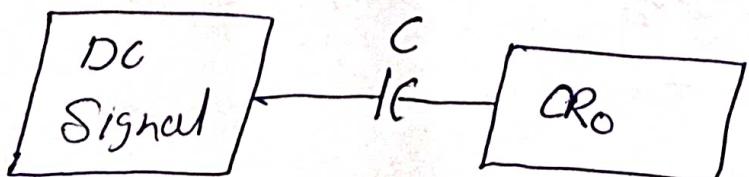
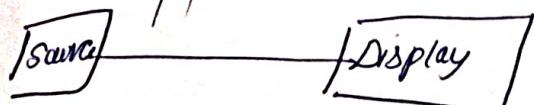
Generally

- All oscillated wave form is unstable.
- Generally all +ve feedback circuit

OP-Amp - high gain direct coupled different amplifiers.

Coupling - Interconnecting two components

- Capacitive Coupling
- Inductive ..
- Direct coupling

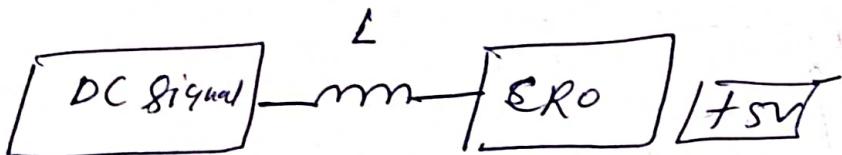


15V  
 $f = 0$

$$X_C = \frac{1}{\omega_C} = \frac{1}{2\pi f_C} = \infty$$

⑧

→ Capacitive Coupling we can't use for DC

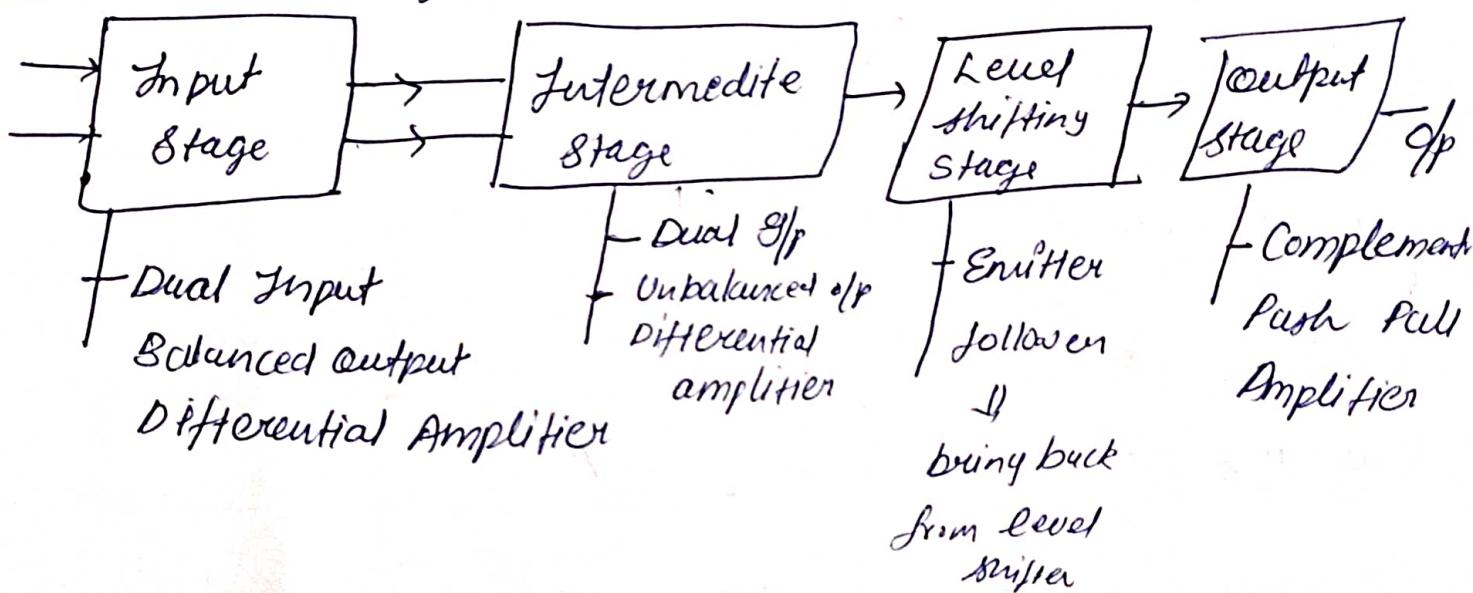


+5V  
 $f=0$

$$\cancel{X_C} \cancel{\omega_L}$$

$$X_L = L\omega = 0$$

↳ Inductors is big in size so we can't use in  $X_C$   
# Op-Amp - 4 stage



# Example of an amplifier is Transistor  
Transistor + amplifier

$$\rightarrow \square \quad \uparrow V = I R \uparrow$$

$Z_C$

Configuration of transistor



~~IE = IB + IC~~

$$I_E = I_B + I_C$$

$$\frac{I_E}{I_C} = \frac{I_B}{I_C} + \frac{I_C}{I_C}$$

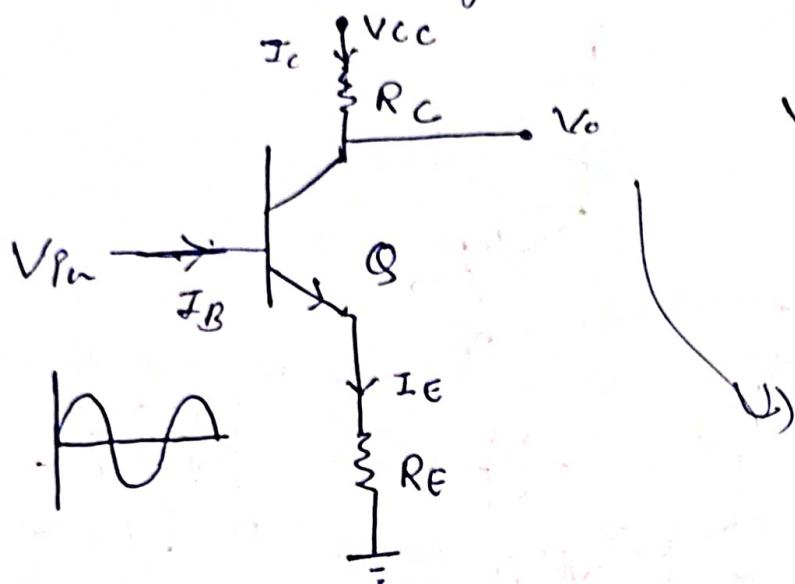
feed forward gain:  $\frac{G_P Z}{G_P Z}$

$$= \frac{I_C}{I_B} = B$$

$$Z_C = \cancel{B} I_B \xrightarrow{20^\circ \text{ f.}} \frac{20^\circ}{C_E} \text{ f.}$$

(9)

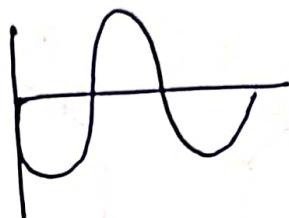
## CE configuration



$$Z_C = B I_B$$

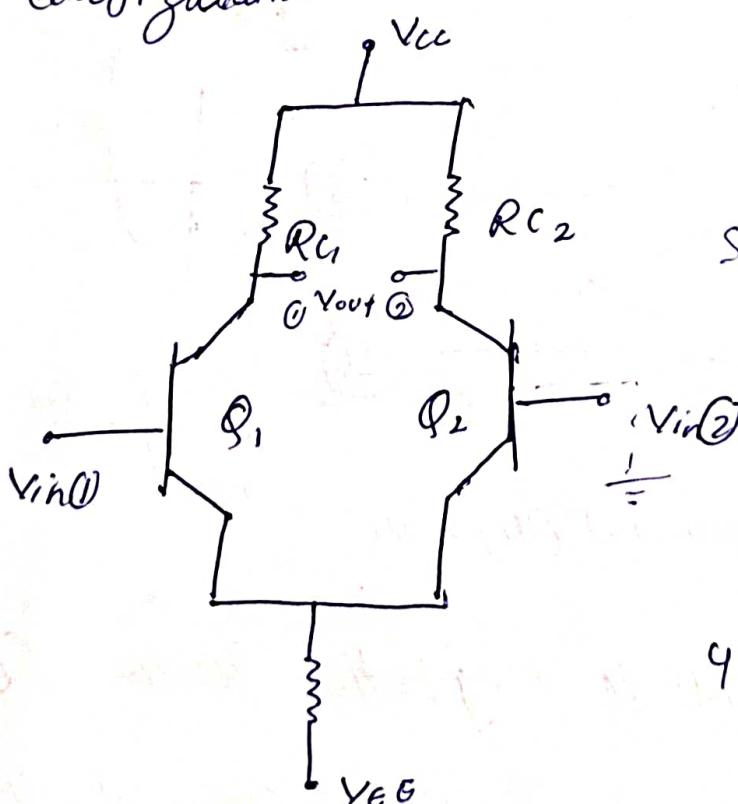
$$\begin{aligned} V_o &= V_{CC} - Z_C R_C \\ &= V_{CC} - B \beta_B R_C \end{aligned}$$

CB → Inphase  
 CC → Inphase  
 CE - Out of Phase



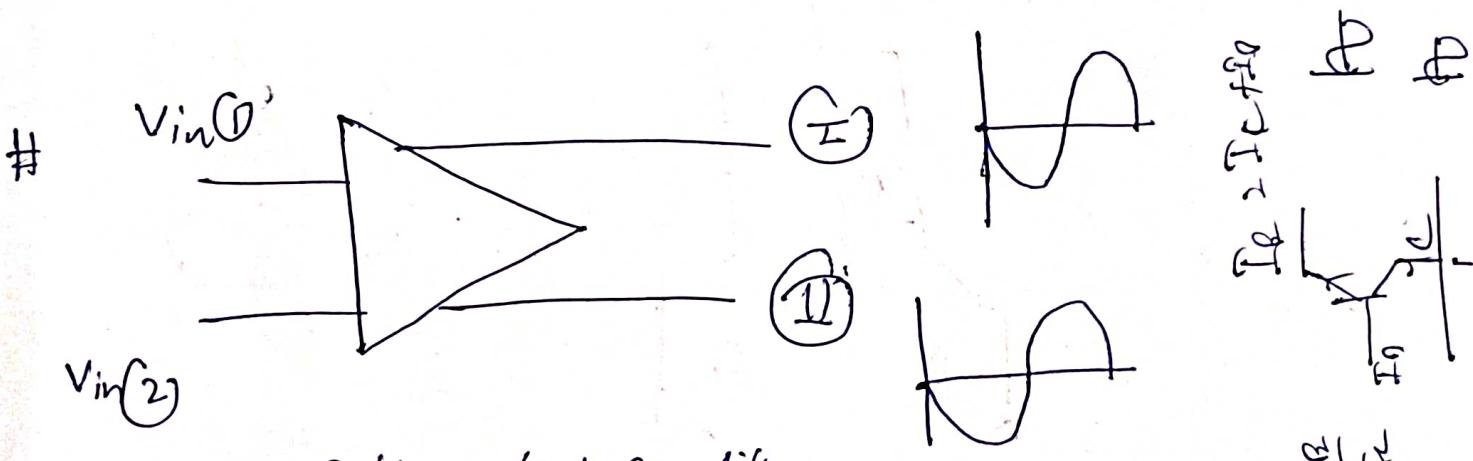
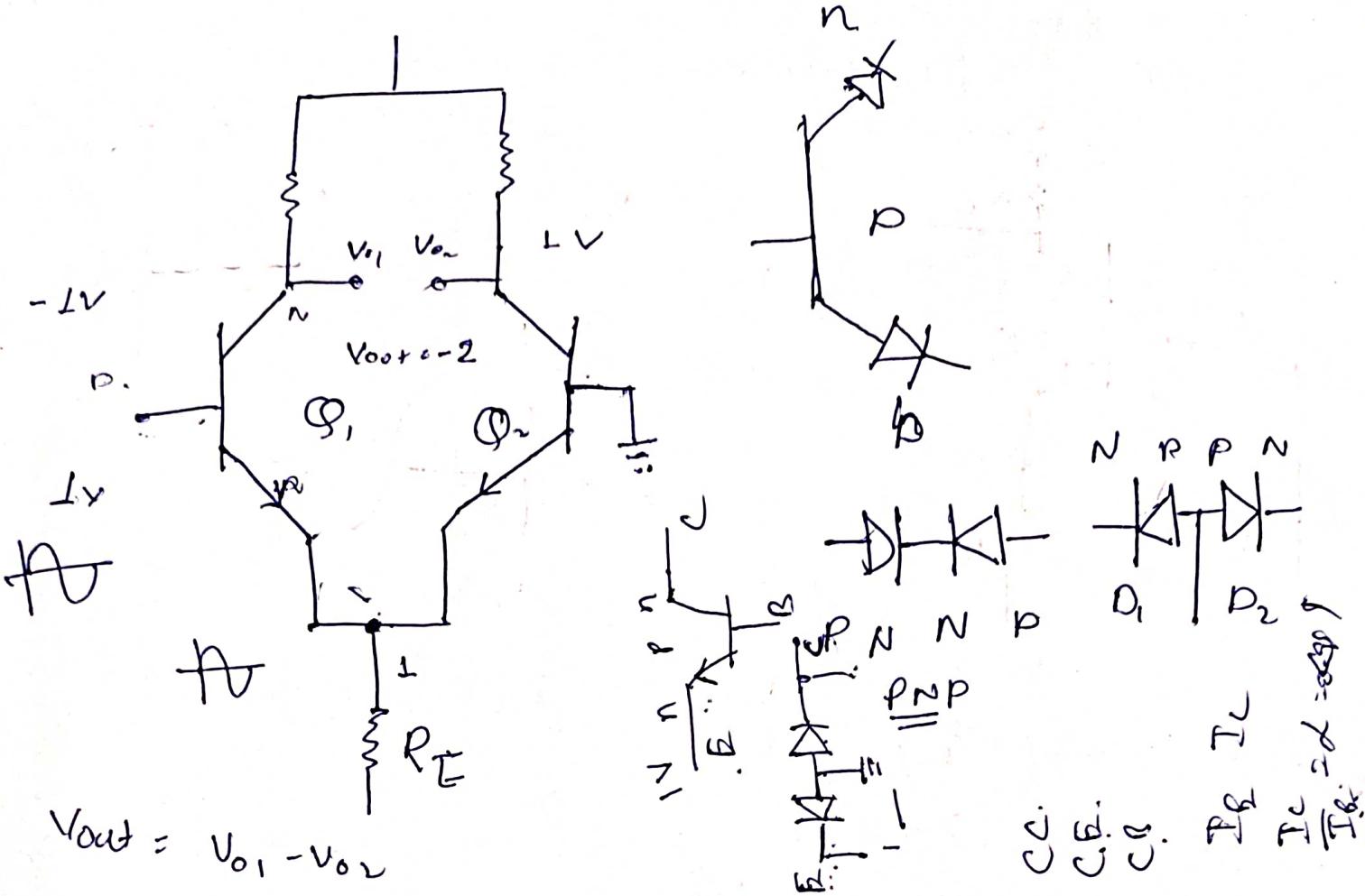
## Differential Amplifier

using CE configuration.



Based on O/p t o/p

- S-1) Dual o/p
- S-2) Balance o/p DA
- 2) Single o/p
- Balanced o/p DA
- 3) Single i/p
- Unbalance o/p DA
- 4) Dual o/p
- Unbalanced o/p DA



Common Mode Rejection Ratio (CMRR)

↳ nullify common mode signal

$CMRR = \frac{A_{dm}}{A_{cm}} \sim$  gain of differential amplifiers for diff. mode  
or  $\sim \frac{A_{dm}}{A_{cm}}$

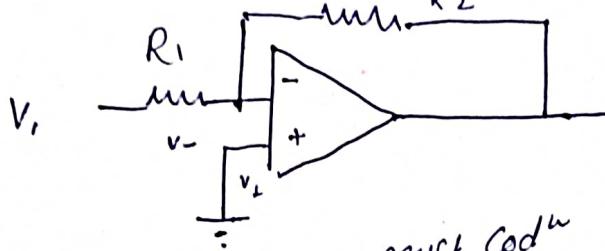
for OA      ↳ gain of PA for common mode signals

$20 \log \left( \frac{A_{dm}}{A_{cm}} \right) \rightarrow \text{in dB}$

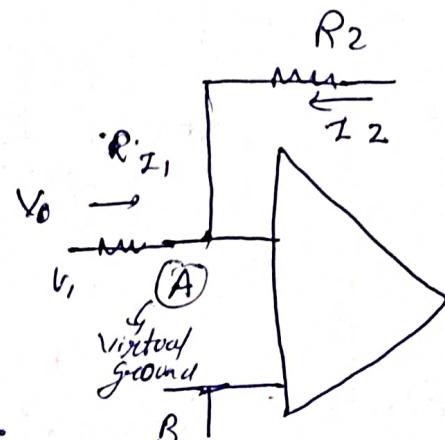
# # Application of Diff. Amplifier

(10)

## 1 Inverting Amplifier



must hold  
In Negative,  $V_A = V_+ = V_- = 0$   
feedback  $Z_+ = Z_- = 0$



$$I_1 + I_2 = 0$$

$$I_1 = -I_2$$

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

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

Problem: Design a Inverting Amplifier with gain of -2 dB

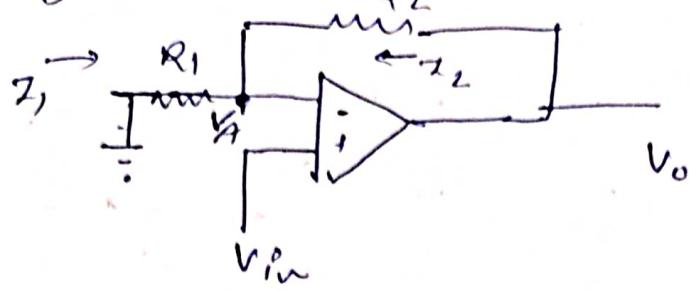
Sol<sup>u</sup> gain =  $20 \log \frac{R_2}{R_1} = -2$

$$\log \frac{R_2}{R_1} = -\frac{2}{20} = 0.2$$

$$A = -\frac{R_2}{R_1} = 10^{\frac{-2}{20}} = 10^{-0.2} = 0.63$$

$$A = 0.63$$

Q: Find gain of ckt



$$v_A = v_{in} \text{ given}$$

### Non Inverting Amplifier

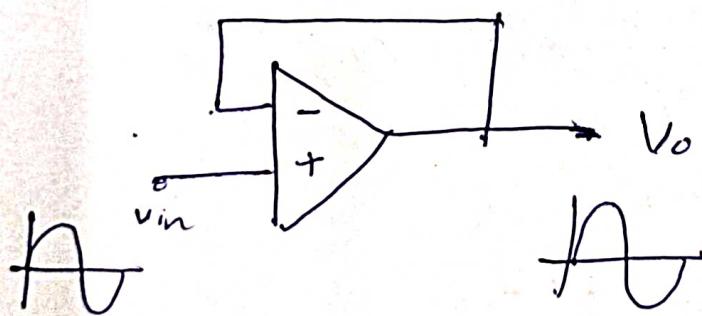
$$I_1 + I_2 = 0 \Rightarrow I_1 = -I_2$$

Vieetbaar grnd

$$\frac{0 - v_{in}}{R_1} = - \left( \frac{v_o - v_{in}}{R_2} \right)$$

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

Q: Draw output for ckt



Non Inverting

$$v_o = \left( 1 + \frac{R_2}{R_{in}} \right) v_{in}$$

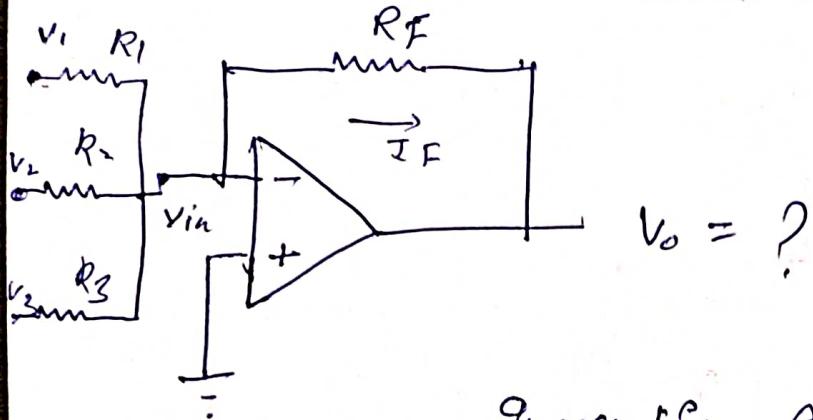
$$v_o = v_{in}$$

fig - Voltage follower or

Input follower or

Buffer. (Delay s/p - delay off)

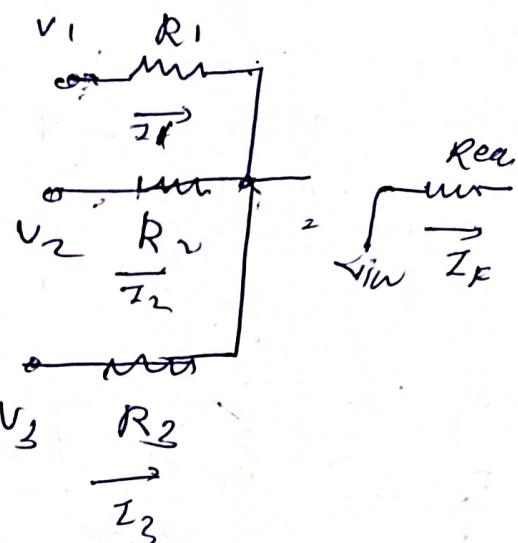
(1)



$$V_o = ?$$

Inverting Amp

$$\frac{V_o}{V_{in}} = -\frac{R_F}{R_1}$$



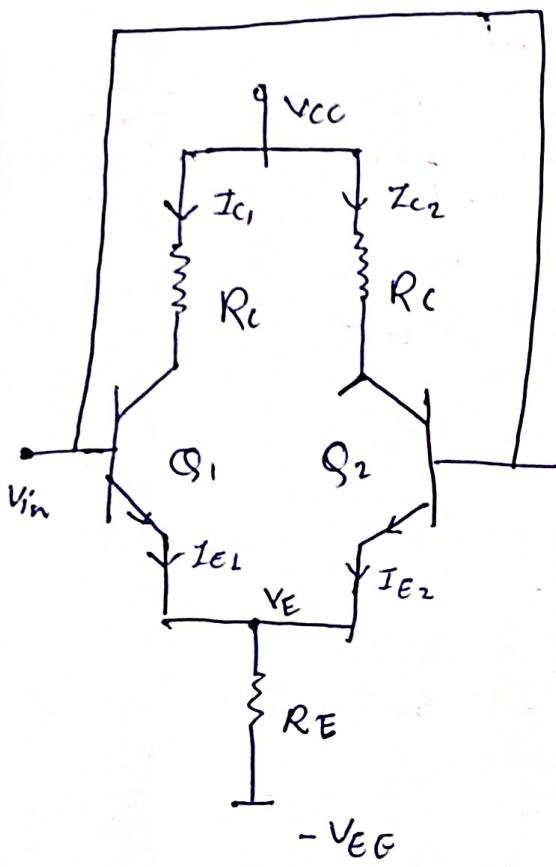
$$I_F = I_1 + I_2 + I_3$$

$$\frac{V_o}{R_{eq}} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

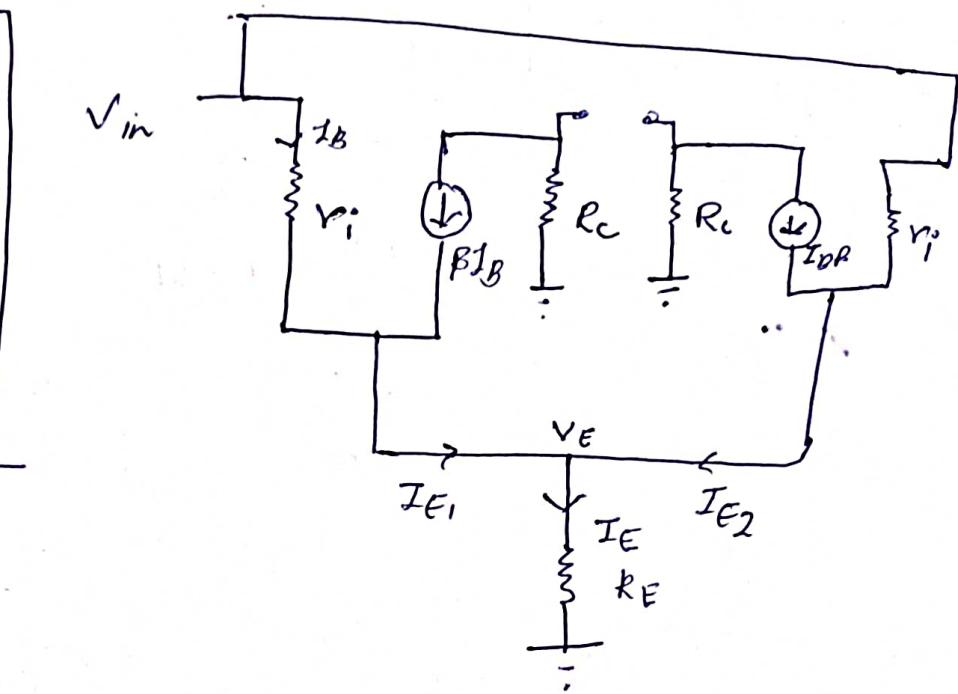
Fig - Summer or  
Adder

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

# # Hybrid Model / π model of Common Node OA



$Q_1 | Q_2$  perfectly  
Matched transistor



In CE

$$I_E = I_B + I_C$$

$$= I_B + B I_B$$

$$I_E = I_B (1 + B) \text{ for transistor}$$

$$I_{E1} = I_{B1} (1 + B_1) \quad I_{E2} = I_{B2} (1 + B_2)$$

$$B_1 = B_2 \quad [Q_1 = Q_2]$$

$$I_{E1} = I_{B1} (1 + B) \quad I_{E2} = I_{B2} (1 + B)$$

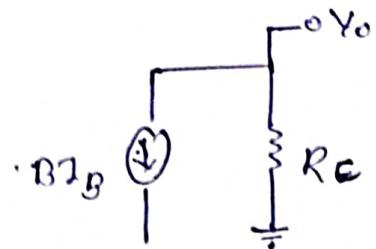
$$I_E = I_{E1} + I_{E2}$$

$$Z_E = 2 I_B (1 + B)$$

$$V_E = I_E R_E = 2 I_B (1 + B) R_E$$

$$V_E = 2 I_B R_E (1 + B)$$

(12)



$$A_{CM} = \frac{V_o}{V_{in}} = \frac{\beta R_C}{V_i + 2(\beta+1)R_E}$$

$$I_{\text{out}} = \beta I_B = I_C$$

$$V_o = \beta I_B R_C$$

$$V_o = \frac{\beta V_{in} R_C}{V_i + 2(\beta+1)R_E}$$

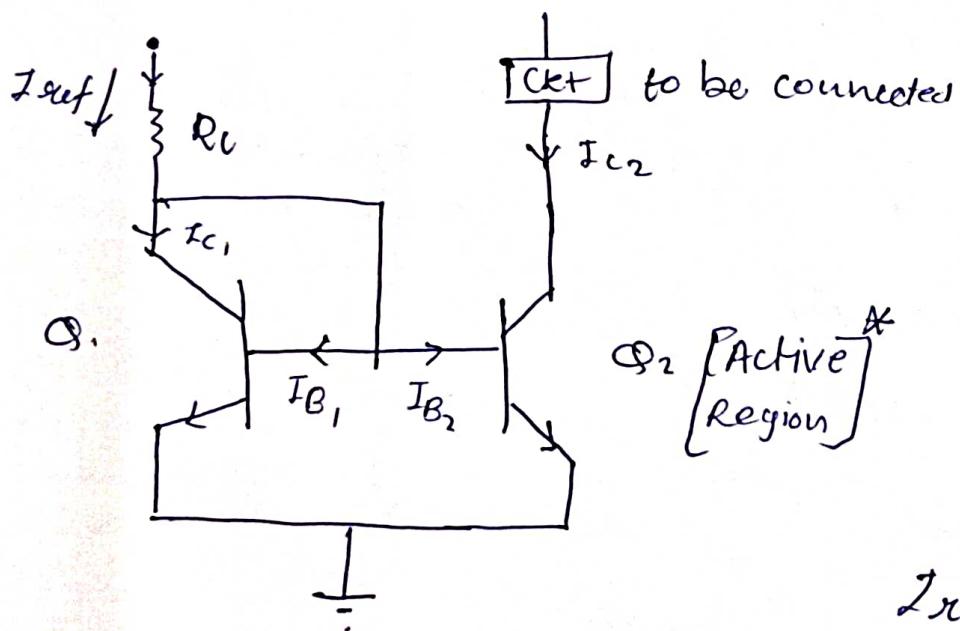
$$V_i \approx \infty, R_L = 0, V_{o \infty}$$

~~\$R\_L = \infty\$~~  
Size bias  
passive load

## # Current Mirror Circuit

↳ Constant Current Source

$$\therefore I_C = \beta I_B$$



$$\begin{aligned} I_{ref} &= I_{C1} + I_{B1} + I_{B2} \\ &= I_{C1} + \frac{I_q}{\beta_1} + \frac{I_{C2}}{\beta_2} \\ &= I_{C1} + I_{C1} + \frac{I_{C2}}{\beta} \quad \beta_1 = \beta_2 : \Omega_1 = \Omega_2 \end{aligned}$$

$$I_{ref} = \left(1 + \frac{1}{\beta}\right) I_{C1} + \frac{I_{C2}}{\beta} \quad \beta \gg 1$$

$$I_{C1} = \alpha_F I_{ES} e^{\frac{V_{BE1}}{V_T}}$$

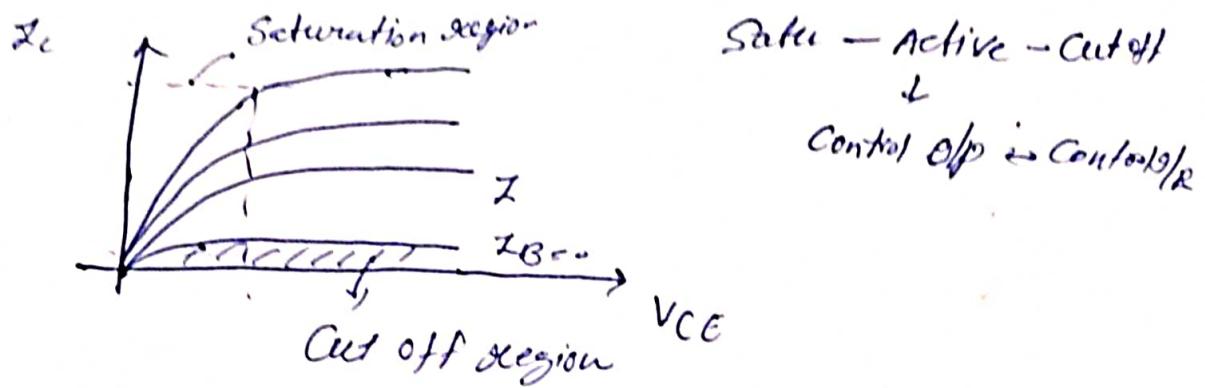
$$I_{C2} = \alpha_F I_{ES} e^{\frac{V_{BE2}}{V_T}}$$

$$I_{C1} = I_{C2}$$

$$V_{BE1} = V_{BE2}$$

$$\boxed{I_{C1} = I_{C2}}$$

Transfer characteristic of transistor.



$$\frac{dV_{CE}}{dI_C} = R = \infty$$

- ↳ The current source or current mirror can be used as active load to achieve high voltage gain without requiring large power supply voltage. The current source provides higher output resistance and occupies minimum area.
- ↳ A Constant Current Source make use of fact that for a transistor in the active mode of operation the collector current is relatively independent of the collector voltage.
- ↳ the output resistance of current source is the output resistance of Transistor Q2

$$R_o = \frac{V_A}{I_{CQ}} = \frac{V_A}{I_{CQ} Z_{C2}}$$

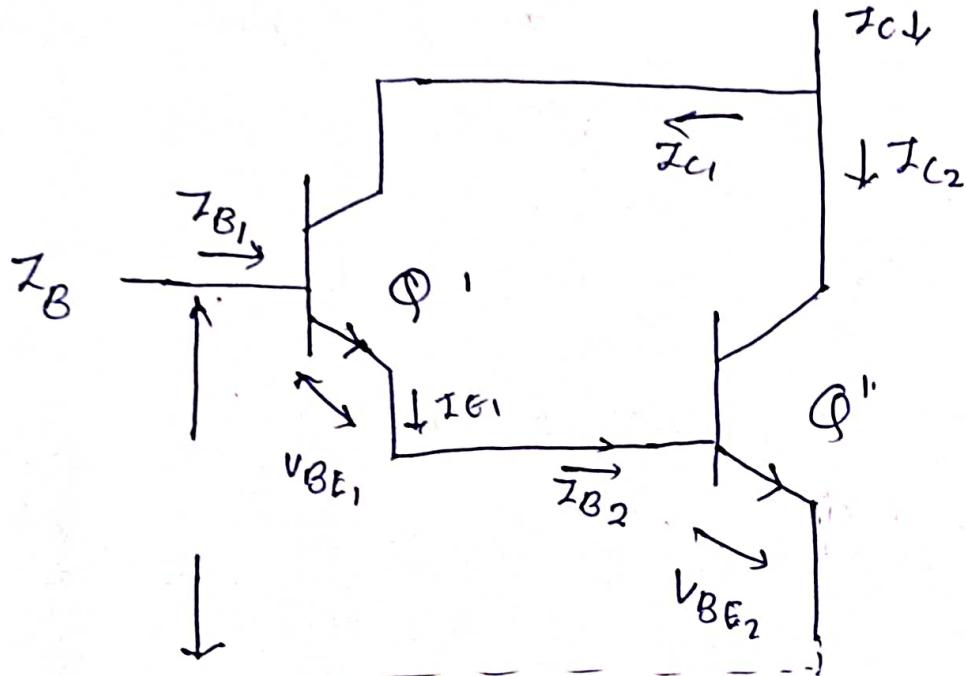
Early Voltage.

- ↳ Collection voltage has some effect on collector current. It increases slightly with increase in voltage. This phenomena is called as Early effect.

## Intermediate Stage #Darlington Pair

(13)

↳ high gain & high input impedance  $R_i = \text{cm } 71$   
 very high  
 (practical)



$$V_{BE} = V_{BE_1} + V_{BE_2}$$

$$\frac{V_{BE}}{I_B} = R_i \left( \frac{1.4}{1 \text{ mA}} \right)$$

High g<sub>p</sub> gain

$$\beta = \frac{I_C}{I_B} = \frac{I_{C1} + I_{C2}}{I_{B1}}$$

$$= \frac{I_{C1}}{I_{B1}} + \frac{I_{C2}}{I_{B1}}$$

$$= \beta_1 + \frac{I_{C2}}{I_{B2}} \times \frac{I_{B2}}{I_{B1}}$$

$$\beta_1 + \beta_2 \frac{I_{B2}}{I_{B1}}$$

$$\Rightarrow \beta_1 + \beta_2 \frac{I_E}{I_B} \quad \therefore I_{B2} = I_{E1}$$

$$= \beta_1 + \beta_2 \left( \frac{I_{B1} + I_{C1}}{I_{B1}} \right)$$

$$\beta = \beta_1 + \beta_2 (1 + \beta_1)$$

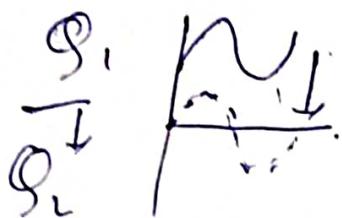
$$\text{Ex: Eg } \beta_1 = 200 = \beta_2$$

$$\Rightarrow \beta = 400$$

$$Z_C = \beta Z_B \uparrow\uparrow$$

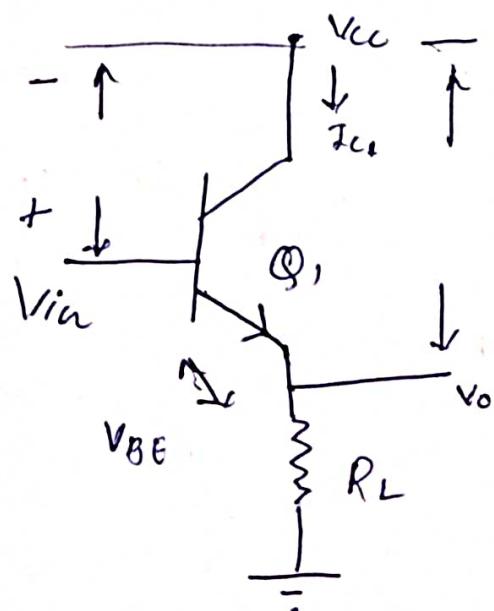
## # Level shifting stage

- ↳ Direct Coupled high gain Amp.
- ↳ Can Amplify both AC & DC → It will do level shifting changing the Q point of the transistor  
Operating Quiescent point



↳ we need a circuit to shift level

# level shifter / level translator / common Collector am. Emitter follower.



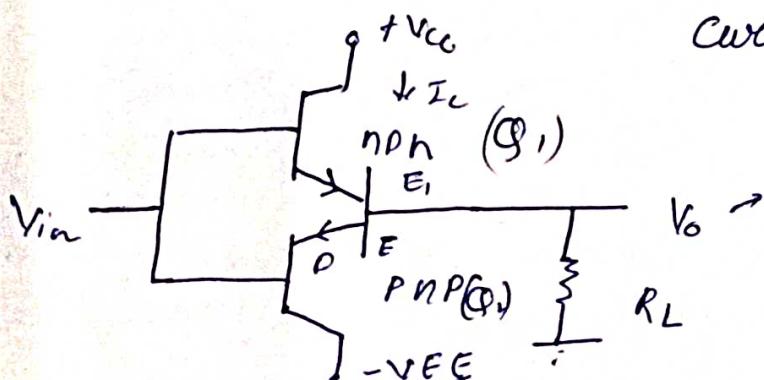
$$V_{in} \approx V_o - V_{BE}$$

$$\boxed{V_o \approx V_{in}} \quad \text{Voltage follower}$$

Buffer.

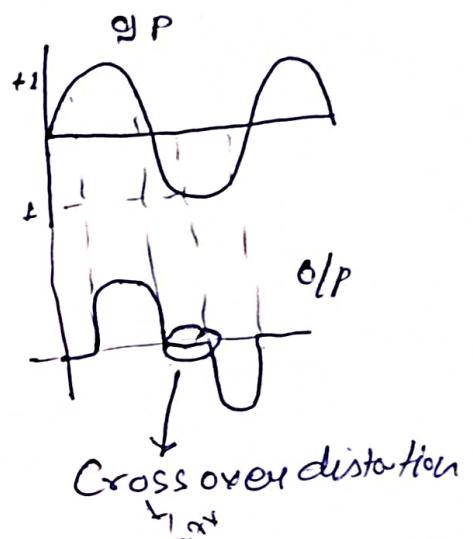
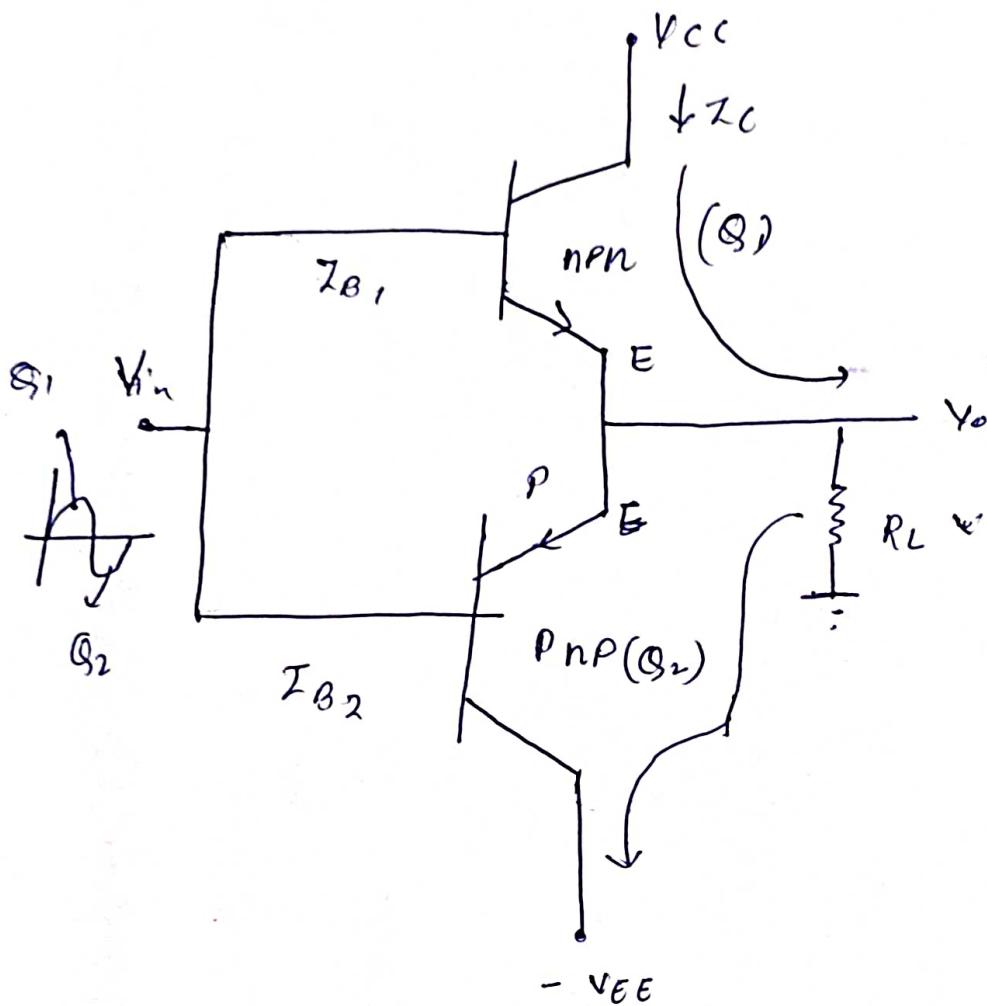
# Output Stage. (Output Impedance Should Be very low or zero)

↳ so it can drive the load current to the other device.



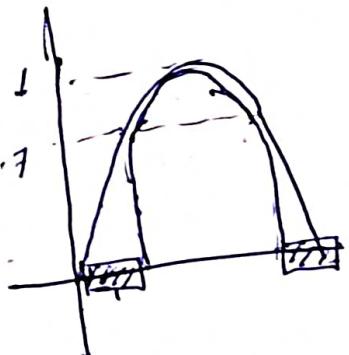
(14)

$$P = \frac{V_{max}^2}{R_L}$$



↳ min  $V_{in}$  to turn on  $Q_1$  &  $Q_2 \approx 0.7V$

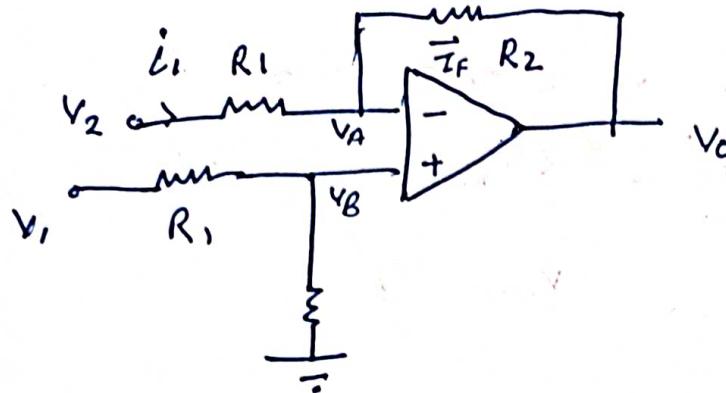
if  $V_{in} = 0 - 0.7$   $V_o = 0$



↳ to solve we need some min volt at g/p

# # Differential Amplifier

(15)



$$V_B - V_A = 0$$

$$V_d = 0$$

$$\hat{V}_i = \hat{V}_F$$

$$\hat{V}_i = \frac{V_2 - V_A}{R_1} = \frac{V_A - V_o}{R_2}$$

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

$$V_A = \frac{V_2 R_2 + V_o R_1}{R_1 + R_2}$$

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

$$V_B = V_A \Rightarrow \frac{R_2}{R_1 + R_2} V_1 = \frac{V_2 R_2 + V_o R_1}{R_1 + R_2} \Rightarrow V_o = \frac{R_2}{R_1} (V_1 - V_2)$$

Eq

$$V_1 = 1004 \text{ mV}$$

$$V_2 = 504 \text{ mV} \Rightarrow V_o = \frac{R_2}{R_1} (1004 - 504) = 504 \text{ mV}$$

$$R_1 = R_2$$

$$V_o = A_1 V_1 + A_2 V_2$$

find differential mode gain in common mode gain

$A_{dm}$

$$V_d = V_1 - V_2$$

$$V_1 = V_d + V_2$$

$A_{cm}$

$$V_{cm} = \frac{V_1 + V_2}{2}$$

$$2V_{cm} = V_1 + V_2$$

$$V_2 = 2V_{cm} - V_1$$

$$V_o = A_1 (V_d + V_2) + A_2 (2V_{cm} - V_1)$$

$$\Rightarrow V_d = V_1 - V_2 \quad \Rightarrow \quad 2V_1 = 2V_{cm} + V_d \\ 2V_{cm} = V_1 + V_2 \quad \Rightarrow \quad 2V_2 = 2V_{cm} - V_d$$

$$V_1 = V_{cm} + V_d/2 \quad V_2 = V_{cm} - \frac{V_d}{2}$$

$$V_o = A_1 V_1 + A_2 V_2$$

$$V_o = A_1 \left( V_{cm} + \frac{V_d}{2} \right) + A_2 \left( V_{cm} - \frac{V_d}{2} \right)$$

$$V_o = \left( \frac{A_1 - A_2}{2} \right) V_d + (A_1 + A_2) V_{cm}$$

$$\left[ A_{dm} = \frac{A_1 - A_2}{2} \right] \quad \left[ A_{cm} = A_1 + A_2 \right]$$

$$CMRR = \left| \frac{A_{dm}}{A_{cm}} \right|$$

# Common mode Rejection Ratio (CMRR)

The relative sensitivity of an operational Amplifier to a different signal as compared to common mode signal is called CMRR.

And if give figure of merit ( $\rho$ ) for the differential amplifier

$$\rho = \left| \frac{A_{dm}}{A_{cm}} \right| \text{ in terms of dB}$$

for  $uA741$  CMRR - 70dB

$uA741A$  - 120dB

↳ Higher the CMRR better the opamp

→ The Output of DE amplifier depend not only the difference signal ( $V_d$ ) but it also affected the average voltage of input signal called common mode signal (16)

$$V_{cm} = \frac{V_1 + V_2}{2} \quad V_d = V_1 - V_2$$

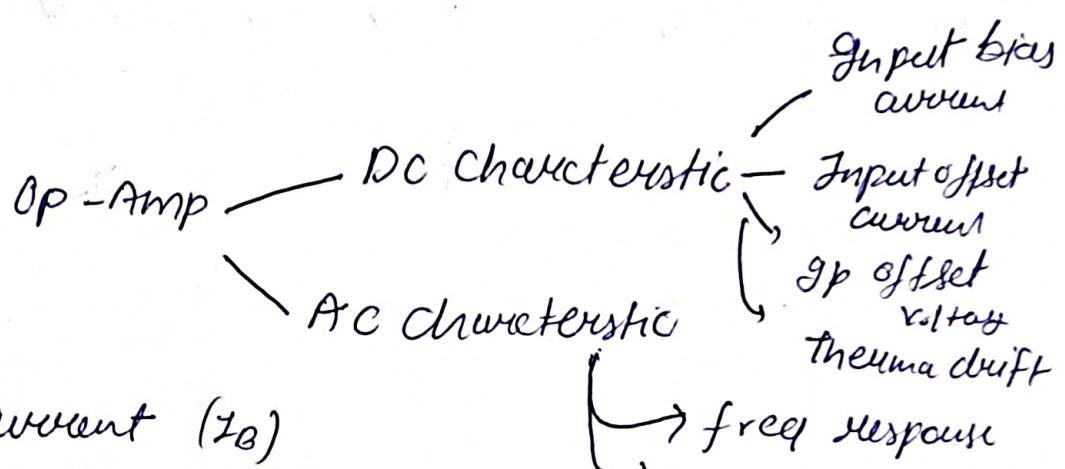
Q: Design an Op-Amp circuit for Expression

$$V_o = 3V_1 + 2V_2 - V_3 \text{ using only one Op-Amp}$$

## # Characteristic of op-Amp

DC  
AC

- ↳ An ideal op-Amp respond equally well at both ac and dc input
- ↳ Practically If both the input are grounded, there will be some dc voltage at o/p. (We need compensation (Ck+))
- ↳ As input to op-amp, the o/p will change w.r.t to frequency.



### (i) Input bias Current ( $I_B$ )

manufacturer.

$$I_B = \frac{I_B^+ + I_B^-}{2}$$

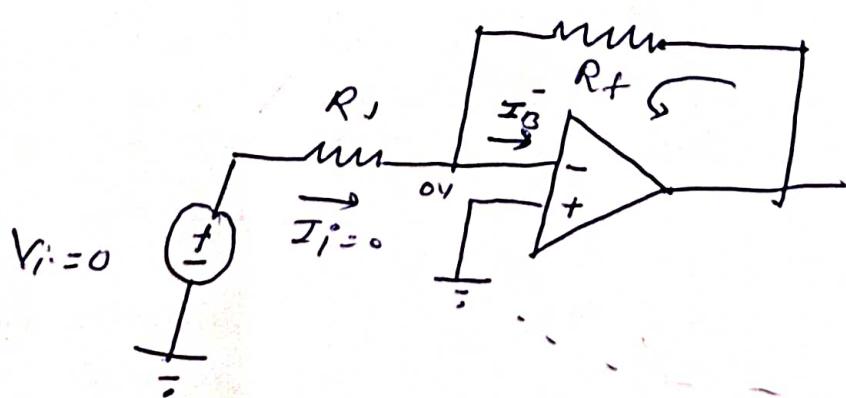
BJT or FET to drive

in Active region / Linear region

$$741 \text{ (BJT)} = I_B \approx 800 \text{ nA} \text{ or less at room temp}$$

$$741 \text{ (FET)} = I_B = 50 \text{ fA}$$

H



$$\Delta I_B = \frac{R_f}{R_i}$$

$$V_o = I_B R_f$$

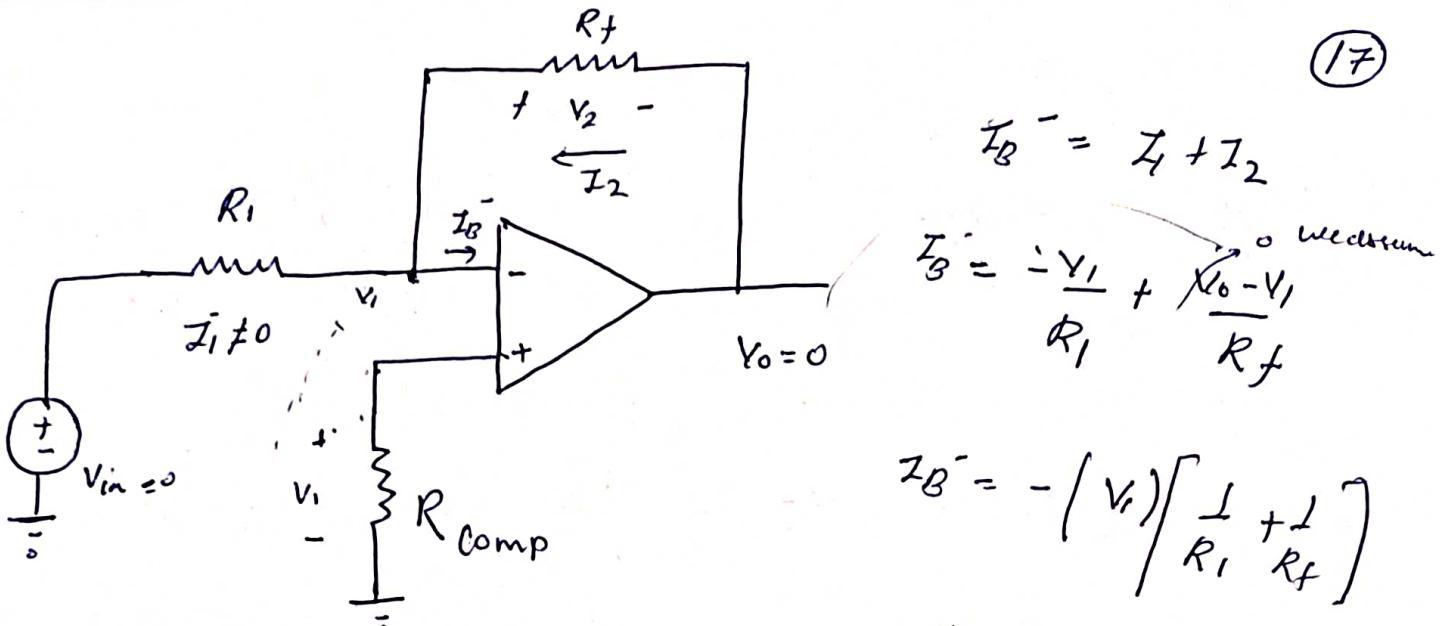
$$= 800 \text{ nA} \times 1M\Omega$$

$$= 800 \text{ mV}$$

↳

to nullify this

we add a resistor to compensate.



$$I_B^- = I_1 + I_2$$

$$I_B^+ = -\frac{V_1}{R_1} + \frac{V_o - V_1}{R_f}$$

(measured)

$$I_B^- = -\left(V_1\right) \left[ \frac{1}{R_1} + \frac{1}{R_f} \right]$$

$$I_B^+ = -\frac{V_1}{R_{comp}}$$

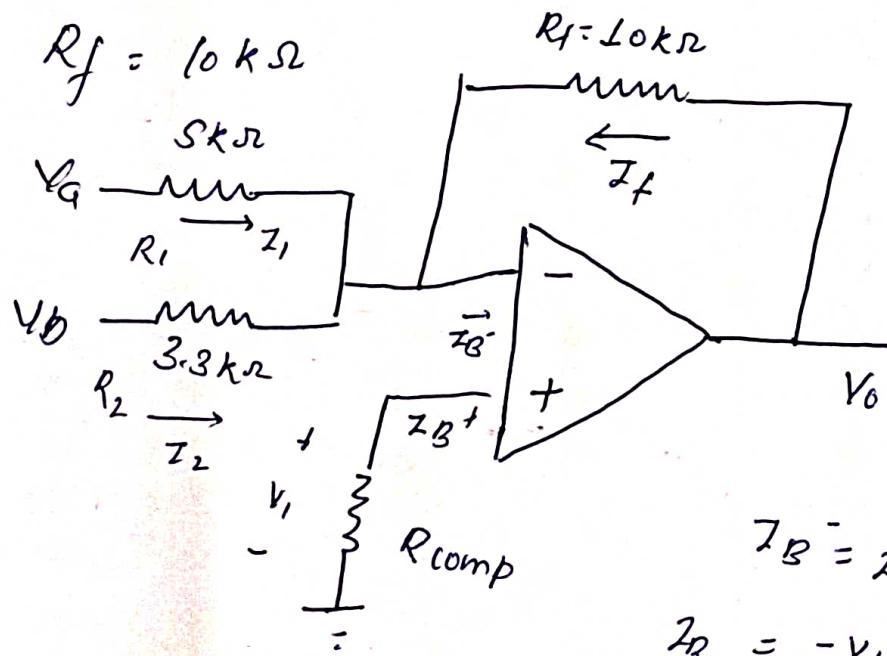
$$\frac{1}{R_{comp}} = \frac{1}{R_1} + \frac{1}{R_f}$$

$$\text{Assume } I_B^+ = I_B^-$$

$$\Rightarrow \frac{V_1}{R_{comp}} = -\frac{V_1}{\left(\frac{1}{R_1} + \frac{1}{R_f}\right)}$$

$$R_{comp} = R_1 // R_f$$

Q: Design an Inverting Summer  $V_o = -2V_1 - 3V_2$   
 OPAMP (BJT)  $I_B = \text{soon } A$ . Draw the suitable Ckt to  
 nullify the effect of Input bias current assume



$$V_o = -(2V_1 + 3V_2)$$

$$\Rightarrow -\left(\frac{R_f V_A + R_f V_B}{R_A R_B}\right)$$

$$\frac{10k\Omega}{R_A R_B} = 2$$

$$R_A R_B = 5k\Omega$$

$$\frac{R_f}{R_B} = 3$$

$$I_B^- = I_1 + I_2 + I_f$$

$$I_B^+ = -\frac{V_1}{R_1} - \frac{V_2}{R_2} - \frac{V_B}{R_f}$$

$$I_B^- = I_B^+$$

$$-\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_f}\right)v_i = -\frac{v_i}{R_{comp}}$$

$$R_{comp} = R_1 // R_2 // R_f$$

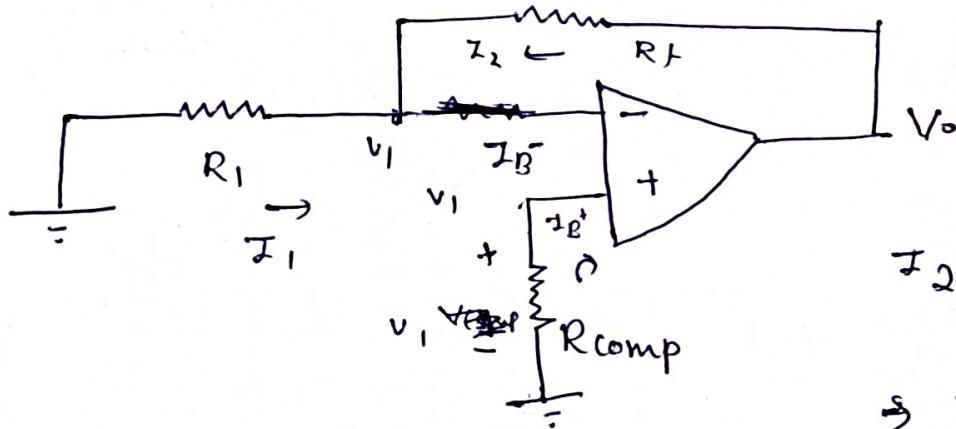
$$= 1 // 3.3 // 10k\Omega = 1.5k\Omega$$

# Input offset current ( $I_{os}$ )

$$|I_{os}| = |I_B^- - I_B^+|$$

Difference b/w S/P bias cur.

$$I_B^- \neq I_B^+ \quad R_{comp}$$



$$200 \times 1M \cdot \\ 200 \times 10^{-9}, 200$$

$$I_2 = \frac{V_0 - V_1}{R_f}$$

$$\Rightarrow V_0 = V_1 + I_2 R_f$$

$$\xrightarrow{\text{R}_1} \frac{V_1}{R_{comp}} = I_B^+$$

$$\xrightarrow{\text{R}_1} \frac{V_1}{R_1} = I_1$$

$$I_2 = I_B^- - \frac{I_B^+ R_{comp}}{R_1}$$

$$V_0 = I_2 R_f + V_1$$

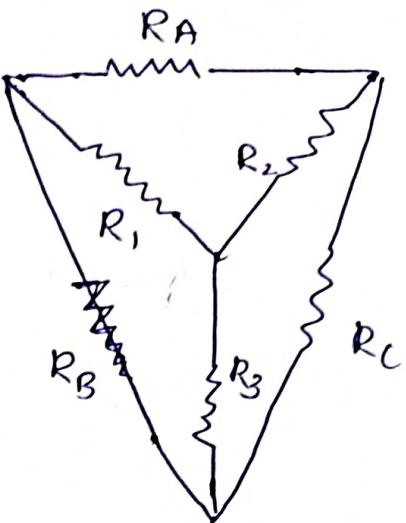
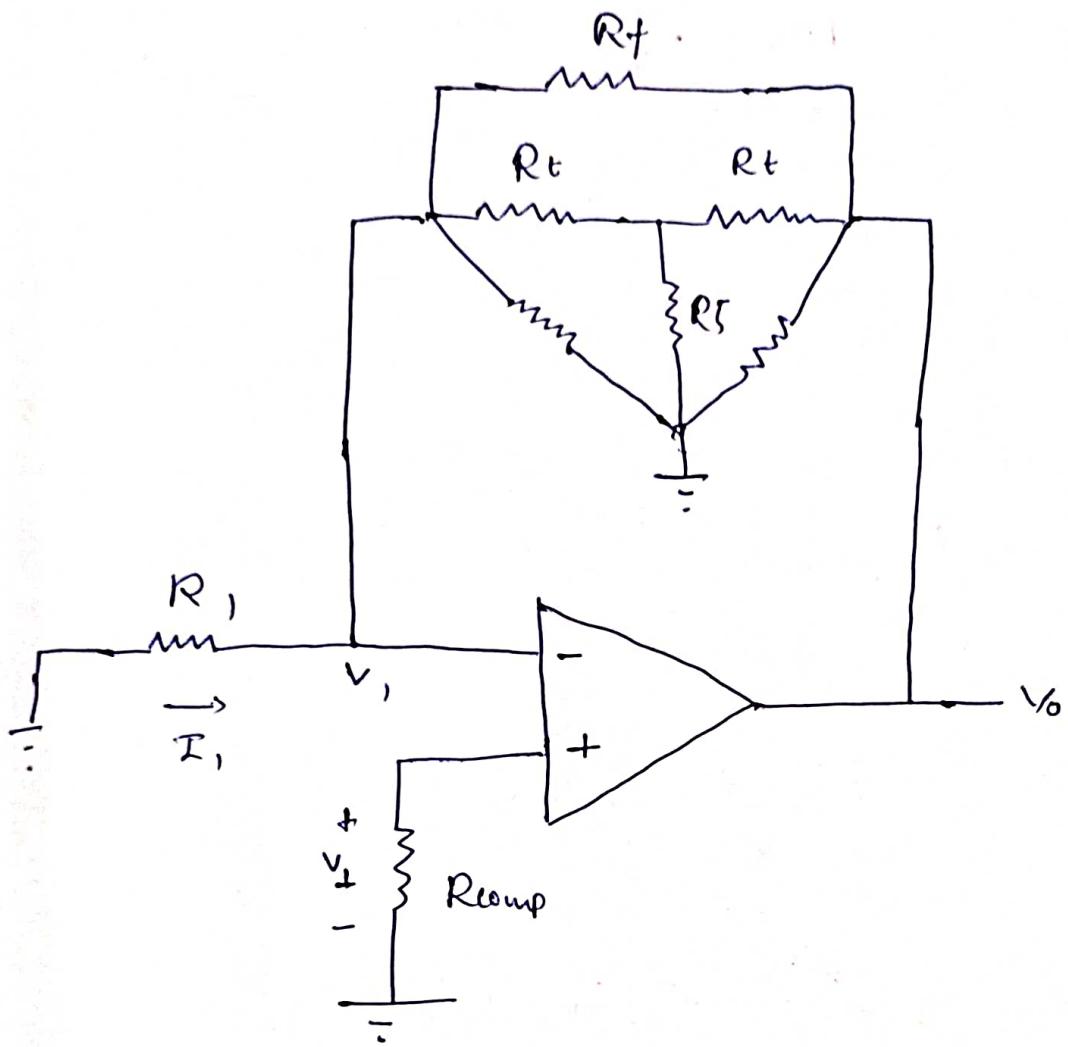
$$V_0 = I_B^- R_f - I_B^+ R_{comp} R_f$$

$$V_0 = (I_B^- - I_B^+) R_f$$

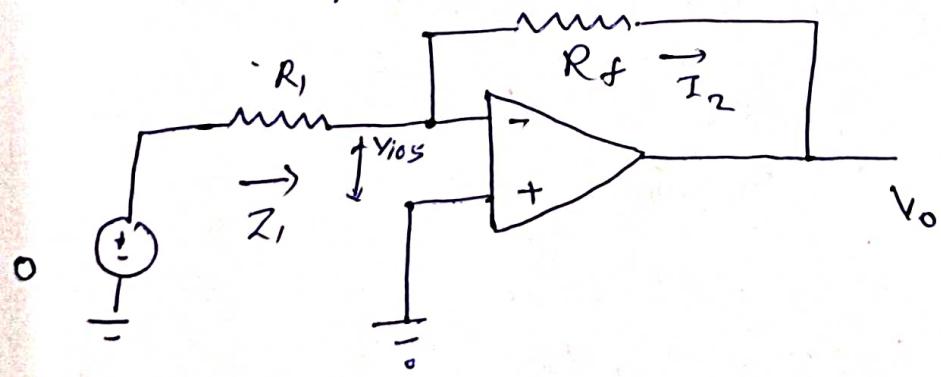
$$\boxed{V_0 = I_{os} R_f}$$

↳ To compensate input offset current

(18)



## # Input offset Voltage ( $V_{ios}$ )



$$V_{ios} = V^+ - V^-$$

$$I_1 = -\frac{V_{ios}}{R_1}$$

$$I_2 = \frac{V_{ios} - V_o}{R_f}$$

$$\Rightarrow V_o = V_{ios} \left( \frac{R_1 + R_f}{R_1} \right)$$

Inverting or  
non-inverting

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

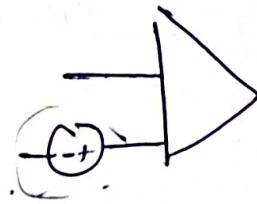
$$\Rightarrow I_1 = I_2$$

$$\Rightarrow \frac{V_{ios} - V_o}{R_f} = -\frac{V_{ios}}{R_1}$$

$$\Rightarrow V_{ios} R_1 - V_o R_1 = -V_{ios} R_f$$

Inverting & Non Inverting

$$V_o = \left(1 + \frac{R_f}{R_i}\right) V_{ios}$$



for BJT  $V_{ios} = 6 \text{ mV}$

The Input offset Voltage is the differential g/p voltage that exist b/w two g/p terminals of an op-amp without any external g/p applied.

- ↳ To Compensate the effect of Input offset voltage to apply a small voltage at input terminals to make o/p voltage is zero
- # Total ~~offset~~ Output offset voltage
  - ↳ the total offset voltage could be either more or less than the offset voltage produced at the output due to Input bias error current or g/p offset voltage alone.
- ↳ The maximum offset voltage at the output of an Inverting or Non Inverting Amplifier without any compensation technique.

$$V_{oT} = \left(1 + \frac{R_f}{R_i}\right) V_{ios} + R_f I_B$$

for both inverting & non inverting

(19)

with  $R_{comp}$ 

$$V_{o7} = \left(1 + \frac{R_f}{R_1}\right) V_{pos} + Z_{os} k_f$$

## # Thermal drift

↳ Bias current, offset current, offset voltage change with temperature ~~will~~

→ A circuit carefully NULled at  $25^\circ\text{C}$  may not remain so when the temperature rises to  $35^\circ\text{C}$  this is called drift.

↳ the offset current drift expressed in  $\text{nA}/^\circ\text{C}$   $\frac{Z_{os}}{Z_E}$

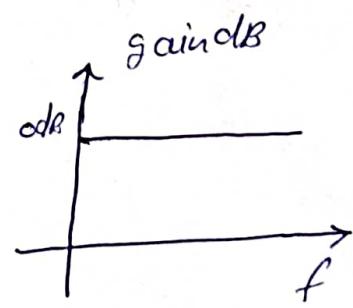
↳ the offset voltage drift expressed in  $\text{mV}/^\circ\text{C}$  ↓  
Rate

 $V_o = 0$  at  $30^\circ\text{C}$  $V_o$  at  $35^\circ\text{C}$ Change  $10 \text{nA}/^\circ\text{C}$ ↳  $10 \times 5 = 50 \mu\text{V}$ .

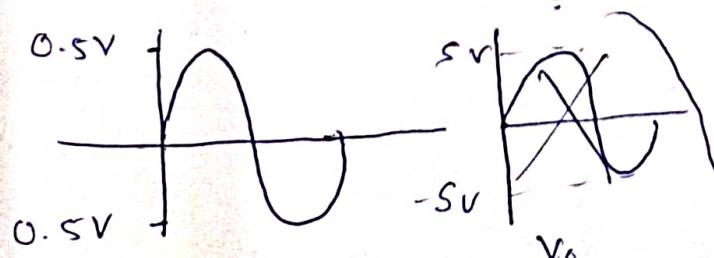
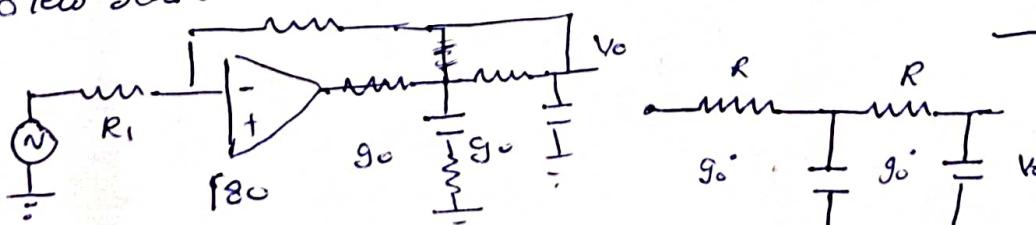
## # AC Characteristics of Op-Amp

1) frequency response

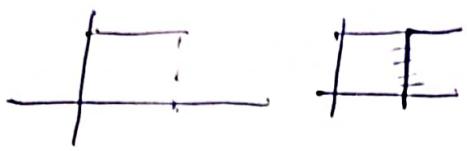
Ideal op Amp



2) slew rate



it will  
act as oscillator? Practically we  
have to check it



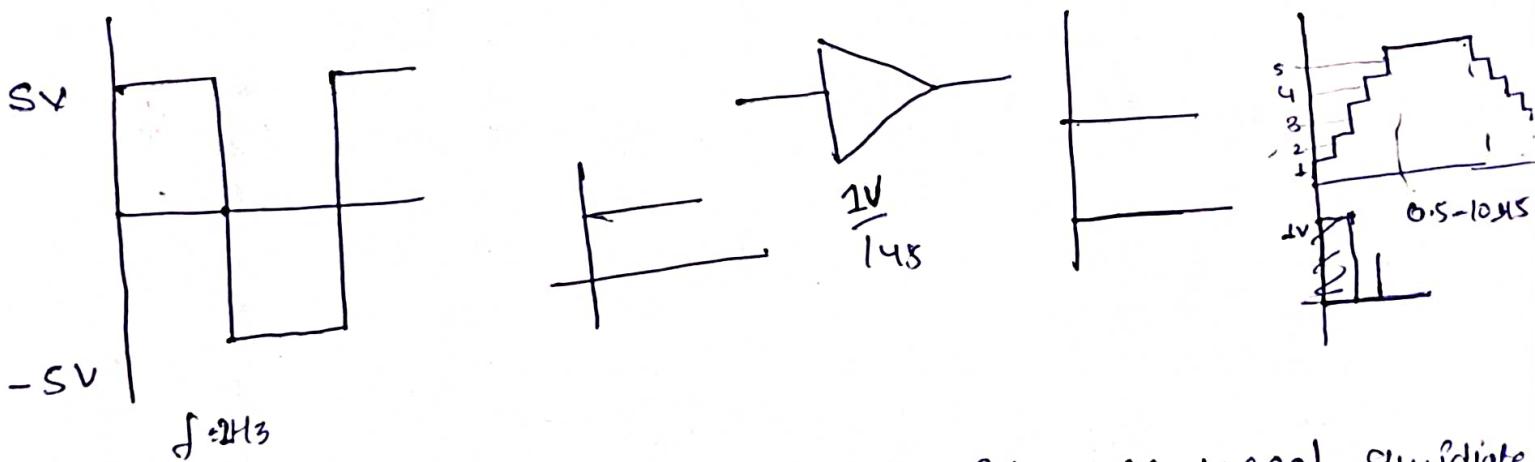
Ques 8  
Ans

### Pole zero compensation

$$H(s) = \frac{(s-z_1)(s-z_2)(s-z_3)}{(s-p_1)(s-p_2)(s-p_3)} \rightarrow \text{fight b/w pole + zero}$$

gain  $\propto \frac{1}{(s-p_1)(s-p_2)(s-p_3)}$

Slew rate - maximum rate of change of o/p voltage caused by step input voltage ( $V_{145}$ )



↳ Slew rate should be infinity if we need immediate output.

$$\cancel{SR} = \cancel{\frac{dV_o}{dt}} \quad SR = \frac{dV_o}{dt}$$

$$SR = \frac{dV_o}{dt}_{\text{max}}$$

$$\text{Eq} \quad V_{in} = V_m \sin \omega_0 t \quad \text{gain} = 1$$

$$V_o = -V_m \sin \omega_0 t$$

$$\frac{dV_o}{dt} = -V_m \omega_0 \cos \omega_0 t$$

$$SR = \frac{V_m \omega_0}{\text{max}} = 2\pi f_{max} V_m$$

$$f_{\text{max}} = \frac{SR}{2\pi V_m}$$

Question  
in sec

Question: find the maximum frequency for a  $\sin(2\omega)$  wave output voltage of 10V peak with one Op-Amp whose slew rate 1V/msec

$$V_o = 10 \sin(\omega_0 t)$$

$$SR = 10 \omega_0$$

$$\frac{dV_o}{dt} = 10 \omega_0 \cos \omega_0 t$$

$$\frac{1}{10^{-6}} = 10 \times 2\pi f_{\max}$$

$$f_{\max} = \frac{\frac{10 \times 10^6}{10 \times 2\pi}}{\frac{10^5}{2\pi} \cdot 3.33 \times 10^4}$$

$$= 33.3 \text{ kHz}$$

$$\rightarrow 33.3 \text{ kHz}$$

Question: A 741C op-amp is used as an inverting amplifier with a gain of 50. the voltage gain vs frequency curve of 741C is flat up to 20 kHz. what maximum peak to peak input signal can be applied without distorting the op-amp

Hint: the slew rate for 741C 0.5 V/us

$$V_o = -50 V_{in}$$

$$V_{m_{in}} = \frac{SR}{2\pi f_{\max}} = \frac{0.5 \times 10^{-3}}{2\pi \times 20 \times 10^3} = 4V$$

we  
should  
get as  
output

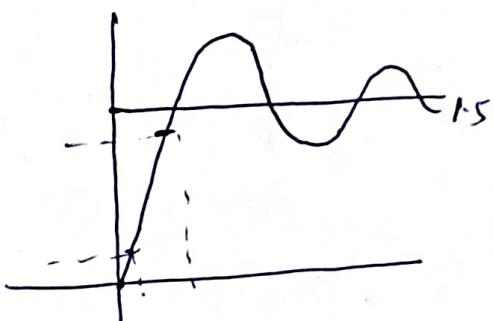
$$\text{Input} = \frac{4}{50 (\text{gain})} = 0.08 \text{ V or } 0.16 \text{ V peak to peak}$$

Question: A square wave of peak to peak amplitude of 200 mV has to be amplified to a peak to peak amplitude of 3V with rise time of 4 μsec or less. Can a 741 be used? For 741 the slew rate is 0.5 V/μs

$$V_{max} \text{ we should get } \frac{3}{2} = 1.5 \text{ V}$$

$$V_{max} = \frac{SR}{2\pi f_c}$$

assume  
2nd order  
system

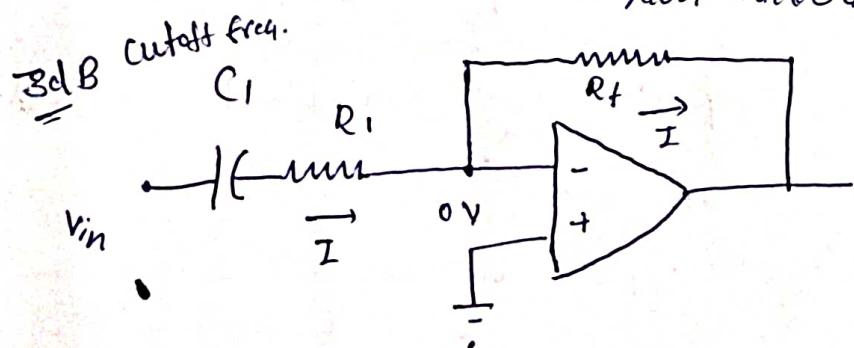


$$\therefore \min \frac{dV_o}{dt}_{max} = \frac{(0.9 - 0.1) 1.5}{4 \mu s}$$

$$\approx \frac{(0.9 - 0.1) 1.5}{4 \times 10^{-6}} = 0.34 \text{ V/}\mu\text{s} \quad (\text{Minimum})$$

~~Not~~ possible

# AC Amplifier : Inverting  
Non Inverting amplifiers.



$$\frac{V_o}{V_{in}} = -\frac{R_f}{R_1 + \frac{1}{j\omega C_1}}$$

$$V_o = -I R_f$$

$$S = j\omega$$

$$I = \frac{V_{in} - 0}{R_1 + \frac{1}{j\omega C_1}}$$

$$V_o = -\frac{V_{in} R_f}{R_1 + \frac{1}{j\omega C_1}}$$

$$V_o = -\frac{V_{in} R_f}{R_1 + \frac{1}{j\omega C_1}}$$

~~$\frac{1}{j\omega C_1} \cdot \frac{1}{R_1 + \frac{1}{j\omega C_1}}$~~

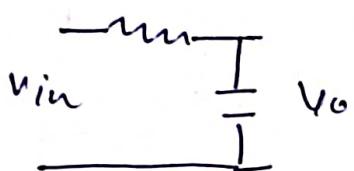
~~$\frac{1}{j\omega C_1} = \frac{1}{R_f} \cdot \frac{R_f}{R_1 + \frac{1}{j\omega C_1}}$~~

~~$\frac{1}{j\omega C_1} = \frac{1}{R_f} \cdot \frac{R_f}{R_1 + \frac{1}{j\omega C_1}}$~~

(24)

$$V_o = -\frac{V_{in} R_f}{R_1 + \frac{1}{j\omega C_1}}$$

Let it will allow low freq & Pt will work as normal amplifying

-3dB

$$\frac{V_o}{V_{in}} = \frac{1}{1 + R_C C_1} = \frac{1}{1 + R_C j\omega C_1}$$

$$\Rightarrow \frac{1}{1 + jRC_1 2\pi f}$$

$$\text{Cutoff freq} \leftarrow f_c = \frac{1}{2\pi R C_1} \Rightarrow \frac{1}{1 + j\frac{f}{f_c}}$$

$$\text{gain} = \frac{1}{1 + j\frac{f}{f_c}}$$

When  $f = f_c$ 

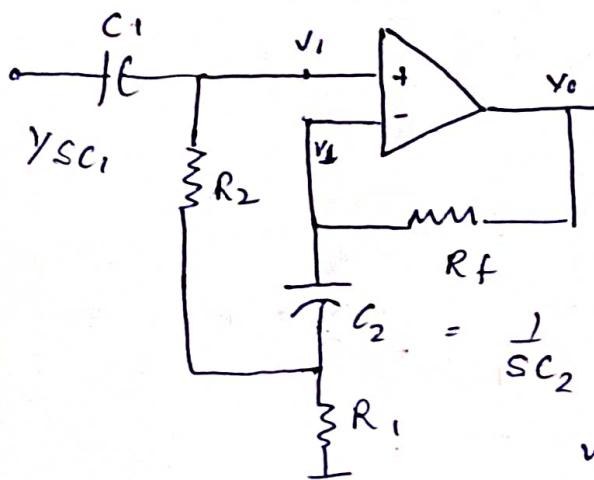
$$\text{gain} = \left| \frac{1}{1 + j} \right| = \frac{1}{\sqrt{2}}$$

$$20 \log \frac{1}{\sqrt{2}} = -20 \log 2^{\frac{1}{2}}$$

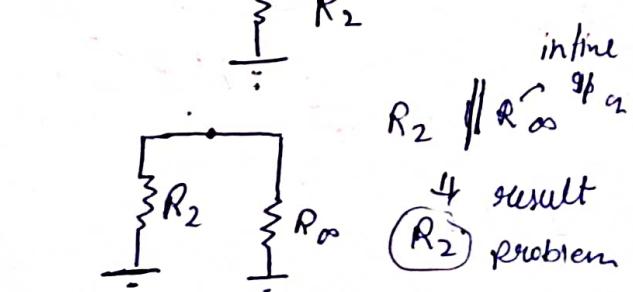
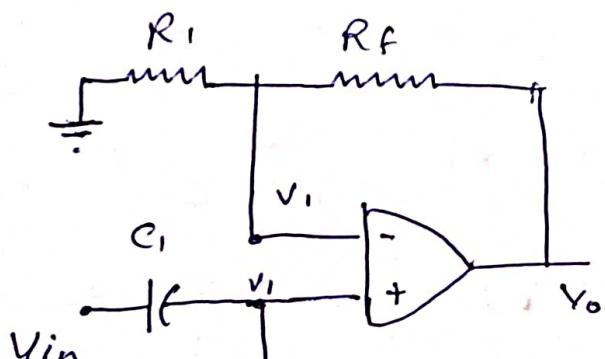
$$\Rightarrow -10 \log 2$$

$$\Rightarrow -3 \text{dB}$$

## # Non Inverting Ac Amp



$$V_o = \frac{V_1}{R_2} = \frac{V_1}{R_2} \cdot \frac{R_o}{R_o + R_2} = \frac{V_1}{R_2} \cdot \frac{1}{1 + \frac{R_2}{R_o}}$$



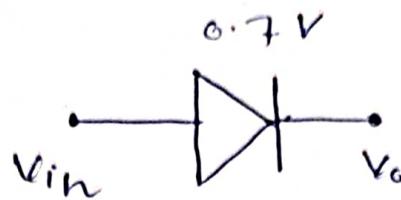
intake  
 $R_2 \parallel R_o$   
 $\frac{1}{(R_2 + R_o)}$  result  
 $(R_2)$  problem

→ Input impedance → Resistance connected to input

### # Precision Diode

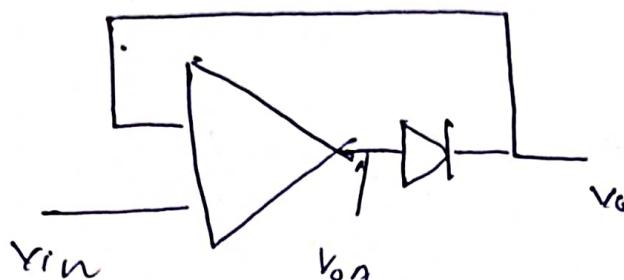
Ideal

$$h_o \rightarrow \infty$$



Practical

$$h_o \rightarrow H_o$$



Voltage follower  
when diode on

when open loop

- b. it will act as op-loop and then  $V_{OA} = +V_{CE}$
- f. diode act as forward bias

$$1mV \text{ } h_o$$

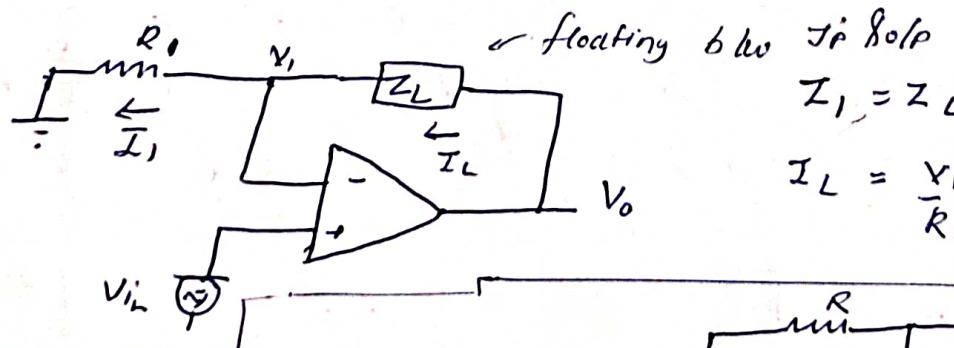
$$1mV \text{ } V_o$$

### # V-I Converter & Transconductance Amplifier

Input Voltage into Output Current (Load current)

(i) V-I converter with floating load

(ii), .. with grounded load.

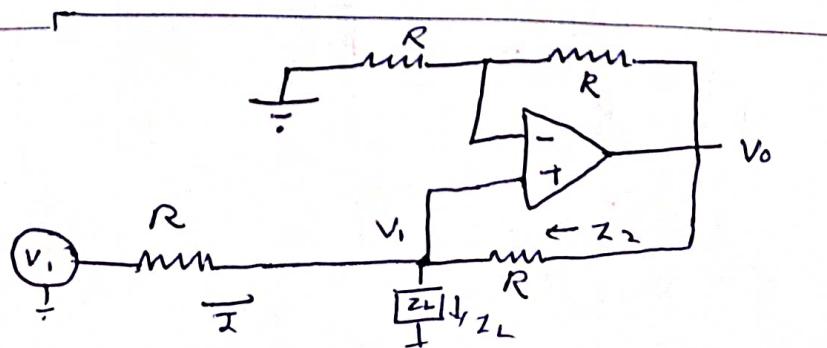


$$I_{L1} = Z_L$$

$$I_L = \frac{V_1}{R}$$

$$Z_L \propto V_1$$

$$I_L = \frac{V_i - V_1}{R} + \frac{V_o - V_1}{R}$$



$$I_L = \frac{V_1 - 2V_1 + V_0}{R}$$

$\therefore$  Non generation,

$$= \frac{V_1 - 2V_1 + 2V_1}{R}$$

$$V_0 = (1+1)V_1$$

$$V_0 = 2V_1$$

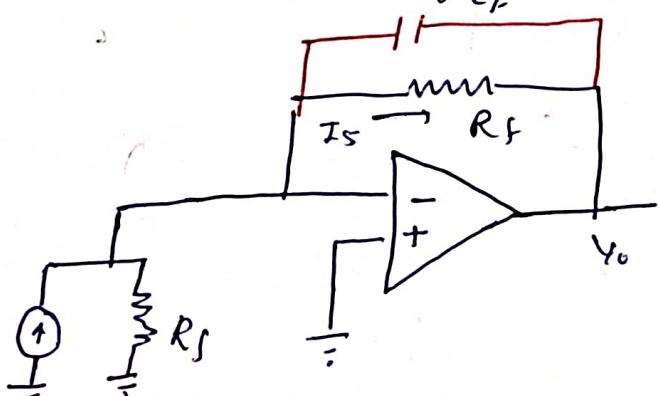
$I_L = \frac{V_1}{R}$

~~App~~: AC + DC Voltmeter, Diode of LED testing

# I to V converter [transistor Amplifier]

Photo Cell - Light Energy  $\xrightarrow{er}$  into electric energy

$\hookrightarrow$  Current  $\rightarrow$  Voltage



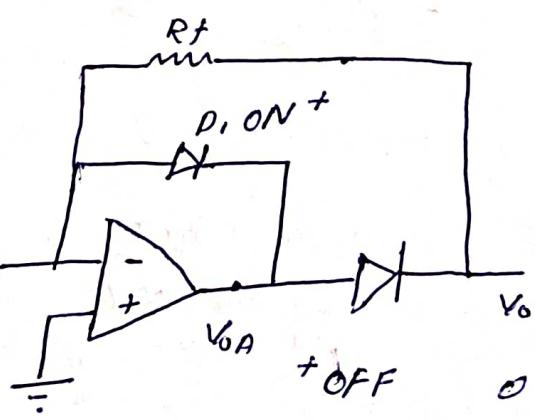
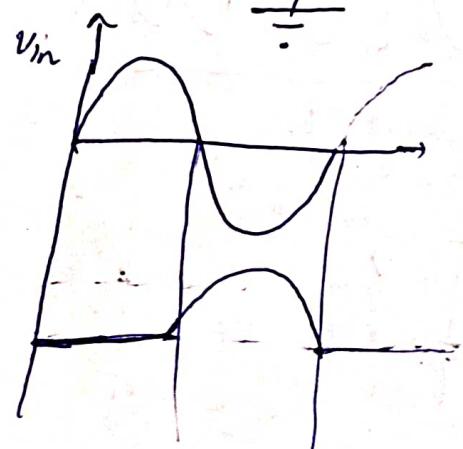
$$V_o = -75 R_f$$

$V_o \propto 75$

$C_F$  to reduce the effect of  
high freq. noise.

# Application of precision diode

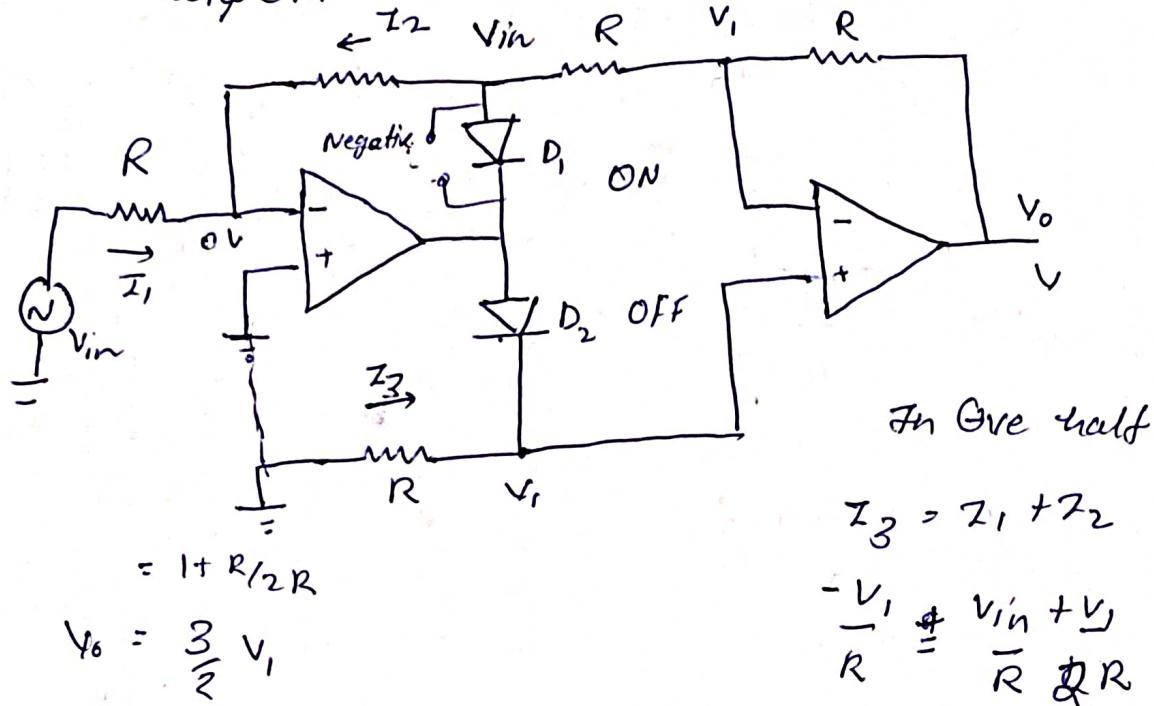
1. Half wave rectifier.  $\rightarrow$
2. Full wave rectifier
3. Peak value detector
4. Clamper
5. Clipper.



open loop - close loop

so we need high  
slew rate.

(iii) Full wave rectifier / Absolute value Ckt

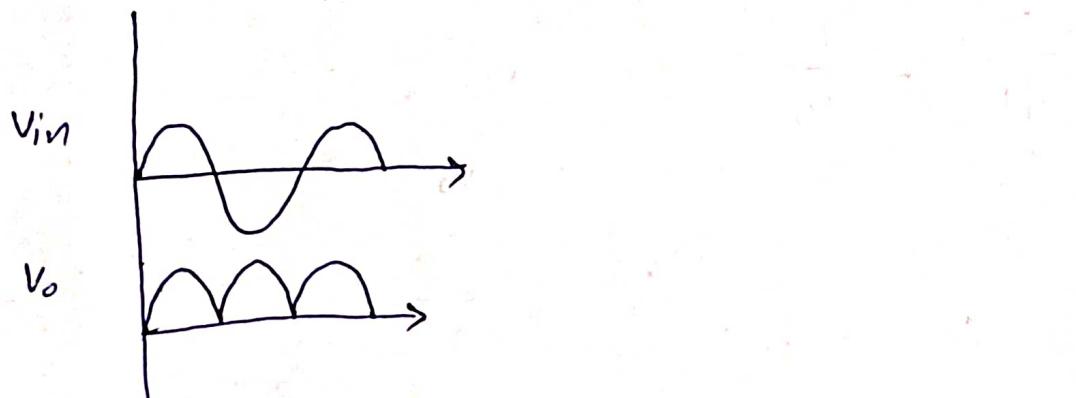


$$V_0 = \frac{3}{2} - \frac{2}{3} V_{in}$$

$$\frac{-V_1}{R} = \frac{V_{in} + V}{R}$$

$$V = -\frac{2}{3} V_{in}$$

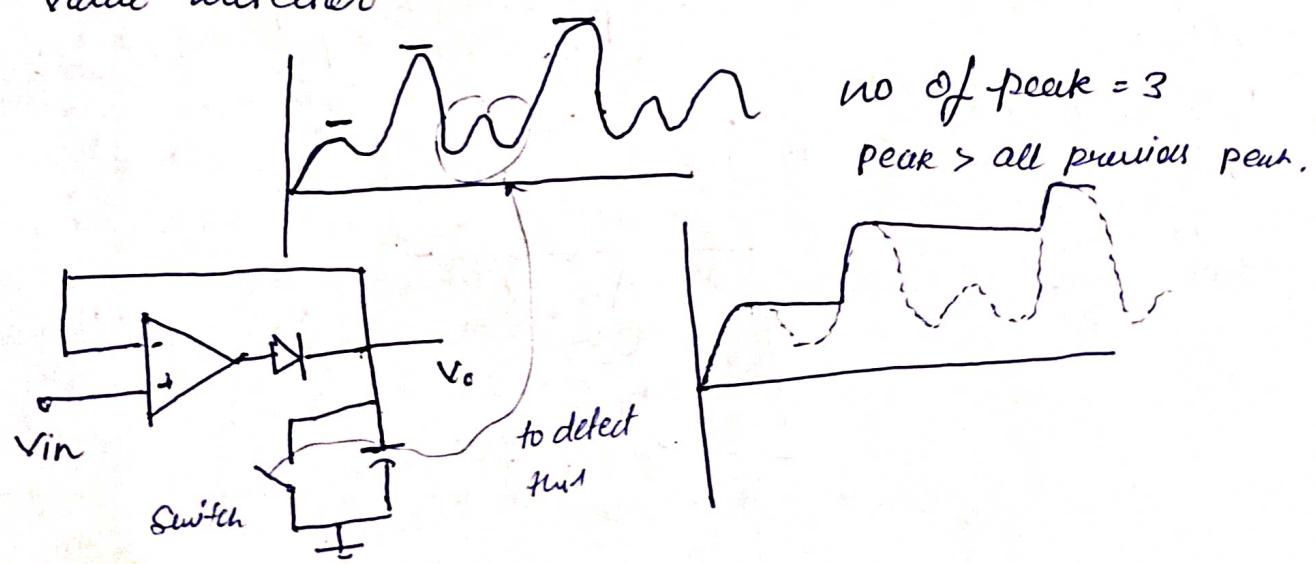
$$V_0 = -V_{in}$$

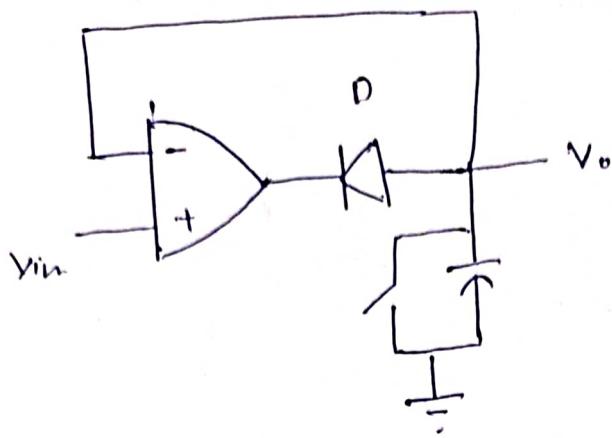


# Application of precision diode

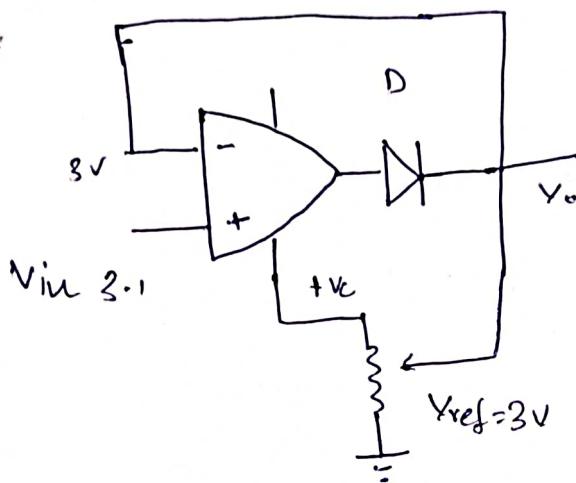
# Absolute value circuit (full wave rectifier)

↪ Peak value detector

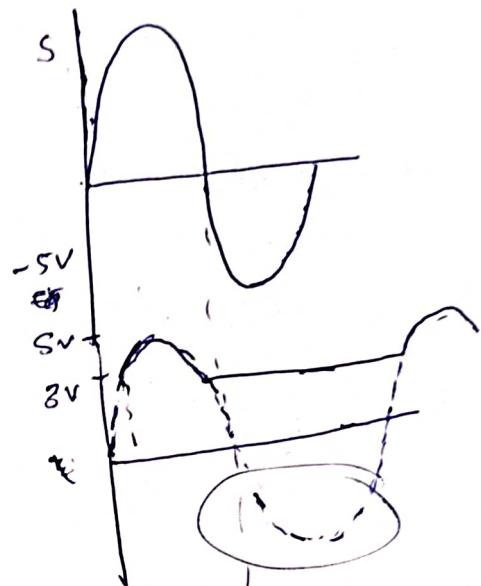




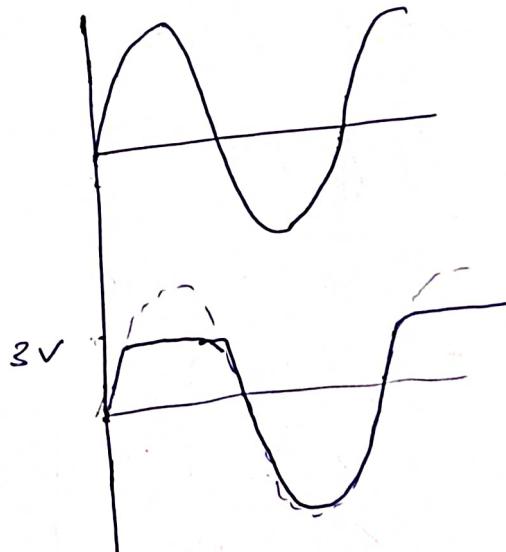
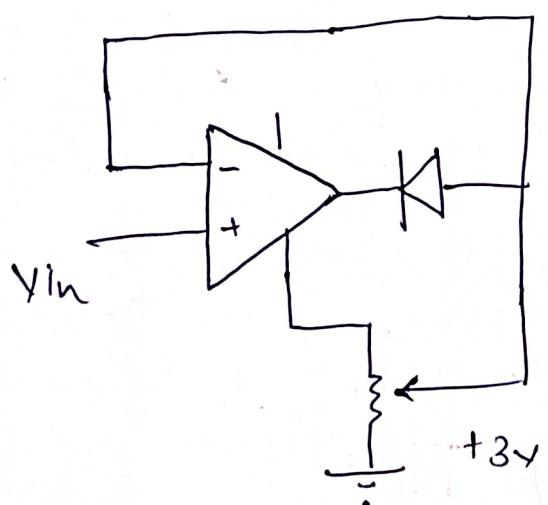
# Clipper



Negative clipper

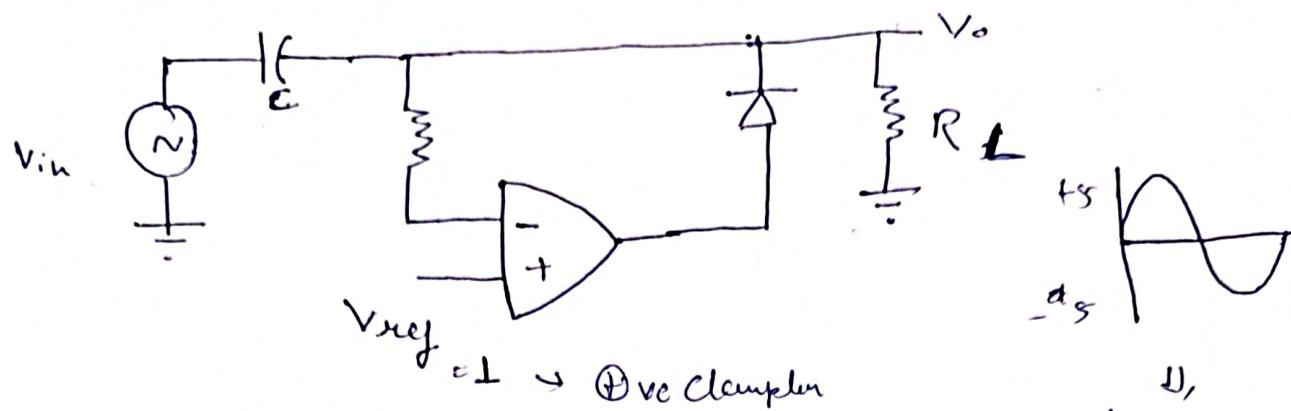


Eliminated



positive clipper

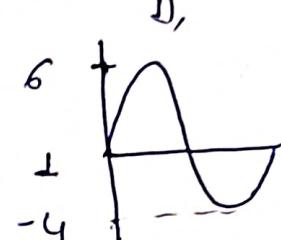
## # Clamper / DC-Injector



Superposition principle

$$V_{o1} \Rightarrow V_{in} = 0 \quad V_{ref} = 1V \Rightarrow V_o = V_{ref}$$

$$V_{o2} \Rightarrow V_{ref} = 0 \quad V_o = V_{in} + V_m$$



Clamp by  $V_{ref} = 1$

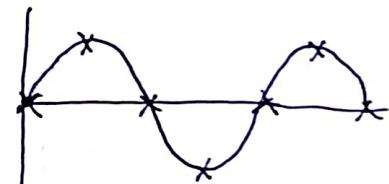
$$V_o = V_{o1} + V_{o2}$$

$$= V_{ref} + V_{in} + V_m$$

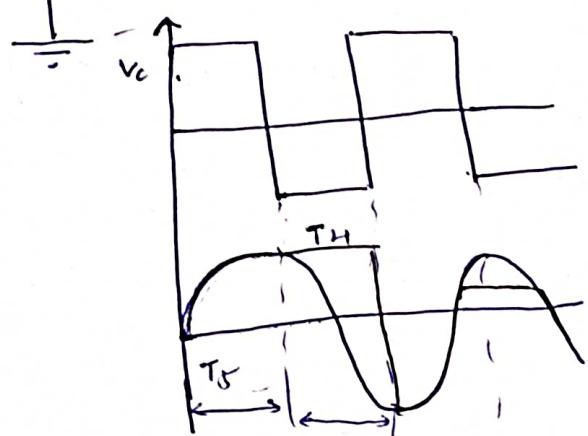
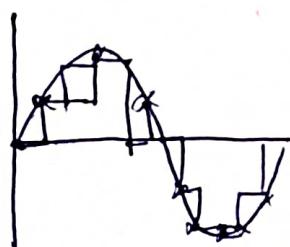
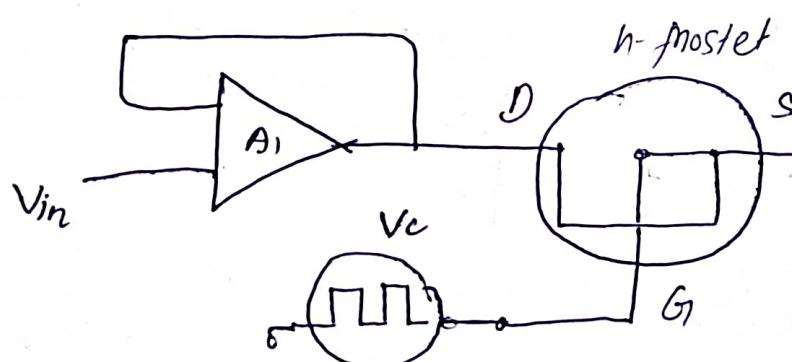
↳ if  $V_{ref} = -1$  negative clamper

# Sample & Hold Circuit

$$T_s = \frac{1}{f_s}$$



Increasing the sampling freq  $\approx$  decreasing sampling interval.

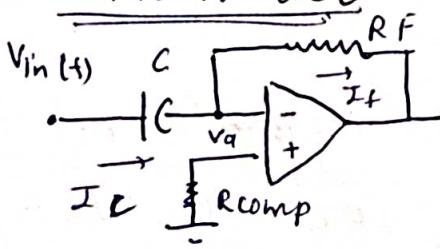


Sampling → Hold Period

- ↳ This ckt samples ~~and~~ input signal & hold on to its last sampled value until the input is sampled it is very useful in digital interfacing, A to D conversion & pulse code modulation system.
- ↳ The N-channel E-mosfet works as switch and controlled by drain control voltage  $V_C$ .
- ↳ The capacitor C stores the charge.
- ↳ The analog signal  $V_{in}$  to be sampled to the drain of the P-mosfet and control voltage DC applied to its gate when control voltage  $V_C$  is 0V the P-mosfet turns off and capacitor C charges to the instantaneous value of input  $V_{in}$  with time constant  $(R_o + R_{ds(on)})C$  where  $R_o$  is output resistance of voltage follower  $A_1$  and  $R_{ds}$  is the resistance of mosfet when on
- ↳  $T_s$  - time during which voltage across this capacitor equal to input voltage is called sample period.
- ↳  $T_h$  - time during the voltage across capacitor held constant is called hold period.
- ↳ low leakage capacitor such as polystyrene Nylon or Teflon should be used to redirect retain the stored charge.

- ↳ This ckt samples ~~and~~ input signal & Hold on to its last sampled value until the input is sampled it is very useful in digital interfacing, A to D Conversion & Pulse Code modulation system.
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### Differentiator



$$I_C = \frac{C dV_{in}}{dt}$$

$$V_o(t) = \frac{dV_{in}(t)}{dt}$$

$$I_C = I_f$$

$$C \frac{dV_{in}}{dt} = -\frac{V_o}{R_f}$$

$$\Rightarrow V_o = -R_f C \frac{dV_{in}}{dt}$$

$$V_o \propto \frac{dV_{in}}{dt}$$

$$H(s) = \frac{V_o(s)}{V_{in}(s)}$$

$$V_o = -R_f C \frac{dV_{in}}{dt}$$

$$V_o(s) = -R_f C V_{in}(s)s$$

$$|H(s)| = \left| \begin{vmatrix} V_o(s) \\ V_{in}(s) \end{vmatrix} \right| = |-R_f C_1 s| = |-R_f C j\omega f|$$

$$= 2\pi R_f C_1$$

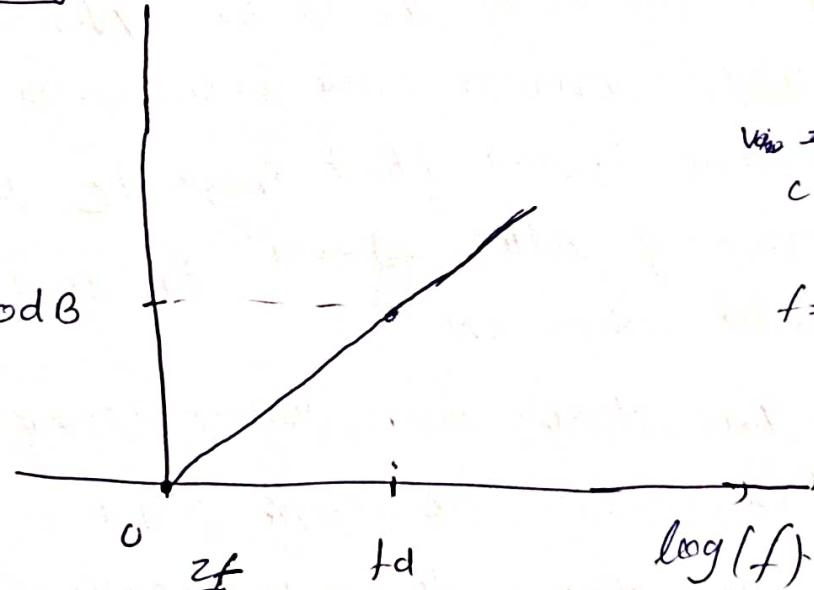
$$\phi = \tan^{-1} \frac{1}{\omega} = 90^\circ$$

$$|H(s)| = \frac{f}{f_d} \quad f_d = \frac{1}{2\pi R_f C_1}$$

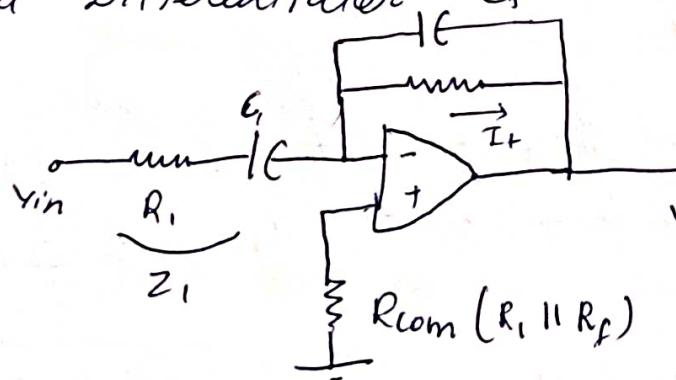
freq Response

①  $f \uparrow c=0$

② gain dependent on  $\text{odB}$   
g/p freq ckt behave  
like oscillator



Practical Differentiator



$$(1) V_{in} = \sin(100\pi t)$$

$$V_o = 100\pi \cos(100\pi t)$$

$$(2) V_{in} = \sin(10000\pi t)$$

$$V_o = 10000\pi \cos(10000\pi t)$$

$$\frac{V_o}{V_{in}} = \frac{Z_f}{Z_1} = \frac{\frac{R_f}{j\omega C_f + jR_f C_f}}{\frac{R_1}{j\omega C_1} + \frac{R_f}{j\omega C_f + jR_f C_f}} = \frac{\frac{R_f}{j\omega C_f + jR_f C_f}}{\frac{j\omega C_1 R_1 + jR_f C_f}{j\omega C_1 R_1 + jR_f C_f}}$$

$$Z_1 = R_1 + \frac{1}{j\omega C_1}$$

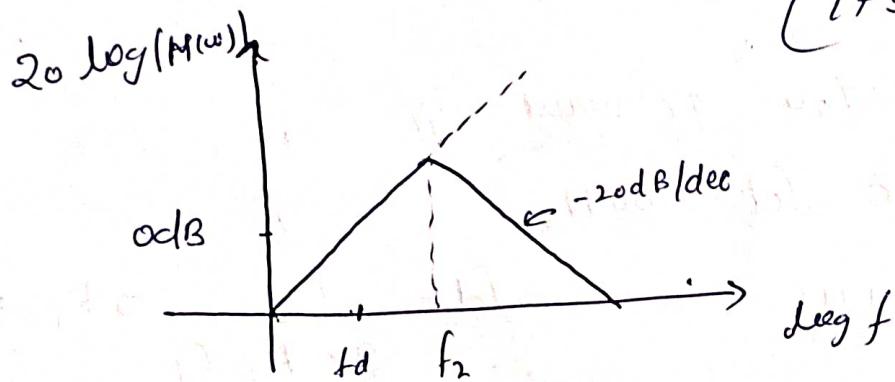
$$Z_f = R_f + \frac{1}{j\omega C_f} = \frac{R_f}{j\omega C_f + jR_f C_f}$$

$$\frac{V_o}{V_{in}} = \frac{-Z_f}{Z_1} = \frac{-j\omega R_f C_1}{(1+j\omega R_f C_1)(1+j\omega R_1 C_1)}$$

$$j\omega = s$$

$$\frac{V_o}{V_{in}} = \frac{-SR_f C_1}{(1+SR_f C_1)(1+SR_1 C_1)} = \frac{-j f / f_d}{(1+j f / f_d)^2}$$

Let  $R_f C_1 = R_1 C_1 \Rightarrow \frac{V_o}{V_{in}} = \frac{-SR_f C_1}{(1+SR_f C_1)^2} =$



↳  $f_d$  is the unity gain bandwidth of op-amp in open loop comp.

↳  $f_2$  is unity gain bandwidth in open loop configuration

↳ for good differentiation one must ensure that the time period  $T$  of input signal is larger than or equal to  $R_f C_1$

$$T \geq R_f C_1$$

↳ It may be noted that for  $R_f C_1 \gg R_1 C_1 + R_f C_f$

$$\frac{V_o}{V_{in}} = \frac{-SR_f C_1}{(1+SR_f C_1)^2}$$

is reduced to

$$\frac{V_o}{V_i} = -SR_f G$$

↳ Design Step of practice Differentiation

S ① Choose a  $f_d$  equal to a highest freq of Input Signal and select  $C_1 \leq T_{diff}$  and find  $R_f$

S ② choose this  $f_2 = 10$  times  $F_d$  Now calculate the values of  $R_1$  and  $R_f$  so that  $R_1 C_1 = R_f C_f$

Q: Design a Op-Am Differentiator that will differentiate a  $\sin$  wave with maximum freq  $100\text{Hz}$  draw the output waveform for a sin wave of +V peak at  $100\text{Hz}$  applied to the differentiator.

Q: Repeat the same for Sqv wave  $\text{g/p}$

$$f_{max} = 100\text{Hz} \text{ i.e } f_d = 100\text{Hz}$$

$$C_1 = 1\text{uf} \quad f_d = \frac{1}{2\pi R_f C_1} \Rightarrow R_f = \frac{1}{2\pi C_1 f_d}$$

$$f_2 = 10 * 100 = 1\text{kHz}$$

$$\text{assume } R_1 C_1 = R_f C_f$$

$$f_2 = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi R_f C_f}$$

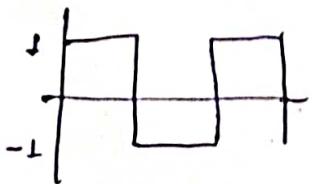
Result  $C_1 = 0.1\text{uf}$   $R_f = 15.9\text{k}$   $R_1 = 1.59\text{k}$ ,  $f_f = 0.01\text{uf}$

②

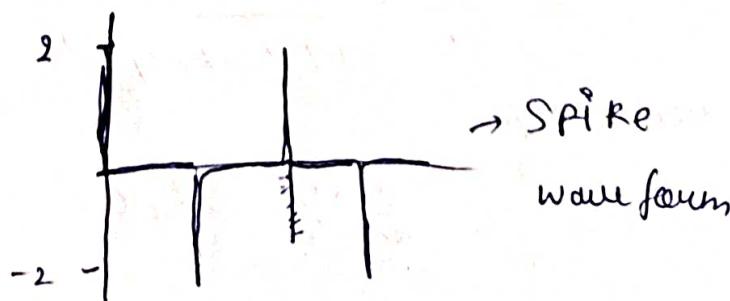
$$V_{in} = 2 \cdot \sin(100\pi t)$$

$$V_o = -R_f C_1 \frac{dV_i}{dt} = -\cos 2\pi 100t$$

③

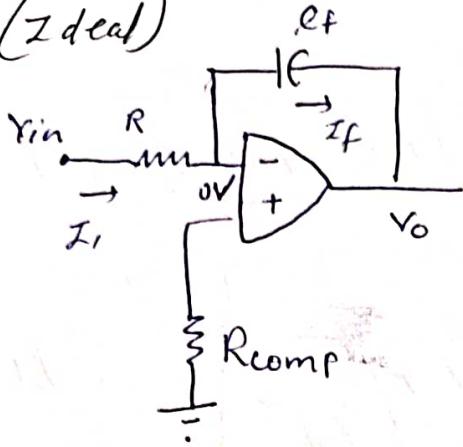


"difference"



(26)

## # Integrator (Z ideal)



$$V_o(s) = -\frac{1}{R_1 C_f} \frac{V_{in}(s)}{s}$$

$$\therefore i_1 = i_f$$

$$\frac{V_{in}}{R_1} = -C_f \frac{dV_o}{dt}$$

$$\frac{1}{R_1} \int_{-\infty}^t V_{in}(t) dt = -C_f V_o(t)$$

$$\boxed{V_o(t) = -\frac{1}{R_1 C_f} \int_{-\infty}^t V_{in}(t) dt}$$

$$\frac{V_o}{V_{in}} = \frac{-1}{s R_1 C_f} \Rightarrow s = j\omega$$

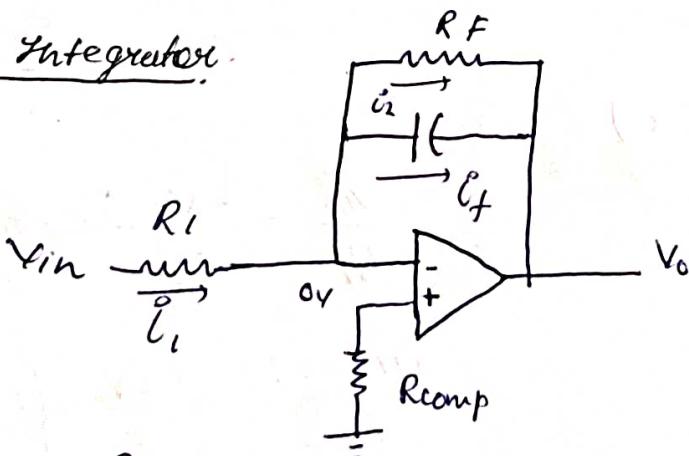
$$\frac{V_o}{V_{in}} = \frac{-1}{R_1 C_f j\omega} \Rightarrow \left| \frac{V_o}{V_{in}} \right| = \frac{1}{R_1 C_f \omega} = \frac{1}{[R_1 C_f 2\pi] f}$$

$$|H(j\omega)| = \frac{V_o}{V_{in}} = \frac{f_a}{f}$$

$$f_a = \frac{1}{2\pi R_1 C_f}$$

↳ when  $f=0$   $H(0) = \infty$  ← problem low freq gain saturated

$$f = \infty \quad H(\infty) = 0$$

Lossy Integrator

$$H(j\omega) = -\frac{R_f}{R_1 (1 + R_f C_f \omega)}$$

$$|H(j\omega)| = \frac{R_f}{R_1 \sqrt{1 + R_f^2 C_f^2 \omega^2}}$$

$$i_1 = i_2 + i_f$$

$$\frac{V_{in}}{R_1} = -\frac{V_o}{R_f} - C_f \frac{dV_o}{dt}$$

Taking Laplace transform

$$\frac{V_{in}(s)}{R_1} = -\frac{V_o}{R_f} - C_f s V_o(s)$$

$$\Leftrightarrow \frac{V_o(s)}{V_{in}(s)} = -\frac{R_f}{R_1 (1 + R_f C_f s)}$$

$$H(jf) = \frac{RF}{R_f \sqrt{1 + 4\pi^2 R_f^2 C_f^2 f^2}}$$

$$\boxed{|H(jf)| = \frac{R_f}{R_f \sqrt{1 + (f/f_q)^2}}} \quad \therefore f_q \geq \frac{1}{2\pi R_f C_f}$$

$$f=0 \quad |H(jf)| = \frac{R_f}{R_f}$$

$$f=f_q \quad = \frac{R_f}{R_f \sqrt{2}}$$

$$f=\infty \quad H(jf) = 0 \rightarrow \text{high noise element}$$

$$f=10 \quad f_q \rightarrow 99\% \text{ accuracy}$$

Q: Consider a lossy integrator with  $R_f = 10 \text{ k}\Omega$   $R_f = 100 \text{ k}\Omega$   $C_f = 10 \text{ nF}$ . Determine the low freq limit of integration and study the response for G/p Sin wave, Step input and Sqr wave.

$$f_q = \frac{1}{2\pi R_f C_f} = \frac{1}{2\pi 100 \times 10^{-9} \times 10^{-9}} = \frac{1000}{2\pi} = \frac{500}{\pi} = 159.43$$

$$V_{in} = \sin(\underbrace{2\pi \times 159 t}_{\omega_q})$$

$$V_o = -\frac{R_f}{R_f \sqrt{1+}} \cdot$$

$$\frac{V_{in}}{R_f} = -\frac{V_o}{R_f} - C_f \frac{dV_o}{dt}$$

$$V_{in}(s) = \frac{\omega_q}{s^2 + \omega_q^2}$$

$$\int \frac{\sin(\omega_q t)}{R_f} dt = \int -\frac{V_o}{R_f} dt - \int C_f \frac{dV_o}{dt}$$

$$V_o = -C_f + \sqrt{C_f^2 - \frac{4C_f \cos \omega_q t}{R_f R_f \omega_q^2}} \cdot \frac{\omega_q^2}{2/R_f}$$

$$\frac{-\cos \omega_q t}{\omega_q R_f} = -\frac{V_o^2}{R_f} - C_f V_o$$

$$\frac{V_o^2}{R_f} + C_f V_o + \frac{\cos \omega_q t}{\omega_q R_f}$$

$$\left| \frac{V_o}{V_{in}} \right| = |H(j\omega)| = \frac{R_f}{R_1 \sqrt{1 + \left(\frac{f}{f_0}\right)^2}} \quad \therefore f = 10f_0$$

$$\frac{V_o}{V_{in}} = \frac{10}{\sqrt{1 + 10^2}} = \frac{10}{\sqrt{101}} \approx \pm 1$$

$$f = \frac{f_0}{10}$$

$$\frac{10}{\sqrt{1 + \left(\frac{f}{f_0}\right)^2}} = \frac{10 \times 10}{\sqrt{101}} \approx 10$$

$$f = 10 \times 159 \text{ Hz}$$

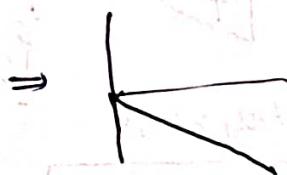
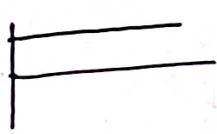
Sin wave  $\Rightarrow$



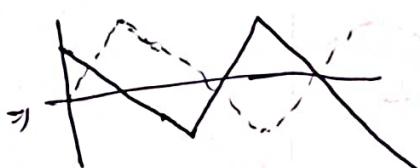
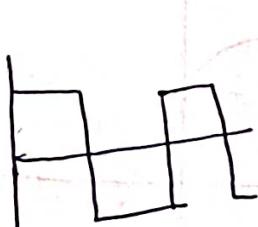
Integrate (-1) =



Square wave =  
unit step



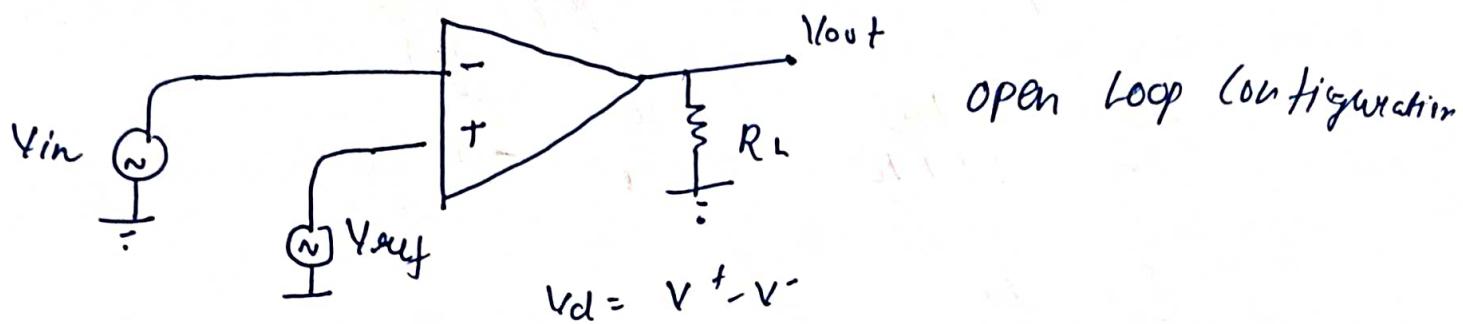
Unit saw  
Sqr wave



$$\frac{V_o}{V_{in}(s)} = \frac{-R_f / R_1}{1 + C_f R_f s} = \frac{-R_f / R_1}{\left( \frac{1}{s} + \frac{1}{C_f R_f} \right)} = -\frac{1}{R_1 C_f \left( \frac{1}{s} + \frac{1}{C_f R_f} \right)}$$

$$H(s) = -\frac{1}{R_1 C_f} \frac{1}{s}$$

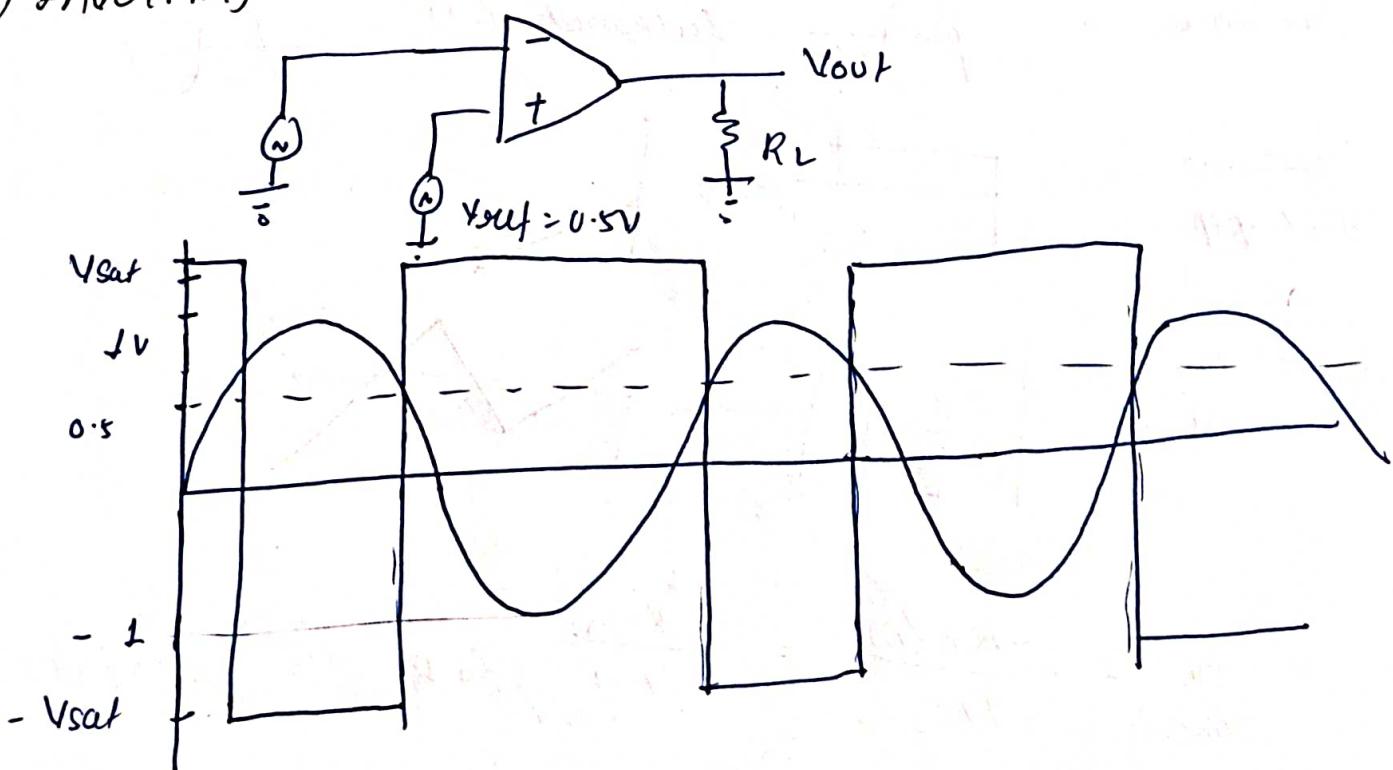
## # Comparator (Non linear operation of Op-Amp)



Based on the g/p → two types of Comparator are there

- 1) Inverting Comparator
- 2) Non-Inverting Comparator

### 1) Inverting



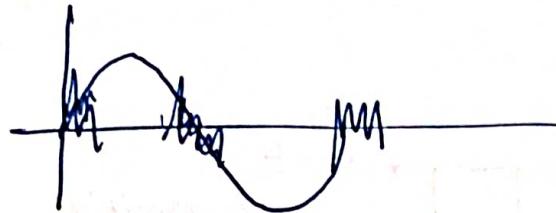
↳ Used for A to D converter

↳ g/f is sine to square wave converter

↳ If  $V_{ref} = 0 \rightarrow g/f$  acts as a "zero detector"

↳ Here input freq = output frequency

Issue

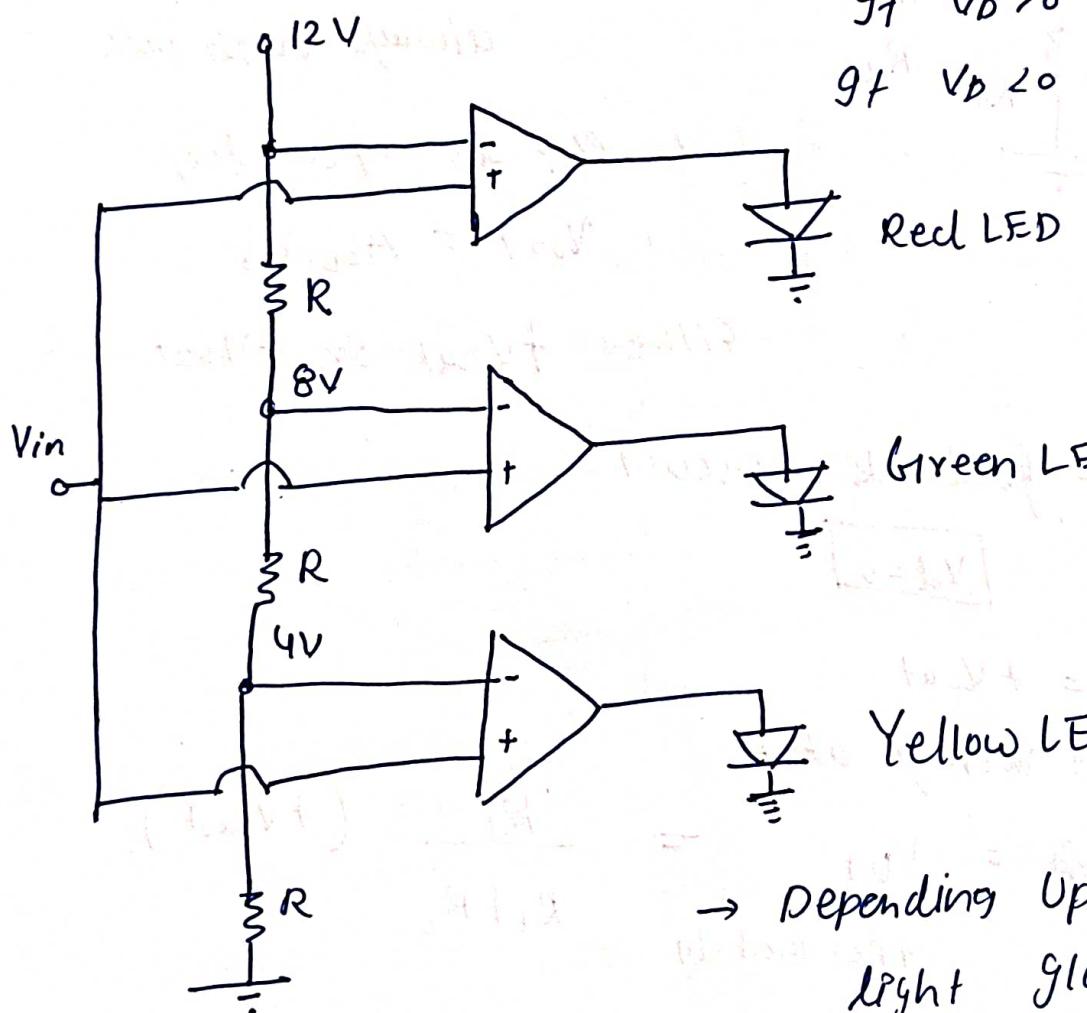


→ Due to Noise

there will be some deviation in o/p sqr wave so we need another Ckt

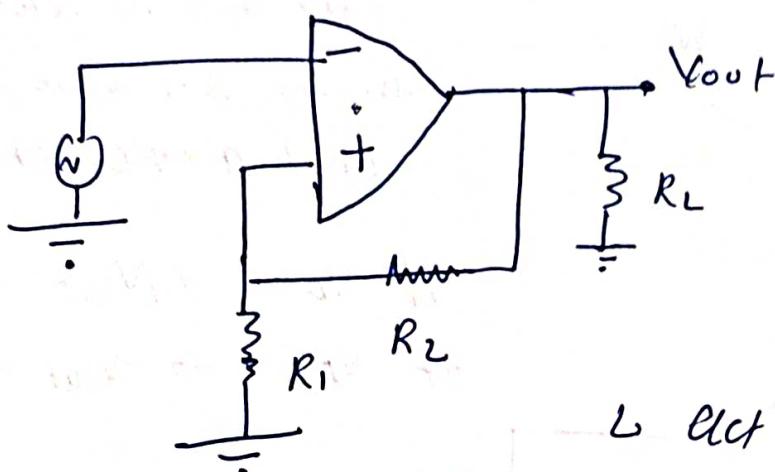
(28)

### Window Detector



V <sub>in</sub>	Red	Green	Yellow
13V	ON	ON	ON
10V	OFF	ON	ON
6V	OFF	OFF	ON
3V	OFF	OFF	OFF

# Regenerative Comparator / Schmitt trigger / positive representation comparator.



↳ positive feedback circuit  $\rightarrow V_d \neq 0$   
always high gain

↳ acts as open loop

$$V_{out} = A_{OL} V_D$$

Either  $+V_{sat}$  or  $-V_{sat}$

↳ ONLY in Gve feedback circuit

$$\boxed{V_d = 0}$$

Case 1  $V_{out} = +V_{sat}$

then Voltage at A,

$$V_A = V_{out} + \frac{R_1}{R_1 + R_2} (+V_{sat})$$

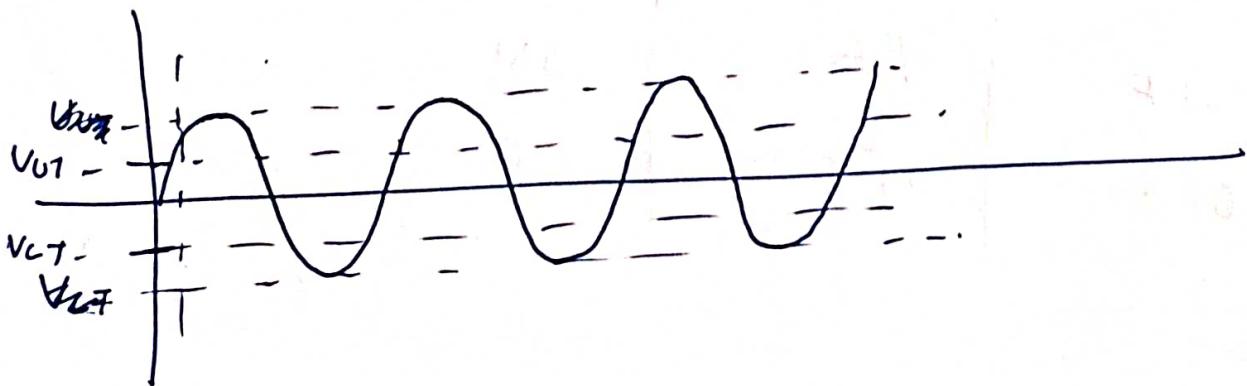
upper threshold

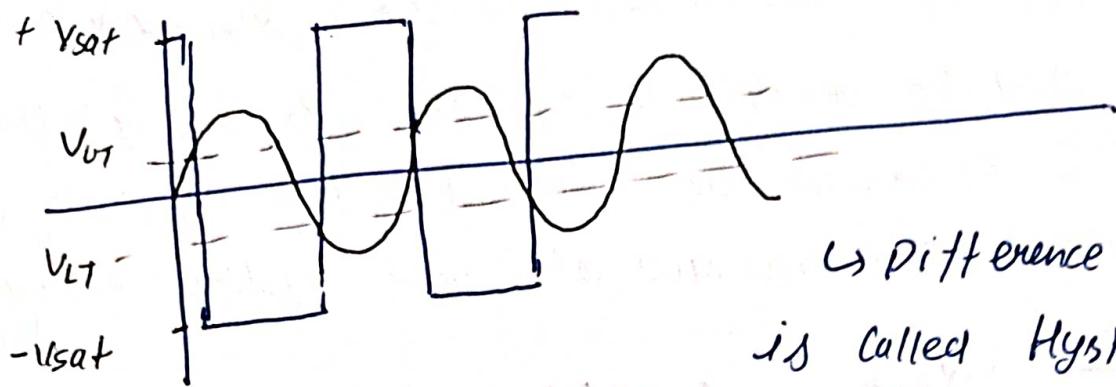
Case 2

$V_{out} = -V_{sat}$ , then Voltage at A

$$V_A = V_{out} + \frac{R_1}{R_1 + R_2} (-V_{sat})$$

lower threshold

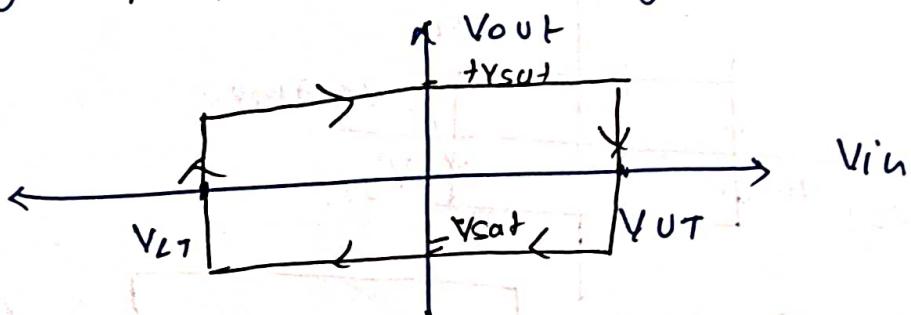




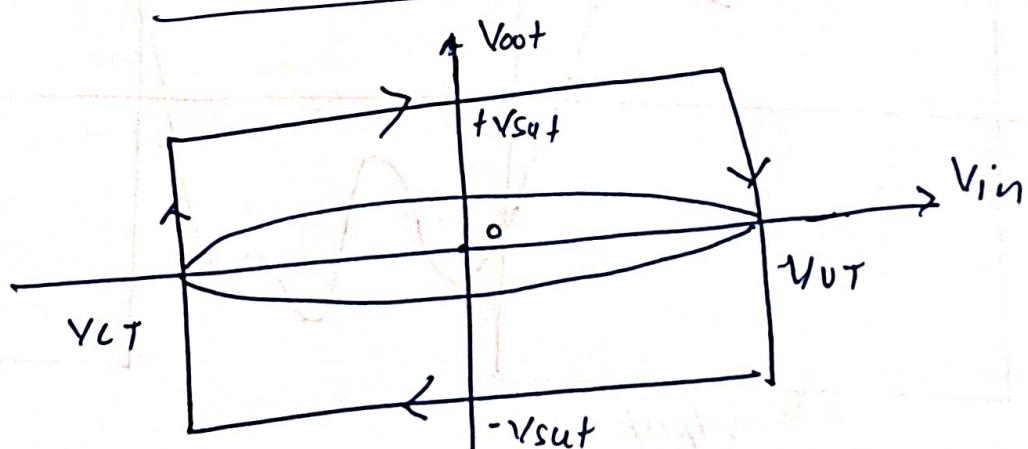
↳ Difference b/w  $V_{UT}$  &  $V_{LT}$   
is called Hysteresis Voltage

$$V_H = V_{UT} - V_{LT}$$

↳ Here, we can see that noise in input voltage does not effect output and we will get perfect square wave generated.



### Transfer characteristic



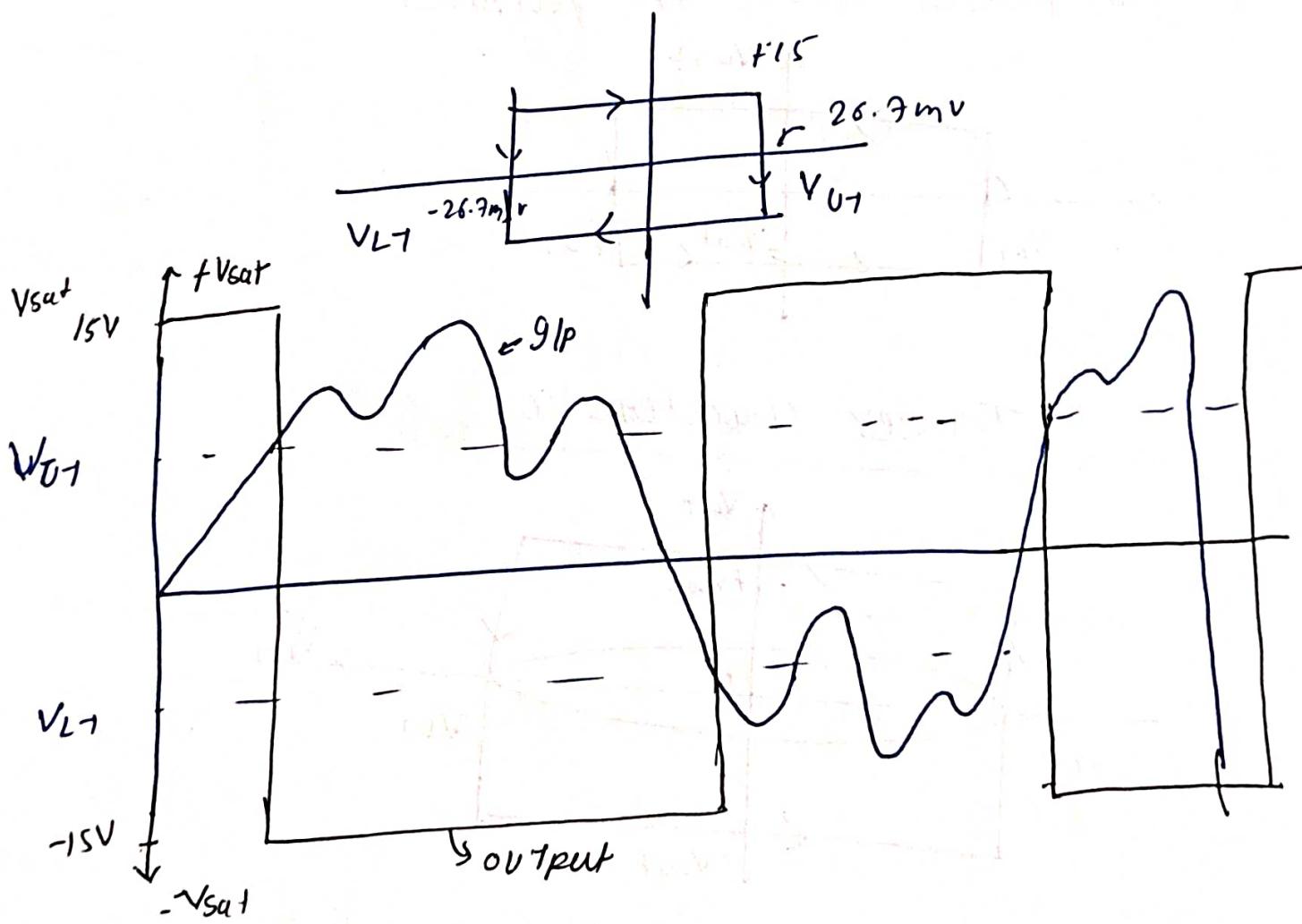
↳ The comparator with the feedback is set to exhibit hysteresis ( $V_H$ ) i.e. hysteresis condition when the input of comparator exhibits  $V_{UT}$ , its output switches from  $+V_{sat}$  to  $-V_{sat}$  and reverse back to its original state the  $+V_{sat}$  when input goes below  $V_{UT}$ .

Q: In this given fig  $R_1 = 100\Omega$ ,  $R_2 = 56k\Omega$ ,  $V_{in} = 2V$  (peak for sine wave), and the op-amp is type 741 with supply voltage +15V and -15V. Determine the threshold voltages  $V_{OL}$  &  $V_{LT}$  and draw output waveform and also find hysteresis voltage ( $V_H$ )

$$V_{01} = \left( \frac{R_L}{R_1 + R_2} \right) V_{sat} = 0.0017 (15) = 0.026 = 26.7 \text{ mV}$$

$$V_H = V_{U7} - V_{L7} \quad V_{LT} = \left( \frac{R_1}{R_1 + R_2} \right) (-V_{sat}) = -26.7 \text{ mV}$$

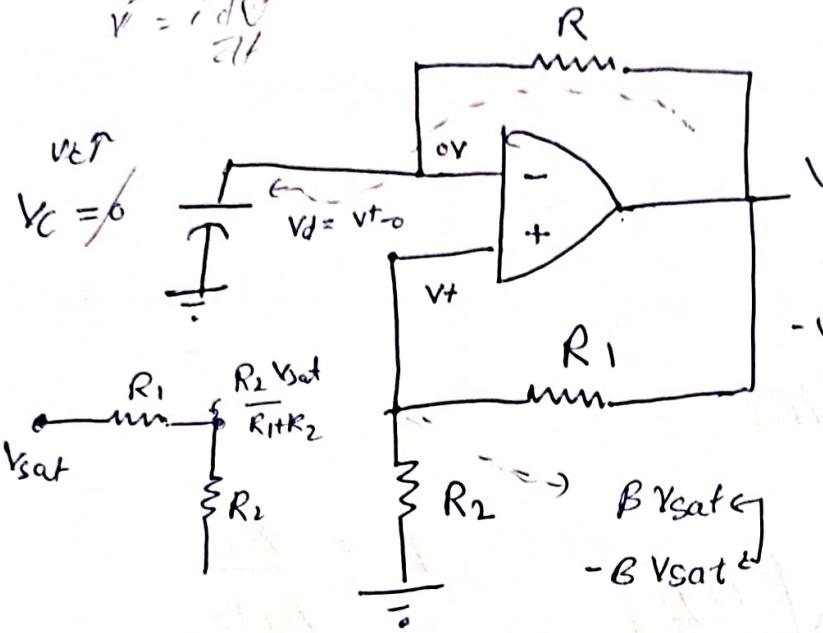
$$V_H = 53.4 m_V$$



# Astable multivibrator/ free running oscillator / Sqr wave genrator.

- ↳ To force the op-Amp to work in saturation mode to generate square wave form.

$$\dot{V} = \frac{dV}{dt}$$



Askable

(39)

↳ Quasi Stable

↳ Despite of  $\Theta$ ve feedback it will work as op-loop op-amp

↳  $V_C$  when charged to  $B V_{sat}$   $V_d$  will be  $\Theta$ ve & output =  $-V_{sat}$

↳ when  $V_C$  charged to  $-B V_{sat}$   $V_d$  will be +ve & output  $\rightarrow +V_{sat}$

Charging

$$V_C(t) = V_f + (V_i - V_f) e^{-\frac{t}{RC}}$$

for charging

$$V_f = +V_{sat} \quad V_i = -B V_{sat}$$

$$V_C(t) = V_{sat} + (-B V_{sat} - V_{sat})$$

$$\text{at } t = t_1 \quad e^{-t_1/RC}$$

$$V_C(t_1) = V_{sat} (1 - e^{-t_1/RC})$$

$$+ V_{sat} e^{-t_1/RC}$$

$$B V_{sat} = V_{sat} (1 - e^{-t_1/RC}) + V_{sat} e^{-t_1/RC}$$

~~$$(B - 1) V_{sat} = V_{sat} (1 - e^{-t_1/RC})$$~~

~~$$B = 1 - e^{-t_1/RC}$$~~

$$\frac{1-\beta}{1+\beta} = e^{-t_1/RC}$$

$$t_1 = RC \ln \left( \frac{1+\beta}{1-\beta} \right)$$

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

Set  $R_2 = R_1 = \beta = \frac{1}{2}$

$$t_1 = RC \ln \left( \frac{1+\frac{1}{2}}{1-\frac{1}{2}} \right) = RC \ln 3$$

$$T = 2t_1 = 2RC \ln \left( \frac{1+\beta}{1-\beta} \right)$$

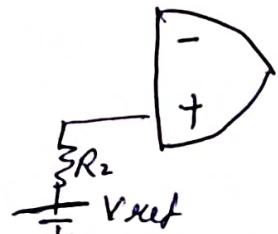
$$= 2RC \ln 3 \approx 2.2RC$$

6. Let  $R_1 = 1.16 R_2$

$$\beta = \frac{R_2}{1.16R_2 + R_2} = \frac{1}{2.16} = 0.46$$

$$T = 2RC \ln \left( \frac{1+0.46}{1-0.46} \right) = 2RC \ln \left( \frac{1.46}{0.54} \right)$$

- (34)
- ↳ to limit the Amplitude of Sqr wave we can use zener diode
  - ↳ to change the width of Clipping or we want unsymmetric Sqr wave → we can give Ref to  $R_2$



# Self study - Triangular wave generator

Sqr → Integrator