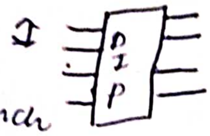
EC352 Linear Integrated Circuit

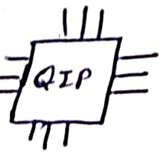
IC (Integrated Circuit) : it is a collection of components like resistor, capacitor, and transistor to perform a certain task which are stuffed into small space.

* IC's are in form of packages.

DIP (Dual Inline Package) QIP (Quad Inline Package)



0.01 inch
2.5 mm



* Based on connection on breadboard or PCB

Through (PTH) Inline — PCB or Breadboard

Surface Mount (SMT) — PCB

SSI Small scale — 1 - 10 components

MSI Medium scale — 1 - 100

VLSI — 1 - 1000
very large scale Integration

* Size is small then it will be difficult to repair & replace.

Notes:
* IC's are a keystone of morden electronics
* the IC's are heart and brain of most electronic circuits

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

* defination: is a collection of electronic components like resis. transistor all stuffed into a tiny chip and connected together to achive a specific task or common goal.

Inside of IC

* IC is a complex layering of semiconductor weffor or Copper and other material which interconnect to form transistors resistor or others components in a circuit

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

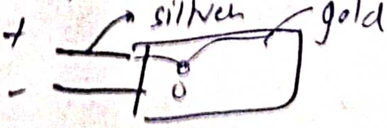
→ the IC itself is tiny, the waffers of S.C ~~tar~~ and layers of copper are ~~of~~ consist very thin

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

package / Completed detail of IC

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

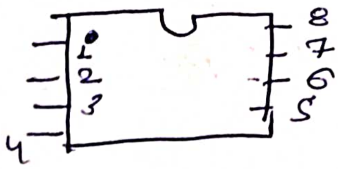
→ The pin's are silver which are used to connect to other part's of circuit



Packages Types

→ Each package has unique dimension, mounting types, and pin Comb.

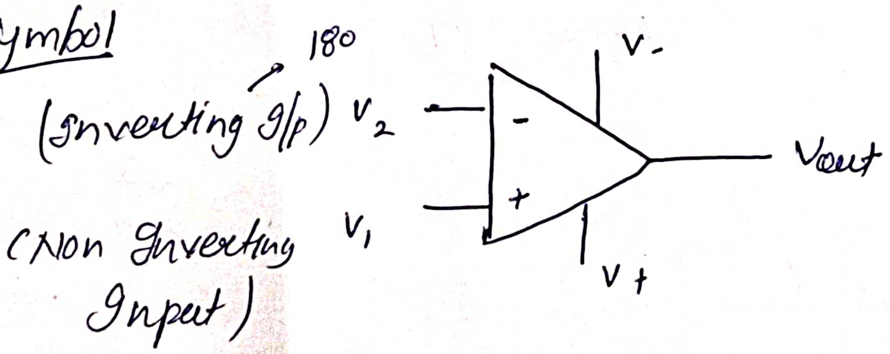
→ pin no. 1 indicated by dot or notch



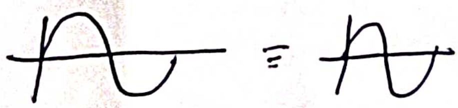
Operational Amplifier (OP AMP) IC 741

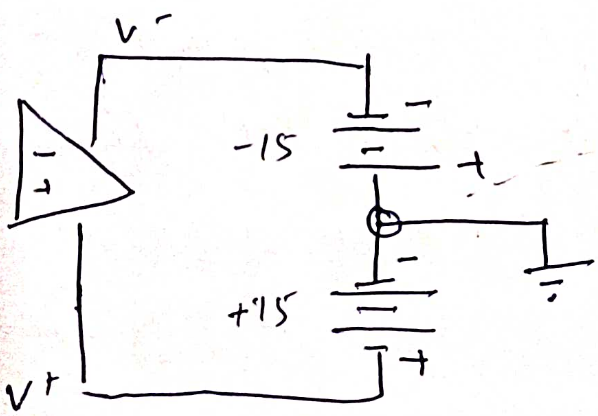
* Basically a high gain direct coupled differential amplifier which can aplify both AC & DC signals
* It has multi stage amplifier circuit, many no of amplifier circuit are interconnected to get high gain in complicated manner.
* It has many number of transistors and resistors
* Used as Amplifier, Adder,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

Symbol



→ We have to use 2 power supply





$V_1 + V_2$

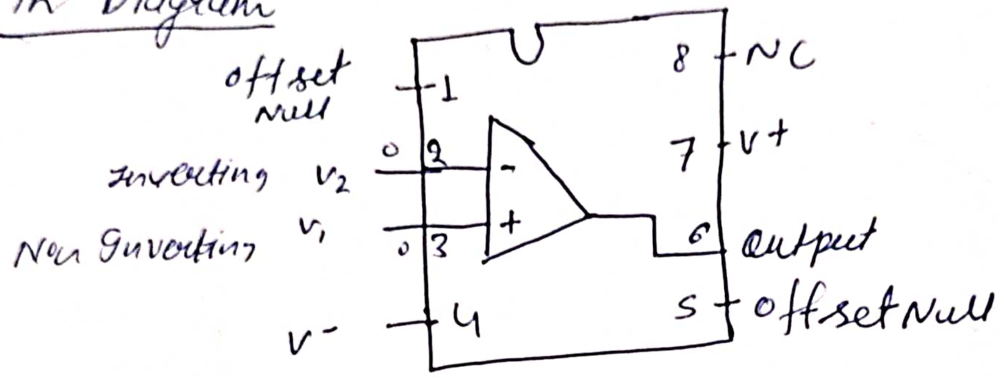
$15+15 = 30v$

741

- DIP
- Flat pakage

Single, Dual, Quad

Pin Diagram



-8 → zero output at zero i/p
5

Manufactures

1. fairchild — μA 741
   Company Name
2. National Semiconductor — ~~NE~~ 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 grade opamp (0 to 70°c)

741A - Improved version of 741

741E - Improved version of 741c

} High Electrical specification

741 S -

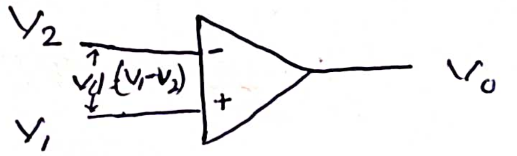
Immidiatly react

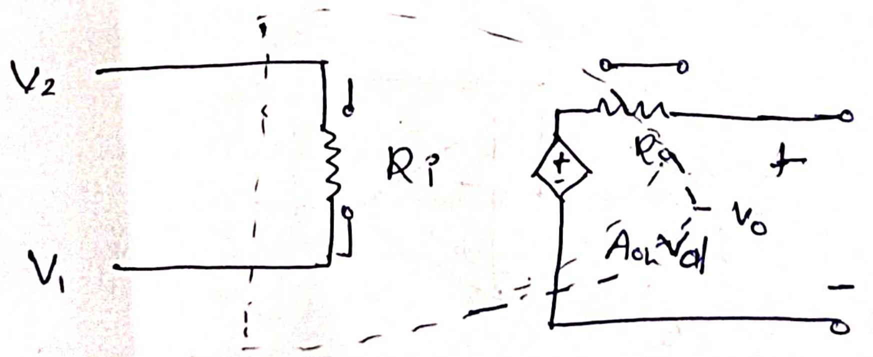
741 S. high ~~slow~~ slew rate with 741

741 SC - 741C with high slew rate.

Characterstic of Ideal Op. Amp

1. Input Impedandance/resistance ($Ri = \infty$)
2. Output Impedance / resistance ($Ro = 0$)
3. Bandwidth ($BW = \infty$)
4. Common mode rejection ratio $(CMRR) = \infty$
5. Slew rate $= \infty$
6. Open loop gain $(A_{OL}) = \infty$

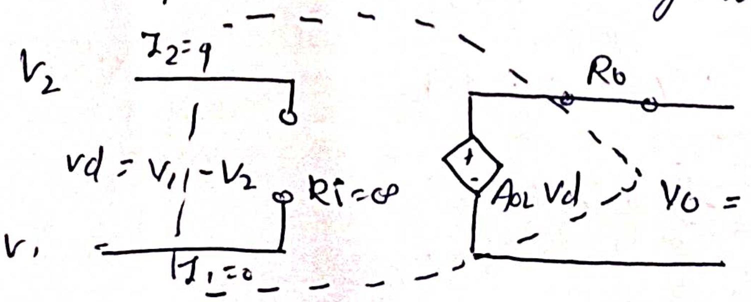




AoL - open loop gain

Equivalent circuit diagram of Ideal opamp

Ideal

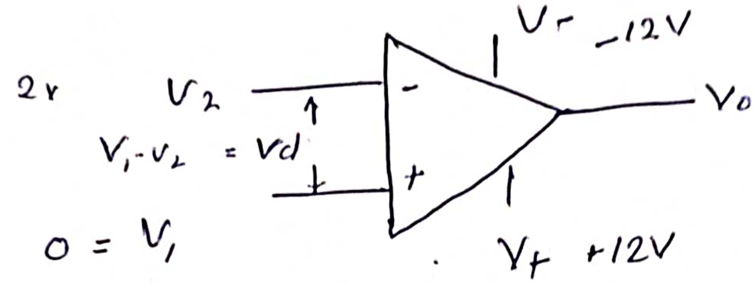


→ when op-Amp connected in negative feedback gain = 0 (∞?) and gain decided by external component

→ Virtual ground for Negative feedback circuit

open loop Configuration

10^6 or 10^5 practical



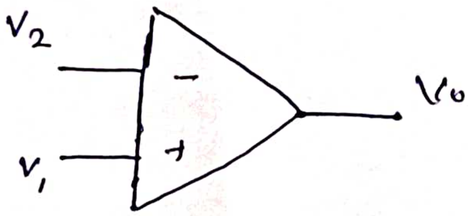
$= A_{OL} V_d$

$V_{asat} = -24$ v

Active device - require power to work (Additional to i/p)
components.

↳ In open loop configuration it act as switch or comparator circuit.

Open loop



∞

$V_o = A_{OL} V_d$

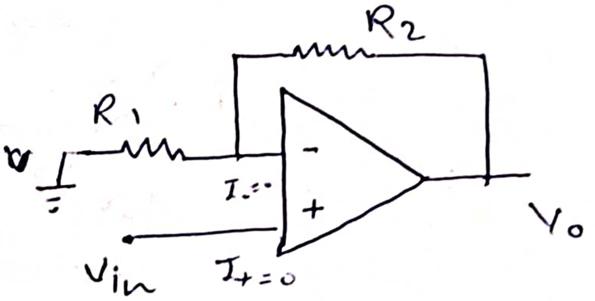
$V_d = V_1 - V_2$

If $V_1 > V_2$ $V_o = +V_{sat}$ (+ve)

If $V_2 > V_1$ $V_o = -V_{sat}$ (-ve)

Closed loop

Negative feedback & ptv feed

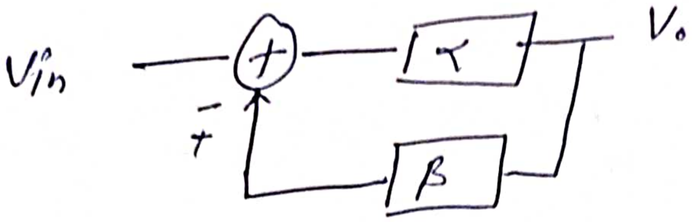


V_{in}

in Negative feedback

① V_d must be = 0

② I_+ & $I_- = 0$



$V_o : \frac{\alpha}{1+\alpha B}$ $\frac{A_{OL}}{1+A_{OL}\beta}$ → finite

$V_o = \frac{\alpha}{1-\alpha B} \to \frac{A_{OL}}{1-A_{OL}B}$ → infinite

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

Barhausan Crèteria

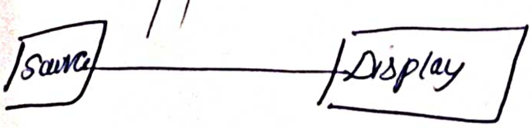
Generally
⇒ ~~All~~ oscillated wave form is unstable.

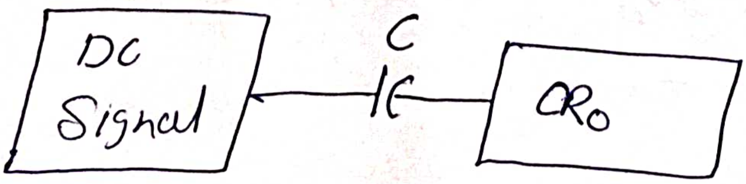
→ Generally all +ve feedback circuit

Op-Amp - high gain direct Coupled different Amplifier.

<u>Coupling</u> - Interconnecting two Components

- → Capacitive Coupling ✗
- → Inductive " ✗
- → Direct Coupling ✓

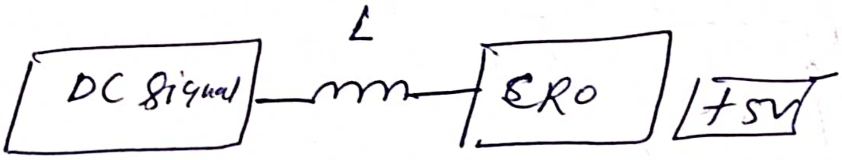




+5V
$f=0$

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

→ Capacitive Coupling we can't use for DC

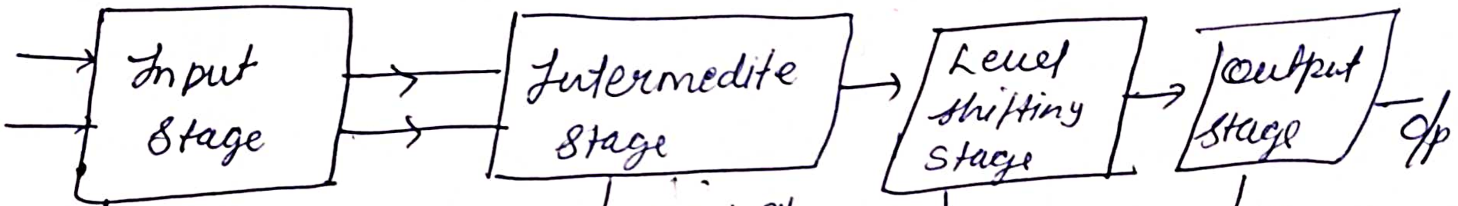


+5V
$f = 0$

$X_C = \frac{1}{\omega C}$ $X_L = L\omega = 0$

↳ Induction is big in Size so we can't use in IC

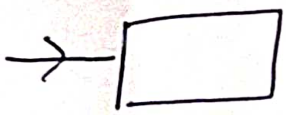
Op-Amp - 4 Stage



- Input Stage: Dual Input Balanced output Differential Amplifier
- Intermedite Stage: Dual I/p Unbalanced o/p Differential amplifier
- Level shifting Stage: Emitter follower ⇓ bring back from level shifter
- Output Stage: Complement Push Pull Amplifier

Example of an amplifier is Transistor

Transistor + amplifier



$\uparrow V = IR \uparrow$

I_C

Configuration of transistor

CB
CC
CE ✓

$\cancel{I_E = I_E + I_B}$

$I_E = I_B + I_C$

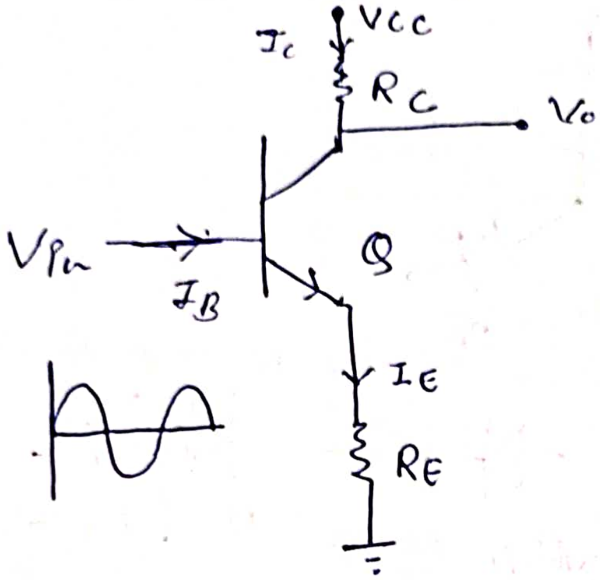
$\frac{I_E}{I_C} = \frac{I_B}{I_C} + \frac{I_C}{I_C}$

feed forw gain $= \frac{O/p\ I}{I/p\ I}$

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

$I_C = B I_B \rightarrow 200\%$ CE

CE configuration

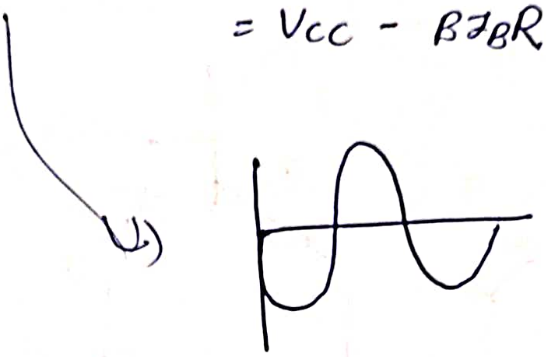


$I_c = \beta I_B$

$V_o = V_{cc} - I_c R_c$

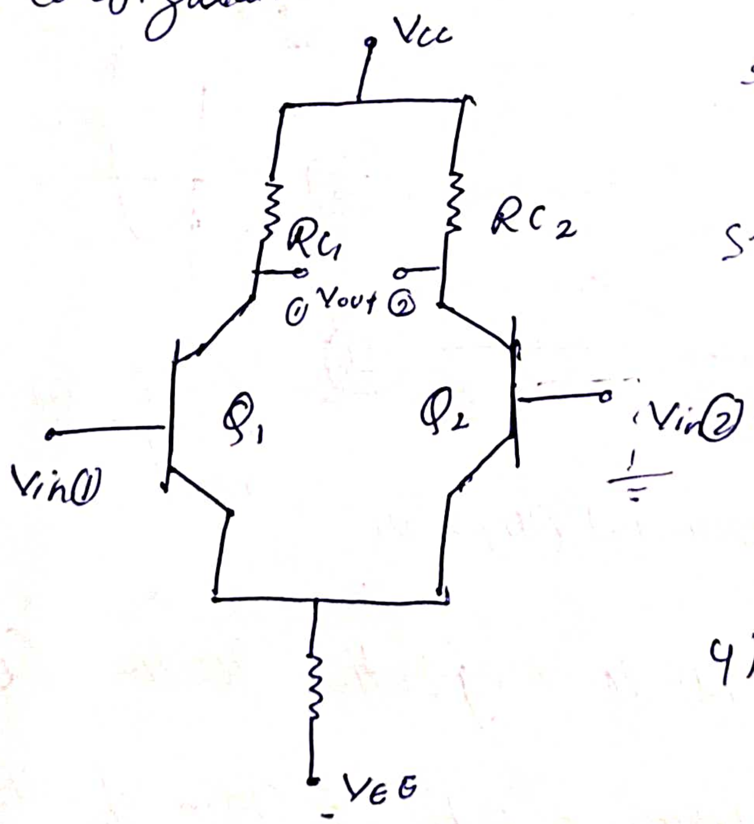
$= V_{cc} - \beta I_B R_c$

CB → Inphase
CC → Inphase
CE – Out of phase



Differential Amplifier

using CE configuration.



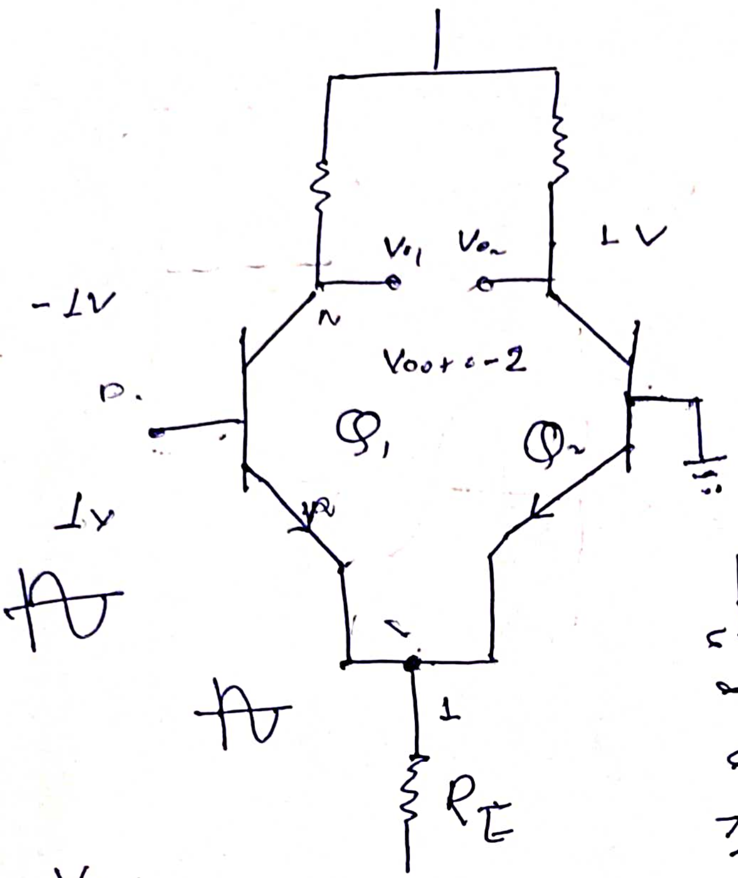
Base on i/p & o/p

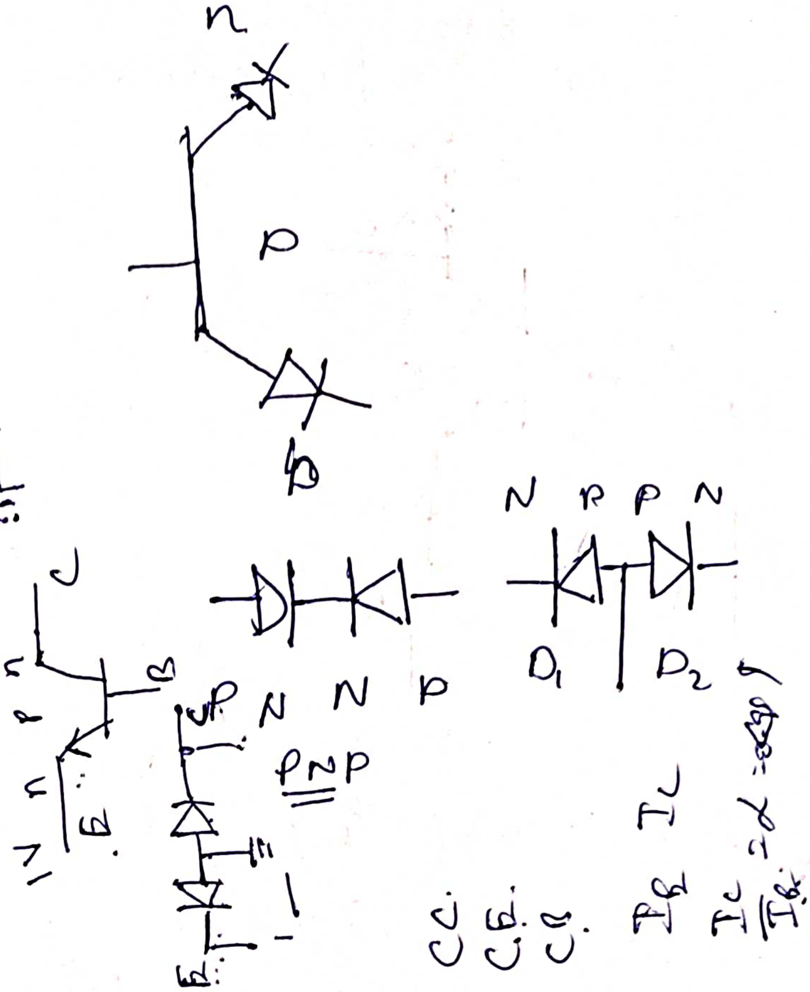
S-I
1) Dual i/p
Balance o/p DA

S-II
2) Single i/p
Balanced o/p DA

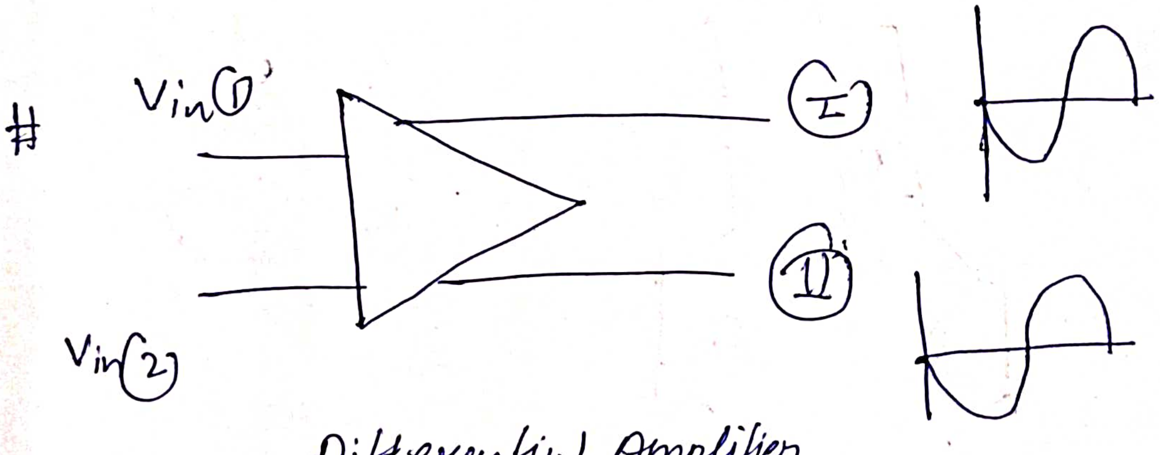
3) Single i/p
Unbalance o/p DA

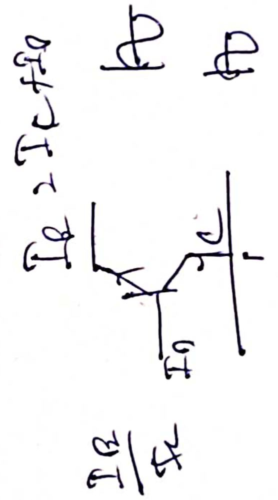
4) Dual i/p
Unbalanced o/p DA





$V_{out} = V_{o1} - V_{o2}$





Differential Amplifier

Common Mode Rejection Ratio (CMRR)

↳

$$CMRR = \frac{A_{dm}}{A_{CM}}$$

A_{dm} → gain of differential Amplifiers for diff. mode

A_{CM} ↳ gain of DA for common mode signal

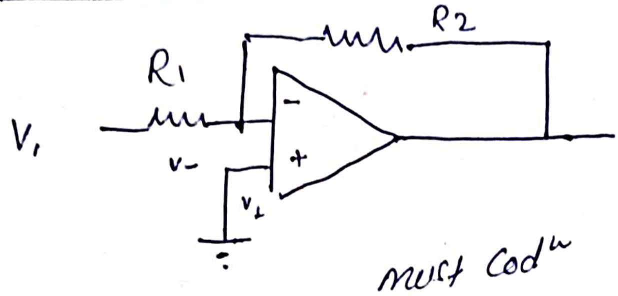
∞ or 0 for DA

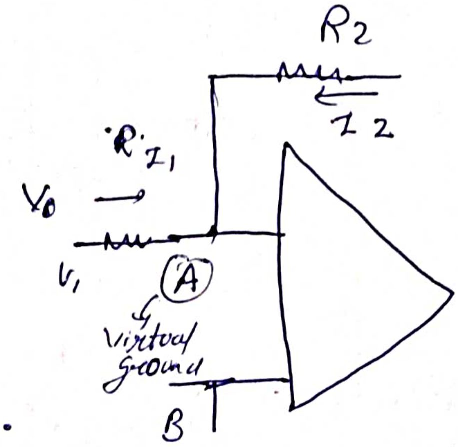
nullify common mode signal

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

Application of Diff. Ampli

1 Inverting Amplifier





must Cod^n

In Negative feedback $V_d = V_+ = V_- = 0$

$I_+ = I_- = 0$

$$I_1 + I_2 = 0$$

$$I_1 = -I_2$$

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

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

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

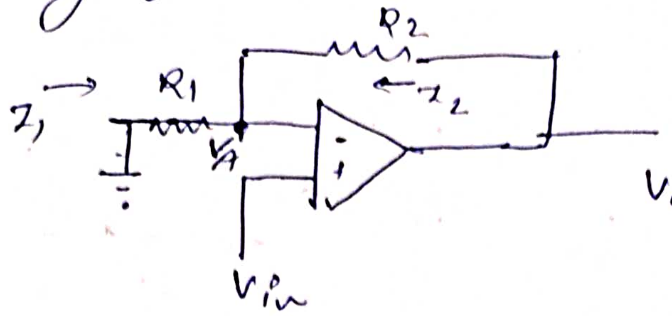
Sol^n gain = $20 \log \overset{A}{\frac{R_2}{R_1}} = -2$

$$\log \frac{R_2}{R_1} = -\frac{2}{10} = 0.2$$

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

$$A = 0.63$$

Q: find gain of ckt



$V_A = V_{in}$ ← Gvefeer

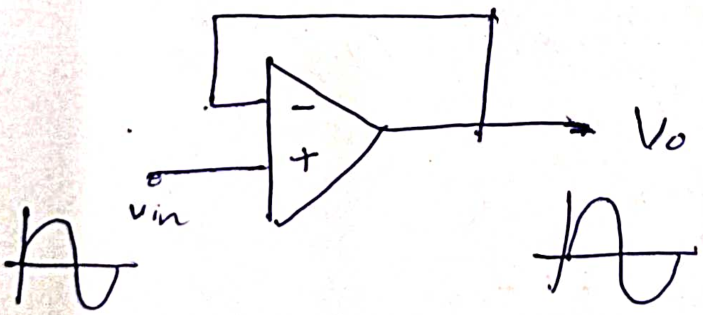
Non Inverting Amplifier

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

virtual grnd → $\dfrac{0 - V_{in}}{R_1} = -\left(\dfrac{V_o - V_{in}}{R_2}\right)$

$$\frac{V_o}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right)$$

Q: Draw output for ckt

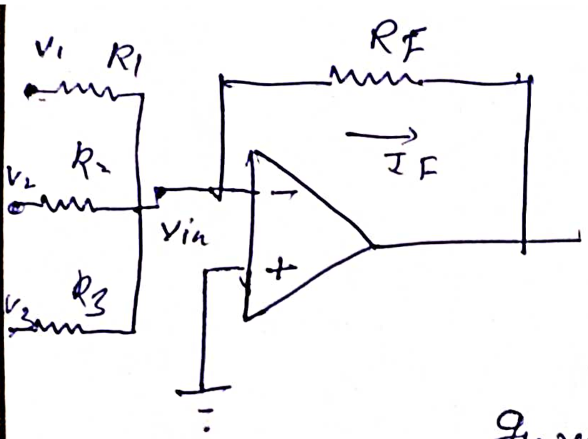


Non Inverting

$V_o = \left(1 + \dfrac{R_2^{\,0}}{R_1 \infty}\right) V_{in}$

$V_o = V_{in}$

fig - Voltage follower or
Input follower or
Buffer. (Delay i/p - delay o/p)



$V_o = ?$

Inverting Amp

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

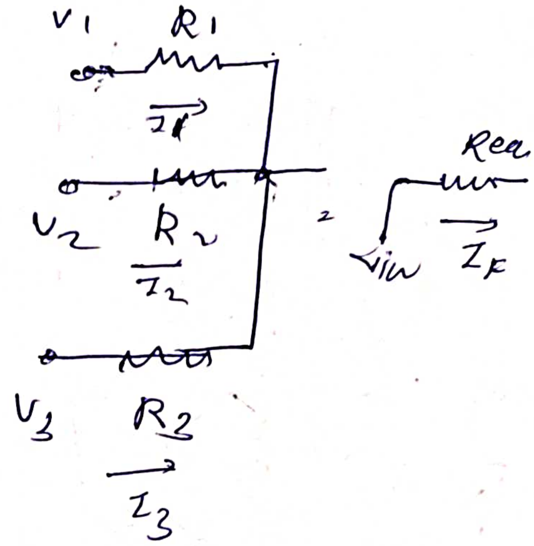


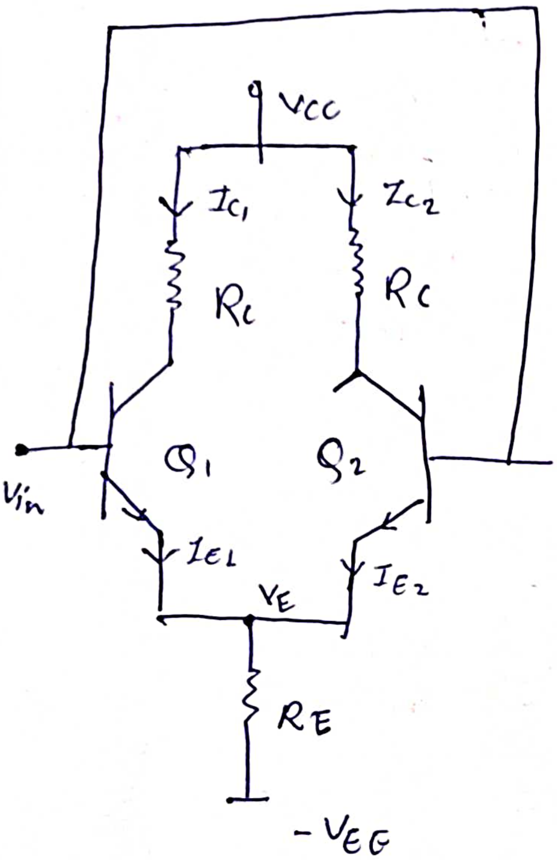
fig - Summer or Adder

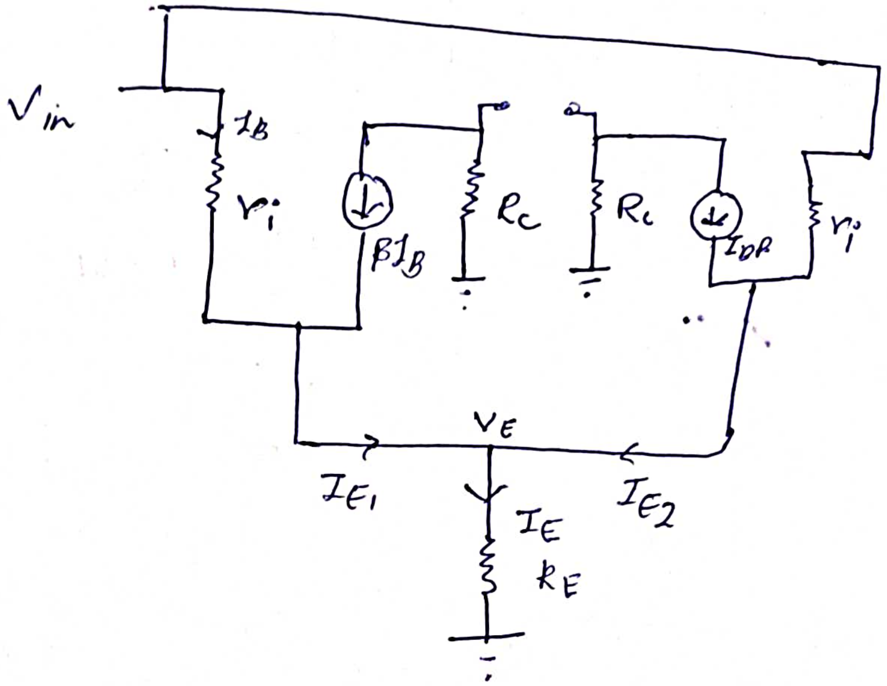
$$I_F = I_1 + I_2 + I_3$$

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

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

Hybrid Model / π model of Common Mode DA





Q_1 / Q_2 perfectly Matched transistor

$$I_B = \frac{V_{in} - V_E}{r_i}$$

$$I_B r_i = V_{in} - 2 I_B R_E (1+B)$$

$$\boxed{I_B = \frac{V_{in}}{r_i + 2(B+1) R_E}}$$

In CE

$$I_E = I_B + I_C \qquad I_C = B I_B$$

$$= I_B + B I_B$$

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

$$I_{E_1} = I_{B_1}(1+B_1) \qquad I_{E_2} = I_{B_2}(1+B_2)$$

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

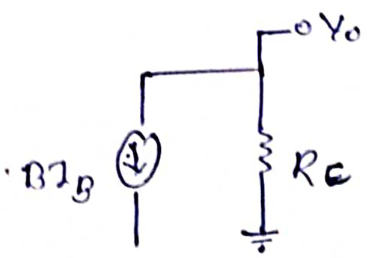
$$I_{E_1} = I_{B_1}(1+B) \qquad I_{E_2} = I_B(1+B)$$

$$I_E = I_{E_1} + I_{E_2}$$

$$\boxed{I_E = 2 I_B (1+B)}$$

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

$$\boxed{V_E = 2 I_B R_E (1+B)}$$



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

$r_i \cancel{\times} = \infty$, $\cancel{r} = 0$, $\cancel{R} = 0$ (Vo = 0)

$\boxed{R_E \cancel{=} \infty}$ → Size big → passive load

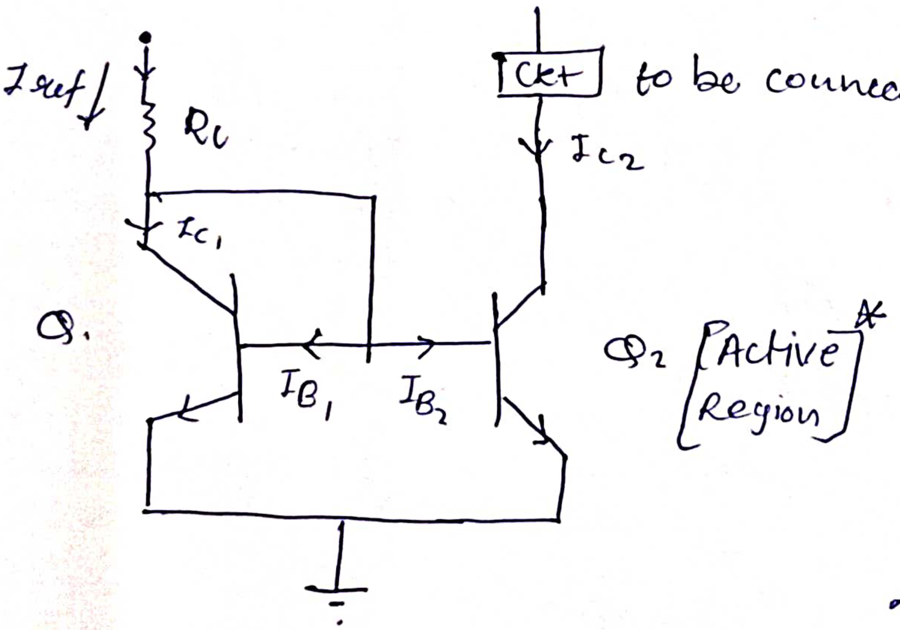
$I_o = \beta I_B = I_C$

$V_o = \beta I_B R_C$

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

Current Mirror Circuit

↳ Constant curr source



$\therefore I_C = \beta I_B$

$I_{ref} = I_{C_1} + I_{B_1} + I_{B_2}$

$= I_{C_1} + \frac{I_{C_1}}{\beta_1} + \frac{I_{C_2}}{\beta_2}$

$\beta_1 = \beta_2 \quad \therefore Q_1 = Q_2$

$= I_{C_1}$

$I_{C_1} + \frac{I_{C_1}}{\beta_1} + \frac{I_{C_2}}{\beta}$

$I_{ref} = \left(1+\frac{1}{\beta}\right) I_{C_1} + \cancel{\frac{I_{C_2}}{\beta}}$

$\beta >> 1$

$I_{ref} = I_{C_1} + \cancel{\frac{I_{C_2}}{\beta}}$

$\boxed{I_{C} = I_{C_1} = I_{C_2}}$

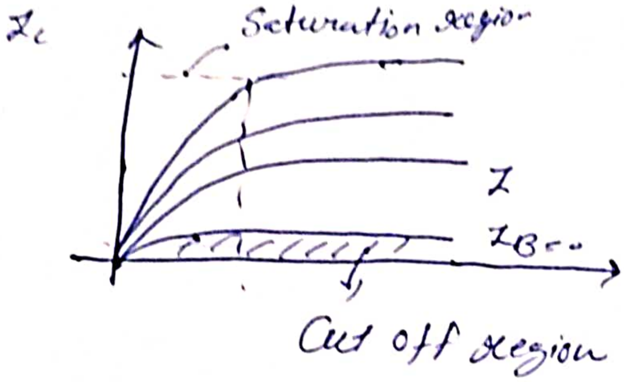
$I_{C_1} = \alpha_F \cancel{I_{ES}}\, e^{\frac{V_{BE_1}}{V_T}}$

$I_{C_2} = \cancel{\alpha_F I_{ES}}\, e^{\frac{V_{BE_2}}{V_T}}$

$V_{BE_1} = V_{BE_2}$

$I_{C_1} = I_{C_2}$

Transfer characteristic of transistor.



Satu — Active — Cut off
↓
Control o/p ↔ Control i/p

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

↳ 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 Q_2

$$R_o = \frac{V_A}{I_{ref}} = \frac{V_A}{I_o \text{ (or) } I_{C2}}$$

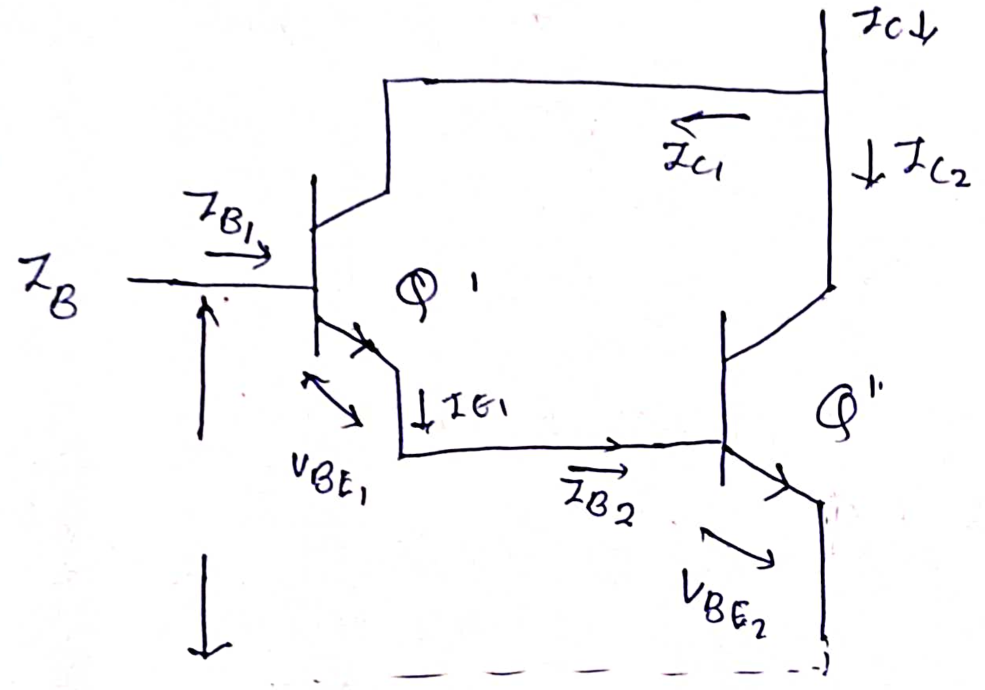
V_A → Early voltage.

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

<u>Intermidiate Stage</u> # Darlington pair

(13)

↳ high gain & high input impedance $R_i = \infty$ ↑↑ very high (Practile)



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

$\frac{V_{BE}}{I_B} = R_i \left[\frac{1.4}{1mA}\right]$

High o/p impedan

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

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

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

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

$\Rightarrow \beta_1 + \beta_2 \frac{I_{E1}}{I_{B1}} \quad \therefore I_{B2} = I_{E1}$

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

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

Eg $\beta_1 = 200 = \beta_2$

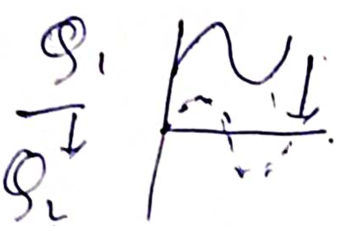
$\Rightarrow \beta \uparrow\uparrow$

$I_C = \beta I_B \uparrow\uparrow$

Level Shifting Stage

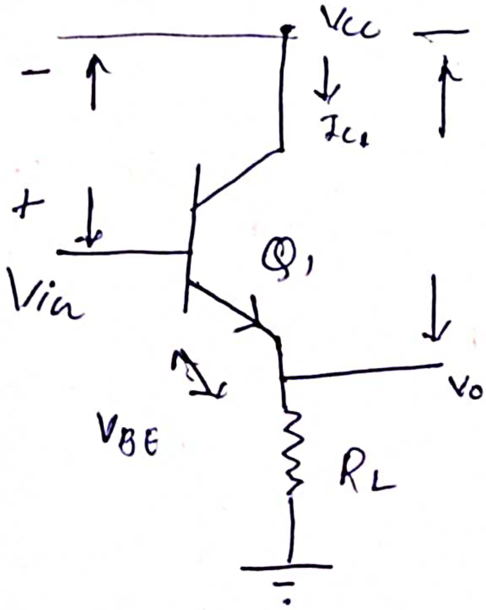
↳ Direct Coupled high gain Amp. → It will do level shifting changing the Q point of the transistor Operating Quiesent point

* can Amplify both AC + DC



↳ we need a circuit to shift level

level Shifter / level translator / Common Collector Amp / Emitter follower.



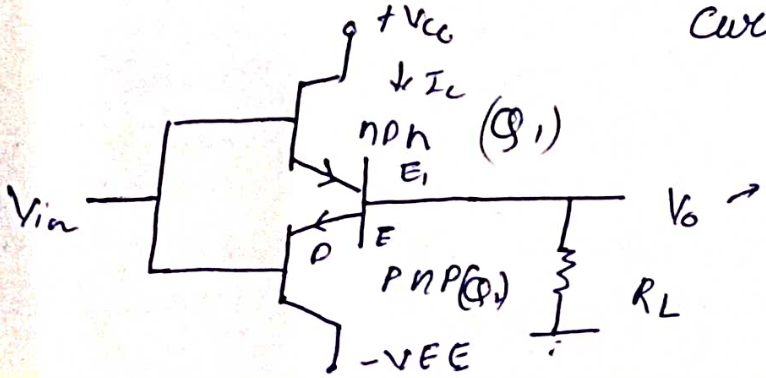
$V_o - V_{in} = V_{BE}$ (0.7)

$\boxed{V_o \simeq V_{in}}$ 'Voltage follower'

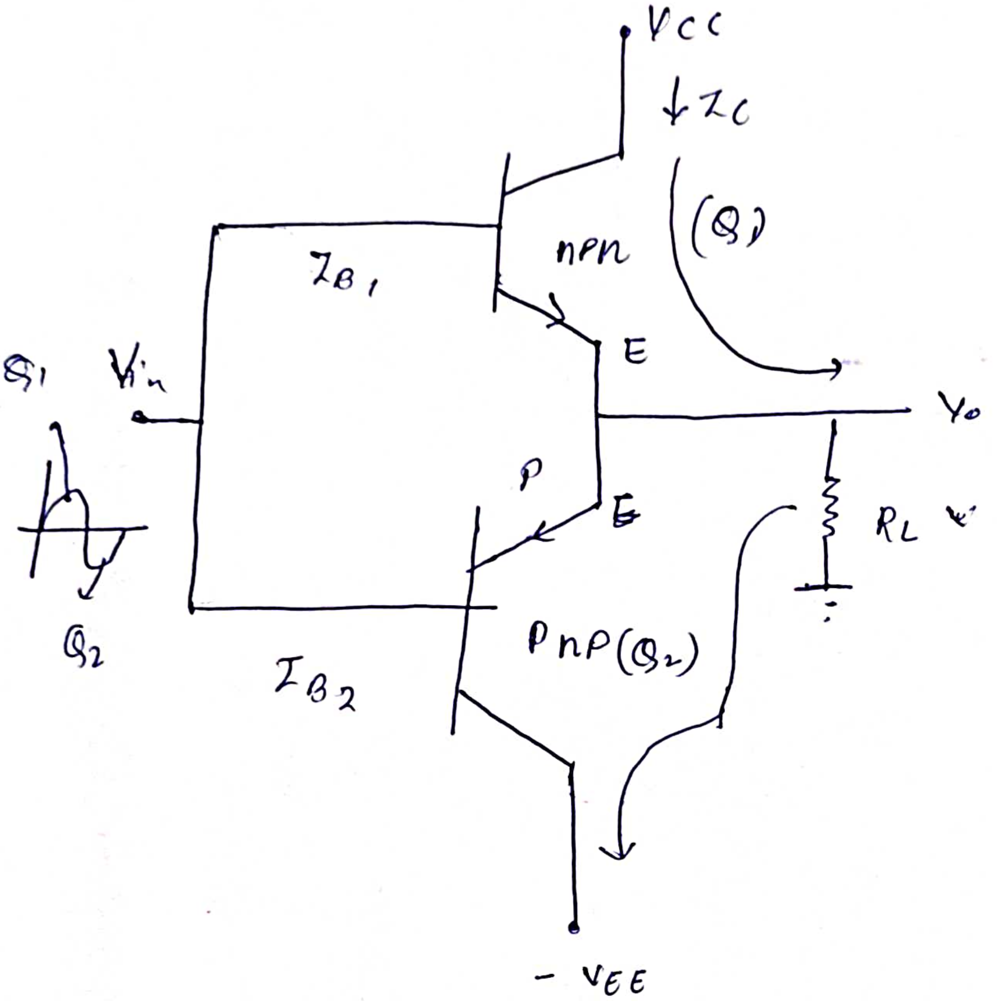
Buffer.

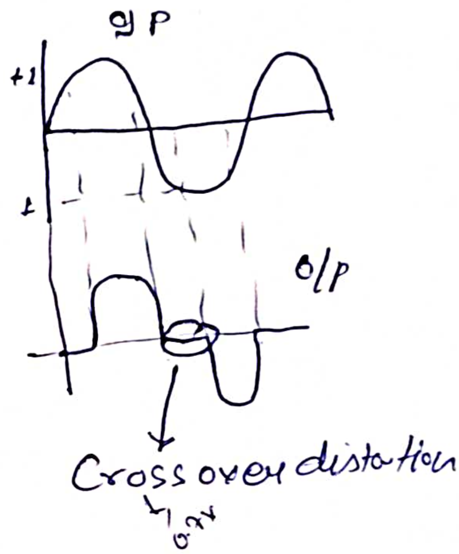
Out put Stage (Output Impedance Should Be very low) or zero

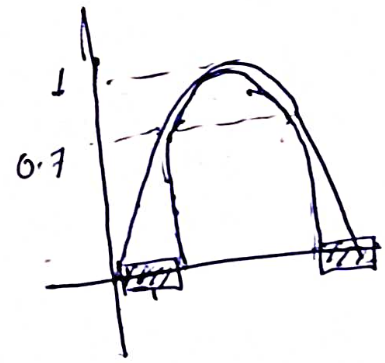
↳ so it can drive the load current to the other device.



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





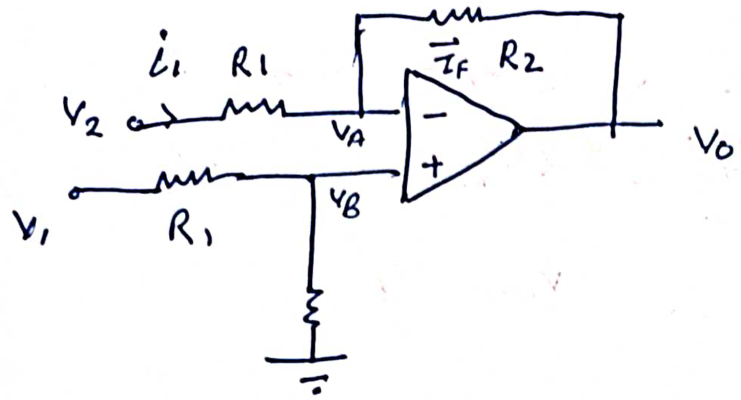


↳ min Vin to turn on Q_1 & Q_2 $\simeq 0.7V$

if Vin $0 - 0.7$ $V_0 = 0$

↳ to Solve we need some min Volt at i/p

Differential Amplifier



$V_B - V_A = 0$

$V_d = 0$

$i_1 = i_F$

$$i_1 = \frac{V_2 - V_A}{R_1} = \frac{V_A - V_o}{R_2}$$

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

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

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

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

Eg $V_1 = 100\mu V$
$V_2 = 50\mu V$ $\Rightarrow$ $V_o = \frac{R_2}{R_1}(100\mu - 50\mu) = 50\mu V$
$R_1 = R_2$

$$V_o = A_1 V_1 + A_2 V_2$$

find differential mode gain & common mode gain

Adm

$V_d = V_1 - V_2$

$V_1 = V_d + V_2$

Acm

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

$2V_{cm} = V_1 + V_2$

$V_2 = 2V_{cm} - V_1$

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

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

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

$$V_o = A_1 V_1 + A_2 V_2$$

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

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

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

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

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 it give figure of merit (ρ) for the differential amplifier

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

for $\mu A741$ CMRR - 70dB

$\mu A741A$ - 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

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

Q: Design an Op-Amp circuit for Expression

$V_o = 3V_1 + 2V_2 - V_3$ using only one op-Amp

Charecterstic of op-Amp

DC
AC

↳ An ideal op-Amp respond equall weel at both ac and dc input

↳ practicly If both the input are grounded, there will be some dc voltage at o/p. (we need compansation ckt)

↳ Ac input to op amp, the o/p will change w.r.t to frequency.

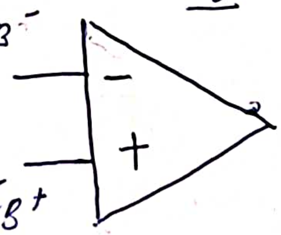
Op-Amp
- DC Charcterstic
  - Input bias current
  - Input offset current
  - Ip offset voltag
  - therma drift
- AC charcterstic
  - freq response
  - Slew rate.

(i) Input bias current (I_B)

manufactur.

BJT or FET ↳ to drive in Active region / linear region

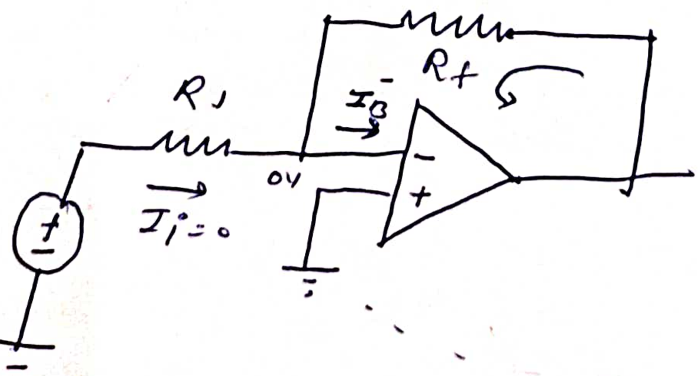
$$\boxed{I_B = \frac{I_B^+ + I_B^-}{2}}$$



741 (BJT) = $I_B \simeq 500\,mA$ or less at room temp

741 (FET) = $I_B = 50\,fA$

#



$V_o = I_B^- R_f$

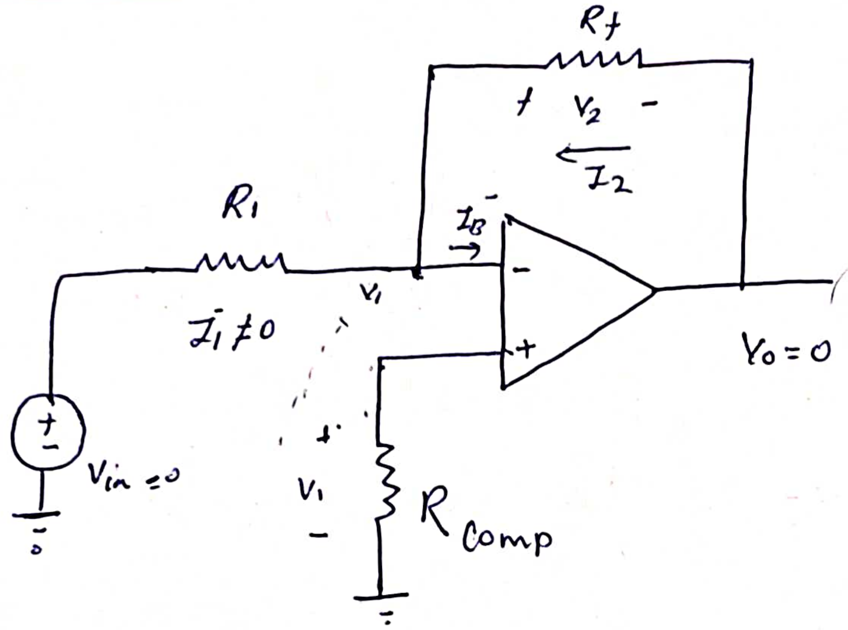
$= 500\,nA \times 1M\Omega$

$= 500\,mV$

⇓

to nullify this we add resistance compansate.

$A_o \; -\frac{R_f}{R_1}$



$I_B^- = I_1 + I_2$

$I_B^- = \frac{-V_1}{R_1} + \frac{\cancel{V_0} - V_1}{R_f}$ 0 we assume

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

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

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

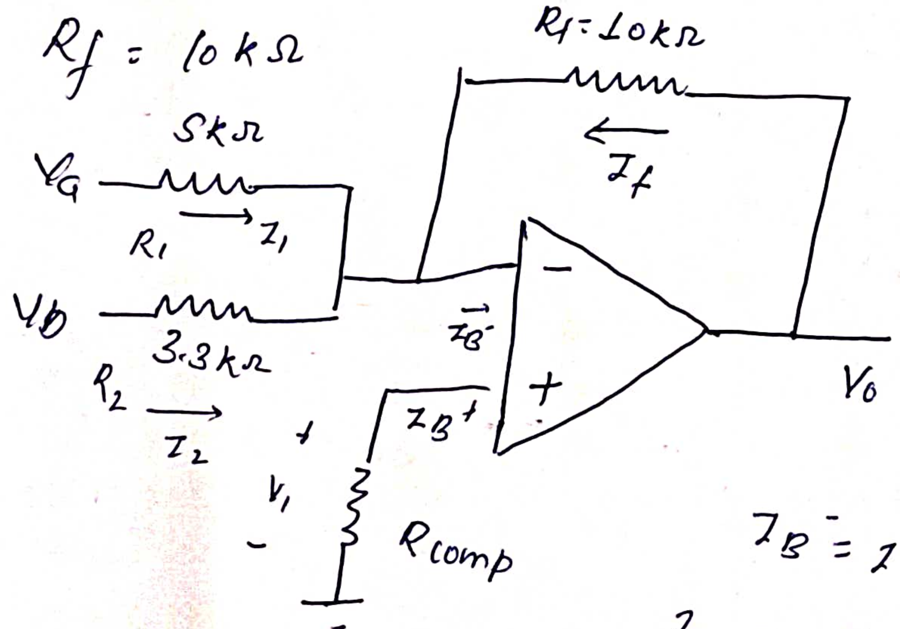
Assume $I_B^+ = I_B^-$

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

$$\boxed{R_{comp} = R_1 \parallel R_f}$$

Q: Design an inverting summer $V_0 = -2V_1 - 3V_2$ opamp (BJT) $I_B = 500nA$. Draw the suitable ckt to nullify the effect of input bias current assume

$R_f = 10k\Omega$



$V_0 = -(2V_1 + 3V_2)$

$= -\left(\frac{R_f}{R_a}V_a + \frac{R_f}{R_b}V_b\right)$

$\frac{10k\Omega}{R_a} = 2$ $R_a = 5k\Omega$

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

$I_B^- = I_1 + I_2 + I_f$

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

$$I_B^- = I_B^+$$

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

$$R_{comp} = R_1 \parallel R_2 \parallel R_f$$

$$5 \parallel 3.3 \parallel 10\,k\Omega = 1.57\,k\Omega$$

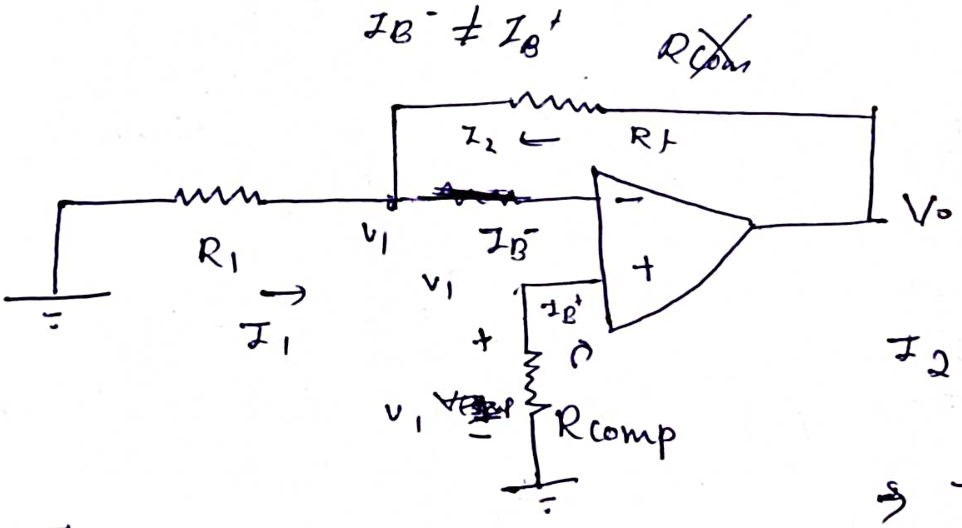
Input offset Current (I_{os})

$$\boxed{|I_{os}| = I_B^- - I_B^+}$$ Difference b/w i/p bias curr

$I_B^- \neq I_B^+$ ~~Rcom~~

400 × 1M

200×10⁻⁹×20



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

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

$$I_B^- = I_1 + I_2$$

$$\frac{0 - V_1}{R_{com}} = I_B^+$$

$$I_2 = I_B^- - I_1$$

$$\frac{0 - V_1}{R_1} = I_1$$

$$I_2 = I_B^- + \frac{V_1}{R_1}$$

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

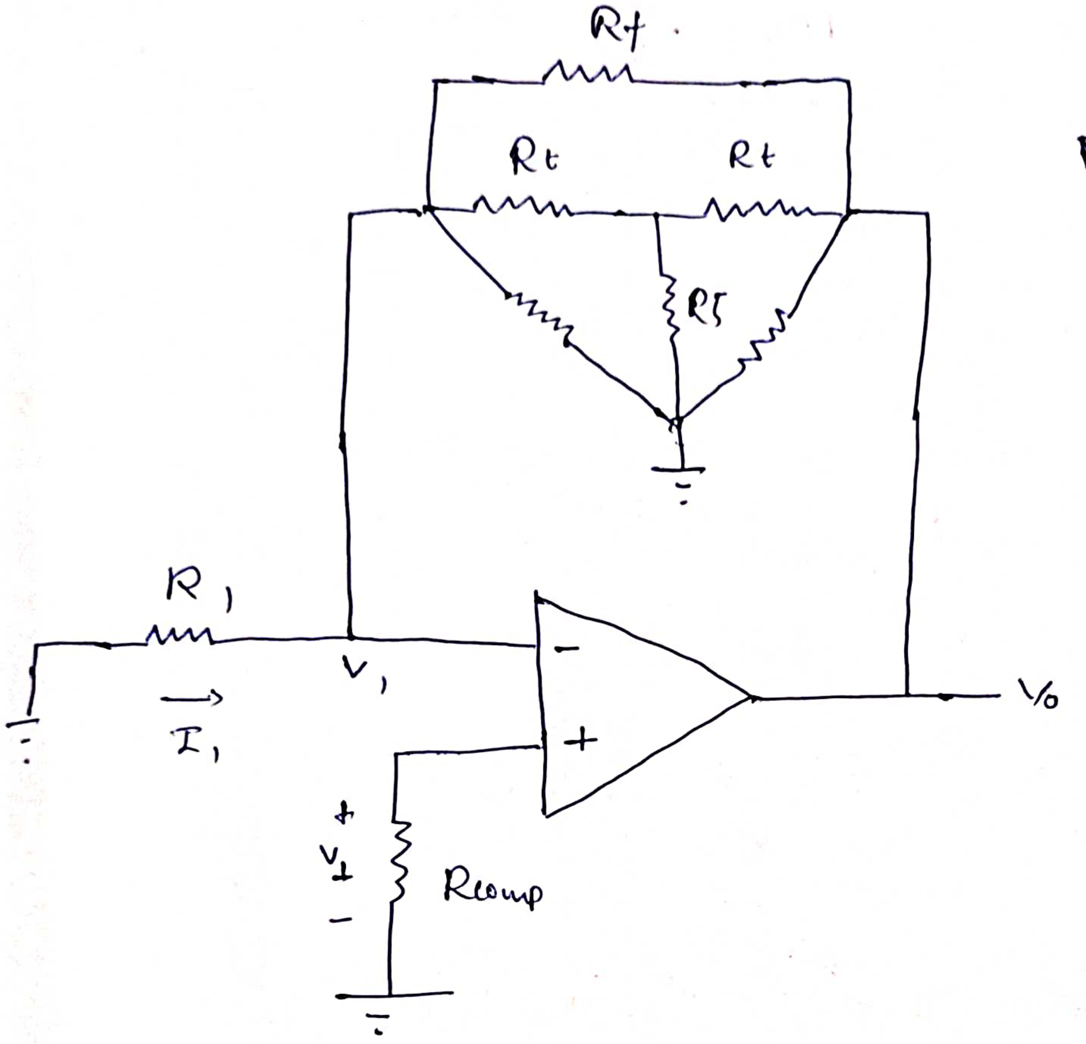
$$V_o = I_2 R_f + V_1$$

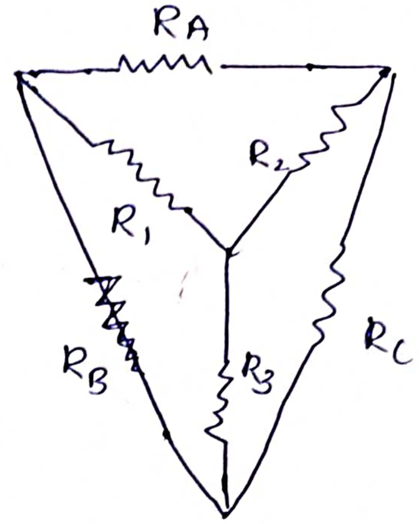
$$V_o = I_B^- R_f - I_B^+ R_{com} R_f$$

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

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

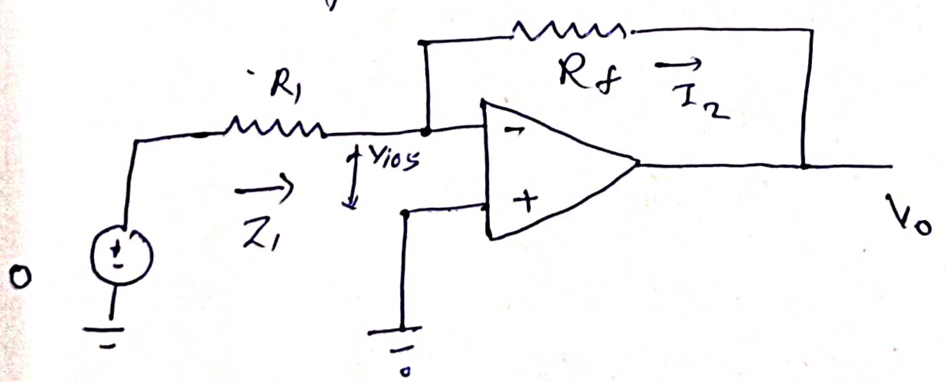
↳ To Compansiate input offset current





$$R_1 = \frac{R_A R_B}{R_A + R_B + R_C}$$

Input offset Voltage (V_{ios})



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

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

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

$\Rightarrow I_1 = I_2$

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

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

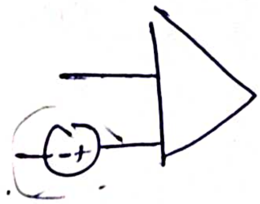
$\Rightarrow V_o = V_{ios}\frac{(R_1 + R_f)}{R_1}$

Inverting or non-inverting

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

Inverting or Non Inverting

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



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

The Input offset Voltage is the differential I/p Voltage that exist b/w two I/p terminals of an op-Amp without any External I/p applied.

↳ To Componsate 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 ~~offput~~ offset voltage could be either more or less than the offset Voltage produced at the output due to Input bias ~~curr~~ current or I/p offset Voltage alone.

↳ The maximum offset voltage at the output of an Inverting or Non Inverting Amplifier without any Compan-sation technique.

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

for both Inverting & non Invertin

with Rcomp

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

Thermal drift

↳ Bias current, offset current, offset voltage change with temprature ~~ai~~

→ a circuit carefully NULLed at 25°c may not remained. so when the temprature rises to 35°c this is called Drift

↳ the offset current drift expressed in nA/°c I_{os} I_B^+

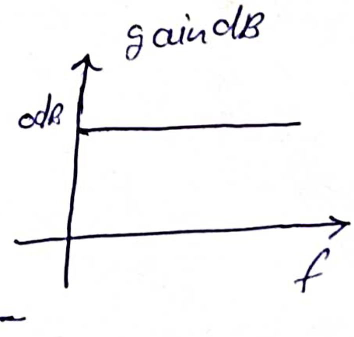
↳ the offset Voltage drift expressed in mV/°c ↓ Rate

$V_o = 0$ at 30°c V_o at 35°c

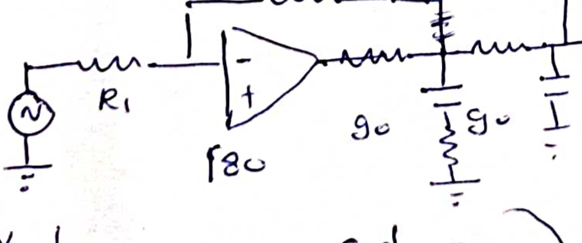
Change 10nA/°c ↳ $10\,nA \times 5 = 50\,nA$.

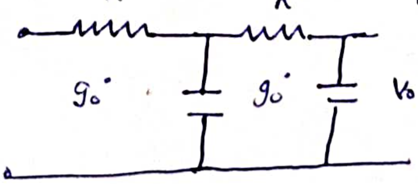
AC characteristics of Op-Amp

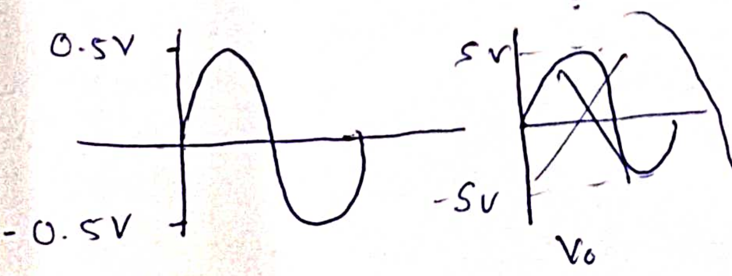
1) frequency response Ideal op Amp



2) Slew rate.

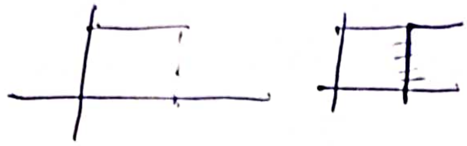






it will act as oscillator

Practically we have to check it

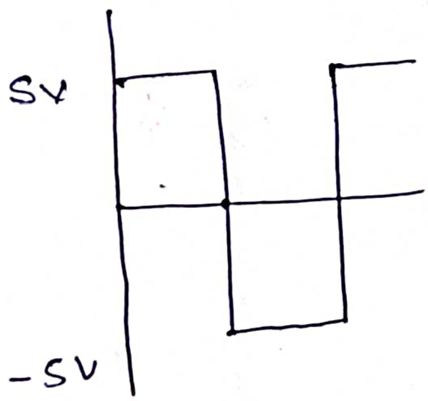


Pole zero composation

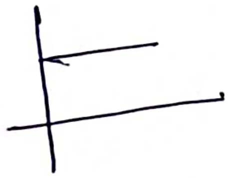
$$H(s) = \frac{(s-z_1)(s-z_2)(s-z_3)}{(s-P_1)(s-P_2)(s-P_2)}$$ → fight b/w pole + zero

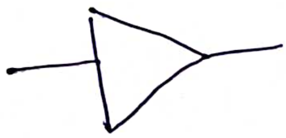
gain o/p / i/p

Slew rate · maximum rate of change of o/p voltage caused by step input voltage (V/μs)

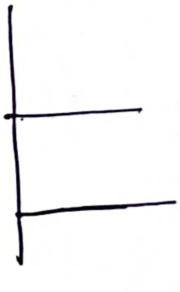


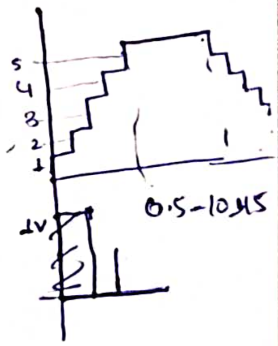
$f = 2Hz$





$\frac{1V}{1\mu s}$





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

~~SR = ~~ $SR = \frac{dV_o}{dR}$

$$SR = \frac{dV_o}{dt}\bigg|_{max}$$

Eg $V_{in} = V_m \sin \omega_o t$ gain = 1

$V_o = -V_m \sin \omega_o t$

$\frac{dV_o}{dt} = -V_m \omega_o \cos \omega_o t$ → 1 max

$SR = V_m \omega_{o\,max} = 2\pi f_{max} V_m$

$$\boxed{f_{max} = \frac{SR}{2\pi V_m}}$$ × 10^6 → in sec — question

Question: find the maximum frequency for a sin (29)
wave output voltage of 10V peak with an Op-Amp whose slew rate 1V/μsec

$V_o = 10\sin(\omega_o t)$ $\quad SR = 10\omega_o$

$\frac{dV_o}{dt} = 10\,\omega_o \cos\omega_o t$ $\quad \frac{1}{10^{-6}} = 10 \times 2\pi f_{o\,max}$

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

$= \frac{10^5}{\pi}$ $\quad 3.33 \times 10^4$

$= 33.3\ kHz$

Question: A 741c Op-Amp is used as an inverting amplifier with a gain of 50. the voltage gain V/s frequency curve of 741c is flat up to 20 kHz. what maximum peak to peak input signal can be applied without distorting the o/p

Hint: the slew rate for 741c 0.5 V/μs

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

$V_{max} = \frac{SR}{2\pi f_{max}} = \frac{0.5 \times 10^{\cancel{6}3}}{2\pi\ 20 \times \cancel{10^3}} = \boxed{4V}$ we should get as output

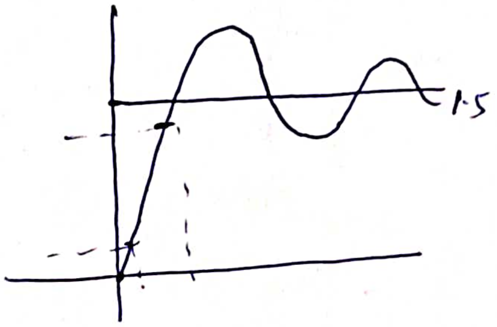
$\text{Input} = \frac{4}{50\,(\text{gain})} = 0.08\,V$ or $0.16V$ peak to peak

Question: A square wave of peak to peak amplitude of 500 mV has to ~~bee~~ amplified to ~~a~~ peak to peak amplitude of 3 V with rise time of 4 μsec or less. Can a 741 be used? for 741 IC slew rate is 0.5 V/μs

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

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

assume 2nd order system



$$SR_{min} = \frac{dV_o}{dt}_{max} = \frac{(90\% - 10\%)\ 1.5}{4\mu s}$$

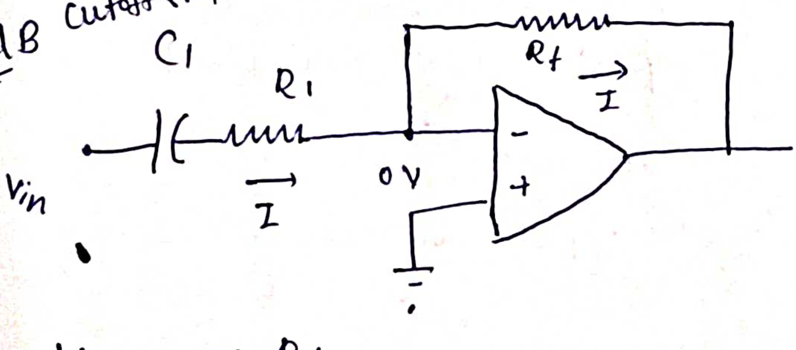
$1.5 \times 8 = 12.0$

$$= \frac{(0.9 - 0.1)\ 1.5}{4 \times 10^{-6}} = 0.3\ V/\mu s \quad (\text{minimum}$$

~~Not~~ possible

AC Amplifier : Inverting ; Non Inverting amplifier.

3dB cutoff freq.



$$\frac{V_o}{V_{in}} = \frac{-R_f}{R_1 + \frac{1}{sC_1}}$$

$V_o = -I R_f$

$S = j\omega$

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

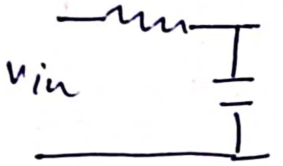
$$\boxed{V_o = \frac{-V_{in} R_f}{R_1 + \frac{1}{sC_1}}}$$

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

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

↳ it will allow low freq
& it will work as normal amplifie

-3dB



$$\frac{V_o}{V_{in}} = \frac{1}{1+RCS} = \frac{1}{1+RCj\omega}$$

$$\Rightarrow \frac{1}{1+jRC\,2\pi f}$$

Cutoff frequ ← $f_c = \frac{1}{2\pi RC}$ $\Rightarrow \frac{1}{1+j\frac{f}{f_c}}$

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

$|H(S)| = \frac{1}{\sqrt{1+f/f_c}} = (\quad)^{1/2}$

When $f = f_c$

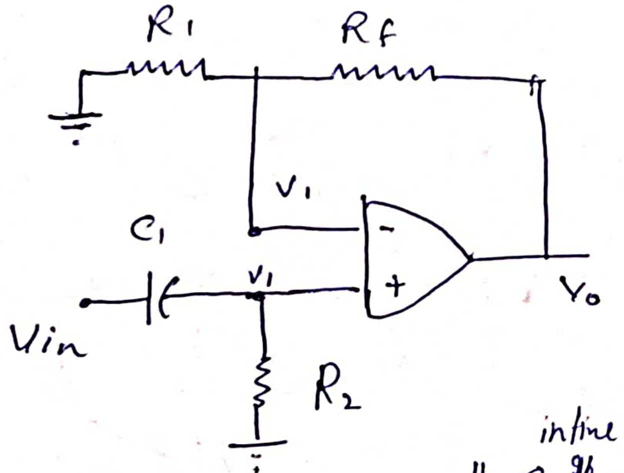
$|H(S)|^2 = \frac{1}{1+\frac{f}{f_c}}$ Squared mgn response.

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

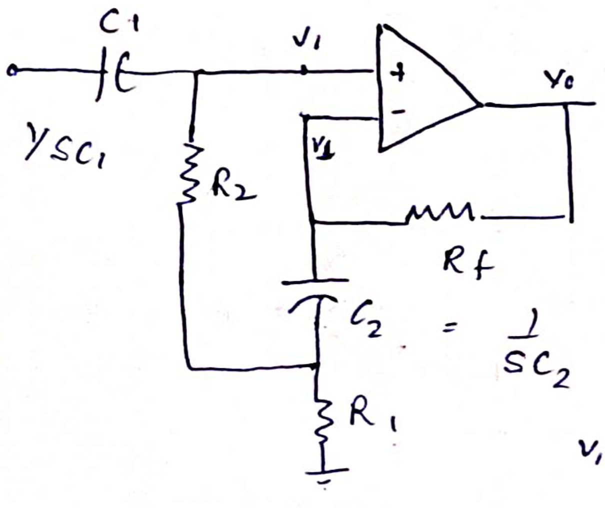
$20 \log \frac{1}{\sqrt{2}} \Rightarrow -20 \log 2^{1/2}$

$\Rightarrow -10 \log 2$

$\Rightarrow -3dB$

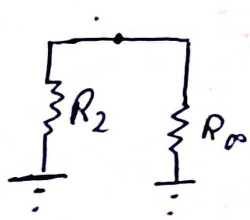


Non Inverting AC Amp



$C_2 = \frac{1}{SC_2}$

infinite ip
$R_2 \parallel R_\infty$



& result (R_2) problem

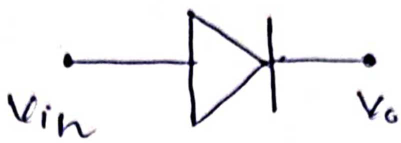
v_1 ~~~ v_1

$R_2 = \infty$ Now ip impedance $= \infty$

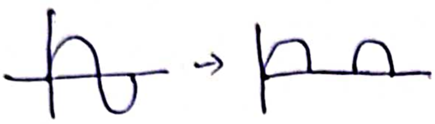
- Input Impedance → Resistance Connected to Input

Precision Diode

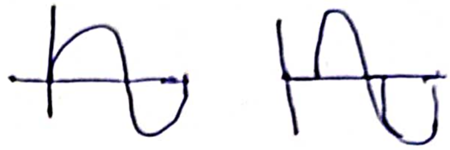
0.7 V

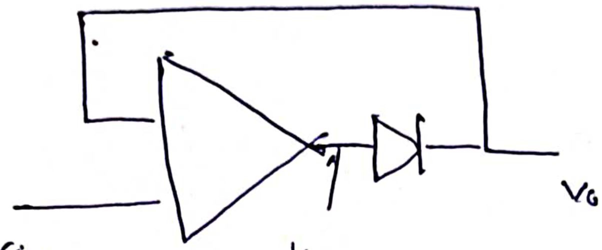


Ideal



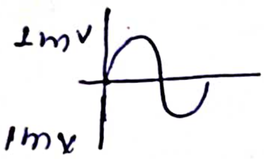
Practicle

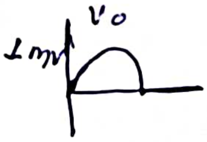




Voltage follower when diode ON

When open loop
↳ It will act as op. loop and then $V_{OA} = +V_{CC}$ & diode act as forward bias



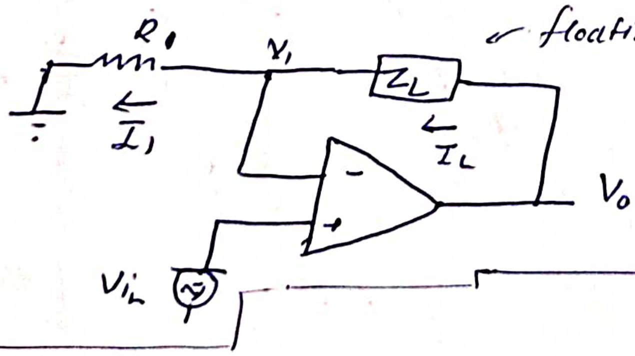


V-I Converter (Transconductance Amplifier)

Input Voltage into Output Current (Load Current)

(i) V-I Converter with floating Load

(ii) " with grounded load.



floating b/w I/p & o/p

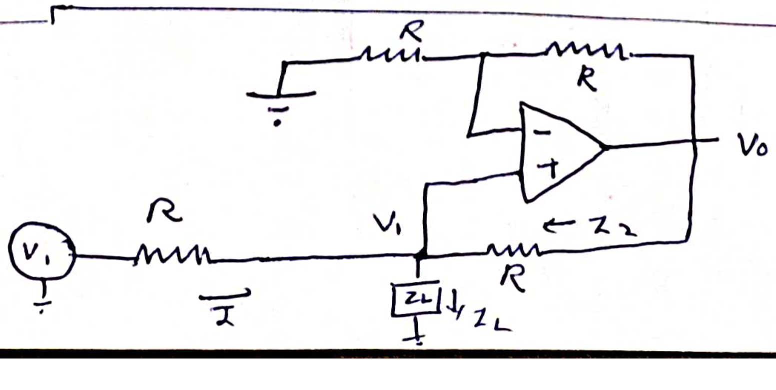
$Z_1 = Z_L$

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

$\boxed{I_L \propto V_1}$

$I_L = I_1 + I_2$

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



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

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

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

∴ Non inverting

$V_0 = (1+1)V_1$

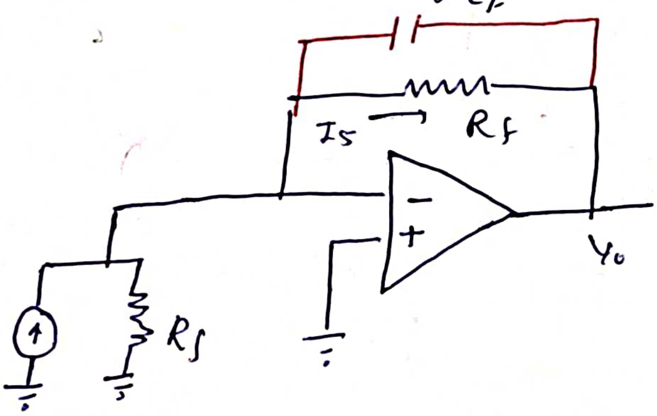
$V_0 = 2V_1$

App:- AC & DC voltmeter, Diode & LED testing

I to V converter [trans Register Amplifier]

Photo cell - Light Energy into electric Energy

↳ Current → Voltage



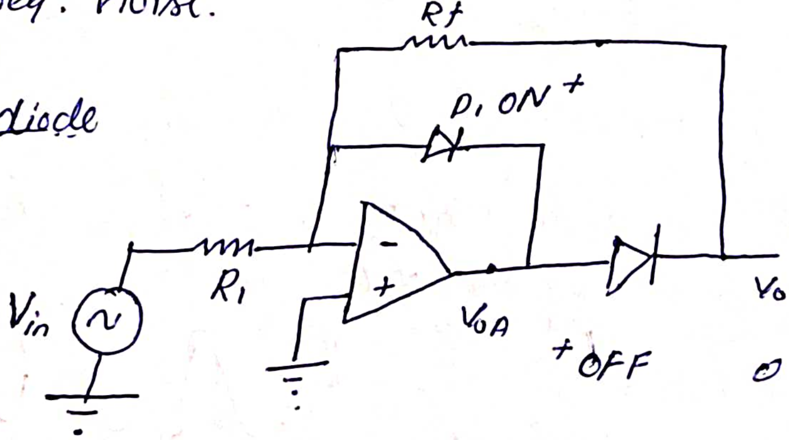
$V_0 = -I_S R_f$

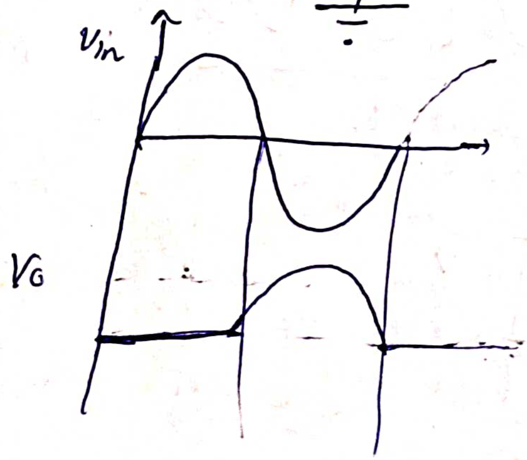
$\boxed{V_0 \propto I_S}$

C_f to reduce the effect of high freq. noise.

Application of precision diode

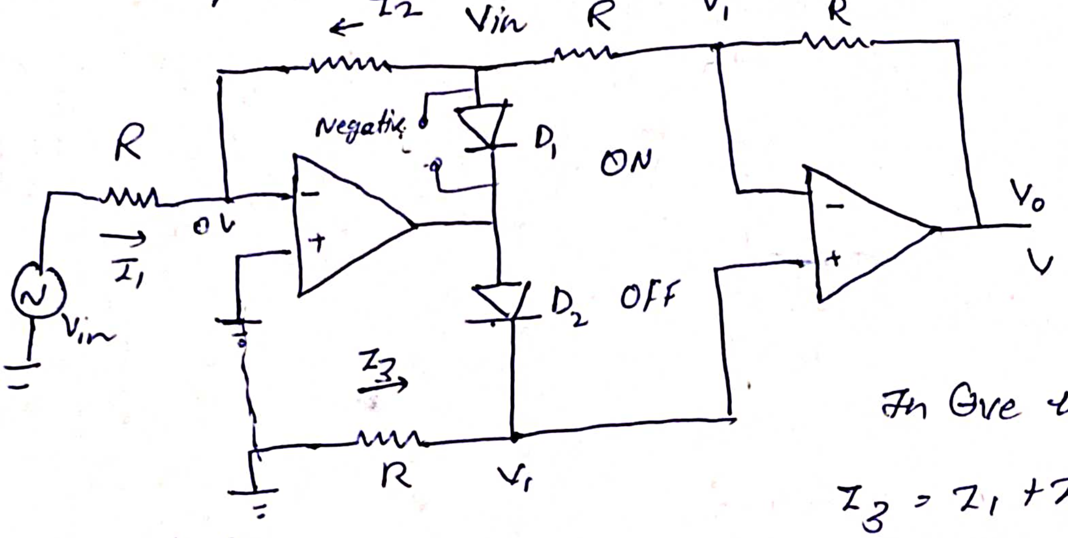
1. Half wave rectifier →
2. Full wave rectifier
3. Peak value detector
4. Clamper
6. Clipper.





open loop - close loop so we need high slew rate.

(ii) Full wave rectifier / Absolute value ckt



In +ve half

$I_3 = I_1 + I_2$

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

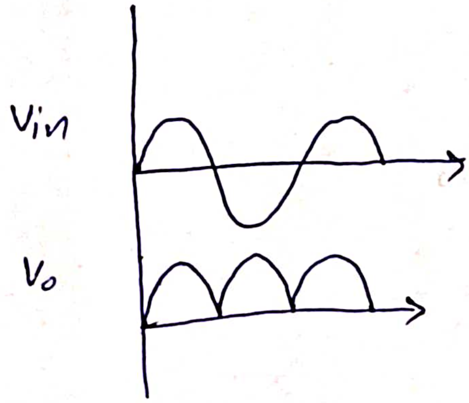
$V_1 = -\frac{2}{3} V_{in}$

$= 1 + R/2R$

$V_o = \frac{3}{2} V_1$

$V_o = \frac{3}{2} \cdot -\frac{2}{3} V_{in}$

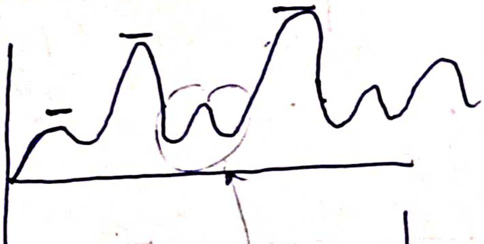
$V_o = -V_{in}$



Application of precision diode

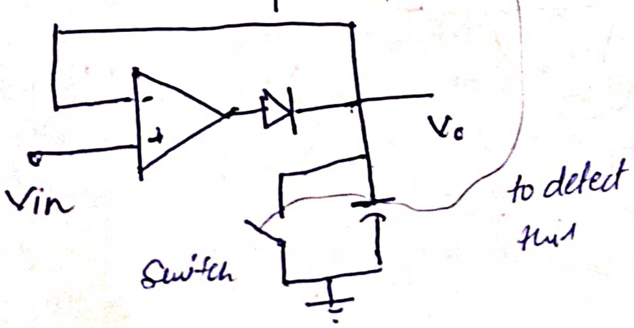
Absolute value circuit (full wave rectifier)

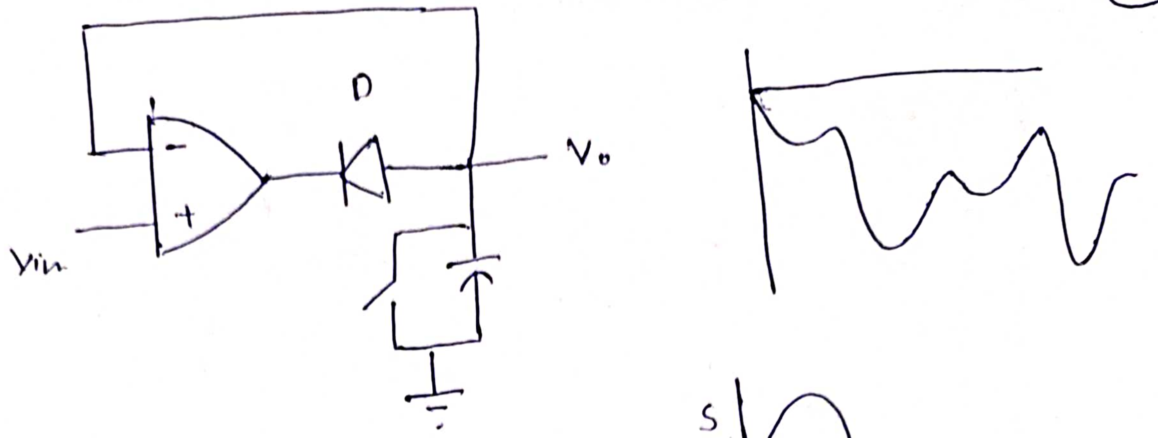
→ Peak value detector



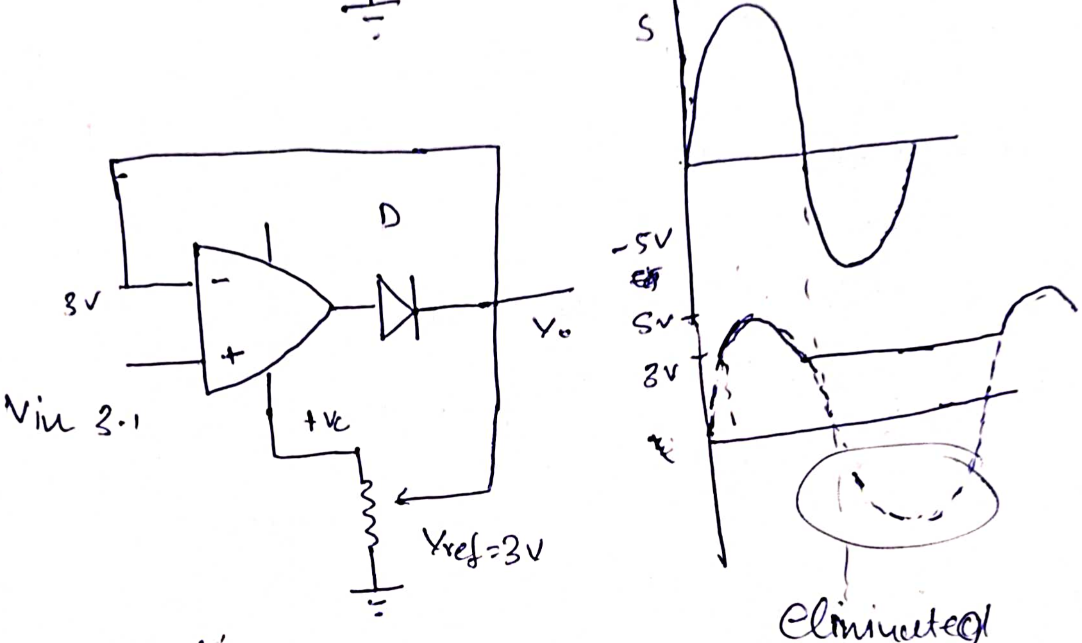
no of peak = 3

peak > all previous peak.

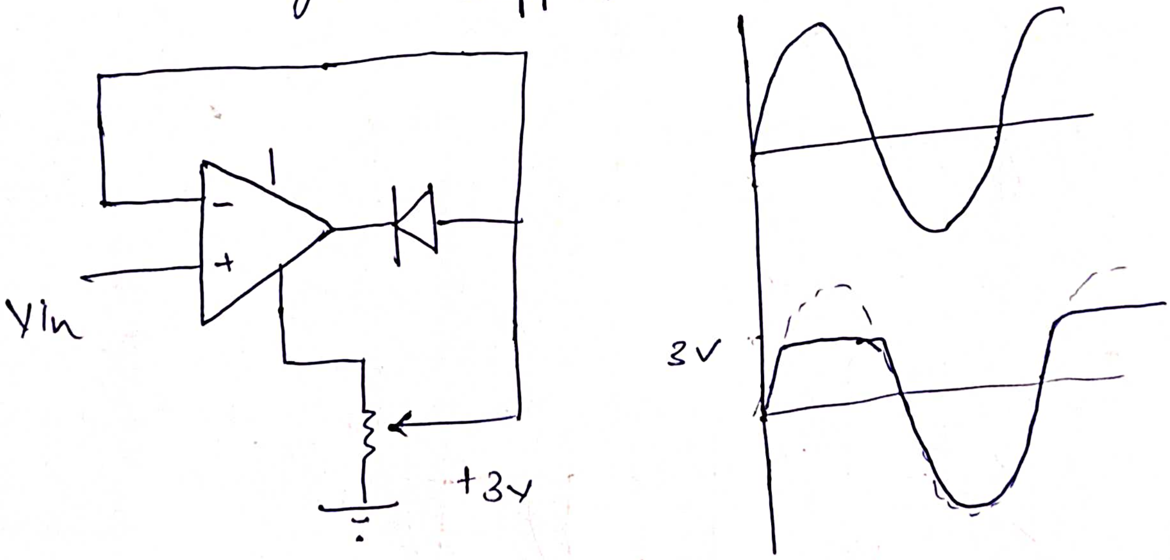




Clipper

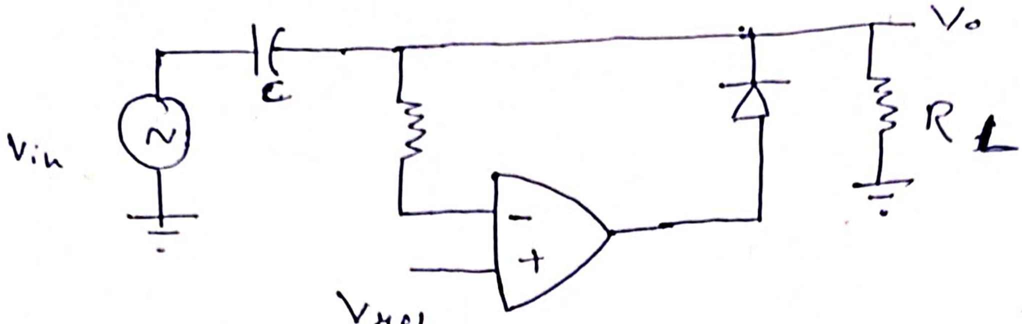


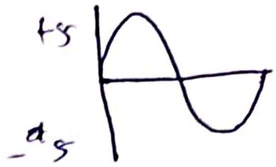
Negative clipper



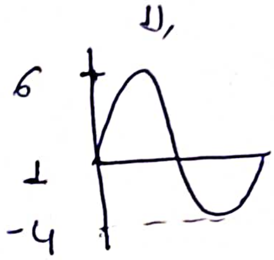
positive clipper

Clamper / DC - Inserter





$V_{ref} = 1 \rightarrow$ ⊕ve Clampler



Clample by $V_{ref} = 1$

Superposition principle

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

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

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

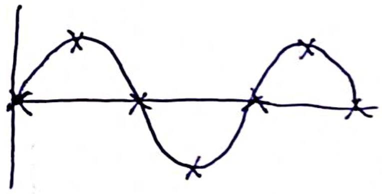
$= V_{ref} + V_{in} + V_m$

↳ if $V_{ref} = -1$ Negative clamper

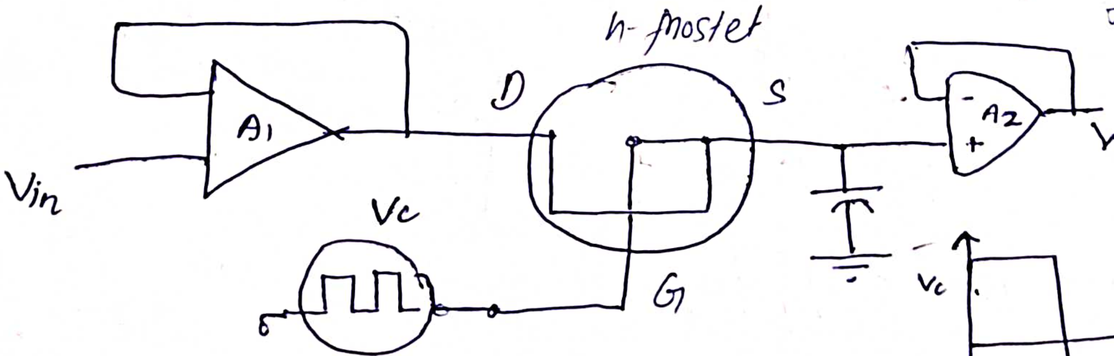
Sample & Hold Circuit

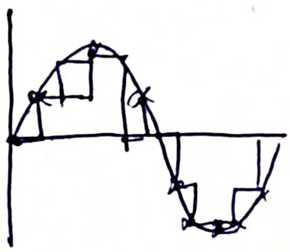
$T_s = \frac{1}{f_s}$

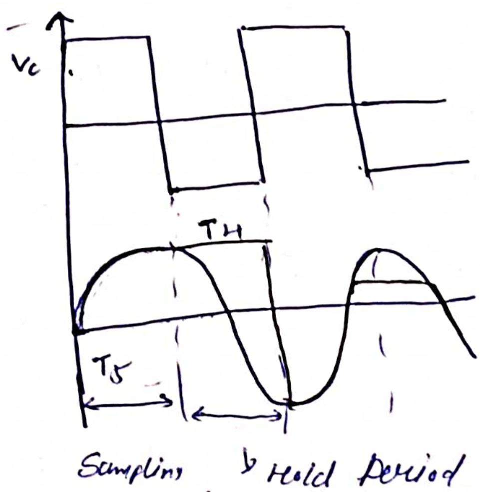
$f_s \geq 2f_m$



Increasing the sampling freq ~ decreasing sampling interval.







↳ 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 convertion & pulse code modulation system.

↳ The N-channel E-mosfet works a switch and controlled by ~~N-chan~~ control voltage V_C.

↳ The capacitor C stores the charge.

↳ The analog signal V_{in} to be sampled to the the drain of the N-mosfet and control voltage DC applied to its gate when control voltage V_C is +ve N-mosfet turns on 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 polystream Nylon or teflon should be used to ~~redirect~~ retain the store charge.

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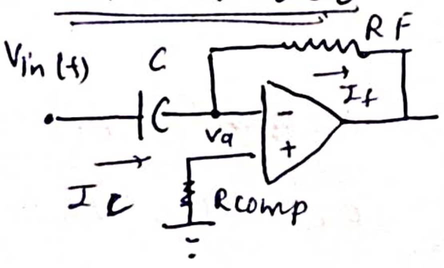
Differentiator



$$V_0(t) = \frac{d\,V_{in}(t)}{dt}$$

$$\Rightarrow \boxed{V_0 = -R_f C \frac{dv_{in}}{dt}}$$

$$I_C = I_f$$

$$V_0 \propto \frac{dv_{in}}{dt}$$

$$C\frac{dv_{in}}{dt} = \frac{-V_0}{R_f}$$

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

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

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

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

$$|H(s)| = \left|\frac{V_o(s)}{V_{in}(s)}\right| = \left|-R_f C_1 s\right| = \left|-R_f C\, j2\pi f\right|$$

$$= 2\pi R_f C_1$$

$$\phi = \tan^{-1}\frac{+}{0} = 90^\circ$$

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

freq Response

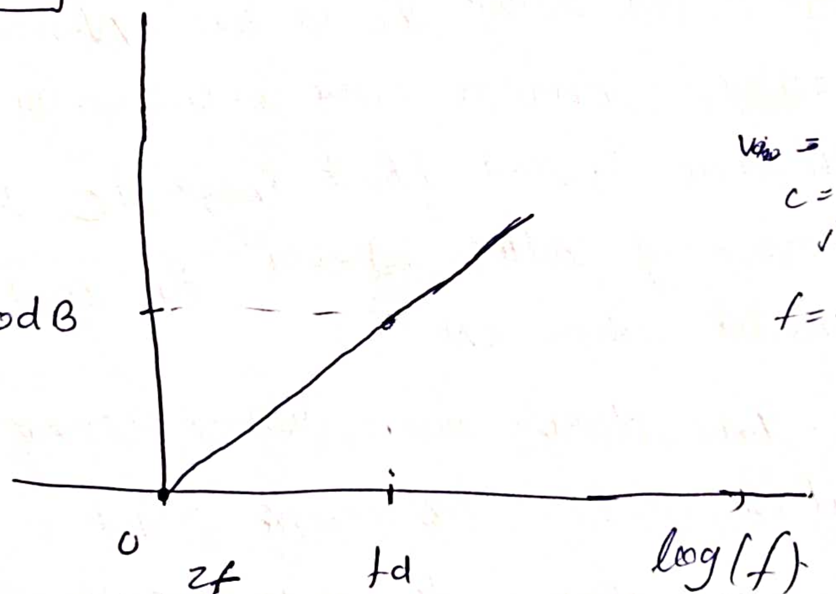
① $f \uparrow$ $c = 0$

② gain depend on i/p freq ckt behave like oscillator

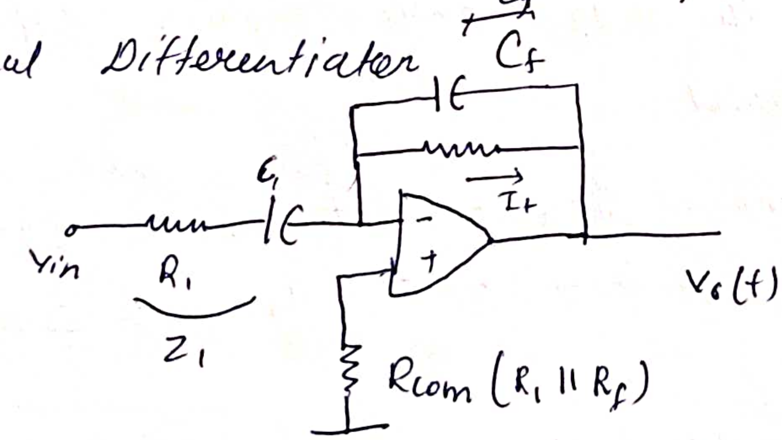
$V_{in} =$

$$c = \frac{1}{j2\pi f}$$

$f = \infty$ $c = 0$



Practical Differentiator



① $V_{in} = \sin(100\pi t)$

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

② $V_{in} = \sin(10000\pi t)$

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

$$\frac{V_o}{V_{in}} = \frac{Z_f}{Z_1} = \frac{\dfrac{R_f}{jR_f\omega_{C_f} + 1}}{\dfrac{1}{j\omega C_1 R_1}} \times j\omega C_1 = \frac{R_f (j\omega C_1 R_1)}{j\omega C_1 R_1 (1 + jR_f\omega C_f)}$$

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

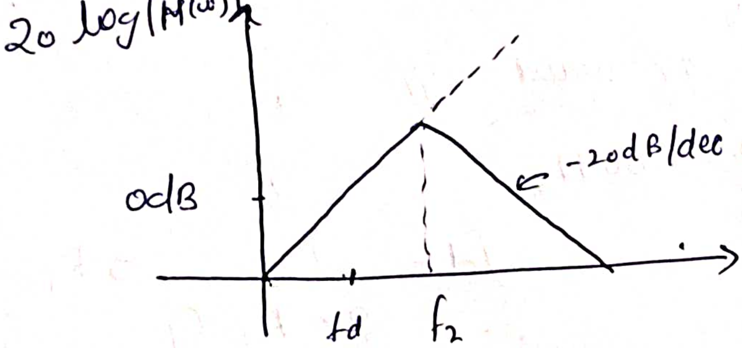
$$Z_f = R_f \parallel \frac{1}{j\omega C_f} = \frac{R_f}{jR_f\omega C_f + 1}$$

$$\frac{V_0}{V_{in}} = \frac{-Z_f}{Z_1} = \frac{-j\omega R_f C_1}{(1+j\omega R_f C_f)(1+j\omega R_1 C_1)}$$

$$j\omega = s$$

$$\frac{V_0}{V_{in}} = \frac{-sR_f C_1}{(1+sR_f C_f)(1+sR_1 C_1)} = \frac{-jf/f_d}{(1+jf/f_2)^2}$$

Let $R_f C_f = R_1 C_1 \Rightarrow \frac{V_0}{V_{in}} = \frac{-sR_f C_1}{(1+sR_f C_f)^2} =$ ~~[illegible]~~



$f_2 > f_d$

$(1+j)(1+j)$

$1+1+2j$

$f_d < f_2 < f_3 \rightarrow$ gain bandwith of op-amp in open loop Comp

↳ f_d

↳ f_3 unity gain bandwith 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 $R_f C_1 >> R_1 C_1$ & $R_f C_f$

$$\frac{V_0}{V_{in}} = \frac{-sR_f C_1}{(1+sR_f C_f)^2}$$

is reduced to

$$\frac{V_0}{V_i} = -sR_f C_1$$

⇔ Design Step of practicle Differentiator

S ① Choose a f_d equal to a highest freq of Input Signal and ~~ttd~~ select $C_1 \leq 1\,\mu f$ and find R_f

S ② Choose this f_2 = 10 times F_d Now Calculate the values of R_1 and ~~R~~ C_f so that $R_1 C_1 = R_f C_f$.

Q: Design a Op. Am Differentiator that will differentiate an i/p signal with maximum freq 100 Hz draw the output waveform for a sign sin wave of 1 V peak at 100 Hz applied to the differentiator.

Q: Repeat the same for Sqr wave i/p

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

$C_1 = 1\,\mu f$ $\qquad f_d = \dfrac{1}{2\pi R_f C_1} \Rightarrow R_f = \dfrac{1}{2\pi C_1 f_d}$

$f_2 = 10 * 100 = 1\,kHz$ $\qquad$ assume $R_1 C_1 = R_f C_f$

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

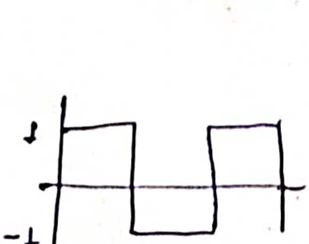
Result $C_1 = 0.1\,\mu f$ $\quad R_f = 15.9\,k$ $\quad R_1 = 1.59\,k$ $\quad C_f = 0.01\,\mu f$

②

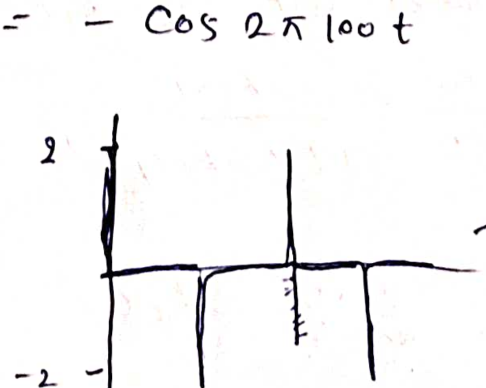
$V_{in} = 1 \cdot \sin(100 \cdot 2\pi t)$

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

②

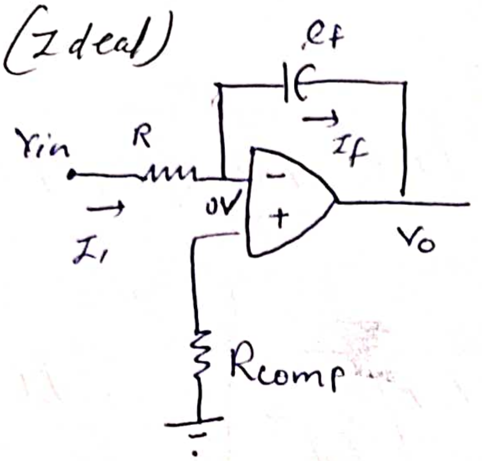


"difference"



→ Spike wave form

Integrator (Ideal)



$i_1 = i_f$

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

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

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

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

$$\frac{V_o}{V_{in}} = \frac{-1}{sR_1C_f} \quad \because s = j\omega$$

$$\frac{V_o}{V_{in}} = \frac{-1}{R_1 C_f j\omega} \Rightarrow \left|\frac{V_o}{V_{in}}\right| = \frac{1}{R_1C_f\omega} = \frac{1}{R_1 C_f 2\pi f}$$

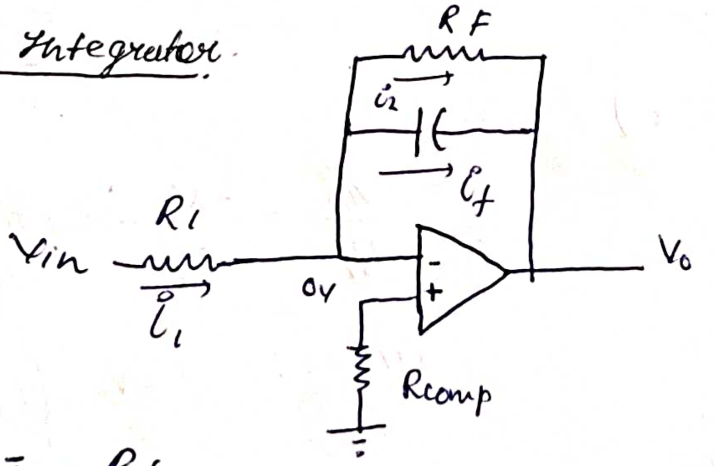
$$f_a = \frac{1}{2\pi R_1 C_f}$$

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

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

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

Lossy Integrator



$i_1 = i_2 + i_f$

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

Taking laplace transform

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

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

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

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

$$H(jf) = \frac{R_F}{R_1\sqrt{1+\underbrace{4\pi^2 R_f^2 C_f^2}_{1/f_a} f^2}}$$

$$\boxed{|H(jf)| = \frac{R_f}{R_1\sqrt{1+\left(f/f_a\right)^2}}}$$

$\therefore f_a \Rightarrow \frac{1}{2\pi R_f C_f}$.

$f=0 \quad |H(jf)| = \frac{R_f}{R_1}$

$f = f_a \quad = R_f / R_1\sqrt{2}$

$f=\infty \quad H(jf) = 0 \rightarrow$ high noise elemented

$f = 10 f_a \rightarrow 99\%$ accuracy

Q: Consider a lossy integrator with $R_1 = 10\,k\Omega$ $R_f = 100\,k\Omega$ $C_f = 10\,nf$. Determine the low freq limit of integration and study the response for i/p sin wave, step input and sqr wave.

$$f_a = \frac{1}{2\pi R_f C_f} = \frac{1}{2\pi\, 100 \times 10^5\, 10 \times 10^{-9=6-3}} = \frac{1000}{2\pi}$$

$$= \frac{500}{\pi} = 159\,Hz$$

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

$$V_o = -\frac{R_f}{R_1\sqrt{1+}}$$

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

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

$$\int \frac{\sin(w_a t)}{R_1} = \int -\frac{V_o}{R_f} - \int C_f \frac{dV_o}{dt}$$

$$V_o = \frac{-C_f \pm\sqrt{C_f^2 - \frac{4\cos w_a t}{R_f R_1 w_a}}}{2/R_f}$$

$$\therefore -\frac{\cos w_a t}{w_a R_1} = -\frac{V_o^2}{R_f} - C_f V_o$$

$$\frac{V_o^2}{R_f} + C_f V_o + \frac{\cos w_a t}{w_a R_1}$$

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

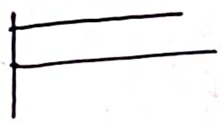
$$\frac{V_o}{V_{in}} = \frac{-10}{\sqrt{1+10^2}} = \frac{10}{\sqrt{101}} \simeq -1$$

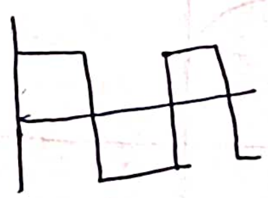
$$f = \frac{f_a}{10}$$

$$\Rightarrow \frac{10}{\sqrt{1+\left(\frac{1}{10}\right)^2}} = \frac{10\times 10}{\sqrt{101}} \simeq -10$$

$$f = 10 \times 159\ Hz$$

Sin wave =  Integrate (-1) = 

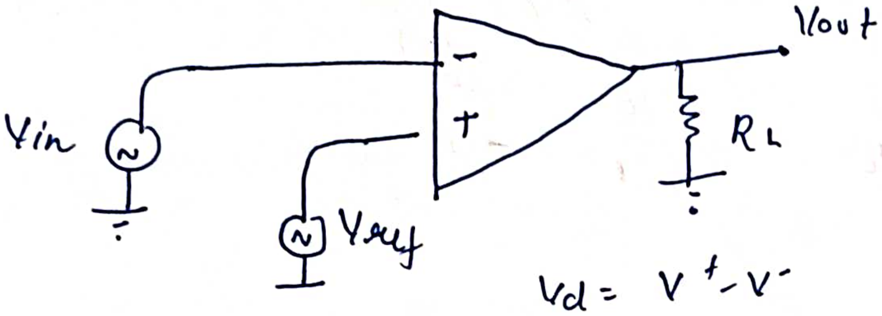
~~Sqr wave~~ unit step =  $\Rightarrow$ 

~~Unit ramp~~ Sqr wave  $\Rightarrow$ 

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

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

Comparator (Non linear operation of Op-Amp)



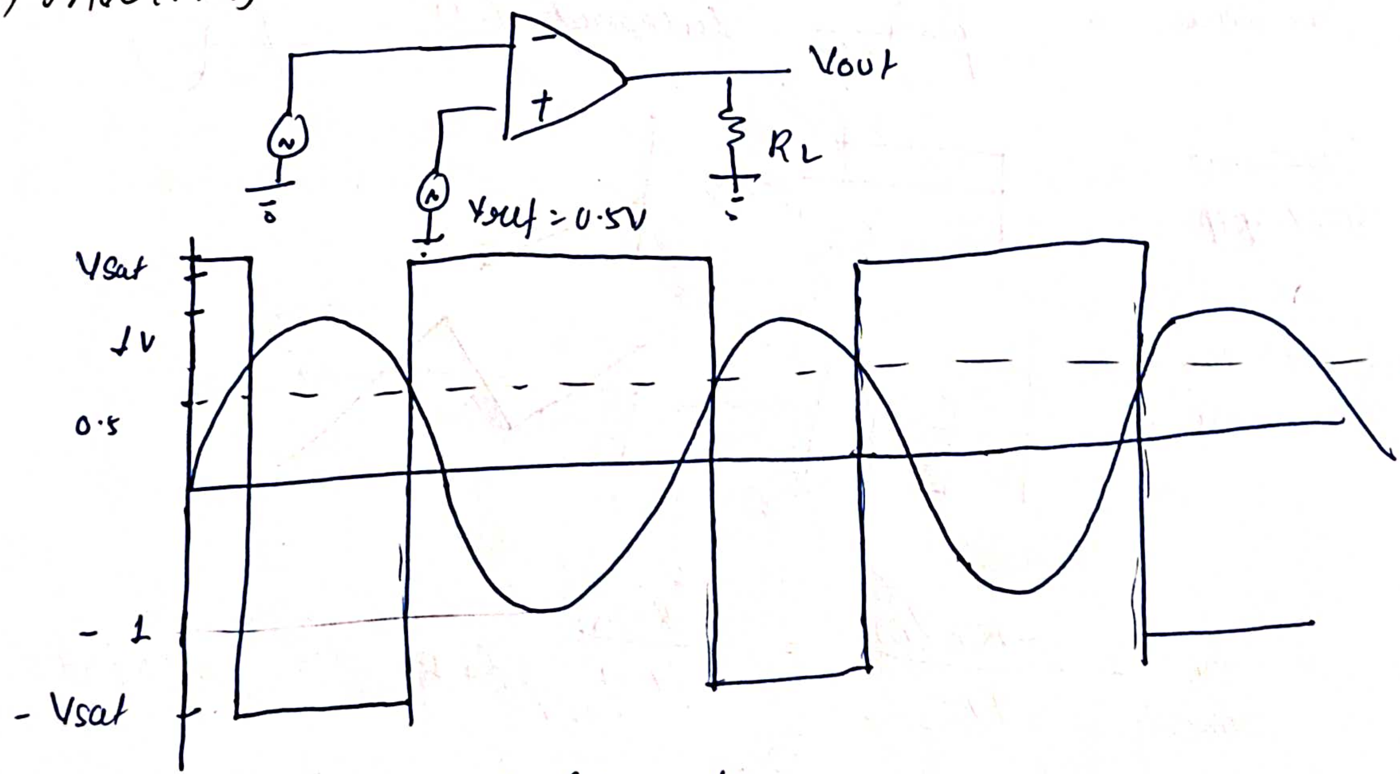
open Loop Configuration

$V_d = V^+ - V^-$

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

1) Inverting Comparator
2) Non-Inverting Comparator

1) Inverting



↳ Used for A to D Converter

↳ It is sine to sqr wave convertor

↳ If Vref = 0 → It acts as a "zero detector"

↳ Here Input freq = Output frequency

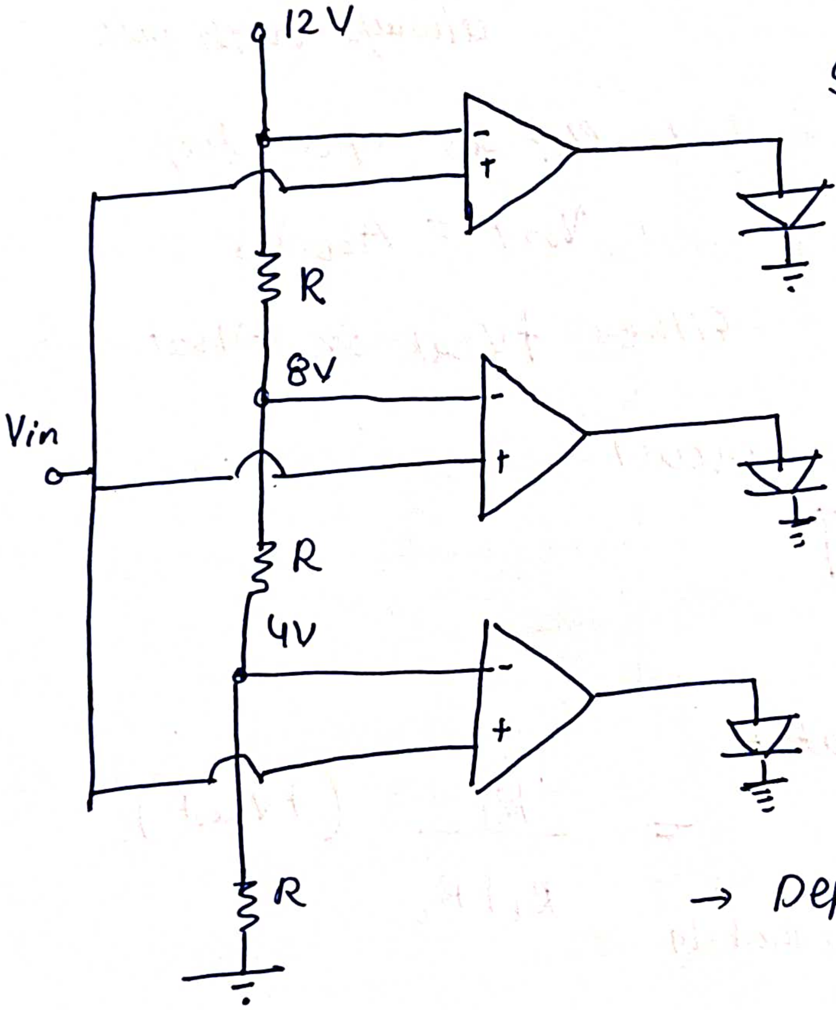
<u>issue</u>

↳ Due to Noise their will be some deviation in o/p sqr wave so we need another ckt

<u>Window Detector</u>

If $V_D > 0 \rightarrow +V_{sat} \rightarrow$ ON

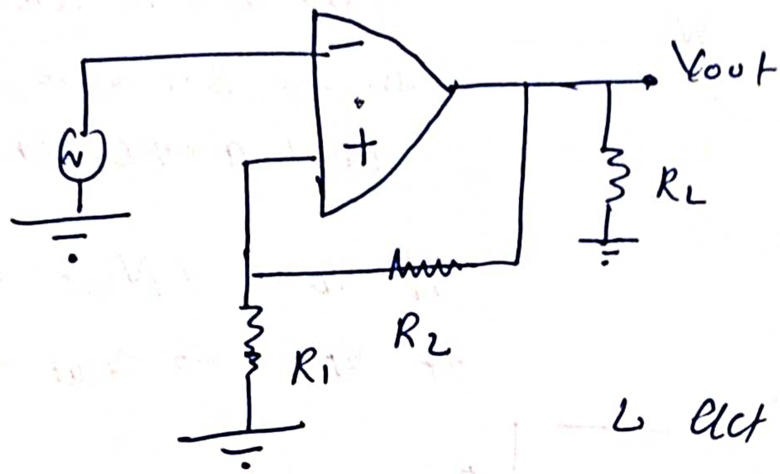
If $V_D < 0 \rightarrow -V_{sat} \rightarrow$ off



→ Depending Upon Vin, LED light glows

Vin	Red	Green	Yellow
13V	ON	ON	ON
10V	OFF	ON	ON
6V	OFF	OFF	ON
3V	OFF	OFF	OFF

Regenrative Comparator / schimit trigger / positive representation comparator.



↳ positive feedback circuit → Vd ≠ 0 always high gain

↳ act as open loop

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

Either +Vsat or −Vsat

↳ Only in -ve feedback circuit

$\boxed{V_d = 0}$

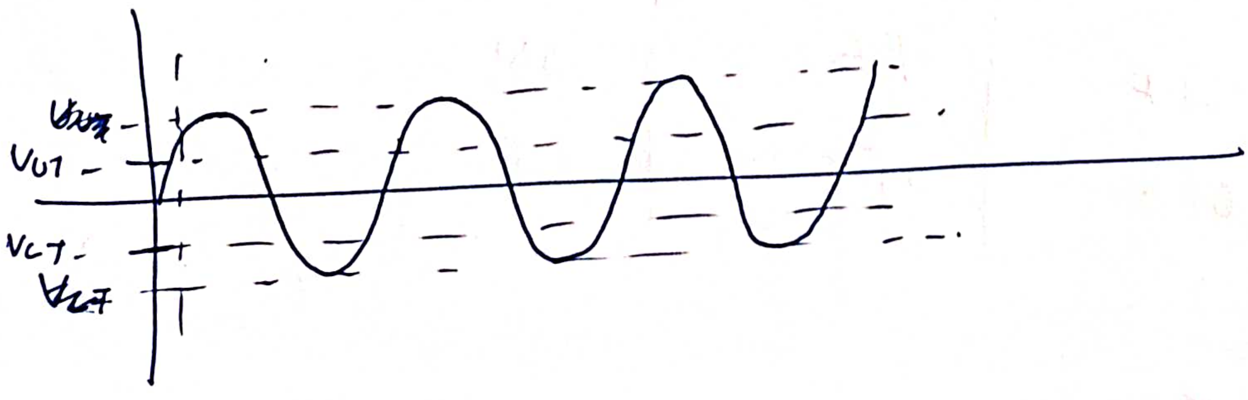
<u>Case 1</u> $V_{out} = +V_{sat}$

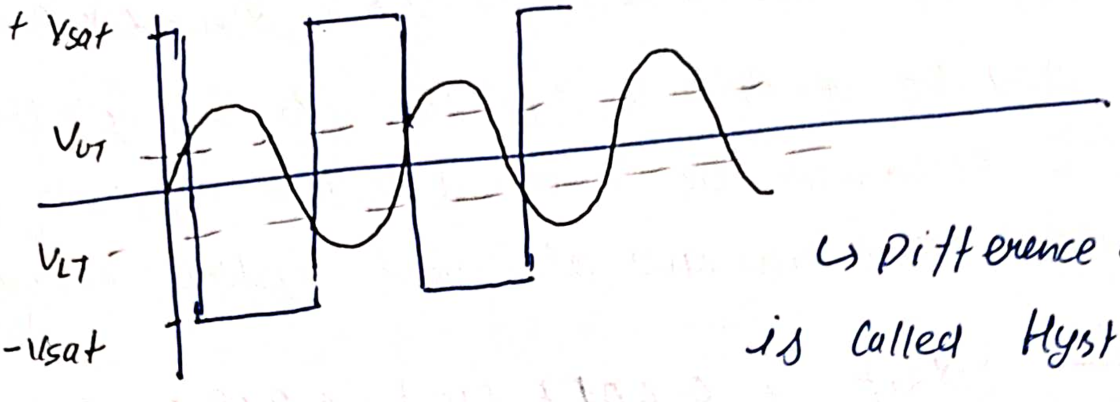
then voltage at A,

$$V_A = \underbrace{V_{UT}}_{\text{upper therhold}} = \frac{R_1}{R_1+R_2}(+V_{sat})$$

<u>Case 2</u> $V_{out} = -V_{sat}$, then voltage at A

$$V_A = \underbrace{V_{LT}}_{\text{lower therhold}} = \left(\frac{R_1}{R_1+R_2}\right)(-V_{sat})$$

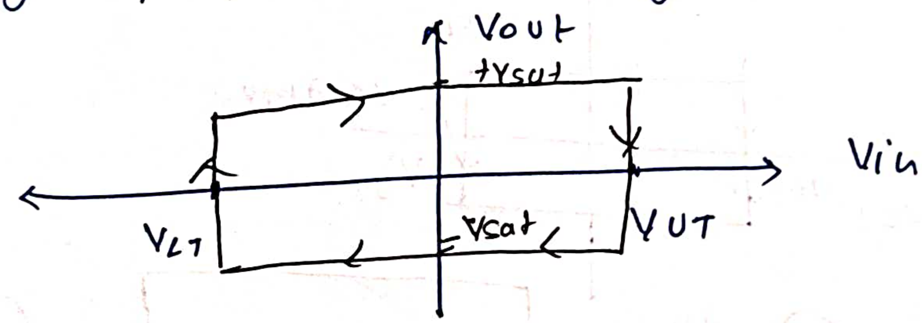




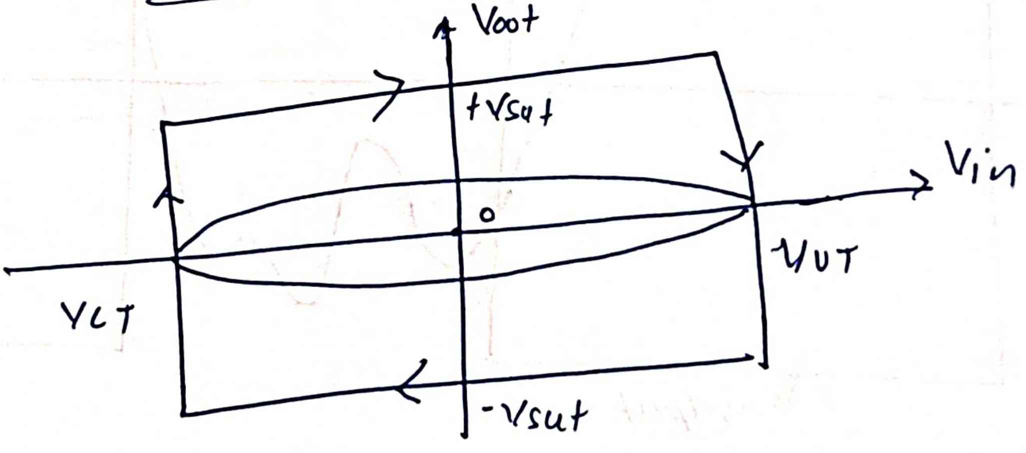
↳ Difference b/w V_{UT} & V_{LT} is called Hysteresis Voltage

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

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



Tranfer charcteristic



↳ The comparator with +ve feedback is set to exibit hysteris (V_H) i.e het band condition when the input of comparator exibits V_{UT}, it's output switches from +Vsat to -Vsat and reverse back to its original state the +Vsat, when input goes below V_{LT}.

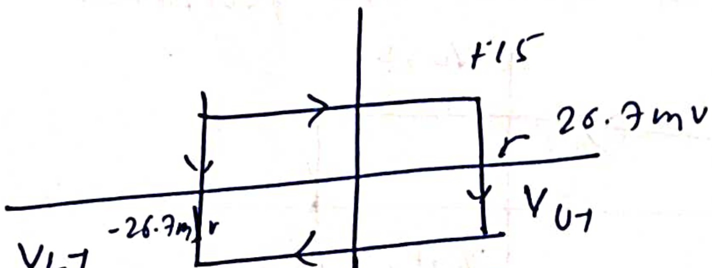
Q: In this given fig $R_1 = 100\,\Omega$, $R_2 = 56\,k\Omega$, $V_{in} = 2V$ (peak to p sine wave, and the op-Amp is type 741 with supply voltage +15V and -15V. Determine the threshold voltage V_{UT} & V_{LT} and draw output waveform and also find Hysteresis Voltage (V_H)

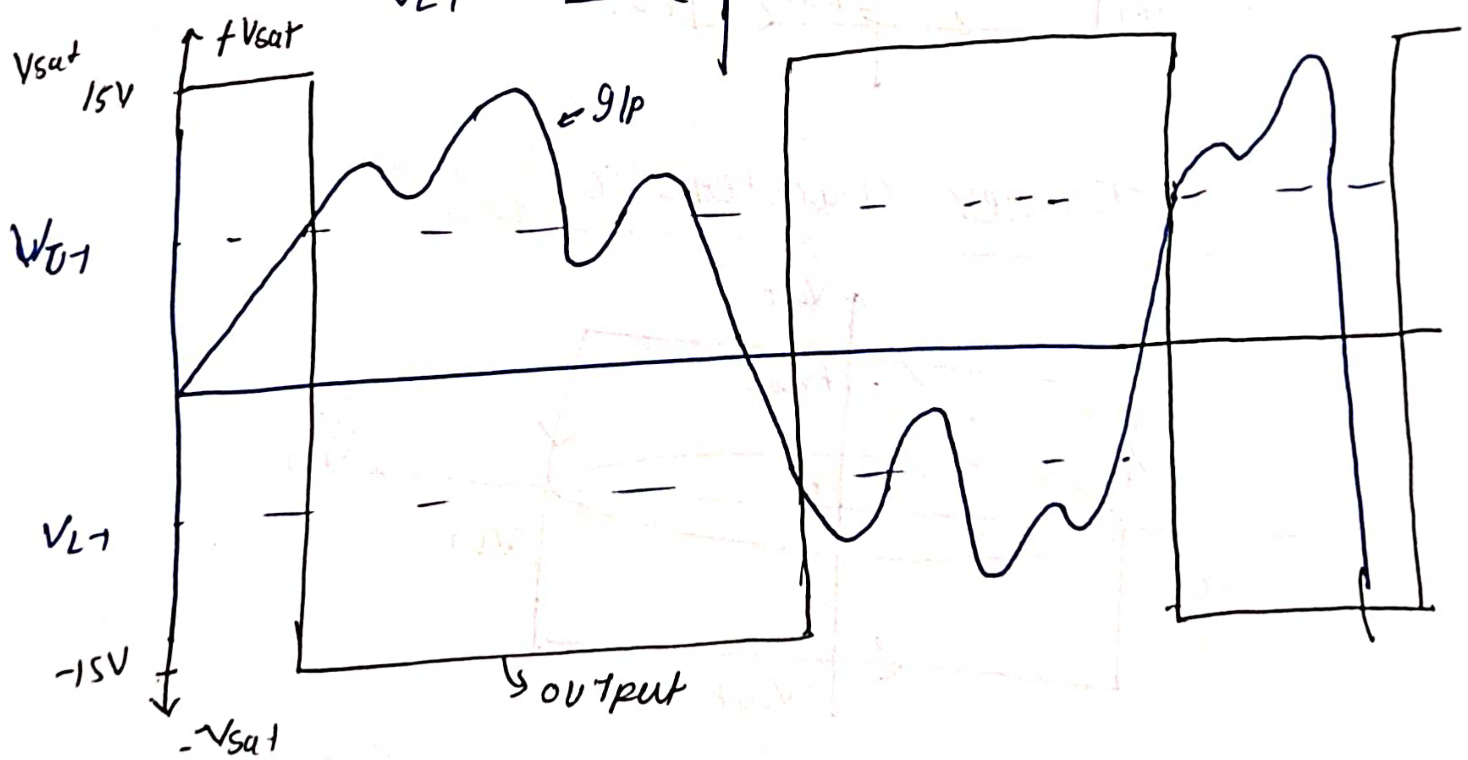
$$V_{UT} = \left(\frac{R_1}{R_1+R_2}\right) V_{sat} = 0.0017\,(15) = 0.026 = 26.7\,mV$$

$$V_{LT} = \left(\frac{R_1}{R_1+R_2}\right)(-V_{sat}) = -26.7\,mV$$

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

$$V_H = 53.4\,mV$$



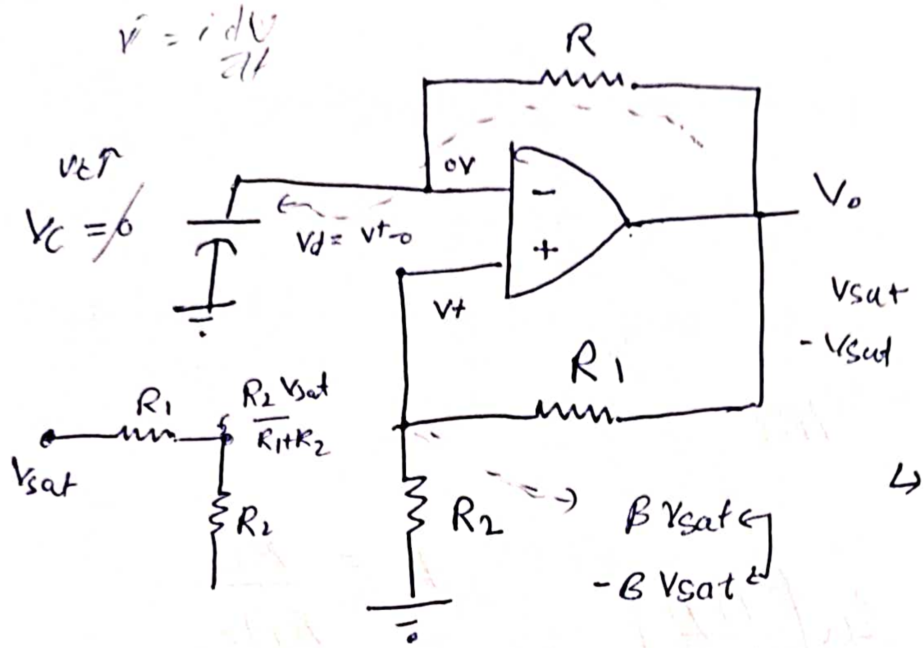


Astable multivibrator/ free running oscillator / sqr wave genator.

↳ To force the op-Amp to work in saturation Mode to genrate Square wave form.

Astable
↳ Quasi Stable

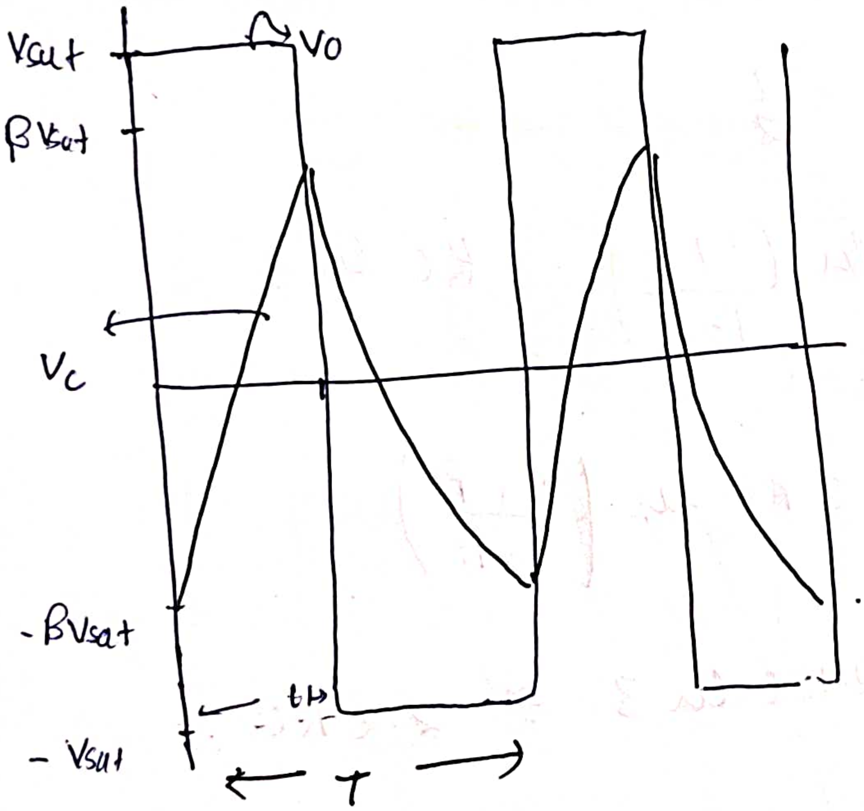
$i = C\frac{dV}{dt}$



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

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

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



$f = \frac{1}{T}$

Charging

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

for charging

$$V_f = +V_{sat} \qquad V_i = -\beta V_{sat}$$

$$V_C(t) = V_{sat} + (-\beta V_{sat} - V_{sat})\, e^{-t/RC}$$

at $t = t_1$

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

$$\beta \cancel{V_{sat}} = \cancel{V_{sat}}(1 - \beta e^{-t_1/RC}) + \cancel{V_{sat}}\, e^{-t_1/RC}$$

$$\cancel{(\beta - e^{-t/RC})V_{sat} = V_{sat}(1 - e^{-t_1/RC})}$$

$\cancel{\beta = 1 -}$

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

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

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

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

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

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

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

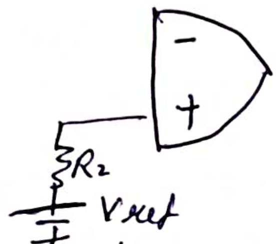
b. Let $R_1 = 1.16 R_2$

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

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

↳ to limit the Amplitude of Sqr wave we can use zener diode

↳ to change the width of Charging or we want Unsymmetric Sqr wave → we can give Vref to R_2



Self study - Tringular wave generator

$\boxed{\text{Sqr}} \rightarrow \boxed{\text{Integrator}}$