Operational Amplifiers:-

Gives large output

May not be enough

∴ Cascade multiple amplifiers together

$V_i \rightarrow \boxed{A_1} - \boxed{A_2} - \cdots\cdots - \boxed{A_n} - V_0 = A_1 A_2 \ldots A_n V_i$

↳ Too bulky

We need something just like this but a single integrated circuit

Op-Amp:-

↳ Has a very high gain integrated into a single ckt

Operations:-

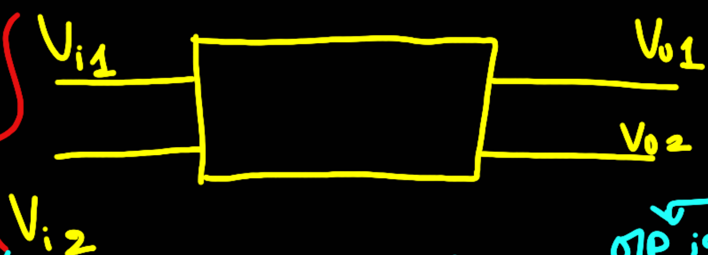
Mathematical (Arithmetic)
Logical
Relational

Has a very high gain & capable of performing certain operations like mathematical, logical & relational.

coz its continuous

Analog Circuit

Op-Amp is a linear Circuit

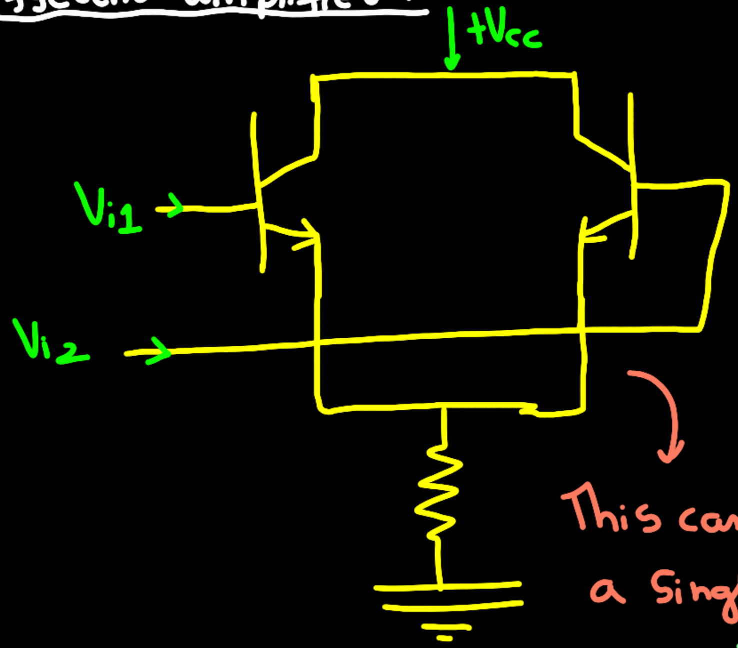


Cancels the common DC voltage ← $V_{i2} - V_{i1}$

$V_{o2} - V_{o1}$ → O/P is balanced

∴ Differential I/P & Differential O/P

Different amblifier :-



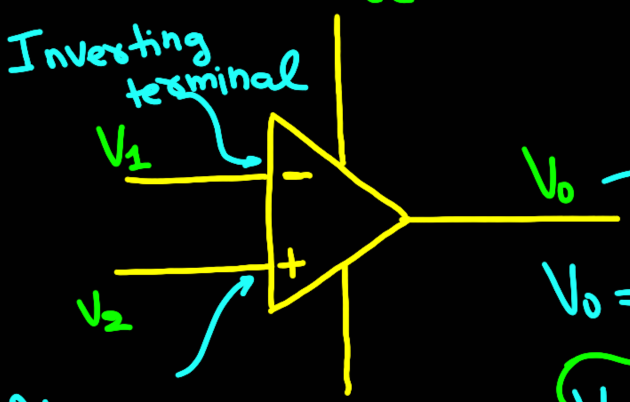
Cabacitors & Biasing resistors eliminated

This can be integrated into a single chip.

↓

Cascading

Symbol:-

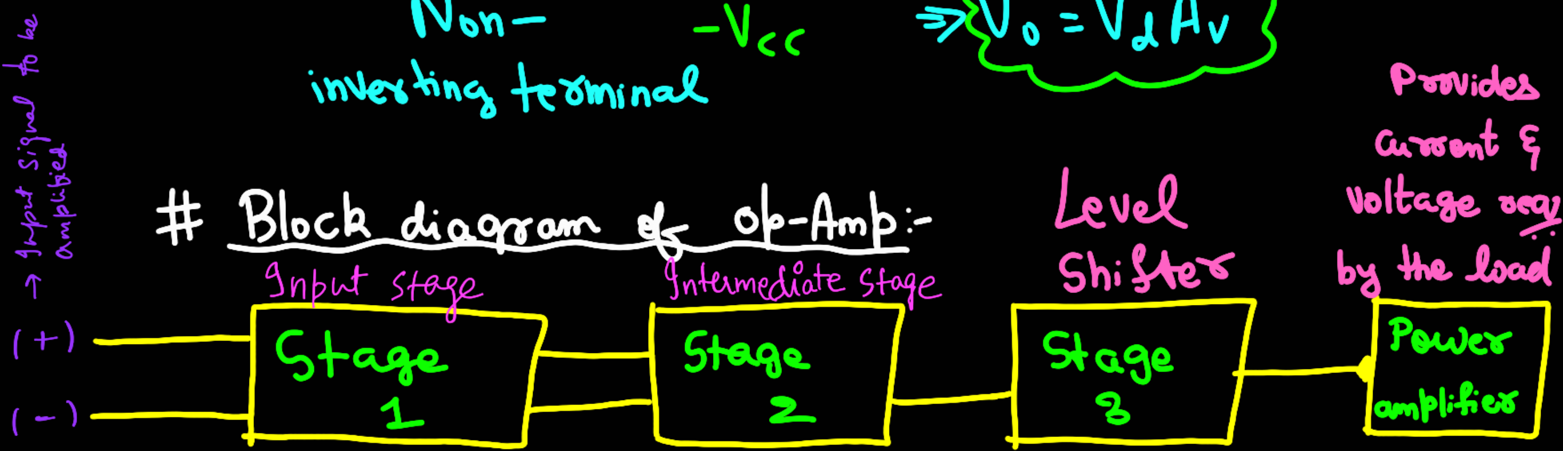


V_0 → O/P terminal

$V_0 = (V_2 \sim V_1) * \text{Gain}$

$\Rightarrow \boxed{V_0 = V_d A_v}$

Block diagram of op-Amp:-



1. It's a differential amplifier
2. It's a dual input, balanced output Diff. Amp. (*DUAL O/P*)
3. Rejects noise
4. This stage also provides high I/P impedance
5. Provides high voltage gain

1. Dual I/P (balanced) and unbalanced O/P amplifier.
2. Provides very high voltage gain

1. The O/P of stage
2. i.e I/P of stage 3 is above GND as direct coupling is used.
2. Level 3 (level shifter) is used to sift the O/P of level 2 downwards (wrt GND)

1. Also called as push pull amplifier
2. Increase the O/P voltage swing
3. Improves current supplying capabilities
4. Provides Min. O/P impedance

Ideal Op-Amp VTC & its characteristics:-

↗ Voltage Transfer characteristics

★ ∞ i/p impedance ⤵
Ideally no loading needed

★ Zero o/p impedance ⤵
O/P can drive ∞ no. of other devices

★ ∞ Bandwidth ⤵
So, that any freq. can be accepted by the ideal op-amp

★ ∞ Voltage gain

★ Perfect Balance, i.e input offset voltage = 0
(If no i/p no o/p at all IDEALLY)

★ ∞ CMRR (Common Mode Rejection Ratio)

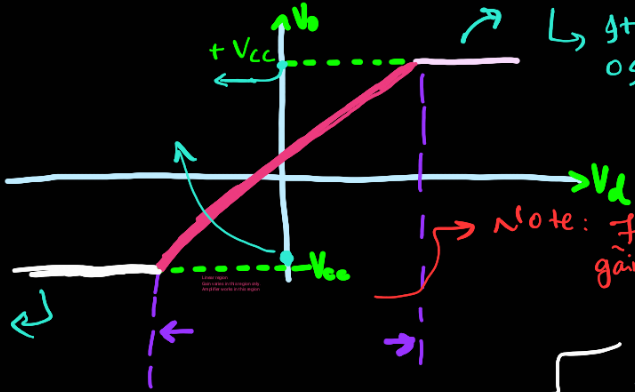
$$= \frac{\text{Differential Gain}}{\text{Common Mode Gain}}$$

Differential Gain → Normal V_{out}, when there is a difference in i/p voltage

Ratio of these 2 is CMRR

Common Mode Gain ↳ If both the input signal are same or grounded, then diff. i/p is 0, ∴ the output is also 0 ideally, but ≠ 0, practically

★ ∞ Slew rate → Rate of change of O/P voltage w.r.t time = $\frac{dV_0}{dt}$
(Tells us how fast the amplificatⁿ process takes place)



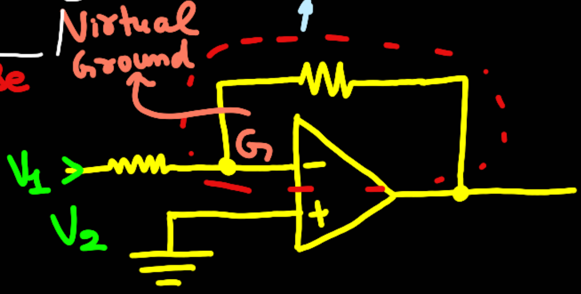
@ Saturatⁿ region
↳ It becomes an oscillator ⤵
(constant gain)

Note: For an amplifier gain must keep on changing

@ Saturatⁿ region
↳ It becomes an oscillator
(constant gain)

A = ∞ → Disadv:- No use

Gain can be reduced using -ve feedback ⟹



★ op-Amp is amplifier with -ve feedback

$\boxed{I_f = -I_1}$

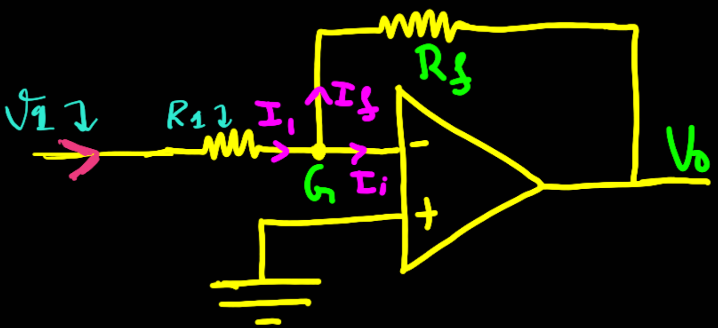
O/P = $-V_0$

O/P is always 180° out of phase

Applications of Op-Amp:-

① Inverting Amplifier:-

* R_f : feedback resistance
* I_i : Inverting current
* I_1 : Net current



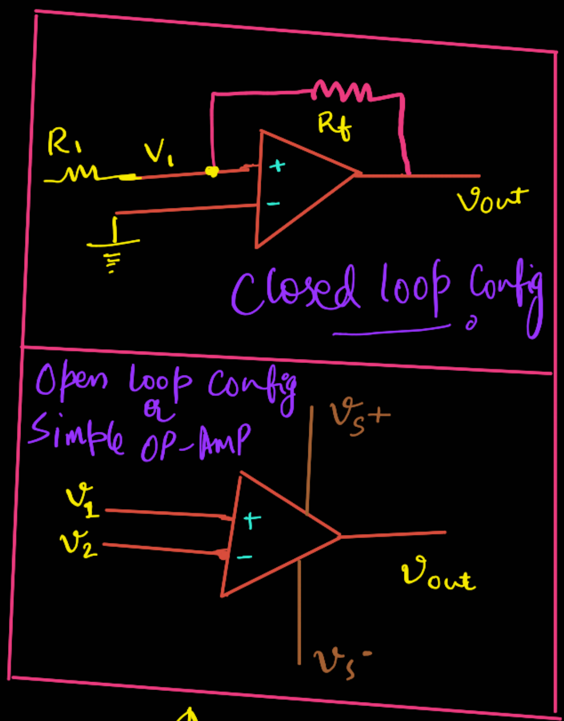
1. Does not exist in electrical ckts, it exists only in Electronic ckts (op-amps)
2. Node whose voltage is zero but not connected to GND physically or mechanically.

$$V_0 = A_V V_1$$

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

$$\boxed{V_G = 0}$$ Virtual Ground

$$\boxed{I_1 = \frac{V_1}{R_1}}$$



$$I_1 = \cancel{I_i}^{\,0} + I_f \Rightarrow I_1 = I_f$$

$$I_f = \frac{V_G - V_0}{R_f} = \frac{-V_0}{R_f}$$

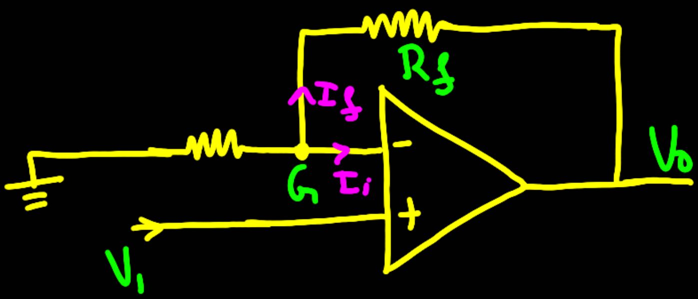
$$\frac{-V_0}{R_f} = \frac{V_1}{R_1} \Rightarrow \boxed{V_0 = -\frac{R_f}{R_1} V_1}$$ → O/P voltage

The open loop gain is extremely high, and because of such high gain The OP AMP becomes unstable, so inordered to avoid such conditions we connect a resistor (Rf) from output back to the input (closed loop OP AMP) to loose some gain, this helps us in reducing amd controlling the gain. It depends on the value of the resistor (Rf) .
Therfore, closed loop OP AMP is more controlled than open loop OP AMP

$$A_V = -\frac{R_f}{R_1}$$ → Gain

O/P is inverted by a phase shift of 180°

Non-inverted amplifier:-



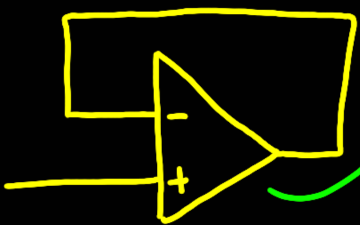
Follow same procedure for V_o & A_v

$$V_o = \frac{R_f}{R_1} + 1$$ → O/P voltage

$$A_v = \frac{R_f}{R_1} + 1$$ → Gain

**O/P phase shift is 0/360⁰

Voltage Follower/Unity Gain Amplifier/Buffer Amplifier:-



→ Gain = 1

Non-inverting amplifier gain $= \frac{R_f}{R_1} + 1$

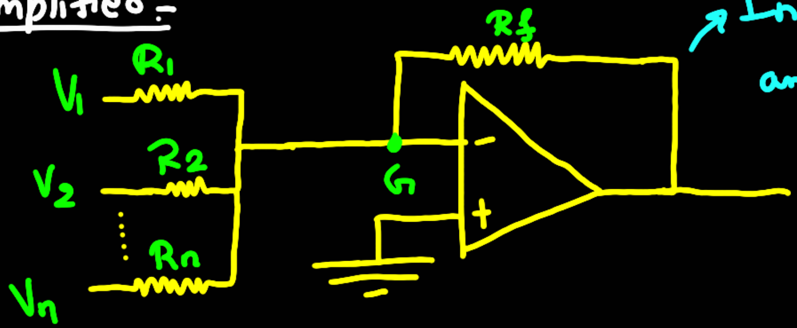
Eliminating $R_f \Rightarrow A_v = 1$

$\therefore V_o = V_i$ → Thus, V_o follows V_i

1. In buffer amplifier the O/P voltage follows I/P voltage, i.e. Vout=Vin
2. Loop gain= 1
3. It's a special case of *Non-inverting (+ve)* amplifier so phase of O/P signal is 0/360⁰
4. Feedback resistance (Rf) =0
   R1=infinity

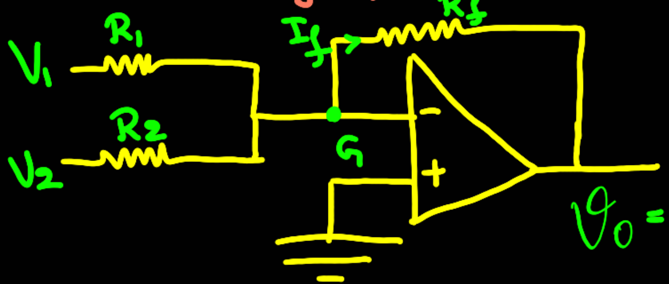
Application:
1. Adds buffer effect to the ckt
2. Used for impedance matching
3. Acts as an Isolator

Summing Amplifier:-



Inverting amplifier Configuration

For analysis, we consider only V_1 & V_2



$v_0 = V_1 + V_2$ To prove this

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

$$I_2 = \frac{V_2 - V_G}{R_2} = \frac{V_2}{R_2}$$

$$\left(V_G = 0\right)$$

★ The sum of currents I_1 & I_2 enter node G

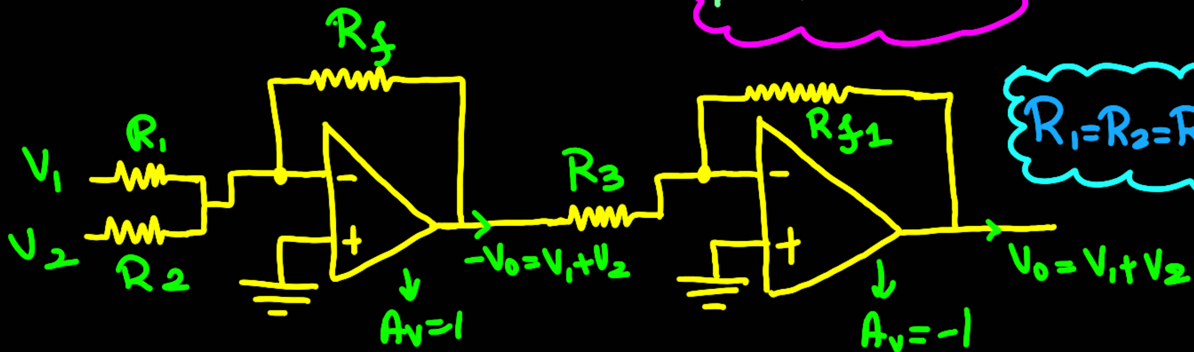
★ Since I_i (current into op-amp) is zero $\Rightarrow I_f = I_1 + I_2$

$$I_f = \frac{V_G - V_0}{R_f} = \frac{-V_0}{R_f}$$

$$\frac{-V_0}{R_f} = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$

Let $R_f = R_1 = R_2 = R$

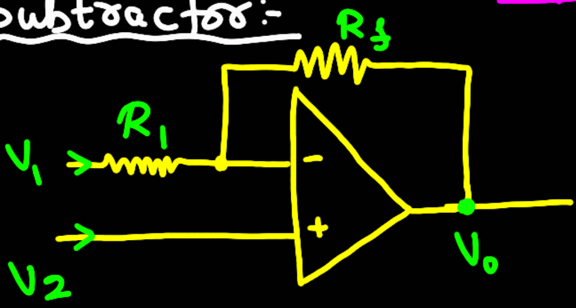
$\Rightarrow -V_0 = V_1 + V_2 \Rightarrow \boxed{|-V_0| = V_1 + V_2}$ Thus, it can be used as adder ckt



$\boxed{R_1 = R_2 = R_f = R_3 = R_{f1}}$

Subtractor:-

To prove:- $V_o = V_2 - V_1$



$$V_{o1} = -\frac{R_f}{R_1}(V_1)$$

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

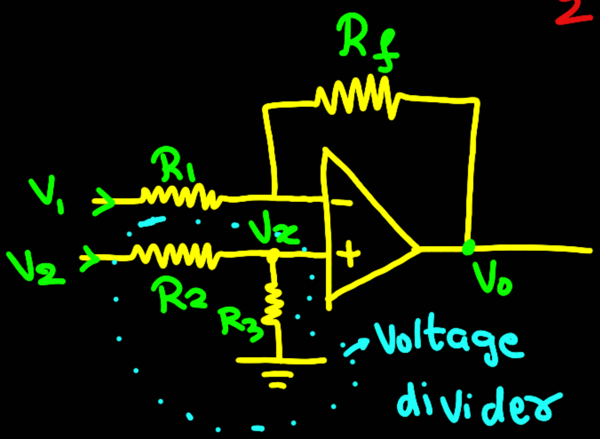
Taking $R_f = R_1 = 1$ $\Rightarrow V_{o1} = -V_1$ → We need this

$\Rightarrow V_{o2} = 2V_2$ → We don't need this

$\overline{2}$ → Thus we need to divide!

↓

Use a voltage divider



$$\boxed{V_x = \frac{V_2}{2}}$$

Expression for O/P voltage:-

O/P voltage due to V_1 is V_{o1} given by

$$V_{o1} = \frac{-R_f}{R_1} V_1 \rightarrow (1)$$

O/P voltage due to V_2 is V_{o2} given by

$$V_{o2} = \left(1+\frac{R_f}{R_1}\right) V_x \rightarrow (2)$$

$$V_x = R_3\left(\frac{R_2}{R_2+R_3}\right) \rightarrow (3)$$

Thus from (3), (2) now becomes

$$V_x = \left(1+\frac{R_f}{R_1}\right)\left(\frac{R_3 V_2}{R_2+R_3}\right)$$

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

$$V_o = \frac{-R_f}{R_1} V_1 + \left(1 + \frac{R_f}{R_1}\right)\left(\frac{R_3}{R_2 + R_3}\right) V_2$$

Let $R_1 = R_2 = R_3 = R_f = R$

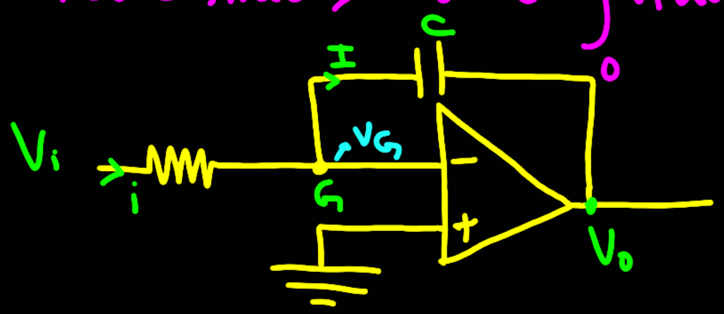
$$V_o = \frac{-R}{R} V_1 + \left(1 + \frac{R}{R}\right)\left(\frac{R}{R+R}\right) V_2 = -V_1 + V_2$$

$\therefore V_o = V_2 - V_1$ → Thus it is used as a subtractor

Integrator:-

↳ op-amp is used for integration

Prove that ⇒ $V_o \propto \int_0^t V_i \, dt$



Voltage across capacitor C is $V_G - V_o = \frac{q}{C} \Rightarrow -V_o = \frac{q}{C}$ → ①

WKT ⇒ $q = \int_0^t i \, dt$ → ②

From the ckt $i = \frac{V_i - V_G}{R} = \frac{V_i}{R}$ → ③ $(V_G = 0)$

Put ③ & ② in ①

$$-V_o = \frac{1}{C}\int_0^t i\,dt = \frac{1}{C}\int_0^t \frac{V_i}{R}\,dt$$

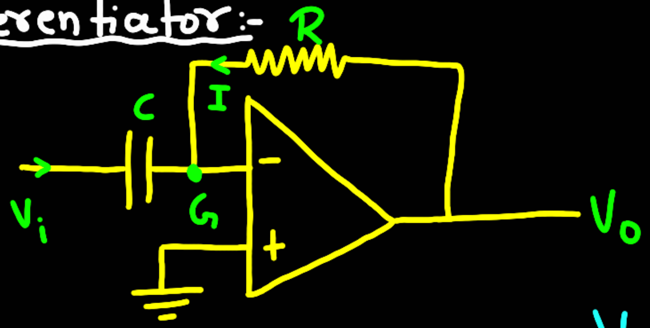
$$V_0 = \frac{-1}{RC}\int_0^t V_i\,dt$$

$$\Rightarrow \boxed{V_0 \propto \int_0^t V_i\,dt}$$

Thus, it can be used as integrator

Differentiator:-

Op-Amp used for differentiation



$$I = \frac{V_0 - V_G}{R} = \frac{V_0}{R} \rightarrow (1)$$

$$V_i - V_G = \frac{q}{C} \Rightarrow q = CV_i \rightarrow (2)$$

$V_G = 0$

Differentiating (2), we get

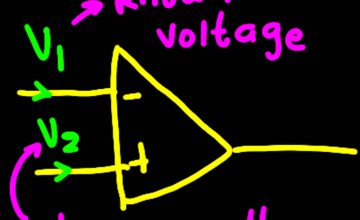
$$\frac{dq}{dt} = C\frac{dV_i}{dt} \Rightarrow \frac{-V_0}{R} = C\frac{dV_i}{dt}$$

$$-V_0 = RC\frac{dV_i}{dt}$$

$$V_0 = -RC\frac{dV_i}{dt} \Rightarrow \boxed{V_0 \propto \frac{dV_i}{dt}}$$

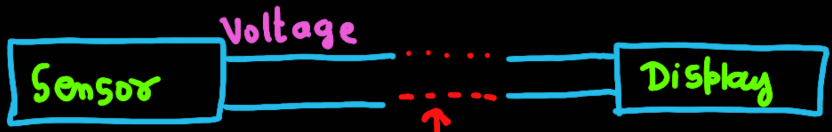
Thus it can be used as differentiator

Comparator:-



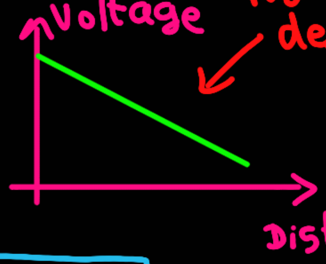
- ★ Compare V_2 with V_1
- ★ $V_2 < V_1 \Rightarrow$ O/P is -ve
- ★ $V_2 > V_1 \Rightarrow$ O/P is +ve
- ★ $V_2 = V_1 \Rightarrow$ O/P is Zero

Voltage to Current converter:-

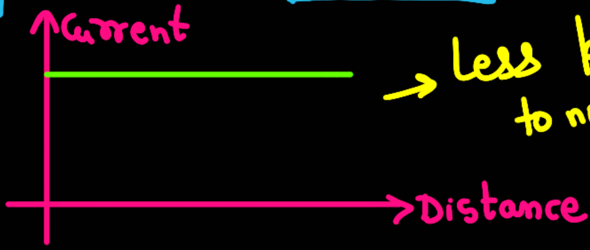


Far off in some industrial devices

+Noise Not desirable

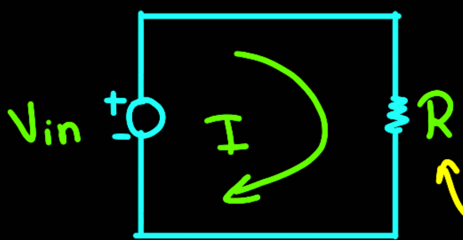


Example of VCIS



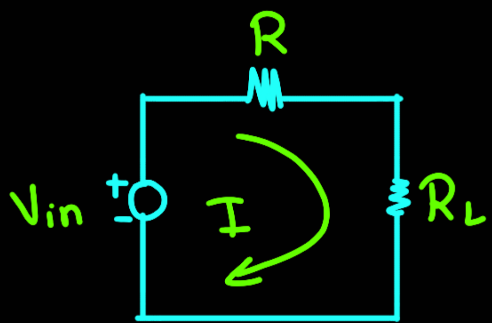
Less prone to noise

→ V-I converter using passive components (Passive converter):-



$$I = \frac{V_{in}}{R}$$

Assumed to have no voltage drop

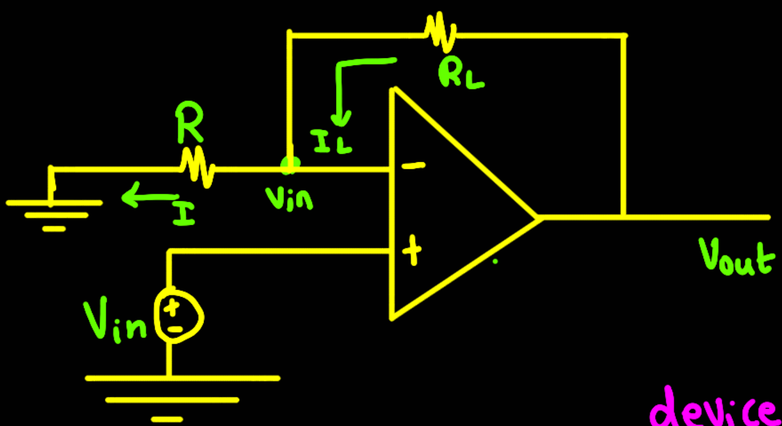


In reality there will be voltage drop across R_L → I depends on R_L

Op-Amps fix this issue

→ Active V-I converter:-

↳ AKA floating load converter → Load is floating



Applying KCL

$I = I_L$

$\frac{V_{in}}{R} = I_L$

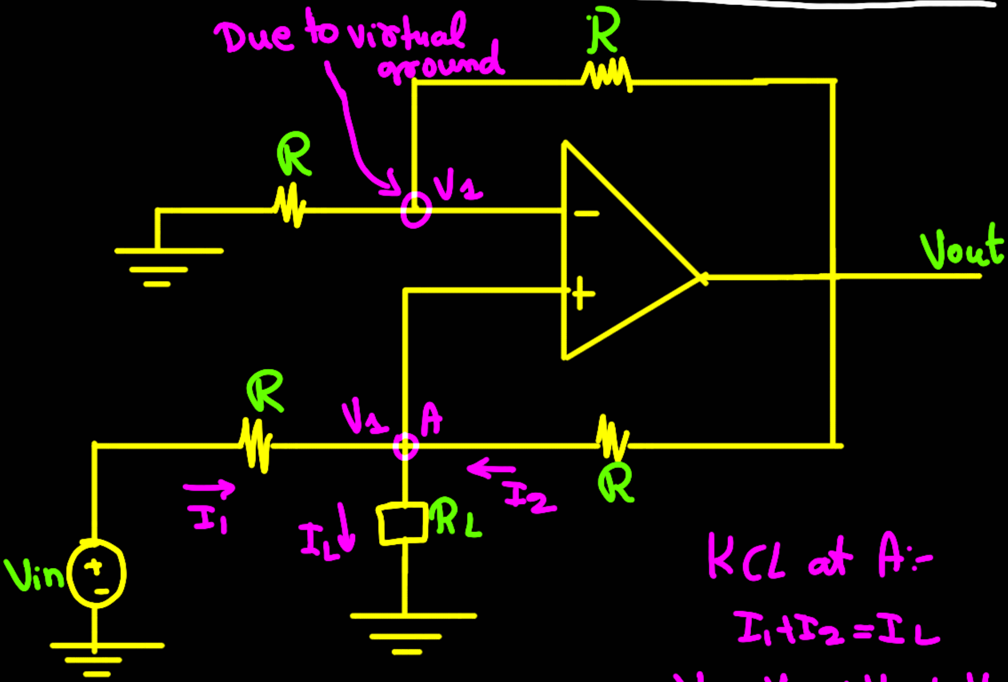
$\Rightarrow \boxed{I_L \propto R}$

Setting R, the device behaves as V-I converter

→ This type of ckt is used to drive LEDs

→ Also used to find matched pair of diodes or Zener diodes

⇒ Ground Load Voltage to Current converter



KCL at A:-

$$I_1+I_2=I_L$$

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

$$V_{in}+V_0-2V_1=I_L\times R$$

$$V_0=\left(1+\frac{R_f}{R_1}\right)V_{in}$$

$$V_0=\left(1+\frac{R}{R}\right)V_1 \Rightarrow \boxed{V_0=2V_1}$$

$$\Rightarrow V_{in}+2V_1-2V_1=I_L\times R$$

$$\boxed{I_L=\frac{V_{in}}{R}}$$

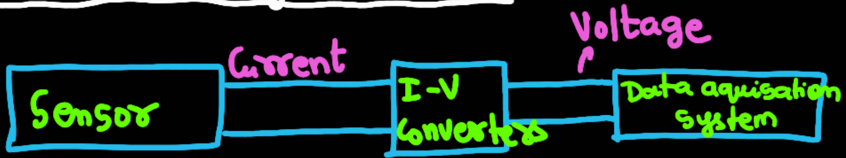
$I_L \propto V_{in}$

once R is set

↳ independent of R_L

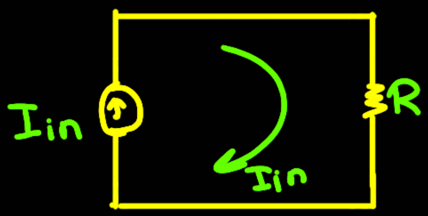
↳ This way it works as V-I converter

Current to Voltage Converter:-

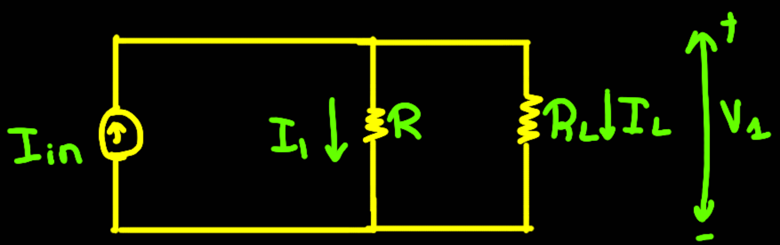


Example of ICVS

Passive I-V converter:-



$\boxed{V = I_{in} \times R}$

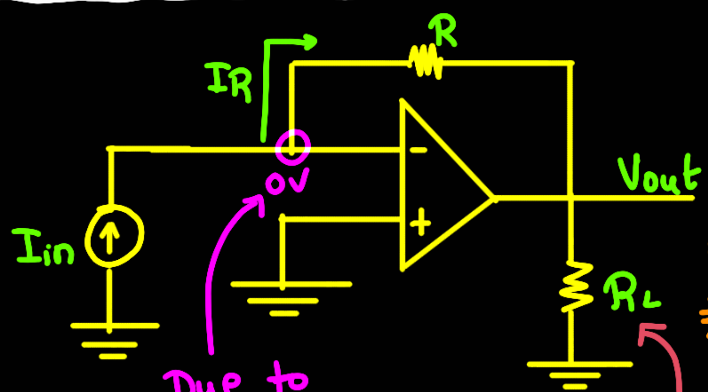


$\boxed{V_1 = I_{in} \times R_P}$ $R_P = R // R_L$

Actual voltage appearing across R_L is less than the converted voltage

This is fixed by op-Amps

Active I-V Converter:-



$I_{in} = I_R$

$= \frac{0 - V_o}{R}$

$\Rightarrow V_o = -I_{in} \times R$

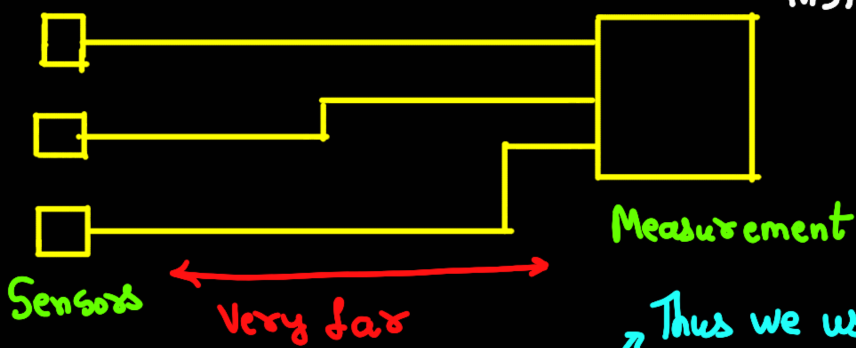
$\Rightarrow \boxed{V_o \propto I_{in}}$

Due to virtual ground

V_o is independent of R_L

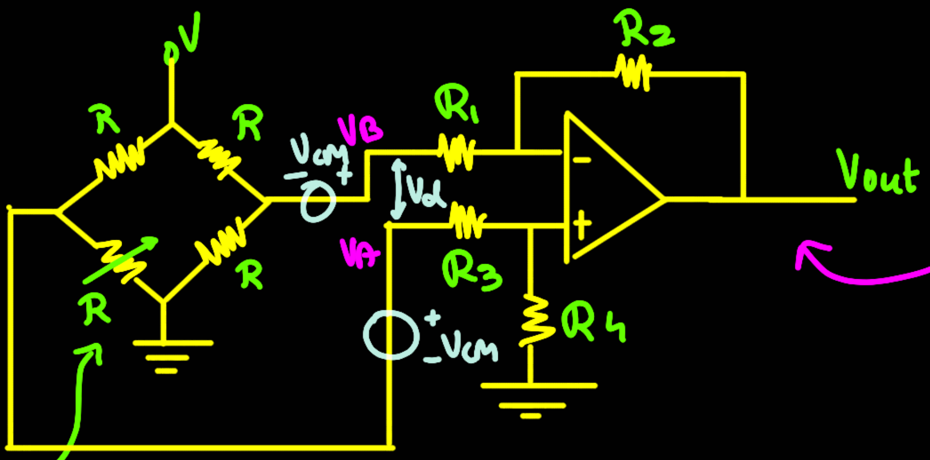
AKA Transimpedance Amplifier

Op-Amp as differential amplifier: Why should it be replaced by instrumentation amplifiers?



↳ Prone to noise

Thus we use differential amplifier



Op-Amp as Differential Amplifier

Std Bridge ckt of sensors

V_A & V_B are voltages that appear at the two terminals of the differential amplifier

$$\therefore V_0 = \frac{R_4}{R_3+R_4} \times \left(1+\frac{R_2}{R_1}\right) V_A - \frac{R_2}{R_1} V_B$$

$$V_0 = \frac{R_4}{R_3} \times V_A \left[\frac{1+\frac{R_2}{R_1}}{1+\frac{R_4}{R_3}}\right] - \frac{R_2}{R_1} \times V_B$$

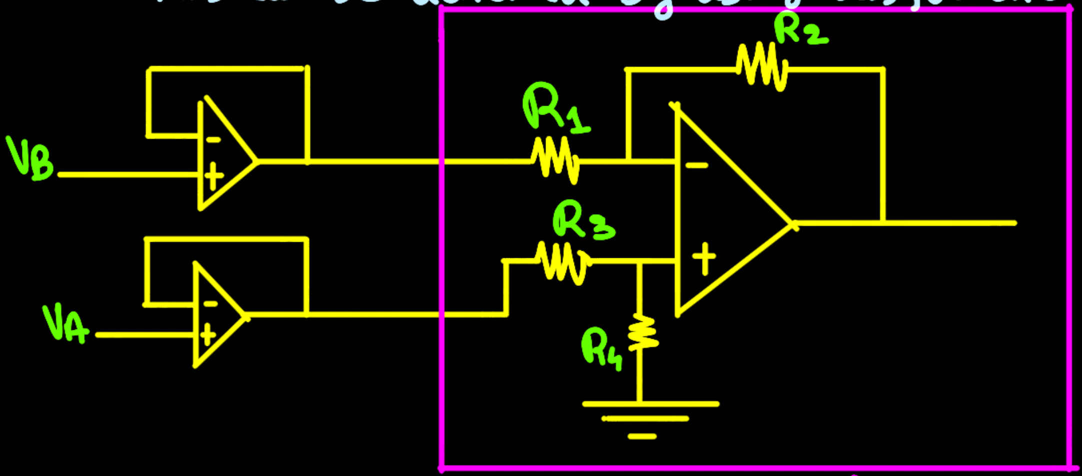
If we assume $\frac{R_4}{R_3} = \frac{R_2}{R_1} \Rightarrow \underbrace{V_0 = \frac{R_2}{R_1}(V_A - V_B)}_{\text{O/P is difference of i/p multiplied by the gain of the ckt.}}$

If V_{cm} is present
↳ Common mode voltage

$$\Rightarrow \boxed{V_o = A_d V_d + A_c V_{cm}}$$

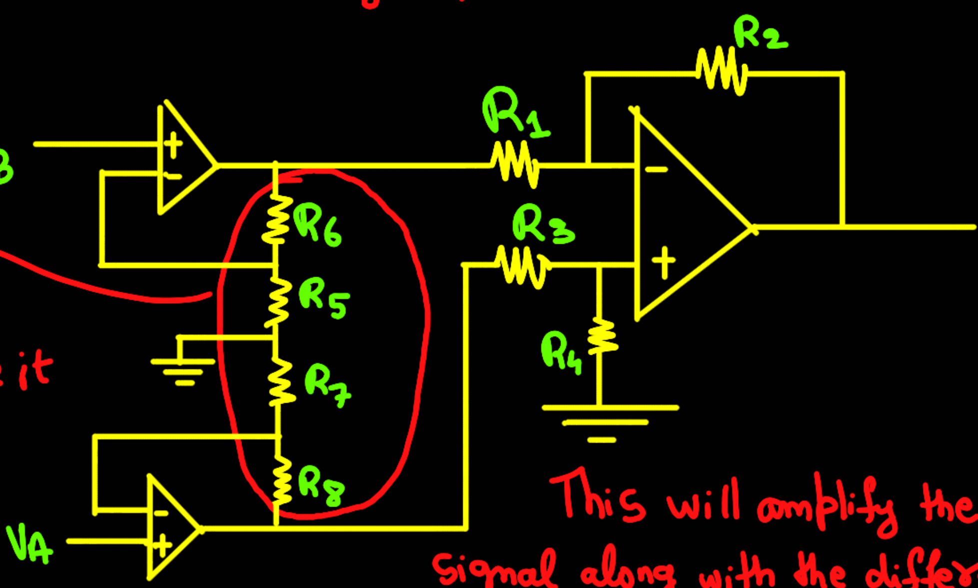
Mismatch in Resistors (say 1% error) causes change in V_o
↓
Undesirable

The i/p impedance of the diff amplifiers must be very high.
This can be acheived by using buffer ckts in i/p



The gain of these ICs cannot be changed
This is fixed by replacing buffer ckts with the non-inverting amplifiers

Inside structure of monolithic ICs

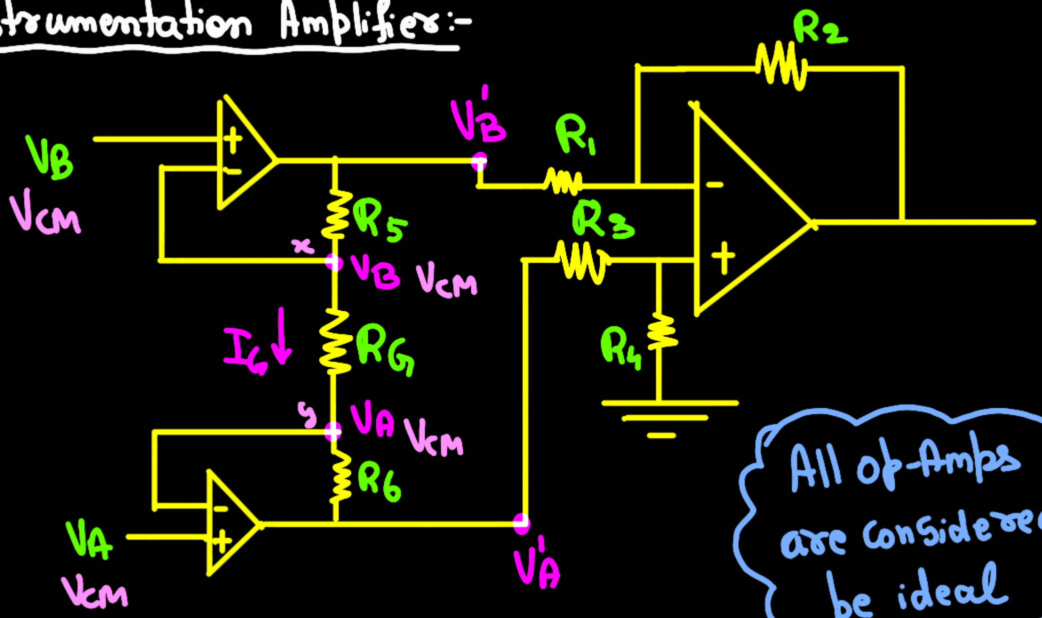


Have to be matched else it will affect its CMRR

This will amplify the common mode signal along with the differential signal.
No improvement in the signal to noise ratio

All of these are solved by instrumentation amplifiers ☺

Instrumentation Amplifier:-



All op-Amps are considered to be ideal

R_G is common to both the op-Amps.

Advantage → Amplifies only differential i/p signal.

Available as an IC ⇒ All resistors except R_G is fabricated internally

↳ Gain can be set by setting R_G externally

★ Deriving expression for V_0:-

$$V_{out} = \frac{R_2}{R_1}(V_A' - V_B') \text{ iff } \frac{R_4}{R_3} = \frac{R_2}{R_1}$$

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

→ This flows through R_5, R_6 & R_G

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

If $R_5 = R_6$

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

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

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

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

* Understanding how the first two amplifiers pass CM voltage :-

$V_{CM} \rightarrow$ Common Mode Voltage.

V_{CM} is present at nodes x, x', y & y' as well

$\Rightarrow \therefore$ No current will flow through R_G

$\therefore$ No current will flow through R_5 & R_6

For common mode voltage, these 2 op-Amps act as buffer

$\therefore V_{CM}$ will not be amplified

Only i/p diff. i/p will be amplified

$\rightarrow$ CMRR can be further increased by this amplifier

$\rightarrow$ Particularly useful when i/p diff. signal is small & $V_{diff} < V_{CM}$

Log & Antilog amplifiers :-

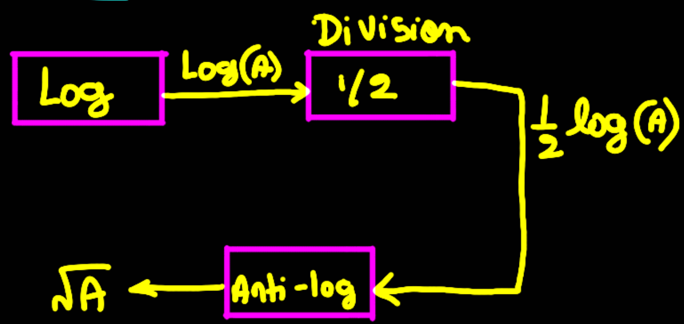
By Using logarithmic properties of ckt elements the following can be achieved

* $\log(AB) = \log(A) + \log(B)$

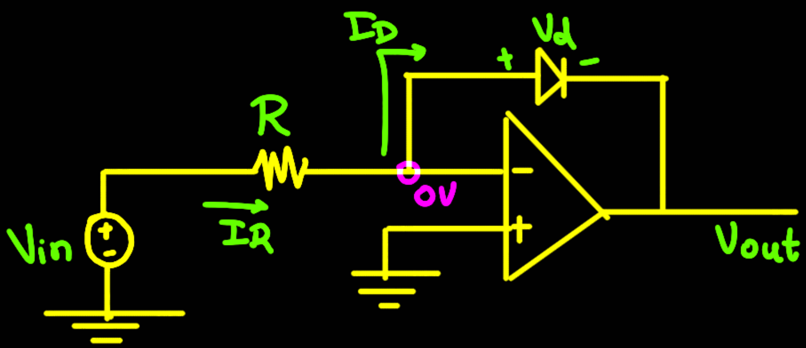
* $\log(A^B) = B\log(A)$

* $\log\left(\frac{A}{B}\right) = \log(A) - \log(B)$

For example:-



✱ Log Amplifier using Op-Amp & Diode :-



From KVL

$V_{out} = -V_D$

$I_R = I_D$

$\Rightarrow I_D = \frac{V_{in}}{R}$

We know from current eq^n of diode

$$\boxed{I_D = I_S\left(e^{\frac{V_d}{\eta V_T}} - 1\right)} \rightarrow \boxed{V_T = \frac{KT}{q}}$$

$V_T = 26mV$ at room temp

I_S - Reverse Saturation Current

V_T - Thermal Voltage

V_D - Forward Voltage of Diode

η - Ideality Factor → 1 for Si, 2 for Ge

For the log amp above $\Rightarrow I_D = I_S\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$

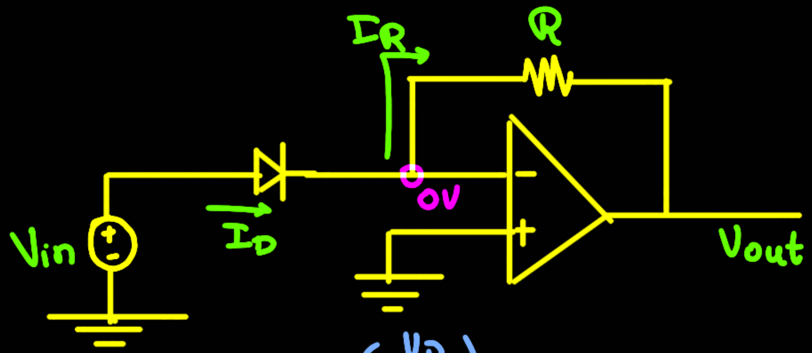
$$I_D = I_S\left(e^{\frac{V_D}{\eta V_T}}\right) \Rightarrow \frac{I_D}{I_S} = e^{\left(\frac{V_D}{\eta V_T}\right)}$$

Taking natural log on both sides

$$\ln\left(\frac{I_D}{I_S}\right) = \frac{V_D}{\eta V_T} \Rightarrow V_D = \eta V_T \ln\left(I_D/I_S\right)$$

$$V_0 = -V_D \Rightarrow \boxed{V_{out} = -\eta V_T \times \ln\left(\frac{V_{in}}{I_S \times R}\right)} \rightarrow \text{o/p voltage}$$

Antilog amplifier using diode:-



$$V_{out} = -R \times I_S \times e^{\left(\frac{V_D}{\eta V_T}\right)}$$

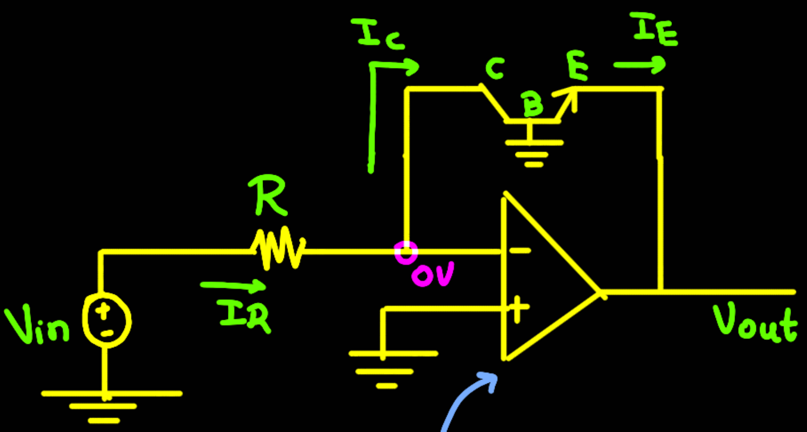
$$V_{in} = V_D$$

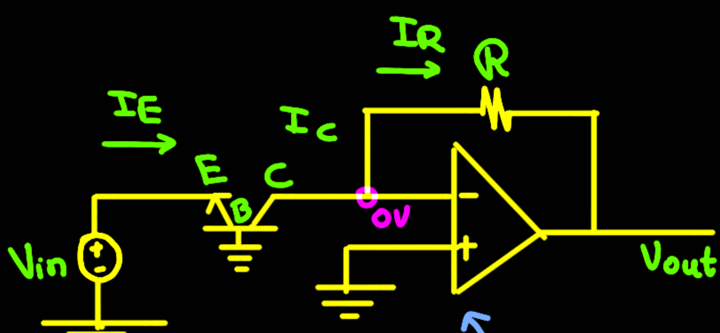
$$\Rightarrow V_{out} = -R \times I_S \times e^{\left(\frac{V_{in}}{\eta V_T}\right)}$$

$\eta \Rightarrow$ The dynamic range of the amplifier reduces due to η

↳ Fixed by transistor base log & antilog amplifiers

Log & Antilog amplifiers using Op-Amp & Transistor :-





$$V_{out} = -V_T \ln\left(\frac{V_{in}}{R \times I_S}\right)$$

$$V_{out} = -R I_S \times e^{\left(\frac{V_{in}}{V_T}\right)}$$

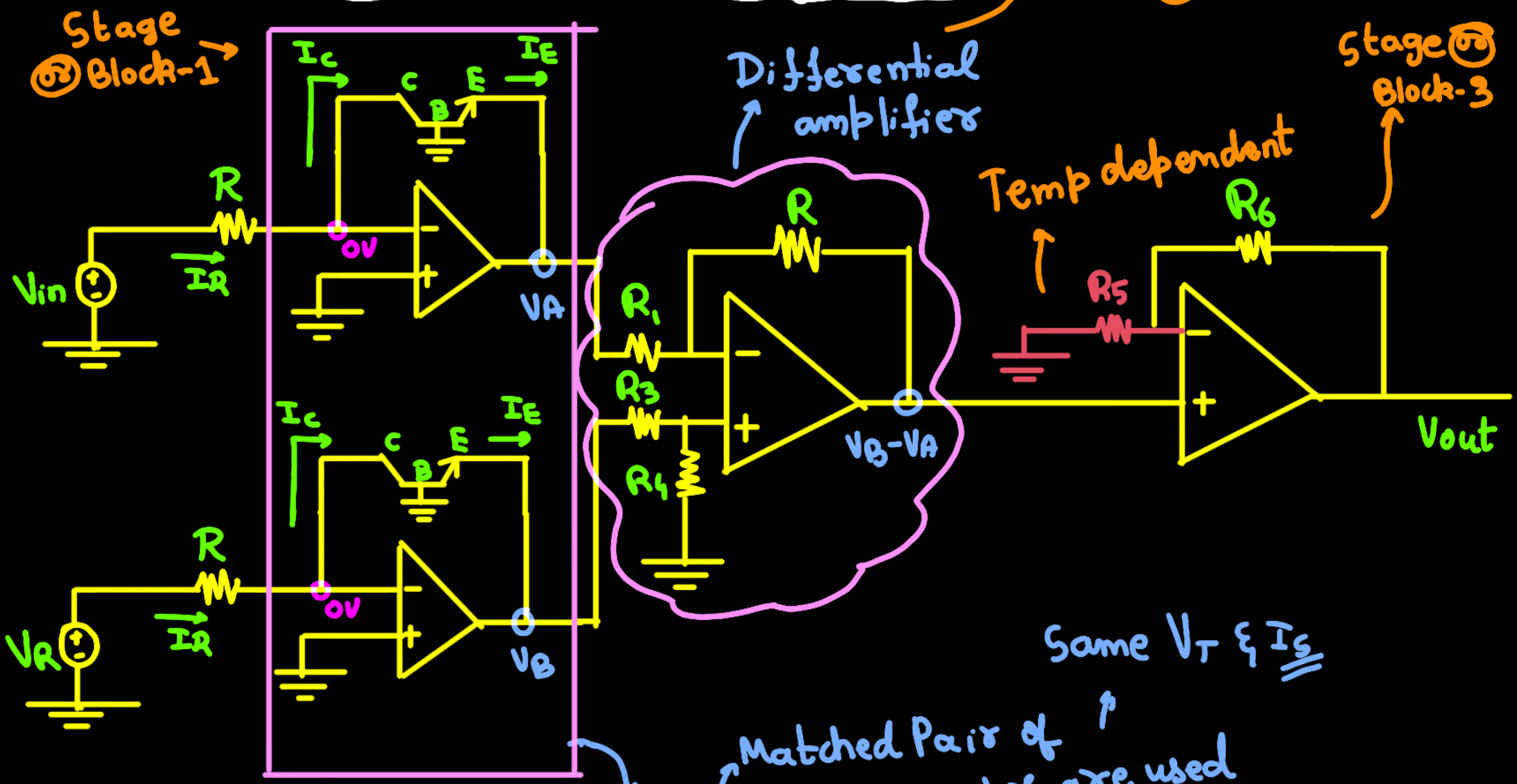
Still depend on V_T & I_S

↳ Temp dependant

$\therefore V_{out}$ changes with temperature

Fixed as follows

Temperature Compensated Log Amplifier :- Stage (or) Block-2



2 log amplifiers are used.

Matched Pair of transistors are used

Same V_T & I_S

→ One log amp gets input voltage & one more some reference voltage

$$V_A = -V_T \times \ln\left(\frac{V_{in}}{R \times I_S}\right) \quad \Big| \quad V_B = -V_T \times \ln\left(\frac{V_R}{R \times I_S}\right)$$

$$V_B - V_A = V_T \times \ln\left(\frac{V_{in}}{R \times I_S}\right) - V_T \times \ln\left(\frac{V_R}{R \times I_S}\right)$$

$$\Rightarrow V_B - V_A = V_T \ln\left(\frac{V_{in}}{V_R}\right)$$

Independent of I_S

But still depends

↳ 3rd Block fixes

Non-inverting op-Amp

This is how temp is compensated

$$V_0 = \left(1 + \frac{R_6}{R_5}\right) \times V_T \times \ln\left(\frac{V_{in}}{V_R}\right)$$

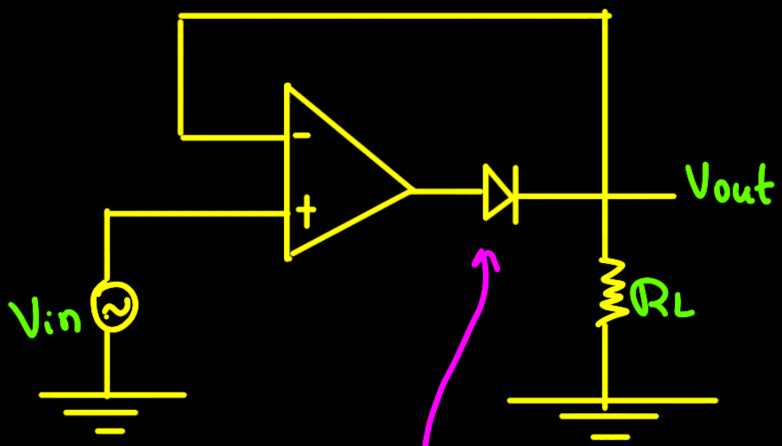
By choosing temp coeff of R_5 we can nullify effect of V_T

Precision Rectifier :-

→ Half-wave rectifier ckt rectifies in real condⁿ only after a certain threshold voltage V_T

→ This is not affected in large signal operation, but in small signal conditioning & signal processing/AM demodulation, it affects a lot

Precision Rectifiers solve this problem

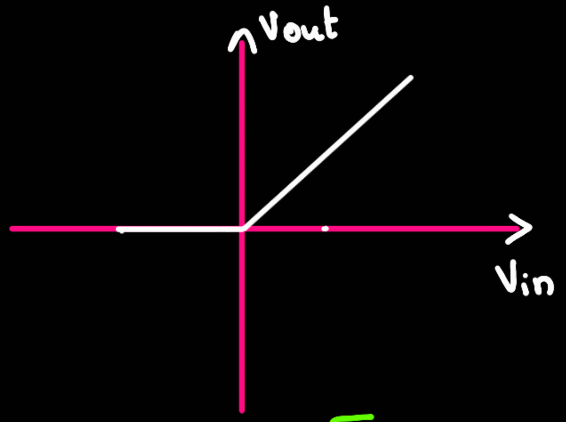
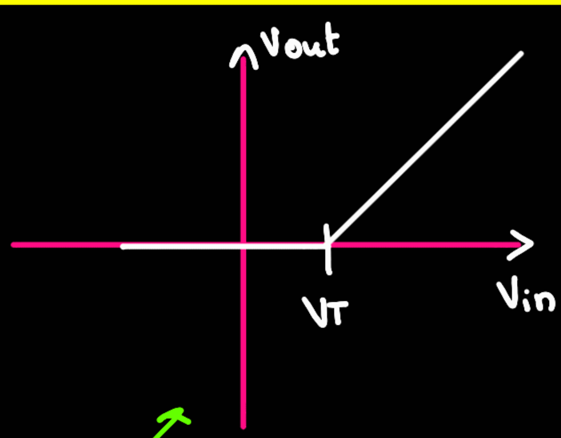


AKA super diode

Here diode behaves as ideal

⇒ Rectifier = ideal

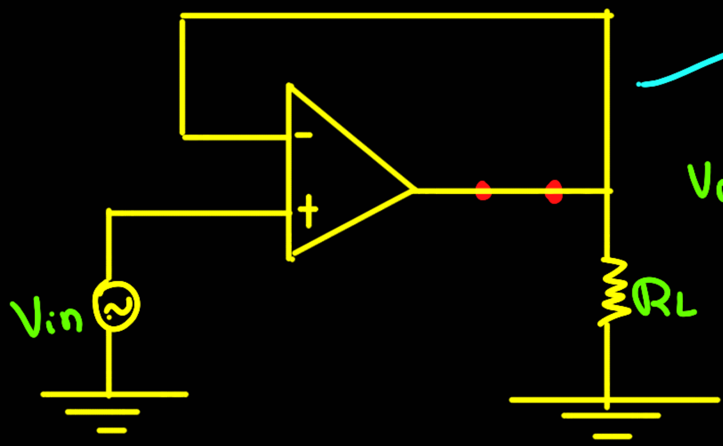
Transfer characters:-

Precision rectifier	Half wave rectifier
	

That's why Precision Rectifier is called super diode

→ **Working:-**

When $V_{in} > 0 \Rightarrow$ diode behaves as closed switch



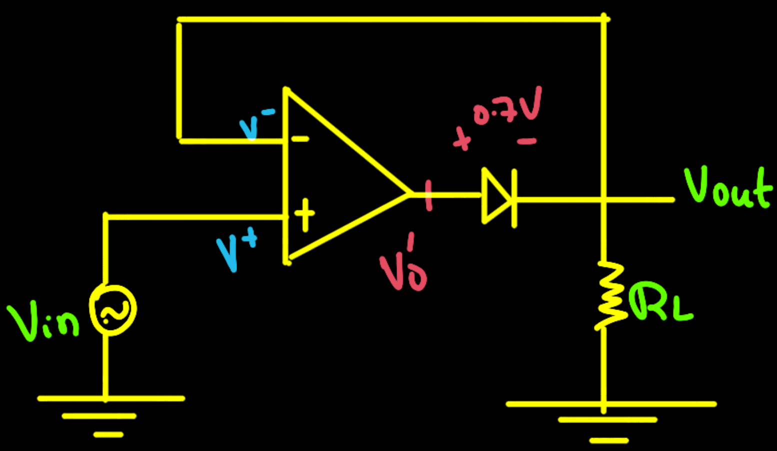
→ This is basically Buffer ckt

↓

I/P follows O/P

when $V_{in} < 0V \Rightarrow$ Simply becomes open switch

↳ $V_{out} = 0$



Let $V_f \Rightarrow$ Voltage drop across diode

In closed loop configuration

$$V_f' = \frac{V_f}{A_{OL}}$$

Effective voltage drop

Open Loop gain of the op-amp.

★ Analysis for different input signals:-

Assume diode is conducting for a given i/p voltage

$V_0' =$ O/P voltage of $\underbrace{\text{Op-Amp}}$; $\overbrace{V_f = 0.7V}^{\text{Assumed Si diode is used}}$

↳ operated with -ve feedback

↳ Virtual ground exists

$$\Rightarrow V_0' = V_0 + 0.7V$$

$$V_0' = A_{OL}(V^+ - V^-) \Rightarrow \frac{V_0 + 0.7V}{A_{OL}} \simeq 0 = V^+ - V^-$$

$$\Rightarrow V^+ = V^- \Rightarrow V_{out} = V_{in}$$

$\therefore$ Whenever diode is conducting $\Rightarrow$ Vout follows Vin

When $V_{in} > 0\,V \Rightarrow$ Diode conducts $\Rightarrow V_{out} = V_{in}$

When $V_{in} < 0V \Rightarrow$ Diode does not conduct $\Rightarrow$ op-Amp goes into -ve saturation with some $-V_{sat}$

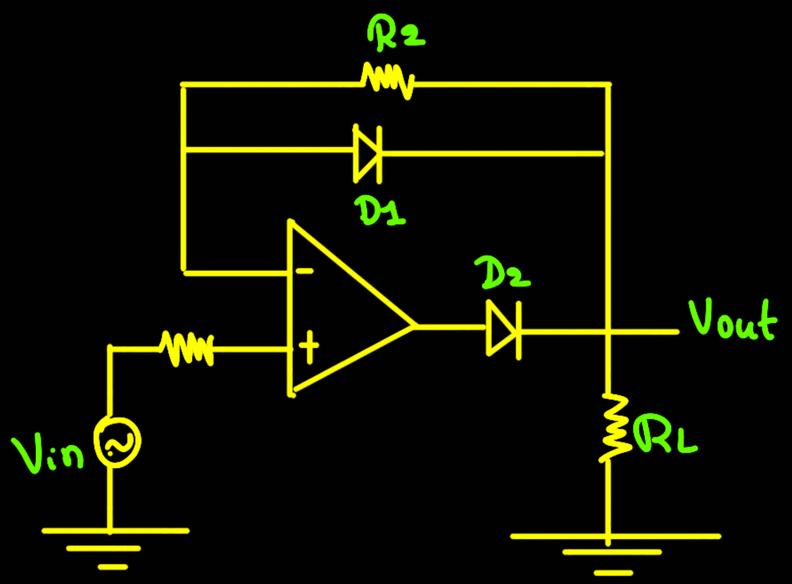
When Vin becomes $> 0V \Rightarrow$ op-Amp needs to come out of negative saturation voltage

Not a problem when operated at low frequencies. (50-100Hz)

Operated at high freq. $\Rightarrow$ o/p becomes distorted

↳ Prevention is done as follows:-

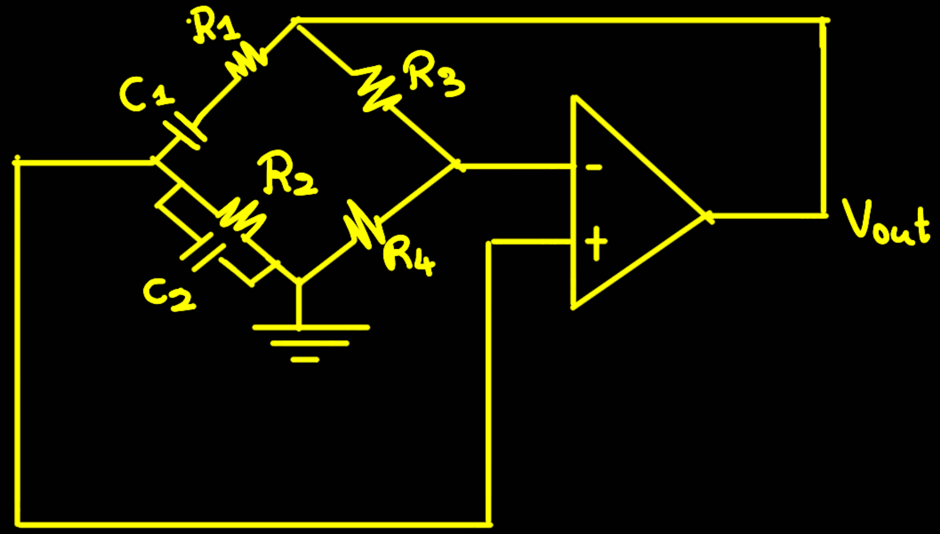
Modified Precision Rectifier:-



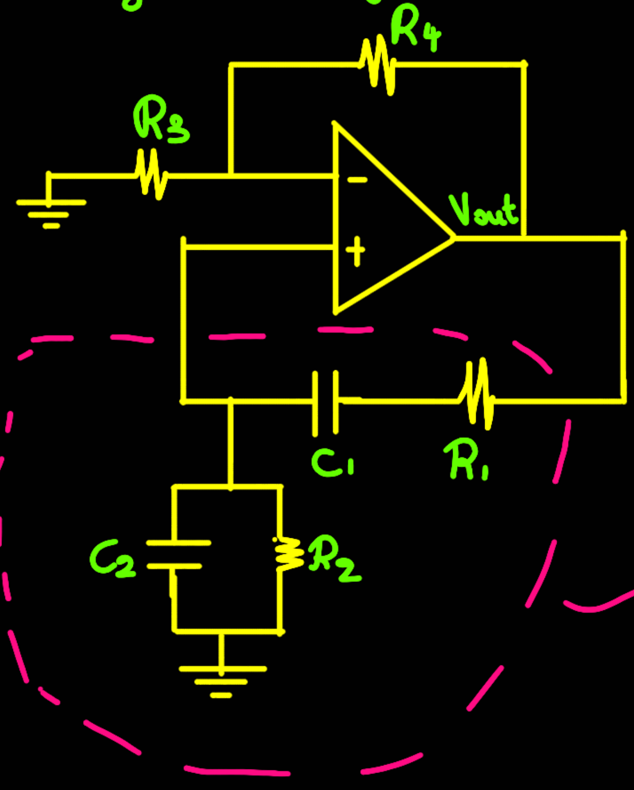
$V_{in} > 0 \Rightarrow V_o = 0$

$V_{in} < 0 \Rightarrow V_o = \frac{-R_2}{R_1 + R_2} \times V_{in}$ $\Rightarrow$ Thus prevents V_o from going into -ve saturation

Wein Bridge Oscillator:-

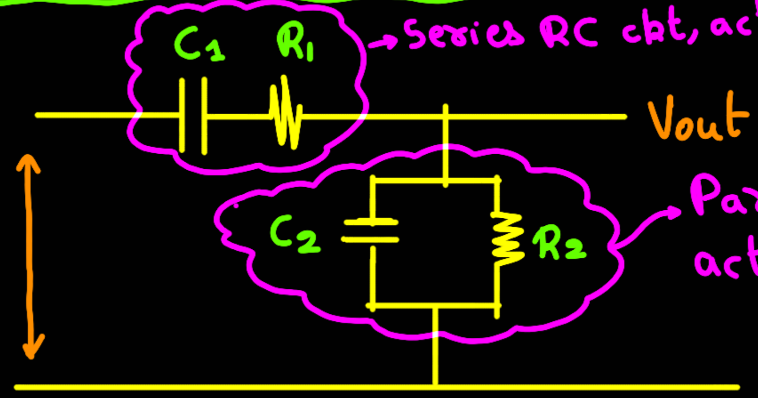


Redrawing this, we get



Feedback network
↳ provides +ve feedback

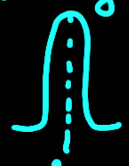
Consider the feedback network:-



→ Series RC ckt, acts as a high pass filter

Parallel RC ckt
acts as low pass frequency

$f_r \rightarrow$ resonant frequency

Response at $f_r \rightarrow$ 

At f_r, phase shift $\phi = 0$ & $\frac{V_o}{V_{in}} = \frac{1}{3}$

If $R_1 = R_2$ & $C_1 = C_2$, then:-

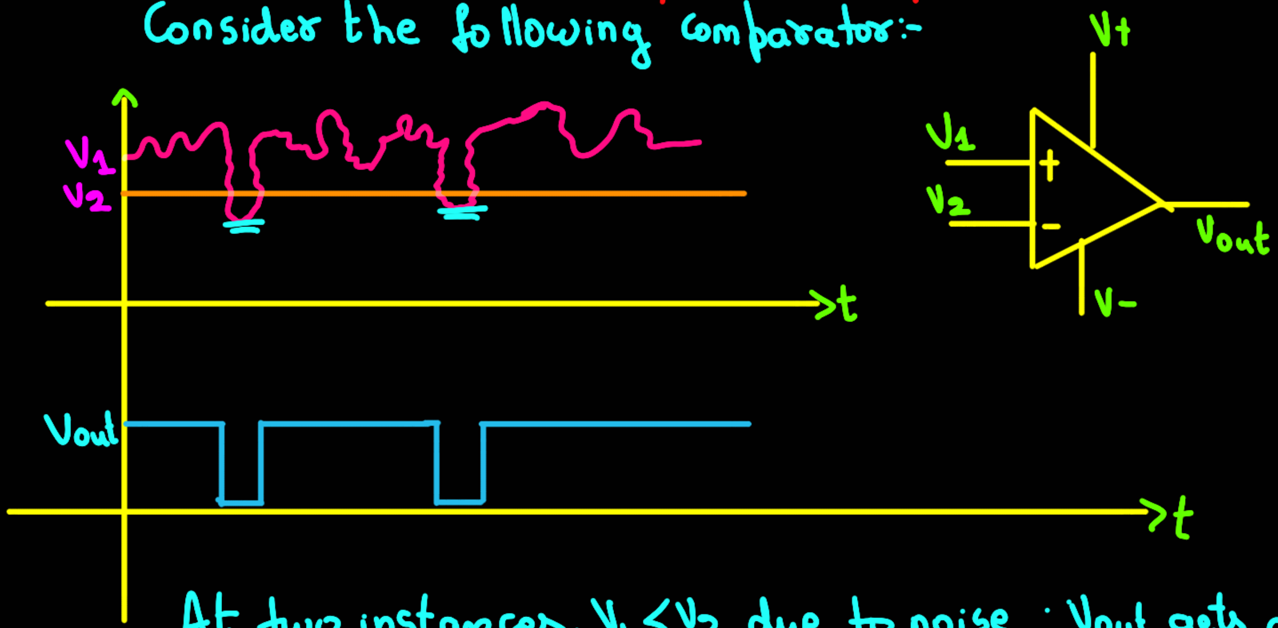
$$f_r = \frac{1}{2\pi RC}$$

RC Phase Shift Oscillator

Same as AEC, replace BJT with $\underbrace{\text{inverting or non-inverting amp}}_{\text{Either works, check gain}}$.

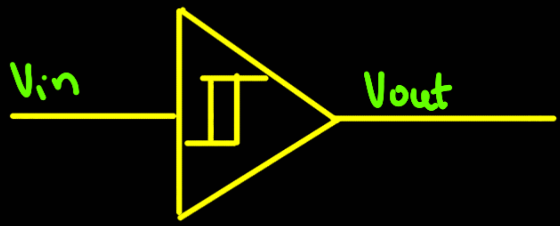
Schmitt Trigger:-

Consider the following $\overbrace{\text{comparator}}^{\text{Not immune to noise}}$:-



At two instances, $V_1 < V_2$ due to noise, $\therefore$ Vout gets affected & is low for that duration

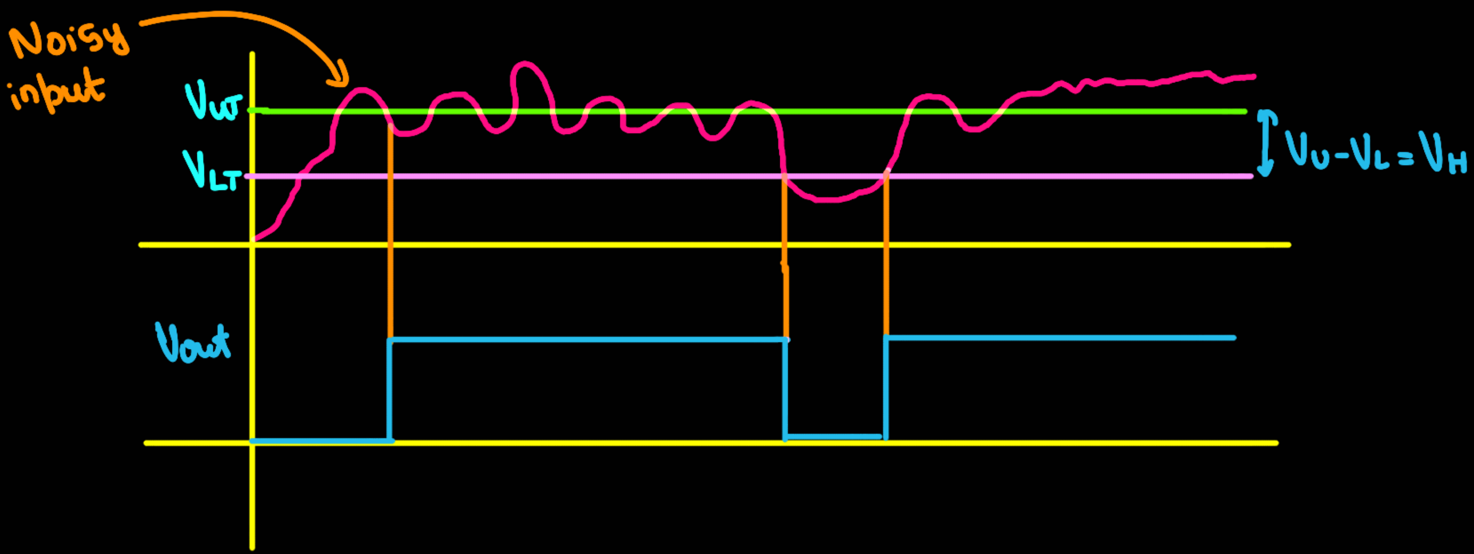
This is fixed by Schmitt Trigger



Comparator with Hysterisis

Has 2 threshold voltages

- Upper $V_T \Rightarrow$ Low to High Transition
- Lower $V_T \Rightarrow$ High to Low Transition



O/P is low until i/p voltage is lower than V_{UT}. Remains high until it goes below V_{LT}

$V_U - V_L = V_H \rightarrow$ Hysterisis voltage of Schmitt Trigger

↳ Defines its noise immunity

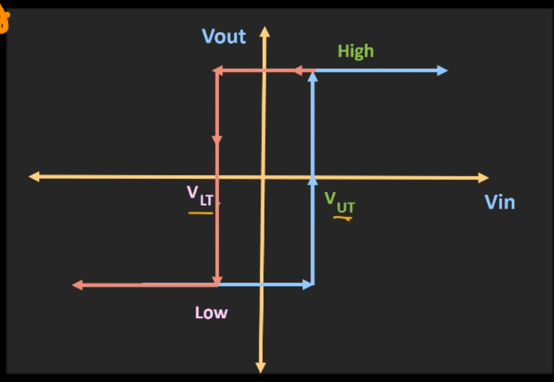
4 parameters are needed to define Schmitt Trigger

1. High o/p level
2. Low o/p level
3. Lower threshold Voltage
4. Upper Threshold voltage

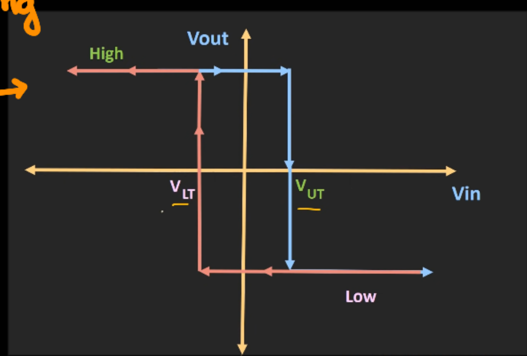
AKA Hysterisis Curve

★ Transfer characteristic of Schmitt Trigger.

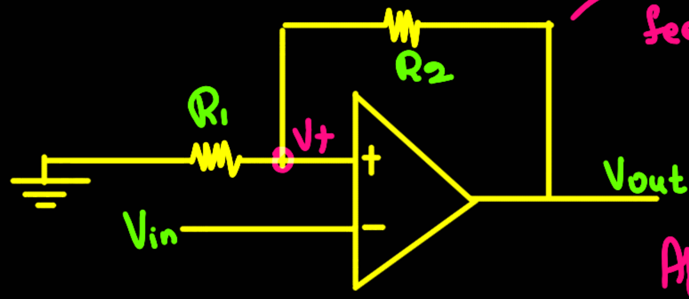
Non-inverting Schmitt Trigger



Inverting



Inverting Schmitt Trigger:-



Has +ve feedback

Apply KCL

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

$V_{in} > V_+ \Rightarrow V_{out} = V_L$

$V_{in} < V_+ \Rightarrow V_{out} = V_H$

$$\boxed{V_+ = \frac{R_1}{R_1+R_2} V_{out}}$$

$\boxed{V_+ = V_1}$

$$\boxed{V_1 = \frac{R_1}{R_1+R_2} \times V_H}$$

Upper threshold Voltage

$V_{in} > V_1 \Rightarrow V_{out} = V_L$

$$\boxed{V_{UT} = \frac{R_1}{R_1+R_2} \times V_H}$$

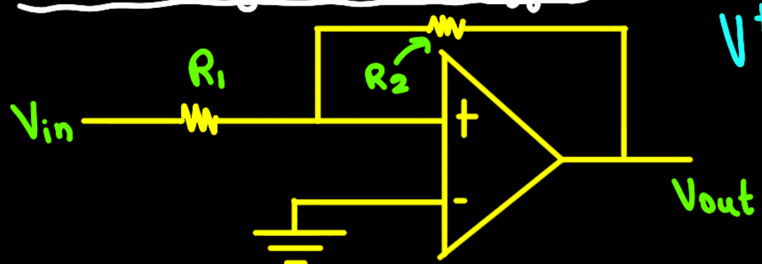
When $V_{in} < V_+$

at that point $V_+ = V_2 \Rightarrow \boxed{V_2 = \frac{R_1}{R_1+R_2} \times V_L}$

Lower Threshold Voltage

$$V_{LT} = \frac{R_1}{R_1+R_2} \times V_L$$

Non-inverting Schmitt Trigger:-



Derive from KCL

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

When $V_{in} > 0 \Rightarrow V_{out} = V_H$

$\Downarrow$

Cond^n:-

Upper Threshold voltage

$$V_{in} > -\frac{R_1}{R_2} V_L \Rightarrow \boxed{V_{UT} = -\frac{R_1}{R_2} \times V_L}$$

When $V_{in} < 0 \Rightarrow V_{out} = V_L$

$\Downarrow$

Cond^n:-

Lower threshold voltage

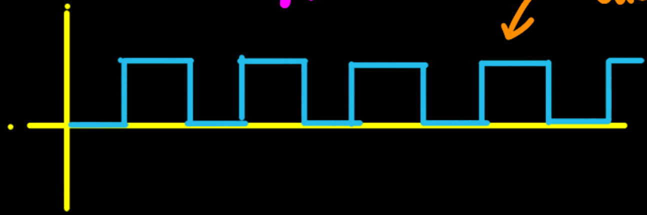
$$V_{in} < -\frac{R_1}{R_2} V_H \Rightarrow \boxed{V_{LT} = -\frac{R_1}{R_2} V_H}$$

Astable Multivibrator :-

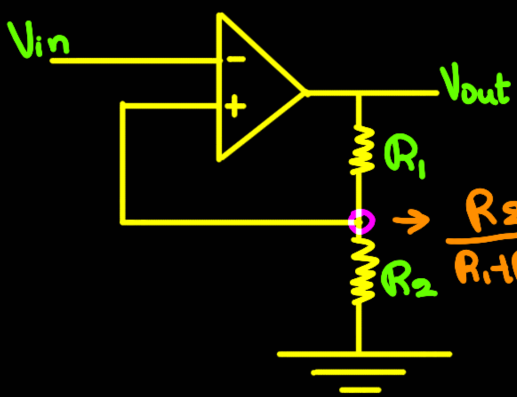
↳ Not stable in high or low.

Used to design relaxation oscillator

Timing diagram



Design using Op-Amp



$\rightarrow \frac{R_2}{R_1+R_2} \times V_{sat}$

Schmitt trigger ckt.
↳ Basic astable Vibrator ckt is similar

Let, initially, $V_{out} = +V_{sat}$

$\underbrace{\beta}_{\text{feedback fraction}} V_{sat}$

If $V_{in} < \beta V_{sat} \Rightarrow V_{out} = +V_{sat}$

When $V_{in} > \beta V_{sat} \Rightarrow V_{out} = -V_{sat}$

@ that time, $V^+ = -V_{sat} \times \frac{R_2}{R_1+R_2} = -\beta V_{sat}$

Transfer characteristics :- Same as inverting Schmitt Trigger

Same explanation

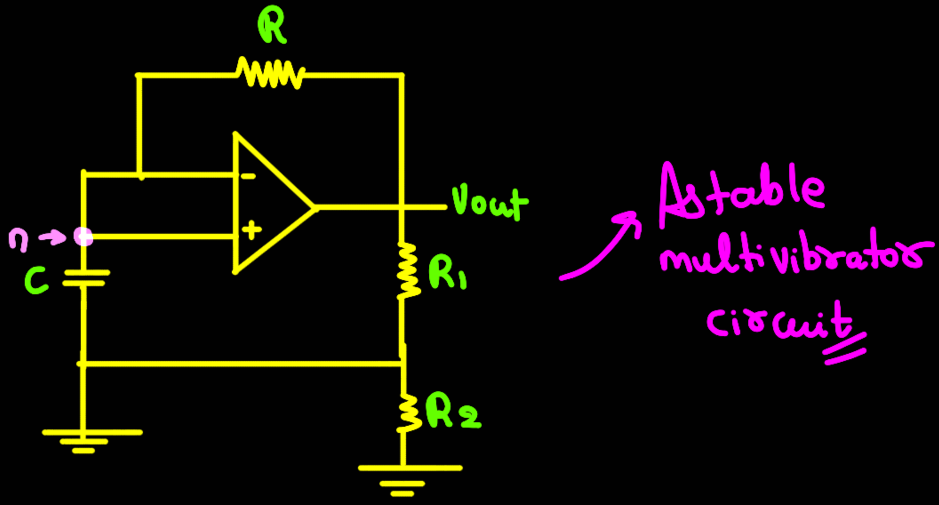
$V_{LT} = -\beta V_{sat}$ $\quad$ $V_{UT} = \beta V_{sat}$

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

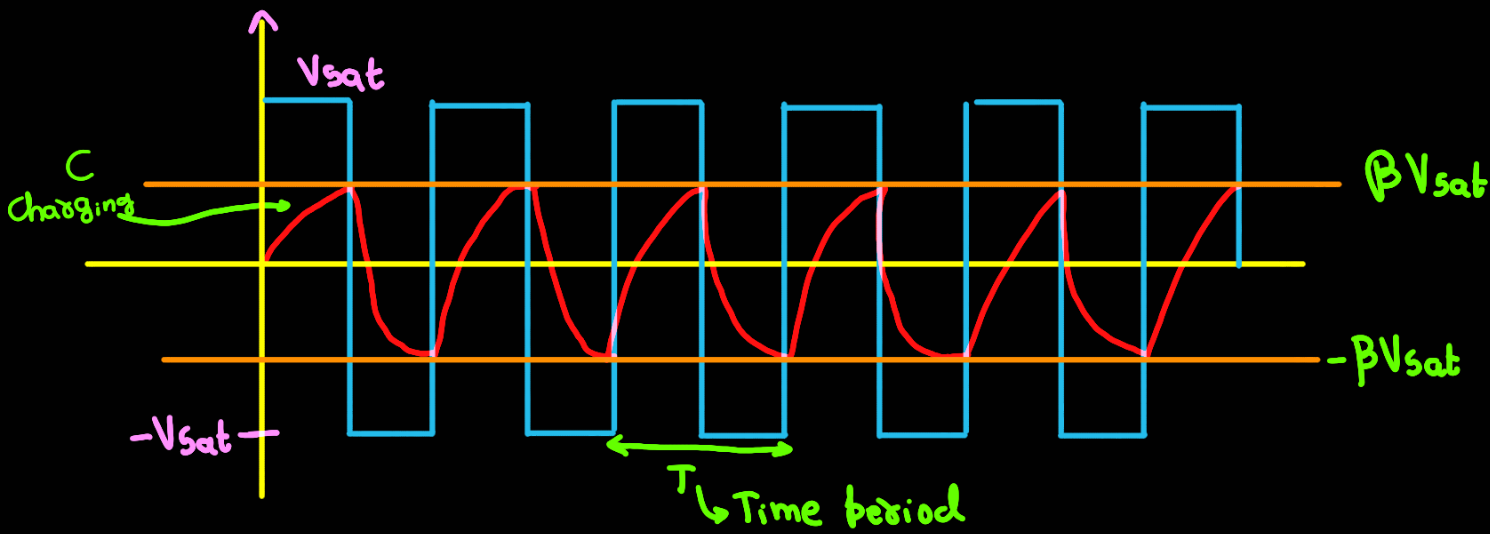
Schmitt Trigger ⇒ External input

Astable Vibrator ⇒ Feedback is fed back to i/p using R & C

The ONLY difference in ckt



Working principle:- Initially $V_0 = +V_{sat}$ (assumed)



★ At the start, capacitor starts charging to V_{sat}. Voltage gets built up across the capacitor.

★ Voltage at node n also gets built up.

★ Once Capacitor charges to $V_{UT} = \beta V_{sat}$, Op-Amp o/p switches from $+V_{sat}$ to $-V_{sat}$

★ The capacitor charges to $-\beta V_{sat} = V_{LT}$. Upon reaching, o/p switches to $+V_{sat}$

★ Time period $T \Rightarrow$ depends on R, C, V_{UT} & V_{LT}. $\Rightarrow R_1$ & R_2

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

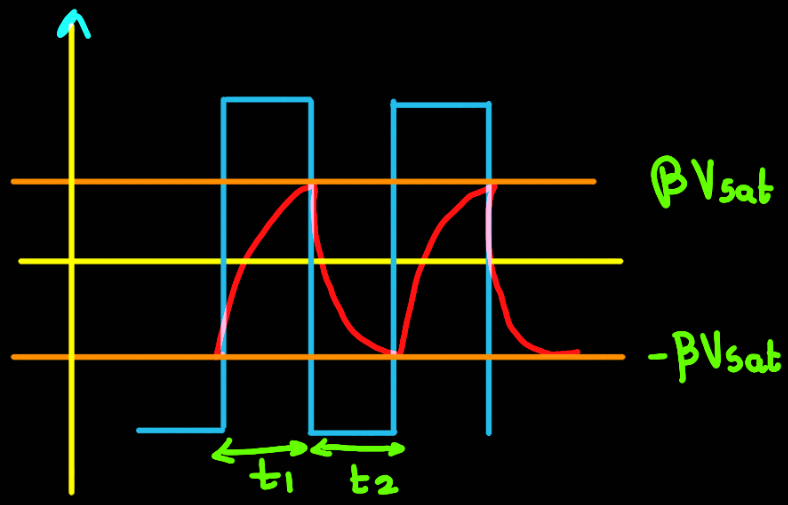
If $V_{sat} = -V_{sat}$

$\Downarrow$

$\boxed{\text{Duty Cycle} = 50\%}$

★Derivation for T:-

Consider steady state condⁿ for the given ckt.



From transient analysis:-

$$V_c(t) = V_{Final} + [V_{initial} - V_{final}]\, e^{-t/RC}$$

$$\left.\begin{array}{l} V_{final} = V_{sat} \\ V_{in} = -\beta V_{sat} \end{array}\right\} V_c(t_1) = V_{sat} + [-\beta V_{sat} - V_{sat}]\, e^{-t_1/RC}$$

$$\beta V_{sat} = V_{sat} - [1+\beta] V_{sat}\, e^{-t_1/RC}$$

$$\beta - 1 = -[1+\beta]\, e^{-t_1/RC} \Rightarrow \left[\frac{1-\beta}{1+\beta}\right] = -e^{t_1/RC}$$

$$\boxed{t_1 = RC \ln\left[\frac{1+\beta}{1-\beta}\right]}$$

$\because$ Duty Cycle = 50%

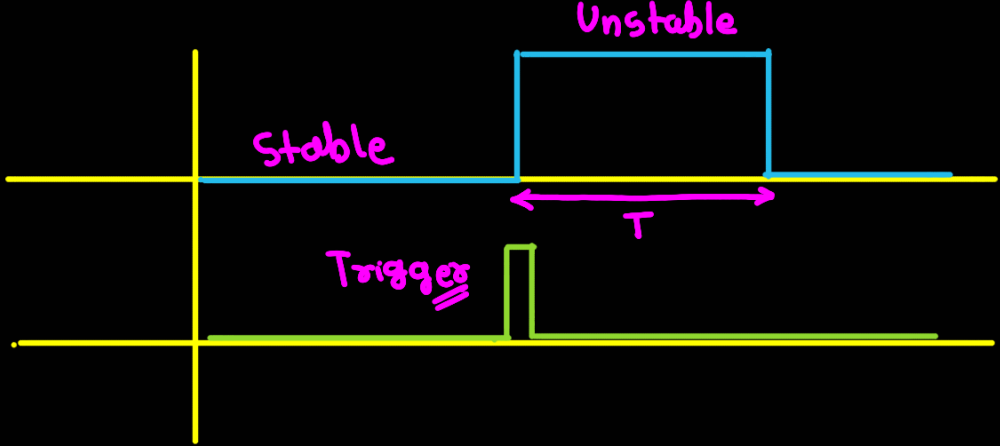
Intuitively $t_2 = RC \ln\left[\frac{1+\beta}{1-\beta}\right]$

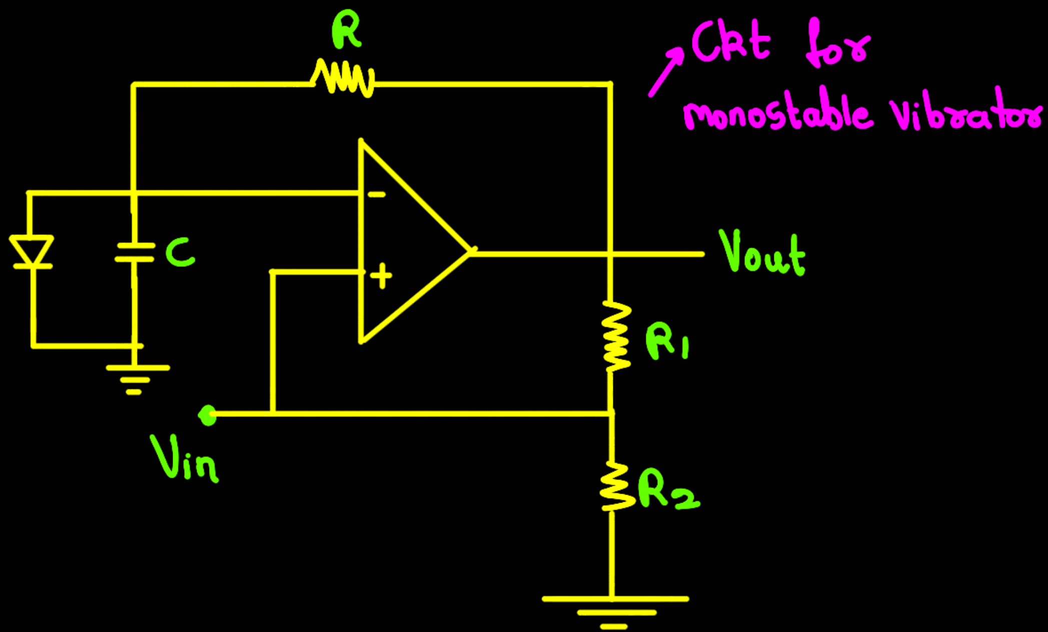
$$\boxed{\therefore T = t_1 + t_2 = 2RC \ln\left[\frac{1+\beta}{1-\beta}\right]}$$

Try:- Design an astable multivibrator for $f = 1\,kHz$. Assume $R_1 = R_2 = R$ & $C = 0.1\,\mu F$

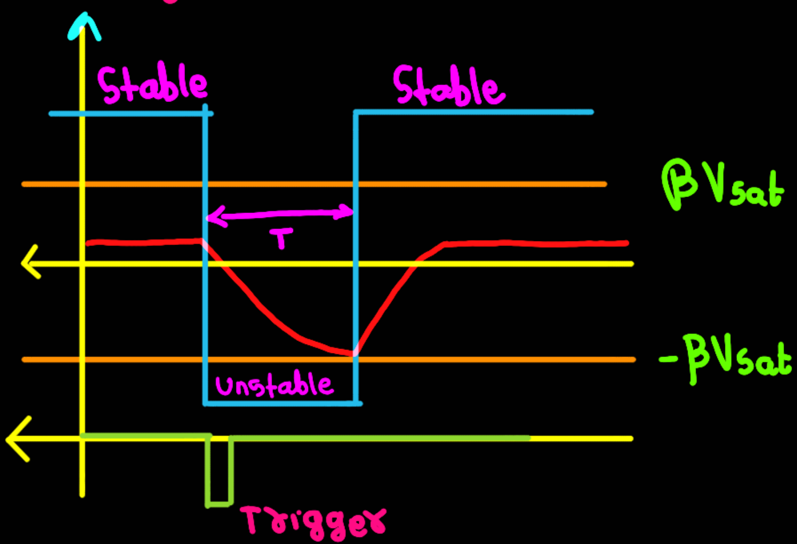
Monostable Vibrator:-

- One state is stable state
- When trigger signal is applied ⇒ O/P goes to unstable state momentarily
- After time T, it reverts back to stable state



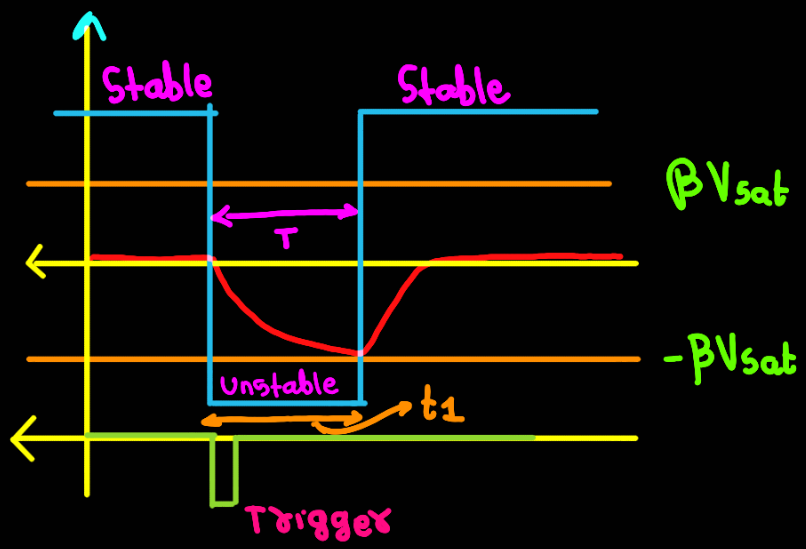


Working Principle:-



$$\boxed{T = RC \ln\left(1+\frac{R_2}{R_1}\right)}$$

★ Derivation for T:-



Assumption:- diode is ideal ⇒ drop across capacitor is ≃ 0

From transient analysis:-

$$V_c(t) = V_{Final} + (V_{initial} - V_{Final})\, e^{-t/RC}$$

$$V_{Final} = -V_{sat} \;;\; V_{initial} = 0V$$

$$V_c(t_1) = -V_{sat} + (0-(-V_{sat}))e^{-t_1/RC}$$

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

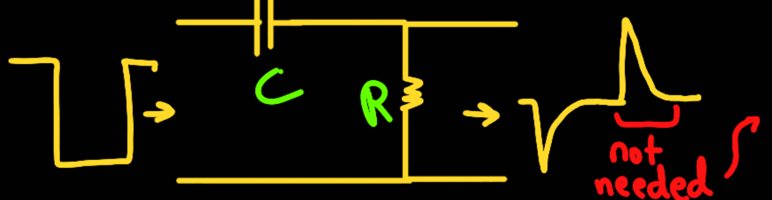
$$\therefore 1-\beta = e^{-t_1/RC} \qquad \left(\because \text{WKT, } \beta = \frac{R_2}{R_1+R_2}\right)$$

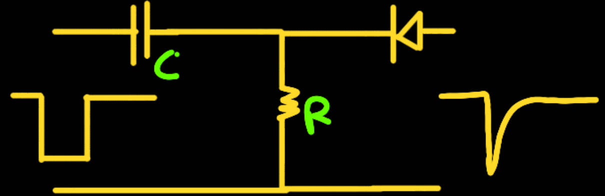
$$1 - \frac{R_2}{R_1+R_2} = e^{-t_1/RC} \Rightarrow \frac{R_1}{R_1+R_2} = e^{-t_1/RC}$$

Time period of trigger must be very small comp to T of unstable mode

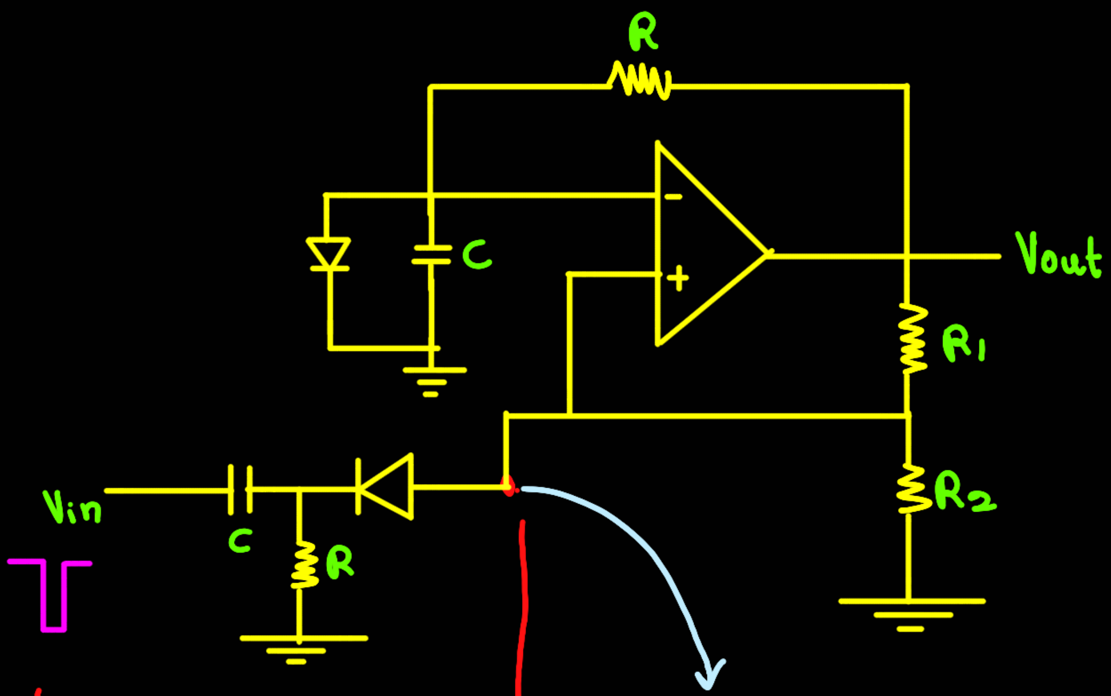
$$\therefore t_1 = -RC \ln\left(\frac{R_1}{R_1+R_2}\right) \Rightarrow \boxed{t_1 = RC \ln\left(1+\frac{R_2}{R_1}\right)}$$

How to generate trigger? ⇒ Using RC differentiator ckt





∴ Overall structure for monostable vibrator:-



RC differentiator crt

The -ve spike at this node due to RC diffⁿ network acts as trigger