PRECISION DIODE:

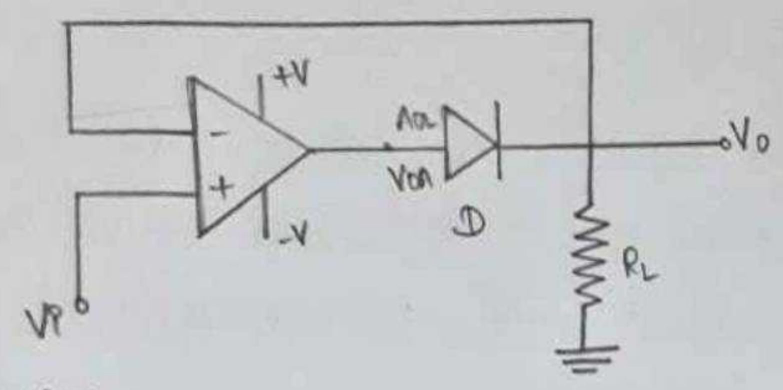
The major limitation of ordinary diode is that it cannot rectify voltages below V_γ ($\sim 0.6V$), the cut-in voltage of the diode. A circuit that acts like an ideal diode can be designed by placing a diode in the feedback loop of an op-amp.

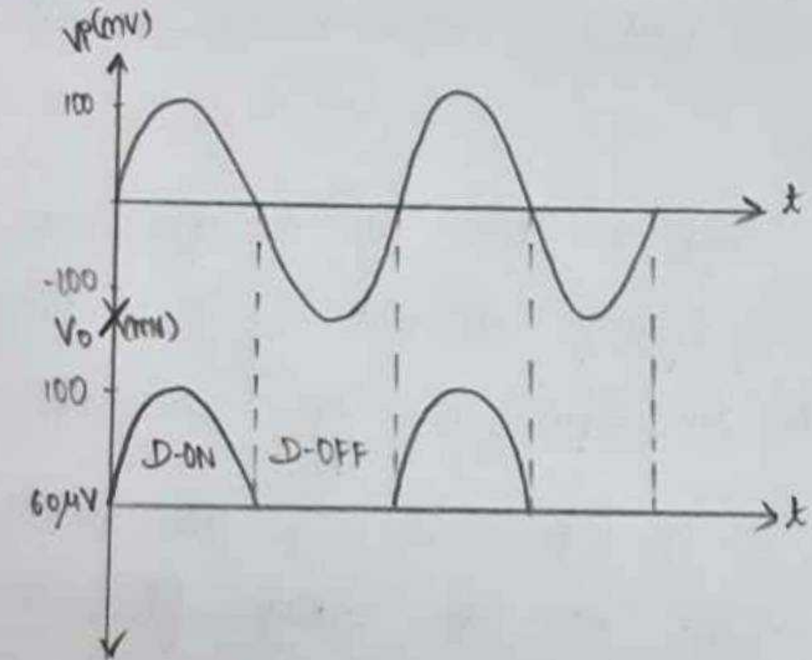
Here, the cut in voltage is divide by the open loop gain A_{OL} ($\sim 10^4$) of the op-amp so that V_γ is virtually eliminated. When the input $V_i > \frac{V_\gamma}{A_{OL}}$, then V_{OA} the output of the op-amp exceeds V_γ and diode D conducts. Then circuit acts like voltage follower.

When V_i is negative or $V_i < \frac{V_\gamma}{A_{OL}}$ then diode D is off and no current is delivered to load R_L except for small bias current of op-amp and reverse saturation current of the diode. This circuit is called precision diode and is capable of rectifying input signals of the order of mV.

APPLICATIONS:

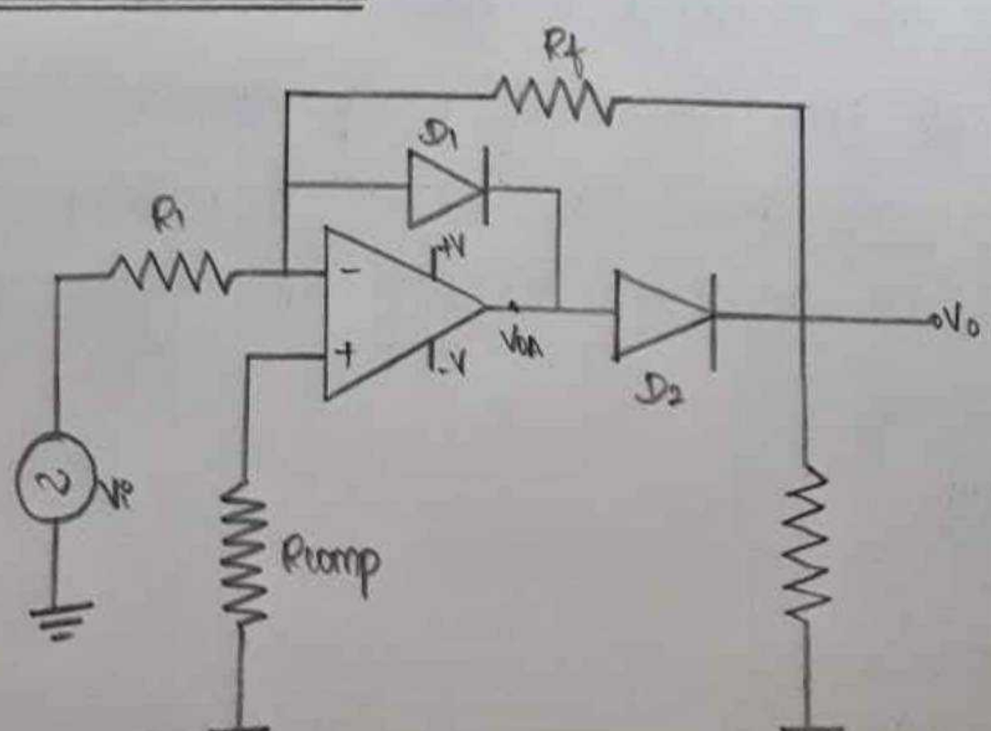
* Half-wave rectifier
* Full-wave rectifier
* Peak-value detector
* Clipper and clamper.





$$\frac{V_\gamma}{A_{ol}} = \frac{0.6}{10^4} = 60\mu V$$

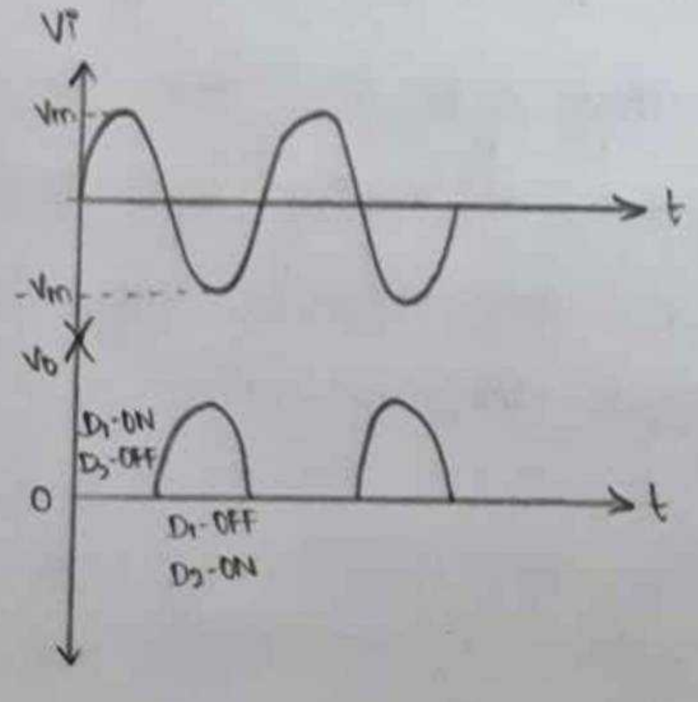
HALF WAVE RECTIFIER:-



An inverting amplifier can be converted into an ideal half wave rectifier by adding two diodes.

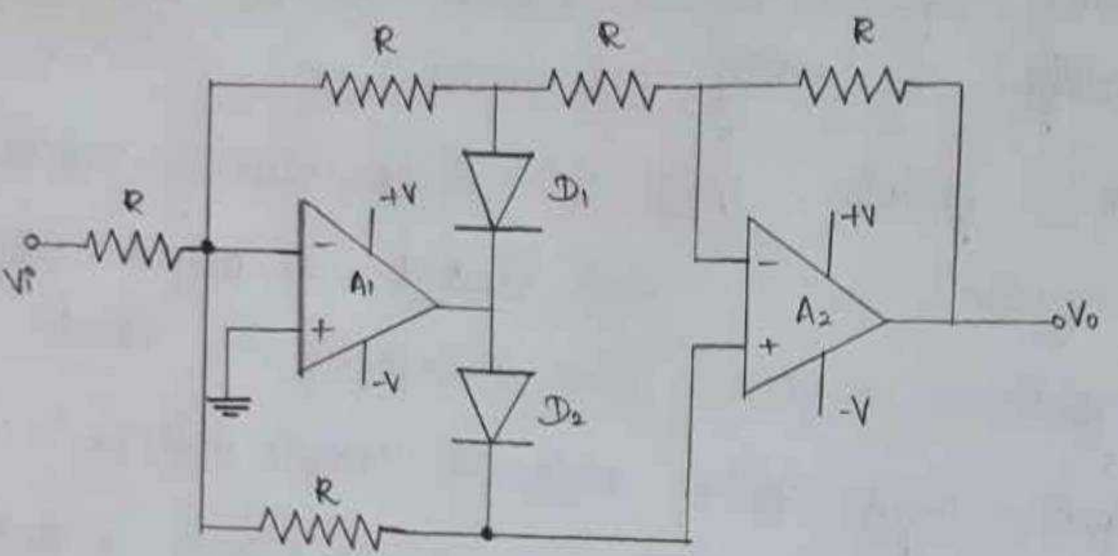
When V_i is positive, diode D_1 conducts causing V_{OA} to go to negative. D_2 is reverse biased. The output voltage V_0 is zero, so no current flows through R_f, D_1 conducts.

For negative input $V_i < 0$, diode D_2 conducts and D_1 is off. The negative input V_i forces the op-amp output V_{OA} positive and causes D_2 to conduct. The circuit acts like inverter for $R_f = R_1$ and V_0 is positive.



FULL-WAVE RECTIFIER:-

A full wave rectifier or absolute value circuit



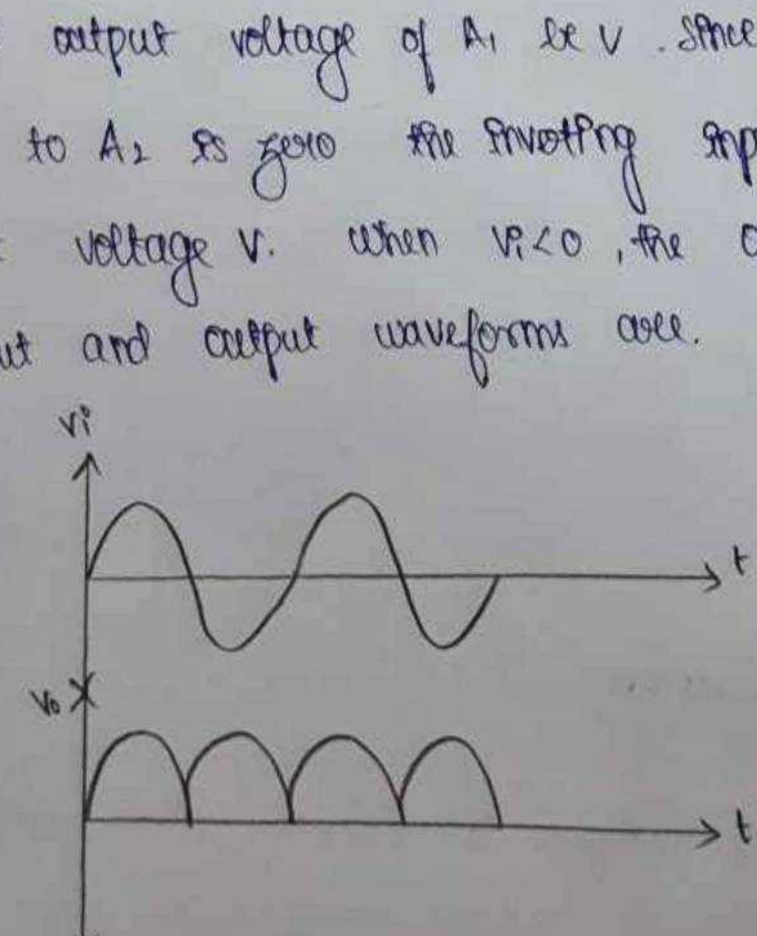
For positive input, $V_i > 0$, diode D_1 is ON and D_2 is OFF

Both the op-amps A_1 and A_2 act as inverter.

For negative input $V_i < 0$ diode D_1 is off and D_2 is ON

Let the output voltage of A_1 be V. Since the differential input to A_2 is zero the inverting input terminal is also at voltage V. When $V_i < 0$, the output is positive

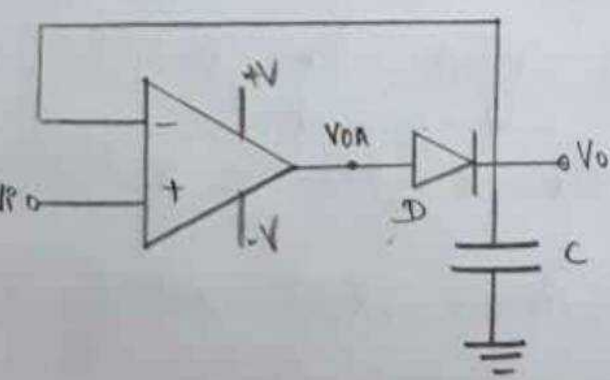
The input and output waveforms are.



This circuit is called absolute value circuit as output is positive even when input is negative.

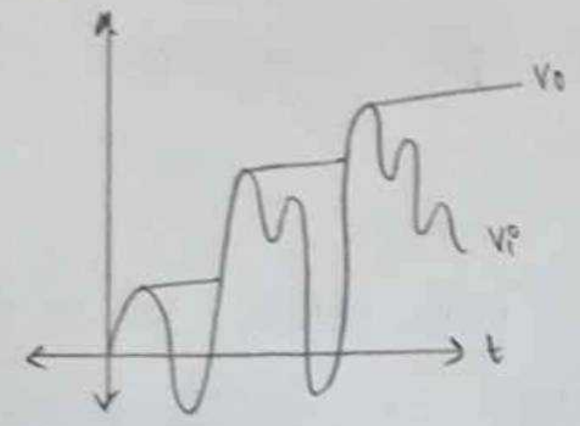
PEAK DETECTOR :-

The function of a peak detector is to compute the peak value of the input. The circuit follows the voltage peaks of a signal and stores the highest value on a capacitor. If a higher peak signal value comes along, this new value is stored. The highest peak value is stored until the capacitor is discharged.



When input $V_i > V_c$ (voltage across capacitor), D is forward biased and circuit becomes voltage follower. The output voltage V_o follows V_i till V_i exceed V_c.

When $V_i < V_c$, D is reverse biased, and capacitor holds charge till V_i again attains value greater than V_c.



Peak detectors find application in test and measurement instrumentation as well as in amplitude modulation (AM) communication.

OSCILLATOR:

Oscillators can generate output signal without any AC input signal. It generates different frequency. Positive feedback is given to oscillators.

An oscillator circuit should satisfy Barkhausen criterion. The conditions are:

(i) $|A\beta| = 1$

where $A \rightarrow$ loop gain

$\rightarrow \beta$ is feedback factor (transfer ratio)

(ii) The total phase shift of around the loop is ~~the network should be~~

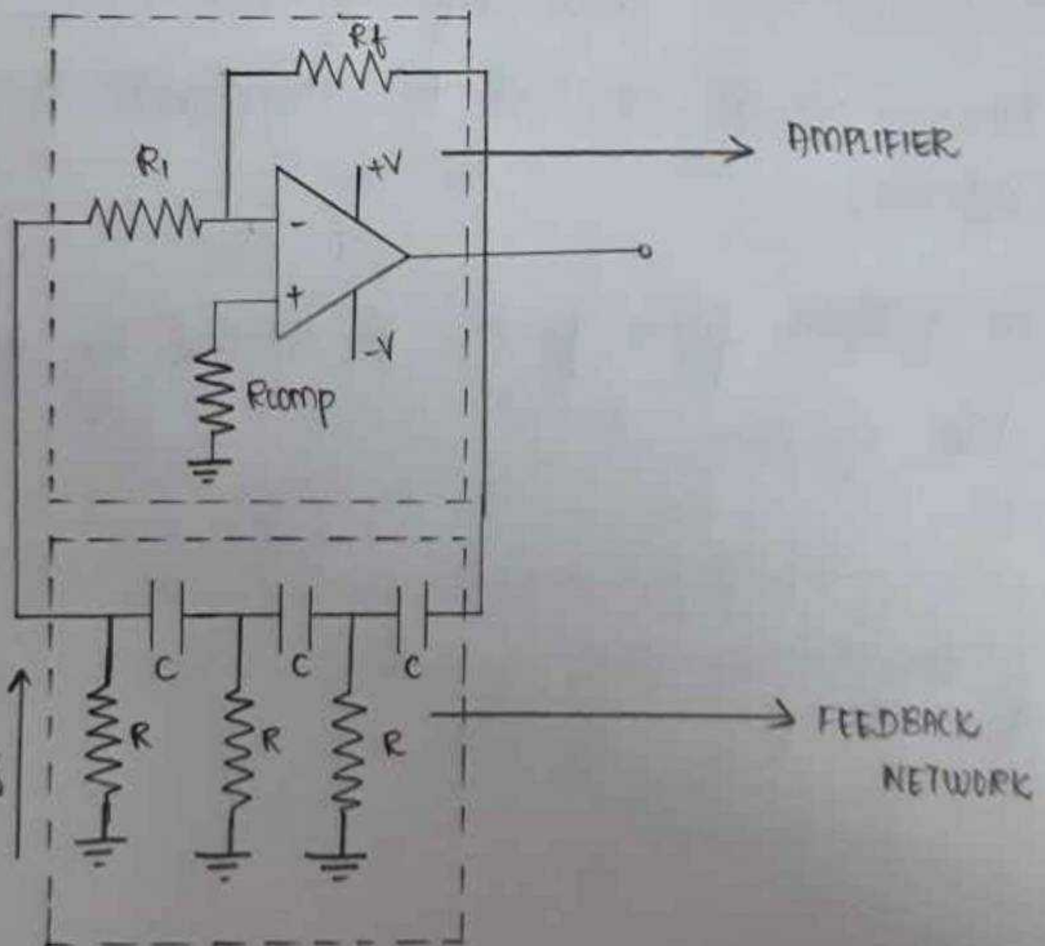
$\theta = 360^\circ$ (or) 0°

TYPES OF OSCILLATOR:

* Low frequency oscillator
    (i) RC phase shift oscillator
    (ii) Wein Bridge oscillator
* High frequency oscillator
    (i) Hartley oscillator
    (ii) colpitts oscillator.

RC -PHASE SHIFT OSCILLATOR:

The circuit of an RC- phase shift oscillator

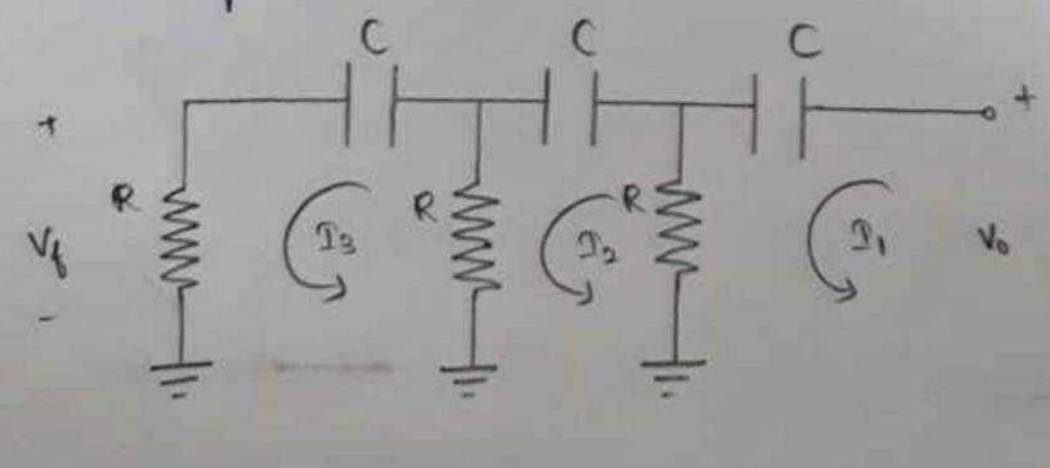


The op-amp is used in inverting mode and therefore provides 180° phase shift the additional phase of 180° is provided by the RC feedback network to obtain a total phase shift of 360°.

The feedback network consists of three identical RC stages. Each of the RC stages provides 60° phase shift so the total phase shift due to feedback network is 180°.

It is not necessary to use identical RC sections, even if non-identical sections of RC are used it is possible to obtain total phase shift of 180°.
This phenomenon can lead to undesirable inter-modal oscillations.

The feedback factor β can be obtained by applying KVL equations:



$$I_1\left(R+\frac{1}{sC}\right)-I_2R=0 \longrightarrow ①$$

$$I_2\left(2R+\frac{1}{sC}\right)-I_1R-I_3R=0 \longrightarrow ②$$

$$I_3\left(2R+\frac{1}{sC}\right)-I_2R=6 \longrightarrow ③$$

$$V_f=I_3R \longrightarrow ④$$

By solving ①, ② and ③ equations

$$I_3 = \frac{V_0R^2s^3C^3}{1+5sRC+6s^2C^2R^2+s^3R^3C^3}$$

substitute I_3 in ④,

$$V_f = \frac{V_0R^3s^3C^3}{1+5sRC+6s^2R^2C^2+s^3R^3C^3}$$

WKT,

$$\beta=\frac{V_f}{V_0}$$

$$\beta = \frac{R^3s^3C^3}{1+5sRC+6s^2R^2C^2+s^3R^3C^3}$$

Divide $R^3s^3C^3$ on both numerator and denominator

$$\beta = \frac{1}{\frac{1}{R^3s^3C^3}+\frac{5}{s^2R^2C^2}+\frac{6}{sRC}+1}$$

In steady state, $s=j\omega$

$$\beta = \cfrac{1}{\frac{1}{R^3 j^3 \omega^3 C^3} + \frac{5}{j^2 \omega^2 R^2 C^2} + \frac{6}{j\omega RC} + 1}$$

$j^2 = -1$; $j^3 = -j$

$$\beta = \cfrac{1}{\frac{-1}{jR^3\omega^3 C^3} - \frac{5}{\omega^2 R^2 C^2} + \frac{6}{j\omega RC} + 1}$$

Take $\alpha = \dfrac{1}{\omega RC}$

$$\beta = \cfrac{1}{-\frac{\alpha^3}{j} - 5\alpha^2 + \frac{6\alpha}{j} + 1}$$

$$= \frac{1}{1 - 6\alpha j - 5\alpha^2 + \alpha^3 j}$$

$$\beta = \frac{1}{(1-5\alpha^2) + \alpha j(\alpha^2 - 6)}$$

For $A\beta = 1$; β should be real, (ie): Imaginary term = 0;

$$\alpha(-6+\alpha^2) = 0$$

$$\alpha^2 - 6 = 0$$

$$\alpha^2 = 6$$

$$\therefore \alpha = \sqrt{6}$$

That is $\dfrac{1}{\omega RC} = \sqrt{6}$

The frequency of oscillation, f_0 is

$$\boxed{f_0 = \frac{1}{2\pi RC\sqrt{6}}}$$

On equating real part to zero, β is

$$[\alpha = \sqrt{6}]$$

$$\beta = \frac{1}{1-5\alpha^2} = \frac{1}{1-5(\sqrt{6})^2}$$

$$= \frac{1}{1-5(6)} = \frac{1}{1-30}$$

$$\boxed{\therefore \beta = \frac{-1}{29}}$$

The negative sign indicates feedback network produces 180° phase shift

$$|\beta| = \frac{1}{29}$$

$$|A\beta| \geq 1$$

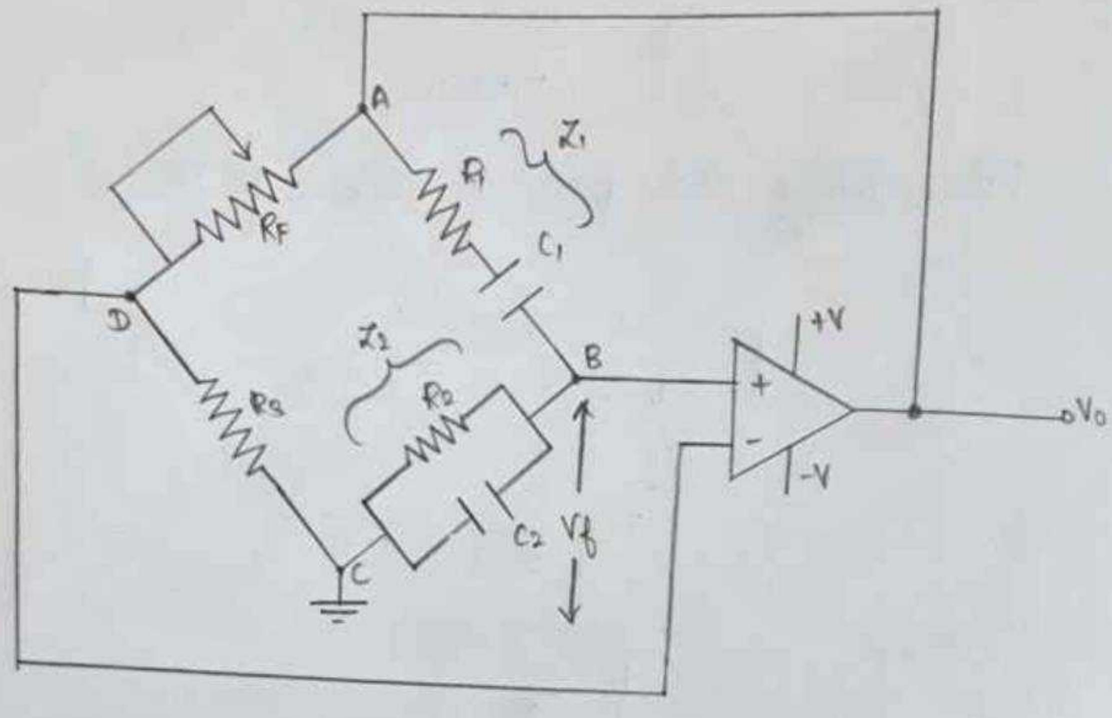
$$|A| \geq 29$$

The gain of inverting op-amp should be atleast 29 (or) $R_f = 29R_1$. The gain A_v is kept greater than 29 to ensure that variations in circuit parameters will not make $|A_v\beta| < 1$, otherwise oscillations will die out.

WEIN BRIDGE OSCILLATION:-

Another commonly used audio frequency oscillator is a

Wein Bridge oscillator.



It may be noted that the feedback signal in this circuit is connected to the non-inverting (+) input terminal so that the op-amp is working as non-inverting amplifier therefore, the feedback network need not provide any phase shift.

The circuit has series RC in one arm and parallel RC in adjoining arm. Resistors R_1 and R_F are connected in remaining two arms.

The condition of zero phase shift around the circuit is achieved by balancing the bridge.

The feedback signal V_f across parallel combination R_2C_2 is applied to non-inverting input terminal of the op-amp.

The gain A is,

$$A = 1 + \frac{R_F}{R_3}$$

feedback factor, β is

$$\beta = \frac{V_f}{V_0} = \frac{Z_2}{Z_1 + Z_2} \longrightarrow (1)$$

$$Z_1 = R_1 + \frac{1}{sC_1}$$

$$\boxed{Z_1 = \frac{R_1 sC_1 + 1}{sC_1}}$$

$$Z_2 = R_2 \parallel \frac{1}{sC_2} = \frac{R_2 \times \frac{1}{sC_2}}{R_2 + \frac{1}{sC_2}}$$

$$\boxed{Z_2 = \frac{R_2}{1 + R_2 sC_2}}$$

sub Z_1, Z_2 in (1),

$$\beta = \frac{\frac{R_2}{1 + R_2 sC_2}}{\frac{1 + R_1 sC_1}{sC_1} + \frac{R_2}{1 + R_2 sC_2}} = \frac{\frac{R_2}{\cancel{(1 + R_2 sC_2)}}}{\frac{(1 + R_1 sC_1)(1 + R_2 sC_2) + R_2 sC_1}{(sC_1)\cancel{(1 + R_2 sC_2)}}}$$

$$= \frac{R_2 sC_1}{R_2 sC_1 + (1 + R_1 sC_1)(1 + R_2 sC_2)}$$

$$= \frac{R_2 sC_1}{R_2 sC_1 + 1 + R_2 sC_2 + R_1 sC_1 + s^2 R_1 R_2 C_1 C_2}$$

In steady state, $s = j\omega$

$$\beta = \frac{j\omega R_2 C_1}{R_2 j\omega C_1 + 1 + R_2 j\omega C_2 + R_1 j\omega C_1 + j^2\omega^2 R_1 R_2 C_1 C_2}$$

WKT, $j^2 = -1$

$$= \frac{j\omega R_2 C_1}{1 + j\omega(R_1C_1 + R_2C_2 + R_2C_1) - \omega^2(R_1R_2C_1C_2)}$$

$$\beta = \frac{j\omega R_2 C_1}{(1 - \omega^2(R_1R_2C_1C_2)) + j\omega(R_1C_1 + R_2C_2 + R_2C_1)}$$

In order β to be a real quantity,

$$1 - \omega^2(R_1R_2C_1C_2) = 0$$

Thus the frequency of oscillation, f_0 is

$$1 = \omega^2(R_1R_2C_1C_2)$$

$$\omega = \frac{1}{\sqrt{R_1R_2C_1C_2}}$$

$$f_0 = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$

$$f_0 = \frac{1}{2\pi\sqrt{R^2C^2}}$$

$$\boxed{\therefore f_0 = \frac{1}{2\pi RC}}$$

On equating imaginary to zero, β is

$$\beta = \frac{\omega R_2 C_1}{\omega(R_1C_1 + R_2C_2 + R_2C_1)}$$

when $R_1 = R_2 = R$ and $C_1 = C_2 = C$

$$\beta = \frac{RC}{RC + RC + RC}$$

$$= \frac{RC}{3RC}$$

$$\boxed{\beta = \frac{1}{3}}$$

WKT,

$$|A\beta| = 1$$

$$|A| \geq 3$$

$$A = 1 + \frac{R_f}{R_3} \Rightarrow 3 = 1 + \frac{R_f}{R_3}$$

$$\therefore R_F = 2R_3$$

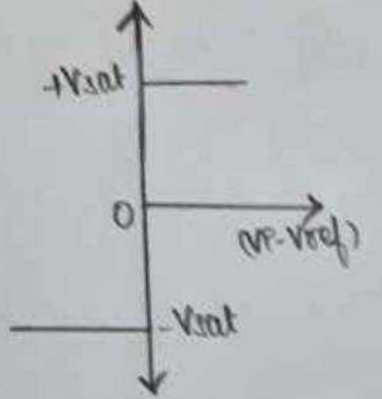
COMPARATOR:

A comparator is a circuit which compares a signal voltage applied at one input of an op-amp with a known reference voltage at the other input.

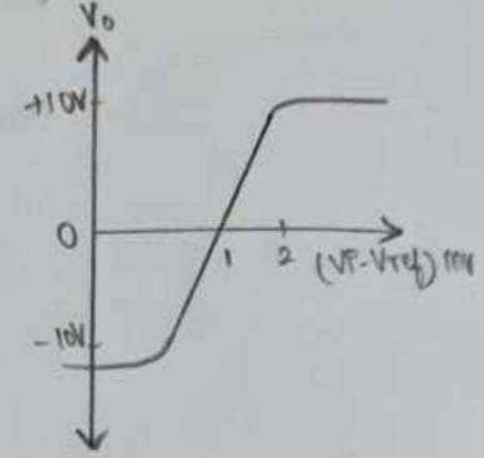
It is basically an open-loop op-amp with output $\pm V_{sat}$ ($= V_{cc}$)

The transfer characteristics of

(i) Ideal comparator



(ii) Practical comparator



It may be seen that the change in the output state takes place with an increment in input V_i of only 2mV. This is uncertainty region, where output cannot be directly defined. This region is due to input offset voltage and offset null compensating techniques can be used to eliminate this.

Types of comparators:

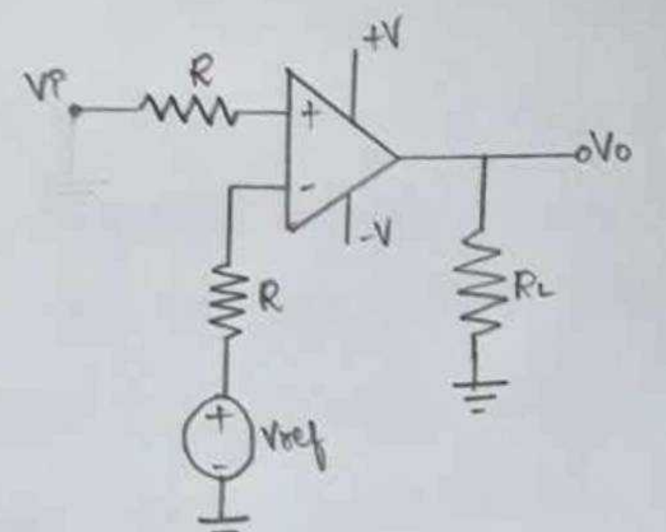
* Non inverting comparator
* Inverting comparator

Non-Inverting comparator:

A fixed reference voltage V_{ref} is applied to (-) input and a time varying signal V_i applied to (+) input. The output voltage is at $-V_{sat}$ for $V_i < V_{ref}$. And V_o goes to $+V_{sat}$

for $v_i > V_{ref}$

The non-inverting comparator circuit and output waveforms.



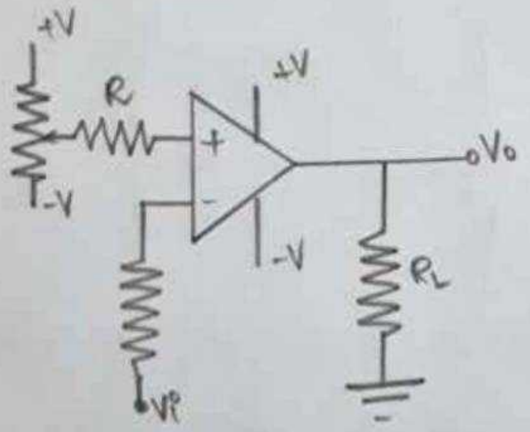
Vref is positive

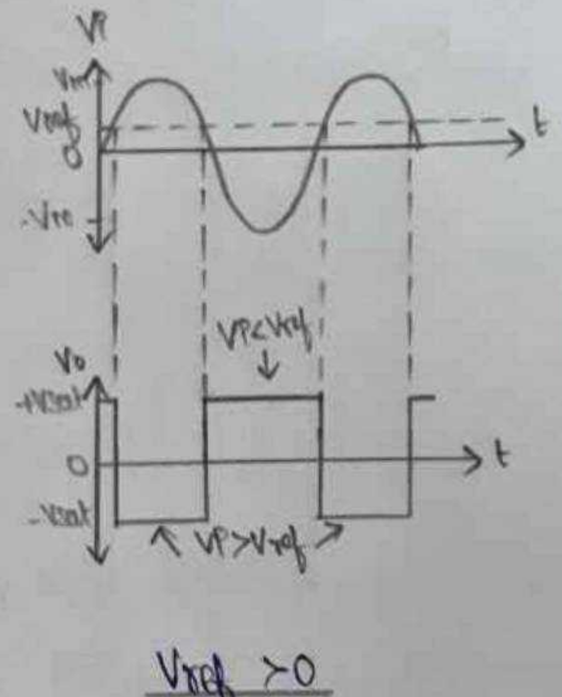
Vref is negative

Inverting Amplifier:

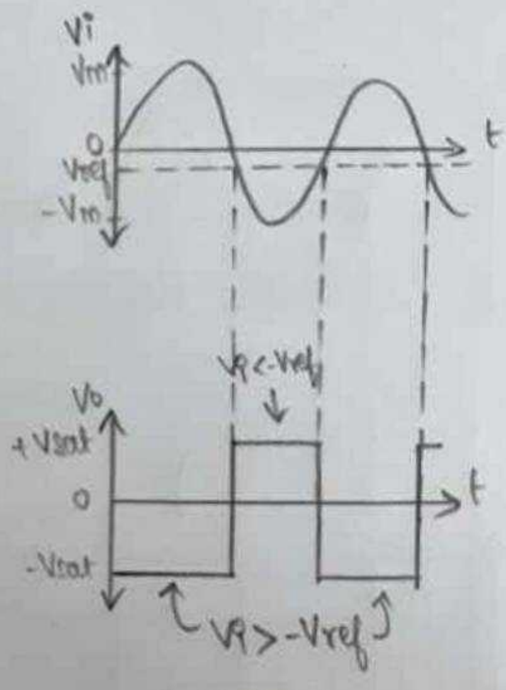
The reference voltage V_{ref} is applied to (+) input and V_i is applied to (−) input. The output voltage is at $-V_{sat}$

for $V_i > V_{ref}$ and V_o goes to $+V_{sat}$ for $V_i < V_{ref}$.
V_{ref} is obtained by connecting a potentiometer to (+) input.
The inverting comparator circuit and output waveforms are:





$V_{ref} > 0$



$V_{ref} < 0$

APPLICATIONS OF COMPARATOR.

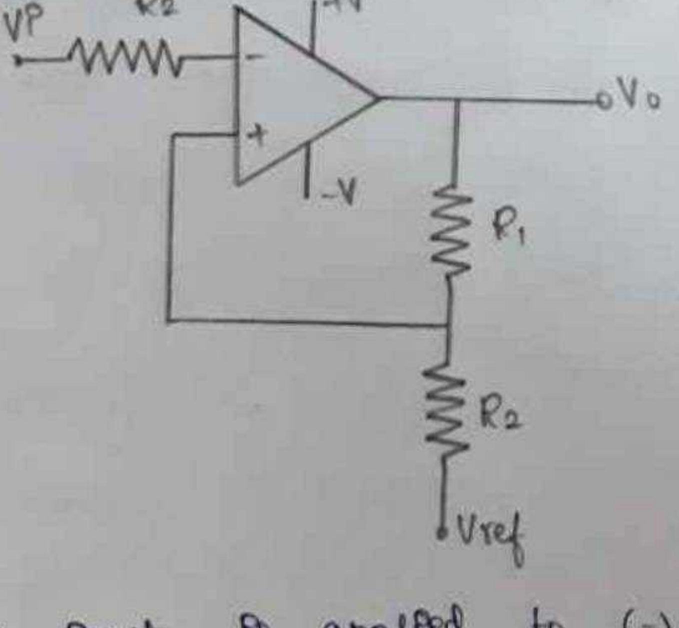
Some important applications of comparator are:

* Zero crossing detector
* Window Detector
* Time marker generator
* Phase meter.

REGENERATIVE COMPARATOR (SCHMITT TRIGGER)

If positive feedback added to comparator circuit, gain can be increased greatly. It may not be possible to maintain loop-gain exactly equal to unity for a long time because of supply voltage and temperature variations, in practical circuits. So value greater than unity is chosen. It also gives output waveform virtually discontinuous at comparison voltage. This circuit exhibits phenomenon called hysteresis or backlash.

Regenerative comparator:



The input is applied to (-) terminal and feedback voltage to (+) terminal. Vi triggers Vo every time it exceeds upper threshold voltage (VUT) and lower threshold voltag (V_{LT}). The hysteresis width is difference between these two threshold valtages.

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

when $V_i < V_{UT}$:

Upper threshold voltage, V_{UT} is

$V_o = +V_{sat}$

$$\boxed{V_{UT} = \frac{V_{ref} R_1}{R_1 + R_2} + \frac{R_2 V_{sat}}{R_1 + R_2}}$$

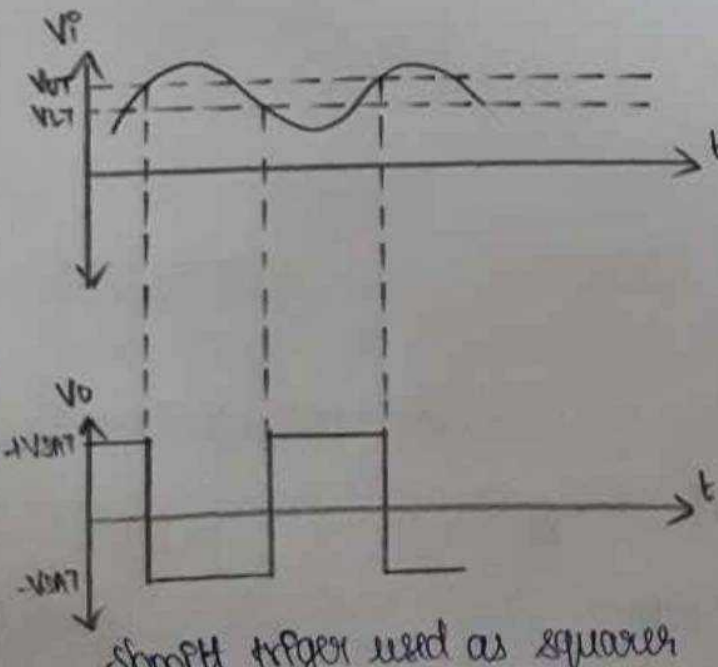
when $V_i > V_{UT}$:

$V_o = -V_{sat}$

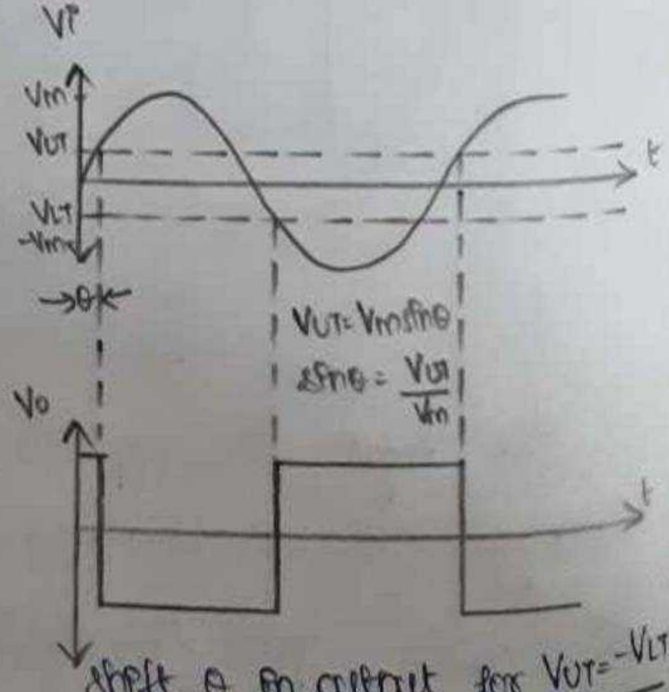
Lower threshold voltage, V_{LT} is

$$\boxed{V_{LT} = \frac{V_{ref} R_1}{R_1 + R_2} - \frac{R_2 V_{sat}}{R_1 + R_2}}$$

The input voltage V_i must become lesser than V_{LT} in order to cause V_o to switch from $-V_{sat}$ to $+V_{sat}$



Shmitt trigger used as squarer



Shift θ in output for $V_{UT} = -V_{LT}$

Hysteresis width is,

$$V_H = V_{UT} - V_{LT} = \frac{V_{ref} R_1}{R_1+R_2} + \frac{R_2 V_{sat}}{R_1+R_2} - \frac{V_{ref} R_1}{R_1+R_2} + \frac{R_2 V_{sat}}{R_1+R_2}$$

$$\boxed{V_H = \frac{2 R_2 V_{sat}}{R_1+R_2}}$$

Because of hysteresis, the circuit triggers at a higher voltage for increasing signals than decreasing.

If $V_i < V_H$, then transition in one direction will never reset itself.

If $V_{ref} = 0$, then

$$V_{UT} = -V_{LT} = \frac{R_2 V_{sat}}{R_1+R_2}$$

The most important application of Schmitt trigger circuit is to convert a very slowly varying input voltage into a square wave output.

MULTIVIBRATOR:-

Multivibrator is a wave shaping circuit.

The output of the multivibrator is a square wave.

Types of Multivibrator:-

(i) Astable Multivibrator

- also called as free running oscillator

- has two quasi stable states

(ii) Monostable multivibrator:

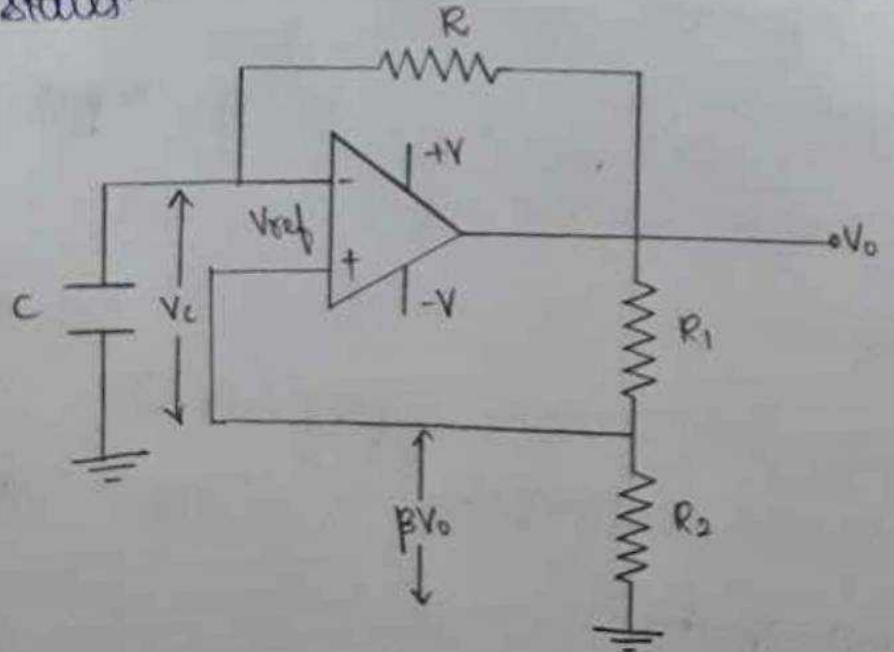
- also called One shot multivibrator
- has one stable and one quasi stable state

(iii) Bistable multivibrator:

- has two stable states
- its applications are flip flops.

ASTABLE MULTIVIBRATOR

A simple op-amp square wave generator. Also called free running oscillator, the principle of generation of square wave output is to force an op-amp to operate in saturation region. In astable multivibrator, both are quasi stable states.



consider an instant of time when output is at +Vsat. The capacitor now charges from -βVsat through resistor R and reaches $+\beta V_{sat}$.

When $V_i > V_{ref}$ transition takes place, therefore the capacitor voltage, $V_c > V_{ref}$ then transition takes place from $+V_{sat}$ to $-V_{sat}$.

Now the output voltage, $V_0 = -V_{sat}$ then the capacitor discharges from $+\beta V_{sat}$ and reaches $-\beta V_{sat}$. The voltage again switches from $-V_{sat}$ to $+V_{sat}$.

$V_c \rightarrow$ ~~causes~~ exponentially increasing and decreasing ~~output~~ voltage, ~~V_0~~

The voltage across capacitor $V_c(t) = V_f + (V_i - V_f)\, e^{-t/RC}$

$$V_f = +V_{sat}$$

$$V_i = -\beta V_{sat}$$

$$V_c(t) = V_{sat} + \left(-\beta V_{sat} - V_{sat}\right) e^{-t/RC}$$

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

At $t = T_1$;

$$\beta V_{sat} = V_{sat}\left[1 + (-1-\beta)\, e^{-t/RC}\right]$$

$$\beta = 1 - (1+\beta)\, e^{-t/RC}$$

$$(1+\beta)\, e^{-t/RC} = 1 - \beta$$

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

$$\frac{1}{e^{T_1/RC}} = \frac{1-\beta}{1+\beta}$$

$$e^{T_1/RC} = \frac{1+\beta}{1-\beta}$$

Take ln on both sides,

$$\frac{T_1}{RC} = \ln\left(\frac{1+\beta}{1-\beta}\right)$$

$$\boxed{T_1 = RC \ln\left(\frac{1+\beta}{1-\beta}\right)}$$

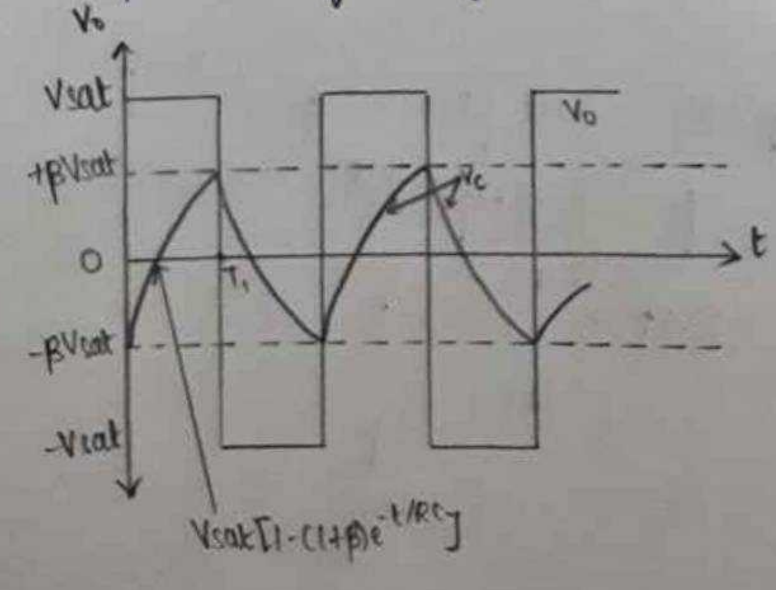
Total time period :

$$T = T_1 + T_2$$

$$T_1 = T_2 = RC \ln\left(\frac{1+\beta}{1-\beta}\right)$$

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

The output waveforms of Astable Multivibrator.



ACTIVE FILTERS :

A frequency selective electric circuit that passes electric signals of specific band of frequencies and attenuates the signals of frequencies outside the band is called an electric filter. The active filters use op-amp as the active element and resistor and capacitor as passive element.

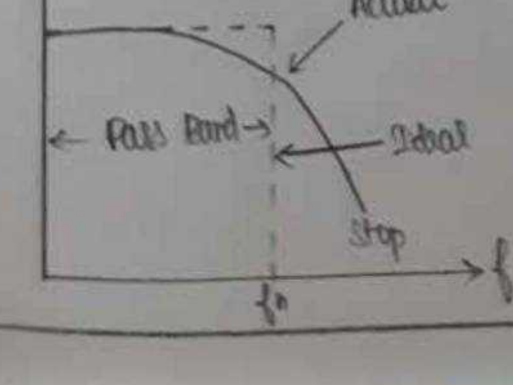
The advantages of using Op-Amp:

* provides gain
* input signal is not attenuated
* high input impedance
* low output impedance
* improves load drive capacity.

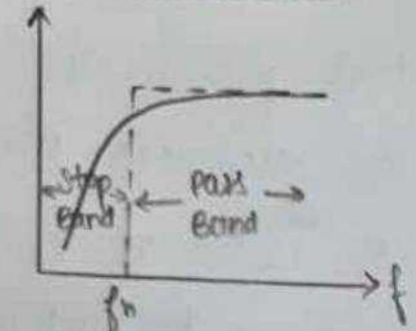
The most commonly used filters are:

* Low Pass Filter (LPF)
* High Pass Filter (HPF)
* Band Pass Filter (BPF)
* Band Reject Filter - also called Band stop Filter (BSF)

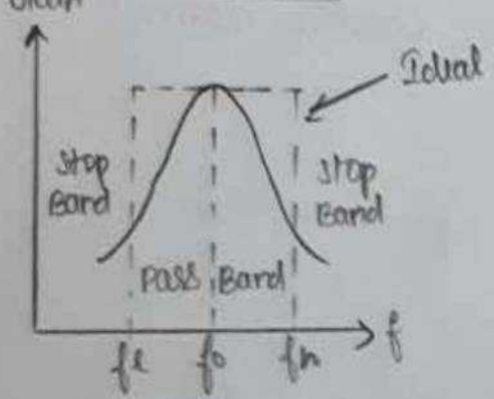
LOW PASS :



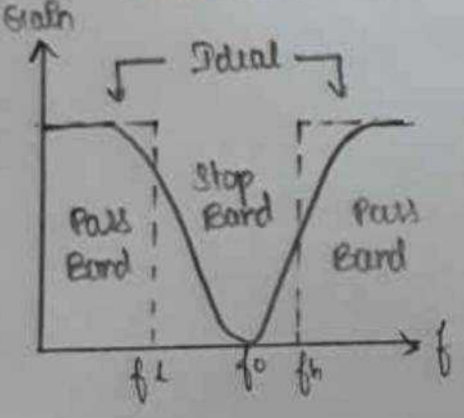
HIGH PASS



BAND PASS

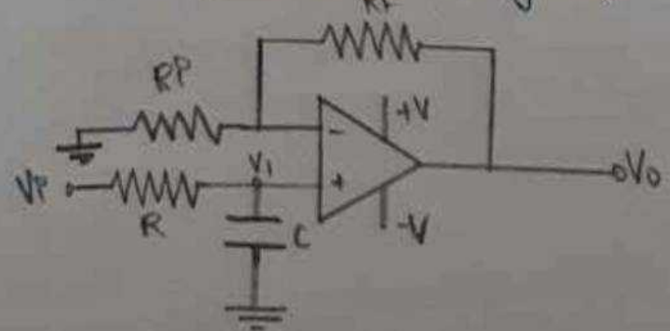


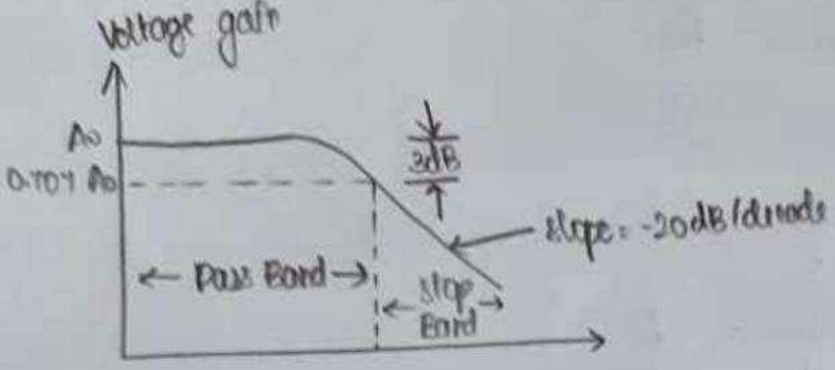
BAND REJECT



FIRST ORDER LOW PASS FILTER :-

This circuit consists of single RC network connected to (+) terminal of non-inverting op-amp.





voltage across capacitor

$$V_1(S) = \frac{\frac{1}{SC} \cdot Vi(S)}{R + \frac{1}{SC}} = \frac{\frac{Vi(S)}{SC}}{\frac{1+RSC}{SC}}$$

$$\boxed{V_1(S) = \frac{Vi(S)}{1+RSC}}$$

$$\boxed{\frac{V_1(S)}{Vi(S)} = \frac{1}{1+RSC}} \longrightarrow (1)$$

WKT,

Gain, $A = \frac{V_0}{Vin}$

closed loop gain :

$$A_0 = \left(1 + \frac{R_f}{Ri}\right) = \frac{Vo(S)}{Vi(S)} \longrightarrow (2)$$

Transfer function $= \frac{Vo(S)}{Vi(S)}$

$$H_{LP}(S) = \frac{Vo(S)}{Vi(S)} = \frac{Vo(S)}{V_1(S)} \cdot \frac{V_1(S)}{Vi(S)} \longrightarrow (3)$$

sub (1) & (2) in (3)

$$\boxed{H_{LP}(s) = \frac{A_0}{1+RsC}}$$

when $s = j\omega$

$$\boxed{H_{LP}(j\omega) = \frac{A_0}{1+jR\omega C}}$$

WKT, $\omega = 2\pi f$

$$= \frac{A_0}{1+j2\pi f RC}$$

Take $f_h = \frac{1}{2\pi RC}$

$$H_{LP}(j\omega) = \frac{A_0}{1+j\left(\frac{f}{f_h}\right)}$$

Magnitude of transfer function is,

$$|H_{LP}(j\omega)| = \frac{A_0}{\sqrt{1+(f/f_h)^2}}$$

<u>case (i):</u>

when $f << f_h$

$|H_{LP}(j\omega)| = A_0$

<u>case (ii):</u>

when $f = f_h$

$|H_{LP}(j\omega)| = \frac{A_0}{\sqrt{2}} = 0.707A_0$

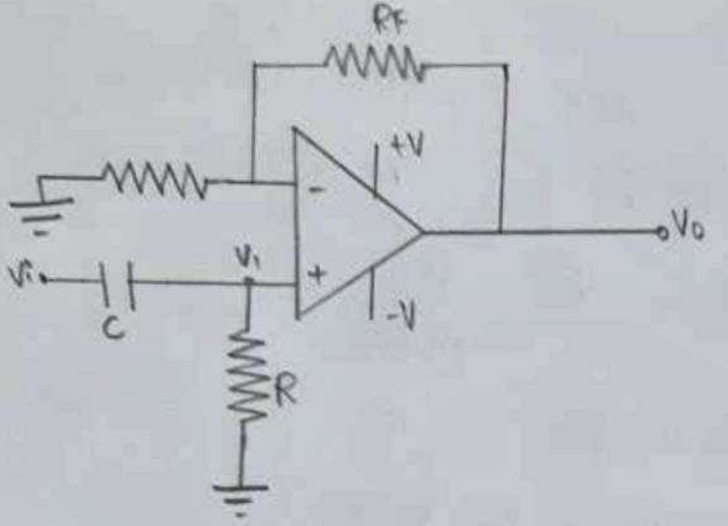
<u>case (iii):</u>

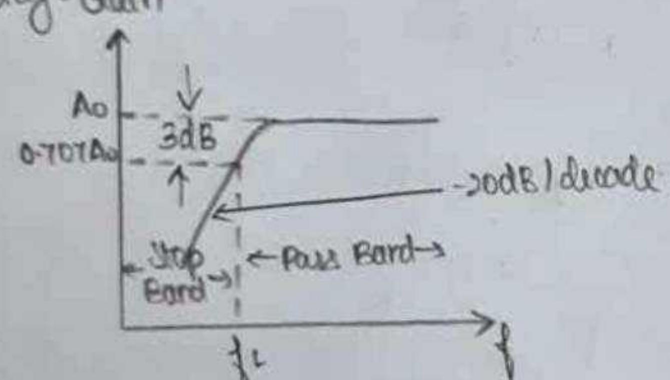
when $f >> f_h$

$|H_{LP}(j\omega)| = 0$

HIGH PASS FILTER :

A high pass filter is a complement of low pass filter and can be obtained by interchanging R and C.





Voltage across capacitor,

$$V_1(s) = \frac{V_i(s) \times R}{R + \frac{1}{sC}} = \frac{V_i(s) \times R}{\frac{RsC+1}{sC}}$$

$$V_1(s) = \frac{V_i(s)\, RsC}{1 + RsC}$$

$$\boxed{\frac{V_1(s)}{V_i(s)} = \frac{RsC}{1+RsC}} \longrightarrow (1)$$

closed loop gain A_0 is

$$A_0 = \left(1+\frac{R_f}{R_1}\right) = \frac{V_0(s)}{V_i(s)} \longrightarrow (2)$$

Transfer function $H_{HP}(s)$ is

$$H_{HP}(s) = \frac{V_0(s)}{V_i(s)} = \frac{V_0(s)}{V_1(s)} \cdot \frac{V_1(s)}{V_i(s)} \longrightarrow (3)$$

Sub (1), (2) in (3),

$$H_{HP}(s) = A_0 \cdot \frac{RsC}{1+RsC}$$

when $s = j\omega$

$$H_{HP}(j\omega) = \frac{A_0 \cdot Rj\omega C}{1+j\omega RC}$$

WKT, $\omega = 2\pi f$

$$H_{HP}(j\omega) = \frac{A_0 \cdot j2\pi fRC}{1+j2\pi fRC}$$

let $f_L = \frac{1}{2\pi RC}$

$$H_{HP}(j\omega) = \frac{A_0 \cdot j\left(f/f_L\right)}{1+j\left(f/f_L\right)}$$

Divide by f/f_L on numerator and denominator

$$= \frac{A_0 \cdot j}{\frac{1}{f/f_L} + j(1)} = \frac{j \cdot A_0}{\frac{f_L}{f} + j}$$

Magnitude of transfer function is

$$\boxed{|H_{HP}(j\omega)| = \frac{A_0}{\sqrt{1+\left(\frac{f_L}{f}\right)^2}}}$$

Case (i):

when $f << f_L$

$$|H_{HP}(j\omega)| = 0$$

Case (ii)

when $f = f_L$

$$|H_{HP}(j\omega)| = \frac{A_0}{\sqrt{2}} = 0.707 A_0$$

Case (iii)

when $f >> f_L$

$$|H_{HP}(j\omega)| = A_0$$

BAND PASS FILTER:-

This allows only a particular range of frequency

It is of two types:

* Narrow Band Pass Filter

 Q factor > 10

* Wide Band Pass Filter

 Q-factor < 10

where, $Q \text{ factor} = \frac{f_0}{BW}$

Depending on band width Q-factor is altered.

BAND REJECT FILTER:-

This rejects the particular range of frequencies.

It is of two types:

* Narrow Band Reject filter / Notch filter.
* Wide Band Reject filter.