Analog Integrated Circuits

Electronics and Telecommunication Engineering

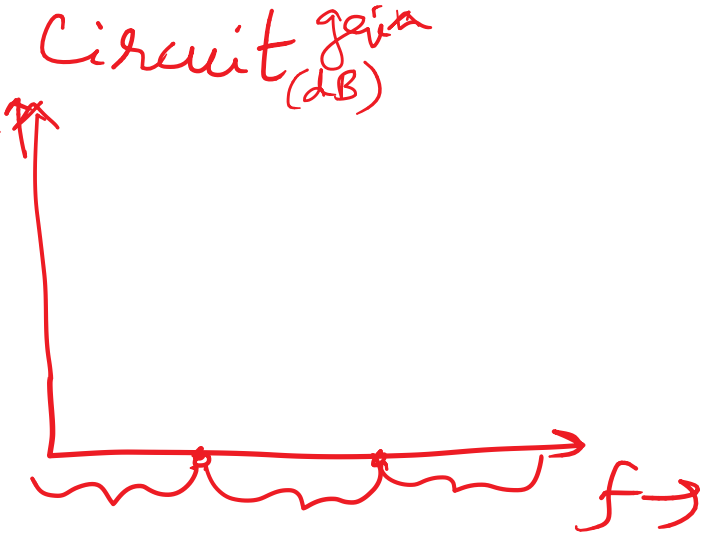
Filters and Oscillators using Op. Amp.

by

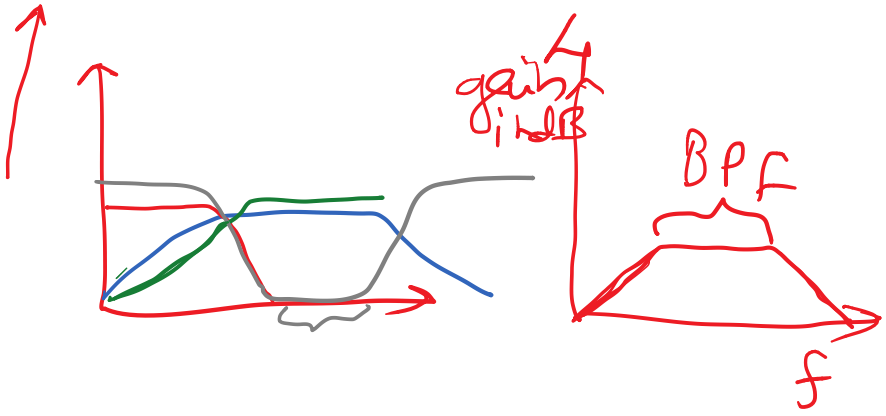
Dr.Swati R. Dixit

Filter - Frequency selective Circuit

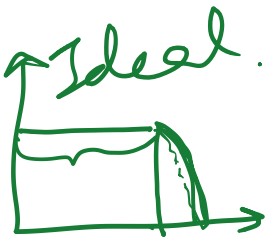
1) Active filters → Op. Amps.
   Passive filters
2) Analog / Digital
3) Audio freq / Radio freq



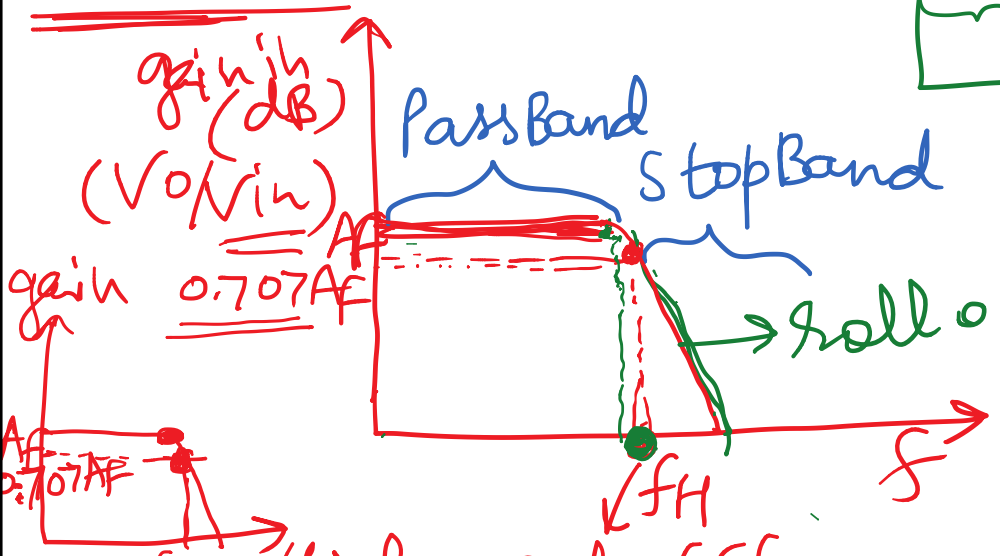
Active filters -
1) Low Pass filter
2) High Pass filter
3) Band Pass filter
4) Band Reject filter
5) All Pass filter



Low Pass filter →

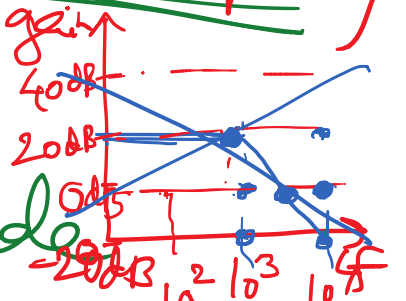


$20 \log_{10}(0.707) = 3\,dB$



3 dB

$f_H \Rightarrow$ 3 dB frequency



20 dB/decade → 1st order filter

40 dB/decade → 2nd order filter

60 dB/decade → 3rd order

80 dB/decade — 4th order

100 dB/decade — 5th order

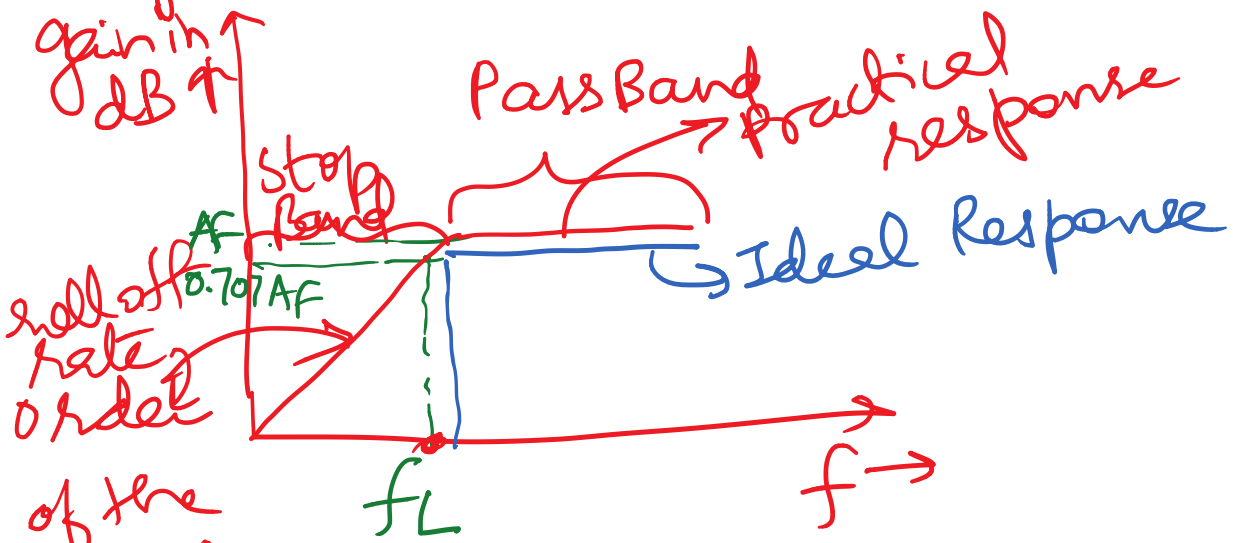
120 dB/decade - 6th order

$10 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5$

1 decade 1 decade

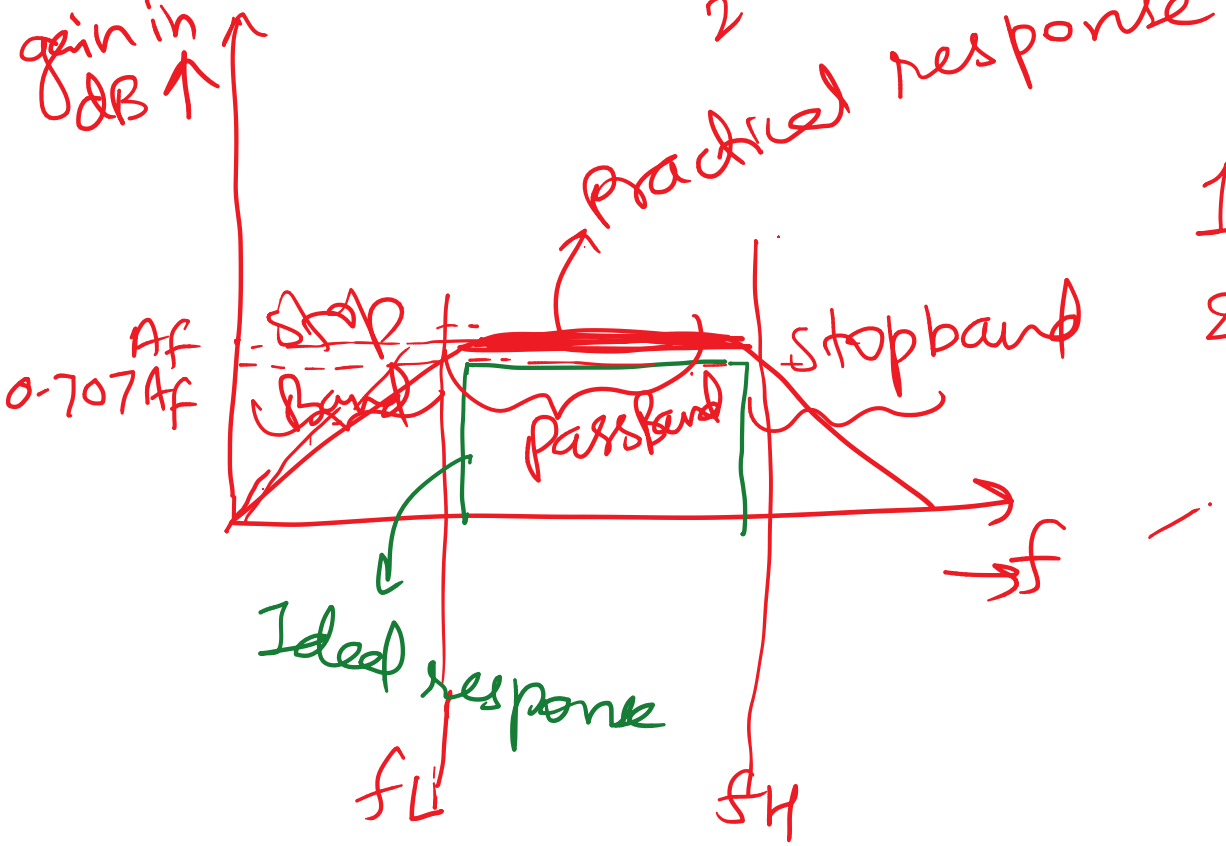
6th order filter.

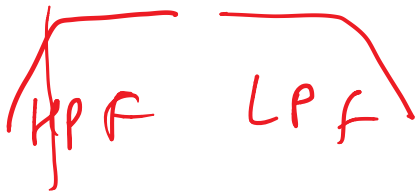
High Pass filter →



Lower cut off frequency
3dB frequency

Band Pass filter → 1st 2nd 3rd order

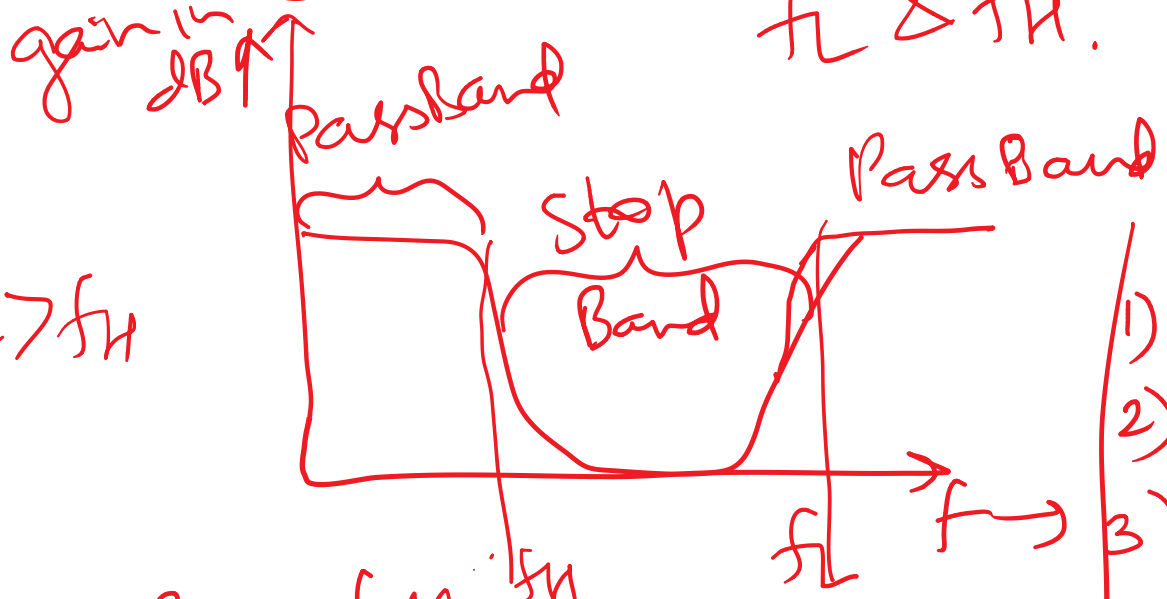




1 passband

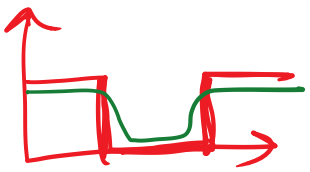
2 stopbands

Band Reject filter →



f_L & f_H.

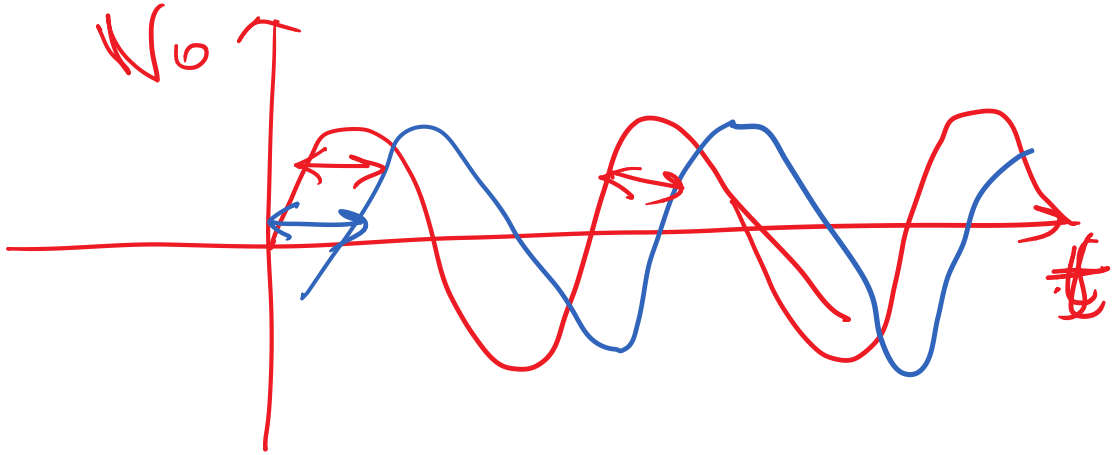
1 stopband
2 passbands



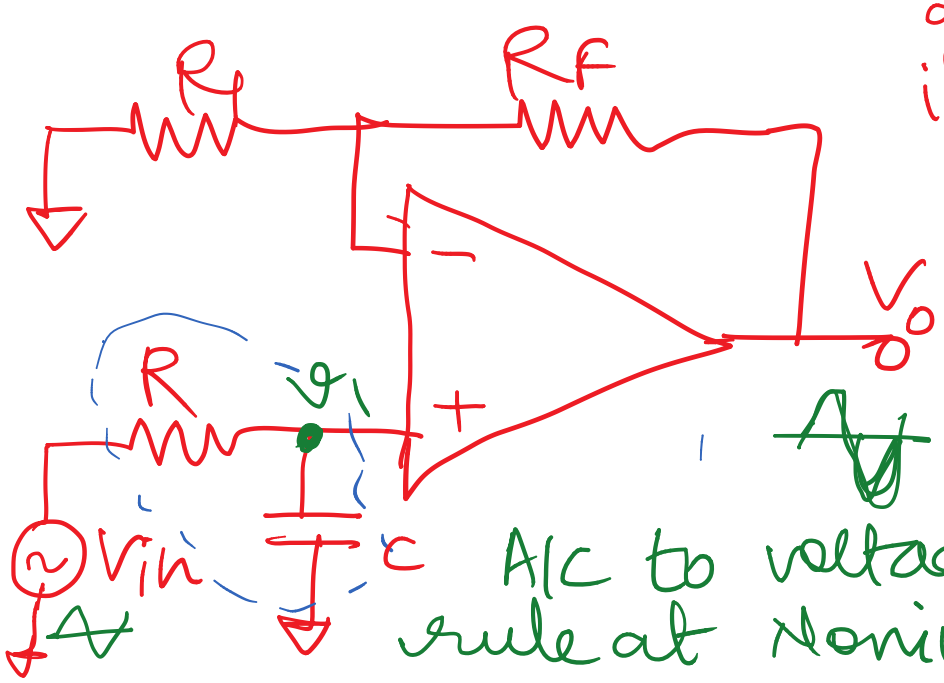
1) Butterworth
2) Chebyshev
3) Cauer

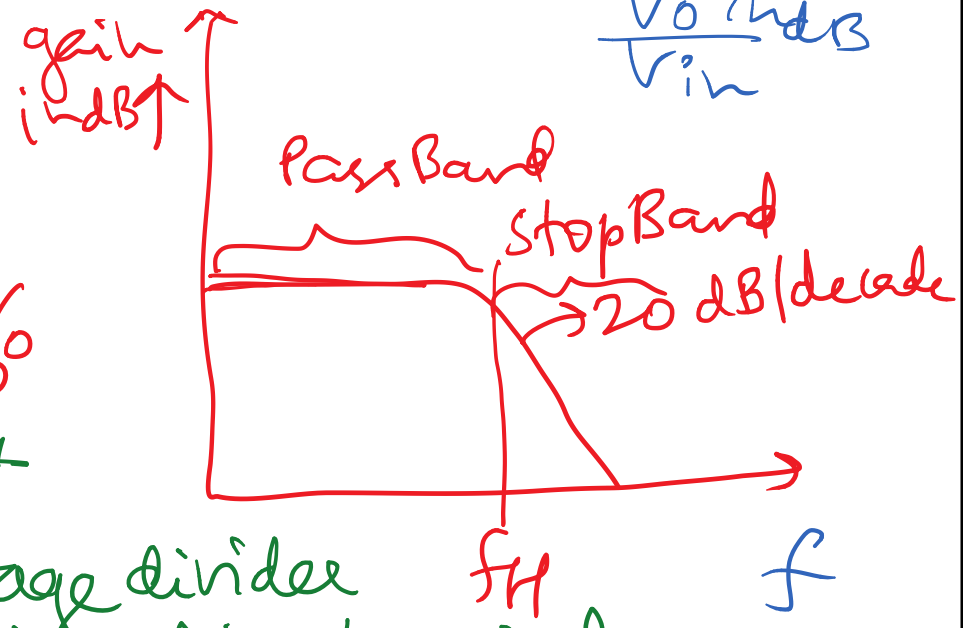
flat Pass Band
& flat Stop Band

All Pass filter



1st order 20 dB/decade low pass Butterworth filter





$$\frac{V_{in}}{V_o \text{ in dB}}$$

$$V_1 = \frac{-jX_C}{R - jX_C} V_{in} = \frac{1/j2\pi fC}{R + \frac{1}{j2\pi fC}} V_{in}$$

$$j = \sqrt{-1}, \quad -jX_C = \frac{1}{j2\pi fC}$$

$$V_1 = \frac{1/j2\pi fC}{R + \frac{1}{j2\pi fC}} V_{in} \Rightarrow \frac{1}{1 + j2\pi fCR} V_{in}$$

$\therefore$ O/P voltage is

$$V_O = \left(1 + \frac{R_f}{R_1}\right) V_1 \Rightarrow V_O = \left(1 + \frac{R_f}{R_1}\right) \frac{V_{in}}{1 + j2\pi fRC}$$

$$\frac{V_O}{V_{in}} = \frac{A_f}{1 + j(f/f_H)} \quad \text{where}$$

$\frac{V_O}{V_{in}}$ → gain of filter as fn of freq.

$A_f = 1 + \frac{R_f}{R_1}$ → Pass Band gain

$f_H = \frac{1}{2\pi RC}$ → High cut-off frequency

f → frequency of the input signal.

$\frac{V_o}{V_{in}} = \frac{Af}{1+j(f/f_H)}$ ⇒ The gain magnitude & phase angle equations of low pass filter can be obtained as

$$\left|\frac{V_o}{V_{in}}\right| = \frac{Af}{\sqrt{1+(f/f_H)^2}}$$

f → i/p signal frequency

f_H → higher cut off frequency of filter.

$\phi = -\tan^{-1}(f/f_H)$ where ϕ is phase angle in degrees.

1) $f < f_H$, At low frequencies, $\left|\frac{V_o}{V_{in}}\right| \cong Af$

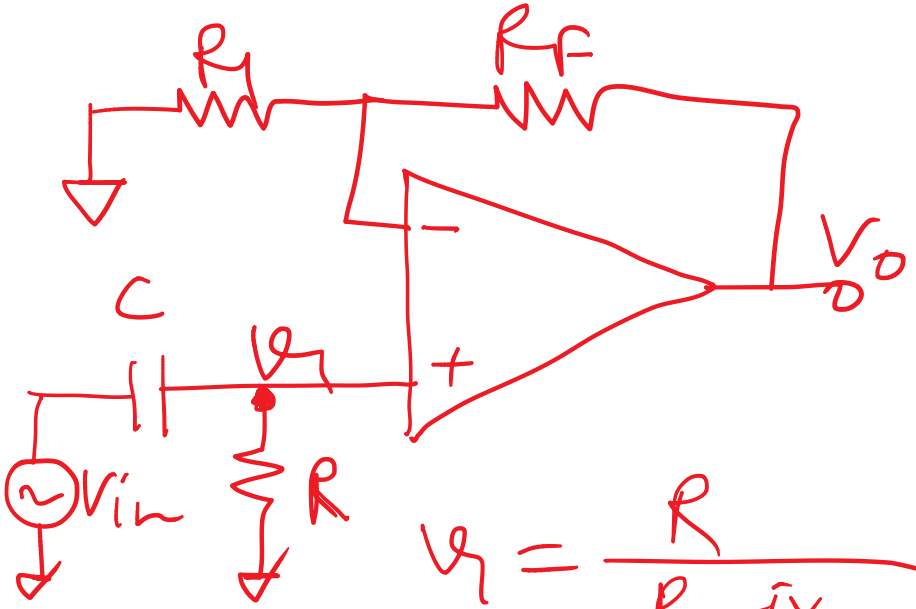
2) $f = f_H$, $\left|\frac{V_o}{V_{in}}\right| = \frac{Af}{\sqrt{1+1}} = \frac{Af}{\sqrt{2}} = 0.707Af$

3) $f > f_H$, At higher frequencies, $\left|\frac{V_o}{V_{in}}\right| < Af$.



1st order High Pass Butterworth filter

Significance of R_1, R_F, R & C





$$V_f = \frac{R}{R - jX_C} = \frac{R}{R + \frac{1}{j2\pi fc}} = \frac{R}{\frac{1 + j2\pi fcR}{j2\pi fc}}$$

$$V_f = \frac{j2\pi fcR}{1 + j2\pi fcR}$$

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

$$= \left(1 + \frac{R_f}{R_1}\right) \cdot \frac{j 2\pi f RC}{1 + j 2\pi f RC} V_{in}$$

$$\frac{V_o}{V_{in}} = \frac{A_f \cdot j(f/f_L)}{1 + j(f/f_L)}$$

where

$f_L = \frac{1}{2\pi RC}$ → lower cut off frequency

$\frac{V_o}{V_{in}}$ = gain of ckt.

A_f → Pass Band gain

f → freq. of i/p signal

So in filters, R_1 & R_F decide the passband gain of the filter $1 + \frac{R_F}{R_1}$

R & C components decide cut off frequency of the filter

$f_H = \frac{1}{2\pi RC}$ $f_L = \frac{1}{2\pi RC}$ $C \leq 1\mu F$.

steps to Design of filter -

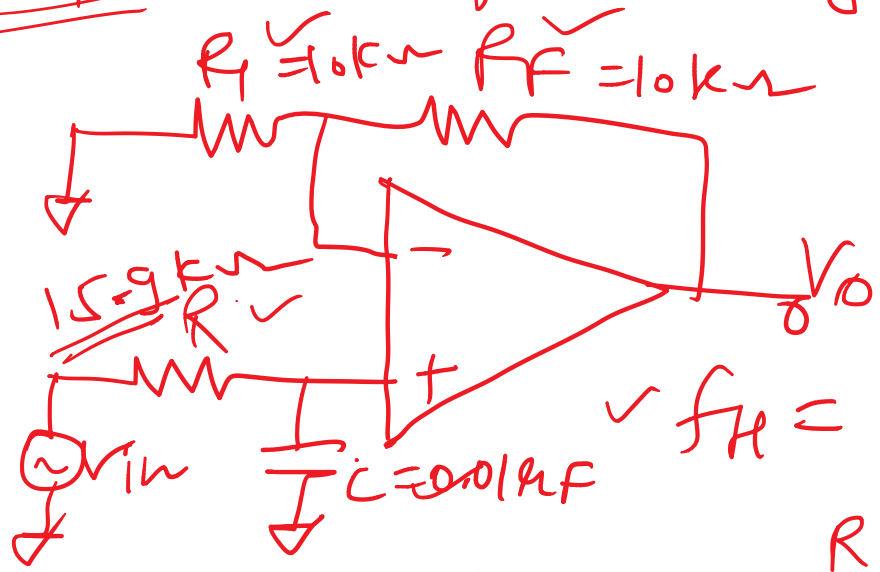
1) Choose a value of cutoff frequency.
2) Select value of C less than or equal to 1 μF.
3) Calculate value of R using

$$R = \frac{1}{2\pi f_H C} \quad \text{or} \quad R = \frac{1}{2\pi f_L C}$$

4) Finally select values of R_1 & R_F depending on desired passband gain A_F using

$$A_F = 1 + \frac{R_F}{R_1}$$

Design a low pass filter at a cutoff frequency of 1 kHz with a passband gain of 2.



$f_H = 1\,kHz = 1 \times 10^3\,Hz$

$A_F = 2$.

$f_H = \frac{1}{2\pi RC}$, let $C = 0.01\mu F$

$R = \frac{1}{2\pi f_H C} = \frac{1}{2\pi \times 1000 \times 0.01 \times 10^{-6}}$

$= 15.9\,k\Omega$

$A_F = 1 + \frac{R_F}{R_1}$

$1 + \frac{R_F}{R_1} = 2$, $\frac{R_F}{R_1} = 1$, $R_F = R_1$

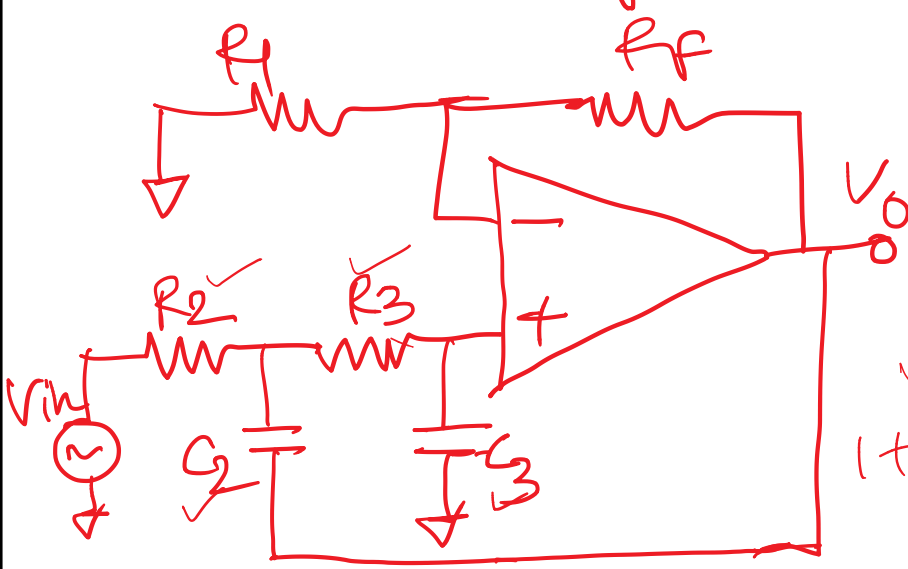
let $R_F = R_1 = 10\,k\Omega$.

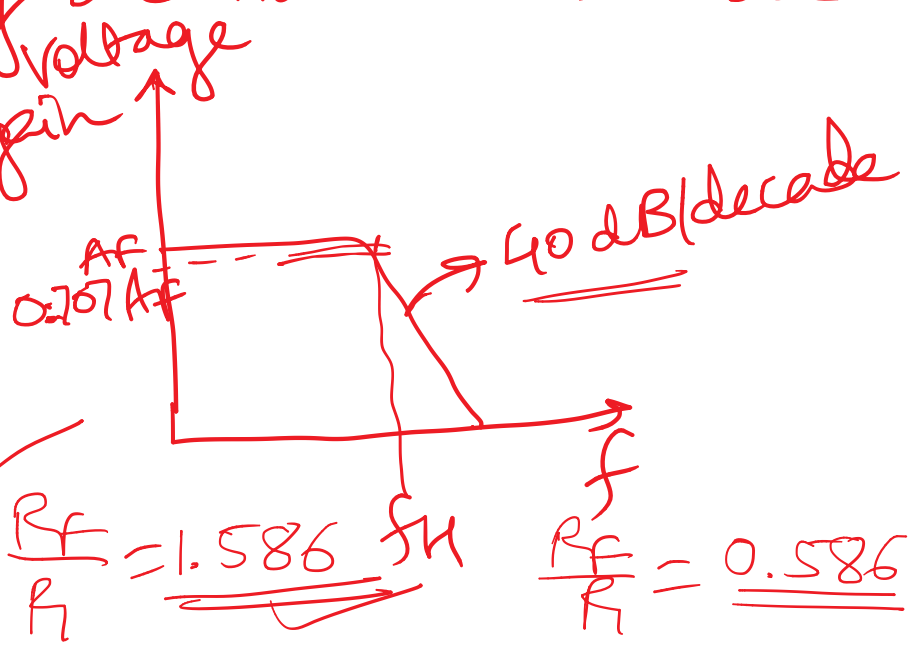
We may use 20kΩ potentiometer for $R_2 = 15.9k\Omega$

Second order low Pass Butterworth filter -

⇒ A stopband response having 40 dB/decade roll off.

⇒ can be designed using additional RC network.





$1 + \frac{R_f}{R_1} = 1.586$ $\quad \frac{R_f}{R_1} = 0.586$

2nd order filters → Important because higher order filters can be designed using them.

Gain set by R_1 & R_f

Cut off frequency set by components R and C [R_2, R_3, C_2, C_3]

Cut off frequency is given as $\frac{1}{2\pi RC}$

$$f_H = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}}$$

For 2nd order LP Butterworth filter, the voltage gain magnitude equation can be given as

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_F}{\sqrt{1+(f/f_H)^4}}$$ where

$A_F \rightarrow$ Passband gain

$f \rightarrow$ freq. of i/p signal.

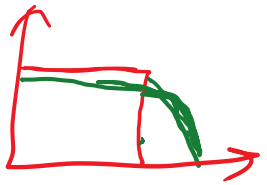
$$f_H = \frac{1}{2\pi\sqrt{R_2R_3C_2C_3}} \rightarrow$$ High cut off frequency

Frequency response of 2nd order filter is same as that of 1st order except twice rolloff rate in stopband region. So design steps remain same.

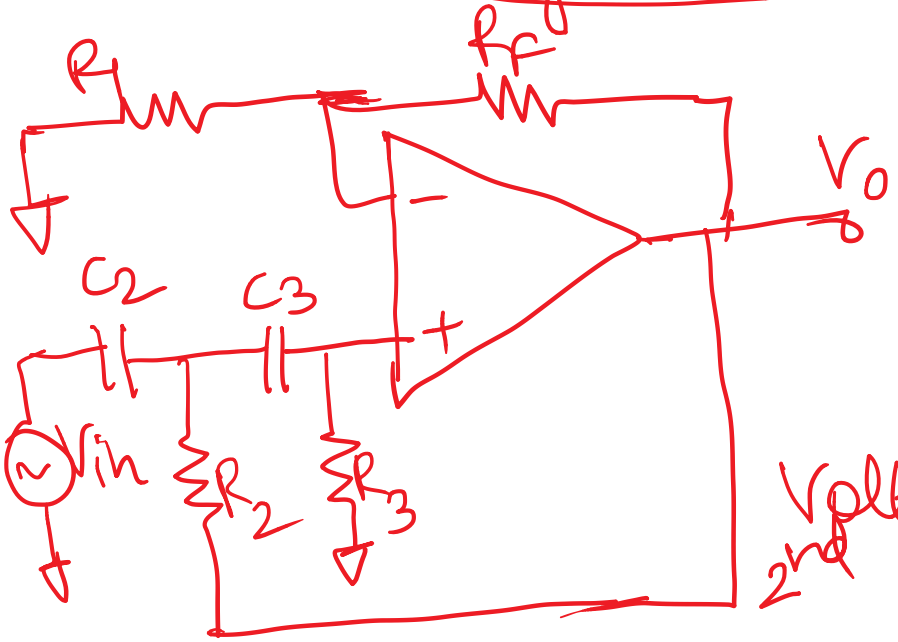
To simplify the design calculations, set $R_2 = R_3 = R$ & $C_2 = C_3 = C$ & find R by choosing $C \leq 1\mu F$ at particular cut off frequency. $f_H = \frac{1}{2\pi RC}$

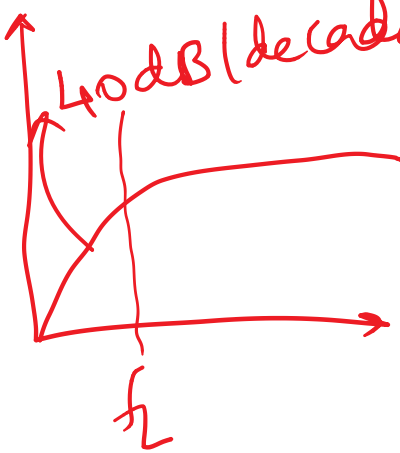
Because of equal resistors ($R_2 = R_3$) and capacitors ($C_2 = C_3$), passband voltage gain $A_F = 1 + \frac{R_F}{R_1}$ of 2nd order filter has to be 1.586. i.e. $R_F = 0.586 R_1$.

This gain is necessary to guarantee Butterworth response.



2nd order High Pass Butterworth filter –





$1 + \frac{R_f}{R_1} = 1.586$

$R_f = 0.586 R_1$

Voltage gain magnitude eqⁿ for 2nd order HPF can be given as

$$\left|\frac{V_o}{V_{in}}\right| = \frac{A_f}{\sqrt{1 + (f_L/f)^4}}$$ where

$$f_L = \frac{1}{2\pi\sqrt{R_2 R_3 C_2 C_3}} = \frac{1}{2\pi RC} \Rightarrow$$ lower cut off frequency

$A_f = 1.586 \Rightarrow$ Passband gain for 2nd order Butterworth response

$f \rightarrow$ frequency of i/p signal.

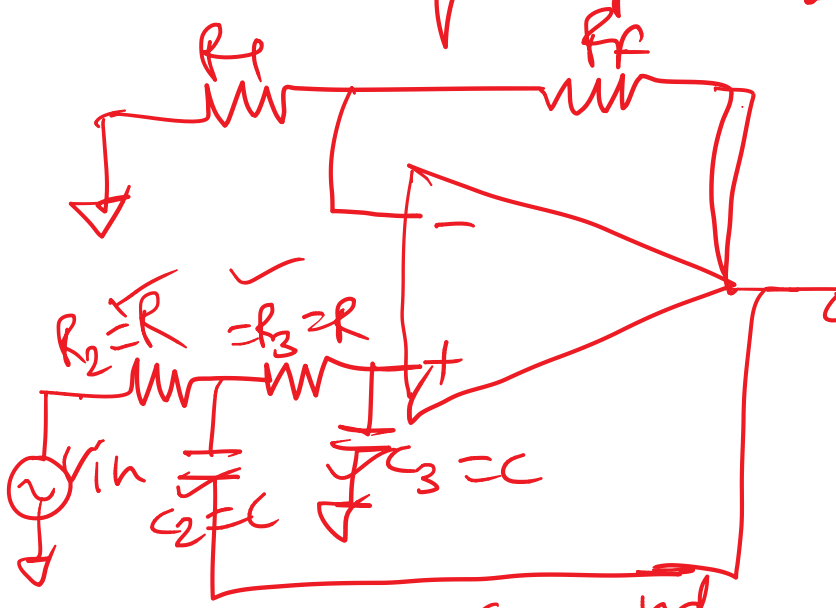
Order of filter	Gain values
1	1
2	1.59
3	1, 2
4	1.15, 2.24
5	1, 1.38, 2.38
6	1.07, 1.59, 2.48
7	1, 1.20, 1.75, 2.56
8	1.04, 1.34, 1.89, 2.61

*

Higher Order Filters:

- Higher order filters are formed simply by using 1st and 2nd order filters.
- i.e.3rd order LPF can be formed by connecting in series or cascading 1st and 2nd order LPF.
- 4th order LPF is composed of two cascaded 2nd order low pass sections.
- Although there Is no limit to order of the filter, but as order of the filter increases, so does its size. Also its accuracy declines.
- The gain values are also predecided as given in table.
- These gain values are necessary to guarantee Butteworth response and must remain the same regardless of filter's cut off frequency.
- Furthermore the overall gain of the filter is equal to product of individual voltage gain of filter sections.
- Thus overgain of 3rd order filter is 2, and that of 4th order filter is (1.152*2.235=2.57)
- Since the frequency determining componets are equal, the higher cut off freuquency of 3rd and 4th order LPF are fH=1/2*Pi*R*C

*Design a second order low pass filter at a high cut off frequency of 1 kHz.



$f_H = 1\,kHz$ ✓

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

let $C = 0.01\,\mu F$

$R = 15.9\,k\Omega$

for 2nd order filter, passband gain A_f is 1.586. ✓

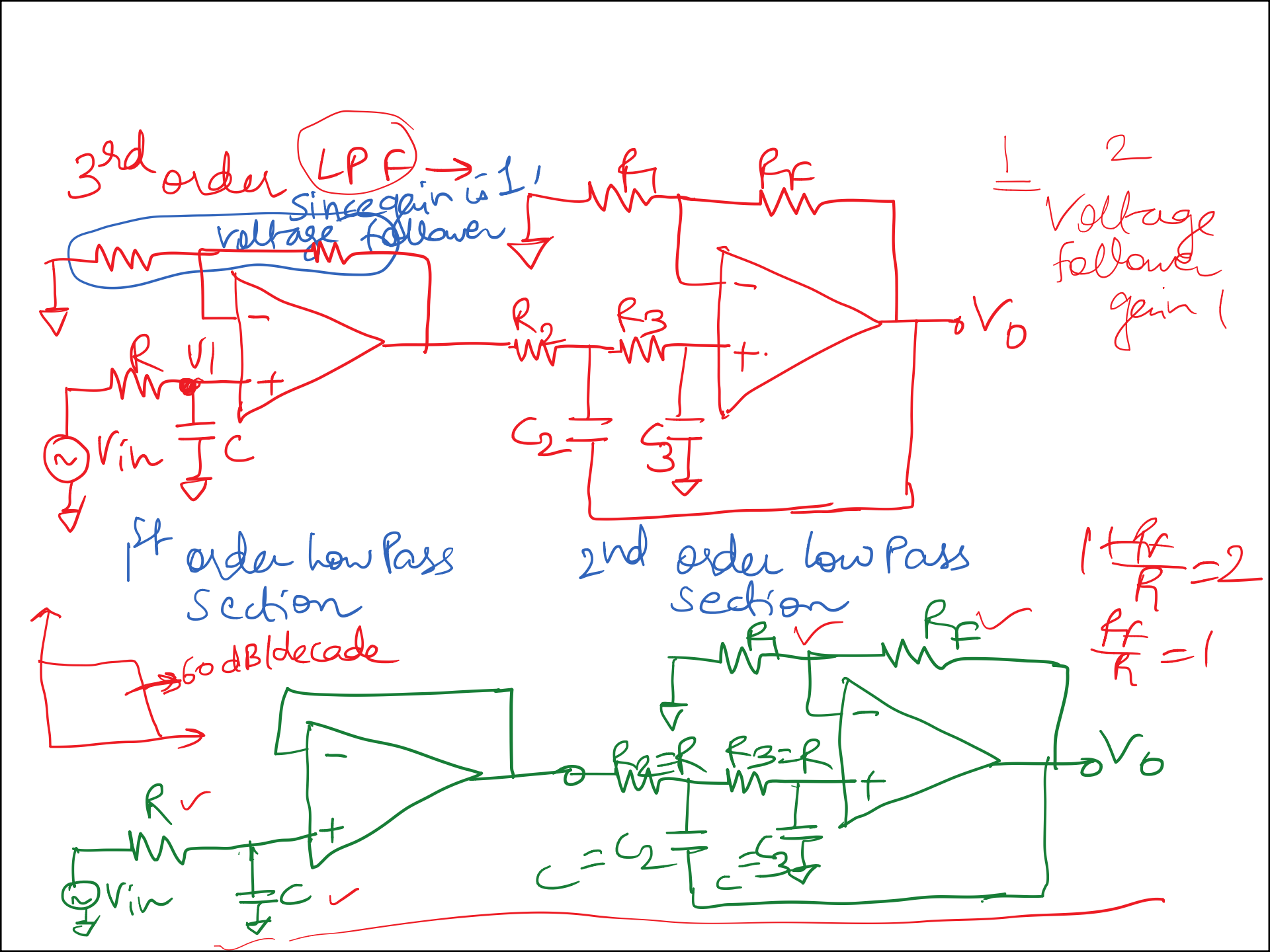
$\therefore 1 + \frac{R_f}{R_1} = 1.586$

$\frac{R_f}{R_1} = 0.586$

$R_f = 0.586 R_1$

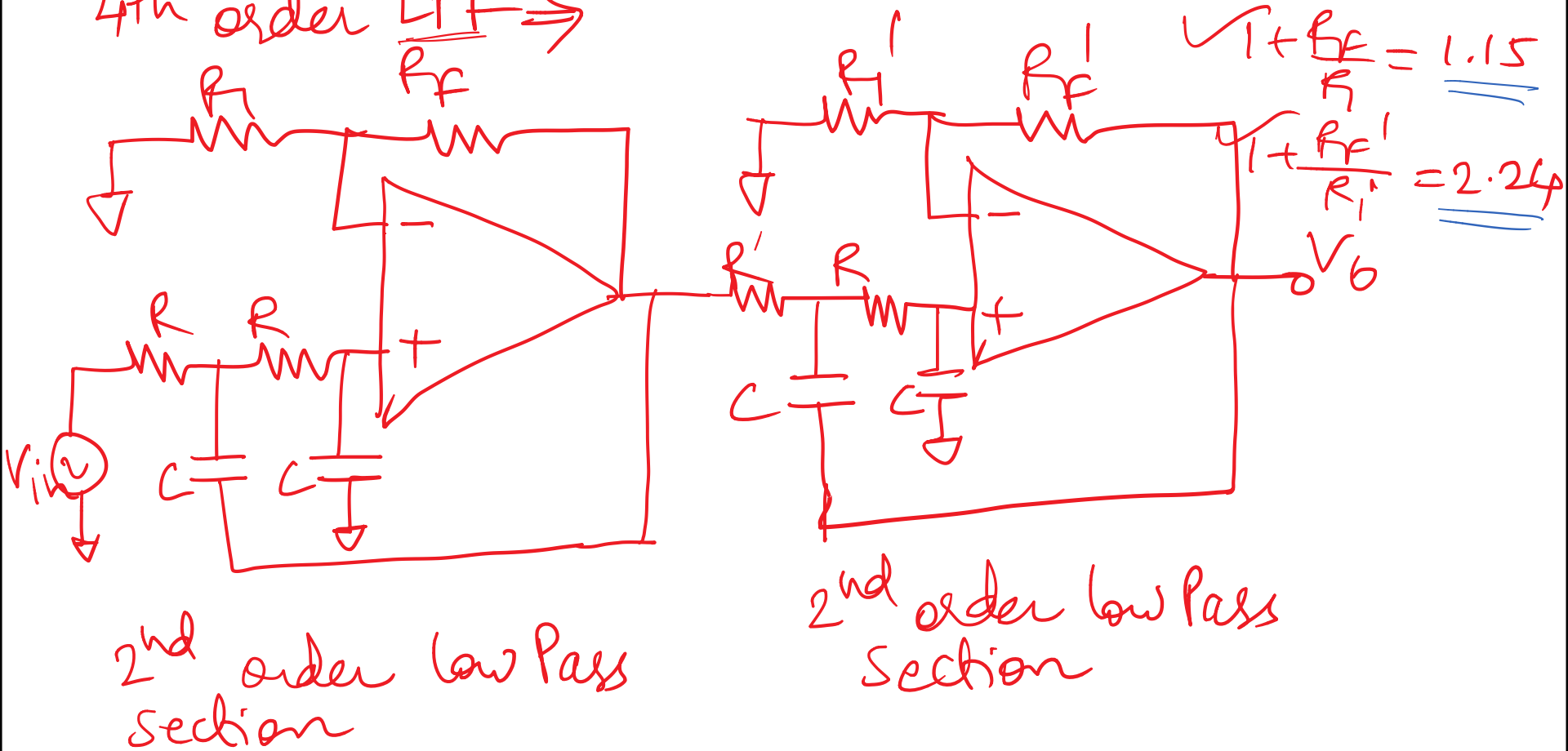
let $R_1 = 10\,k\Omega$,

$R_f = 5.86\,k\Omega$.


3rd order LPF → 1
Since gain is 1
voltage follower
R
V1
C
Vin
Rf
Rf
R2
R3
C2
C3
Vo
1
2
Voltage follower gain 1
1st order low Pass Section
60 dB/decade
2nd order low Pass section
R
C
Vin
R2=R
R3=R
C=C2
C=C3
Vo
1 + Rf/R = 2
Rf/R = 1

HPF

4th order LPF ⇒



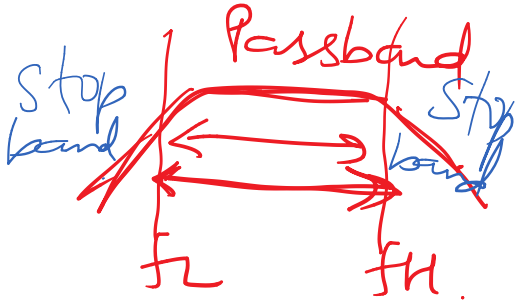
2nd order low Pass section

2nd order low Pass section

1 pass band, 2 stopbands.

Band Pass filter →

It has a passband between two cut off frequencies, f_H & f_L such that $f_H > f_L$. Any input frequency outside this band is attenuated.



Two types of Band Pass filters –

1) Wide Band Pass
2) Narrow Band Pass

But there is no set dividing line between two.

However a filter is defined as wide band pass if its figure of merit or quality factor $Q < 10$.

On the other hand if $Q \geq 10$, it is called Narrow Band Pass filter.

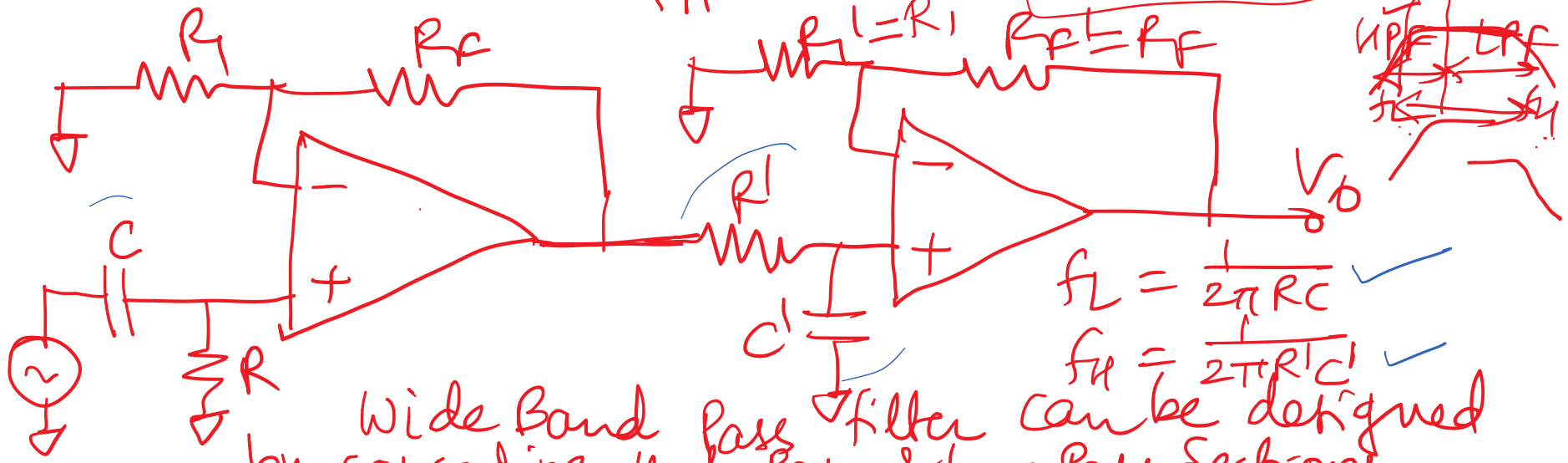


Thus Q is measure of selectivity. Higher the value of Q, more selective is the filter or narrower its bandwidth.

$$Q = \frac{f_c}{BW} = \frac{f_c}{f_H - f_L}, \quad (f_H - f_L)$$

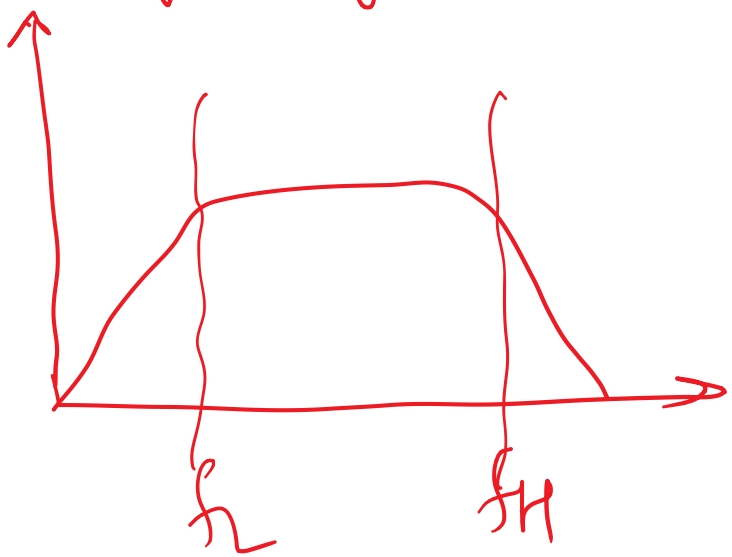
$f_c \rightarrow$ center frequency

$$f_c = \sqrt{f_H \cdot f_L}$$



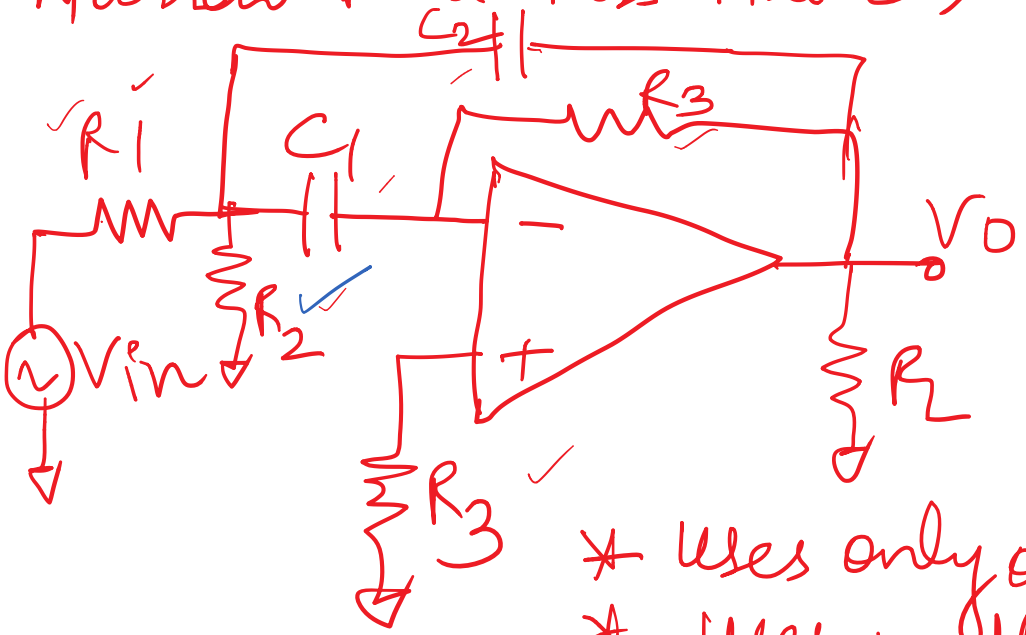
Wide Band Pass filter can be designed by cascading High Pass & low Pass Sections.

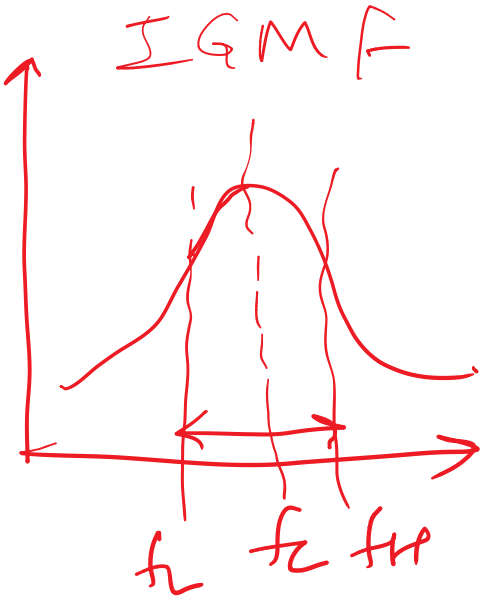
The order of Band pass filter depends on order of high pass & low pass sections.



[High pass & low pass sections must have same order]

Narrow Band Pass Filter





* Uses only one op amp
* Uses multiple feedback - since it has two feedback paths,
* Op amp in inverting mode.

So IGMF → Inverting gain multiple feedback

f_c, f_H, f_L

$$R_1 = \frac{Q}{2\pi \cdot f_c \cdot C \cdot A_f}$$

$$R_2 = \frac{Q}{2\pi f_c \cdot C(2Q^2 - A_f)}$$

$$R_3 = \frac{Q}{\pi . f_c . C}$$

To simplify the design calculations, choose

$$C_1 = C_2 = C.$$

where A_f is the gain at f_c & is given by

$$A_f = \frac{R_3}{2R_1}$$



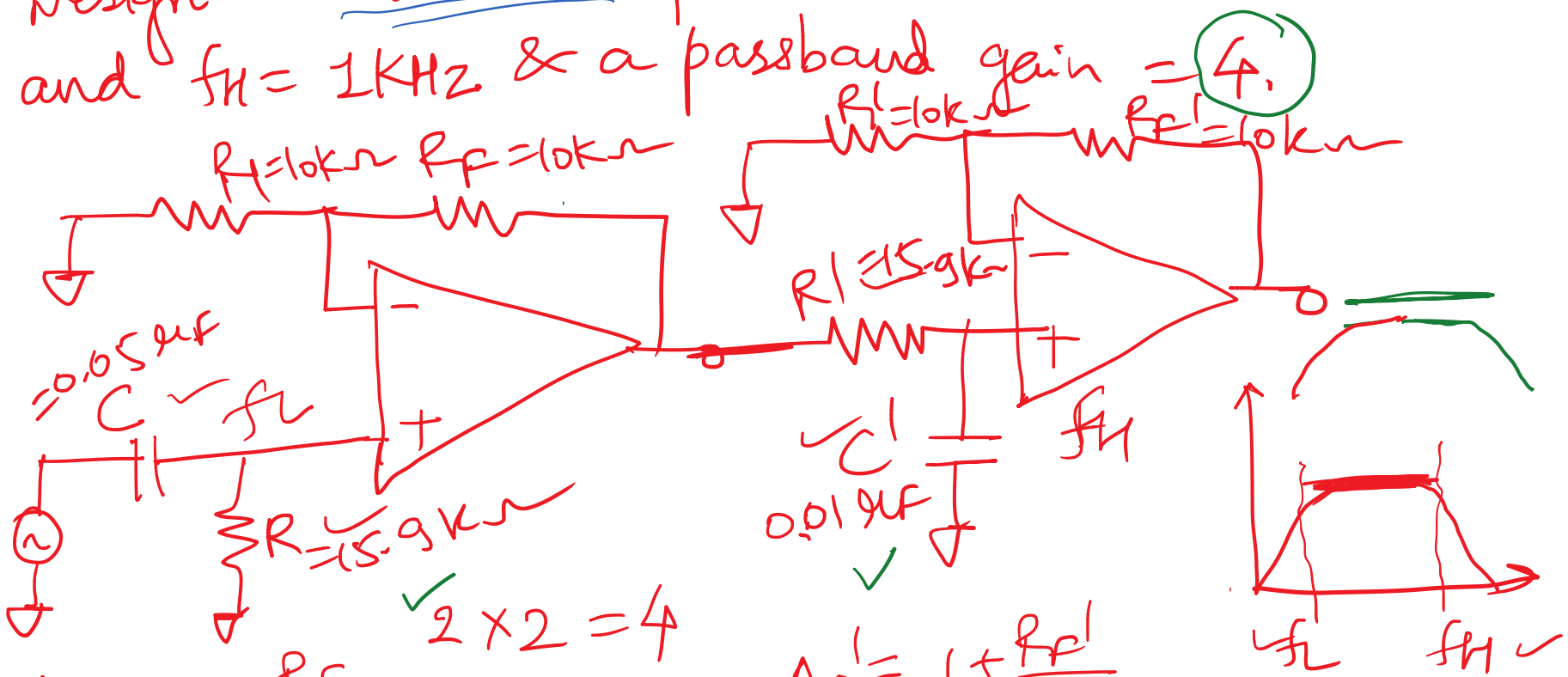
$$R_2' = R_2 \left[\frac{f_c}{f_{c1}}\right]^2$$

f_c → original freq

f_{c1} → new freq

R_2' → new value of R_2 if centre frequency f_c is to be changed.

Design a wide band pass filter with $f_L = 200\,Hz$ and $f_H = 1\,KHz$ & a passband gain = 4.



$2 \times 2 = 4$ ✓

$A_F = 1 + \frac{R_F}{R_1} = 2$

$A_F' = 1 + \frac{R_F'}{R_1}$

$= 2$

$\therefore R_F = R_1 = R_F' = R_1' = 10\,k\Omega$

$f_L = 200\,Hz \quad f_L = \frac{1}{2\pi R C} = 200\,Hz$

Let $C = 0.05\mu F$

$\therefore R = 15.9\,k\Omega$ ✓

$f_H = 1\,kHz$ $\quad f_H = \frac{1}{2\pi R'C'}$

Let $C' = 0.01\,\mu F$

$R' = 15.9\,k\Omega$

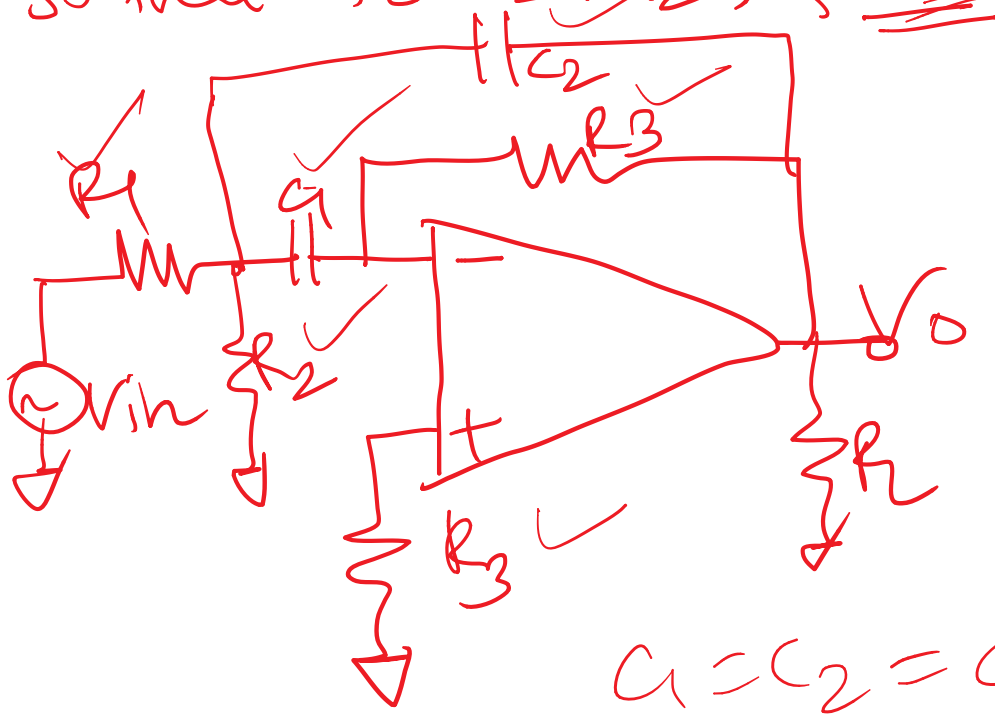
Calculate value of Q for the filter.

$$Q = \frac{f_c}{B.W.} = \frac{f_c}{(f_H - f_L)} = \frac{\sqrt{f_H \cdot f_L}}{(f_H - f_L)} = \frac{447.2}{800}$$

$$Q = 0.56$$

$Q < 10$

Design the bandpass filter as shown in figure so that $f_c = 1\ KHz$, $Q = 3$ & $A_f = 10$.



$$R_1 = \frac{Q}{2\pi f_c . C . A_f}$$

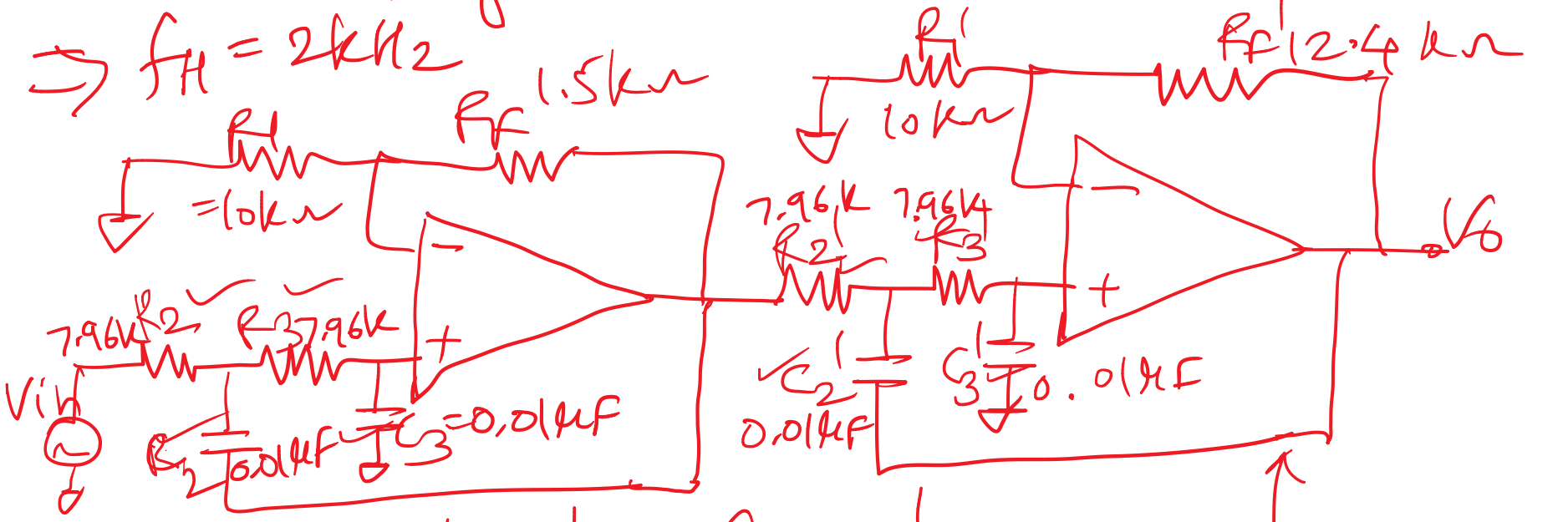
$$R_2 = \frac{Q}{2\pi f_c . C (2Q^2 - A_f)}$$

$$R_3 = \frac{Q}{\pi . f_c . C}$$

$$C_1 = C_2 = C = 0.05\ \mu F$$

Design 4th order Butterworth low pass filter for an upper cut off frequency of 2 kHz. The Butterworth polynomial is $(s^2+0.765s+1)(s^2+1.848s+1)$

$\Rightarrow f_H = 2kHz$



$R_2 = R_3 = R_2' = R_3' = R$

$C_2 = C_3 = C_2' = C_3' = C$

$f_H = \frac{1}{2\pi RC}$.

Let $C = 0.01\mu F$

$$R = \frac{1}{2\pi \times 2 \times 10^3 \times 0.01 \times 10^{-6}}$$

$$R = 7.961 \times 10^3 = 7.96 k\Omega$$

$A_f = 1.15$ ✓

for 1st section

$$A_f = 1 + \frac{R_f}{R_1}$$

$$1.15 = 1 + \frac{R_f}{R_1}$$

$$\frac{R_f}{R_1} = 0.15$$

let $R_1 = 10\,k\Omega$ ✓

$$R_f = 0.15 \times 10 \times 10^3$$ ✓

$$R_f = 1.5\,k\Omega$$

$A_f' = 2.24$ ✓

for 2nd section

$$A_f' = 1 + \frac{R_f'}{R_1'}$$

$$2.24 = 1 + \frac{R_f'}{R_1'}$$

$$\frac{R_f'}{R_1'} = 1.24$$

let $R_1' = 10\,k\Omega$ ✓

$$R_f' = 1.24 \times 10 \times 10^3$$ ✓

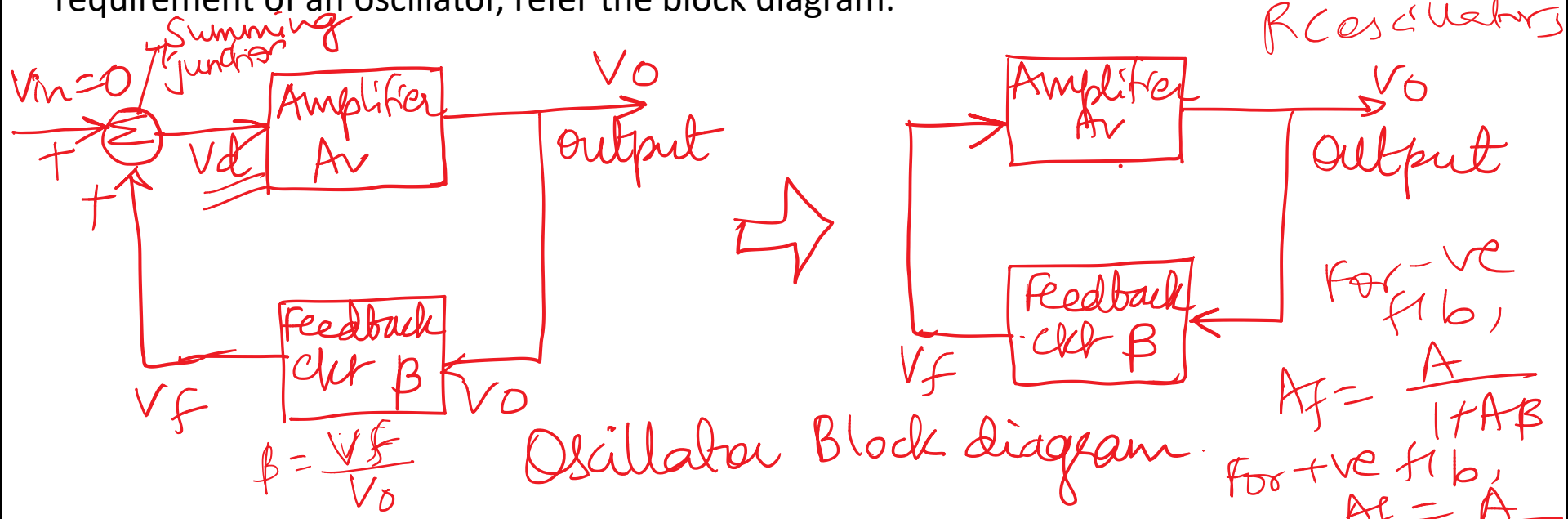
$$R_f' = 12.40\,k\Omega$$

Oscillators

- The function of oscillator is to generate alternating voltage or current waveforms.
- A circuit that generates a repetitive waveform of fixed amplitude and frequency without any external input signal.
- Used in radio, television,computers, and communications.
- Although there are different types of oscillators , they all work on the same basic principle.

Oscillator Principle

An oscillator is a type of feedback amplifier in which part of the output is fed back to the input via a feedback circuit. If the signal fed back is of proper magnitude and phase, the circuit produces alternating currents or voltages. To visualise the requirement of an oscillator, refer the block diagram.



Oscillator Block diagram.

Here we can observe, input voltage is zero. Also the feedback is positive because most oscillators use positive feedback. The closed loop gain of the amplifier is denoted by Av.

Vd=vin+vf

Vo=Av.Vid

Vf=βvo

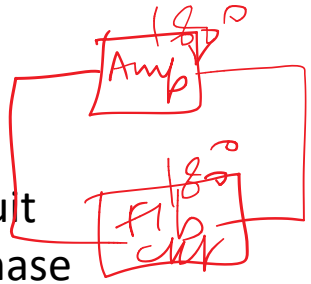
Using these relationships, eq^n can be obtained as $\frac{Vo}{Vin} = \frac{Av}{1 - Av\beta}$

The two requirements for oscillations are: (Barkhausen Criteria)

1)The magnitude of the loop gain Av.β must be at least 1.

2)The total phase shift of the loop gain Av.β must be equal to 0^0 or 360^0

i.e.if the amplifier causes a phase shift of 180 degrees, the feedback circuit must provide an additional phase shift of 180 degrees so that the total phase shift around the loop is 360 degrees



The type of waveform generated by an oscillator depends on the components in the circuit and hence may be sinusoidal, square or triangular. In addition, the frequency of oscillation is determined by the components in the feedback circuit.

The ability of the oscillator circuit to oscillate at one exact frequency is called frequency stability.

Temperature and power supply changes cause variations in the op amp's gain and frequency.

Types of Components used	**Frequency of Oscillation**	**Types of waveform generated**
RC Oscillator	Audio frequency (AF)	Sinusoidal
LC Oscillator	Radio frequency (RF)	Square Wave
Crystal Oscillator		Triangular Wave
		Sawtooth Wave etc.

- Another important factor that determines frequency stability is the figure of merit Q of the circuit. Higher the Q, greater is the stability.
- So Crystal Oscillators are more stable than RC or LC Oscillators, especially at high frequencies.
- LC Circuits and Crystals are generally used for generation of high frequency signals. While RC components are most suitable for audio frequency applications.

audio freq ampli.

radio freq



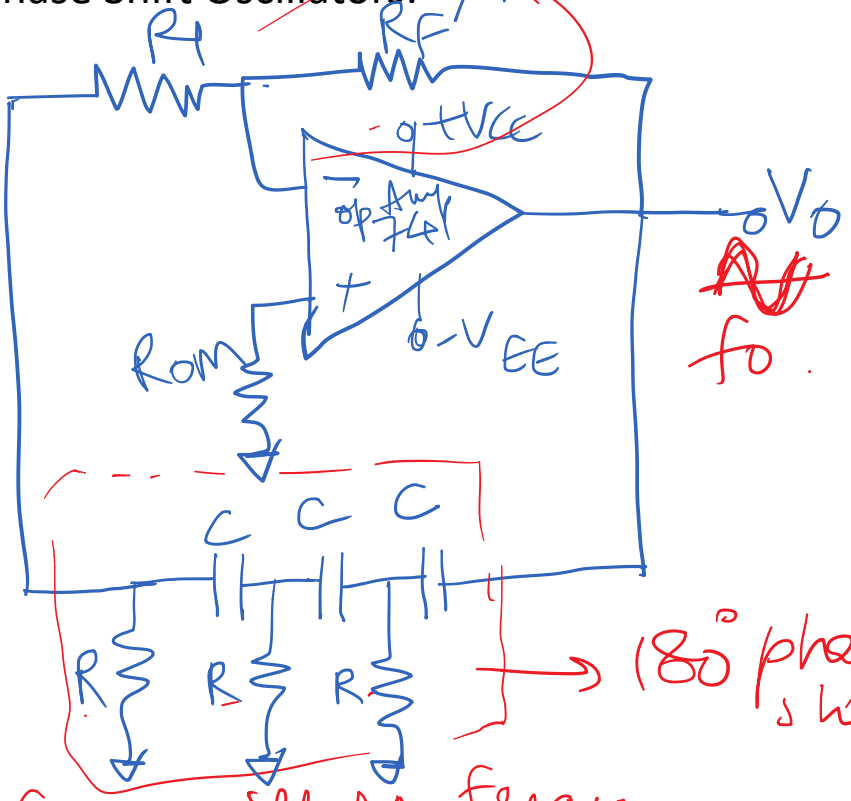
Conditions for oscillation - [Barkhausen Criteria]

1) $A\beta \geq 1$, $A\beta \rightarrow$ loop gain

2) Total phase shift in the circuit must be 0° or 360°.

Phase Shift Oscillators:

RC Phase shift oscillator



It consists of an op amp as amplifying stage and three RC cascaded networks as the feedback circuit. The feedback circuit provides feedback voltage from the output back to the input of the amplifier. The op amp is used in the inverting mode, therefore any signal that appears at the inverting terminal is shifted by 180 degrees at the output. An additional 180 degrees phase shift required for oscillation is provided by cascaded RC networks. Thus total phase shift around the loop is 360 degrees (or zero degree). At some specific frequency when the phase shift of cascaded RC networks is exactly 180 degrees and the gain of the amplifier is sufficiently large, the circuit will oscillate at that frequency.

fo → oscillating frequency

$$f_o = \frac{1}{2\pi\sqrt{6}RC} = \frac{0.065}{RC}$$

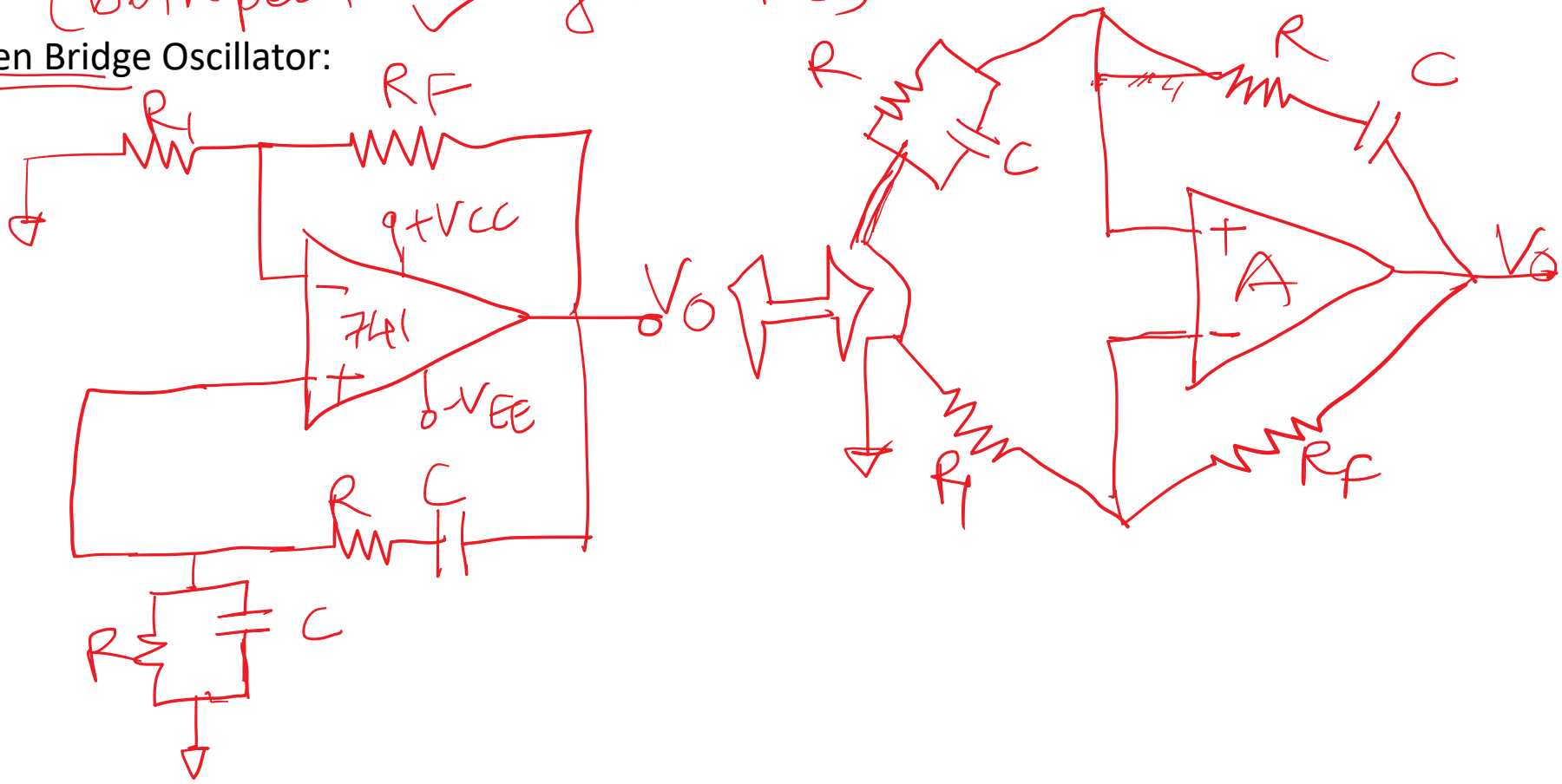
At this frequency, the gain Av must be at least 29.

i.e. $\left|\frac{R_F}{R_1}\right| = 29$ i.e $R_F = 29R_1$

& $R_1 = 10R$

(both positive & negative fib)

Wien Bridge Oscillator:



It is one of the most commonly used audio frequency oscillator. Wien Bridge circuit is connected between the amplifier input terminals and output terminal. The bridge has a series RC network I one arm and a parallel RC network in the adjoining arm. In the remaining two arms of the bridge, resistors R1 and Rf are connected.

$f_o \rightarrow$ resonant freq

The phase angle criteria for oscillation is that the total phase shift around the circuit must be 0 degree. This condition occurs only when the bridge is balanced that is at resonance. The frequency of oscillation fo is exactly the resonant frequency of the balanced bridge and is given as

$f_o \rightarrow$ oscillating frequency $= \frac{1}{2\pi RC} = \frac{0.159}{RC}$

assuming that the resistors are equal in value and capacitors are equal in value in reactive leg of the Wien Bridge.

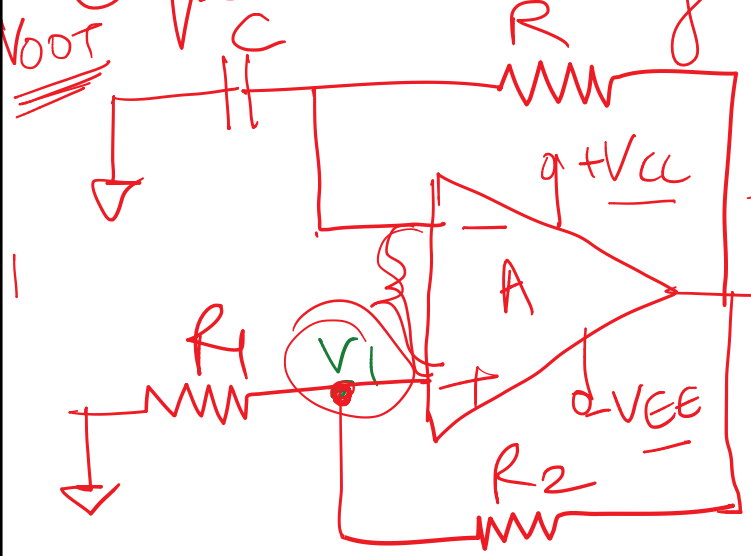
At this frequency, the gain required for sustained oscillation is

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

$$1 + \frac{R_F}{R_1} = 3 \quad , \quad \frac{R_F}{R_1} = 2, \quad R_F = 2R_1$$

Here, Op amp is forced to operate in saturated region. i.e. o/p of op. amp swings repetitively betⁿ positive saturation & negative saturation ($\pm V_{sat}$) resulting in square wave o/p. Also called as Free running or Astable multivibrator.

Square Wave Generator (using op. amp) →



Initially, assume voltage across C → zero at instant when +Vcc & -VEE are applied. So voltage at inverting terminal is zero initially. But voltage at noninverting terminal is a small finite value that is fⁿ of output offset voltage V_{OOT} so V_{id} equal to V_1

Though V_1 is very small → drives op amp to saturation. If V_{OOT} → +ve, V_1 → +ve, O/P → +Vsat. So C starts charging towards +Vsat through R. As soon as, voltage across C is slightly greater than V_1, O/P switches to -Vsat.

$$V_1 = \frac{R_1}{R_1+R_2}(-V_{sat})$$

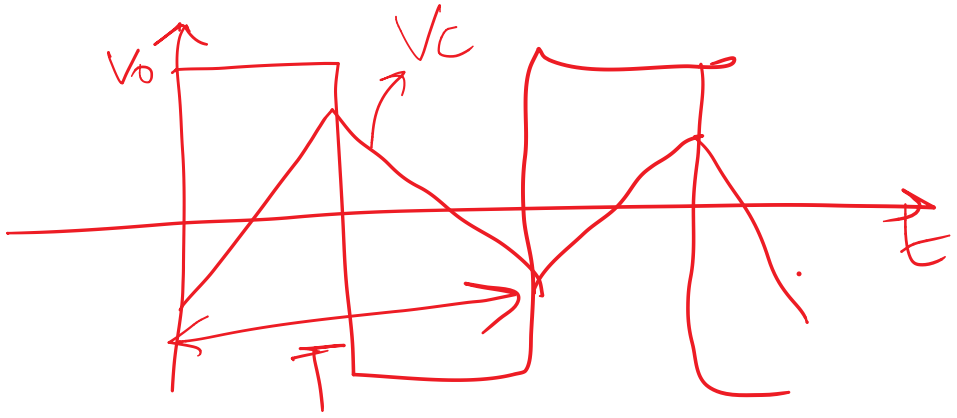
O/P remains -Vsat until C discharges & cycle repeats.

$$T = 2RC \ln\left(\frac{2R_1 + R_2}{R_2}\right)$$

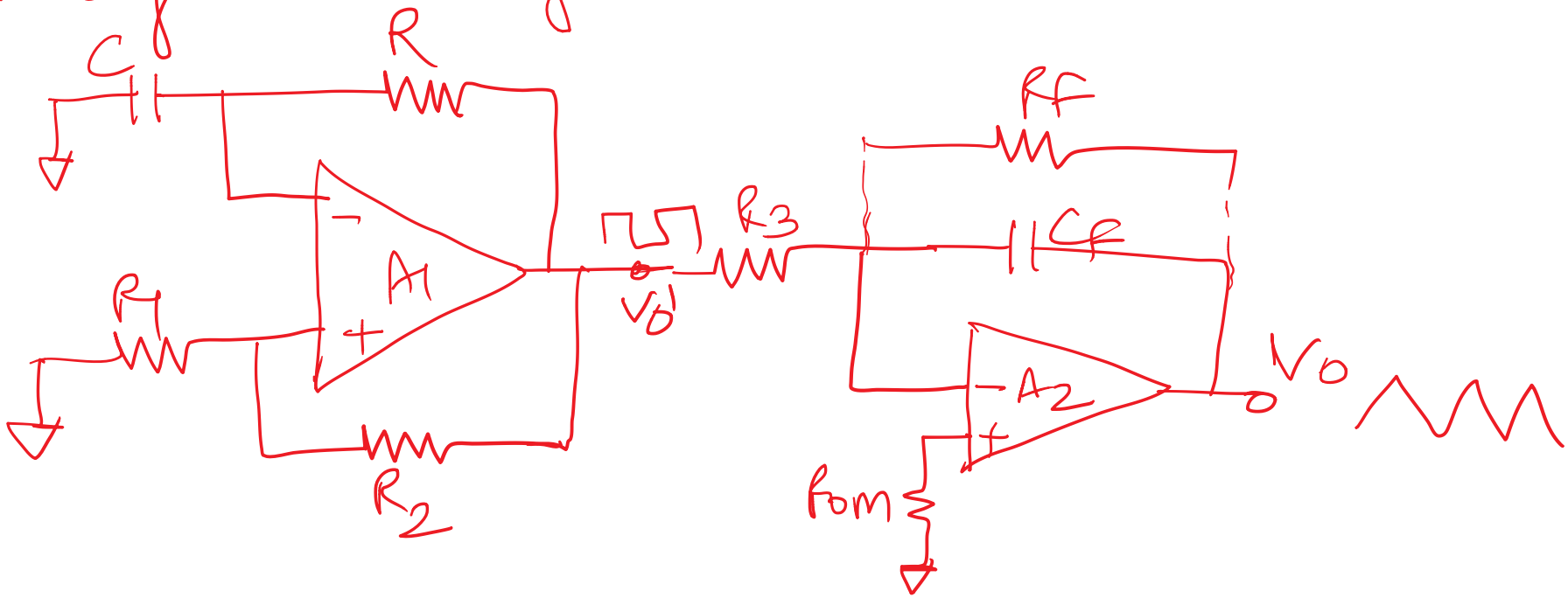
$$f_0 = \frac{1}{2RC \ln\left[(2R_1 + R_2)/R_2\right]}$$

$$f_0 = \frac{1}{2RC}$$

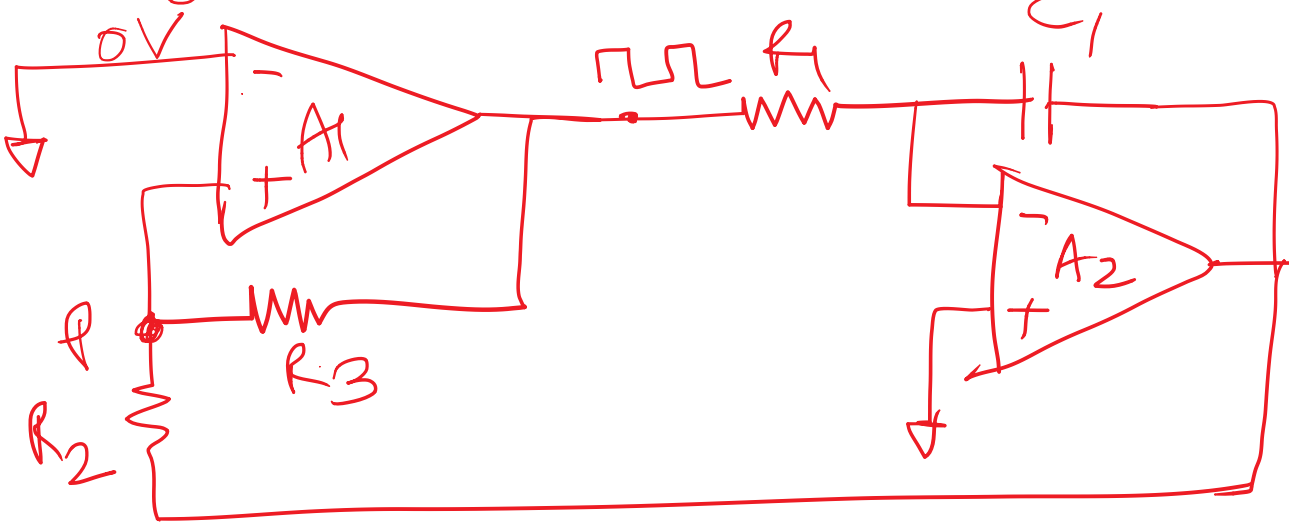
$$R_2 \cong 1.16 R_1$$

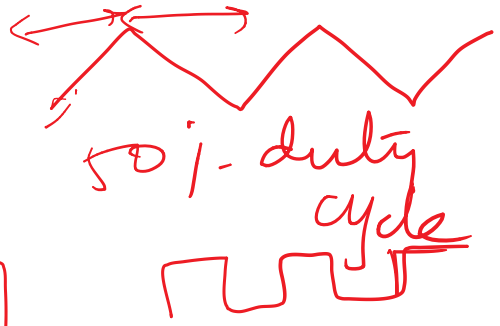


Triangular Wave Generator -



Triangular Wave Generator →







$f_0 =$

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

Let $C = 0.1\ \mu F$

$R =$ ____.

$R_1 = ?$ $R_f = ?$

$R_1 \cong 10R =$ $\left|\frac{R_F}{R_1}\right| = 29$

$f_0 =$

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

Let $C = 0.05\ \mu F$

$R =$.

$\frac{R_F}{R_1} = 2$

Let $R_1 =$

$R_f = 2R_1$