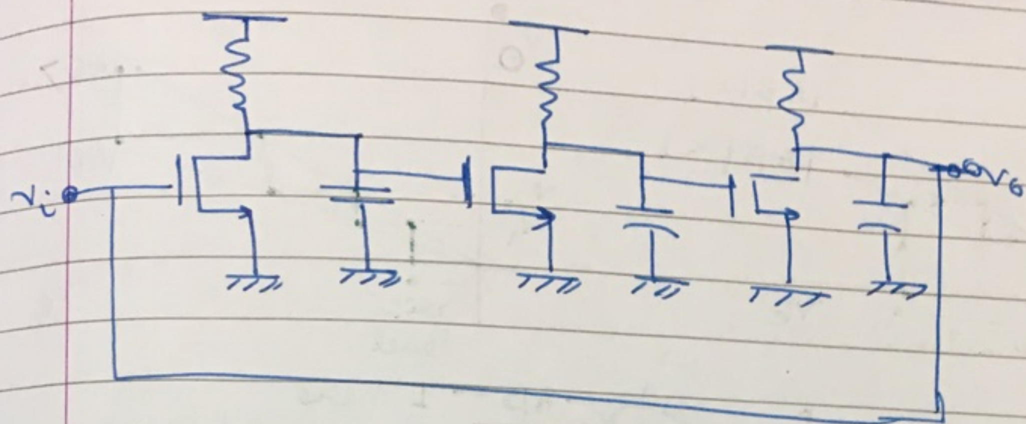
→ 3 Stage



$$A\beta = GH = \frac{v_o}{v_i} = \frac{-A^3}{(1+sRC)^3} \qquad \angle\frac{v_o}{v_i} = \pi - 3\tan^{-1}\omega RC$$

→ If we take, $\tan^{-1}\omega RC = \frac{\pi}{3}$ → Ring Oscillator

$$\tan^{-1}\omega_o RC = \frac{\pi}{3} \Rightarrow \omega_o RC = \sqrt{3}$$

{target frequency}

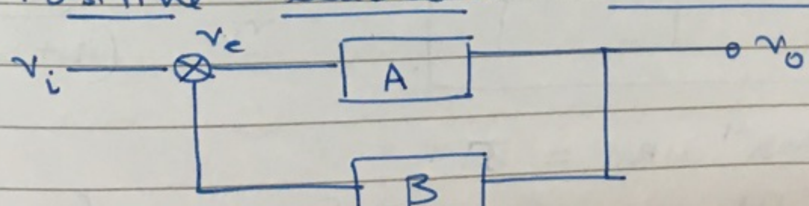
$\Rightarrow$ pick: $RC = \frac{\sqrt{3}}{\omega_o}$

$$GH = -\frac{A^3}{\left(1 + \frac{j\omega}{\omega_o}\sqrt{3}\right)^3}$$

At $\omega = \omega_o$, $\left|\frac{v_o}{v_i}\right| = \frac{A^3}{8} = 1$, $\Rightarrow \boxed{A = 2}$

12.3.18

Positive Feedback - Oscillations



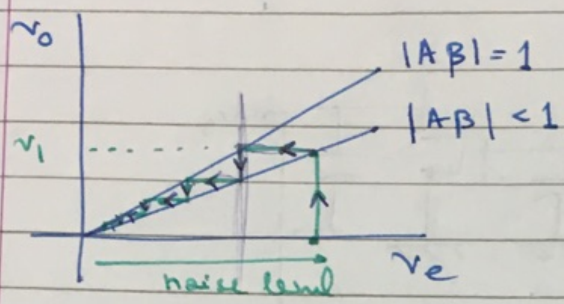
$$\frac{v_o}{v_i} = \frac{A}{1 - A\beta}$$

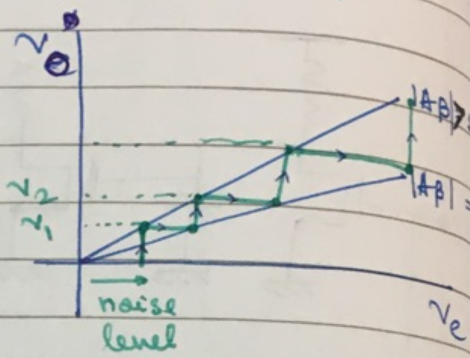
→ Criteria for oscillation,

$$|A\beta| = 1$$
$$\angle A\beta = 2n\pi$$

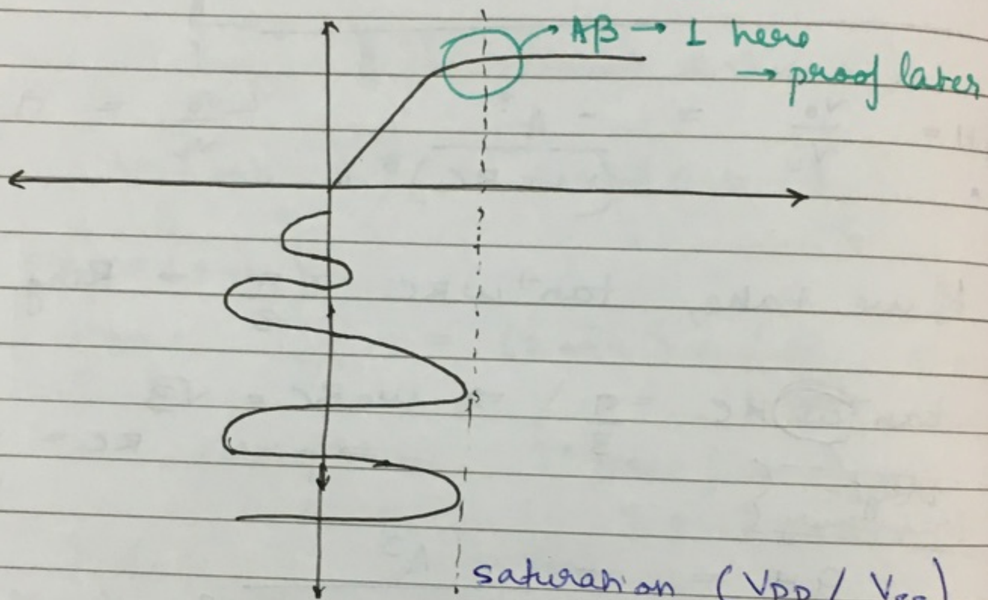
~~$v_f^t \neq v_o$ (Next v_e)~~

$A\beta \equiv$ Loop Gain, Go around the loop.



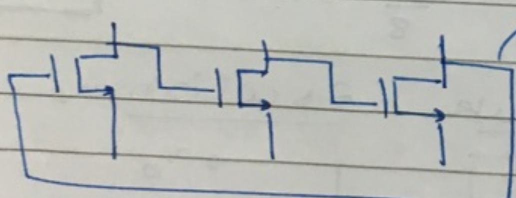


→



- Example from previous lecture. → Direct / No Mixer

here $\beta = 1$



$$\frac{v_o}{v_i} = \frac{-(g_m R_d)^3}{(1 + sRC)^3}$$

$$3 \tan^{-1} \omega RC = \pi$$

$$\Rightarrow \omega_{osc} = \frac{\sqrt{3}}{RC} = \sqrt{3}\,\omega_0 \qquad \left(\frac{1}{RC} = \omega_0\right)$$

$$\frac{v_o}{v_i} = \frac{-(g_m R_D)^3}{(1 + j\omega/\omega_0)^3}$$

$$\frac{v_o}{v_i}(\omega = \omega_{osc}) = -\frac{(g_m R_D)^3}{(1+j\sqrt{3})^3}$$

$$\left|\frac{v_o}{v_i}\right| = \frac{(g_m R_D)^3}{(\sqrt{1+3})^3} = \frac{(g_m R_D)^3}{8}$$

Hence, required cond. $\rightarrow$ $g_m R_D = 2$

$$A_f = \frac{A}{1-A\beta} \qquad A = \frac{v_o}{v_i}(OL) \boxed{= -\frac{A_o^3}{(1+sRC)^3}}$$

$$= \frac{-A_o^3/(1+sRC)^3}{1 + \frac{A_o^3}{(1+sRC)^3}}$$

this term is leading to substraction in D^r

$$= \frac{-A_o^3}{\left(1+\frac{s}{\omega_o}\right)^3 + A_o^3}$$

$$D_r = \left(1+\frac{s}{\omega_o}\right)^3 + A_o^3 = \left(1+\frac{s}{\omega_o}+A_o\right)\left(\left(1+\frac{s}{\omega_o}\right)^2 + A_o^2 - \left(1+\frac{s}{\omega_o}\right)A_o\right)$$

<u>Pole I</u>, $1+\frac{s}{\omega_o} + A_o = 0 \Rightarrow s = -\omega_o(A_o+1)$

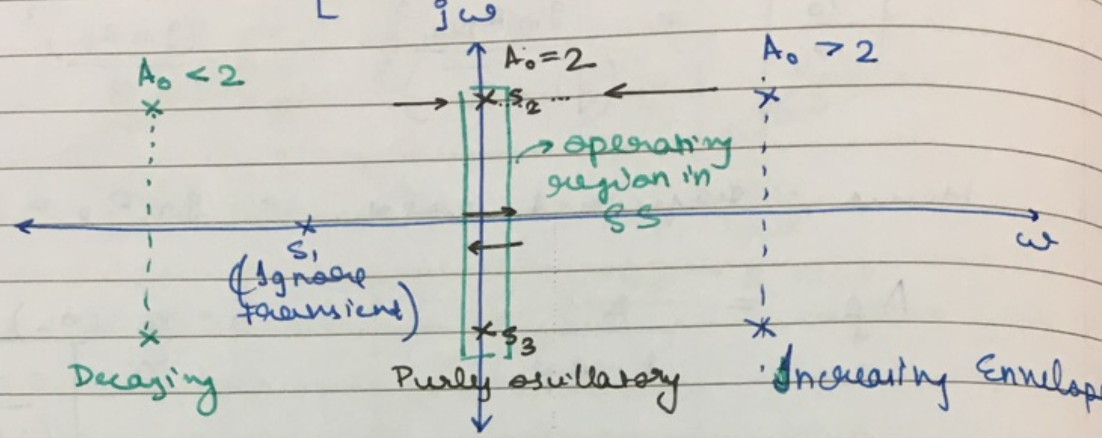
Pole <u>II/III</u> $\left(1+\frac{s}{\omega_o}\right) = \frac{A_o \pm \sqrt{A_o^2 - 4A_o^2}}{2} = \frac{A_o}{2}(1 \pm j\sqrt{3})$

$$s_{2,3} = \left[\frac{A_o}{2}(1 \pm j\sqrt{3}) - 1\right]\omega_o$$

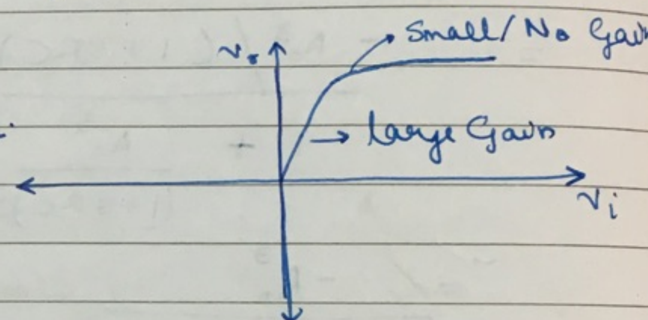
$$A_f = \frac{A}{1-A\beta} = \underbrace{\frac{k_1}{(s \pm s_1)}}_{k_1 e^{s_1 t}} + \underbrace{\frac{k_2}{(s \pm s_2)}}_{k_2 e^{s_2 t}} + \underbrace{\frac{k_3}{(s \pm s_3)}}_{k_3 e^{s_3 t}}$$

$S_1 = -\omega_0 (1 + A_0)$ → Surely Dies out

$S_{2/3} = \left[\frac{A_0}{2}(1 \pm j\sqrt{3}) - 1\right]\omega_0$



→ Large Signal Char.



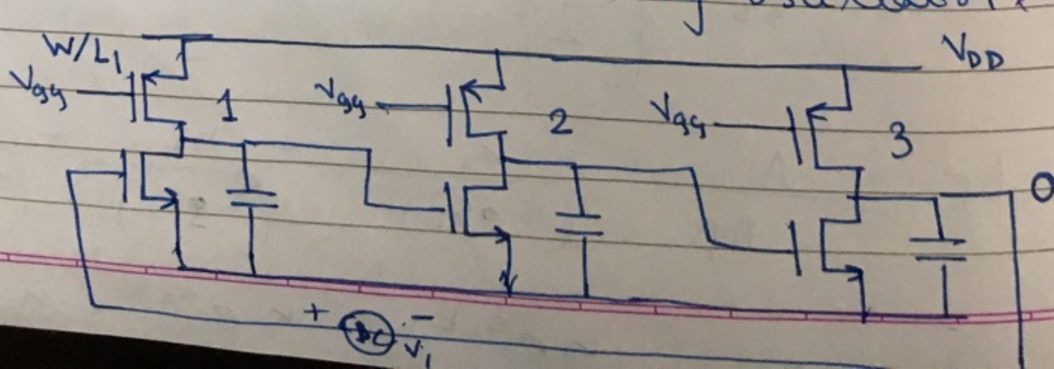
- At start if $A_0 > 2$, it Grows and $A_0 \downarrow$
  - → We overshoot $A_0 = 2$ & go into decaying region.
  - → The decaying region will push it back since A_0 will ↑ with decay.

→ At start if $|AB| > 1$, then the system adjusts itself in a way that $|AB| \rightarrow 1$

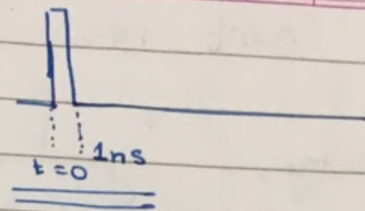
(Simulation Results)

13.3.18

Positive feedback : Ring oscillator



→ Given an input:

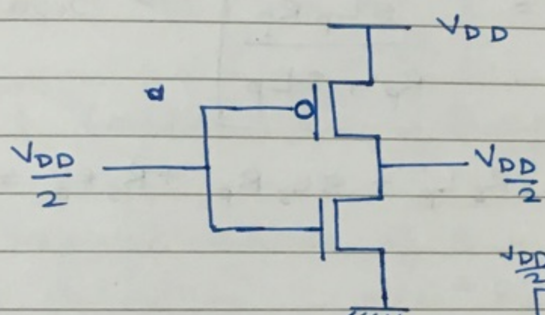


$$\omega_{osc} = \frac{\sqrt{3}}{RC}, \quad |g_m R_d| = 2$$

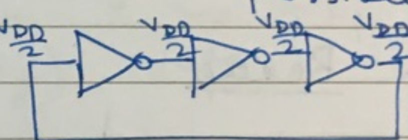
$$C = 20nF \qquad V(3)[t=0] = 5.5V$$

0 V
↓ vary & see transient

Razavi on poles in Non linear ckt
→ The poles Begin in the RHP & eventually move to imaginary axis to stop growth.
→ The Average Loop Gain is still 1
→ Meta stable conditions

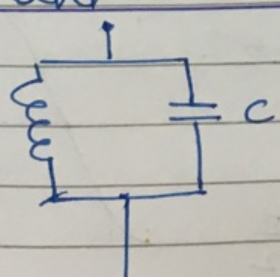


→ Theoretically possible



→ But practically cannot happen : like pencil on its tip.
some Noise like Gust of Wind

→ Imp: Why doesn't Ring oscillator (Inverter based) have ∿ output ? (Ans: Discussion with Anamika)



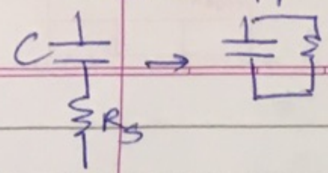
→ LC Oscillator / Tank Oscillator (Stores energy)

$$Z = \frac{\cancel{s}Ls \times \cancel{\frac{1}{sC}}}{Cs^2L + 1 \cdot \frac{1}{\cancel{sC}}}$$

$$\frac{\cancel{s}sL}{\cancel{s}1+s^2LC}$$

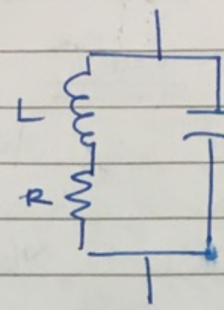
$$\frac{sL}{1+s^2LC} = \frac{1}{s^2C + \frac{1}{L}} = \boxed{\frac{sL}{1+s^2LC}}$$

Same Approximations are valid for RC Network

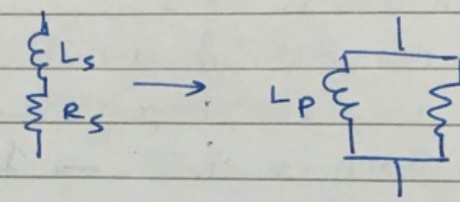


conversion where Q of series comb. is $R_s/(C\omega)$

→ In reality,



→ Convert:



for conversion

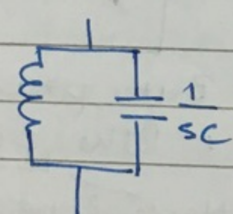
$$\boxed{sL_s + R_s = \frac{sL_pR_p}{R_p + sL_p}}$$

→ Series ↔ Parallel conversion

$$\Rightarrow \quad s^2L_pL_s + sR_sL_p + sL_sR_p + R_sR_p = sL_pR_p$$

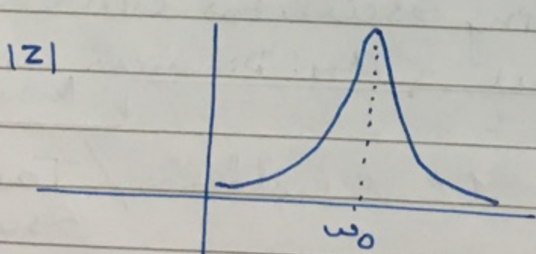
15.3.18

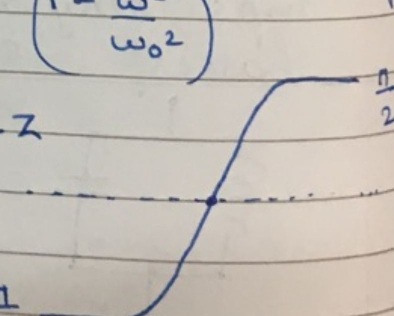
Recap



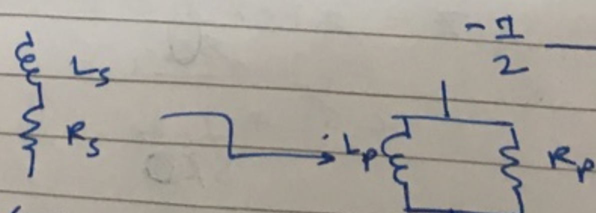
$$Z = \frac{Ls\frac{1}{sC}}{Ls + \frac{1}{sC}} = \frac{Ls}{s^2LC+1}$$

$$= \frac{j\omega L}{\left(1 - \frac{\omega^2}{\omega_0^2}\right)} \qquad \omega_0 = \frac{1}{\sqrt{LC}}$$



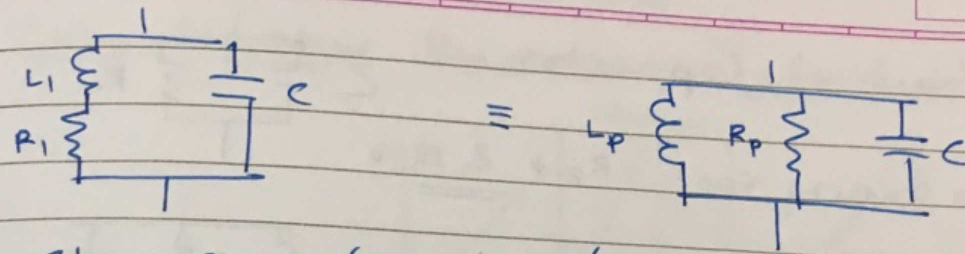


→ Convert :



Why?: Calc./Analysis easier.

~~Note~~



$\omega_0 = \dfrac{1}{\sqrt{CL_p}}$

$Z(\omega_0) = R_p$

$$sL_1 + R_1 = (sL_pR_p)/(R_p + sL_p)$$

$$\Rightarrow \quad s^2L_1L_p + sR_1L_p + sL_1R_p + R_1R_p = sL_pR_p$$

$$s = j\omega$$

$$\Rightarrow \quad \left.\begin{aligned} -\omega^2 L_1L_p + R_1R_p &= 0 \\ \& \quad R_1L_p + L_1R_p &= L_pR_p \end{aligned}\right\} \text{Solve.}$$

$$L_p = L_1\left[1 + \frac{R_1^2}{\omega^2 L_1^2}\right] = L_1\left[1 + \frac{1}{Q^2}\right]$$

→ Quality factor (Q) $\boxed{Q = \left(\dfrac{\omega L_1}{R_1}\right)}$ (typically = 3 − 4 near resonance)

Quality of Inductor, Different from Quality factor

- For typical values of R_1, L_1 → $L_p \approx L_1$

$$R_p \approx \frac{\omega^2 L_1^2}{R_1} = (Q^2 R_1) \qquad (Q^2R_1)$$

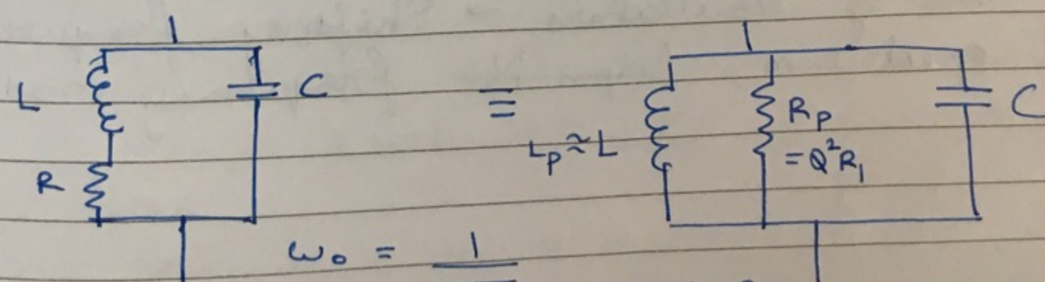
Solving,

$$\cancel{R_1 = \left(\frac{L_pR_p - L_1R_p}{L_p}\right)}$$

$$\cancel{-\omega^2 L_1L_p + \frac{R_p}{L_p}(L_pR_p - L_1R_p) = 0}$$

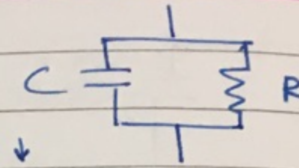
$$\cancel{R_p = \frac{\omega^2 L_1 L_p^2}{R_p}}$$

→ Approximate Eqvt Ckt.



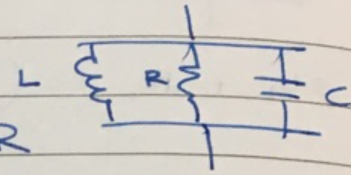
$\omega_0 = \dfrac{1}{\sqrt{CL_p}}$ $\quad Z(\omega_0) = R_p$

→ Practical Capacitor

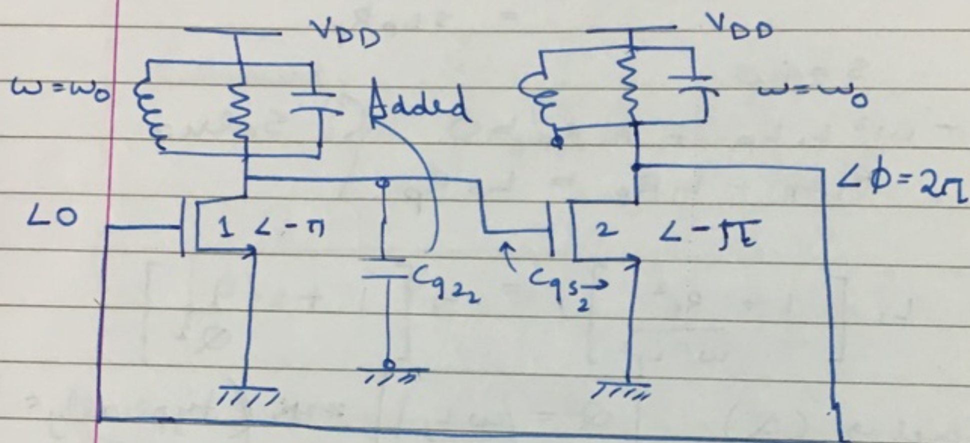


Poor Quality Cap: $R_p \downarrow$ & $Q \downarrow$

→ General RCL Network:



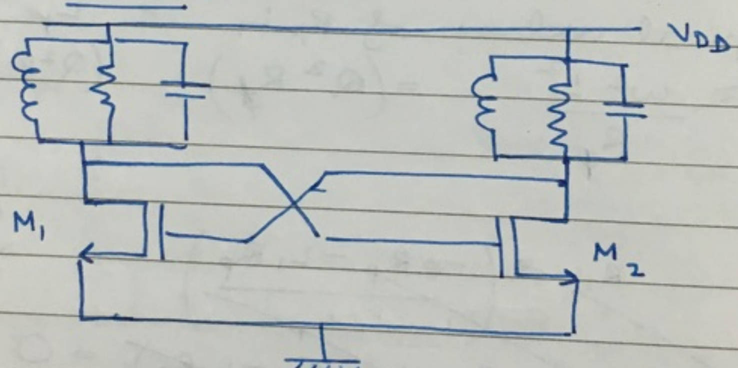
$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad Z(\omega = \omega_0) = R$$



$|(-g_{m_1}R_1)(-g_{m_2}R_2)| \geq 1$ → oscillation condition

$$\boxed{g_m \geq \frac{1}{R}}$$

- Bistable Network



18.3.18

- Advantages

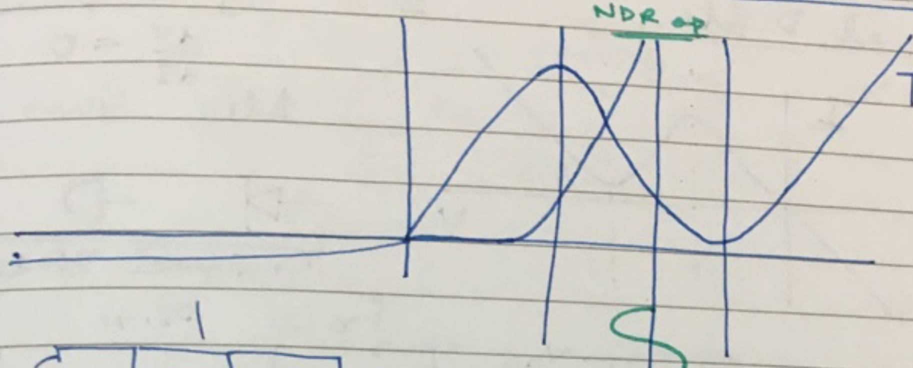
→ Can Achieve oscillation in 2 stages (Just 2x

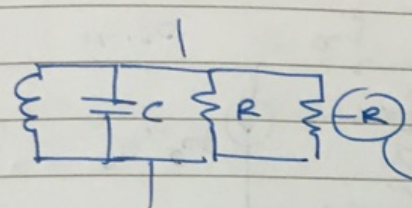
→ High o/p swing possible ⇒ High power application

→ Use of Oscillators → Shifting frequency spectrum, ~~Amp. M.~~ frequency modulation

→ Using Negative Resistance – Tunnel Diode

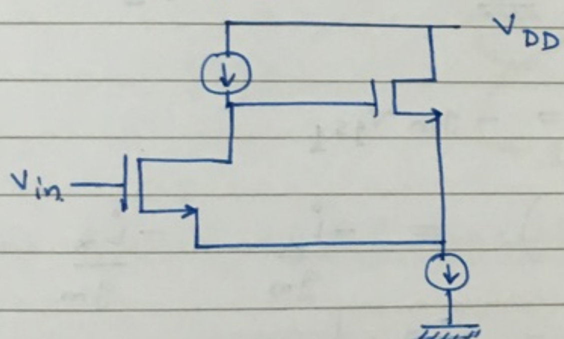
–ve AC / Differential Resistance (NDR)





Ideal Tank / L–C

→ Another configuration



18.3.18

→ Negative F.B Examples (Self Notes)

h parameters (Series – Shunt F.B)

$$V_1 = h_{11} I_1 + h_{12} V_2$$
$$I_2 = h_{21} I_1 + h_{22} V_2$$

z parameters.

$$V_1 = z_{11} I_1 + z_{12} I_2$$
$$V_2 = z_{21} I_1 + z_{22} I_2$$

Y para.

$$I_1 = y_{11} V_1 + y_{12} V_2$$
$$I_2 = y_{21} V_1 + y_{22} V_2$$

g para.

$$I_1 = g_{11} V_1 + g_{12} I_2$$
$$V_2 = g_{21} V_1 + g_{22} I_2$$

19.3.18

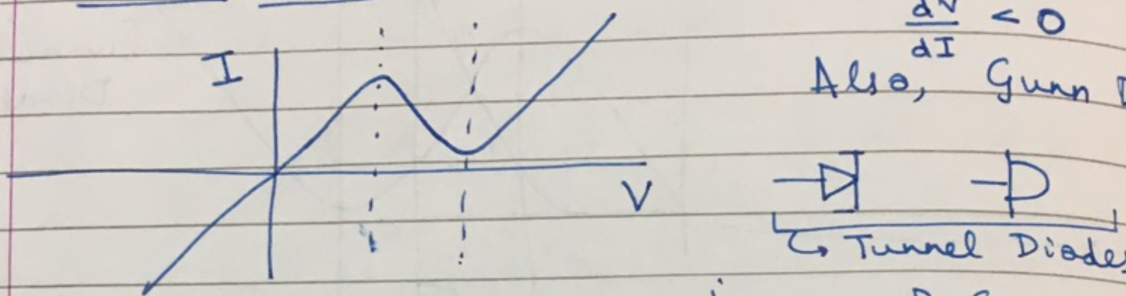
Negative Differential Resistors

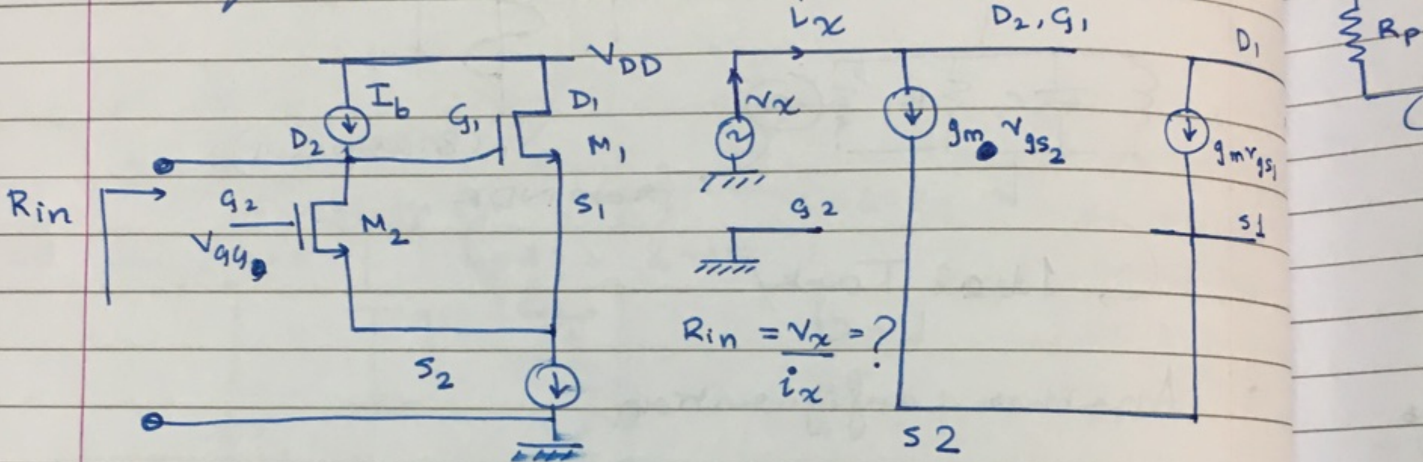
Tunnel Diode

$\frac{V}{I} > 0$, can't generate power.

$\frac{dV}{dI} < 0$

Also, Gunn Diode





$R_{in} = \frac{v_x}{i_x} = ?$

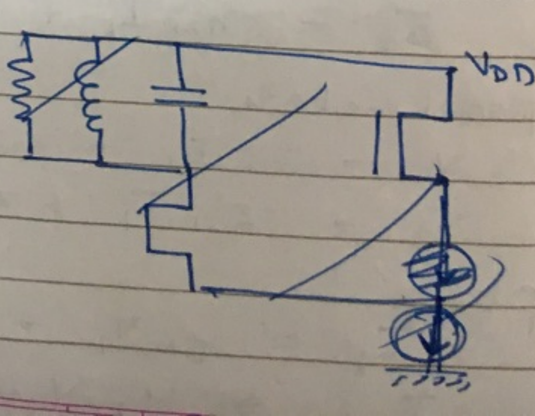
$$i_x = g_m v_{gs_2} = -g_m v_{gs_1}$$

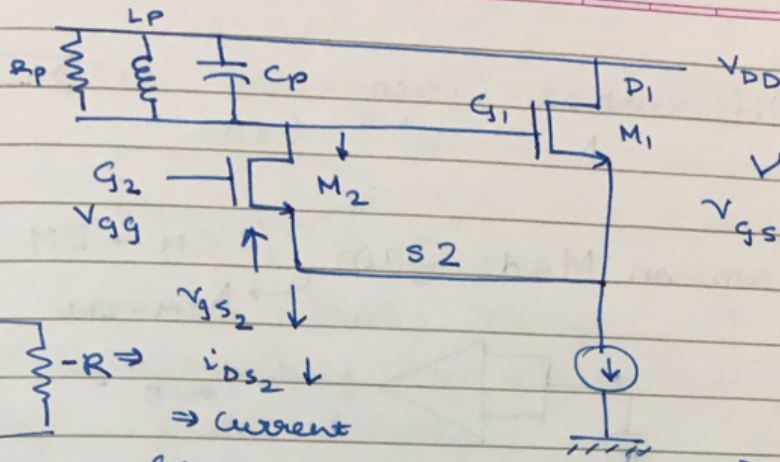
$$v_x = (v_{g_1} - v_{s_1}) = \frac{-i_x}{g_m} \quad \frac{-i_x}{g_m}$$

$$\Rightarrow \boxed{R_{in} = \frac{-2}{g_m}}$$

→ Qualitatively : $v_x \uparrow \Rightarrow v_{g_2 s_2} \downarrow \Rightarrow I_{DS_2} \downarrow$
Hence the excess current of I_b must go out of v_x node.

→ Use it in an oscillator

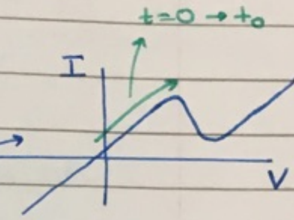


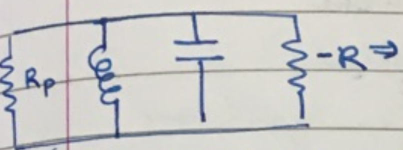


$V = v_{DC} + v_{ac}$

$v_{GS_2} = v_{G2} - v_{S2}$

$= \cdots$



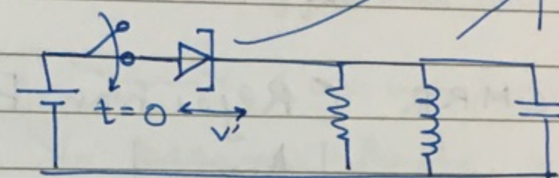


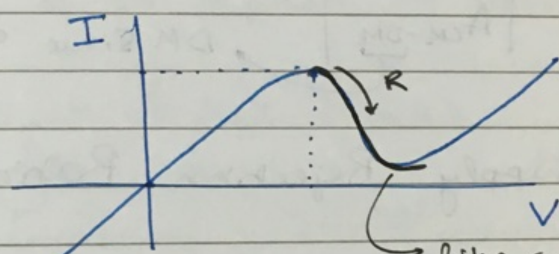
i_{DS_2} ↓

⇒ current flow out

$\hookrightarrow Z = \dfrac{Ls \cdot 1/sC_1}{Ls + 1/sC}$

$= \left(\dfrac{Ls}{s^2 LC_1 + 1}\right)$





like saturation in a differential Amplifier.

- Building Block of RF Oscillator.

Feedback

- −ve: A−A, A−B, B−A, B−B
  - Z_{in}
  - Z_o
  - A (G_m, R_m, A_v, A_I)
- +ve: Oscillator (sinusoidal) (Barkhausen)
  - Ring Osc
  - LCR
  - −ve R

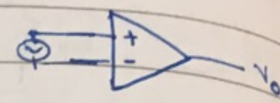
Book: Razavi : Design of Analog & CMOS

20.3.18

Opamp Characteristics

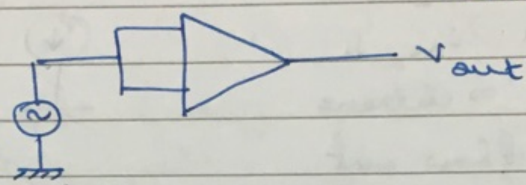
1) Differential Gain

$A \simeq 10^{4-5}$ (80



2) Common Mode Gain (CM → DM conversion)

→ A_{CM-DM}



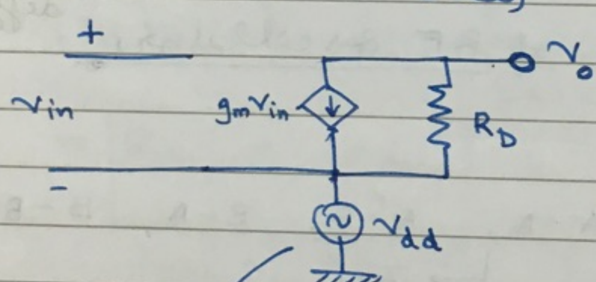
3) CMRR (Rejection Ratio) $10^2 - 10^4$

$$\left|\frac{A_{DM}}{A_{CM-DM}}\right|$$

→ DM since o/p is b/w v_{out} & Ground

4) Power supply Rejection Ratio

Non Ideal DC sources



$$\left(\frac{v_o}{v_{dd}}\right) = PSRR$$

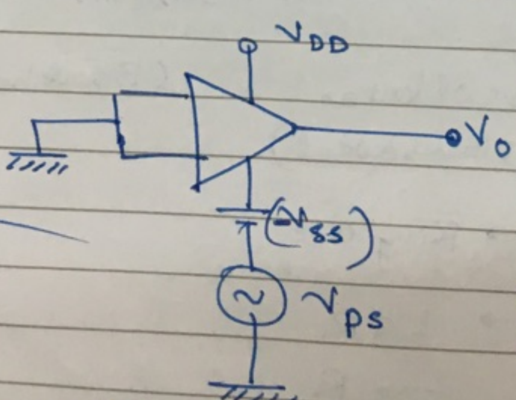
10^{-3}

→ small

→ Fluctuations in V_{DD}

$$A = \left|\frac{V_o}{v_{ps}}\right|$$

→ small

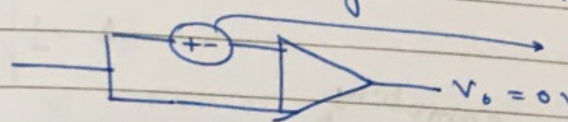


PSRR depends on frequency

($10^3 - 10^4$ if Rejection)

→ Will be different for $+V_{DD}$ & $-V_{SS}$

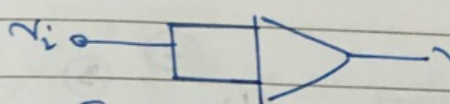
5) I/P offset voltage : 1 - 10 mV



Small source to Balance out.

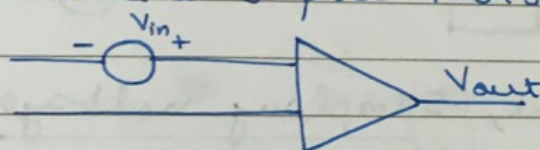
6) I/P Common - Mode range ~ 10 - 20 μV
(Subtracting i/p offset voltage 1 at a time)

→ Beyond this Non linearity comes in.



Beyond the Range, V_o becomes finite, due to violation of ss Approx. in later stages.

7) Equivalent Input Noise



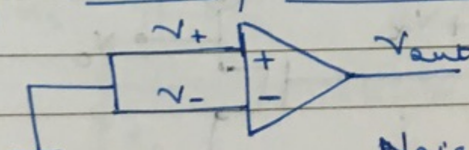
NEV → $1 \frac{V}{\sqrt{Hz}}$

→ If BW = ~~1KHz~~ 1MHz (f) ⇒ Noise power $= (A \times NEV)^2 \times f$

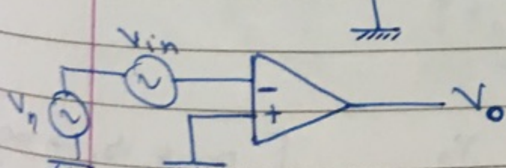
Band width

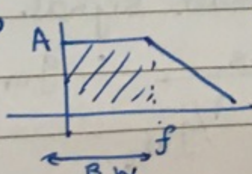
typical NEV → 1 nV / $\sqrt{Hz}$

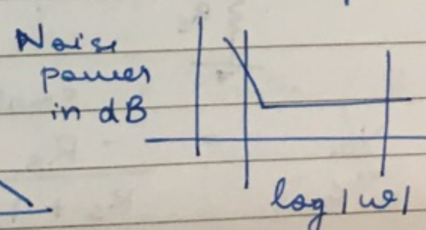
→ Measuring Noise power / noise



1/f noise
Capacitance







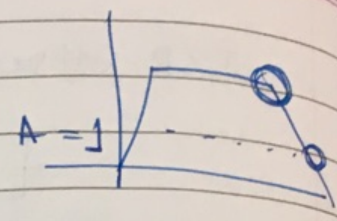
→ NEE
NEV
NEP

NEP is the Integral of $(A \times NEV)^2$ over BW?

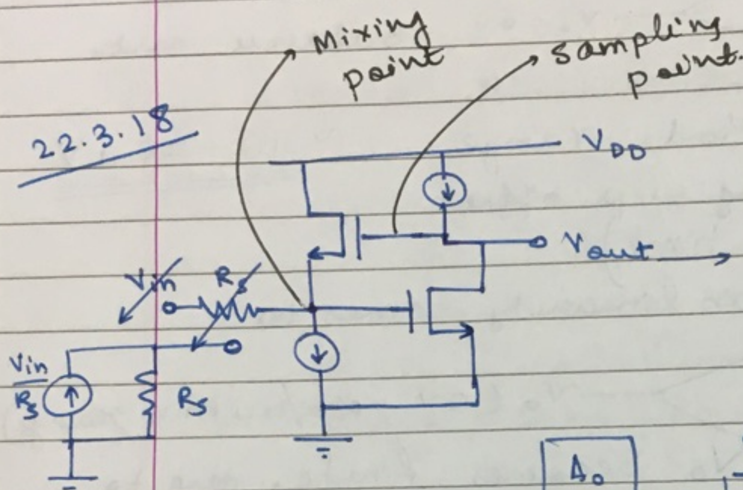
Typical : ~100 nV / $\sqrt{Hz}$

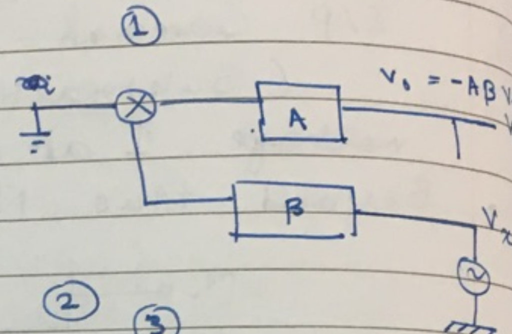
$\int_0^f NEV \times A \, df$

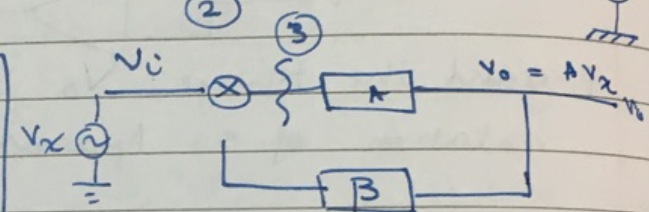
8) Unity Gain frequency



22.3.18







Z_{in}	$Z_{in\,f}$	A_0
Z_0	$Z_{0\,f}$	β
A	A_f	Z_{in}
		Z_0

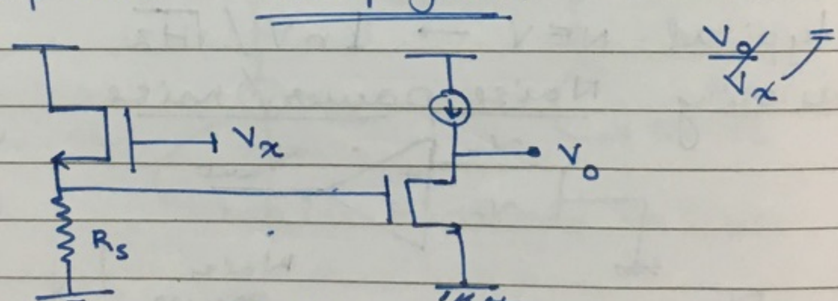
or at ③

→ mixing current, sampling voltage feedback

Hence make Norton equiv.

Open loop ckt

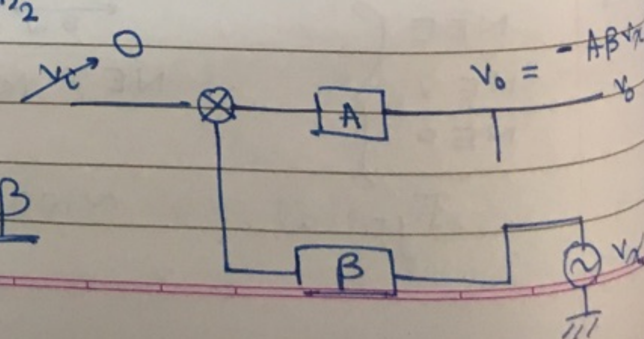
Loop Gain



small signal.

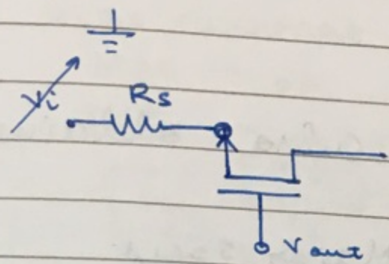
$$\frac{V_o}{V_x} = \frac{-R_s}{R_s + 1/g_{m_2}} \cdot g_{m_1} r_{o_1} \qquad [\text{put } r_{o_1} \to \infty$$

↳ corresponds to

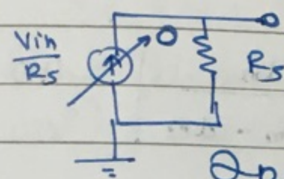


Hence Aloone is $A\beta$

→ <u>Setting Input to 0</u>

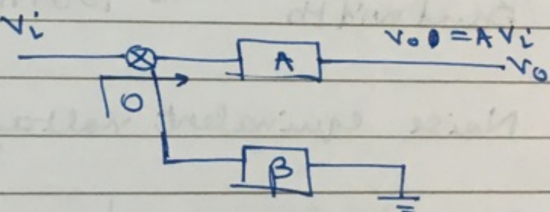


If current source, simply open

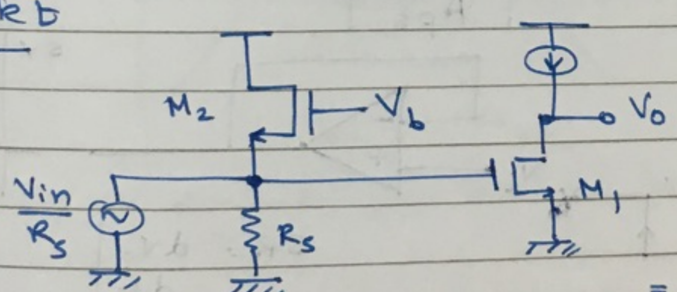


<u>Open loop Gain</u>

→ Get other parameters → put $V_x = 0$
& put some V_i



→ <u>Ckt</u>



$$\frac{V_{out}}{V_{in}/R_S} = -g_m r_{o_1}\left(R_S \| \frac{1}{g_{m_2}}\right)$$

$R_d \to \infty$

$$= -g_m r_{o_1}\left(R_S \| \frac{1}{g_{m_2}}\right)$$

imp. of a MOS when $r_o \to \infty$

$\boxed{= G_R}$ → $\underline{\underline{A}}$

$$\Rightarrow \text{Get } \beta = \frac{R_S}{\left(R_S + \frac{1}{g_{m_2}}\right)} \Bigg/ \frac{R_S \cdot \frac{1}{g_{m_2}}}{\left(R_S + \frac{1}{g_{m_2}}\right)} = \boxed{g_{m_2}}$$

$$\text{Gain} = \frac{A}{1 - A\beta}$$

→ We could have also obtained β direc...

26.3.18

Recap : op amp Major specs.

1) DC Gain $20\log|A_{dm}|$ 60-80dB (Diff. Gain at $\omega \to 0$)

2) CMRR $20\log\left|\frac{A_{dm}}{A_{cm-dm}}\right|$ 40-60dB

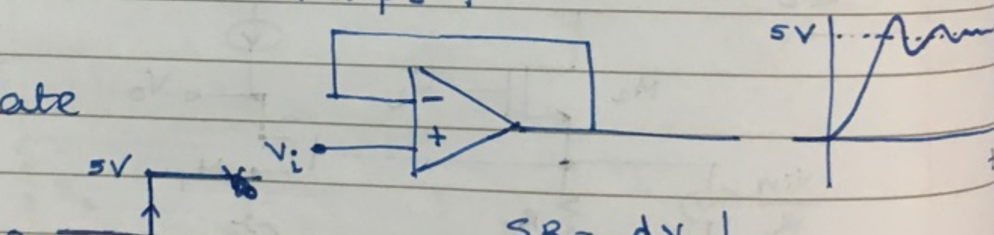
3) offset : (V_{os}) ≈ 4-6mV

4) Bandwidth ~ 100MHz

5) Noise equivalent voltage (I/P ref. Noise) 50nV/√...

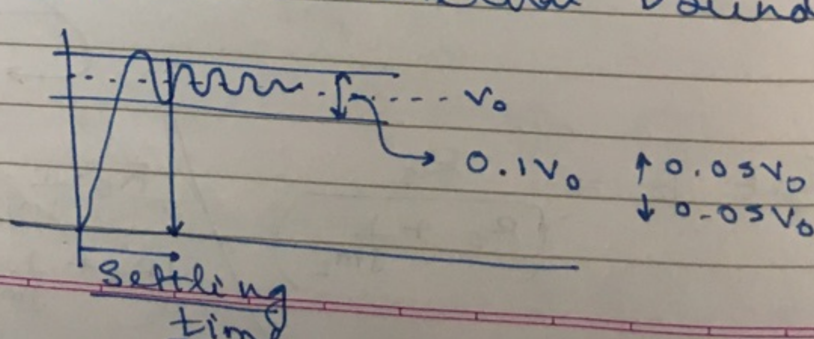
6) PSRR $20\log\left|\frac{A_{dm}}{A_{ps}}\right|$ 30-60 dB

7) Slew Rate



$$SR = \left.\frac{dV_o}{dt}\right|_{Max}$$

→ Settling time (5% Internal boundedness)



8) Settling time $\approx 0.1\mu s$

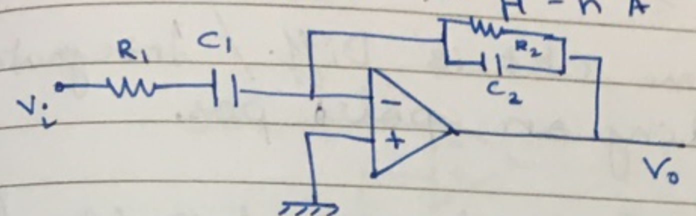
9) Input bias current (huge difference for MOS/BJT)

MOS → pA

BJT → μ - nA

1) Phase shifter
2) All pass

I



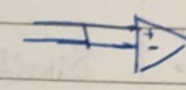
$v_o = A(v_+ - v_-)$

$(v_+ - v_-) = \lim_{A \to \infty} \frac{v_o}{A}$

$= 0$

$v_+ \approx v_-$ [Virtual Ground]

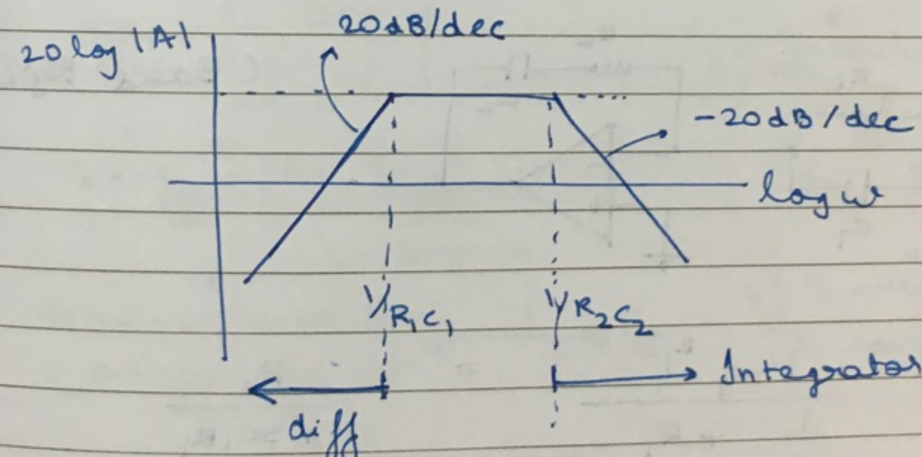
↳ But there is a slight potential difference (crucial) we can't short them



→ Transfer function:

$$\frac{v_o}{v_i} = -\frac{Z_2}{Z_1} \Rightarrow A = \frac{sC_1R_2}{(1+sC_2R_2)(1+sC_1R_1)}$$

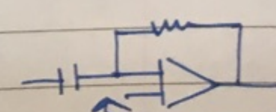
(Ideal op-amp)



Can also be made all-pass

Recap (EE112) Differentiator:

$$v_o = -RC\frac{dv_i}{dt}$$

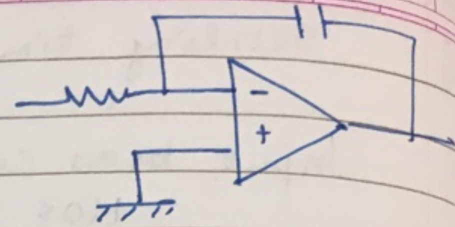


$\left|\frac{Z_2}{Z_1}\right| = \underline{\underline{sRC}}$

→ Push $\frac{1}{R_1C_1}$ & $\frac{1}{R_2C_2}$ to Right to get Diff.

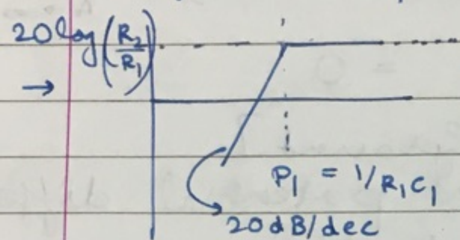
<u>Good</u> Diff: ⇒ $R_1 \downarrow$ & $C_2 \downarrow$

Good Integrator



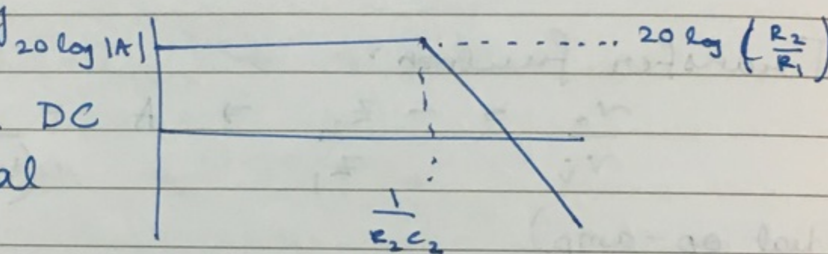
($C_1 \uparrow$, $R_2 \uparrow$)

→ Hence the same ckt is Diff. / Integrator / filter depending on poles pos.



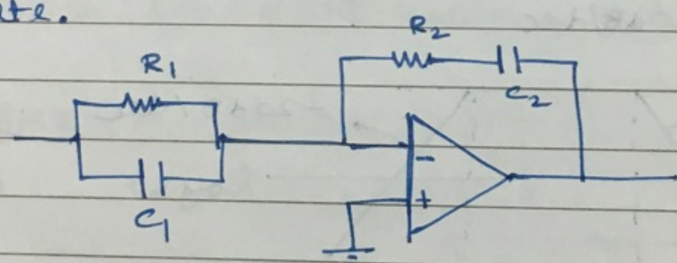
→ Such char. is desirable for differentiator else noise will make O/P blow up

→ Similarly



→ Since low freq. DC will cause ideal integrator to saturate.

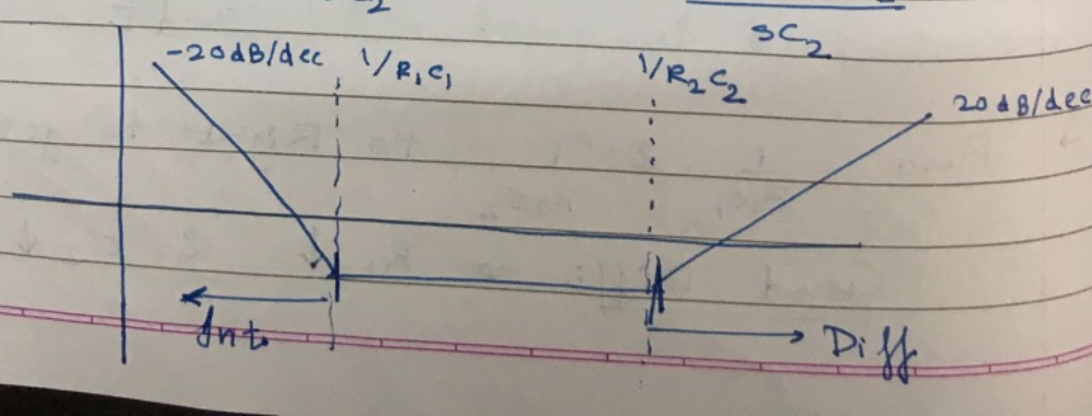
II



(Band Reject)

$$Z_1 = \frac{1/sC_1 \cdot R_1}{\frac{1}{sC_1} + R_1} = \frac{R_1}{1 + sC_1R_1}$$

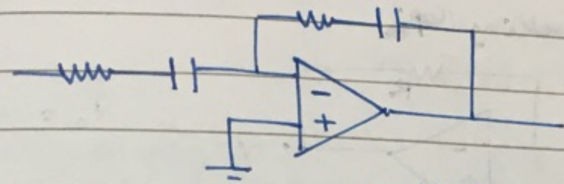
$$Z_2 = R_2 + \frac{1}{sC_2} = \frac{1 + sC_2R_2}{sC_2}$$



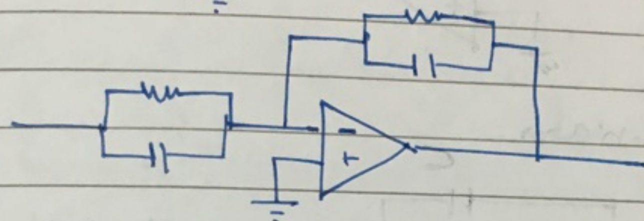
→ Can be used as both Integrator & Differentiator (but will saturate because of noise)

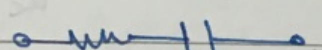
→ May saturate even in Band Reject mode. (Noise)

III



IV



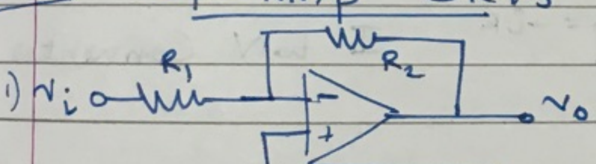


→ Can be Added to a branch to get pole/zero

27.3.18

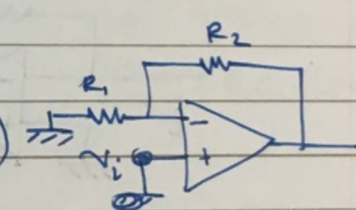
Op-Amp Ckts

1)



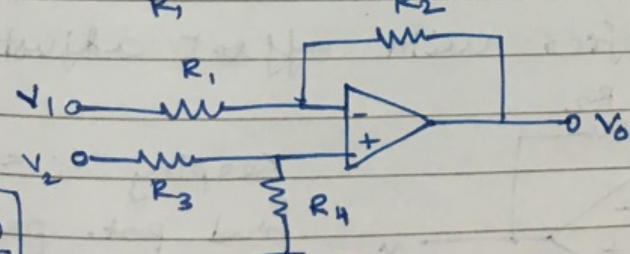
$v_o = -\frac{R_2}{R_1} v_i$ $\boxed{\text{Inv. Amp.}}$

2)



$v_o = \left(1 + \frac{R_2}{R_1}\right) v_i$ $\boxed{\text{Non-Inv. Amp.}}$

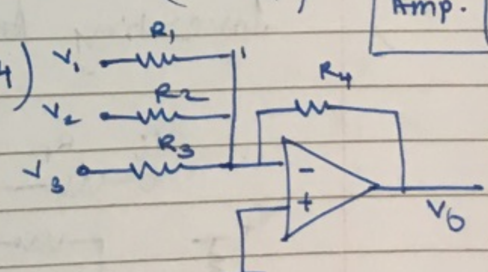
3)



$\boxed{\text{Diff. Amp}}$

$v_o = \left(1 + \frac{R_2}{R_1}\right) \frac{R_4 V_2}{(R_3+R_4)} - \frac{R_2}{R_1} V_1$

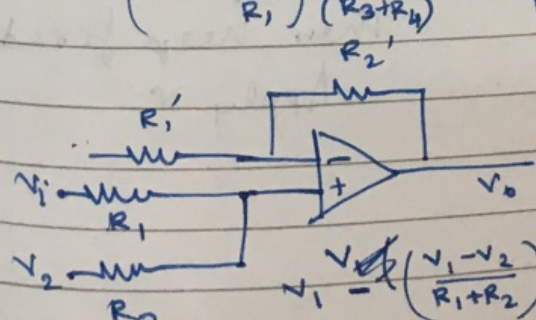
4)



$v_o = -R_4 \left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$

$\boxed{\text{Inv. Summer}}$

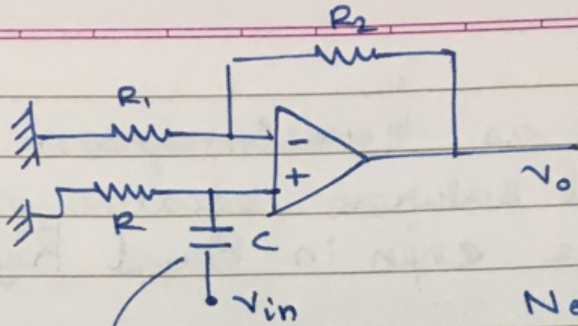
5)



$V_1 - \left(\frac{V_1 - V_2}{R_1 + R_2}\right) R_1$

$\boxed{\text{Non inv. summer}}$

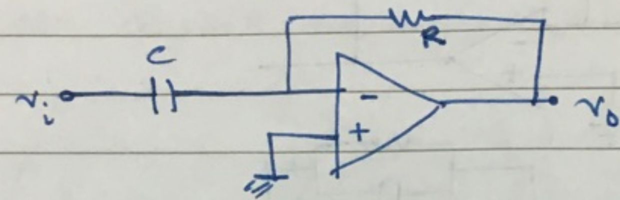
$v_o = \left(1 + \frac{R_2'}{R_1'}\right) v_i'$, $v_i' = \frac{1}{R_1 + R_2}(V_1 R_2 + V_2 R_1)$

6) 

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

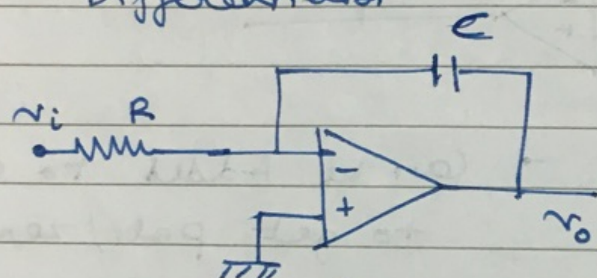
Non-Inv. AC Amp.

Blocking Cap.

7) 

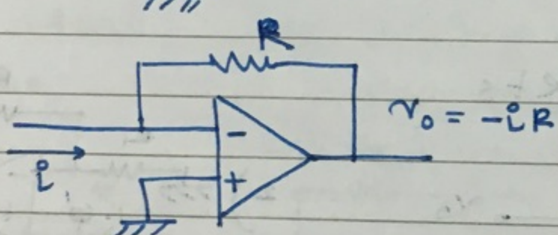
$$v_o = -RC\frac{dv_i}{dt}$$

Differentiator

8) 

$$v_o = \frac{-1}{RC}\int v_i \, dt$$

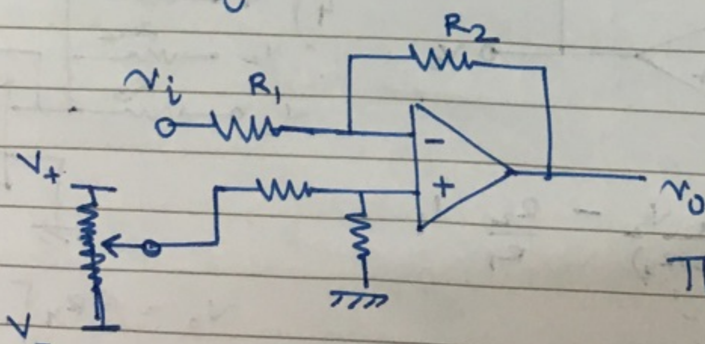
Integrator

9) 

$v_o = -iR$

I to V Converter

10) Inverting Amplifier with offset adjustment

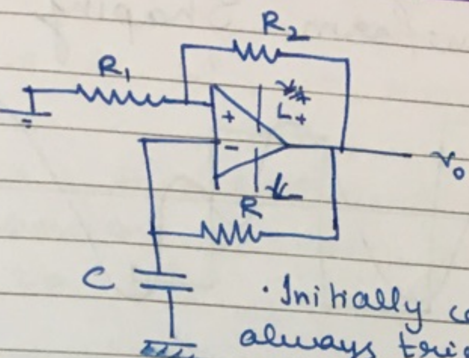


Keeping $v_i = 0$ find pot. position for zero o/p. Then keep fixed & Apply v_i

Multivibrators

- Astable
- Bistable
- Monostable

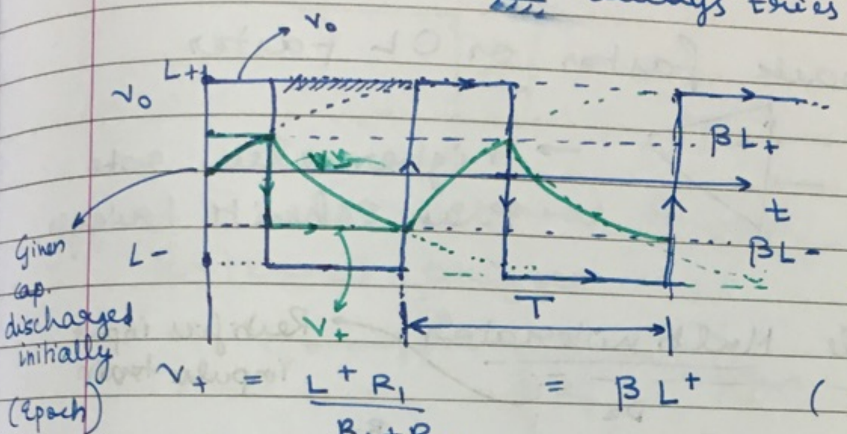
→ Astable (CLK)



$v_- = v_{cap}$

Start: Either L_+ or L_- ∴ of +ve F.B

· Initially cap. was discharged, always tries to charge to V_o



square wave at o/p.

Squarewave at v_+

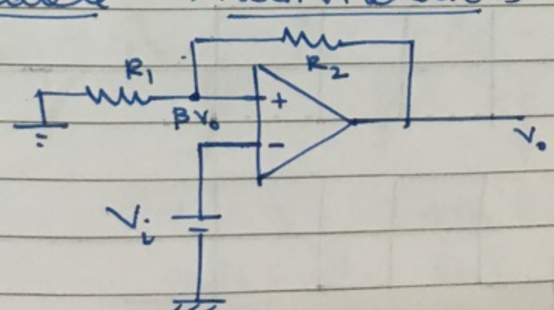
$$v_+ = \frac{L^+ R_1}{R_1 + R_2} = \beta L^+ \quad (\text{When } v_o = L^+)$$

When v_o switches to L^- (Due to $v_+ - v_-$ pol. reversal)

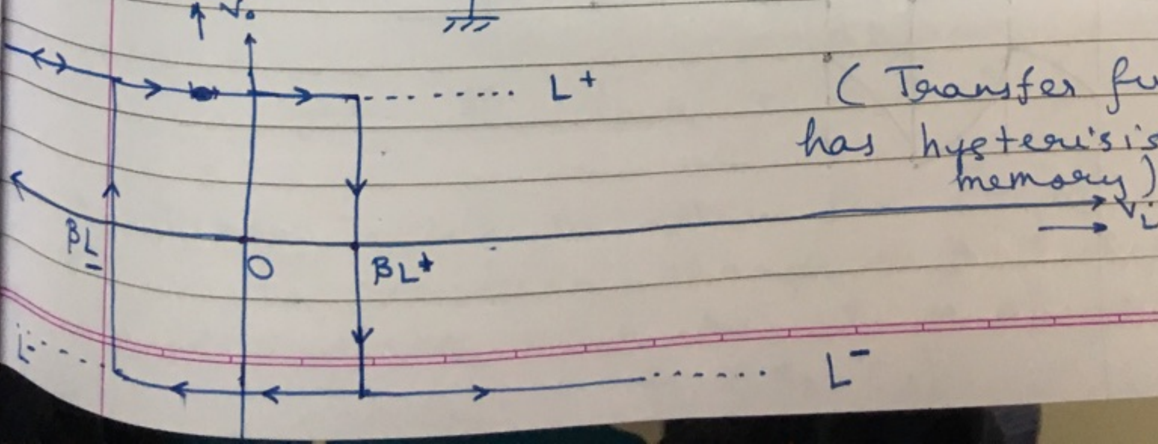
$$v_+ = L^- \beta \quad \rightarrow \text{Derive} \quad T = 2RC \ln\left(\frac{1+\beta}{1-\beta}\right)$$

~~What if~~

→ Bistable Multivibrators

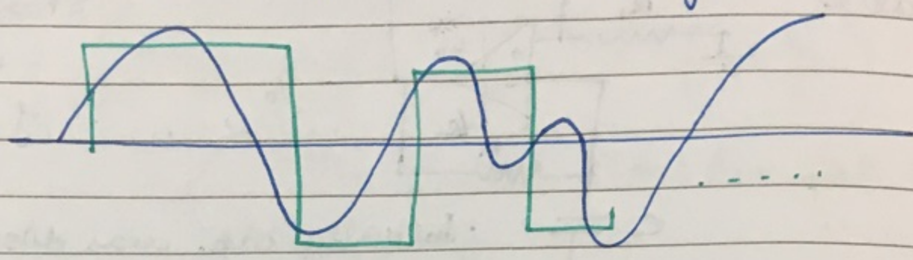


$$\beta = \frac{R_1}{R_1 + R_2}$$

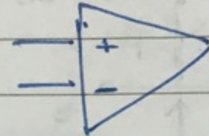


(Transfer function has hysteresis/ memory)

→ Used in waveform Shaping



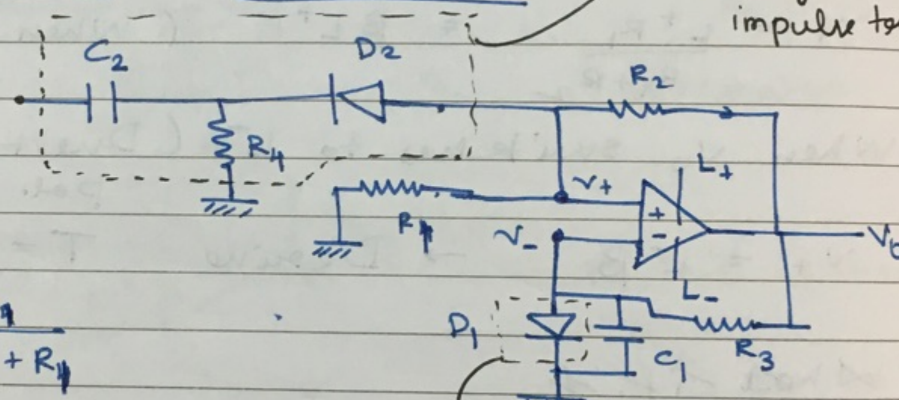
→ +ve feedback faster or OL faster



→ higher slew rate than schmitt trigger

Monostable Multivibrator

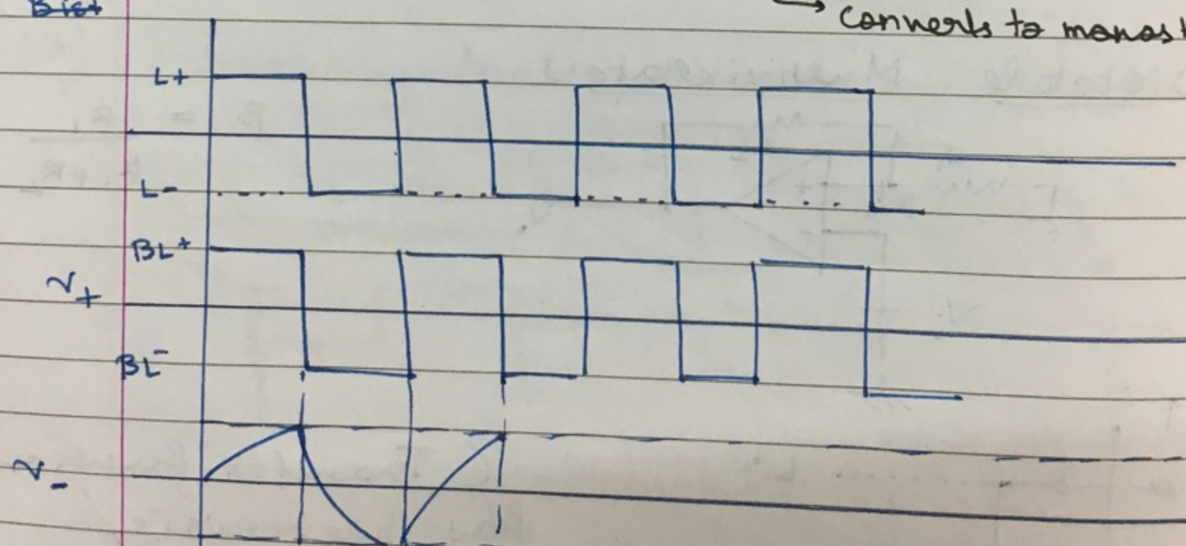
Rectifies input impulse train



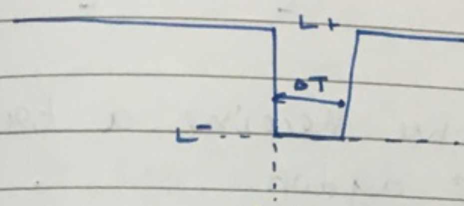
converts to monostable

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

Astable ~~Bist~~

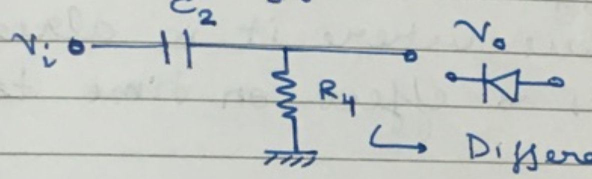


- If ~~ckt~~ v_o is in L^+, it remains in L^+ till ∞
- If v_o is L^-, then it stays in L^- for a transient period and then switches back to L^+.



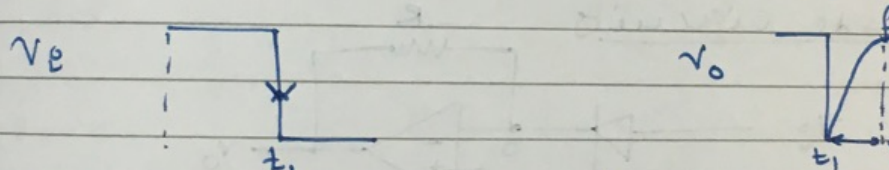
external trigger

- External trigger

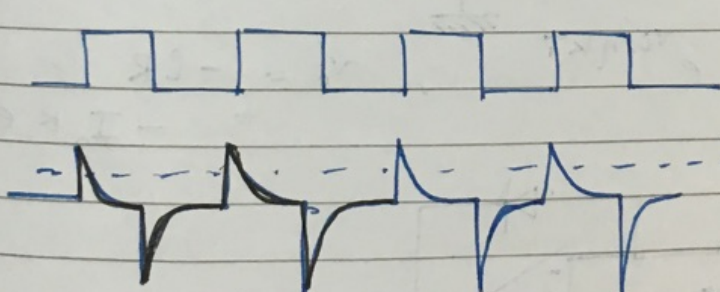


$$\frac{v_o}{v_i} = \frac{R_4}{R_4 + \frac{1}{sC_2}} \left(= \frac{sC_2R_4}{sC_2R_4+1} \right)$$

↳ Differentiator / High pass filter



→ Non ideal diff.



Diode (D_2) Rectifies this out

$$v_o \approx v_i s C_2 R_4 \quad ; \quad sC_2R_4 << 1$$

$$v_o(t) \approx R_4 C_2 \left(\frac{dv_i}{dt}\right)$$

Get ~~(1)~~ $T_{pulse} = R_3 C_1 \ln\left(\frac{1}{1-\beta}\right)$

- Diode needed to allow for (C_1, R_3) ckt to completely charge to βL^- before it switches back to L^+ ⇒ ensures $T_{pulse} = f(R_3, C_1)$

→ Closely spaced pulses

Say our pulse duration is 10 s

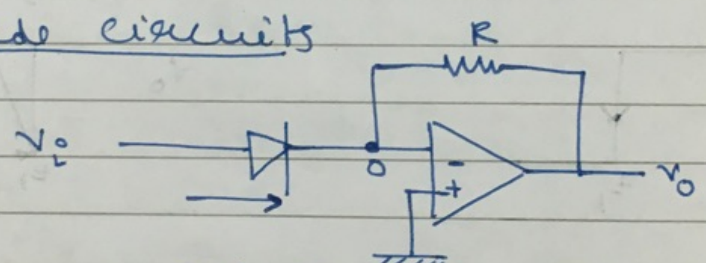
	Trigger ↓	Trigger ↓	Trigger ↓	
t	0s	5s	8s	10s
v_o	L^-	L^-	L^-	L^+

→ In above ex. after we receive a trigger it takes 10s to reach L^+ again.

→ If we trigger in b/w, then we are forcing a pin to a value where it is already present, hence it has no effect on time to convergence

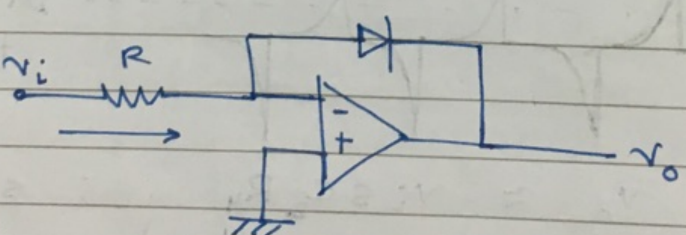
Diode circuits

1)



$$i = I_o e^{v_i/\eta kT}, \quad v_o = -iR$$
$$= -I_o R e^{v_i/\eta kT}$$

2)



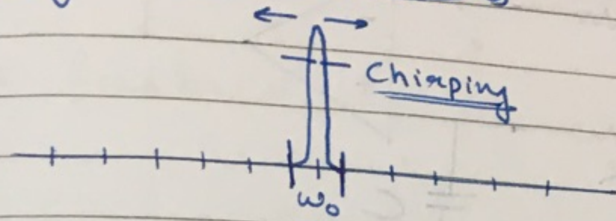
$$\frac{v_i}{R} = I_o e^{-v_o/\eta kT}$$

$$\boxed{v_o = -\eta kT \ln\left(\frac{v_i}{I_o R}\right)}$$

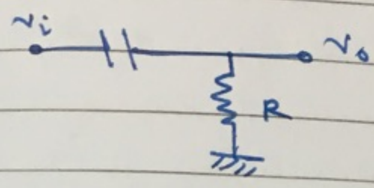
→ Used in Signal Conditioning.

3.4.18

Chirping in oscillators



Spectrum of oscillator output

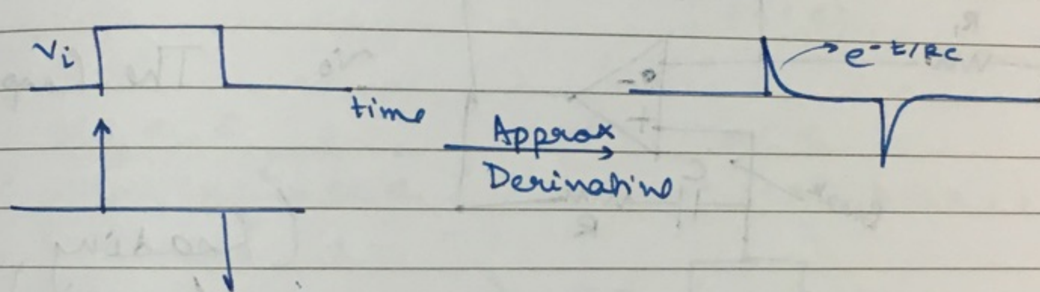


$$\frac{v_o}{v_i} = \frac{R}{R + 1/sC}$$

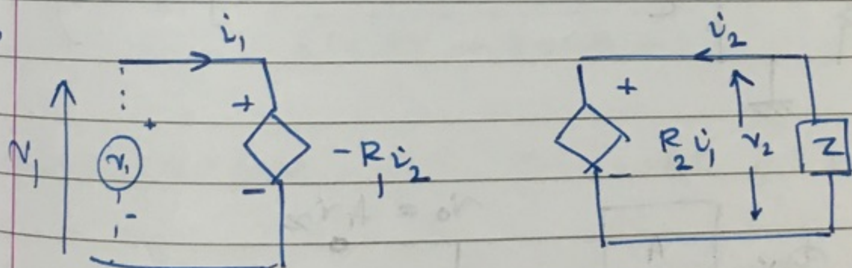
$$\frac{v_o}{v_i} = \frac{sCR}{1+sCR}$$

say $v_i = u(t)$, $v_o = \frac{1}{s} \cdot \frac{sCR}{1+sCR}$

$$\Rightarrow v_o(t) = e^{-t/RC}$$



Q→



$\frac{v_i}{i_1} = ?$

$v_1 = -R_1 i_2$

$-Z i_2 = R_2 i_1$

$i_2 = -\frac{R_2 i_1}{Z}$

$$v_1 = -R_1 \left(-\frac{R_2 i_1}{Z} \right)$$

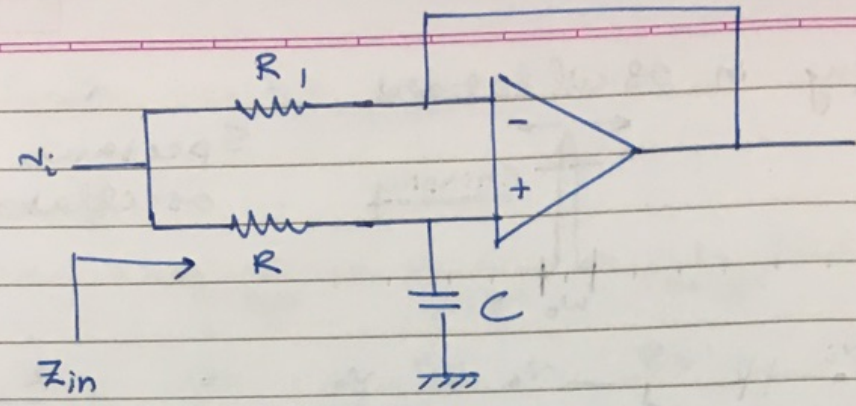
$$\frac{v_1}{i_1} = \frac{R_1 R_2}{Z}$$

take $Z = \frac{1}{sC}$ (cap)

$$\Rightarrow \frac{v_1}{i_1} = sCR^2 \Rightarrow \boxed{\text{We get } L = R^2C}$$

simulated inductor $\boxed{LS}$

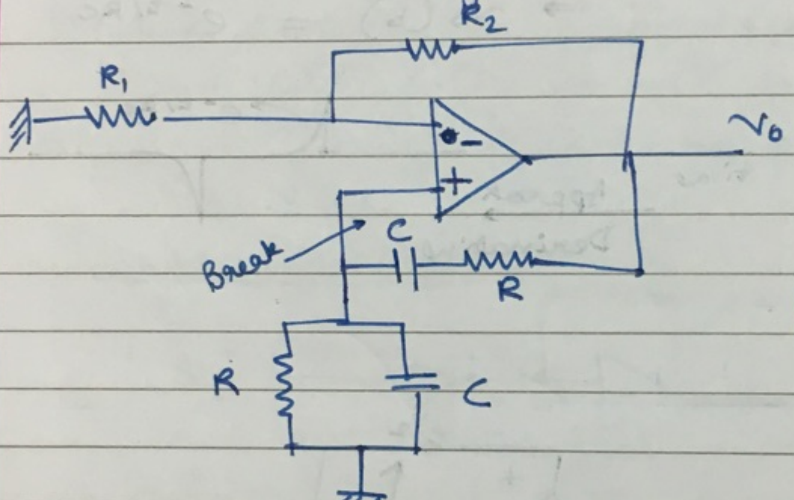
Q →



5.4.18

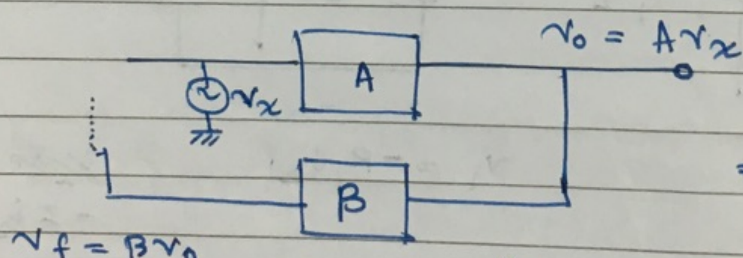
Op amp Oscillators

15 Wien Bridge Oscillator

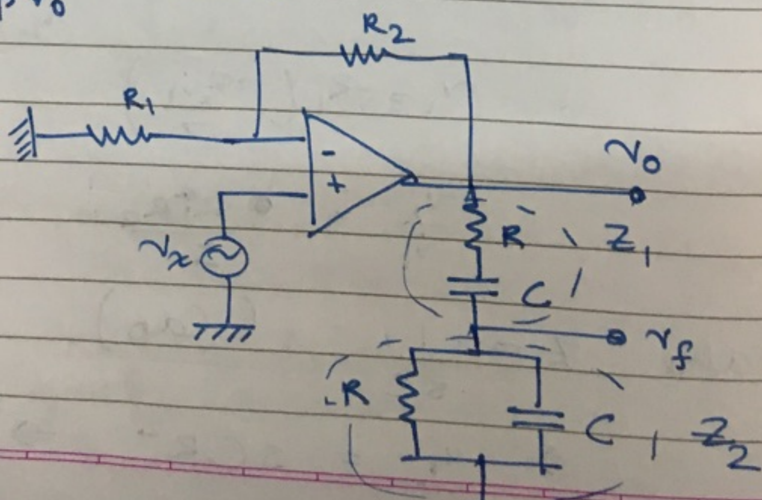


The Loop

(Loading Ignored)



$\Rightarrow v_f = A\beta v_x$



+ve feedback → $\frac{v_o}{v_i} = \frac{A}{1-A\beta}$

-ve feedback → $\frac{v_o}{v_i} = \frac{A}{1+A\beta}$

$A = \left(1 + \frac{R_2}{R_1}\right)$ Non-Inverting Amp.

$\because \; v_o = \left(1 + \frac{R_2}{R_1}\right) v_x$

$$\beta = \frac{Z_2}{Z_1 + Z_2} = \frac{R/(1+sCR)}{\frac{R}{(1+sCR)} + \frac{sCR+1}{sC}}$$

$$= \frac{sCR}{(1+sCR)^2 + sCR} = \frac{sCR}{s^2C^2R^2 + 3sCR + 1}$$

$$A\beta = \frac{(1 + R_2/R_1)\, sCR}{s^2C^2R^2 + 3sCR + 1}$$

put $s = j\omega$, $= \frac{j\omega RC\,(1 + R_2/R_1)}{3j\omega RC + (1 - \omega^2R^2C^2)}$

At $\omega = 1/RC$

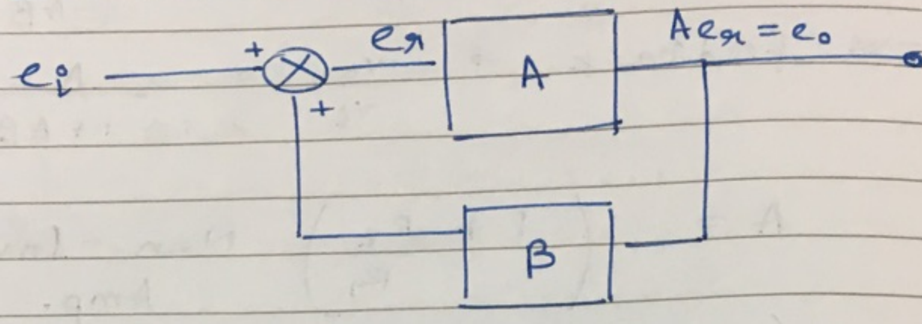
$$A\beta = \frac{1}{3}\left(1 + \frac{R_2}{R_1}\right)$$

$$\frac{1}{3}\left(1 + \frac{R_2}{R_1}\right) > 1$$

⇒ Oscillations happen at $\omega = \frac{1}{RC}$

if $\boxed{R_2 > 2R_1}$

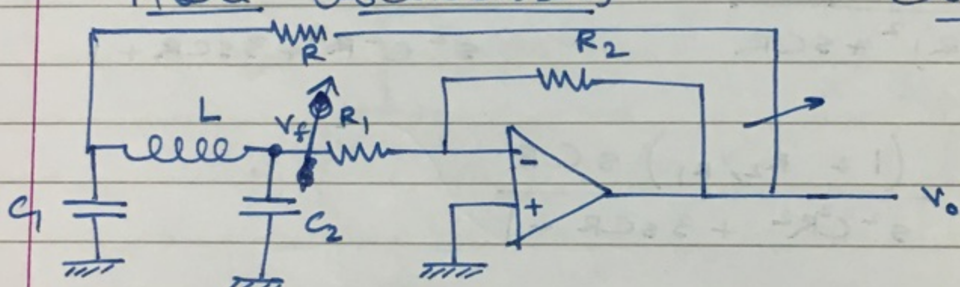
→ <u>When is F/B +ve</u>



$\beta \longrightarrow -\beta$ F.B +ve $\longrightarrow$ −ve

Note: Here, Formula used is $\frac{A}{1-A\beta}$
Since we are connecting to ~~the~~ ~~non~~ + terminal of op amp

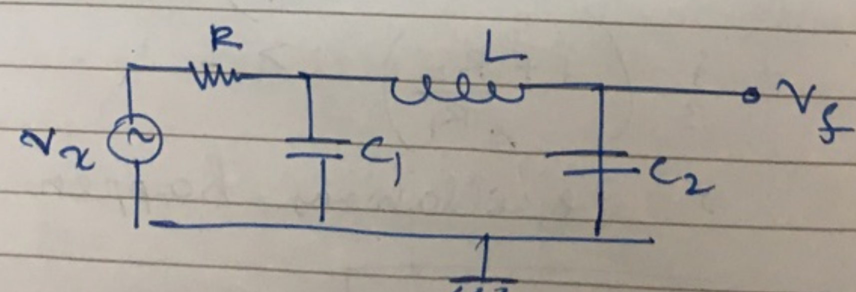
→ <u>More Oscillators</u> <u>Collpit's Oscillator</u>



$$A = -\frac{R_2}{R_1}$$

We know $\frac{V_o}{V_f} = A = -\frac{R_2}{R_1}$ (OL Gain)

⇒ To get β, cut open F.B Network

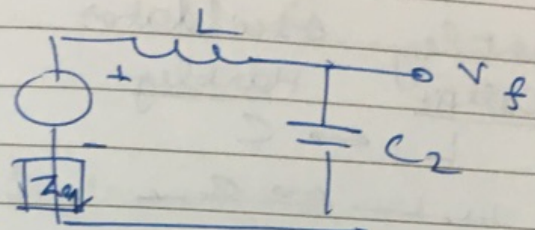


$$\cancel{V_f =}$$

$$\cancel{Z_{eq} = R + \left(sL + \frac{1}{sC_2}\right) \parallel \frac{1}{sC_1}}$$

→ Thévenin Equivalent

$$\left(\frac{V_x}{1+sC_1R}\right)$$



$$Z_{eq} = R \parallel \frac{1}{sC_1}$$

$$\Rightarrow \beta = \frac{\left(\frac{1}{1+sC_1R}\right) \times \frac{1}{sC_2}}{\frac{R}{1+sC_1R} + Ls + \frac{1}{sC_2}}$$

$$sC_1R >> 1$$

Dr at $s = j\omega$

$$= j\left[\omega L - \frac{1}{\omega}\left(\frac{1}{C_1} + \frac{1}{C_2}\right)\right]$$

$$\omega \simeq \frac{1}{\sqrt{L\left(\frac{C_1C_2}{C_1+C_2}\right)}} \quad \text{for } Dr = 0$$

We have $\angle A = \pi \Rightarrow \angle\beta = \pi$ for oscillation

→ How to get $\angle\beta = \pi$

$$\beta = \frac{\left(\frac{1}{1+sC_1R}\right) \cdot \frac{1}{sC_2}}{\frac{R}{1+sC_1R} + Ls + \frac{1}{sC_2}}$$

Claim (Proof in Assignment), that

$\angle D_r$ when $D_r \to 0 = 0$

then $\angle N_r \approx \pi \Rightarrow$ we get what we want

Hartley oscillator

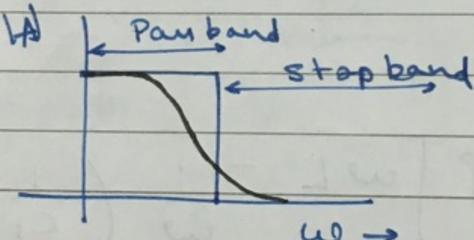
Collpit	Hartley
L	$\leftrightarrow C$
~~L_1, L_2~~	~~$\leftrightarrow C_{1,2}$~~
C_1, C_2	$\leftrightarrow L_1, L_2$

9.4.18

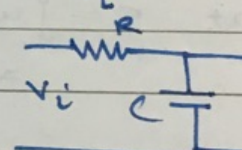
Filters

1) Low pass filter

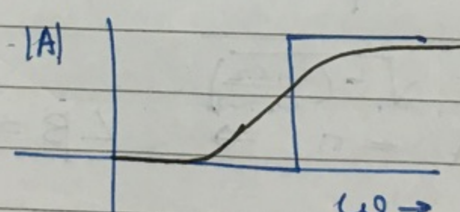
Implementation

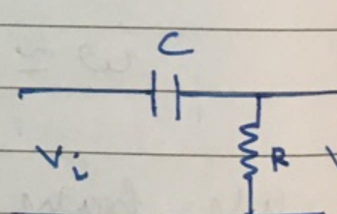


$$\frac{V_o}{V_i} = \frac{1}{1+sCR}$$



2) High pass

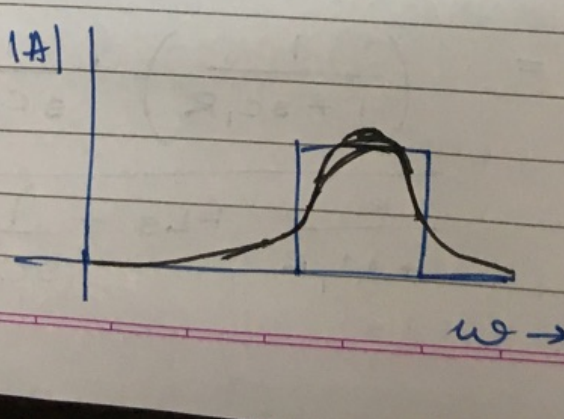




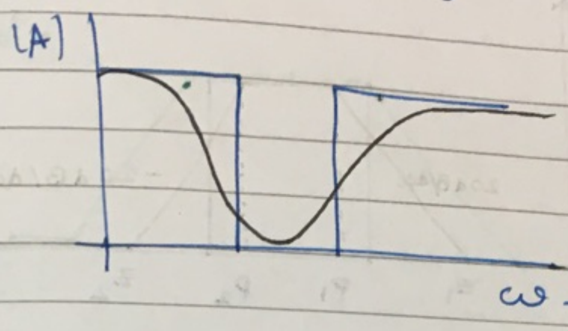
$$\frac{V_o}{V_i} = \frac{sCR}{1+sCR}$$

3) Band pass

$$\frac{V_o}{V_i} = \frac{Rs/L}{s^2 + \frac{sR}{L} + \frac{1}{LC}}$$

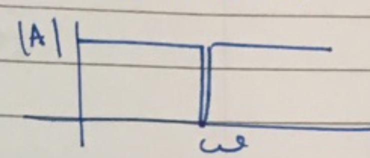


4) Band Reject (Notch)



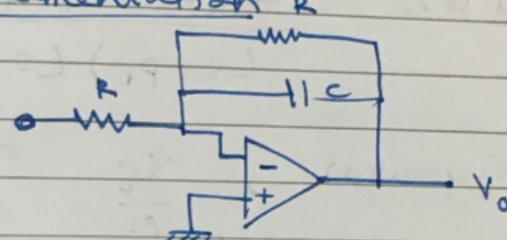
$$\frac{V_o}{V_i} = \frac{s^2 + 1/LC}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

→ True Notch

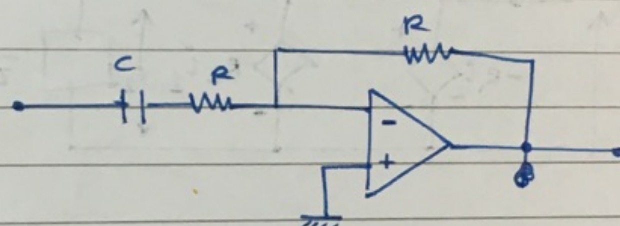


Op - Amp Implementation

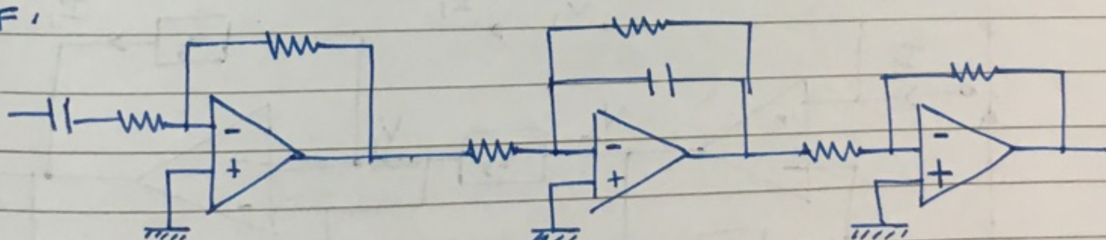
LPF :



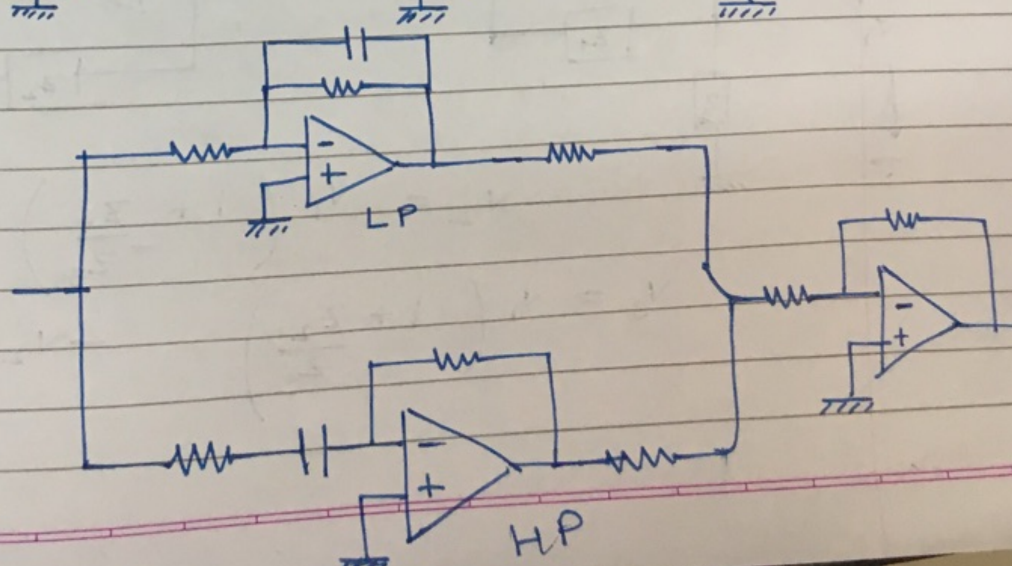
HPF :



BPF :



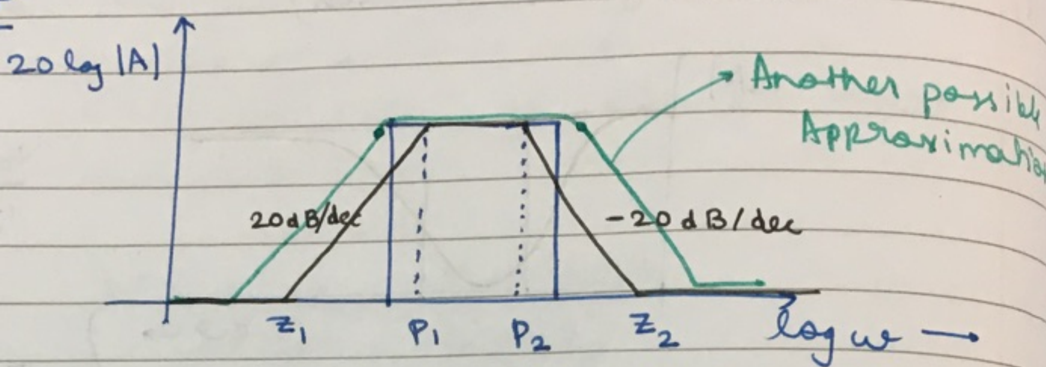
Notch:



Page No.:

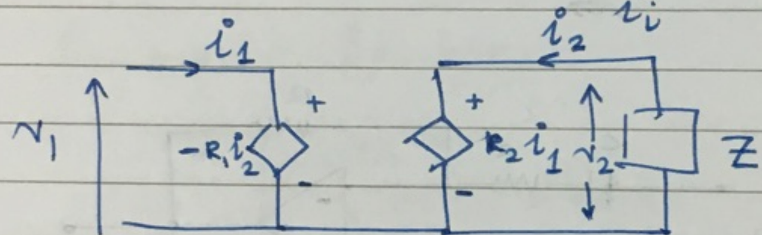
Filter Transfer functions

BPF

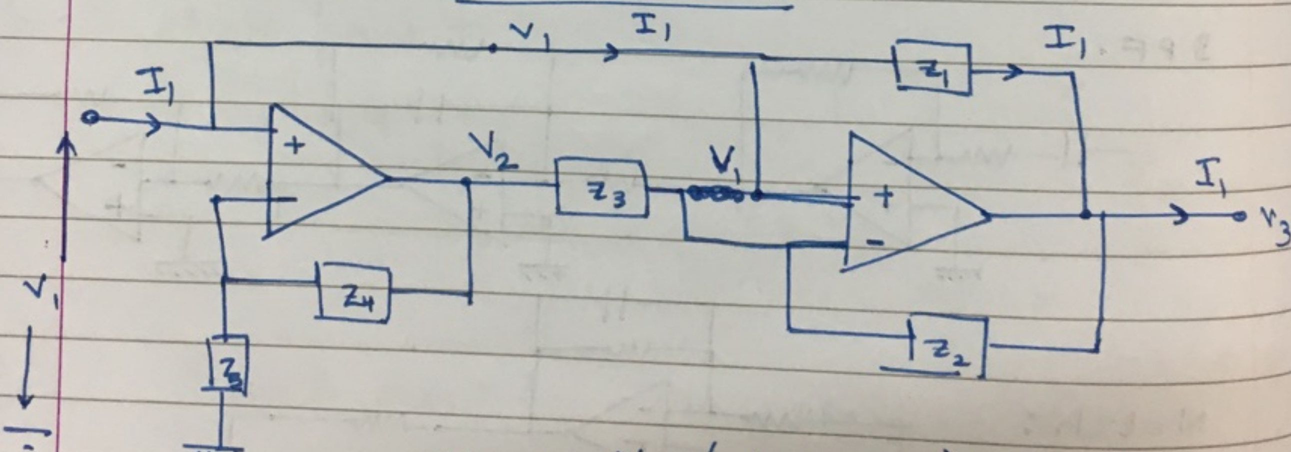


$$G(s) = \frac{k(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)}$$

→ Recap: Gyrator, $\frac{v_i}{i_i} = \left(\frac{R_1 R_2}{Z}\right)$



Riordan Ckt



$$v_2 = v_1\left(1 + \frac{Z_4}{Z_5}\right)$$

$$v_3 = v_1\left(1 + \frac{Z_2}{Z_3}\right) - v_2\frac{Z_2}{Z_3}$$

$$V_3 = V_1\left(1 - \frac{Z_2 Z_4}{Z_3 Z_5}\right)$$

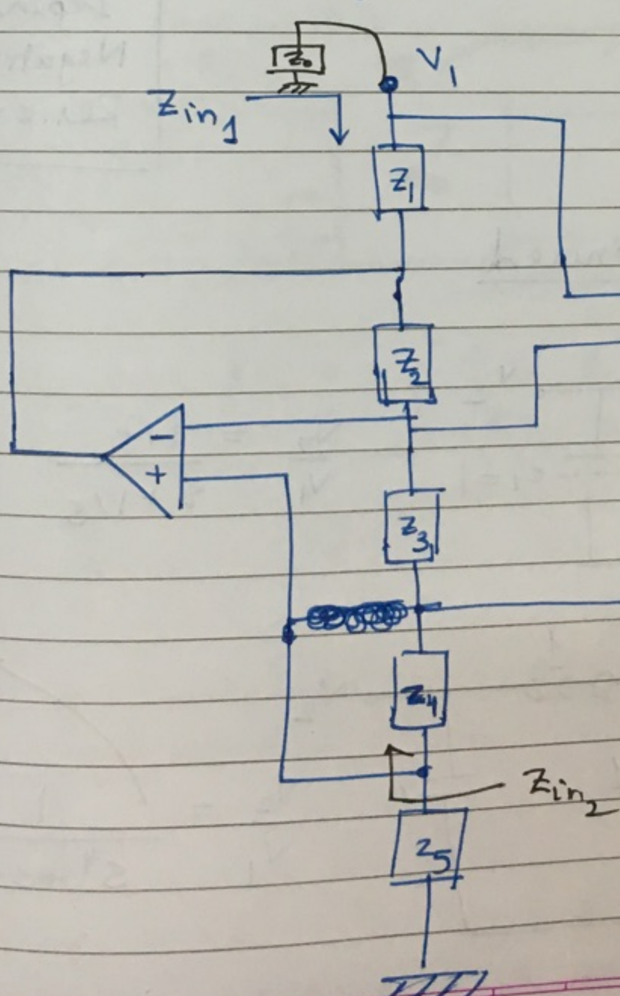
$$I_1 = \frac{V_1 - V_3}{Z_1} = \left(\frac{Z_2 Z_4}{Z_1 Z_3 Z_5}\right) V_1$$

$$\cancel{\frac{I_1}{V_1}} \cancel{=} \quad \boxed{Z_{in} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}}$$

We can get any transfer function we want using this.

GIC: Generalised Impedance Convertor

→ Application of GIC (Antoniou's Gyrator)
→ Another GIC



$$Z_{in_1} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$$

$$Z_{in_2} = \frac{Z_4 Z_2 Z_0}{Z_1 Z_3}$$

In/out Symmetry

→ Pick,

$$z_1 = R_1, \quad z_3 = R_3, \quad z_5 = R_5$$
$$z_2 = R_2 \quad z_4 = \frac{1}{sC_4}$$

$$Z_{in_1} = \left(\frac{R_1 R_3 R_5}{R_2}\right) sC_2 = L_{eq} s = j\omega L_{eq}$$

remove Z_5, take $Z_0 = \frac{1}{sC_0}$, $Z_4 = \frac{1}{sC_4}$
rest are resistors

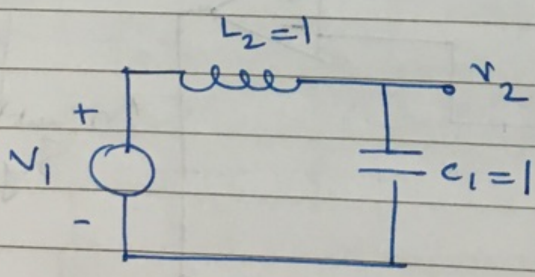
$$Z_{in_2} = \frac{Z_4 Z_2 Z_0}{Z_3 Z_1} = \frac{1/sC_4 R_2 \times \frac{1}{sC_0}}{R_1 R_3}$$

$$= \frac{R_2 C_4}{R_1 R_3 C_0} \cdot \frac{1}{s^2} = -\frac{\alpha}{\omega^2}$$

FDNR
Frequency Dependant Negative Resistance

10.4.18 **Filters continued**

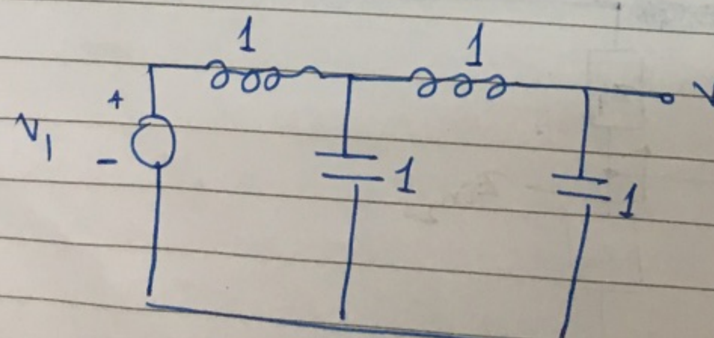
1)



$$\frac{V_2}{V_1} = \frac{1/s}{s + 1/s} = \frac{1}{1+s^2}$$

No odd power

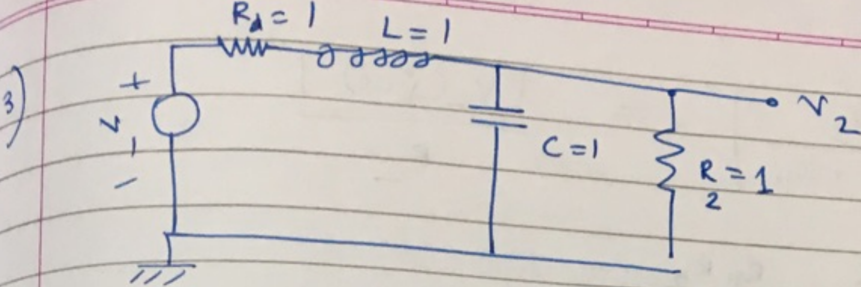
2)



$$\frac{V_2}{V_1} = \frac{1}{s^4 + 3s^2 + 1}$$

$$V_1 = Z_{11} I_1 + Z_{12} I_2$$

3)



$$\frac{V_2}{V_1} = \frac{1}{s^2+2s+2}$$

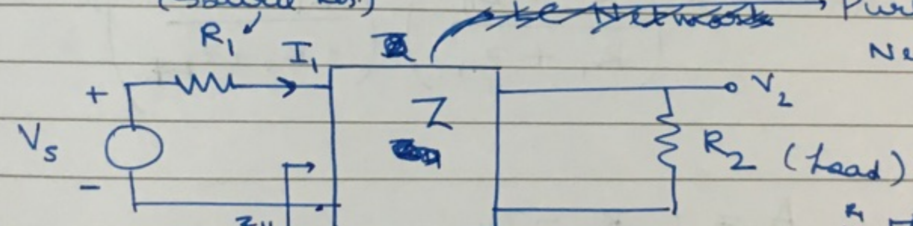
↳ odd powers present if R present

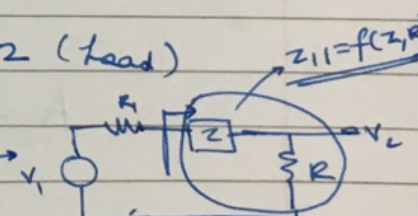
$$\frac{V_2}{V_1} = \frac{1}{s^2+2s+2}$$

General, $$T = \frac{k}{b_n s^n + b_{n-1} s^{n-1} + \dots + b_0}$$

$$T(s=0) = \frac{k}{b_0} = \frac{R_2}{R_1+R_2} = \frac{1}{2} \text{ for } (3)$$

→ <u>How to get General Transfer function T</u>





$$Z_{11} = f(Z, R)$$
$$= \underbrace{R_{11}}_{} + jX_{11}$$

↳ only appears because we are looking in & R_2 is affecting Z_{11}

$$I_1 = \frac{V_s}{R_1 + Z_{11}} = \frac{V_s}{(R_1+R_{11}) + jX_{11}}$$

$$\boxed{|I_1(j\omega)|^2 R_{11} = \frac{|V_2(j\omega)|^2}{R_2}}$$

↳ Since Z is a purely LC Network power dissipated is only at R_2

$$R_{11}\left|\frac{V_s}{R_1+z_{11}}\right|^2 = \frac{|V_2(j\omega)|^2}{R_2}$$

$$|T|^2 = \frac{R_{11}R_2}{|R_1+z_{11}|^2}$$

$$|A(j\omega)|^2 = 1 - 4\frac{R_1}{R_2}|T(j\omega)|^2$$

$$1 - 4\frac{R_1}{\cancel{R_2}}\frac{R_{11}\cancel{R_2}}{|R_1+z_{11}|^2} \to \left(\times\frac{z_{11}}{R_{11}}\right)$$

$$|A(j\omega)|^2 = \left|\frac{R_1-z_{11}}{R_1+z_{11}}\right|^2$$

$$AA^* = \left(\frac{R_1-z_{11}}{R_1+z_{11}}\right)\left(\frac{R_1-z_{11}}{R_1+z_{11}}\right)^*$$

$$A = \frac{R_1-z_{11}}{R_1+z_{11}}$$

$$z_{11} = R_1\left(\frac{1-A}{1+A}\right)$$

→ General Butterworth filter

$$T = \frac{k}{1+\omega^{2n}} = \frac{k}{Q(s)Q(-s)}, \text{ say}$$

take n = 1

$$D^n = 1+\omega^2, \text{ then}$$
$$Q(s) = (1+s)$$
$$Q(-s) = (1-s)$$
$$Q(s)Q(-s) = 1-s^2 \ : s=j\omega \Rightarrow \ =(1+\omega^2)$$

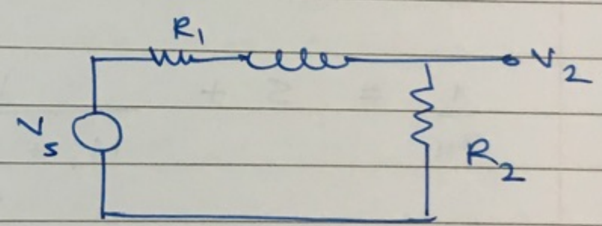
$\Rightarrow$ pick $Q(s) = (s+1)$, take $R_1 = 1$

then pick k such that when, $R_1 = R_2 = 1$

$$A(s) = \frac{s}{s+1}$$

$$Z_{11} = \frac{1 - \frac{s}{s+1}}{1+\frac{s}{s+1}} = \frac{1}{2s+1}$$

Equivalent to



n=2 case

$$T = \frac{k}{1+\omega^4} = \frac{k}{Q(s)Q(-s)}$$

$$Q(s) = s^2+\sqrt{2}s+1$$

say

for n=2,

$$Z_{11} = \frac{\sqrt{2}s+1}{s^2+\sqrt{2}s+1}$$

$$\frac{1}{Z_{11}} = \frac{s^2 + \sqrt{2}s + 1}{(\sqrt{2}s + 1)}$$

$$\begin{array}{r|l} & \frac{s}{\sqrt{2}} + \frac{1}{2} \\ \sqrt{2}s+1 & s^2 + \sqrt{2}s + 1 \\ & s^2 + \frac{s}{\sqrt{2}} \\ \hline & \frac{s}{\sqrt{2}}\left(\cancel{\sqrt{2} - \frac{1}{\sqrt{2}}}\right) + 1 \\ & \sqrt{2}s + \frac{1}{2} \\ \hline & \frac{1}{2} \end{array}$$

$$(s^2 + \sqrt{2}s + 1) = (\sqrt{2}s + 1)\left(\frac{s}{\sqrt{2}} + \frac{1}{2}\right) + \frac{1}{2}$$

$$\frac{1}{Z_{11}} = \left(\frac{s}{\sqrt{2}} + \frac{1}{2}\right) + \frac{1}{2(\sqrt{2}s+1)}$$

$$\frac{1}{Z_{11}} = s + \cfrac{1}{M_1 + \cfrac{1}{s\left(\sqrt{2} - \frac{1}{\sqrt{2}}\right) + 1}}$$