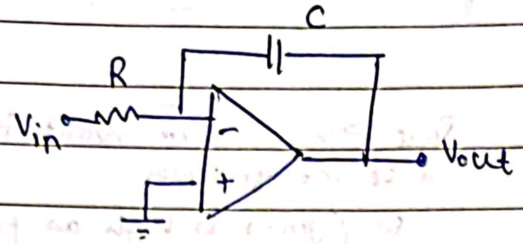
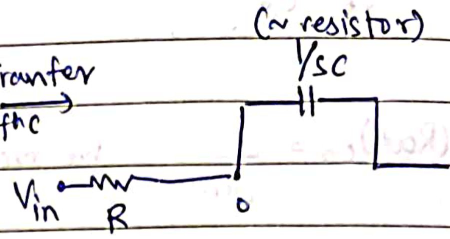
BODE PLOTS

For an op-amp integrator



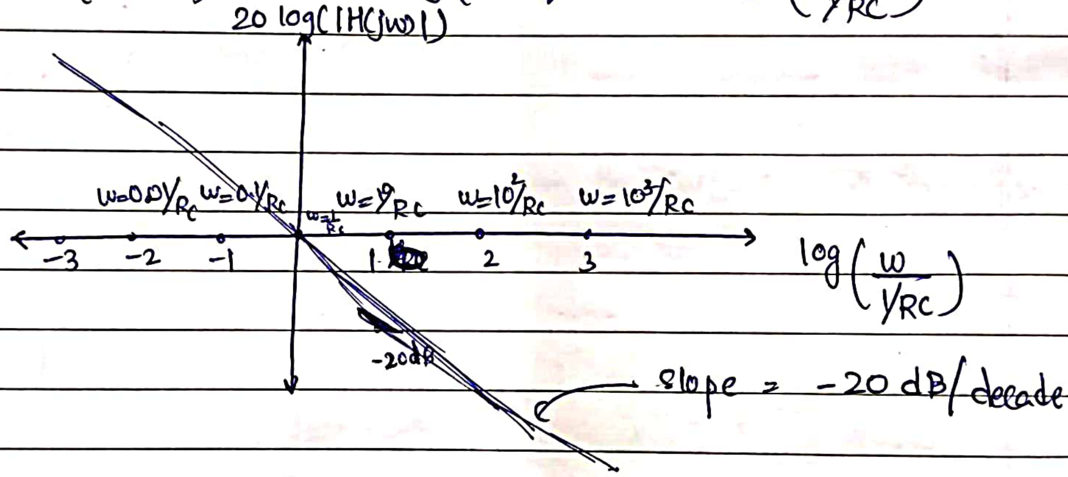
Tranfer $f^n c$ →



$$\frac{V_{in}-0}{R} = \frac{0-V_{out}}{1/sC} \Rightarrow \boxed{V_{out} = \left(\frac{-1}{RCs}\right)V_{in}}$$

$$H(j\omega) = \frac{-1}{RCj\omega} \Rightarrow |H(j\omega)| = \frac{1}{RC\omega}$$

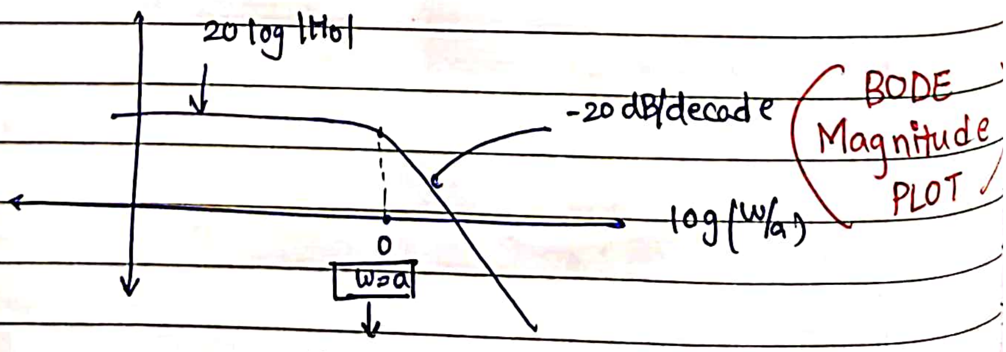
$$20\log(|H(j\omega)|) = -20\log(RC\omega) = -20\log\left(\frac{\omega}{1/RC}\right)$$



$$H(j\omega) = \frac{H_0}{1+j\omega/a}$$ ~~$|H(j\omega)| = 20\log|H_0| - 20\log|1+j\omega/a|$~~

$$20\log|H(j\omega)| = 20\log|H_0| + 20\log\left|\frac{1}{1+j\omega/a}\right|$$

$\omega=a$ cut off frequency of a low-pass filter



$\boxed{\omega=a}$ 3 dB cutoff frequency

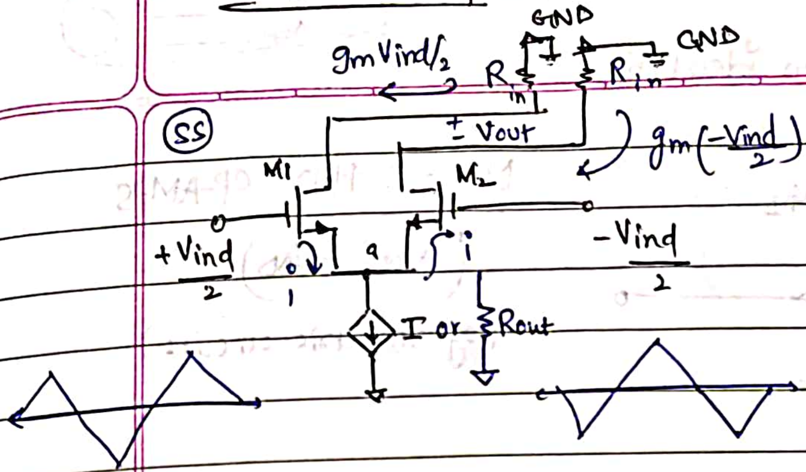
$$20\log|H_0| + 20\log\left|\frac{1}{\sqrt{2}}\right| \quad \text{at } \omega=a$$

$\omega=a$ → cut-off frequency

$$20\log|H_0| - 3$$

OP-AMP IC Analysis

(SS)



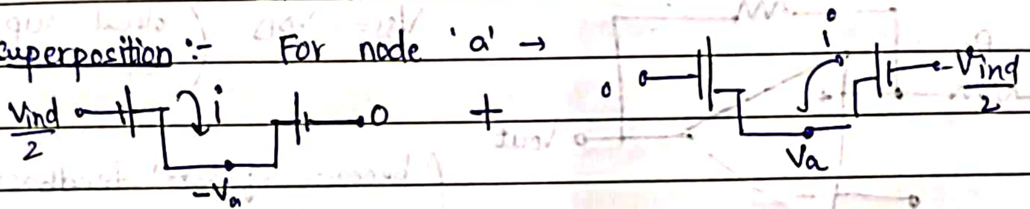
→ The voltage at node 'a' won't change
↓
2 symmetric transistors & resistors

→ This is a small-signal model. ⇒ (a) is a common-node

→ if $(V_{gs})_1$ and $(V_{gs})_2$ have opposite polarities

$\xrightarrow[s1]{} \overset{\bullet}{a} \xrightarrow[s2]{}$ s1 and s2 are same.

⇒ superposition :- For node 'a' →



→ current changes its dir^n, Va changes its polarity

→ superpose :- $\boxed{V_a = 0}$

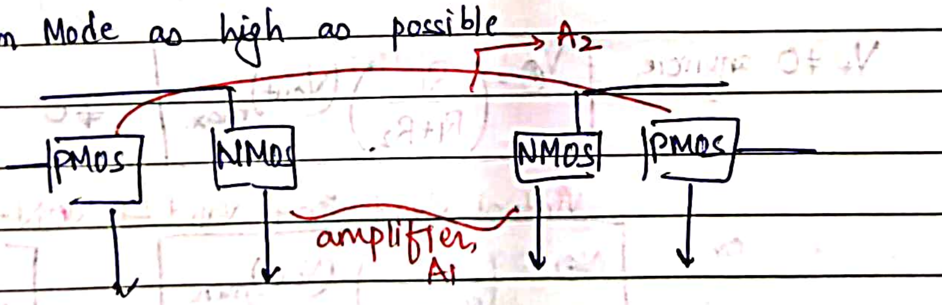
$$V_{out} = g_m \left(2 \cdot \frac{V_{ind}}{2}\right) \Rightarrow g_m V_{ind}$$

→ In Common-Mode → $i \neq 0$ through Rout

so,

$$\boxed{V_{out} = -(g_m V_{id}) \cdot R_{in}} \longrightarrow \boxed{\text{CS Amplifier}}$$

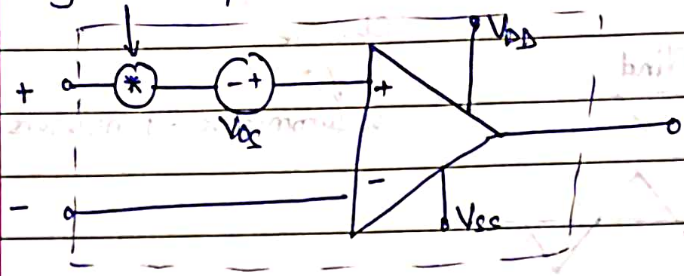
→ Common Mode as high as possible



currents from A1 & A2 are added up

More Op-Amp Non-idealities

Any internal/external noise



DUAL-SUPPLY OP-AMPS

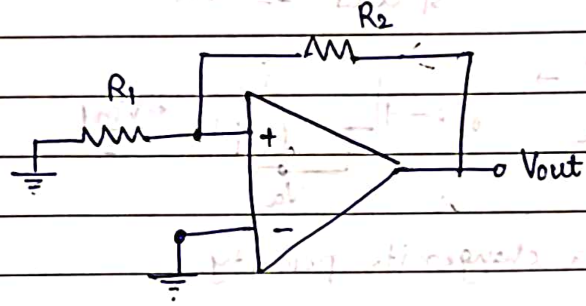
($V_{SS} = -V_{DD}$)

~~(symmetric circuits)~~

V_{offset} → reason for putting it is due to all 'internal mismatches' [represents all internal mismatches]

↳ DC ; ~ few mV. (best)

Familiar Config but with +ve feedback



$V_{SS} = -V_{DD}$ (dual supply op-amp)

(because of (+ve) feedback, + and - terminals don't have the same voltage.

$V_+ \Uparrow$ → $V_{out} \Uparrow$ → more I flows → $V_+ \Uparrow\Uparrow$

if output slightly increases → it keeps on increasing → clamped to + or - VDD.

$V_{out} = (V_{out})_{max}$ or $(V_{out})_{min}$

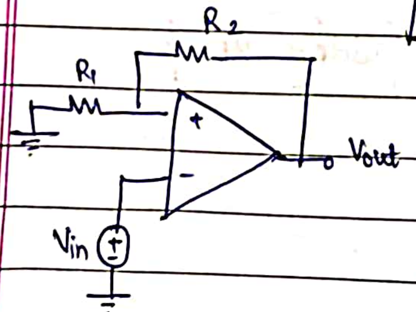
depends on NOISE → +ve noise, -ve noise } both create a regenerative loop.

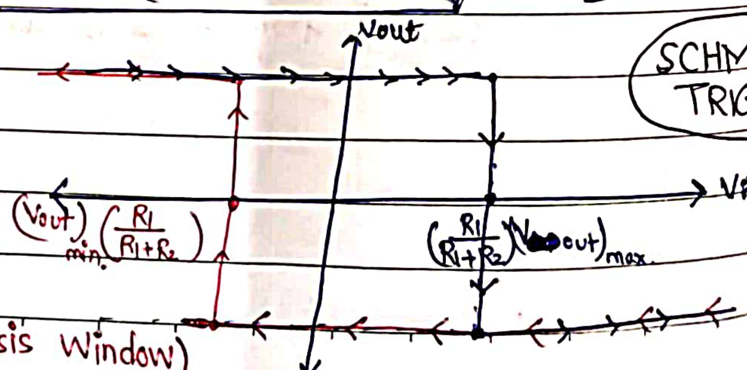
$V_+ \neq 0$ anymore, $\boxed{V_{\oplus} = \left(\frac{R_1}{R_1+R_2}\right)(V_{out})_{max}}$ $\neq 0$ $\left[\begin{matrix} V_{\oplus} > V_{\ominus} \\ V_{out} = +V_{DD} \end{matrix}\right]$

Virtual short isn't valid ⇒ NON-LINEAR OP-AMP

or $\boxed{V_{\oplus} = \left(\frac{R_1}{R_1+R_2}\right)(V_{out})_{min}}$ $\left[\begin{matrix} V_+ < V_- \\ V_{out} = -V_{DD} \end{matrix}\right]$

(Comparator)





SCHMIDT TRIGGER

(Hysteresis Window)

input is heavily (-ve) → $\underbrace{V_{in}}^{\text{very -ve}} < V_+$ as V_+ is either $\left(\frac{R_1}{R_1+R_2}\right)(V_{DD})$ or $\left(\frac{R_1}{R_1+R_2}\right)(-V_{DD})$

↳ $V_{out} = (V_{out})_{max}$

when, $V_{in} = \left(+\left(\frac{R_1}{R_1+R_2}\right)V_{DD}\right)^+$ → $V_- > V_+$

⇒ $V_{out} = (V_{out})_{min}$

when they are equal → op-amp gain becomes ∞ → slight change in input causes a change in Vout.

⇓

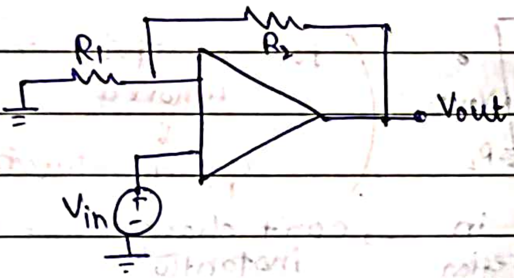
$\boxed{\text{Hysteresis window}}$ → uncertainity

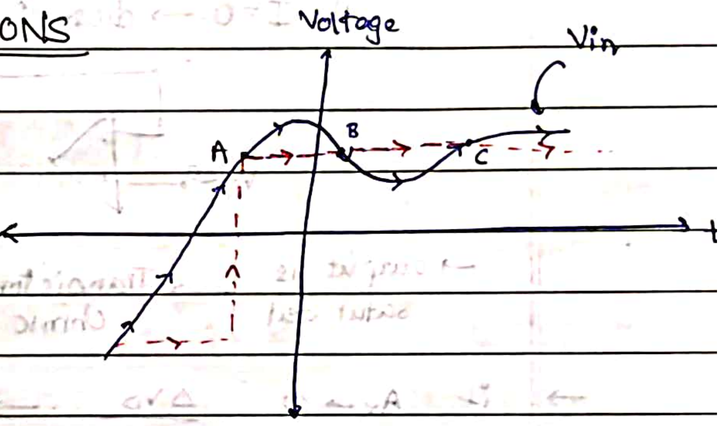
↓

if the input is b/w $\left(\frac{R_1}{R_1+R_2}\right)(-V_{DD})$ and $\left(\frac{R_1}{R_1+R_2}\right)V_{DD}$,

we don't know what Vout is

SCHMITT TRIGGER APPLICATIONS





NOISE fluctuations etc. → output of Schmitt Trigger doesn't change.

A → B → C
⇓
Here the input reduces but output remains same.

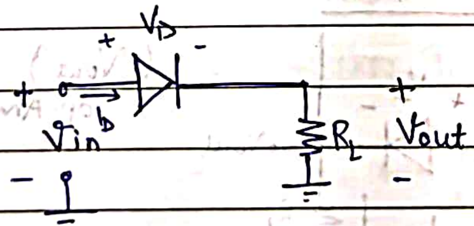
Hysteresis window ⟷ b/w the window of noise

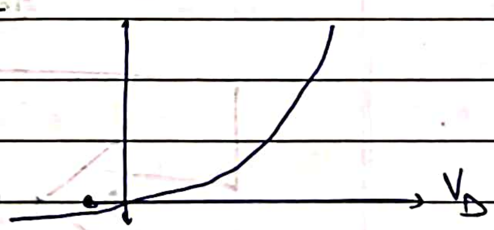
1) shape output

2) Reduce fluctuations.

NON-LINEAR ELEMENTS

DIODE (rectifiers)





pass +ve & block -ve, but $V_D \neq 0$

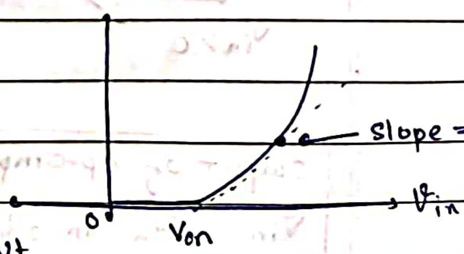
↓

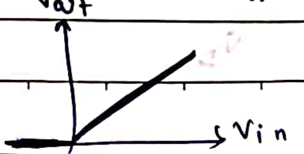
some part of input signal isn't transmitted

when diode is on,

$V_{out} = V_{in}$

$\Rightarrow \left(\frac{\Delta V_{out}}{\Delta V_{in}} = 1\right)$





ideally expected

Date ____
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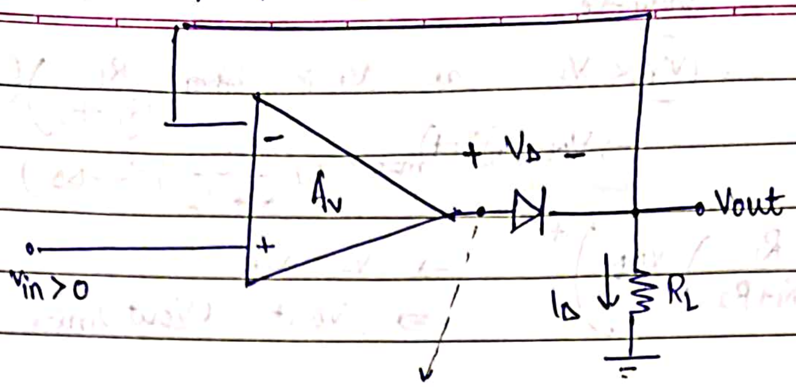
(Dual Supply Op-Amp)



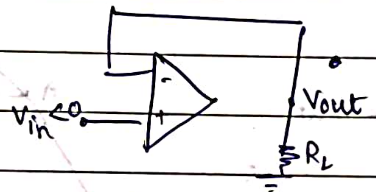
Here, $(\Delta V_{in} - R_L \Delta I_D) A_V - \Delta V_D = R_L(\Delta I_D)$

So, $\Delta I_D R_L (1 + A_V) = A_V \Delta V_{in} - \Delta V_D$

$$\boxed{(\Delta I_D) R_L = \frac{\Delta V_{in} \times A_V}{(1+A_V)} - \frac{\Delta V_D}{(1+A_V)}}$$

small signal equation.

if $I = 0$ → diode is broken (input is -ve) → output = 0



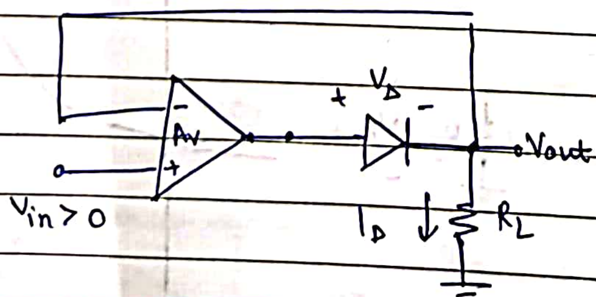
(for -ve inputs, feedback is removed ↓ op-amp saturates)

→ output is saturated → Transistors in ohmic region → can't change instantly → open-loop current

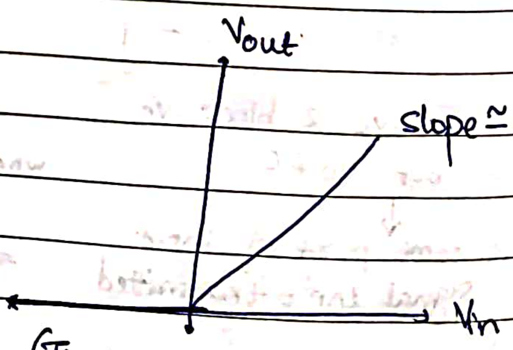
→ if $A_V \to \infty$ $\quad \frac{\Delta V_D}{(1+A_V)} \to 0$

loop-gain = A_V, $\beta = 1$

Simple Half-wave Rectifier using Diode And Op-Amp in the Feedback



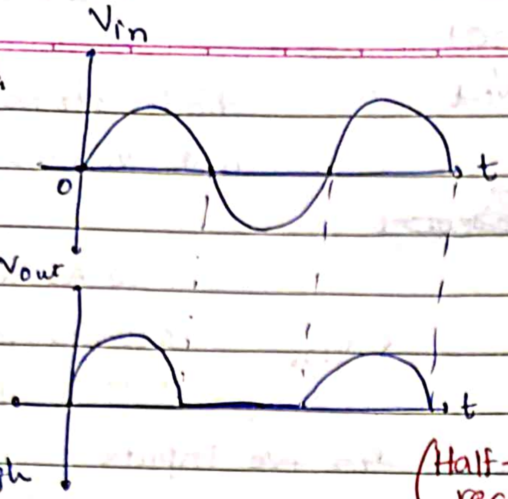
$(V_{out})_{\text{op-Amp}} = V_D + V_{in}$



Output of op-amp follows V_{in} with an additional V_D.

(Turn-on Voltage is very low)

→ (energy-harvesting)



avg.=0

avg.≠0

(Half-wave rectifier)

remove -ve cycles to increase average
↳ pass-through low-pass filter & generate DC.

we don't need to know V_D explicitly if $A_v \to \infty$.

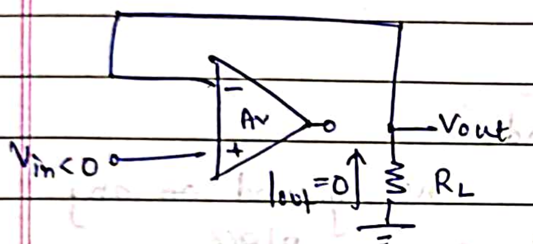
effective turn-on voltage → 0

For -ve input ⇒ output → 0

DIODE IS OFF
(I = 0)
(or I<0)

diode will be off (as inp. <0)

→ When $V_{in} < 0$



⇒ HALF-WAVE Rectifier

Op-Amp gets saturated → Speed limitation
(No feedback)

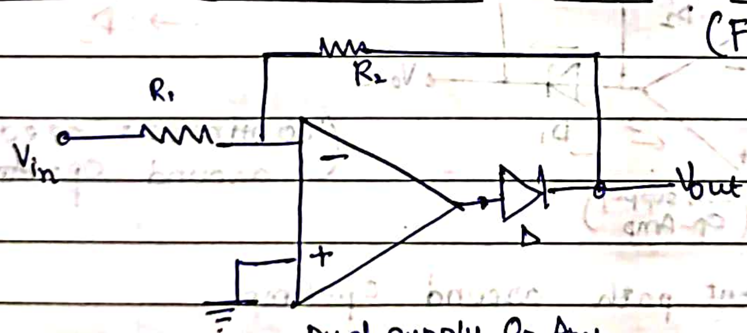
Transistors ON→OFF
⇓
If the frequency of sine wave is very high → waveform distorts

parasitic capacitance of diode

Transistors in op-amp.

(HIGH FREQ. → OP-AMP not the best choice)

INVERTING OP-AMP BASED SIMPLE HALF-WAVE RECTIFIER
(FULL)



Dual supply Op Amp

Problem:
$\boxed{R_2 \text{ is load}}$

$\boxed{V_{in} < 0 \ : \ D \text{ is ON}}$

$V_{out} = -\left(\frac{R_2}{R_1}\right) V_{in}$

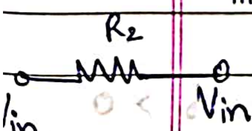
$\boxed{V_{in} > 0 : D \text{ is OFF}}$

$V_{in} < 0$: $V_{out} > 0$ I: Right to left in R_2 ⇒ I from →|▷|→ in diode

D is ON ← D can conduct

$V_{in} < 0$: $V_{out} = \left(-\frac{R_2}{R_1}\right) V_{in}$

$V_{in} > 0$: $V_{out} = V_{in}$
⇓
when diode is off, Op Amp is in OPEN-LOOP

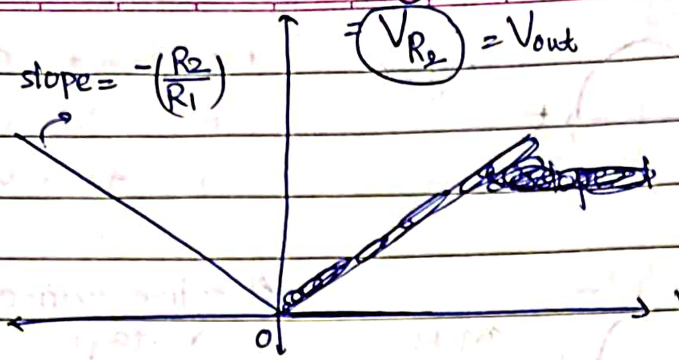


load → connected b/w output & virtual ground
↳ can't connect directly from output to ground → ~~always will have a resistance~~ path from Vin to GND.

Voltage across R_2 connected to virtual GND

$V_{out} - V_{\ominus}$ $(V_- = 0)$

$= V_{R_2} = V_{out}$

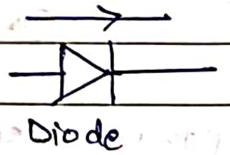


diode stops conducting with $V_{in} < 0$.

DUAL Version is always possible by changing dir^n of diode

→ we can change the dir^n of diode → conduct for +ve inputs.

→ as no current in op-amp, no current in R_2 ⇒ $V_{out} = 0$.



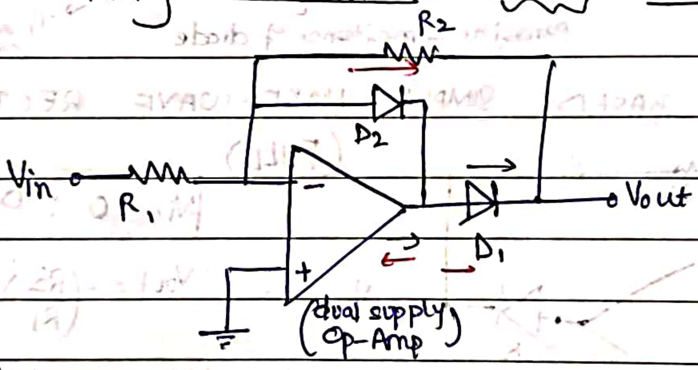
conducts in this dir^n only

Limitations → 1) 'R_2' is the load, not ground on any place

V_{in} —R_2— V_{in}

2) Speed limitation.

Overcoming Limitations :- MORE clamping diodes in HWR



→ : D_1

→ : D_2

(continuous feedback around Op-Amp)

bidirectional - current path around Op-Amp

both can't be ON at the same time

$V_{in} < 0$: $D_1 \to$ ON, $D_2 \to$ OFF, $V_{out} = -\left(\frac{R_2}{R_1}\right) V_{in} > 0$

$V_{in} > 0$: $D_1 \to$ OFF, $D_2 \to$ ON, $V_{out} = 0$

$\boxed{V_{in} < 0}$

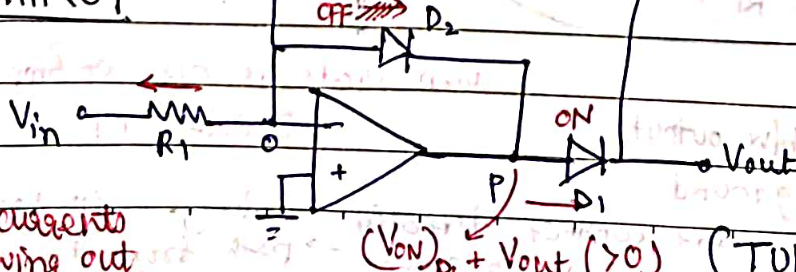
assume

→ R_2

→ D_2

← R_1

⊗ all currents flowing out.



$(V_{ON})_{D_1} + V_{out}$ (>0)

$V_{out} > 0$

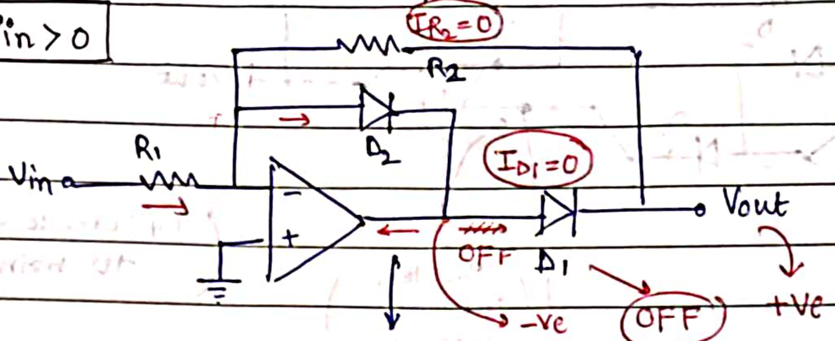
at P, $V = V_{out} + V_D > 0$

↓

D_2 can't conduct (TURN OFF) $\boxed{I_{D_2} = 0}$

D_2: Keep feedback loop 'active' when D_1 is OFF.

$\boxed{V_{in} > 0}$



(Output of op amp is -ve) (OpAmp sinks the current)

D_1 : OFF

D_2 : ON.

Op Amp remains in closed loop

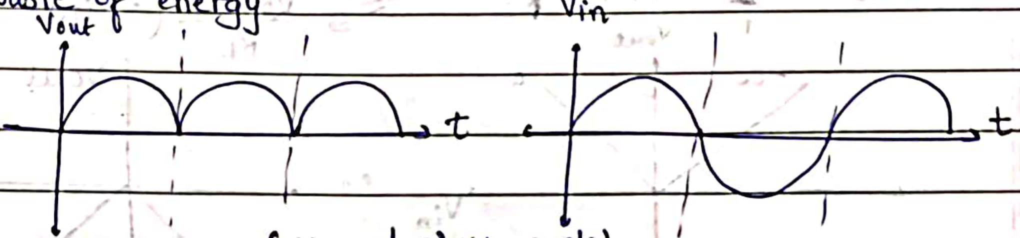
$\boxed{V_{out} = 0}$

(R_2 is good to be a load.)

FULL-WAVE RECTIFIER
(FWR)

HWR: waste of energy

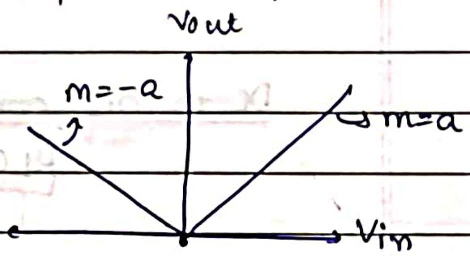
FWR
$\boxed{V_{out} = |V_{in}|}$

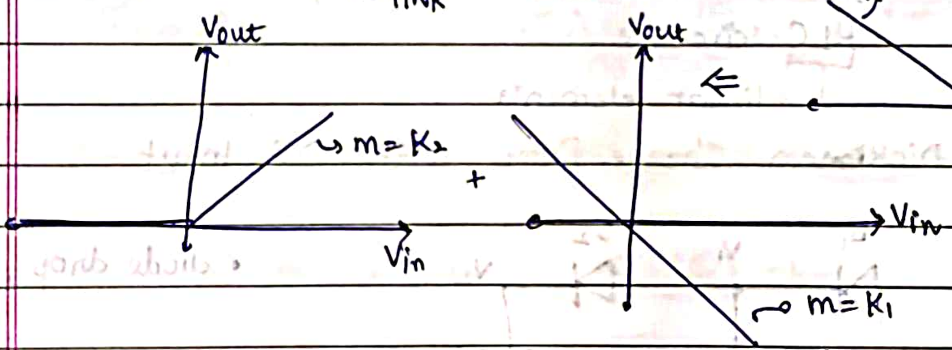


(-ve cycle ⇒ +ve cycle)

→ (Circuit → gives you absolute value of the input as output)

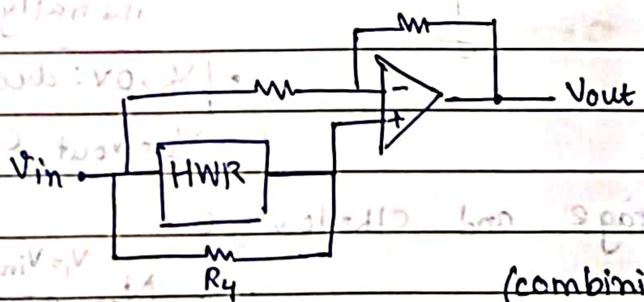
$V_{out} = K_2 (V_{in})_{HWR} + K_1 (+V_{in})$





(linear circuit)

L.C such that slope remains 'a' always. (opp. polarity, same magnitudes)



HWR + Non-inverting Amplifier

(R_4 → WHY?)

(combining the two parts)

(Dual Supply Op-Amps)

Date ______
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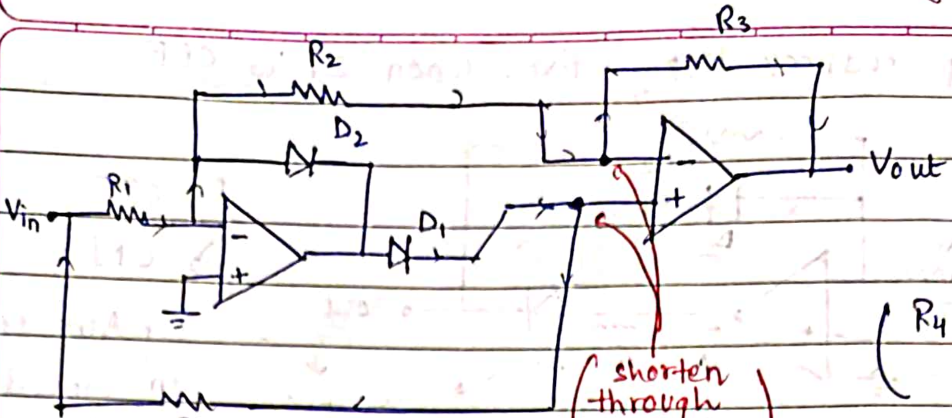


shorten through Virtual ground

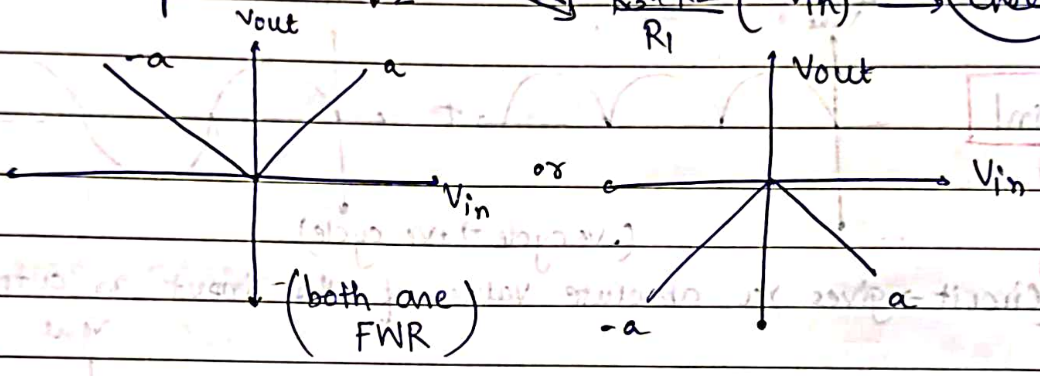
(R_4 : create a path to bring V_{in})

To get the non-inverting amplifier

I_{R_2} : output I of the HWR

→ $V_{in} > 0$: $D_1 \to$ ON, $D_2 \to$ OFF $\Rightarrow$ $\boxed{V_{out} = \left(1 + \frac{R_3}{R_2}\right) V_{in}}$ ($V_{in} > 0$)

$V_{in} < 0$: $D_1 \to$ OFF, $D_2 \to$ ON $\Rightarrow$ $\frac{R_3 + R_2}{R_1}(-V_{in}) \longrightarrow$ check

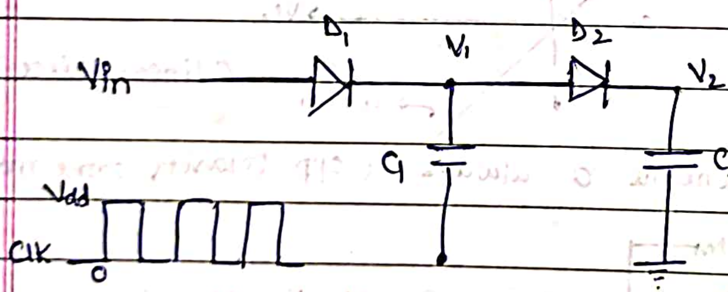


(both are FWR)

<u>DC to DC conversion using Diode-Capacitor Network</u>

RLC circuits
└→ linear elements

<u>2-stage Dickson Charge Pump with DC Input</u>



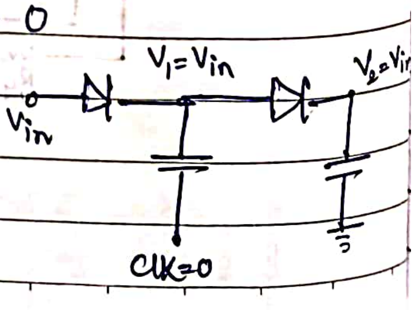
- diode drop, $V_D = 0$ (ideal)
- capacitors are initially uncharged
- $\boxed{V_D > 0V : \text{diode is 'ON'}}$
- $V_2 = V_{out}$, $C_1 = C_2 = C_c$.

→ Vin is a low DC Voltage and Clk = low = 0

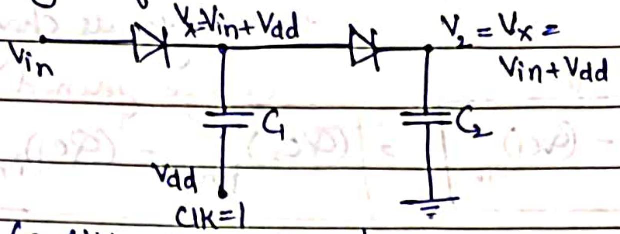
→ $V_1 = V_2 = V_{in}$

Q across each capacitor, $Q_1 = Q_2 = C_c V_{in}$

Total charge $Q_{T\_low\_clk} = 2 C_c V_{in}$



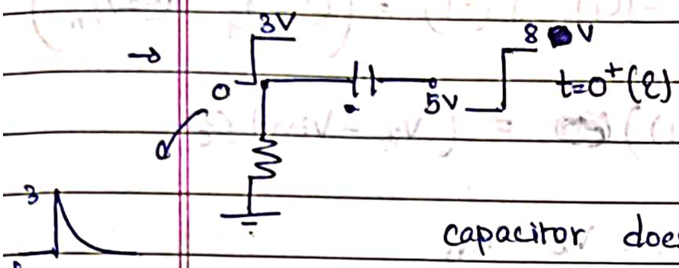
charge of $+V_{DD}$ at the node of C_1 $\longrightarrow$ so $V_1 = V_{in} + V_{dd}$

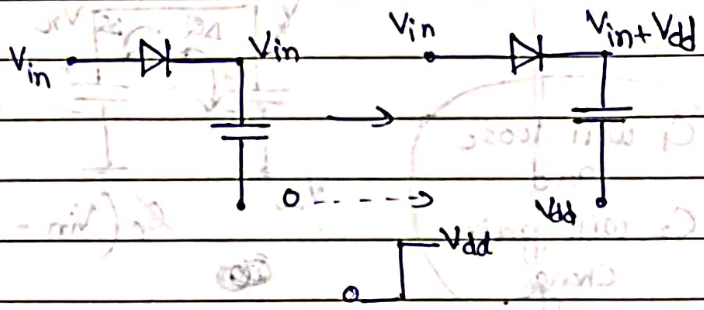


Here, $V_1 = V_2 = V_x$

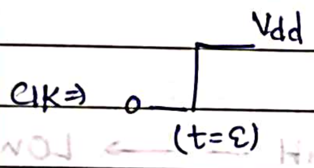
(a little after rising edge)

$(\tau \to 0)$



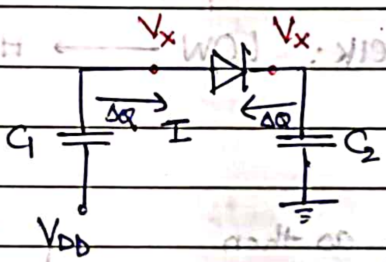


capacitor doesn't allow voltage difference across it to change



$V_1 = V_{in} + V_{dd}$ $\longrightarrow$ $\boxed{D_1 : OFF}$

$\longrightarrow$ $\boxed{D_2 : ON}$



(steady state?)

I : same

Q : same

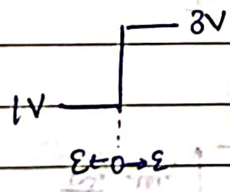
~~$(I_{I\ to\ R})$ or I branch~~

$(Q_{C1})_{(n)} = (Q_{C1})_i + \Delta Q$

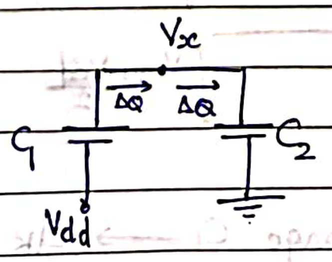
Huge current flows b/w two capacitors.

$\downarrow$

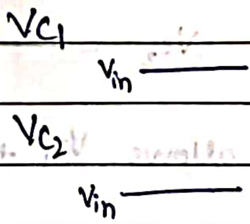
impulsive current $\Rightarrow$ (ΔQ) change in charge in $t \to 0$.

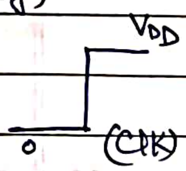


as $\left(\Delta t \to 0 \quad C\frac{dV}{dt} \to \infty \quad I \to \infty \right)$



$V_{C1} = V_{C2} = V_{in}$ (initially)





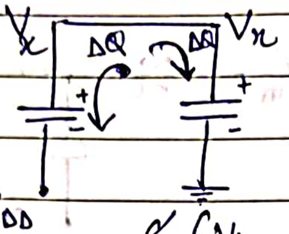
both can't be $V_{in} + V_{dd}$ as both can't be sourcing current.

CHARGE CONSERVATION

if one capacitor changes its charge → the other one also has to change its charge.

charge lost | change gained

$$(\Delta Q_{C_1}) = \boxed{(Q_{C_1})_{final} - (Q_{C_1})_{in}} = \boxed{(Q_{C_2})_{final} - (Q_{C_1})_{in}}$$



C1 will loose and C2 will gain charge.

CHARGE CONSERVATION

$$\left((C_1)_f - (C_1)_{in}\right)(-1) = \left((C_2)_f - (C_2)_{in}\right)$$

$$\cancel{C}\left(V_{in} - (V_x - V_{dd})\right) = (V_x - V_{in})\cancel{C}$$

$$-V_x + V_{dd} + V_{in} = V_x - V_{in}$$

$$2V_x = 2V_{in} + V_{dd}$$

$$\boxed{V_x = V_{in} + \frac{V_{dd}}{2}}$$

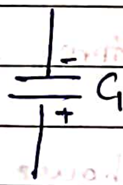
Now, when ClK: LOW ⟶ HIGH ⟶ LOW

$V_1 \to V_{in}$

$V_2 \to V_{in} + \frac{V_{dd}}{2}$

(V_x can't be $V_{in} + V_{dd}$ as then Q_{C_1} = constt but Q_{C_2} has increased)

D2 is OFF



(polarity also may reverse)

$$V_{C_1}(0^+) = \left(V_{in} + \frac{V_{dd}}{2}\right) - (V_{dd}) = V_{in} - \frac{V_{dd}}{2}$$

$$V_{C_2}(0^+) = \left(V_{in} + \frac{V_{dd}}{2}\right)$$

(diff. = V_{dd})

⇒ ClK is LOW ⟶ allows V_{in} to charge C_1 ⟶ clK is high

Transfer charge to C_2

(condition most be used if there is a voltage drop also)

→ After many cycles, V_x becomes so high that D_2 can never be ON.

Clk → C_2 charges   Vin → C_1 charges.

⇒ K- CYCLES

$$V_2 = V_{in} + \left(\frac{V_{dd}}{2}\right) + \left(\frac{V_{dd}}{2^2}\right) + \dots + \frac{V_{dd}}{2^K}$$

so, $\boxed{V_2 = V_{in} + V_{dd}\left(1 - \frac{1}{2^K}\right)}$ $\xrightarrow{K\to\infty}$ $\boxed{V_2 = V_{in} + V_{dd}}$

2nd cycle

$$\cancel{C}\left(V_{dd} - V_x + V_{in}\right) = \left(V_x - \left(V_{in} + V_{dd}/2\right)\right)\cancel{C}$$

$$2V_x = 2V_{in} + V_{dd} + \frac{V_{dd}}{2} \Rightarrow V_x = V_{in} + \frac{V_{dd}}{2} + \frac{V_{dd}}{2^2}$$

and so on.

For $V_{in} \simeq V_{dd}$ ⇒ $\boxed{V_2 \simeq 2V_{out}}$

⇒ we can stack them such that V_2 is a GND of next stage

→ Uses of the circuit → 1) NO supply needed
2) Instead of a clock, an AC signal can be used.

Sine wave (AC) (which can go -ve) → (Vin=0 also works here) → output (DC)

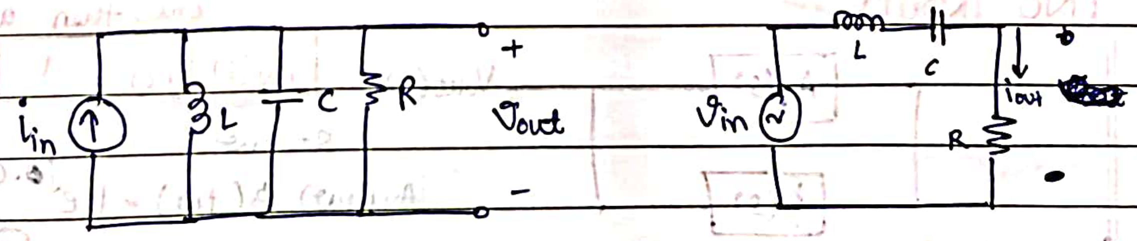
$V_{in} = 0$
Clk: min. value ≠ 0

$V_{DD}/2$, $-V_{DD}/2$ → get a DC output

$\boxed{\text{AC to DC converter}}$ → without any supply

OSCILLATORS

RLC circuits →



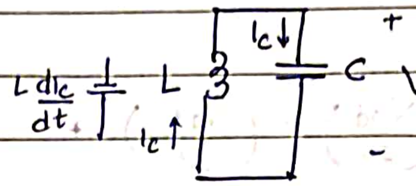
parallel-RLC   Series - RLC

the only lossy element : resistor

(never can have a sustainable oscillation with a lossy element)

Parallel RLC : $R \to \infty$ Series RLC : $R \to 0$

$$I_c = C\frac{dV_c}{dt}$$



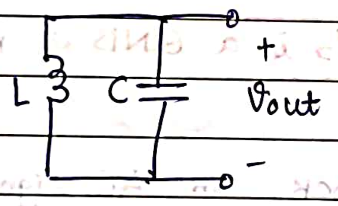
$$V_c = -L\frac{dI_c}{dt}$$

$$V_L = -V_c = L\frac{dI_c}{dt} \qquad -V_c = L\frac{dI_c}{dt}$$

$$-\frac{dV_c}{dt} = L\frac{d^2 I_c}{dt^2}$$

$$\Rightarrow \boxed{I_c + LC\frac{d^2 I_c}{dt^2} = 0} \qquad \boxed{\text{resonance}}$$

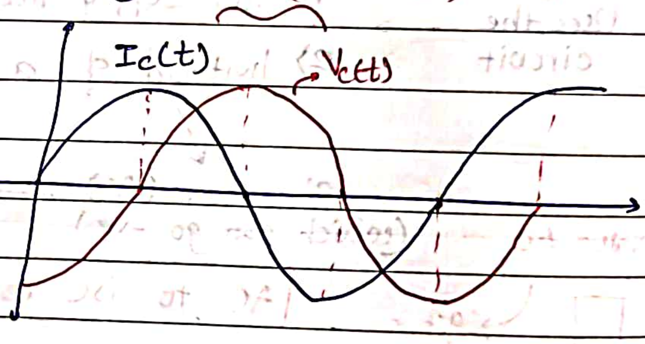
(exchange of energy b/w inductor & capacitor)



$$V_{out} = \frac{1}{C}\int I \cdot dt \quad (\Delta\phi = -90^\circ)$$

$I_c(t) = I_{cm}\sin(\omega_0 t)$

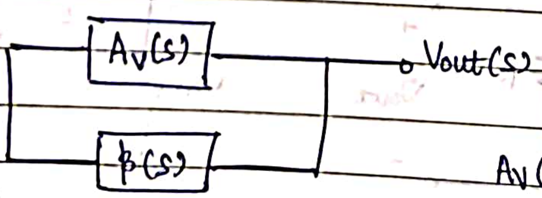
$$\omega_0 = \frac{1}{\sqrt{LC}}$$



To compensate losses $\Longrightarrow$ Active elements to supply energy

Oscillation Based On Linear Feedback

(NO INPUT)



(+ve feedback)

only then an oscillator $\boxed{A_v(s)\beta(s) = 1}$

$s = j\omega$,

$$A_v(j\omega)\beta(j\omega) = 1 \cdot e^{j0.0}$$

$$\boxed{|T(j\omega)| = 1} \quad \boxed{\angle T(j\omega) = 0}$$

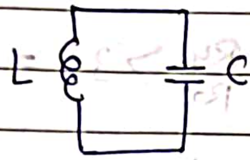
(Barkhausen's Criteria)

Date
Page

if $A_v(s)\beta(s) > 0 \longrightarrow$ non-linear
$< 0 \longrightarrow$ oscillations decay down

Barkhausen's Criteria $\Rightarrow$ $\boxed{|T(j\omega)| = 1}$ $\boxed{\measuredangle T(j\omega) = 0}$ ($T(j\omega)$: loop gain)

Lossless Circuit

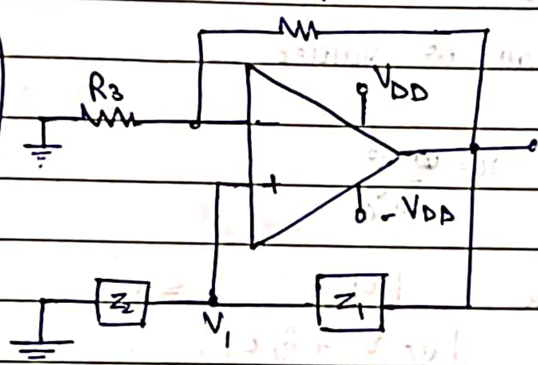


LC oscillator $\longrightarrow$ energy only transfers, NO LOSS.

WIEN-BRIDGE OSCILLATOR

(Ideal Op-Amp)

(1 op-amp + 2 resistances + 2 impedances)



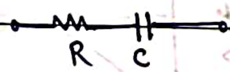
$V_+ = V_-$

$$\frac{V_{out}\cdot Z_2(s)}{Z_1(s)+Z_2(s)} = \frac{V_{out}\cdot R_3}{R_3+R_4}$$

$$\boxed{\frac{Z_2(s)}{Z_1(s)+Z_2(s)} = \frac{R_3}{R_3+R_4}}$$

Z_1, Z_2 are made of R, C elements.
↳ avoid inductors as (integrated) circuits are NOT energy-efficient.
inductors in CMOS are lossy → E-friendly and not B-friendly

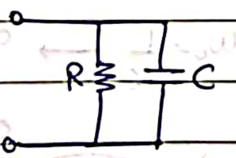
(simplest)
Z_1: First-order series to open +ve feedback at $s=0$.



(Series RC)

Z_1: open → series RC
Z_2: close → bias the terminal at DC
↓
be connected to the GND

Z_2: First-order parallel R-C + bias +ve terminal at DC



FOR DC

$$V_1(s) = \frac{\left(\frac{R}{RCs+1}\right)}{\left(\frac{R}{RCs+1}\right)+\left(R+\frac{1}{sC}\right)} \quad V_{out} = \frac{RCs}{RCs + RCs(1+RCs) + RCs + 1}$$

$$V_1(s) = \frac{RCs}{R^2C^2s^2 + 3RCs + 1} \quad \frac{V_{out}(s)}{}$$

$V_{out}(s) = K\cdot V_1(s)$ $K = 1 + \frac{R_4}{R_3}$

So,

$$\left(\frac{jRC\omega}{(1-R^2C^2\omega^2)+3jRC\omega}\right)\times(K)=1$$

Loop-Gain $=1$

$$\omega=\omega_0=\frac{1}{RC}\Rightarrow T(j\omega_0)=\frac{K}{3}$$

practical condition

Then, $\frac{K}{3}\geq 1 \Rightarrow K\geq 3 \Rightarrow 1+\frac{R_4}{R_3}>3 \Rightarrow \boxed{\frac{R_4}{R_3}>2}$

$\left(|T(j\omega)|\leq\frac{K}{3}\text{ for all }\omega\text{ values}\right)$

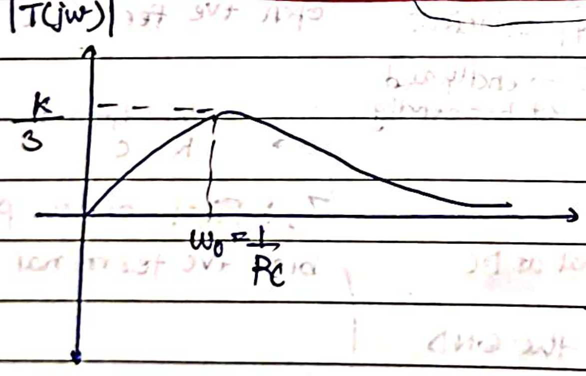
$$|T(j\omega)|\leq\frac{K}{3}\quad\text{for all }\omega\text{ values}$$

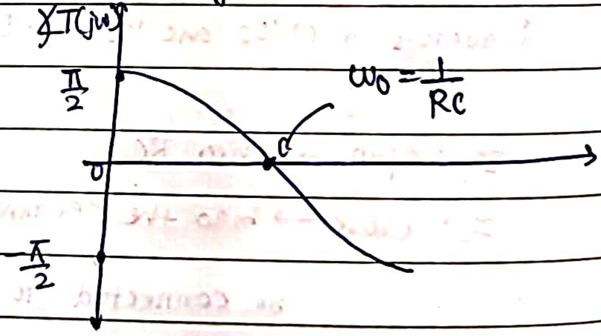
Consider $\boxed{x=RC\omega}$ or $x=\frac{\omega}{\omega_0}$

Then, $|T(j\omega)|=K\frac{|x|}{|(1-x^2)+3jx|}\leq 1$

$$\boxed{|T(j\omega)|=\frac{K|x|}{|(1-x^2)+3jx|}}$$

always ≤ 1.





$\omega=\omega_0=\frac{1}{RC}\longrightarrow$ only frequency where the phase of loop-gain $=0$.

(Barkhausen's criteria)

eg.- Target value of oscillation frequency $=20\text{ KHz}$

$$\omega_0=2\pi\times 20\text{ KHz}\Rightarrow\frac{1}{RC}=2\pi\times 20\text{ KHz}\Rightarrow\boxed{RC=8\,\mu s}$$

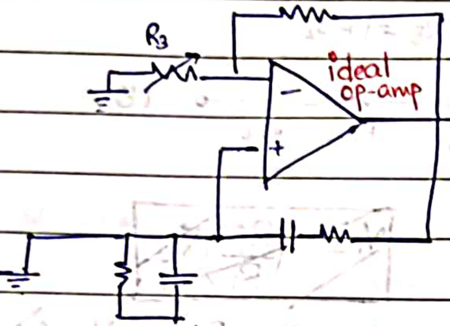
$1 + \frac{R_4}{R_3} = 3 \Rightarrow \frac{R_4}{R_3} = 2 \rightarrow$ Start Value

(has one-side grounded.)

$R = 40\,K\Omega \Rightarrow$

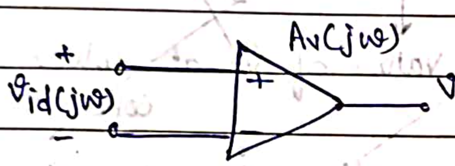
$C = 400\,pF$

$R_4 = 20\,K\Omega \rightarrow$ start $\rightarrow$ change $R_3 = 10\,K\Omega$ and then change until Loop gain = 1



unity-gain frequency of Op-Amp $\gg$ 20 KHz

(magnitude of gain (loop) becomes ONE)



$$\boxed{|A(j\omega)| \simeq \frac{A_{(0)}}{1 + j\omega/P_1}}$$

$\omega \gg P_1$

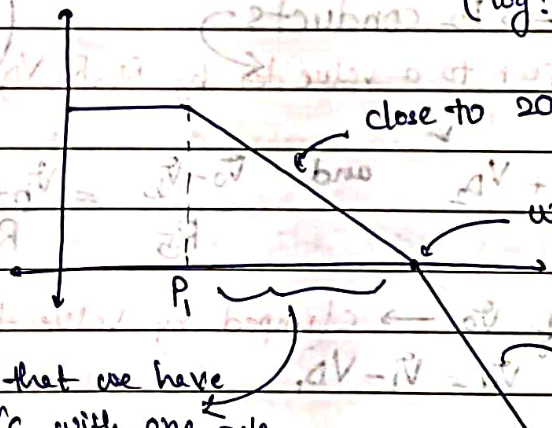
Then, $|A(j\omega)| \simeq \frac{A_{(0)} P_1}{\omega}$

$A_v(0) = 10^4$

$20 \log 10^4 = 80$ dB

$f_1 = 1$ MHz

(∵ log ∴ slope is −ve)



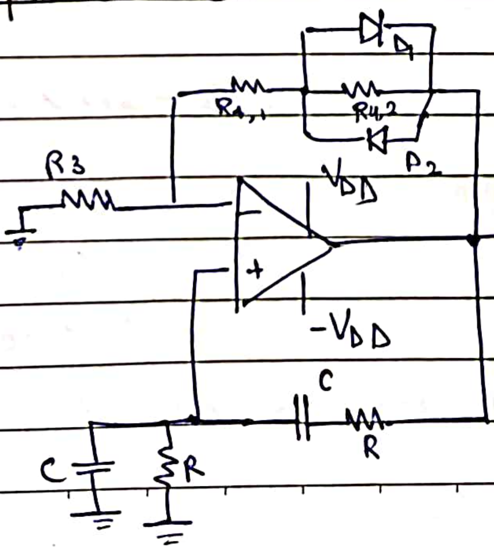
close to 20 dB/dec

$\omega_1 = 2\pi f_1$

40 dB/dec

we assume that we have a Transfer f^n^c with one pole.

Amplitude Control in Wien-Bridge Oscillator



$\Rightarrow$ amplitude of Vout - ?

if $V_{R4,2} \simeq V_{ON,D} \Rightarrow$

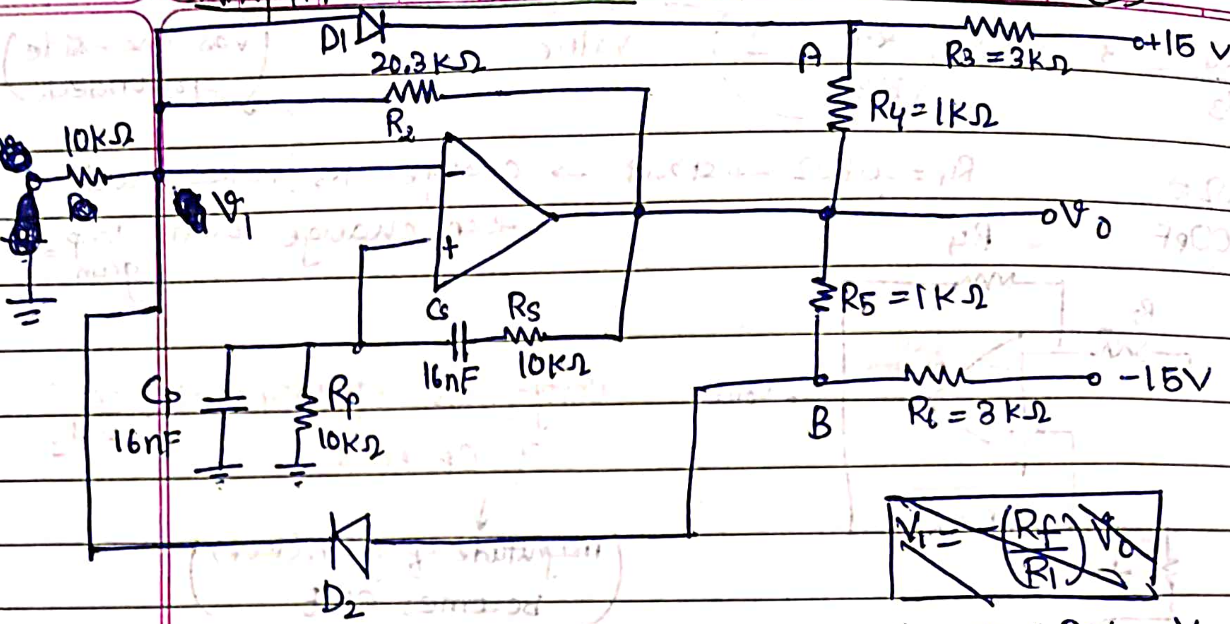
$$\left(\frac{R_{42}}{R_3 + R_{41} + R_{42}}\right) V_{out,lim} \simeq V_{ON,D}$$

So,

$$V_{out,lim} \simeq V_{ON,D} \times \left(\frac{R_3 + R_{41} + R_{42}}{R_{42}}\right)$$

$\frac{R_{41}}{R_3} < 2 \longrightarrow$ oscill^n^ amplitude decays if diode is ON

Amplitude Controller (limiter circuit - A)



~~$V_1 = -\left(\frac{R_f}{R_1}\right) V_0$~~

~~as we see in the limiter circuit,~~ ~~$L- = -V\frac{R_4}{R_3} - V_D\left(1+\frac{R_4}{R_3}\right)$~~ ↓ values of V_0 at which D_1 conducts (lower limit)

~~and $L+ = V\frac{R_5}{R_6} + V_D\left(1+\frac{R_5}{R_6}\right)$~~

~~If $V_1 > -\left(\frac{R_f}{R_1}\right)L- \rightarrow v_A$ remains at $-V_D \Rightarrow i_{R_3} = \text{const.}$~~

→ at the +ve peak of V_0, $V_b > V_1$ ↳ D_2 conducts

$\left(V_1 = V_0/3\right)$

$V_0 - V_b = \frac{V_b + 15}{3}$ $\quad 3V_0 = 4V_b + 15$ $\quad V_b = \frac{3V_0 - 15}{4}$

$5V_0 > 45 \rightarrow V_0 > 9$

clamps the peak to a value det. by R_5, R_6, V_D, -ve power supply

$V_b = V_1 + V_{D_2}$ and $\frac{V_0 - V_b}{R_5} = \frac{V_b + 15}{R_6}$ $\quad V_0 = \left(1 + \frac{R_5}{R_6}\right)\left(V_1 + V_{D_2}\right) +$ CLAMP

→ -ve peak of V_0 → clamped by value that causes D_1 to conduct.
↳ $V_a = V_1 - V_{D_1}$