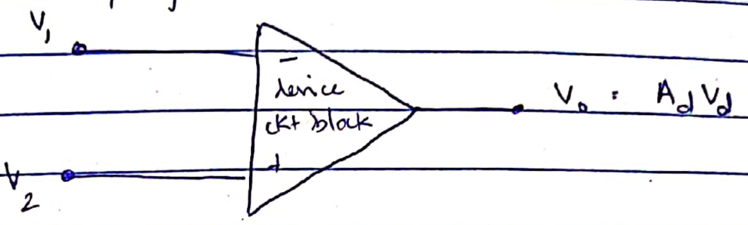
What is IC ?
A device consisting of transistors to perform certain task.

OpAmp Characteristics 17.01.19

Differential Amplifier

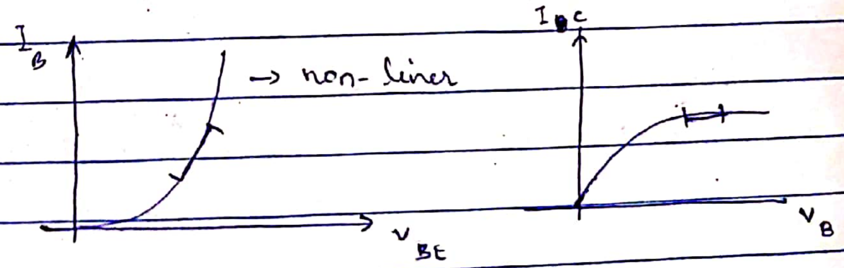


Amplifies the difference in signal.

$$V_d = V_1 - V_2$$

Using BJT and MOS we build a device i.e OpAmp

BJT & MOS are non-linear devices.



Taking the non-linear device we build OpAmp & it is linear

As these non-linear device operate as linear in certain area

The IC is not just amplifing the diff in signal but also the common voltage

$$V_c = \frac{V_1 + V_2}{2}$$

$$V_o = A_d V_d + \cancel{A_c V_c}$$

But we want to just amplify the diff only

$$\text{Common mode reduction ratio} = \frac{A_d}{A_c}$$

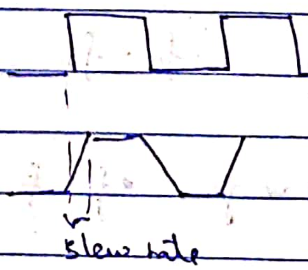
Here A_d must be large & $A_c \downarrow$

NOTE : The larger the CMRR, the better the OpAmp.

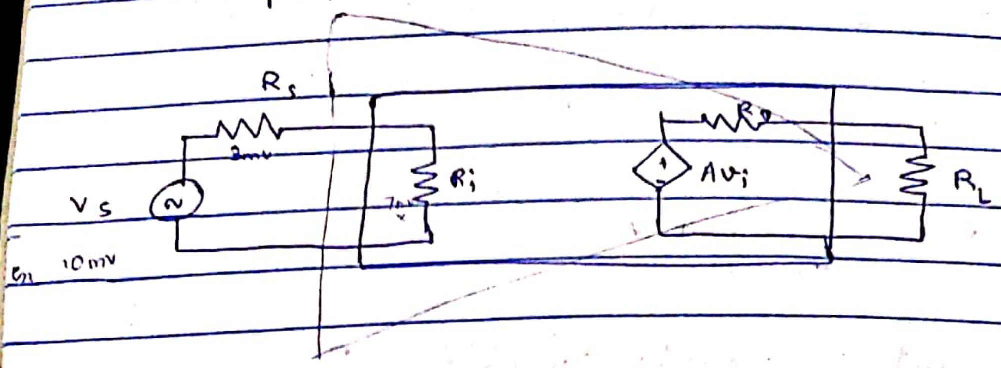
Terminal Characteristics of OpAmp

- Gain : $\overset{\infty}{A_d}$, $\overset{0}{A_c}$
- Input impedance $R_i >>$
- Output impedance $R_o \approx 0$
- Bandwidth
- CMRR
- Slew Rate : The max permissable rate of signal

i/p



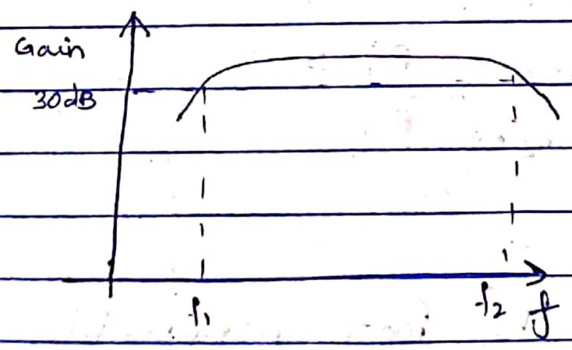
Amplifier model

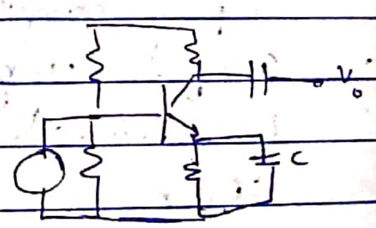


(1) R_i should be very large from R_s because we want the entire voltage to be across R_i

(2) R_o should be 0, as max current should come to R_L

(3) Bandwidth





$\underline{BW} = f_2 - f_1$

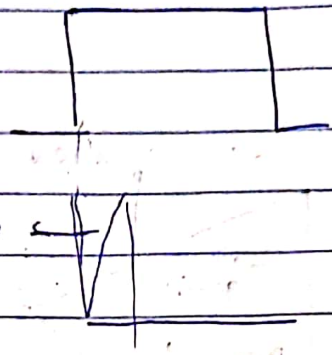
for what range of freq gain is const.

ideally BW should be very large (As it should amplify all freq)

(4) CMRR : ∞ ideal

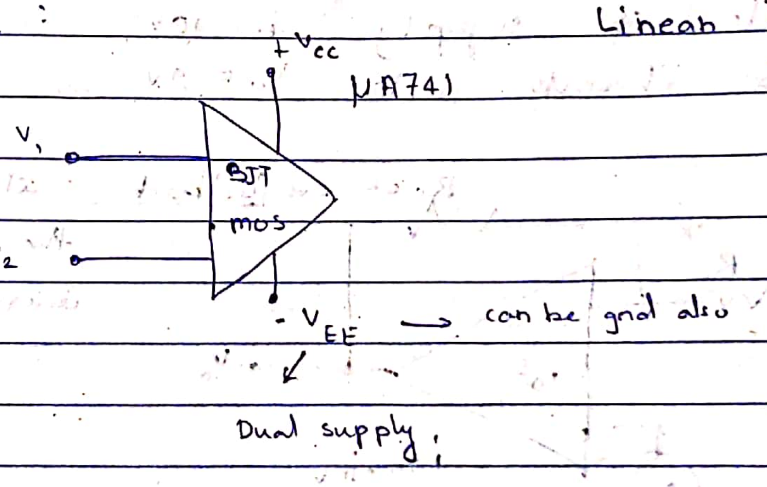
practical values are the one buildt using BJT, MOS i.e 10^4.

(5) Slew rate :



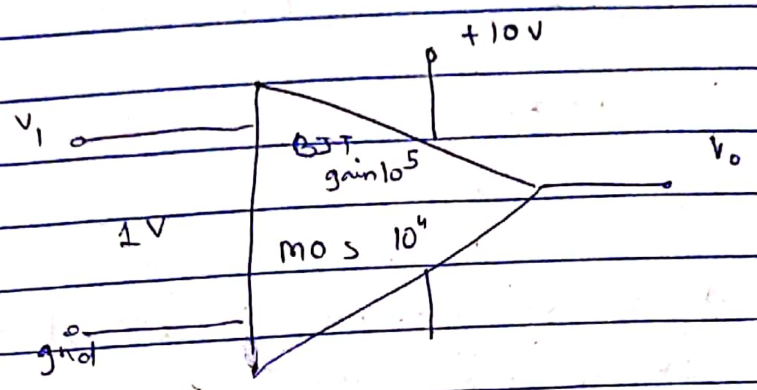
We expect the o/p to come immediately, the rise time should be very less.
Ideally it should be ∞, practical 0.5 V/μs

Device : Linear I.C

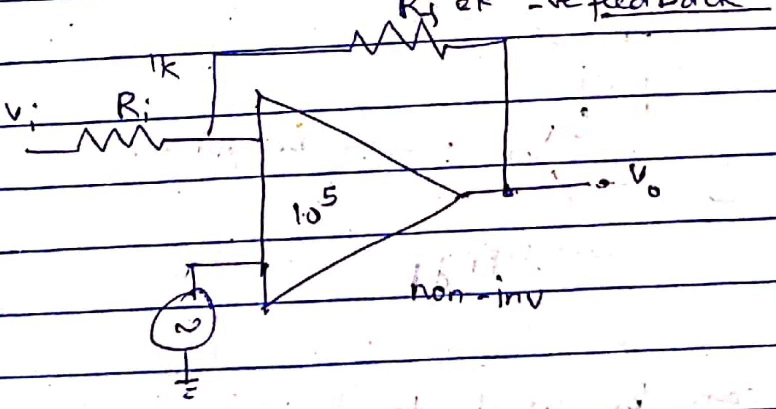


This IC can be used to build
- Inverting Amp
- Non-inverting
- Integrator
- Log
- Add
- Sub
- Differentiation
- Waveform generator
- Filter
- comparator

ckt — linear applications
ckt — non-linear appli



Gain 10^5, but we can't expect V_o to be 10^4 not possible, as supply is 10V.
So thumb rule: $V_o \approx 9V$.



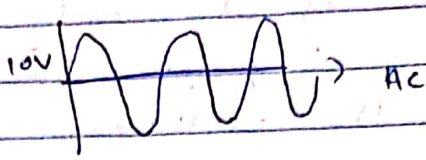
R_f 2k -ve feedback: it reduces the gain & increases bandwidth

$$\text{Gain} = \frac{V_o}{V_i} = 1 + \frac{R_f}{R_i} = 3$$

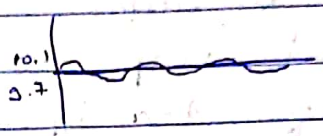
So here we are reducing the gain & ↑ BW

NOTE : OpAmp rejects ripples

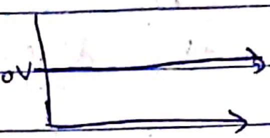
en :



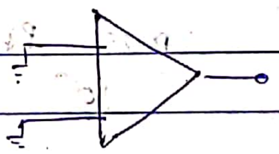
in dc



but in OpAmp



NOTE : Offset error/voltage : If we gnd both v_1 & v_2, then v_0 is expected to be 0, but practically it is not 0, but has some minute voltage.



V_0 = mV → offset.

Questions :

1. What is OpAmp?

→ It is a high gain, low bandwidth amplifier, which amplifies the difference in input voltages.

2. Why name OpAmp?

→ Because it operates only in certain range of frequencies & perfoms many operations

3. What is the difference between OpAmp and convential amp?

→ A convential amp has a single i/p & amplifies the i/p signal while a OpAmp has 2 i/p voltages & it amplifies the difference in i/p signals.

4. When does

6. Discuss the

(i) i/p offset voltage $V_{io} = V_{00}/A_d$

(ii) $R_i = \infty$ ideally

(iii) CMRR = >> ∞ ideally

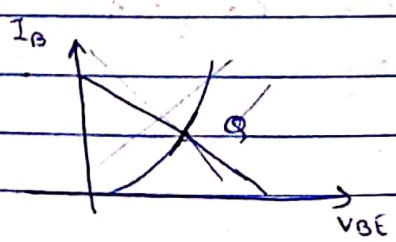
(iv) $V_0 = A_d V_d$

(v) slew rate : ∞ ideally

7.

	Ideal	MOS Practical	BJT
Gain	∞	10^4	10^5
Bandwidth			
R_i	∞		
R_o	0		

4. The OpAmp operates in the linear region of the VI characteristics in CM config.



5. Ideal OpAmp must have.

Gain ∞

R_i ∞

R_o 0

slew rate 0

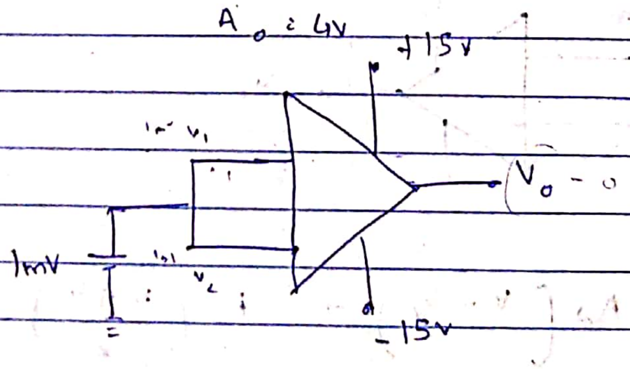
Bandwidth <<

4. When two i/p signals are same, then its diff. $V_d = 0$, so it operates ($V_c = 2V$) in CM configuration.

8. In open loop gain OpAmp, the gain is very high (i.e 10^5, 10^4) which ideally is not possible to achieve, the OpAmp would reach saturation

Eg V_o is not 10^5.

Questions.



But here offset is there 0

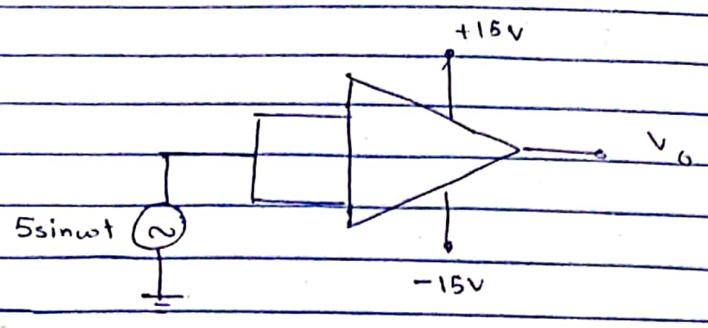
$V_o = \cancel{A_d V_d} + A_c V_c$

$V_o = 10 \times \left(\frac{1m + 1m}{2}\right) + 4$

$= 10 \times (1m) + 4$

$= 4.01\,V$

$A_c = 10$



$$V_o = \cancel{A_d V_d}^{\,0} + A_c V_c$$
$$= 0 + 10 \times (5)$$
$$= 50\,V \longrightarrow \text{not possible}$$

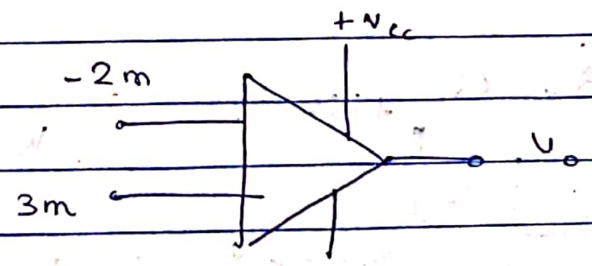
So V_o will be $\approx 15\,V$

(a) $A_d = 10^5$

$A_c = 10$

$V_{00} = 4V$

(i) $V_1 = -2m$ $\quad V_2 = 3m$

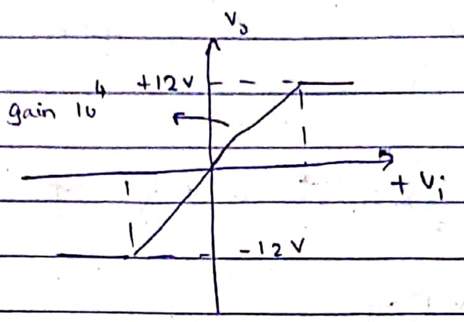


$$V_o = A_d\left(V_1 - V_2\right) + A_c\left(\frac{V_1 + V_2}{2}\right)$$
$$= 10^5(-2-3)m + 10\left(\frac{-2+3}{2}\right)m$$
$$= 10^2(-5) + 10^{-2}\left(\frac{1}{2}\right)$$
$$= -499.995$$

input offset : The voltage given at i/p to make offset '0V'

? For transfer characteristics of diff amplifier

i) Identify diff regions of operations

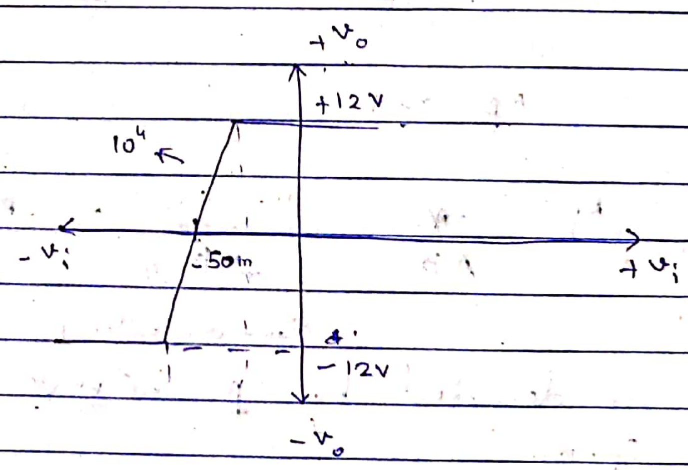


V_o will saturate after 12V
It operates in linear mode at 12V to -12V.

$$\frac{V_o}{V_i} = 12$$

$$V_i = \frac{12}{10^4} = 1.2\,mV$$

?



$V_{io} = -50mV$

$V_o = A_d V_i$

$-50\times10^{-3} = 10^4 \times V_i$

$\frac{V_o}{V_i} = 10^4$ $\boxed{V_i = 1.2\,mV}$ $\boxed{V_i = -5\mu V}$

Opamp with negative feedback.

- Ideally, Opamp has high gain & low bandwidth but due to negative feedback when connected as a circuit, gain decreases & bandwidth increases.

- Also improves the linearity of the system

- Reduces offset voltage

- The gain is reduced by a factor of $(1+A\beta)$ which is called desenstivity of the amp.
- By same factor Bandwidth, linear will ↑ & offset vol ↓

$$A_f = \frac{A}{1+A\beta} \quad \begin{matrix} \rightarrow \text{order of } 10^5 \\ \rightarrow \text{in } 0.25,\ 0.33 \end{matrix}$$

$$A\beta >>> 1$$

$$A_f = \frac{\cancel{A}}{\cancel{A}\beta} = \frac{1}{\beta} = \frac{R_1+R_2}{R_1}$$

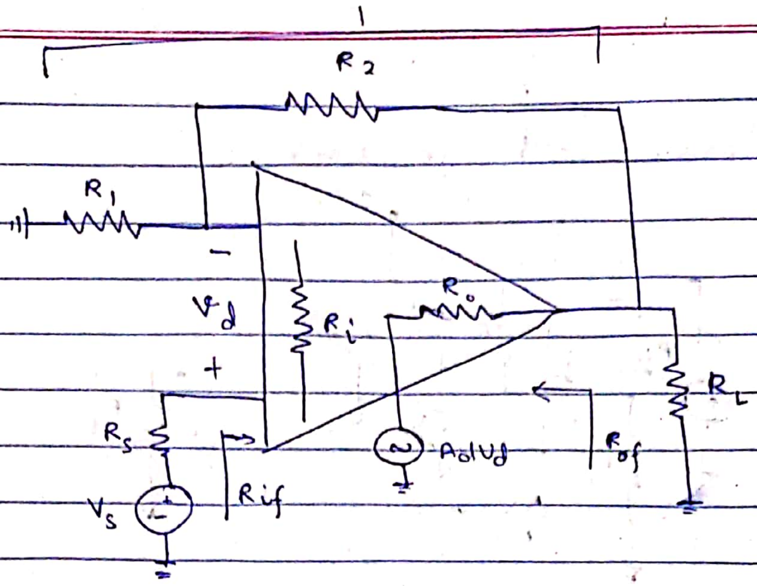
(inverse ratio)

Gain is decided by 'β' network & not by OpAmp

This means gain of opamp can fluctuate

This is called desentization.

β - network



- R_{if} is input impedence of amp as seen by signal source
R_{if} not same as R_i

$$R_{if} = R_i \underline{(1 + A\beta)} \nearrow \text{very large}$$

$\therefore$ R_{if} very large

By virtrue of feedback we have achieved input impedence virtually ∞

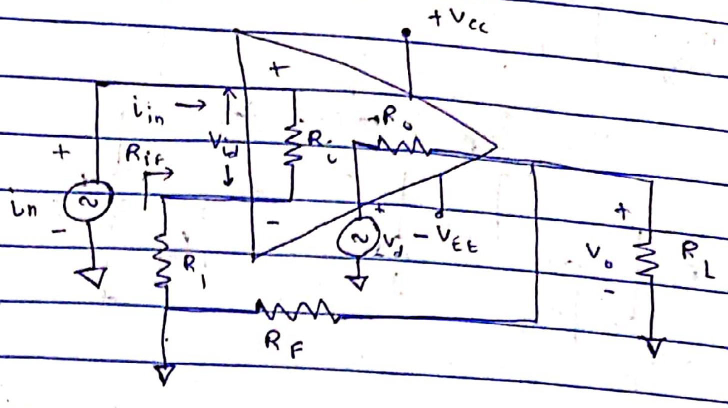
$||^{ly}$ for o/p resistance i.e R_o is of finite value.

R_{of} is o/p resistance as seen by load resistance R_L.

$$\downarrow R_{of} = \frac{R_o}{1 + A\beta \uparrow} \qquad \underline{R_{of}} = \text{very small}$$

The effective value of R_{of} gets reduces

Input resistance with feedback



$$R_{iF} = \frac{V_{in}}{i_{in}} = \frac{V_{in}}{V_{id}/R_i}$$

$$V_{id} = \frac{V_o}{A} \quad \text{and} \quad V_o = \frac{A}{1+A\beta} V_{in}$$

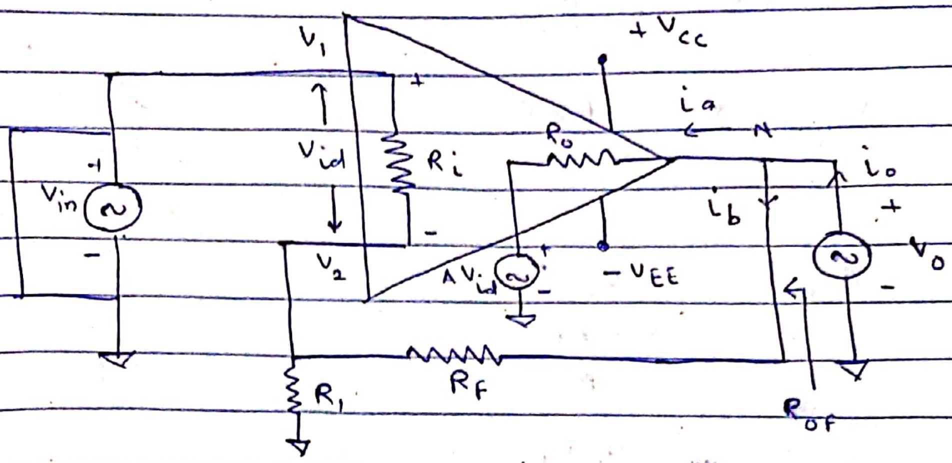
$$R_{iF} = R_i \frac{V_{in}}{V_o/A}$$

$$R_{iF} = A R_i \frac{V_{in}}{A V_{in}/1+A\beta}$$

$$\boxed{R_{iF} = R_i(1+A\beta)}$$

Output resistance with feedback

Output resistance is the resistance determined looking back into feedback amplifier from output terminal.



It is obtained by using Thevenin's theorem for dependent sources

$$R_{OF} = \frac{V_o}{i_o}$$

Writing KVL at output node N

$$i_o = i_a + i_b$$

since $[(R_F + R_1) \parallel R_i] >> R_o$ & $i_a >> i_b$

$$\therefore \boxed{i_o \approx i_a}$$

Writing KVL for o/p loop,

$$V_o - R_o i_o - AV_{id} = 0$$

$$i_o = \frac{V_o - AV_{id}}{R_o}$$

$$V_{id} = V_1 - V_2$$

$$= 0 - V_f$$

$$V_{id} = \frac{-R_o V_o}{R_1 + R_f}$$

Scanned by CamScanner

$$V_{id} = -\beta V_o$$

$$i_o = \frac{V_o + A\beta V_o}{R_o}$$

$$R_{of} = \frac{V_o}{\frac{V_o + A\beta V_o}{R_o}}$$

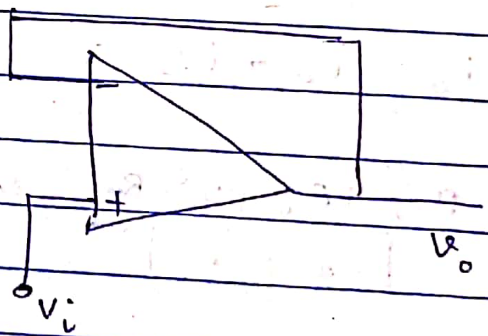
$$= \frac{V_o R_o}{V_o(1 + A\beta)}$$

$$\boxed{R_{of} = \frac{R_o}{1 + A\beta}}$$

~~Band~~

24.01.19

Unity gain



Buffer

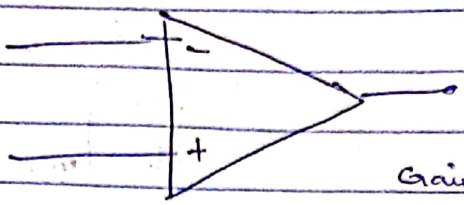
$$v_o = v_i$$

$$A = 1 + \cancel{R_2}/\cancel{R_1}$$

$$\boxed{A = 1}$$

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

Consider

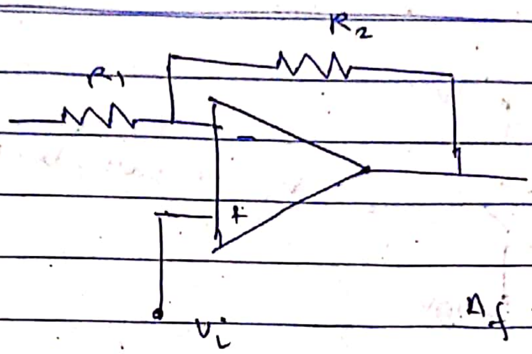


Gain 10^5

$BW = \omega_1$

$\boxed{\omega_1 < UGB}$

(1) op Amp.



$$A_f = 1 + \frac{R_2}{R_1}$$

(2) Non-inverting amp → An amplication built using opAmp

$BW = \omega_{if}$

$\omega_{if} > \omega_1$

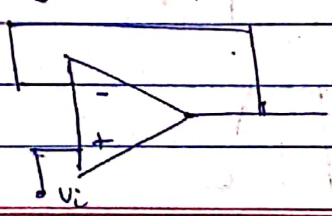
$A_f << A$

Here $UGB >> \omega_{if}$

[UGB (Unity gain bandwidth) =

UG × B.W]

(3) Voltage Follower



$v_o = v_i$

$A_f = 1$; $\omega_{if} = BW$

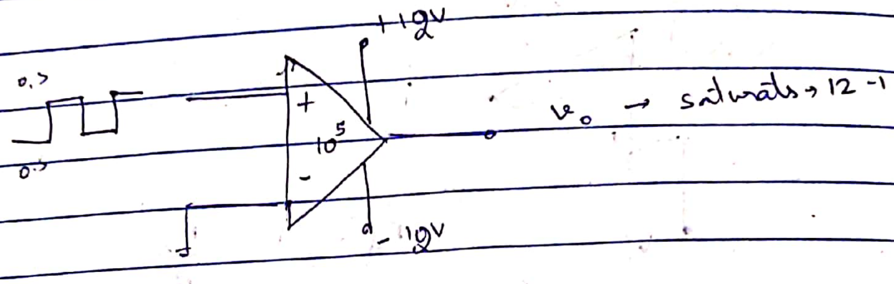
$UGB = UG \times BW = \omega_{if}$

Gain cannot go < 1, min is 1.

Slew Rate :

By defn. $SR = \left.\frac{dV_o}{dt}\right|_{max}$.

consider a open loop OpAmp



Gain is 10^5, V_{cc}, V_{EE} is 12V.

$V_d = 1 - 0 = 1$

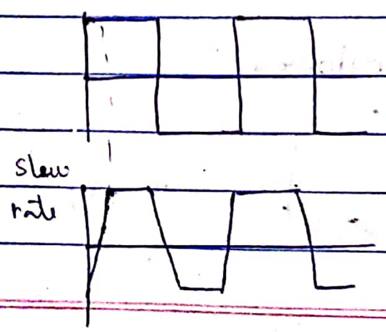
$V_o = A_d V_d$

$= 10^5 \times 1$

$= 10^5\ V \rightarrow$ expected

not possible

KVL says in a loop all volts sum to 0
So it does'nt justify KVL

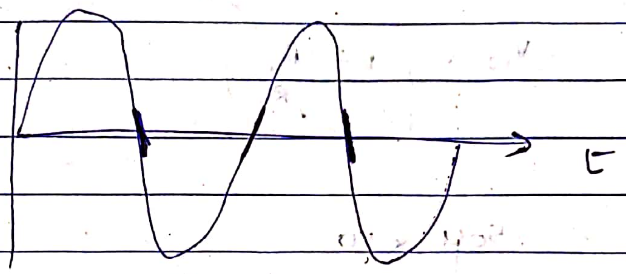


Slew rate is the max rate of change of the output terminal voltage.

In Case of amplifier,

consider

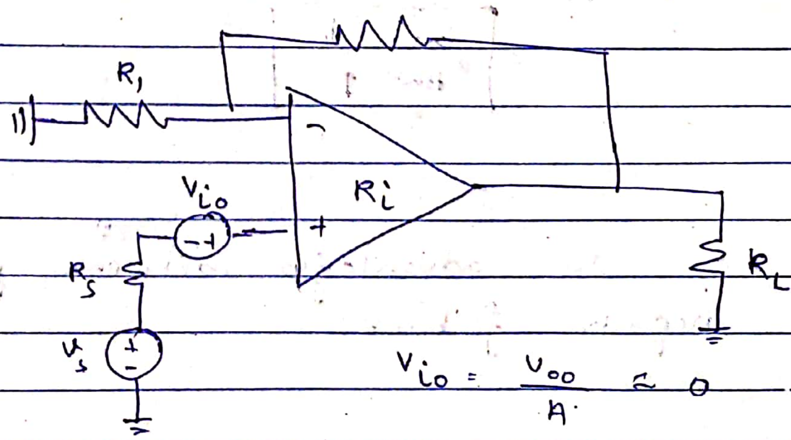
i/p	o/p
sine wave	sine
1 V	2 V
1.5 V	3 V



max rate of change occurs at zero crossing

slew rate will put a constraint on bandwidth.

<u>Feedback Affects offset error</u>



$$V_{io} = \frac{V_{oo}}{A} \approx 0$$

input referred offset voltage

Using Superposition

$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_c + \left(1 + \frac{R_2}{R_1}\right) V_{io}$$

Ex: OpAmp

if $V_{oo} = 5V$ then $V_{io} = \frac{V_{oo}}{A} = \frac{5}{10^5} = 50\,\mu V$

Amplifier effect of V_{io} on the o/p

$$= V_{io} \times \left(1 + \frac{R_2}{R_1}\right) \quad \left(\frac{R_2}{R_1} \to 10\right)$$

$$= 50\mu \times 10$$

$= 0.5mV$ → still not zero.

(DC pedistal)

Conclusion

$\boxed{\text{OpAmp - char - not ideal}}$

$\boxed{\text{use feedback}}$

$\boxed{\text{Gain} \downarrow \quad \text{BW} \uparrow}$

Applications of OpAmp

?) What are the advantages between positive and negative feeback?

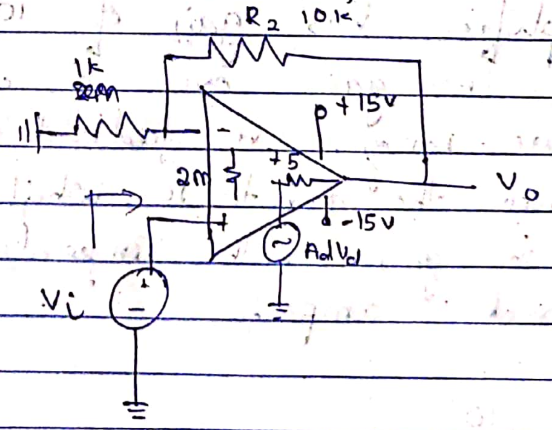
→ Negative feedback of the amplifier reduces the gain & increases the bandwidth of the OpAmp, it brings the ideal characteristics of the opAmp. In case of +ve feedback gain ↑.

2. How does negative feedback affect on gain, input impedance, output impedance and bandwidth

→ Gain decreases ↓
input impedance increases ↓
output impedance decreases ↓
bandwidth increases ↑

loop gain → desensitivity.

1. An Opamp (741 C) having parameters $A = 2\times10^5$, $R_i = 2M\Omega$, $R_o = 75\,\Omega$, $f_o = 5\,Hz$ supply voltage = +/- 15 V, output voltage swing = +/- 13V is connected as a non-inverting amplifier with $R_1 = 1k\Omega$, $R_f = 10k\Omega$ compute A_f, R_{if}, R_{of}, F_f & V_o

→ 

$R_{if} =$

$$A_f = 1 + \frac{R_2}{R_1} = 1 + \frac{10k}{1k} = 11$$

$$A_f = \frac{A}{1+A\beta} \approx \frac{1}{\beta}$$

$$\beta = \frac{R_1}{R_1 + R_2} = \frac{1K}{11K} = \frac{1}{11}$$

$$R_{if} = R_i (1 + A\beta)$$

$$R_{if} = 2M \left(1 + 2\times10^5 \times \frac{1}{11}\right)$$

$$R_{if} = 3.6 \times 10^{10}\ \Omega$$

$$R_{of} = \frac{R_o}{1 + A\beta} = \frac{75}{1 + \left(\frac{2\times10^5}{11}\right)}$$

$$= 4.12\ m\Omega$$

$$F_f = f_o(1 + A\beta)$$

$$= 5\left(1 + \frac{2\times10^5}{11}\right)$$

$$= 90.9\ KHz$$

$$V_o = 11 \times v_i$$

? An amplifier has gain of 10^5 & 5% variation in gain over a certain temperature range. -ve feedback is used to reduce the gain to 10. What is the variation in gain with temperature of the feedback amplifier

→ $A_f = 10$

$A = 10^5$

$\therefore \left(1 + g_m R_D R_S\right)$ ①

5% variation : $10^5 + \frac{5 \times 10^5}{100}$

$A_f = 10.5 \times 10^4$

$A_f = \frac{A}{1 + A\beta} = \frac{10.5 \times \cancel{10^4}}{1 + (10.5 \times \cancel{10^4})\left(\frac{1}{11}\right)}$

Given $A_f = 10,$

$A_f = \frac{A}{1 + A\beta}$

$10 = \frac{10^5}{1 + 10^5\beta}$

$10 + 10^6\beta = 10^5,$

$\boxed{\beta = \frac{1}{10}}$

It will not vary.

HW An amplifier has gain of 800. After adding negative feedback the gain is measured as 25. Find feeback factor.

→ $A_f = \frac{A_{OL}}{1 + \beta A}$ $25 = \frac{800}{1 + 800\beta}$

wherever there is 0 cross the rate of change of v_o is max.

$\beta = 0.0388$

Loop gain $= 800\beta$
$= 800 \times 0.0388$
$= 31.04$

Slew Rate

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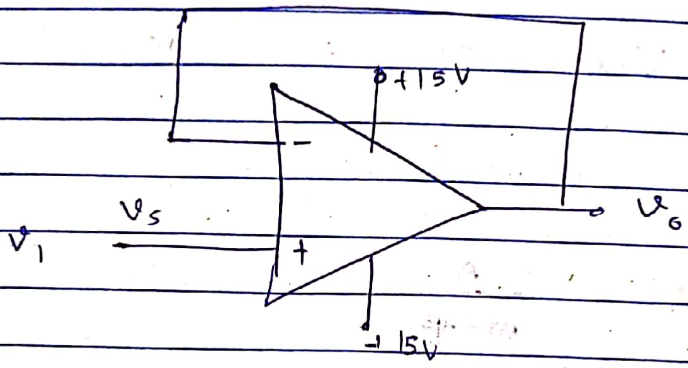
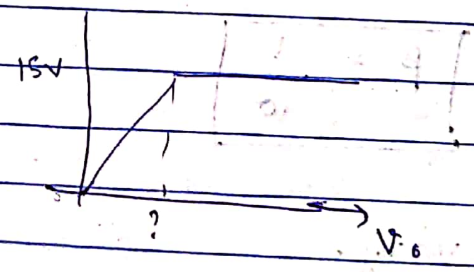


Slew rate - 0.5V/μs.
Gain = 1

v_o = ? at what time



$$\frac{15}{0.5} = \underline{\underline{30\mu s.}}$$

ii) input is $v_s = V_m \sin\omega t$

$$v_o = V_m \sin\omega t = v_s$$

what is maximum freq of i/p signal that this amp can handle without distortion

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

$$V_o = V_m \sin\omega t$$

$$\frac{dV_o}{dt} = \omega V_m \cos\omega t$$

It is max when $\cos\omega t = 1$

$\omega t = 0$

$$\left.\frac{dV_o}{dt}\right|_{max} = \omega \cdot V_m$$

$$0.5\,V/\mu s = 2\pi f V_m$$

$$\boxed{f = \frac{0.5 \times 10^6}{2\pi V_m}}$$

NOTE : If $V_m = 1V$

$f = 79.5$ KHz

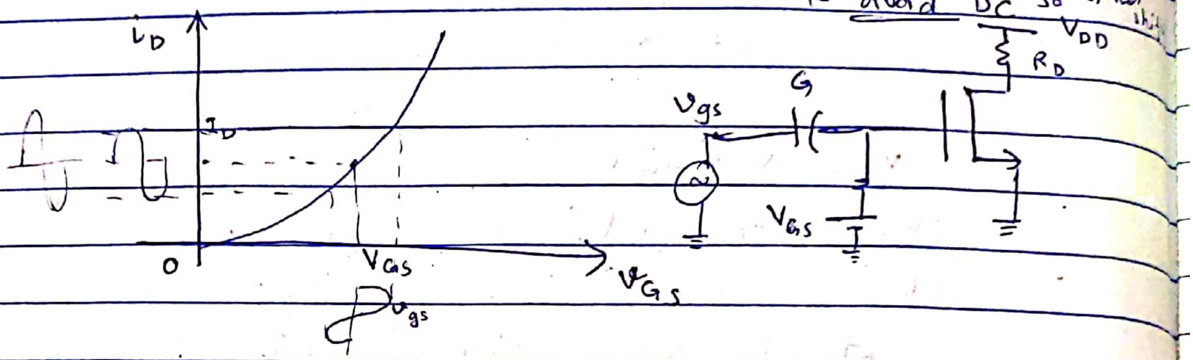
$V_m = 15V$

$f = 5.3$ KHz

Non-linear (harmonic) distortions :-

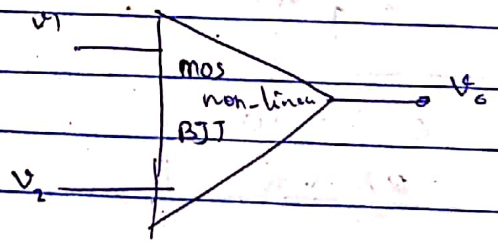
OpAmp is a linear IC built using non-linear (MOS, BJT).

Charatasitic of MOS



NOTE :

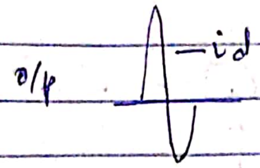
v_{gs}	-	small signal
V_{GS}	-	DC
v_{GS}	-	Total instantaneous
V_{gs}	-	RMS



So opAmp also non-linear working in linear mode only in certain region. Along with dominant -ve feedback.

$V_x / (1 + g_m r_{ds} ...)$

Mathematically, fourier analysis says that all the non-linear distortions are getting added to o/p



fundamental (i/p)

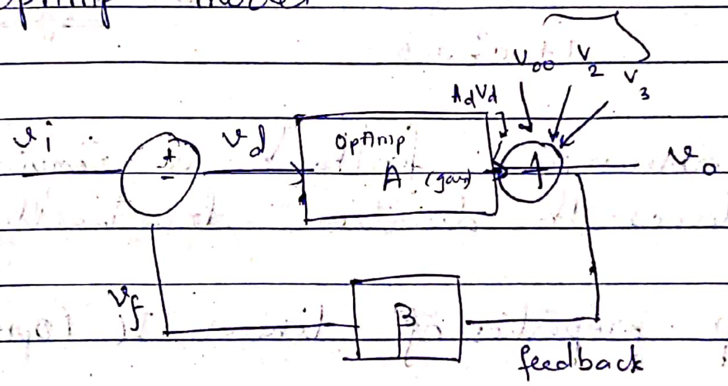
$$i_d = I_{1m} \sin \omega t + \underbrace{I_{2m} \sin 2\omega t + I_{3m} \sin 3\omega t + \ldots}_{\text{harmonics}}$$

non linear

The distortion due to the non-linearity of device.

OpAmp model -

cannot ignore



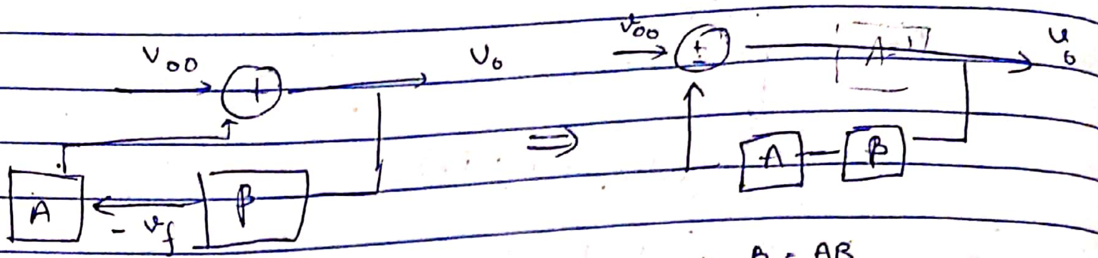
This is not a SISO (due to V_{00}, V_2, V_3) it is MISO.

Now finding v_o, we use superposition

(i) consider v_i & nullify V_{00}, V_2, V_3

$$v_o = \boxed{\frac{A}{1 + A\beta}} v_i +$$

(ii) consider V_{00}



$\beta \cdot A\beta$

$$\frac{v_o}{v_{oo}} = \frac{1}{1 + 1 \times A\beta} = \frac{1}{1 + A\beta}$$

Ex take $V_{oo} = 2V$

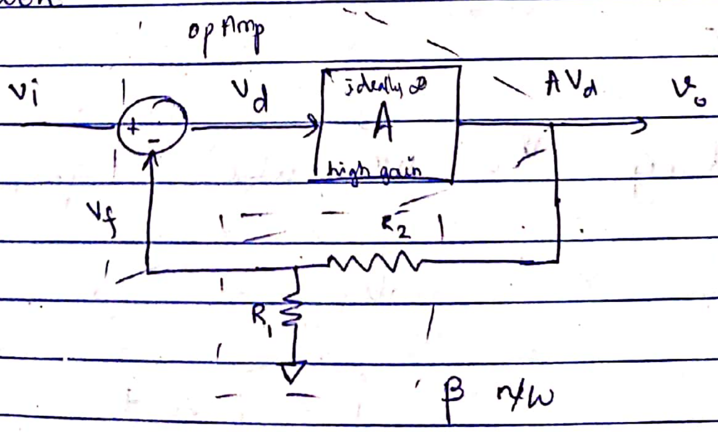
$A = 10^5$

$$v_o = \frac{2}{1 + 10^5 \times 0.5} = 4 \times 10^{-4}$$ very small

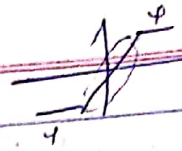
So a dominant feedback is required so reduces the disortion drastically.

Two imp properties of linear IC (opAmp)

- Follower
- Inversion



(1) Follower



if OpAmp o/p is unsaturated

$V_d = V_i - V_f$

$V_o = A V_d$

$$V_d = \frac{V_o}{A} = \frac{V_o}{10^5} = \frac{V_o}{\infty} \approx \frac{V_o}{10^5}$$

$$\boxed{V_d \approx 0}$$

$$V_i - V_f = 0$$

$$\boxed{V_i = V_f}$$

This is called as follower property
V_f follows V_i.

(2) Inversion property :

$$\frac{V_o}{V_i} = \frac{A}{1 + A\beta}$$

A - very large (∞ or 10^5)

$$\boxed{V_o = \frac{V_i}{\beta}} \rightarrow \text{inversion relation}$$

V_o is independent of opAmp, depends on $\boxed{\beta \text{ n/w.}}$

$$\boxed{\frac{V_o}{V_i} = \frac{1}{\beta}}$$ (in denominator, so called inversion)

Because of these 2 properties, called linear IC.

1. Why OpAmp is called linear IC?

→ OpAmp is a linear device, built using non linear devices. Due to its dominant negative feedback it acts as a linear ckt.

2. What do you mean by harmonic distortion?

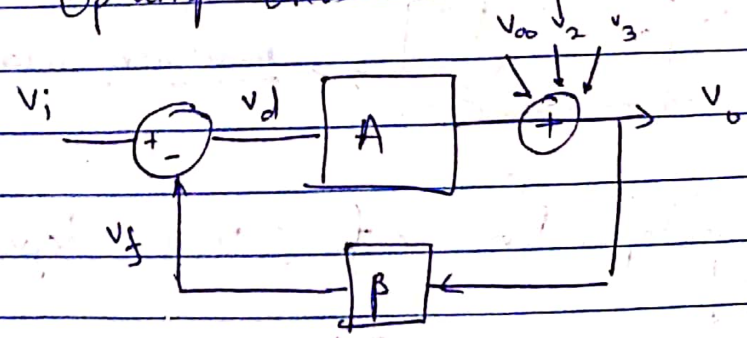
→ Along with the linear component, the non linear components adding up to the output of signal is known as harmonic distortion.

3. What is loop gain, improvement factor.

→ loop gain = $A\beta$

improvement factor = $1 + A\beta$

4. Explain the process of amplification taken in Op-amp under -ve feedback condition

→ 

5. State the condition for Op-amp to operate in linear mode of operation.

→ Op-amp must have a dominant -ve feedback so that the output is unsaturated.

6. What is meant by follower property and inversion property.

→ When the Opamp is operating under linear mode.

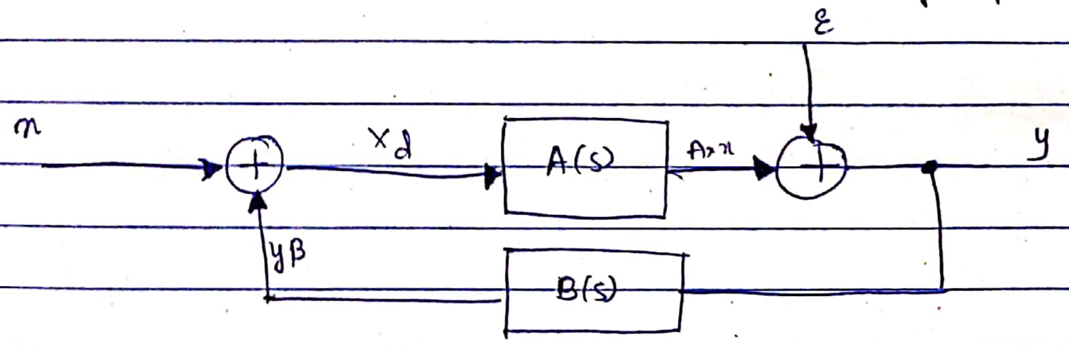
- The input followers the feedback voltage. This property is known as follower property.
- Inversion property is

$$V_o = \frac{V_i}{\beta}$$

$$\frac{V_o}{V_i} = \frac{1}{\beta}$$

The gain is independent of opamp ckt it only depends on β n/w. Since gain is dependent on inverse of β, it is known as inversion property.

7.



$$y = \frac{Ax + \mathcal{E}}{1 + AB}$$

$$\frac{A}{1+\ldots}$$

$$X_d = X + yB \qquad y = AX_d$$

$y = A x_d = A(x + y\beta)$

$y(1 - A\beta) = Ax$

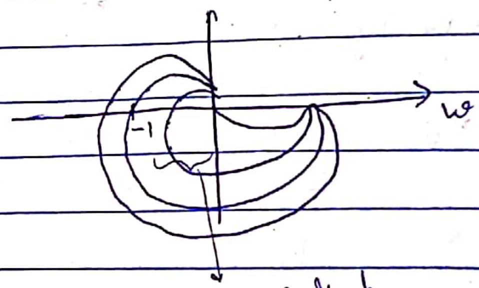
$$\boxed{\frac{y}{x} = \frac{A}{1 - A\beta}}$$

NOTE: if $A\beta < 1 \longrightarrow$ negative feedback

$A\beta > 1 \longrightarrow$ ossillations

$A\beta = -1$ +ve

polar plot

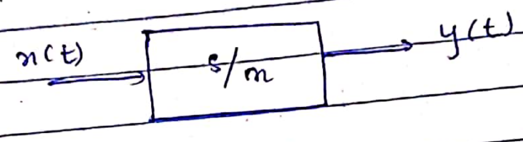


-ve feedback.

Linear Symmetric Networks

For a linear system, it has to obey

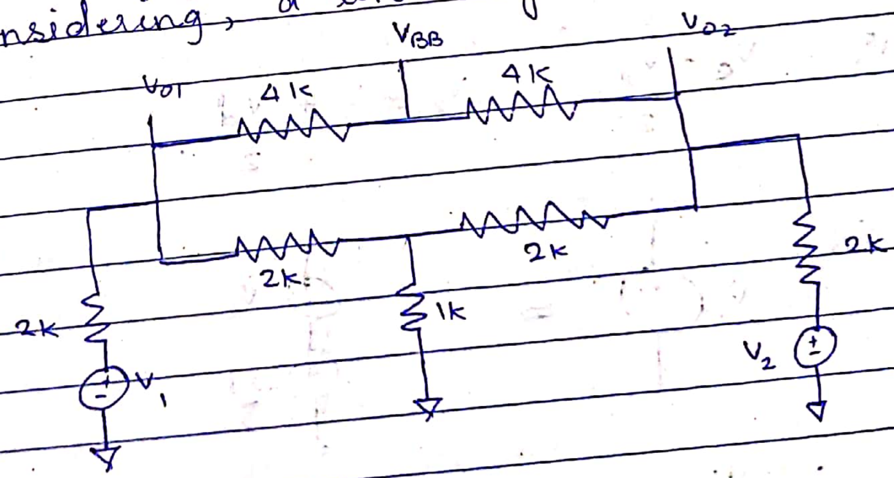
- Homogenous
- Superposition principle



$$\alpha x_1(t) + \beta x_2(t) \longrightarrow \alpha y_1(t) + \beta y_2(t)$$

- Each component is independent of each other

Considering, a linear symmetric circuit -

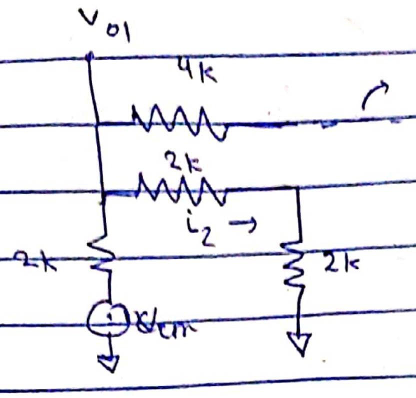


$$V_{cm} = \frac{V_1 + V_2}{2} \qquad V_d = V_1 - V_2$$

odd component

$$V_1 = -\frac{V_d}{2} + V_{cm} \qquad V_2 = +\frac{V_d}{2} + V_{cm}$$

Because of symmetric of network



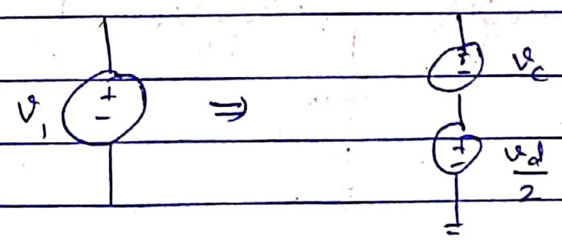
no current in dotted line

Here $V_{o1} = V_{o2}$

Symmetric
- ckt
- even: v_c
- odd: $\pm \frac{v_d}{2}$

$v_1 = v_c - \frac{v_d}{2}$ $\qquad$ $v_2 = v_c + \frac{v_d}{2}$

So



Splitting v_1 & v_2 in this form.

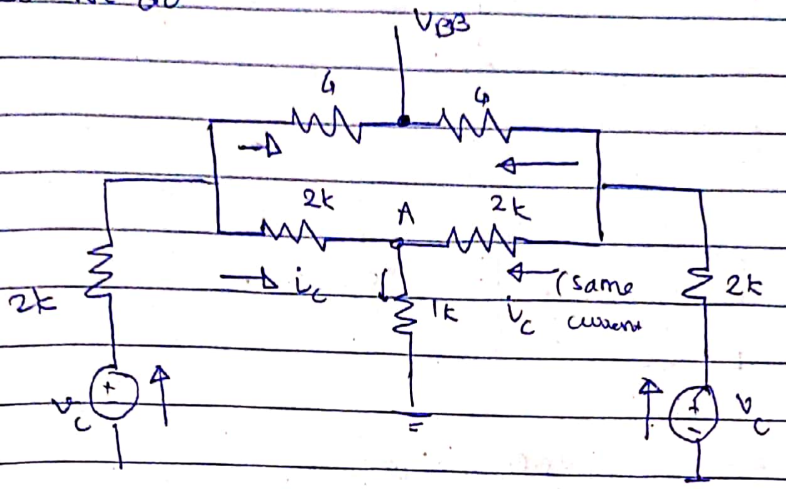
Once we consider v_c then $\frac{v_d}{2}$ then the DC bias V_{BB}.

i/p
- $V_{o1}\ (V_c) = V_{o2}$
- $V_{o1}\ (V_d/2) = V_{o2}$
- $V_{o1}\ (V_{BB}) = V_{o2}$

Scanned by CamScanner

We can calculate v_1, v_2 with KVL or KCL but it tedious.

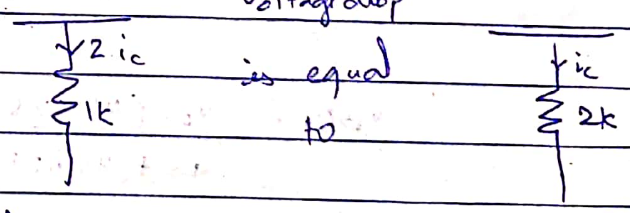
So we do -



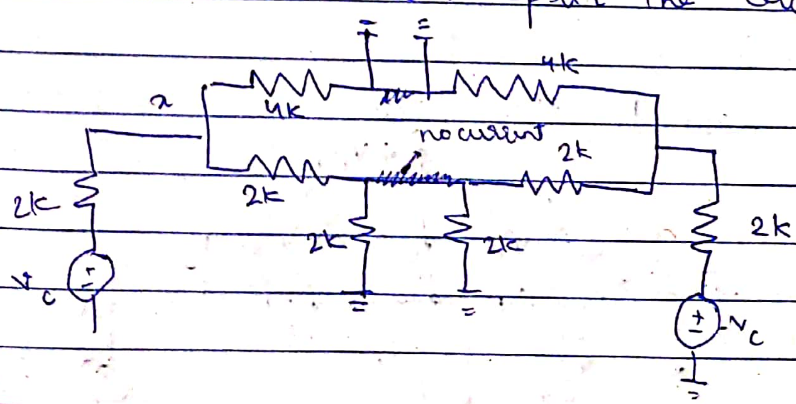
At node A, the summation of both current pass i.e $2i_c$

$$2i_c \times 1k = 2i_c\,kV$$
$$i_c \times 2k = 2i_c\,kV$$

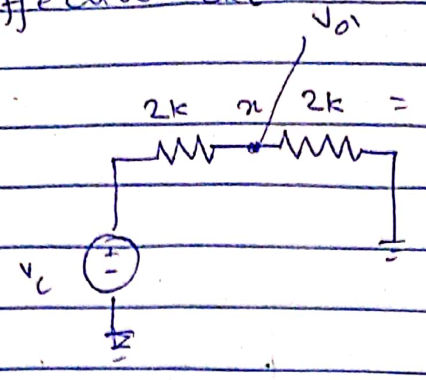
Meaning, voltage drop is equal to



So that we can split the circuit in 2 parts



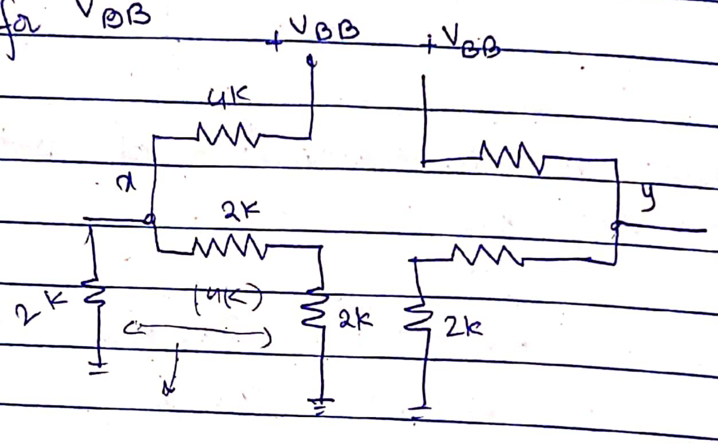
The effective ckt



$= (2k+2k) \parallel 4k$

$$\boxed{V_{01} = \frac{V_c}{2}} = V_{02}$$

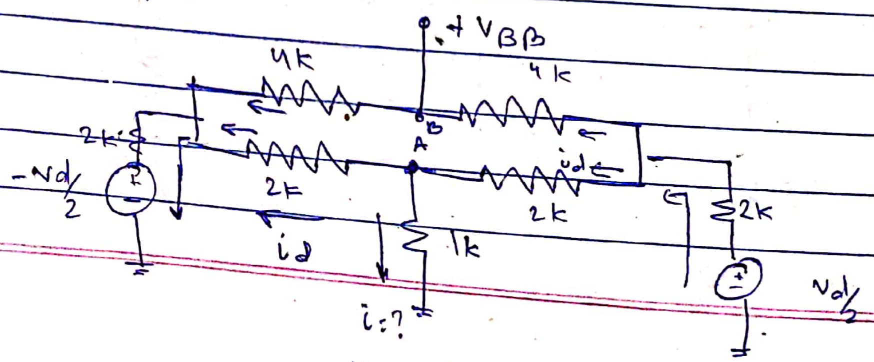
(2) Now for V_{BB}



$4k \parallel 2k$

$$V_{BB} = \frac{V_{01}(4k \parallel 2k)}{4k + (4k \parallel 2k)} = \frac{V_{02}(4k \parallel 2k)}{4k + (4k \parallel 2k)}$$

(3) With respect to $V_d/2$.



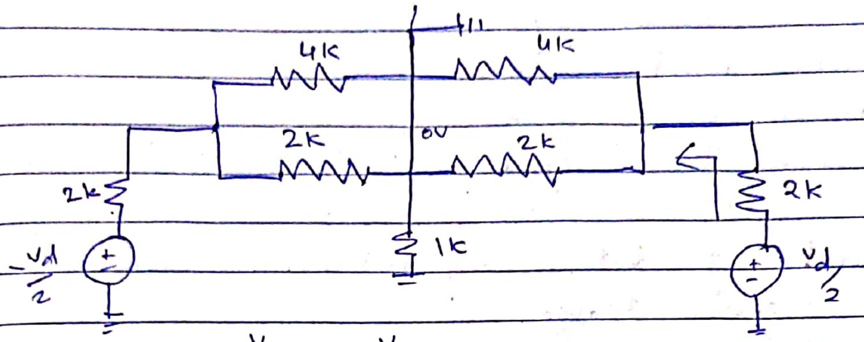
Here it is '0' as same current id flows from 2k to 2k.

$V_x\left(\frac{1}{r_{ds}} + g_m\right)$

$V_x\left(1 + g_m r_{ds}\right)$ — ①

So voltage at A is '0V'
$\parallel^y$ for 'B' node

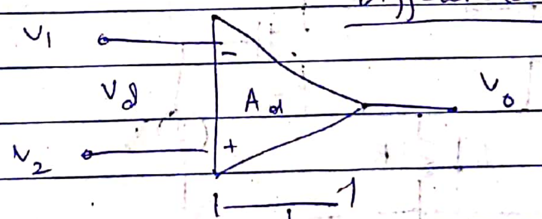
so the entire line becomes '0' potential



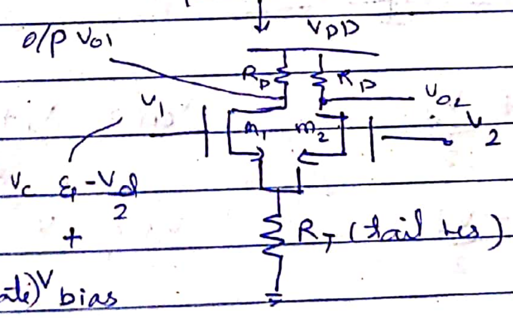
$V_{10} = -V_{02}$

So whenever we have a symmetric network, we try to solve by superposition.

Differential Amplifier



Amplifies the diff in signal



Basic differential amp.

R_D is the load for ckt.

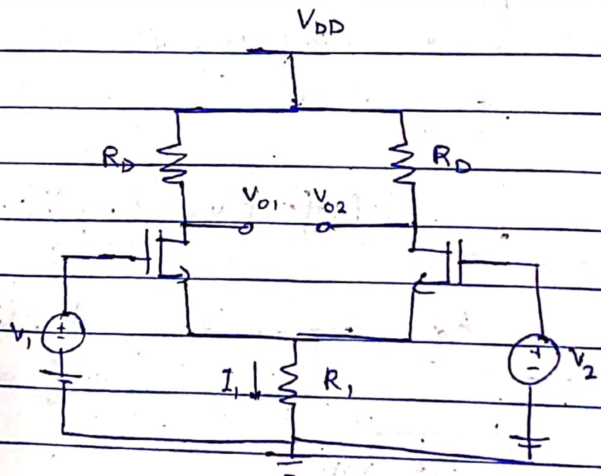
V_c $\varepsilon_1 - \frac{V_d}{2}$
+

(To provide at gate) V bias voltage)

Differential Amplifier Basics

- Basic differential amplifier
- common mode signals
- difference mode gain
- common mode gain
- difference mode gain

To make it better by reducing common mode signal range
The diff mode signal



R_D - drain resistance

$$V_1 = V_c + \frac{V_d}{2} \qquad V_{cm} = \frac{V_1 + V_2}{2}$$

$$V_2 = V_c - \frac{V_d}{2} \qquad V_d = V_1 - V_2$$

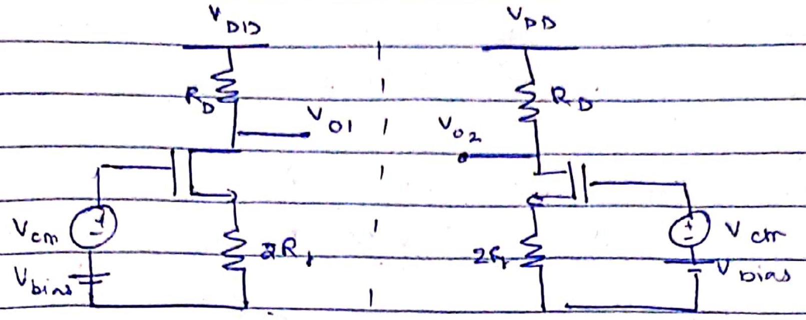
The differential amplifier is biased and operated in the 'small signal' range

The amplifier is considered a linear system

$(1 + g_m r_{ds})$ — (1)

V_{bias} is voltage req. by device to work in saturation.

difference mode signal $+\frac{V_d}{2}$ & $-\frac{V_d}{2}$



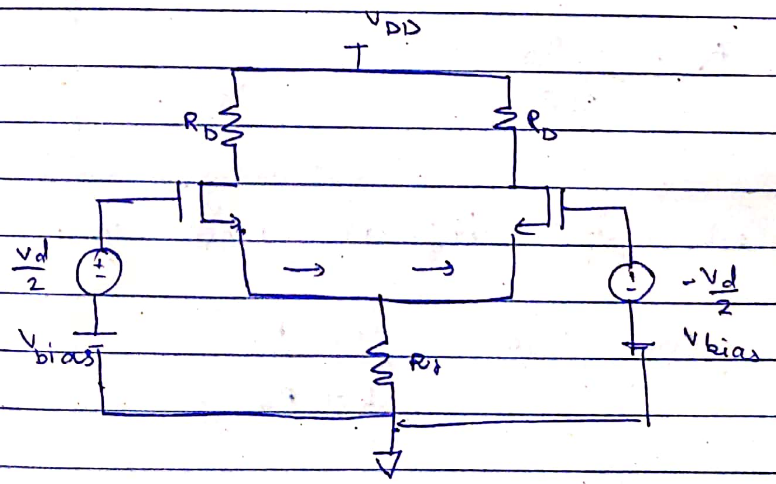
$$V_{O1} = V_{O2} = \frac{-\mu R_D V_{cm}}{r_{ds} + R_D + (1+\mu)2R_L}$$

$$A_c \approx \frac{-\mu R_D}{(1+\mu)2R_L} = \frac{\sim R_D}{2R_L}$$

Single ended o/p common mode gain

$$A_c = \frac{-R_D}{2R_L}$$

Difference mode analysis



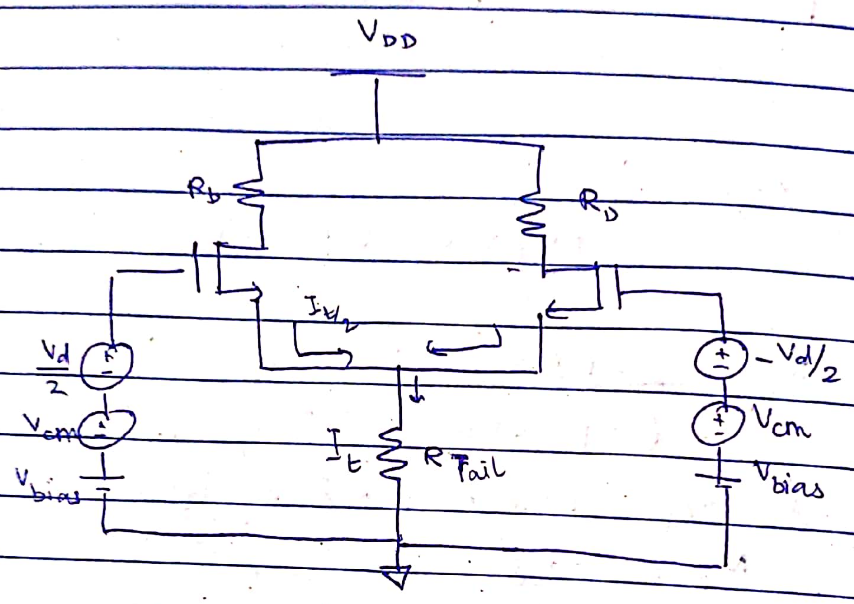
$$V_1 = V_c + \frac{V_d}{2}$$

$$V_2 = V_c - \frac{V_d}{2}$$

$$A_{d_1} = \frac{V_{o1}}{V_d} = -\frac{g_m}{2}\frac{r_{ds} R_D}{(R_D + r_{ds})}$$

$$A_{d_2} = \frac{V_{o2}}{V_d} = \frac{g_m}{2}\frac{r_{ds} R_D}{(r_{ds} + R_D)}$$

$$A_{d_2} - A_{d_1} = \frac{V_{o2} - V_{o1}}{V_d} = g_m \frac{r_{ds} R_D}{(r_{ds} + R_D)}$$



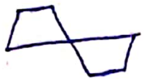
Single ended output common mode gain

$$A_c = \frac{-R_D}{2R_t}$$

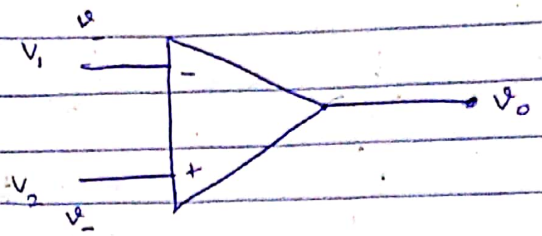
Single ended output difference mode gain

$$A_{d_2} = \frac{g_m}{2} = \frac{r_{ds} \cdot R_D}{r_{ds} + R_D}$$

$$CMRR = \rho = \frac{A_{d_2}}{A_c} = g_m \frac{r_{ds} R_t}{r_{ds} + R_D}$$

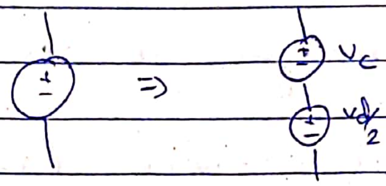
 this signal means the range is not in saturation 'linear ranged' region.

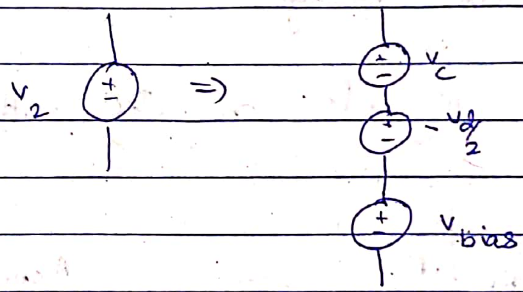
3.1.19



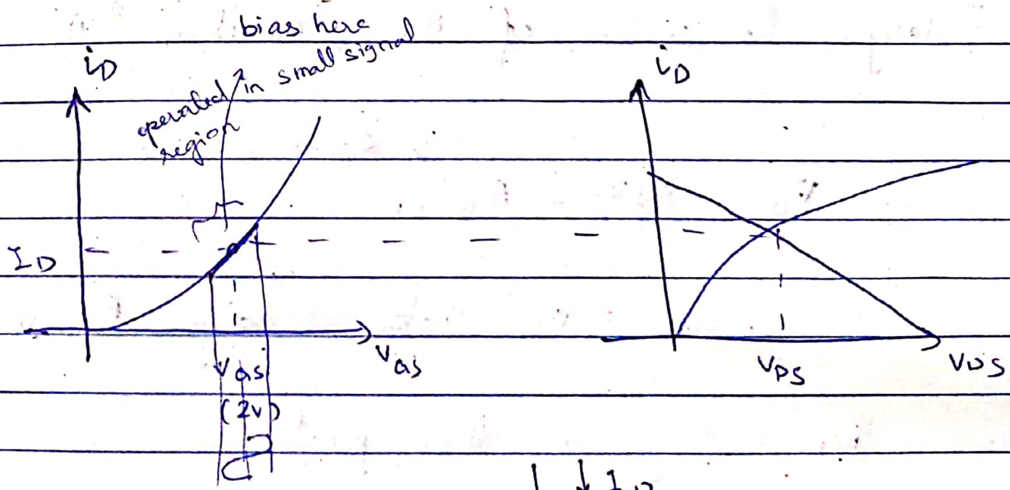
$$V_d = V_+ - V_-$$

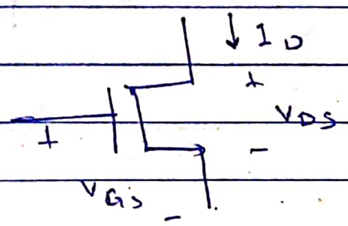
$$V_c = \frac{V_1 + V_2}{2}$$

$V_1 =$ 

V_2 

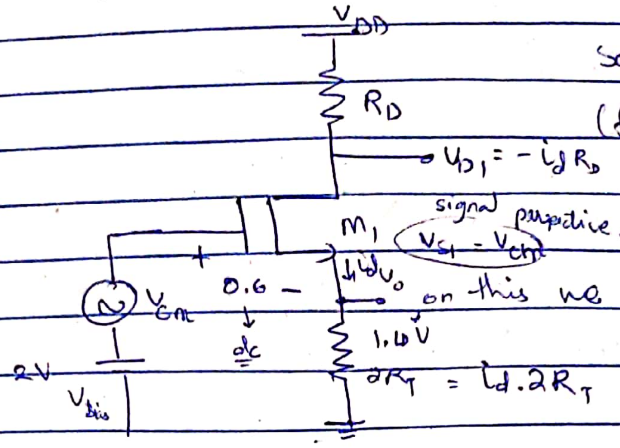
(including DC)





when we say signal, DC terminals go off.

CS amplifier with "source degeneration"



Source follower
(follows gate)

$A_{CM} = \frac{V_{O1}}{V_{CM}} = \frac{-R_D}{2R_T}$ due to symm.

Whenever we analyse a amplifier,

(i) DC analysis : Device must conduct with bias voltage

(ii) Put the signals on DC voltage.

If we make $R_T = \infty$ $A_{cm} \approx 0$
larger the value of R_T, smaller A_{cm}

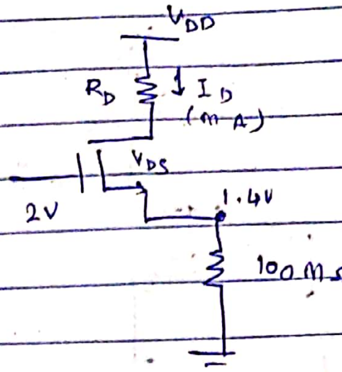
$$V_o = A_d V_d + \cancel{A_{cm}}^{0} v_{cm}$$

To remove A_{cm}, take a large R_T value,

then voltage at that point

Ex, $I = \frac{1.4}{100 M}$ = very small

$V_x\left(1+g_m r_{ds}\right)$



(higher the resistance more drop)

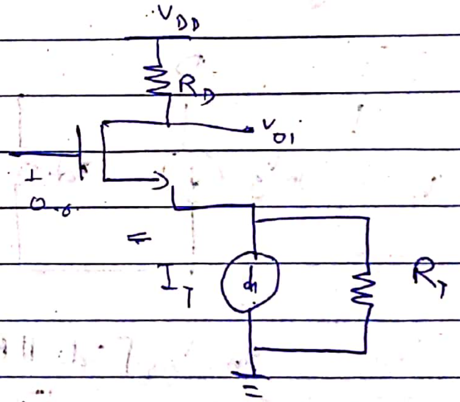
To make $A_{cm} \approx 0$,

R_T = large I_D

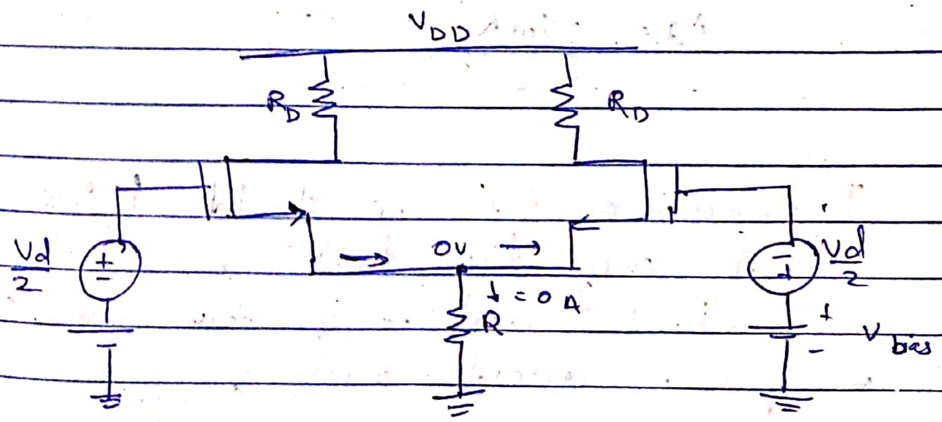
But signal current should not get disturbed

But changing R_T will not fix it

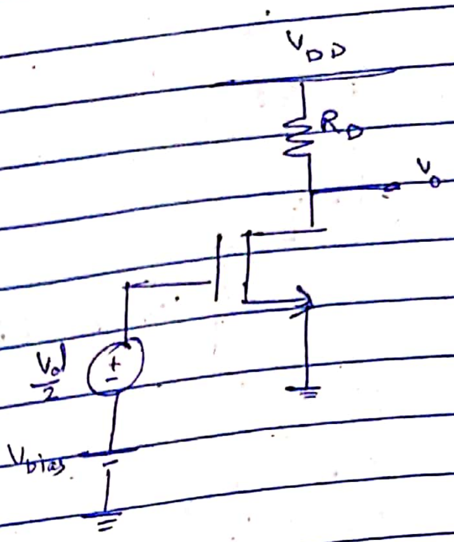
So we connect a current source



Difference mode Analysis

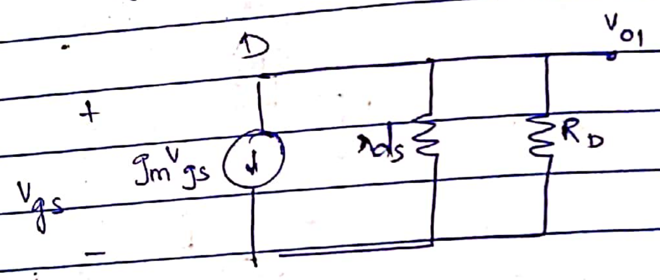


equivalent
½ ckt ⇒



$$V_o = \cancel{\frac{V_d}{2}} - R_D i_D$$

Small signal model



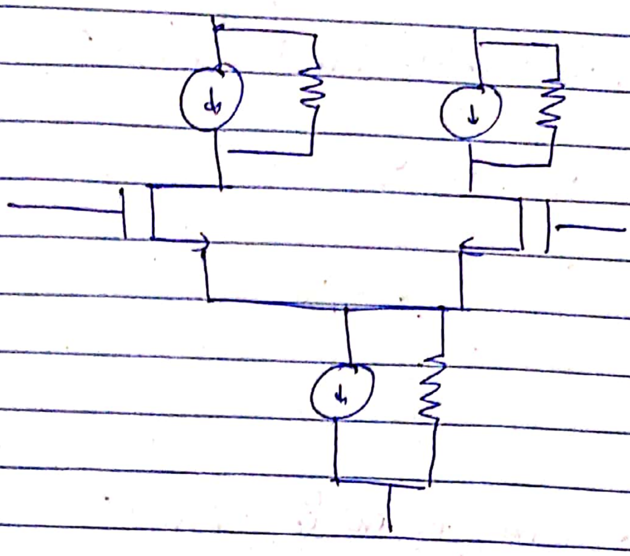
$$V_{o1} = -g_m V_{gs} [r_{ds} \parallel R_D]$$

$$\boxed{\frac{V_{o1}}{V_d} \approx \frac{-g_m R_D}{2}} \qquad \boxed{V_{gs} = \frac{V_d}{2}}$$

$$A_d = \frac{-g_m R_D}{2}$$

To increase A_d, we should ↑ R_D
not only till saturation,
So without disturbing bias condition
we put a current source.

$\triangleright$ double o/p (in this case $A_{cm} = 0$)



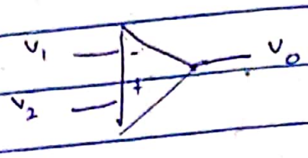
	Single ended o/p	Differential o/p
v_{cm} $\cancel{A}_{o1}$	$= \frac{-R_D \cdot V_{cm}}{2R_T} = V_{o2}$	$v_{o2} - v_{o1} = 0$
A_{cm}	$= \frac{-R_D}{2R_T}$	$V_{o2} = -V_{o1}$
		$= \frac{g_m R_D \cdot V_d}{2}$
v_{o1}	$= -\frac{g_m R_D v_d}{2}$	$V_{o2} - V_{o1} = g_m R_D v_d$
A_d	$= -\frac{g_m R_D}{2}$	$A_d = g_m R_D$

Common mode rejection ratio (ideally ∞) $= \frac{A_d}{A_{cm}} = \frac{-g_m \cancel{R_D}}{\cancel{2}} \times \frac{\cancel{2} R_T}{-\cancel{R_D}}$

$= g_m R_T$ //

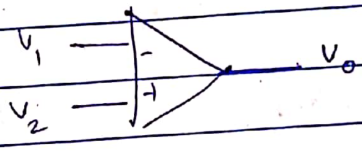
1 What is a differential signal?

→ $v_d = v_1 - v_2$



2. What is common mode signal?

→ $v_{cm} = \frac{v_1 + v_2}{2}$



3) How do we amplify a differential signal

→ By using a differential amplifier we amplify a differential signal.

4) What is a differential amplifier?

→ A amplifier which amplifier the difference in input signals.

5) What is the purpose of differential amplifier?

→ To increase the bandwidth & reduce gain.

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.. $(1+g_m r_{ds})$

6) What is the o/p if same signal is given to both inputs to differential amplifier?

→ There will be a small component of A_{cm} which will appear accross V_O

$$V_o = A_d V_d + A_{cm} V_{cm}$$
$$\downarrow$$
$$0$$

7] How does the gain of differential amplifier differ from common source stage

→ In case of diff. amp

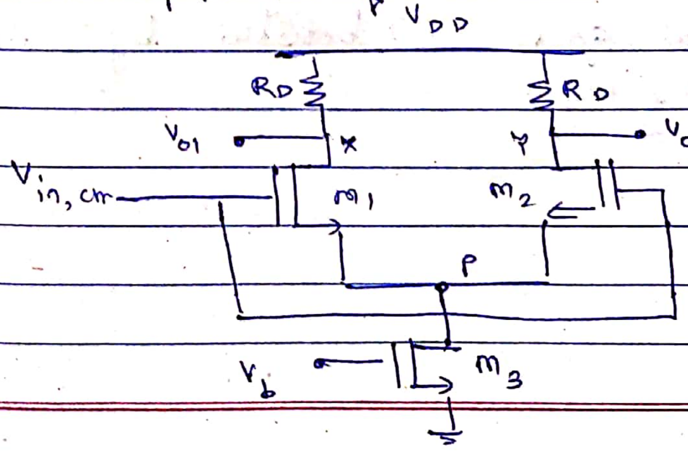
$$A_d = -g_m R_D$$

while in case of C.S

$$A_d = g_m R_D$$

There is inversion in case of diff. amp.

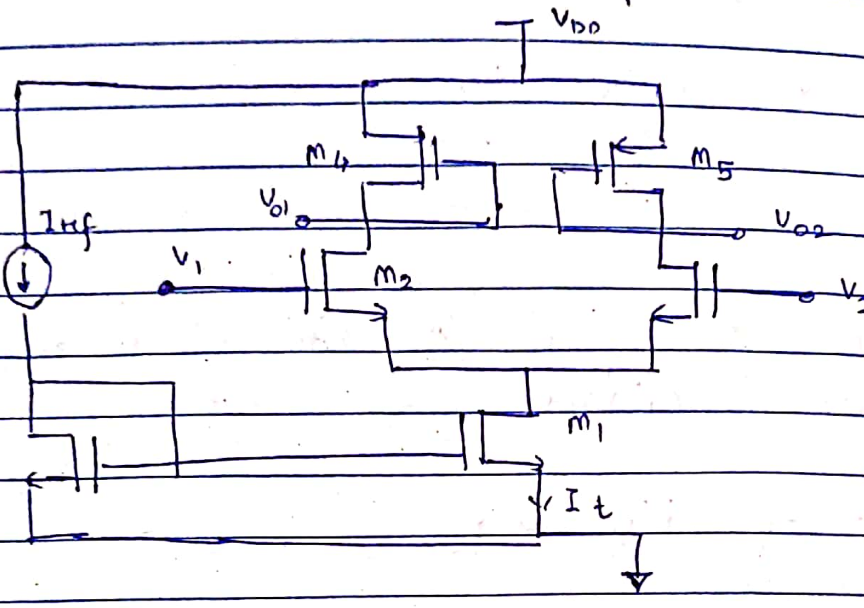
8] What happens if $V_{cm} = 0$



$V_{in,cm}$ i.e dc is 0, it is not biased, so V_{o1} & V_{o2} = V_{DD}

HW

Differential Amp. 7.2.19



$$A_{d1} = \frac{V_{o1}}{V_d} = \frac{-g_{m2}}{2} \cdot \left[\frac{r_{ds2}}{1+g_m+r_{ds2}}\right] \approx -0.5$$

low gain, high Bandwidth

Active load Amplifier

It improves CMRR
differential gain is boosted by active loads (M_4, M_5)

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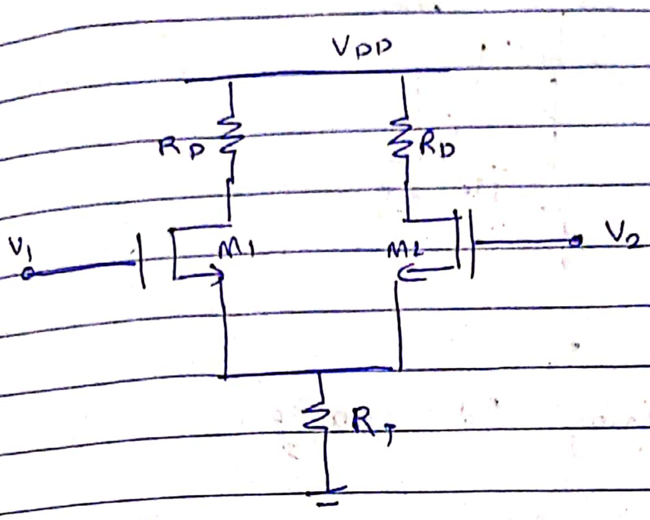
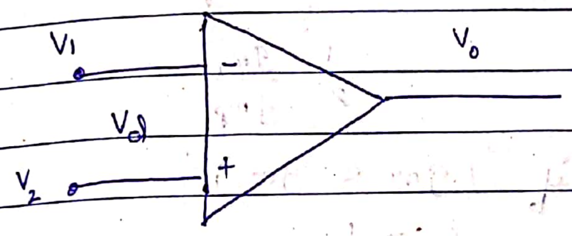
Basic Differential Amplifier

7.2.19





$V_o = A_d V_d + A_c V_c$

$$A_d = -\frac{g_m R_D}{2} \to \infty$$

$$A_c = -\frac{R_D}{2R_T} = 0$$

To increse A_d, $R_D \uparrow$

How to increase R_D?

10K, 100K, 1M, 100M ...

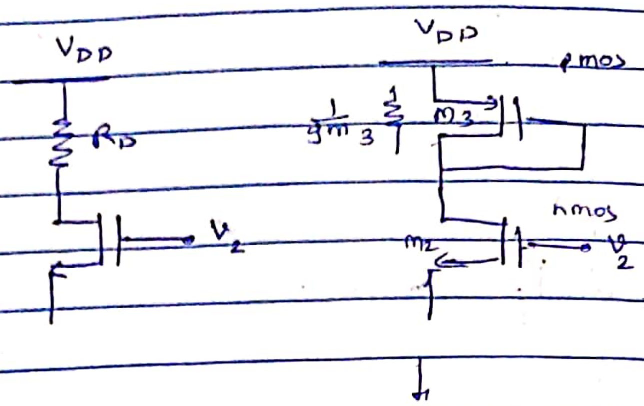
$\Rightarrow$ not possible $\because$ (it can make M2 in triode region coz of the volta(ge) it has to sustain)

Replace R_D — MOS Diode

— MOS device (active load)

Ⓘ Resistance load. Diff amp with diode load

So



↓

Replacing $A_d = -\frac{g_m R_D}{2}$.

by $A_d = -\frac{g_{mn}}{2} \times \frac{1}{g_{mp}}$

$= -\frac{1}{2} \frac{g_{mn}}{g_{mp}}$

if ($g_{mn} \approx g_{mp}$).

$= -\frac{1}{2}$ //

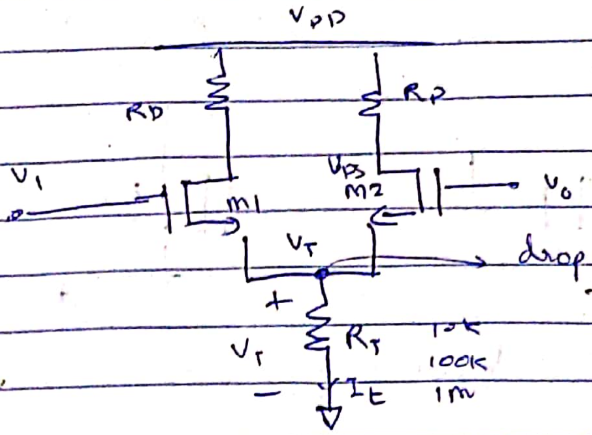
So we conclude that we don't want to change R_D values as M_2 goes to triode region. replace R_D by MOS device then the gain is around -0.5 (doesn't act as amp but it is good ckt as everywhere we have saturation)

One more condition we look is,

we say $A_c = -\frac{R_D}{2R_T}$ (ideally 0 or lowest)

To have $A_c \approx 0$, $R_T \rightarrow \infty$ (large value of R_T)

If



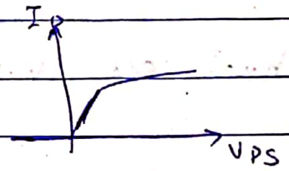
drop increases if R increases

if $V_T \uparrow$, $V_{DS} \downarrow$

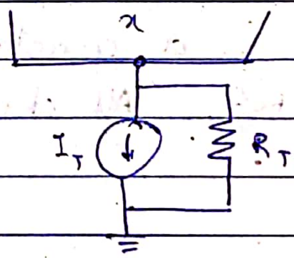
so M_2 can go into-triode region

I_t – changing

I_t can go on reducing & into triode

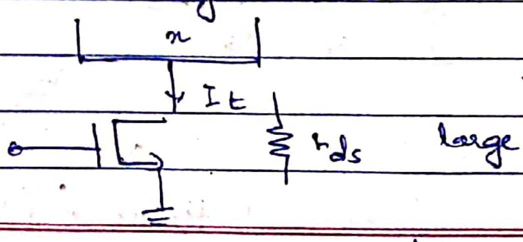


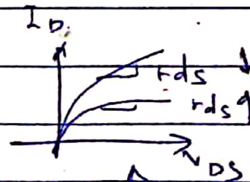
So, a soln for this is replace R_T by current source.



We want current to be fix & R_T to change.

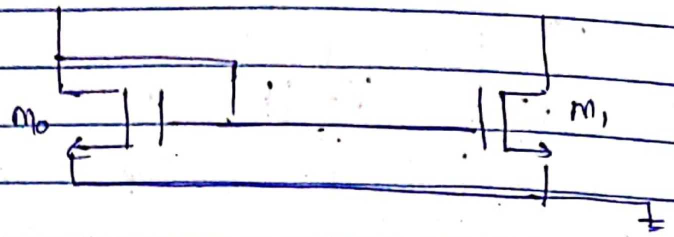
So we replace R_D by nmos



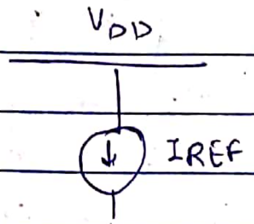


larger the r_{ds} flatter the I_D curve

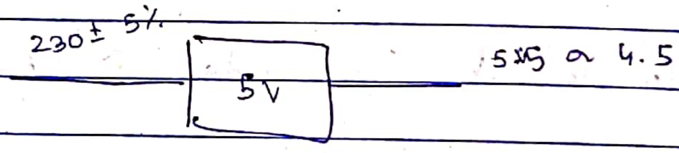
Then why do we need M_0 ?

→ 

In fig, we have

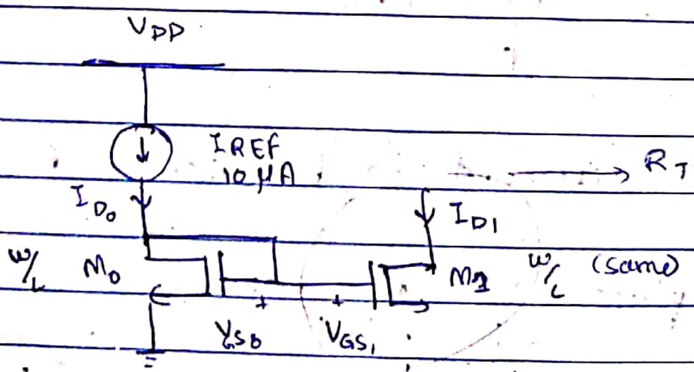


In reality, there are variations in supply voltages



So ~~hw~~ we need to a const. current / voltage

So we have I_{ref}. (∴ All ckt must have I_{ref})



$V_{GS_0} = V_{GS_1}$

fixed

$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)^2$

$$I_D = (f_{n}d) \times V_{GS}$$

$$I_{D_0} = I_{REF} = 10\,\mu A$$

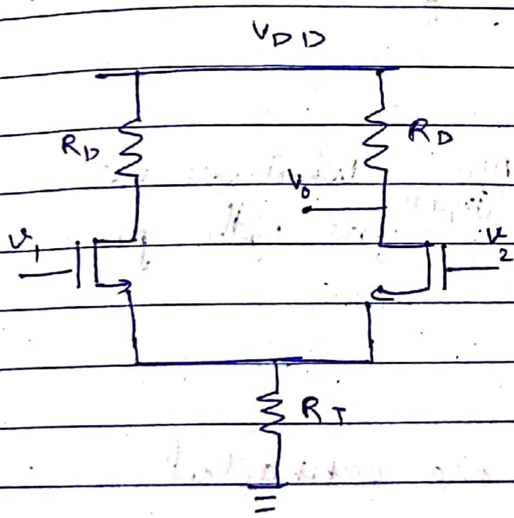
$$I_{D_1} = I_{D_0}$$

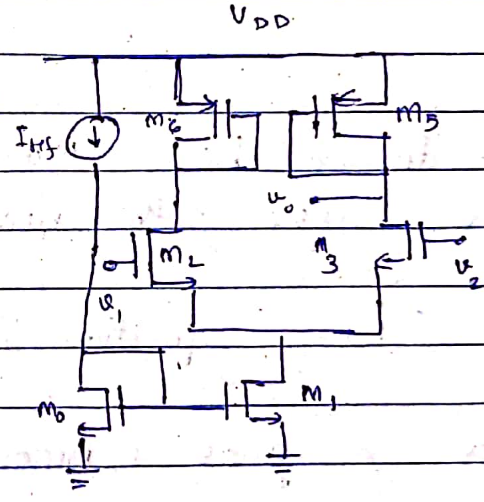
So to bias M_1, we take M_0, to make V_{GS} same for same current (I_{D_0} & I_{D_1}) to flow, If we want different current then we change W & L.

So we wanted to make $A_d \uparrow = -g_m R_D/2$

$A_c \downarrow = -R_D/2R_T$

is achieved by putting diodes.





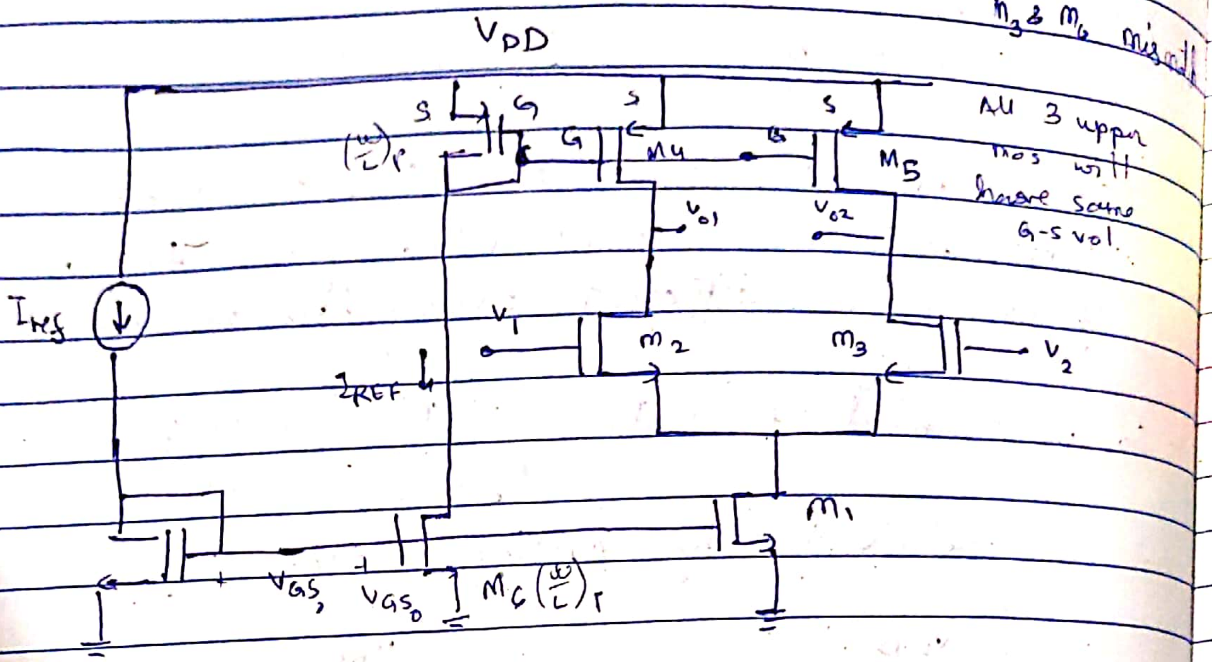
$$A_{d_1} = \frac{V_{o1}}{V_d} = \frac{-g_{m2}}{2}\left[\frac{r_{ds2}}{1+g_{m4}r_{ds2}}\right]$$

$$\simeq \sim -0.5$$

$$= -A_{d_2}$$

2) Differential Amplifier with Active load

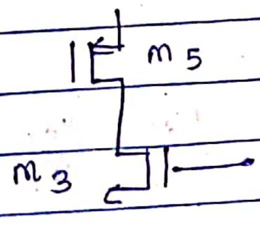
Another topology to increase $A_d \uparrow$ & $A_c \downarrow$.

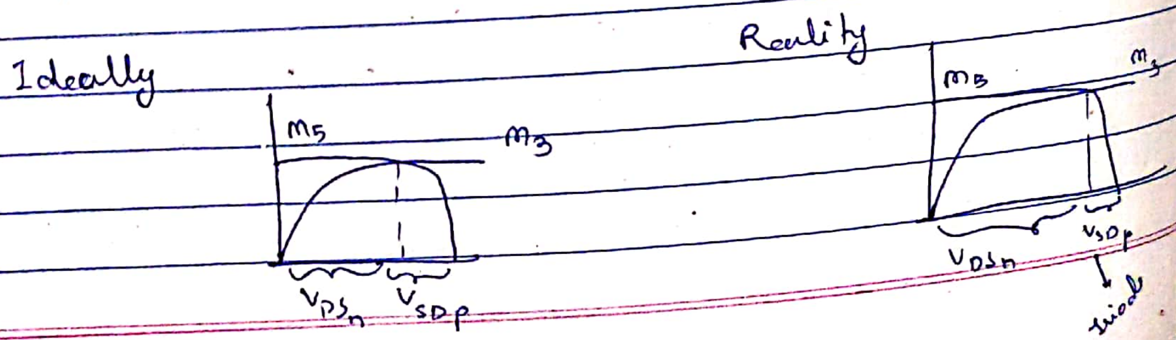


How do we bias m_4 m_5, Whatever we have done with nmos $(m_1 \& m_2)$, same with pmos.

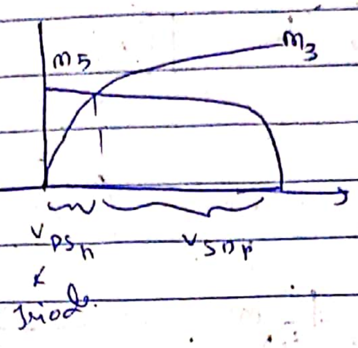
But a basic question is

when a pmos & nmos are connected



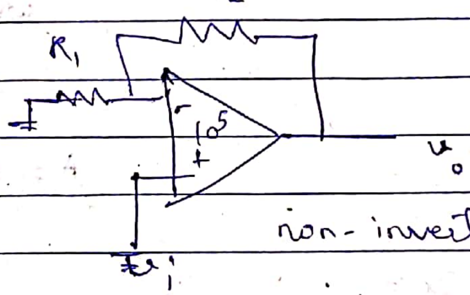


There is a mis-match b/n m_5 & m_3
always one of the device will go in triode.



So we can't connect nmos & pmos.

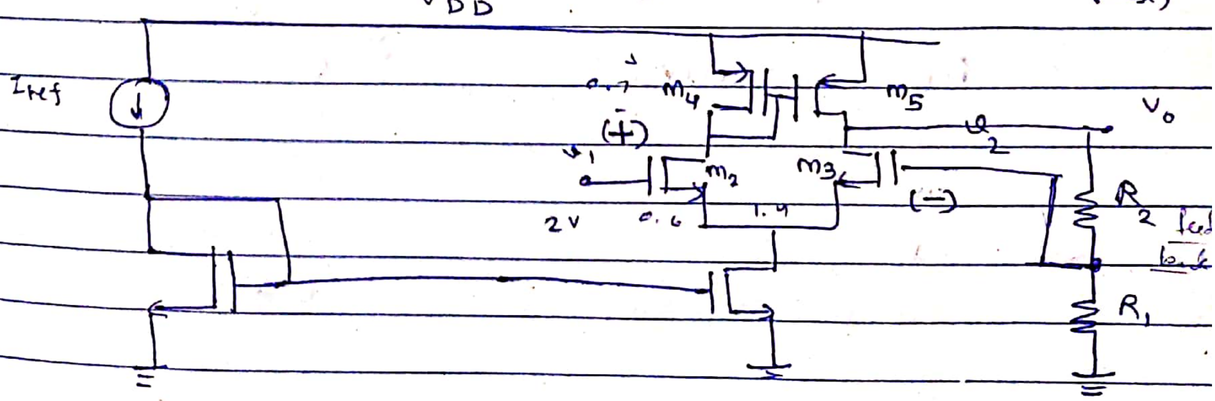
Case :. Feedback



non-inverting

$$A = 1 + \frac{R_2 \cdot (1K)}{R_1 (1K)} = 2$$

So here also we try to build a feedback to keep ckt linear. (v_2 & v_o → 180 phase)

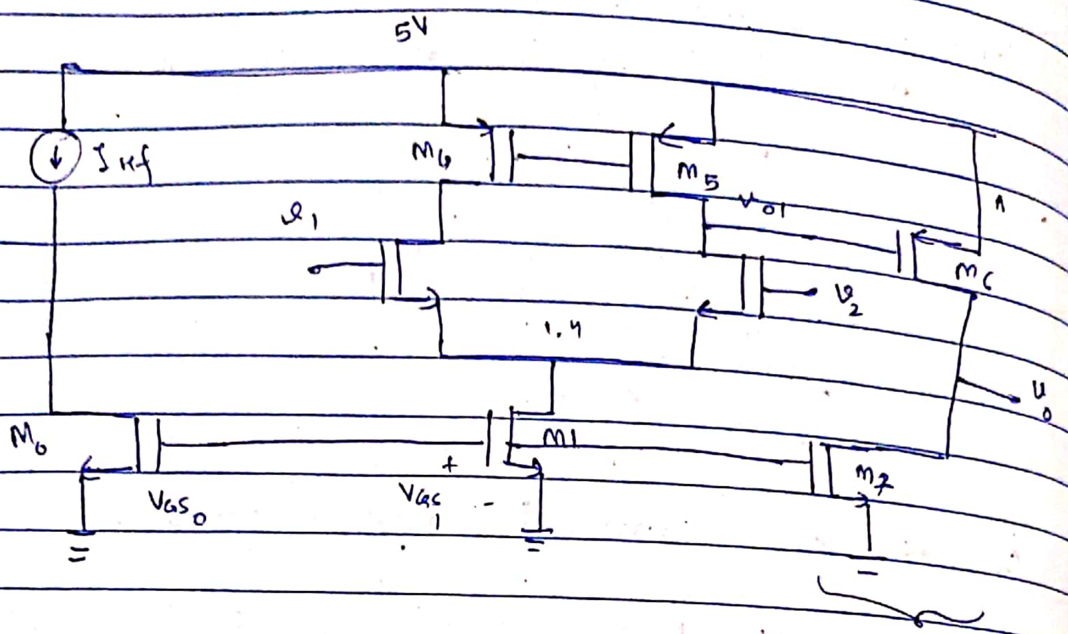


③ 5 - pack differential amp

L.N Gd CMOS
or Baker

2-stage Op Amp.

7 pack differential amplifier



Post test

A = 5

v_0 =

R_2 = 30k

R_1 = 10k

$\frac{V_0}{V_i}$ =

20 log 106

To design a Op Amp,

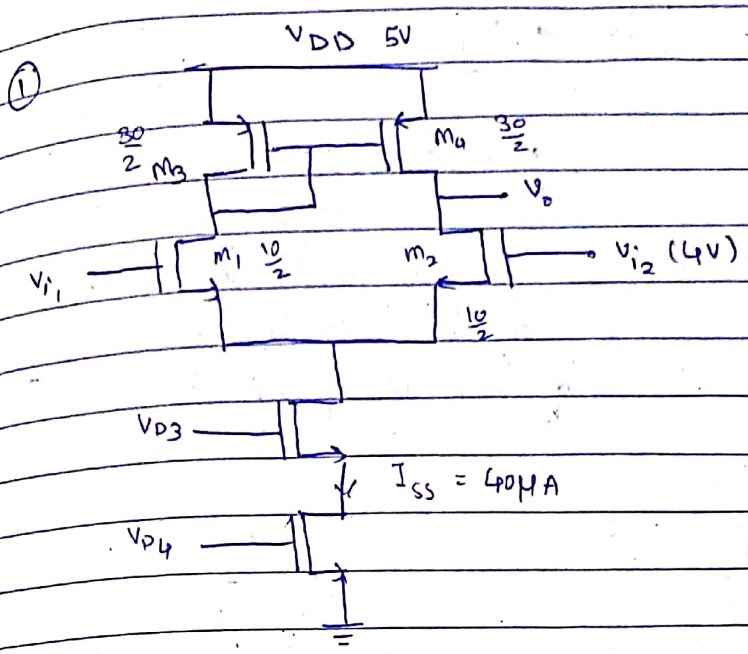
- MOS structure
- I_D 5 V_{GS}, V_{DS}
- gm
- rds
- Temp variation,

* CS
* CG
* CD
* C mirror
* D-A

1|12.19

Problems :

①



If gate of M_2 is held at 4V cal. the diff amp i/p swing.

$V_{DS\,sat} = V_{SP(sat)} = 250mV$

$V_{GS_N} = 1.05V$

$\rightarrow$ $V_{D,max} = V_{DD} - V_{SD_4}(sat)$

$= 5 - 0.25$

$= 4.75\ V$

$V_{S1,2} = 4 - V_{GS2}$

$= 4 - 1.05$

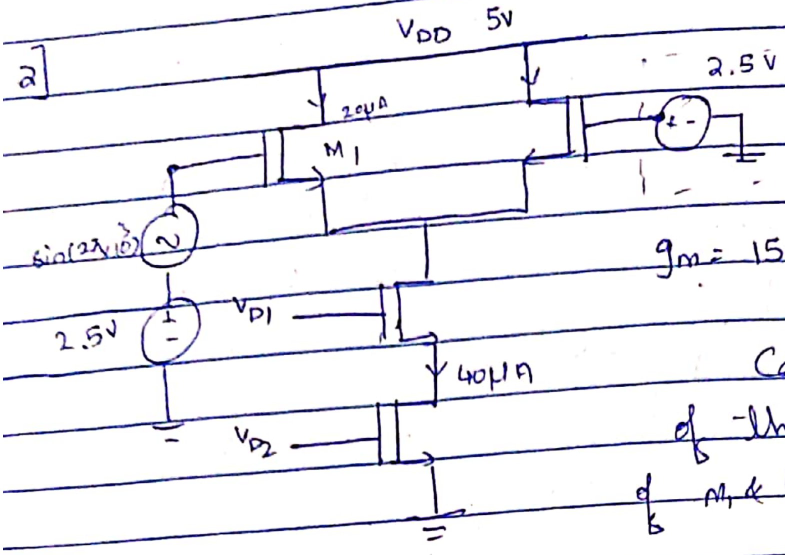
$= 2.95V$

$V_{D,min} = V_{S1,2} + V_{DS2}(sat)$

$= 2.95 + 0.25$

$= 3.2$ volts

2]



$g_m = 150\mu A/V$.

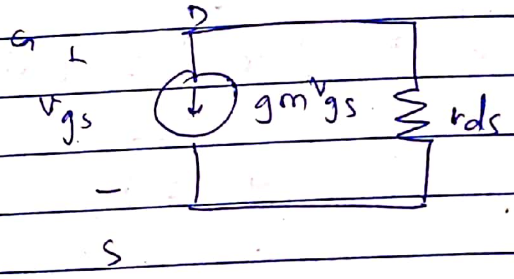
Calculate AC content of the drain current of M_1 & M_2 if $v_{i1} = 2.5V + 1\times10^{-3}\sin 2\pi \cdot 10^3$

$i_D = I_D + i_d$

$= 20\mu + i_d$.

To find i_d

eq. model



$$\boxed{i_d = g_m v_{gs}}$$

v_{gs1} & v_{gs2} =

$$i_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_t)^2$$

$20\mu =$

$-v_{gs2} + v_{gs2} - 1mV = 0$.

M_1 & M_2 are matched

$v_{gs1} = -v_{gs2}$

$v_{gs1} = 0.5mA$

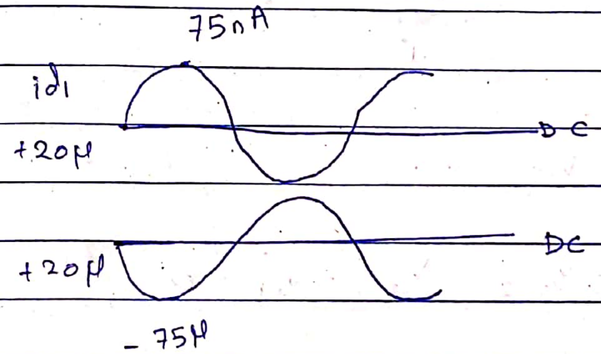
$i_{d_1} = 150\mu \times 0.5m$

$= 75nA$

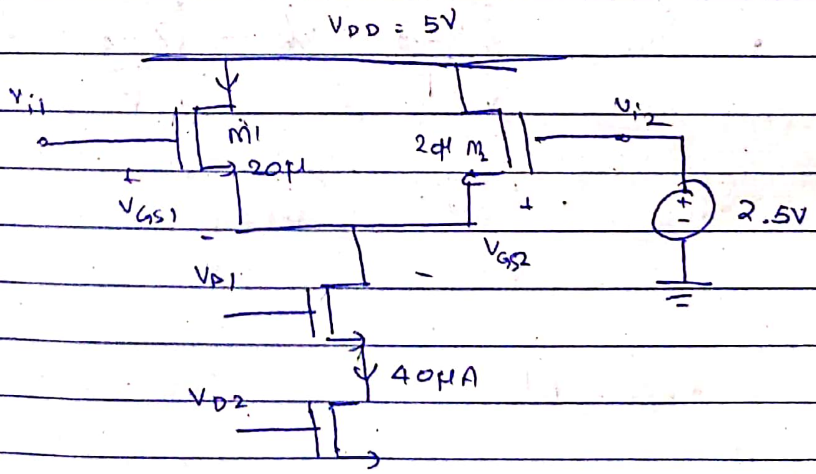
$i_{d_2} = -75nA$.

$v_{i1} = 1m\sin 2\pi \times 10^3 t$

$v_{i2} = 0$



(2)



Cal. the main & max vol. in the gate of M1 that ensures neither M1 nor M2 shut off

$$I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) (V_{GS} - V_t)^2$$

$$(V_{GS} - V_t)^2 = \frac{2 I_D}{\mu_n C_{ox} W/L \rightarrow \beta}$$

$$V_{GS} = \sqrt{\frac{2 I_D}{\beta}} + V_{th}$$

$$V_{GS_1} = \sqrt{\frac{2 I_{D_1}}{\beta}} + V_t$$

$$V_{GS_2} = \sqrt{\frac{2 I_{D_2}}{\beta}} + V_t$$

KVL from V_{i_2} to V_{i_1}

$$+V_{i_2} - V_{GS2} + V_{GS1} - V_{i_1} = 0$$

$$V_{i_2} - V_{i_1} = V_{GS2} - V_{GS1}$$

$$V_{i_2} - V_{i_1} = \sqrt{\frac{2 I_{D_2}}{\beta}} + \cancel{V_{th}} - \sqrt{\frac{2 I_{D_1}}{\beta}} - \cancel{V_t}$$

$$V_{i_2} - V_{i_1} = \sqrt{\frac{2}{\beta}(I_{D_2} - I_{D_1})}$$ //

$$\mu_n C_{ox} = 120 \mu A/V^2$$

$$\frac{W}{L} = \frac{10}{2}$$

$V_{2}i_{2} = 0 \Rightarrow I_{D1} = 40\mu A, \; I_{D2} = 0$

max vol

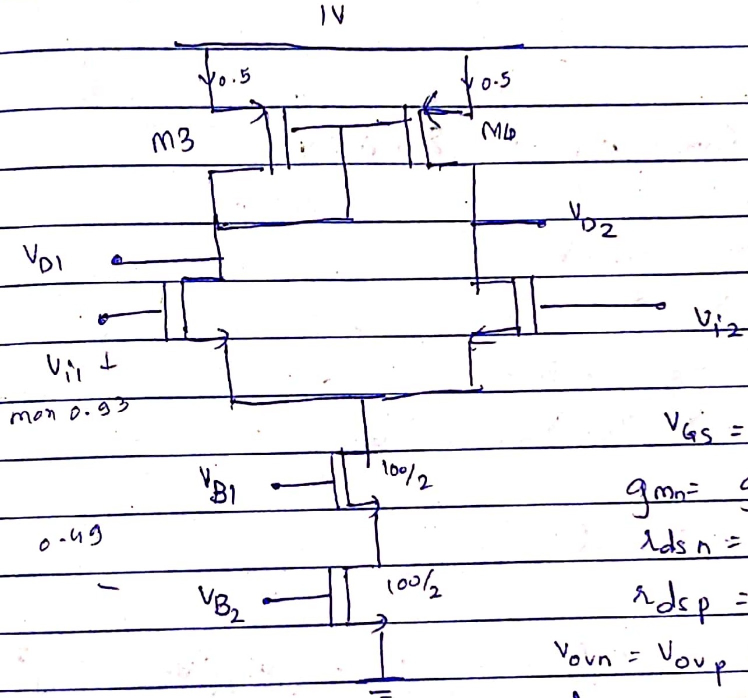
$$+v_{i1} = -\sqrt{\frac{2}{\beta}}\sqrt{I_{D1}}$$

$$= -0.365\,V$$

max $= 2.5 + 0.365\,V = 2.865V$

min. $2.5 - 0.365 = 2.135V$

(3)



$V_{GS} = V_{SG} = 350\,mV$

$g_{mn} = g_{mp} = 150\,\mu A/V$

$r_{dsn} = 167\,k\Omega$

$r_{dsp} = 333\,k\Omega$

$V_{ovn} = V_{ovp} = 70\,mV$

Determine the small signal gain & the i/p (cmr) common mode rejection ratio

$V_{DS}(sat) = V_{SD}(sat) = 50mV$

diff gain

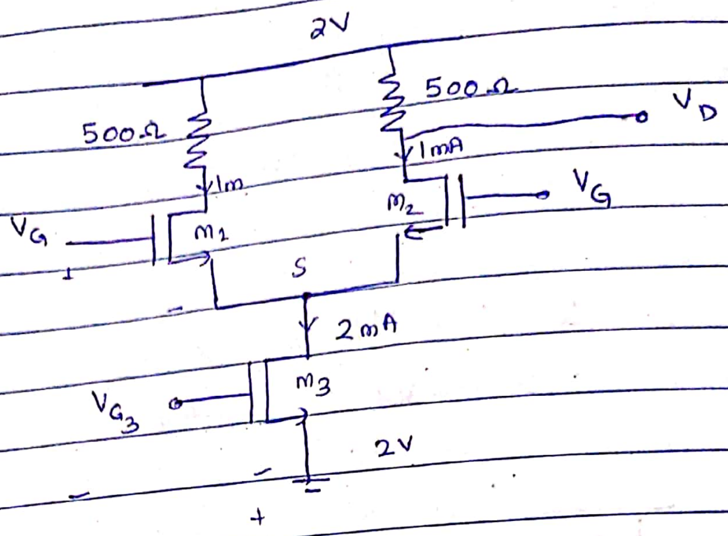
$$\frac{V_{o2} - V_{o1}}{V_d} = ?$$

→ $A_d = \frac{V_o}{V_{in}} = 16.7$

CM (max) $V = 0.93V$

min $= 0.49V$

DA Basics.



$$\mu_n C_{ox} \left(\frac{W}{L}\right) = 8 mA/V^2$$

$V_T = 0.5 V$

$\lambda = 0$

$V_{OV_3} = 0.5 V$

Compute V_S, V_D, V_{DS} & V_{GS}

(i) $V_G = 0$ ② $V_G = 1$

→ $I_D = 1mA = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS_1} - V_t)^2$

$1m = \frac{1}{2} \times 8 \times 10^{-3} (V_{GS_1} - 0.5)^2$

$2\cancel{m} = 8\cancel{m} (V_{GS} - 0.5)^2$

$\boxed{1V = V_{GS_1}}$

Using KVL,

V_S is wrt gnd. so 2V won't come.

$+ V_S + V_{GS_1} - \cancel{V_G}^{0} = 0$

$+ V_S + 1 = 0$

$\boxed{V_S = -1V}$

$V_{D_1} = V_{DD} - i_D R_D$

$= 2V - (1m)(500)$

$\boxed{V_{D_1} = 1.5V}$

$V_{DS} = V_D - V_S$

$= 2.5V$ //

Case 2: When $V_G = 1V$

$i_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS_1} - V_t)^2$

$1m = \frac{1}{2}(8 \times 10^{-3})(V_{GS_1} - 0.5)^2$

$\boxed{V_{GS_1} = 1V}$

$V_{GS_1} = 1$

$V_G - V_S = 1$

$1 - V_S = 1$

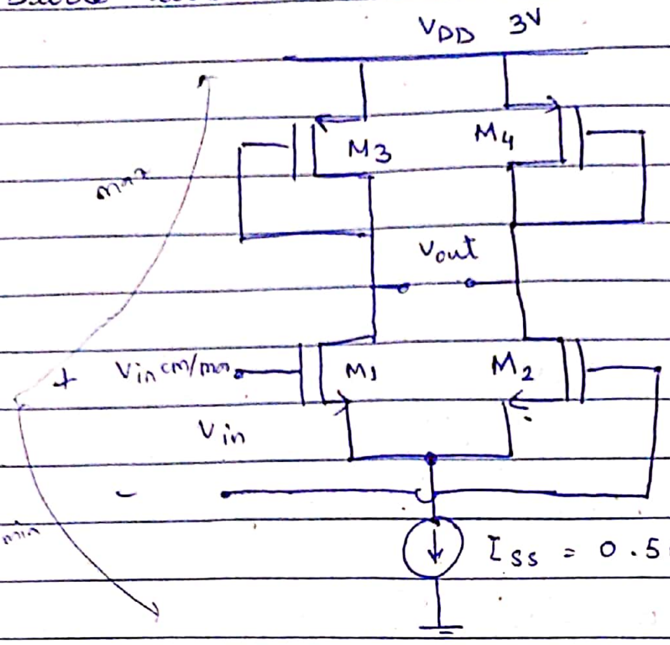
$\boxed{V_S = 0}$

$V_D = V_{DD} - i_D R_D$

$\boxed{V_D = 1.5V}$

$\boxed{V_{DS} = 1.5V}$

Diode load :-



$\left(\frac{W}{L}\right)_{1,2} = \frac{50}{0.5}$

$\left(\frac{W}{L}\right)_{3,4} = \frac{10}{0.5}$

I_{ss} is implement using Nmos of $\left(\frac{W}{L}\right)_{ss} = \frac{50}{0.5}$

① $V_{incm/min} = ?$

② $V_{in\,cm/max} = ?$

If differential amplifier at i/p & o/p are small. $V_{THN} = 0.7V$ $V_{THP} = -0.8V$ $\mu_n C_{ox} = 134\mu A/V^2$ $\mu_p C_{ox} = 38\mu A/V^2$

$$\rightarrow A_d = \frac{-g_{m1}}{g_{m3}} = -\sqrt{\frac{\cancel{1/2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 \cancel{I_{D1}}}{\cancel{1/2}\mu_p C_{ox}\left(\frac{W}{L}\right)_3 \cancel{I_{D1}}}}$$

$$A_d = -\sqrt{\frac{\mu_n (W/L)_1}{\mu_p (W/L)_3}} \,//$$

$$I_{ss} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_{ss}\left(V_{GS(ss)} - V_{THN}\right)^2$$

$$0.5m = \frac{1}{2} \times 134 \times 10^{-6} \times 100 \times \left(V_{GS(ss)} - 0.7\right)^2$$

$$\left(V_{GS(ss)} - V_{THN}\right) = V_{OVss} = 0.273 \ V$$

$$I_{D_1} = \frac{I_{SS}}{2} = 0.25\,mA$$

$$(V_{GS_1} - V_{THN}) = \sqrt{\frac{2 \times I_{D_1}}{\underset{134\mu}{\mu_n C_{ox}} \left(\frac{W}{L}\right)_1 \times 100}}$$

$$V_{ov_1} = 0.193V$$

$$V_{GS_1} = V_{ov_1} + V_{THN}$$
$$= 0.193 + 0.7$$
$$= 0.893\,V$$

$$V_{in\,cm}\Big|_{min} = V_{GS_1} + V_{ov_{ss}}$$
$$= 0.893 + 0.273$$
$$= 1.17\,V$$

$$V_{in,\,cm}\Big|_{max} = 2.09\,V$$

HW

$$A_d = -\frac{g_{m_2}}{g_{m_4}} = -\sqrt{\frac{\cancel{1/2}\,\mu_n C_{ox} (W/L)_2 (I_{D_2})}{\cancel{1/2}\,\mu_p C_{ox} (W/L)_4 (I_{D_2})}}$$

$$A_d = -\sqrt{\frac{\mu_n (W/L)_2}{\mu_p (W/L)_4}}$$

$$I_d = -\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_4 (V_{GS_4} - V_{TH_p})^2$$

$$0.25m = -\frac{1}{2} \times 38 \times 10^{-6} \times \frac{10}{0.5}(V_{GS_4} + 0.8)^2$$

$$\boxed{V_{GS_4} = 0.346V}$$

KVL ① across V_{in} & SS

$$+V_{OSS} + V_{GS1} - V_{incm}|_{max} = 0$$

KVL ② across VDD

$$V_{OVSS} + V_{OV1} + V_{GS3} - V_{DD} = 0$$

$$V_{OVSS} = V_{DD} - V_{OV1} - V_{GS3}$$
$$= V_{DD} - (V_{GS1} - V_{THN}) - V_{GS3}$$
$$= V_{DD} - V_{GS1} + V_{THN} - V_{GS3}$$

$$V_{in\,cm}|_{max} = V_{OVSS} + V_{GS1}$$
$$= V_{DD} - V_{GS1} + V_{THN} - V_{GS3}$$

$$V_{in\,cm}|_{max} = V_{DD}' - |V_{GB}| + V_{THN}$$

$$V_{GS3} = ?$$
$$= V_{THP} + \sqrt{\frac{2I_{D3}}{\mu_p C_{ox}(W/L)_3}}$$

$$= 0.8 + \sqrt{\frac{2\times 0.25\times 10^{-3}}{38\times 10^{-6}\times 20}}$$

$$= 1.61\ V$$

$$V_{in\,cm}|_{max} = 3 - 1.61 + 0.7$$

$$= 2.08\ V$$

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H. W

Part B :-

If $v_{incm} = 1.2V$, sketch the small signal differential voltage gain as V_{DD} goes from 0-3V.

Q2] In above problem, if m1 and m2 have V_T mismatch of 1mV, calc. the CMRR.

Suppose m1 & m2 have a threshold vol of 1mV, what is the CMRR

→ Both currents are different ; $g_{m1} \neq g_{m2}$

$g_{m3} \neq g_{m4}$

$$i_{D1} = \frac{1}{2} K_n' \frac{W}{L} (V_{GS1} - V_t)^2$$

$$i_{D1} = \frac{1}{2} \times 134 \times 10^{-6} \times (0.893 - \cancel{0.7}V_t)^2$$

$i_{D1} = \cancel{134\mu A}$ 0.25mA

$$i_{D2} = \frac{1}{2} \times K_n' \left(\frac{W}{L}\right) (V_{GS} - (V_t - 1))^2$$

$$= \frac{1}{2} \times 134 \times 10^{-6} (0.893 - 0.699)^2$$

=

$i_{D1} = g_{m1} v_{gs1}$

$= g_m [v_{incm} - v_s]$

$i_{D2} = g_{m2} [v_{incm} - v_s]$

$$v_{out1} = -i_{D1} \times \frac{1}{g_{m3}} = \frac{-g_{m1} [v_{incm} - v_s)}{g_{m3}}$$

$$V_{out2} = -i_{D2} \times \frac{1}{g_{m4}}$$

$$= -\frac{g_{m2}}{g_{m4}}(V_{incm} - V_S)$$

$$\frac{g_{m1}}{g_{m3}} = \sqrt{\frac{2I_{D1}\mu_n C_{ox}(W/L)_1}{2I_{D3}\mu_p C_{ox}(W/L)_3}} = \sqrt{\frac{\mu_n (W/L)_1}{\mu_p (W/L)_3}}$$

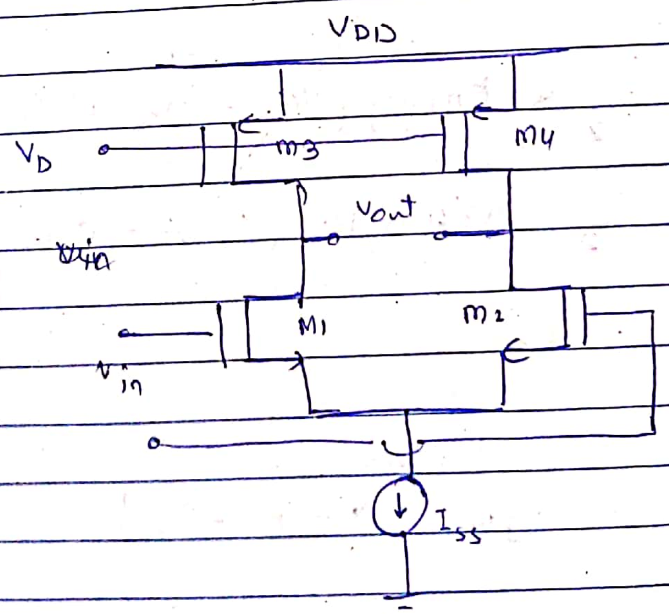
$$\frac{g_{m2}}{g_{m4}} = \sqrt{\frac{\mu_n (W/L)_2}{\mu_p (W/L)_p}}$$

Since μ_n & $\frac{W}{L}$ are same for M_1, M_2

μ_p & $\frac{W}{L}$ are same for M_3, M_4

$V_{out1} = V_{out2}$

H.W



$\left(\frac{W}{L}\right)_{1to4} = \frac{50}{0.5}$

$I_{SS} = 1\,mA$

(a) Calc. small signal D. Gain

$\lambda_n = 0.1$

$\lambda_p = 0.2$

(b) Find $V_{incm} = 1.5V$

max o/p swing = ?

$g_m = 3.66\,m℧$

$\rightarrow \quad r_{ds1} = \dfrac{1}{\lambda_n \times I_{D1}}$

$= \dfrac{1}{0.1 \times 0.5m}$

$= 20k\Omega$

$r_{ds3} = \dfrac{1}{\lambda_p I_{P3}}$

$= \dfrac{1}{0.2 \times 0.5m} = 10k\Omega$ //

Gain = $A_d = -g_m(r_{ds1} \parallel r_{ds3})$

$= -3.66m \left[\dfrac{r_{ds1} \times r_{ds3}}{r_{ds1} + r_{ds3}} \right]$

$= -3.66m \times$

$\boxed{A_d = -24.5}$ //

(b) ~~Ans Vin~~ min o/p V = 0.8 V

max = 2.49 V

$2(2.49 - 0.8) = 3.38V$ //

~~1.5 - (0.75 - 0.001)~~

KVL eq. to o/p min

$+ V_P + V_{ov1} - V_{out,min} = 0$

$(V_P = V_{in,cm} - V_{GS})$ $\quad V_{out,min} = V_{in,cm} - \cancel{V_{GS1}} + (\cancel{V_{GS1}} - V_{THN})$

$= V_{in,cm} - V_{THN}$

$= 1.5 - 0.7$

$= 0.8V$ //

$$* \quad V_{out,max} = V_{DD} - V_{SD3}(sat)$$

$$= V_{DD} - V_{OV3}$$

$$= V_{DD} - (V_{GS3} - V_{THP}) \;//$$

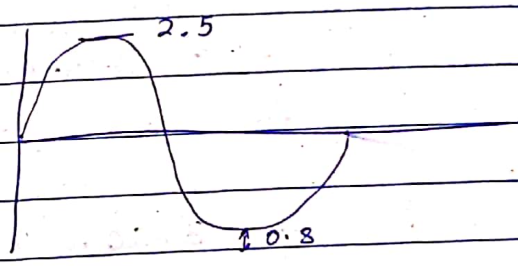
$$= V_{DD} - |V_{GS3}| + V_{THP}$$

$$3 - 1.261 + 0.8$$

$$\left(\sqrt{\frac{2 I_{D3}}{\mu_p C_{ox}(W/L)}} + V_{THP}\right)$$

$$= 3 - \sqrt{\frac{2 (0.5m)}{38\mu \times 100}}$$

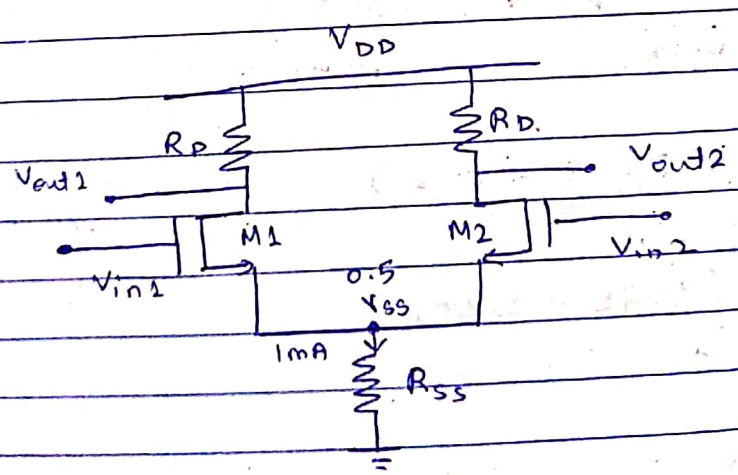
$$= 2.487 \text{ V} \;//$$



$$\text{max o/p swing} = 2(2.5 - 0.8)$$

$$= 3.38\text{V} \;//$$

Qn:



$$\left(\frac{W}{L}\right)_{1,2} = \frac{25}{0.5}$$

$$\mu_n C_{ox} = 50\,\mu A/V^2$$

$$V_{th} = 0.6\text{V}$$

$$\lambda = \gamma = 0$$

(a) What is the req. input CM voltage for which R_{SS} sustains 0.5 V

$\rightarrow$ $R_{SS} = \frac{0.5}{1m} = \frac{V_S}{I_{SS}} = 500\,\Omega$

Common mode voltage

$V_{GS} = ?$

$i_d = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS} - V_t)^2$

$0.5m = \frac{1}{\cancel{2}} \times 50\mu \times \overset{25}{\cancel{50}} (V_{GS_1} - 0.6)^2$

$\boxed{V_{GS_1} = 1.23V}$

$V_{in,cm} = V_{GS_1} + V_{SS}$

$= 1.23 + 0.5$

$= 0.73\ V$

(b) Calc. Rd for diff. gain of 5.

$A_d = +g_m\left(\frac{R_d}{2}\right) + g_m \frac{R_d}{2}$

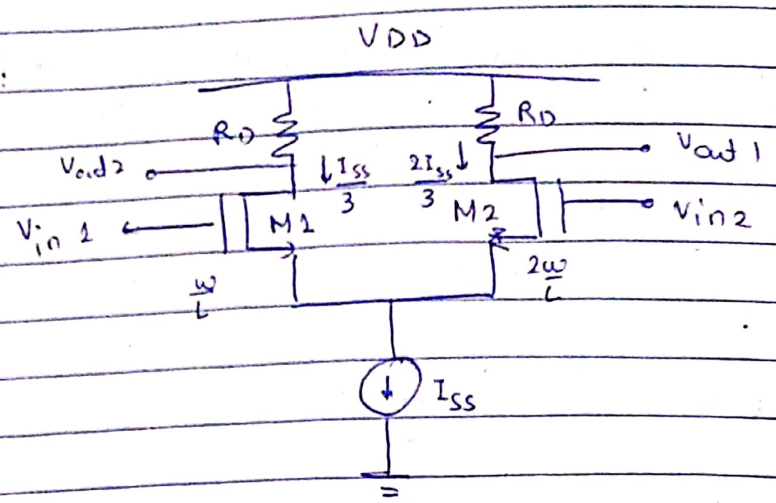
$= g_m R_d$

$= \sqrt{\frac{2 I_D}{\mu_n C_{ox}(W/L)}}$

$5 = \sqrt{\frac{2 \times 0.5m}{50\mu \times 50}} \; ; R_D$

$\boxed{R_D = 3.16\,k\Omega}$

Ex 2:



If $V_{in1} = V_{in2}$ find small signal gain

$|A_V| = \frac{4}{3} g_{m1} R_D$

→

$$g_{m1} = \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} W/L}} \longrightarrow I_{ss}/3$$

$$g_{m2} = \sqrt{\frac{2 \cdot I_{D2}}{\mu_n C_{ox} W/L}}$$

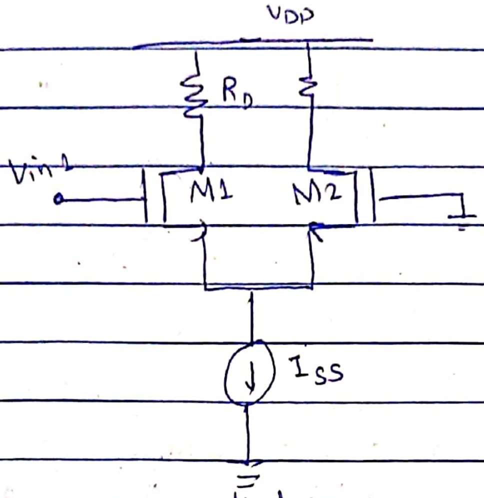
$$g_{m1} = \sqrt{2 \frac{I_{ss}}{3} \mu_n C_{ox} \left(\frac{W}{L}\right)}$$

$$g_{m2} = \sqrt{2\left(\frac{2I_{ss}}{3}\right) \mu_n C_{ox} \left(\frac{2W}{L}\right)}$$

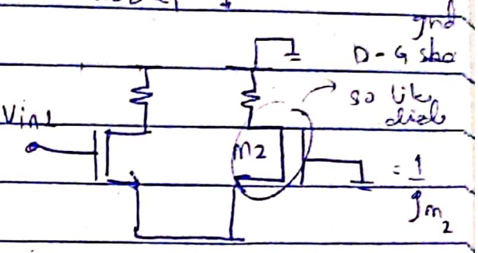
$g_{m2} = 2 g_{m1}$

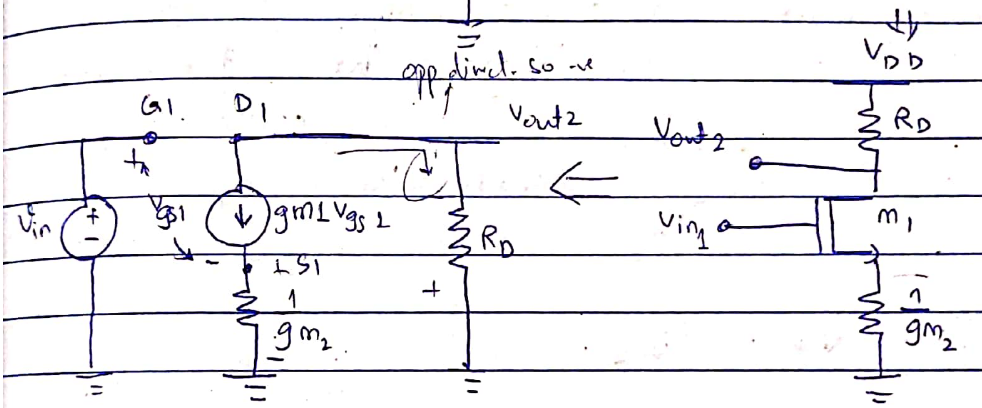
consider V_{in_1} ~~and~~ make $V_{in_2} = 0$

$$V_{out2} = V_{DD} - \cancel{(V_{in1} + V_{SS})}$$
$$= 3 -$$



for small signal model -1





$$V_{gs1} = ?$$

$$V_{s_1} + V_{gs1} - V_{in1} = 0$$

$$g_{m1} V_{gs1} \times \frac{1}{g_{m2}} + V_{gs1} - V_{in1} = 0$$

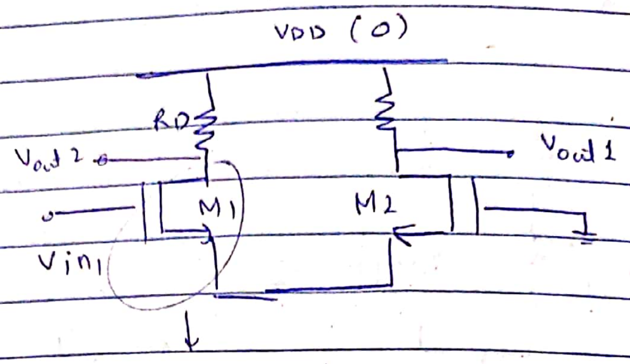
$$V_{gs1}\left(\frac{g_{m1}}{g_{m2}} + 1\right) = V_{in1} \qquad V_{gs1} = \frac{V_{in1}}{1 + \frac{g_{m1}}{g_{m2}}}$$

$$V_{out2} = -g_{m1} V_{gs} R_D$$
$$= -g_{m1}\left(\frac{V_{in1}}{1 + \frac{g_{m1}}{g_{m2}}}\right) R_D$$

$$\boxed{\frac{V_{out2}}{V_{in1}} = \frac{-R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}}$$

(b) Take V_{out1}

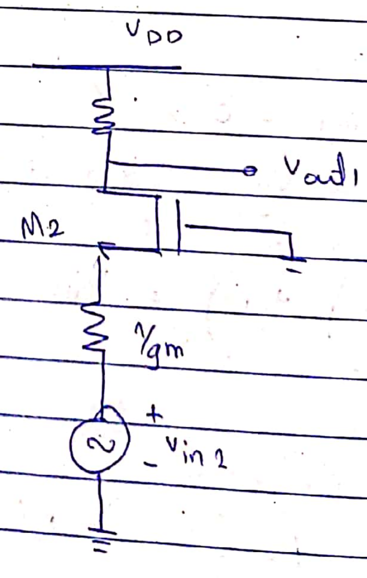
Let $V_{in2} = 0$

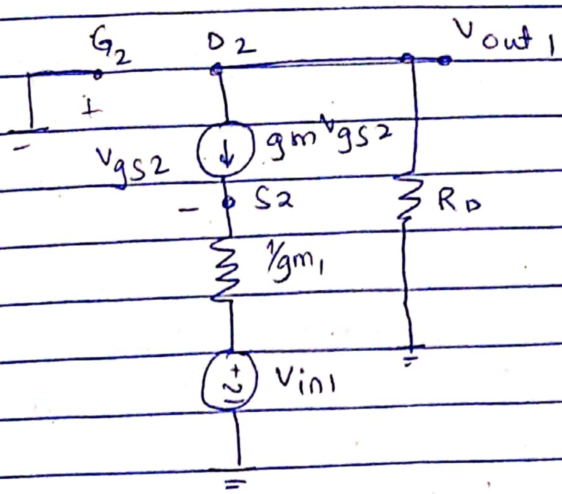


Thevenin's resis (small signal analysis, D_1 − gnd
$V_{in1} \to$ gnd ∵ we want to find R_T
(inactive ckt))

$R_T = \frac{1}{g_m}$ (Everything is 0 except M_1)

$V_{th} = V_{in2}$





$$+V_{in1} + g_{m2} V_{gs2} \times \frac{1}{g_{m2}} + V_{gs2} = 0$$

$$V_{gs2} = \frac{-V_{in1}}{1 + \frac{g_{m2}}{g_{m1}}}$$

$$V_{out1} = -R_D g_{m2} V_{gs2}$$

$$= -R_D g_{m2} \left(\frac{-V_{in1}}{1 + \frac{g_{m2}}{g_{m1}}} \right)$$

$$\boxed{\frac{V_{out1}}{V_{in1}} = \frac{R_D}{\frac{1}{g_{m2}} + \frac{1}{g_{m1}}}}$$

$$\therefore \frac{V_{out1}}{V_{in1}} - \frac{V_{out2}}{V_{in2}}$$

$$= \frac{2R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}$$

$||^{ly}$ $\dfrac{V_{out1} - V_{out2}}{V_{in2}} = \dfrac{-2R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}$

phase change.

$A_d = \cancel{\dfrac{V_{out1}}{V_{in1}}}$

$= \dfrac{1}{V_{in1}}(V_{out1} - V_{out2})$

$$A_d = \frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}}$$

$$= \frac{V_{out1}}{V_{in1} - V_{in2}} - \frac{V_{out2}}{V_{in1} - V_{in2}}$$

$$1/A_d = \frac{V_{in1} - V_{in2}}{V_{out1} - V_{out2}}$$

$$= \frac{V_{in1}}{V_{out1} - V_{out2}} - \frac{V_{in2}}{V_{out1} - V_{out2}}$$

$$= \frac{1/2R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}} + \frac{1/2R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}$$

$$= \frac{1}{\frac{2R_D}{\frac{g_{m1}+g_{m2}}{g_{m1}g_{m2}}}} + \frac{1}{\frac{2R_D}{\frac{g_{m1}+g_{m2}}{g_{m1}g_{m2}}}}$$

$$= \frac{\cancel{2}g_{m1}g_{m2}}{\cancel{2}R_D(g_{m1}+g_{m2})}$$

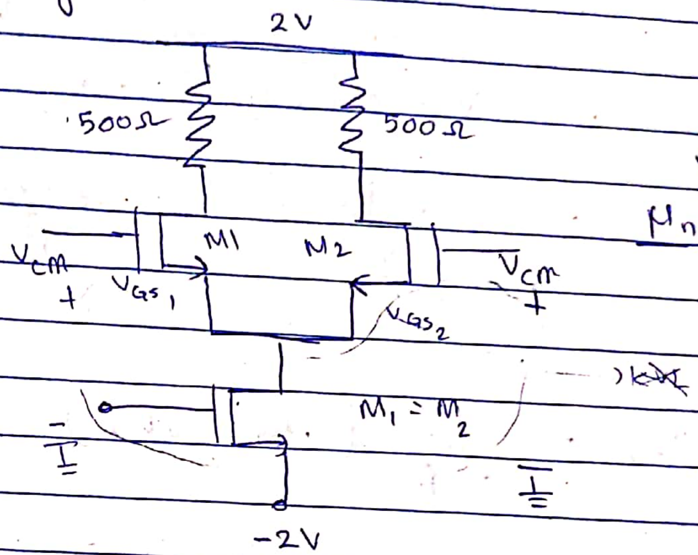
*(cnd back) Done using superposition in grp

$$= \frac{R_D(g_{m_1} + g_{m_2})}{g_{m_1} g_{m_2}}$$

$$= \frac{R_D g_{m_1} + R_D g_{m_2}}{g_{m_2} g_{m_1}}$$

CM Range = ?

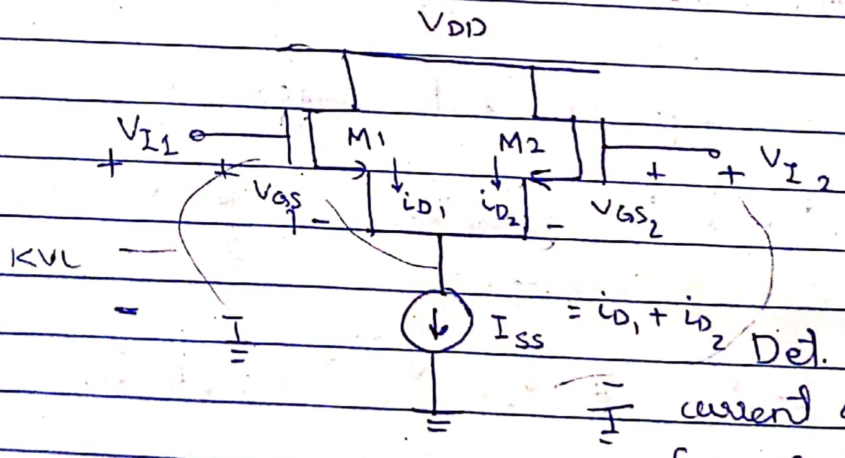
?



$V_t = 0.5V$

$\mu_n C_{ox}\left(\frac{W}{L}\right) = 8\,mA/V^2$

?



$= i_{D_1} + i_{D_2}$ Det. the drain current of M1 as a fun. of input voltages. $(V_{I_1} - V_{I_2})$

KVL for m_1 & m_2

$$V_{I_2} - V_{GS2} + V_{GS_1} - V_{I_1} = 0$$

$$\boxed{V_{GS_1} - V_{GS2} = V_{I_1} - V_{I_2}}$$

m_1 & m_2 - sat.

$$i_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)^2$$

$$V_{GS} = \sqrt{\frac{2 i_D}{\mu_n C_{ox} W/L}} + V_{TH}$$

$$V_{I_1} - V_{I_2} = \sqrt{\frac{2 i_{D1}}{\mu_n C_{ox} (W/L)_1}} + \cancel{V_{TH}} - \sqrt{\frac{2 i_{D2}}{\mu_n C_{ox} (W/L)_2}} - \cancel{V_{TH}}$$

matched

$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$

$$= \sqrt{\frac{2 i_{D1}}{\beta}} - \sqrt{\frac{2 i_{D2}}{\beta}}$$

$$V_{I_1} - V_{I_2} = \sqrt{\frac{2}{\beta}} \left(\sqrt{i_{D_1}} - \sqrt{i_{D2}}\right)$$

$$\sqrt{i_{D_1}} - \sqrt{i_{D2}} = V_{I_1} - V_{I2} \sqrt{\frac{\beta}{2}}$$

Sq. on both sides

$$i_{D_1} + i_{D_2} - 2\sqrt{i_{D_1} i_{D2}} = \frac{\beta}{2} (V_{I_1} - V_{I_2})^2$$

$$i_{D_1} = \frac{\beta}{2} (V_{I_1} - V_{I_2})^2 + 2\sqrt{i_{D_1} i_{D_2}} - i_{D_2}$$

$$I_{SS} - 2\sqrt{i_{D_1} i_{D_2}} = \frac{\beta}{2} (V_{I_1} - V_{I_2})^2$$

$$I_{SS} - \cancel{\frac{\beta}{2} (V_{I_1} - V_{I_2})^2} = 2 \sqrt{i_{D_1}} \sqrt{i_{D_2}}$$

SOBS

$$I_{SS}^2 + \left[\frac{\beta}{2}\left(V_{I_1}^2 + V_{I_2}^2 - 2V_{I_1}V_{I_1}\right) - 2I_{SS}\frac{\beta}{2}(V_{I_1} - V_{I_2})^2\right]^2 = 4 i_{D_1} i_{D_2}$$

$$I_{SS}^2 + \left[\frac{\beta V_{I_1}^2}{2} + \frac{\beta V_{I_2}^2}{2} - \frac{\beta 2 V_{I_1} V_{I_2}}{2}\right]^2 = 4 i_{D_1} i_{D_2}$$

$$I_{SS}^2 + \frac{\beta^2 V_{I_1}^4}{4} + \frac{\beta^2 V_{I_1}^4}{4} + \frac{\beta^2 4 V_{I_1}^2 V_{I_2}^2}{4} - 2\beta^2 V_{I_1}^2$$

$$I_{SS}^2 + \frac{\beta^2 (V_{I_1} - V_{I_2})^4}{4} - 2 \times I_{SS} \times \frac{\beta}{2}(V_{I_1} - V_{I_2})^2 = 4 i_{D_1} i_{D_2}$$

$$(\qquad\qquad) = 4 i_{D_1}(I_{SS} - i_{D_1})$$

$$\boxed{i_{D_1}^2 = -\frac{I_{SS}^2}{4} + \frac{I_{SS}\beta(V_{I_1} - V_{I_2})^2}{4} - \frac{\beta^2(V_{I_1} - V_{I_2})^4}{16} + i_{D_1} I_{SS}}$$

(b) what does derivation give to i_{D_1} when $V_{I_1} \gg V_{I_2}$

$$V_{I_1} \gg V_{I_2}$$

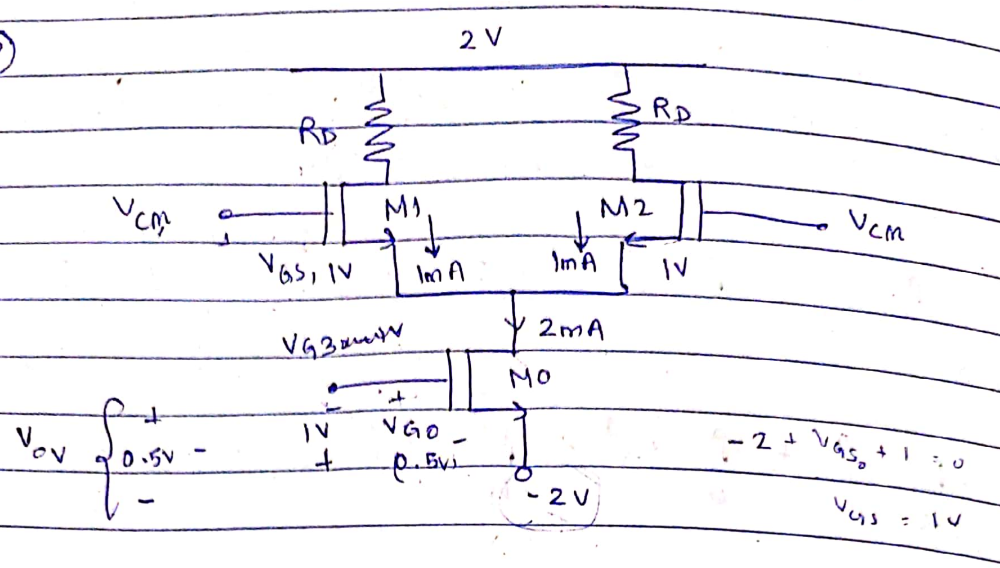
$$I_{SS} = i_{D_1} + \cancel{i_{D_2}}$$

$$I_{SS} \approx i_{D_1}$$

$$\therefore \quad i_{D_1} = \sqrt{+\frac{3 I_{SS}^2}{4} + \frac{I_{SS}\beta(V_{I_1} - V_{I_2})^2}{4} - \frac{\beta^2(V_{I_1} - V_{I_2})^4}{16}}$$

Here although -ve 1V is supplied cal, V_{GS} if is +ve

(P)



$-2-\cancel{1}+\cancel{1}+1-V_{cm}=0$

$-1V + \cancel{V_{cm\,min}} + \cancel{...} - 1V \mp 2V + 1 = 0$

$+0.5 \quad +1$

$-2-\cancel{1}+\cancel{1}+\cancel{... } - V_{cm\,min} = 0$

$$\boxed{V_{cm\,min} = \cancel{1V} - 0.5}$$

$V_{cm\,max}$:-

$+2-2-1+1+1 \mp V_{cm\,max} + 500(1m) = 0$

$\cancel{V_{cm\,max}} = 1.5V.$

$+2 - 2 + 0.5 + 1 - V_{cm\,max} + 500(1m) = 0$

$$\boxed{V_{cm\,max} = -2V}$$

Mam's

$-2 + V_{ov,3} + V_{GS_1} - V_{cm,\,min} = 0$

$V_{cm,\,min} = V_{GS_1} + V_{ov,3} - 2$

For max

$-2 + V_{DS_1} + V_{GS_1} - V_{cm,\,max}.$

$-2 + V_{DS_1} + V_{ov,1} + I_{D_1}R_D - V_{DD} = 0$

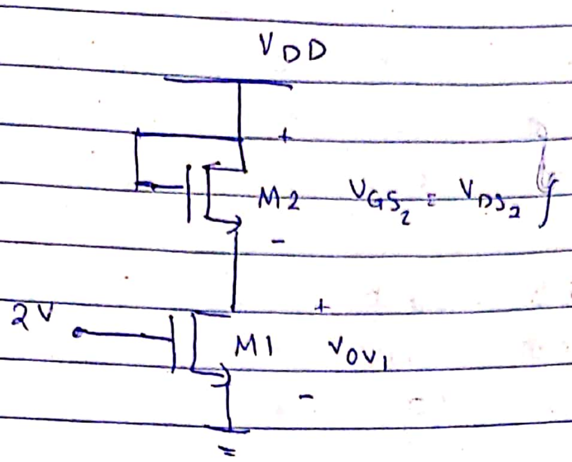
$V_{D_1} = V_{DD} - I_{D_1}R_D - V_{ov_1} + 2$

$(V_{GS_1} - V_T)$

28.02.19

Unit II

MOS Characteristics.



$$V_{DD,min} = V_{GS_2} + V_{OV_1}$$
$$+ 1$$

Assume $\frac{W}{L} = 1$

$$i_{D_1} = \frac{1}{2} k_n' \left(\frac{W}{L}\right) (V_{GS_1} - V_t)^2$$

$i_{D_1} = 0.5mA$

$i_{D_1} = i_{D_2}$

$$0.5m = \frac{1}{2}(1mA)(V_{GS_2} - 1)^2$$

$V_{OV_2} = 1V$

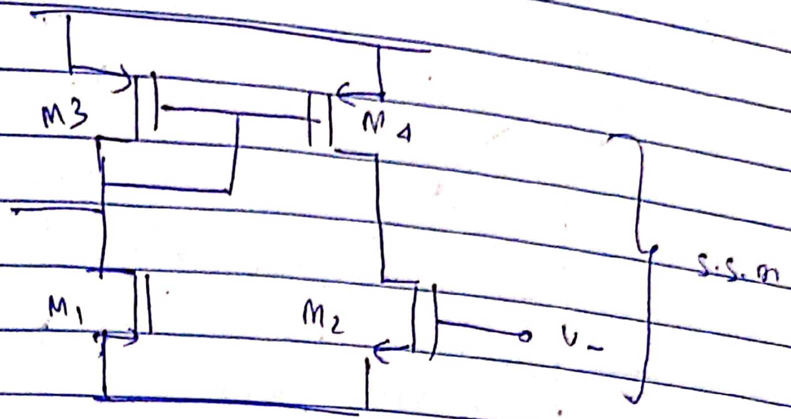
$V_{GS_2} - 1 = 1V$

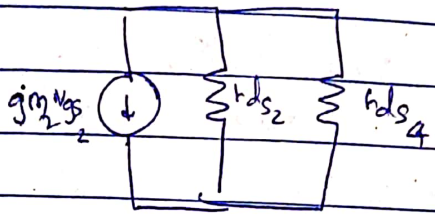
$V_{GS_2} = 2V$

$V_{DD\,min} = 2 + 1 = 3V$

5 pack

will be always fixed $V_{DD} - V_{DS}$





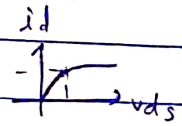
If M_2 & M_4 are matched

$$A_d = -g_m (r_{ds_2} \| r_{ds_4})$$

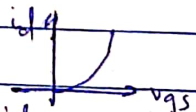
Current Mirror.

$$I_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right) (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$$

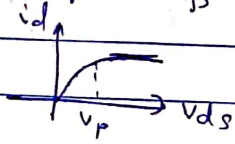
$I_D \propto \frac{W}{L}$ — linear relation



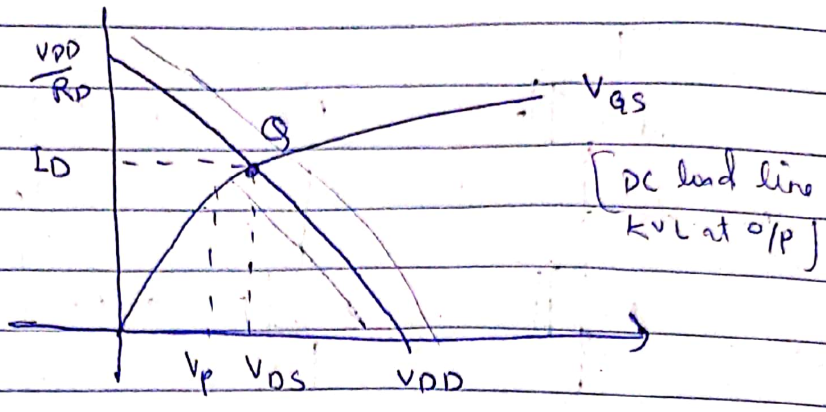
$I_D \propto (V_{GS} - V_t)^2$ — parabolic



$I_D \propto (1 + \lambda V_{DS})$ — small signal



MOS characteristic



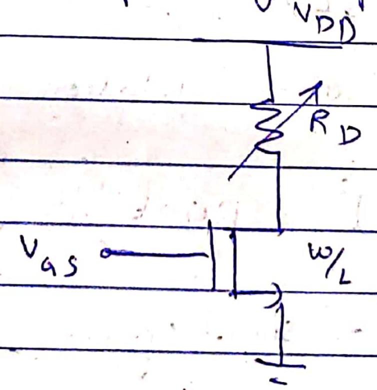
$$V_{DS} = V_{DD} - I_D R_D$$

load line $\quad V_{DS}\Big|_{I_D=0} = V_{DD}$

$$I_D\Big|_{V_{DS}=0} = \frac{V_{DD}}{R_D}$$

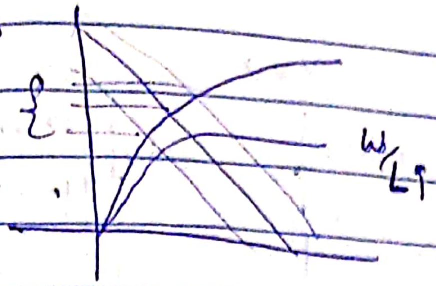
'Q' show always be to right of V_p point. So we have to design OpAmp in such way.

If R_D value is different, we get different operating points.



So the intersection of load line & characteristic curve depends on your device & R_D value.

w.r.t. $R_P r_{ds}$



So to build current mirror, we need a flatter curve.
So if we used a large channel device, curve is flatter.

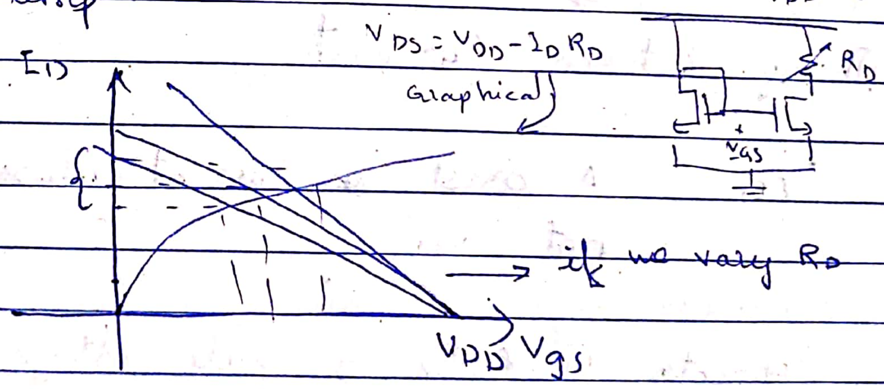
Current Mirror

17.03.19

- Biasing the MOS using current
- Used as active load ; facilitates high gain.

Why?

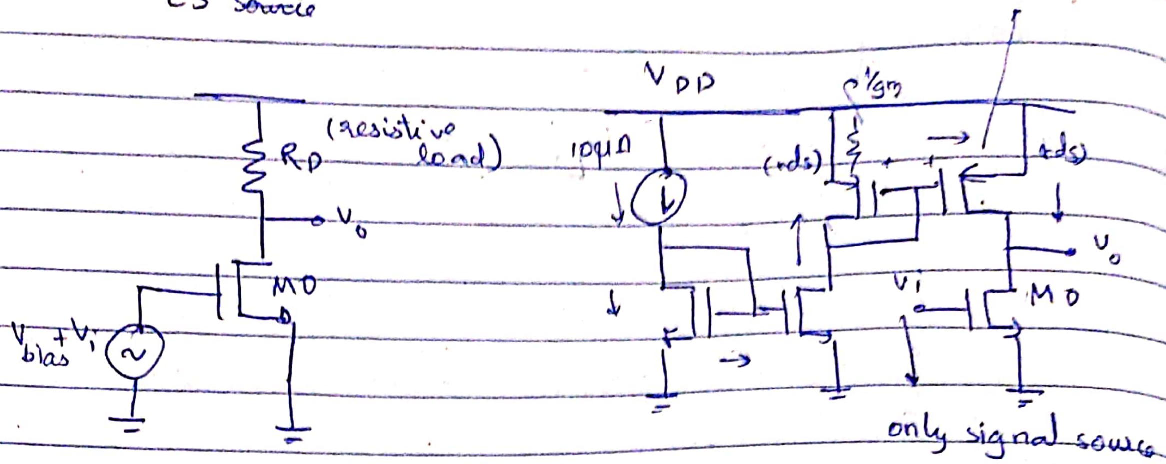
→ It gives a const. current, doesn't vary with temp.



- Using this mirror we can generate a current source - active load.

CS Source amp

active load



Voltage biasing

$A = -g_m R_D$

Current biasing

$\frac{v_o}{v_i} = -g_m(r_{ds} \| r_{ds})$

$= -g_m \frac{r_{ds}}{2}$

I_D is made function of V_{GS}

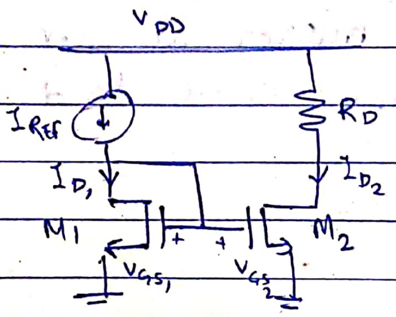
$$I_D = \underbrace{\frac{1}{2}\mu_n C_{ox}}_{const} \frac{W}{L}(V_{GS} - \underset{const}{V_T})^2$$

$I_D = f(V_{GS})$

Theory between Current

I_{REF} : A const current whose supply is not varying.

Connected M_1 & M_2 ∃ gate voltages are same. Connect a R_D, then we have I_{D1} & I_{D2}



$I_{D1} = f(V_{GS1})$

$V_{GS2} = V_{GS1}$

$I_{D2} = f(V_{GS2})$

$= f(V_{GS1})$

$V_{GS_1} = f^{-1}(I_{D1})$

$I_{D2} = f[f^{-1}(I_{D1})]$

$\boxed{I_{D2} = I_{D1}}$ → * $\mu_n C_{ox}\left(\frac{W}{L}\right)$ & V_t of M_1 & M_2 are same

Mirroring the current,

* If ~~$\mu_n C_{ox}$~~ parameters $\left(\frac{W}{L}\right)$ are not ~~cons~~ same.

$$\frac{I_{D_2}}{I_{D_1}} = \frac{\cancel{\frac{1}{2} k_n'} (W/L)_2 \cancel{(V_{GS} - V_T)^2}}{\cancel{\frac{1}{2} k_n'} (W/L)_1 \cancel{(V_{GS} - V_T)^2}}$$

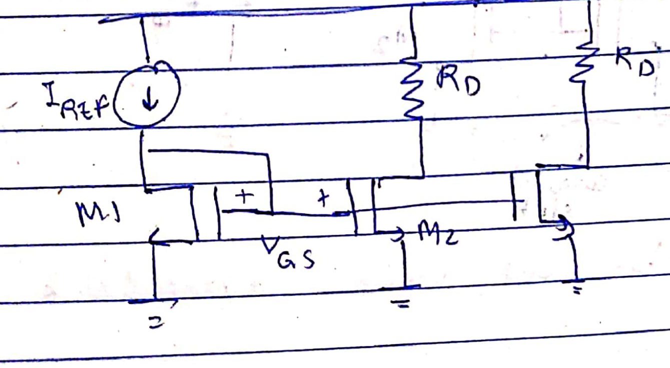
$$\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1}$$

$\boxed{I_{D_2} = k I_{D_1}}$; $k > 1$ → current amplification

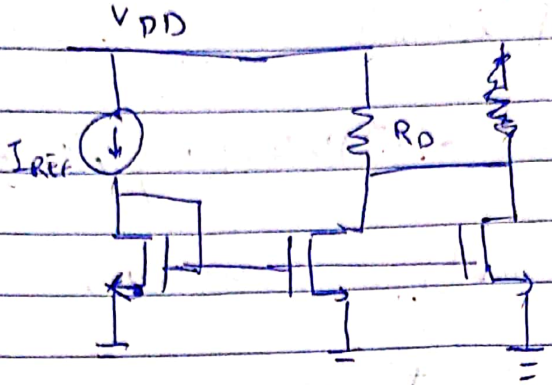
$K < 1$ → attenuation

~~Difficulties encountered~~

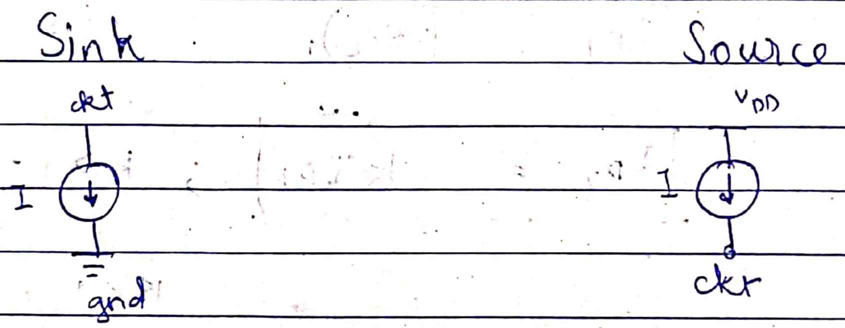
We can mirror into multiple branches

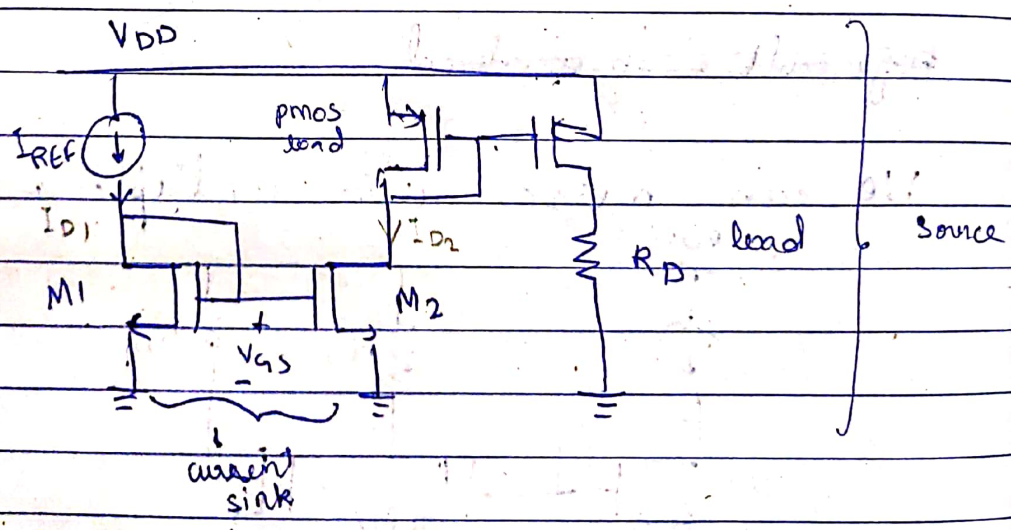


~~But instead we~~ With only 1 Rd.



Here there will be minute change in current as there is only 1 R_D, but it is neglected





In this ckt which is source & sink

$\delta\phi \cdot \delta y + \frac{\partial\phi}{\partial x}\delta x$

Merits of current source

1) O/P swing of current source. (be high)

★★2) Output resistance = ∞

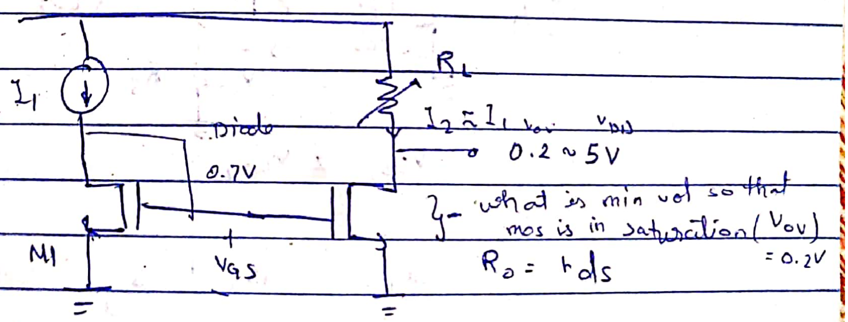
MOS is a non linear device.

$I_{D2} = K I_{D1}$ → linear eqn.

$$I_{D2} = \frac{(W/L)_2}{(W/L)_1} \times I_{D1}$$

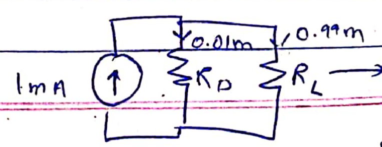
So either you have a high o/p resistance a small swing a vice versa. So based on these combination we have 4 types of current mirror.

We have to understand what is o/p resistance & o/p swing.



So o/p voltage can be 0.2 ~ 5V

O/P Resistance



→ Here I is not 1m it is 0.99m

So we assume a small current in R_o.

So $R_o >>> R_L$

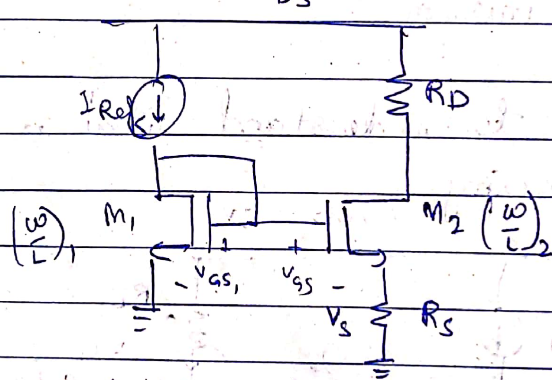
The higher the output resistance, better the OpAmp.

So the different topologies are -

- Widlar
- Cascode
- Wilson (Regulated cascode)

1) Widlar Current Mirror

In the source branch of 2nd MOS, a resistance is brought

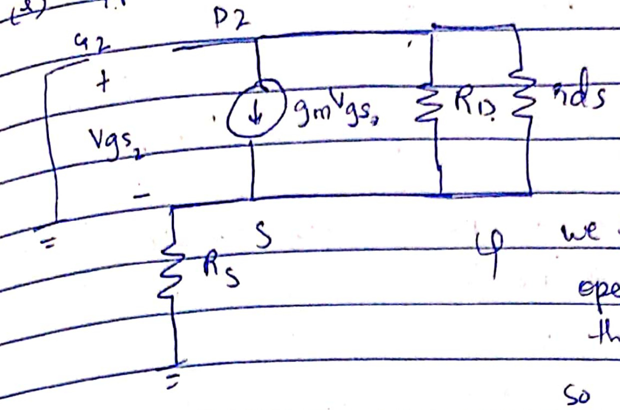


$V_{GS_1} \neq V_{GS_2}$

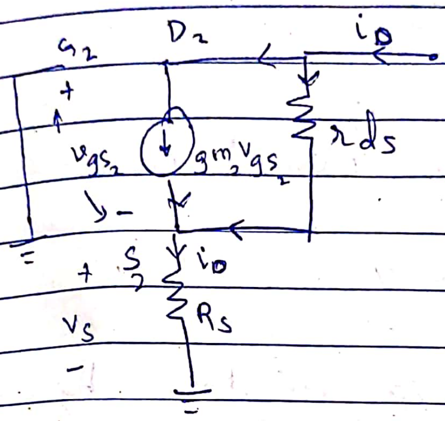
$V_{GS_1} = V_{GS_2} + V_S$

So currents are not same
To make them equal, we adjust $\frac{W_2}{L_2}$ of 2nd transistor.

(i) O/P resistance



as we have opened the M_2 so no R_D



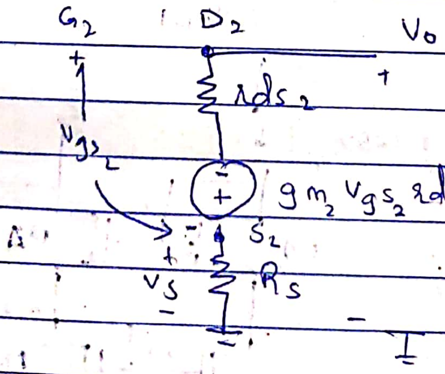
$R_o \uparrow = r_{ds_2} + R_s + g_m R_s r_{ds}$

V_o swing $\downarrow$

test source ← $\dfrac{V_o}{i_o} = R_o$ → test current

$V_{gs_2} = -V_s$

$= -i_o \times R_s$



KVL eq. $\dfrac{V_o}{I_o}$ $\quad V_o = r_{ds_2} I_o + g_{m_2} V_{gs_2} r_{ds_2} + R_s I_o$

if R_s was not connected

$\boxed{R_o = r_{ds_2}}$

$$\frac{V_o}{I_o} = r_{ds_2} + R_s + g_{m_2} r_{ds_2} R_s$$

B.C.M $R_o = r_{ds}$

$V_{oswing} \uparrow$

$g_m = \frac{\Delta I_D}{\Delta V_{gs}}$

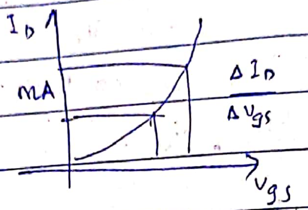
En taking $R_S = 1K$

$r_{ds_2} = 100k$

$R_o = r_{ds_2} + R_S + g_m r_{ds_2} R_S$

$= 100k + 1k + (1m)\, 100k \times 1k$

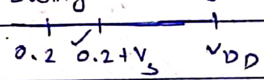
$= 201K$



But with basic current mirror

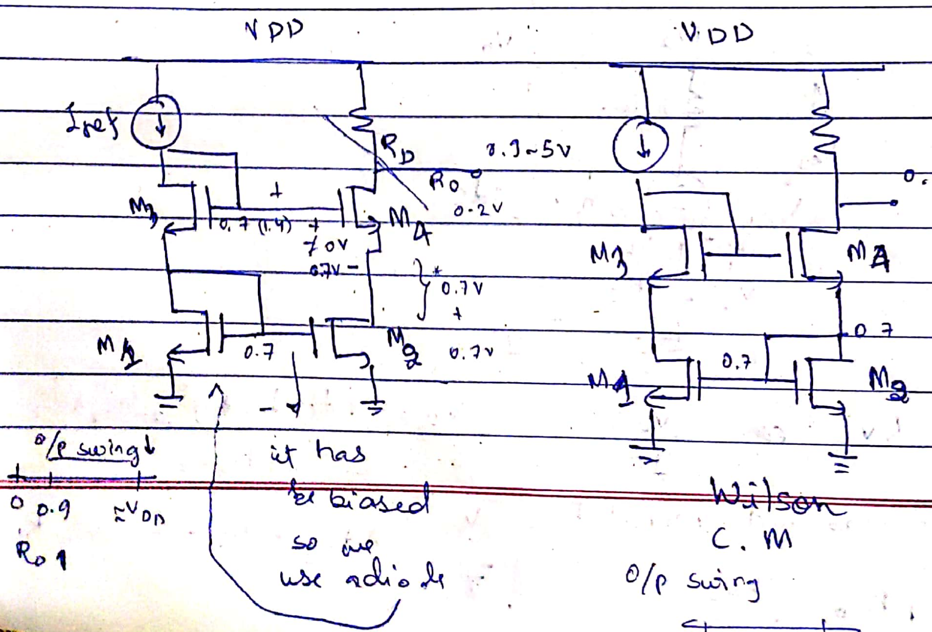
$R_o = 100K$

So we increase o/p resistance by adding R_S. But with a very high R_S, the swing decreases



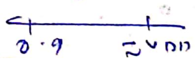
II Cascode

So instead of R_S we use active element



Wilson C.M

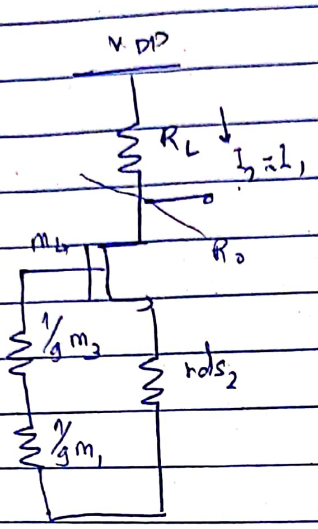
o/p swing



* 0.7 as there has to be some gate to source voltage

H.W — Calc. R_o & $V_{o\,swing}$?

Equivalent ckts

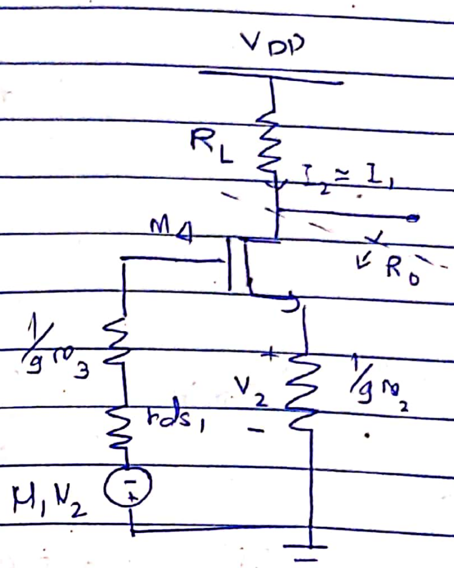


$R_o = r_{ds_4} + r_{ds_2} + g_{m_4} r_{ds_4} r_{ds_2}$

O/P R_o is ↑

$R_o = (2+\mu) r_{ds}$, $\mu = g_m r_{ds_4}$

Equivalent ckts



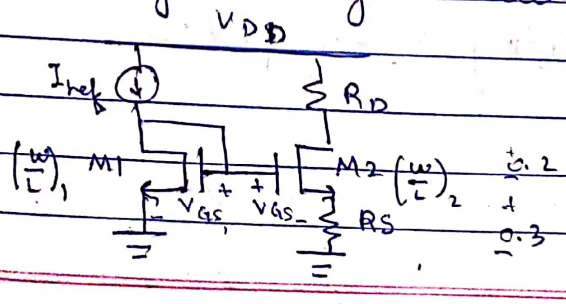
$R_o = (2+\mu) r_{ds}$

Problems

1) For the above Widlar current mirror $V_{DD} = 5V$; $V_{GS_1} = 0.7V$ $V_{GS_2} = 0.4V$ $I_1 = I_2 = 10\mu A$, $V_t = 0.2V$

Determine the value of R_S & Range of R_L & O/P voltage swing. Assume $V_{DS,min} = 0.2V$.

→



$$V_{GS_1} = V_{GS_2} + I_2 R_S$$

$$R_S = \frac{V_{GS_1} - V_{GS_2}}{I_2}$$

$$= \frac{0.7 - 0.4}{10\mu}$$

$$= 30 k\Omega$$

$$V_{o\,min} = 0.3 + 0.2$$

$$= 0.5 V$$

If $V_o = 0.5 V$

$$R_L = \frac{V_{DD} - V_o}{I_2}$$

$$= \frac{5 - 0.5}{10\mu}$$

$$= 450 k\Omega$$

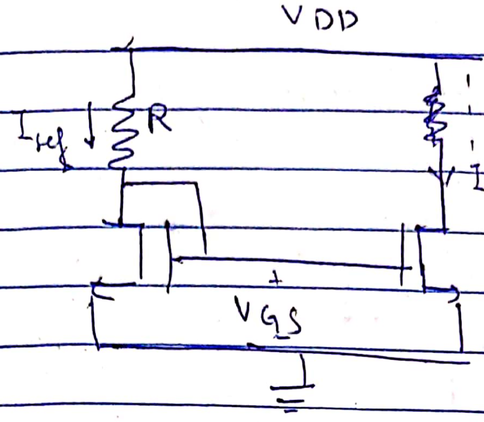
So R_L varies from 0 to $450 k\Omega$

if $V_o = 5V$

$R_L = 0 \Omega$

o/p voltage swing = 0.5 - 5 V

2] Design the current mirror when $I_o = 100\,\mu A$, $V_{DD} = 3V$, $\lambda = 0$, $V_t = 1V$, $k_n' \frac{W}{L} = 90\,mA/V^2$.



$$I_D = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS} - 1)^2$$

$$20\cancel{0}\,\cancel{\mu}^{m} = 9\cancel{0}\cancel{m}\,(V_{ov})^2$$

$$\sqrt{2.2m} = V_{GS} - 1$$

$$\boxed{V_{GS_1} = 1.047\,V = V_{GS_2}}$$

$$R = \frac{V_{DD} - V_{GS_1}}{I_{ref}}$$

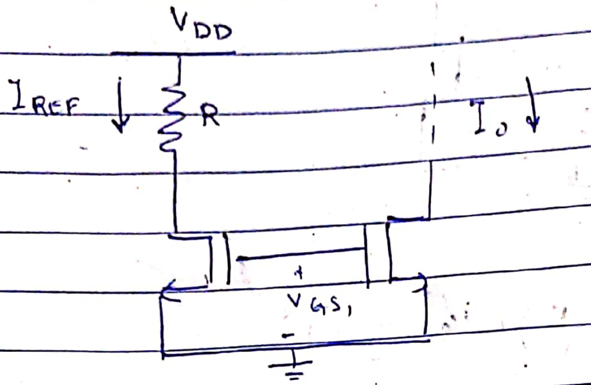
$$= \frac{3 - 1.047}{100\mu}$$

$$= 20\,k\Omega$$

3] In a basic current mirror, let $V_{DD} = 5V$, $V_t = 1V$, $K_n' = 20\mu A/V^2$, $R = 1K\Omega$,

(a) Find out $\left(\frac{W}{L}\right)_1$ to create $I_{ref} = 1mA$

(b) $\left(\frac{W}{L}\right)_2$ for $I_o = 7mA$



$$I_{REF} = \frac{V_{DD} - V_{DS_1}}{R}$$

$$1mA = \frac{V_{DD} - V_{GS_1}}{R}$$

$$V_{GS_1} = V_{DD} - (1\times10^{-3} \times 1\times10^{3})$$

$$V_{GS_1} = 5 - 1 = 4V$$

$$I_{ref} = \frac{1}{2} k_n' \left(\frac{W}{L}\right) (V_{GS_1} - V_t)^2$$

$$= \frac{1}{2} \times 20\times10^{-6} \left(\frac{W}{L}\right)_1 (4-1)^2$$

$$\left(\frac{W}{L}\right)_1 = 11.11$$

Scanned by CamScanner

$$\frac{I_o}{I_{ref}} = \frac{(W/L)_2}{(W/L)_1}$$

$$\Rightarrow (W/L)_2 = \frac{I_o}{I_{ref}} \times \left(\frac{W}{L}\right)_1$$

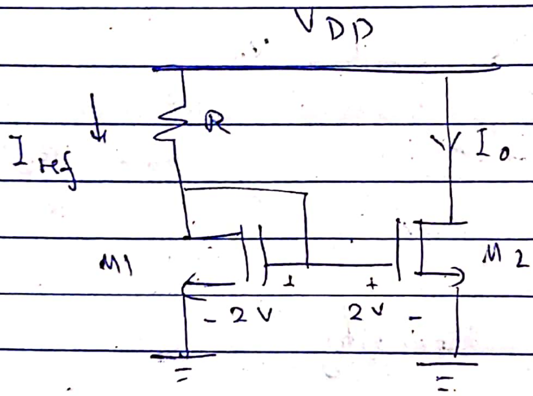
$$= 11.11 \times 7$$

$$\left(\frac{W}{L}\right)_2 = 77.77 \quad //$$

4] Calculate the mirror ratio for MOS current mirror for $V_{GS} = 2V$, $V_{DS} = 10V$, $\lambda = 0.02V^{-1}$

mirror ratio : ?

→



$$I_2 = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(\cancel{V_{GS}}\ 4 + \lambda V_{DS})$$

$$I_1 = \frac{1}{2} k_n' \left(\frac{W}{L}\right)(V_{GS} - V_t)^2$$

$$\frac{I_2}{I_1} = \frac{1 + \lambda V_{DS2}\ (10)}{1 + \lambda V_{DS1}\ (2)}$$

$$\cancel{1 + 0.02 V_{DS1}} = 1 + 0.02(10)$$

$$\cancel{V_{DS1}} = \quad \text{ratio} : 1.15 \quad //$$

5] Calculate the output current I_o for the MOS current mirror if $V_{DD} = 10V$, $\mu_n C_{ox} \left(\frac{W}{L}\right)(1+\lambda V_{DS})$

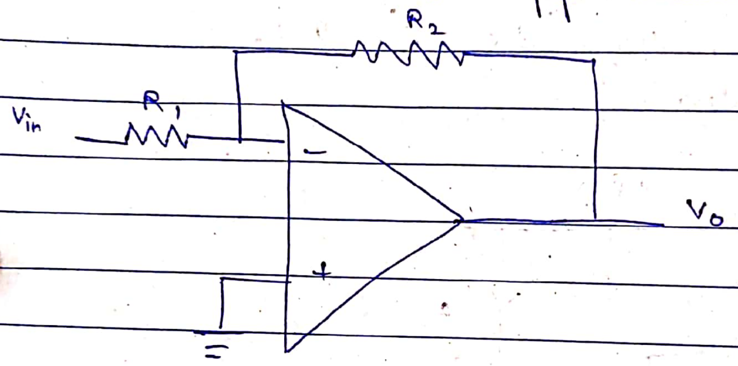
$= 250 \mu A/V^2$

$V_t = 1V$, $\lambda = 0.0133 V^{-1}$, $I_{ref} = 150 \mu A$,

$V_{DS_2} = 10V$ & $\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2$

→

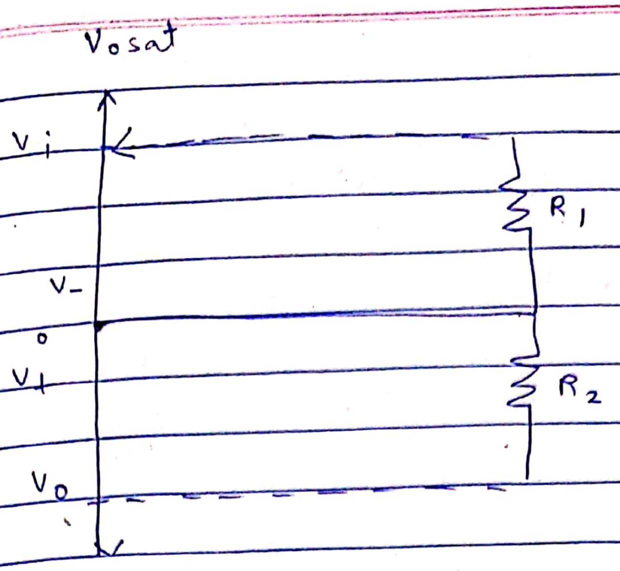
Linear Applications 1.4.19



$V_o = \frac{R_2}{R_1} V_i$

Condition for linearity

- Dominant negative feedback
- $V_d = \frac{V_o}{A}$
- $V_+ = 0$
- Output must be unsaturated

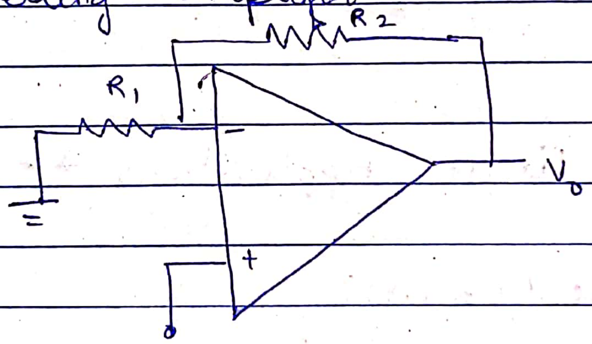


$$V_- = \frac{V_i R_2 + V_o R_1}{R_1 + R_2}$$

Noise:

$V_N \uparrow = (V_d + V_N \uparrow) \Rightarrow V_d + A V_N \downarrow \Rightarrow (V_d + V_N \uparrow + A\beta V_N \downarrow)$

Non-inverting amplifier

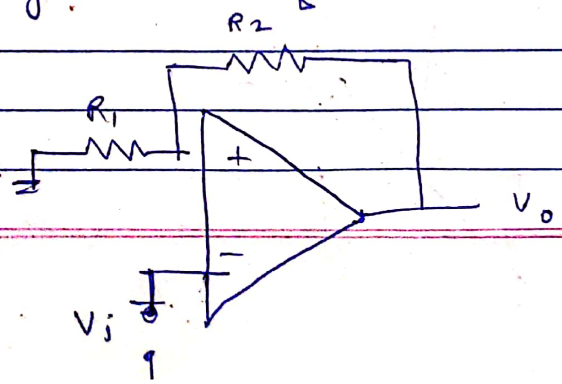


$$\frac{R_1 + R_2}{R_1} V_i$$

$$V_- = \frac{R_1}{R_1 + R_2} \cdot V_o$$

$$V_o = A V_d$$

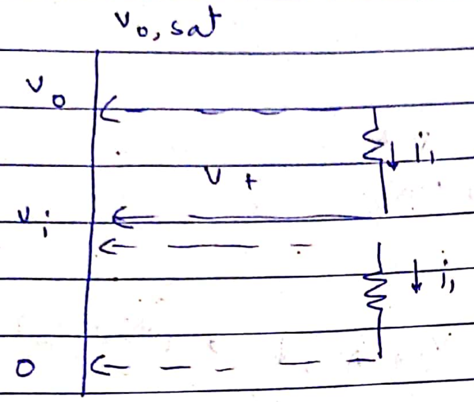
3) Regenerative feedback



$V_- = V_i \; ; \; V_+ = \frac{R_1}{R_1 + R_2} V_0$

$V_d = V_+(\uparrow) : -V_- > +\frac{V_{o,sat}}{A}$

$V_d = V_+(\downarrow) : -V_- < -\frac{V_{o,sat}}{A}$



$V_+ = \frac{R_1}{R_1 + R_2} V_o$

$V_d = V_+ - V_- = +ve$

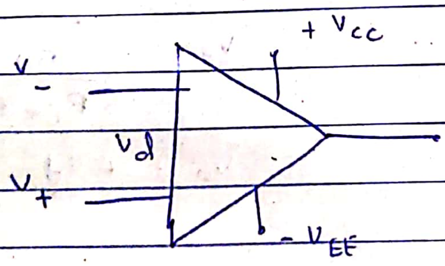
$V_o = A V_d = +ve$

$V_N \uparrow = (V_d + V_N \uparrow) \Rightarrow (V_o + A_N) \uparrow \Rightarrow (V_d + V_N \uparrow + A\beta V_N)$

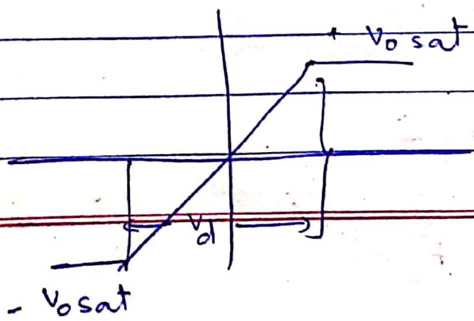
** Linear Applications ** 1.4.19

why seperate (l & n.l)?

$\rightarrow$



~~$V_o = A_d V_d + A_c V_c$~~



feedback — +ve non linear

— −ve → linear

unsaturated o/p -

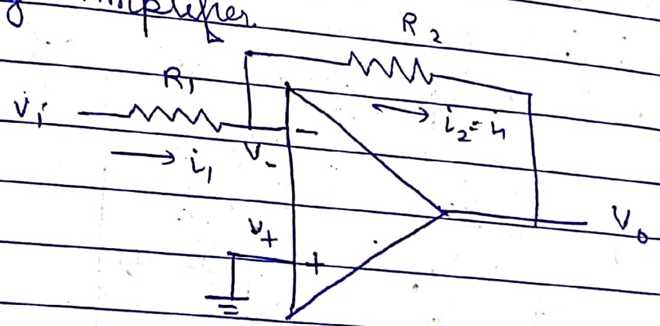
$V_d \simeq 0$

$V_d = V_+ - V_-$

⇒ virtual ground.

For any app to be in linear, the −ve feedback must be dominant.

Inverting Amplifier



Difference $V_d = V_+ - V_-$

because o/p is unsaturated

$$i_1 = i_2$$

$$\frac{V_i - 0}{R_1} = \frac{0 - V_0}{R_2}$$

Gain of inverting amplifier

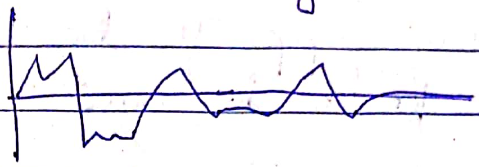
$$\boxed{A_f = \frac{V_0}{V_1} = -\frac{R_2}{R_1}}$$

If $V_o = -\frac{R_2}{R_1}$ is this stable?

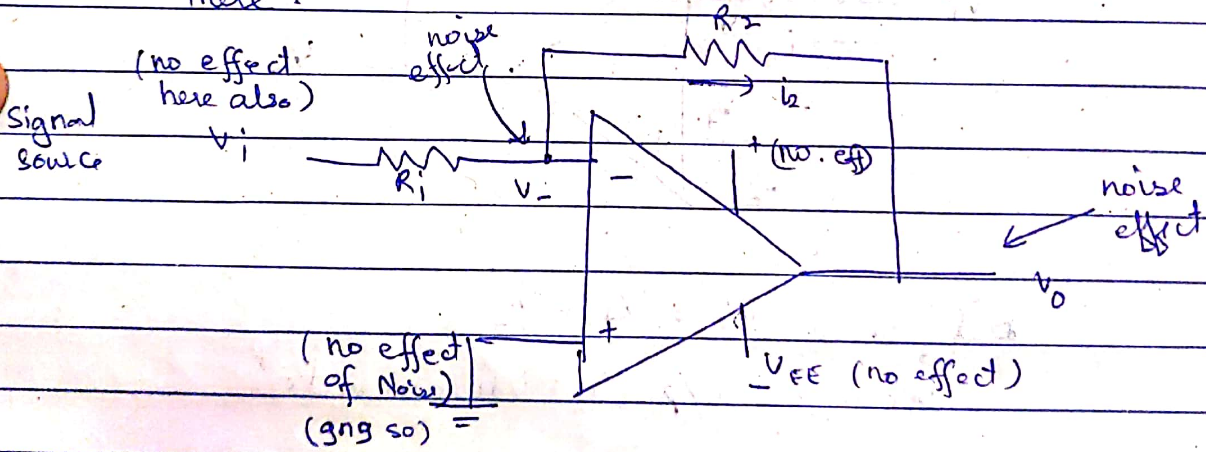
There are some factors which change the voltages & make change in o/p vol.

So we try to understand if there is a noise* which will alter the signal

* Noise is bidirectional signal



can affect at all frequencies but prominent at higher freq.
We can't escape from noise, it is always there.



So remaining are V_o
We have few ohm of o/p impedance
So we have noise at inverting terminal & V_o

So using Superposition
$V_i = 0$ $\qquad V_- = \frac{V_o R_1}{R_1 + R_2}$

$V_o = 0$ $\qquad V_- = \frac{V_i R_2}{R_1 + R_2}$

So Resultant

$$V_- = \frac{V_i R_2 + V_o R_1}{R_1 + R_2} \quad //$$

V_N - Noise voltage.

Suppose $\Delta V_N \uparrow$ i.e $V_- + V_N \uparrow$ (Noise getting added)

$V_d = V_+ - V_-$

$= 0 - (V_- + V_N \uparrow)$

$V_d = - V_- - V_N \uparrow$

$V_- \uparrow$ & $V_d \uparrow$ but, in -ve direction.

a $\Delta V_N \uparrow \Rightarrow V_- \uparrow \Rightarrow |V_d| \uparrow = |V_o| \uparrow \Rightarrow V_- \downarrow$

V_o(nois)

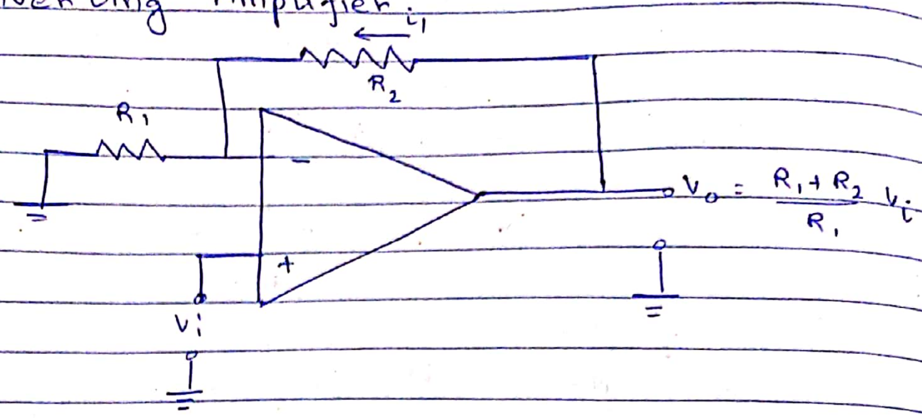
$\downarrow V_- = \left(\frac{R_1}{R_1 + R_2}\right) V_i - \left(\frac{R_2}{R_1 + R_2}\right) V_o$

Considering the sign.

The feedback is counteracting on noise, its makes the output stable.

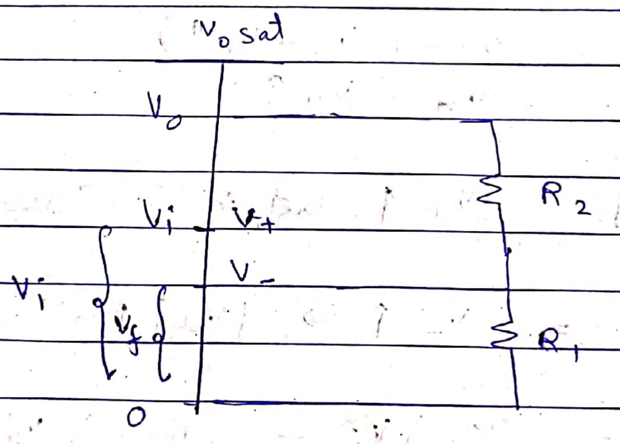
V_o is stable as linear mode signal.

2. Non inverting Amplifier



$V_+ = V_i$ virtual short

$V_- = V_i$



$V_N \uparrow \Rightarrow V_d + V_N \uparrow \Rightarrow V_o + A V_N \downarrow \Rightarrow V_d + V_N \uparrow + A\beta V_N \downarrow$

$\Delta V_N \uparrow \Rightarrow V_- \uparrow \Rightarrow |V_d| \downarrow = |V_o| \downarrow \Rightarrow V_- \downarrow$

$$V_d = V_+ - V_-$$

$$= V_+ - (V_- + \Delta V_N \uparrow)$$

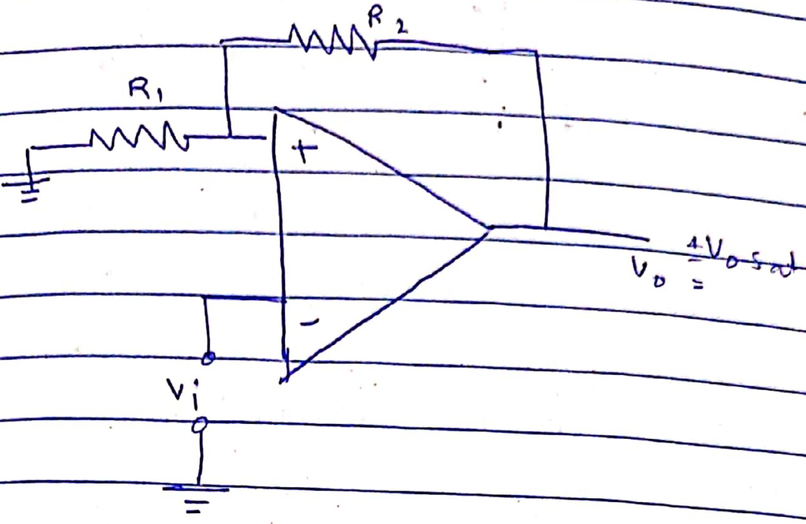
$$V_d = V_+ - V_- - \Delta V_N \uparrow$$

$|V_d|$ decreases $\Rightarrow |V_o| \downarrow \Rightarrow V_-$ decreases

$V_d = \frac{V_o}{A}$ $\qquad V_- = \frac{R_1}{R_1 + R_2} V_o$

V_o - stable output.

Regenerative feedback



$V_- = V_i$ but $V_+ \neq V_i$

$$V_+ = \frac{R_1}{R_1 + R_2} \cdot V_o$$

$V_N \uparrow \Rightarrow (V_d + V_N\uparrow) \Rightarrow (V_o + AV_N\uparrow) \Rightarrow (V_d + V_N\uparrow + A\beta V_N\uparrow)$

V_o = unstable as linear mode signal

$V_o = \pm V_{osat}$ = stable under saturation cond.

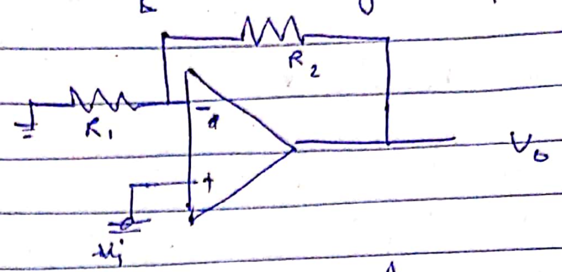
$\Delta V_N \uparrow \Rightarrow \underset{V_+ + \Delta V_N}{V_+ \uparrow} \Rightarrow |V_d|\uparrow \Rightarrow |V_o|\uparrow \Rightarrow V_+ \uparrow\uparrow$

$\because V_d = V_+ - V_-$

$= V_+ + \Delta V_N\uparrow - \underset{\text{fixed}}{V_i}$

= increases till it hits saturation.

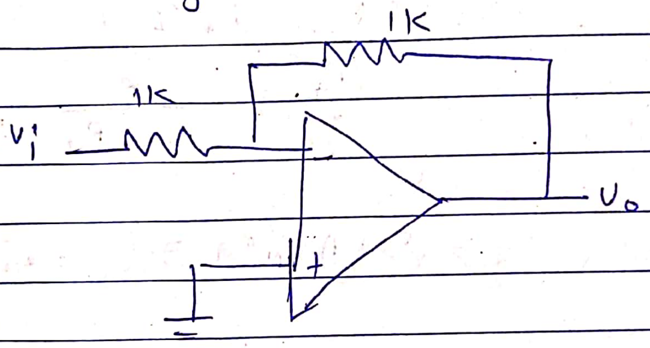
1) Draw ckt of inverting amp, & write gain



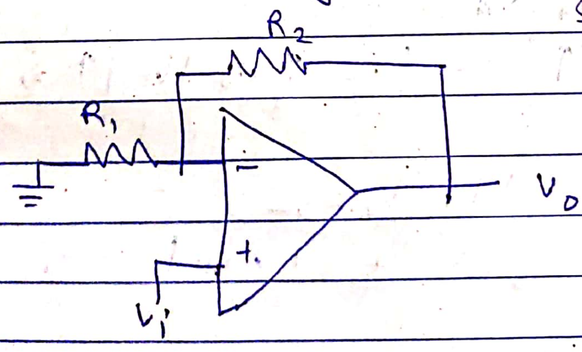
$$A_f = \frac{-R_2}{R_1}$$

5) Draw an Op-amp circuit

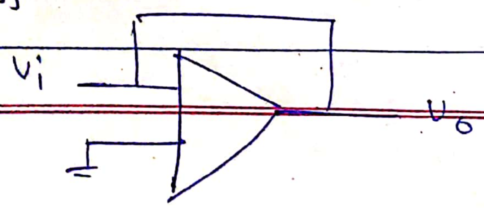
(i) Analog inverter - a inverting amp with gain 1



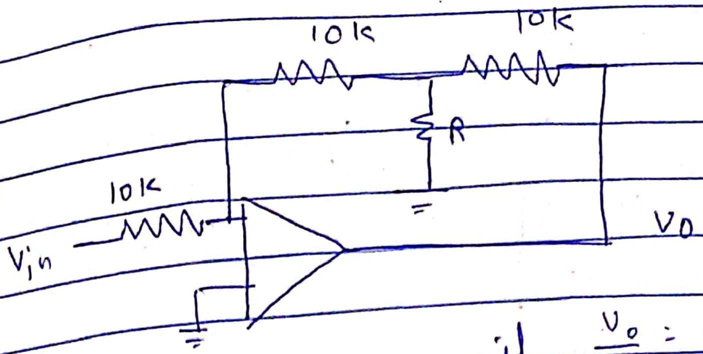
(ii) Scale changer - non-inverting with some K gain



(iii) Buffer



1)



R = 1k

if $\frac{V_o}{V_{in}} = -12$ R = ?

$A = -12$

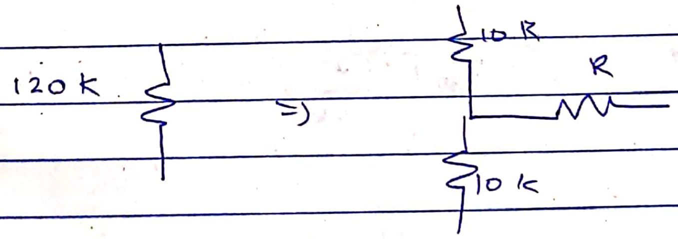
$\frac{V_o}{V_{in}} = -12$

$V_o = -12 V_{in}$

$$V_o = -\frac{R_2}{R_1} V_i$$

$$\cancel{-}12 V_i = -\frac{R_2}{10k} V_i$$

$R_2 = 120k$



$$120k = 10k + \frac{10k\,R}{R + 10k}$$

$$110k = \frac{10k \cdot R}{R + 10k}$$

$110R + 1100 = 10R$

$1100 = 100R$

$120k = 10k + (10k \,\|\, R)$

$110 = \frac{10R}{10+R} \Rightarrow 1100 + 110R = 10R.$

$1100 = 100R$

Scanned by CamScanner

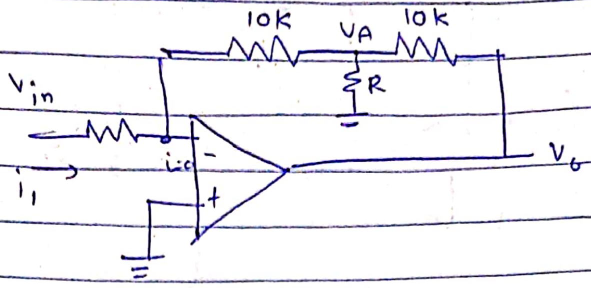
$-12 V_{in} = -\frac{R_2}{10k} \cdot V_{in}$ 12 V

$5k + R$

$R_2 = 120k$

Ans

$i_1 = i_2$



$$i_1 = i_2$$

$$\frac{V_{in}}{10k} = -\frac{V_A}{10k}$$

$$V_{in} = -V_A$$

$$i_2 = i_3 + i_4$$

$$\frac{V_A}{10k} = \frac{V_A}{R} + \frac{V_A - V_0}{10k}$$

$$\frac{V_{in}}{10k} = -\frac{V_{in}}{R} + \left(\frac{-V_{in} - V_0}{10k}\right)$$

$$V_{in}\left[\frac{2}{10k} + \frac{1}{R}\right] = \frac{-V_0}{10k}$$

$$V_d = V_+ - V_- = 1 - 0 = 1$$

Given $\frac{V_0}{V_{in}} = -12$

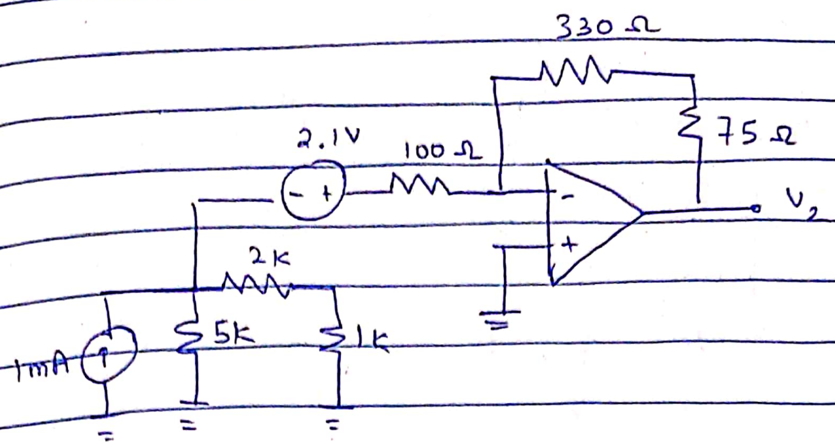
$$-\frac{V_0}{V_{in}} = 10k\left[\frac{2}{10k} + \frac{1}{R}\right]$$

$$12 = 10\left[\frac{2}{10k} + \frac{1}{R}\right]$$

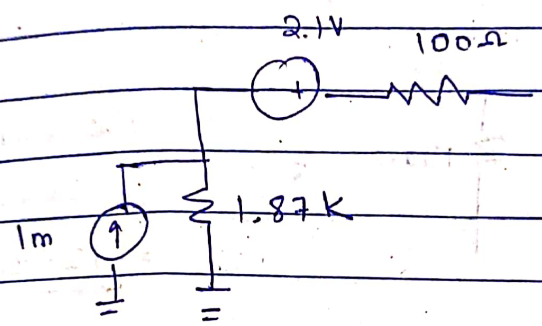
$$\boxed{R = 1k}$$

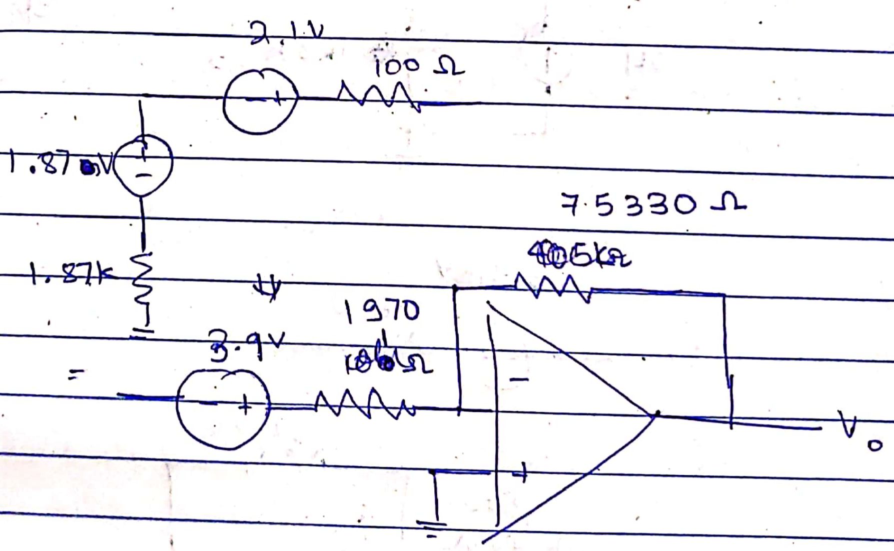
$\overline{R_1 + R_L}$

3] . Calc. V_2



V = IR



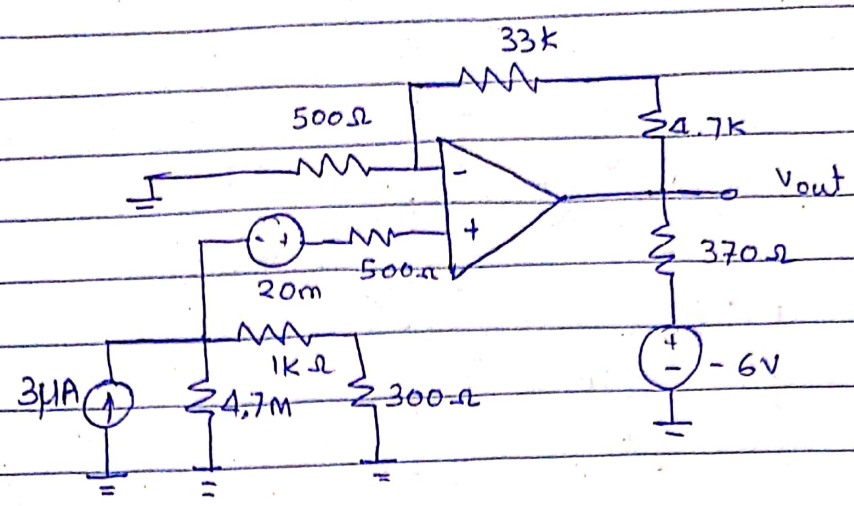


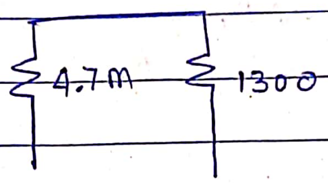
$$\frac{V_o}{3.9} = -\cancel{\frac{405}{1001}} - \frac{75330}{1970}$$

V_o = ~~8215V~~ ~~18.6V~~

149.1 V //

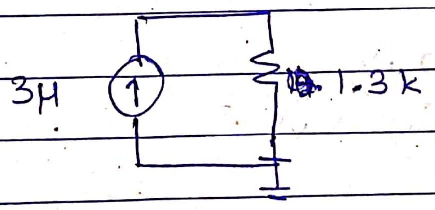
5]





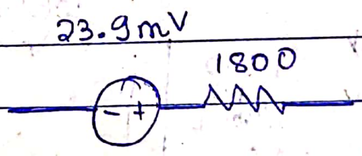
$$= \frac{1300 \times 4700000}{1300 + 4700000}$$

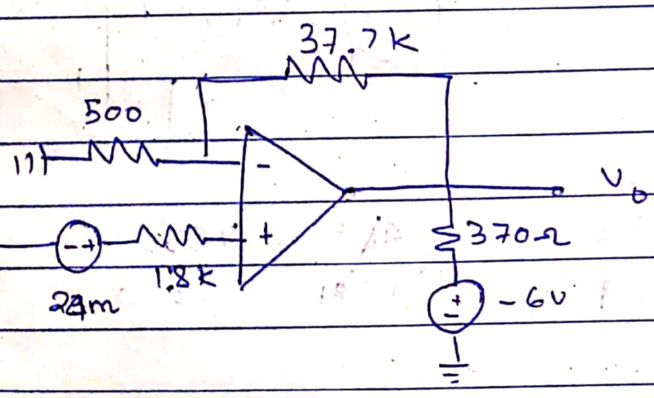
$$= 1299.6\ \Omega$$



$$= 3\mu \times 1.3k$$

$$= 3.9\text{mV}$$





$$\frac{V_o}{V_{in}} = 1 + \frac{R_2}{R_1}$$

$$\frac{24m}{V_{in}} = 1 + \frac{37.7k}{500}$$

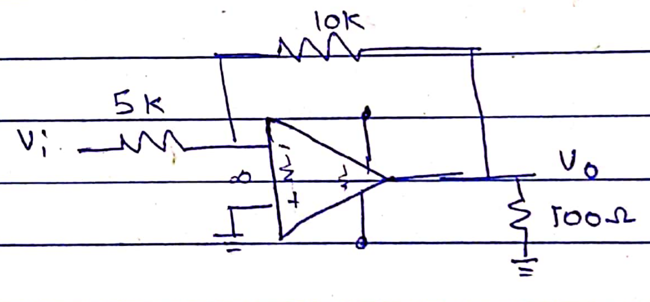
$$\frac{24m}{V_{in}} = 76.4$$

$$V_{in} = 314\ \mu V$$

$$\frac{V_o}{24m} = 76.4$$

$$\boxed{V_o = 1.826V}$$

HW. An inverting amplifier with load resistor $R_L = 100\Omega$, $R_1 = 5k$, $R_2 = 10k\Omega$. $A_V = 50k$, $R_o = 500\Omega$, $R_i \to \infty$



(a) Determine voltage across R_L for an rms input signal of 1.5V

(b) Repeat part a, consider ideal opamp.

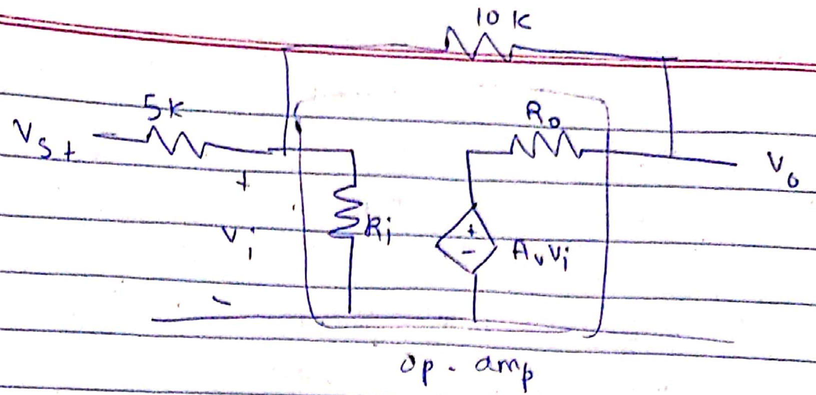
Ans. (a) $V_o = -2.99V$

→ $V_i = 1.5V$

$$\frac{V_o}{V_i} = -\frac{10k}{5k}$$

$$\boxed{V_o = -3V}$$

$V_{RL} =$



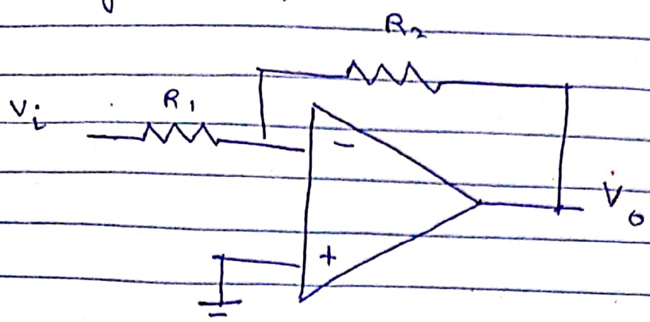
Thevenin eqn.

H.W 2 different microphones are used in a recording studio, one fo

H.W A sinsodidual signal is riding on a 2V dc offset (in other words avg value of total signal is 2V). Design a circuit to remove the dc offset and amplify the sinosoidal signal (without phase reversal) by a facto of 100.

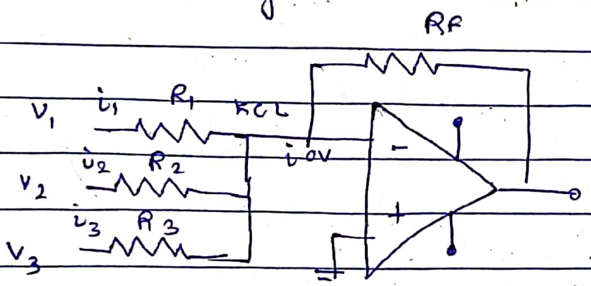
5.4.19

Summing Amplifier



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

Instead of one input, we can combine different input & then put to an amplifier with a gain



$$i = i_1 + i_2 + i_3$$

$$A_f = -\frac{R_F}{R_1 \parallel R_2 \parallel R_3}$$

$$-\frac{V_0}{R_F} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$-V_0 = R_f\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

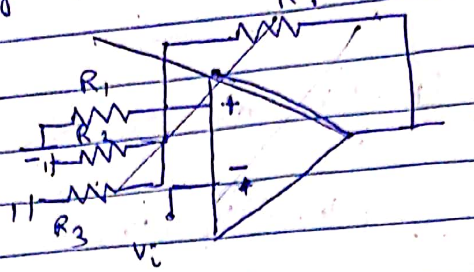
$$= -\left[\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right]$$

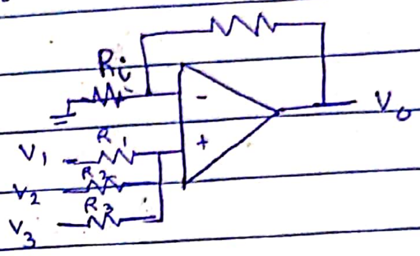
Taking same resistances,

Sup

$$V_o = -[V_1 + V_2 + V_3].$$

Similarly for a non-inverting summer.



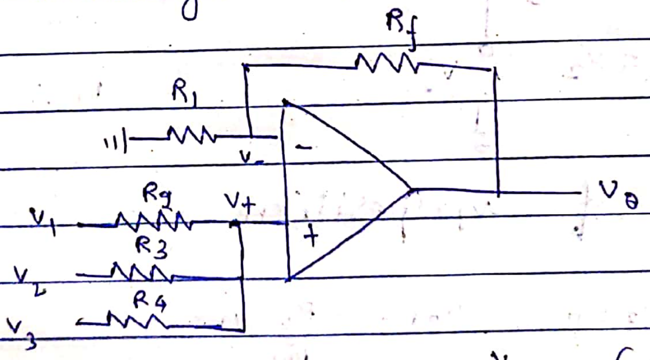


$$-\frac{V_o}{R_F} =$$

$$V_o = \left(1 + \frac{R_F}{R_i}\right)V_i + \left(1 + \frac{R_F}{R_i}\right)V_2 + \left(1 + \frac{R_F}{R_i}\right)V_3$$

$$V_o = 2[V_1 + V_2 + V_3].$$

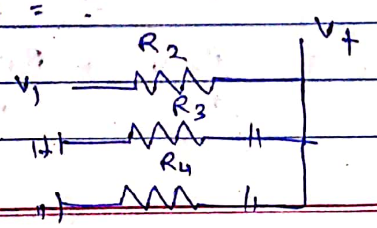
Non-inverting summer



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

So $V_+ = ?$

Superposition



$$V_+ = \frac{\left(\frac{R_3R_4}{R_3+R_4}\right)V_1}{R_2 + \frac{R_3R_4}{R_3+R_4}}$$

* There will be no drop across R_3 as no current enters opamp.

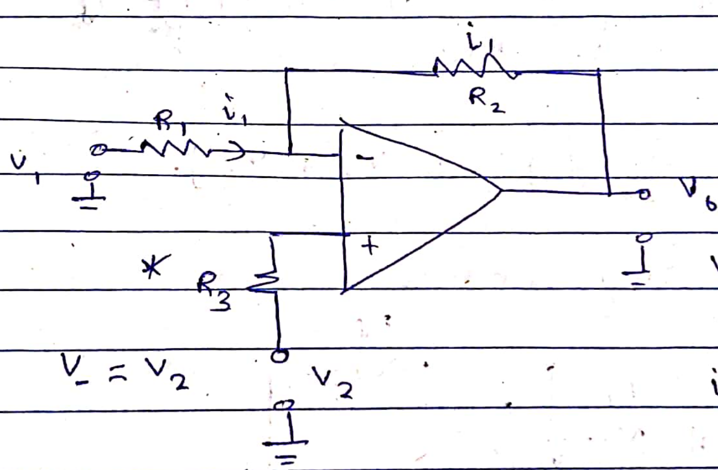
$$V_+ = \frac{\left(\frac{R_2 R_4}{R_2 + R_4}\right) V_2}{R_3 + \frac{R_2 R_4}{R_2 + R_4}} \qquad V_+ = \frac{\left(\frac{R_2 R_3}{R_2 + R_3}\right) V_3}{R_4 + \frac{R_2 R_3}{R_2 + R_3}}$$

So add all ; assume $R_2 = R_3 = R_4$

$$V_+ = \frac{1}{3}\left(V_1 + \frac{1V_2}{3} + \frac{1V_3}{3}\right)$$

$$V_+ = V_1 + V_2 + V_3 \quad //$$

Dual input amplifier



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

$V_- = V_2$

$$i_1 = \frac{V_1 - V_2}{R_1}$$

Principle of Superposition

case 1 : $V_2 = 0$: $V_{01} = -\frac{R_2}{R_1} V_1$

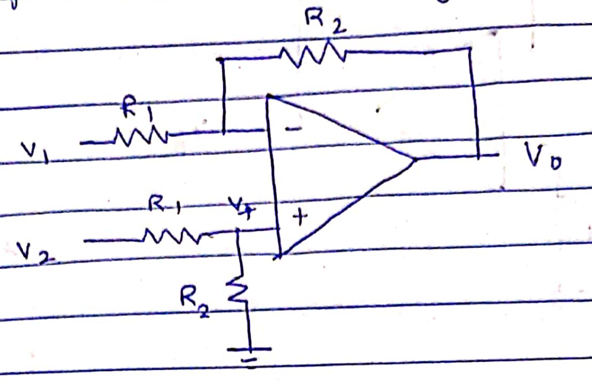
Case 2 : $V_1 = 0$: $V_{02} = \frac{R_1 + R_2}{R_1} V_2$

case 3 : $V_0 = V_{01} + V_{02} = -\frac{R_2}{R_1} V_1 + \frac{R_1 + R_2}{R_1} V_2$

Wherever we come across more than one i/p always use superposition

Basic Differential amplifier 1

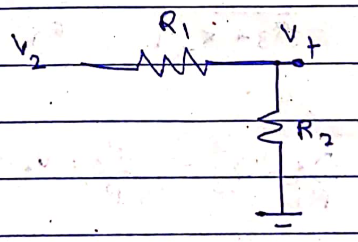
Application built using op Amp.



when $V_2 = 0$; $V_0 = -\frac{R_2 \cdot V_1}{R_1}$

$V_1 = 0$ $V_0 = \left(1 + \frac{R_2}{R_1}\right) V_+$

How do we find V_+



Thevenin's eq. model

$$V_+ = \frac{R_2}{R_1 + R_2} \cdot V_2$$

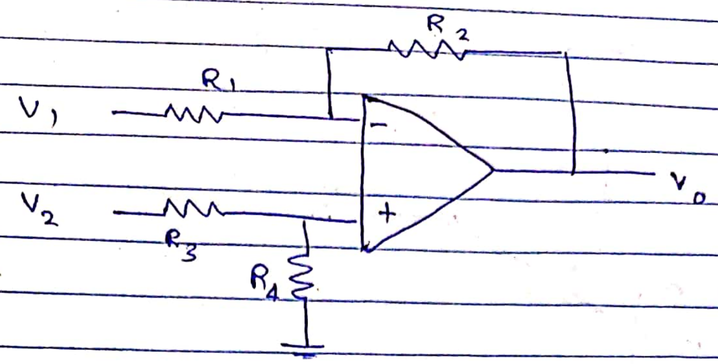
$$R_{th} = \frac{R_1 R_2}{R_1 + R_2}$$

$\therefore$

$$V_0 = -\frac{R_2}{R_1} V_1 + \left(\frac{\cancel{R_1 + R_2}}{R_1}\right)\left(\frac{R_2}{\cancel{R_1 + R_2}}\right) V_2$$

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

Basic Differential Amplifier 2



condition $\frac{R_2}{R_1} = \frac{R_4}{R_3}$

$$\frac{R_1 + R_2}{R_1} = \frac{R_3 + R_4}{R_3}$$

inverting non inverting

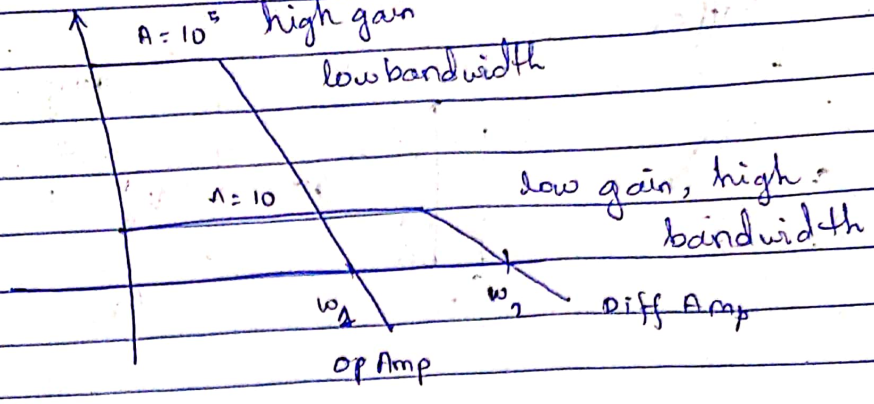
$$V_0 = -\frac{R_2}{R_1} V_1 + \frac{R_4}{R_3 + R_4}\left(\frac{R_1 + R_2}{R_1}\right) V_2$$

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

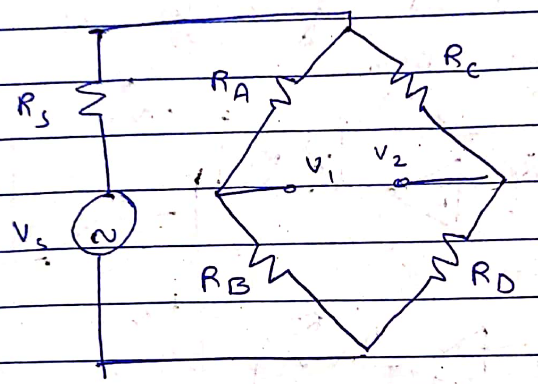
OpAmp is a Diff Amp with

High Gain $\{ A_d = 10^4 - 10^5 \}$
low bandwitdh
Uncontrollable, unpredictable gain

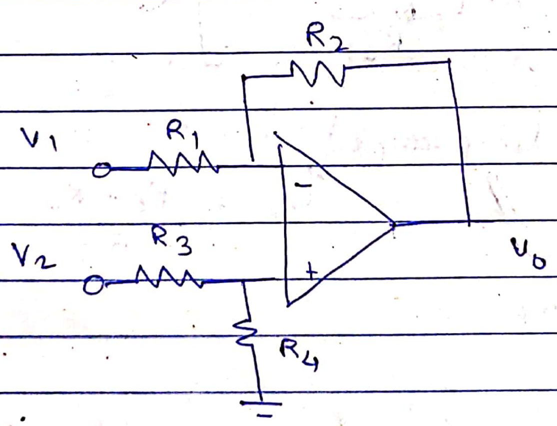
Diff Amp using OpAmp with
low gain $\{ A_d = \frac{R_2}{R_1} = 5 \sim 50 \}$
High Bandwidth
controllable, predictable gain



Differential Amplifier 3



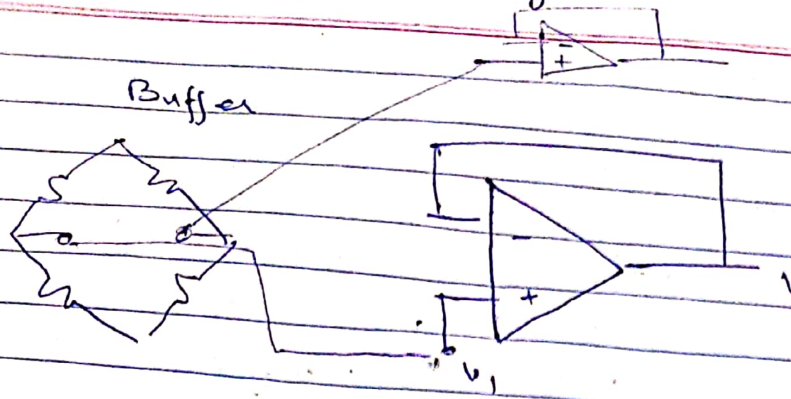
When we connect an OpAmp we do not get the correct voltage drop



This is due to loading effect
resistance RA & RB get loaded to R_1
& RC & RD get loaded to R_3
So we do not get the correct drop across V_1 & V_2
So to resolve this we connect a buffer

loading : drawing current

Buffer

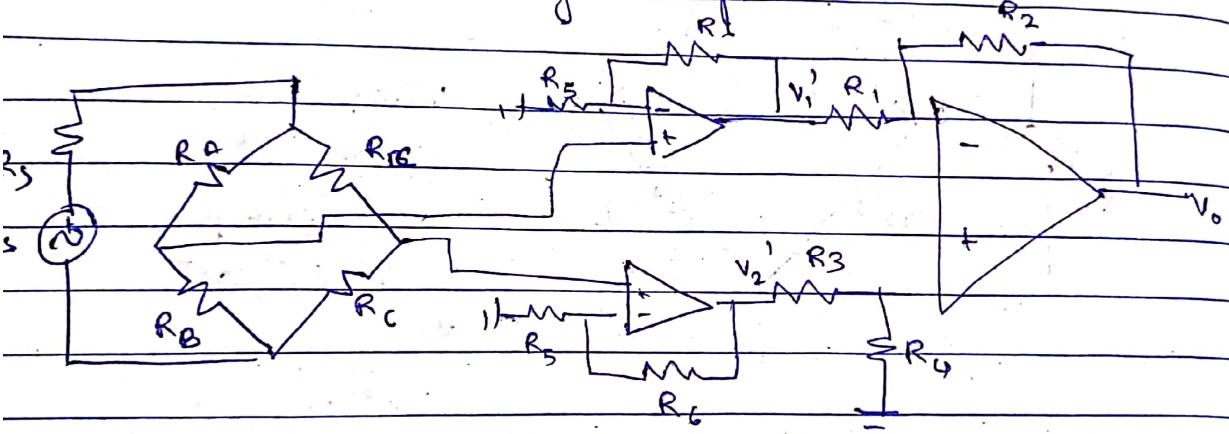


very large resistance
no current
no loading effect

$A_v = 1$

Differential Amplifier 5

For the previous ckt, if the i/p signals are weak, instead of buffer we use non-inverting amp.



Gain of non inverting amplifier

$G_1 = \frac{R_5 + R_6}{R_5}$ // $G_2 = \frac{R_5 + R_6}{R_5}$

$\frac{V_1'}{V_1} = \frac{R_5 + R_6}{5}$

$\therefore V_1' = V_2' = \left(\frac{R_5 + R_6}{R_5}\right) V_1 \; a \; V_2$

Differential amplifier

$$\frac{\delta u}{\delta y} = x + 2x \frac{\partial x}{\partial n} \qquad \frac{\delta v}{\delta y} = 1+$$

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}$$

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

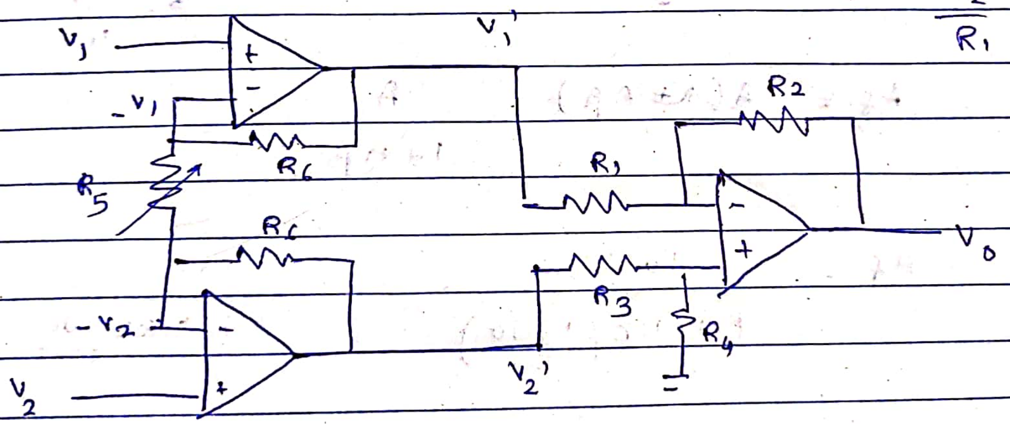
$$V_o = \frac{R_2}{R_1}\left(V_2' - V_1'\right)$$

$$= \frac{R_2}{R_1} \cdot \left(\frac{R_5 + R_6}{R_5}\right)\left(V_2 - V_1\right) \quad //$$

Using this concept we build

Instrumentation Amplifier

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}$$

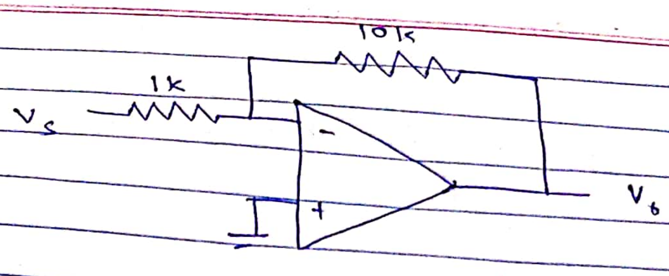


$$V_1' = \frac{R_5 + R_6}{R_5} V_1 - \frac{R_6}{R_5} V_2 \qquad V_2' = -\frac{R_6}{R_5} V_1 + \frac{R_5 + R_6}{R_5} V_2$$

$$V_o = \frac{R_2}{R_1}\left(V_2' - V_1'\right) = \frac{R_2}{R_1} \cdot \frac{R_5 + 2R_6}{R_5} \cdot \left(V_2 - V_1\right) = A_d\left(V_2 - V_1\right)$$

$$A_d = G_1 G_2$$

(7)



The inverting OpAmp shown has an open loop gain of 100.
Determine the closed loop gain $\frac{V_o}{V_s}$

→ $A = 100$

$$\frac{V_s}{V_o} = 100$$

$$V_s = 100\, V_o$$

$$\beta = \frac{1k}{11k}$$

$$A_f = \cancel{A(1+A\beta)} \quad \frac{A}{1+A\beta}.$$

$$A_f = \frac{100}{1+100(1+10)} = \frac{100}{1+\cancel{1100}\ \frac{100}{11}}$$

$$= 9.9$$

β is wrt 2 inputs

$$\beta = (\quad) V_s + (\quad) V_o$$

$$= \frac{R_1}{R_2} = \frac{1}{10}$$

$$A_f = \frac{100}{1 + 100(1/10)}$$

$= 9.09$ ✓

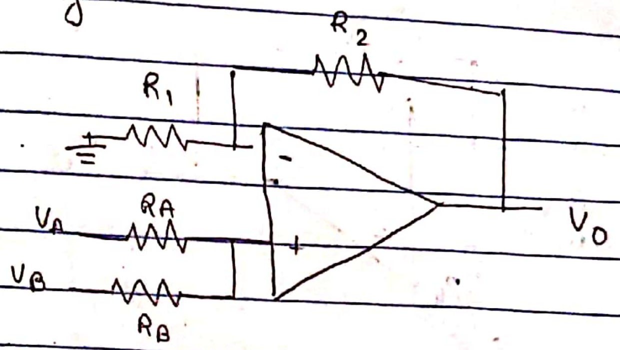
$$A_f = \frac{100}{1+100(1/10)}$$

$$= -9.09 \checkmark$$

8.4.18

1. construct summing, scaling & averaging amplifier using opamp.

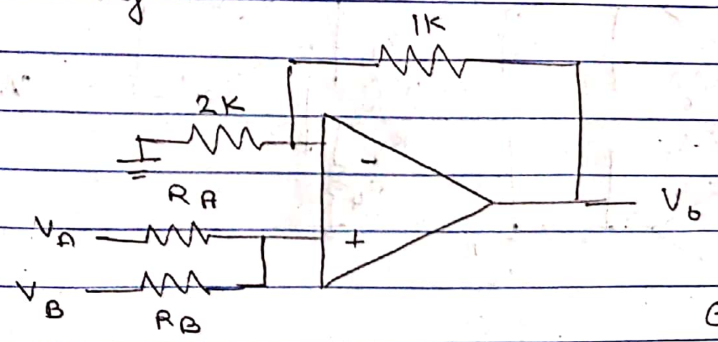
→ (i) Summing



$$V_{in} = V_A + V_B$$

$$\frac{V_o}{V_{in}} = -\frac{R_2}{R_1}$$

(ii) Average

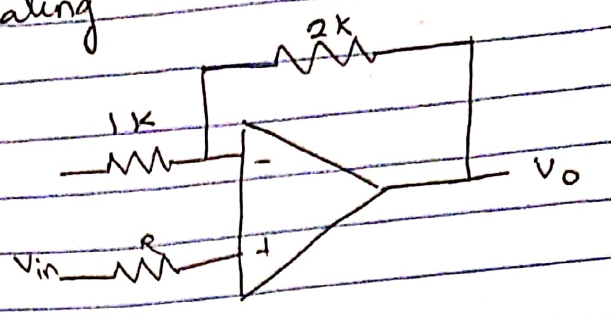


$$\frac{\Sigma n}{2}$$

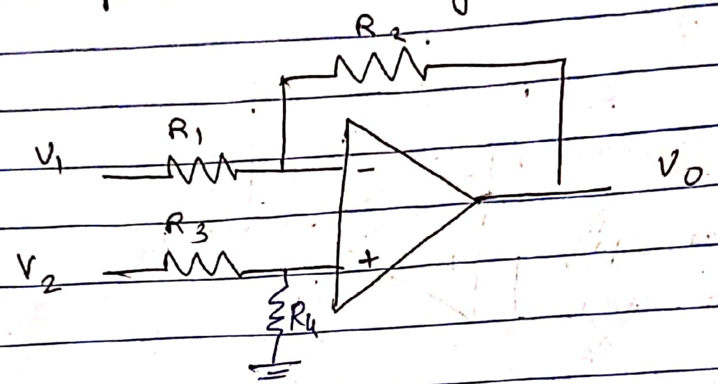
$$\text{Gain} = \frac{1}{2} \quad -\frac{R_2}{R_1}$$

$$\frac{R_2+R_1}{R_1} = 1$$

(iii) Scaling

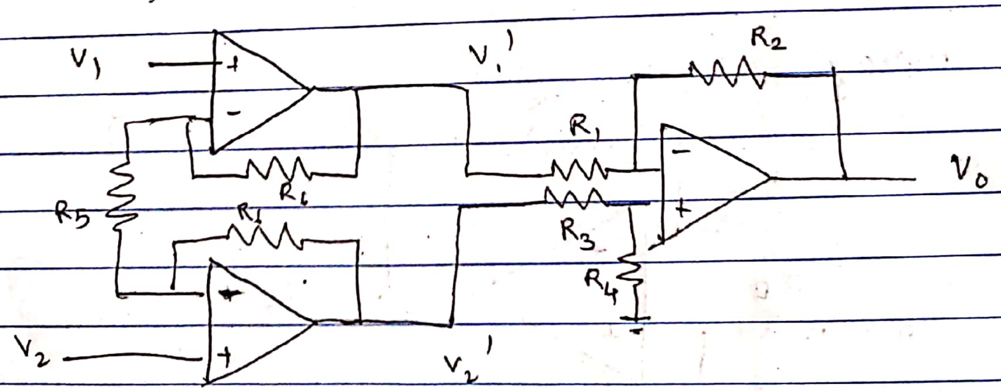


Diff. Amp built using Op Amp



$$\text{Gain} = + \frac{R_2}{R_1}$$

4] Instrumentation Amp



$$V_0 = G_1 G_2 (V_1 - V_2)$$

Applications:

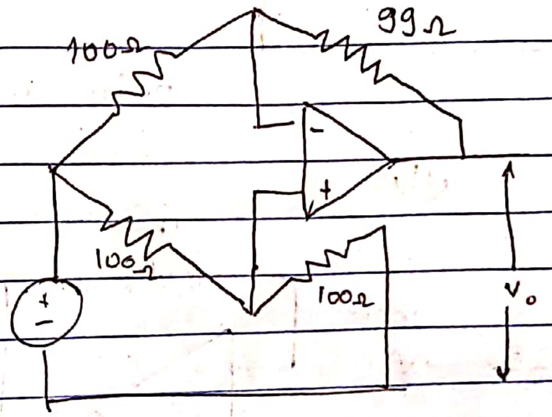
wherever small diff. in voltage has to be measured

strain gauge

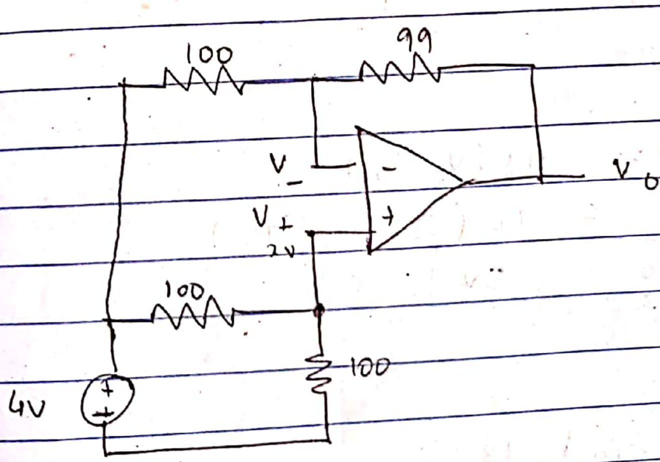
Diff b/n diff-amp & instrumentation

I.A is meant to measure vol. b/n 2 points whereas D.A will amplify the diff. signal.

Q) Find o/p voltage.



$\frac{200 \times 4}{300}$ 2.6



$\frac{4 \times 100}{300}$

= 1.

$$\frac{V_+ - 4}{100} + \frac{V_+}{100} = 0$$

$\boxed{V_+ = 2V}$

At V_- $(V_+ = V_-)$

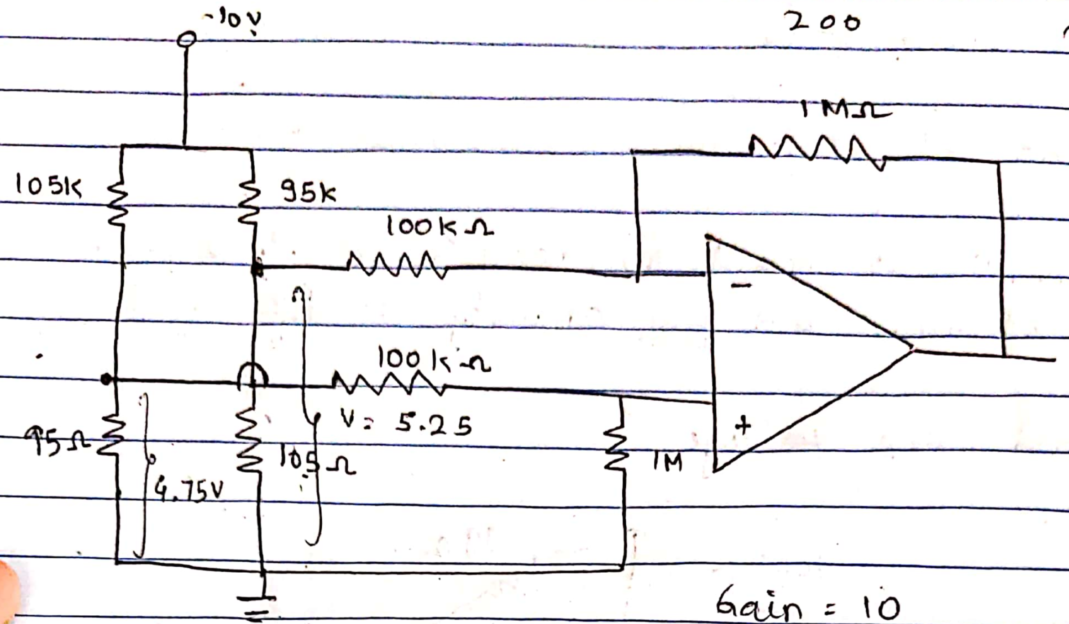
$$\frac{V_+ - 4}{100} + \frac{V_+ - V_o}{99} = 0$$

$\boxed{V_o = -0.02V}$

Scanned by CamScanner

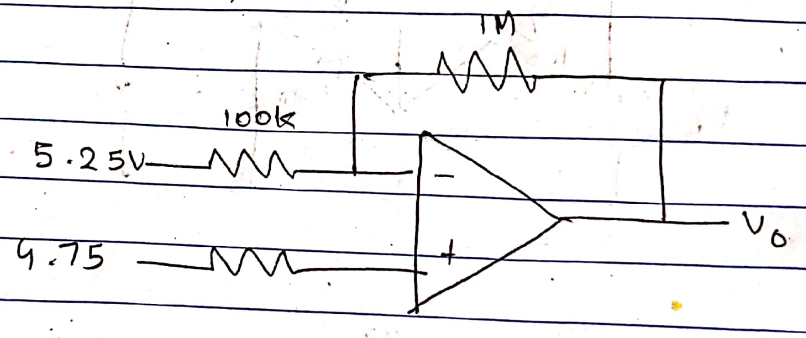
?] Determine V_o

$V_- = \frac{10 \times 105}{200}$ $\quad V_+ = \frac{10 \times 95}{200}$



Gain = 10

⇓

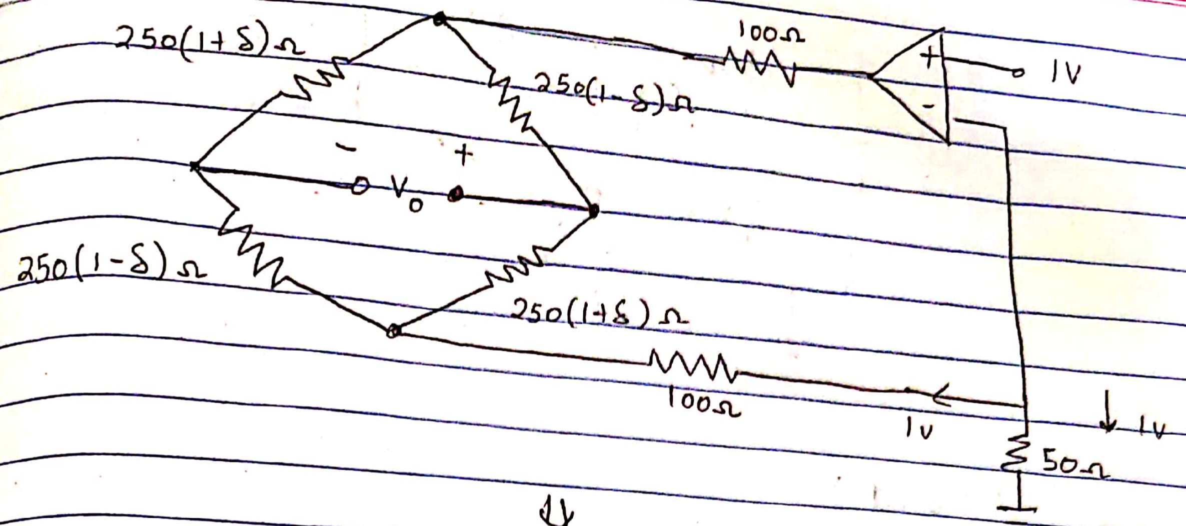


$V_o = A_d (V_2 - V_1)$

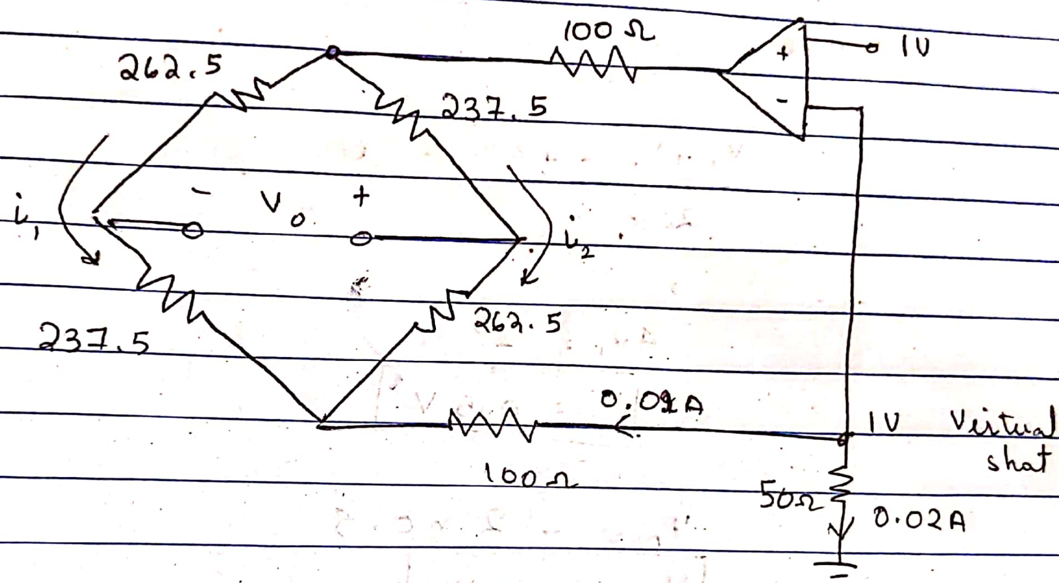
$= 10 (5.25 - 4.75)$

$\boxed{V_o = 5V}$

③ $\delta = 0.05$; Find V_o



⇓



~~450Ω~~

$i_1 = i_2$

KVL: $250(1+\delta)0.01 - V_0 - 250(1-\delta)0.01 = 0$

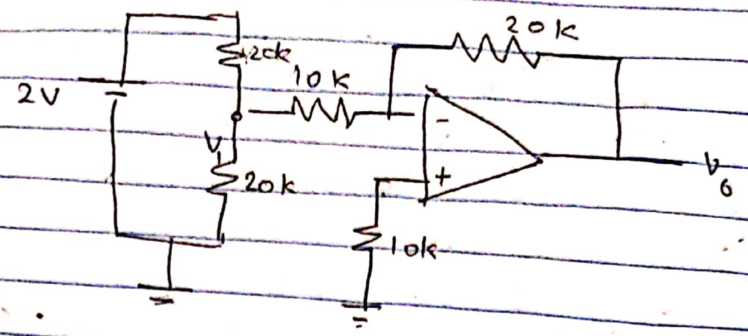
$V_0 = 0.25\,V$

$= 250\,mV$ //

(4) calc. V_0 assume ideal opAmp

⟶

-ve feedback ∴ o/p unsaturated
so virtual gnd.



KVL at V_1

$$\frac{V_1}{20k} + \frac{V_1 - 2}{20k} + \frac{V_1}{10k} = 0$$

$$\frac{V_1 + V_1 - 2 + 2V_1}{20k} = 0$$

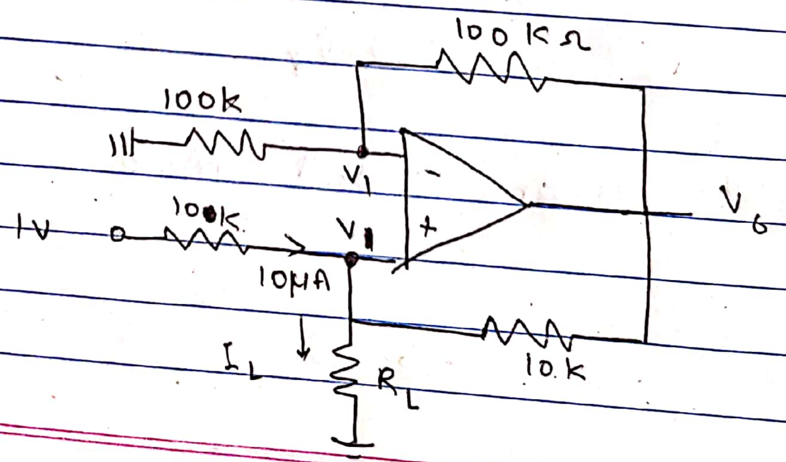
$$4V_1 = 2$$

$$\boxed{V_1 = 0.5\ V}$$

$$V_o = -2 \times 0.5$$

$$\boxed{V_o = -1\ V}$$

5. Calculate I_L.



$$A = 1 + \frac{R_2}{R_1}$$

$$= 1 + \frac{100k}{100k}$$

$$= 2$$

$$\frac{V_1 - V_0}{10k} + \frac{V_1 - 1}{100k} + \cancel{\frac{V_1}{R_L}}^{I_L} = 0 \quad — (1)$$

$$I_L = 10k \times 10\mu$$

$$\frac{V}{100k} + \frac{V - V_0}{100k} = 0$$

$$\boxed{2V_1 = V_0}$$

$$\frac{V_1 - 2V_1}{100k} + \frac{V_1 - 1}{100k} + I_L = 0$$

$$\frac{10(-V_1)}{100k} + \frac{V_1 - 1}{100k} + \frac{100kI_L}{100k} = 0$$

$$-10V_1 + V_1 - 1 + 100k\,I_L = 0$$

$$-9V_1 - 1 + 100k\,I_L = 0$$

$$I_L = \frac{9V_1 + 1}{100k}$$

(1)

$$\frac{-1}{10k} = -I_L$$

$$\boxed{I_L = 100\mu A}$$