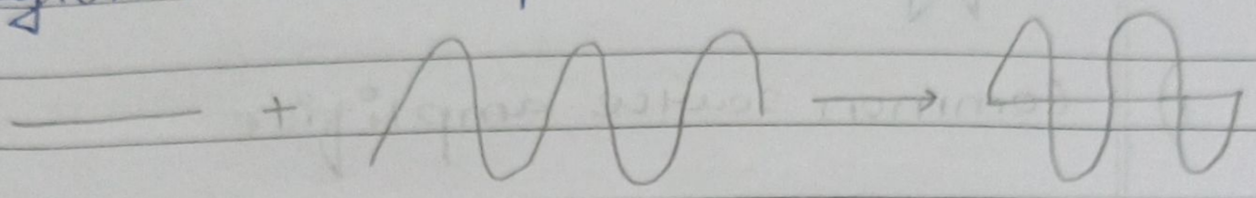
Unit-3-MOSFET as an Amplifier

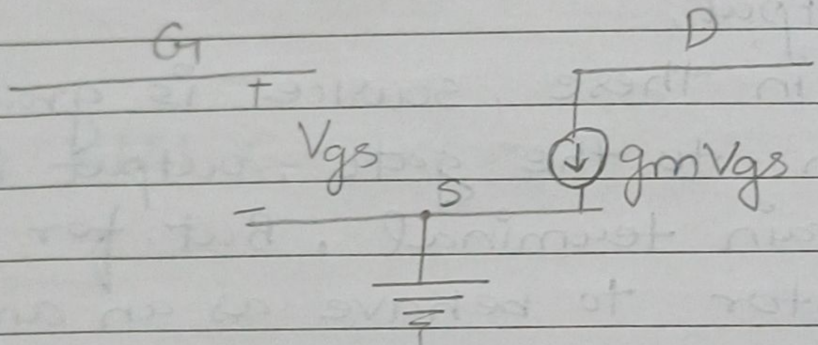
Date :

: Small signal equivalent circuit

An amplifier will have AC signal as the input (because it has to amplify) and a DC voltage is there to bias the transistor to push it into saturation region. The output is AC-DC mixed.



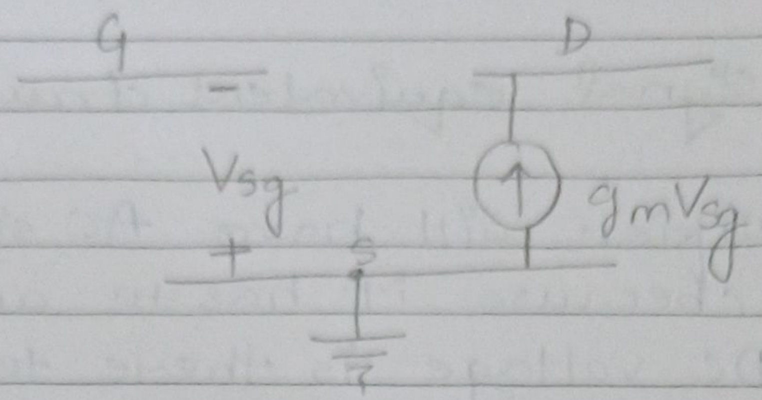
Small signal model for NMOS (AC signal input)



Gate and source have no physical connection they are connected by gate voltage Vgs (small letter - g and s as input is ac signal). We apply +ve gate voltage for NMOS so gate is +ve and S is -ve. When Vgs is applied, drain current flows from D to S. Id = gmVgs. We prefer writing gmVgs rather than Id as it is voltage controlled current device.

PMOS:

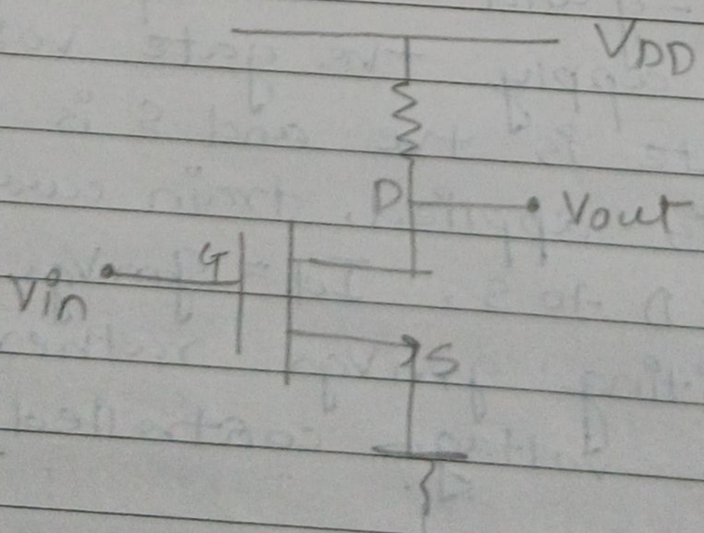
In channel length modulation there is a Resistance r_o between D and S.



: Configuration

1) Common source amplifier

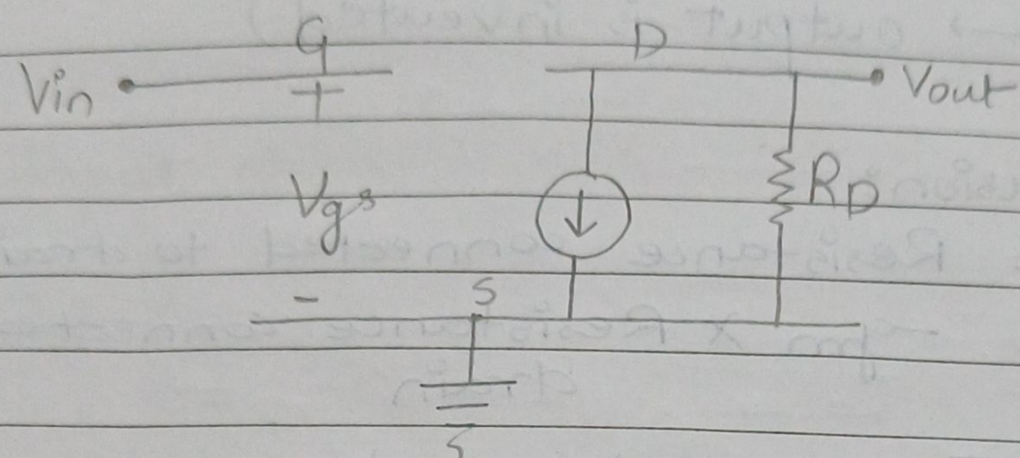
When small signal model is drawn, source terminal is common to input and output.
Always in these, source is grounded, input is given to the gate, output is given by drain terminal. But for the transistor to behave as an amplifier, it must be in SR. But Vdd cannot be applied directly to drain as then $V_{out} = V_{DD}$. That's why load resistance is used.



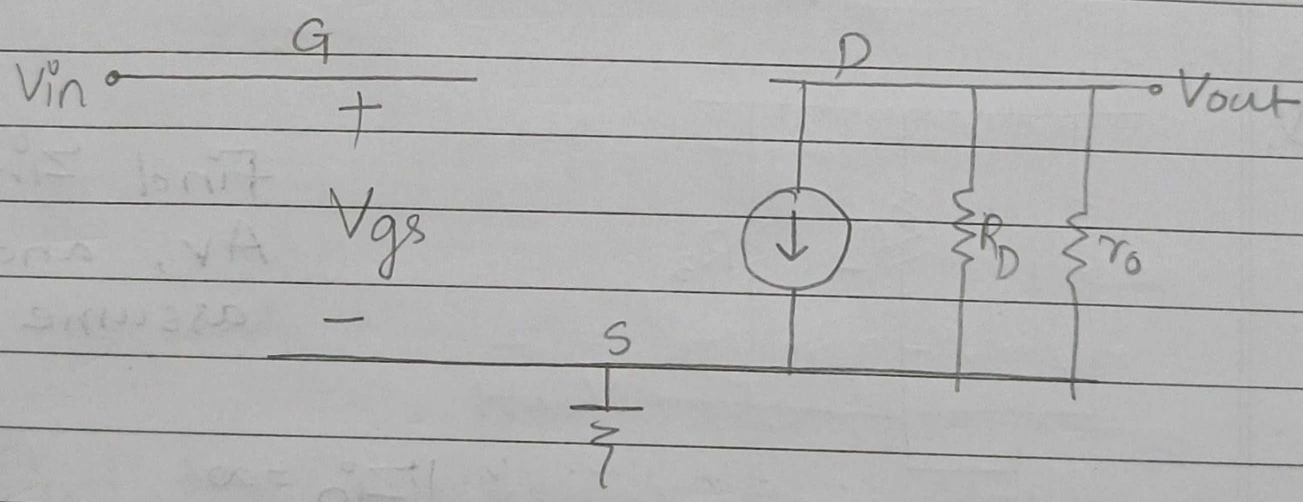
Analysis:
(Drawing small signal model)

Analysing the transistor only when AC is applied without DC voltage (biasing) is called small signal model. (All DC voltages are shorted and DC currents are open circuited)

Without CLM ($\lambda = 0$)



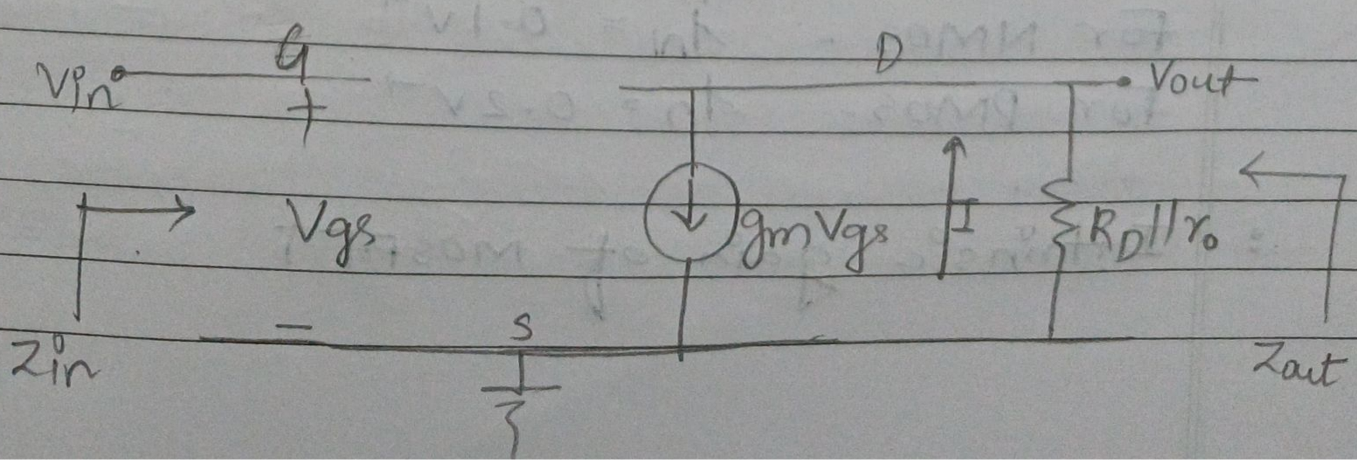
With CLM ($\lambda \neq 0$)



$$r_o = \frac{V_A}{I_D} = \frac{-1}{\lambda I_D}$$

If $\lambda = 0$ $\quad r_o = \infty$

$R_D \parallel r_o = R_D$.



CS amplifier: Phase reversal

$Z_{in} = \infty$ current flows from sh[illegible] in $R_D \| r_o$

$Z_{out} = R_D \| r_o$

$$A_V = \frac{V_{out}}{V_{in}} = \frac{-g_m V_{gs} (R_D \| r_o)}{V_{gs}}$$

$$A_V = -g_m (R_D \| r_o)$$

($-ve \rightarrow$ output is inverted)

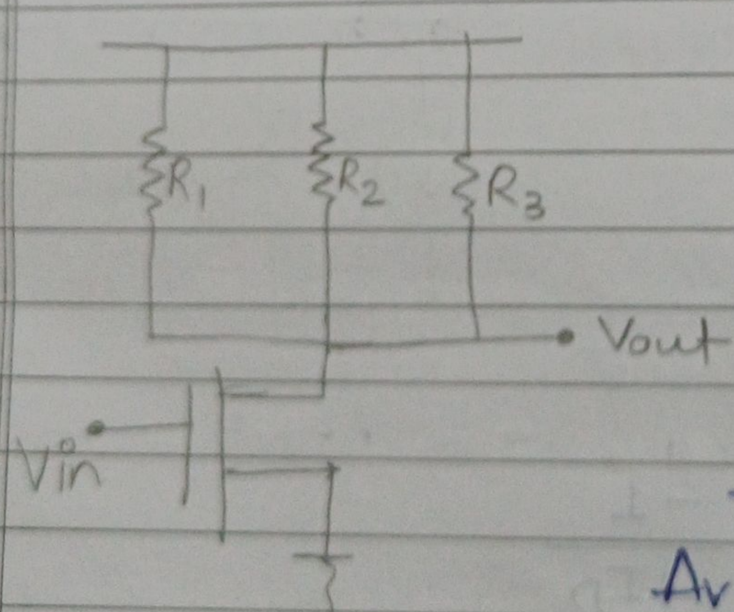
Conclusion:

Z_{out} = Resistance connected to drain

Gain = $-g_m$ x Resistance connected to drain

= Transconductance of input transistor $\times R$

Q.



Find Z_{in}, Z_{out}, A_V, and assume $\lambda \neq 0$

$Z_{in} = \infty$

$Z_{out} = R_1 \| R_2 \| R_3 \| r_o$

$A_V = -g_m (R_1 \| R_2 \| R_3 \| r_o)$

Standard values:

For NMOS - $\lambda_N = 0.1 V^{-1}$

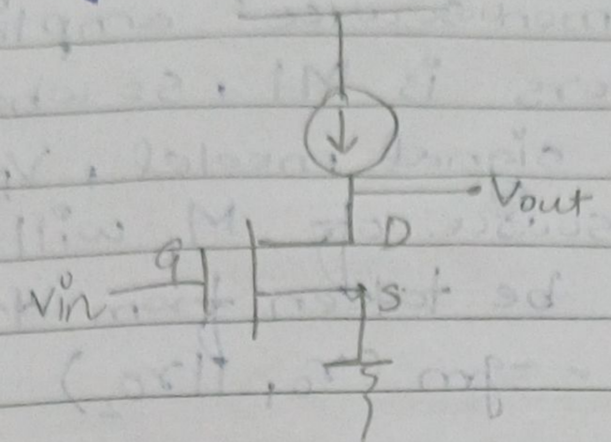
For PMOS - $\lambda_P = 0.2 V^{-1}$

: Intrinsic gain of MOSFET

$V_b \rightarrow$ Biasing Voltage which is a DC voltage.

S to D

To find intrinsic gain of MOSFET, replace R_D by a current source.



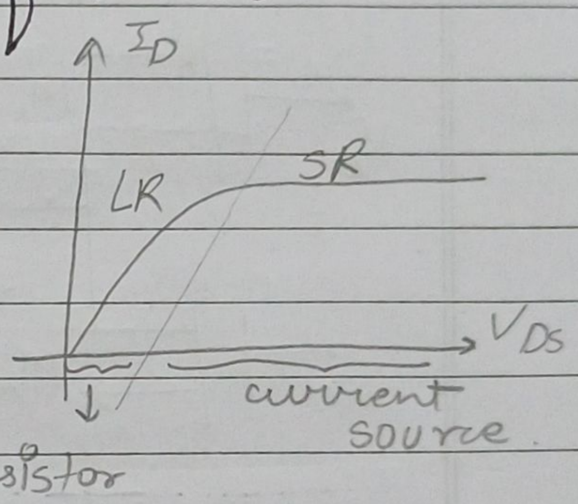
Input characteristics of MOSFET

$$R = \frac{\Delta V}{\Delta I} = \frac{\Delta V}{0}$$

$$= \infty$$

$$A_V = -g_m (r_o \| \infty)$$

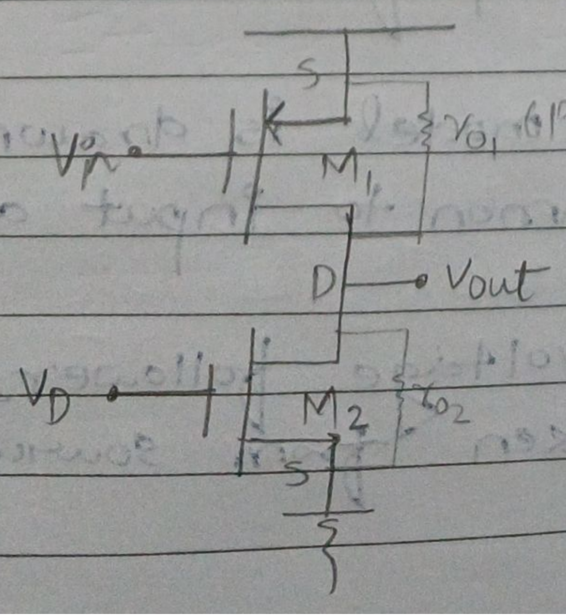
$$A_V = -g_m r_o$$



$$g_m = \frac{2 I_D}{V_{ov}}, \quad r_o = \frac{V_A}{I_D}$$

$$A_V = \frac{-2 V_A}{V_{ov}}$$

Q. Find the voltage gain of following configurations.

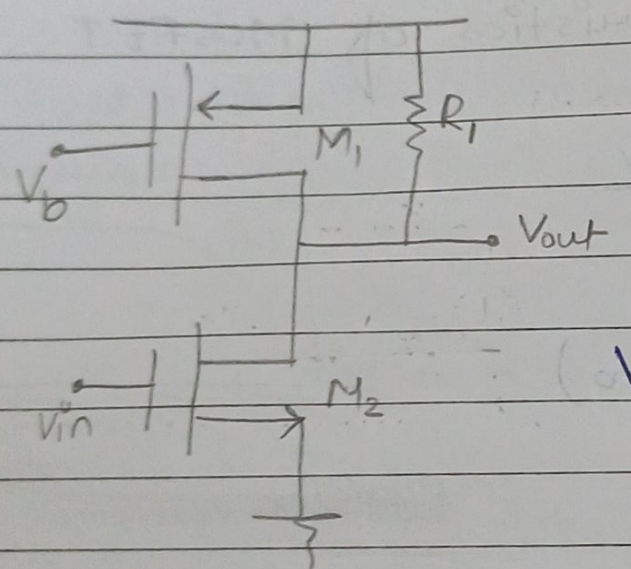


Input transistor = M_1 (Input is given to or of M_1)

This is a common source amplifier because input transistors is M1, so when you draw small signal model, V_D is grounded which here source of M_1 will be grounded and O/p will be taken from drain.

$$A_V = -g_m (r_{o_1} \| r_{o_2})$$

Q.



Find Av if
i) $\lambda = 0$
ii) $\lambda \neq 0$

V_b = Biasing voltage (DC)

i) $\lambda = 0$

$$A_V = -g_{m_2} R_1$$

ii) $\lambda \neq 0$

$$A_V = -g_{m_2} (r_{o_2} \| R_1 \| r_{o_1})$$

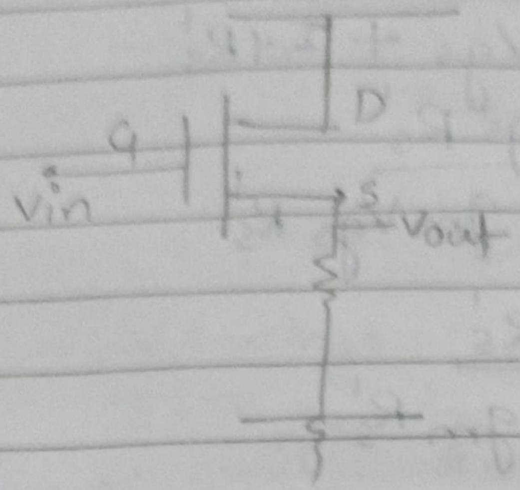
2) Common drain amplifier

→ When small signal model is drawn, source terminal is common to input and output.

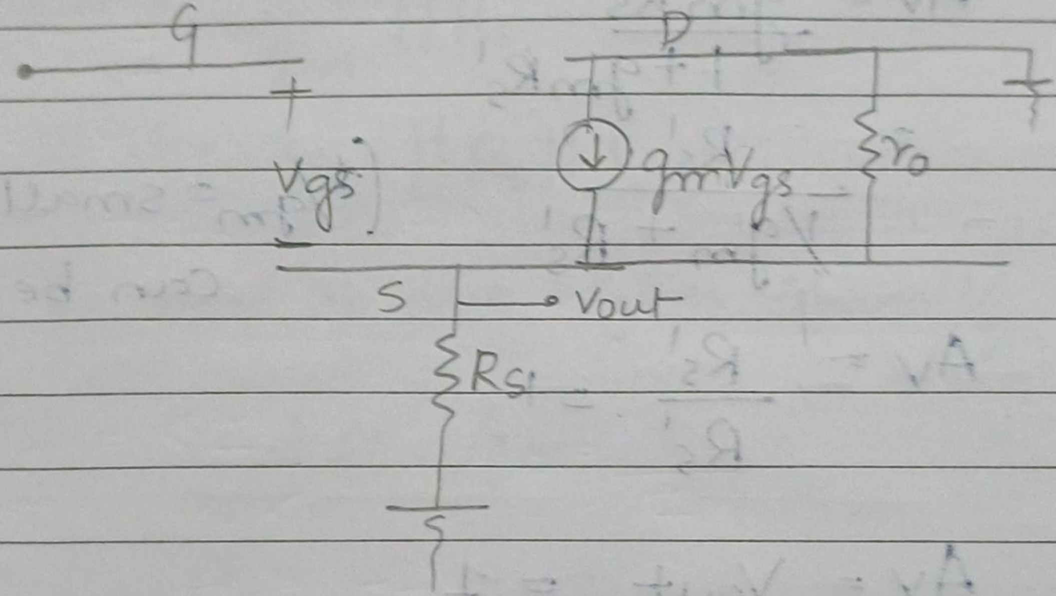
→ Also known as voltage follower.

→ Output will be taken from source terminal.

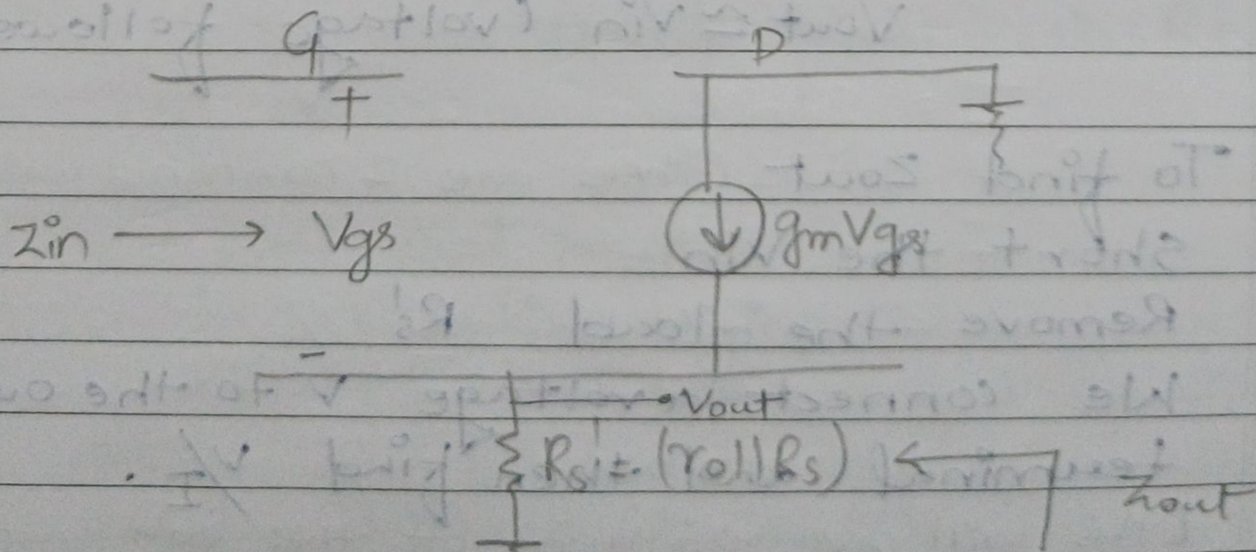
Input will be given to gate. Load is connected to source terminal.



Small signal model.



This is initial circuit ro and Rs are in parallel.



Input impedance $Z_{in} = \infty$

Voltage gain $A_v = \frac{V_{out}}{V_{in}}$

$$= \frac{I_d R_s'}{V_{gs} + I_d R_s'}$$

$$= \frac{g_m V_{gs} R_s'}{V_{gs} + g_m V_{gs} R_s'}$$

$$A_v = \frac{g_m R_s'}{1 + g_m R_s'}$$

R_s' = load resistance = $K\Omega$

$$A_v = \frac{g_m R_s'}{1 + g_m R_s'}$$

$$= \frac{R_s'}{1/g_m + R_s'}$$

($1/g_m$ = small quantity can be neglected)

$$A_v = \frac{R_s'}{R_s'} = 1$$

$$A_v = \frac{V_{out}}{V_{in}} = 1$$

$V_{out} \simeq V_{in}$ (voltage follower)

: To find Zout (there are 2 branches unlike cs)

1) Short the Vin

2) Remove the load R_s'.

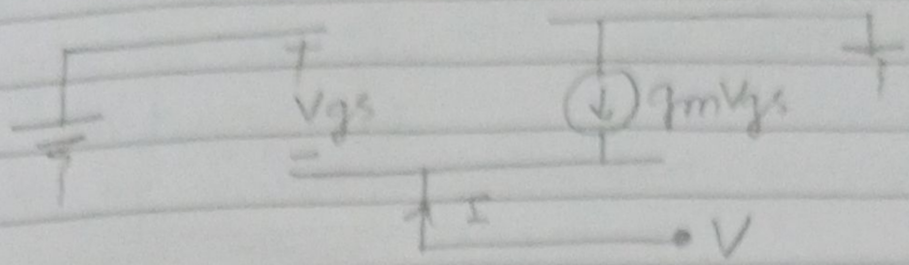
3) We connect a voltage V to the output terminal and then find V/I.

(this will give resistance of the top part in a small signal model)

4)

NOT

4) $Z_{out} = \frac{V}{I} \parallel R_s'$



$V = -V_{gs}$

$I = -g_m V_{gs}$

$\frac{V}{I} = \frac{1}{g_m}$

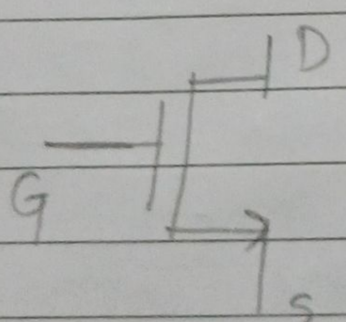
$Z_{out} = \frac{1}{g_m} \parallel R_s'$

$Z_{out} = \frac{1}{g_m} \parallel R_S \parallel r_o$

As R_S and r_o are higher than $1/g_m$.

$Z_{out} \simeq 1/g_m$

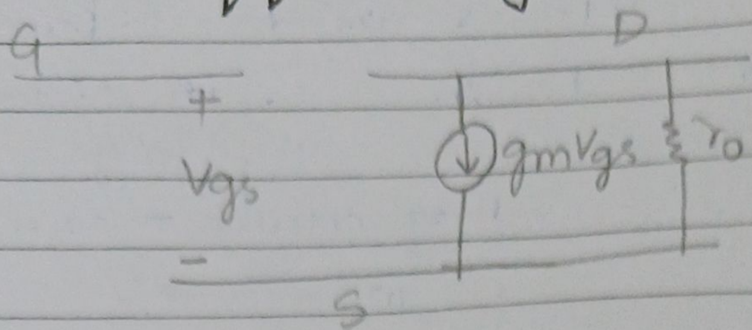
<u>NOTE:</u>



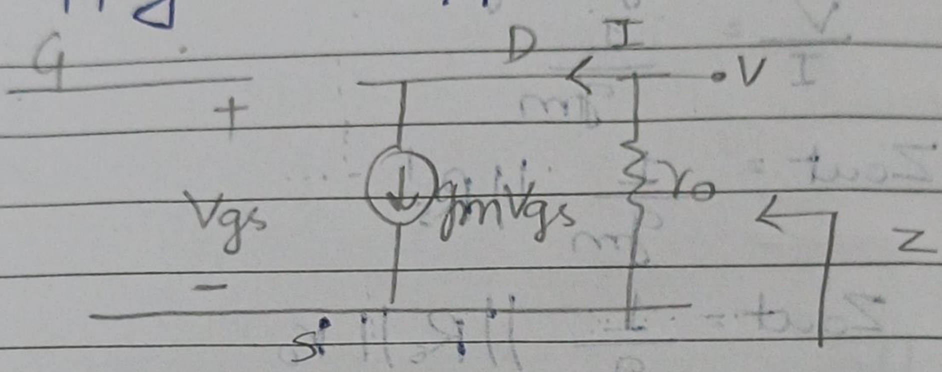
looking from source: $R = 1/g_m$
looking from gate: $R = \infty$
looking from drain: $R = r_o$

: Diode connected load
↳ Saturation region
↳ MOSFET behaves as a 2-terminal device, it is called as Diode and offers only resistance (∴ load)

Resistance offered by diode connected load

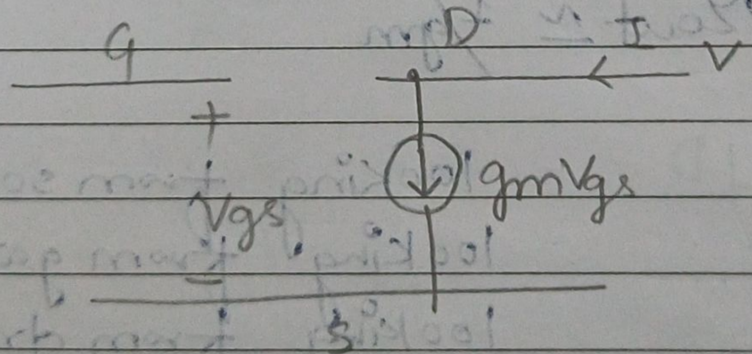


To find the impedance from output side, apply V to o/p side.



$V = V_{gs}$

To find I, remove r_o load temporary.



$I = g_m V_{gs}$

$$\frac{V}{I} = \frac{1}{g_m}$$

$$Z = \frac{1}{g_m} \| r_o \simeq 1/g_m$$

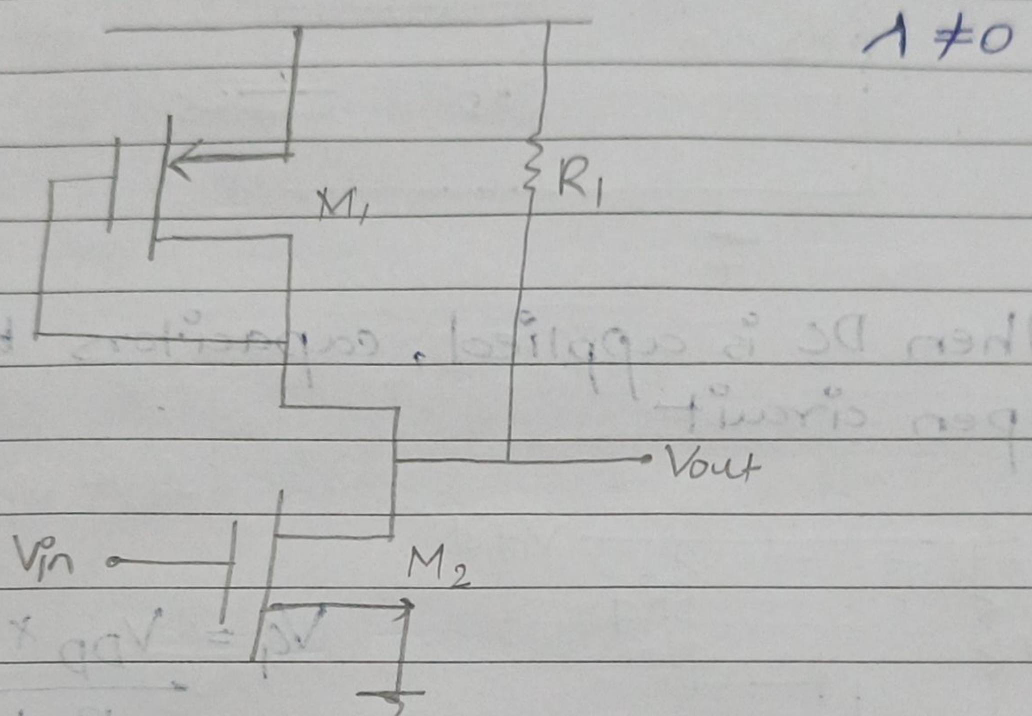
(r_o value = very high)

$$Z \simeq \frac{1}{g_m}$$

(impendance offered by a diode connected load is very low)

In saturation region, Z offered should be ∞. But in case of diode connected load although it is in SR, it will offer very low impedance. Diode connected load cannot be used as current source because it offer very low Z.

Q find A_v of the following circuit



M_2 is the input transistor.
source of M_2 is ~~and~~ grounded, so it is CS amplifier.

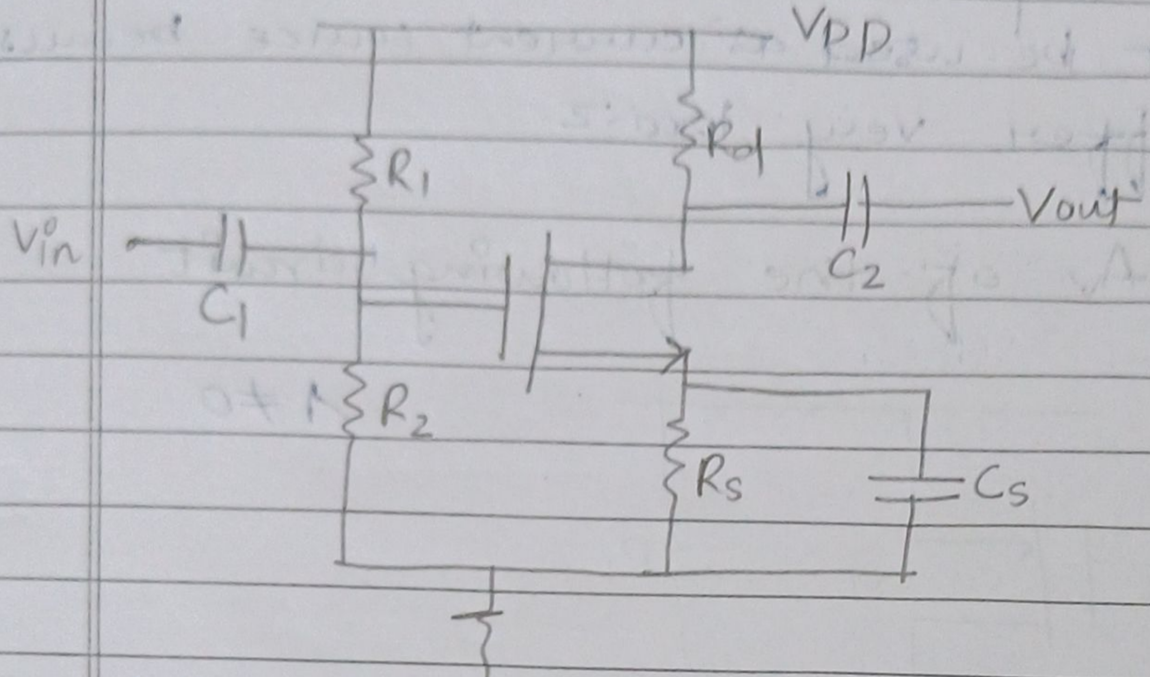
$$A_V = -g_{m_2}(R_1 \,||\, r_{o_1} \,||\, r_{o_2} \,||\, 1/g_{m_1})$$

Only $1/g_m$ is lower

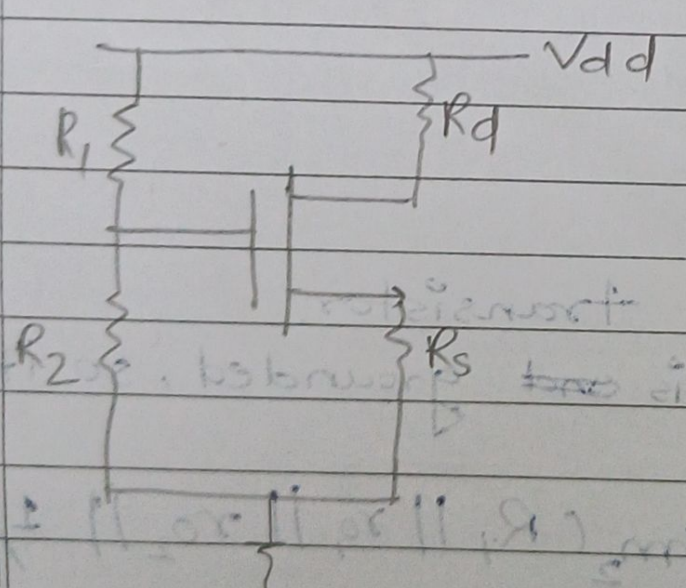
$$A_V = \frac{-g_{m_2}}{g_{m_1}}$$

Q. find the gain, zin, Zout and maximum signal handling capacity of the

transistor if $V_t = 1V$, $k_n'(W/L) = 2\ mA/V^2$,
$V_A = 67.5V$, $V_{DD} = 24V$, $R_1 = 8.5M\Omega$,
$R_2 = 3.5M\Omega$, $R_D = 6K$, $R_S = 2K$



When DC is applied, capacitors behave as open circuit



$$V_G = \frac{V_{DD} \times R_2}{R_1 + R_2}$$

$$= \frac{24 \times 3.5 \times 10^6}{12 \times 10^6}$$

$$V_{GS} = 7V$$

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

$$R_G = \frac{8.5 \times 3.5 \times 10^6}{12}$$

$$= 2.47\ M\Omega$$

$$I_D = \frac{K_n'(W/L)}{2}(V_g - V_s - V_t)^2$$

$$I_d = \frac{2}{2}[7 - 2I_d - 1]^2$$

$$I_d = (6 - 2I_d)^2$$

$$4I_d^2 - 25I_d + 36 = 0$$

$$I_D = 2.25\,mA$$

$V_S = 2I_D$ (From $I_d R_S$)

$V_S = 4.5V$

$$V_d = V_{DD} - I_D R_D$$
$$= 24 - 2.25(6)$$
$$V_D = 10.5V$$

Small signal parameter:

$$g_m = \sqrt{2 I_D K_n'(W/L)}$$

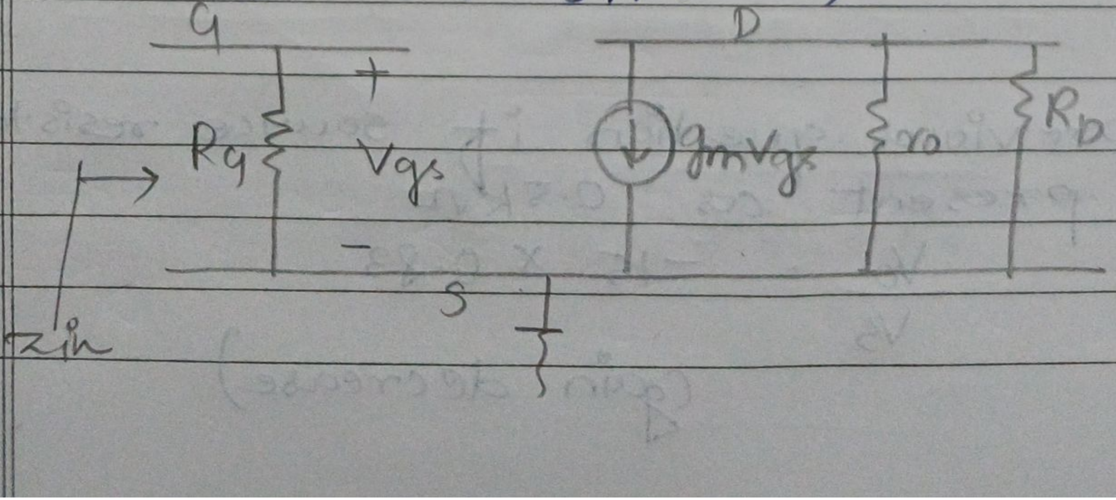
($g_m = \frac{2I_D}{V_{ov}}$ don't use until necessary)

$$g_m = 3\,mA/V^2$$

$$r_o = \frac{V_A}{I_D} = \frac{67.5}{2.25m} = 30k\Omega$$

Ac:

Short all DC voltages and open all DC current sources, capacitor shorted ($C_S = 0$, $R_S || C_S = 0$)



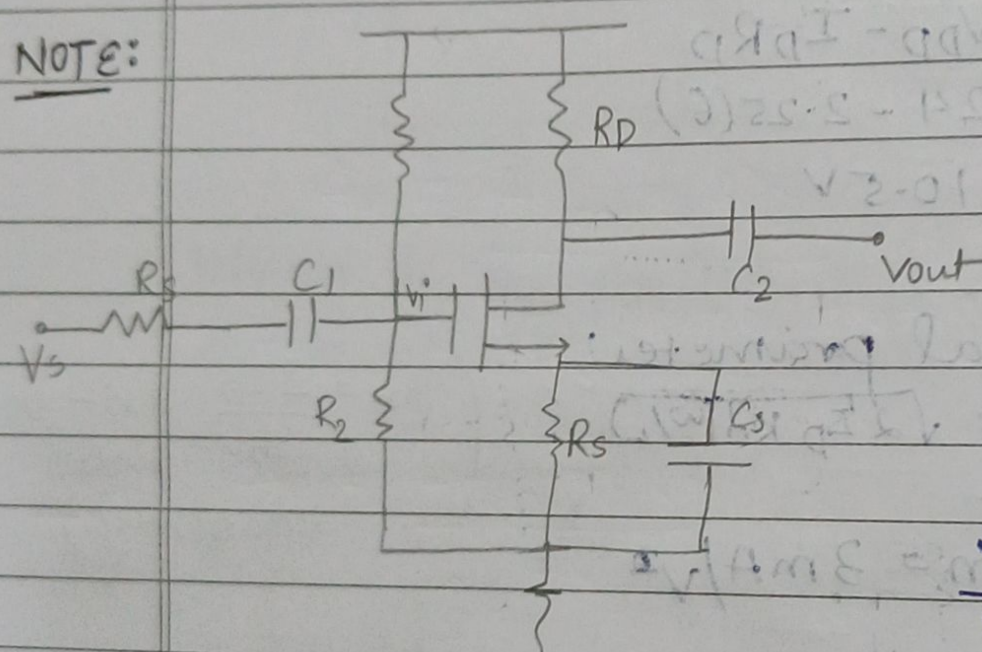
$\hat{V}_i \to$ max input to g...
$A_V = \frac{V_{out}}{V_{in}}$

$Z_{in} = R_G = 2.47\,M\Omega$
$Z_{out} = r_o \| R_D$
$= 5\,k\Omega$

$A_V = -g_m$ (Resistance connected to drain)
$= -15$

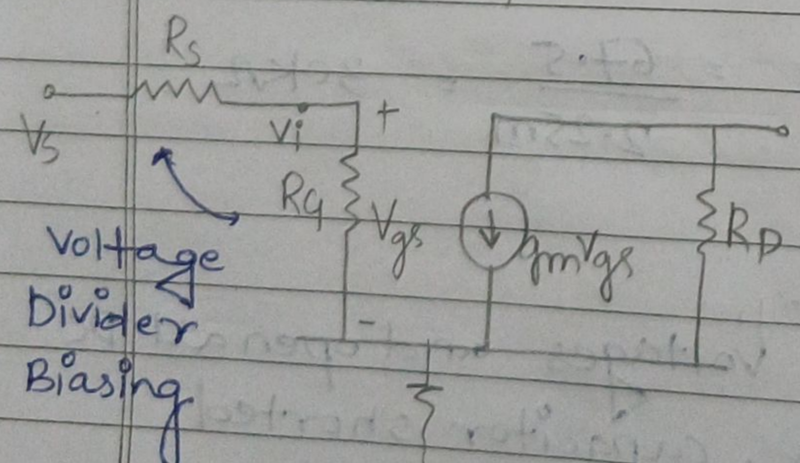
Max. signal handling capacity
$V_{DS} \geq V_{GS} - V_t$
$V_D(DC) + V_D(AC) \geq V_G(DC) + V_G(AC) - V_t$
$10.5 + A_V \hat{V}_i \geq 7 + \hat{V}_i - V_t$
$\hat{V}_i \leq 0.28\,V$

NOTE:



$A_V = \frac{V_o}{V_{in}}$

$\frac{V_o}{V_s} = \underbrace{\frac{V_o}{V_{in}}}_{A_V} \times \frac{V_{in}}{V_s}$



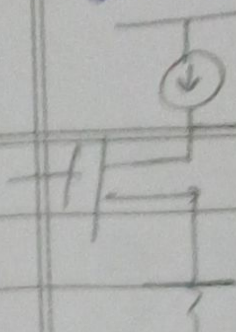
$V_i = \frac{V_s \cdot R_G}{R_s + R_G}$

$\frac{V_o}{V_s} = A_V \cdot \frac{R_G}{R_s + R_G}$

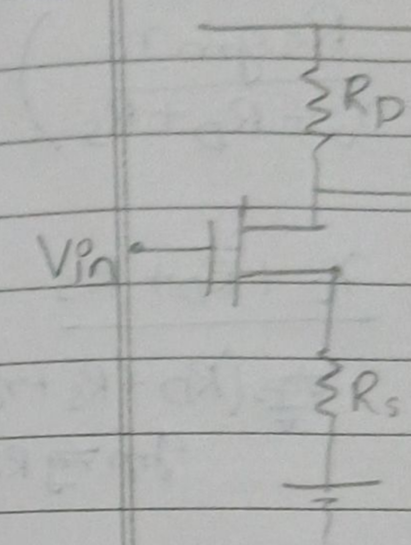
In previous question if source resistance is present as $0.5\,k\Omega$
$\frac{V_o}{V_s} = -15 \times 0.83$

(gain decrease)

current sou...



Common s...
derivation (Boost th...
Important



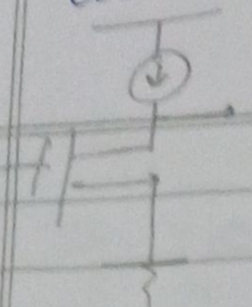
G

Vout =
$(0 - V_o$

$i =$

Vout

current source = infinite resistance r_0 = between S and D



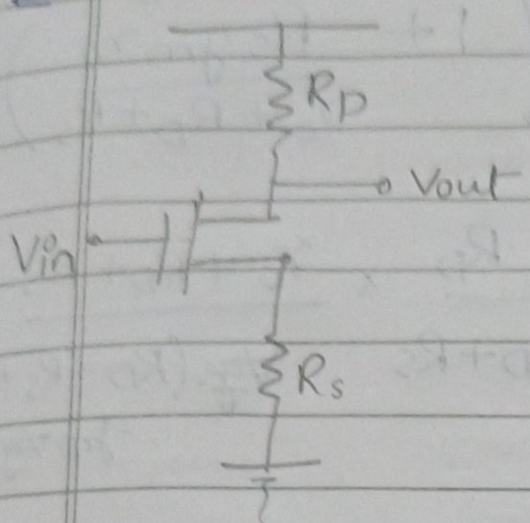
$-g_m(r_0 \| \infty)$

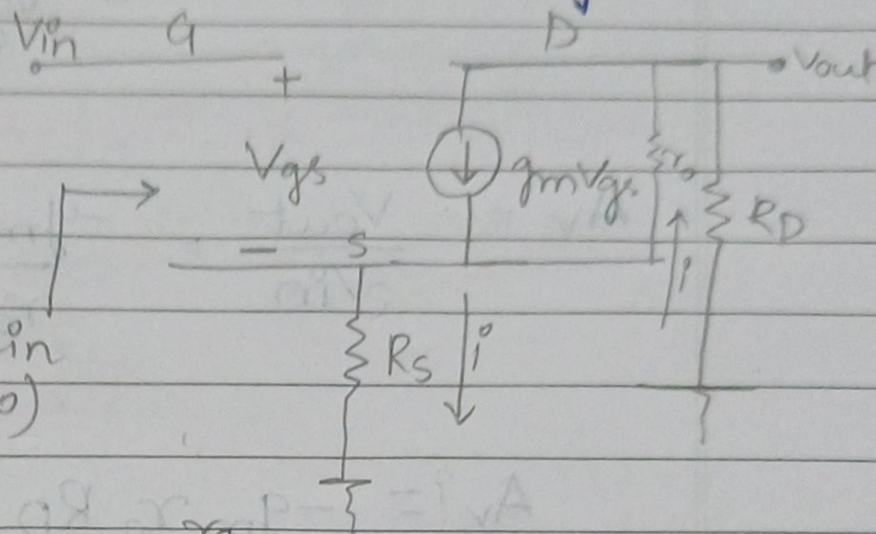
$-g_m r_0$ = gain.

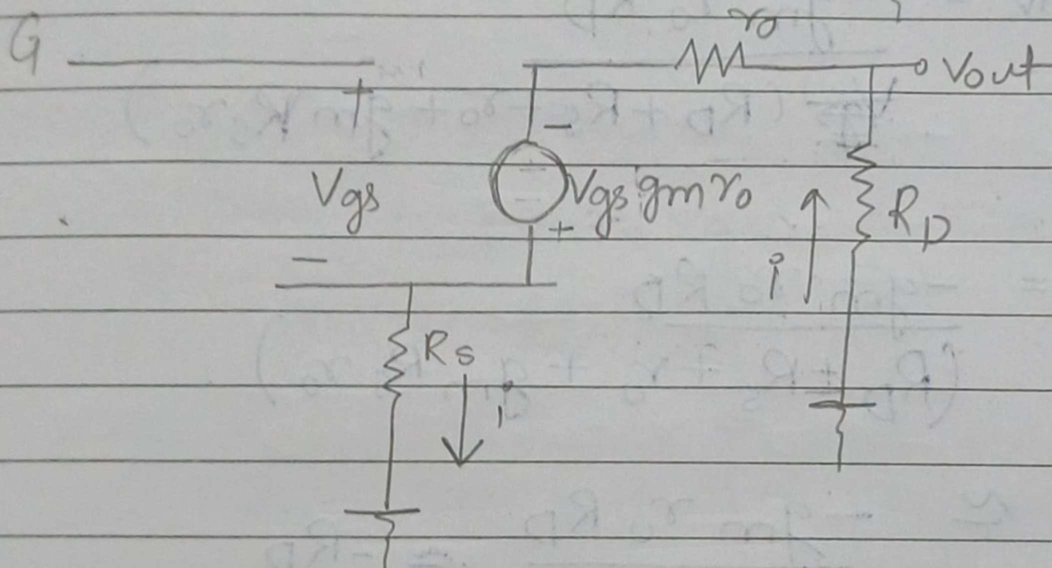
drain)

derivation Important

: Common source with degeneration:
(Boost the output impedance)
↳ cascading becomes easy.







$V_{out} = -iR_D$ (i from ground to Vout)

$(0 - V_{out} = iR_D)$

$$i = \frac{V_{gs}\, g_m r_0}{r_0 + R_D + R_S}$$

$$V_{out} = \frac{-V_{gs}\, g_m r_0 R_D}{r_0 + R_D + R_S}$$

Also, $V_{in} - V_{gs} - R_s \cancel{V} i = 0$

$$V_{in} = V_{gs} + R_s i$$

$$= V_{gs} + R_s\left(\frac{g_m V_{gs} r_o}{r_o + R_D + R_s}\right)$$

$$= V_{gs}\left(1 + \frac{R_s g_m r_o}{r_o + R_D + R_s}\right)$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{-g_m r_o R_D}{r_o + R_D + R_s} \times \frac{r_o + R_D + R_s}{\cancel{V_{gs}}(R_D + R_s + r_o + g_m \cancel{V_g} R_s r_o)}$$

$$A_v = \frac{-g_m r_o R_D}{\cancel{V_{gs}}(R_D + R_s + r_o + g_m R_s r_o)}.$$

NOTE: ① $A_v = \dfrac{-g_m r_o R_D}{(R_D + R_s + r_o + g_m R_s r_o)}$

$$\simeq \frac{-g_m r_o R_D}{+g_m r_o R_s} \simeq \frac{-R_D}{R_s}$$

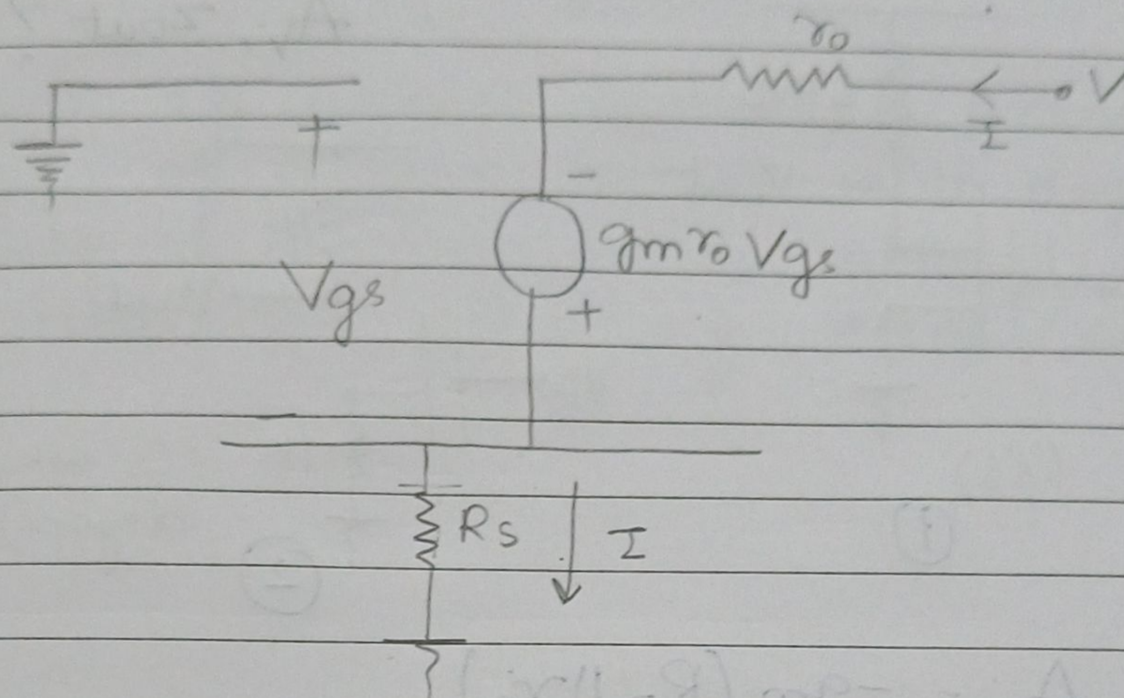
② If $\lambda = 0$;

$$A_v = \frac{-g_m r_o R_D}{R_D + R_s + r_o + g_m r_o R_s} = \frac{-g_m R_D}{\frac{R_D + R_s}{\cancel{r_o}}^{\to 0} + 1 + g_m R_s}$$

$$= \frac{-g_m R_D}{1 + g_m R_s} = \frac{-R_D}{R_s}$$

If CLM is neglected then gain is negative of Resistance connected to drain by Resistance connected to source.

Zout:



$$V - I r_o + g_m r_o V_{gs} = I R_S$$
$$V + g_m r_o V_{gs} = I(r_o + R_S)$$
} KVL to output loop

$$-V_{gs} - R_S I = 0$$
$$V_{gs} = -R_S I$$
} KVL to input loop

$$V + g_m r_o (-R_S I) = I(r_o + R_S)$$

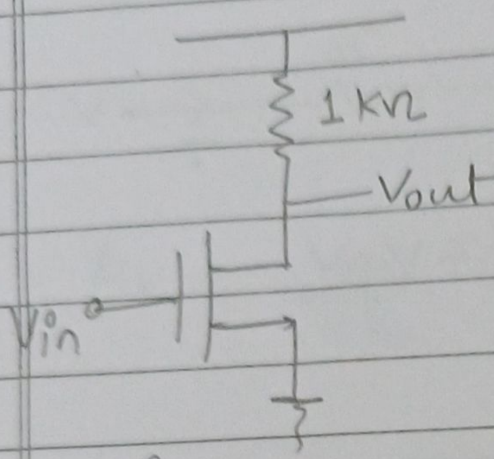
$$V = I(r_o + R_S + g_m r_o R_S)$$

$$\frac{V}{I} = r_o + R_S + g_m r_o R_S$$

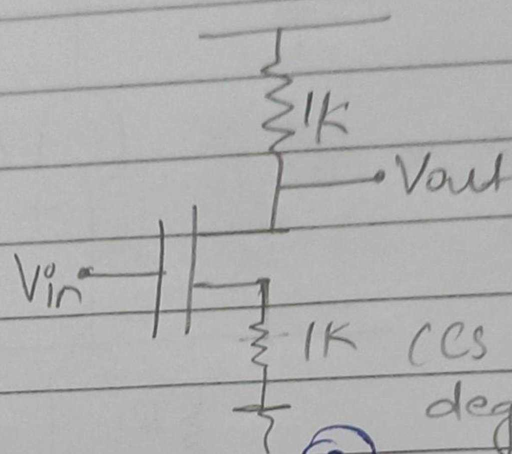
<u>NOTE:</u> $R_D \parallel V/I = R_D$ so there will be no gain of using CS with degeneration so use current source in place of R_D which will provide infinite resistance.

R_D should be a very high value and hence a current source is selected.

Q. $K_n' = 100\ \mu A/V^2$, $W/L = 10$, $I_D = 1mA$
$r_o = 10K\Omega$
A_V, Z_{out}?



(CS)
①



(CS with degen.)
②

① $A_V = -g_m(R_D \| r_o)$

$= -g_m(1K\Omega \| 10K)$

$= -\sqrt{2 I_D K_n' \left(\frac{W}{L}\right)}\ \frac{10K}{11}$

$= -\sqrt{2 \times 10^{-3} \times 100 \times 10^{-6} \times 10}\ \frac{10K}{11}$

$= -\sqrt{2 \times 10^{-6}}\ \frac{10K}{11}$

$= -1.41 \times 10^{-3} \cdot \frac{10K}{11}$ $\qquad R_{out} = R_D \| r_o$

$= -1.28$

② $A_V = \frac{-g_m r_o R_D}{R_D + R_S + r_o + g_m r_o R_S}$

$= -\frac{1.41 \times 10^{-3} \times 10 \times 10^3 \times 10^3}{10^3 + 10^3 + 10 \times 10^3 + 1.41 \times 10^{-3} \times 10 \times 10^3 \times 10^3}$

$= -\frac{1.41 \times 10^4}{12 \times 10^3 + 1.41 \times 10^4}$

$$\frac{-1.41 \times 10^4}{26.1 \times 10^3} = \frac{-14.1}{26.1}$$

$$= -0.54$$

$$R_{out} = r_o + R_s + g_m r_o R_s$$

NOTE: Gain of common source is greater than gain of common source with degen.
Rout of common source with degen is greater than Rout of common source.