dc model parameters

$$\text{Linear}: \; I_{DS} = \beta_N \left\{ (V_{GS} - V_{THN}) V_{DS} - \frac{V_{DS}^2}{2} \right\}$$

$$\text{Saturation}: \; I_{DS} = \frac{\beta_N}{2} (V_{GS} - V_{THN})^2 [1 + \lambda_n V_{DS}]$$

$$\beta_N = kP_N \cdot \frac{W}{L}$$

$$\lambda_N$$

$$V_{THN} = V_{THN0} + \gamma \left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right)$$

$$V_{THNO} = 1V; \gamma = 0.7\, V^{1/2}; 2\phi_F = 0.7V;$$

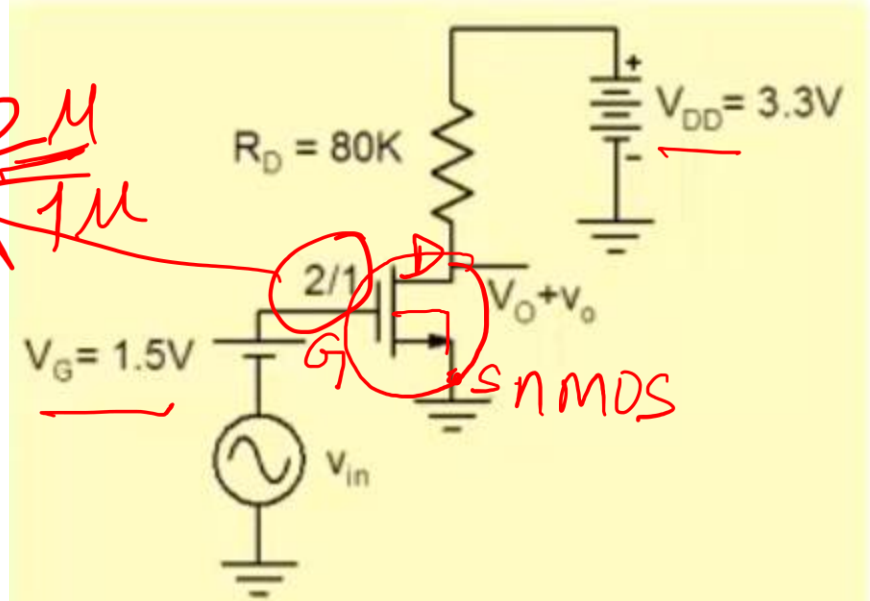
$$KP_N = 100\mu A / V^2; L = 1\mu m; \lambda = 0.01V^{-1}$$

Common Source Amplifier with Resistive load

Calculate Bias point → ac sources are shorted

✓ dc analysis

Assume : MOS is in saturation



$\frac{W}{L} = \frac{2\mu}{1\mu}$

$$I_{DSQ} = \frac{\beta_n}{2}(V_{GS} - V_{TN})^2 = 25\mu A \quad \checkmark$$

$K_p \frac{W}{L}$

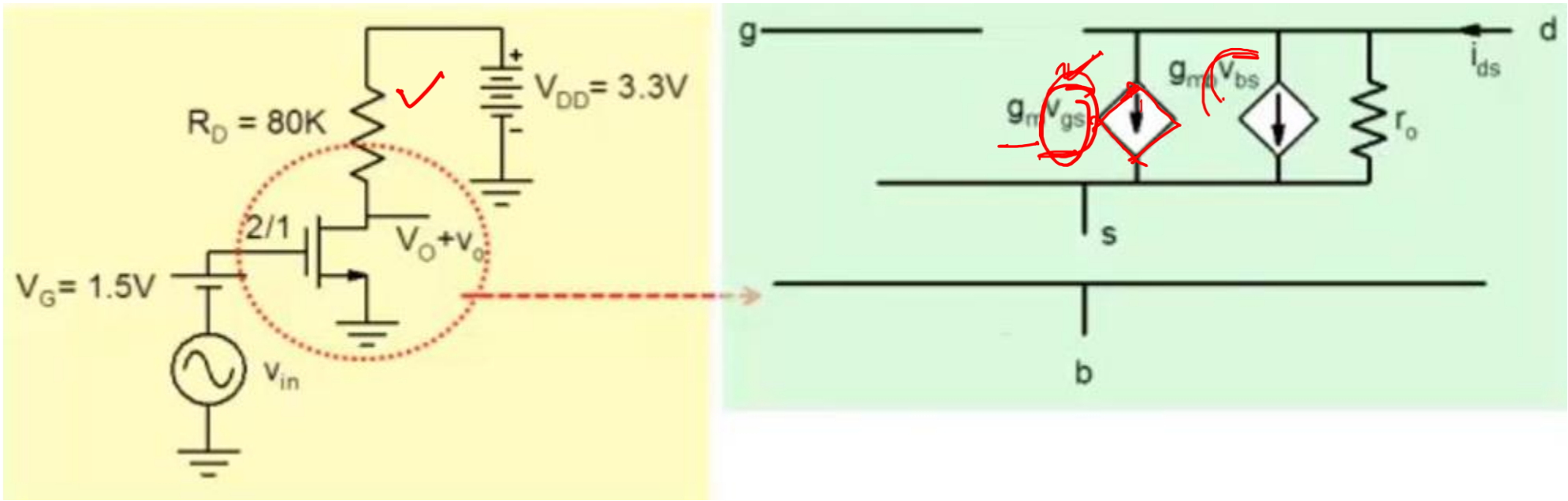
$$V_{DSQ} = V_{DD} - I_{DSQ} \times R_D = 1.3V \quad \checkmark$$

$3.3V - 25\mu A \times 80K = 1.3V$

Bias point $\Rightarrow$ $[I_{DSQ}, V_{DSQ}]$ ✓

$$V_{sat} = V_{GSQ} - V_{TN} = 0.5V \quad \text{so Tr. is in Saturation}$$

Small Signal Model → dc sources are shorted



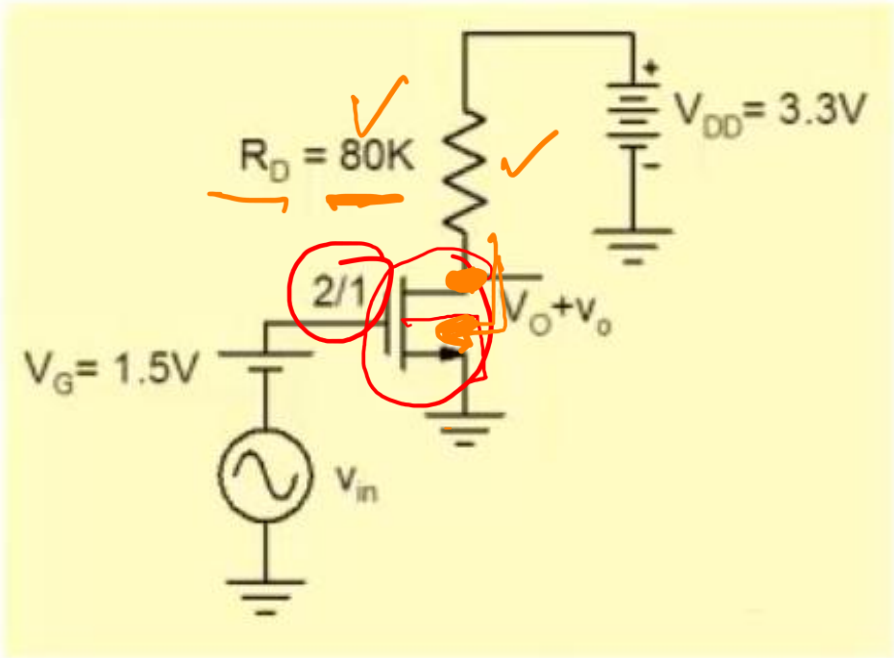
$$g_m = \frac{2I_{DSQ}}{V_{GSQ} - V_{THN}} = \sqrt{2I_{DSQ}\beta} = 100\mu A/V$$

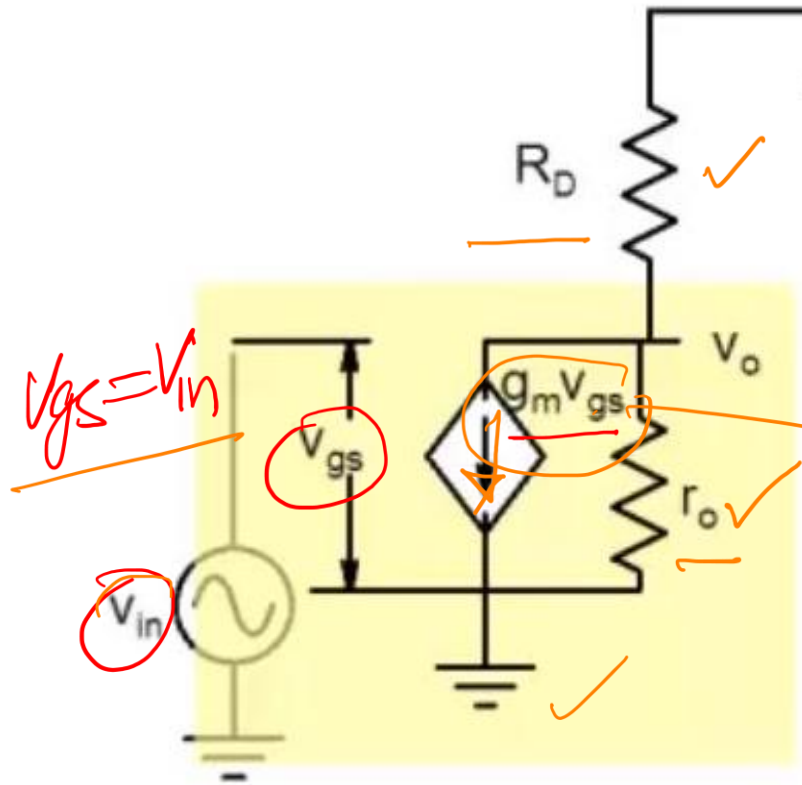
$$r_o = \frac{1}{\lambda_n I_{DSQ}} = 4M\Omega$$

$$g_{mb} = g_m \cdot \eta = 41.83\mu A/V$$

→ Now, we have small-signal terms / values

1. Voltage Gain





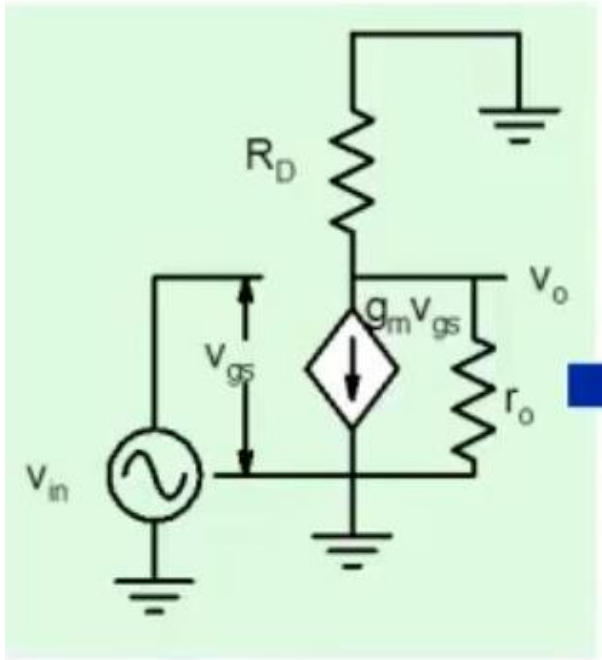
Body is connected to most negative potential, V_{bs} = 0.

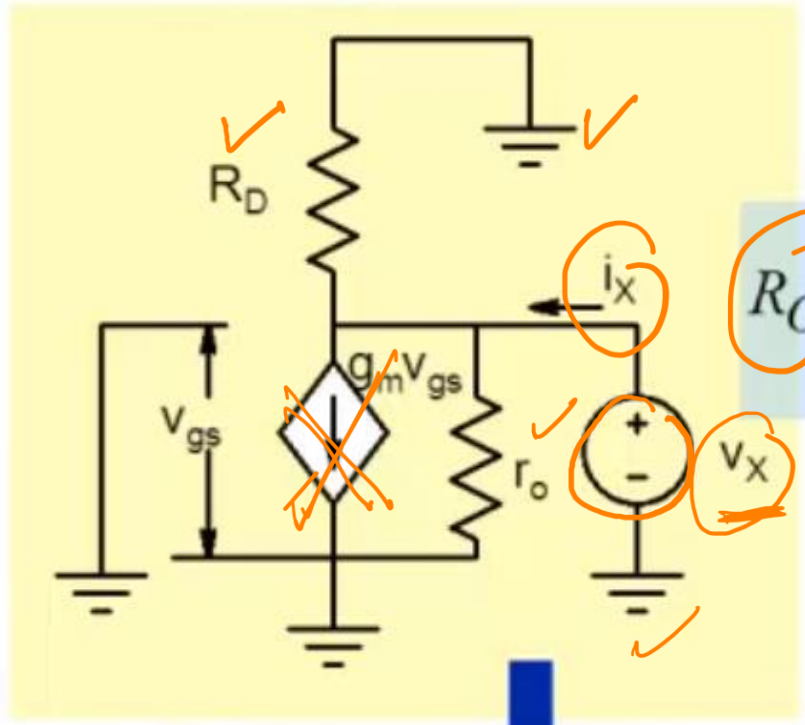
$$v_o = -g_m v_{in} \times R_D \| r_o$$

$$A_V = \frac{v_o}{v_{in}} = -g_m \times R_D \| r_o \cong -g_m R_D = -8$$

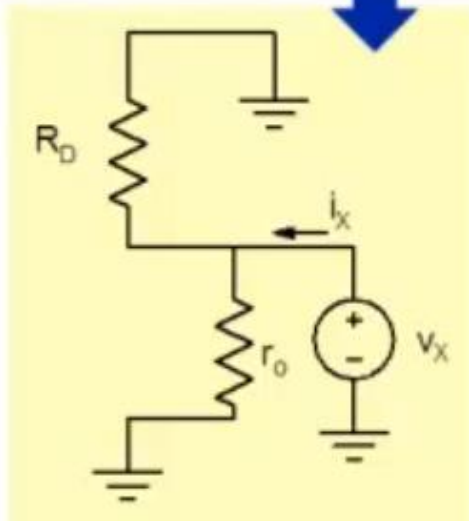
2. Output Resistance

To calculate o/p resistance → Remove i/p source
↳ $V_{gs}=0$
↓
$I=0$



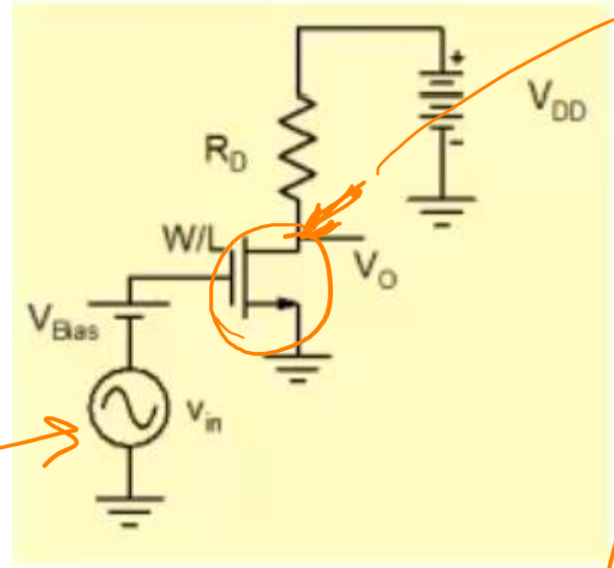


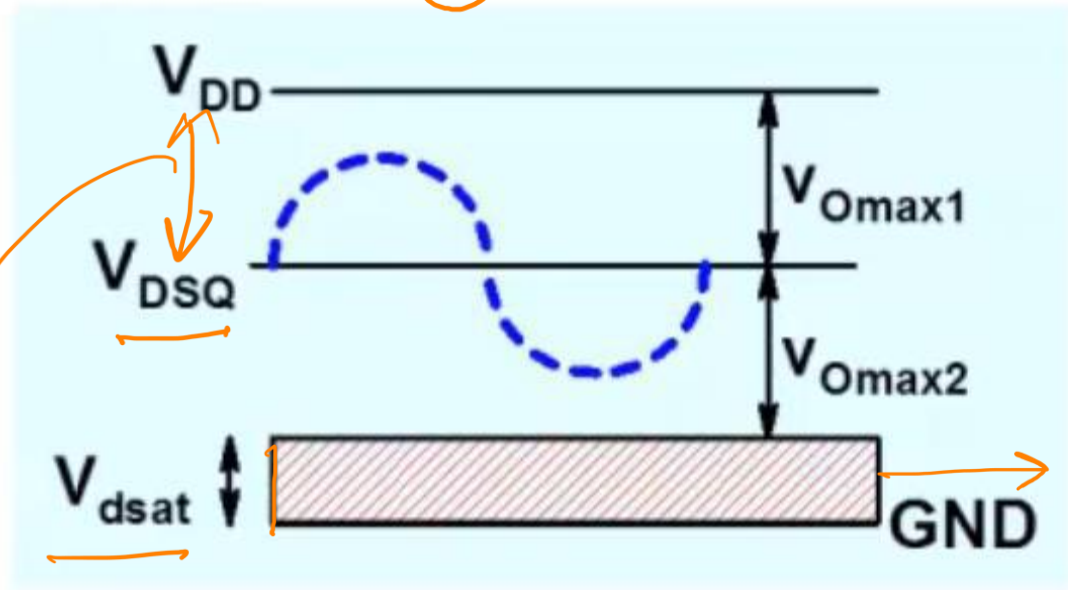
$$R_O = \left.\frac{v_x}{i_x}\right|_{v_{in}=0}$$



$$R_O = R_D \| r_o \cong R_D = 80K$$

3. Output Voltage Swing





Ensure MOS remain in saturation

$$v_{omax1} = V_{DD} - V_{DSQ}$$

$$v_{omax2} = V_{DSQ} - V_{dsat}$$

$$v_{omax} = Min\{v_{omax1}; v_{omax2}\}$$

[However, this will not match with actual results/values]

Voltage swing limited by harmonic distortion

- Harmonic distortion in CS amplifier occurs because the relationship between drain current and gate voltage is nonlinear.

$$I_{DSQ} + i_{ds} = \frac{\beta}{2} \times (V_{GSQ} + v_{gs} - V_T)^2$$

$$i_{ds} = g_m v_{gs} + \left(\frac{0.5}{V_{GSQ} - V_T}\right) \times g_m v_{gs}^2$$

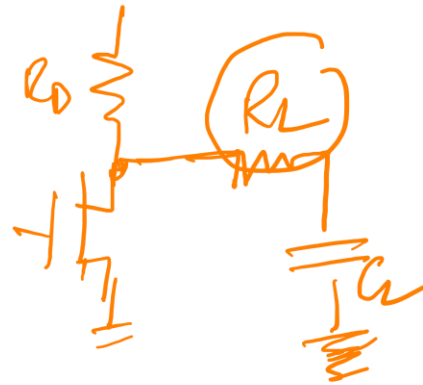
Let's take $v_{gs} = a_o \sin(2\pi f_o t)$

$$i_{ds} = g_m a_o \sin(2\pi f_o t) + \left(\frac{a_o^2 g_m}{4V_{GSQ} - V_T}\right) - \left(\frac{a_o^2 g_m}{4(V_{GSQ} - V_T)}\right)\cos(2\pi 2 f_o t)$$

$$HD_2(\%) = \frac{a_o/4}{V_{GSQ} - V_T} \times 100$$

Amplitude distortion

Output Voltage Swing



$$v_{in} = a_o \sin(2\pi f_o t)$$

$$HD_2(\%) = \frac{a_o/4}{V_{GSQ} - V_T} \times 100 = \frac{v_{in}}{V_{dsat}} \times 25$$

$$v_{in} = \frac{HD_2}{25} \times V_{dsat}$$

put for the sake of completeness

Now, $A_v = \frac{v_o}{v_{in}}$

$$v_o = A_v \times v_{in} \cong g_m R_D \| R_L \times v_{in}$$

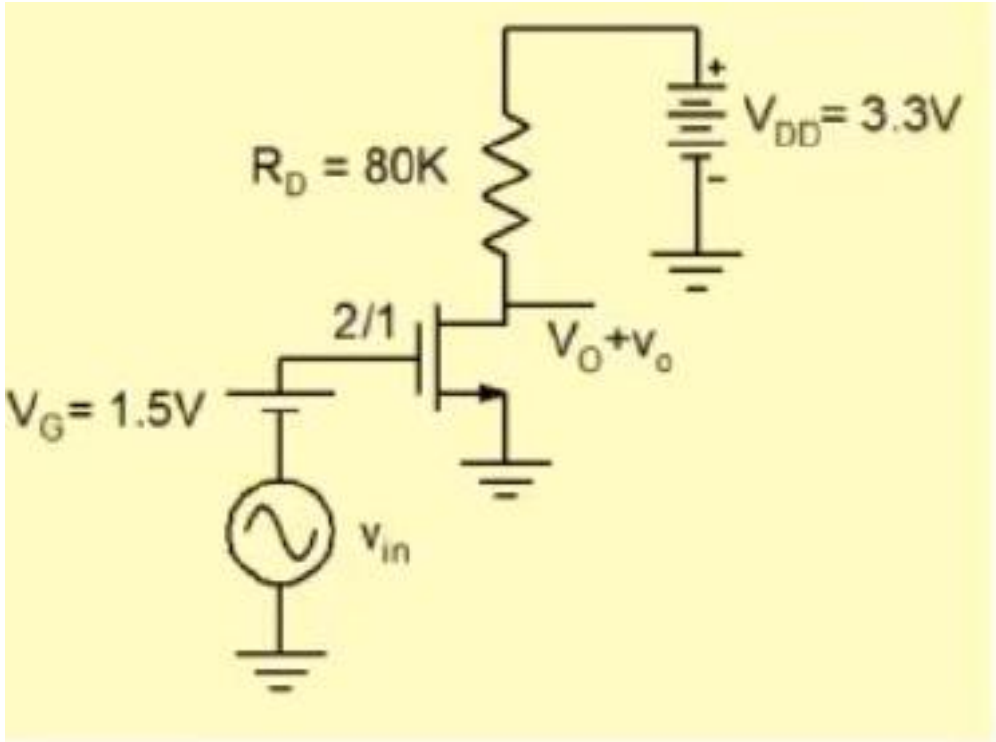
$$g_m = \frac{2I_{DSQ}}{V_{GSQ} - V_T}$$

$$v_{omax3} \cong I_{DSQ} R_D \| R_L \times \frac{HD_2}{12.5}$$

(This is the swing determined by the distortion)

$$v_{omax1} = V_{DD} - V_{DSQ} = I_{DSQ} R_D$$

$$v_{omax3} < v_{omax1}$$



$$V_{DSQ} = 1.3V; V_{sat} = 0.5V$$

$$v_{o\max} \le V_{DSQ} - V_{sat} = 0.8V$$

$$v_{o\max 3} \cong I_{DSQ} R_D \| R_L \times \frac{HD_2}{12.5}$$

$$= 0.8V \text{ for } HD_2 = 5\%$$

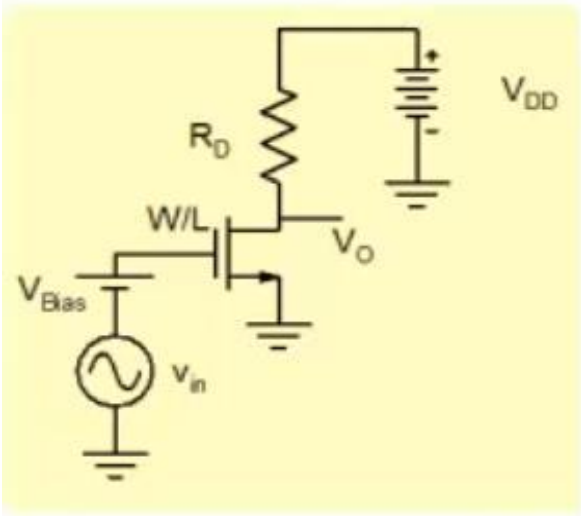
$$25\mu A \cdot 80K \cdot \frac{5}{12.5}$$

$$25\times10^{-6} \cdot 80\times10^{3} \cdot \frac{5}{12.5}$$

$$= 0.8V$$

How to get the maximum swing (at given V_{DD})

Design problem



$$v_o \cong I_{DSQ} R_D \| R_L \times \frac{HD_2}{12.5}$$

(v_{omax3})

$$v_o \le V_{DSQ} - V_{sat}$$

(v_{omax2})

Optimum drain-source bias

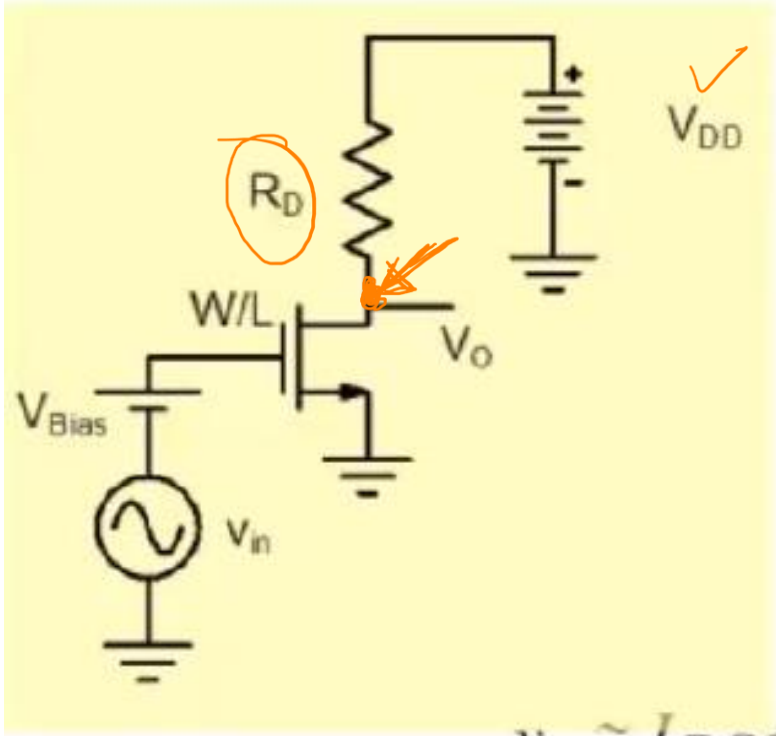
$$I_{DSQ} R_D \times \frac{HD_2}{12.5} \times \frac{1}{1 + R_D/R_L} = V_{DSQ} - V_{sat}$$

$$V_{DSQ} = \frac{V_{DD} \times \frac{HD_2}{\chi} + V_{sat}}{1 + \frac{HD_2}{\chi}}$$

$$v_{o\max} = \frac{V_{DD} - V_{sat}}{1 + \frac{\chi}{HD_2}}$$

$$\chi = 12.5 \times (1 + R_D/R_L)$$

Voltage Gain (including voltage swing)



$$A_V = -g_m R_D \qquad g_m = \sqrt{2 I_{DSQ} \beta}$$

$$R_D = \frac{V_{DD} - V_{DSQ}}{I_{DSQ}}$$

$$A_v = \sqrt{\frac{2\beta}{I_{DSQ}}} \times (V_{DD} - V_{DSQ})$$

$\mu_n C_{ox} \times \left(\frac{W}{L}\right)$

$$v_o \cong I_{DSQ} R_D \| R_L \times \frac{HD_2}{12.5}$$

one limit

$$v_o \le V_{DSQ} - V_{sat}$$

second limit

$V_{DSQ} \ge \vartheta_0 \; V_{sat}$

$$A_v \le \sqrt{\frac{2\beta}{I_{DSQ}}} \times (V_{DD} - v_{om} - \sqrt{\frac{2 I_{DSQ}}{\beta}})$$

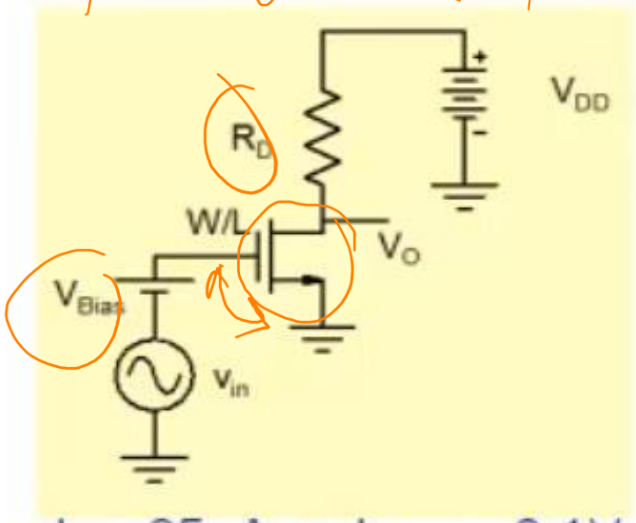
max voltage swing

$$I_{DSQ} = \frac{\beta}{2}(V_{GS} - V_t)$$

$$\sqrt{\frac{2 I_{DSQ}}{\beta}} = (V_{GS} - V_t) \to V_{sat}$$

Trade-off
Gain - voltage swing

How to improve gain (for example)



$$A_v \le \sqrt{\frac{2\beta}{I_{DSQ}}} \times \left(V_{DD} - v_{om} - \sqrt{\frac{2I_{DSQ}}{\beta}}\right)$$

1) Fix W=2μm and v_{om} = 0.1V →

for example
Low swing
+ May be we want to use This Amp in first stage

Fix I_{DS}=25μA and v_{om} = 0.1V, R_D =108k

W (μm)	A_V	V_{GS} (V)
2	10.8	1.5
5	18.24	1.316
10	26.6	1.22
20	38.47	1.158
50	62	1.1
100	88.5	1.07

High Width → Cap ↑ → Bw ↓

I_{DS} (μA)	A_V	R_D (MΩ)	V_{GS} (V)
100	4.4	0.022	2
50	7.05	0.05	1.707
25	10.8	0.108	1.5
10	18.2	0.29	1.316
5	26.6	0.59	1.224
2	43.2	1.53	1.14
1	62	3.1	1.1

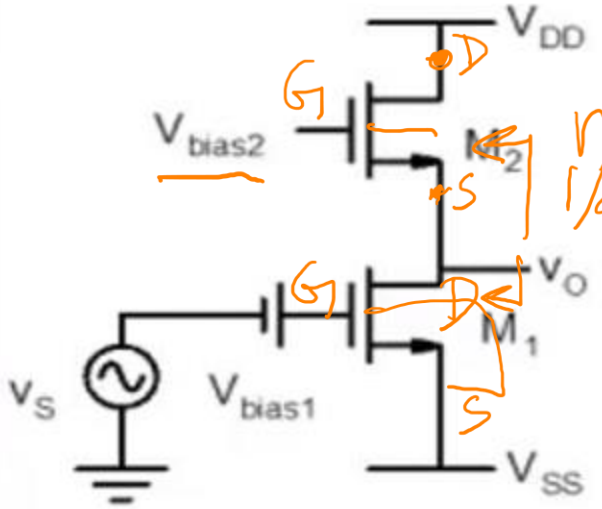
V_{TH} = 1V

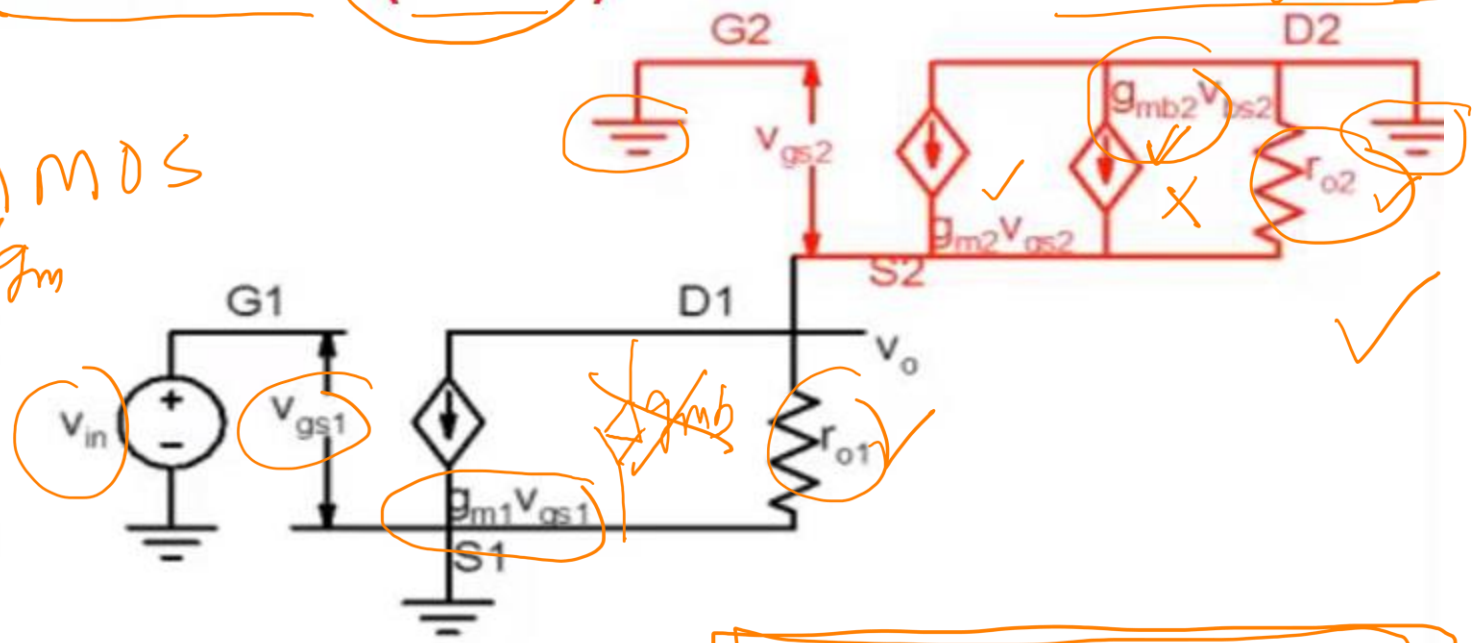
Further decrease → sub-VT

- Low current or large size is needed to obtain large gain. → High R
- Gain saturates as transistor gets closer to threshold voltage → Not good for fabrication

CS amplifier with Active Load

CS Amplifier with Active Load (NMOS)



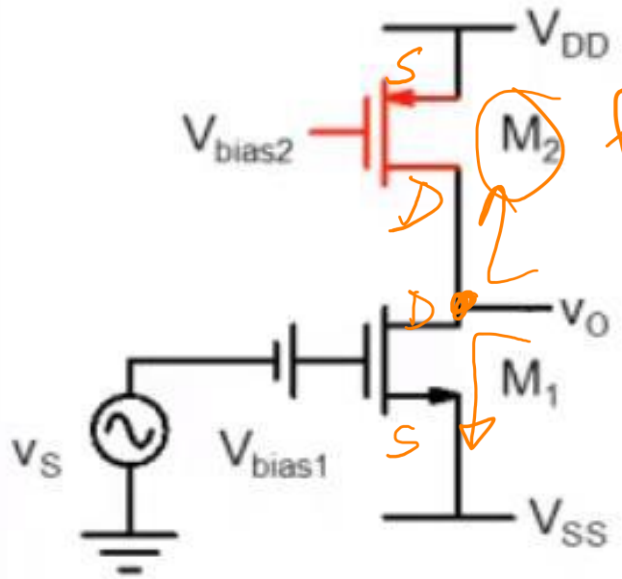


$$v_o = -g_{m1}v_{in} \times \left\{ r_{o1} \left\| r_{o2} \right\| \frac{1}{g_{m2}(1+\eta)} \right\}$$

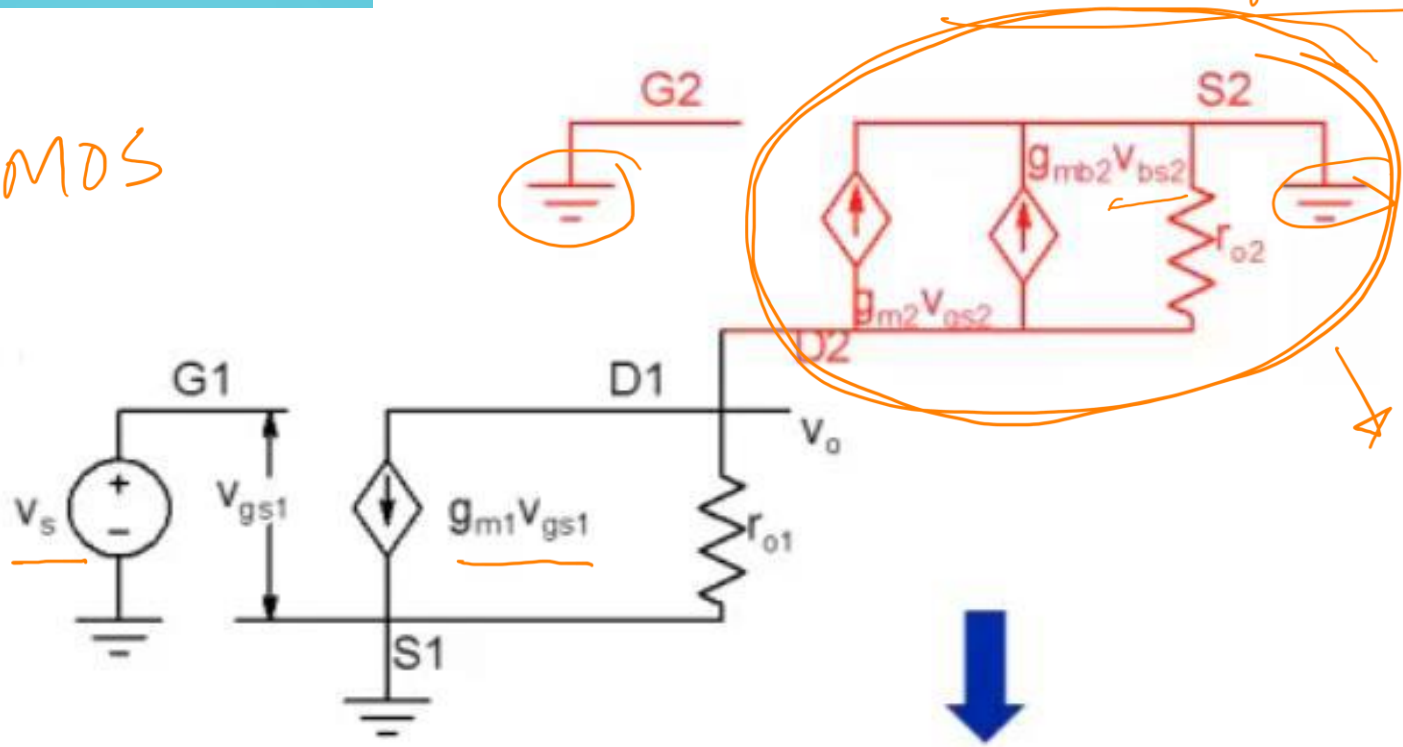
$$A_v \cong -\frac{g_{m1}}{g_{m2}(1+\eta)}$$

$$= \frac{\sqrt{2KP \times (W/L)_1 \times I_{DSQ1}}}{\sqrt{2KP \times (W/L)_2 \times I_{DSQ1}}} \times \frac{1}{1+\eta} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} \times \frac{1}{1+\eta}$$

CS Amplifier with PMOS active load

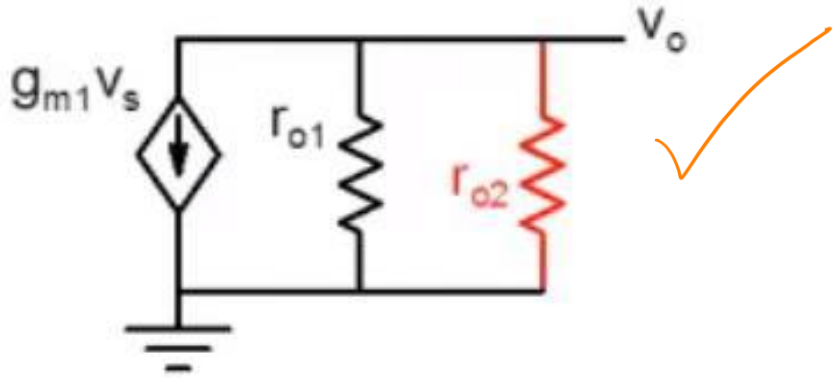


Small-signal Model



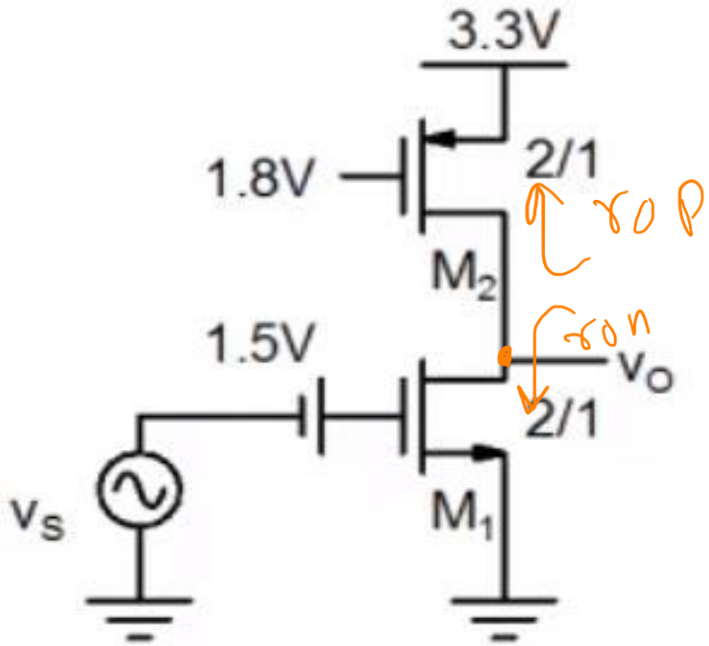
r_{O2}

r_{Op}



$$A_V = -g_{m1} \times r_{o1} \| r_{o2}$$

Example



$$I_{DSQ} = 25\mu A; V_{DSQ} = 1.65(?)$$

$$g_{mn} = g_{mp} = 100\mu A/V \; ; r_{on} = r_{op} = 4M\Omega$$

$$|A_V| = g_{mn} \times r_{on} \| r_{op}$$

$$= -200$$

$$R_O = r_{on} \| r_{op} = 2M\Omega$$

Large gain is easily obtained without requiring large resistors which are difficult to fabricate