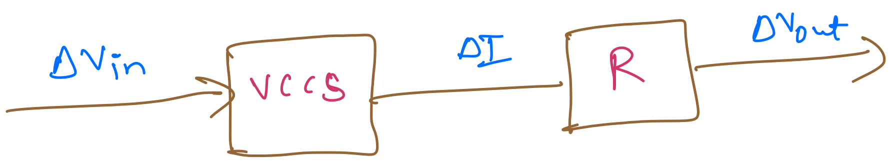
Lecture - 2

Note:-
We skip the derivation of the 'I_D' saturation current and start from the Amplification stage.

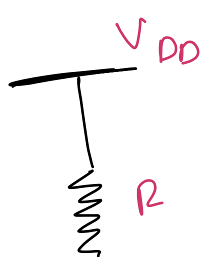
How to Amplify ?

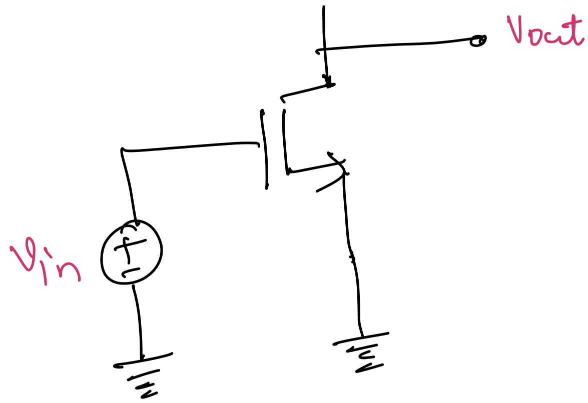


- The VCCS will generate current in response to the voltage variations
- The resistor R converts the current back to voltage domain
- If the product of conversion rations is larger than '1' then we have a voltage gain.

$$\boxed{A_V = \frac{\Delta V_{out}}{\Delta V_{in}}}$$

Common Source Amplifier with proper Biasing can act as a "VCCS"





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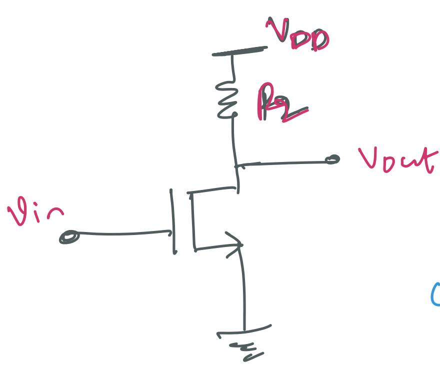
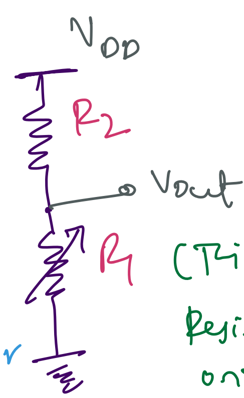
Here $\boxed{V_{out} = V_{dd} - I_D R \text{ (or) } V_{DS}}$

By varying the input voltage V_{in} we will check the variations in the output voltage.
To do that we will do graphical Analysis



≈

This circuit can be modeled as a Voltage divider and



(This varying Resistor depends on the Applied input)

→ R_1 is a function of input voltage V_i

∴ from the voltage divider circuit

$$\Rightarrow \boxed{V_{out} = \frac{R_1}{R_1+R_2} V_{DD}}$$

from the above equation we can see that

if $R_1 \uparrow \Rightarrow V_{out} \uparrow$

(It gets closer to the V_{DD})

If $R_1 = \infty \Rightarrow \boxed{V_{out} = V_{DD}}$

→ Now let's try and apply the current formula we derived for Triode Region and Saturation Region for a MOS device

let's look at primary conditions for a Transistor to be ON.

(i) $V_{GS} > V_T \Rightarrow V_{in} > V_T$

Transistor ON with well formed channel

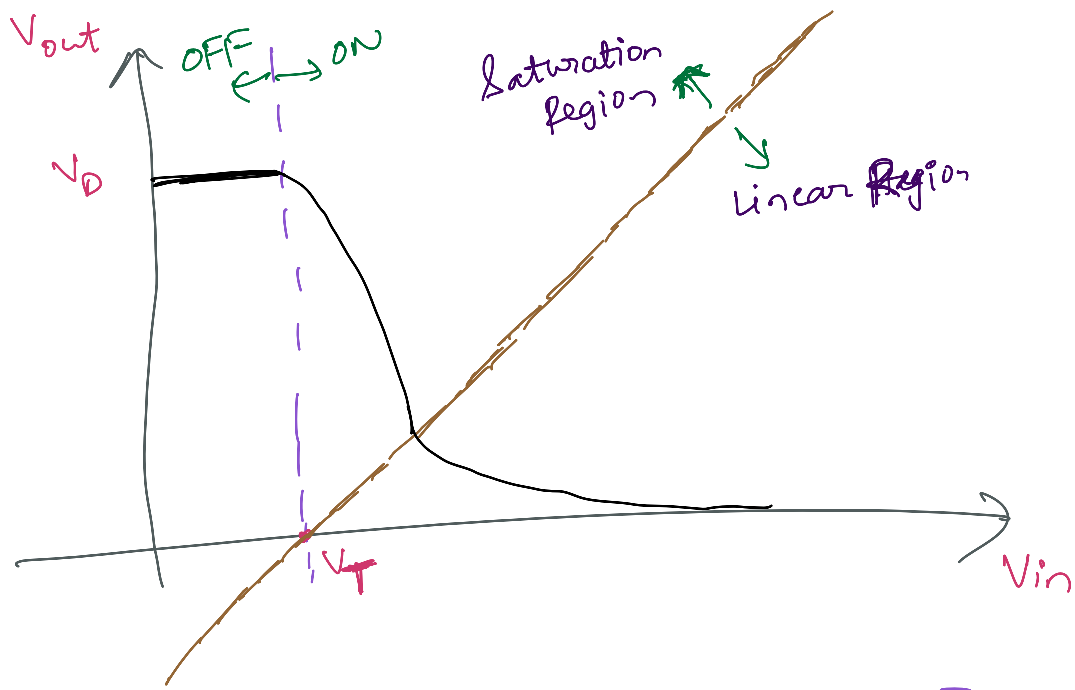
(ii) The device works in saturation when

$$\boxed{V_{DS} > V_{GS} - V_T}$$

⇒ ∴ for the current circuit above the equation translates to

$$\boxed{V_{out} \geq V_{in} - V_T}$$

This is the equation of line with slope = 1, y intercept = $-V_T$



→ when the Transistor is OFF then the $I_D = 0$ Then $V_{out} = V_{DD}$

∴ In off Region $V_{out} = V_{DD}$

→ we know from the above equation that if

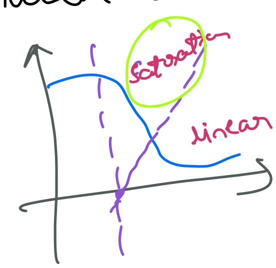
$R_L \downarrow$ Then $V_{out} \downarrow$

Q There fore what happens when we increase the value of V_{in} above Threshold ?

→ Firstly R_1 decreases because the channel size will increase and as V_{in} increases R_1 keeps decreasing.

∴ according to our observation $V_{out} \downarrow$

Q More specifically what happens when we are in Saturation Region?



→ we have discussed that saturation current

$$\boxed{I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_i - V_T)^2} \quad \text{—(1)}$$

$$\boxed{V_{out} = V_{DD} - R_2 I_D}$$

let $\mu_n C_{ox}\frac{W}{L} = \beta$ → It is called intrinsic conductivity

$$\boxed{I_D = \frac{\beta}{2}(V_i - V_T)^2} \quad \text{—(2)}$$

$$\boxed{\beta = \beta'\frac{W}{L}}$$

$$\boxed{I_D = \beta'\frac{W}{L}(V_i - V_T)^2} \quad \text{—(3)}$$

where

$$\boxed{\beta' = \mu \cdot C_{ox}}$$

→ we use either one of the above equations for I_D depending on our convenience.

In LTSPICE it is referred to as K_P

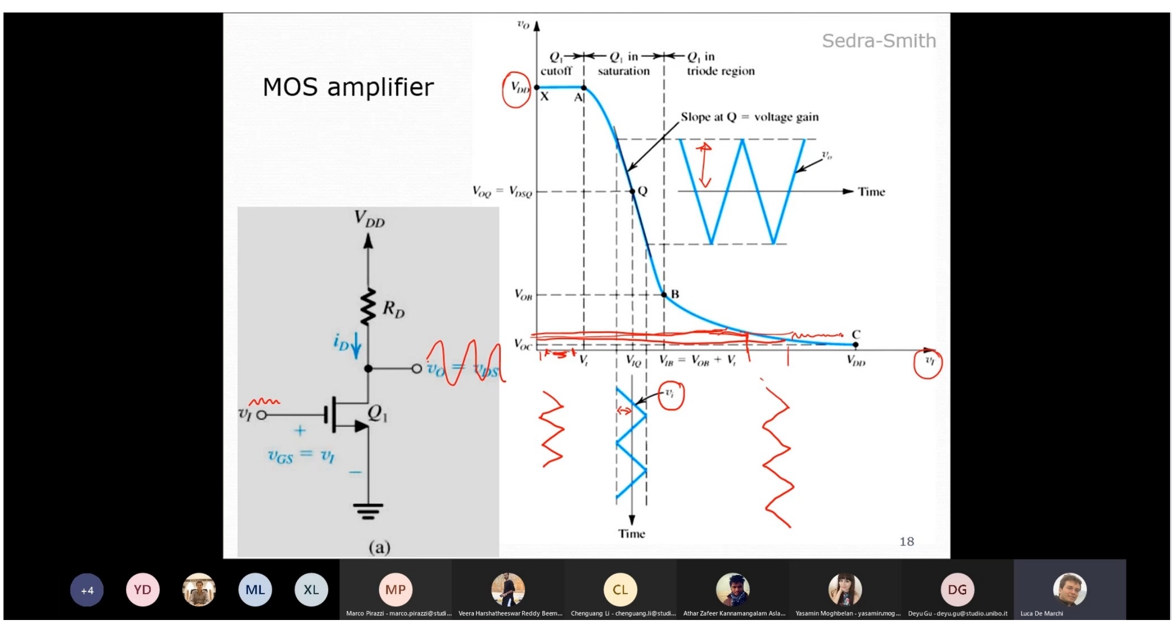
β' : Technological parameter

$\frac{W}{L}$: Geometric property which are under designers control.

→ For Linear Region

$$I_D = \beta\left[(V_{GS}-V_T) - \frac{V_{DS}}{2}\right]V_{DS}$$

$$\Rightarrow \beta\left[(V_{in}-V_T) - \frac{V_{out}}{2}\right]V_{out}$$



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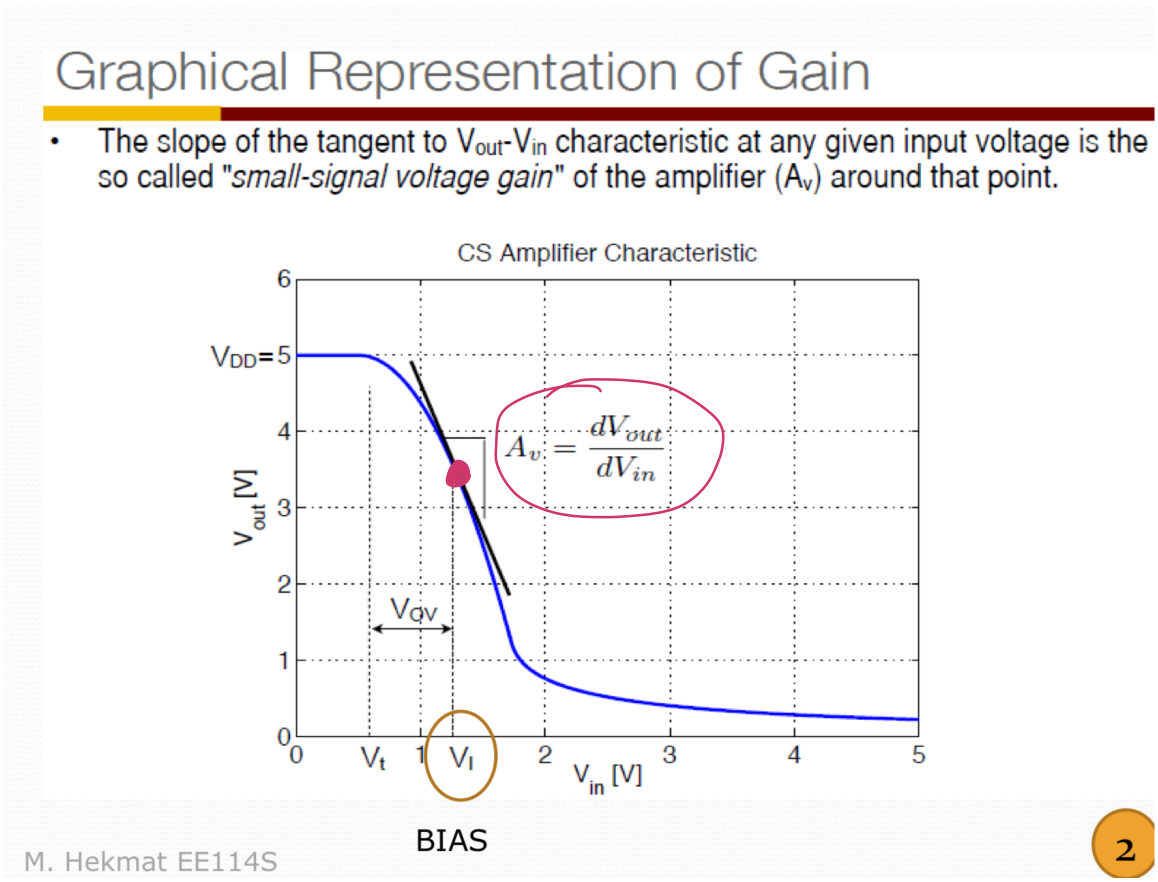
Note
From the above study and figure it is clear that MOS Transistor can be used as an Amplifier but only in Saturation Region.



→ even in the Saturation Region the Gain is not same. This Non-linearity is a problem.

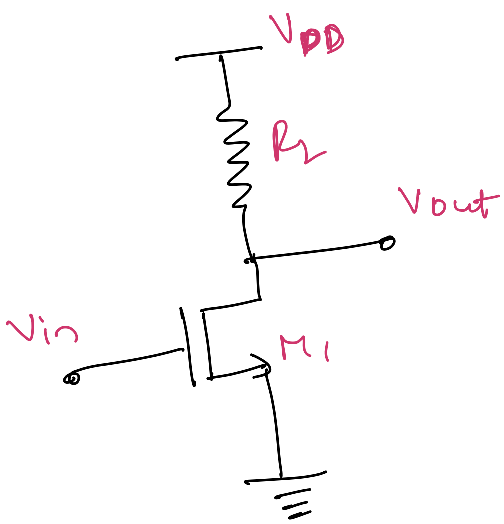
→ when we have $V_{in} = V_I$ we can approximate the Non-linear behaviour into a linear one as indicated by the line.

→ What we want ~~to~~ do is develop a linear model for an MOS device which is intrinsically non-linear.

Q How can we do this?

We can exploit the Taylor Expansion concept.

* If we look at the circuit.



$$\boxed{I_{R_2} = I_{D1}}$$

(current through Resistor R_2 = Saturation current of the MOSFET M_1

$$I_{R_2} = I_{D1}$$

∴

$$\Rightarrow \boxed{\frac{V_{DD}-V_{out}}{R_2} = \underbrace{\frac{\beta}{2}\left(V_{in}-V_T\right)^2}}$$

This is clearly a Non linear Relationship because we have this Quadratic Expression.

$\rightarrow$ $\therefore$ we have that

$$\boxed{V_{out} = f(V_{in})}$$

Using Taylor's series Expansion.
If we have a Arbitary function.

$$y = f(x)$$

Then we can define a operating point (or) Quescent point

$$Y_0 = f(x_0)$$

Then if we move the input from the Quescent (or) Operating point to an other position we can express this movement as

$$x = x_0 + \Delta x$$

This variation in the i/p also causes

variation in the o/p. This shall be given by

$$Y = Y_0 + \Delta Y$$

$\therefore$ with certain degrees of Approximation we can express.

$$\boxed{Y = Y_0 + \Delta y = f(x_0) + f'(x_0)\,\Delta x}$$

$\Downarrow$

Taylor series expansion in linear term only

$$\therefore \boxed{\Delta y \approx f'(x_0)\,\Delta x}$$

This approximation becomes equality if the variation are infinitely small.

$\rightarrow$ Applying this concept to our Amplifier cay where $V_{out} = f(V_{in})$

$$\Rightarrow \quad \frac{V_{DD} - V_{out}}{R_2} = \frac{\beta}{2}\left(V_i - V_T\right)^2$$

$\Rightarrow$ $$\boxed{V_{out} = V_{DD} - \frac{\beta}{2}(V_{in} - V_T)^2 \cdot R_2}$$

Here $y = V_{out}$, $x = V_{in}$

$\Rightarrow$ let's calculate the derivative of $y = f(x)$

$\Rightarrow$ $$\frac{dV_{out}}{dV_{in}} = 0 - \frac{\beta}{\cancel{2}} \cancel{2}(V_{in} - V_T) R_2$$

$\Rightarrow$ $$\boxed{\frac{dV_{out}}{dV_{in}} = -\beta \cdot R_2 \cdot (V_{in} - V_T)}$$

Gain $\Rightarrow$ $$\boxed{A_V = \frac{dV_{out}}{dV_{in}} = -\mu_n C_{ox} \frac{W}{L} R_2 V_{ov}}$$

$V_{ov} = V_{in} - V_T$ = Overdrive Voltage

→ This Linearization concept is Really purvasive in Analog design Analysis. Which we will ~~talk~~ talk about in Small signal Analysis

→ If we consider small variations close to the operating point. Then we can turn non linear relationship into a linear one with decent Approximations.

Fixing an Operating point ⟹ Proper Biasing of the circuit

→ Linearity hugely benefits the analysis of the circuit because we can Apply an important tool "Superposition Principle"

i.e $\boxed{f(a+b) = f(a) + f(b)}$

$\boxed{f(2a) = 2f(a)}$

} Benefits of Superposition

Another way to solve the Gain formula

A small additional signal in the active region...

$$V_{out} = V_{\mathrm{DD}} - \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{in} - V_t)^2 \times R$$

$$\begin{aligned} V_{out} + \Delta v_o &= V_{\mathrm{DD}} - \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{\mathrm{OV}} + \Delta v_i)^2 \times R \\ \longrightarrow \Delta v_o &= -\frac{1}{2}\mu C_{ox}\frac{W}{L}\left[2V_{\mathrm{OV}}\Delta v_i + \Delta v_i^2\right] \times R \\ &= -\frac{2I_D}{V_{\mathrm{OV}}}\Delta v_i\left[1 + \frac{\Delta v_i}{2V_{\mathrm{OV}}}\right] \times R \end{aligned}$$

$$\boxed{\Delta v_i \ll V_{OV} \longrightarrow \Delta v_o \approx -\frac{2I_D}{V_{OV}}R\Delta v_i}$$

Take away message:

If we assume Δv_o is infinitely small we have:

$$\frac{dV_o}{dV_i} = -\frac{2I_D}{V_{OV}}R = -\mu C_{ox}\frac{W}{L}V_{OV}R = A_v$$

We can have gain (A_v>1) if we choose the parameters properly.

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