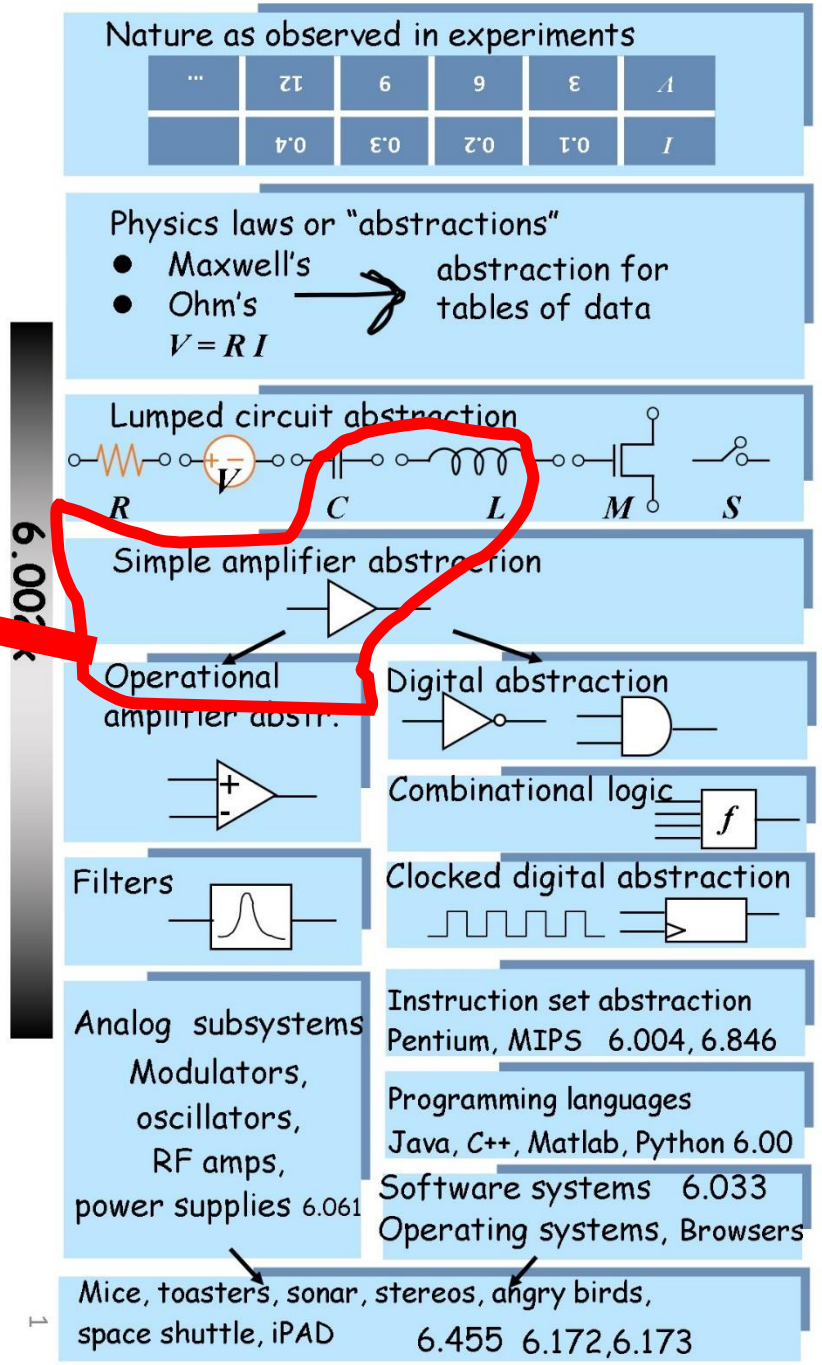
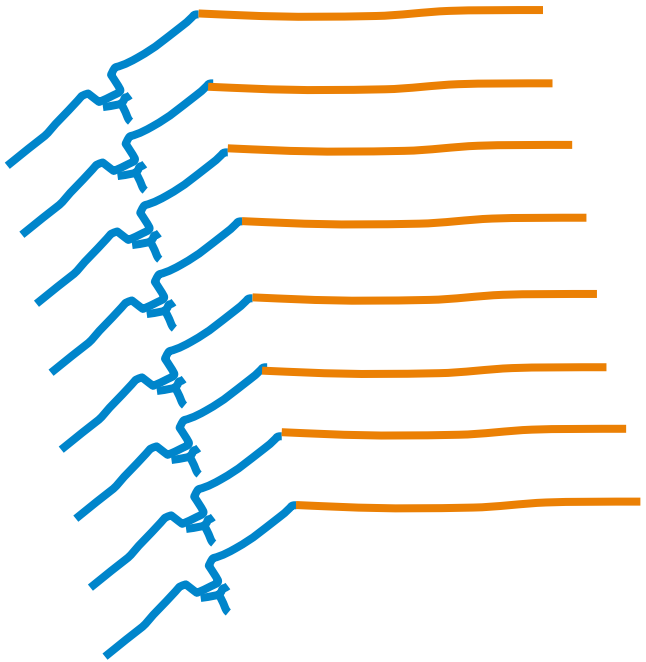
6.002.2x
Circuits and Electronics 2



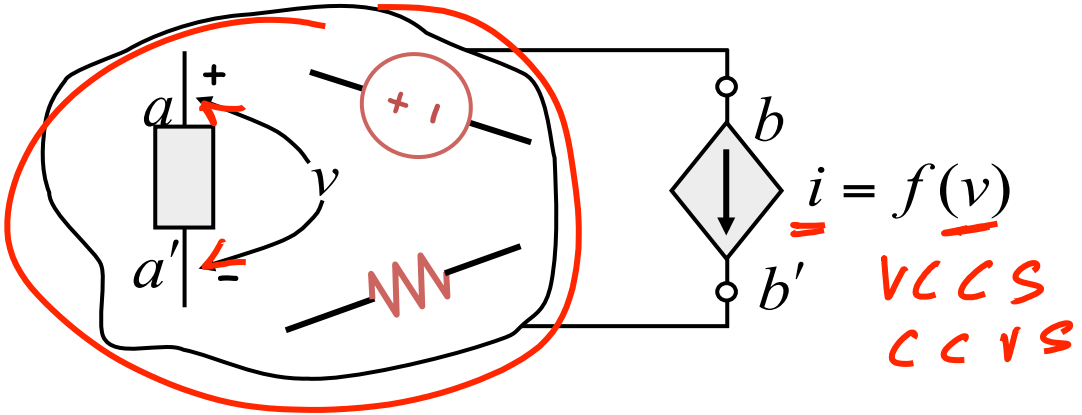
6.002x CIRCUITS AND ELECTRONICS

MOSFET SCS Model
MOSFET Amplifier



Review

- Dependent source in a circuit

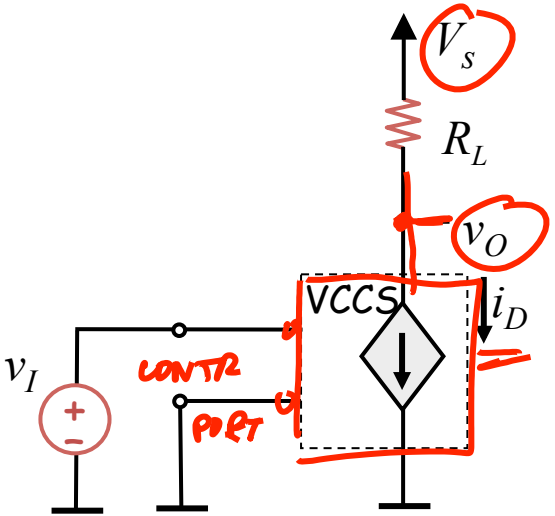


VCCS
CCVS

- Superposition with dependent sources. One approach:
  - leave all dependent sources in;
  - solve for one independent source at a time
  - [section 3.5.1 of the text]

Review

Next, quick review of amp. **Reading:** Chapter 7.3-7.7



$$i_D = \frac{K}{2}(v_I - 1)^2 \quad \text{for } v_I \geq 1V$$

$$= 0 \text{ otherwise}$$

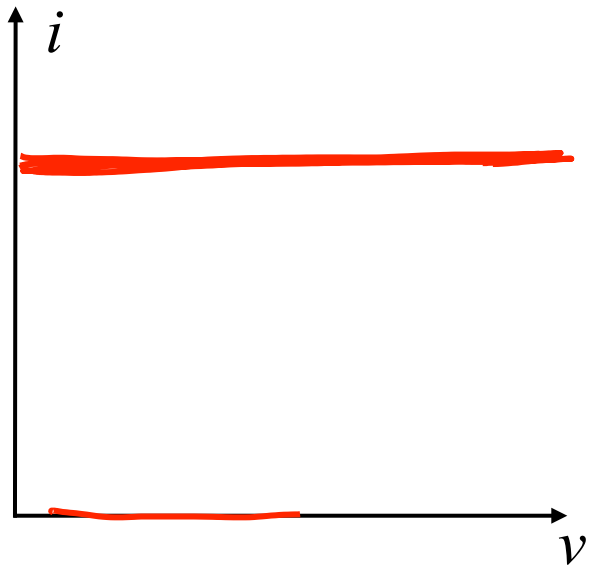
$$\frac{v_O - V_S}{R_L} + i_D = 0$$

Patterns

$$v_O = V_S - i_D R_L$$

$$\frac{K}{2}(v_I - 1)^2$$

The i-v relation for a current source

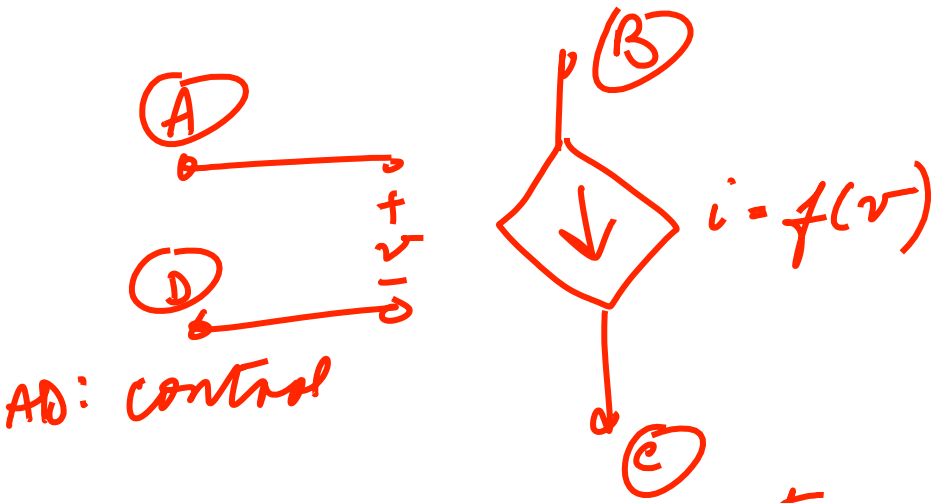


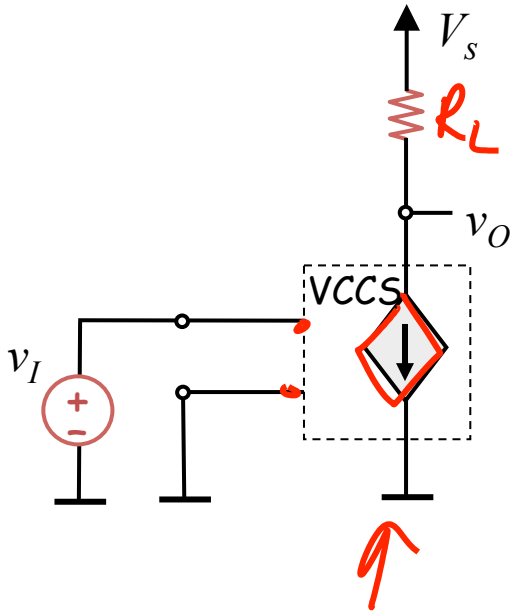


current source

Hold the thought

Key device Needed

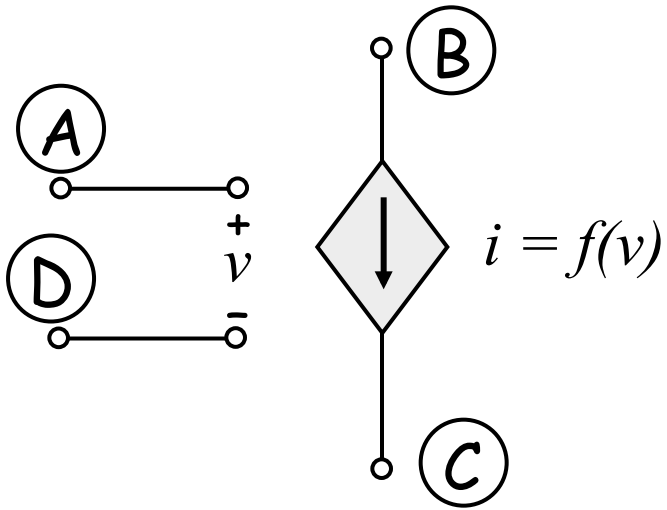


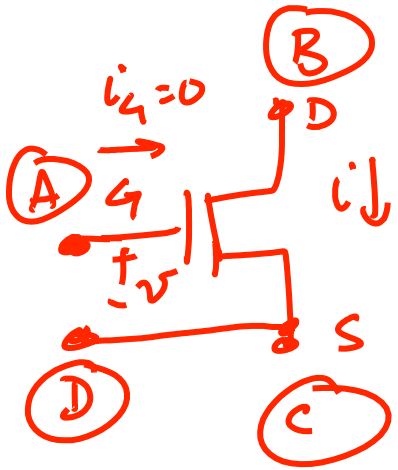


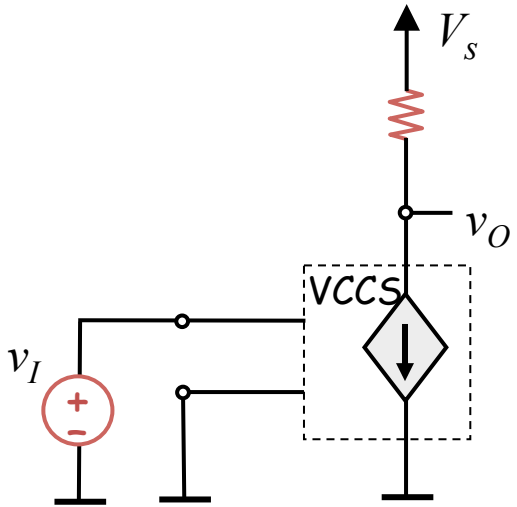
voltage controlled current source

Key device Needed

VCCS





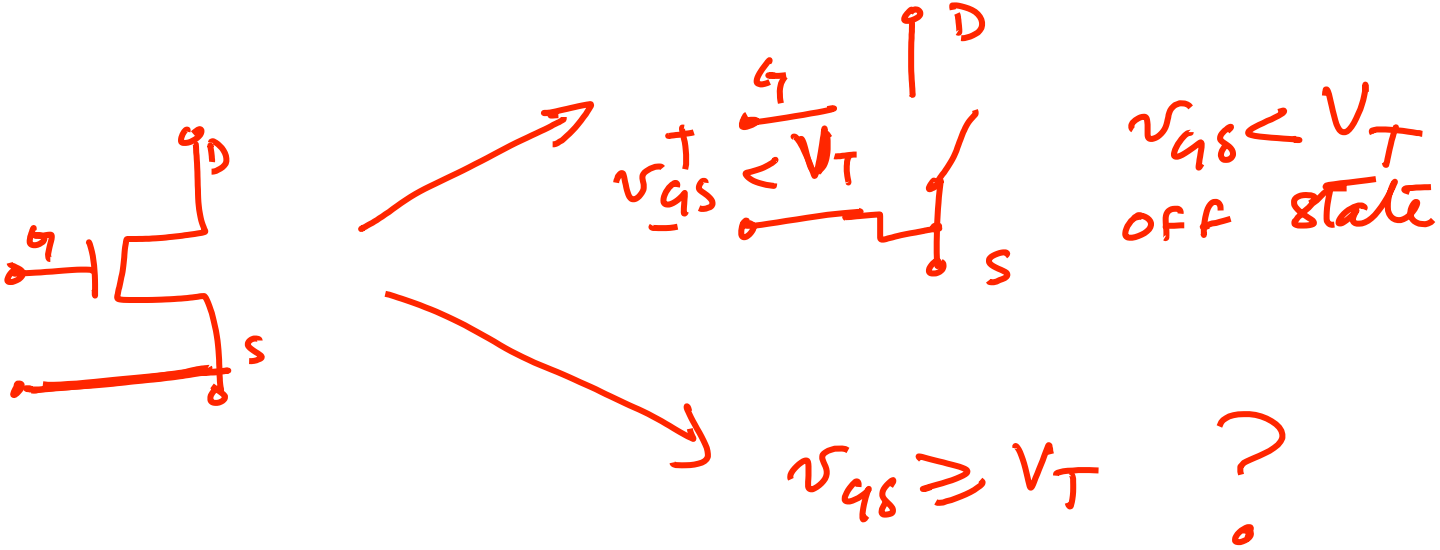


under certain condition

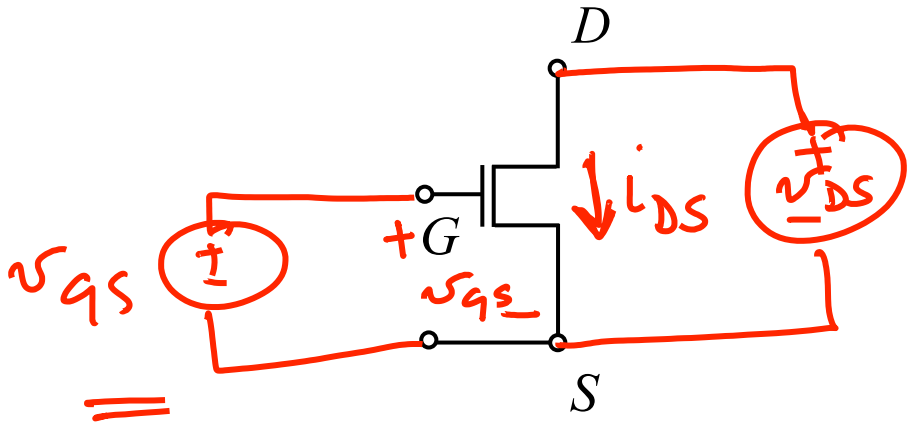
Let's look at our old friend, the MOSFET …

Our old friend, the MOSFET

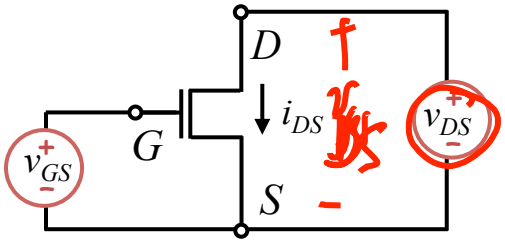
First, we sort of lied. The on-state behavior of the MOSFET is quite a bit more complex than either the ideal switch or the resistor model would have you believe.

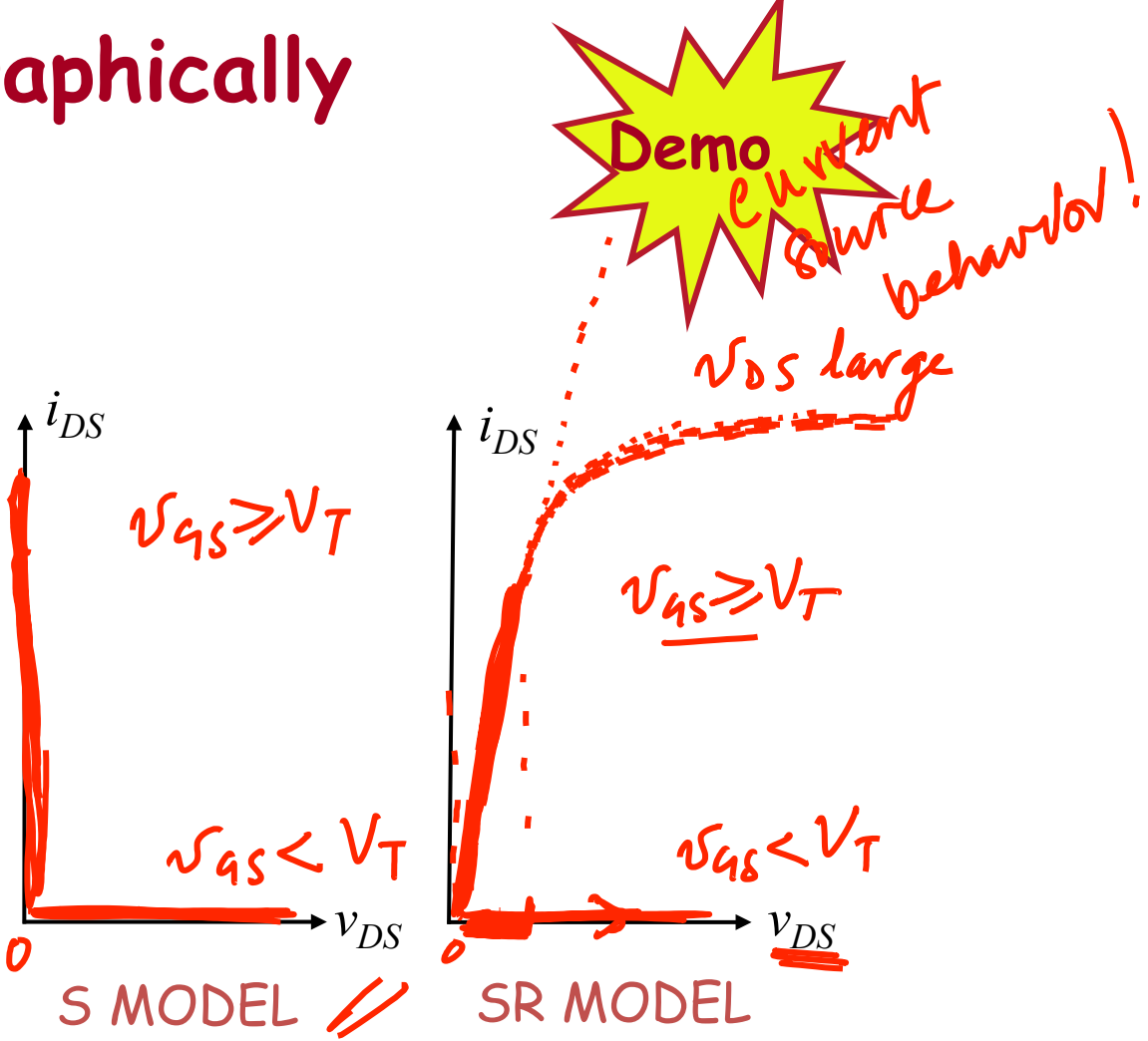


Let's Look at the MOSFET Behavior Graphically



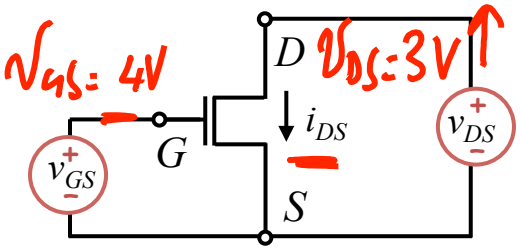
Graphically





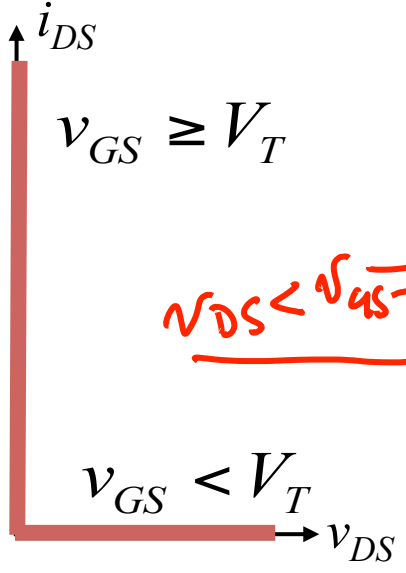
Graphically

Demo



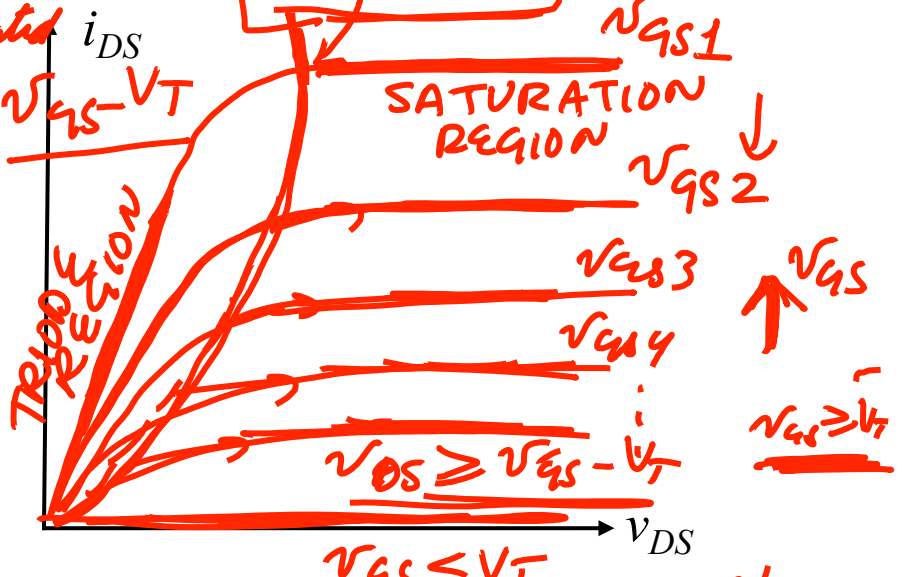
$v_T = 1V$

$v_{DS} = v_{GS} - V_T$



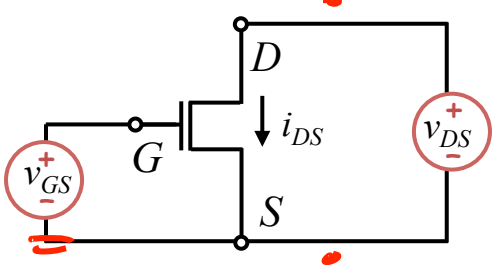
S MODEL

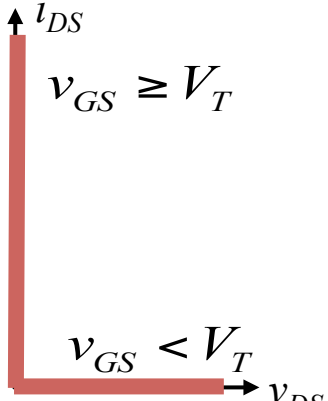
SR MODEL



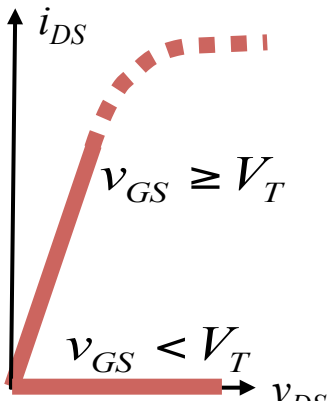
SCS SWITCH CURRENT SOURCE MODEL

Graphically

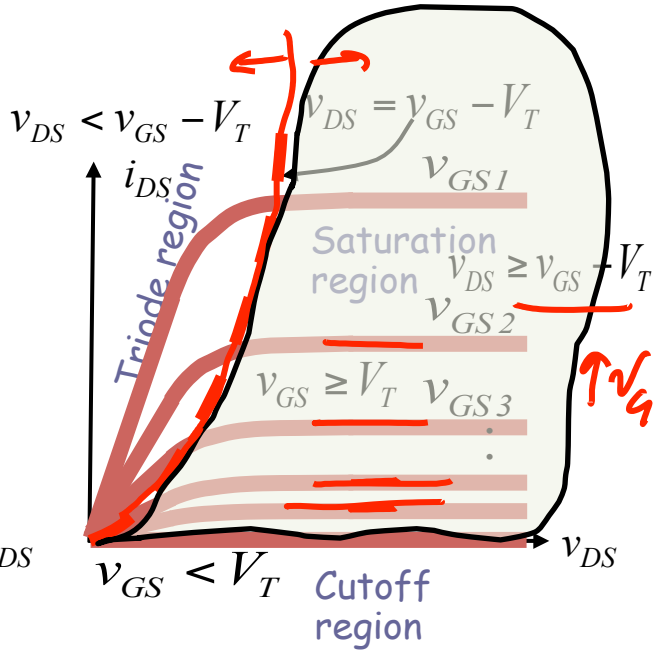




S MODEL



SR MODEL

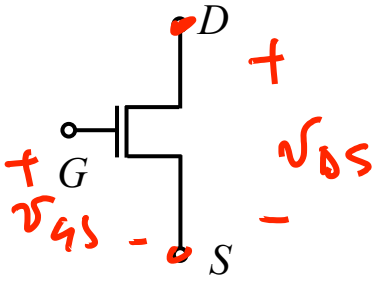


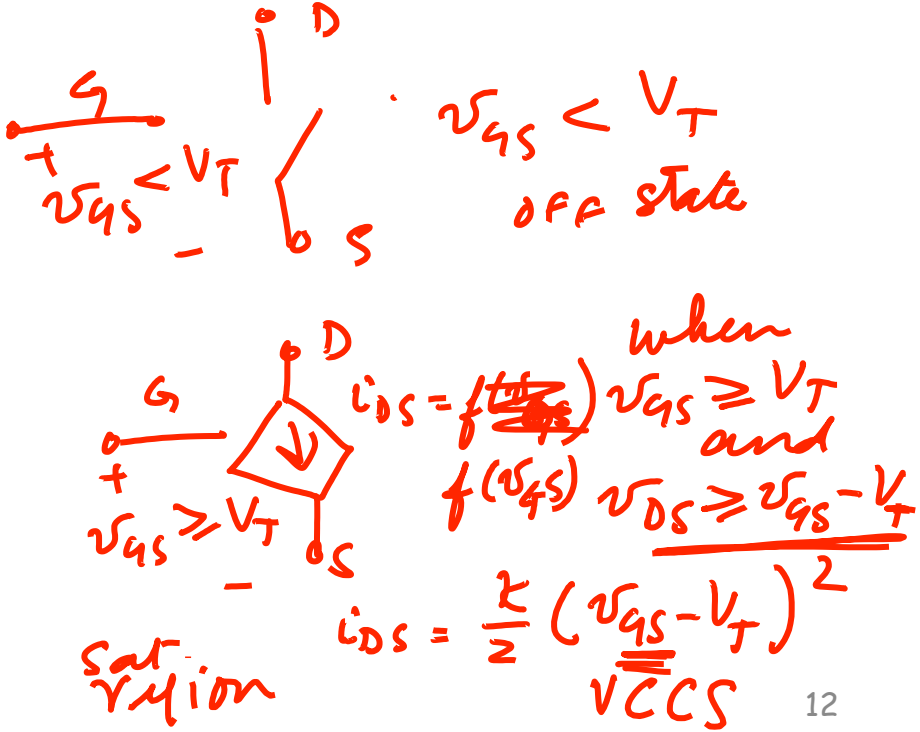
when $v_{DS} \geq v_{GS} - V_T$

Notice that MOSFET behaves like a current source

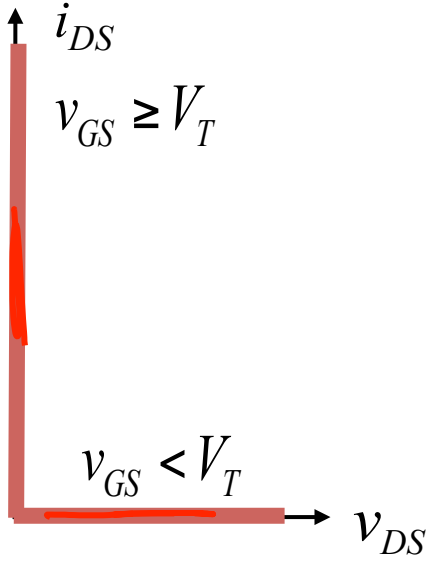
MOSFET SCS Model

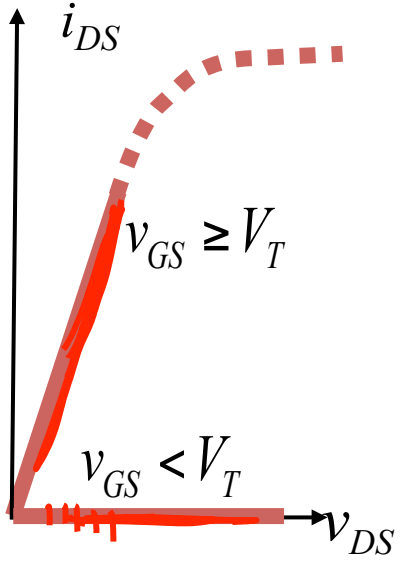
When $v_{DS} \geq v_{GS} - V_T$ and $v_{GS} \geq V_T$
the MOSFET is in its saturation region, and the switch current source (SCS) model of the MOSFET is more accurate than the S or SR model

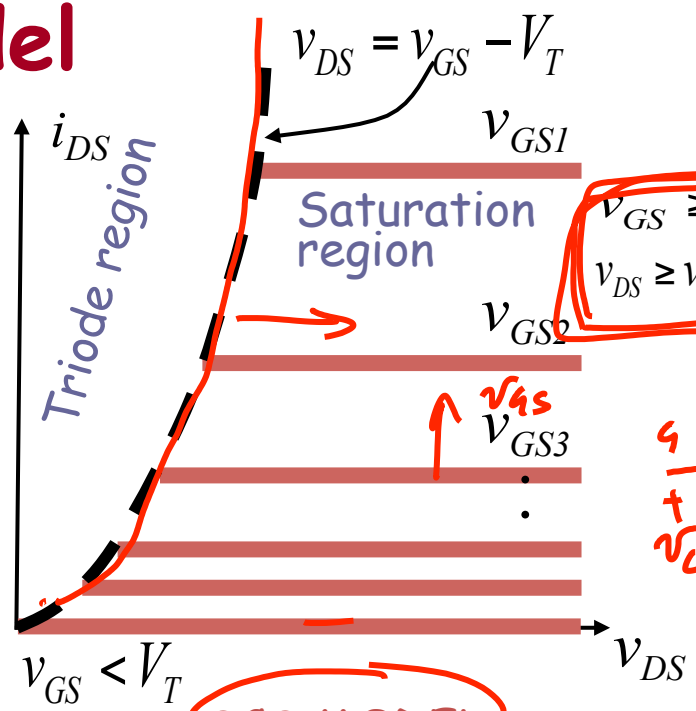




When to use which model







S MODEL

for fun!

SR MODEL

for digital designs

SCS MODEL

for analog designs

When to use each model in 6.002x ?

In More Advanced Courses...

SR - dig. — R
SCS - analog → CS

Note: alternatively (in more advanced courses)

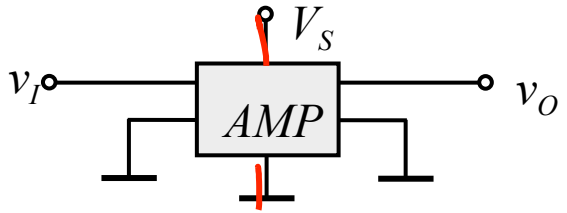
CS $v_{DS} \geq v_{GS} - V_T$ use SCS model

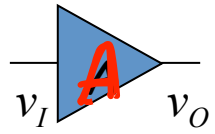
R $v_{DS} < v_{GS} - V_T$ use SR model

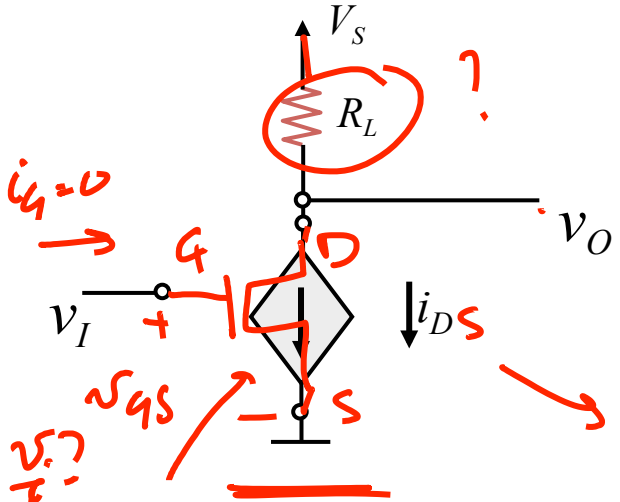
not in 6.002x

or, use SU (Switch Unified) Model (Section 7.8 of A&L)

Back to Amplifier







$$i_D = \frac{K}{2}(v_I - 1)^2$$

$i_{DS} = \frac{k}{2}(v_I - V_T)^2$ in saturation region only

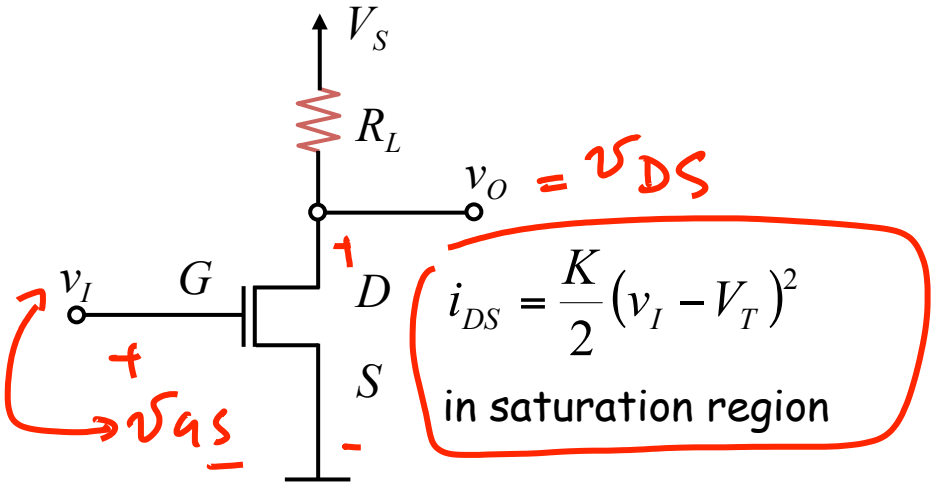
To ensure the MOSFET operates as a VCCS, we must operate it in its saturation region only. To do so, we promise to adhere to the

"saturation discipline"

rules

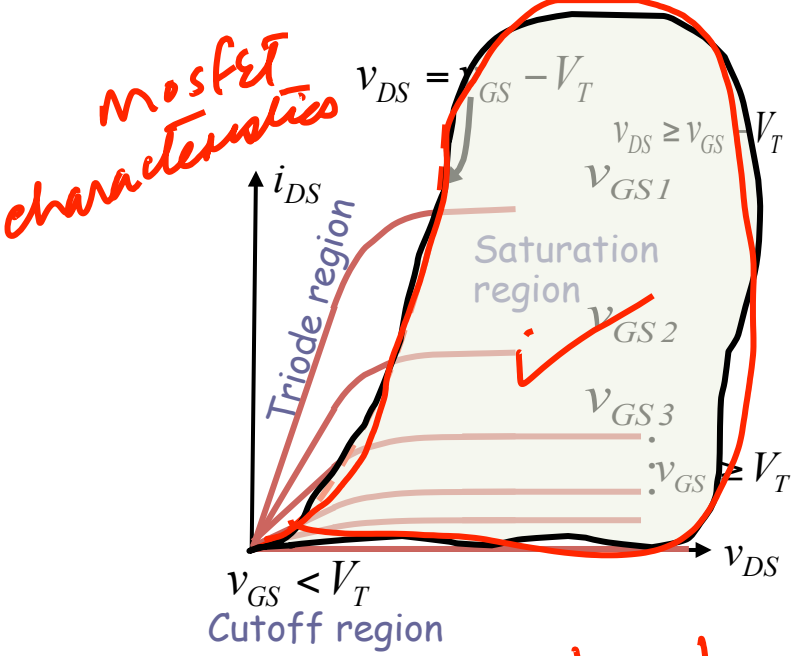
MOSFET → devices

MOSFET Amplifier



$$i_{DS} = \frac{K}{2}(v_I - V_T)^2$$

in saturation region

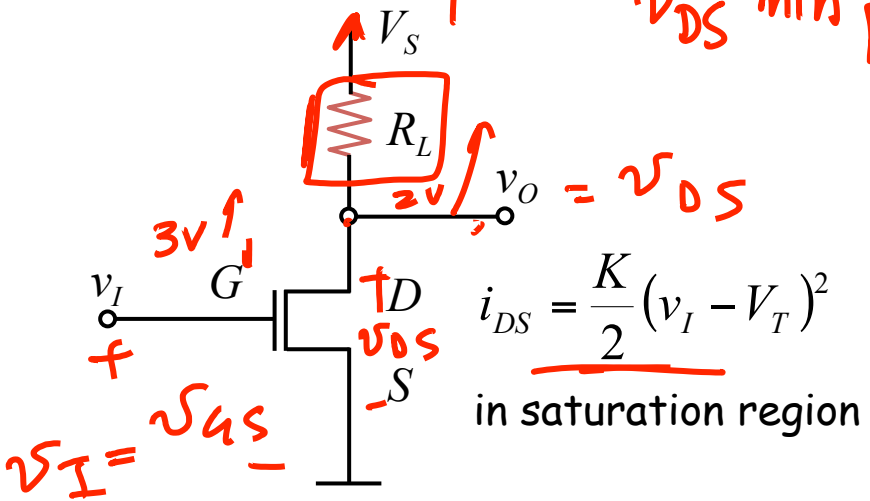


"Saturation discipline"

In other words, we will operate the amp circuit such that:

1. 2.

MOSFET Amplifier



v_{DS} min for sat. 2V

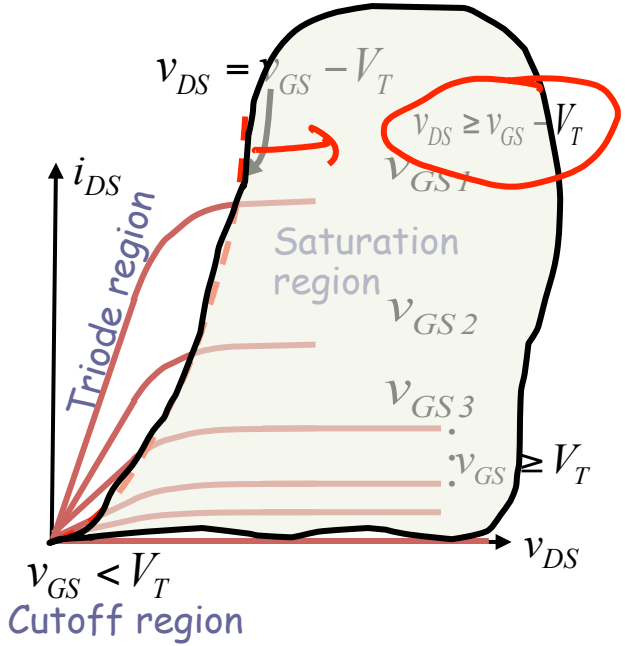
$v_O = v_{DS}$

3V

$v_I = v_{GS}$

$V_T = 1V$ eg.

"Saturation discipline"



In other words, we will operate the amp circuit such that

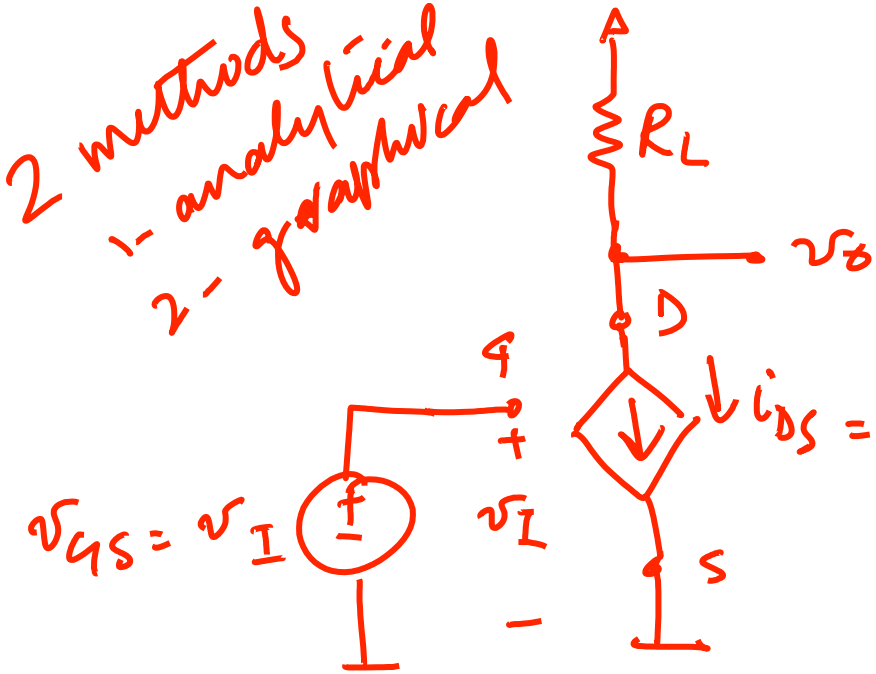
$v_{GS} \geq V_T$ AND $v_{DS} \geq v_{GS} - V_T$ at all times

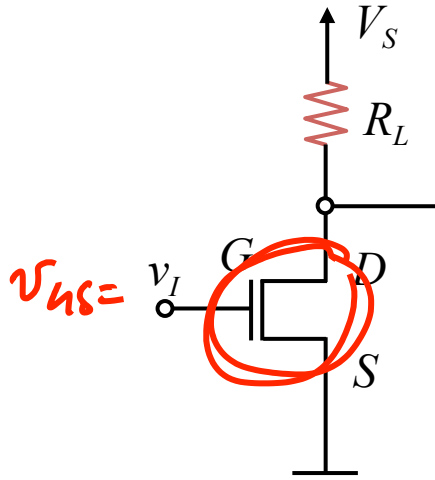
same as $v_I \geq V_T$ same as $v_O \geq v_I - V_T$

① ②

Let's analyze the circuit

First, replace the MOSFET with its SCS model





$$i_{DS} = \frac{K}{2}(v_I - V_T)^2$$

in saturation region

$v_{GS} \geq V_T$

$v_{DS} \geq v_{GS} - V_T$

Two methods:

1. Analytical
2. Graphical

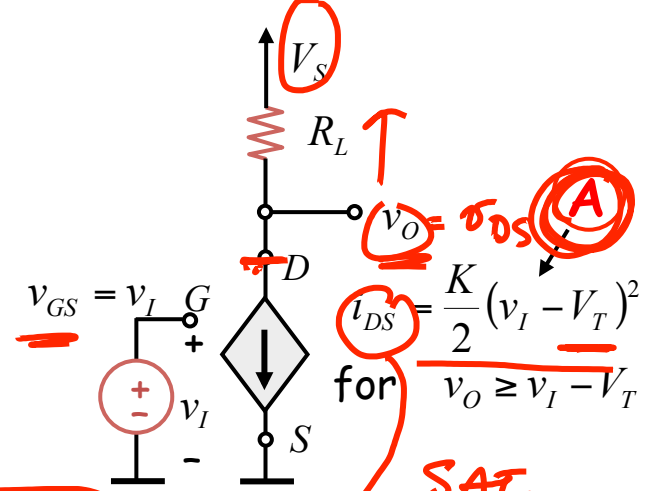
$v_I \geq V_T$

$\left.\begin{array}{l} v_O \geq v_I - V_T \end{array}\right\}$

Let's analyze the circuit

Find v_O vs v_I ($v_O = v_{DS}$ in our example)

1. Analytical method: v_O vs v_I



Use node method @ v_O

$$\frac{v_O - V_S}{R_L} + i_{DS} = 0$$

$$v_O = V_S - i_{DS} R_L \quad \text{(B)}$$

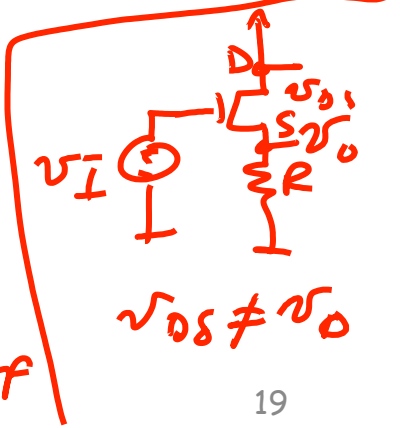
or $v_O = V_S - \frac{K}{2}(v_I - V_T)^2 \cdot R_L$

for $v_I \geq V_T$

$v_O \geq v_I - V_T$

for $v_I < V_T$ MOSFET is OFF

$v_O = V_S$



② Graphical method

From (A) : $i_{DS} = \frac{K}{2}(v_I - V_T)^2$

sat begins for $v_O = v_I - V_T$

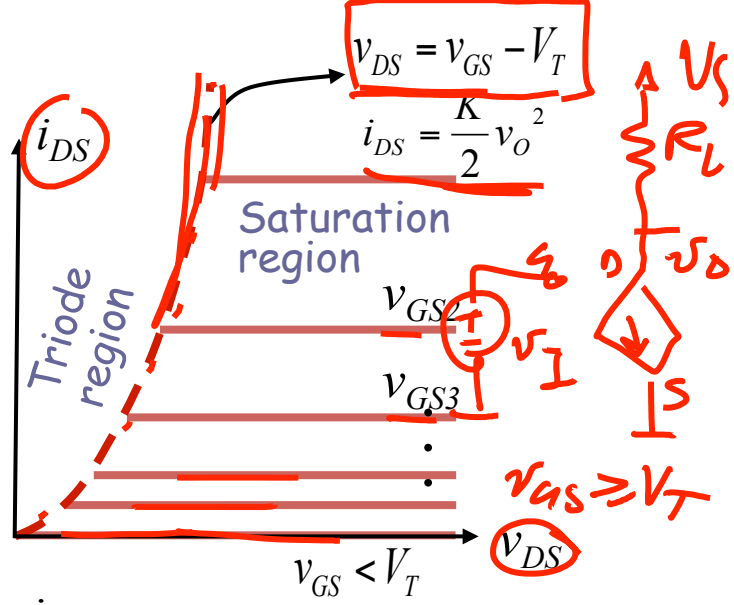
sat ≥

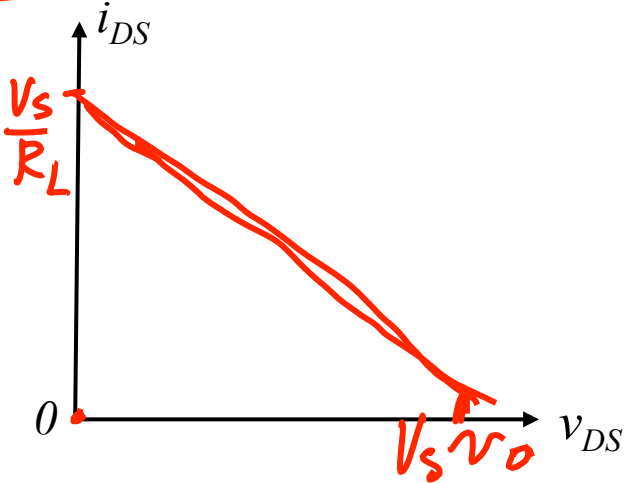
or, for $i_{DS} \le \frac{K}{2} v_O^2$

sat reg. op.

From (B) : $v_O = V_S - i_{DS} R_L$

$i_{DS} = \frac{V_S}{R_L} - \frac{v_O}{R_L}$





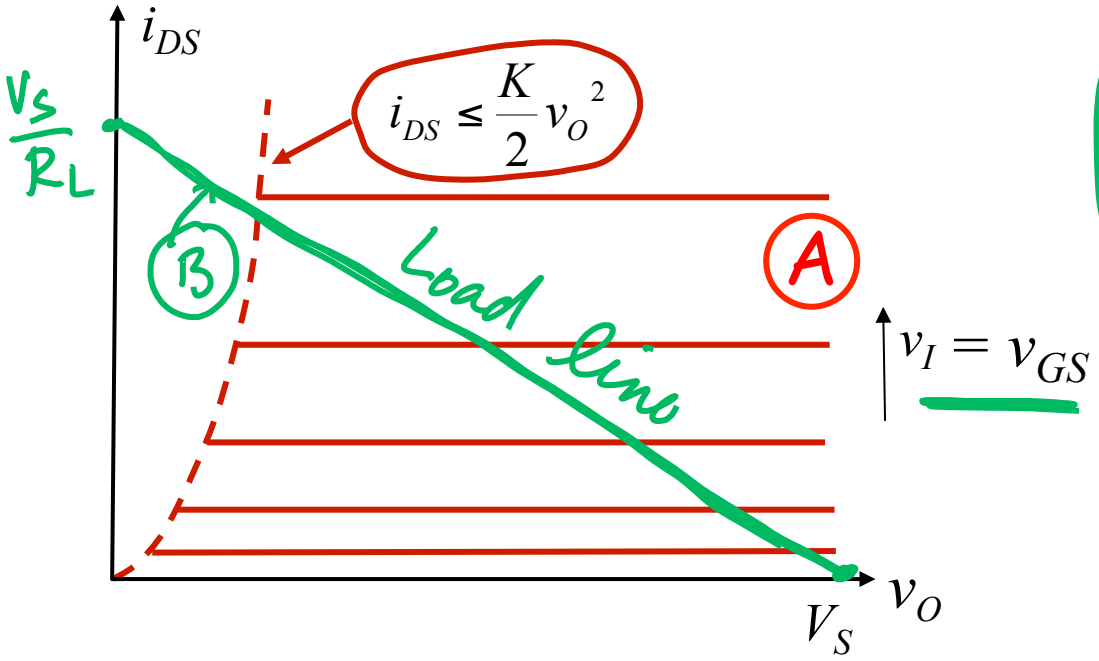
② Graphical method

v_O vs v_I

Remember, superimpose "loadline due to rest of circuit (B)" over device relation (A)

(A) : $i_{DS} = \frac{K}{2}(v_I - V_T)^2$, for $i_{DS} \le \frac{K}{2} v_O^{\,2}$

(B) : $i_{DS} = \frac{V_S}{R_L} - \frac{v_O}{R_L}$



Constraints (A) and (B) must be met

② Graphical method

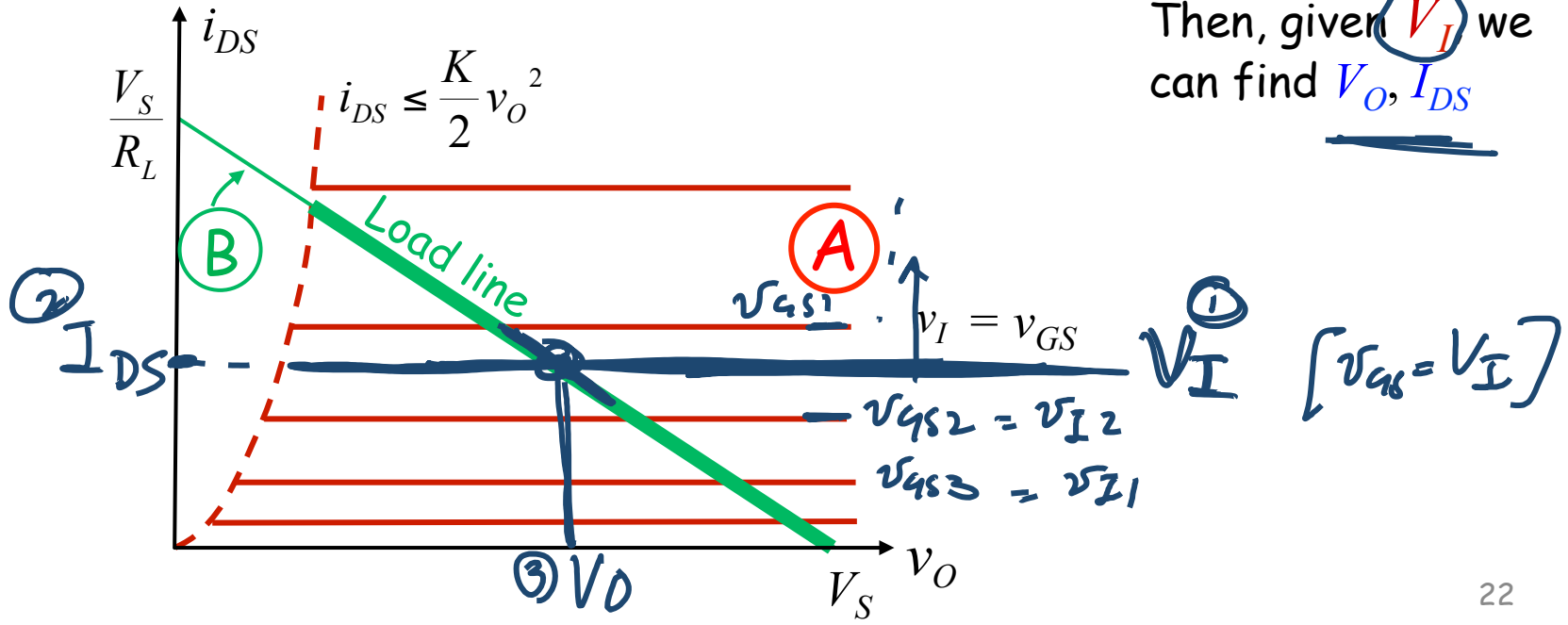
v_O vs v_I

Ⓐ : $i_{DS} = \frac{K}{2}(v_I - V_T)^2$, for $i_{DS} \le \frac{K}{2} v_O^{\,2}$

Ⓑ : $i_{DS} = \frac{V_S}{R_L} - \frac{v_O}{R_L}$

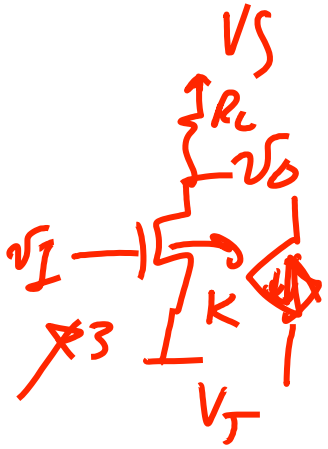
Constraints Ⓐ and Ⓑ must be met

Then, given V_I we can find V_O, I_{DS}



Large Signal Analysis

of Amplifier (under "saturation discipline")

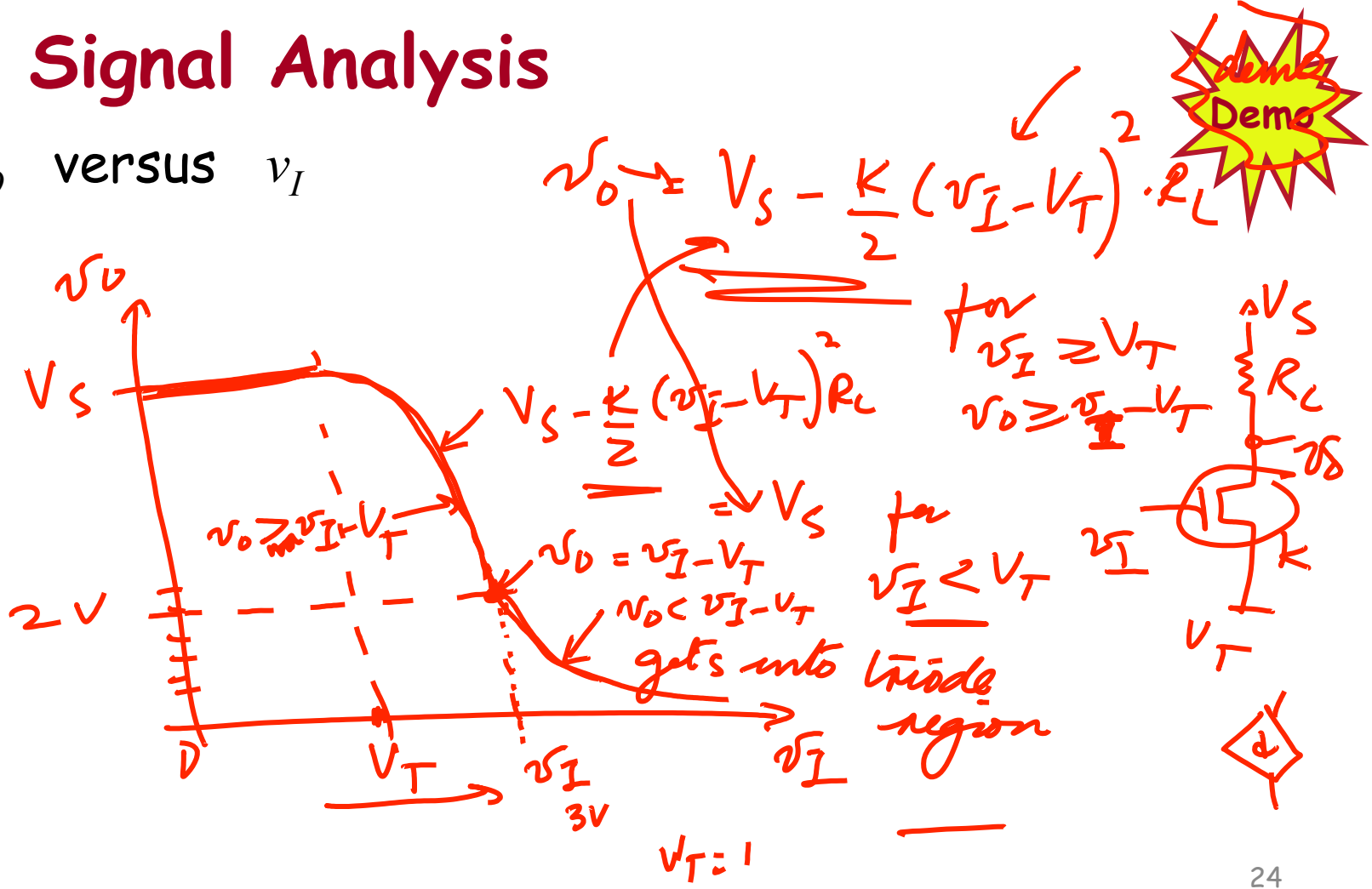


① v_O versus v_I

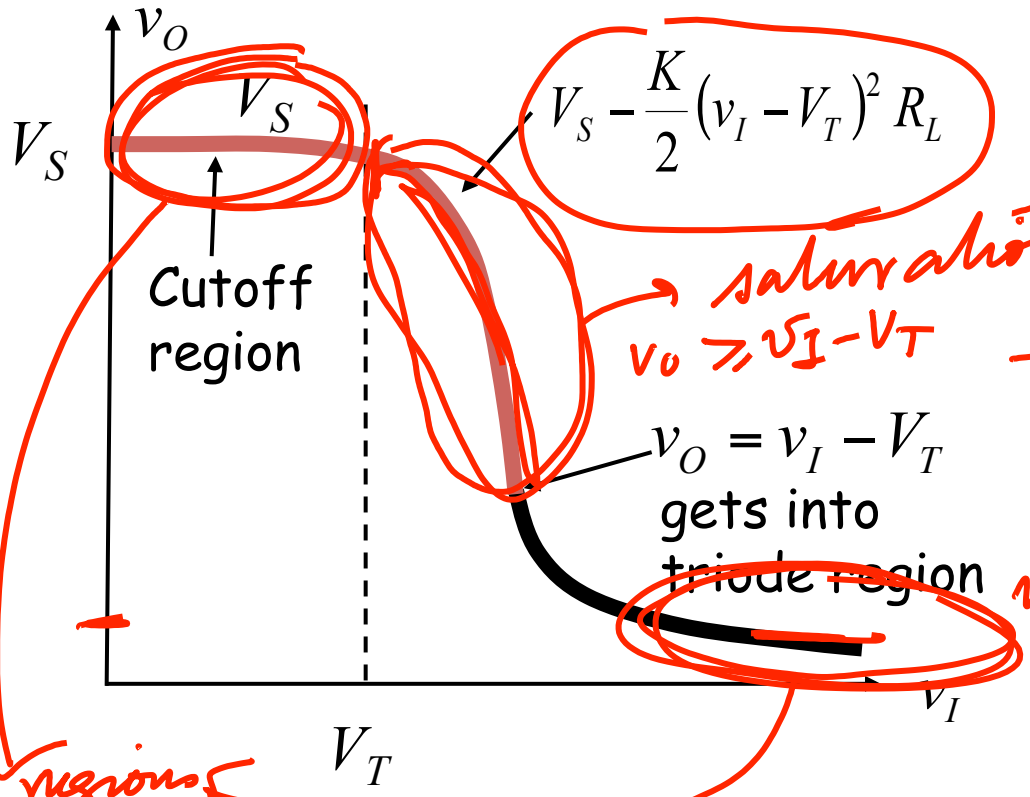
② Valid input operating range and valid output operating range (to guarantee saturation region operation)

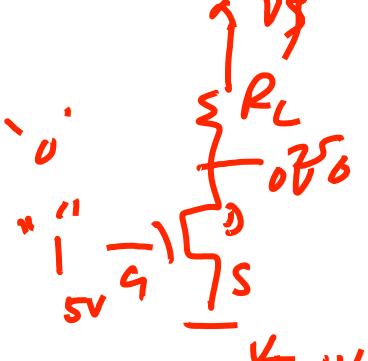
Large Signal Analysis

① v_O versus v_I



A Curious Aside





saturation region - $v_O \geq v_I - V_T$ - valid region for analog systems

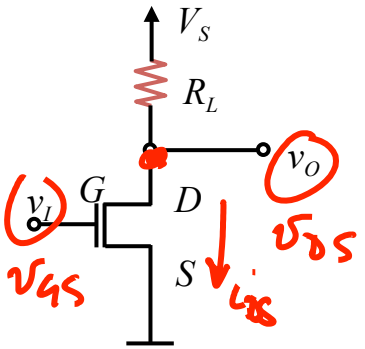
$v_O < v_I - V_T$

Valid regions for digital systems

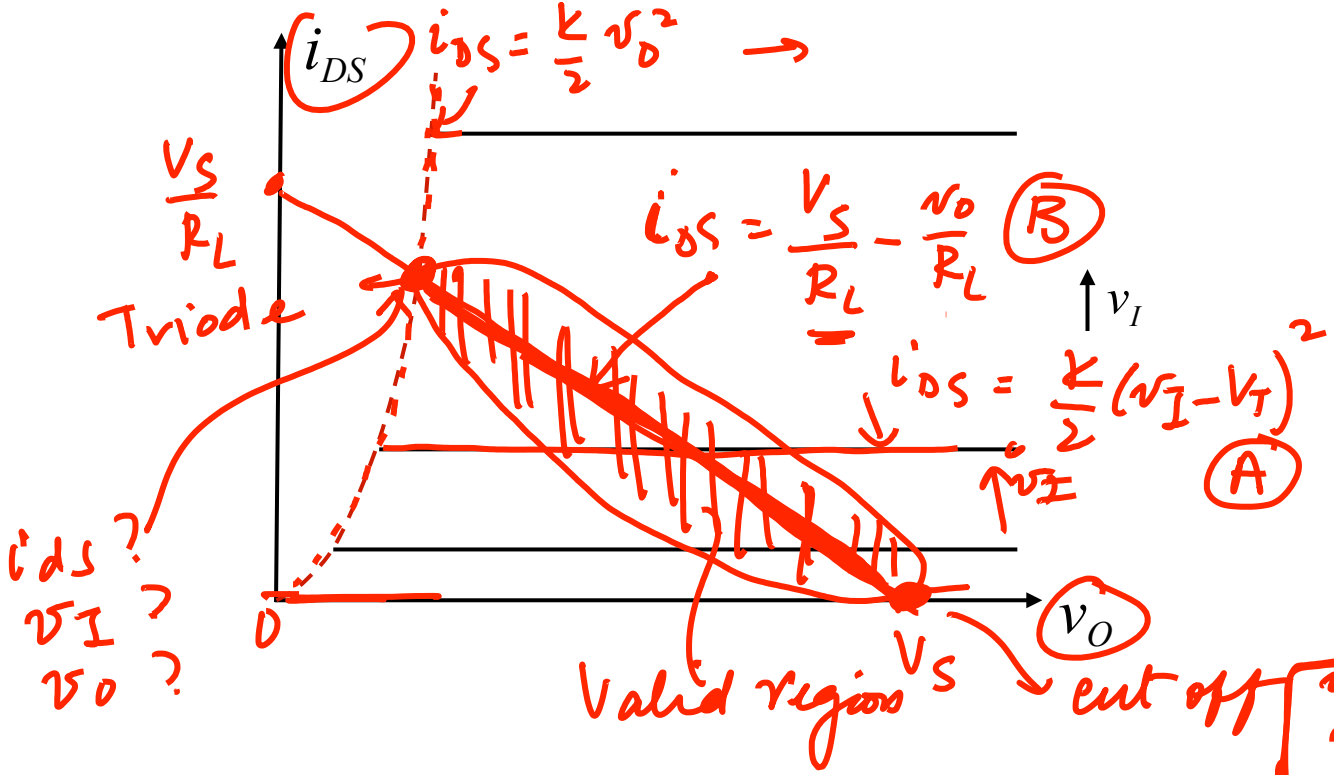
Large Signal Analysis

① v_o vs v_I

② What are the valid operating ranges under the saturation discipline?



Our Constraints



for sat. op.

$v_I \geq V_T$

$v_O \geq v_I - V_T$

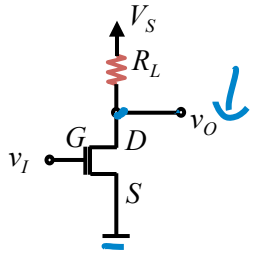
$\hookrightarrow i_{DS} \leq \frac{k}{2} v_O^2$

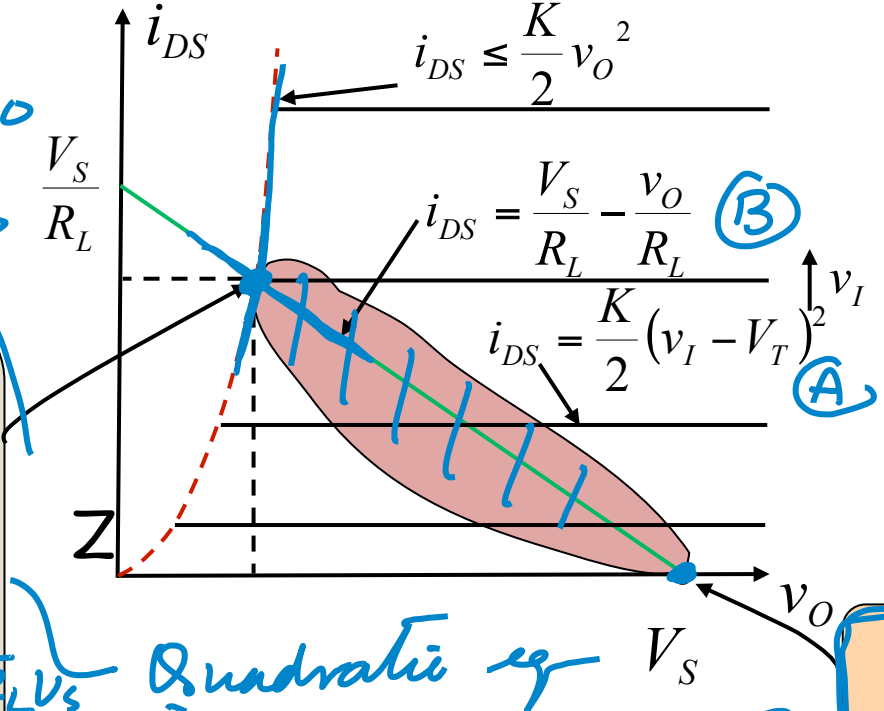
$v_I = V_T$ $i_{DS} = 0$

$v_O = V_S$

Large Signal Analysis

② What are the valid operating ranges under the saturation discipline?





$\frac{K}{2} v_O^2 + \frac{v_O}{R_L} - \frac{V_S}{R_L} = 0$

$\frac{KR_L}{2} v_O^2 + v_O - V_S = 0$

a b c

$i_{DS} = \frac{V_S}{R_L} - \frac{v_O}{R_L}$

$i_{DS} = \frac{K}{2} v_O^2$

$\frac{K}{2} v_O^2 = \frac{V_S}{R_L} - \frac{v_O}{R_L}$

Solve...

$v_O = \frac{-1 + \sqrt{1 + 2KR_L V_S}}{KR_L}$

Quadratic eq

v_I, i_{DS} ?

Our Constraints

$v_I \ge V_T$

$v_O \ge v_I - V_T$

$i_{DS} \le \frac{K}{2} v_O^2$

$v_I = V_T$

$v_O = V_S$ and $i_{DS} = 0$

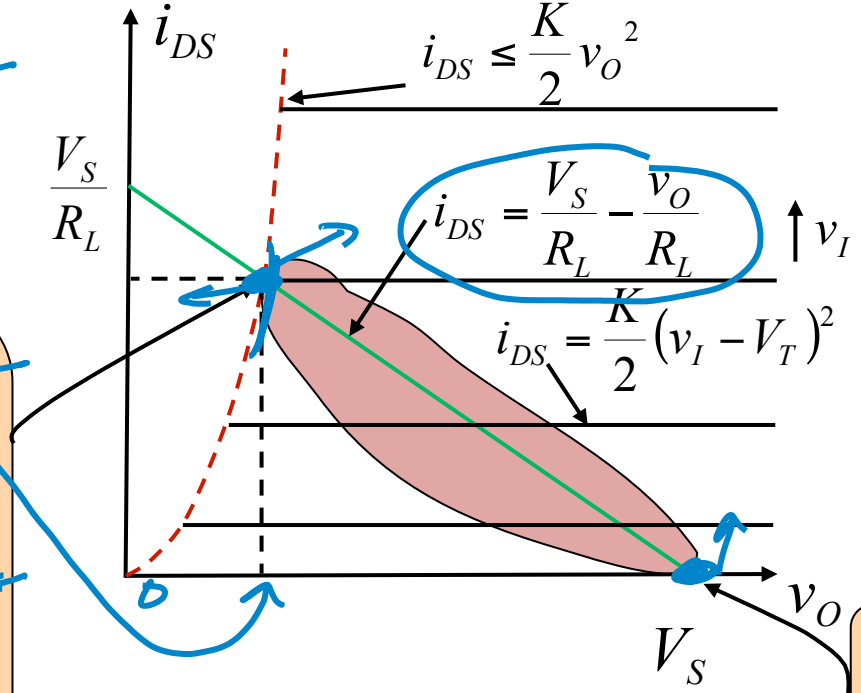
Large Signal Analysis

② What are the valid operating ranges under the saturation discipline?

$v_O \geq v_I - V_T$ ←

$v_O = v_I - V_T$

$v_I = v_O + V_T$



$$v_O = \frac{-1 + \sqrt{1 + 2KR_L V_S}}{KR_L}$$

$v_I = V_T + v_O$

$i_{DS} = \frac{V_S}{R_L} + \frac{v_O}{R_L}$ ←

Our Constraints

$v_I \geq V_T$

$v_O \geq v_I - V_T$

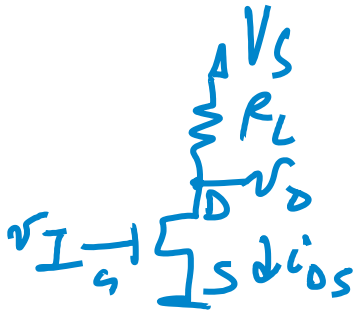
$i_{DS} \leq \frac{K}{2} v_O^2$

$v_I = V_T$
$v_O = V_S$ and $i_{DS} = 0$

Large Signal Analysis Summary

1. v_O versus v_I

$$v_O = V_S - \frac{K}{2}(v_I - V_T)^2 \cdot R_L$$

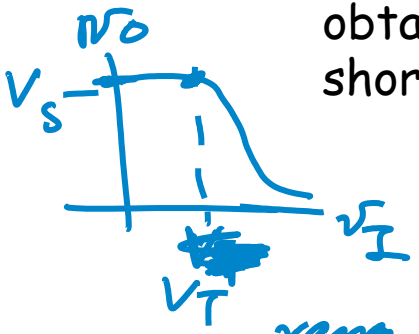


We will look at another way of obtaining (2) shortly

2. Valid operating ranges under the saturation discipline?

→ Valid input range:

$$v_I : V_T \longrightarrow V_{T+}$$



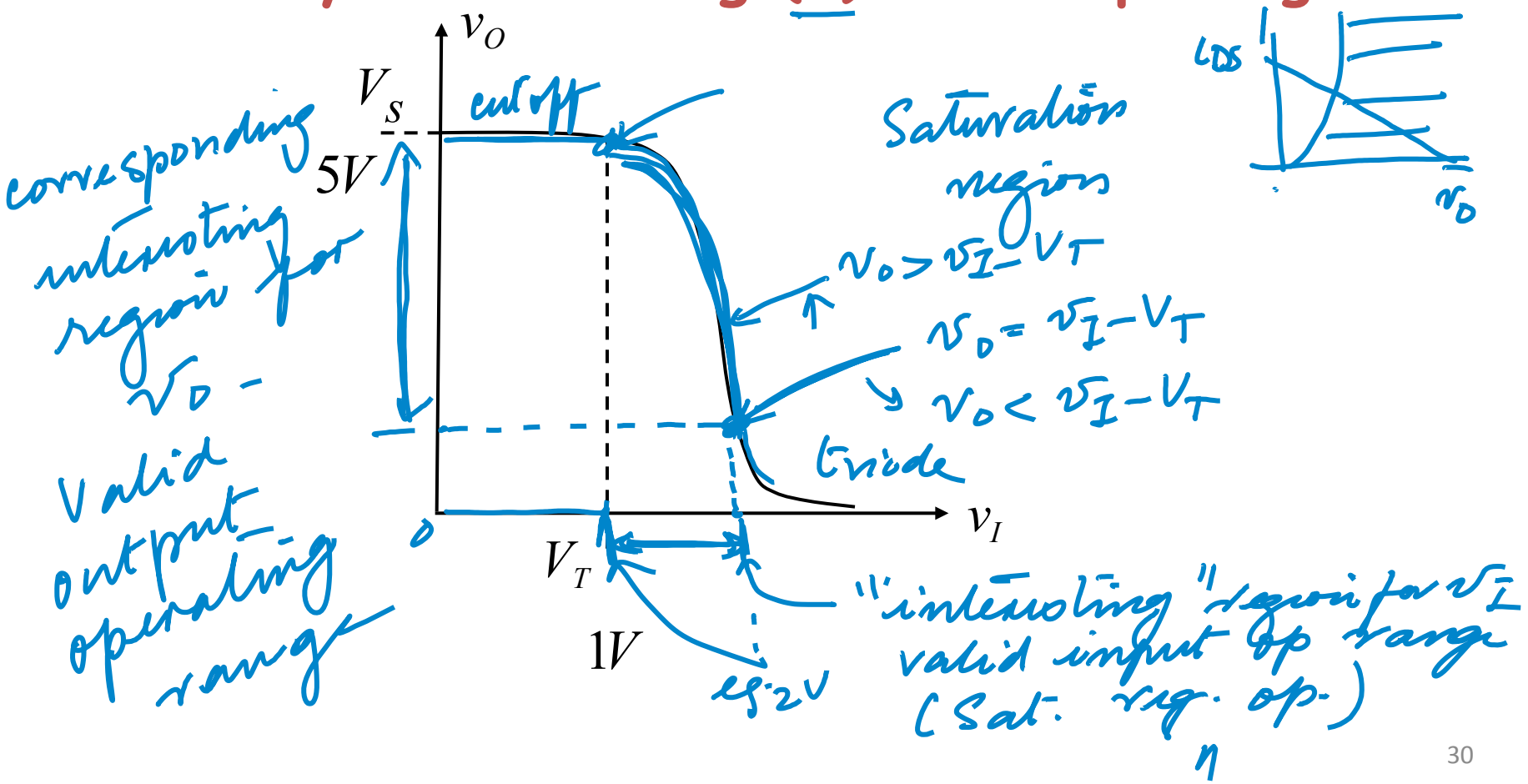
→ Corresponding output range:

$$v_O : V_S \longrightarrow \frac{-1 + \sqrt{1 + 2KR_L V_S}}{KR_L}$$

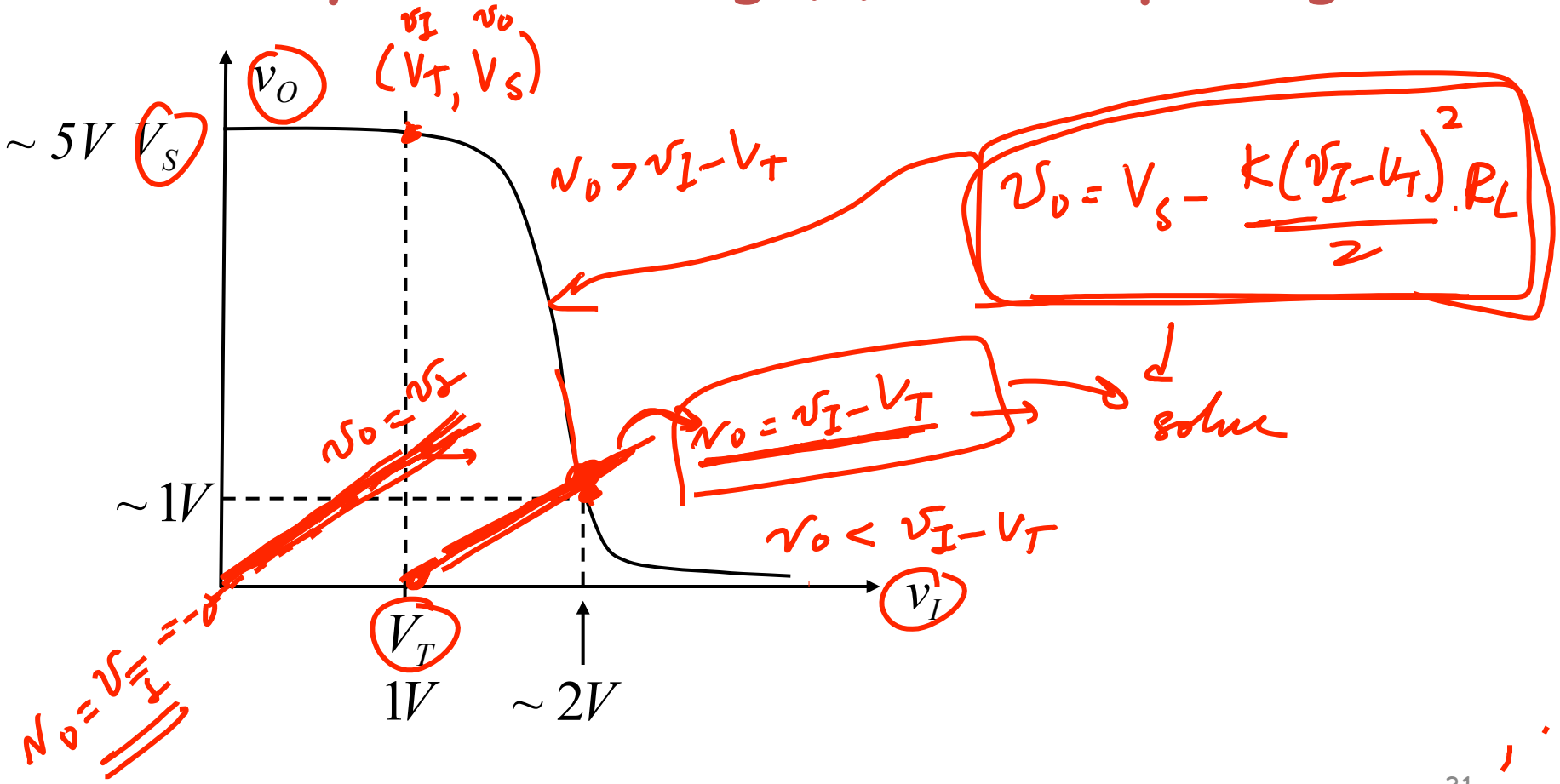
range for i_{DS}

$$\frac{V_S}{R_L} - \frac{v_O}{R_L}$$

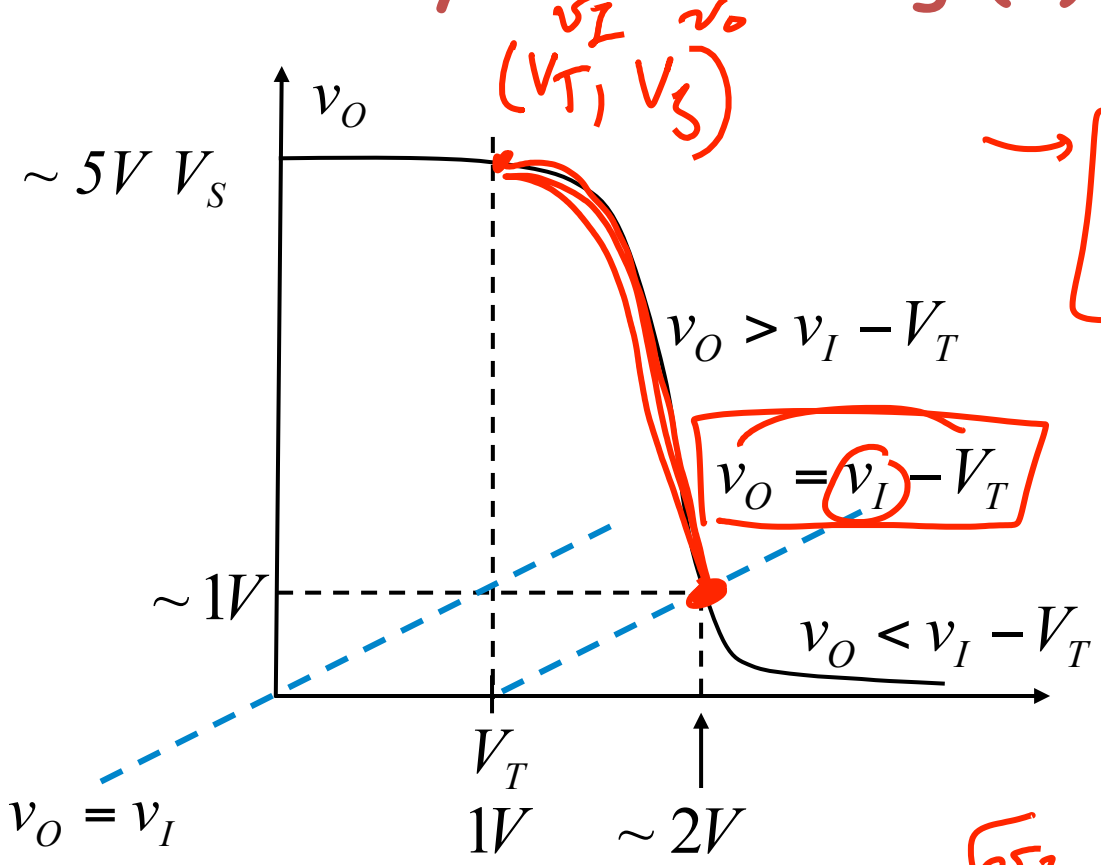
Another Way of Obtaining (2) Valid Op Range



Another Way of Obtaining (2) Valid Op Range



Another Way of Obtaining (2) Valid Op Range



v_I v_O
(V_T, V_S)

$$v_O = V_S - \frac{K(v_I - V_T)^2}{2} R_L$$

$$v_O = v_I - V_T$$

$$v_O = V_S - \frac{K v_O^2 R_L}{2}$$

$$\frac{K v_O^2 R_L}{2} + v_O - V_S = 0$$

$$v_O = \frac{-1 + \sqrt{1 + 2 K R_L V_S}}{K R_L}$$

$$v_I = v_O + V_T = V_T + 2$$