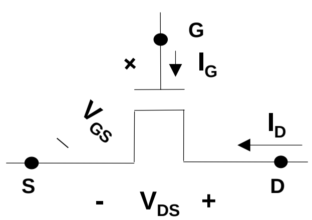
Today we will

- Review NMOS and PMOS I-V characteristic
- Practice useful method for solving transistor circuits
- Build a familiar circuit element using a transistor

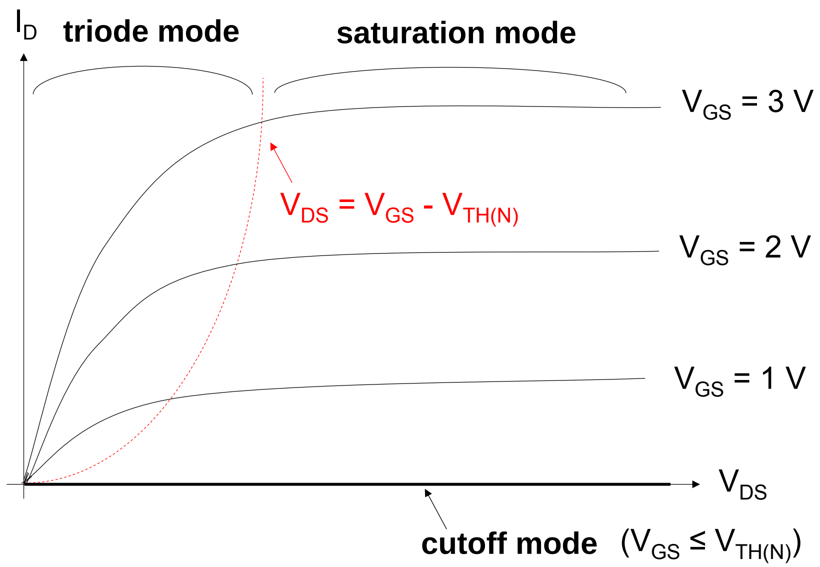
NMOS I-V CHARACTERISTIC



- Since the transistor is a 3-terminal device, there is no single I-V characteristic.
- Note that because of the gate insulator, I_G = 0 A.
- We typically define the MOS I-V characteristic as

  I_D vs. V_{DS} for a fixed V_{GS}.
- 3 modes of operation

NMOS I-V CHARACTERISTIC



NMOS I-V CHARACTERISTIC

Cutoff Mode

- Occurs when $V_{GS} \leq V_{TH(N)}$

$$I_D = 0$$

Triode Mode

- Occurs when $V_{GS} > V_{TH(N)}$ and $V_{DS} < V_{GS} - V_{TH(N)}$

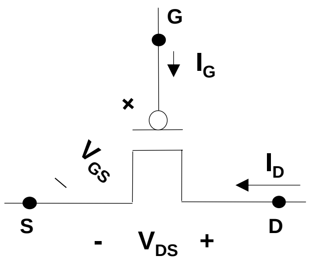
$$I_D = \frac{W}{L}\mu_n C_{OX}\left(V_{GS} - V_{TH(N)} - (V_{DS}/2)\right)V_{DS}$$

Saturation Mode

- Occurs when $V_{GS} > V_{TH(N)}$ and $V_{DS} \geq V_{GS} - V_{TH(N)}$

$$I_D = \frac{W}{L}\mu_n C_{OX}\frac{1}{2}\left(V_{GS} - V_{TH(N)}\right)^2(1+\lambda_n V_{DS})$$

PMOS I-V CHARACTERISTIC



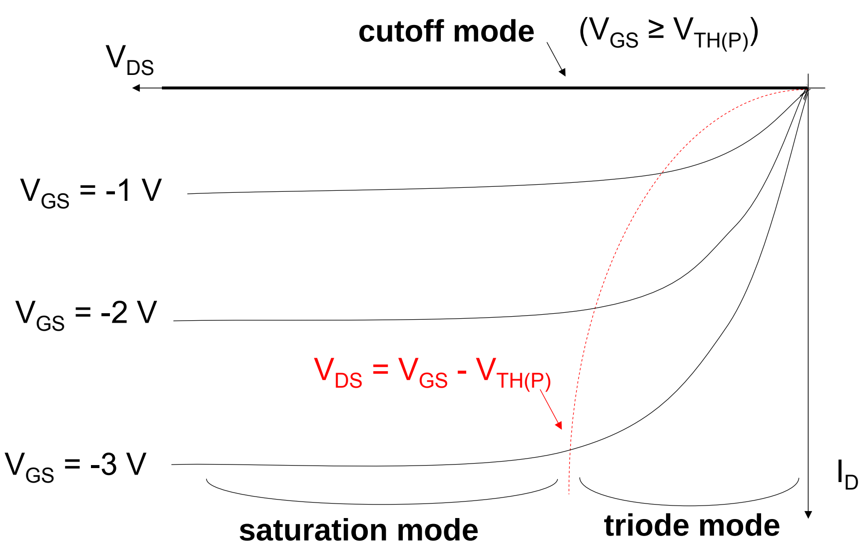
Symbol has “dot” at gate. NMOS does not.

I_D, V_{GS}, V_{DS}, and $V_{TH(P)}$ are all **negative for PMOS**.
These values are **positive for NMOS**.

Channel formed when $V_{GS} < V_{TH(P)}$. Opposite for NMOS.

Saturation occurs when $V_{DS} \leq V_{GS} - V_{TH(P)}$. Opposite for NMOS.

PMOS I-V CHARACTERISTIC



PMOS I-V CHARACTERISTIC

Cutoff Mode

- Occurs when $V_{GS} \geq V_{TH(P)}$

$$I_D = 0$$

Triode Mode

- Occurs when $V_{GS} < V_{TH(P)}$ and $V_{DS} > V_{GS} - V_{TH(P)}$

$$I_D = -\frac{W}{L}\mu_p C_{OX}\left(V_{GS} - V_{TH(P)} - (V_{DS}/2)\right)V_{DS}$$

Saturation Mode

- Occurs when $V_{GS} < V_{TH(P)}$ and $V_{DS} \leq V_{GS} - V_{TH(P)}$

$$I_D = -\frac{W}{L}\mu_p C_{OX}\frac{1}{2}\left(V_{GS} - V_{TH(P)}\right)^2\left(1 + \lambda_p V_{DS}\right)$$

SATURATION CURRENT

Since λ is small or zero, current I_D is almost constant in saturation mode.

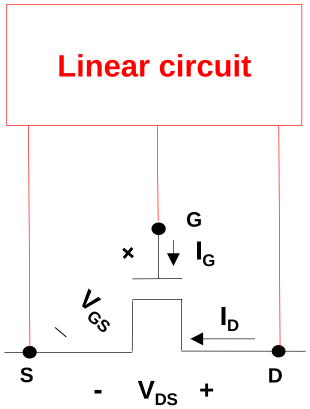
We can call this current I_{DSAT}:

$$I_{DSAT} = \frac{W}{L}\mu_n C_{OX}\frac{1}{2}\left(V_{GS} - V_{TH(N)}\right)^2 \quad \text{for NMOS}$$

$$I_{DSAT} = -\frac{W}{L}\mu_p C_{OX}\frac{1}{2}\left(V_{GS} - V_{TH(P)}\right)^2 \quad \text{for PMOS}$$

LINEAR AND NONLINEAR ELEMENTS

We need to find out how transistors behave as part of a circuit.



To solve a transistor circuit, obtain:

1) the **nonlinear** I_D vs. V_{DS} characteristic equation for the transistor

2) The **linear** relationship between I_D vs. V_{DS} as determined by the surrounding linear circuit

Then simultaneously solve these two equations for I_D and V_{DS}.

SOLVING TRANSISTOR CIRCUITS: STEPS

1) Guess the mode of operation for the transistor. (We will learn how to make educated guesses).

2) Write the I_D vs. V_{DS} equation for this mode of operation.

3) Use KVL, KCL, etc. to come up with an equation relating I_D and V_{DS} based on the surrounding linear circuit.

4) Solve these equations for I_D and V_{DS}.

5) Check to see if the values for I_D and V_{DS} are possible for the mode you guessed for the transistor. If the values are possible for the mode guessed, stop, problem solved. If the values are impossible, go back to Step 1.

CHECKING THE ANSWERS

NMOS

- V_{DS} must be positive
- I_D must be positive

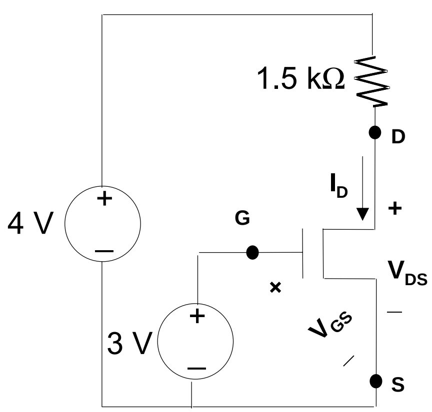
- $V_{DS} < V_{GS} - V_{T(N)}$ in triode
  $V_{DS} \geq V_{GS} - V_{T(N)}$ in saturation
- $V_{GS} > V_{T(N)}$ in triode or saturation
  $V_{GS} \leq V_{T(N)}$ in cutoff

PMOS

- V_{DS} must be negative
- I_D must be negative

- $V_{DS} > V_{GS} - V_{T(P)}$ in triode
  $V_{DS} \leq V_{GS} - V_{T(P)}$ in saturation
- $V_{GS} < V_{T(P)}$ in triode or saturation
  $V_{GS} \geq V_{T(P)}$ in cutoff

EXAMPLE



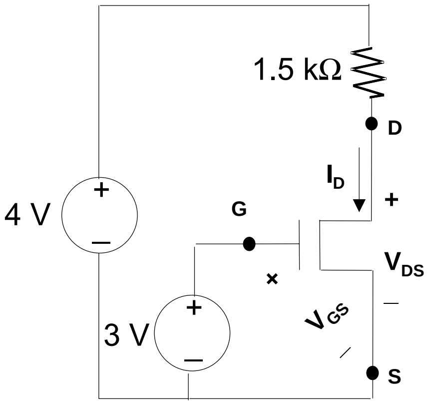
$V_{TH(N)} = 1$ V,
$\frac{1}{2}$ W/L $\mu_n C_{OX} = 250\ \mu$ A/V^2,
$\lambda = 0$ V^{-1}.

1) Guess the mode:

2) Write transistor I_D vs. V_{DS}:

3) Write I_D vs. V_{DS} equation using KVL:

EXAMPLE



4) Solve:

5) Check:

$V_{TH(N)} = 1$ V,
$\frac{1}{2}$ W/L $\mu_n C_{OX} = 250\ \mu$ A/V^2,
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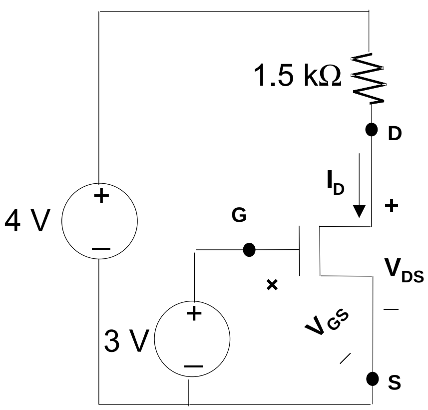
WHAT IF WE GUESSED THE MODE WRONG?

1) Guess the mode:



2) Write transistor I_D vs. V_{DS}:

3) Write I_D vs. V_{DS} equation using KVL:

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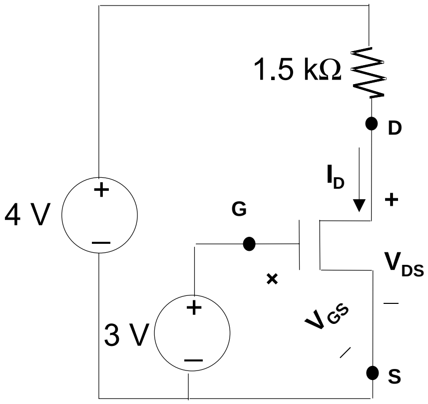

$V_{TH(N)} = 1$ V,
$\frac{1}{2}$ W/L $\mu_n C_{OX} = 250\ \mu$ A/V^2,
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4) Solve for V_{DS} with quadratic equation:

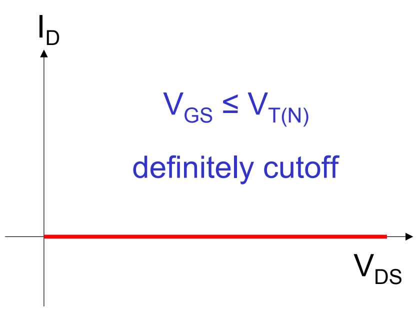
5) Check:

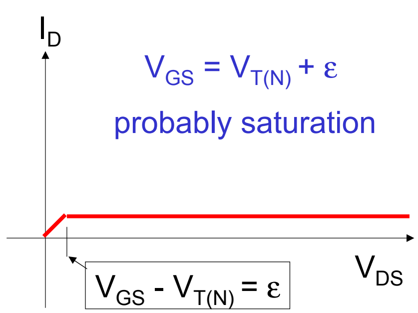
GUESSING RIGHT

How do you guess the right mode?

Often, the key is the value of V_{GS}.

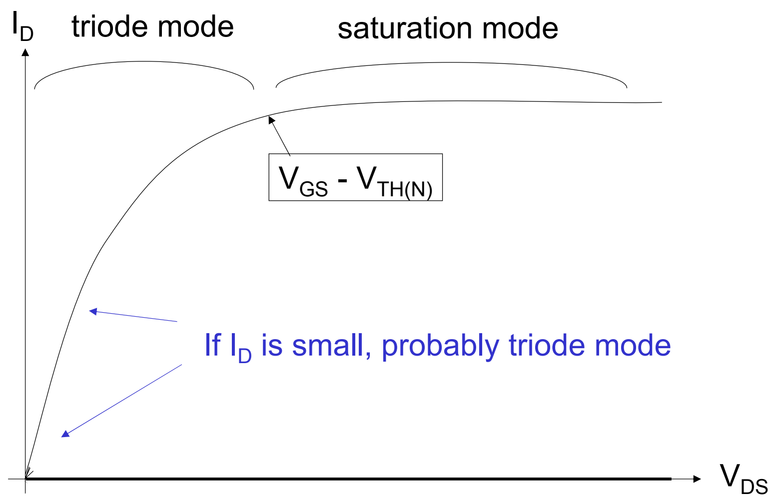
(We can often find V_{GS} directly without solving the whole circuit.)





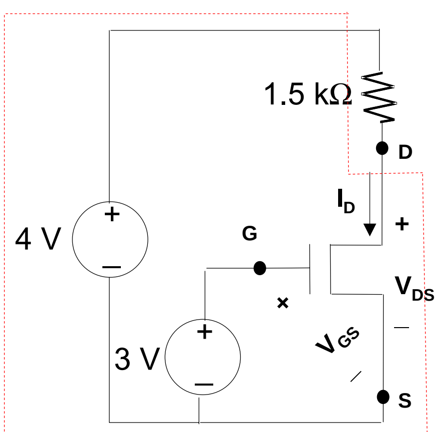
GUESSING RIGHT

When $V_{GS} >> V_{TH(N)}$, it's harder to guess the mode.



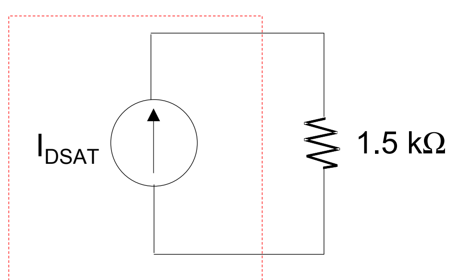
A CLOSER LOOK

In this circuit, the transistor delivered a constant current I_{DSAT} to the 1.5 kΩ resistor.



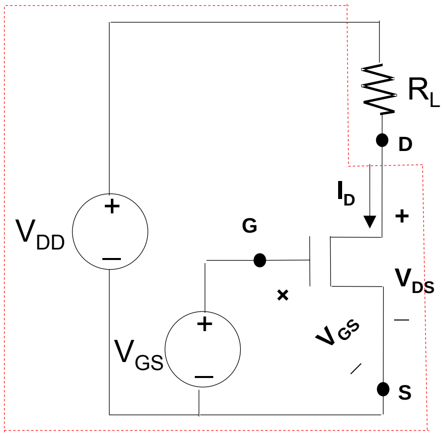
This circuit acts like a constant current source, as long as the transistor remains in saturation mode.

I_{DSAT} does not depend on the attached resistance if saturation is maintained.



A CLOSER LOOK

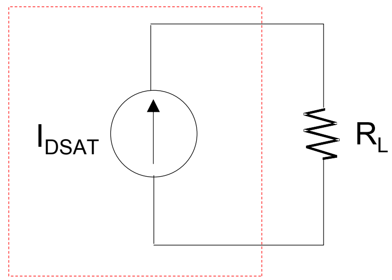
I_{DSAT} does depend on V_{GS}; one can adjust the current supplied by adjusting V_{GS}.



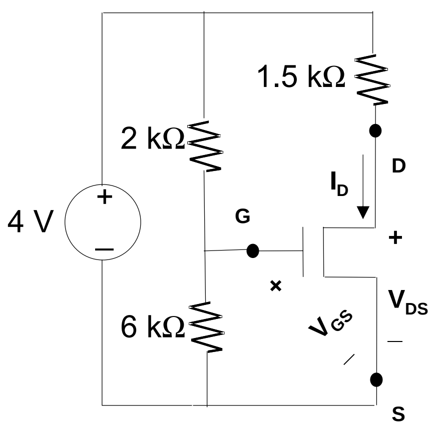
The circuit will go out of saturation mode if

- $V_{GS} < V_{T(N)}$ **or**
- $V_{DS} < V_{GS} - V_{T(N)}$

This can happen if V_{GS} is too large or too small, or if the load resistance is too large.



ANOTHER EXAMPLE



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1) Guess the mode:

2) Write transistor I_D vs. V_{DS}:

3) Write I_D vs. V_{DS} equation using KVL:

Effectively the same circuit as previous example: only 1 source.