

---

# **MOSFET Theory**

**ECE 320 Electronics I**

**Jake Glower - Lecture #22**

Please visit [Bison Academy](#) for corresponding lecture notes, homework sets, and solutions

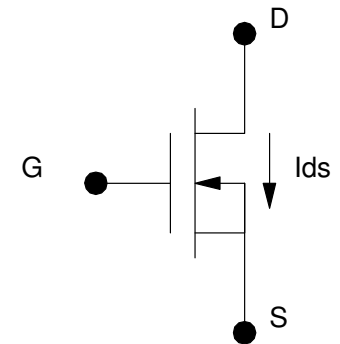
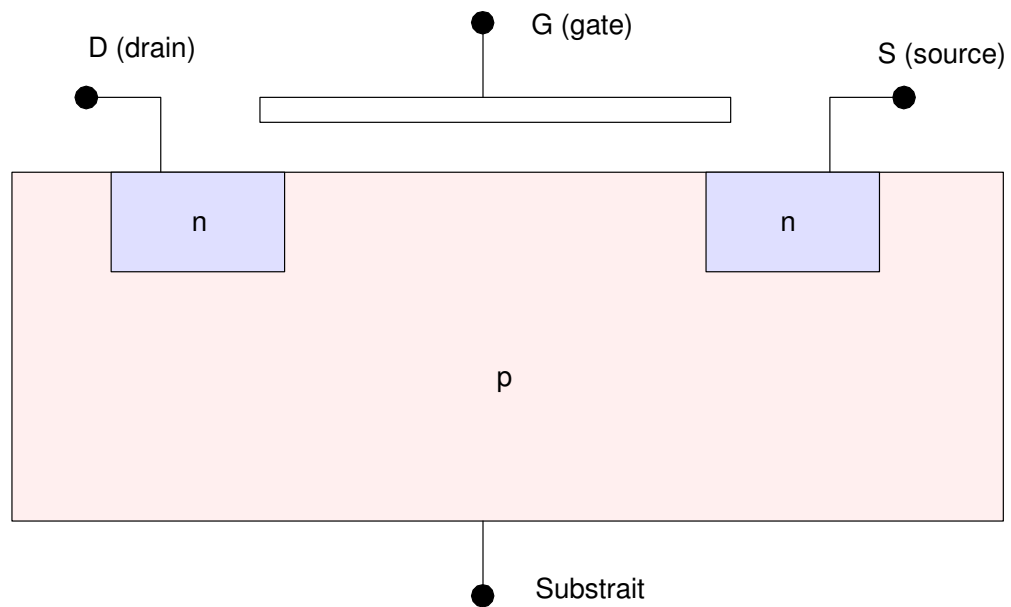
---

# MOSFET Theory

Another type of 3-terminal device is called a MOSFET. In essence,

- A transistor is a current-controlled current source.
- A MOSFET is a voltage controlled resistor.

The design of an n-channel MOSFET is as follows:



Symbol

---

---

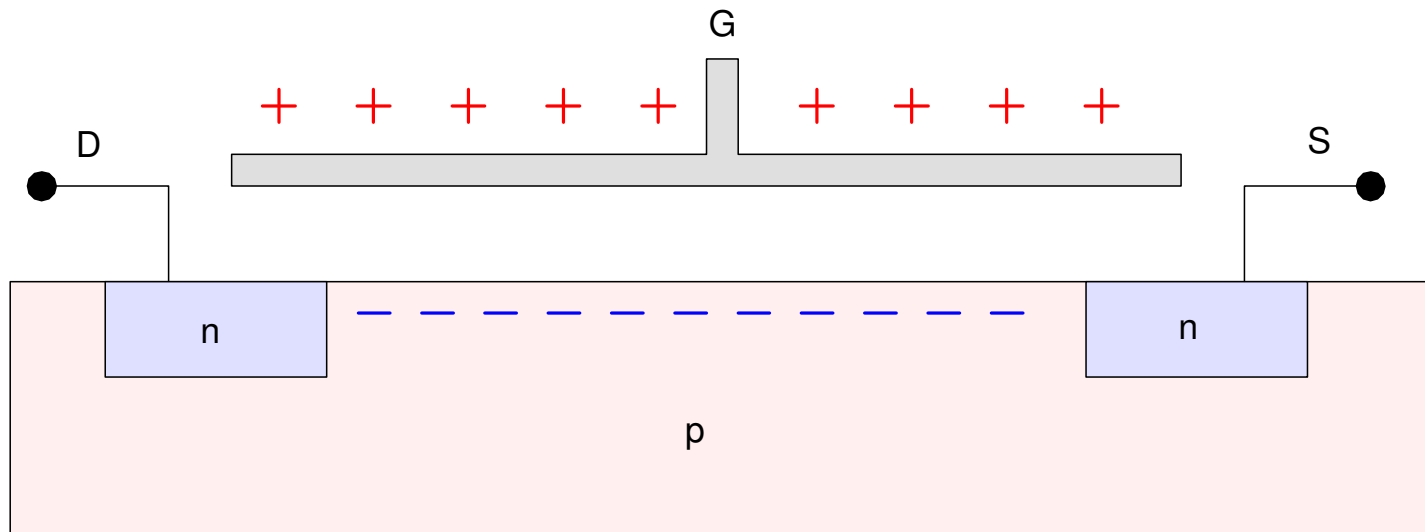
# MOSFET Operation

$V_{gs} = 0V$

- Current = 0

$V_{gs} = 5V$

- Electrons attracted to the surface
- Creates an n-channel
- Higher  $V_{gs}$  makes n-channel bigger (lower R)



# Three Modes of Operation

Off:

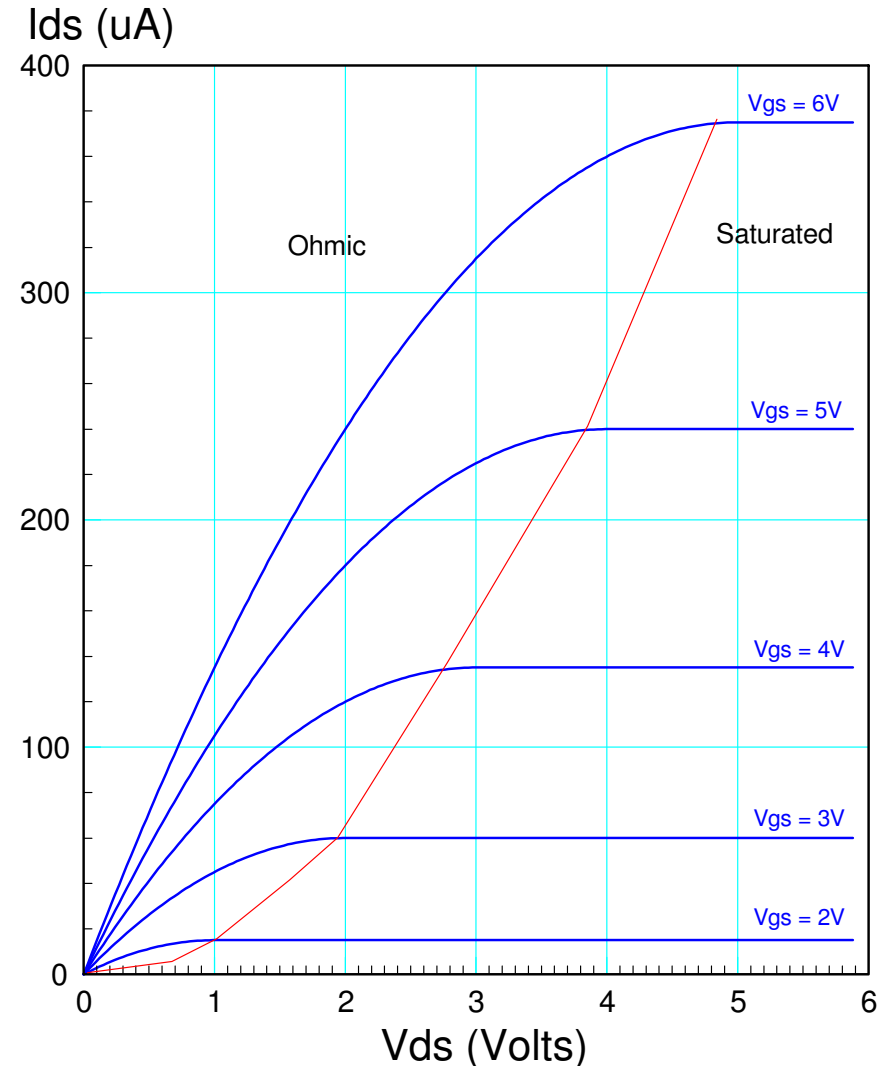
- $V_{gs} < V_{th}$
- No channel exists (current = 0)

Ohmic (Triode)

- $V_{th} < V_{gs} < V_{ds} + V_{th}$
- Resistance =  $f(V_{gs})$
- $I_{ds} = k_n \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds}$

Saturated

- Ran out of charge carriers
- Current =  $f(V_{gs})$
- $I_{ds} = \frac{k_n}{2} (V_{gs} - V_{th})^2$



Example: Plot the VI characteristic for a MOSFET with

- $V_{th} = 1V$
- $V_{gs} = 4V$
- $k_n = 250\mu A/V^2$

Ohmic Region:

```
Vgs = 4;
```

```
Vds = [0:0.03:6]';
```

```
Vth = 1;
```

```
Kn = 250e-6;
```

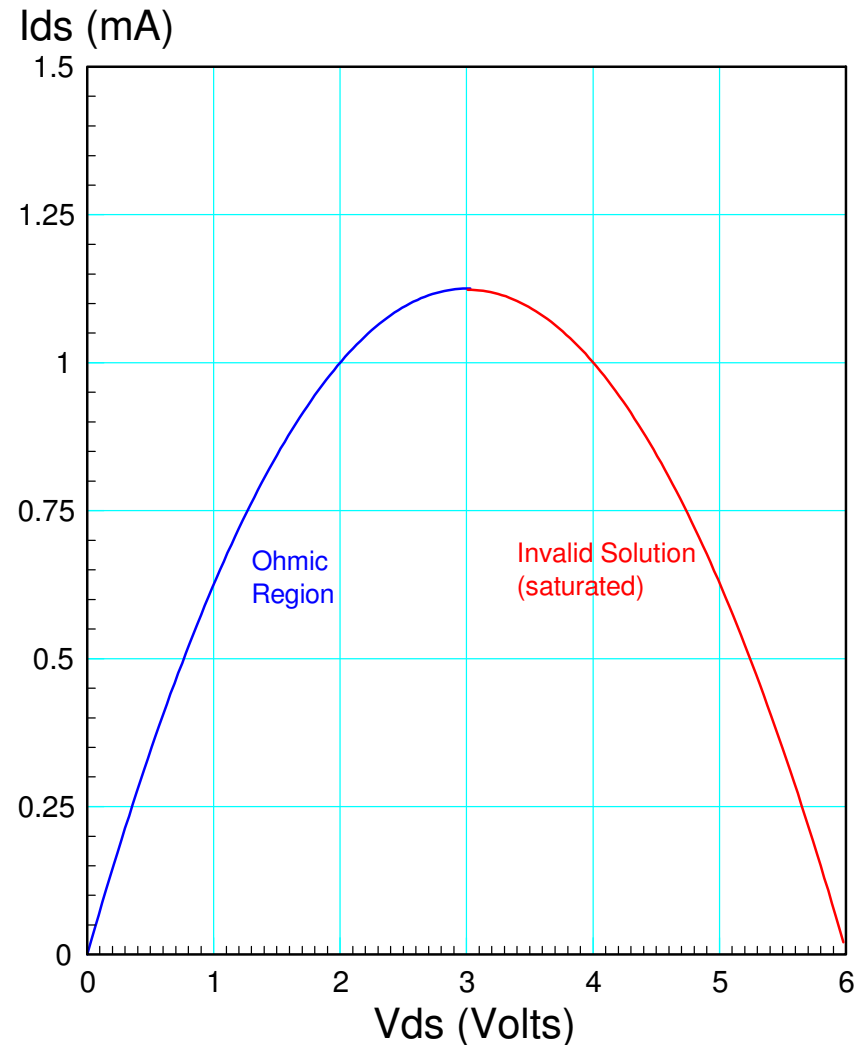
```
% Ohmic
```

```
Ids = Kn*(Vgs - Vth - Vds/2).*Vds;
```

```
plot(Vds, Ids*1000)
```

```
xlabel('Vds (V)');
```

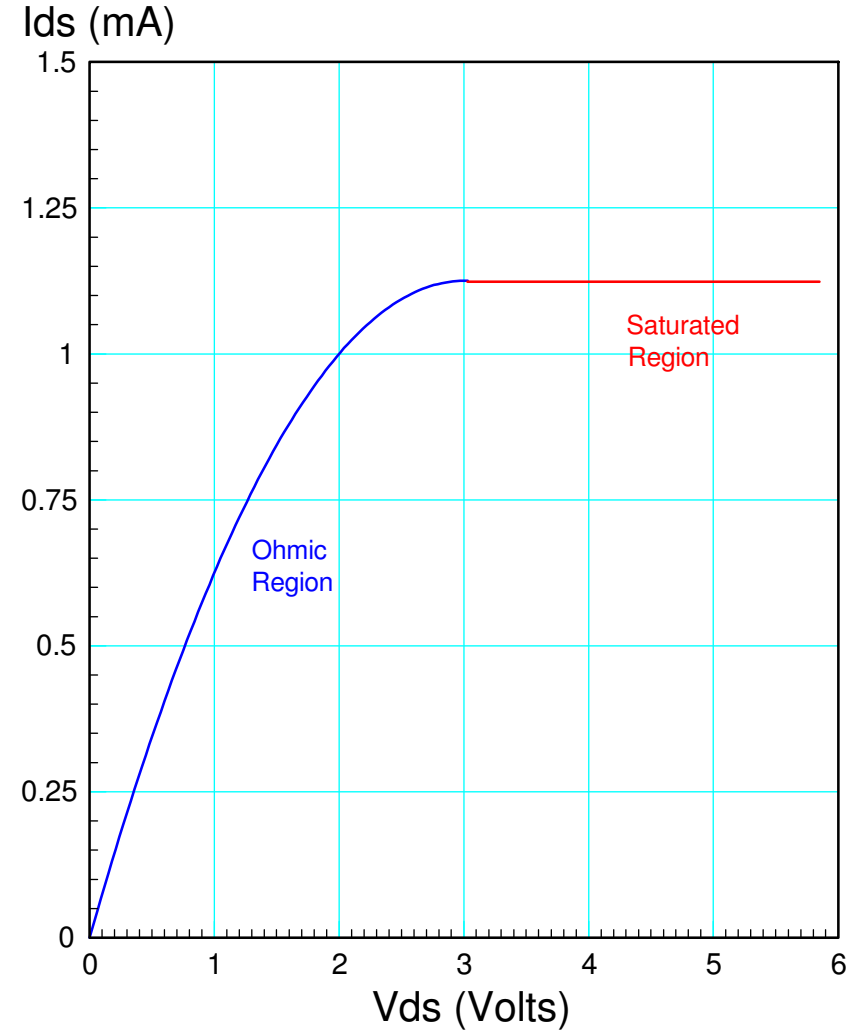
```
ylabel('Ids (mA)')
```



# Saturation (Pinch-Off) Region

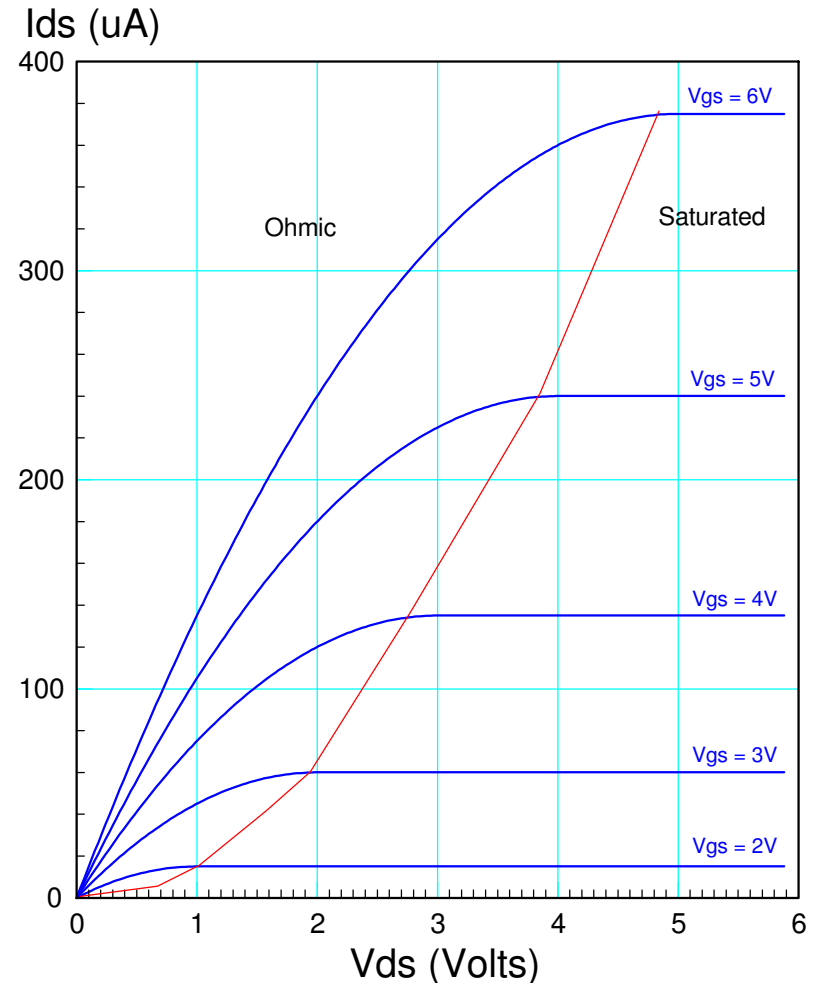
When the slope becomes negative,  $I_{DS} =$  constant

- Ran out of charge carriers
- $V_{DS} > V_{GS} - V_{TN}$
- $I_{DS} = \frac{K_n}{2}(V_{GS} - V_{TN})^2$



# V/I Relationship for a MOSFET

```
Vth = 1;  
Kn = 0.03;  
Vds = [0:0.03:5.9]' + 1e-6;  
DATA = [];  
  
for i=1:5  
    Vgs = Vth + i;  
    % Ohmic  
    Ids1 = Kn*(Vgs - Vth - Vds/2).*Vds;  
    Ids1 = Ids1 .* (Vgs - Vth > Vds);  
    % Saturated  
    Ids2 = Kn/2 * (Vgs - Vth).^2;  
    Ids2 = Ids2 .* (Vds > Vgs - Vth);  
    Ids = Ids1 + Ids2;  
    DATA = [DATA, Ids];  
end  
plot(Vds, DATA);  
xlabel('Vds (V)');  
ylabel('Ids (mA)')
```



## Example 1: Determine $K_n$ and $V_{th}$

$$V_{th} = 2V$$

- Turns on at something less than 3V

$k_n$ :

- Ohmic region (A)

$$I_{ds} = k_n \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds}$$

$$2mA = k_n \left( 7V - 2V - \frac{2V}{2} \right) 2V$$

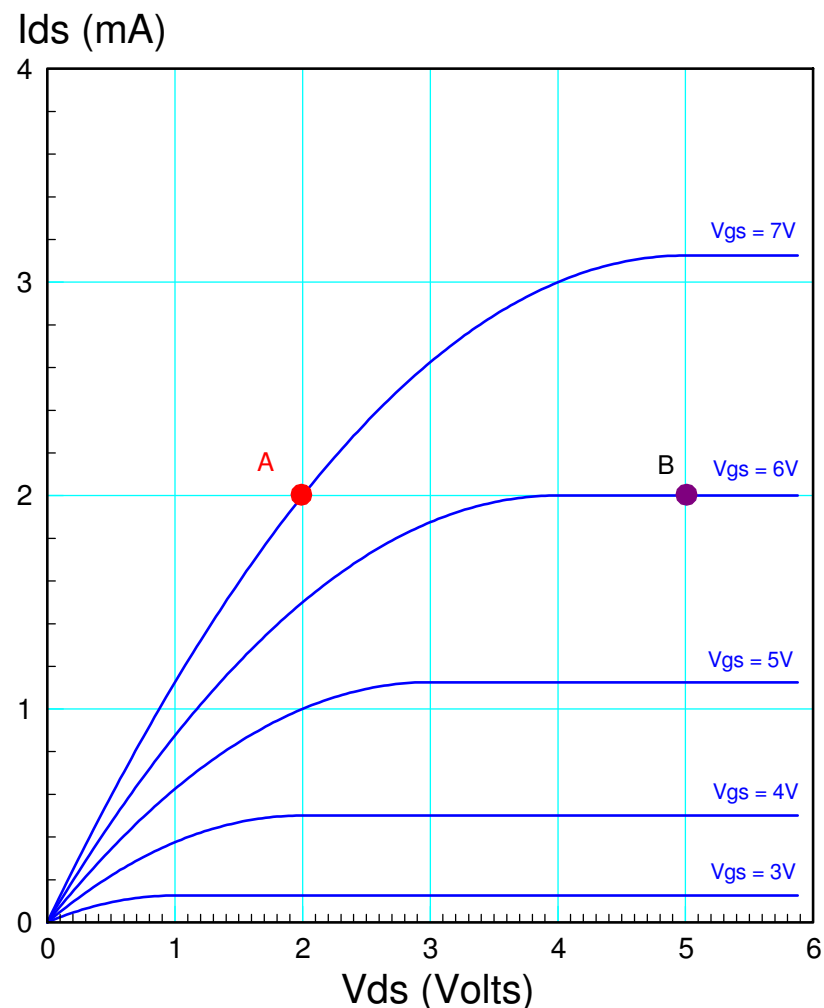
$$k_n = 0.25mA/V^2$$

- Saturated Region (B)

$$I_{ds} = \frac{k_n}{2} (V_{gs} - V_{th})^2$$

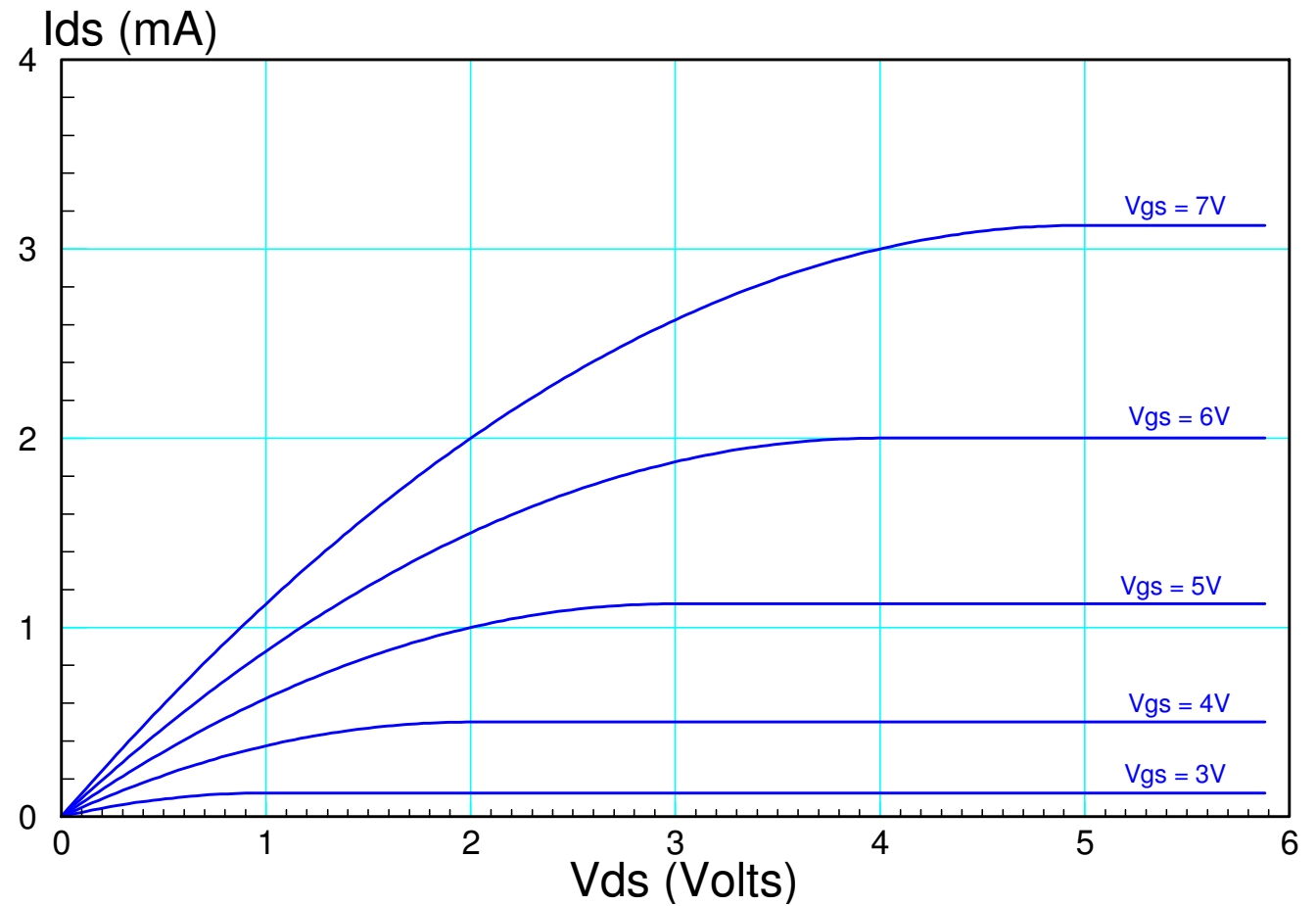
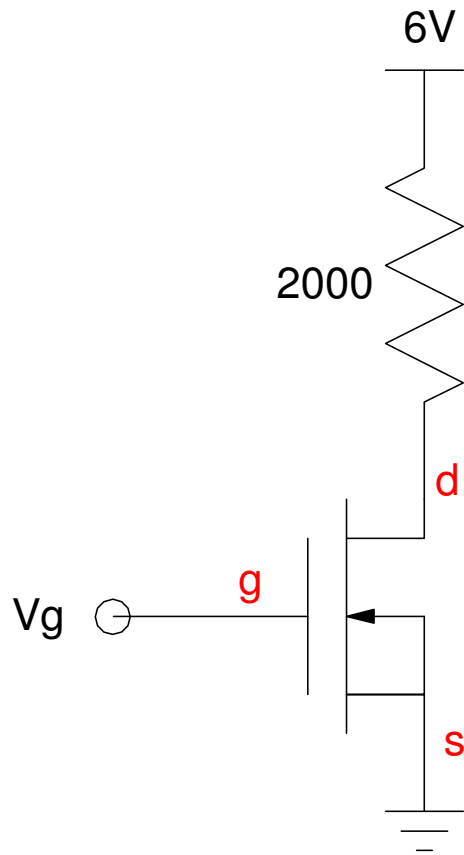
$$2mA = \frac{k_n}{2} (6V - 2V)^2$$

$$k_n = 0.25mA/V^2$$

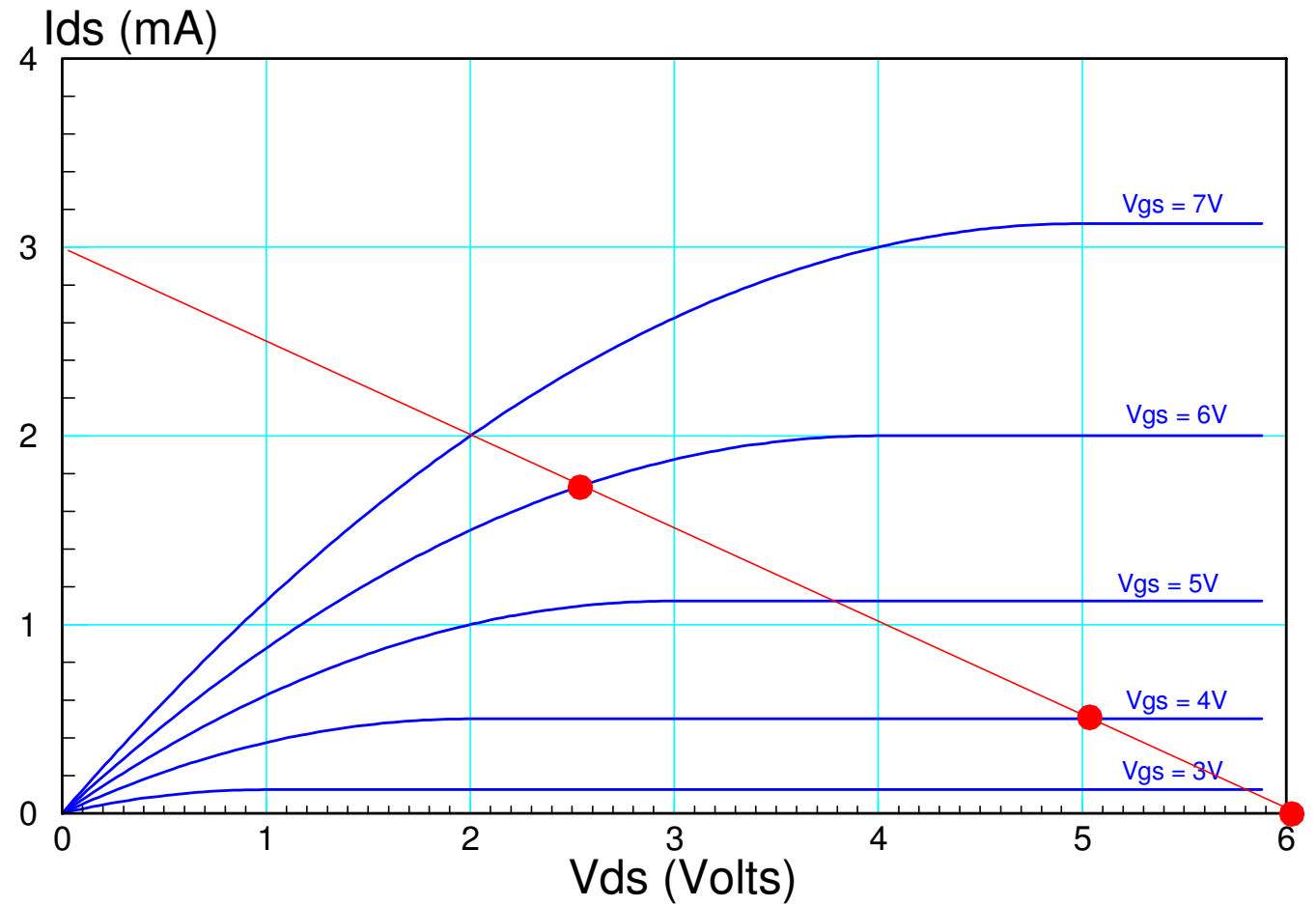
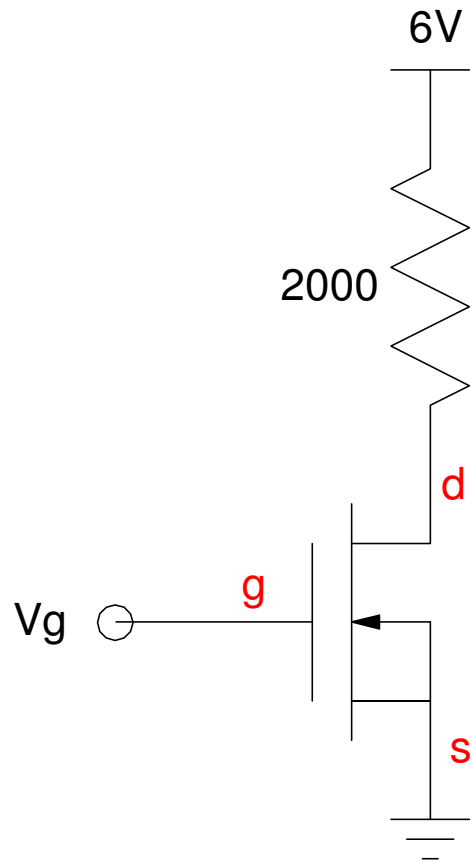




## Example 2: Determine ( $V_{ds}$ , $I_{ds}$ ) for $V_g = \{ 0V, 4V, 6V \}$

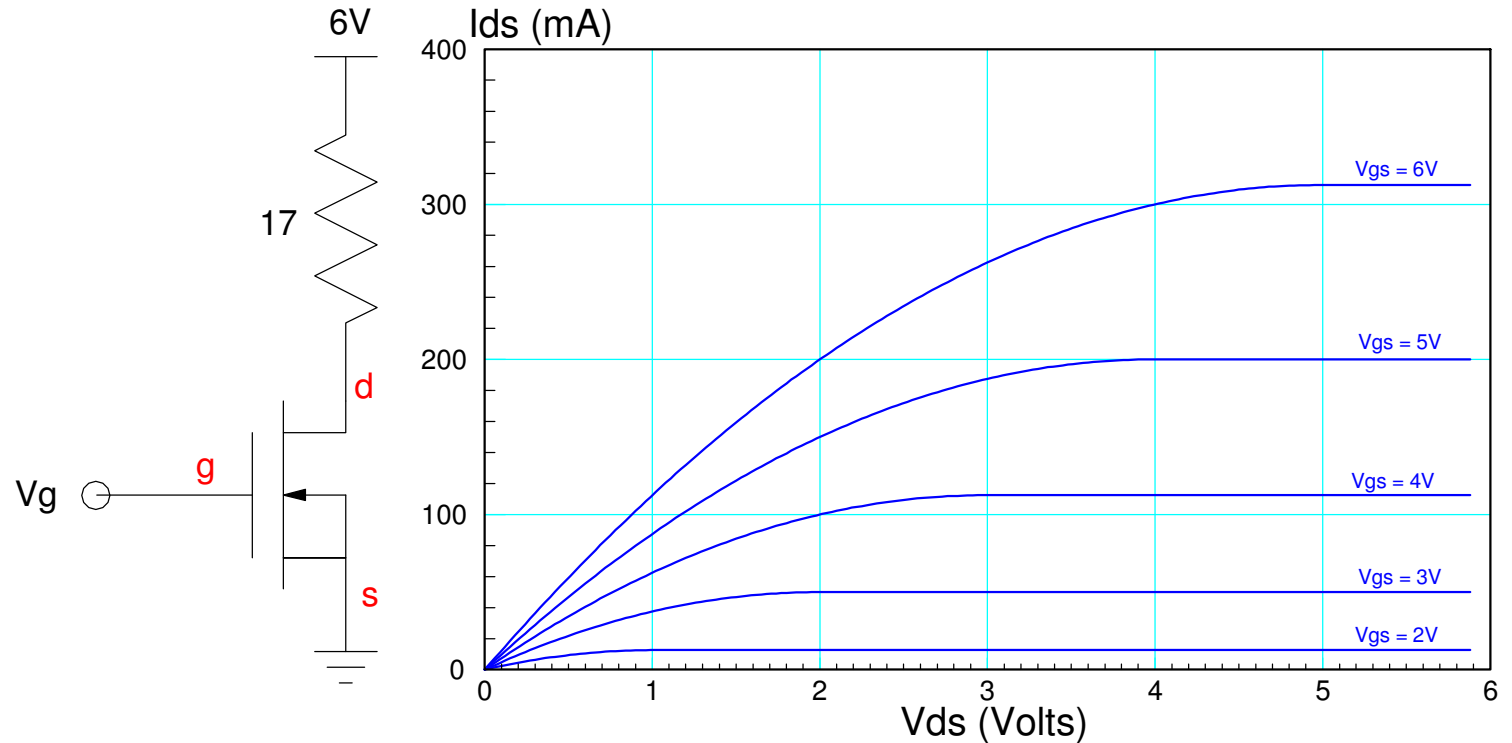


## Solution (graphical): Draw the load line



# Handout

- 1) Label the off / Saturated / Ohmic regions
- 2) Determine  $k_n$ . Assume  $V_{tn} = 1.0V$
- 3) Draw the load line for the following circuit
- 4) Determine the Q-point when  $V_g = \{ 0V, 4V, 6V \}$



## Numerical Solution: $V_g = 4V$

Assume Saturated

$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

$$I_{ds} = \left(\frac{0.25 \frac{mA}{V^2}}{2}\right)(4V - 1V)^2$$

$$I_{ds} = 1.125mA$$

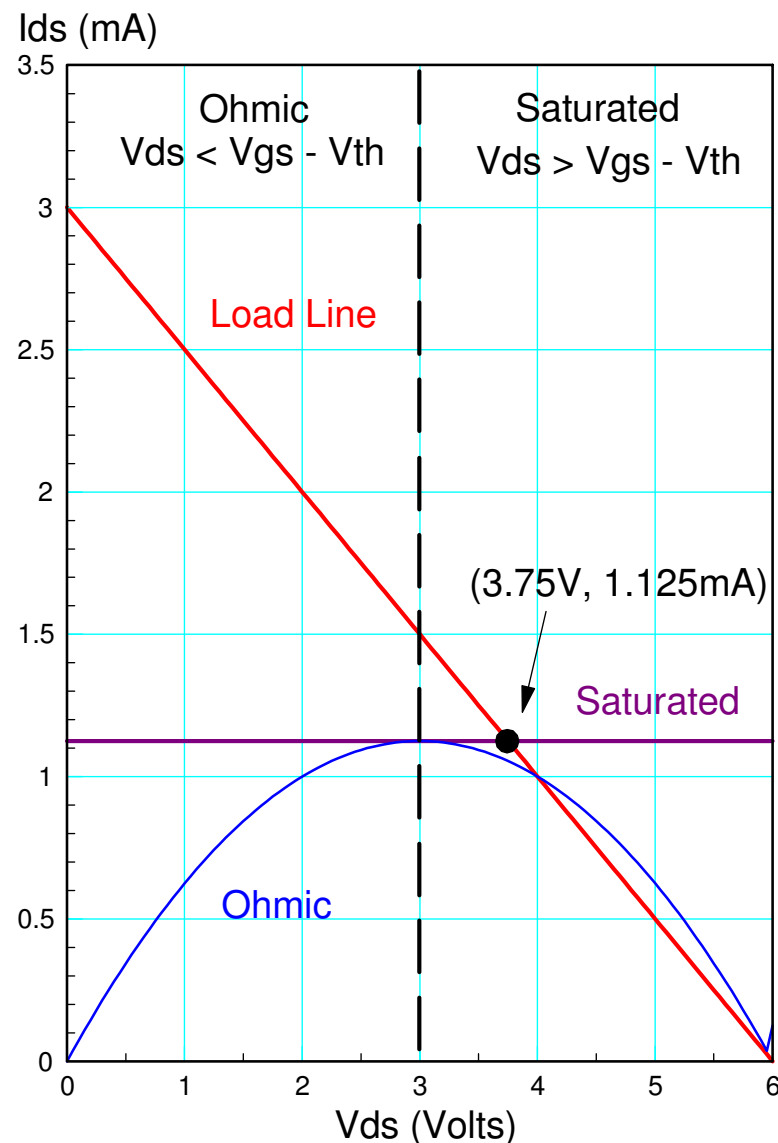
$$V_{ds} = 6V - 2000\Omega \cdot I_{ds}$$

$$V_{ds} = 3.75V$$

Check

$$V_{ds} > V_{gs} - V_{th}$$

$$3.75V > 4V - 1V$$



## Numerical Solution: $V_g = 4V$

Assume Ohmic

$$I_{ds} = k_n \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds}$$

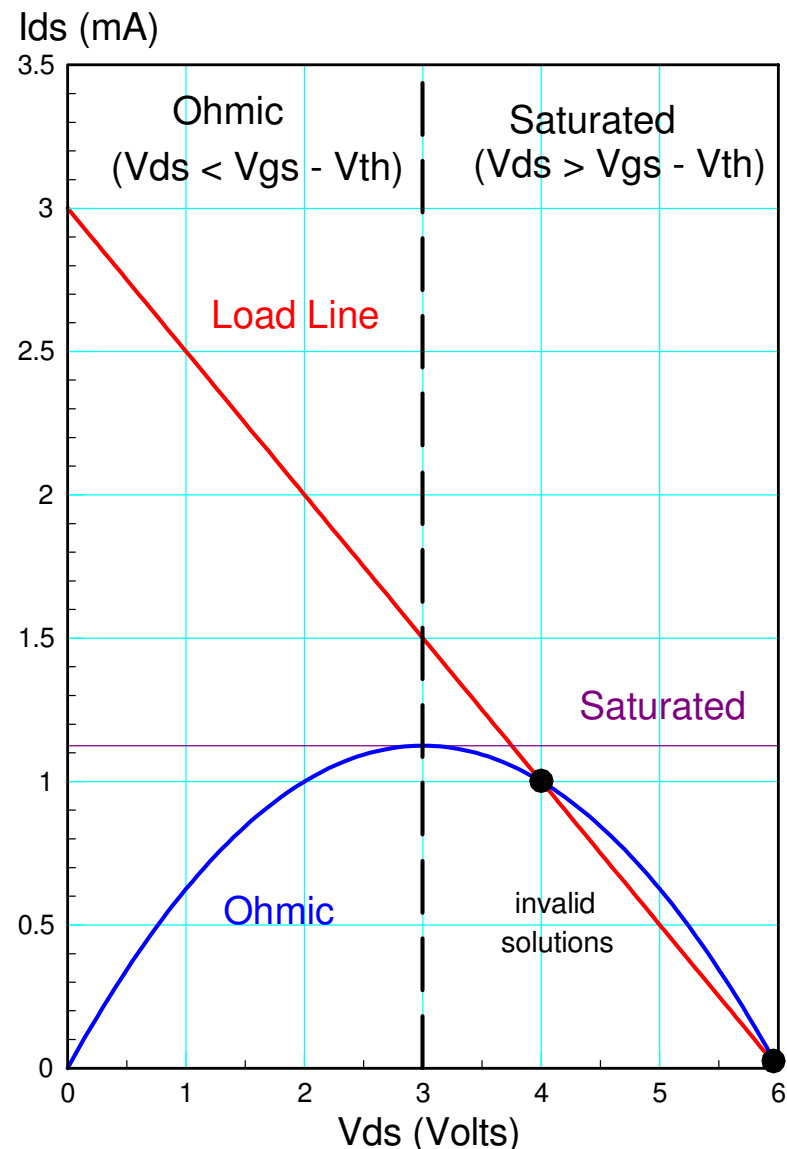
$$I_{ds} = \left( 0.25 \frac{\text{mA}}{\text{V}^2} \right) \left( 4V - 1V - \frac{V_{ds}}{2} \right) V_{ds}$$

$$V_{ds} + 2000 I_{ds} = 6V$$

Solution:

$V_{ds} > 3V$  (invalid solution)

often results in no solution



## Numerical Solution: $V_{gs} = 6V$

Assume Saturated

$$I_{ds} = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

$$I_{ds} = \frac{0.25 \frac{mA}{V^2}}{2}(6V - 1V)^2$$

$$I_{ds} = 3.125V$$

$$V_{ds} = 6V - 2k\Omega \cdot I_{ds}$$

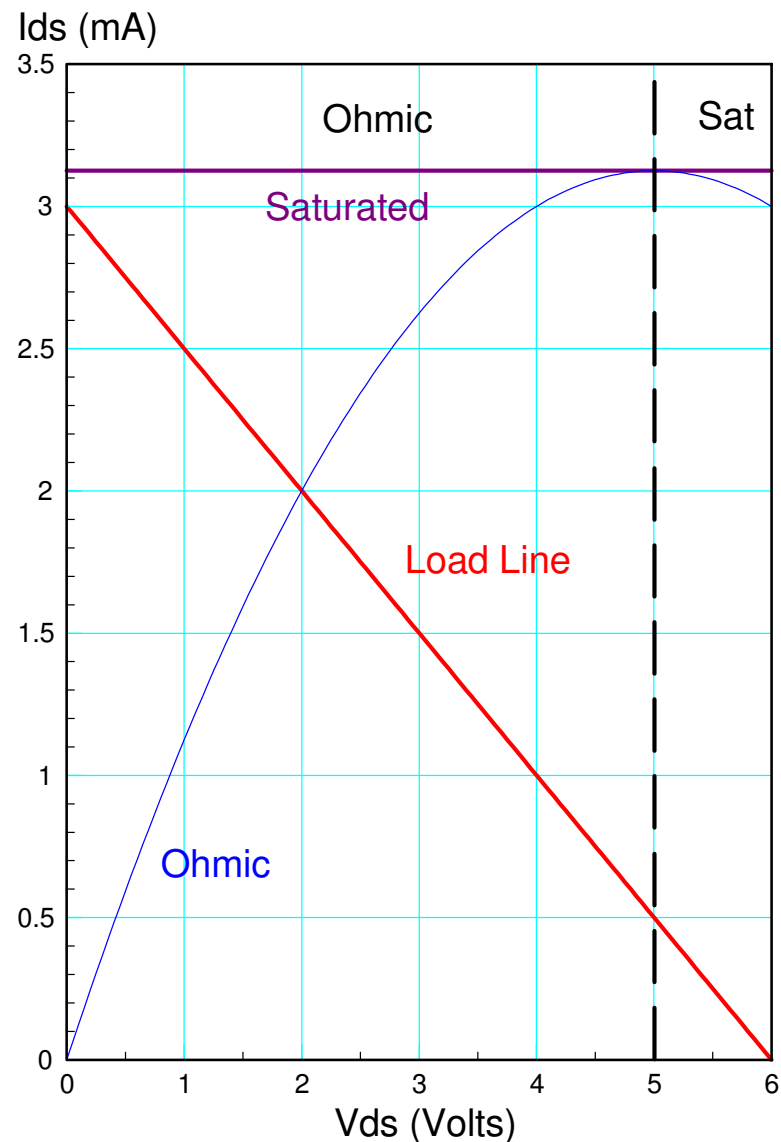
$$V_{ds} = 0.25V$$

Check

negative  $V_{ds}$  isn't possible

it's not saturated

$$V_{ds} > V_{gs} - V_{th}$$



## Numerical Solution: $V_{gs} = 6V$

Assume Ohmic

$$I_{ds} = k_n \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds}$$

$$I_{ds} = \left( 0.25 \frac{\text{mA}}{\text{V}^2} \right) \left( 6V - 1V - \frac{V_{ds}}{2} \right) V_{ds}$$

$$6V = V_{ds} + 2000I_{ds}$$

Solution (solved numerically)

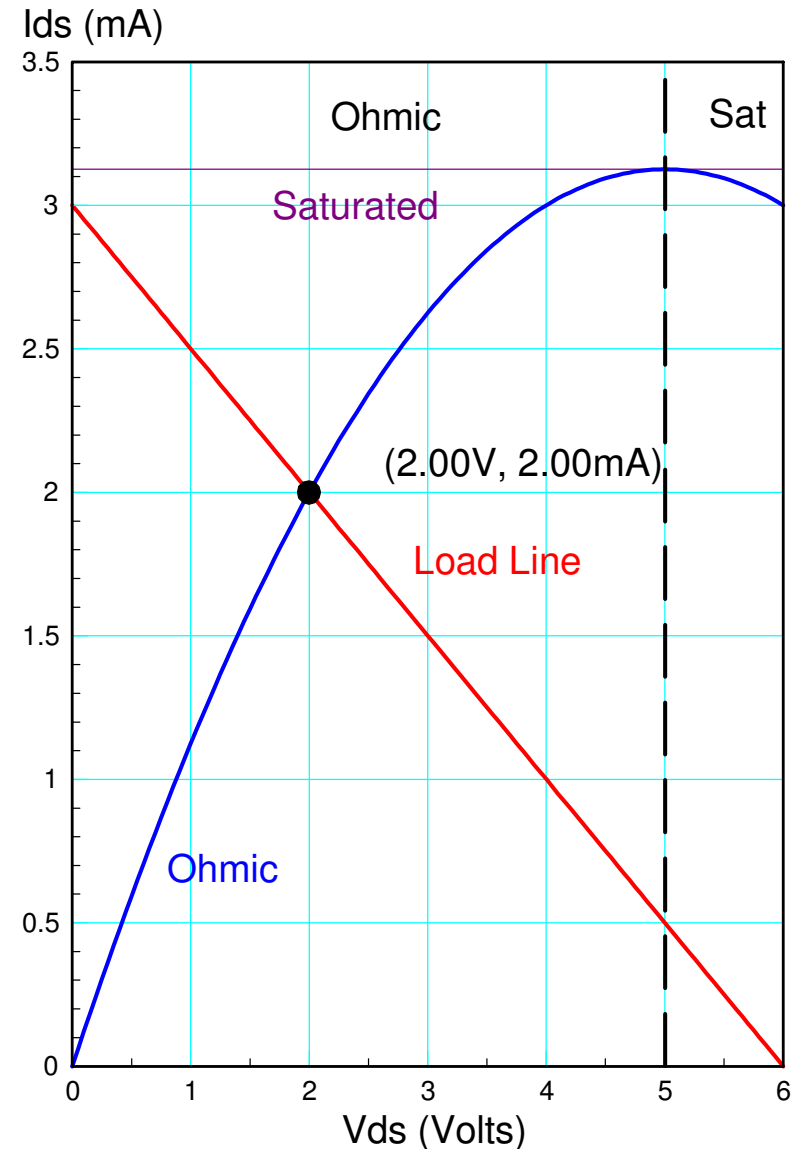
$$V_{ds} = 2.000V$$

$$I_{ds} = 2.000\text{mA}$$

Check

$$V_{ds} < V_{gs} - V_{th}$$

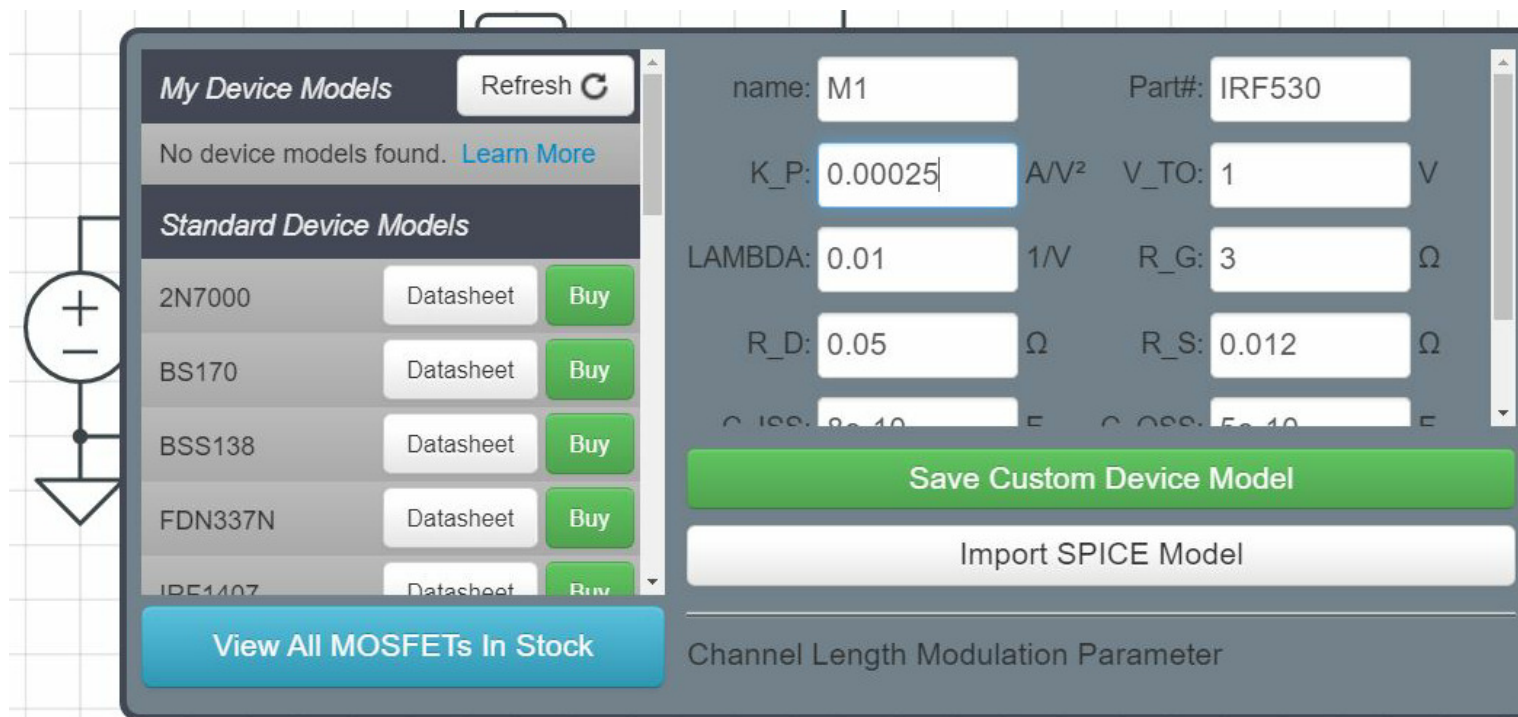
$$2V < 6V - 5V$$



## Solution: CircuitLab

Change the MOSFET properties to match

- $k_n = 0.25 \text{ mA} / \text{V}^2$
- $V_{th} = 1 \text{ V}$



The screenshot displays the CircuitLab interface for configuring a MOSFET model. On the left, a circuit diagram shows a DC voltage source connected to the gate of an N-channel MOSFET. The main panel is divided into two sections: 'My Device Models' and 'Standard Device Models'. The 'Standard Device Models' section lists several MOSFETs with 'Datasheet' and 'Buy' buttons. A blue button at the bottom left of this section reads 'View All MOSFETs In Stock'. The right panel shows the configuration for a MOSFET named 'M1' with part number 'IRF530'. The 'K\_P' parameter is set to 0.00025 A/V<sup>2</sup>, and the 'V\_TO' parameter is set to 1 V. Other parameters include LAMBDA: 0.01 1/V, R\_G: 3 Ω, R\_D: 0.05 Ω, R\_S: 0.012 Ω, C\_ISS: 8e-10 F, and C\_OSS: 5e-10 F. A green button labeled 'Save Custom Device Model' and a white button labeled 'Import SPICE Model' are visible. At the bottom, the text 'Channel Length Modulation Parameter' is partially visible.

Model Name	Part#	K_P (A/V <sup>2</sup> )	V_TO (V)	LAMBDA (1/V)	R_G (Ω)	R_D (Ω)	R_S (Ω)	C_ISS (F)	C_OSS (F)
M1	IRF530	0.00025	1	0.01	3	0.05	0.012	8e-10	5e-10




# Solution: CircuitLab

- (3.75V, 1.125mA) calculated

▼ DC

V(Vds) 3.668 V  

I(M1.nD) 1.166 mA  

[+ Add Expression](#)

 Export Results...

[Run DC Solver](#)

---

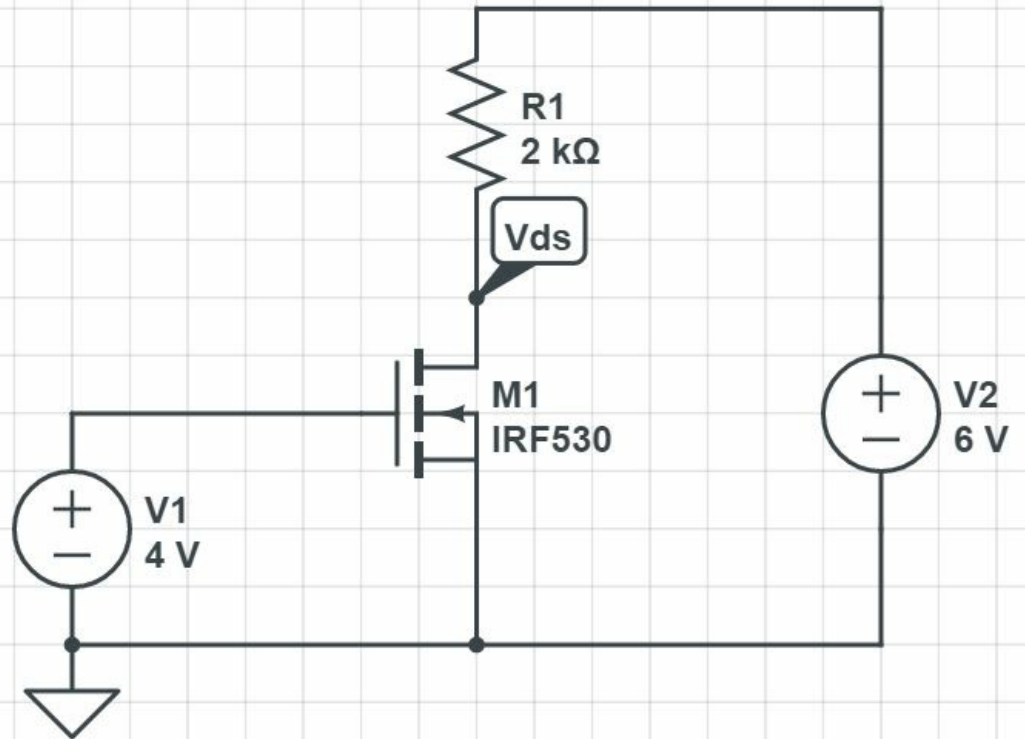
▶ DC Sweep

---

▶ Time Domain

---



▶ Frequency Domain





# Solution: CircuitLab


- (2.00V, 2.00mA) calculated

▼ DC

V(Vds) 1.969 V  

I(M1.nD) 2.015 mA  

[+ Add Expression](#)

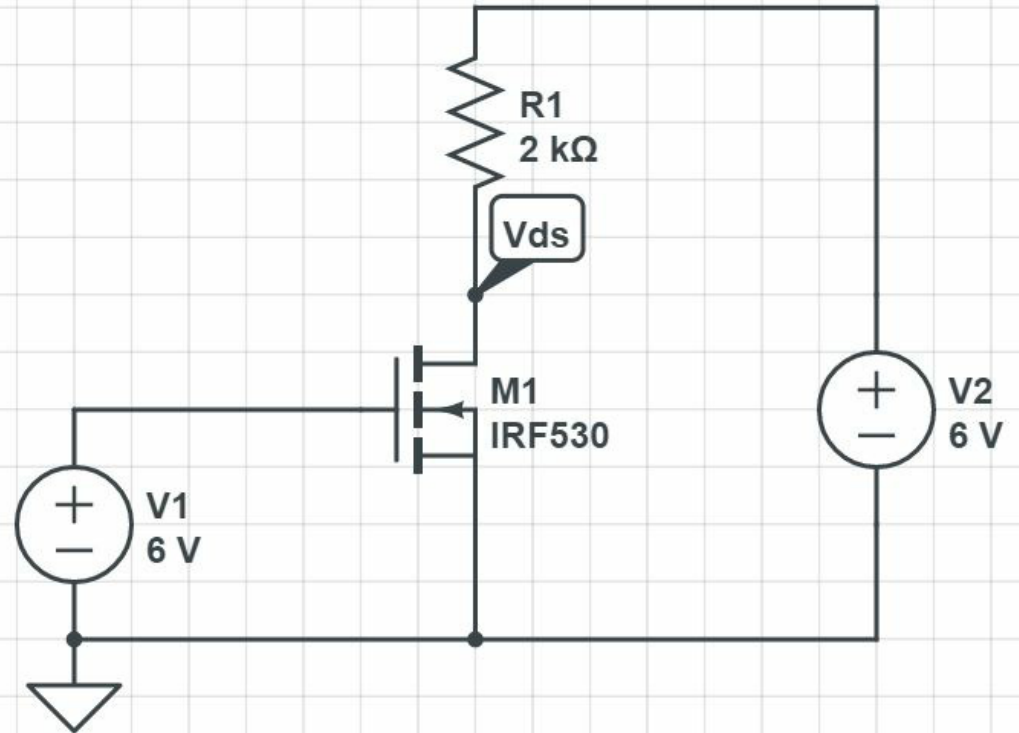
 Export Results...

[Run DC Solver](#)

▶ DC Sweep

▶ Time Domain

▶ Frequency Domain



### Example 3: Determine the Q-point ( $V_{ds}$ , $I_{ds}$ ) when

- $V_{gs} = 5V$
- $V_{gs} = 6.2V$

Assume

- $k_n = 0.6 \text{ A/V}^2$
- $V_{th} = 4V$

Ohmic Region (option #1 for first equation)

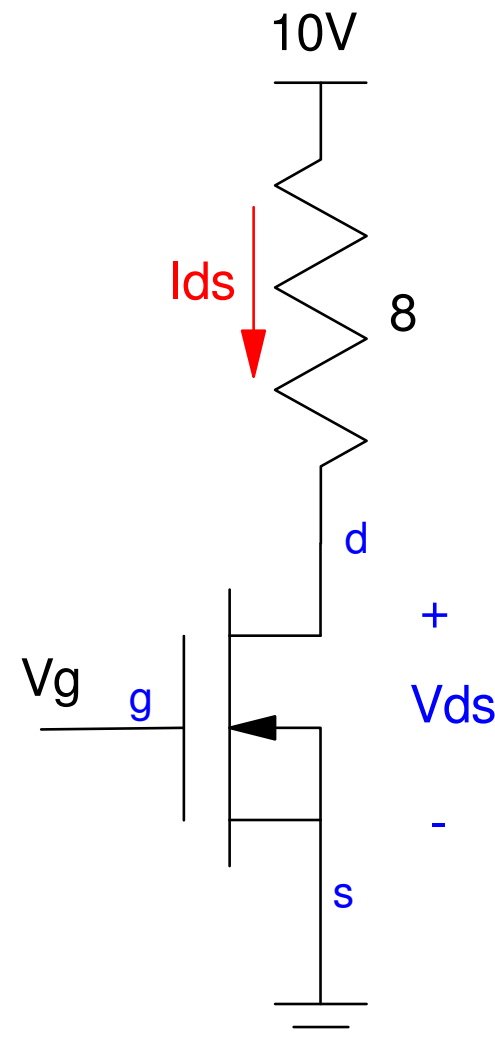
$$I_{ds} = k_n \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds}$$

Saturated Region (option #2 for first equation)

$$I_{ds} = \frac{k_n}{2} (V_{gs} - V_{th})^2$$

Load Line (second equation)

$$V_{ds} + 8I_{ds} = 20$$



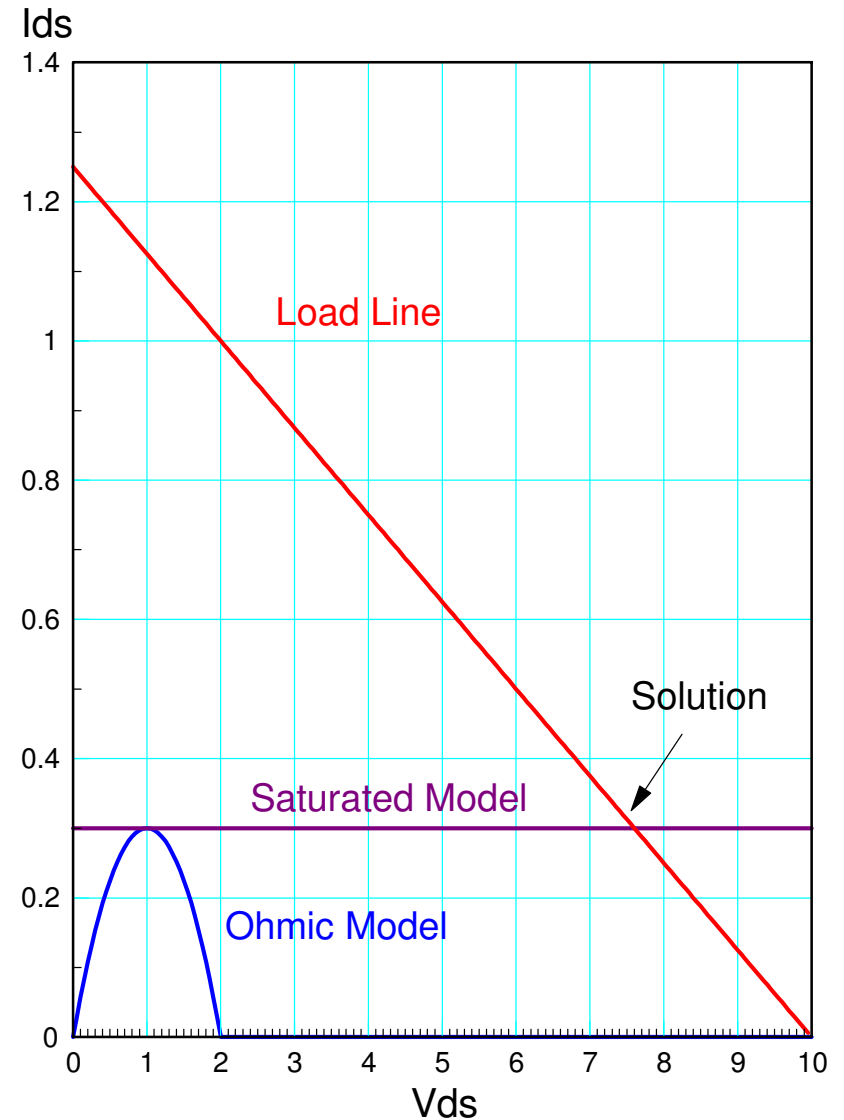
## Case 1: $V_g = 5V$

### Matlab Code

```
kn = 0.6;  
Vth = 4;  
Vg = 5;  
Vds = [0:0.05:10]';  
I1 = kn*(Vg - Vth - Vds/2).*Vds;  
I2 = 0*I1 + max(I1);  
I3 = (10 - Vds) / 8;  
plot(Vds, I1, Vds, I2, Vds, I3)  
ylim([0, 1.5])
```

You're in the saturated region

- Ohmic model has no solution
- Saturated model works



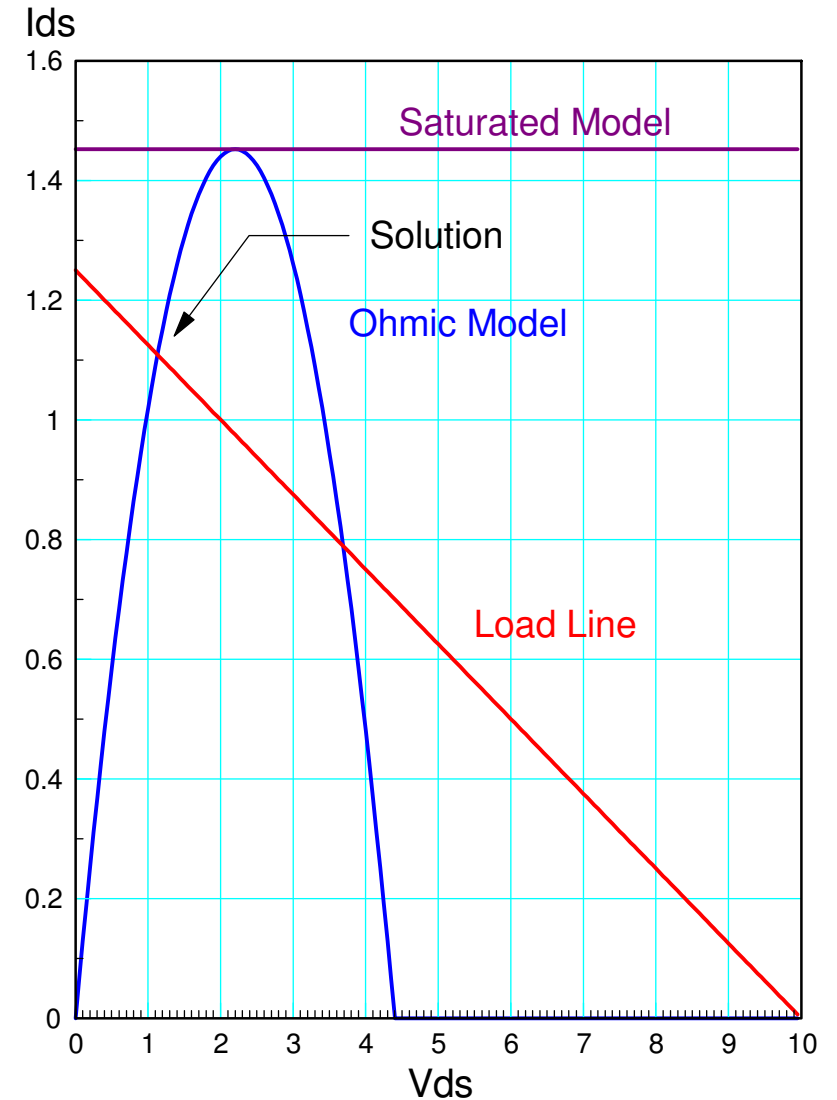
## Case 2: $V_g = 6.2V$

### Matlab Code

```
kn = 0.6;  
Vth = 4;  
Vg = 6.2;  
Vds = [0:0.05:10]';  
I1 = kn*(Vg - Vth - Vds/2).*Vds;  
I2 = 0*I1 + max(I1);  
I3 = (10 - Vds) / 8;  
plot(Vds, I1, Vds, I2, Vds, I3)  
ylim([0, 1.5])
```

### You're in the ohmic region

- Saturated model results in negative  $V_{ds}$
- Ohmic model gives two solutions
- The solution close to  $V_{ds} = 0$  is the correct one



---

# Summary

MOSFETs are voltage controlled resistors

- n-channel MOSFET (similar to NPN transistors)
- p-channel MOSFET (similar to PNP transistors)

MOSFETs have three modes of operation

- Off

$$I_{ds} = 0$$

- Saturated

$$I_d = \frac{k_n}{2}(V_{gs} - V_{th})^2$$

- Ohmic

$$I_d = k_n \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds}$$

