Spring 2019 Purdue University

ECE 255: L15

DC MOSFET Circuits

(Sedra and Smith, 7th Ed., Sec. 5.3)

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PURDUE UNIVERSITY

Announcements

1) HW5 due Monday, Feb 18 5:00 PM in EE-209 Dropbox

2) Exam 1 can be picked up from Mary Ann Satterfield in MSEE 140

Outline

1) DC MOSFET Circuit **Analysis**
2) DC MOSFET Circuit **Design**
3) Examples

IV Summary (enhancement mode)

N-channel saturation

$$V_{GS} > V_{tn} \qquad V_{tn} > 0\ \mathrm{V}$$

$$V_{DS} > V_{DSsat} \qquad V_{DSsat} = V_{GS} - V_{tn}$$

$$I_D = \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2$$

$$I_D = \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2\left(1 + \lambda V_{DS}\right)$$

P-channel saturation

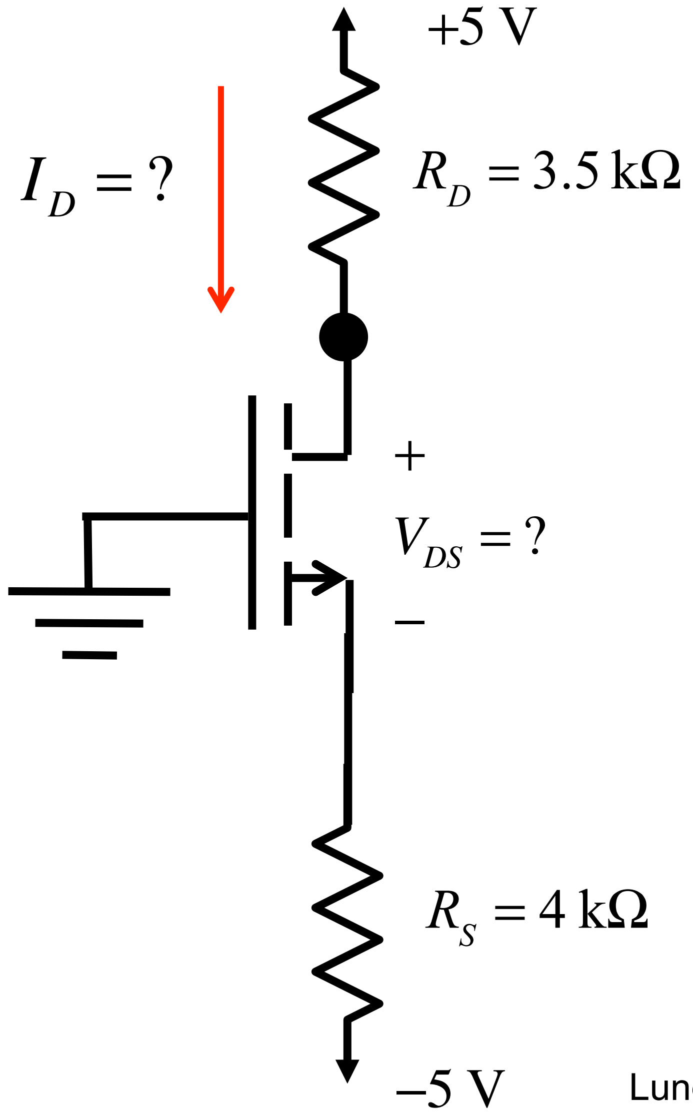
$$V_{SG} > \left|V_{tp}\right| \qquad V_{tp} < 0\ \mathrm{V}$$

$$V_{SD} > V_{SDsat} \qquad V_{SDsat} = V_{SG} - \left|V_{tp}\right|$$

$$I_D = \frac{k_p'}{2}\frac{W}{L}\left(V_{SG} - \left|V_{tp}\right|\right)^2$$

$$I_D = \frac{k_p'}{2}\frac{W}{L}\left(V_{SG} - \left|V_{tp}\right|\right)^2\left(1 + \lambda V_{SD}\right)$$

MOSFET circuit **analysis**



Transistor model:

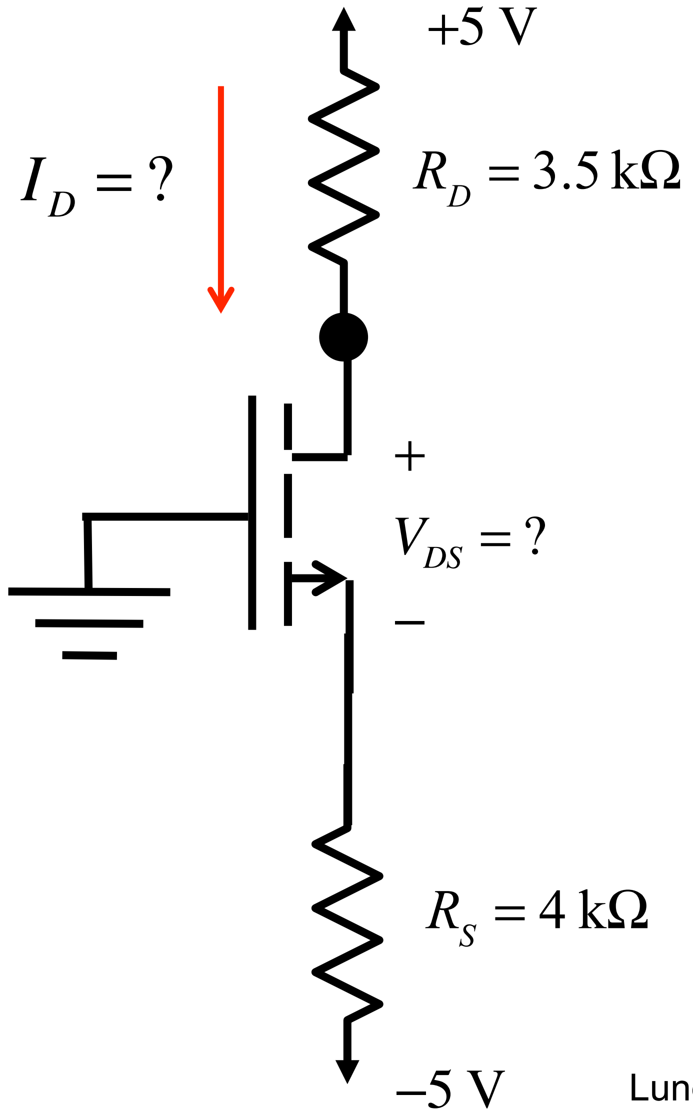
$$I_D = \frac{k'_n}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2$$

$$\frac{k'_n}{2}\frac{W}{L} = 1\ \text{mA/V}^2 \qquad V_{tn} = 1.0\ \text{V}$$

$$I_D = 1\left(V_{GS} - 1.0\right)^2$$

$$V_{GS} = ?$$

MOSFET circuit analysis (ii)



$$I_D = 1\left(V_{GS} - 1.0\right)^2$$

$$V_{GS} = ?$$

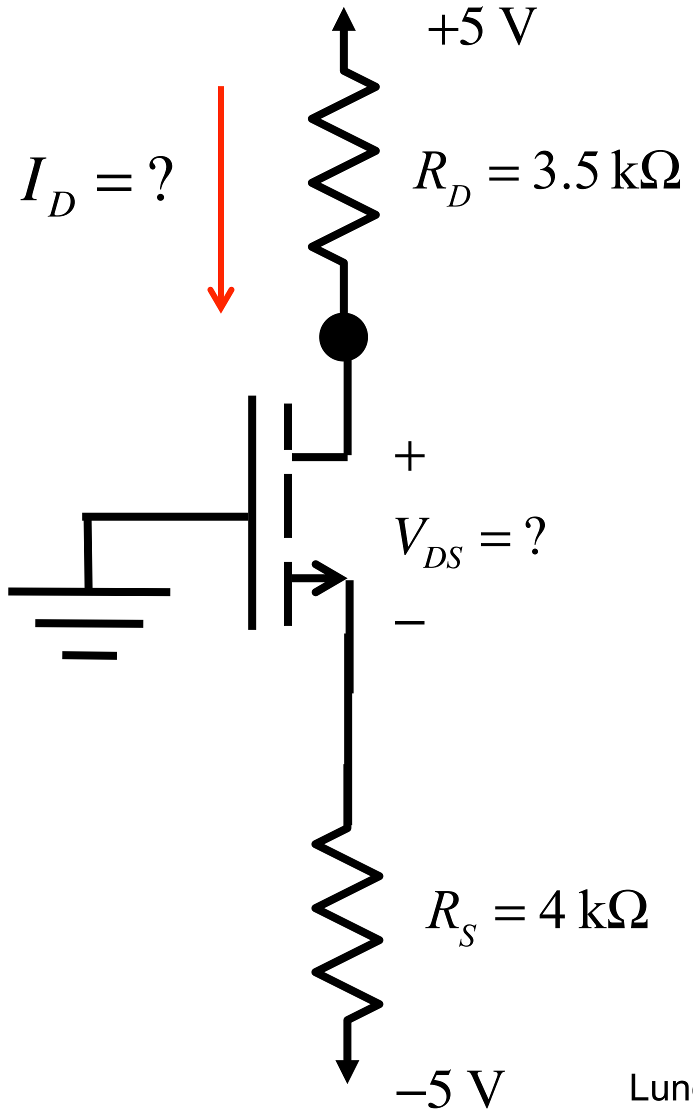
$$V_{GS} = V_G - V_S$$

$$V_S = -5 + I_D R_S$$

$$V_{GS} = 5 - I_D R_S$$

$$I_D = \left(5 - I_D R_S - 1.0\right)^2$$

MOSFET circuit analysis (iii)



$$I_D = \left(5 - I_D R_S - 1.0\right)^2$$

$$I_D = \left(4 - I_D R_S\right)^2 = 16 - 8 I_D R_S + I_D^2 R_S^2$$

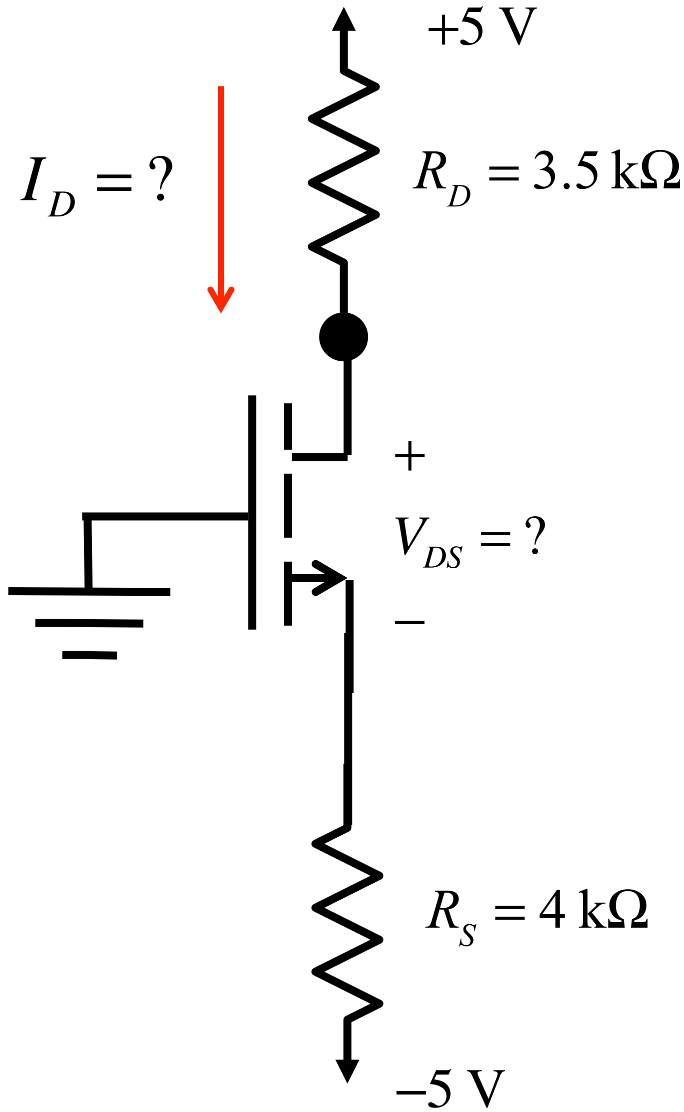
$$I_D^2 R_S^2 - 8 I_D R_S - I_D + 16 = 0$$

$$16 I_D^2 - 33 I_D + 16 = 0$$

$$I_D^2 - 2.06 I_D + 1 = 0$$

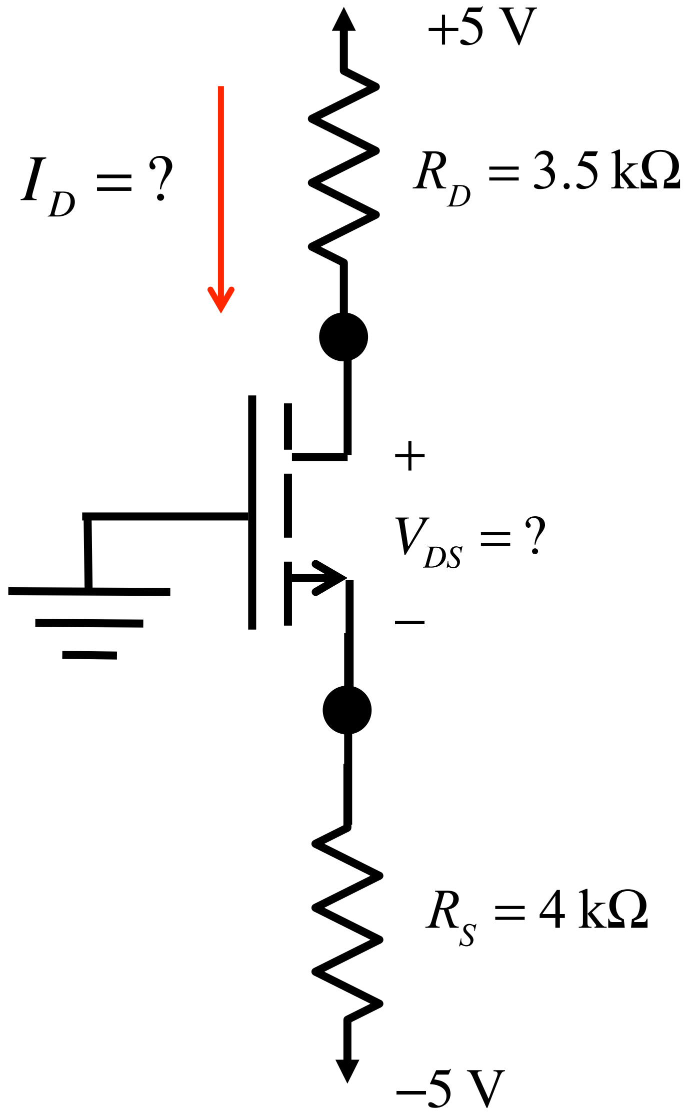
$$I_D = \frac{2.06 \pm \sqrt{\left(2.06\right)^2 - 4}}{2} = 1.28 / 0.76$$

MOSFET circuit analysis (iv)



$I_D = 1.28\ \text{mA}$ **Does not work.**

MOSFET circuit analysis (iv)



$$I_D = 0.76\ \text{mA}$$

$$V_D = 5 - I_D R_D = 2.3\ \text{V}$$

$$V_S = -5 + I_D R_S = -1.96\ \text{V}$$

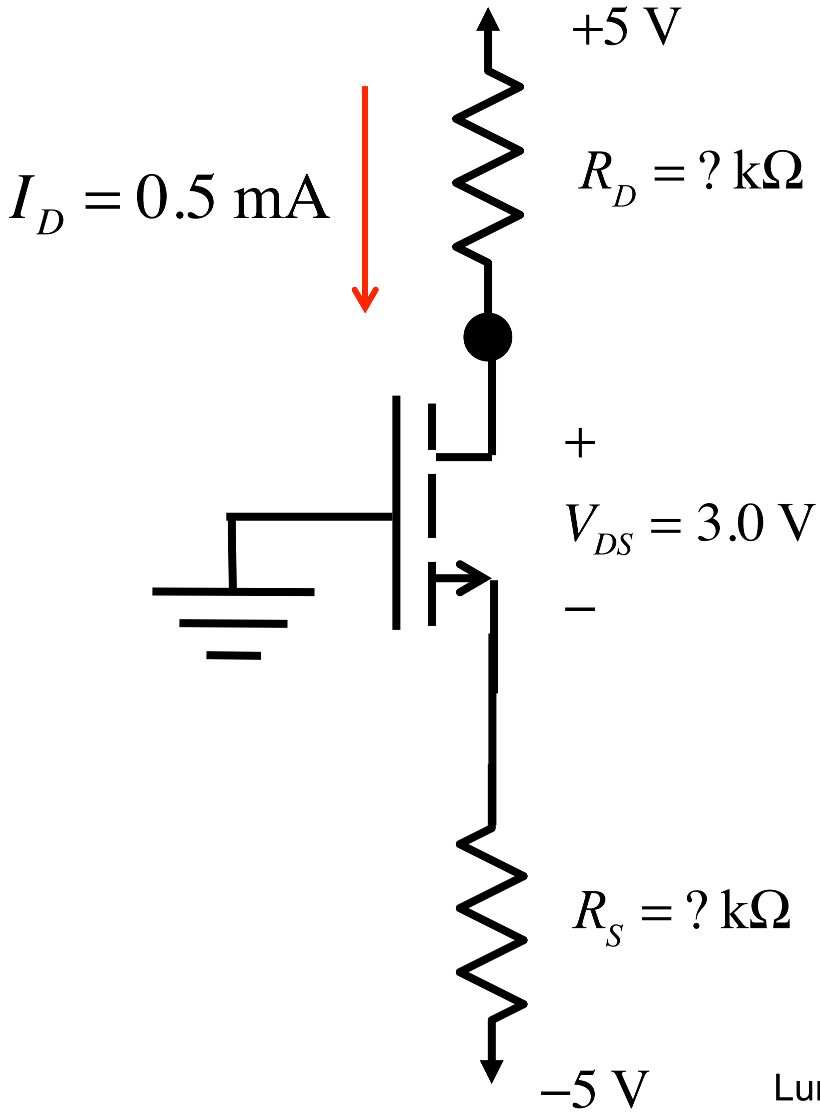
$$V_{GS} = -V_S = 1.96\ \text{V} > V_{tn} \quad ✓$$

$$V_{DS} = V_D - V_S = 4.26\ \text{V}$$

$$V_{DSsat} = V_{GS} - V_{tn} = 0.96\ \text{V}$$

$$V_{DS} > V_{DSsat} \quad ✓$$

MOSFET circuit **design**



Transistor model:

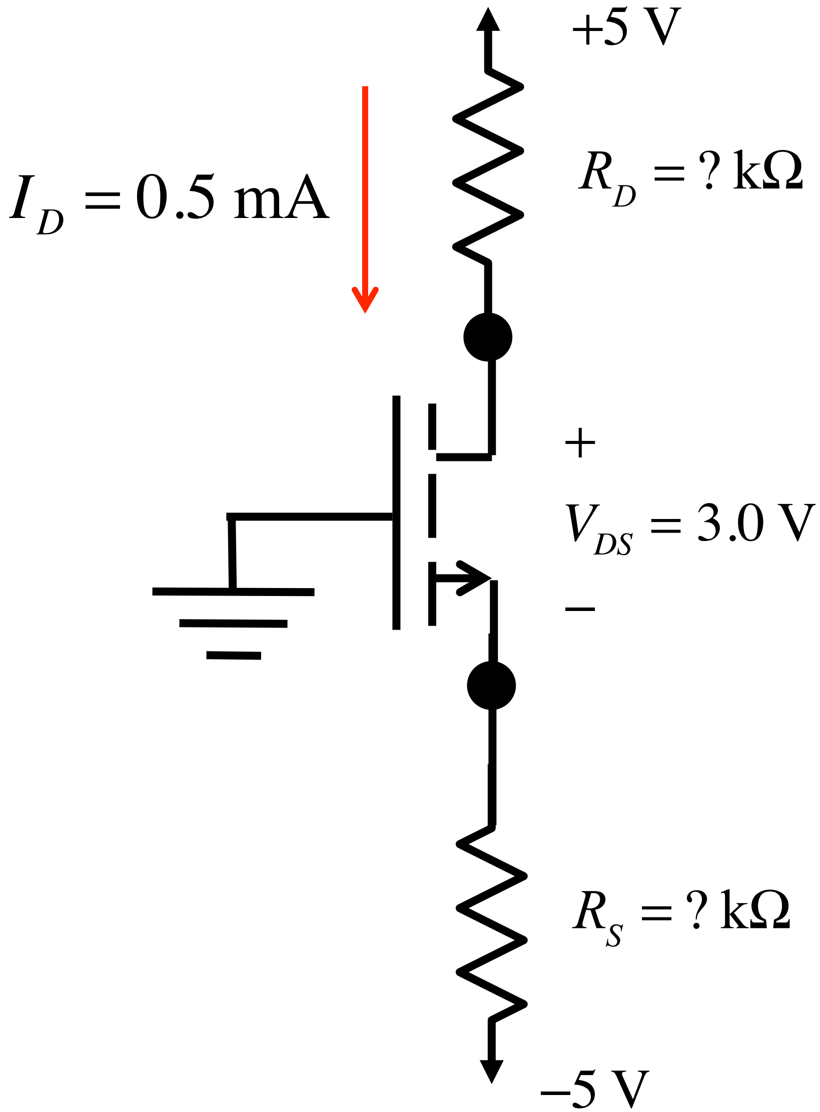
$$I_D = \frac{k'_n}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2$$

$$\frac{k'_n}{2}\frac{W}{L} = 1\ \text{mA/V}^2 \qquad V_{tn} = 1.0\ \text{V}$$

$$I_D = 1\left(V_{GS} - 1.0\right)^2 = 0.5$$

$$V_{GS} = 1.707$$

MOSFET circuit design (ii)



$$V_{GS} = 1.707$$

$$V_{GS} = V_G - V_S = 1.707$$

$$V_S = -1.707 = -5 + I_D R_S$$

$$R_S = 6.6\ \text{k}\Omega$$ ✓

$$V_{DS} = V_D - V_S = V_D + 1.707 = 3.0$$

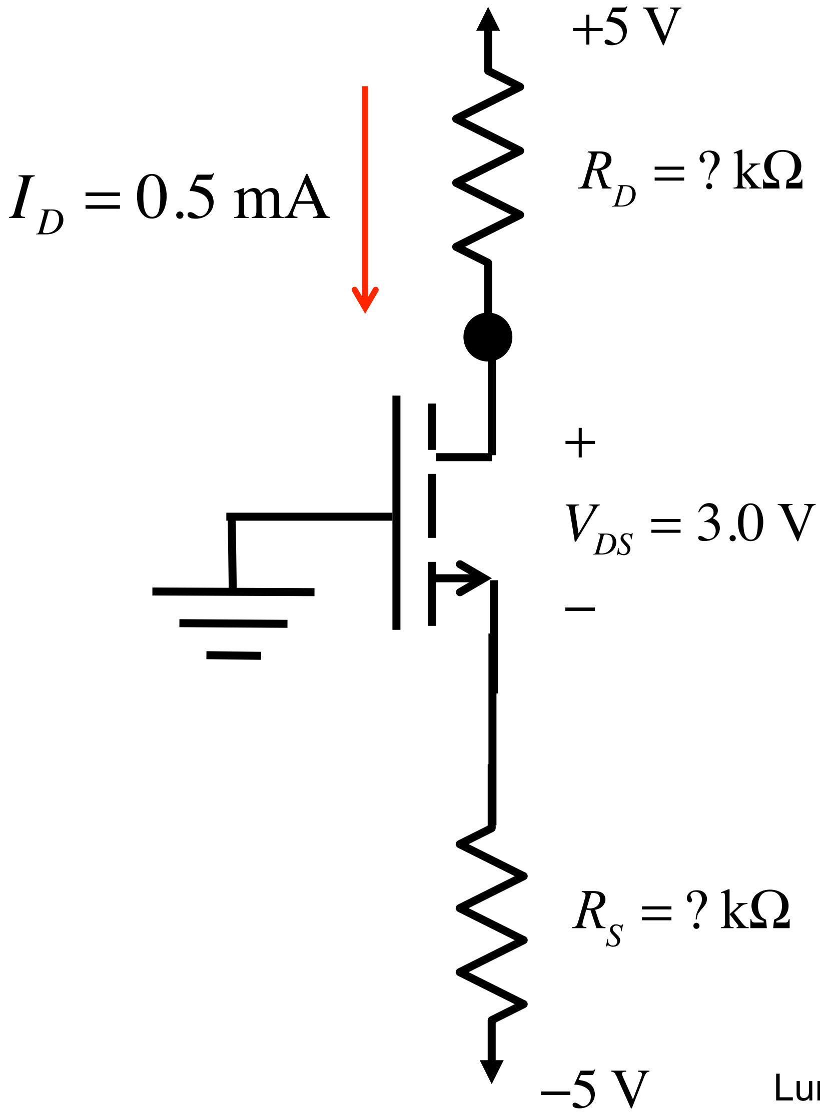
$$V_D = 1.29 = 5 - 0.5 R_D$$

$$R_D = 7.4\ \text{k}\Omega$$ ✓

Outline

1) DC MOSFET Circuit **Analysis**
2) DC MOSFET Circuit **Design**
3) Examples

MOSFET circuit **design**



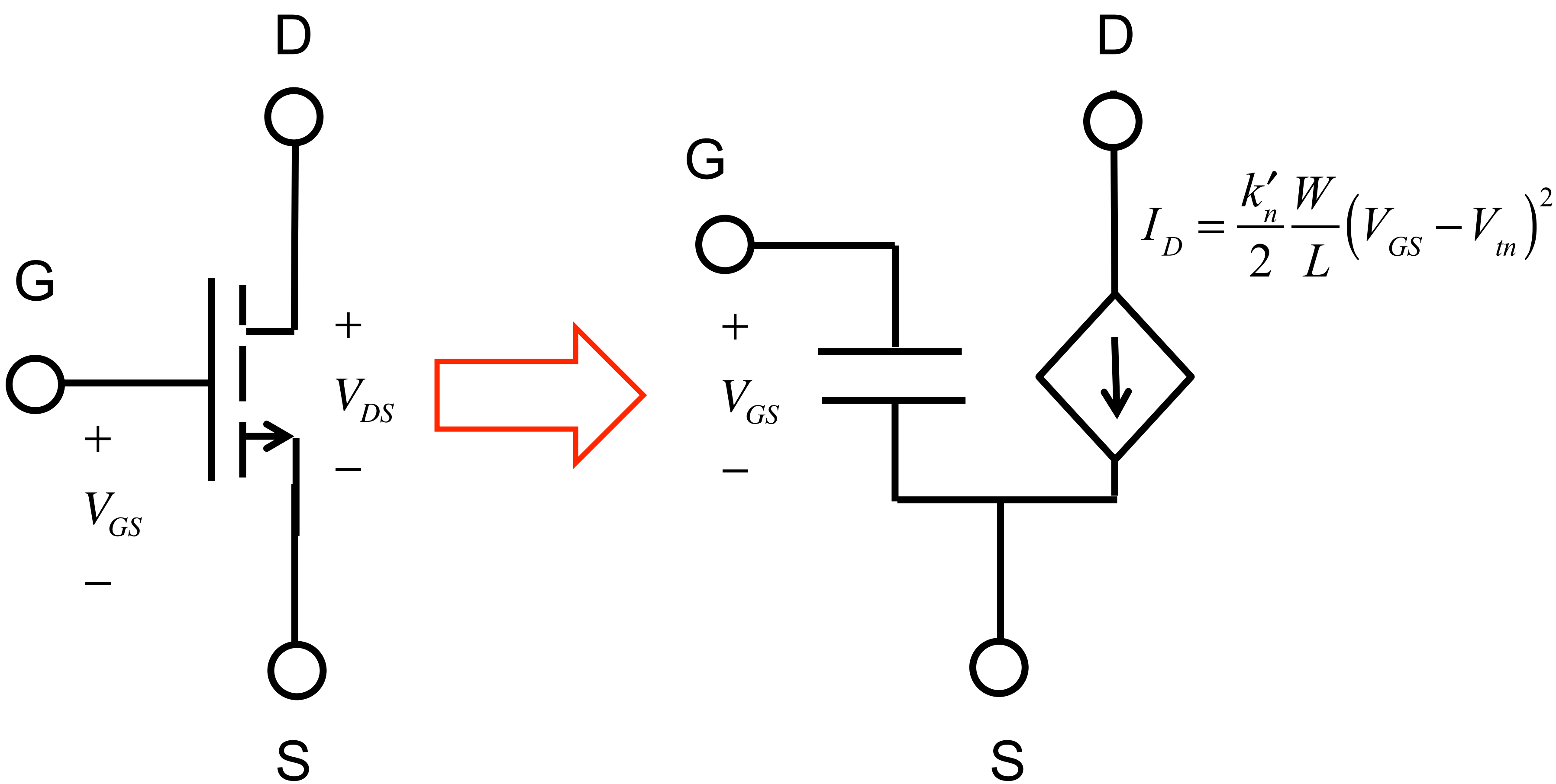
Transistor model:

$$I_D = \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2$$

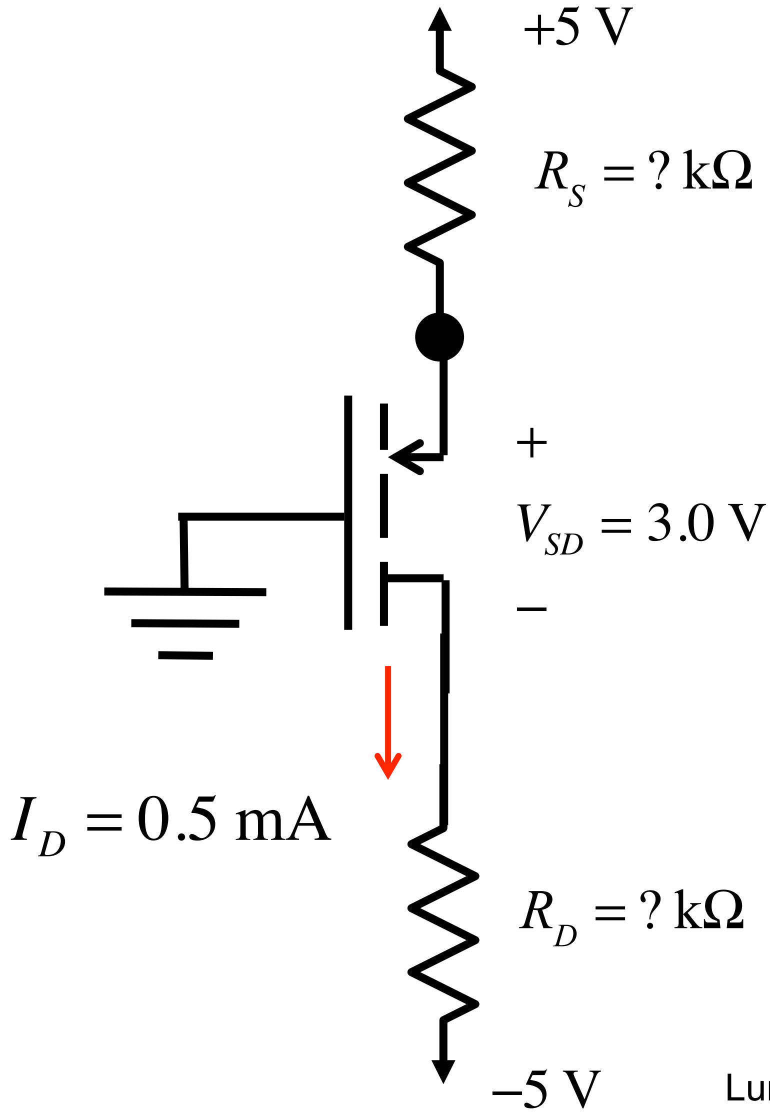
$$\frac{k_n'}{2}\frac{W}{L} = 1\ \text{mA/V}^2 \qquad V_{tn} = 1.0\ \text{V}$$

Select the resistors to produce a given I_D and V_{DS}

MOSFET DC model



P-MOSFET circuit **design**



Transistor model:

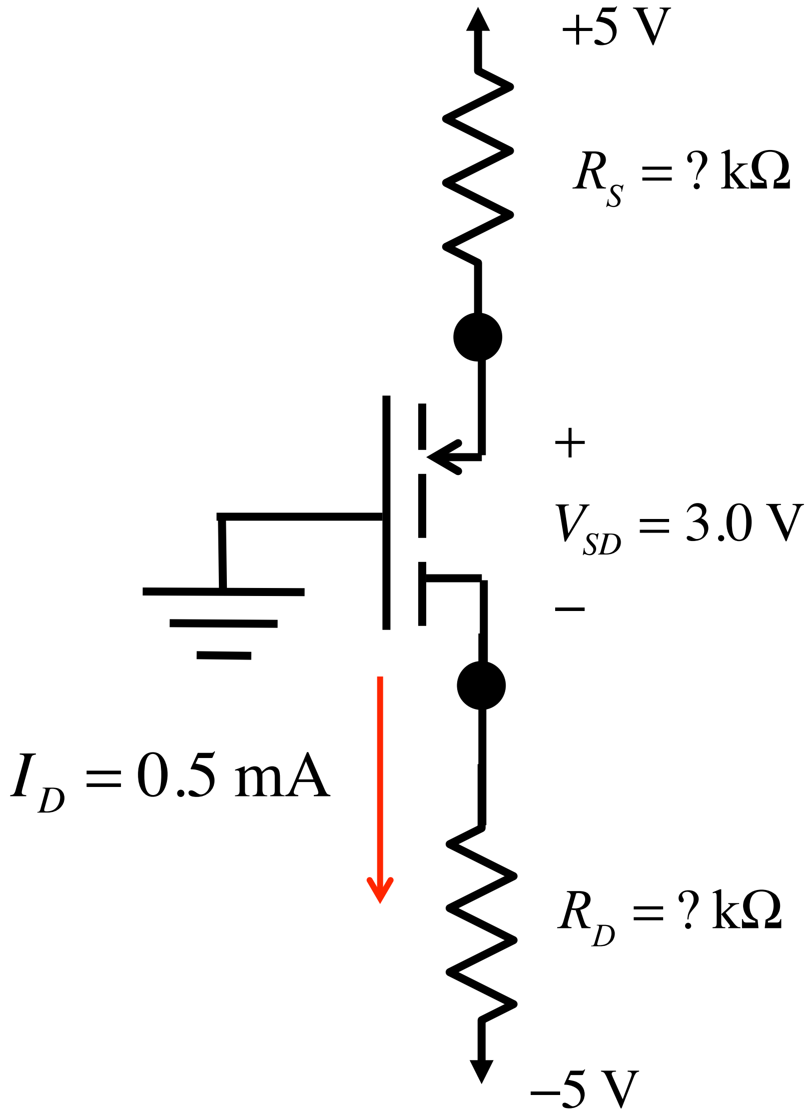
$$I_D = \frac{k'_p}{2}\frac{W}{L}\left(V_{SG} - \left|V_{tp}\right|\right)^2$$

$$\frac{k'_p}{2}\frac{W}{L} = 1\ \text{mA/V}^2 \quad V_{tp} = -1.0\ \text{V}$$

$$I_D = 1\left(V_{SG} - 1.0\right)^2 = 0.5$$

$$V_{SG} = 1.707$$

P-MOSFET circuit design (ii)



$$V_{SG} = 1.707$$

$$V_{SG} = V_S - V_G = 1.707$$

$$V_S = 5 - I_D R_S = 1.707$$

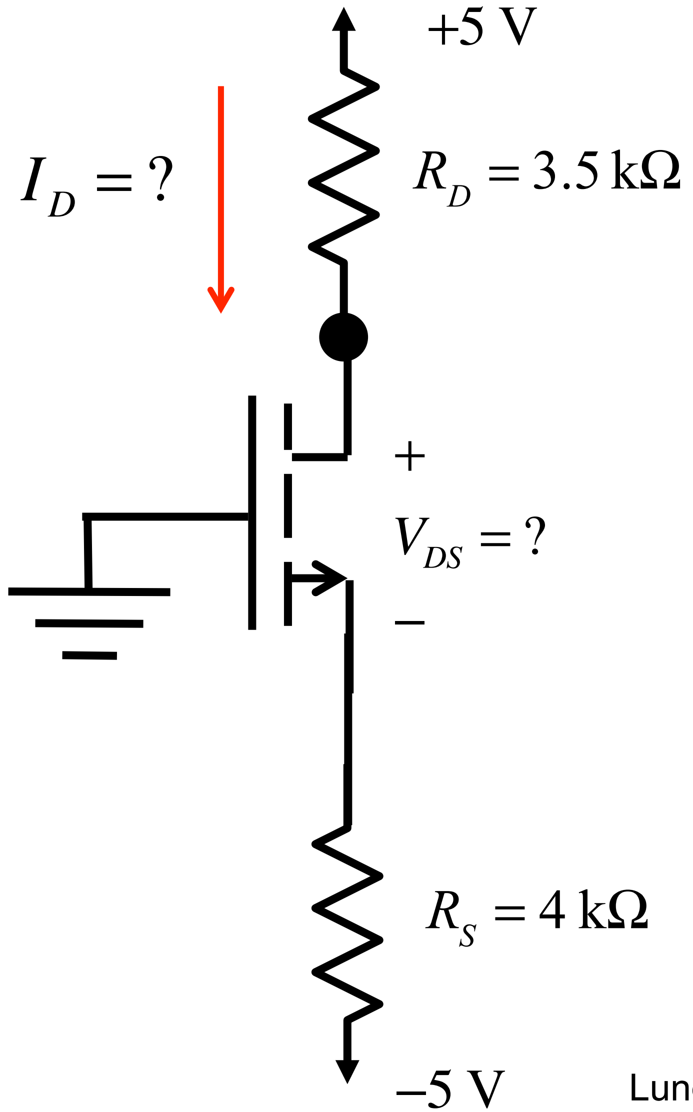
$$R_S = 6.6\ \text{k}\Omega$$ ✓

$$V_{SD} = V_S - V_D = 1.707 - V_D = 3.0$$

$$V_D = -1.29 = -5 + 0.5 R_D$$

$$R_D = 7.4\ \text{k}\Omega$$ ✓

MOSFET circuit **analysis**



Transistor model:

$$I_D = \frac{k'_n}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2$$

$$\frac{k'_n}{2}\frac{W}{L} = 1\ \text{mA/V}^2 \qquad V_{tn} = 1.0\ \text{V}$$

Given a transistor and a circuit, find I_D and V_{DS}

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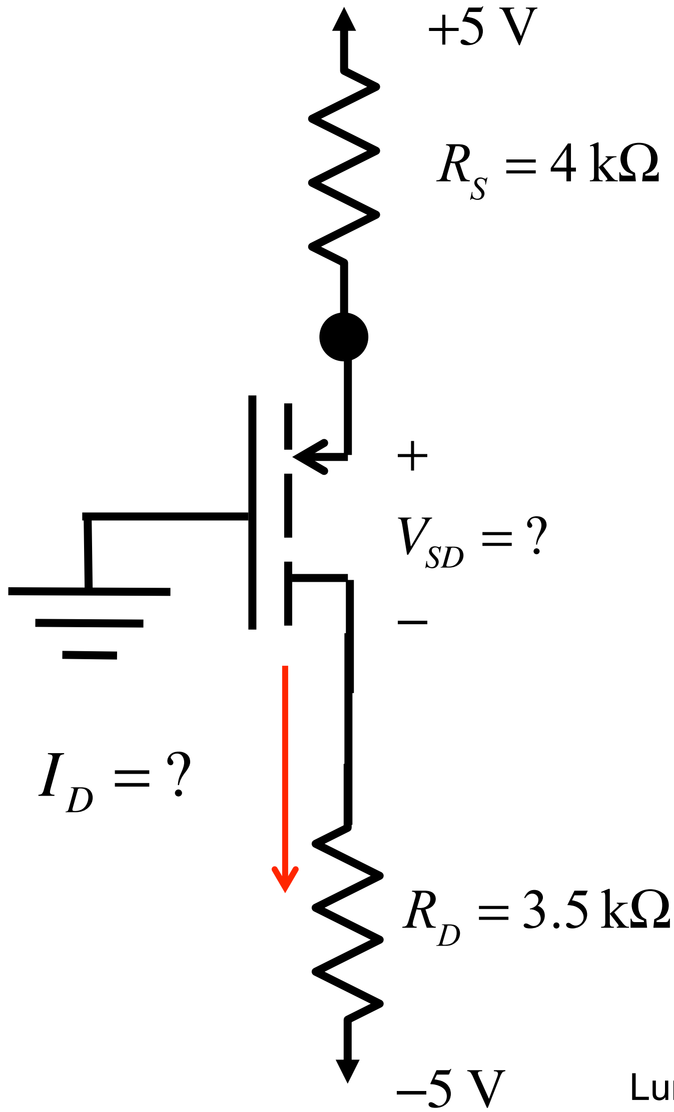
P-MOSFET circuit analysis



Transistor model:

$$I_D = \frac{k'_p}{2}\frac{W}{L}\left(V_{SG} - \left|V_{tp}\right|\right)^2$$

$$\frac{k'_p}{2}\frac{W}{L} = 1\ \text{mA/V}^2 \qquad V_{tp} = -1.0\ \text{V}$$

$$I_D = 1\left(V_{SG} - 1.0\right)^2$$

$$V_{SG} = 5 - I_D R_S$$

P-MOSFET circuit analysis

$$I_D = 1(V_{SG} - 1.0)^2 \qquad V_{SG} = 5 - I_D R_S$$

$$I_D = (5 - I_D R_S - 1.0)^2$$

$$I_D^2 - 2.06 I_D + 1 = 0$$

$$I_D = 1.28 \text{ or } 0.76$$

$$\boxed{I_D = 0.76}$$

$$I_D = (5 - V_{SG})/R_S = (5 - V_{SG})/4$$

$$4V_{SG}^2 - 7V_{SG} - 1 = 0$$

$$V_{SG} = 1.88 \text{ or } -0.13$$

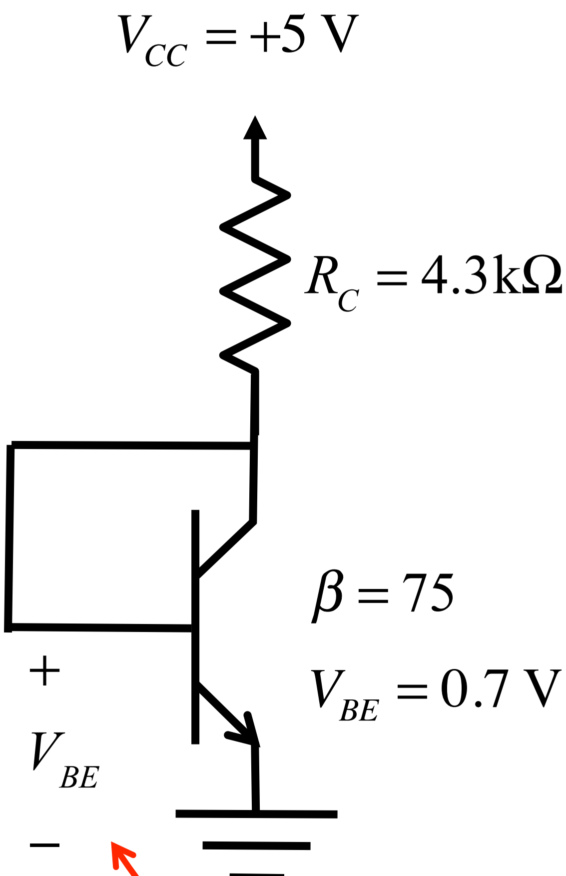
$$V_{SG} = 1.88$$

$$\boxed{I_D = 0.77}$$

Examples

To ***really*** learn this, we need to work out a lot of examples.

Example 1a: analysis



1) Operating region?

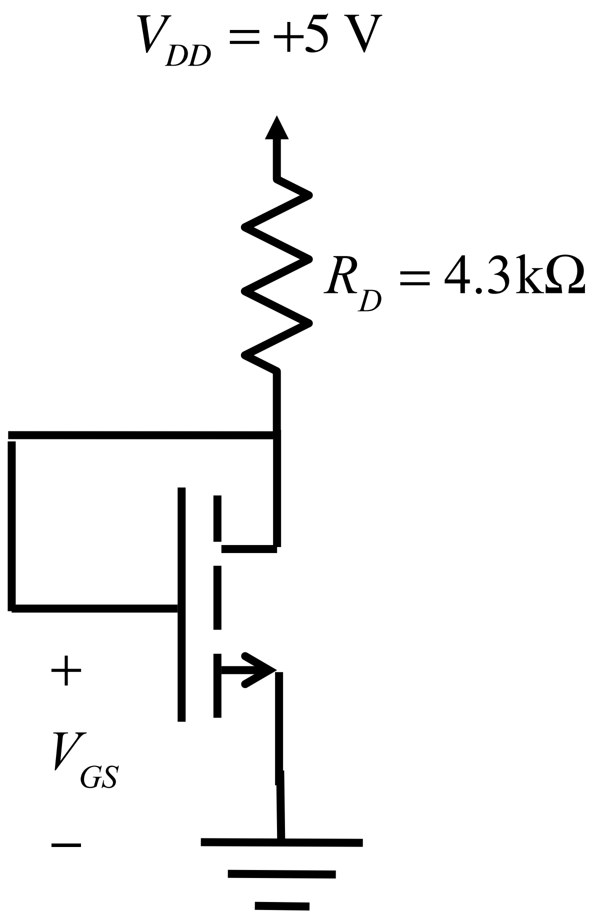
$$I_R = \frac{5-0.7}{R_C} = \frac{4.3}{4.3} = 1.0\text{ mA}$$

$$I_C + I_B = I_R$$

$$I_C = I_R \frac{\beta}{\beta+1} = 1.0 \frac{75}{76} = 0.99\text{ mA}$$

We can guess this voltage

Example 1b: analysis



1) Operating region?

$$V_{GS} = V_D$$

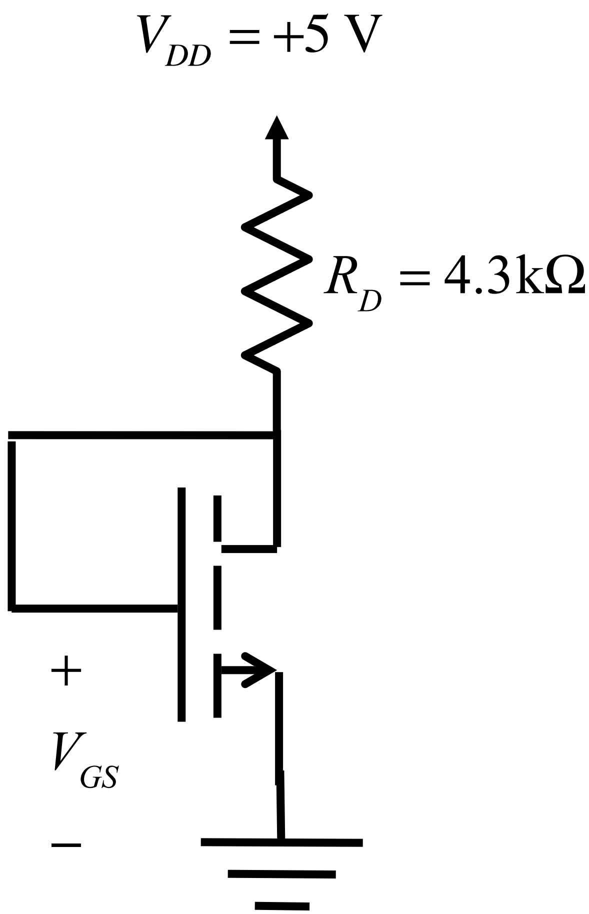
$$V_{DS} = V_D$$

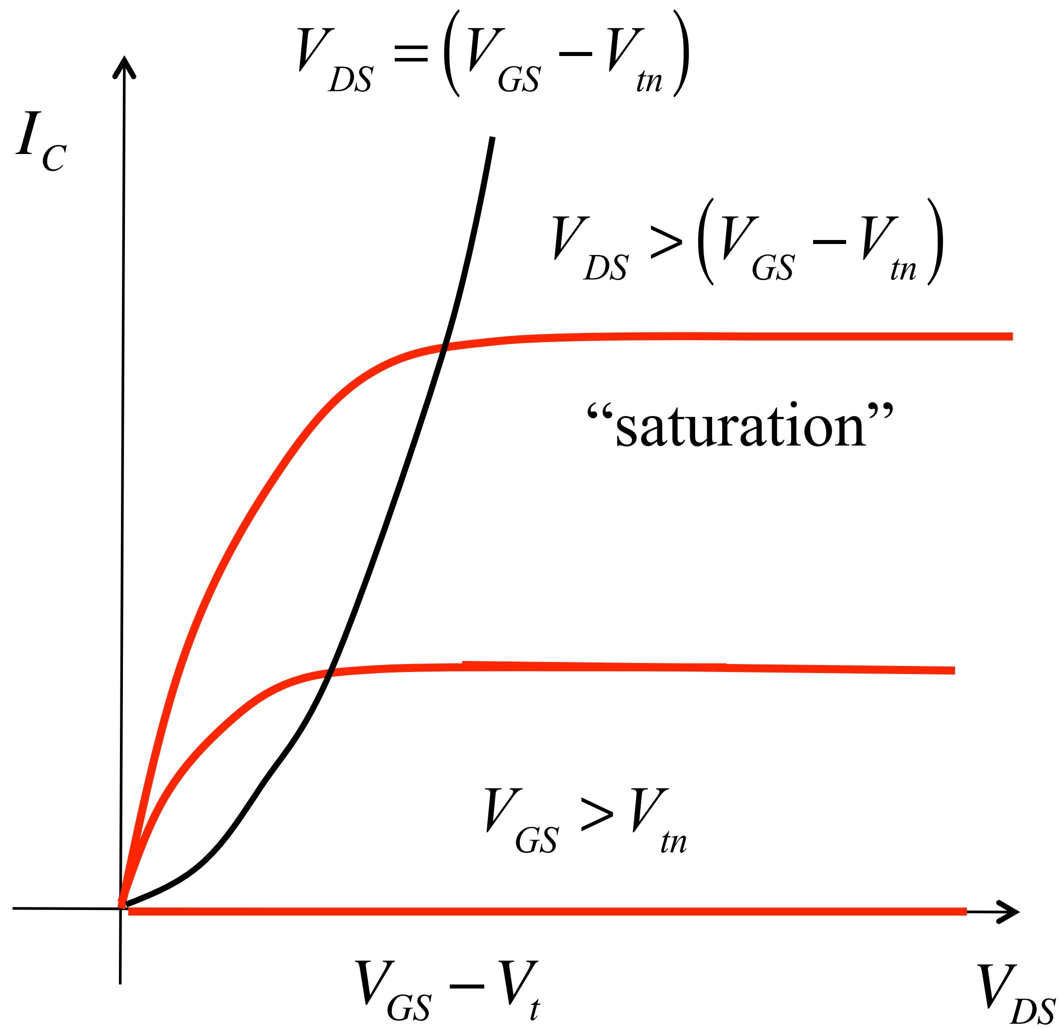
$$V_{DS} > V_{GS} - V_{tn}$$

Saturation

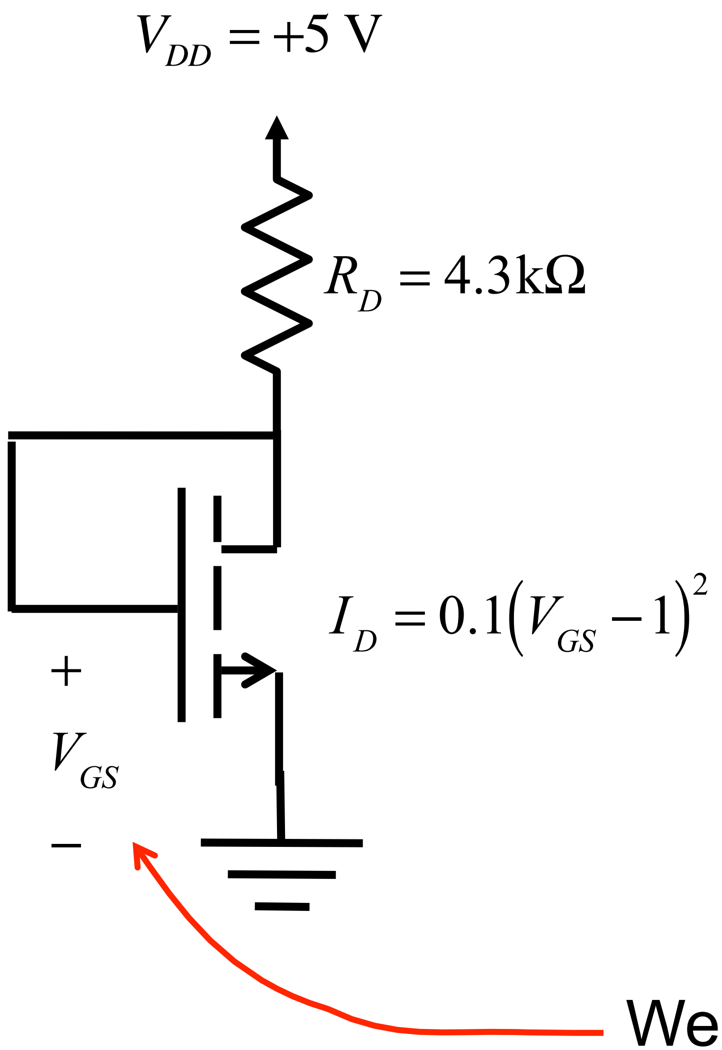
$$I_D = \frac{k'_n}{2}\frac{W}{L}\left(V_{GS} - V_{tn}\right)^2$$

Example 1b: analysis





Example 1b: analysis



$$I_D = 0.1\left(V_{GS} - 1\right)^2$$

$$V_{GS} = 5 - I_D R_D = 5 - 4.3 I_D$$

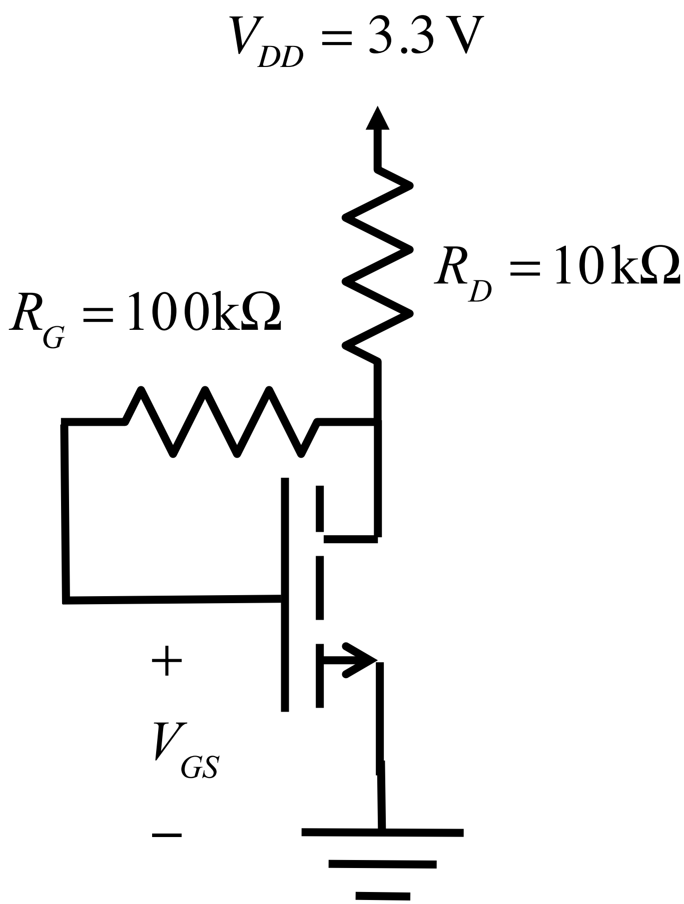
$$I_D^2 - 2.86 I_D + 1.35 = 0$$

$$I_D = 2.26 \text{ or } 0.60$$

$$\boxed{I_D = 0.60}$$

We **can't** guess this voltage

Practice



Transistor model:

$$I_D = \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - |V_{tn}|\right)^2$$

$$I_D = \frac{k_n}{2}\left(V_{GS} - |V_{tn}|\right)^2$$

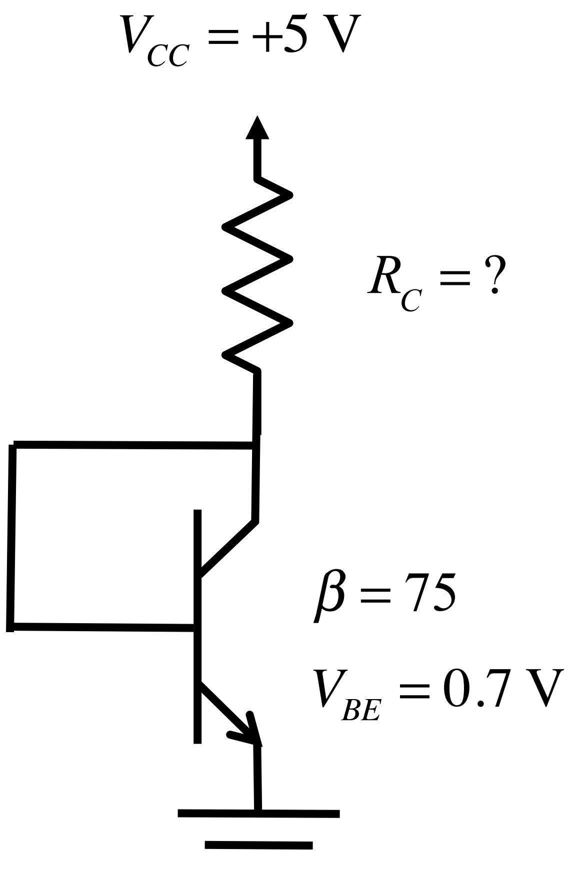
$k_n = 260\,\mu\text{A/V}^2 \qquad V_{tn} = 1.0\,\text{V}$

Show that:

$$I_D = 0.13\,\text{mA}$$

$$V_{DS} = 2.0\,\text{V}$$

Example 2a: design



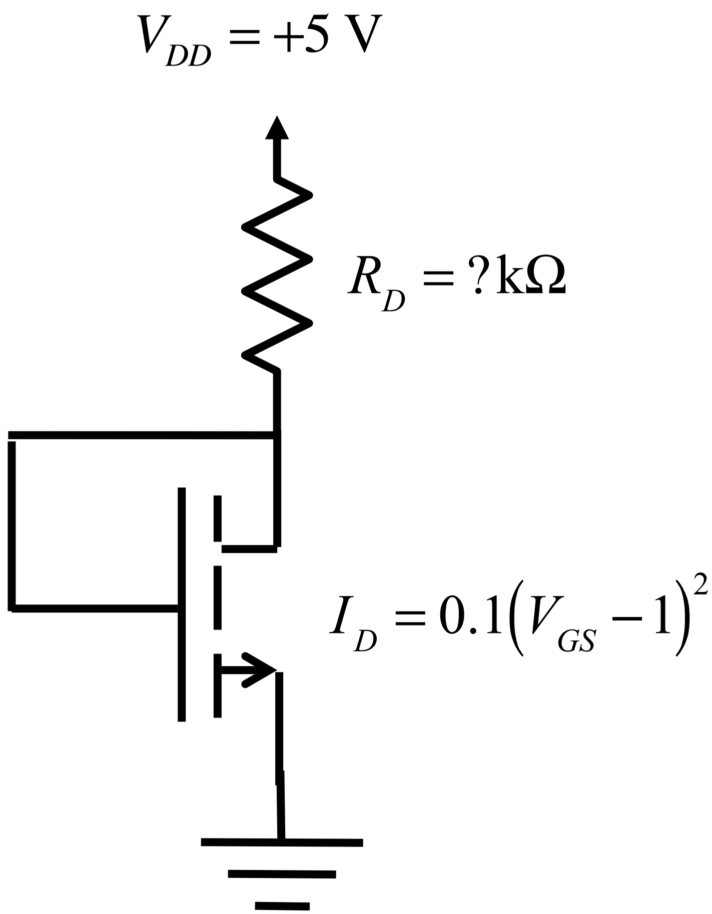
Design for: $I_C = 0.5\,\text{mA}$

$$I_R = I_C\frac{\beta+1}{\beta}$$

$$I_R = 0.5\frac{76}{75} = \frac{5-0.7}{R_C}$$

$$R_C = 8.49\,\text{k}\Omega$$

Example 2b: design



Design for: $I_D = 0.5\,\text{mA}$

$$I_D = 0.1(V_{GS} - 1)^2$$

$$0.5 = 0.1(V_{GS} - 1)^2$$

$$V_{GS} = 3.24\text{ V}$$

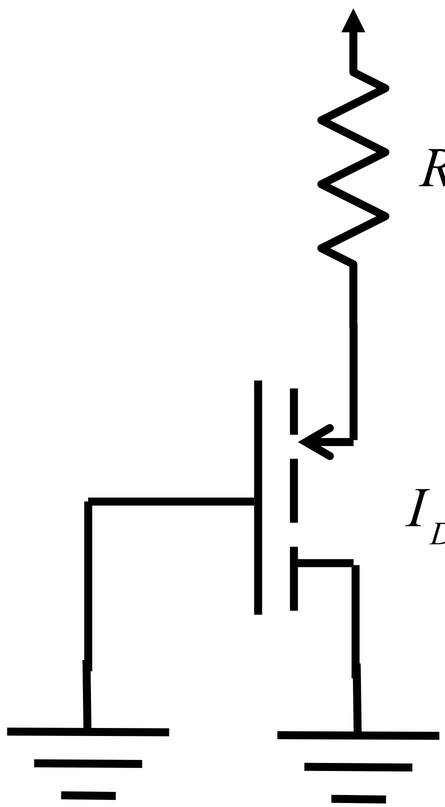
$$V_{GS} = V_D = 3.24\text{ V}$$

$$R_D = \frac{5 - 3.24}{0.5} = 3.53\,\text{k}\Omega$$

$$I_D = \frac{k'_n}{2}\frac{W}{L}(V_{GS} - V_{tn})^2$$

Example 3: design (i)

$V_{DD} = +5\ \text{V}$



$R_S = ?\ \text{k}\Omega$

$I_D = 0.1\left(V_{SG} - 1\right)^2$

$$I_D = \frac{k'_p}{2}\frac{W}{L}\left(V_{SG} - \left|V_{tp}\right|\right)^2$$

Design for: $I_D = 0.5\,\text{mA}$

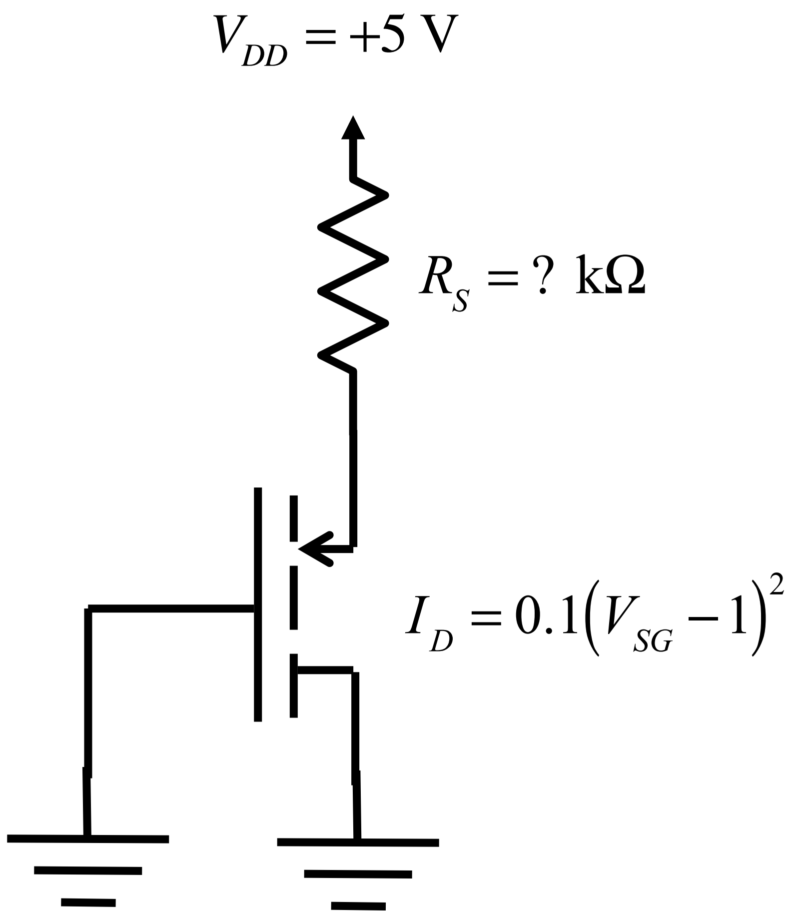
1) Operating region?

$V_{DS} > V_{GS} - V_{tn}$?

$V_{SD} > V_{SG} - \left|V_{tp}\right|$?

saturation

Example 3: design (ii)



$$I_D = \frac{k'_p}{2}\frac{W}{L}\left(V_{SG} - \left|V_{tp}\right|\right)^2$$

Design for: $I_D = 0.5\,\text{mA}$

$$I_D = 0.1\left(V_{SG} - 1\right)^2$$

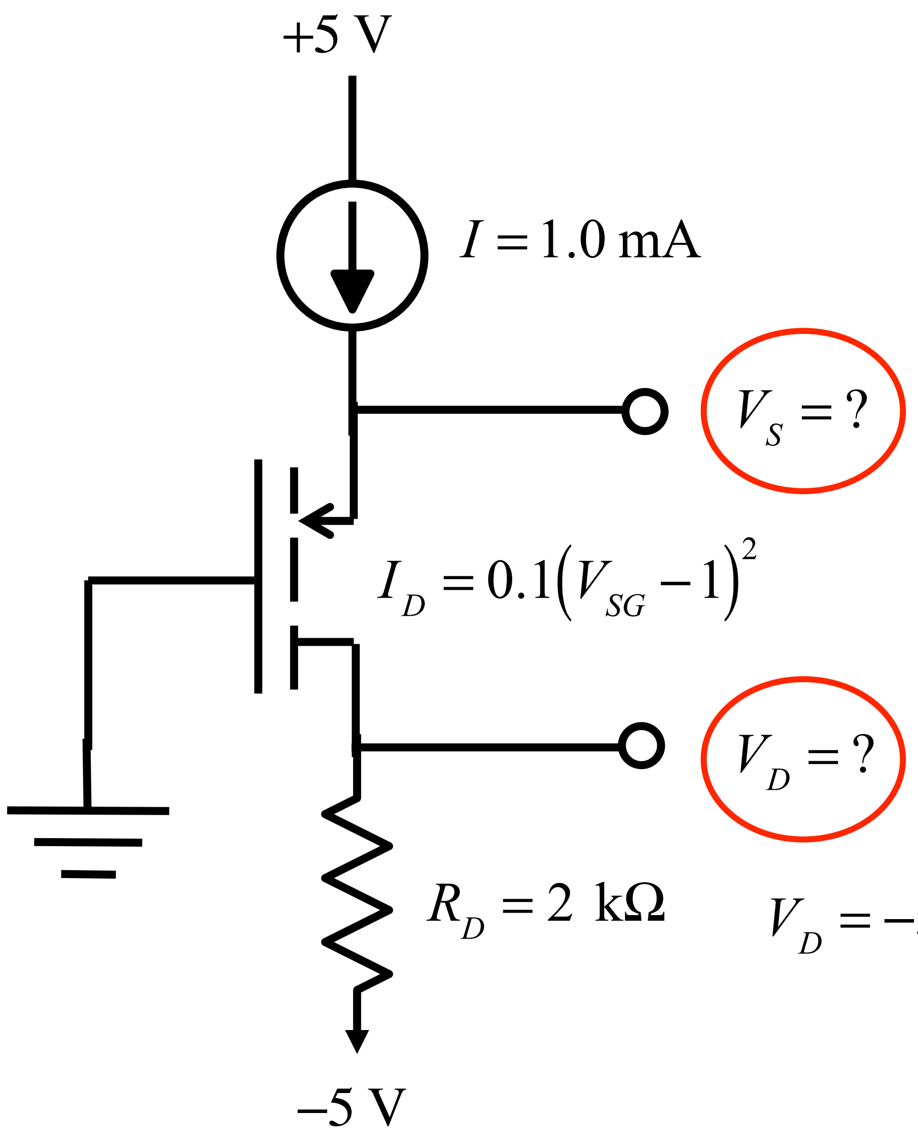
$$0.5 = 0.1\left(V_{SG} - 1\right)^2$$

$$V_{SG} = 3.24\text{ V}$$

$$V_{SG} = V_S = 3.24\text{ V}$$

$$R_D = \frac{5 - 3.24}{0.5} = 3.53\,\text{k}\Omega$$

Example 4



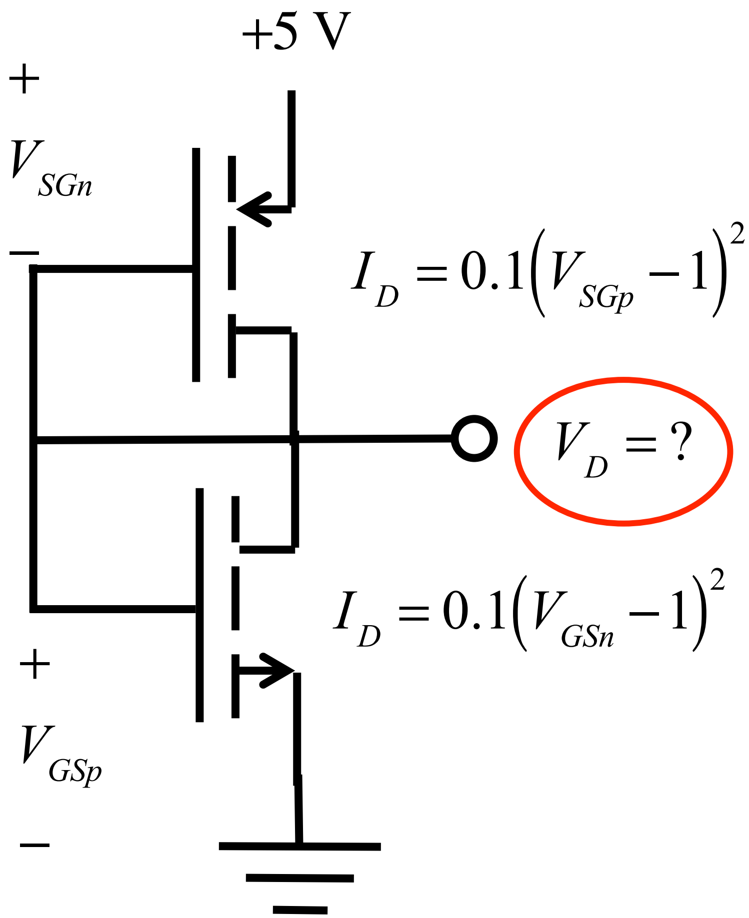
$$V_S = V_{SG}$$

$$1 = 0.1(V_{SG} - 1)^2$$

$$V_{SG} = V_S = 4.16 \text{ V}$$

$$V_D = -5 + I_D R_D = -5 + 1 \times 2 = -3 \text{ V}$$

Example 5



1) Operating region?

$$V_{DSn} = V_D \quad V_{GSn} = V_D$$

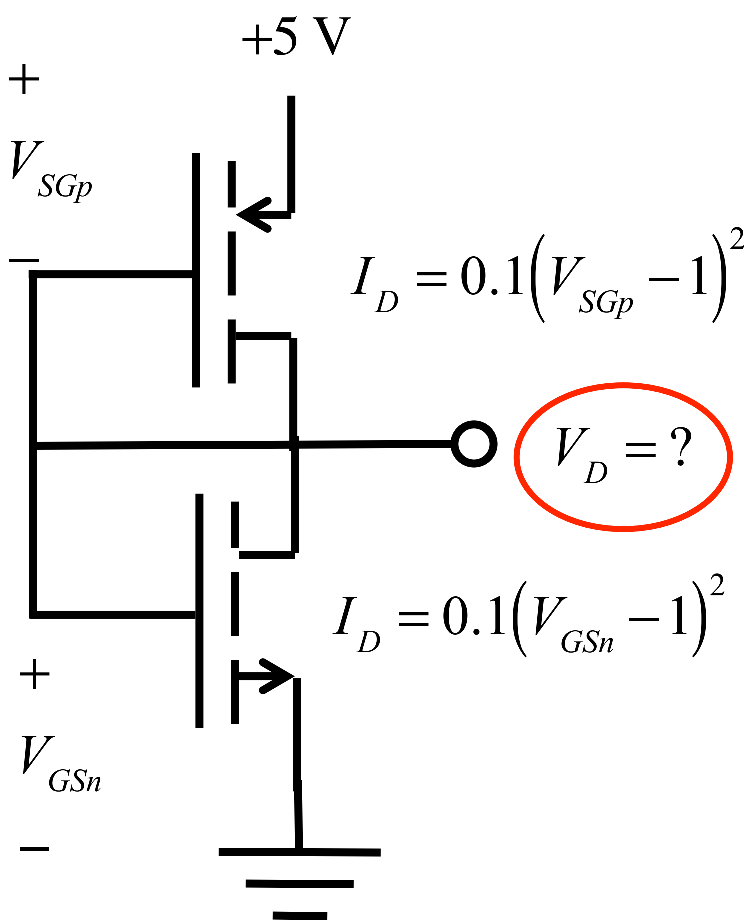
$$V_{DSn} > \left(V_{GSn} - V_{tn}\right)$$

$$V_{SDp} = 5 - V_D \qquad V_{SGp} = 5 - V_D$$

$$V_{SDp} > \left(V_{SGp} - \left|V_{tp}\right|\right)$$

saturation

Example 5



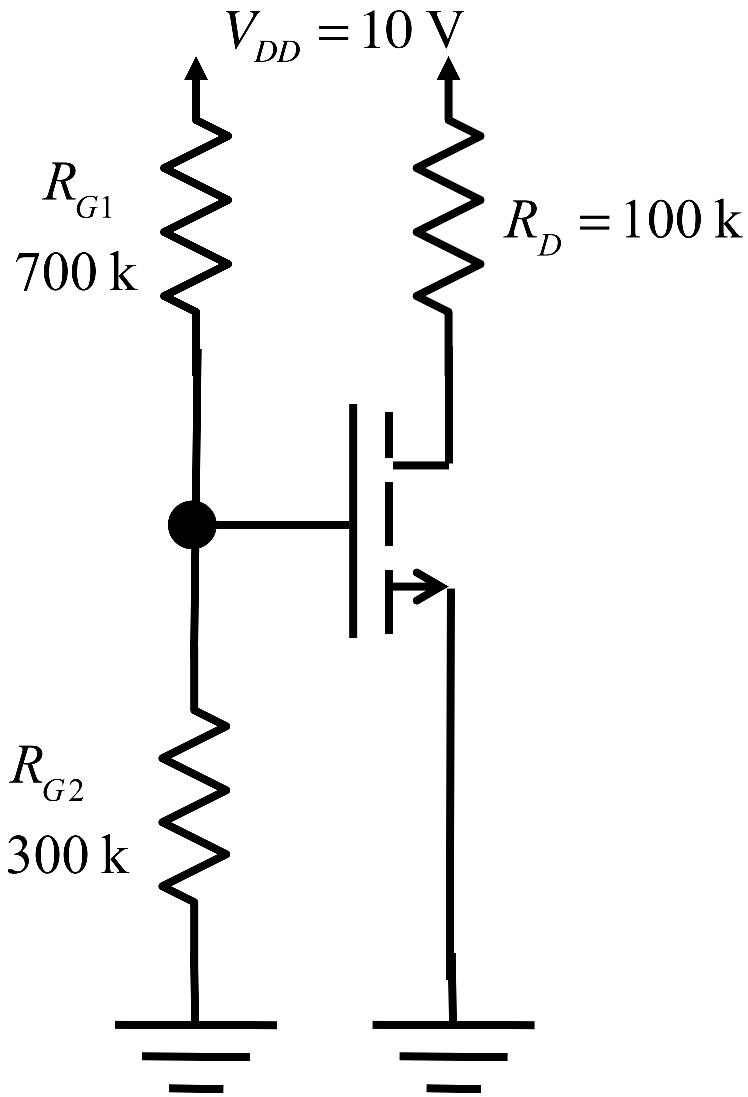
$$V_{GSn} = V_{SGp}$$ Why?

$$V_{GSn} + V_{SGp} = 5$$

$$V_D = 2.5$$

$$I_D = 0.1\left(2.5 - 1\right)^2 = 0.225\ \text{mA}$$

Example 6: Analysis



Transistor model:

$$I_D = \frac{k'_n}{2}\frac{W}{L}\left(V_{GS} - |V_{tn}|\right)^2$$

$$I_D = \frac{k_n}{2}\left(V_{GS} - |V_{tn}|\right)^2$$

$k_n = 25\ \mu\text{A/V}^2$ $\qquad$ $V_{tn} = 1.0$ V

$$I_D = \frac{0.025}{2}\left(V_{GS} - 1\right)^2 \text{ mA} \qquad V_{GS} = 3$$

$$I_D = 0.05 \text{ mA}$$

$$V_{DS} = 5 \text{ V} > V_{GD} - V_{tn}$$

Summary

1) DC MOSFET **analysis** often involves solving a quadratic equation and throwing away the unphysical solution.

2) DC MOSFET **design** is easier.

DC MOSFET Circuits

1) DC MOSFET Circuit **Analysis**
2) DC MOSFET Circuit **Design**
3) Examples