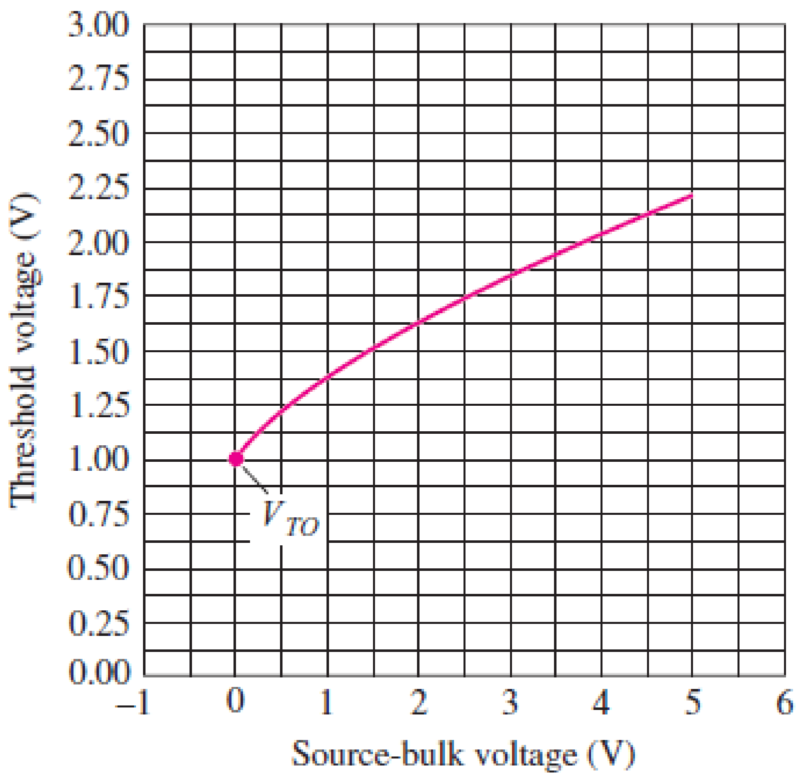
# Announcements

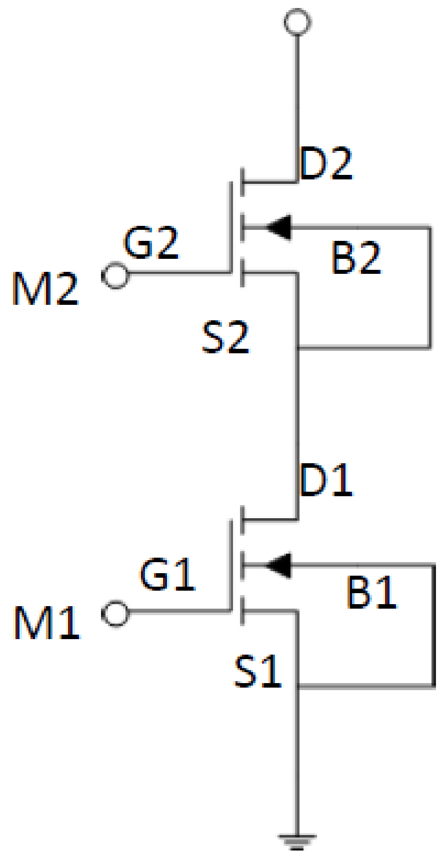
- Exam 1 grading issues:
  - Write out the basis for your request for regrading and staple it to your exam.
  - Return to me by class on Tuesday.
  - Grades can either rise or fall on regrade (will look at whole problem).

# Body Effect (Substrate Sensitivity)



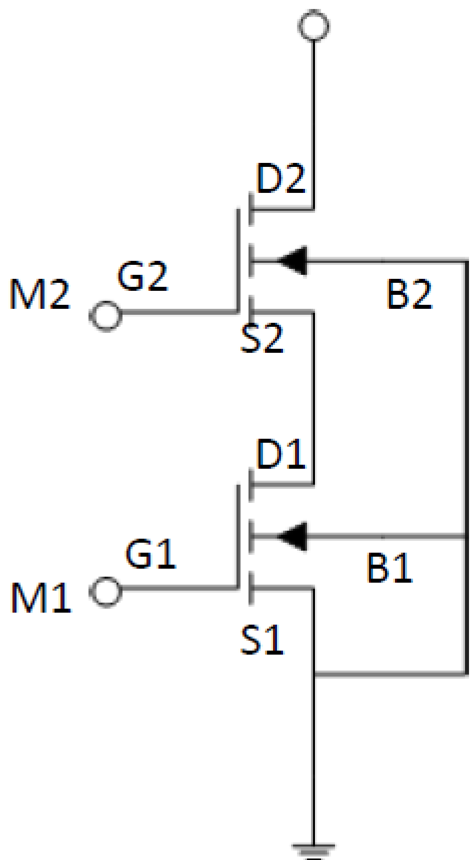

$$V_{TN} = V_{TO} + \gamma(\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F})$$

# Body Effect (Substrate Sensitivity)




- Transistor M1: S1 and B1 tied together, $v_{SB1} = 0$. No Body effect
- Same as Transistor M2.

# Body Effect (Substrate Sensitivity)

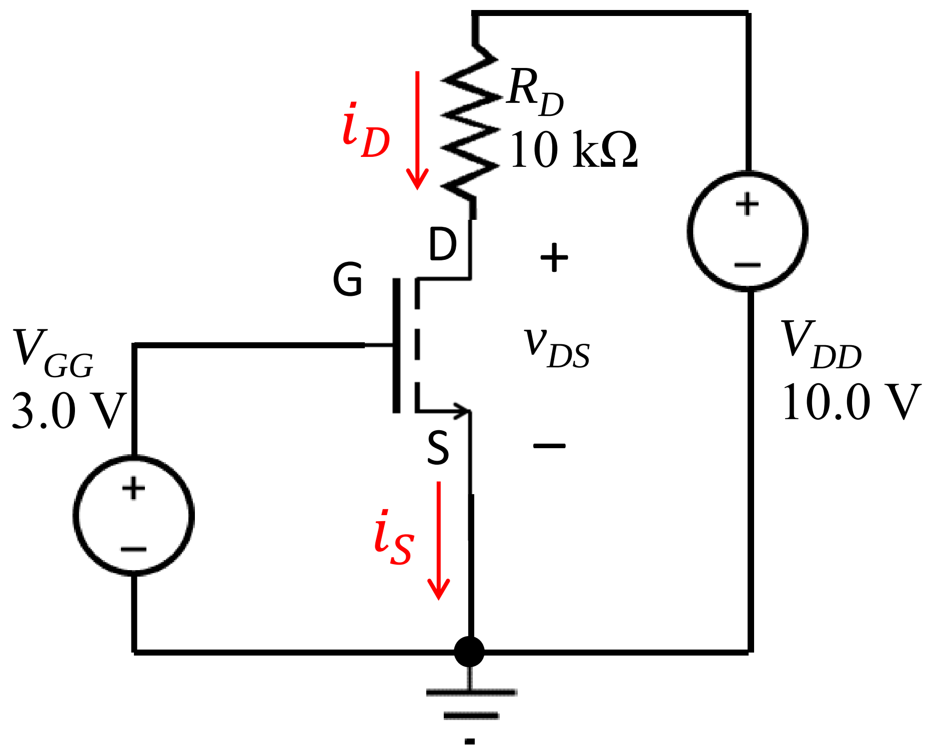



- Transistor M1: S1 and B1 tied together, $v_{SB1} = 0$. No Body effect
- Transistor M2:

$$v_{B2} = 0, v_{S2} = v_{D1} \neq 0$$

$v_{SB2} \neq 0$. Body effect exists!

# MOSFET Circuit Analysis (e.g. 1)




Known: NMOS, $V_{TO} = 1.0\text{ V}, \lambda = 0, K_n' = 25\mu\text{A/V}^2, \frac{W}{L} = 10$

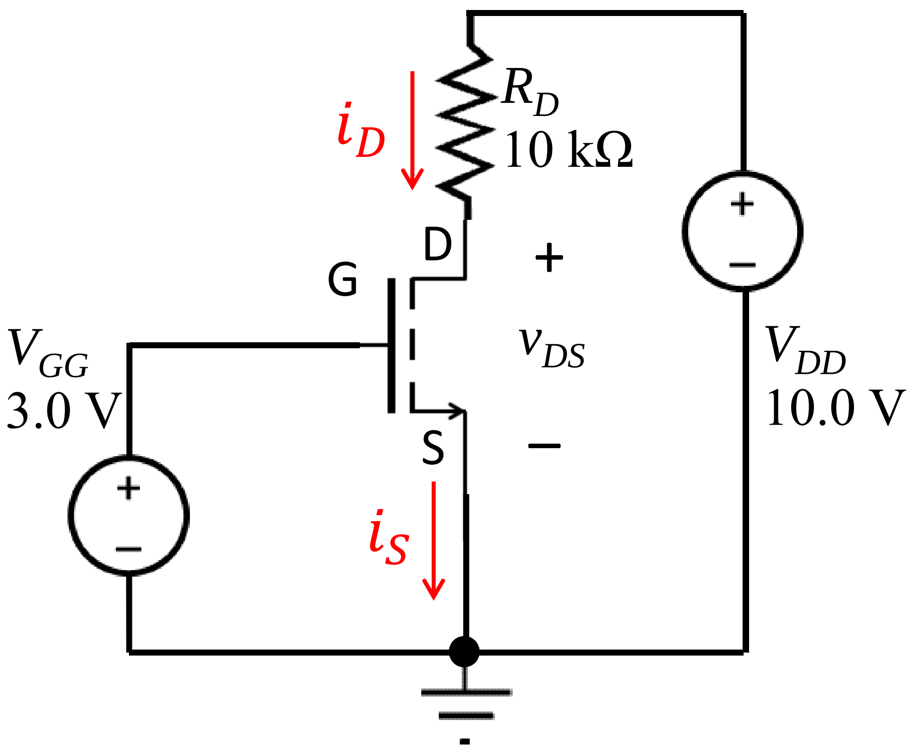
Solve: Q-point $(i_D, v_{DS})$

- First determine threshold voltage:

  Since $v_{SB} = 0$, so no body effect.
  $V_{TN} = V_{TO} = 1.0\text{ V}$
- Step #1: Guess operation region.

  $v_{GS} = 3.0\text{ V} > V_{TN}, V_{DD} = 10\text{ V}$, guess ON and saturation.

# MOSFET Circuit Analysis (e.g. 1)




- Step #2: Use proper equation

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2$$

- Step #3: Solve the circuit

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 = \frac{25\ \mu\text{A}}{2} \cdot 10 \cdot (3 - 1)^2\text{V}^2 = 500\mu\text{A}$$

$$v_{DS} = V_{DD} - i_D \cdot R_D = 10\ \text{V} - 500\ \mu\text{A} \cdot 10\ \text{k}\Omega = 5\ \text{V}$$

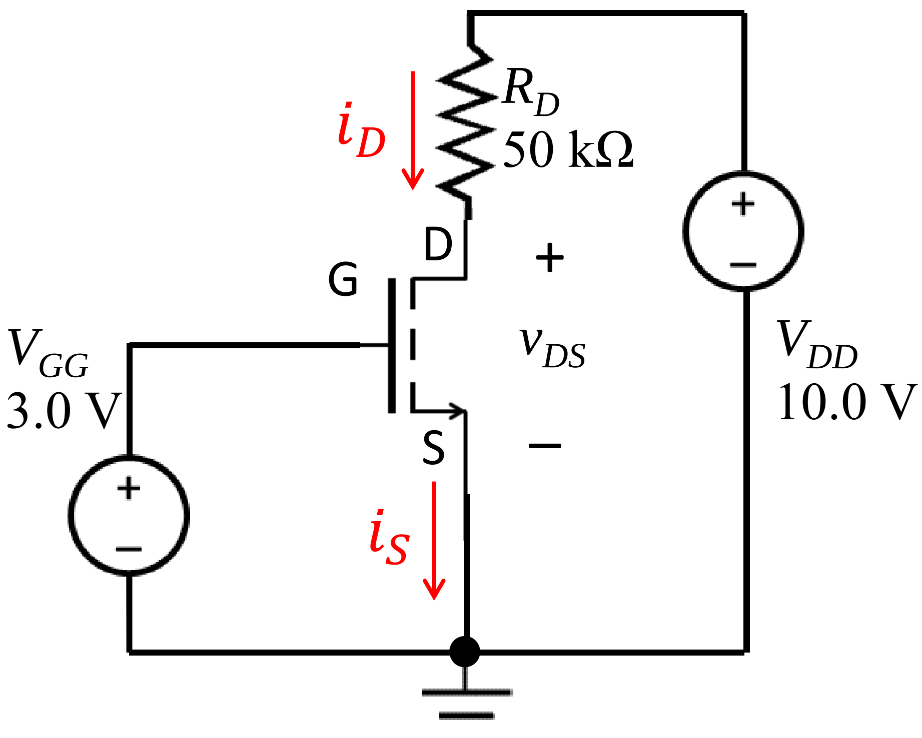
- Step #4: Double check

$v_{DS} > v_{GS} - V_{TN} = 2\ \text{V}$ => Saturation. Correct!

**Q-point: (500 µA, 5.0 V)**

# MOSFET Circuit Analysis (e.g. 1')

Now $R_D$ changes to $50\ \text{k}\Omega$




Known: NMOS, $V_{TO} = 1.0\ \text{V}, \lambda = 0, K_n' = 25\mu\text{A/V}^2, \frac{W}{L} = 10$

Solve: Q-point $(i_D, v_{DS})$

- First determine threshold voltage:

  Since $v_{SB} = 0$, so body effect.

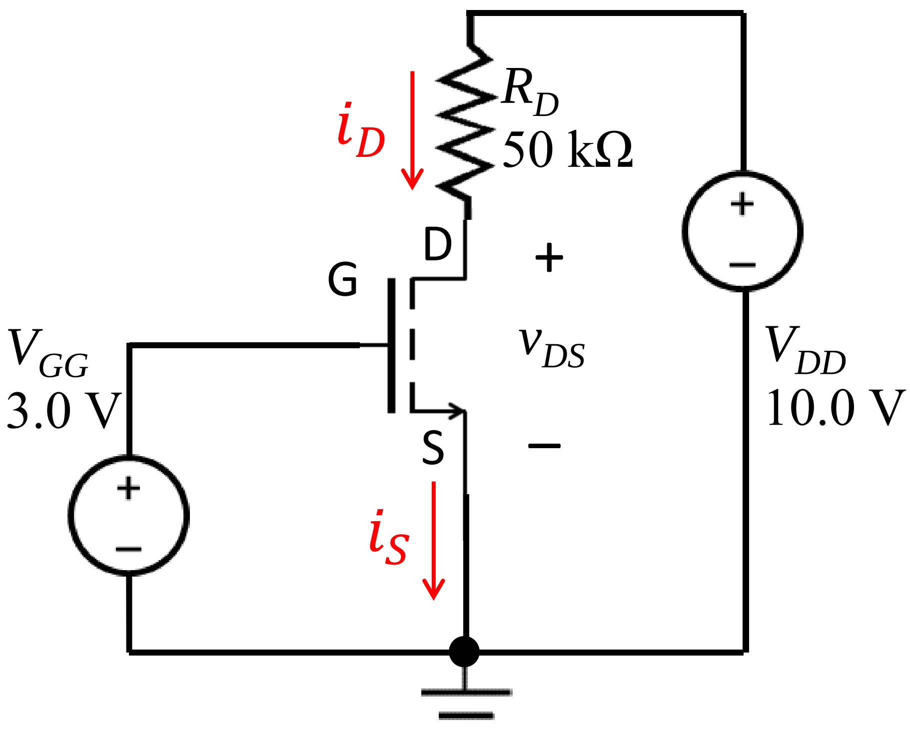
$V_{TN} = V_{TO} = 1.0\ \text{V}$

- Step #1: Guess operation region.

  $v_{GS} = 3.0\ \text{V} > V_{TN}, V_{DD} = 10\ \text{V}$,

guess ON and saturation.

# MOSFET Circuit Analysis (e.g. 1')




- Step #2: Use proper equation

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2$$

- Step #3: Solve the circuit

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 = \frac{25\ \mu\text{A}}{2} \cdot 10 \cdot (3 - 1)^2\text{V}^2 = 500\mu\text{A}$$

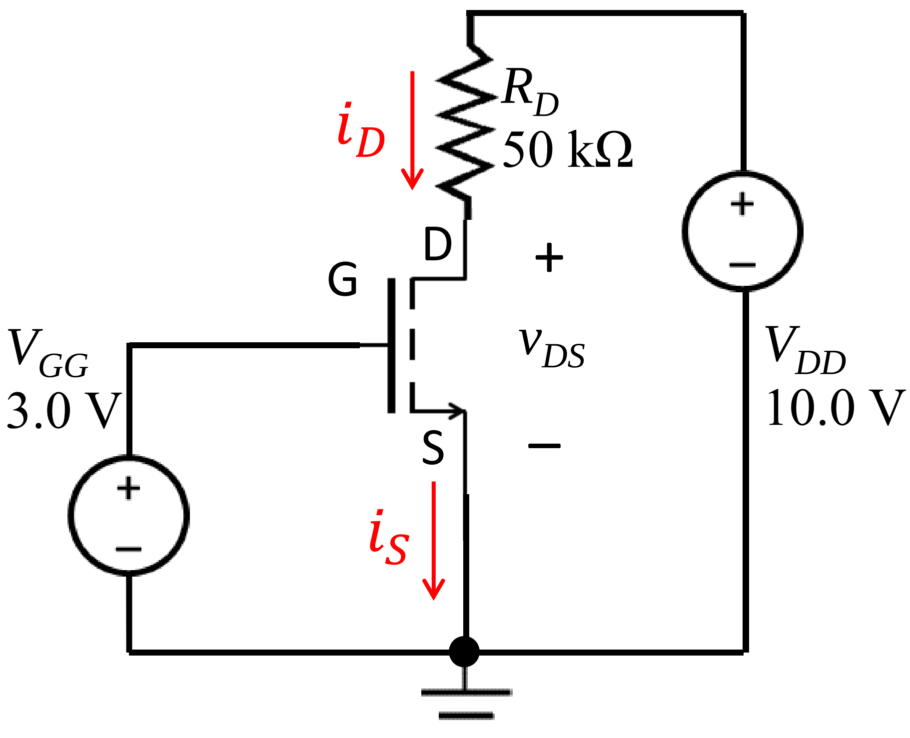
$$v_{DS} = V_{DD} - i_D \cdot R_D = 10\text{ V} - 500\ \mu\text{A} \cdot 50\text{ k}\Omega = -15\text{ V}$$

- Step #4: Double check

$v_{DS} < v_{GS} - V_{TN} = 2\text{ V}$ => NOT in saturation. Wrong guess!

# MOSFET Circuit Analysis (e.g. 1')




- Guess ON and triode.

  $i_D = K_n' \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}$ ①
- KVL: $v_{DS} = V_{DD} - i_D R_D \Rightarrow i_D = \frac{V_{DD} - v_{DS}}{R_D}$ ②
- Eliminating $i_D$ using ①②, and plugging in numbers, we get

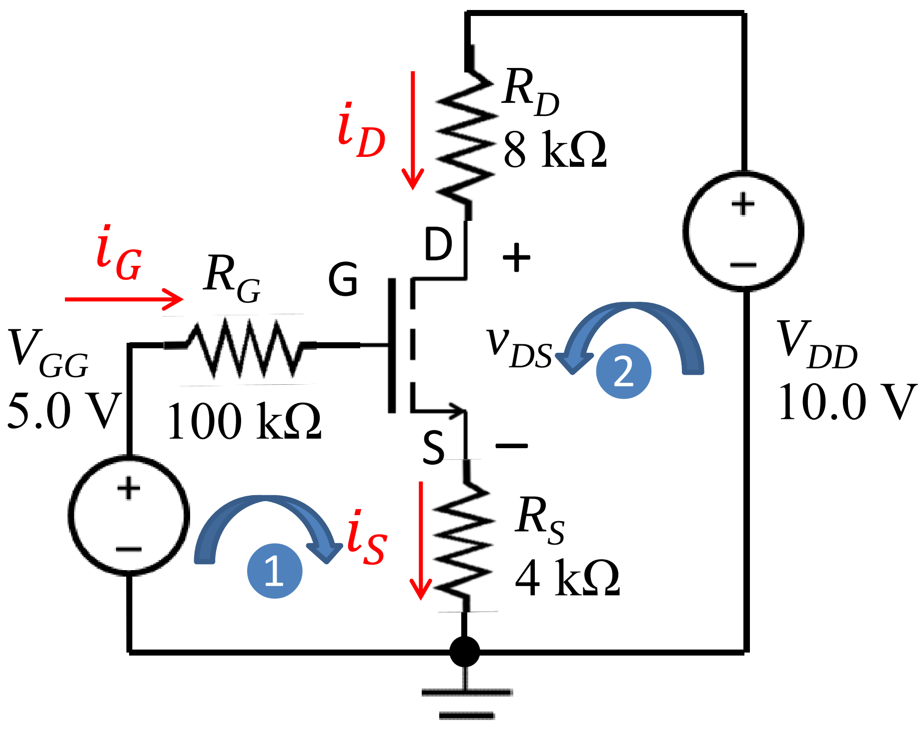
  $$25v_{DS}^2 - 104v_{DS} + 40 = 0$$
- Solving the quadratic equation:

  $$v_{DS} = 0.43 \text{ V or } 3.73 \text{ V}$$
- Triode region:

  $$v_{GS} > v_{DS} + V_{TN} \Rightarrow v_{DS} < 2 \text{ V}$$
- Thus $v_{DS} = 0.43$ V, $i_D = \frac{10-0.43}{50\text{ k}}\frac{\text{V}}{\text{A}} = 191\ \mu\text{A}$

**Q-point: (191 µA, 0.43 V)**

# MOSFET Circuit Analysis (e.g. 2)




Known: NMOS, $V_{TO} = 1.0\text{ V}, \lambda = 0, K_n' = 25\mu\text{A/V}^2, \frac{W}{L} = 10$

Solve: Q-point $(i_D, v_{DS})$

- First determine threshold voltage:

  Since $v_{SB} = 0$, so body effect. $V_{TN} = V_{TO} = 1.0\text{ V}$

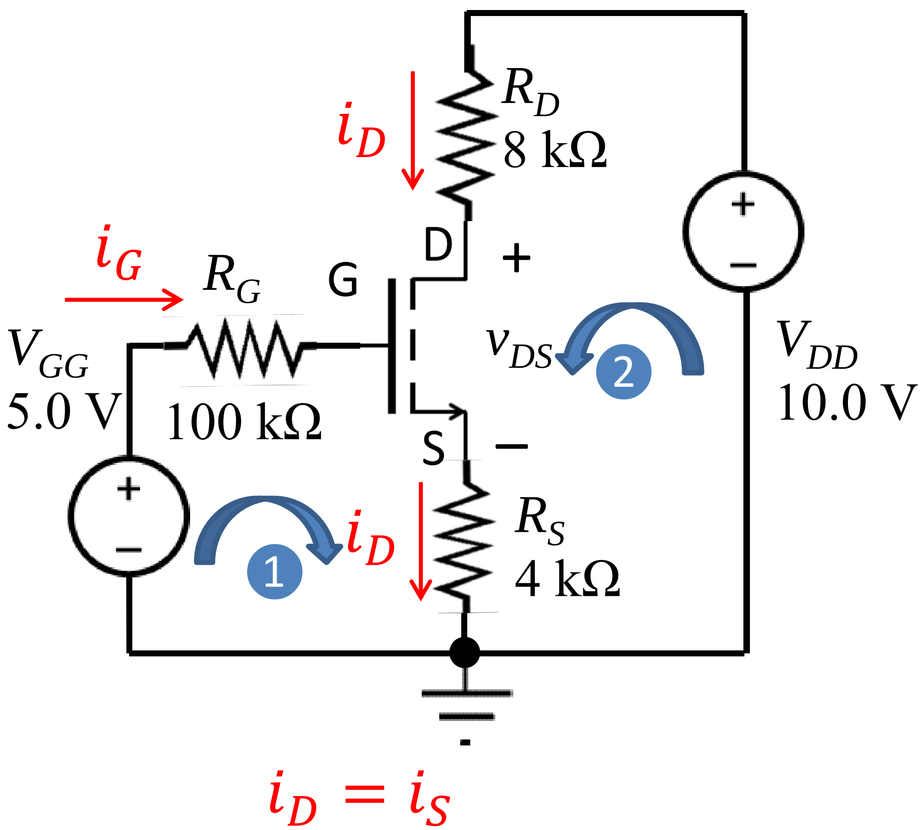
- Analyze circuit loops:

Loop ❶: $V_{GG} = i_G R_G + v_{GS} + i_S R_S = v_{GS} + i_S R_S$

Loop ❷ : $V_{DD} = i_D R_D + v_{DS} + i_S R_S$

# MOSFET Circuit Analysis (e.g. 2)




- Guess: CUTOFF
- $i_D = 0$, $v_{GS} = V_{GG} = 5\text{ V} > V_T = 1\text{ V}$
  Not CUTOFF!
- Guess: Saturation

$$i_D = \frac{K_n'}{2}\frac{W}{L}(v_{GS} - V_{TN})^2 \quad ①$$

$$v_{GS} = V_{GG} - i_D R_S \Rightarrow i_D = \frac{V_{GG} - v_{GS}}{R_S} \quad ②$$

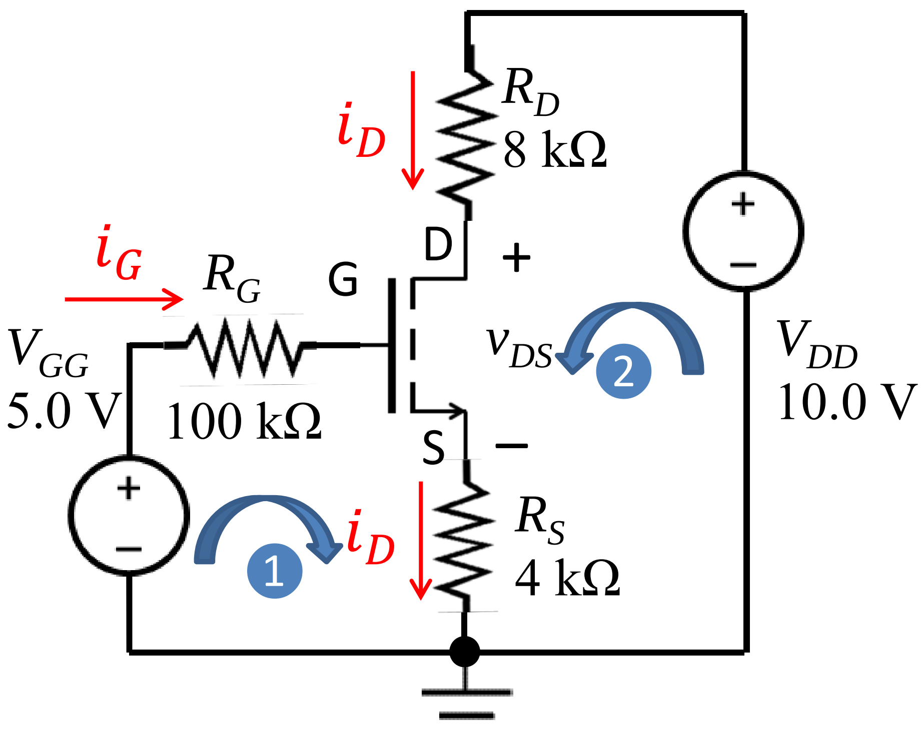
- Eliminating $i_D$ using ①②, and plugging in numbers, we get

$$v_{GS}^2 - 9 = 0$$

- Solving the quadratic equation:

$$v_{GS} = 3\text{ V or } -3\text{ V}$$

# MOSFET Circuit Analysis (e.g. 2)




$i_D = i_S$

$$v_{GS} = 3\text{ V or } \sout{-3\text{ V}}$$

$$i_D = \frac{(5-3)\text{V}}{4\text{k}\Omega} = 500\ \mu\text{A}$$

$$v_{DS} = V_{DD} - i_D(R_D + R_S) = 4\text{ V}$$

- Check:

$$v_{GS} = 3\text{ V} > V_{TN} = 1\text{ V}$$

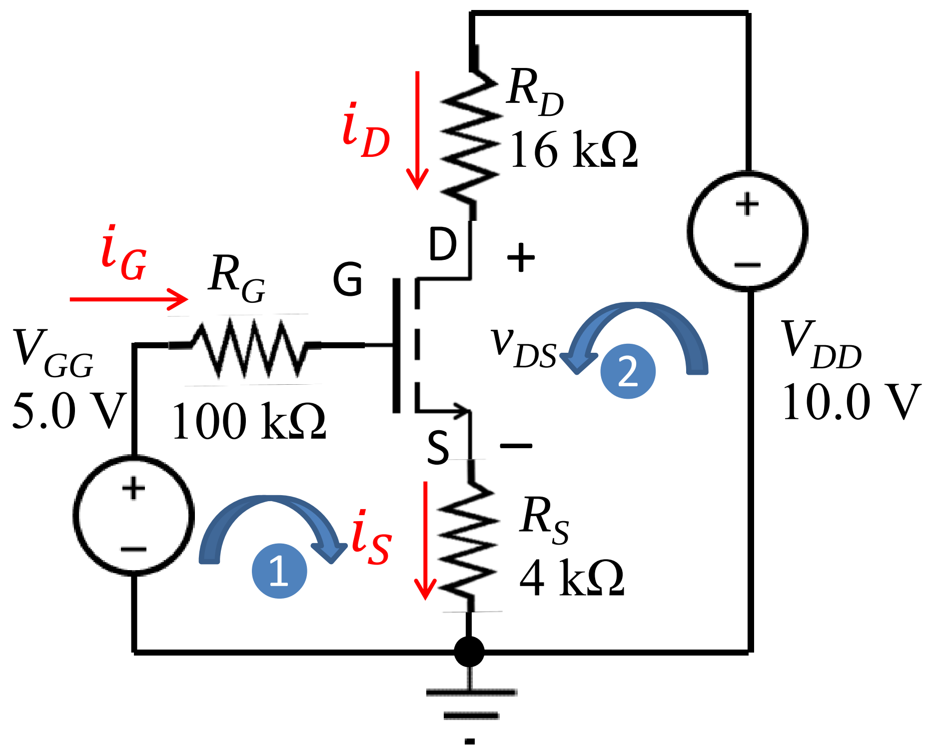
$$v_{DS} = 4\text{ V} > V_{GS} - V_{TN} = 2\text{ V}$$

So, Saturation it is!

**Q-point: ($i_D$=500 μA, $v_{DS}$=4.0 V)**

# MOSFET Circuit Analysis (e.g. 2’)

Now $R_D$ changes to $16\ \mathrm{k\Omega}$




Known: NMOS, $V_{TO} = 1.0\text{ V}, \lambda = 0, K_n' = 25\mu\text{A/V}^2, \frac{W}{L} = 10$

Solve: Q-point $(i_D, v_{DS})$

- Everything would be the same until the last check for saturation:

$$v_{DS} = V_{DD} - i_D(R_D + R_S)$$
$$= 10\text{V} - 500\mu\text{A} \cdot 20\text{k}\Omega = 0\text{V}$$

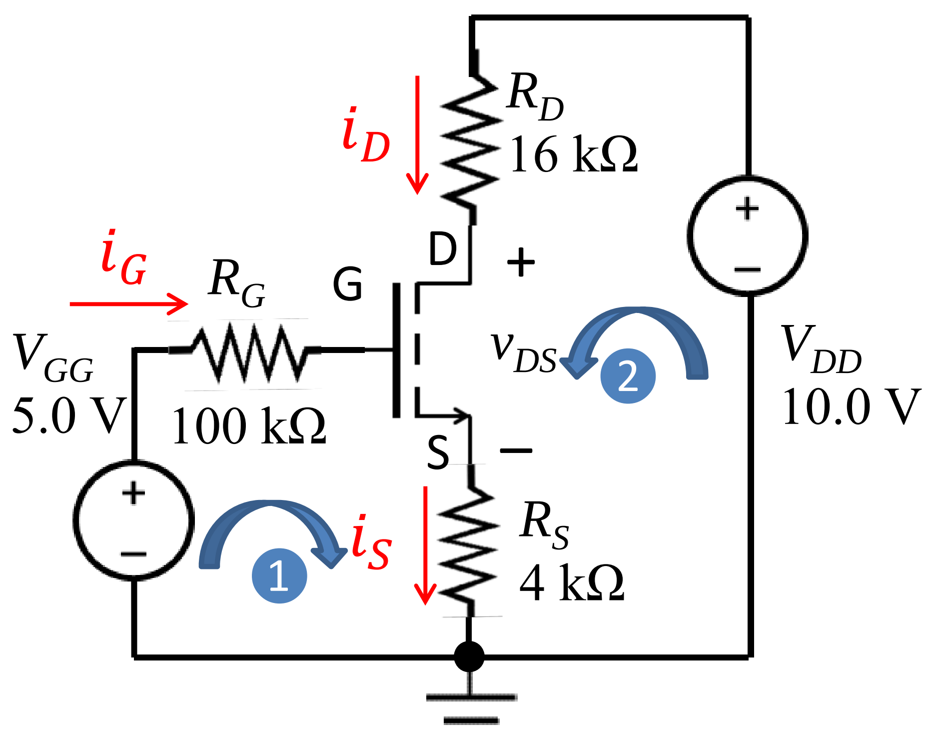
$v_{DS} = 0\text{ V} < V_{GS} - V_{TN} = 2\text{ V}$. Not in saturation.

- Guess in triode:

$$i_D = K_n' \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS} \quad (1)$$

# MOSFET Circuit Analysis (e.g. 2')

Now $R_D$ changes to 16 kΩ




**Q-point: (447 μA, 1.06 V)**

- KVL:

  $v_{DS} = V_{DD} - i_D(R_D + R_S)$ ②

  $v_{GS} = V_{GG} - i_D R_S$ ③
- Substituting ② ③ into ①, we get a quadratic equation of $i_D$. Solution is:

  $$i_D = 186\ \mu\text{A or } 447\ \mu\text{A}$$
- Check:
  - First root:

    $v_{GS} = V_{GG} - i_D R_S = 4.25\text{ V} > V_T$ √

    $v_{DS} = V_{DD} - i_D(R_D + R_S)$
    $= 6.27\text{ V} > v_{GS} - V_{TN}$ ×
  - Second root:

    $v_{GS} = V_{GG} - i_D R_S = 3.21\text{ V} > V_T$ √

    $v_{DS} = 1.06\text{ V} < v_{GS} - V_{TN}$ √