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# Introduction to Electronics

*An introduction to electronic components and a study of circuits containing such devices.*

School of Electrical and Computer Engineering

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# Week 6: MOSFETs

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# Introduction and MOSFET Physics

**Dr. Bonnie Ferri**
Professor and Associate Chair
School of Electrical and
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*Study the physics of MOSFETs*

# Lesson Objective

- Introduce the uses of transistors
- Investigate the physics of MOSFETs

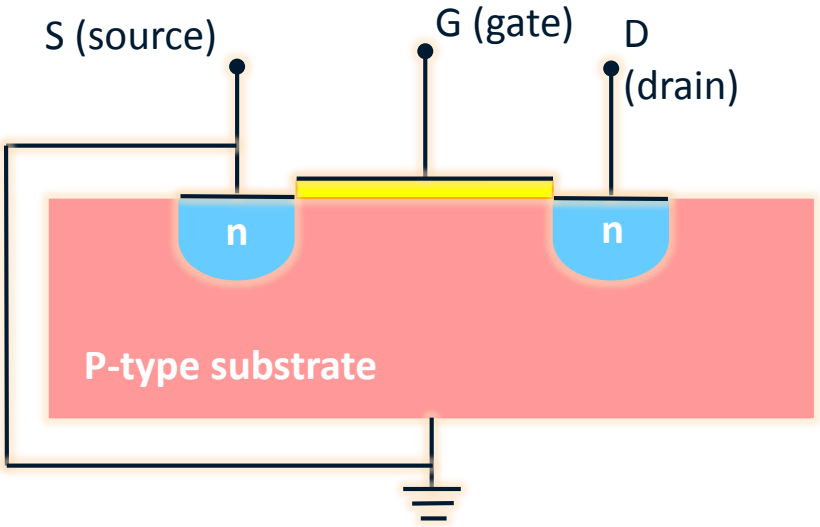
# Types of Transistors

- MOSFET (metal-oxide-semiconductor silicon field-effect transistor)
- BJT (bipolar junction transistor)

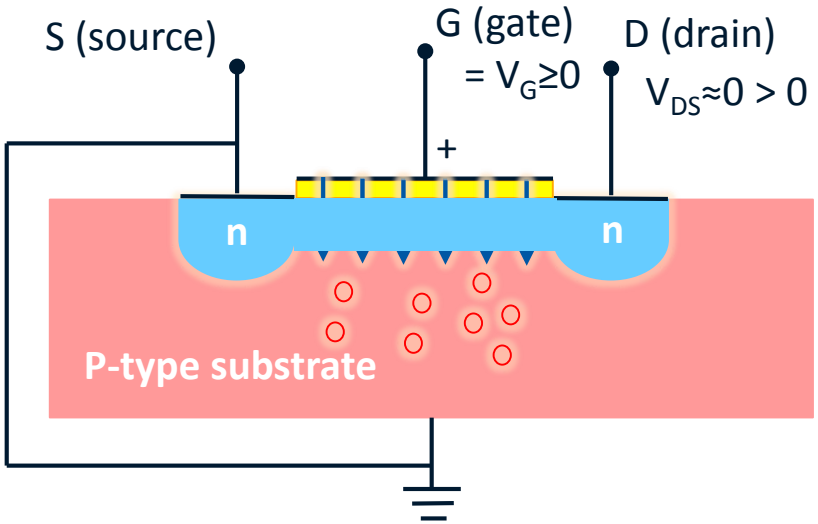
# Uses of Transistors

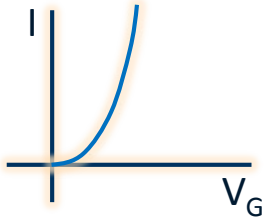
- Electrically controlled switch (digital circuits/computers)
- Amplifier (op amps)
- Resistor with value electrically controlled

# NMOS (N-type MOSFET)



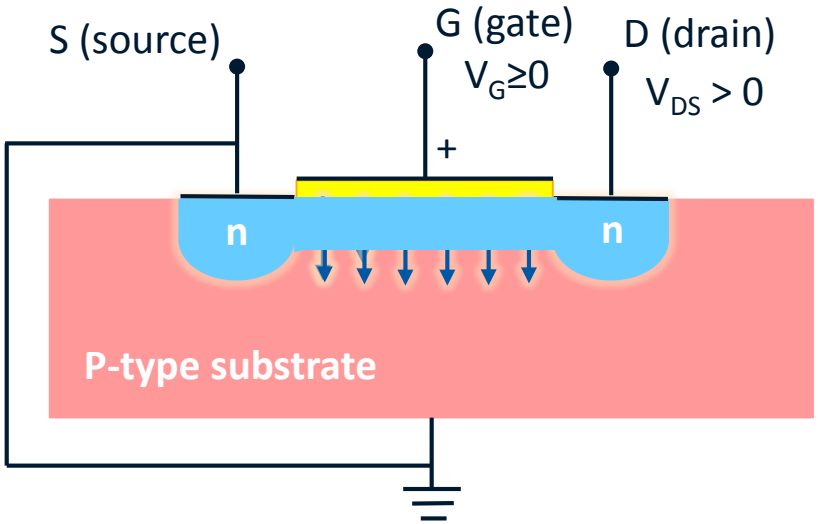
# NMOS: Vary $V_G$

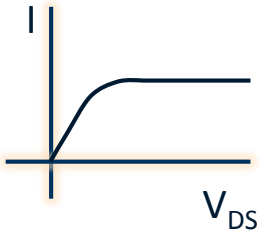



$V_{DS}$ small and constant

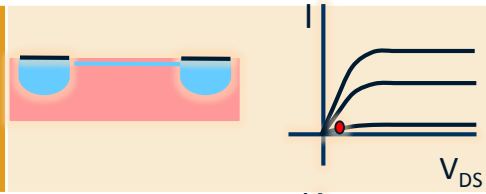
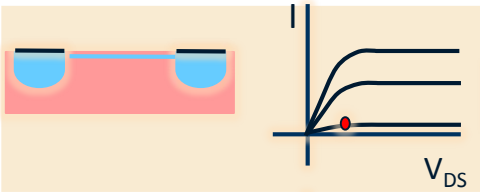
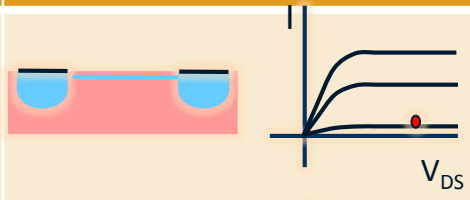
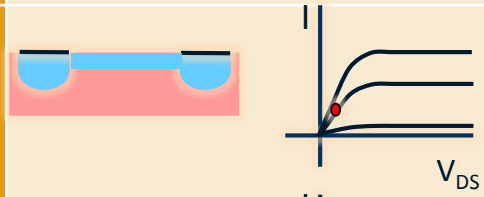
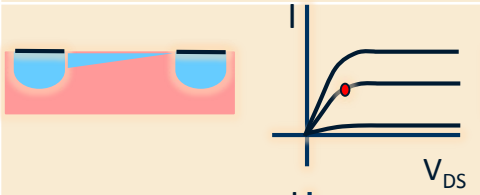
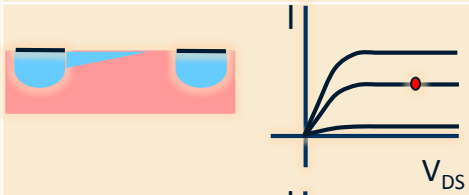
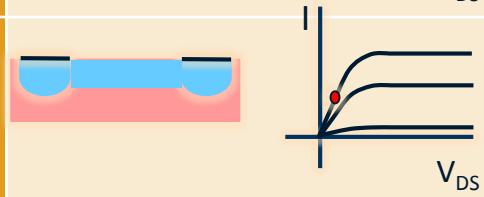
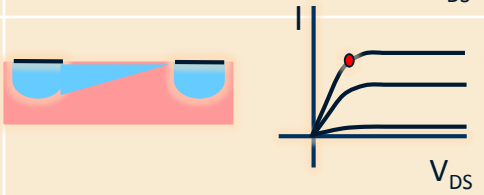
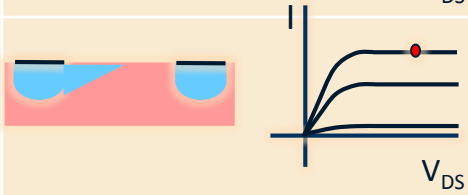
# NMOS: Vary $V_{DS}$




$V_G$ constant

# Summary

| | $V_{DS}$ small | $V_{DS}$ medium | $V_{DS}$ large |
|---|---|---|---|
| $V_G$ small |   |   |   |
| $V_G$ medium |   |   |   |
| $V_G$ large |   |   |   |

# Remainder of Module

- MOSFET switches
- MOSFET amplifiers
- BJTs

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# MOSFET Switches

**Dr. Bonnie Ferri**
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*Introduce the use of MOSFETs as switches in circuits*

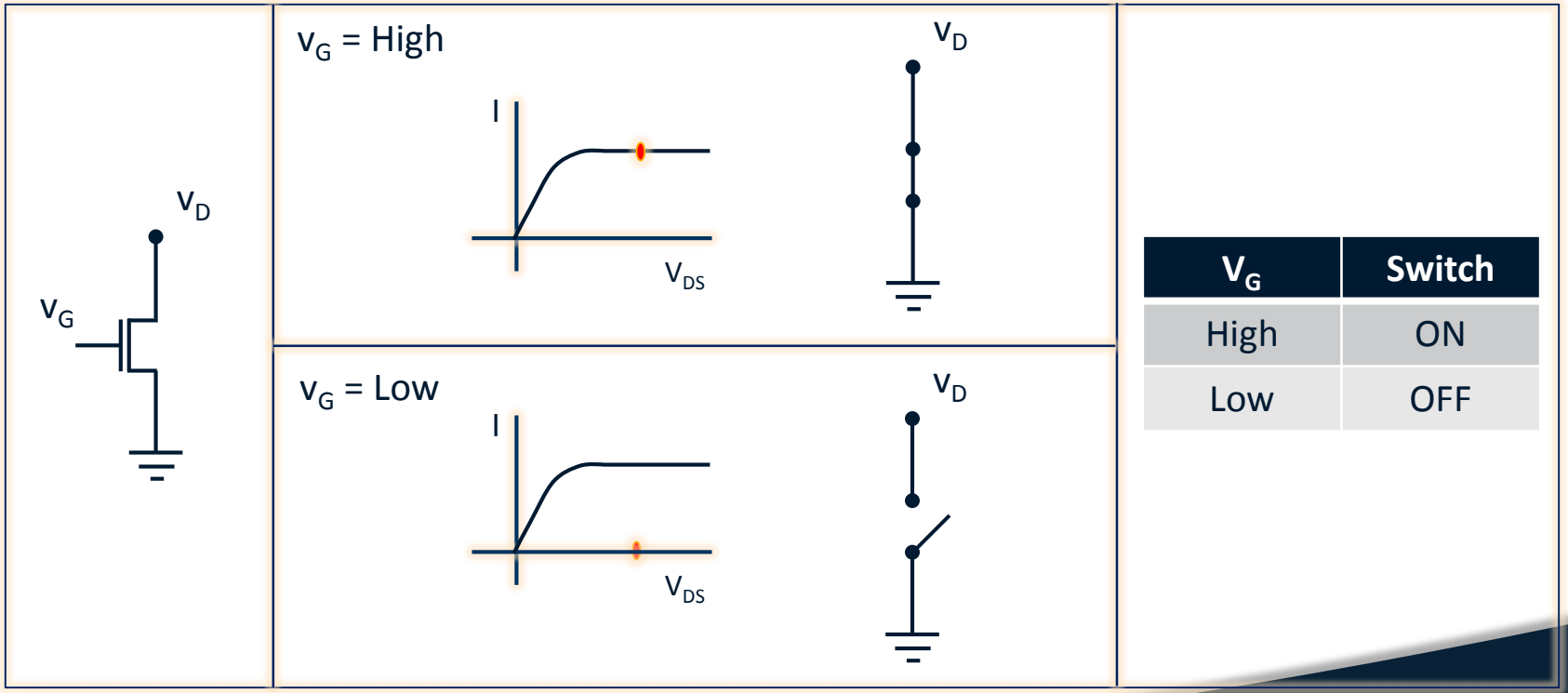
# Previous Lesson

- Introduction to MOSFETs
- The physics of MOSFETs

# Lesson Objectives

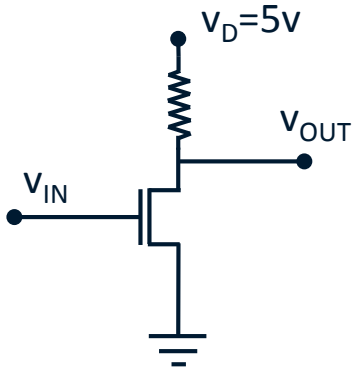
- Examine the use of MOSFET as a switch in a circuit
- Introduce CMOS devices

# NMOS Switch Behavior

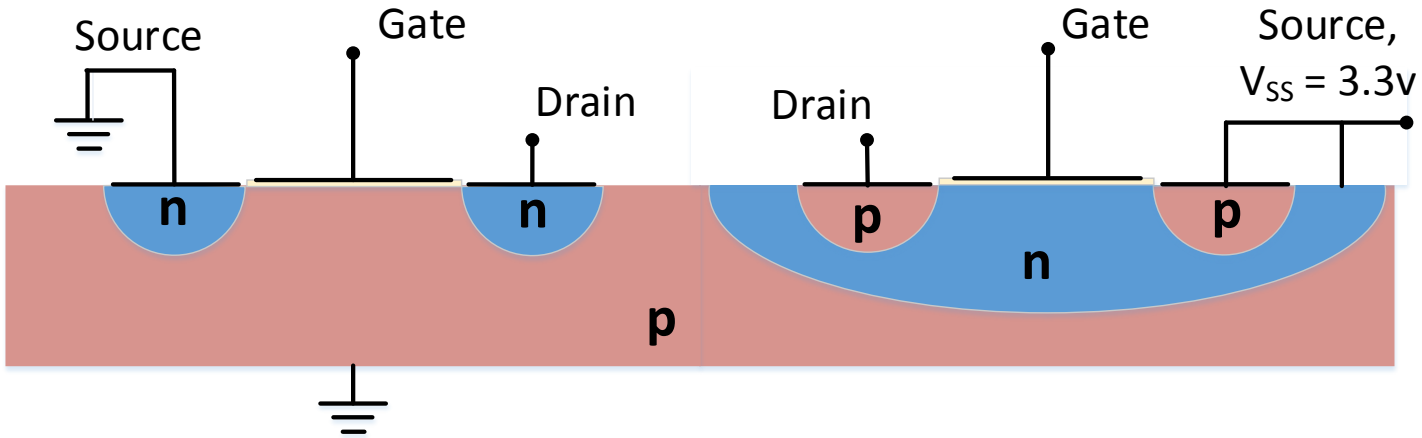



| $V_G$ | Switch |
|---|---|
| High | ON |
| Low | OFF |

# Simple NMOS Inverter Circuit



# CMOS Devices




**NMOS:**

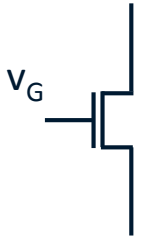
| $V_G$ | Switch |
|---|---|
| High | ON |
| Low | OFF |

**PMOS:**

| $V_G$ | Switch |
|---|---|
| High | OFF |
| Low | ON |

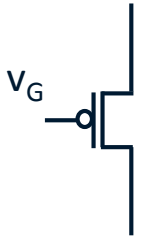
# Summary of Switch Behavior

## NMOS



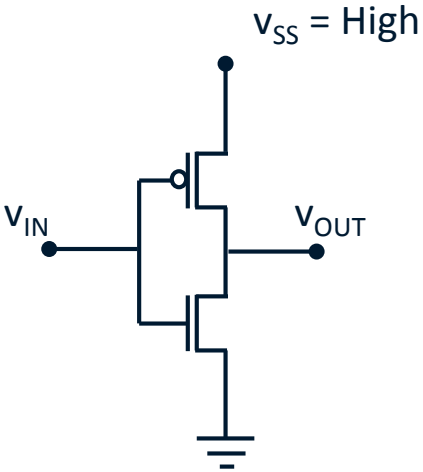

| $V_G$ | Switch |
|---|---|
| High | ON |
| Low | OFF |

## PMOS




| $V_G$ | Switch |
|---|---|
| High | OFF |
| Low | ON |

# CMOS Inverter Circuit




| $V_{IN}$ | $V_{OUT}$ |
|---|---|
| High | Low |
| Low | High |

# Summary

- Examine the use of MOSFET as an electrically controlled switch in a circuit
- Introduced CMOS for complementary p-type and n-type transistor behavior
- Introduced inverter circuits

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# CMOS Logic Gates

**Dr. Bonnie Ferri**
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*Introduction to logic gates made from CMOS transistors*

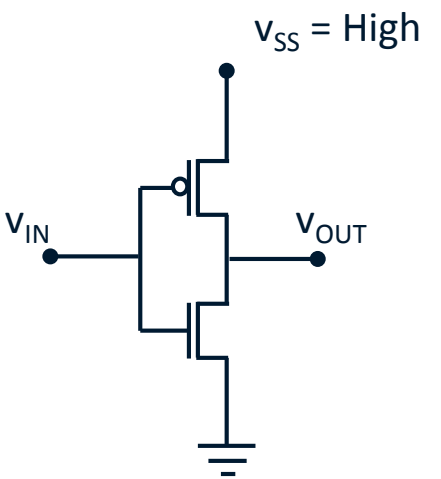
# Previous Lesson

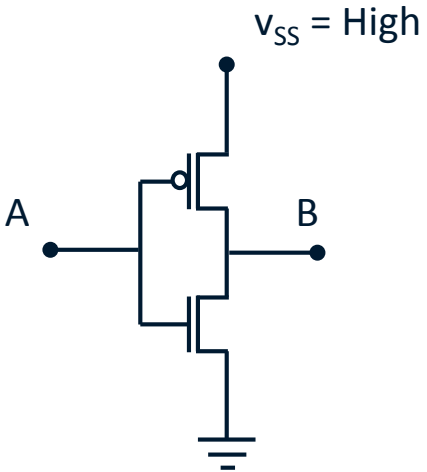
- MOSFET Switches

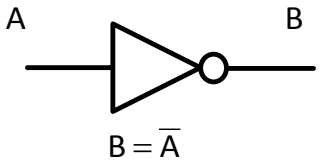
# Lesson Objectives

- Introduce logic gates and their transistor circuits
  - NOT, NAND, NOR, AND, OR

# CMOS NOT Gate (Inverter Circuit)




| $V_{IN}$ | $V_{OUT}$ |
|---|---|
| High | Low |
| Low | High |

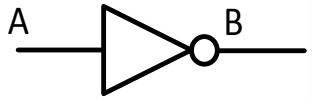
**Truth Table**

| A | B |
|---|---|
| 0 | 1 |
| 1 | 0 |

# Logic Gates

## NOT

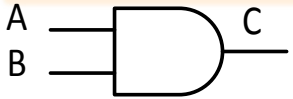
| A | B |
|---|---|
| 0 | 1 |
| 1 | 0 |




$B = \overline{A}$

## AND

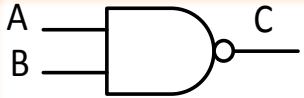
| A B | C |
|---|---|
| 0 0 | 0 |
| 0 1 | 0 |
| 1 0 | 0 |
| 1 1 | 1 |




$C = A \bullet B$

## NAND

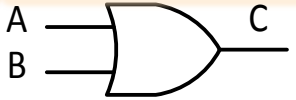
| A B | C |
|---|---|
| 0 0 | 1 |
| 0 1 | 1 |
| 1 0 | 1 |
| 1 1 | 0 |




$C = \overline{A \bullet B}$

## OR

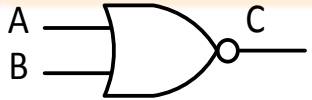
| A B | C |
|---|---|
| 0 0 | 0 |
| 0 1 | 1 |
| 1 0 | 1 |
| 1 1 | 1 |




$C = A + B$

## NOR

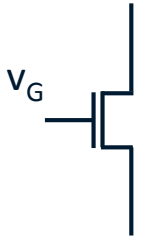
| A B | C |
|---|---|
| 0 0 | 1 |
| 0 1 | 0 |
| 1 0 | 0 |
| 1 1 | 0 |




$C = \overline{A + B}$

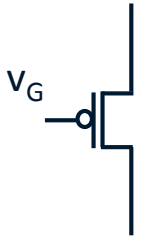
# PMOS Switch Behavior

## NMOS




| $V_G$ | Switch |
|---|---|
| High | ON |
| Low | OFF |

## PMOS

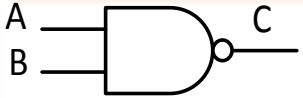



| $V_G$ | Switch |
|---|---|
| High | OFF |
| Low | ON |

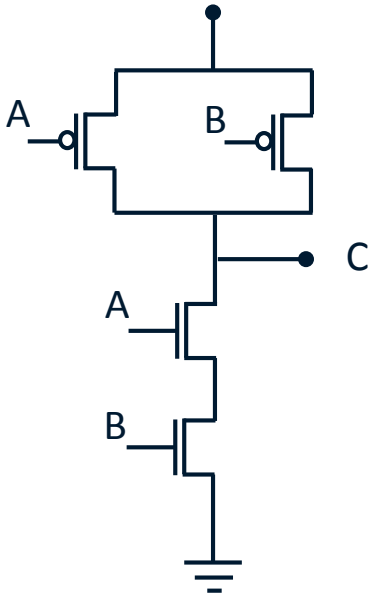
# NAND Gate

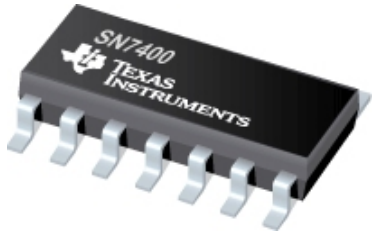
## NAND

| A B | C |
|---|---|
| 0 0 | 1 |
| 0 1 | 1 |
| 1 0 | 1 |
| 1 1 | 0 |




$C = \overline{A \bullet B}$

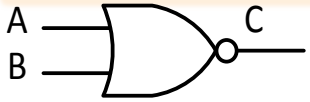


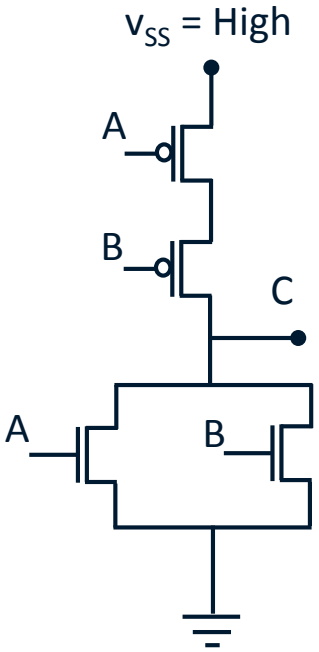
# NOR Gate

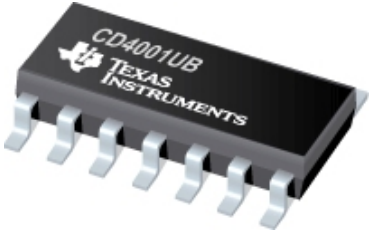
**NOR**

| A B | C |
|---|---|
| 0 0 | 1 |
| 0 1 | 0 |
| 1 0 | 0 |
| 1 1 | 0 |




$C = \overline{A + B}$



# Summary

- Logic gate circuits are made from CMOS n-type and p-type transistors

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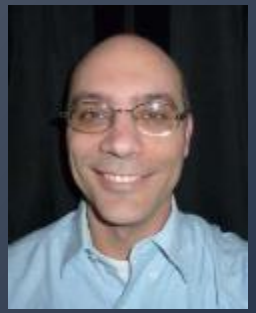

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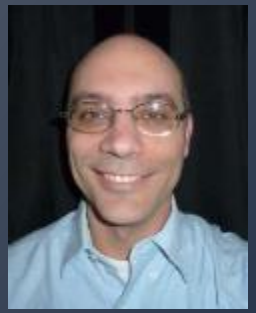

# MOSFET Characteristics

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*Introduce MOSFET characteristic curves and biasing*

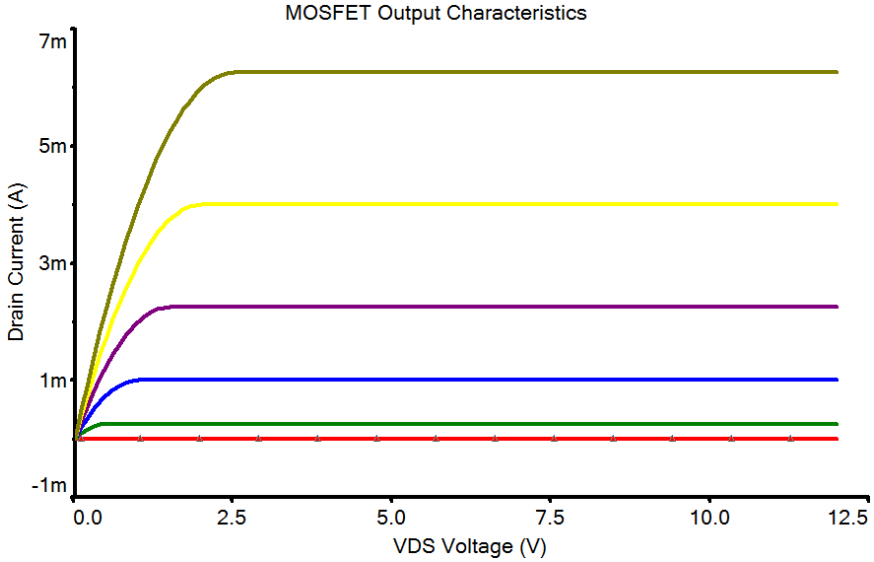
# Previous Lesson

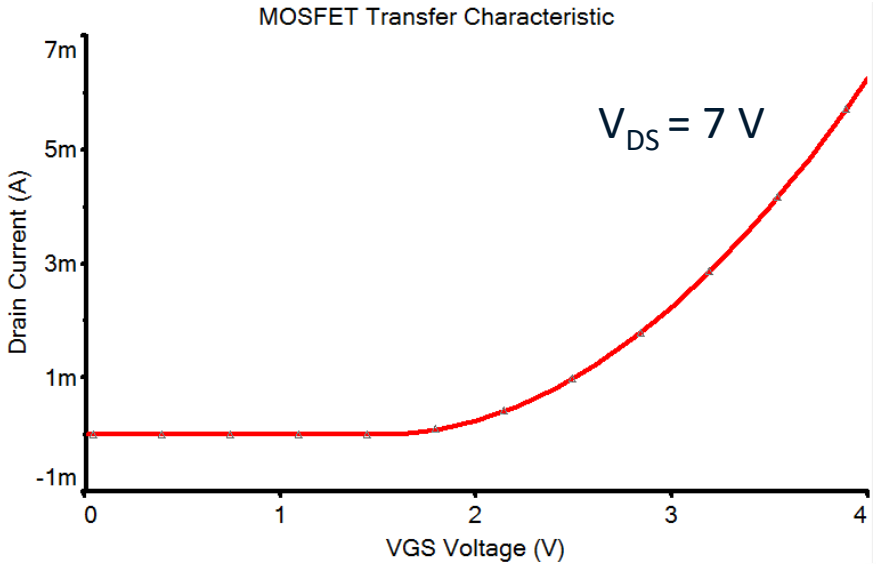
- Introduced CMOS logic gates

# Lesson Objectives

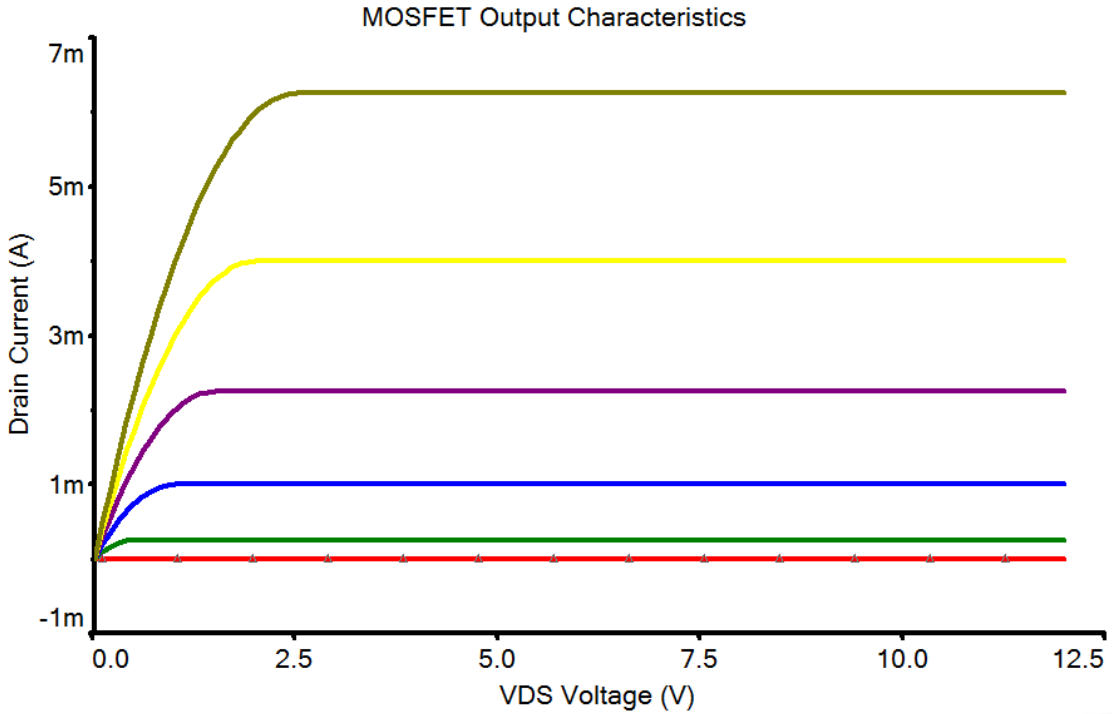
- Introduce MOSFET characteristic curves
- Introduce dc biasing

# Characteristic Curves



# Regions of Operation



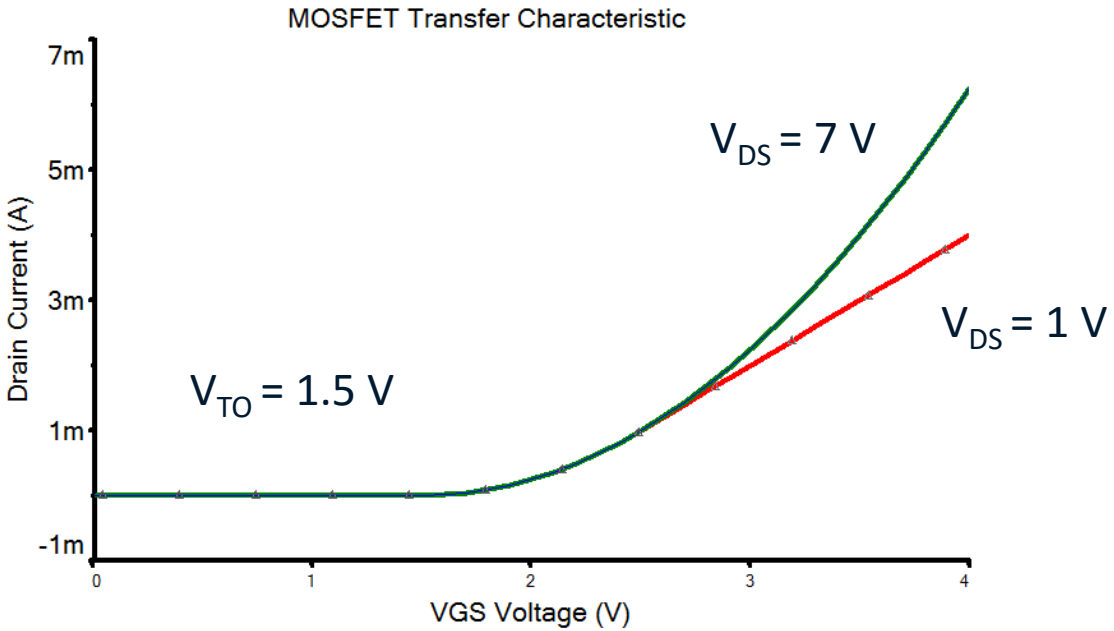
# Regions of Operation

| Cutoff Region | Linear/Triode Region | Saturation Region |
|---|---|---|
| $V_{GS} < V_{TO}$ | $V_{GS} > V_{TO}$ | $V_{GS} > V_{TO}$ |
| | $V_{DS} < V_{GS} - V_{TO}$ | $V_{DS} > V_{GS} - V_{TO}$ |
| $I_D = 0$ | $I_D = 2K\left[(V_{GS} - V_{TO})\,V_{DS} - \frac{V_{DS}^2}{2}\right]$ | $I_D = K(V_{GS} - V_{TO})^2$ |

K = Transconductance parameter. Units of $A/V^2$

$V_{TO}$ = Threshold or turn on voltage. Minimum value of $V_{GS}$ for $I_D$ to flow.

# Transfer Characteristics



# Summary

- Introduced MOSFET characteristics
- Introduced dc biasing

# Next Lesson

- Common Source Amplifier: DC Analysis

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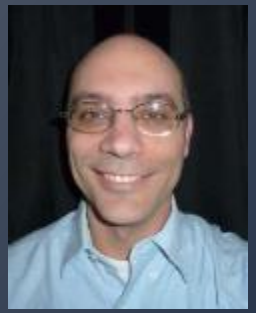

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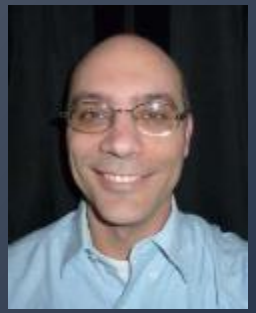

# Common Source Amplifier: DC Analysis

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*Introduce common source amplifier*

# Previous Lesson

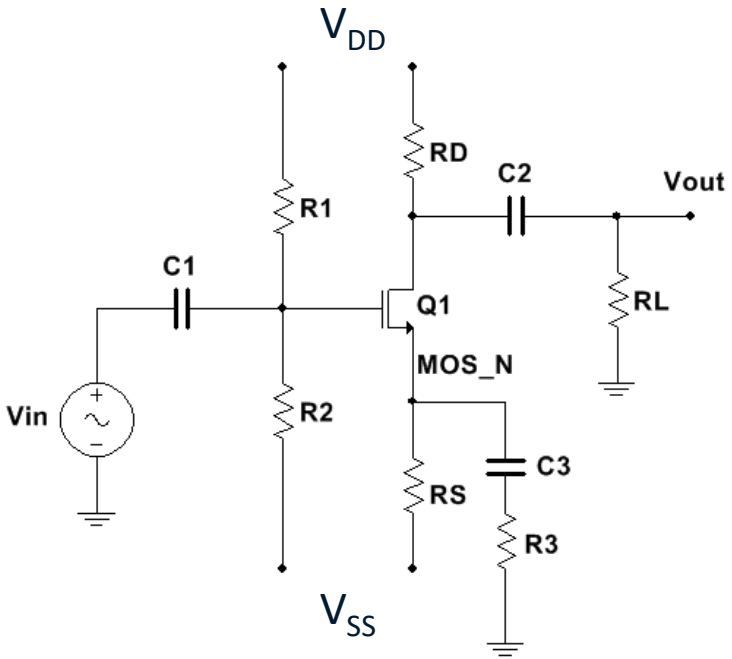
- Examined MOSFET characteristic curves and biasing

# Lesson Objectives

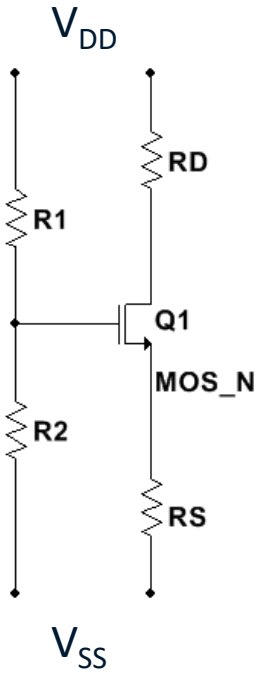
- Introduce common source amplifier
- Analyze common source amplifier dc circuit

# MOSFET Gain Stage

# Common Source Amplifier



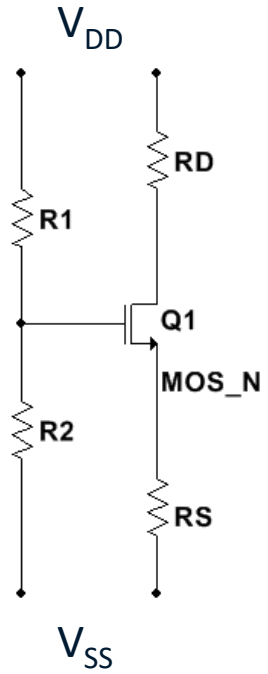
# Common Source Amplifier DC Circuit




$$I_G = 0$$

$$I_D = I_S$$

# Common Source Amplifier DC Formulas




$$I_G = 0$$

$$I_D = I_S$$

$$V_G = \frac{V_{DD}R_2 + V_{SS}R_1}{R_1 + R_2}$$

$$V_{GS} = \sqrt{\frac{I_D}{K}} + V_{TO}$$

$$V_1 = V_G - V_{SS} - V_{TO}$$

$$I_D = \left(\frac{\sqrt{1 + 4KV_1R_S} - 1}{2\sqrt{K}R_S}\right)^2$$

$$V_D = V_{DD} - R_D I_D$$

$$V_S = V_{SS} + R_S I_S$$

# Summary

- Introduced common source (CS) amplifier
- Introduced dc analysis of CS amplifier

# Next Lesson

- Common Source Amplifier: AC Analysis

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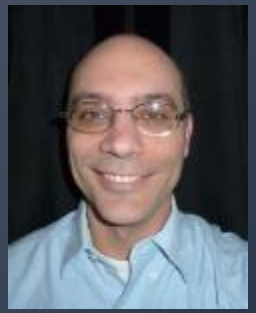
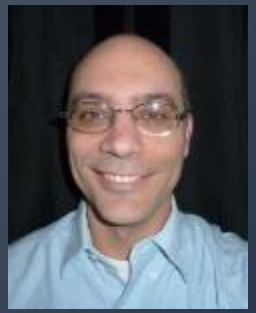


# Introduction to Electronics

**Dr. Allen Robinson**
Academic Professional
School of Electrical and Computer Engineering

*An introduction to electronic components and a study of circuits containing such devices.*

Georgia Institute of Technology

# Common Source Amplifier: AC Analysis

**Dr. Allen Robinson**
Academic Professional
School of Electrical and Computer Engineering

*Examine ac behavior of the common source amplifier*

# Previous Lesson

- Introduced common source amplifier
- Introduced dc biasing

# Lesson Objectives

- Introduce ac behavior of CS amplifier
- Analyze CS amplifier circuit

# Small Signal Parameters and Gain

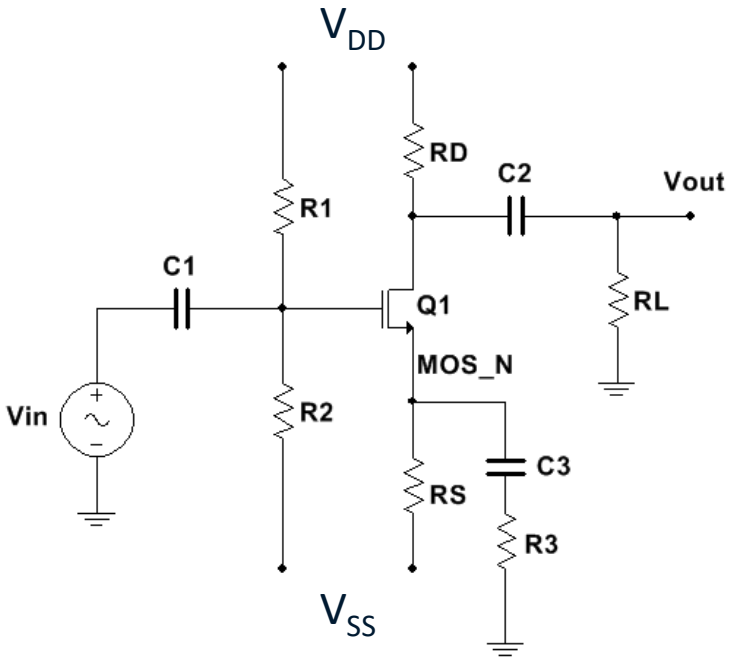
Perform small-signal analysis to obtain:

$g_m = 2\sqrt{KI_D}$ Transconductance

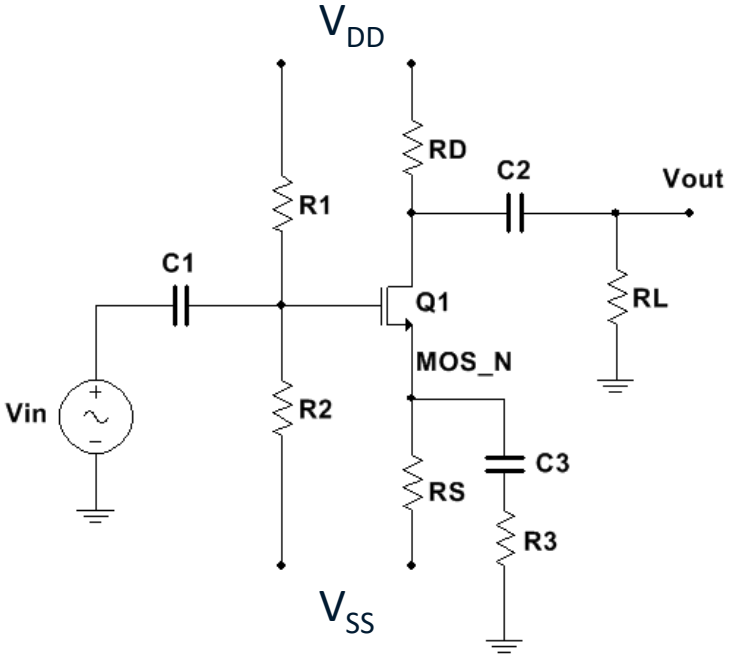
$r_s = 1/g_m$ Intrinsic source resistance

$\frac{V_{out}}{V_{in}} = -\frac{R_D||R_L}{r_s + R_S||R_3}$ Midband Gain

# Common Source Amplifier



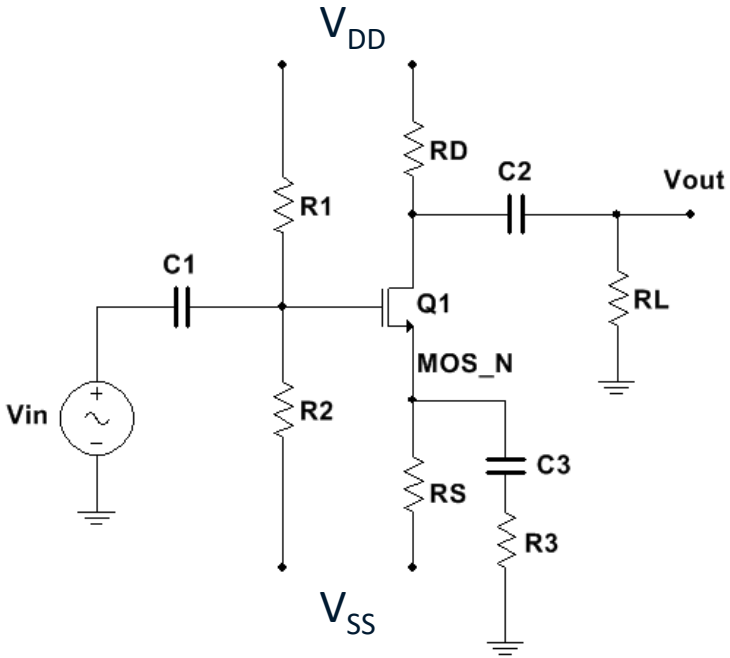
# Common Source Amplifier Example




Determine Q point and Gain Given:

$$R_1 = 1\,\text{M}\Omega \qquad V_{DD} = +15\,\text{V}$$
$$R_2 = 200\,\text{k}\Omega \qquad V_{SS} = -15\,\text{V}$$
$$R_S = 3\,\text{k}\Omega$$
$$R_L = 20\,\text{k}\Omega$$
$$R_3 = 51\,\Omega$$
$$R_D = 15\,\text{k}\Omega$$
$$K = 0.001\,\text{A/V}^2$$
$$V_{TO} = 1.5\,\text{V}$$

# Common Source Amplifier Example



# Summary

- Introduced AC analysis of CS amplifier
- Analyzed CS amplifier circuit

# Next Lesson

- Bipolar Junction Transistor (BJT)