

# EE 330

## Lecture 6

- Basic Logic Circuits
- Complex Logic Gates
- Pass Transistor Logic

# Office Hours

**Tuesdays 2:00 p.m.**

**Thursdays 11:00 a.m.**

**<https://iastate.zoom.us/j/91692566556>**

**Other times by appointment**

**Send email request and suggest times**

Photo courtesy of the director of the National Institute of Health ( NIH)



As a courtesy to fellow classmates, TAs, and the instructor

**Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status**

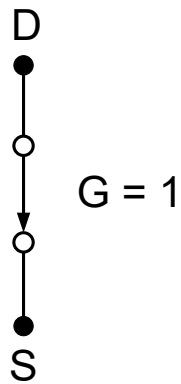
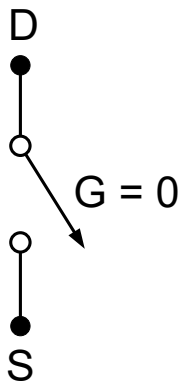
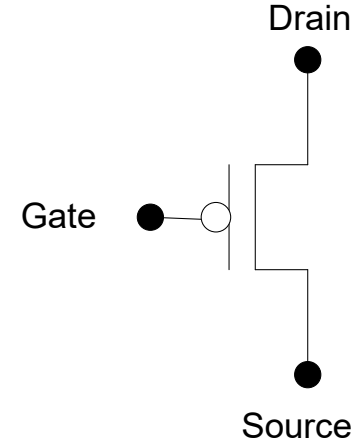
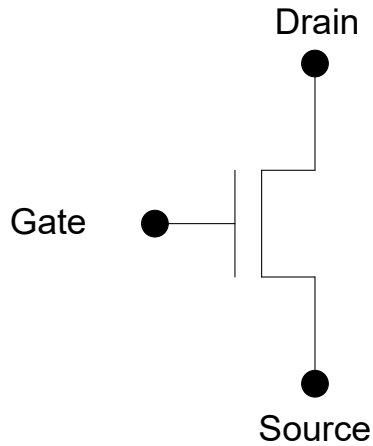
# Models of Devices

- Several models of the electronic devices will be introduced throughout the course
  - Complexity
  - Accuracy
  - Insight
  - Application
- Will use the simplest model that can provide acceptable results for any given application

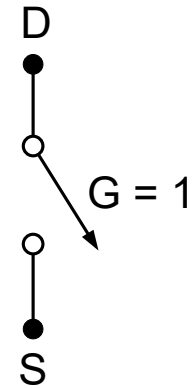
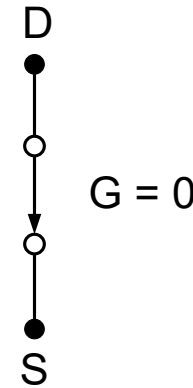
Review from Last Time

# MOS Transistor

## Comparison of Operation



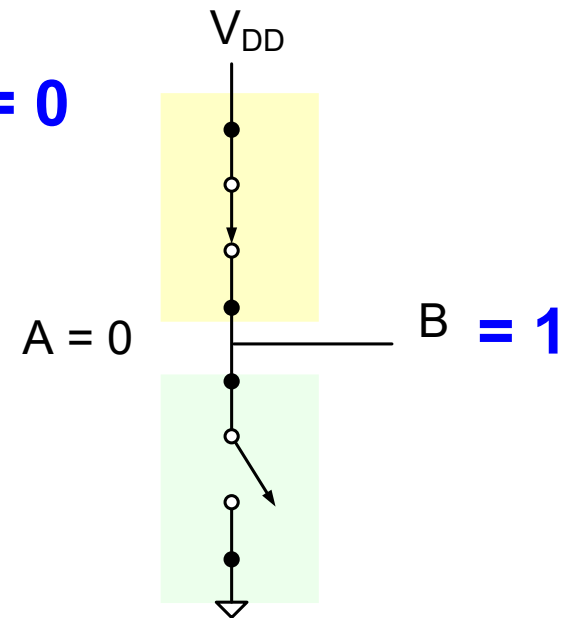
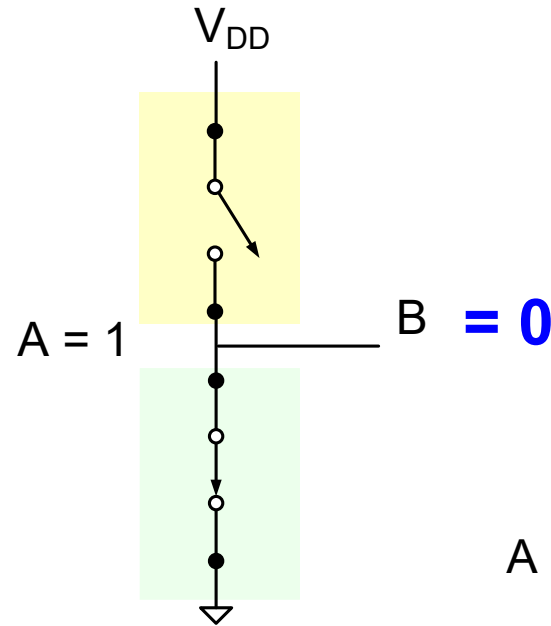
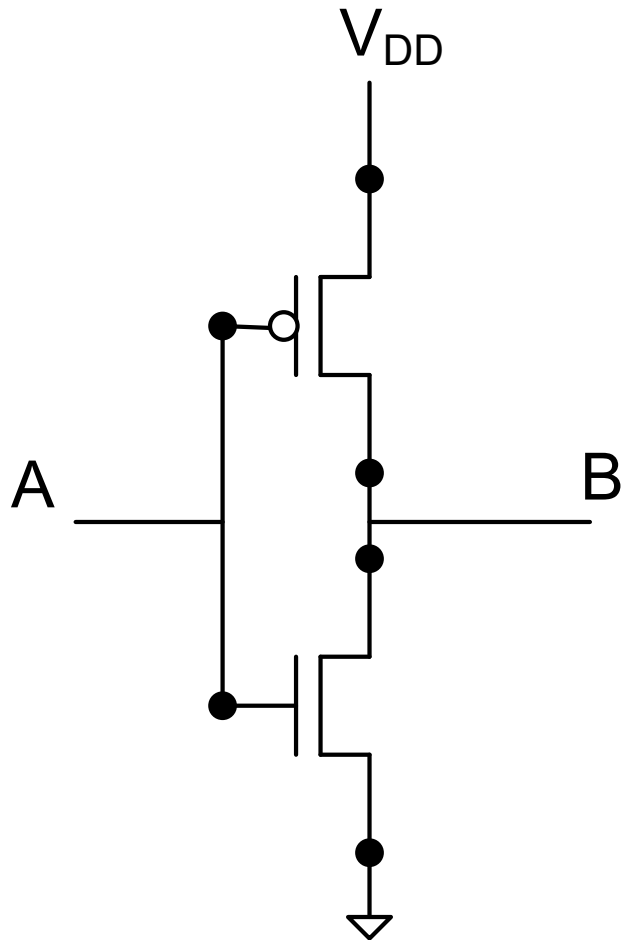
Source assumed  
connected to (or close to)  
ground



Source assumed connected to (or close to) positive  $V_{DD}$  and Boolean G at gate is relative to ground

## Review from Last Time

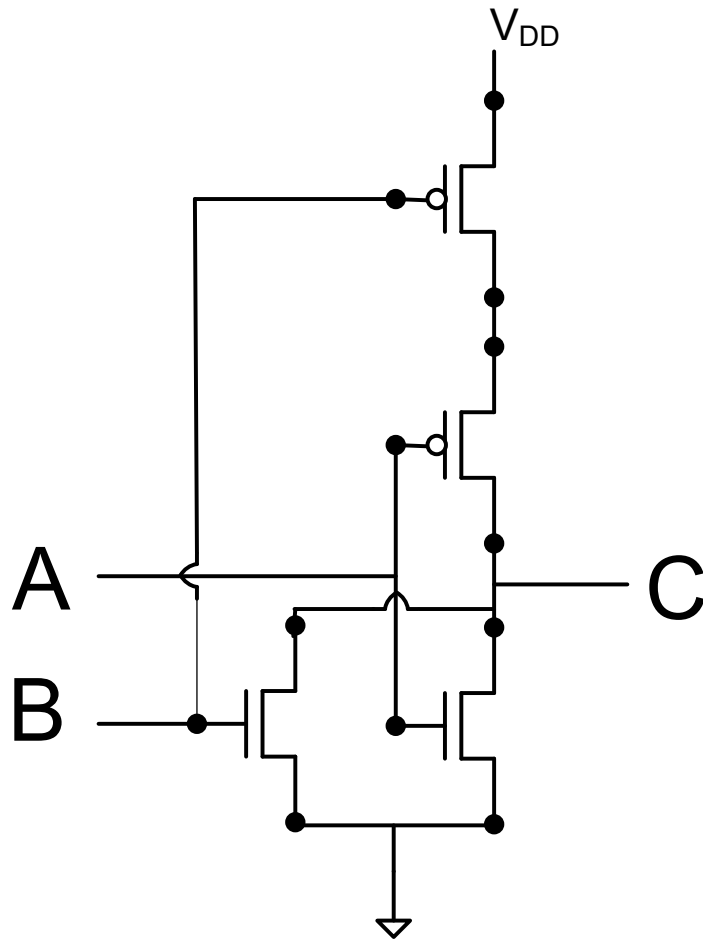
# Logic Circuits



**Circuit Behaves as a Boolean Inverter**

## Review from Last Time

# Logic Circuits



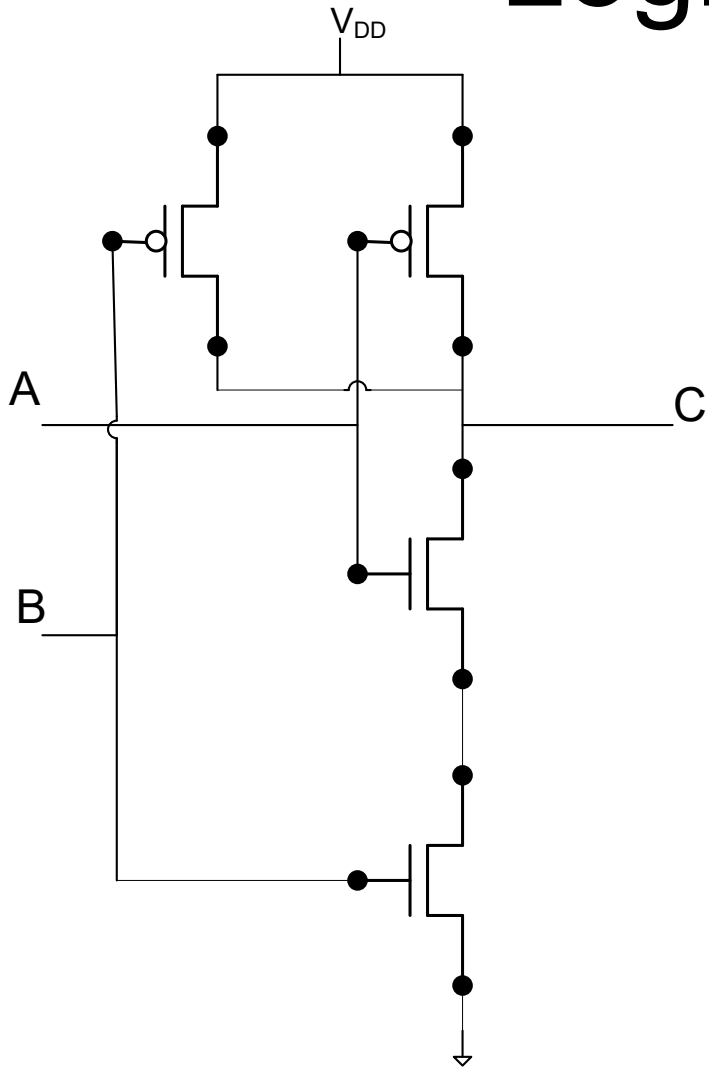
**NOR Gate**

**Truth Table**

A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

## Review from Last Time

# Logic Circuits



**NAND Gate**

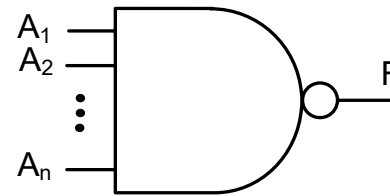
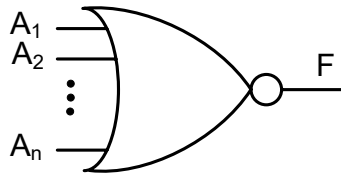
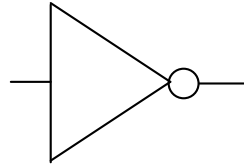
**Truth Table**

A	B	C
0	0	1
0	1	1
1	0	1
1	1	0



Review from Last Time

# Complete Logic Family



**Family of n-input NOR gates forms a complete logic family**

**Family of n-input NAND gates forms a complete logic family**

**Having both NAND and NOR gates available is a luxury**

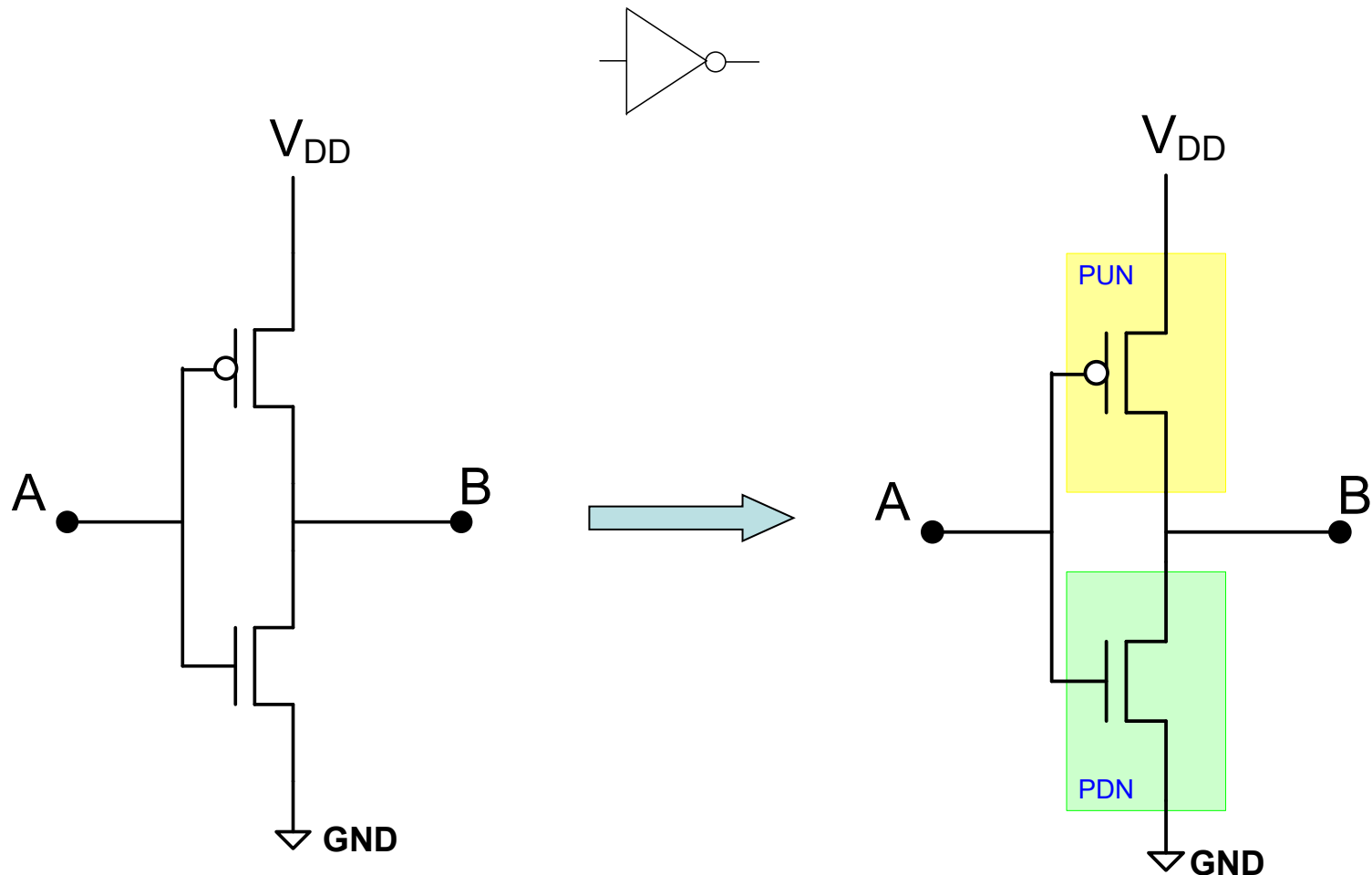
**Can now implement any combinational logic function !!**

**If add one flip flop, can implement any Boolean system !!**

**Flip flops easy to design but will discuss sequential logic systems later**

Review from Last Time

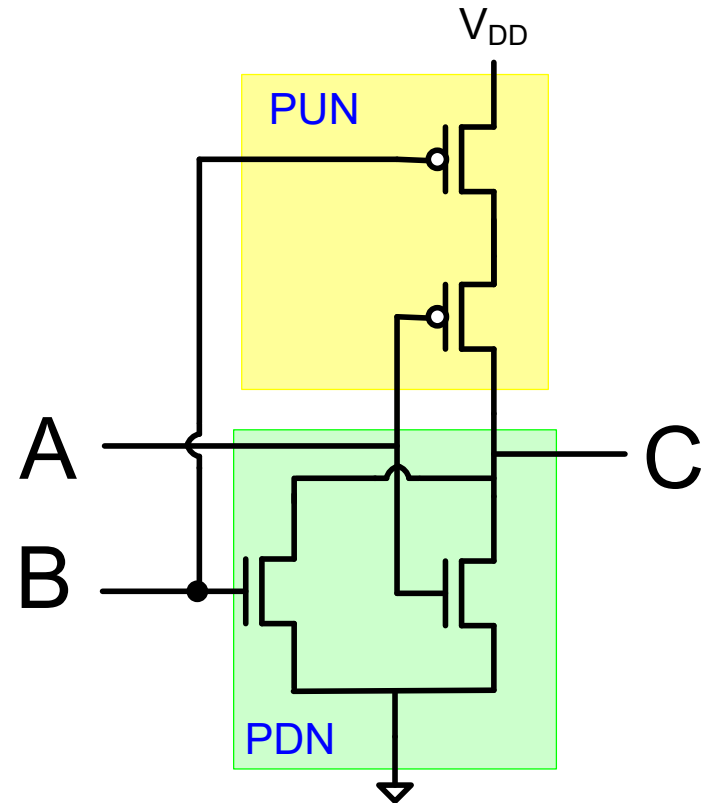
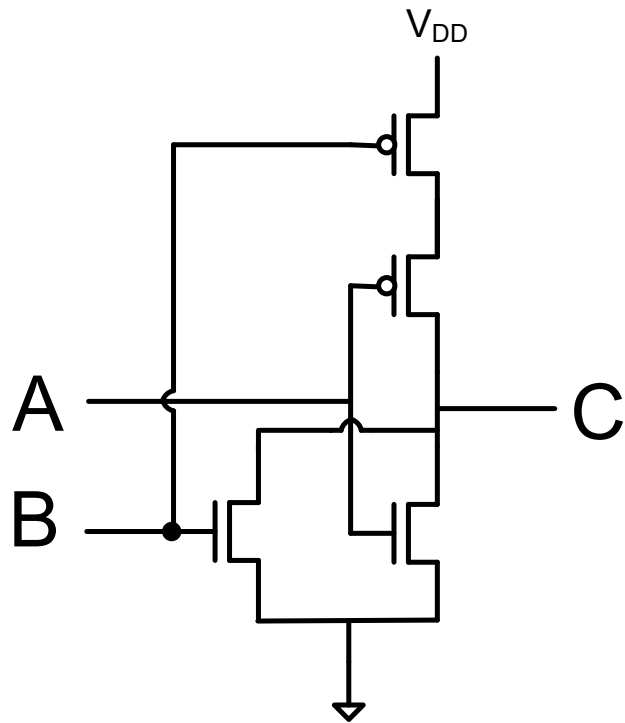
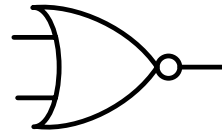
# Pull-up and Pull-down Networks



**PU network** comprised of p-channel device and “tries” to pull **B** to  $V_{DD}$  when conducting  
**PD network** comprised of n-channel device and “tries to pull **B** to **GND** when conducting  
One and only one of these networks is conducting at the same time (to avoid contention)

## Review from Last Time

# Pull-up and Pull-down Networks



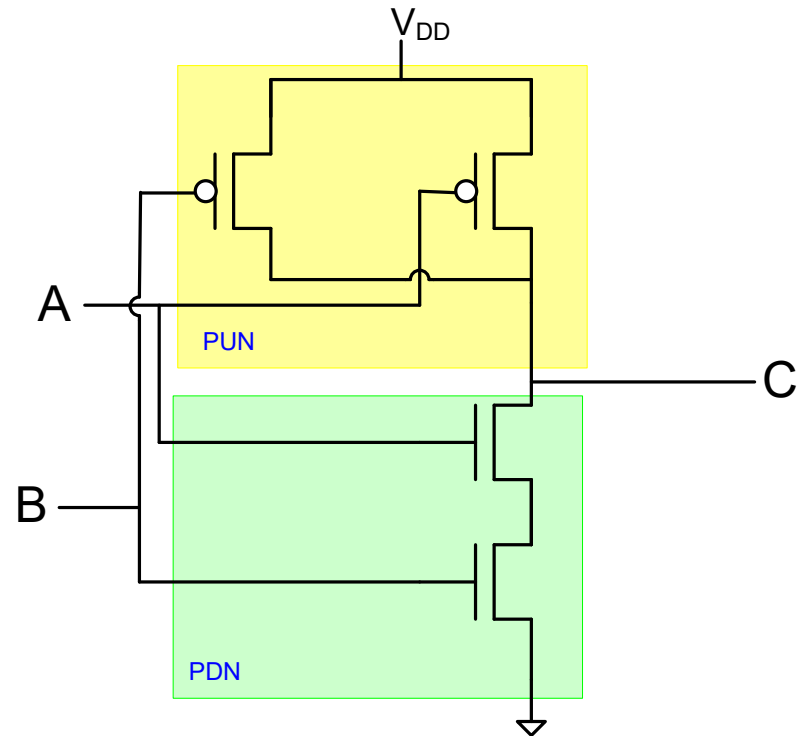
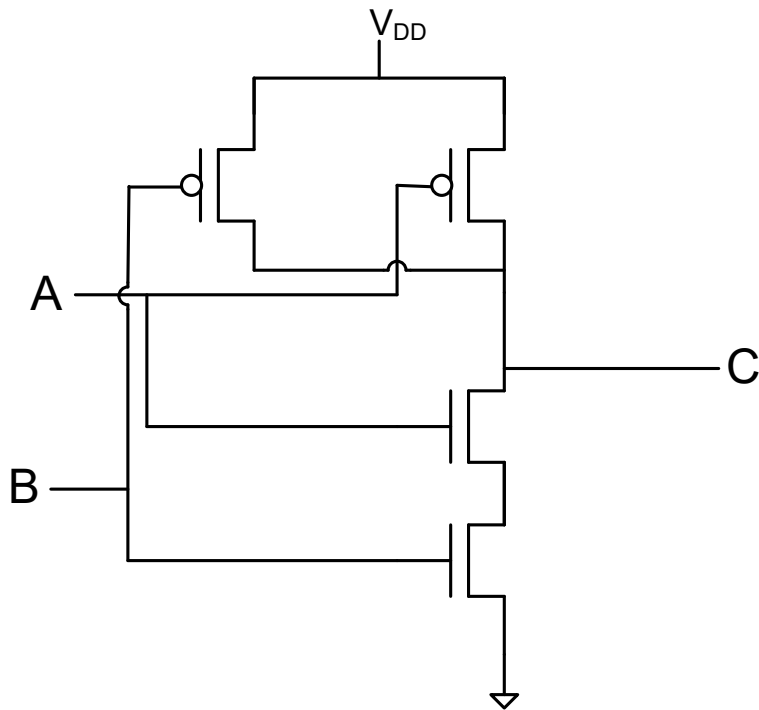
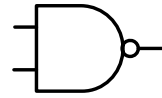
**PU network comprised of p-channel devices**

**PD network comprised of n-channel devices**

**One and only one of these networks is conducting at the same time**

## Review from Last Time

# Pull-up and Pull-down Networks

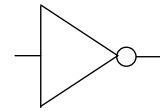
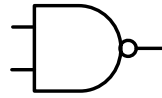
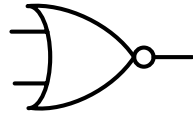


**PU network comprised of p-channel devices**

**PD network comprised of n-channel devices**

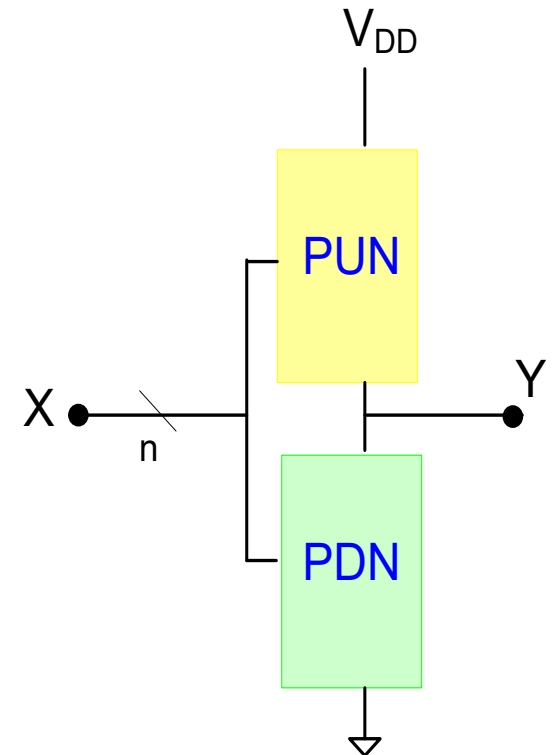
**One and only one of these networks is conducting at the same time**

# Pull-up and Pull-down Networks



In these circuits, the PUN and PDN have the 3 interesting characteristics

1. PU network comprised of p-channel devices
2. PD network comprised of n-channel devices
3. One and only one of these networks is conducting at the same time



**What are  $V_H$  and  $V_L$ ?**

**What is the power dissipation?**

**How fast are these logic circuits?**

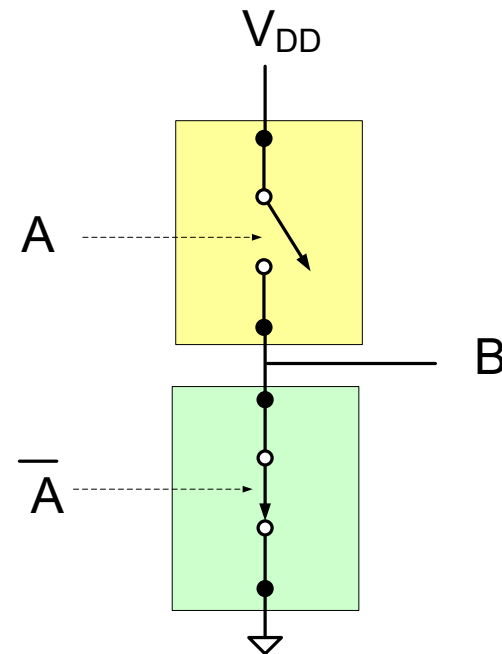
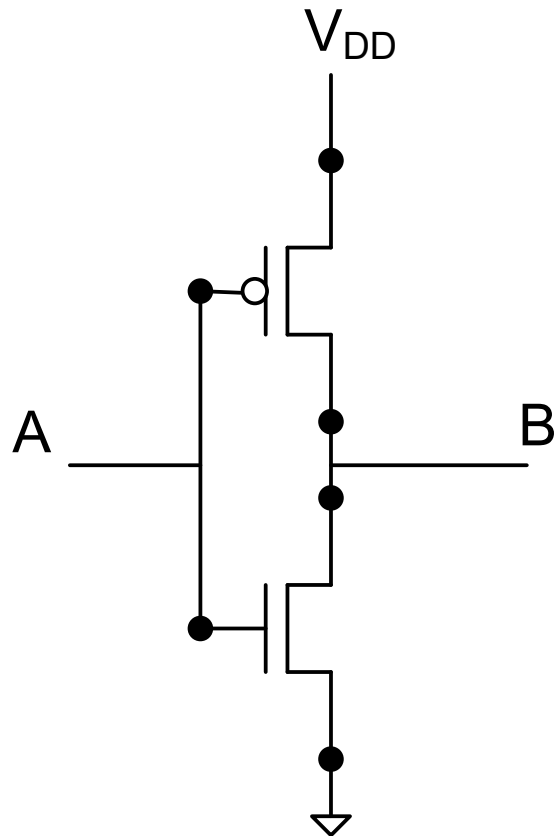
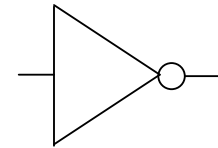
What are  $V_H$  and  $V_L$ ?

What is the power dissipation?

How fast are these logic circuits?

Consider the inverter

Use switch-level model for MOS devices



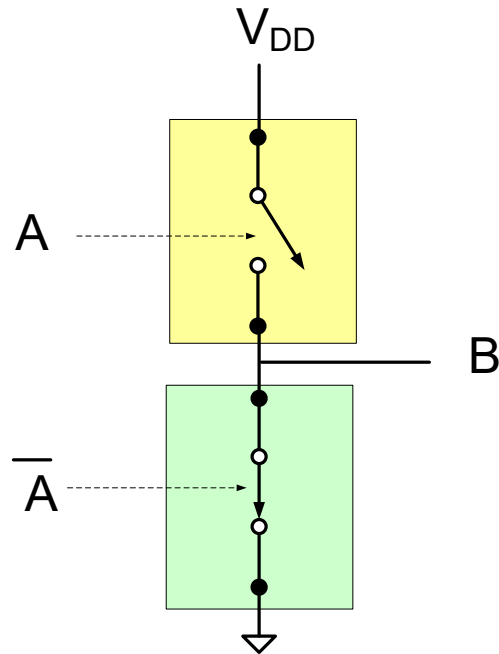
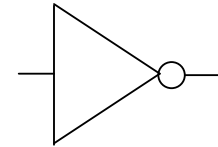
What are  $V_H$  and  $V_L$ ?

What is the power dissipation?

How fast are these logic circuits?

Consider the inverter

Use switch-level model for MOS devices



$$V_H = V_{DD}$$

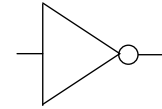
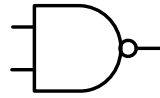
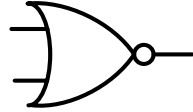
$$V_L = 0$$

$$I_D = 0 \text{ thus } P_H = P_L = 0$$

$$t_{HL} = t_{LH} = 0$$

(too good to be true?)

# Pull-up and Pull-down Networks



For these circuits, the PUN and PDN have 3 interesting characteristics

## Three key characteristics of these Static CMOS Gates

1. PU network comprised of p-channel devices
2. PD network comprised of n-channel devices
3. One and only one of these networks is conducting at the same time

## Three key properties of these Static CMOS Gates

1. What are  $V_H$  and  $V_L$ ?

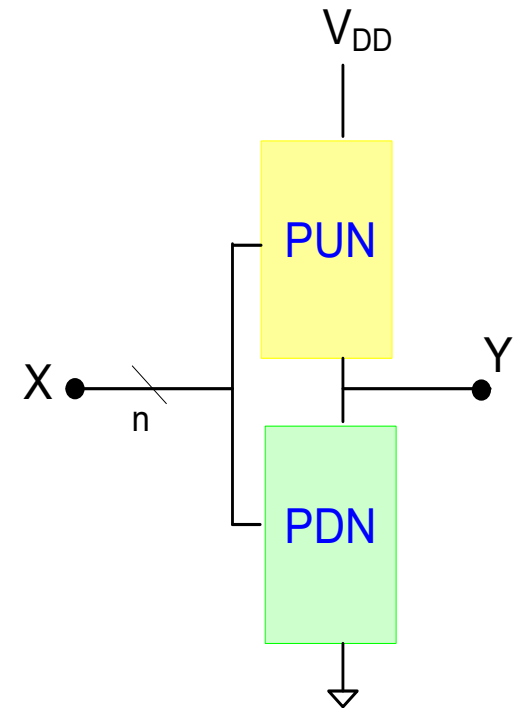
$$V_H = V_{DD}, V_L = 0 \quad (\text{too good to be true?})$$

2. What is the power dissipation?

$$P_H = P_L = 0 \quad (\text{too good to be true?})$$

3. How fast are these logic circuits?

$$t_{HL} = t_{LH} = 0 \quad (\text{too good to be true?})$$



These 3 properties are inherent in all Boolean circuits that have these 3 characteristics !!!



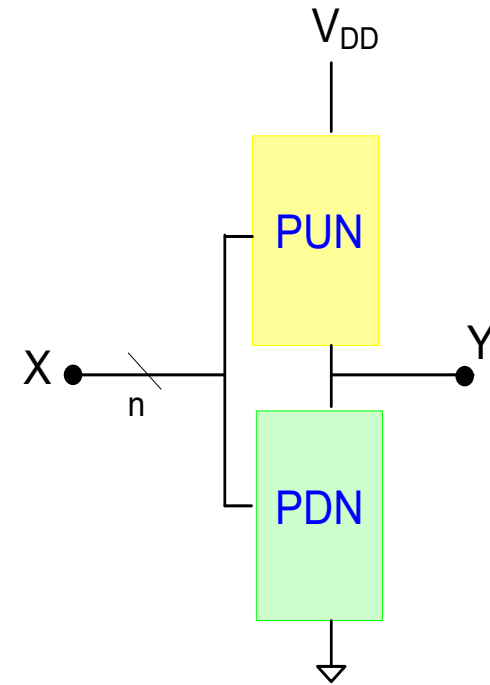
# Pull-up and Pull-down Networks

## Three key characteristics of Static CMOS Gates

1. PU network comprised of p-channel devices
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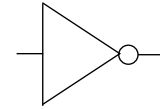
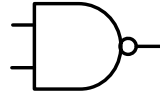
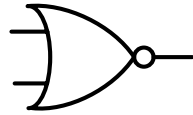
## Three properties of Static CMOS Gates (based upon simple switch-level model)

1.  $V_H = V_{DD}$ ,  $V_L = 0$  (too good to be true?)
2.  $P_H = P_L = 0$  (too good to be true?)
3.  $t_{HL} = t_{LH} = 0$  (too good to be true?)



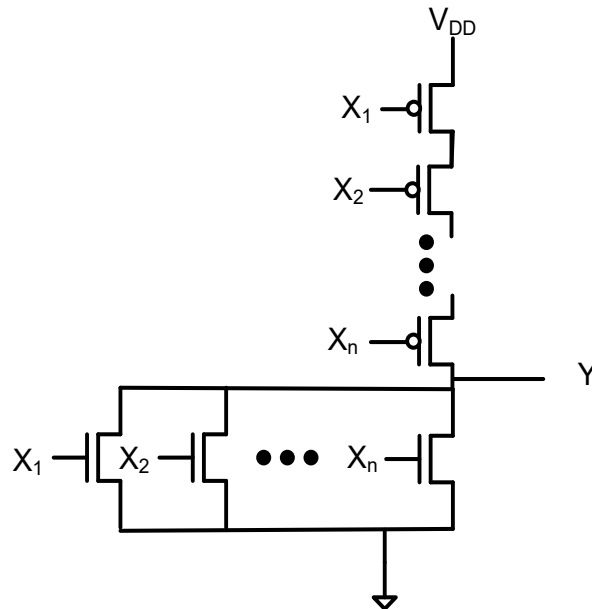
These 3 properties are inherent in Boolean circuits with these 3 characteristics

# Pull-up and Pull-down Networks

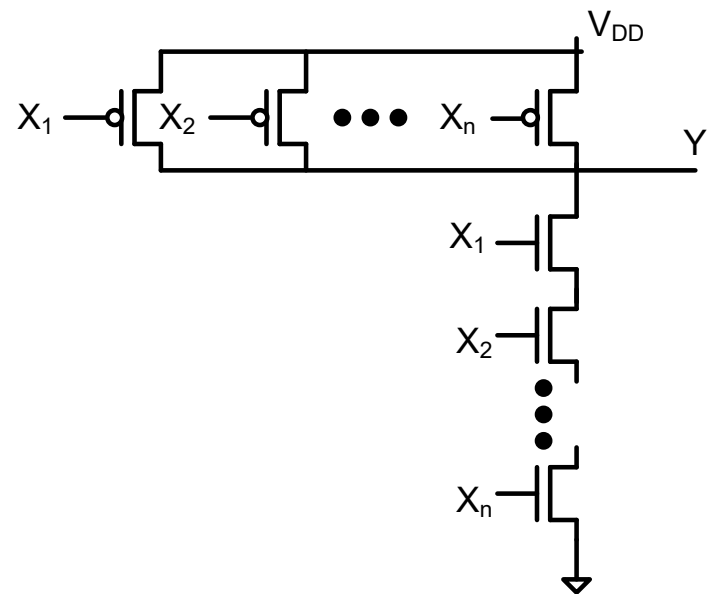


Concept can be extended to arbitrary number of inputs

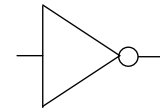
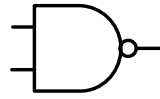
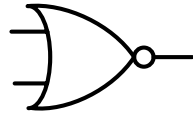
**n-input NOR gate**



**n-input NAND gate**

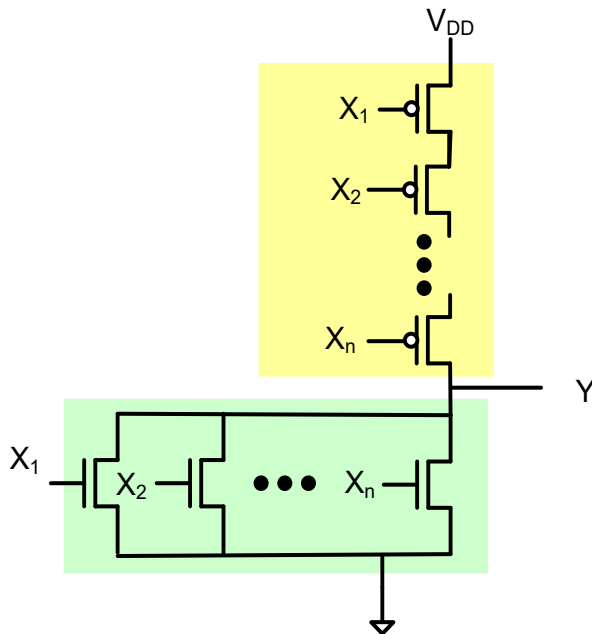


# Pull-up and Pull-down Networks

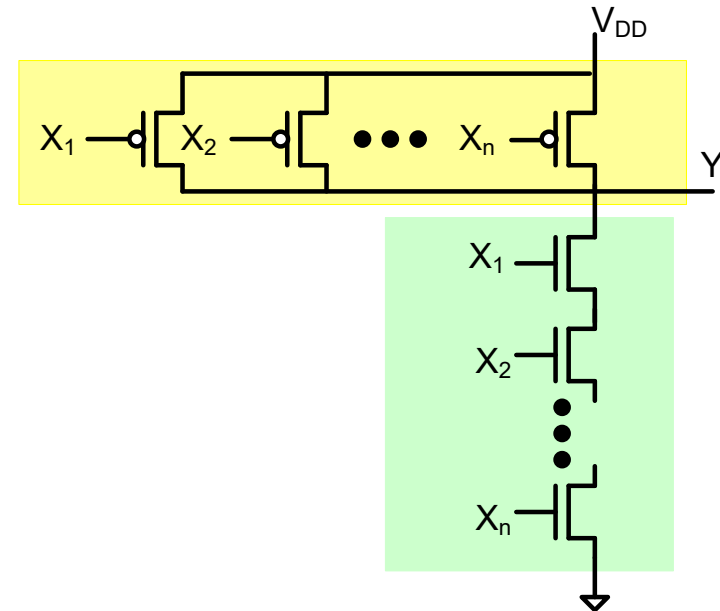


Concept can be extended to arbitrary number of inputs

**n-input NOR gate**

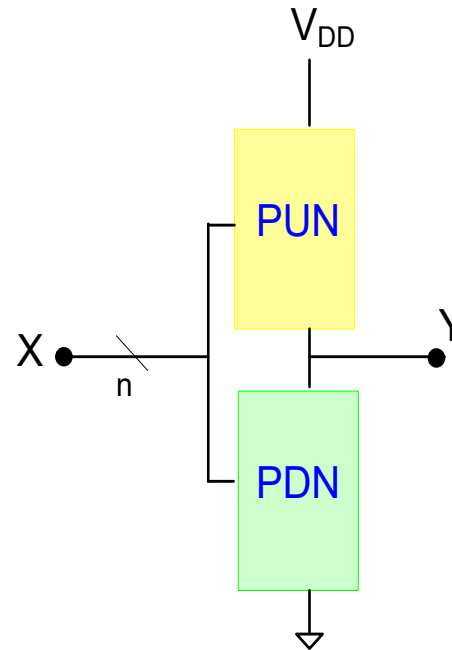
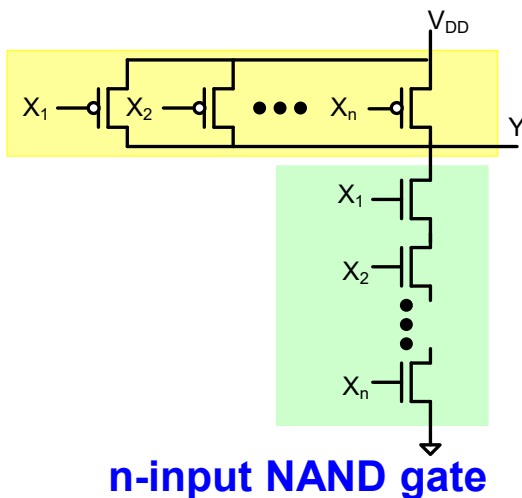
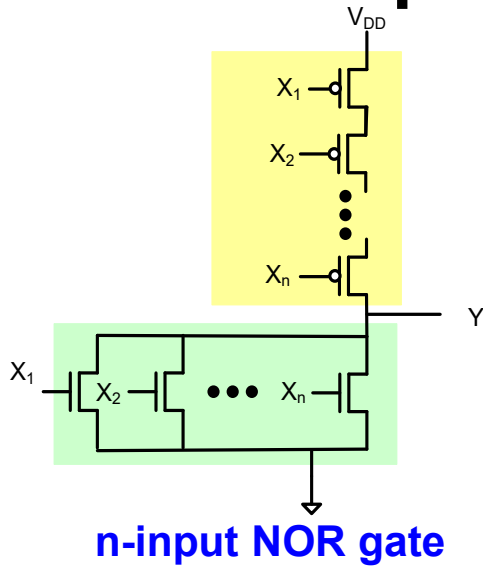


**n-input NAND gate**



1. PU network comprised of p-channel devices
2. PD network comprised of n-channel devices
3. One and only one of these networks is conducting at the same time

# Pull-up and Pull-down Networks



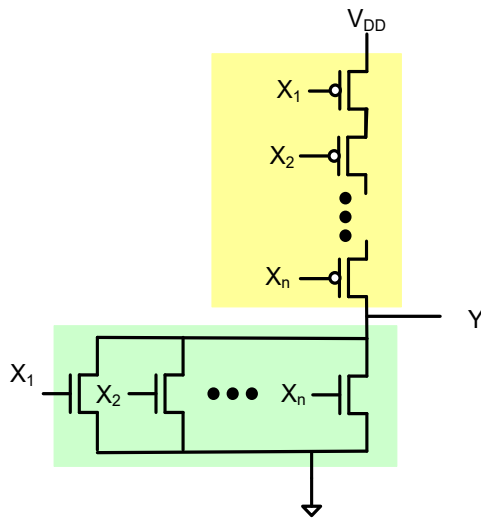
1. PU network comprised of p-channel devices
2. PD network comprised of n-channel devices
3. One and only one of these networks is conducting at the same time

$$V_H = V_{DD}, \quad V_L = 0$$

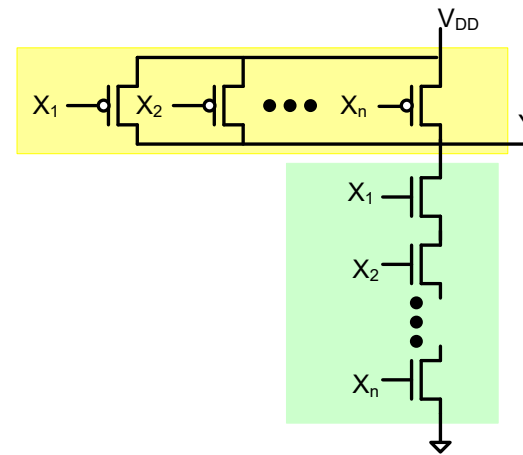
$$P_H = P_L = 0$$

$$t_{HL} = t_{LH} = 0$$

# Nomenclature



**n-input NOR gate**



**n-input NAND gate**

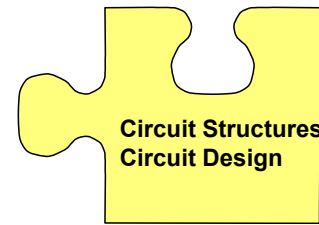
In this class, logic circuits that are implemented by interconnecting multiple-input NAND and NOR gates will be referred to as “Static CMOS Logic”

Since the set of NAND gates is complete, any combinational logic function can be realized with the NAND circuit structures considered thus far

Since the set NOR gates is complete, any combinational logic function can be realized with the NOR circuit structures considered thus far

Many logic functions are realized with “Static CMOS Logic” and this is probably the dominant design style used today!

## Example 1:



How many transistors are required to realize the function

$$F = \overline{A} \cdot \overline{B} + \overline{A} \cdot C$$

in a basic CMOS process if static NAND and NOR gates are used? Assume A, B and C are available.

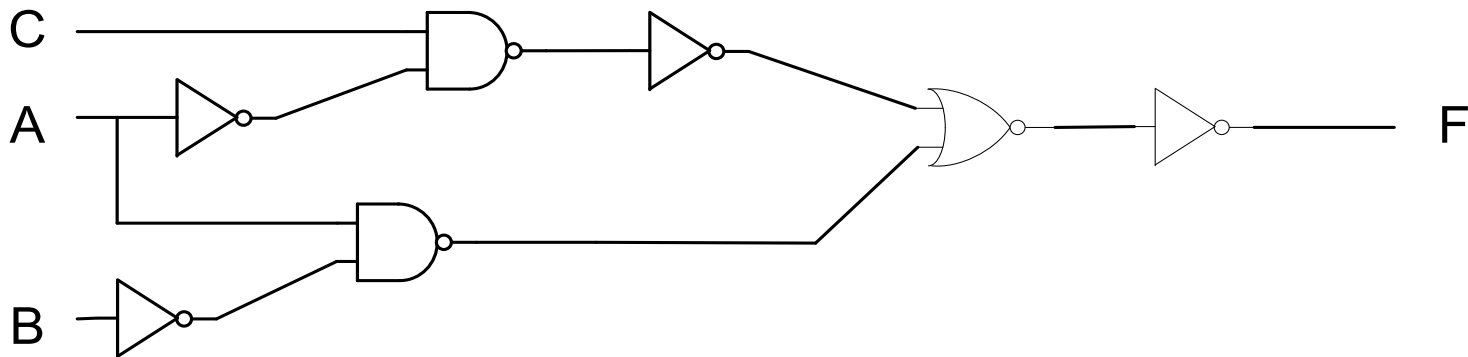
## Example 1:

How many transistors are required to realize the function

$$F = \overline{\overline{A} \cdot \overline{B}} + \overline{A} \cdot C$$

in a basic CMOS process if static NAND and NOR gates are used? Assume A, B and C are available.

**Solution:**



**20 transistors and 5 levels of logic**

## Example 1:

How many transistors are required to realize the function

$$F = \overline{\overline{A} \cdot \overline{B}} + \overline{A} \cdot C$$

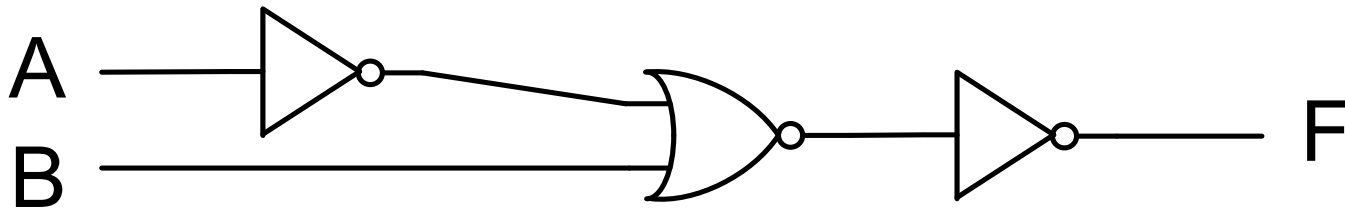
in a basic CMOS process if static NAND and NOR gates are used? Assume A, B and C are available.

**Solution (alternative):**

From basic Boolean Manipulations

$$F = \overline{\overline{A} \cdot \overline{B}} + \overline{A} \cdot C = \overline{A} + B + \overline{A} \cdot C$$

$$F = \overline{A} \cdot (1 + C) + B = \overline{A} + B$$



**8 transistors and 3 levels of logic**



## Example 1:

How many transistors are required to realize the function

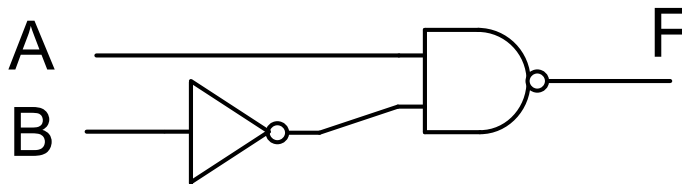
$$F = \overline{\overline{A} \cdot \overline{B}} + \overline{A} \cdot C$$

in a basic CMOS process if static NAND and NOR gates are used? Assume A, B and C are available.

**Solution (alternative):** From basic Boolean Manipulations

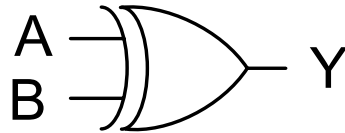
$$F = \overline{\overline{A} \cdot (1 + C)} + B = \overline{\overline{A} + B}$$

$$F = \overline{\overline{\overline{\overline{A} + B}}} = \overline{A \cdot \overline{B}}$$



**6 transistors and 2 levels of logic**

# Example 2: XOR Function

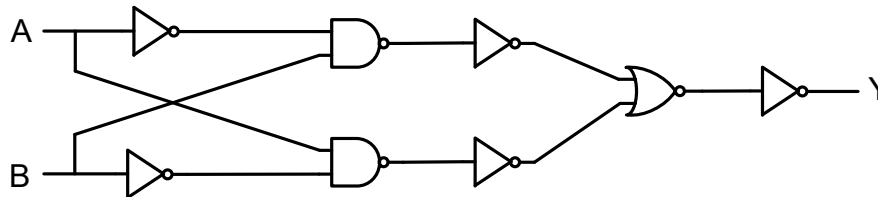


$$Y = A \oplus B$$

A widely-used 2-input Gate

Static CMOS implementation

$$Y = A\bar{B} + \bar{A}B$$

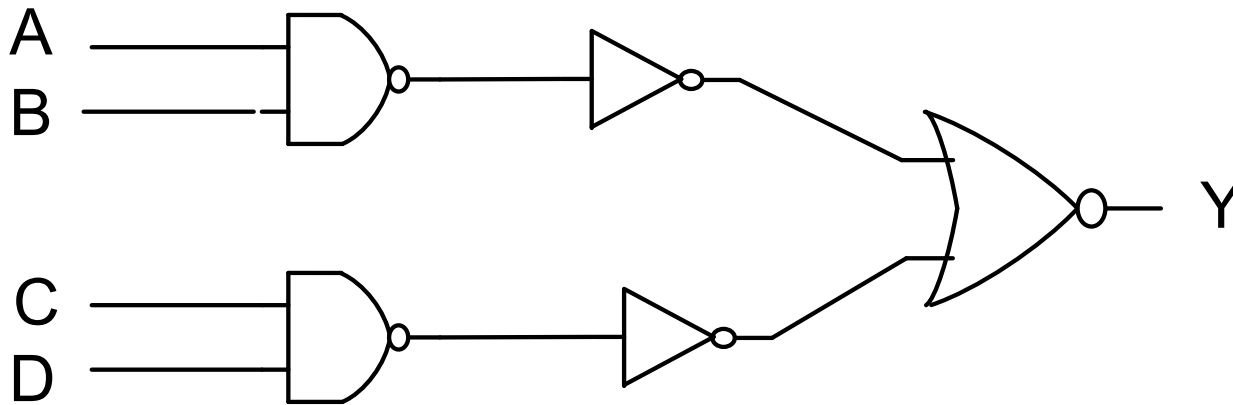


*22 transistors 5 levels of logic*

**Delays unacceptable (will show later) and device count is too large !**

Example 3:  $Y = \overline{(A \cdot B) + (C \cdot D)}$

## Standard Static CMOS Implementation



**3 levels of Logic**

**16 Transistors if Basic CMOS Gates are Used**

**Can the same Boolean functionality be obtained with less transistors?**

# Complex Logic Gates

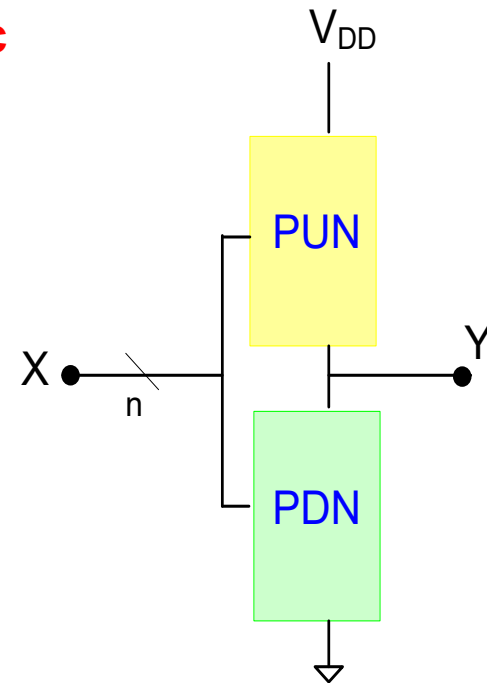
Some circuits other than multiple-input NAND and NOR gates can also have the three key characteristics

## Three key characteristics of low static power CMOS logic

1. PU network comprised of p-channel devices
2. PD network comprised of n-channel devices
3. One and only one of these networks is conducting at the same time

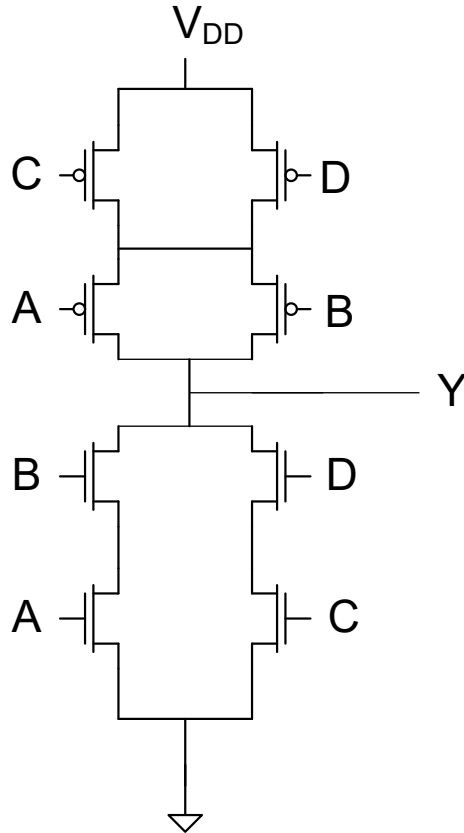
## Three properties of circuits with these 3 characteristics

1.  $V_H = V_{DD}$ ,  $V_L = 0$  (too good to be true?)
2.  $P_H = P_L = 0$  (too good to be true?)
3.  $t_{HL} = t_{LH} = 0$  (too good to be true?)

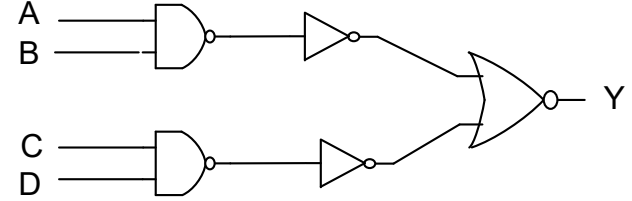


These 3 properties are inherent in Boolean circuits with these 3 characteristics

# Observe:



Recall from previous example:



$$Y = \overline{(A \cdot B) + (C \cdot D)}$$

3 levels of Logic, 16 Transistors if Basic CMOS Gates are Used

$$Y = \overline{(A \cdot B) + (C \cdot D)}$$

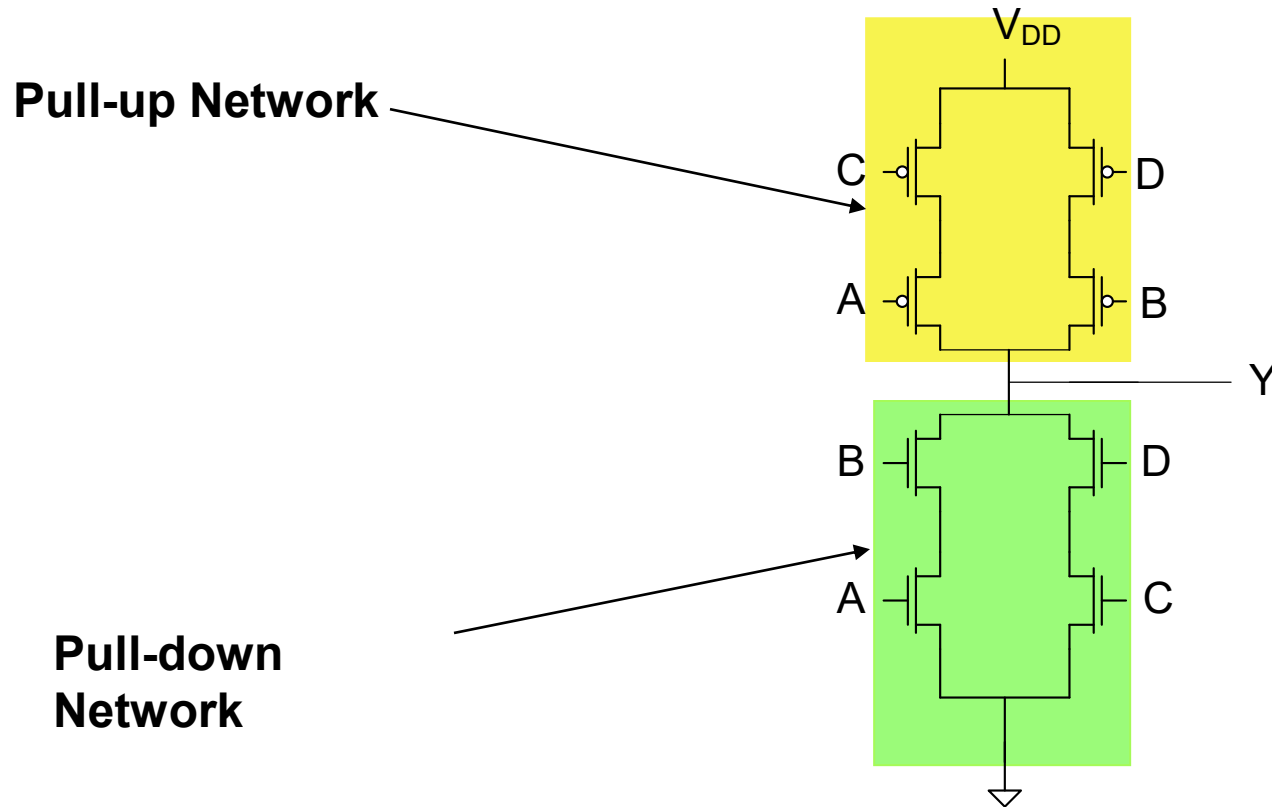
1 level of logic and 8 transistors in this example

Significant reduction in transistor count and levels of logic for realizing same Boolean function

Termed a “Complex Logic Gate” implementation

Some authors term this a “compound gate”

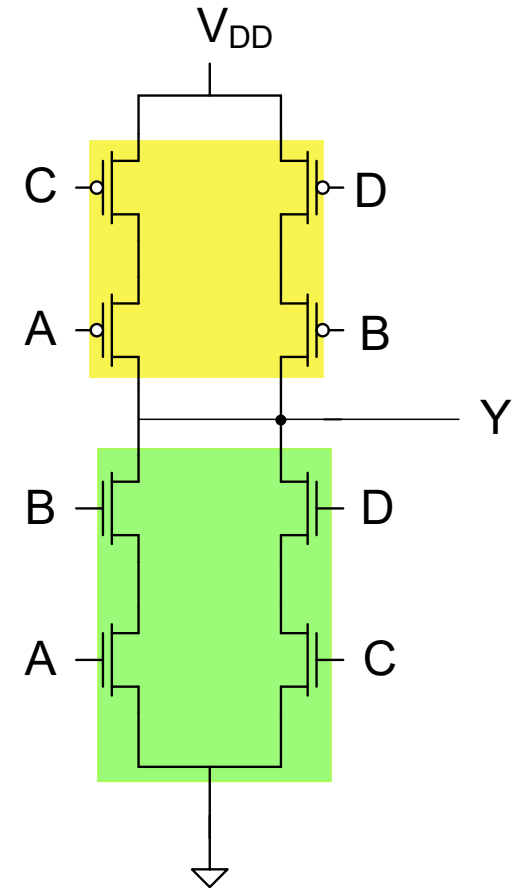
# Complex Logic Gates



$$Y = \overline{(A \bullet B) + (C \bullet D)}$$

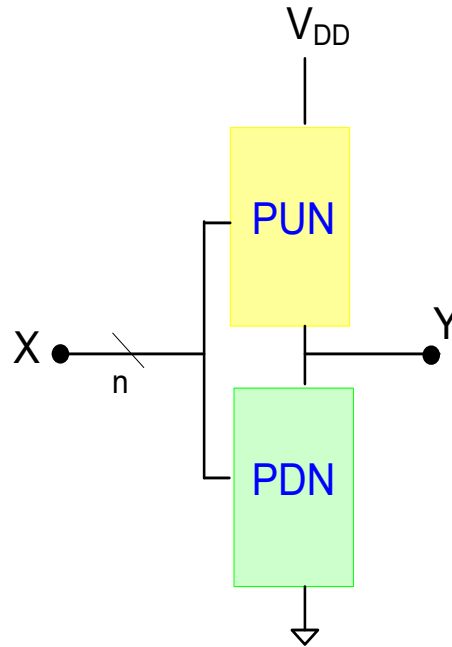
# Complex Gates

1. PU network comprised of p-channel devices
2. PD network comprised of n-channel devices
3. One and only one of these networks is conducting at the same time



# Complex Gates

**Nomenclature:**

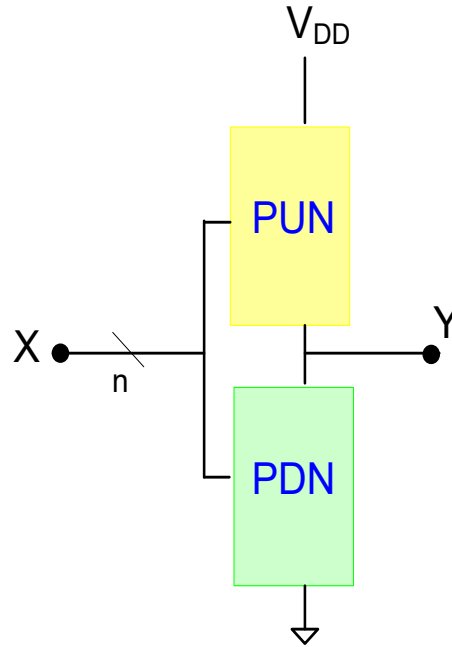


**When the logic gate shown is not a multiple-input NAND or NOR gate but has Characteristics 1, 2, and 3 above, the gate will be referred to as a Complex Logic Gate**

**Complex Logic Gates also implement static logic functions and some authors would refer to this as Static CMOS Logic as well but we will make the distinction and refer to this as “Complex Logic Gates”**



# Complex Gates

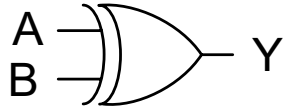


## Complex Gate Design Strategy:

1. Implement  $\bar{Y}$  in the PDN
2. Implement  $Y$  in the PUN (must complement the input variables since p-channel devices are used)

( $Y$  and  $\bar{Y}$  often expressed in either SOP or POS form)

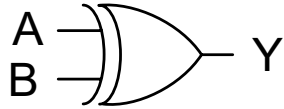
# XOR in Complex Logic Gates



$$Y = A \oplus B$$

Will express  $\overline{Y}$  and Y in standard SOP or POS form

# XOR in Complex Logic Gates



$$Y = A \oplus B$$

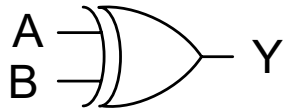
$$Y = A\bar{B} + \bar{A}B$$

$$\bar{Y} = \overline{(A\bar{B} + \bar{A}B)}$$

$$\bar{Y} = \overline{A\bar{B}} \cdot \overline{\bar{A}B}$$

$$\bar{Y} = (\bar{A} + B) \cdot (A + \bar{B})$$

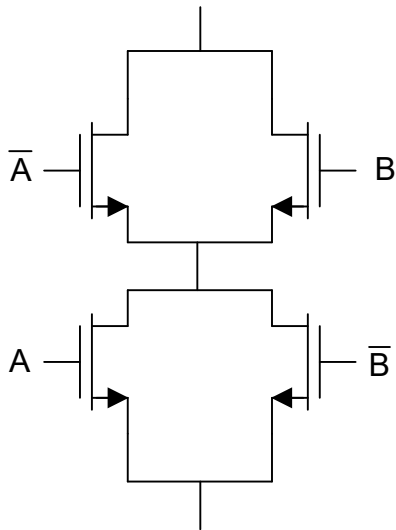
# XOR in Complex Logic Gates



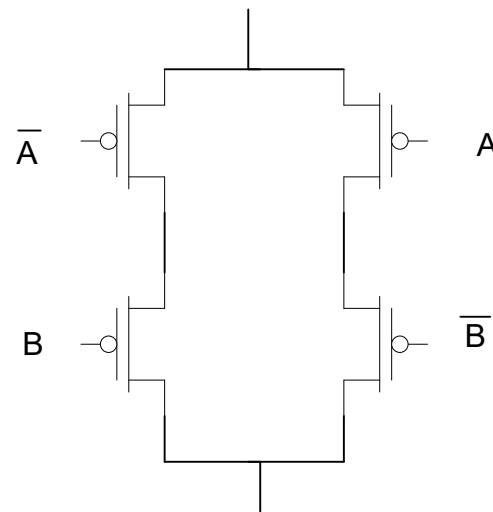
$$Y = A\bar{B} + \bar{A}B$$

$$\bar{Y} = (\bar{A} + B) \cdot (A + \bar{B})$$

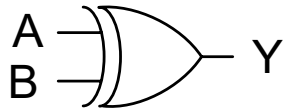
**PDN**



**PUN**

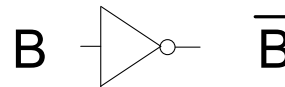
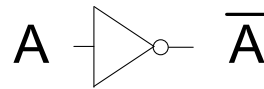


# XOR in Complex Logic Gates



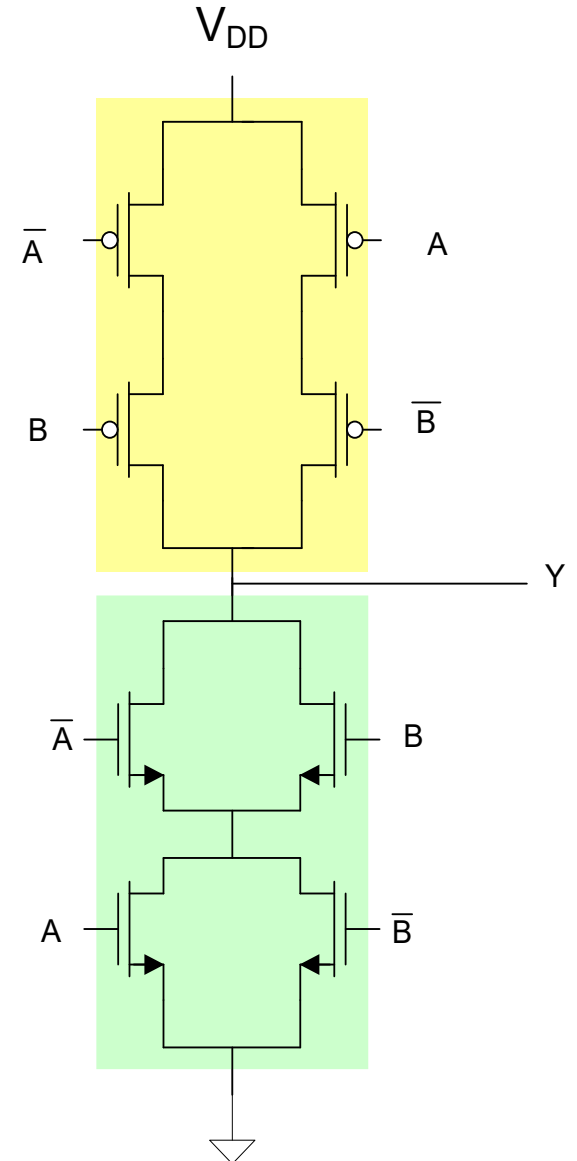
$$Y = A\bar{B} + \bar{A}B$$

$$\bar{Y} = (\bar{A} + B) \cdot (A + \bar{B})$$

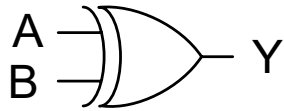


**12 transistors and 2 levels of logic**

**Notice a significant reduction in the number of transistors required**



# XOR in Complex Logic Gates

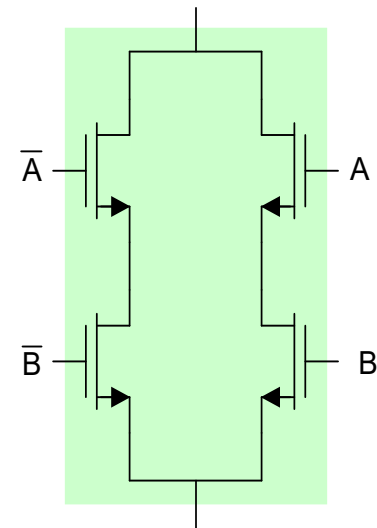
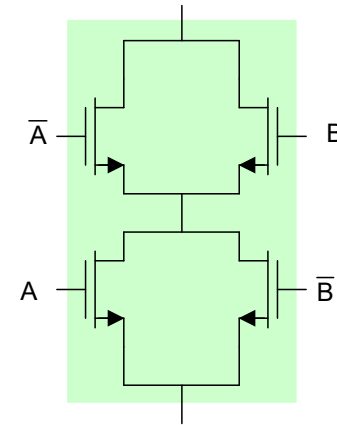


$$Y = A\bar{B} + \bar{A}B$$

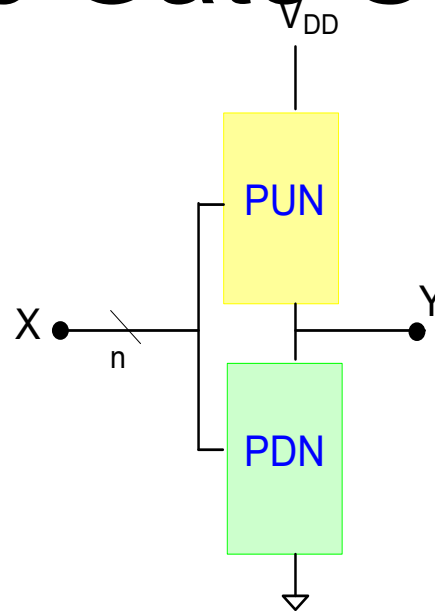
$$\bar{Y} = (\bar{A} + B) \cdot (A + \bar{B})$$

Multiple PU and PD networks can be used

$$\begin{aligned}\bar{Y} &= (\bar{A} + B) \cdot (A + \bar{B}) \\ &= (\bar{A} \cdot (A + \bar{B})) + (B \cdot (A + \bar{B})) \\ &= (\bar{A} \cdot \bar{B}) + (A \cdot B)\end{aligned}$$



# Complex Logic Gate Summary:



If PUN and PDN satisfy the characteristics:

1. PU network comprised of p-channel device
2. PD network comprised of n-channel device
3. One and only one of these networks is conducting at the same time

**Properties of PU/PD logic of this type (with simple switch-level model):**

**Rail to rail logic swings**

**Zero static power dissipation in both Y=1 and Y=0 states**

**Arbitrarily fast (too good to be true? will consider again with better model)**

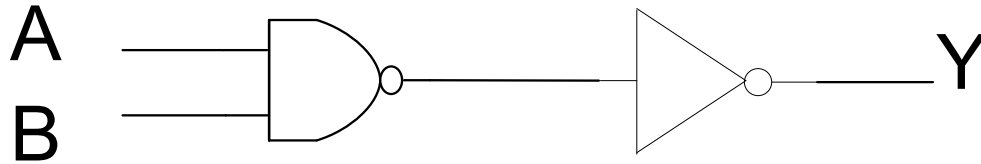
## Pass Transistor Logic

- Improved Switch-Level Model
- Propagation Delay
- Stick Diagrams
- Technology Files



Consider  $Y = A \cdot B$

## Standard CMOS Implementation

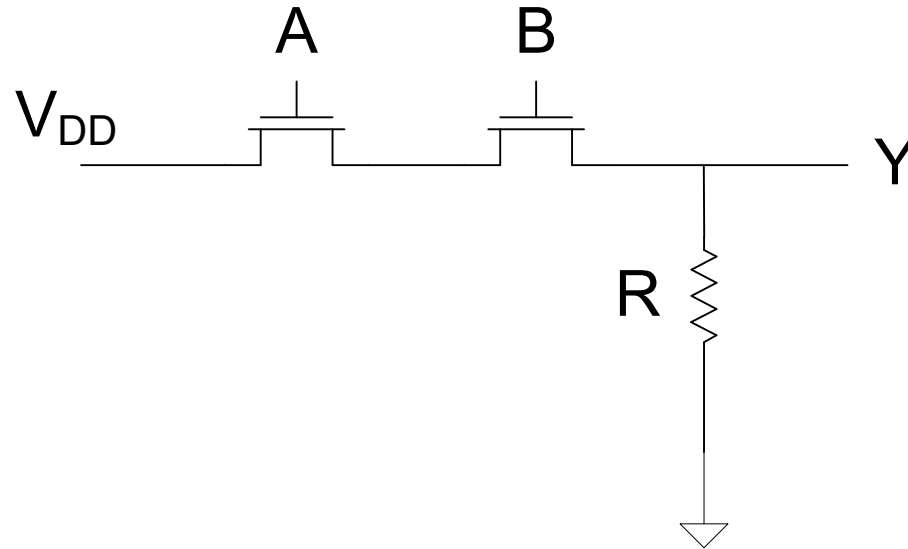


**2 levels of Logic**

**6 Transistors if Basic CMOS Gates are Used**

**Basic noninverting functions generally require more complexity if basic CMOS gates are used for implementation**

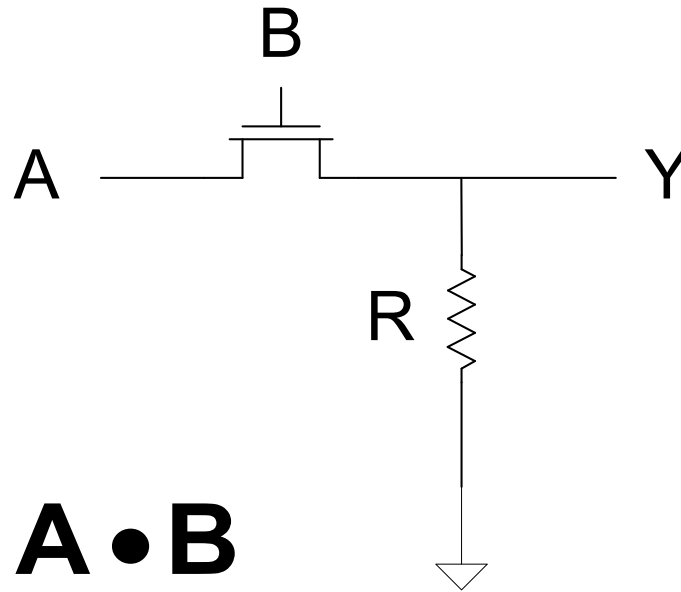
# Pass Transistor Logic



$$Y = A \bullet B$$

Requires only 2 transistors rather than 6 for a standard CMOS gate (and a resistor).

# Pass Transistor Logic



$$Y = A \bullet B$$

Even simpler pass transistor logic implementations are possible

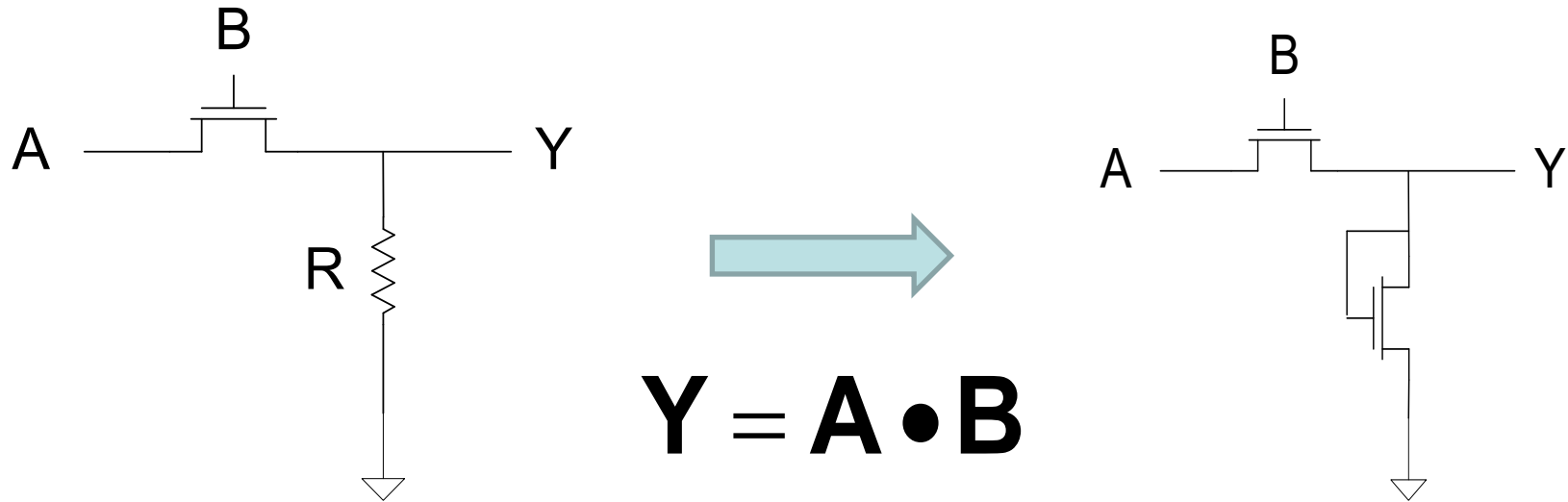
Requires only 1 transistor (and a resistor).



Will see later that the area of a single practical resistor for this circuit may be comparable to that needed for hundreds or even thousands of transistors



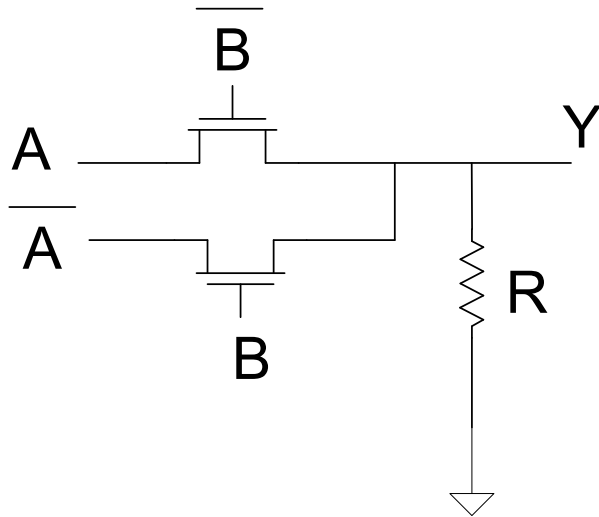
# Pass Transistor Logic



- **May be able to replace resistor with transistor (one of several ways shown)**
- **But high logic level can not be determined with existing device model (or even low logic level for circuit on right)**
- **Power dissipation can not be determined with existing device model for circuit on right**

**Better device model is needed (Power? Signal Swing? Speed?)**

# Pass Transistor Logic

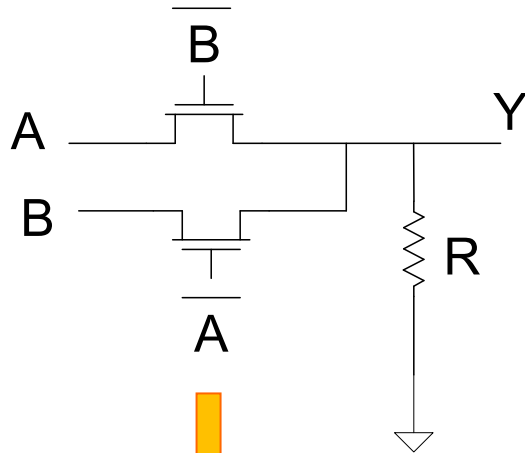


$$Y = A \oplus B$$

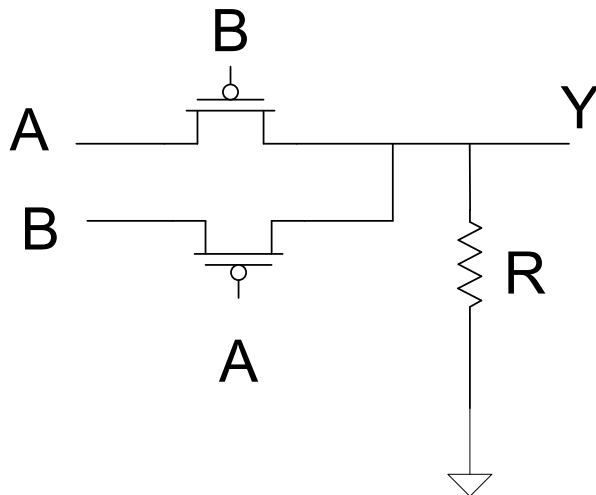
**6 transistors, 1 resistor, two levels of logic**

(the 4 transistors in the two inverters are not shown)

# Pass Transistor Logic



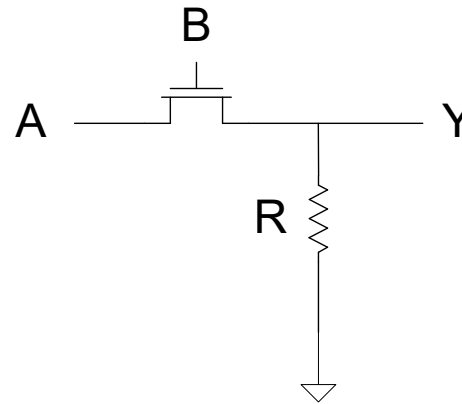
$$Y = A \oplus B$$



$$Y = A \oplus B$$

**2 transistors, 1 resistor, one level of logic**

# Pass Transistor Logic



$$Y = A \cdot B$$

## Requires only 1 transistor (and a resistor)

- Pass transistor logic can offer significant reductions in complexity for some functions (particularly noninverting)
- Resistor may require more area than several hundred or even several thousand transistors
- Signal levels may not go to  $V_{DD}$  or to 0V
- Static power dissipation may not be zero
- Signals may degrade unacceptably if multiple gates are cascaded
- “resistor” often implemented with a transistor to reduce area but signal swing and power dissipation problems still persist
- Pass transistor logic is widely used

# Logic Design Styles

- Several different logic design styles are often used throughout a given design (3 considered thus far)
  - Static CMOS
  - Complex Logic Gates
  - Pass Transistor Logic
- The designer has complete control over what is placed on silicon and governed only by cost and performance
- New logic design strategies have been proposed recently and others will likely emerge in the future
- The digital designer needs to be familiar with the benefits and limitations of varying logic styles to come up with a good solution for given system requirements



- Pass Transistor Logic
- Improved Switch-Level Model
- Propagation Delay
- Stick Diagrams
- Technology Files

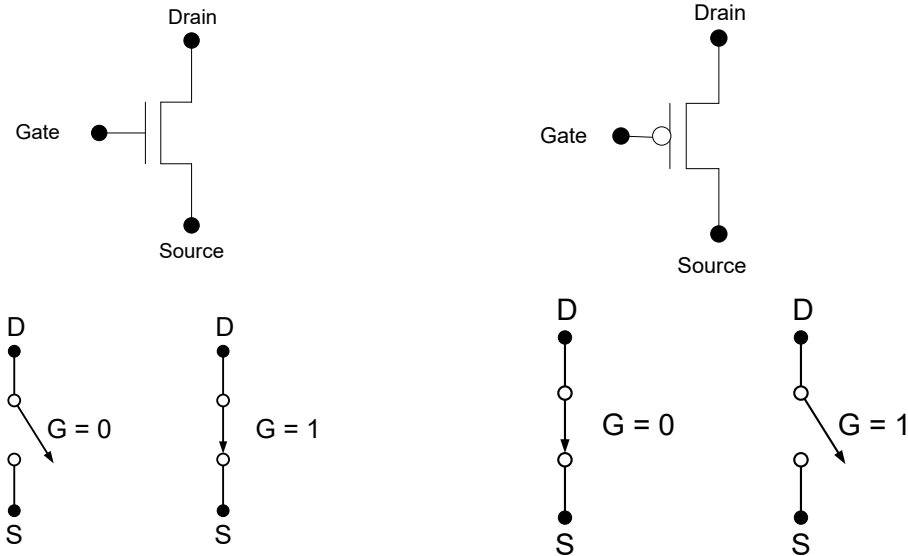
# MOSFET Modeling



- Simple model of MOSFET was developed (termed switch-level model)
- Simple gates designed in CMOS Process were introduced
  - Some have zero power dissipation
  - Some have or appeared to have rail to rail logic voltage swings
  - All appeared to be Infinitely fast
  - Logic levels of some can not be predicted with simple model
  - Simple model is not sufficiently accurate to provide insight relating to some of these properties
- MOSFET modeling strategy
  - hierarchical model structure will be developed
  - generally use simplest model that can be justified

# MOS Transistor Models

## 1, Switch-Level model



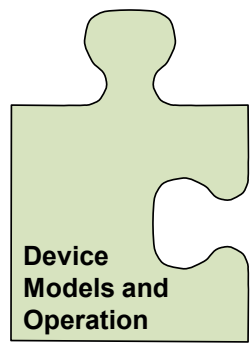
### Advantages:

Simple, does not require understanding of semiconductor properties, does not depend upon process, adequate for understanding basic operation of many digital circuits

### Limitations:

Does not provide timing information (surfaced when looking at static CMOS circuits, and several others that have not yet become apparent from the applications that have been considered) and can not support design of “resistor” used in Pass Transistor Logic

# Improved Device Models



With the simple switch-level model, it was observed that basic static CMOS logic gates have the following three properties:

- Rail to rail logic swings
- Zero static power dissipation in both  $Y=1$  and  $Y=0$  states
- Arbitrarily fast (too good to be true? will consider again with better model)

It can be shown that the first two properties are nearly satisfied in actual fabricated circuits with p-channel/n-channel PU/PD logic but though the circuits are fast, they are observably not arbitrarily fast

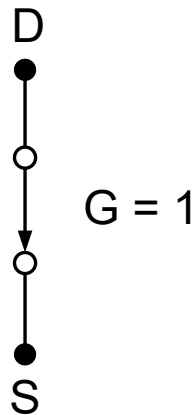
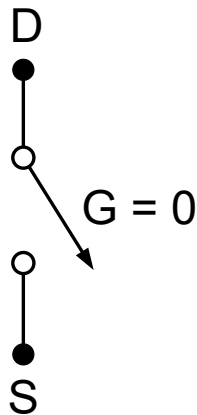
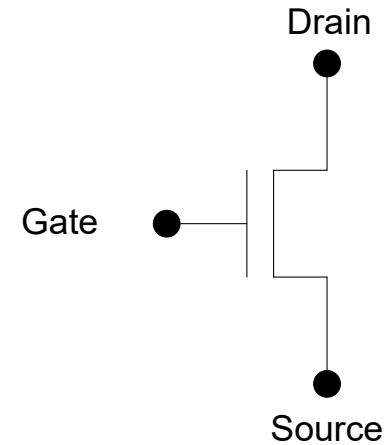
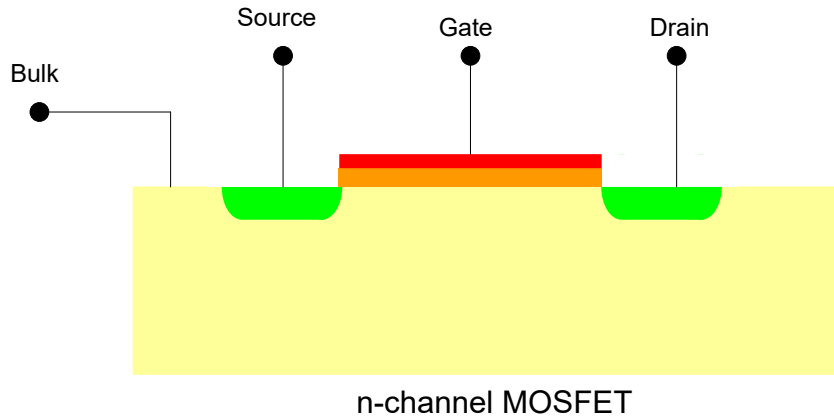
None of these properties are observed for some logic styles such as Pass Transistor Logic

**Will now extend switch-level model to predict speed of basic gates in static CMOS and logic levels and power dissipation in PTL**

# Recall

# MOS Transistor

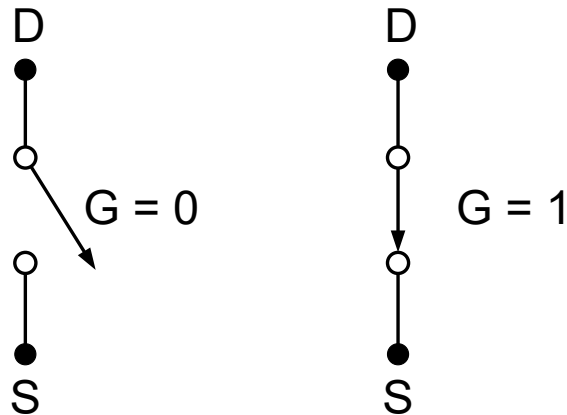
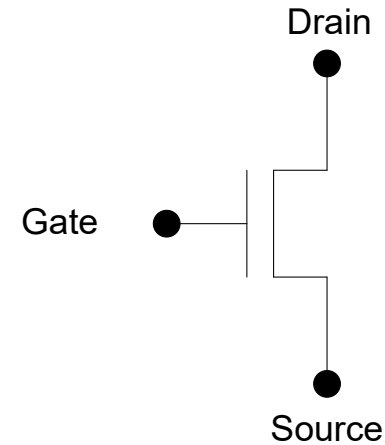
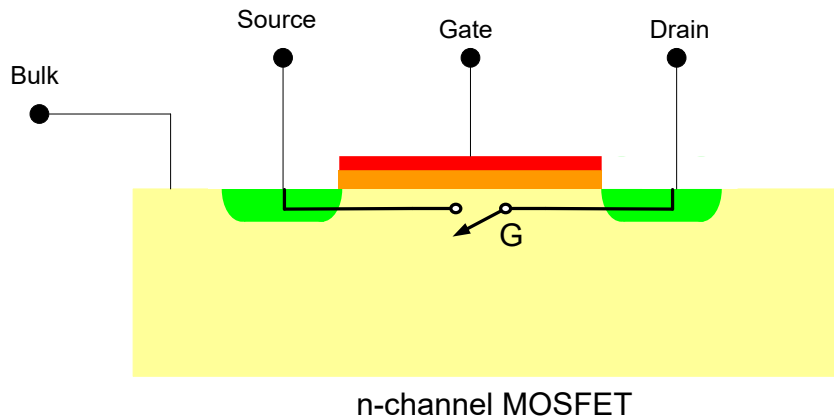
## Qualitative Discussion of n-channel Operation



This was the first model introduced and was termed the basic switch-level mode

# MOS Transistor

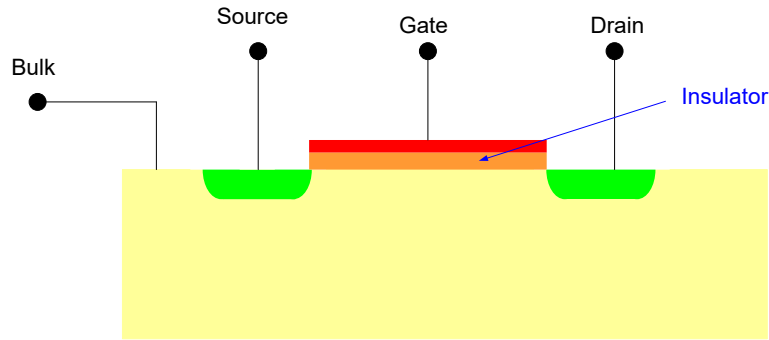
## Qualitative Discussion of n-channel Operation



Conceptual view of basic switch-level model

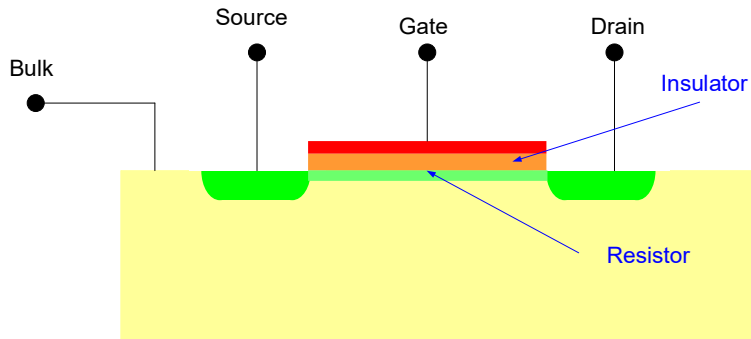
# MOS Transistor

## Qualitative Discussion of n-channel Operation



n-channel MOSFET

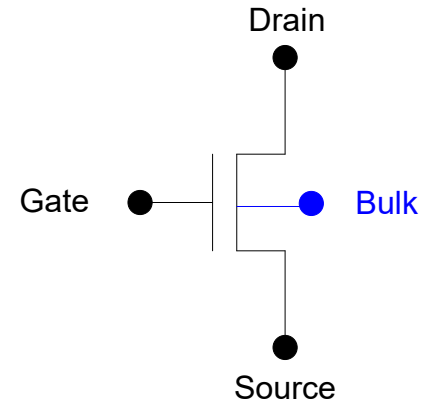
For  $V_{GS}$  small



n-channel MOSFET

For  $V_{GS}$  large

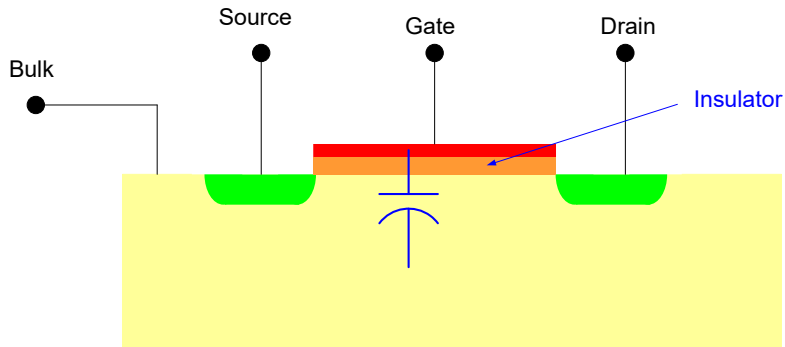
- Region under gate termed the “channel”
- When “resistor” is electrically created, region where it resides in channel is termed an “inversion region”



MOSFET actually 4-terminal device

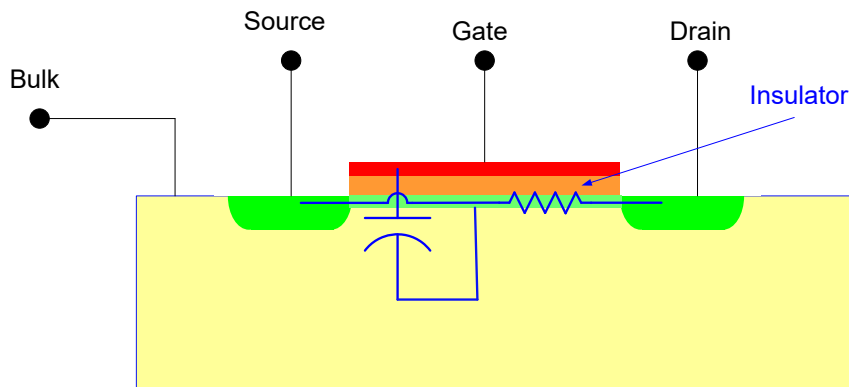
# MOS Transistor

## Qualitative Discussion of n-channel Operation



n-channel MOSFET

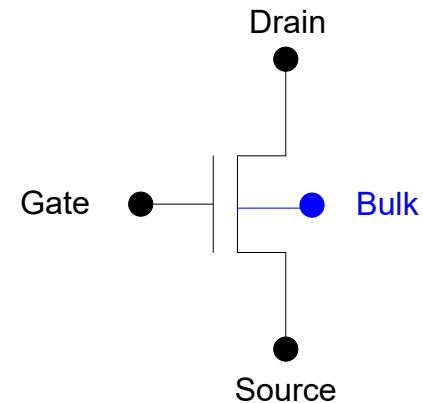
For  $V_{GS}$  small



n-channel MOSFET

For  $V_{GS}$  large

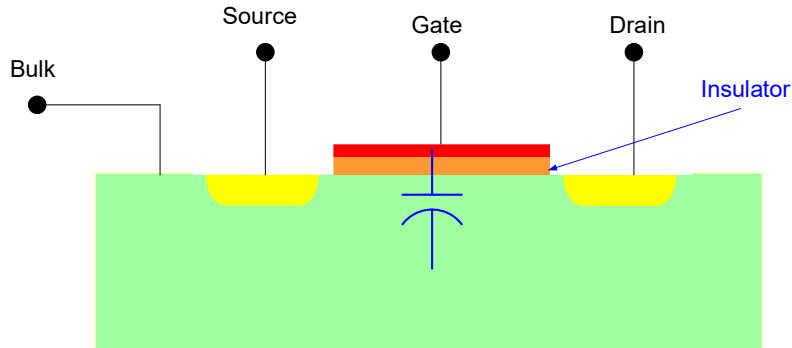
- Electrically created inversion layer forms a “thin “film” resistor
- Capacitance from gate to channel region is distributed
- Lumped capacitance much easier to work with





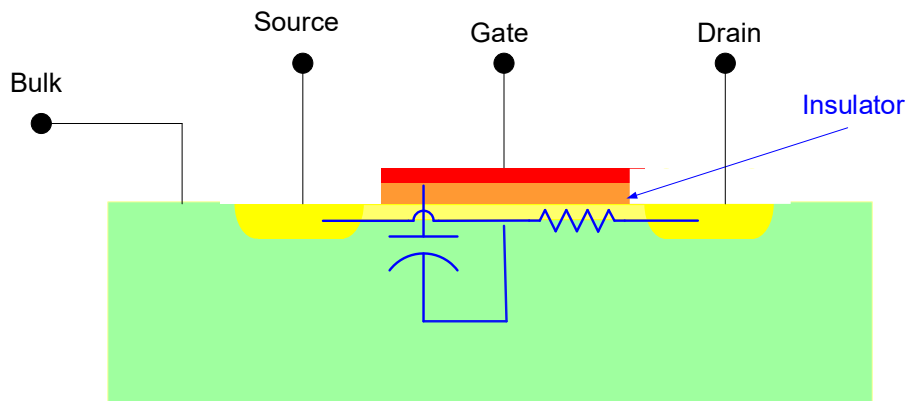
# MOS Transistor

## Qualitative Discussion of p-channel Operation

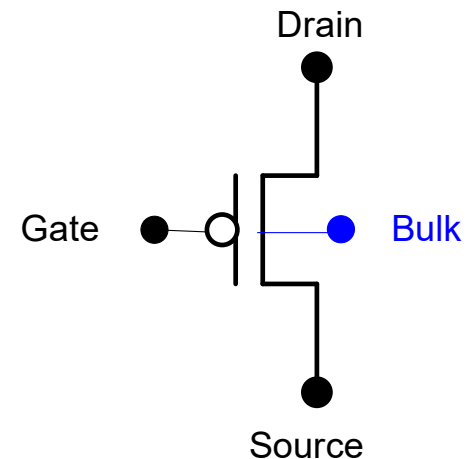


p-channel MOSFET

For  $|V_{GS}|$  small



p-channel MOSFET

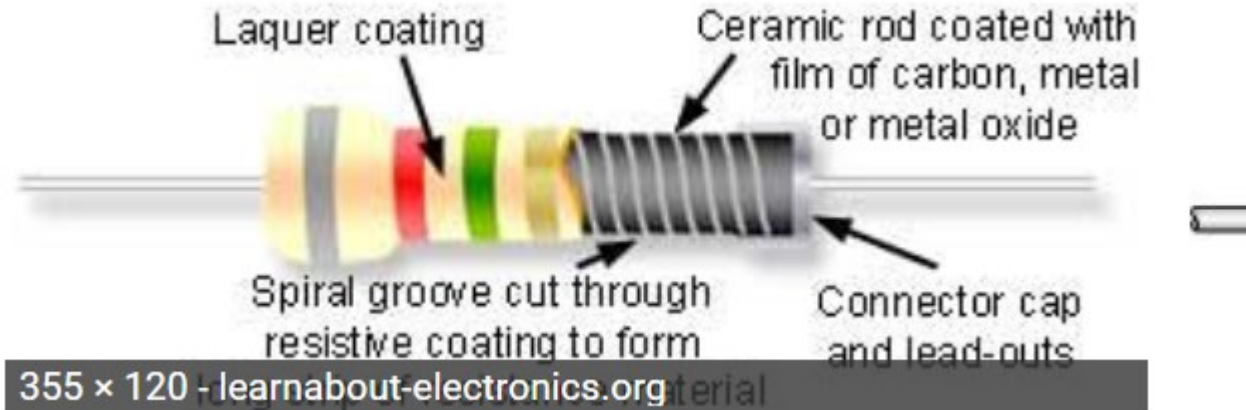


For  $|V_{GS}|$  large

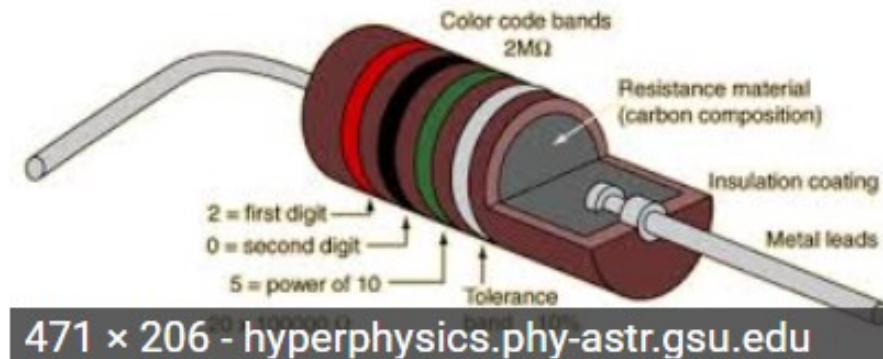
- Electrically created inversion layer forms a “thin “film” resistor
- Capacitance from gate to channel region is distributed
- Lumped capacitance much easier to work with

# Discrete Resistors often use thin films too though not electrically created

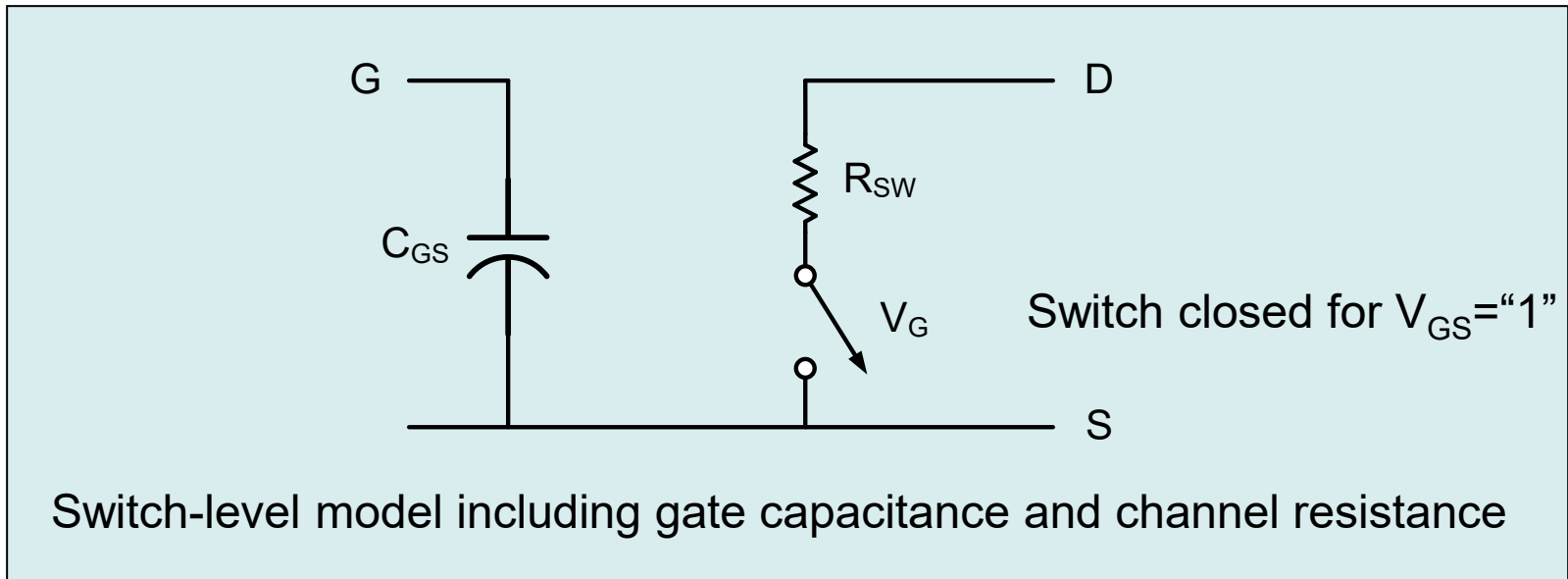
- Thin-film spiral wound



- Carbon composition

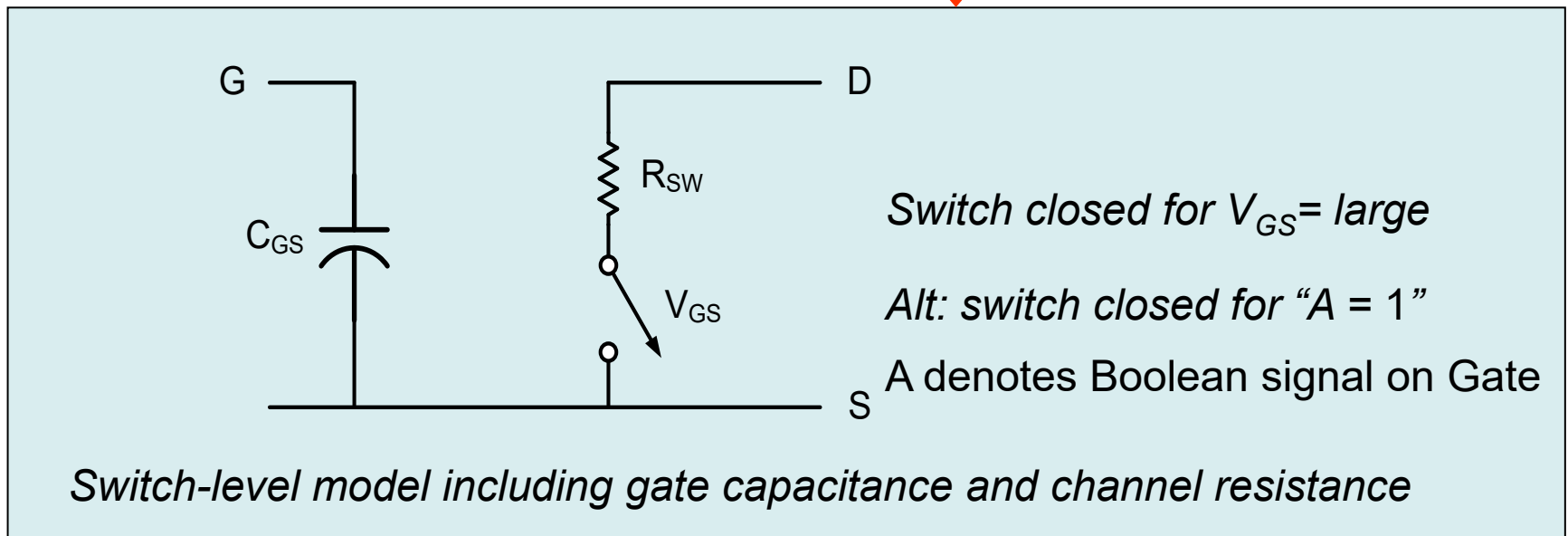
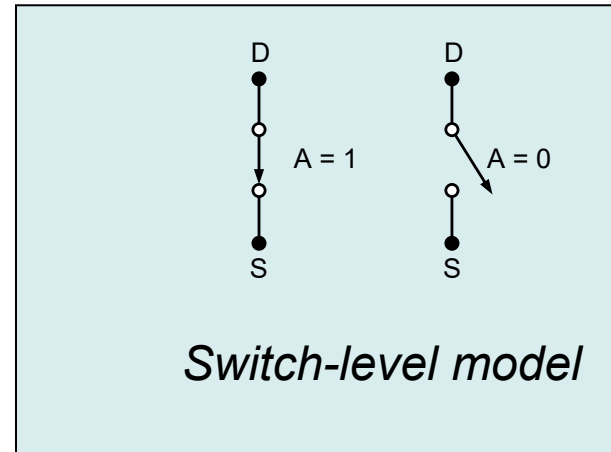
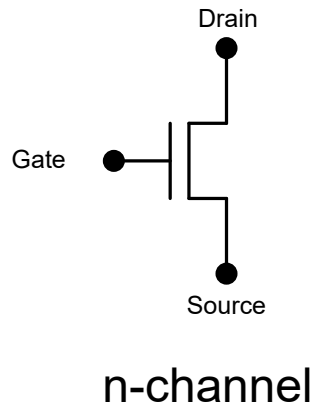


# Improved Switch-Level Model

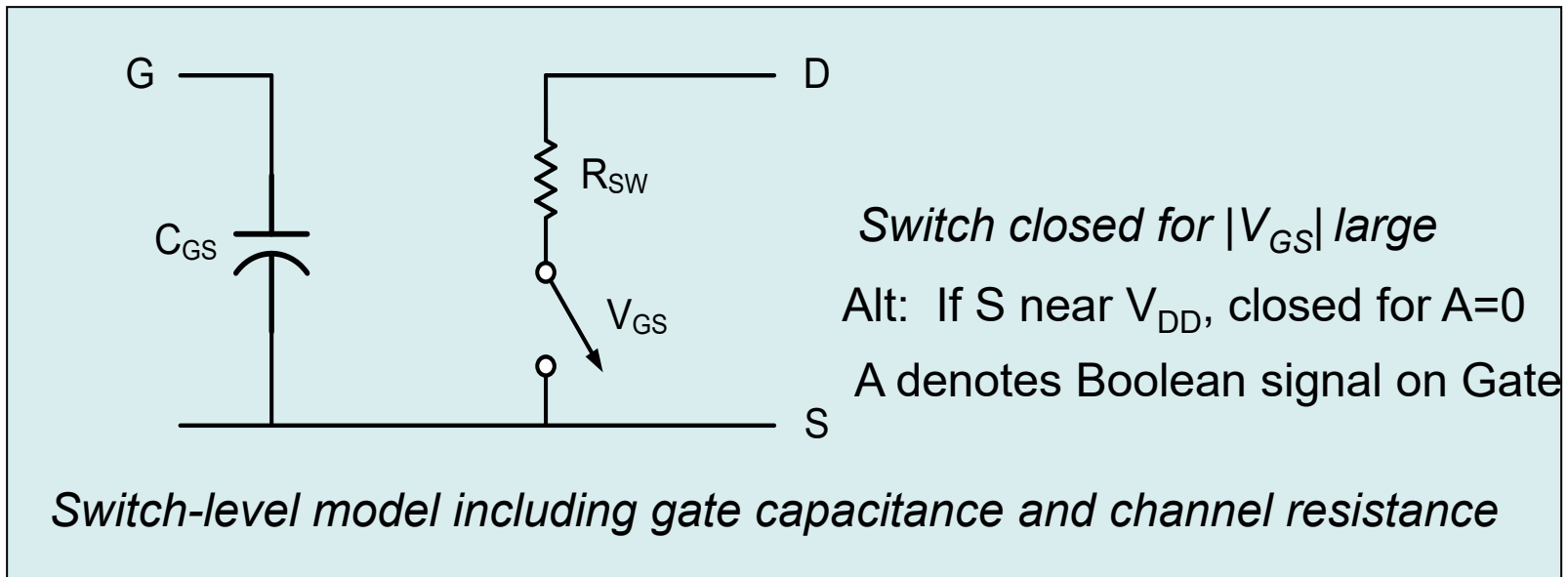
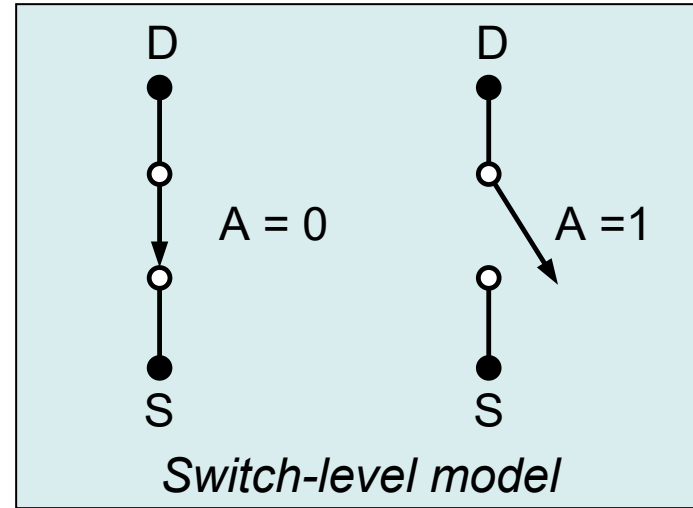
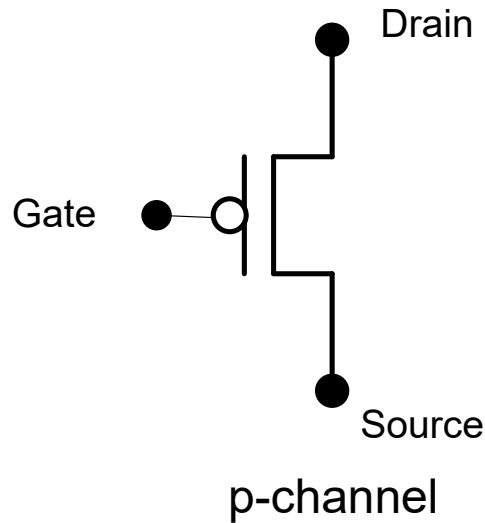


- Connect the gate capacitance to the source to create lumped model
- Still neglect bulk connection

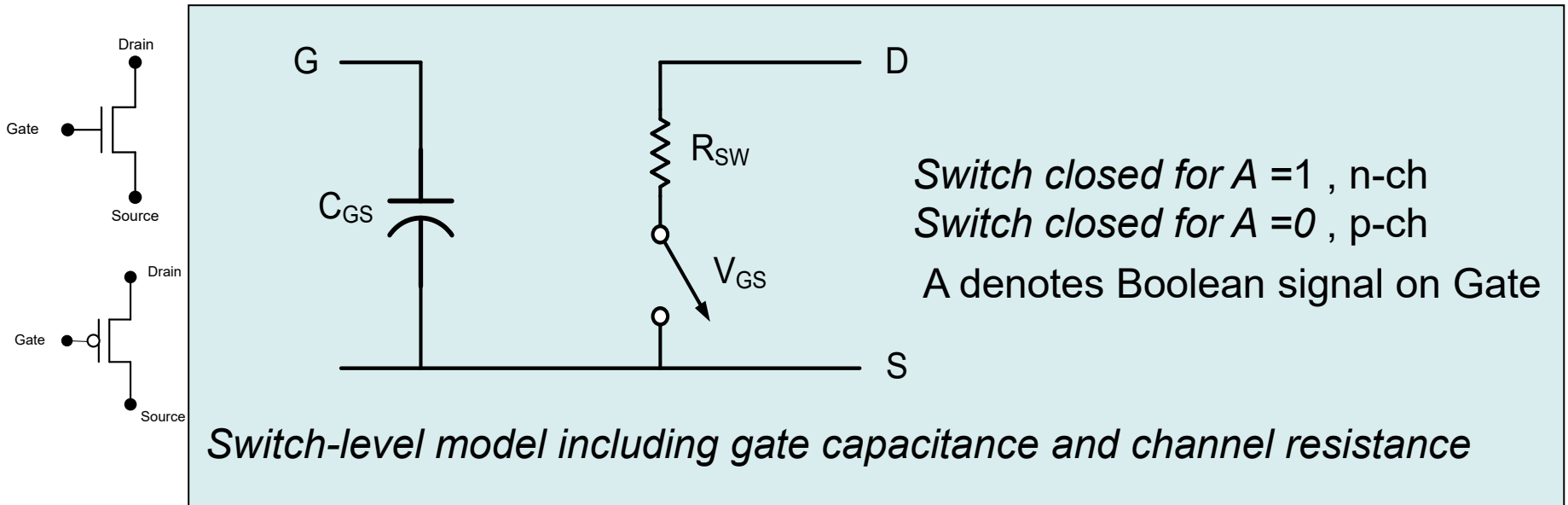
# Improved Switch-Level Model



# Improved Switch-Level Model



# Improved Switch-Level Model



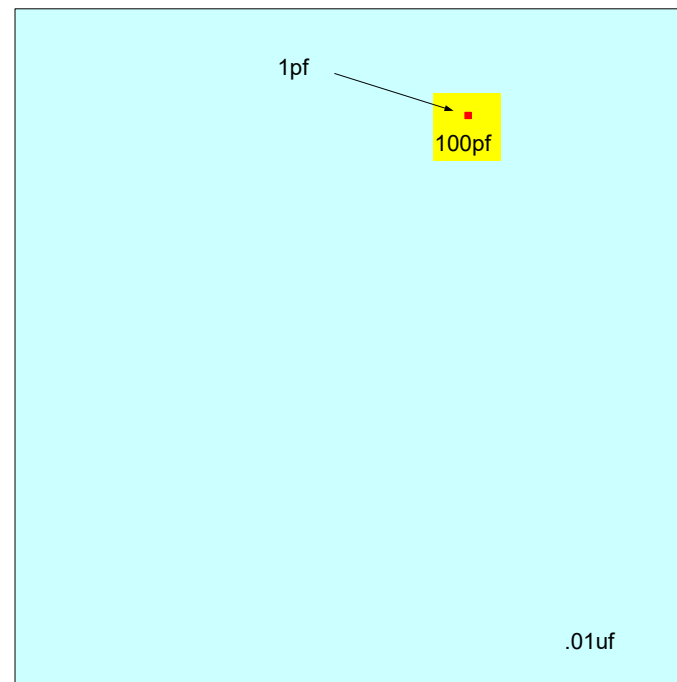
$C_{GS}$  and  $R_{SW}$  dependent upon device sizes and process

For minimum-sized devices in a 0.5 $\mu$  process with  $V_{DD}=5V$

$$\mathbf{C_{GS} \cong 1.5fF} \quad \mathbf{R_{sw} \cong \left. \begin{array}{l} 2K\Omega \text{ n-channel} \\ 6K\Omega \text{ p-channel} \end{array} \right\}}$$

*Considerable emphasis will be placed upon device sizing to manage  $C_{GS}$  and  $R_{SW}$*

# Is a capacitor of 1.5fF small enough to be neglected?

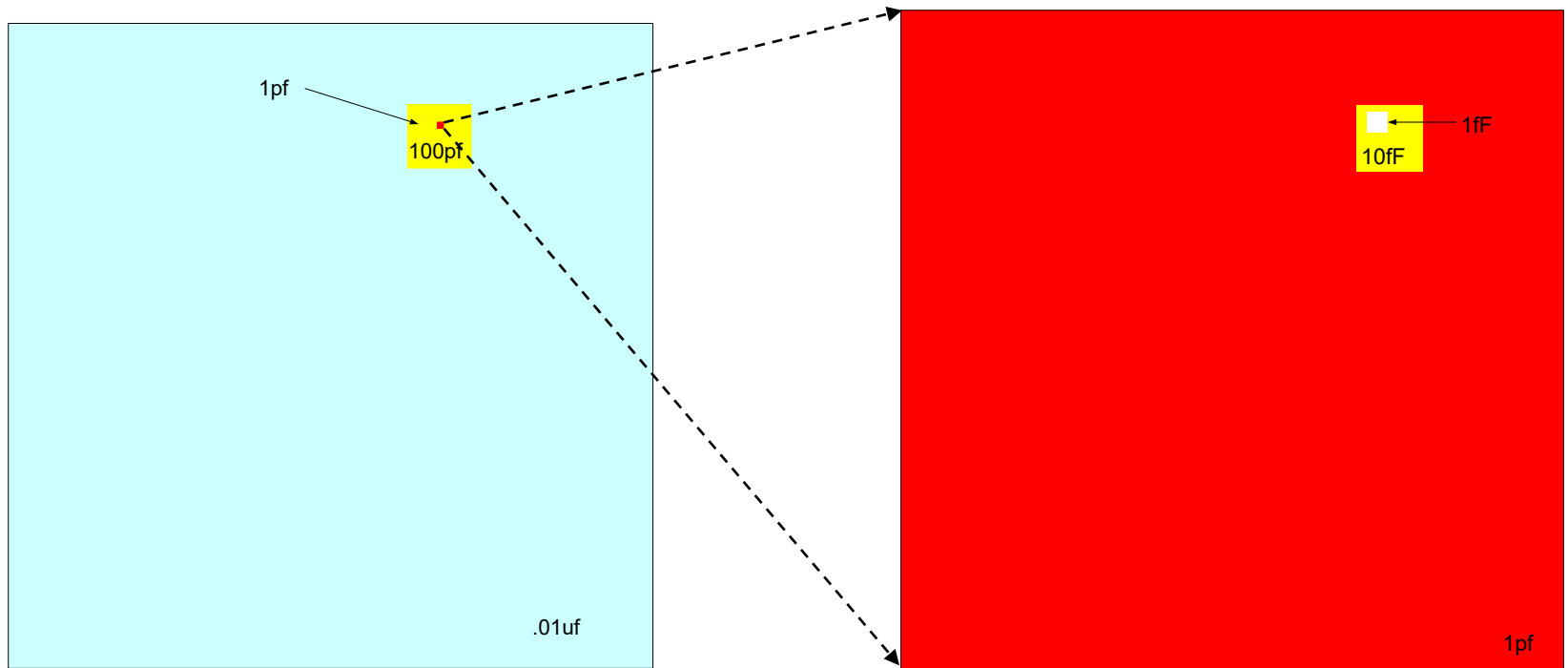


## From EE 201 Parts Kit

Capacitors (Farads)		
100p	3	
470p	3	
0.001u	3	2
0.0047u	3	2
0.01u	3	
0.047u	3	
0.1u	3	1
0.47u	3	
1u	3	
10u	3	
100u	3	

**Area allocations shown to relative scale:**

# Is a capacitor of 1.5fF small enough to be neglected?

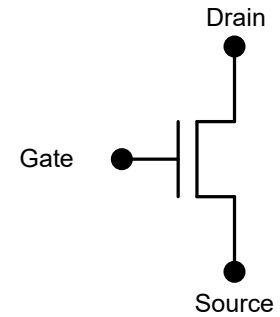


**Area allocations shown to relative scale:**

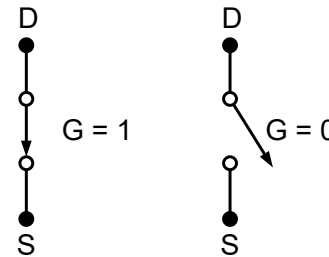
- Not enough information at this point to determine whether this very small capacitance can be neglected
- Will answer this important question later



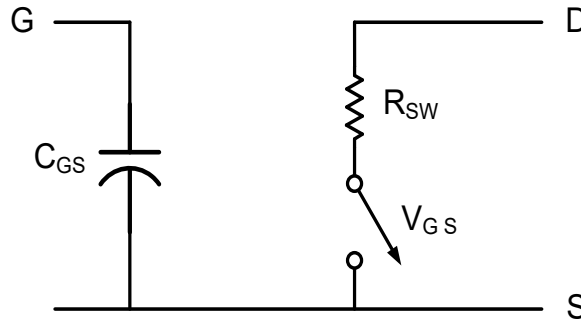
# Model Summary (for n-channel)



## 1. Switch-Level model



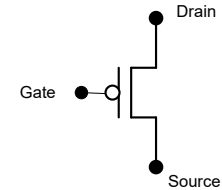
## 2. Improved switch-level model



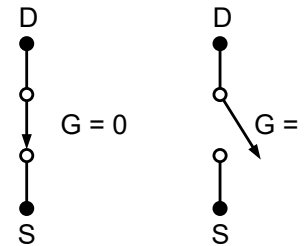
**Switch closed for  $V_{GS} = \text{large}$**   
**Switch open for  $V_{GS} = \text{small}$**

**Other models will be developed later**

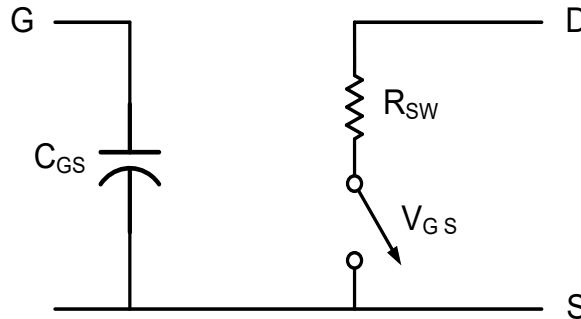
# Model Summary (for p-channel)



## 1. Switch-Level model



## 2. Improved switch-level model



**Switch closed for  $|V_{GS}| = \text{large}$**   
**Switch open for  $|V_{GS}| = \text{small}$**

**Other models will be developed later**



**Stay Safe and Stay Healthy !**

**End of Lecture 6**