CMOS Transistor Circuits

Introduction to Computer Systems, Fall 2024

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- How are you? Any Questions from last lecture?

Upcoming Due Dates

- HW02 (C Strings!): Due This Friday
  - If you are having issues with valgrind, add –gdwarf-4 to all of the compilation commands in the makefile
- HW03 (RPN):
  - Due Friday Next week, posted sometime tomorrow.
  - Demo in beginning of lecture on Tuesday
- Next Lecture Check-in posted tonight or tomorrow

Recitation

- Wednesday's 4PM – 5PM
  - DRL 3C6
- Super useful if you need any extra help or want to review topics.
- Slides are posted and it is recorded
- GDB, Valgrind, Makefiles, and etc. covered this week
- Makefile slides look really solid!

Lecture Outline

- `void*`
- Boolean Algebra
- Physics Background
- CMOS Transistor
- CMOS Logical Circuits
- CMOS Circuit Design

memcpy

```
void *memcpy(void *dest, const void *src, size_t n);
```

- **memcpy** is a function that copies a specified number of bytes at one address to another address.
- It copies the next **n** bytes that **src** points to to the location pointed to by **dest**. (It also returns **dest**). It does not support regions of memory that overlap.

```
int x = 5;
int y = 4;
memcpy(&x, &y, sizeof(x)); // just like x = y;
```

memmove

```
void *memmove(void *dest, const void *src, size_t n);
```

- **memmove** is the same as memcpy but supports overlapping regions of memory. (Unlike its name implies, it still "copies").
- It copies the next **n** bytes that **src** points to to the location pointed to by **dest**. (It also returns **dest**).

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    // store a copy of data1 in temporary storage
    memcpy(temp, data1ptr, nbytes);

    // copy data2 to location of data1
    // copy data in temporary storage to location of data2

}
```

We can copy the bytes ourselves into temp! This is equivalent to **temp = *data1ptr** in non-generic versions, but this works for *any* type of *any* size.

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);

    // copy data2 to location of data1
    // copy data in temporary storage to location of data2

}
```

How can we copy data2 to the location of data1?

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);

    // copy data in temporary storage to location of data2

}
```

How can we copy data2 to the location of data1?
memcpy!

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);
    memcpy(data2ptr, temp, nbytes);
}
```

Our last step, copy data in **temp** into **data2**

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);
    memcpy(data2ptr, temp, nbytes);
}
```

```
int x = 2;
int y = 5;
swap(&x, &y, sizeof(x));
```

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);
    memcpy(data2ptr, temp, nbytes);
}
```

```
short x = 2;
short y = 5;
swap(&x, &y, sizeof(x));
```

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);
    memcpy(data2ptr, temp, nbytes);
}
```

```
char *x = "2";
char *y = "5";
swap(&x, &y, sizeof(x));
```

Introducing Void *

```
void swap(void *data1, void * data2, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);
    memcpy(data2ptr, temp, nbytes);
}
```

```
mystruct x = {…};
mystruct y = {…};
swap(&x, &y, sizeof(x));
```

C Generics and Void *

- We can use **void *** and **memcpy** to handle memory as generic bytes.
- If we are given where the data of importance is, and how big it is, we can handle it!

```
void swap(void *data1ptr, void *data2ptr, size_t nbytes) {
    char temp[nbytes];
    memcpy(temp, data1ptr, nbytes);
    memcpy(data1ptr, data2ptr, nbytes);
    memcpy(data2ptr, temp, nbytes);
}
```

C Generics and HW02

- Problem: We need to implement our own memcpy in the homework, we can't call memcpy ourselves ☹

- How do we implement memcpy?

```
void *memcpy(void *dest, void* src, size_t n) {
  char *dest_ptr = (char*) dest;
  char *src_ptr = (char*) src;
  // ...
  // can now dest_ptr[0] = src_ptr[0]
  // to copy one byte
}
```

Lecture Outline

- `void*`
- **Boolean Algebra**
- Physics Background
- CMOS Transistor
- CMOS Logical Circuits
- CMOS Circuit Design

Disclaimer

- We just talked about bit-wise logical operators, and I will be using bit-wise operator syntax for the next section
  - 1 is still equal to TRUE
  - 0 is still equal to FALSE

- It may be easier to think of this next section as applying specifically to Boolean data types
  - (Though this can also be applied to bit-wise operators)
    - Treat True as the "all 1" bit pattern
    - Treat False as the "all 0" bit pattern

Boolean rules

- Identity
  - A & 1 = A
  - A & 0 = 0
  - A | 1 = 1
  - A | 0 = A
  - ~~A = NOT NOT A = A
- Associative
  - A & (B & C) = (A & B) & C
  - A | (B | C) = (A | B) | C
- Distributive
  - A & (B | C) = (A & B) | (A & C)
  - A | (B & C) = (A | B) & (A | C)
- More Identity
  - A & A = A
  - A | A = A
  - A & ~A = 0
  - A | ~A = 1

More on De Morgan's later

- De Morgan's Law
  - ~(A & B) = ~A | ~B
  - ~(A | B) = ~A & ~B

Truth Tables

- A table you can write for an expression to represent all possible combinations of input and output for an expression

- Truth Table for (A & (A & ~B)):

A (input)	B (input)	Output
0	0	0
0	1	0
1	0	1
1	1	0

Boolean Simplification

- We can apply rules to simplify Boolean patterns

- Consider the previous example
  - (A & (A & ~B))
  - ((A & A) & ~B) // By associative property
  - (A & ~B) // By distributive Property

- Consider:
  - (A | B) & (A | ~B)

Boolean rules

- Identity
  - A & 1 = A
  - A & 0 = 0
  - A | 1 = 1
  - A | 0 = A
  - ~~A = NOT NOT A = A
- Associative
  - A & (B & C) = (A & B) & C
  - A | (B | C) = (A | B) | C
- Distributive
  - A & (B | C) = (A & B) | (A & C)
  - A | (B & C) = (A | B) & (A | C)
- More Identity
  - A & A = A
  - A | A = A
  - A & ~A = 0
  - A | ~A = 1

More on De Morgan's soon

- De Morgan's Law
  - ~(A & B) = ~A | ~B
  - ~(A | B) = ~A & ~B

Simplify:
(A | B) & (A | ~B)

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Boolean Simplification

- We can apply rules to simplify Boolean patterns

- Consider the previous example
  - (A & (A & ~B))
  - ((A & A) & ~B) // By associative property
  - (A & ~B) // By distributive Property

- Consider:
  - (A | B) & (A | ~B)
  - A | (B & ~B) // by distributive property
  - A | 0 // by identity property
  - A // by identity property

Simplification can have
Multiple correct simplifications

De Morgan's Law

- De Morgan's Law
  - ~(A & B) = ~A | ~B
  - ~(A | B) = ~A & ~B
- Provides a way to convert between AND to OR
  - (with some help from NOT)

- Truth Tables for proof:

A	B	~(A | B)	~A & ~B	~(A & B)	~A | ~B
0	0	1	1	1	1
0	1	0	0	1	1
1	0	0	0	1	1
1	1	0	0	0	0

De Morgan's Law: Demo

- Write a statement equivalent to OR, but without using OR
  - A | B
  - ~~(A | B) // identity property
  - ~(~A & ~B) // De Morgan's Law

- This still works for multi-bit data and bitwise operations

Boolean rules

These apply to multi-bit operations as well!

- Identity
  - A & 1 = A
  - A & 0 = 0
  - A | 1 = 1
  - A | 0 = A
  - ~~A = NOT NOT A = A
- Associative
  - A & (B & C) = (A & B) & C
  - A | (B | C) = (A | B) | C
- Distributive
  - A & (B | C) = (A & B) | (A & C)
  - A | (B & C) = (A | B) & (A | C)

Bit-wise operations just follow these N times for N bits

- More Identity
  - A & A = A
  - A | A = A
  - A & ~A = 0
  - A | ~A = 1
- De Morgan's Law
  - ~(A & B) = ~A | ~B
  - ~(A | B) = ~A & ~B

Lecture Outline

- `void*`
- Boolean Algebra
- **Physics Background**
- CMOS Transistor
- CMOS Logical Circuits
- CMOS Circuit Design

Disclaimer:

- This course is NOT assuming you know E&M Physics
  - It may help to have some background
  - I am going to give a VERY simplified view of E&M Physics

- If you want to know more of the details with transistors & how they work, courses like ESE 2150 (Electrical Circuits and Systems) may appeal to you

Charge, Current, Voltage

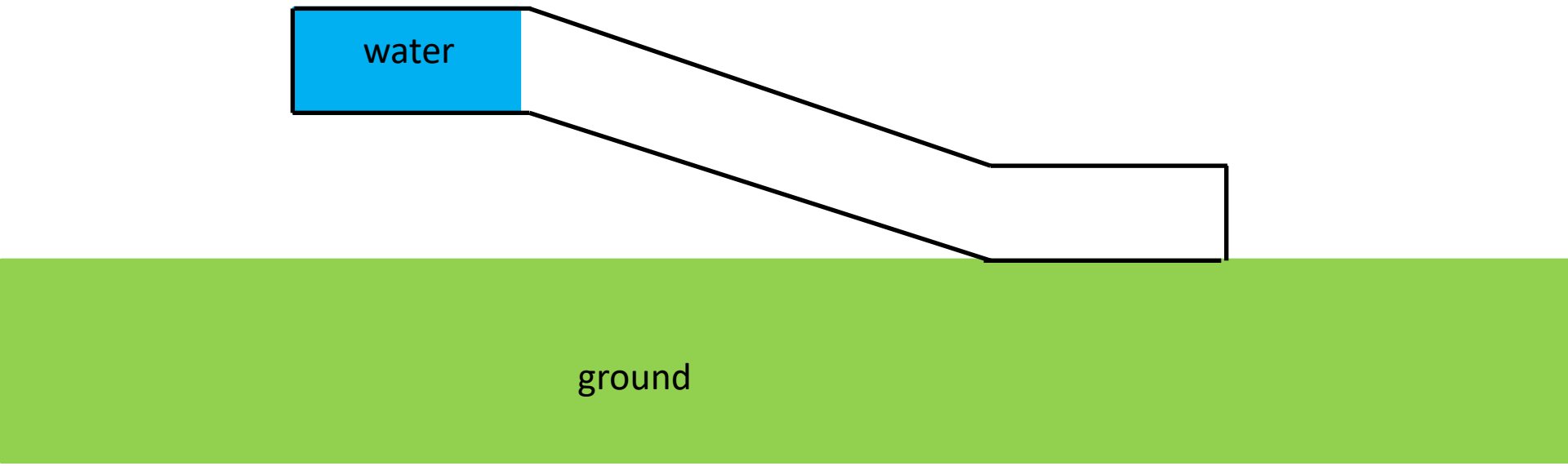
This is a big simplification

- Charge can be either positive or negative
  - Electrons are common units of negative charge and can move through conductive material
  - Like charges repel, opposite charges attract
- Current: the rate of flow of positive charge
- Voltage: Positive charge want to move from places with high voltage to lower voltage
  - (vice versa for negative charge)
  - sometimes called “electric pressure”
  - Measured relative to a reference point (usually called “ground”)

Voltage & Current Analogy

This is a big simplification

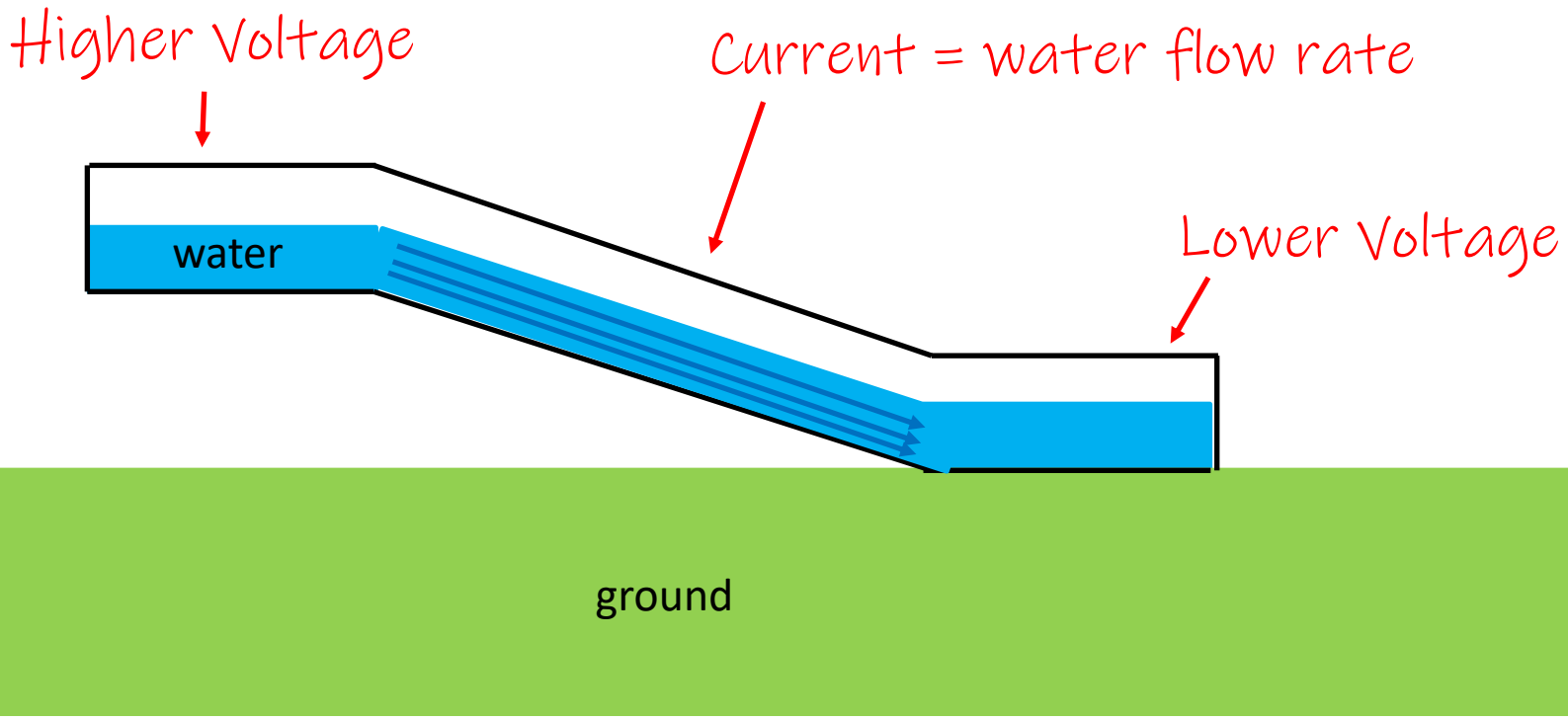
- Imagine we have a slanted pipe
  - One end on the ground, the other end is in the air
  - Water is placed in the high end of the pipe
  - What happens next?



Voltage & Current Analogy

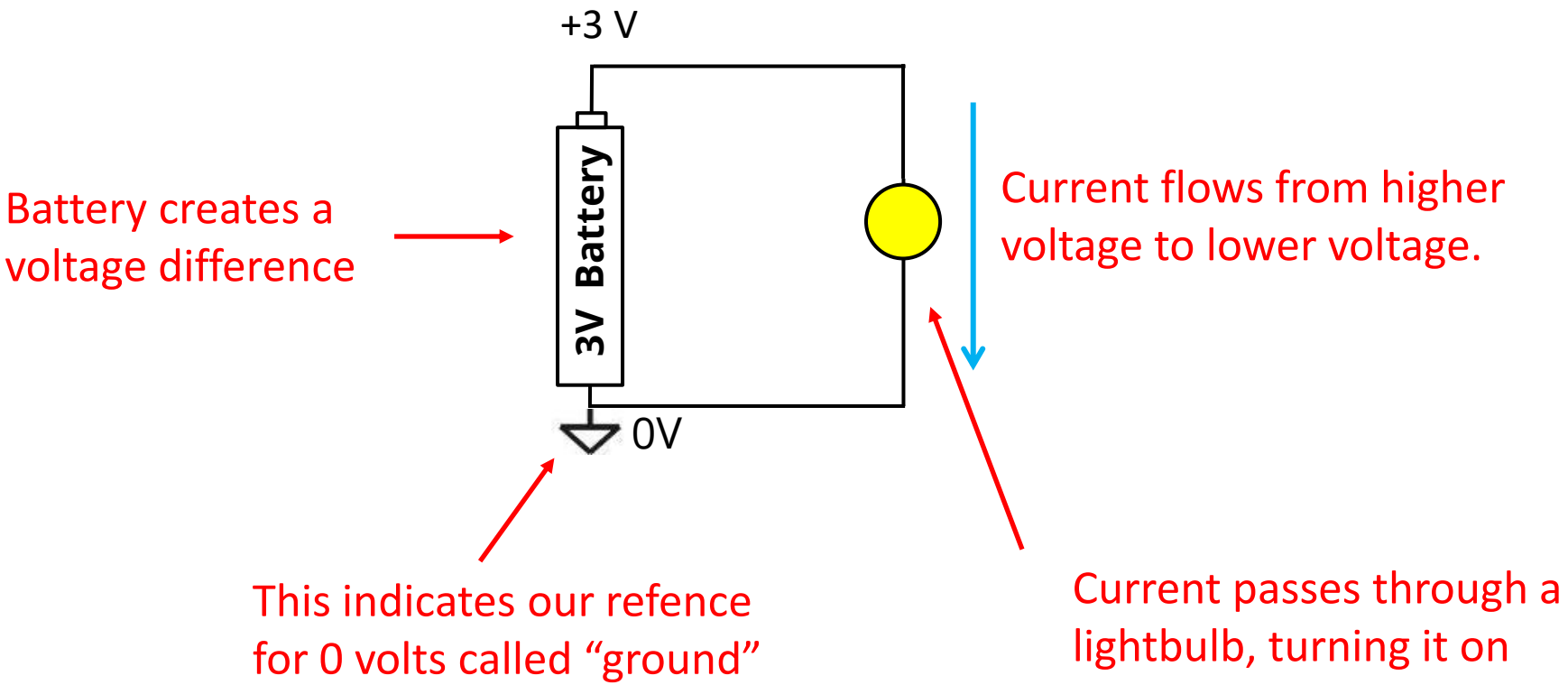
This is a big simplification

- Water flows to the bottom!
  - The water can be thought of positive charge
  - Positive charge moves form higher voltage to lower voltage



Circuit example

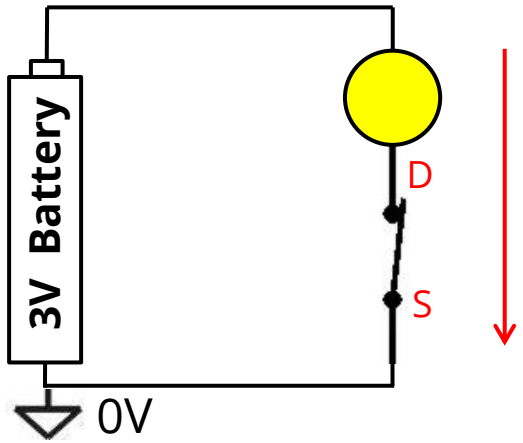
- Consider the following example circuit



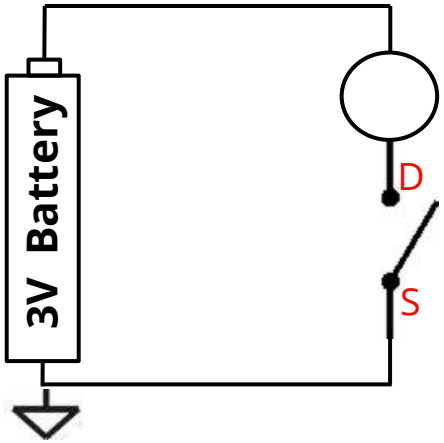
Circuit example w/ Switch

- Circuits can also have a switch
  - The switch can be open or close

If the switch is closed, charge can flow through like it is a wire

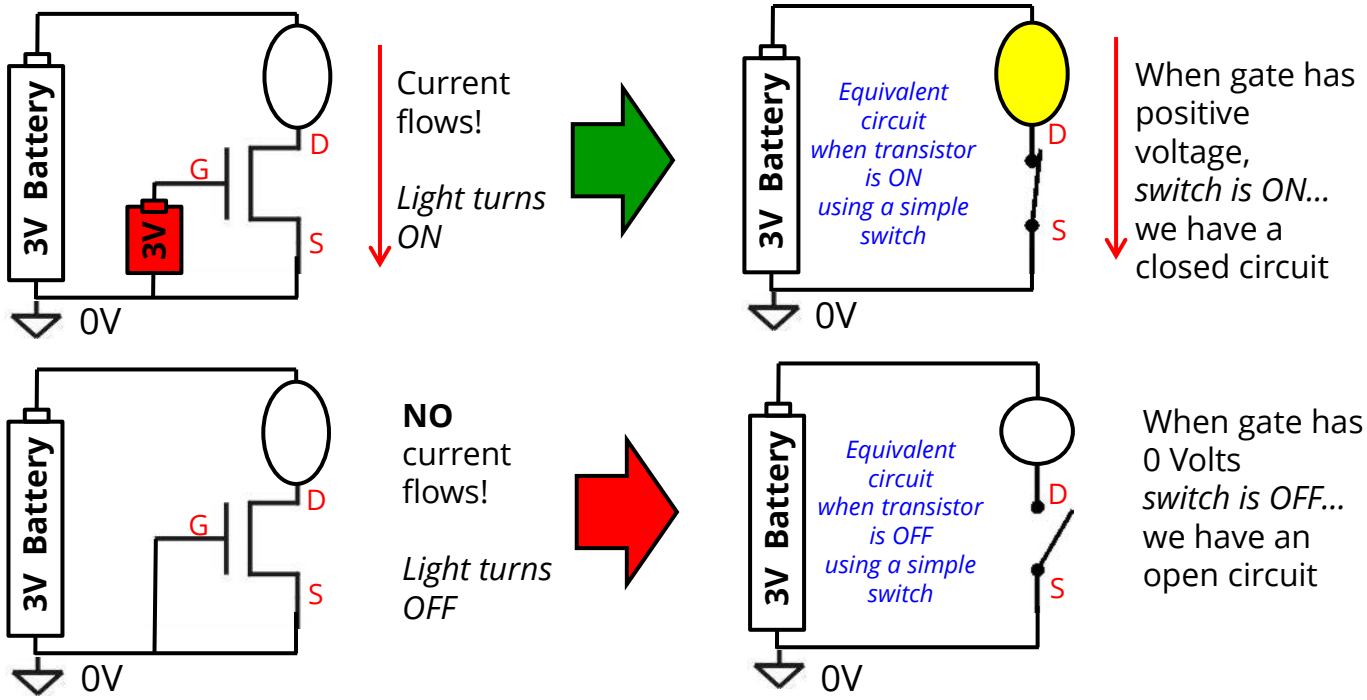


If the switch is open, charge cannot flow through



What Is a Transistor (MOSFET Type)?

- An electrical device that acts as an **electrical switch**; it's typically made from Silicon
  - 3 electrical contacts/terminals: Gate, Drain, Source
  - *Gate* controls flow of current between *Drain* and *Source* terminals; this style transistor is called a MOSFET



Lecture Outline

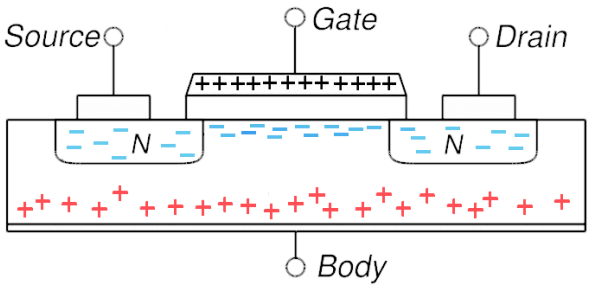
- `void*`
- Boolean Algebra
- Physics Background
- **CMOS Transistor (Skipped)**
- CMOS Logical Circuits
- CMOS Circuit Design

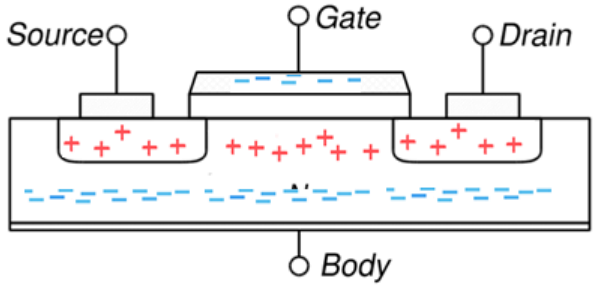
Two Types of MOSFET

Skipped in Lecture, here if you want to see it though

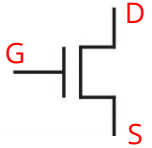
There is also extra slides on website

- nMOS
  - **GATE Voltage MUST BE > Body, Source, Drain to be ON**
  - **(voltage must be high)**
- pMOS
  - **GATE Voltage MUST BE < Body,Source, Drain to be ON**
  - **(Voltage must be low)**

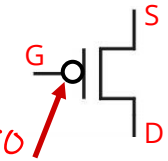




nMOSFET



pMOSFET



Do not forget to draw the circle.

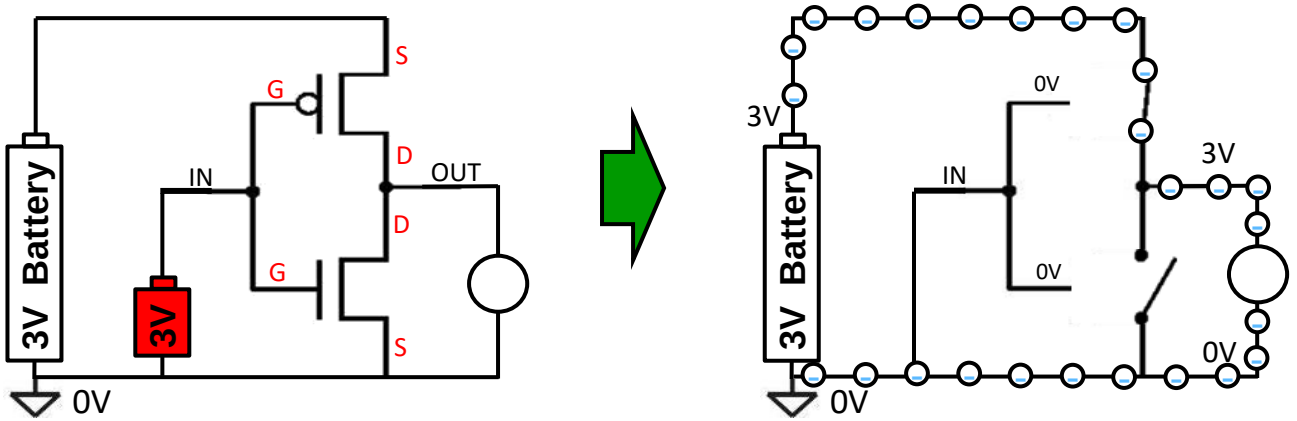
CMOS: pMOSFET & nMOSFET in Complement

Skipped in Lecture, here if you want to see it though

There is also extra slides on website

3V on the input (the gates) turns the light OFF!

- What if the input is set to 0V?
  - 0V turns NMOS **OFF**
  - 0V turns PMOS **ON**
  - **Light has "3V" across it!**
  - Current flows in this circuit, so light turns **ON**!



CMOS: pMOSFET & nMOSFET in Complement

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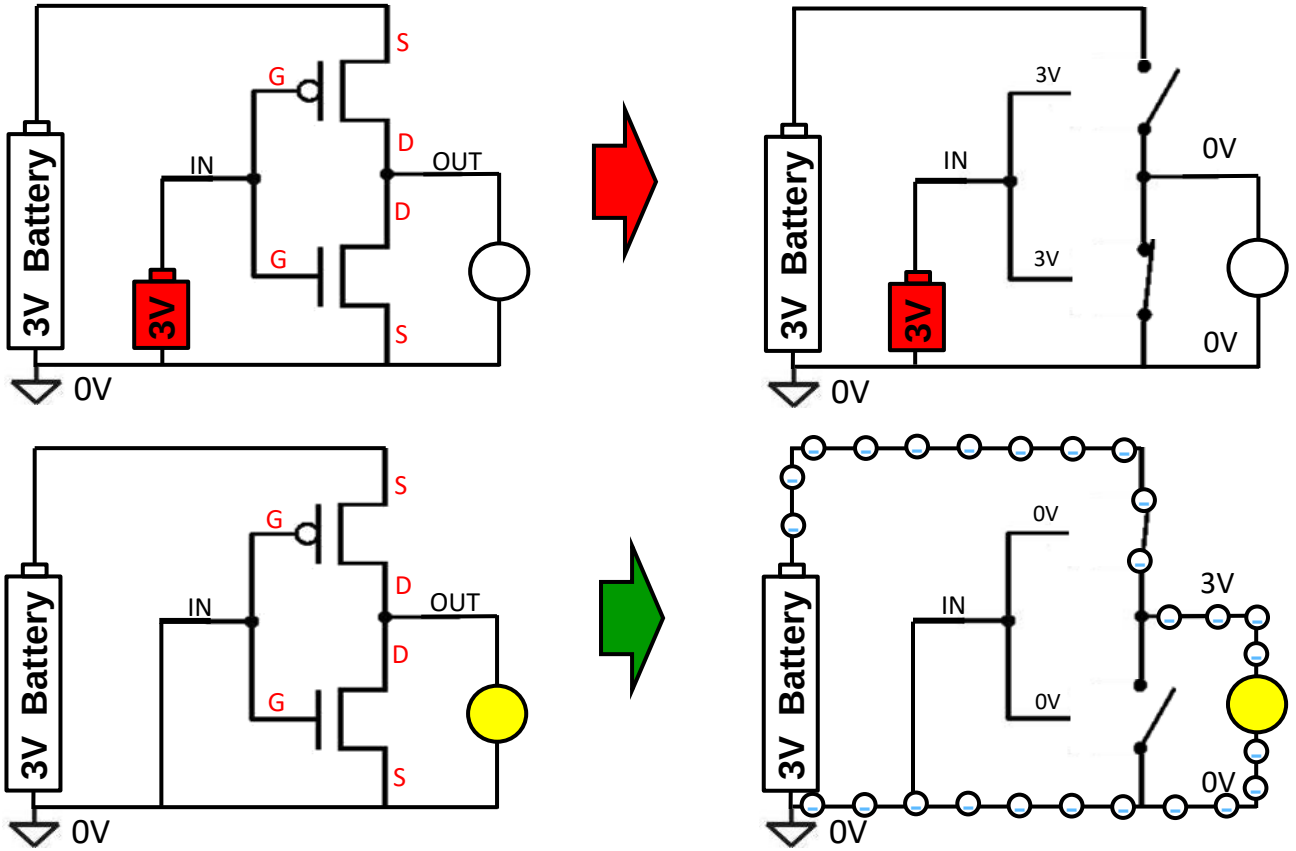
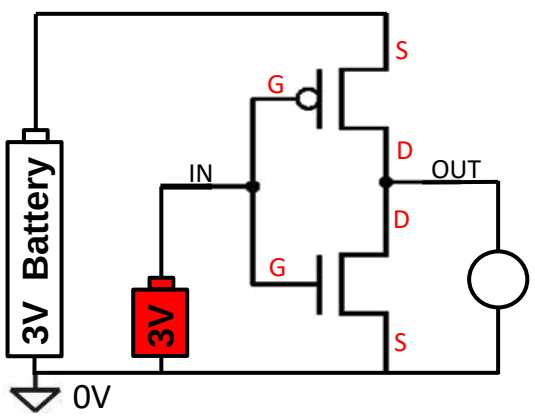
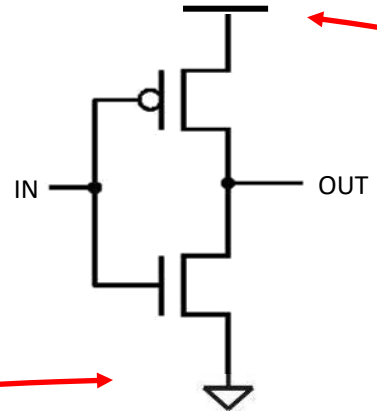


More Common Electrical Symbols

Skipped in Lecture, here if you want to see it though

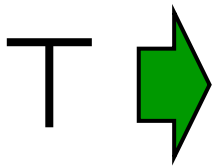
There is also extra slides on website



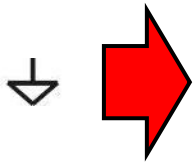


Circuit Drawings so far

Standard notation to use going forward



High Voltage (3V, Vdd, etc)



Low Voltage (0V), typically ground (GND)

Lecture Outline

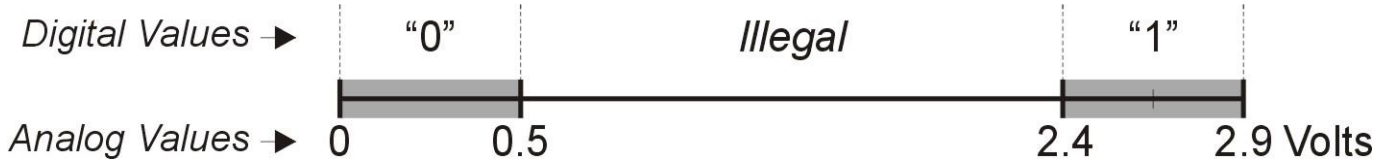
- `void*`
- Boolean Algebra
- Physics Background
- CMOS Transistor
- **CMOS Logical Circuits**
- CMOS Circuit Design

Voltages as Bits

- Transistors are the basis for all digital electronics
  - We've seen that they work by controlling the flow of charge

- We can map bits onto different voltages:
  - High voltage – we'll call this state "1"
  - Low voltage – we'll call this state "0"

**Only two relevant voltages



Computers use transistors as switches to manipulate bits
- Before transistors: tubes, electro-mechanical relays (pre 1950s)
- Mechanical adders (punch cards, gears) as far back as mid-1600s

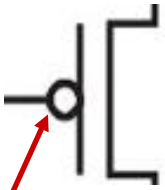
CMOS Transistors Simplified

nMos

Input	Output
1	Connected
0	Dis-connected

CMOS Transistors Simplified

pMos

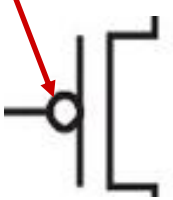


Circle = "negation"

Input	Output
1	Dis-connected
0	Connected

CMOS Transistors Simplified

Circle = "negation"



pMos

Input	Output
1	Dis-connected
0	Connected

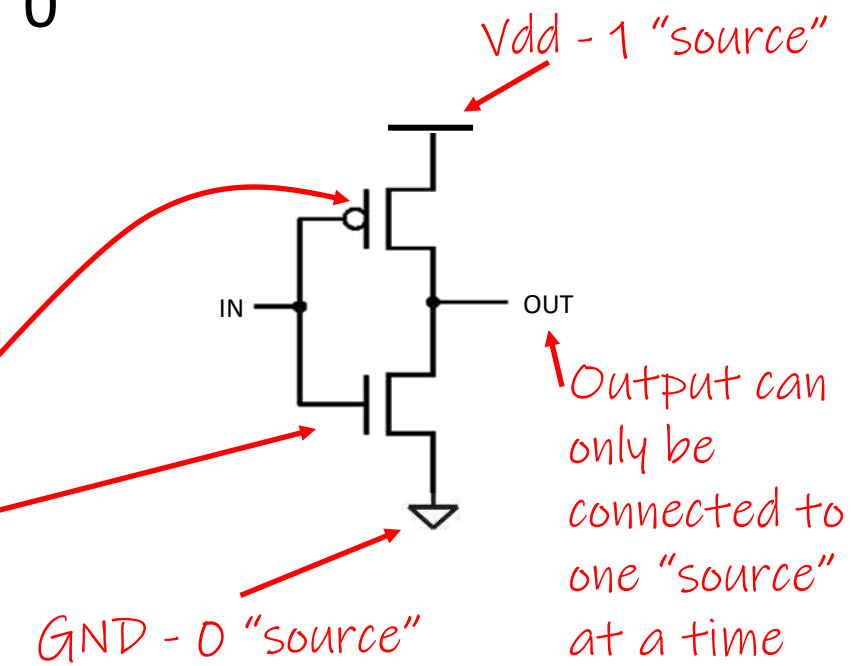
nMos

Input	Output
1	Connected
0	Dis-connected

CMOS Circuits as Logical Circuits

- Instead of thinking of voltages, we can analyze our circuit think of in terms of bits "1" or "0"

- Consider our previous circuit:
  - Output is the same as whatever "source" it is connected to
  - pMOS: on when input is low
  - nMOS: on when input is high



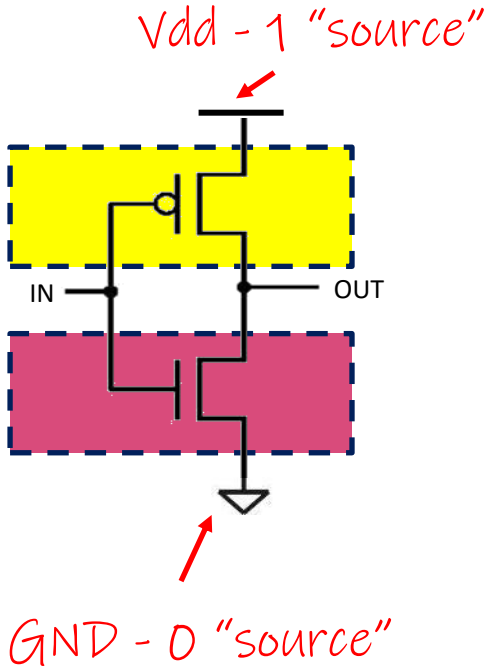
- Truth Table

Input	pMOS State	nMOS state	Output
1	Disconnected	Connected	0
0	Connected	Disconnected	1

This is the same as a "NOT" operation

PUN & PDN

- We can split our "NOT" circuit into two halves:



- Pull Up Network (PUN)
  - "Pulls" the output "Up" to "1"
  - **Can only contain pMOS Transistors**
- Pull Down Network (PDN)
  - "Pulls" the output "down" to "0"
  - **Can only contain nMOS Transistors**

- Output can only be connected to "1" or "0" at any time
  - **Exactly one** of PUN or PDN can be "ON" at a time
- We will see more complex examples in a moment

nMOS & pMOS in PUNs & PDNs

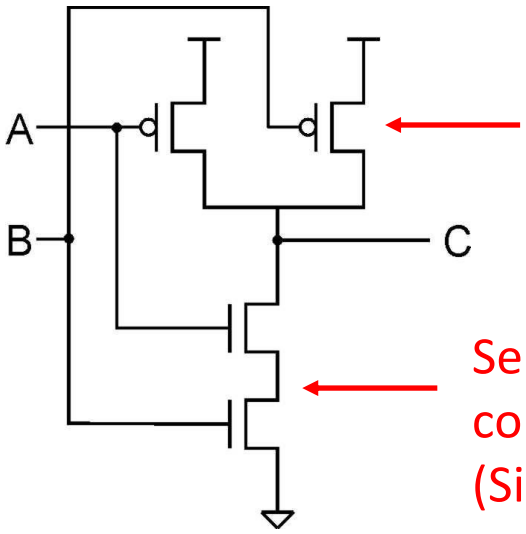
- **In a digital circuit there are only two relevant voltage levels, the low voltage level, GND (0), and the high voltage level, Vdd (1).**
  - An nMOS transistor is only ON when the gate voltage is **higher** than the source and drain voltages
  - A pMOS transistor is only ON when the gate voltage is **lower** than the source and drain voltages
- Therefore, an nMOS transistor can only be used to pass a low voltage and a pMOS transistor can only be used to pass a high voltage

- nMOS can only be used for the PDN
- pMOS can only be used for the PUN

The NAND (NOT-AND) Circuit

- NAND == NOT AND == ~(A & B)

Note: parallel structure on top, series on bottom



NAND Transistor Level

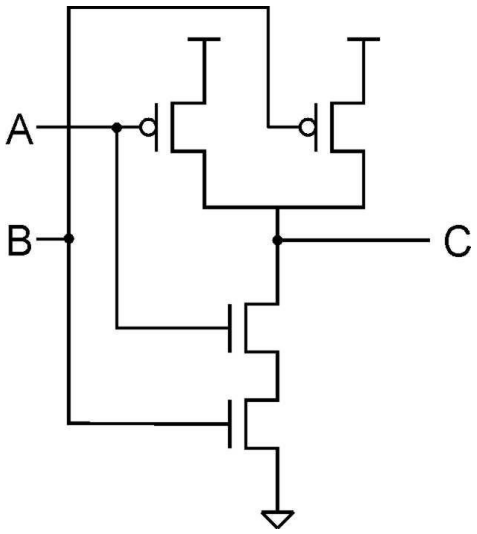
Parallel Transistors: only one needs to be on for a connection to be made across them
(Similar to using an OR)

Series Transistors: BOTH need to be on for a connection to be made across them
(Similar to using an AND)

The NAND (NOT-AND) Circuit

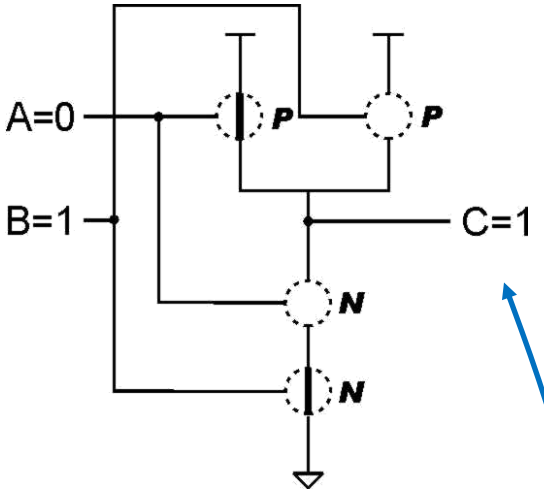
- NAND == NOT AND == ~(A & B)

Note: parallel structure on top, series on bottom



NAND Transistor Level

Sample Input: A=0, B=1



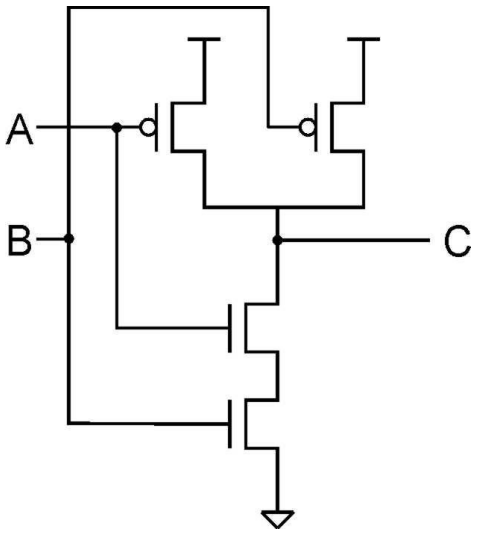
NAND Truth Table

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

The NAND (NOT-AND) Circuit

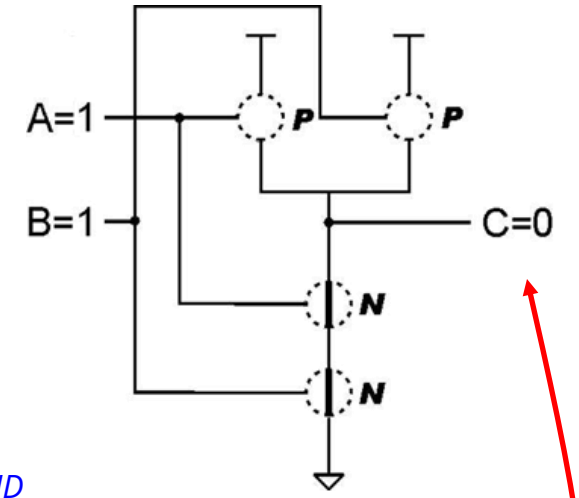
- NAND == NOT AND == ~(A & B)

Note: parallel structure on top, series on bottom



NAND Transistor Level

Sample Input: A=1, B=1

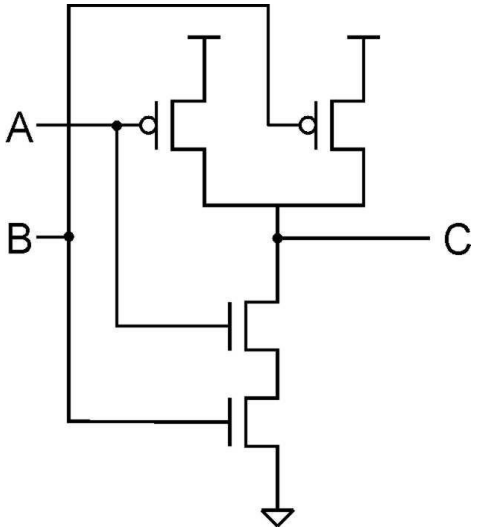


NAND Truth Table

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

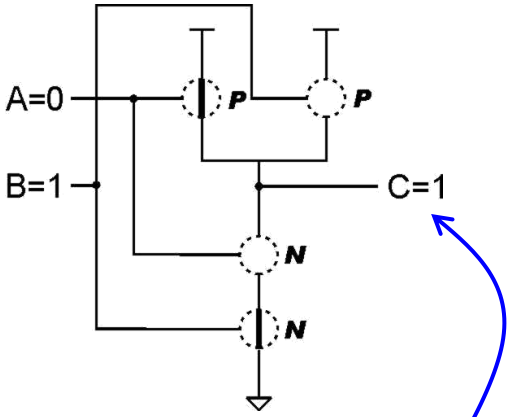
The NAND (NOT-AND) Circuit

Note: parallel structure on top, series on bottom



NAND Transistor Level

Sample Input: A=0, B=1



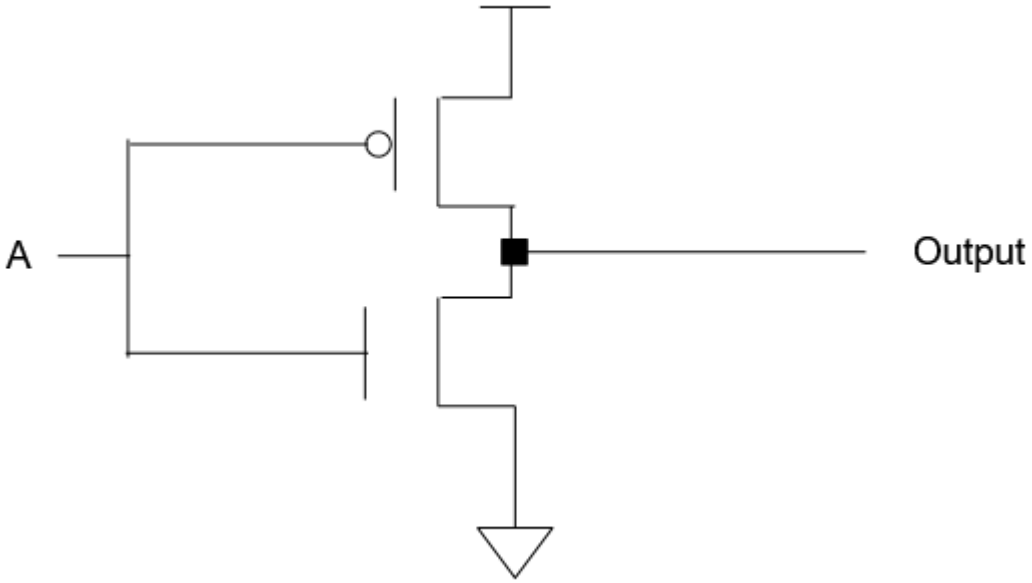
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

NAND Gate Truth Table

Poll Everywhere

pollev.com/tqm

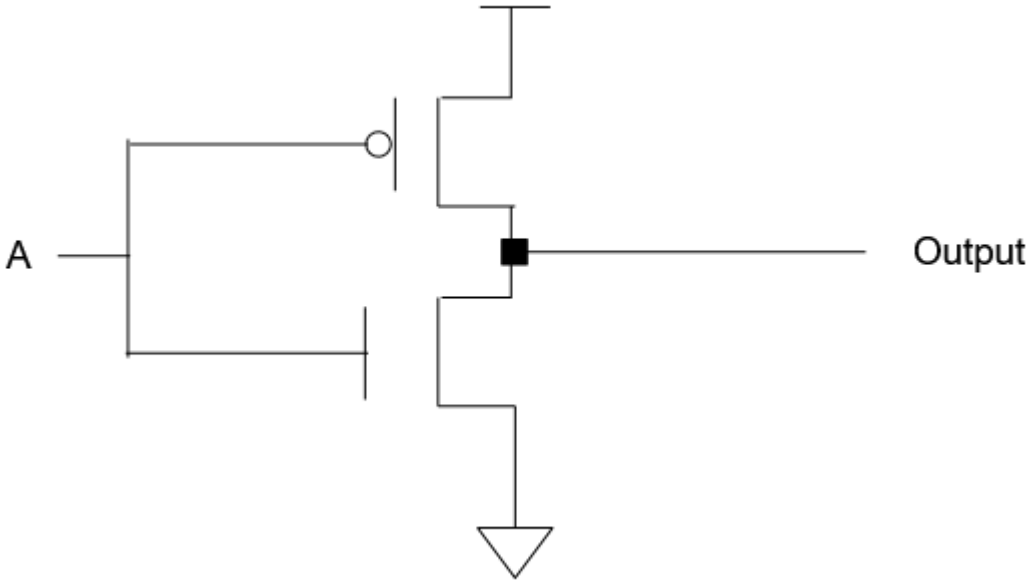
- Is this legal, if so, what's the truth table? If not, why?



Poll Everywhere

pollev.com/tqm

- Is this legal, if so, what's the truth table? If not, why?



Legal!

A	Output
0	1
1	0

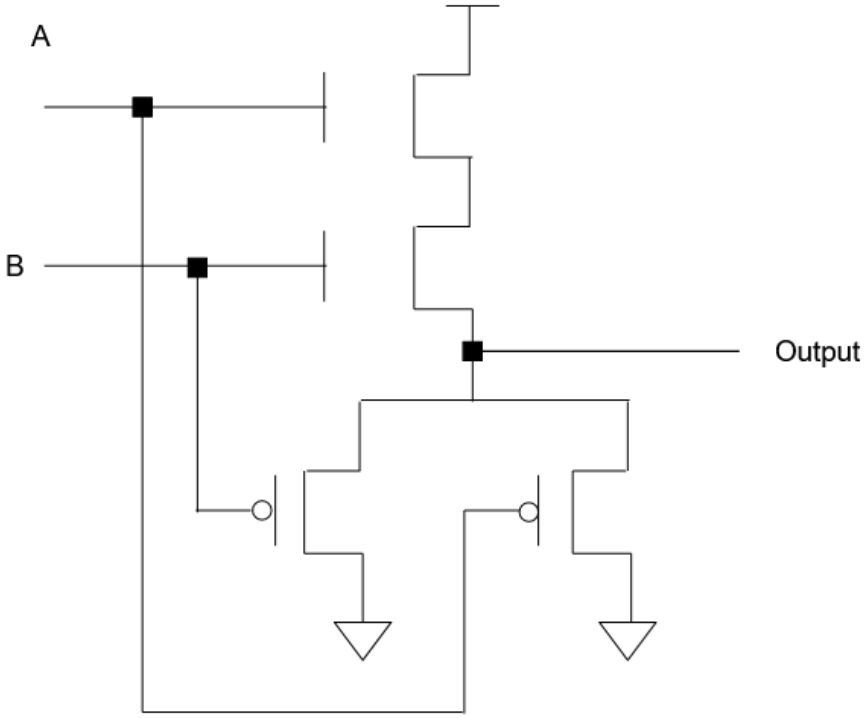
~A = output

This is the "not" circuit

Poll Everywhere

pollev.com/tqm

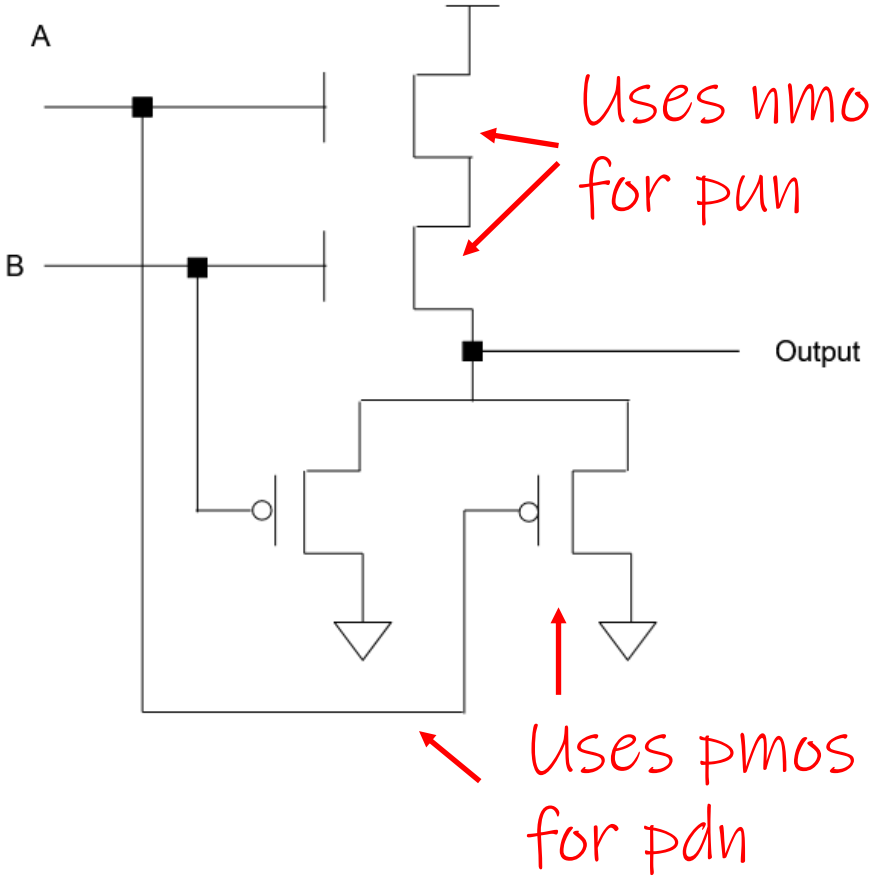
- Is this legal, if so, what's the truth table? If not, why?



Poll Everywhere

pollev.com/tqm

- Is this legal, if so, what's the truth table? If not, why?



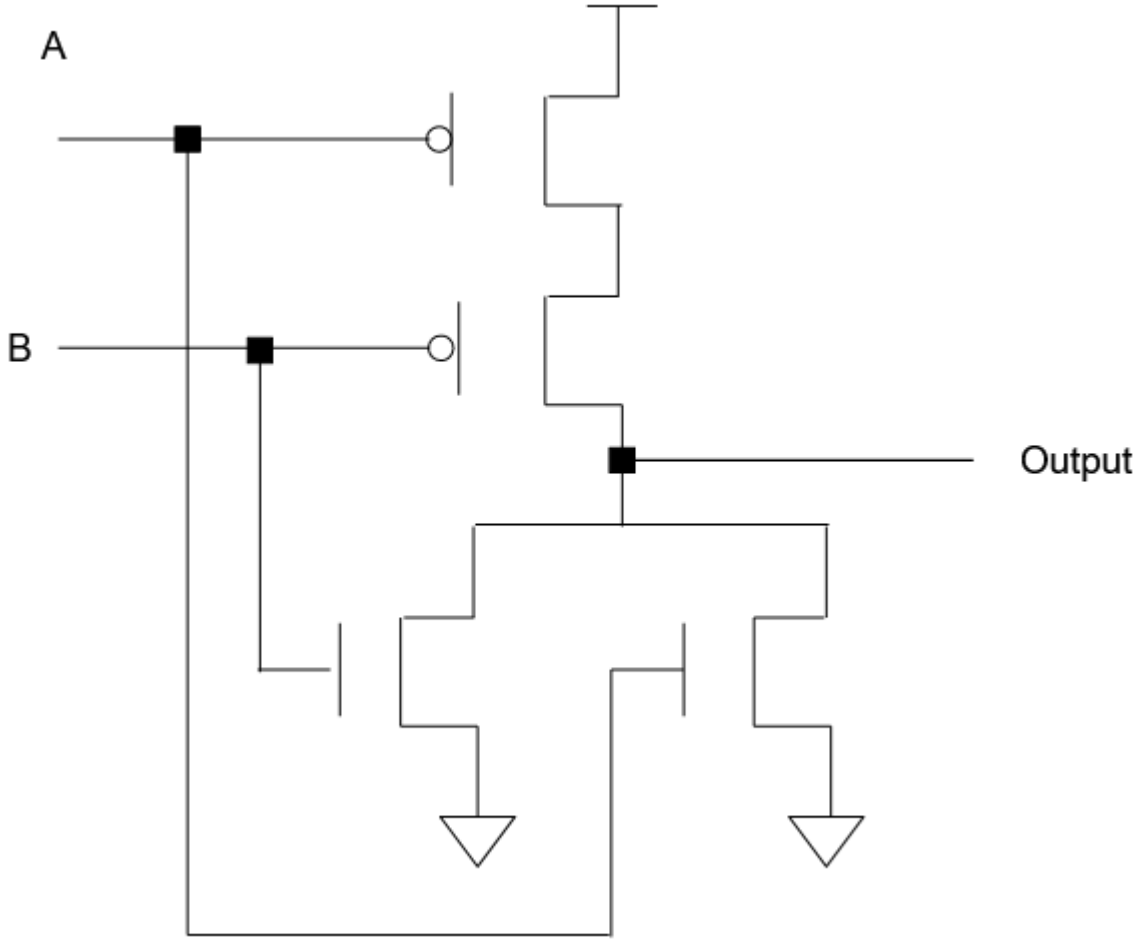
Illegal

Why?

Poll Everywhere

pollev.com/tqm

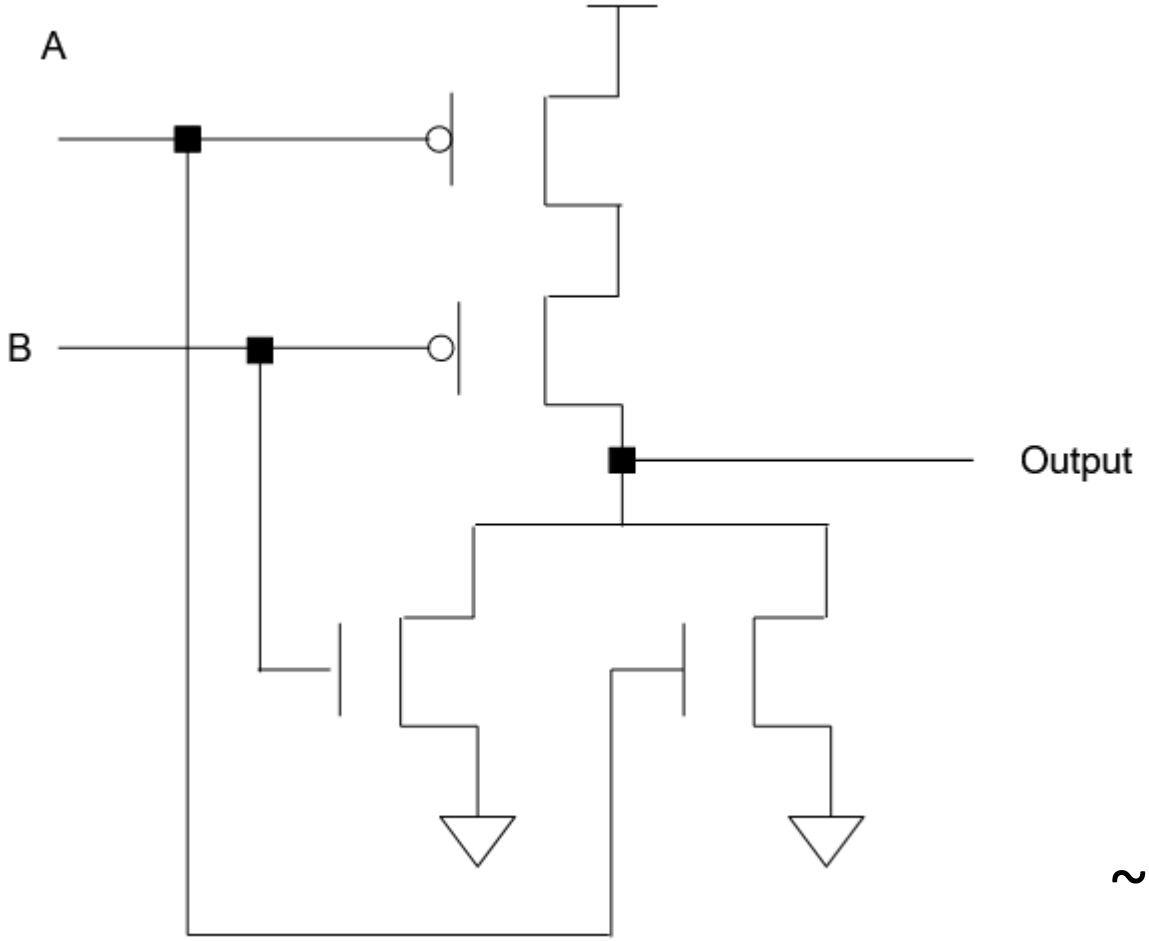
- Is this legal, if so, what's the truth table? If not, why?



Poll Everywhere

pollev.com/tqm

- Is this legal, if so, what's the truth table? If not, why?



Legal!

A	B	Output
0	0	1
0	1	0
1	0	0
1	1	0

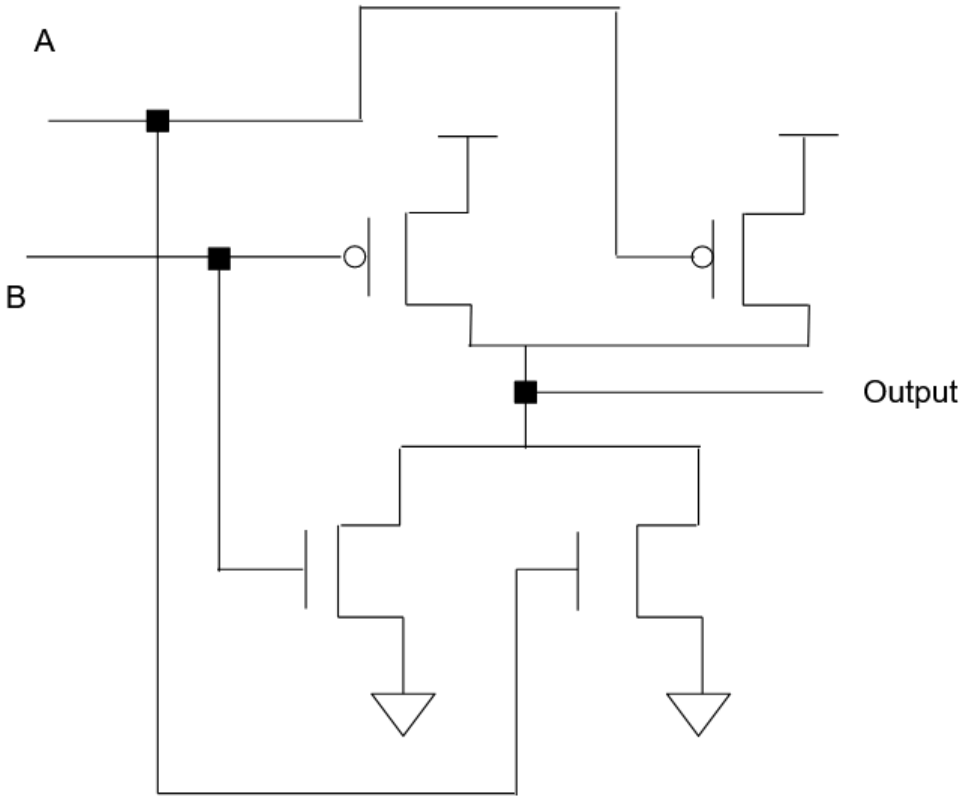
~(A|B) = output

This is "nor"

Poll Everywhere

pollev.com/tqm

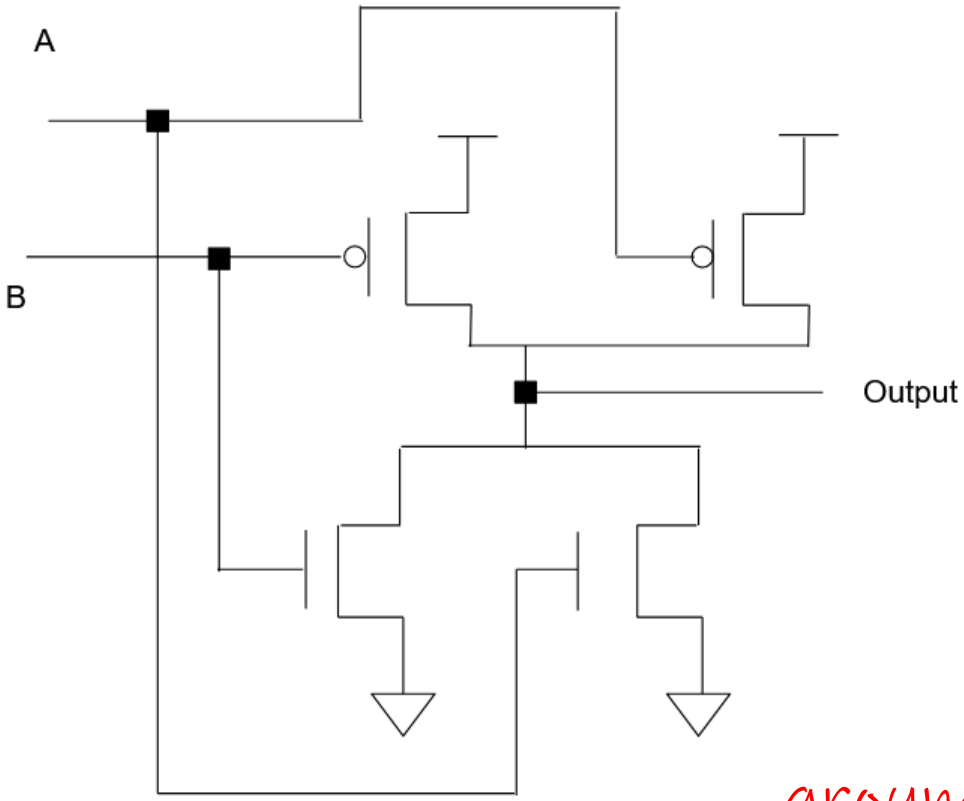
- Is this legal, if so, what's the truth table? If not, why?



Poll Everywhere

pollev.com/tqm

- Is this legal, if so, what's the truth table? If not, why?



Illegal

Why?

Consider inputs
a = 0
b = 1

ground and power both connected to output!!!!!!

Lecture Outline

- `void*`
- Boolean Algebra
- Physics Background
- CMOS Transistor
- CMOS Logical Circuits
- **CMOS Circuit Design**

Rules & Suggestions For Design

- Rules:
  - You cannot have pMOS transistors in the PDN
  - You cannot have nMOS in the PUN
  - Exactly one of PDN/PUN must be “on” at a time
    - Cannot have neither connected to output
    - Cannot have both connected to output
  - Every transistor in the PDN must have a complimentary transistor in the PUN
    - When any transistor is PDN is ON, its compliment transistor is OFF

- Suggestions
  - Start with the PDN and then do the PUN (most find it easier)
  - Simplify logic before you design any part of the circuit

NOR Circuit Design Walkthrough

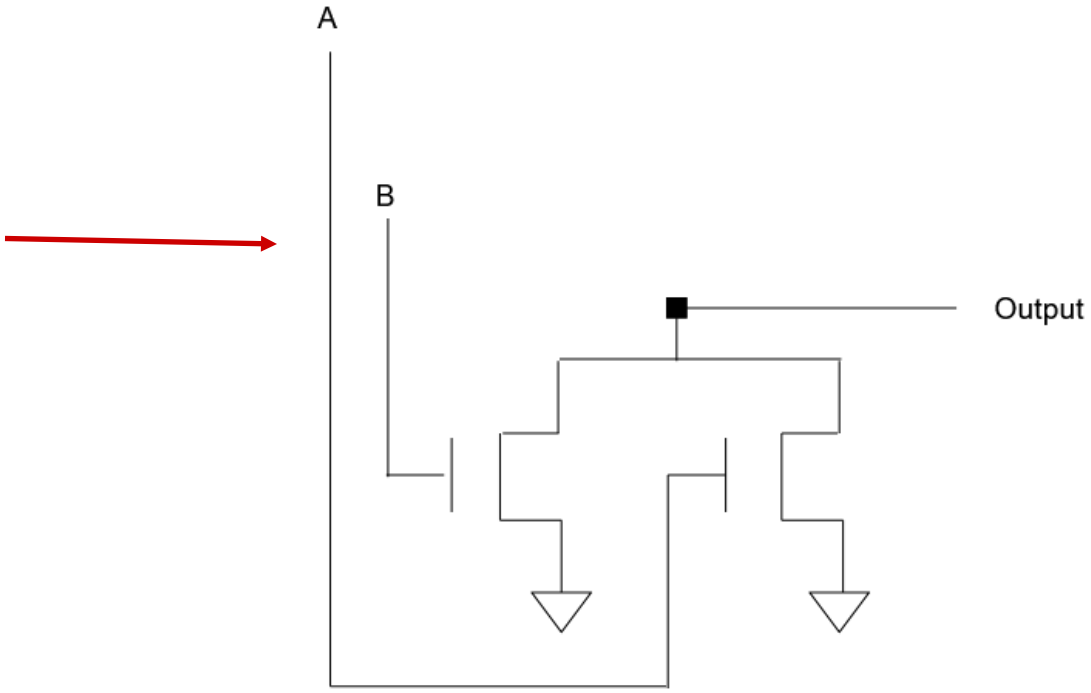
- First, start with the Boolean Expression
  - NOR is NOT-OR, which is
    ~(A | B) <- statement for when output is 1 (True)

- Since I like to start with PDN, find the cases when output is FALSE, then simplify
  - This can be done by negating the original expression
  - ~~(A | B) <- statement for when output is 0 (False)
  - (A | B) <- simplified by identity property

NOR Circuit Design Walkthrough

- With the expression for the PDN (when output is 0), translate it to a circuit diagram for the PDN
  - OR's become transistors in parallel
  - AND's become transistors in series

(A | B) becomes



NOR Circuit PUN (Strategy 1)

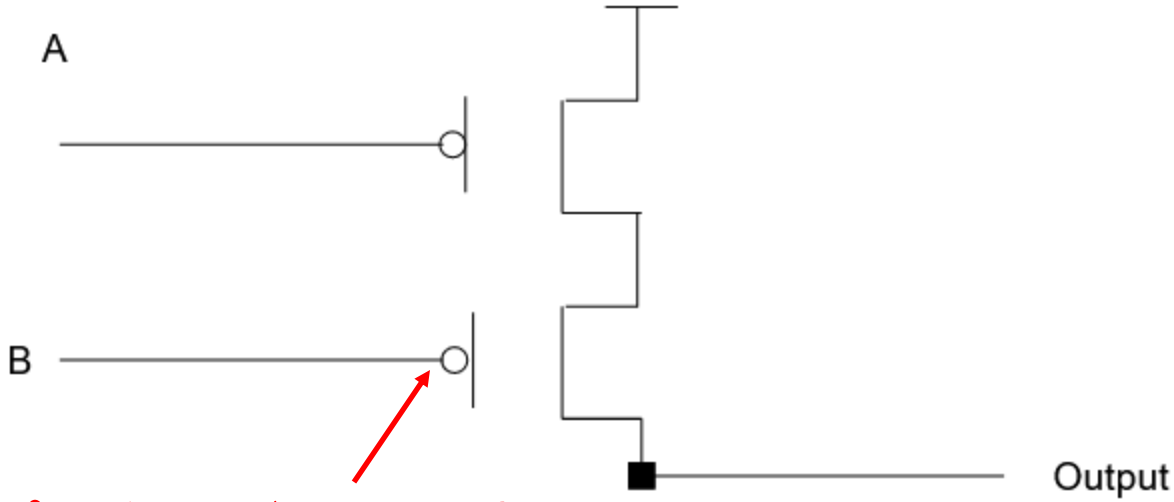
- With the simplified expression for PDN, negate it to get the expression for PUN
  - (A | B) becomes ~(A | B)
  - Simplify
    - ~(A | B)
    - (~A & ~B) // by De Morgan's Law

In this example, initial PUN expression is the same as the original expression. This is not always the case

- From here, we can convert (~A & ~B) into a PUN

NOR Circuit PUN (Strategy 1)

- From here, we can convert (~A & ~B) into a PUN
  - OR's become transistors in parallel
  - AND's become transistors in series
  - pMOS transistors have an implicit "NOT"
    - pMOS only turns on when input is low (0)

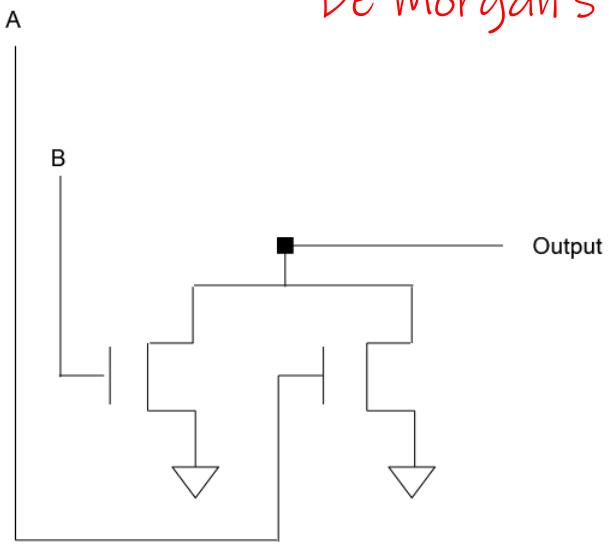


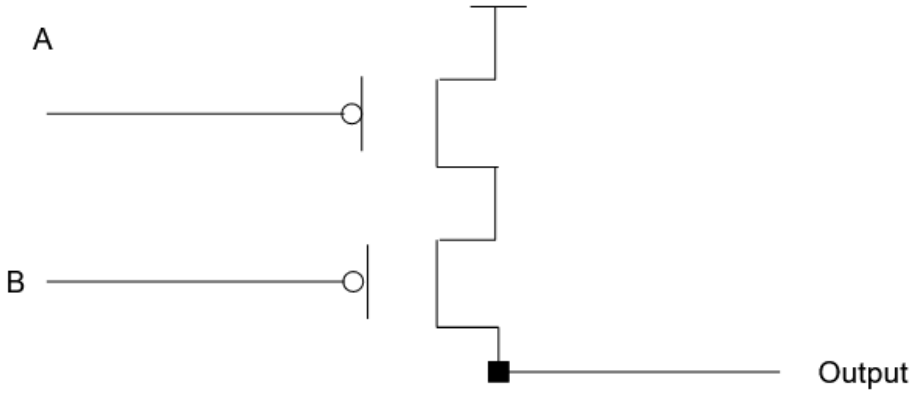
The reason for the circle in pMOS:
Circle represents a "Not" or negation

NOR Circuit PUN (Strategy 2)

- Alternative way to get the PUN from the PDN
  - Series relations in PDN become Parallel relations in PUN
  - Parallel relations in PDN become Series relations in PUN
  - nMOS transistors become pMOS transistors

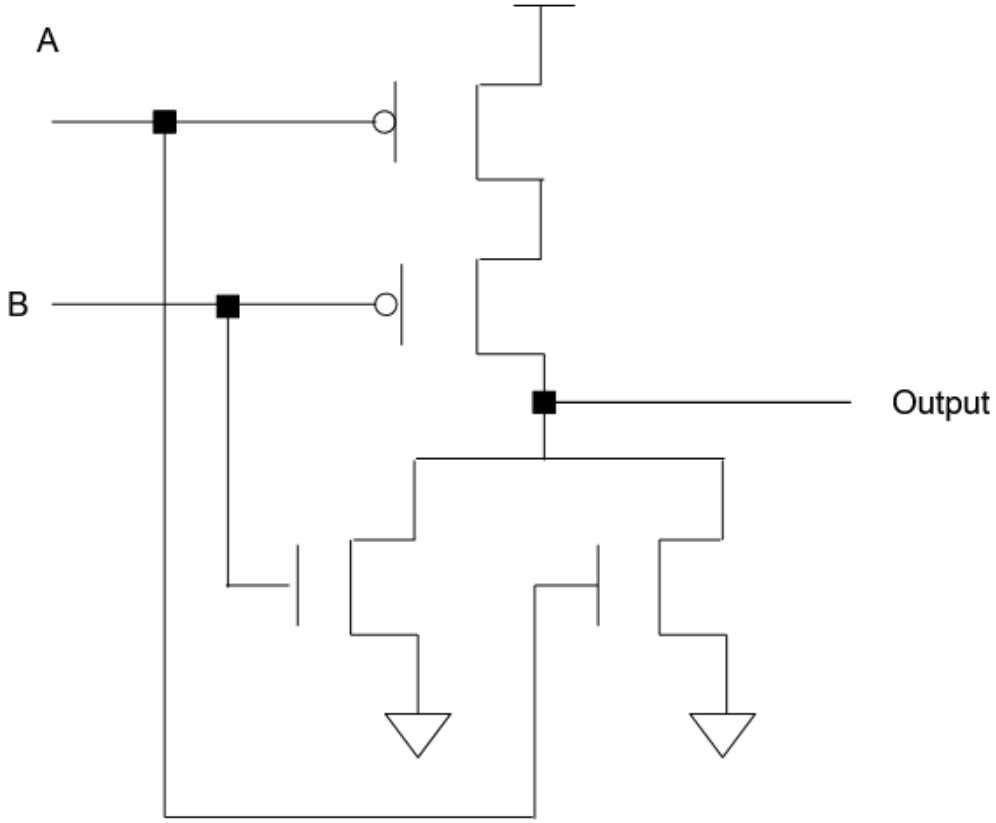
This is just a "short-cut" for applying De Morgan's to the PDN





Completed NOR Circuit

- Finally, all you have to do is combine the PDN and PUN
  - To be safe, check your work and create a truth table



A	B	Output
0	0	1
0	1	0
1	0	0
1	1	0