# Advanced Lab 1

## Transistors and Bitwise Operators

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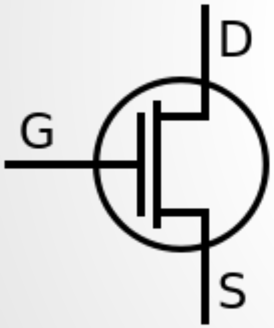
# Topics

- Transistors
  - Fundamentals
  - From Truth Tables to Circuits
- Bitwise Operators
  - How They Work
  - Mask Generation
  - Optimizing with Bitwise Operators

# Transistors: Fundamentals

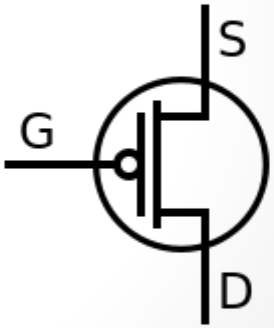
There are two types of transistors:

N-type:




Attached to ground

P-type:

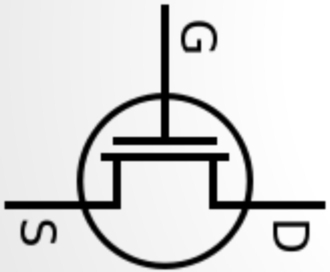



Attached to power

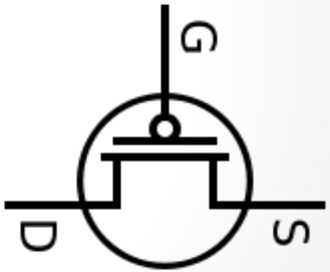
# Transistors: Fundamentals

The base allows a signal through based on its value:

N-type:




P-type:



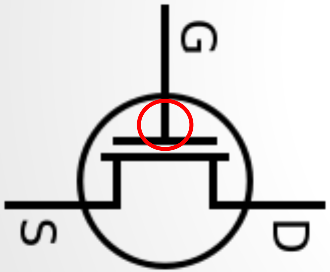

Allow a signal through when base == 1

Allow a signal through when base == 0

# Transistors: Fundamentals

My memorization mnemonic:

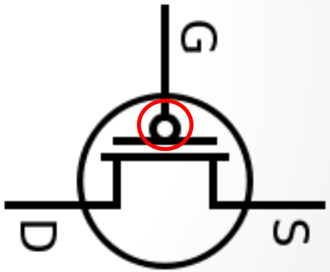
N-type:




Looks like a 1

Allow a signal through when base == 1

P-type:

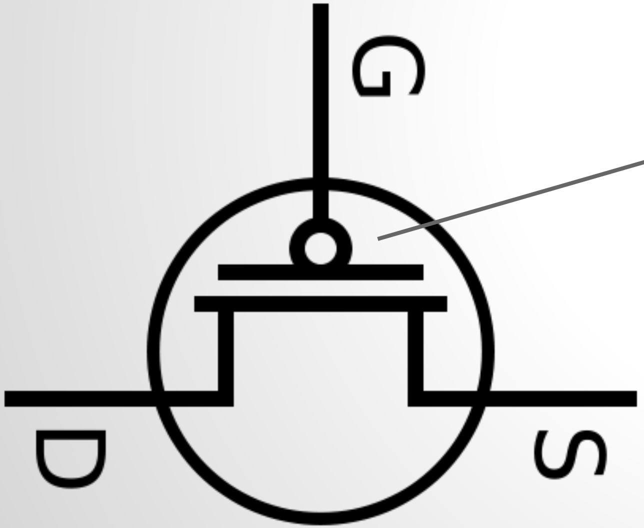



Looks like a 0

Allow a signal through when base == 0

# Transistors: Fundamentals

My memorization mnemonic:



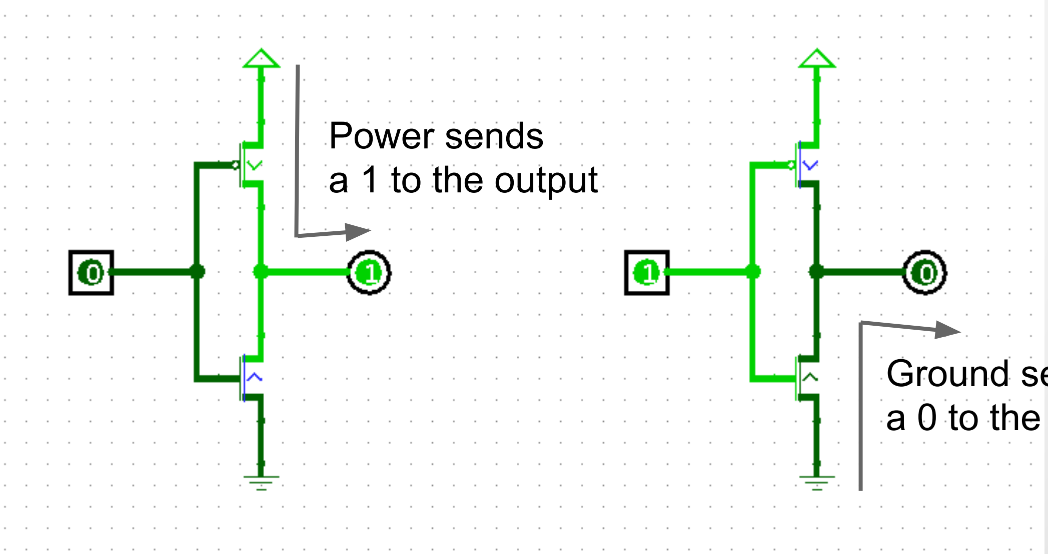

Has a loop like a P

P-type = Power

(hook these up to power)

# From Truth Tables to Circuits

Forget any science you’ve learned about electrons traveling from power to ground; for the purpose of practicing with transistor logic, think of each as simply “sending” a logical signal to the output:



# From Truth Tables to Circuits

The easiest way to figure out how to wire a NAND or NOR gate is to construct a truth table. For example, here is the truth table for NAND:

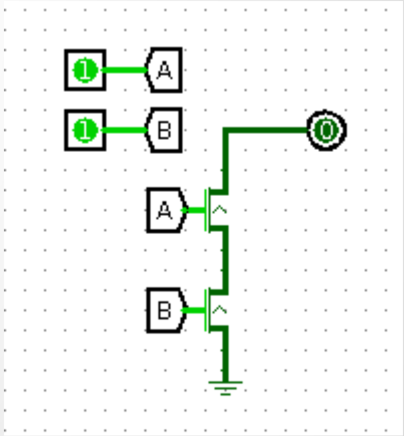
| A | B | Out |
|---|---|---|
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

# From Truth Tables to Circuits

Find the unique output for the truth table, and wire that first in series. The reason for this is that a series circuit requires that all the conditions be true:

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

Only when all the conditions, that is, A == 1 and B == 1, will the output be zero, so use a series of transistors

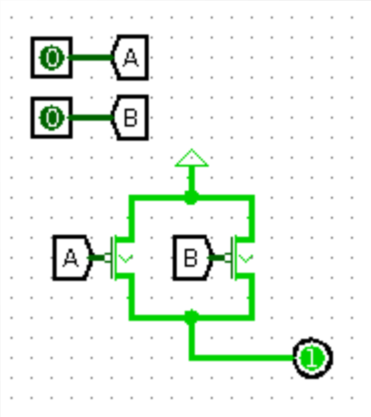


# From Truth Tables to Circuits

Next, wire all the other outputs in parallel. We use parallel because parallel transistors simply allow any of the conditions to be true:

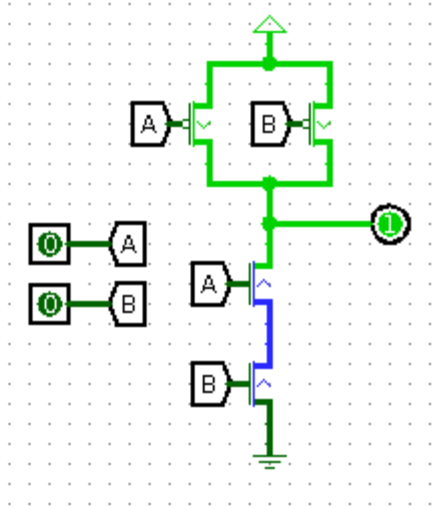
| A | B | Out |
|---|---|---|
| 0 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

Output a 1 if either A == 0, B == 0, or both are 0, so use parallel transistors



# From Truth Tables to Circuits

Combine the two parts together for the completed NAND:



# From Truth Tables to Circuits

Let’s design a circuit for A NOR B NOR C!

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

# From Truth Tables to Circuits

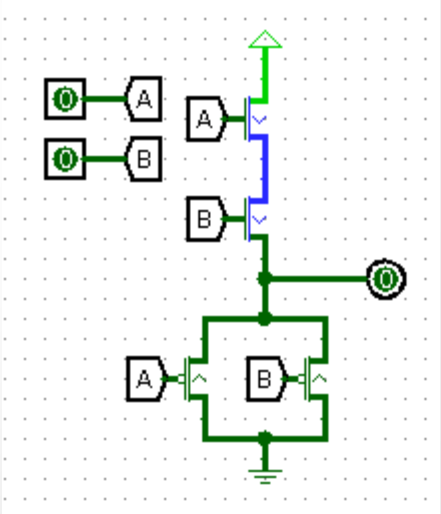
Caveat: AND, OR - is this correct?

(AND)

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

Unique case: Series

Non-unique case: Parallel



# From Truth Tables to Circuits

Caveat: AND, OR - is this correct?

NO!

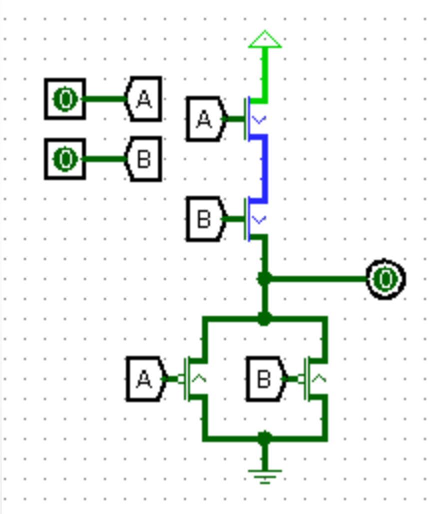
**P-type should connect to power, N-type to ground**

(AND)

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

Unique case: Series

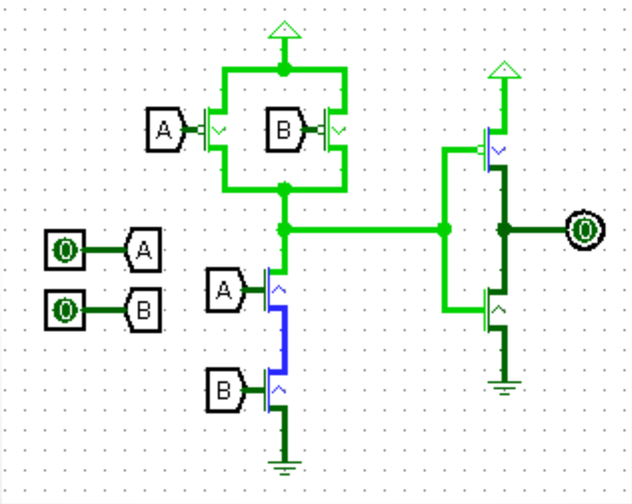
Non-unique case: Parallel



# From Truth Tables to Circuits

Caveat: AND, OR

[AND, OR] should be implemented with [NAND, NOR] + NOT



# Bitwise Operators: How They Work

Bitwise operators are fast, simple operations that can be performed on sets of bits.

&   bitwise AND

|   bitwise OR

~   bitwise NOT

<<   >>   shift operator

^   bitwise XOR (can be made with AND, OR, NOT)

# Bitwise Operators: How They Work

~ (Flip bits)

The ~ operator can be used to flip the bits in a number.

```
~ 0100
------
  1011
```

# Bitwise Operators: How They Work

| (Set bits)

The | operator can be used with a mask to set bits.

```
  0100
| 0010
------
  0110
```

# Bitwise Operators: How They Work

& (Reset bits)

The & operator can be used with a mask to reset bits.

```
  1011
& 1101
------
  1001
```

# Bitwise Operators: How They Work

^ (Toggle bits)

The ^ operator can be used with a mask to toggle bits.

```
  1010
^ 0110
------
  1100
```

# Bitwise Operators: How They Work

<< or >> (Shift bits)

The shift operators << or >> can move bits left or right.

```
00011010  <<  2
---------------
01101000
```

```
10110100  >>  2
---------------
11101101
```

Zeros are shifted in from the right

MSB is shifted in from the left

# Bitwise Operators: Mask Generation

Need a single 1 at location *n* to set or toggle a bit?
Shift a 1 over to the location:

```
00000001 << 3
-------------
00001000
```

# Bitwise Operators: Mask Generation

Need a single 0 at location *n* to reset a bit?
Shift a 1 over to the location, and flip the bits:

```
00000001 << 3
-------------
00001000     ~
-------------
11110111
```

# Bitwise Operators: Mask Generation

## Case study: get_a_byte

Problem: We want to get a single byte from a 32-bit integer value, given an index 0 - 3 for which byte.

```
01001101 00111010 01010000 10110101
-------- -------- -------- --------
   B3       B2       B1       B0
```

# Bitwise Operators: Mask Generation

## Case study: get_a_byte

Answer: Shift the byte over to the least significant 8 bits (which = 2):

```
01001101 00111010 01010000 10110101

00000000 00000000 01001101 00111010
```

But there's still some garbage above the desired byte...

# Bitwise Operators: Mask Generation

## Case study: get_a_byte

Mask using & to remove undesired bits:

```
  00000000 00000000 01001101 00111010
& 00000000 00000000 00000000 11111111
-------------------------------------
  00000000 00000000 00000000 00111010
```

# Bitwise Operators: Mask Generation

## Case study: get_a_byte

What this looks like in code:

```
return (n >> (which * 8)) & 0xFF;
```

Shift the number...

...in increments of 8 bits...

...and mask the result.

# Optimizing with Bitwise Operators

Powers of 2 are very useful!

- Operating system uses them for page size and buddy allocators (more on that later).
- Cryptography uses them to bound key and cipher block sizes.
- You can use them to efficiently perform multiplication, division and modulus!

# Optimizing with Bitwise Operators

Multiplication:

When you multiply by a power of 2, you essentially shift the bits left:

```
00000101  * 8   (5)
-----------------
00101000        = 40
```

# Optimizing with Bitwise Operators

Multiplication:

When you multiply by a power of 2, you essentially shift the bits left:

```
00000101 << 3 (5)
-----------------
00101000      = 40
```

It's the same as left shifting by $\log_2(n)$!

# Optimizing with Bitwise Operators

Division:

When you divide by a power of 2, you essentially shift the bits right:

```
00101000 / 8   (40)
------------------
00000101        = 5
```

# Optimizing with Bitwise Operators

Division:

When you divide by a power of 2, you essentially shift the bits right:

```
00101000 >> 3 (40)
------------------
00000101      = 5
```

It's the same as right shifting by $\log_2(n)$!

# Optimizing with Bitwise Operators

Modulus:

When you mod by a power of 2, you zero out all the bits above the first $\log_2(n)$ bits:

```
00110110 % 16 (54)
------------------
00000110       = 6
```

# Optimizing with Bitwise Operators

Modulus:

When you mod by a power of 2, you zero out all the bits above the first $\log_2(n)$ bits:

```
00110110 & 15 (54)
------------------
00000110       = 6
```

It’s the same as bitwise AND with (n-1)!

# Optimizing with Bitwise Operators

## Case study: get_a_byte

Let’s return to our old code:

```
return (n >> (which * 8)) & 0xFF;
```

How can we improve this line?

# Optimizing with Bitwise Operators

## Case study: get_a_byte

Let's return to our old code:

```
return (n >> (which * 8)) & 0xFF;
```

How can we improve this line? Use the shift operator!

```
return (n >> (which << 3)) & 0xFF;
```

# Optimizing with Bitwise Operators

Case study: power_of_2

Look at these powers of 2:

00100000 = 32

00001000 = 8

01000000 = 64

Notice a pattern?

# Optimizing with Bitwise Operators

## Case study: power_of_2

Look at these powers of 2:

00100000 = 32

00001000 = 8

01000000 = 64

Notice a pattern?

Only one bit set.

# Optimizing with Bitwise Operators

## Case study: power_of_2

How can we determine if only one bit is set?

```
int set = 0;
for(int i = 0; i < 31; ++i)
    if(n & (1 << i) != 0)
        ++set;
return n > 0 && set == 1;
```

Can we do better than a loop?

# Optimizing with Bitwise Operators

## Case study: power_of_2

Something else special about powers of 2:

For any power of 2 “n”, the only bit activated in n is farther left than all the activated bits of values less than n. This property only applies to powers of 2!

These bits didn’t change!

```
n  : 0010000        m  : 00011010
n-1: 0001111        m-1: 00011001
```

# Optimizing with Bitwise Operators

## Case study: power_of_2

```
n  : 0010000
n-1: 0001111
```

Since these values do not share any activated bits, a bitwise AND operation will produce 0 for powers of 2!

```
16 & 15 = 0        26 & 25 = 24
```

**16 is a power of 2**

**26 is not a power of 2**

# Optimizing with Bitwise Operators

## Case study: power_of_2

What this looks like in code:

```
return n > 0 && (n & (n-1)) == 0;
```

Number must be positive

Power of 2 property

*This is sometimes an interview question! Know how to do it!*