CSC 252: Computer Organization
Fall 2021: Lecture 2

Bits, Bytes & Transistors
Bitwise operations
Integers

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Action Items:

- **Get CSUG account**
- **Make sure you have VPN setup!!!!**
- **Sign up for Blackboard, Piazza**

Announcement

Make sure you can access CSUG machines!!!

Programming assignment 1 will be posted tonight.

C language. Seek help from TAs. Ask questions on Piazza forum so everyone can benefit.

Announcement

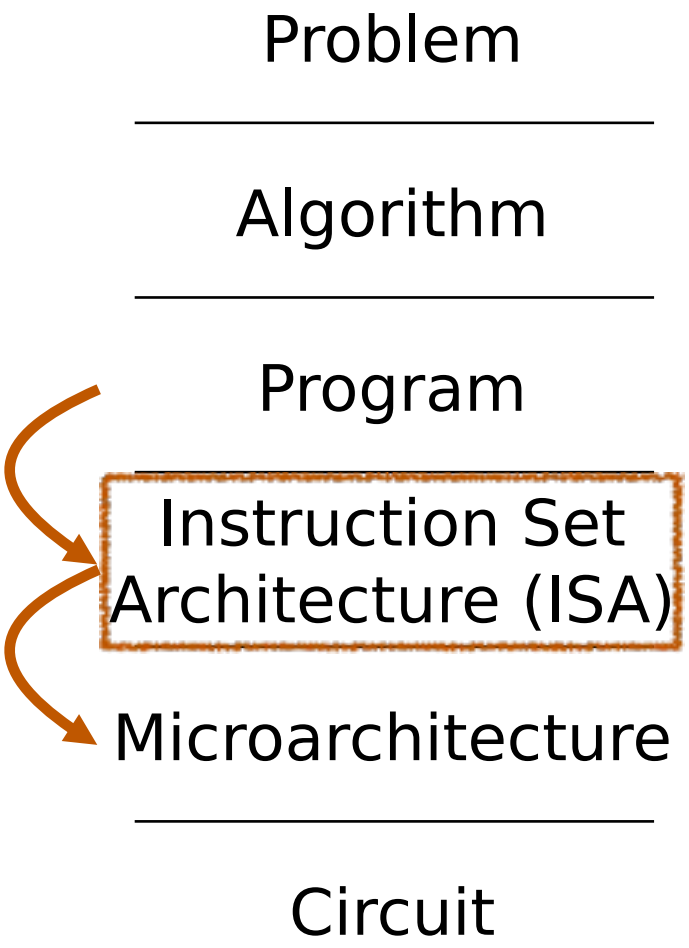
You may work on assignments in pairs

Can use Piazza to find someone to work with

You have 3 slip days

Previously in 252...

- How is a human-readable program translated to a representation that computers can understand?
- How does a modern computer execute that program?



ISA is the contract between software and hardware.

Previously in 252...

C Program

```
void add() {
  int a = 1;
  int b = 2;
  int c = a + b;
}
```

Assembly program

```
movl    $1, -4(%rbp)
movl    $2, -8(%rbp)
movl    -4(%rbp),
%eax
addl    -8(%rbp), %eax
```

Previously in 252...

Assembly program

```
movl    $1, -4(%rbp)
movl    $2, -8(%rbp)
movl    -4(%rbp),
%eax
addl    -8(%rbp),
%eax
```

Executable Binary

```
00011001   ...
01101010   ...
11010101   ...
01110001   ...
```

What's the difference between an assembly program and an executable binary?

Previously in 252...

Assembly program

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movl    $1, -4(%rbp)
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Executable Binary

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00011001   ...
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What's the difference between an assembly program and an executable binary?

- They refer to the same thing — a list of instructions that the software asks the hardware to perform
- They are just different representations

Previously in 252...

Assembly program

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movl    $1, -4(%rbp)
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Executable Binary

```
00011001   ...
01101010   ...
11010101   ...
01110001   ...
```

What's the difference between an assembly program and an executable binary?

- They refer to the same thing — a list of instructions that the software asks the hardware to perform
- They are just different representations

Instruction = Operator + Operand(s)

Bits Bytes & Transistors

Everything is bits

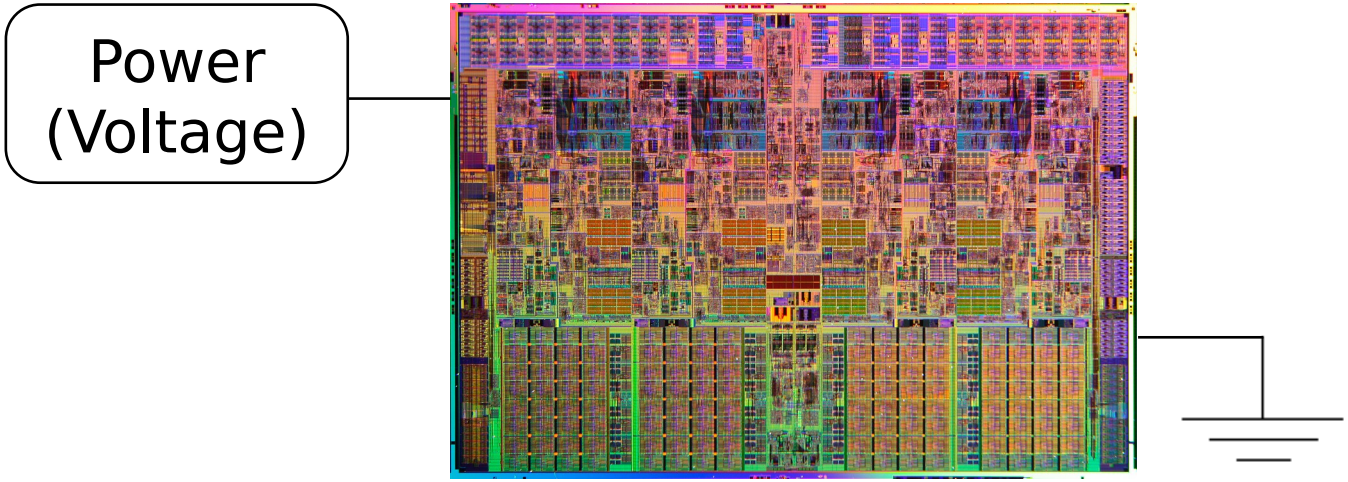
Each bit is 0 or 1. Bits are how programs talk to the hardware

Programs encode instructions in bits

Hardware then interprets the bits

Why bits? Electronic Implementation

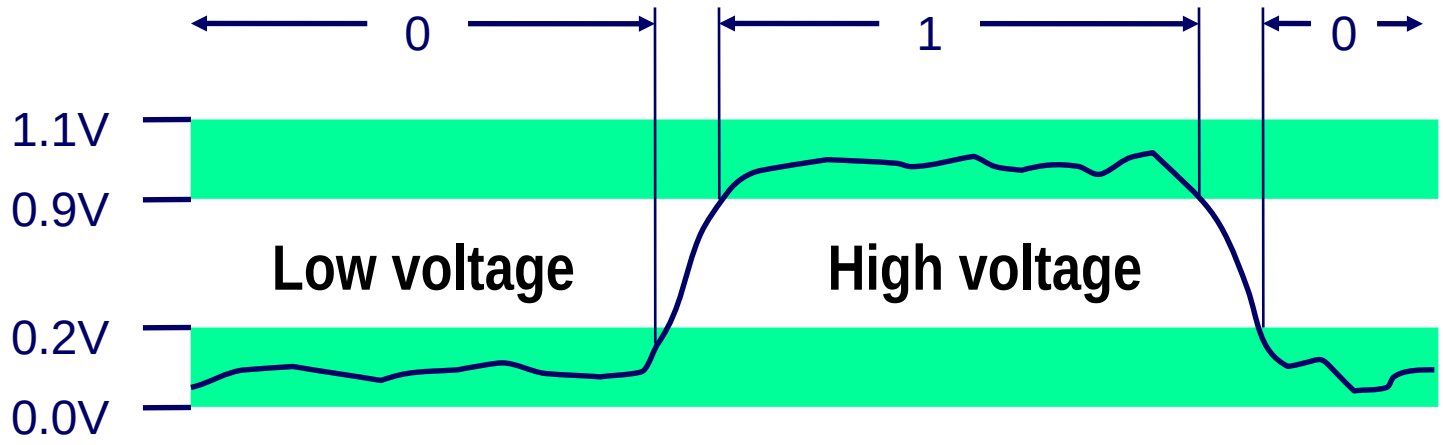
Software is bits, data is bits, everything is bits in memory



Why Bits?

Use high voltage to represent 1
Use low voltage to represent 0

“Noise” is less likely to cause errors with only two possibilities
Two-value logic gates are easy/cheap to build and combine



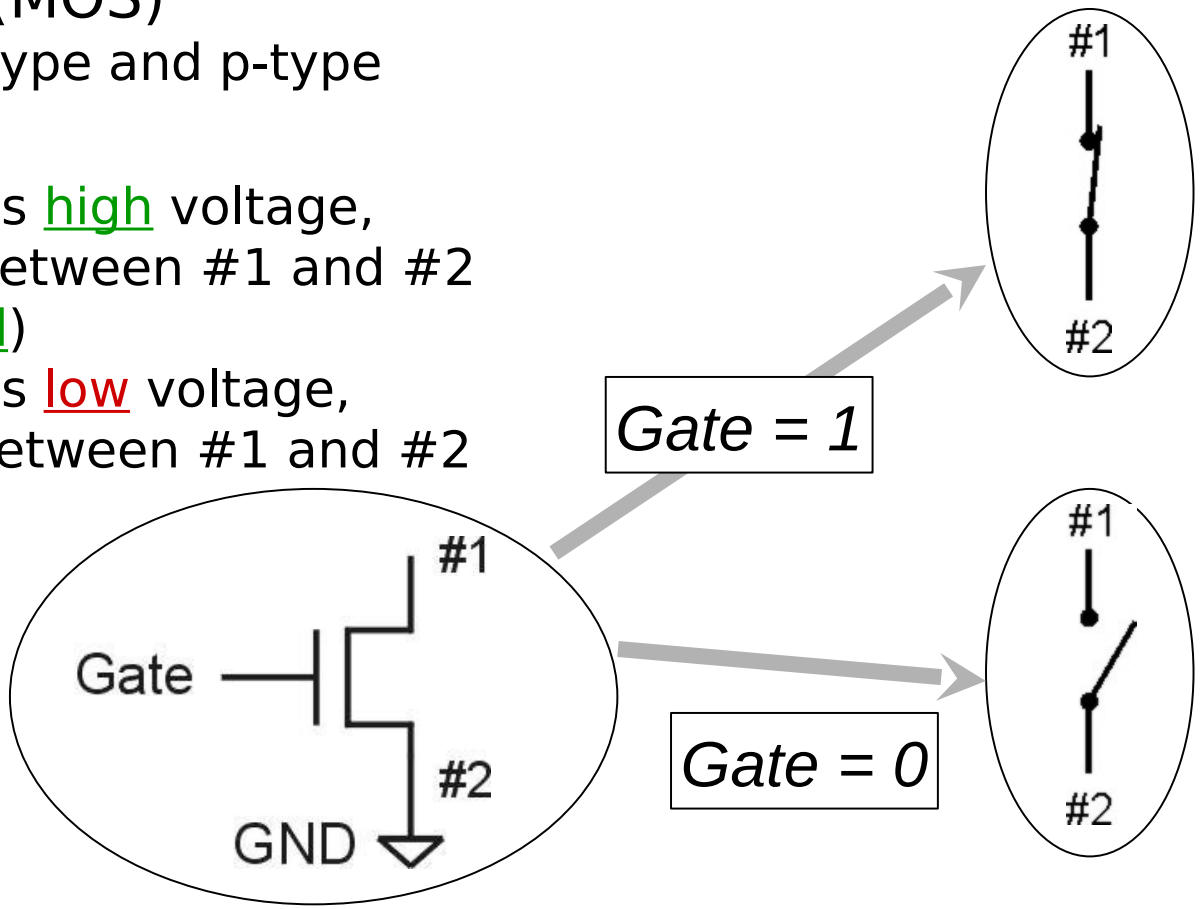
Why Bits?

Processors are made of transistors, which are Metal Oxide Semiconductor (MOS)

- two types: n-type and p-type

n-type (NMOS)

- when Gate has high voltage, short circuit between #1 and #2 (switch closed)
- when Gate has low voltage, open circuit between #1 and #2 (switch open)

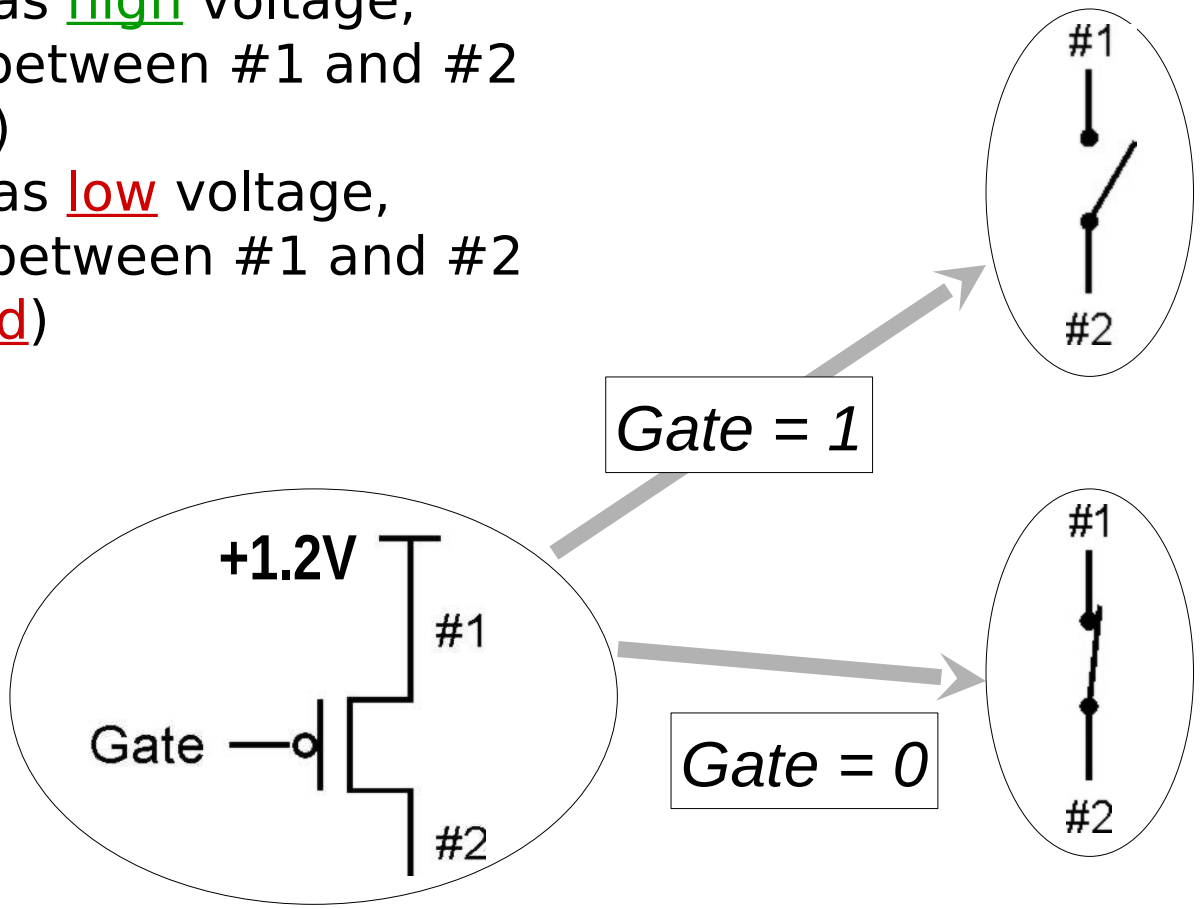


Terminal #2 must be connected to GND (0V).

Why Bits?

p-type is *complementary* to n-type (PMOS)

when Gate has high voltage,
open circuit between #1 and #2
(switch open)
when Gate has low voltage,
short circuit between #1 and #2
(switch closed)

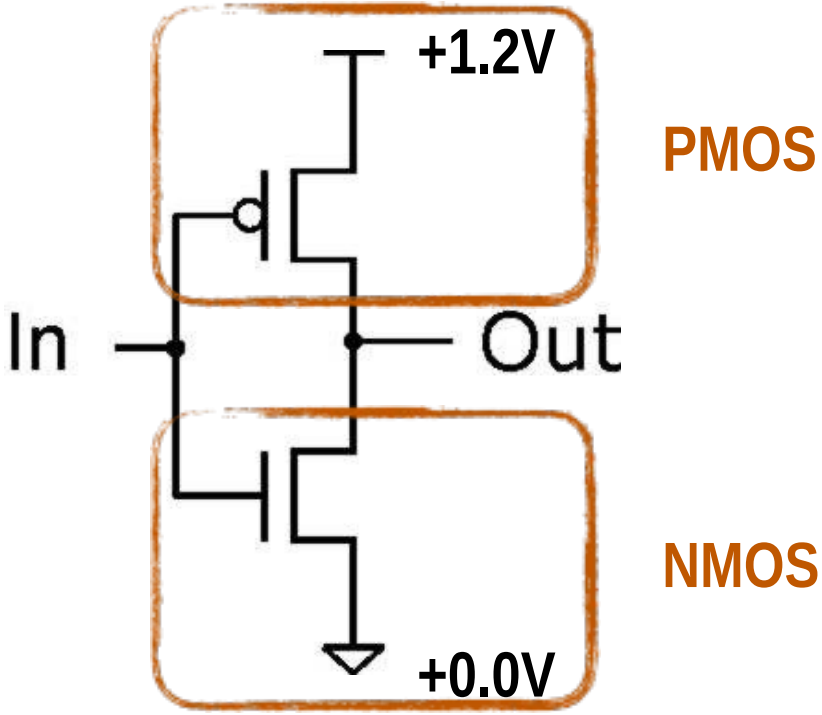


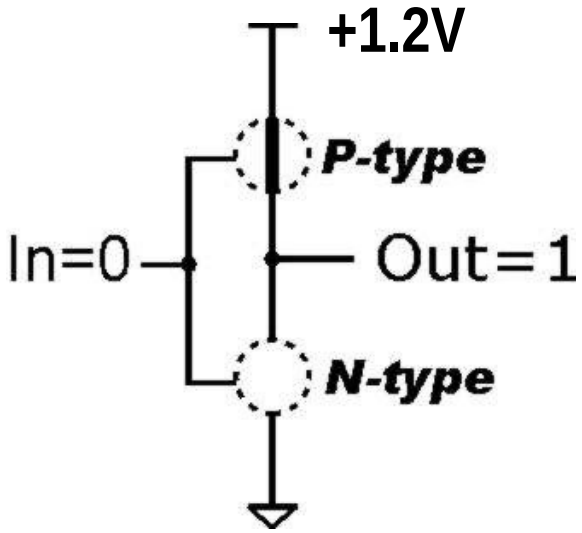
Terminal #1 must be connected to +1.2V

CMOS Circuit

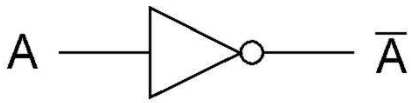
- Complementary MOS
- Uses both n-type and p-type MOS transistors
  - p-type
    - Attached to + voltage
    - Pulls output voltage UP when input is zero
  - n-type
    - Attached to GND
    - Pulls output voltage DOWN when input is one

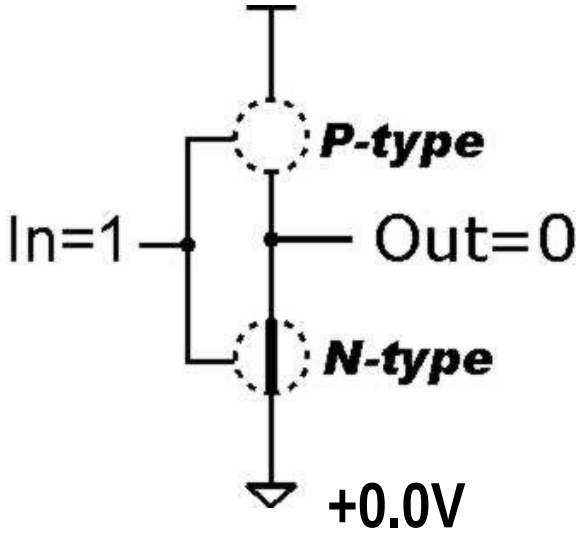
CMOS Inverter



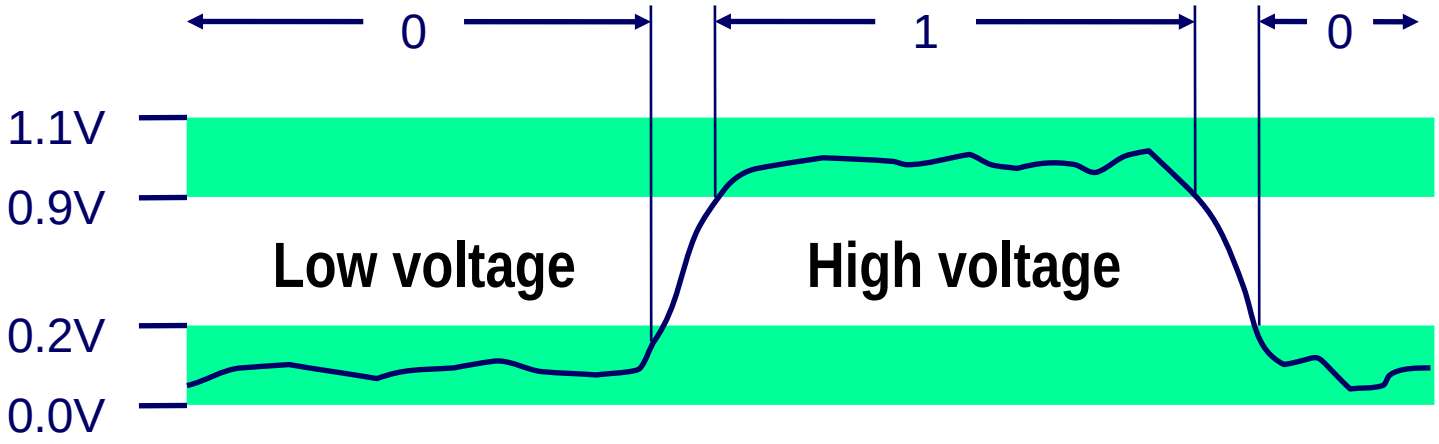


In	Out
0	1
1	0



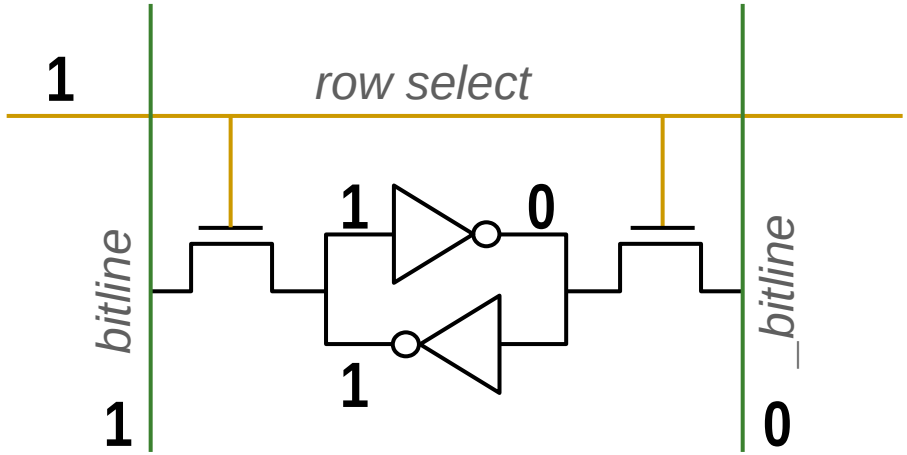


Store/Access Data



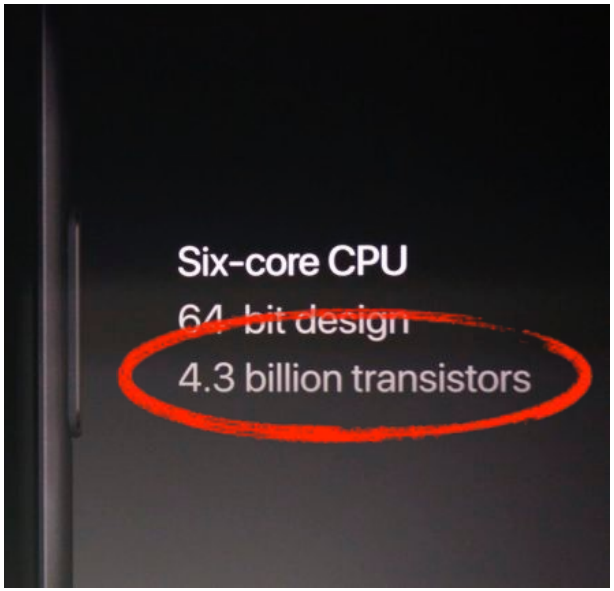
Two cross coupled inverters store a single bit

- Feedback path persists the value in the “cell”
- 4 transistors for storage
- 2 transistors for access
- A “6T” cell

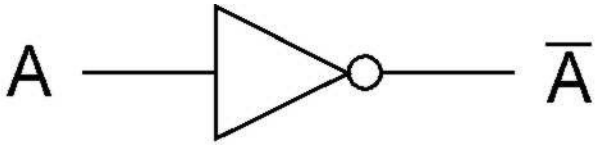


Transistors

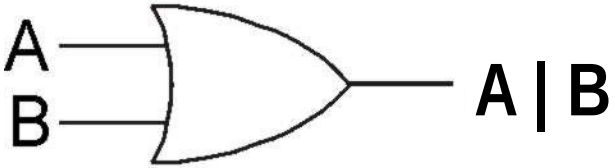
- Computers are made of transistors
- Transistors have become smaller over the years
  - Not so much anymore…



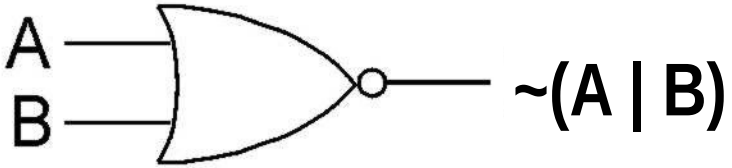
Basic Logic Gates



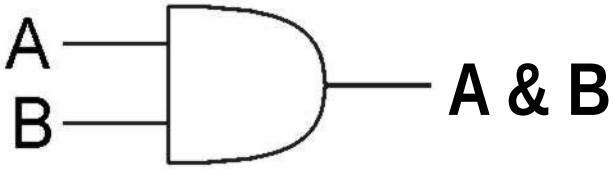
NOT



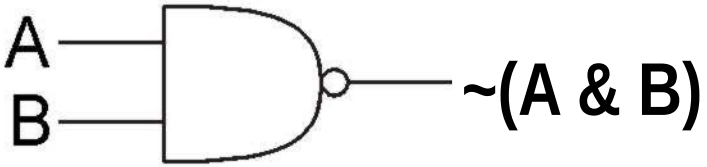
OR



NOR



AND



NAND

Binary Notation

Base 2 Number Representation (Binary)

Weighted Positional Notation

Each bit has a weight depending on its position

$1011_2 = 1*2^0 + 1*2^1 + 0*2^2 + 1*2^3 = 11_{10}$

$b_3b_2b_1b_0 = b^0*2^0 + b^1*2^1 + b^2*2^2 + b^3*2^3$

Binary Arithmetic:

```
  0110
+ 0101
------
  1011
```

```
  6
+ 5
---
 11
```

Decimal	Binary
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

Binary Notation

For example,

What is 00010111_2 in decimal?

0 0 0 1 0 1 1 1

Decimal	Binary
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

Binary Notation

For example,

What is 00010111_2 in decimal?

0	**0**	**0**	**1**	**0**	**1**	**1**	**1**
128	64	32	**16**	8	**4**	**2**	**1**

Decimal	Binary
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

Binary Notation

For example,

What is 00010111_2 in decimal?

0	**0**	**0**	**1**	**0**	**1**	**1**	**1**
128	64	32	**16**	8	**4**	**2**	**1**

16 + 4 + 2 + 1 = 23

Decimal	Binary
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

Hexdecimal Notation

Base 16 Number Representation

- Use characters ‘0’ to ‘9’ and ‘A’ to ‘F’
- Four bits per Hex digit
- $11111110_2 = FE_{16}$

- Two hex digits = 8 bits = 1 byte

Write $FA1D37B_{16}$ in C as:

0xFA1D37B

Or:

0xfa1d37b

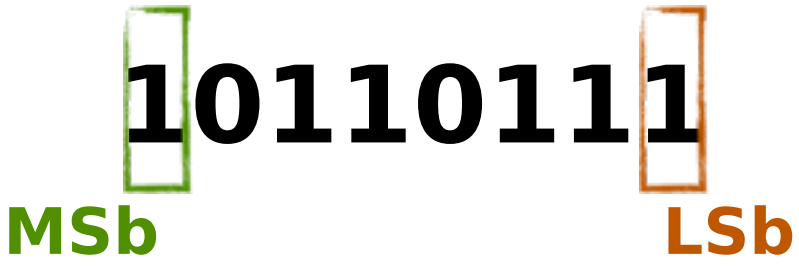
Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Bytes and Words

Byte = 8 bits

Binary 00000000_2 to $11111111_{2;}$ Decimal: 0_{10} to 255_{10}; Hex: 00_{16} to FF_{16}

Least Significant Bit (LSb) vs. Most Significant Bit (MSb)



A word is one or bytes together, depending on the “word size” of the machine

Word = 4 Bytes (32-bit machine) / 8 Bytes (64-bit machine)

Least Significant Byte (LSB) vs. Most Significant Byte (MSB)

Bitwise Operations

Bit-level manipulations

Not

- **~A = 1 when A=0**

~	
0	1
1	0

Or

- **A|B = 1 when either A=1 or B=1**

|	0	1
0	0	1
1	1	1

And

- **A&B = 1 when both A=1 and B=1**

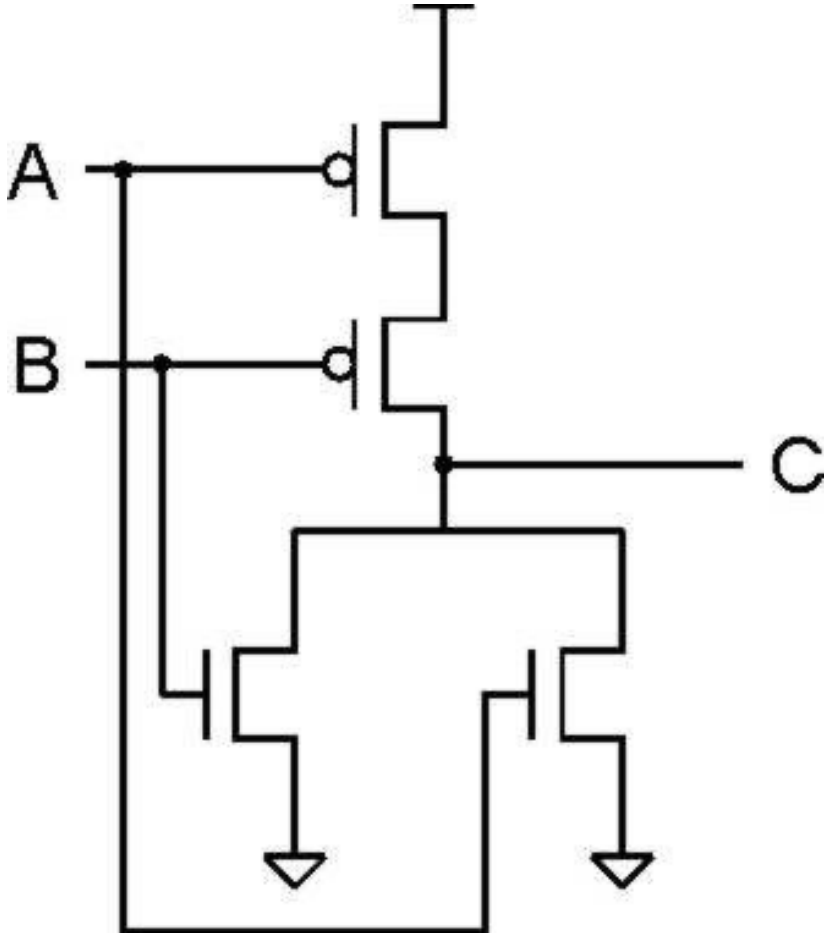
&	0	1
0	0	0
1	0	1

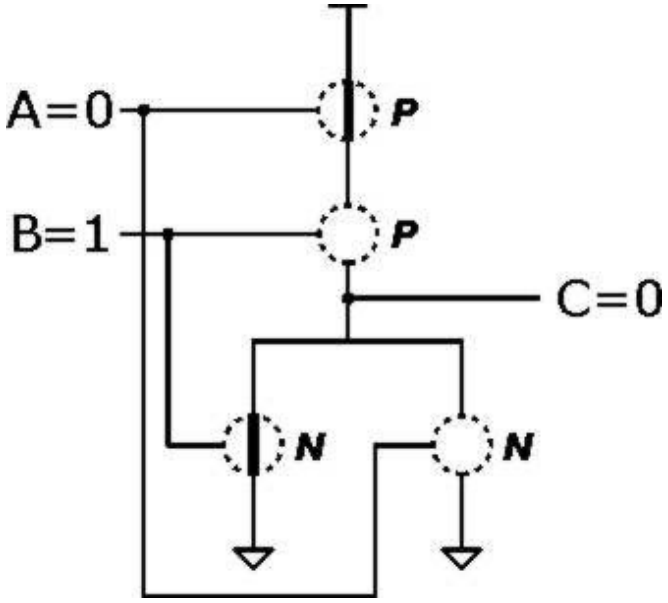
Exclusive-Or (Xor)

- **A^B = 1 when either A=1 or B=1, but not both**

^	0	1
0	0	1
1	1	0

NOR (OR + NOT)





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

Bit Vector Operations

Operate on Bit Vectors

Operations applied bitwise

and

```
  01101001
& 01010101
----------
  01000001
```

or

```
  01101001
| 01010101
----------
  01111101
```

xor

```
  01101001
^ 01010101
----------
  00111100
```

not

```
~ 01010101
----------
  10101010
```

Bit-Level Operations in C

- Operations &, |, ~, ^ Available in C
  - Apply to any “integral” data type
    - long, int, short, char, unsigned
  - View arguments as bit vectors
  - Arguments applied bit-wise
- Examples (Char data type)
  - **~0x41 → 0xBE**
    - $\sim 01000001_2 \rightarrow 10111110_2$
  - **~0x00 → 0xFF**
    - $\sim 00000000_2 \rightarrow 11111111_2$
  - **0x69 & 0x55 → 0x41**
    - $01101001_2 \;\&\; 01010101_2 \rightarrow 01000001_2$
  - **0x69 | 0x55 → 0x7D**
    - $01101001_2 \mid 01010101_2 \rightarrow 01111101_2$

Contrast: Logic Operations in C

These are not bitwise, so don’t confuse them

- &&, ||, !
  - View 0 as “False”
  - Anything nonzero as “True”
  - Always return 0 or 1
  - Early termination (e.g., 0 && 1 && 1)

Examples (char data type)

!0x41 → 0x00
!0x00 → 0x01
!!0x41 → 0x01

0x69 && 0x55 → 0x01
0x69 || 0x55 → 0x01

Shift Operations

Left Shift: x << y

Shift bit-vector **x** left **y** positions

Throw away extra bits on left

Fill with 0's on right

Argument x	**01100010**
<< 3	**00010*000***

Argument x	**10100010**
<< 3	**00010*000***

Shift Operations

Left Shift: x << y

Shift bit-vector **x** left **y** positions

Throw away extra bits on left

Fill with 0's on right

Right Shift: x >> y

Shift bit-vector **x** right **y** positions

Throw away extra bits on right

Logical shift:

Fill with 0's on left

Argument x	01100010
<< 3	00010***000***
Log. >> 2	***00***011000

Argument x	10100010
<< 3	00010***000***
Log. >> 2	***00***101000

Shift Operations

Left Shift: x << y

- Shift bit-vector **x** left **y** positions
  - Throw away extra bits on left
  - Fill with 0's on right

Argument x	01100010
<< 3	00010***000***
Log. >> 2	***00***011000
Arith. >> 2	***00***011000

Right Shift: x >> y

- Shift bit-vector **x** right **y** positions
  - Throw away extra bits on right

Logical shift:

- Fill with 0's on left

Arithmetic shift

- Replicate most significant bit on left

Argument x	10100010
<< 3	00010***000***
Log. >> 2	***00***101000
Arith. >> 2	***11***101000

Shift Operations

Left Shift: x << y

- Shift bit-vector **x** left **y** positions
  - Throw away extra bits on left
  - Fill with 0's on right

Argument x	01100010
<< 3	00010***000***
Log. >> 2	***00***011000
Arith. >> 2	***00***011000

Right Shift: x >> y

- Shift bit-vector **x** right **y** positions
  - Throw away extra bits on right

Argument x	10100010
<< 3	00010***000***
Log. >> 2	***00***101000
Arith. >> 2	***11***101000

- Logical shift:
  - Fill with 0's on left
- Arithmetic shift
  - Replicate most significant bit on left

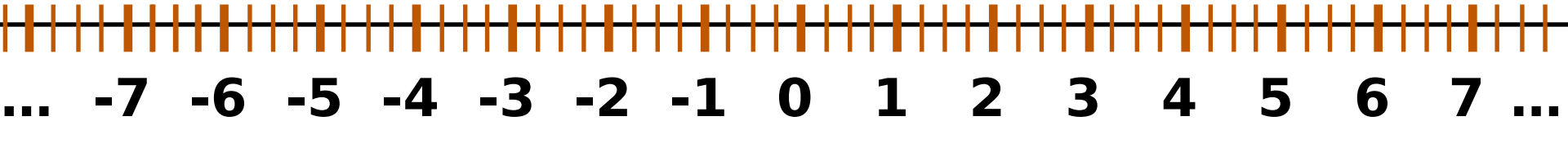
Undefined Behavior

- Shift amount < 0 or ≥ total amount of bits

Integers

Representing Numbers in Binary

- Different types of number
  - Integer (Negative and Non-negative)
  - Fractions
  - Irrationals



Encoding Negative Numbers

So far we have been discussing non-negative numbers: (called unsigned integers)

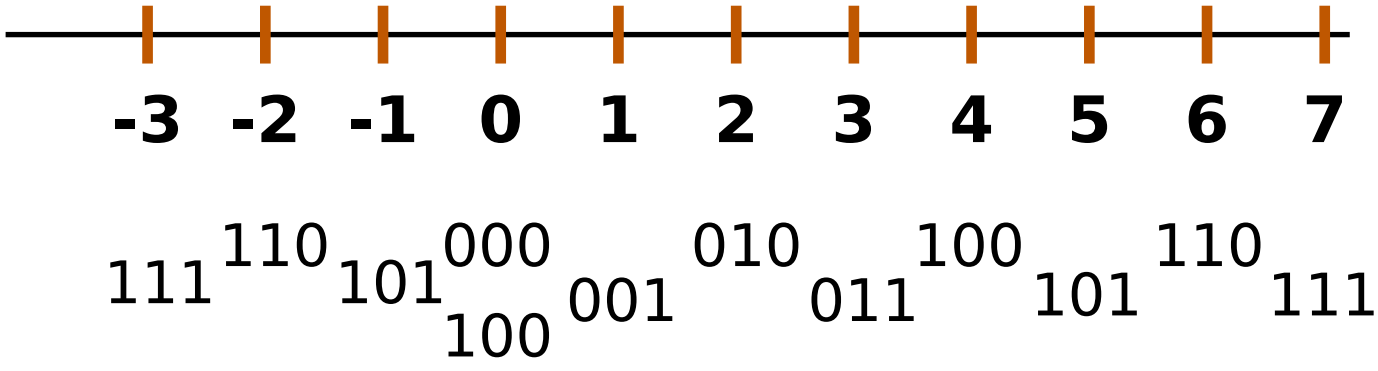
How about negative numbers?

Encoding Negative Numbers

Solution 1: Sign-magnitude

First bit represents sign; 0 for positive; 1 for negative

The rest represents magnitude



Sign-Magnitude Implications

- Bits have different semantics
- Two zeros…

```
   010
+) 101
```

```
    2
+) -1
```

Signed Value	Binary
0	000
1	001
2	010
3	011
-0	100
-1	101
-2	110
-3	111

Sign-Magnitude Implications

- Bits have different semantics
- Two zeros…
- Normal arithmetic doesn't work which would make hardware design harder

```
  010
+) 101
-----
  111
```

```
   2
+) -1
-----
  -3
```

Signed Value	Binary
0	000
1	001
2	010
3	011
-0	100
-1	101
-2	110
-3	111

Encoding Negative Numbers

Solution 2: Two's Complement

Instead of the msb simply being a sign bit, just interpret that place as a negative value

Signed Weight	Unsigned Weight	Bit Position
2^0	2^0	0
2^1	2^1	1
-2^2	2^2	2

$101_2 = 1*2^0 + 0*2^1 - 1*2^2 = -3_{10}$

Signed	Unsigned	Binary
0	0	000
1	1	001
2	2	010
3	3	011
-4	4	100
-3	5	101
-2	6	110
-1	7	111

Two’s Complement

For example,

What is 10010111_2?

1 0 0 1 0 1 1 1

Two’s Complement

For example,

What is 10010111_2?

1	**0**	**0**	**1**	**0**	**1**	**1**	**1**
-128	64	32	**16**	8	**4**	**2**	**1**

-128 + 16 + 4 + 2 + 1 = -105

Two’s Complement

$10010111_2 = -105$

It’s very easy to invert a two’s complement number

Two’s Complement

$10010111_2 = -105$

It’s very easy to invert a two’s complement number

Just flip all the bits

and add 1:

Two’s Complement

$10010111_2 = -105$

It’s very easy to invert a two’s complement number

Just flip all the bits

01101000

and add 1:

$01101001_2 = 105$

Two’s Complement

$10010111_2 = -105$

It’s very easy to invert a two’s complement number

Just flip all the bits

01101000

and add 1:

$01101001_2 = 105$

To go back, do the same thing (really!):

$10010111_2 = -105$

Two-Complement Encoding Example

```
x =      15213: 00111011 01101101
y =     -15213: 11000100 10010011
```

Weight	15213		-15213	
1	1	1	1	1
2	0	0	1	2
4	1	4	0	0
8	1	8	0	0
16	0	0	1	16
32	1	32	0	0
64	1	64	0	0
128	0	0	1	128
256	1	256	0	0
512	1	512	0	0
1024	0	0	1	1024
2048	1	2048	0	0
4096	1	4096	0	0
8192	1	8192	0	0
16384	0	0	1	16384
-32768	0	0	1	-32768
Sum		**15213**		**-15213**

Two’s-Complement Implications

Only 1 zero!

Usual arithmetic still works!

There is a bit that tells us the sign!

Most widely used in today’s machines

Signed	Binary
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

```
   010          2
+) 101       +) -3
-----        ----
   111          -1
```

Numeric Ranges

Unsigned Values

UMin = 0

000…0

UMax = $2^w - 1$

111…1

Two's Complement Values

- *TMin* = -2^{w-1}

  100…0

- *TMax* = $2^{w-1} - 1$

  011…1

Values for *W* = 16

	Decimal	Hex	Binary
UMax	**65535**	**FF FF**	**11111111 11111111**
TMax	**32767**	**7F FF**	**01111111 11111111**
TMin	**-32768**	**80 00**	**10000000 00000000**
-1	**-1**	**FF FF**	**11111111 11111111**
0	**0**	**00 00**	**00000000 00000000**

Data Representations in C (in Bytes)

By default variables are signed

Unless explicitly declared as unsigned (e.g., `unsigned int`)

Signed variables use two-complement encoding

C Data Type	32-bit	64-bit
`char`	1	1
`short`	2	2
`int`	4	4
`long`	4	8

Data Representations in C (in Bytes)

	W			
	8	16	32	64
UMax	255	65,535	4,294,967,295	18,446,744,073,709,551,615
TMax	127	32,767	2,147,483,647	9,223,372,036,854,775,807
TMin	-128	-32,768	-2,147,483,648	-9,223,372,036,854,775,808

C Data Type	32-bit	64-bit
char	1	1
short	2	2
int	4	4
long	4	8

C Language

`#include <limits.h>`

Declares constants, e.g.,

- `ULONG_MAX`
- `LONG_MAX`
- `LONG_MIN`

Values platform specific