CSC 252: Computer Organization
Spring 2025: Lecture 2

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Announcement

- Make sure you can access CSUG machines!!!
- Programming assignment 1 will be posted this week.
    - I will send an announcement when it's out.
    - It is in C language. Seek help from TAs.
    - TAs are best positioned to answer your questions about programming assignments!!!
- Programming assignments do NOT repeat the lecture materials. They ask you to synthesize what you have learned from the lectures and work out something new.

Previously in 252…

Problem

Algorithm

Circuit

- How is a human-readable program translated to a repre
com
unde
- How
mod
exec
prog

:t
e and

	Renting
Service provider	Landlord
Service receiver	YOU
Contract	Lease
Contract's language	Natural language (e.g., English)

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 *Executable Binary*

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

```
00011001  …
01101010  …
11010101  …
01110001  …
```

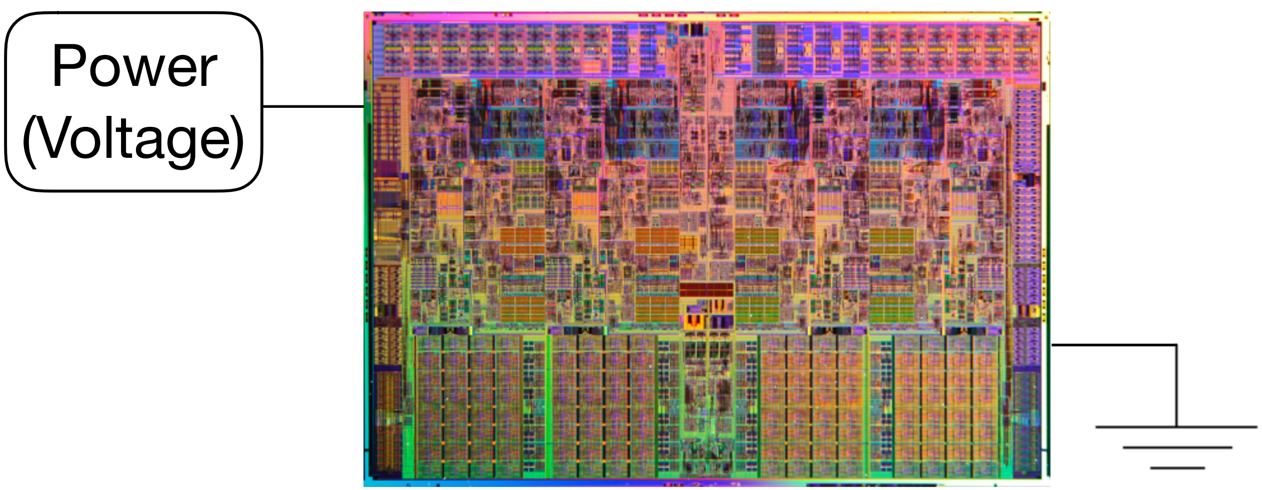
- What's the difference between an assembly program and an executable binary?
  - They refer to the same thing — a list of instructions that the software asks the hardware to perform
  - They are just different representations
- Instruction = Operator + Operand(s)

Today: Representing Information in Binary

- Why Binary (bits)?
- Bit-level manipulations
- Integers
  - Representation: unsigned and signed
  - Conversion, casting
  - Expanding, truncating
  - Addition, negation, multiplication, shifting

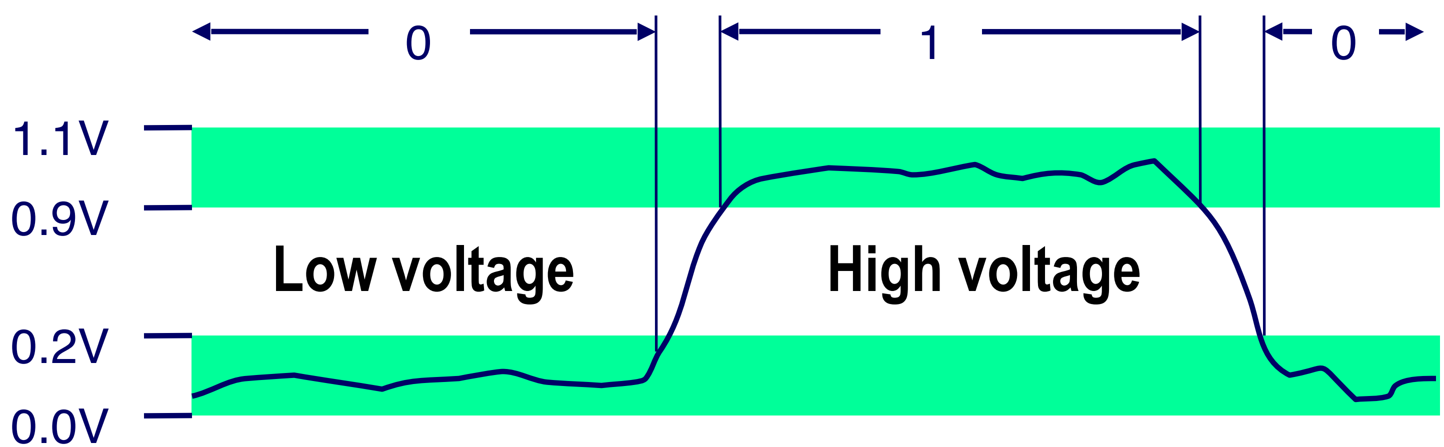
Everything in Computers is bits

- 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



Everything in Computers 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
  - Use high voltage to represent 1
  - Use low voltage to represent 0



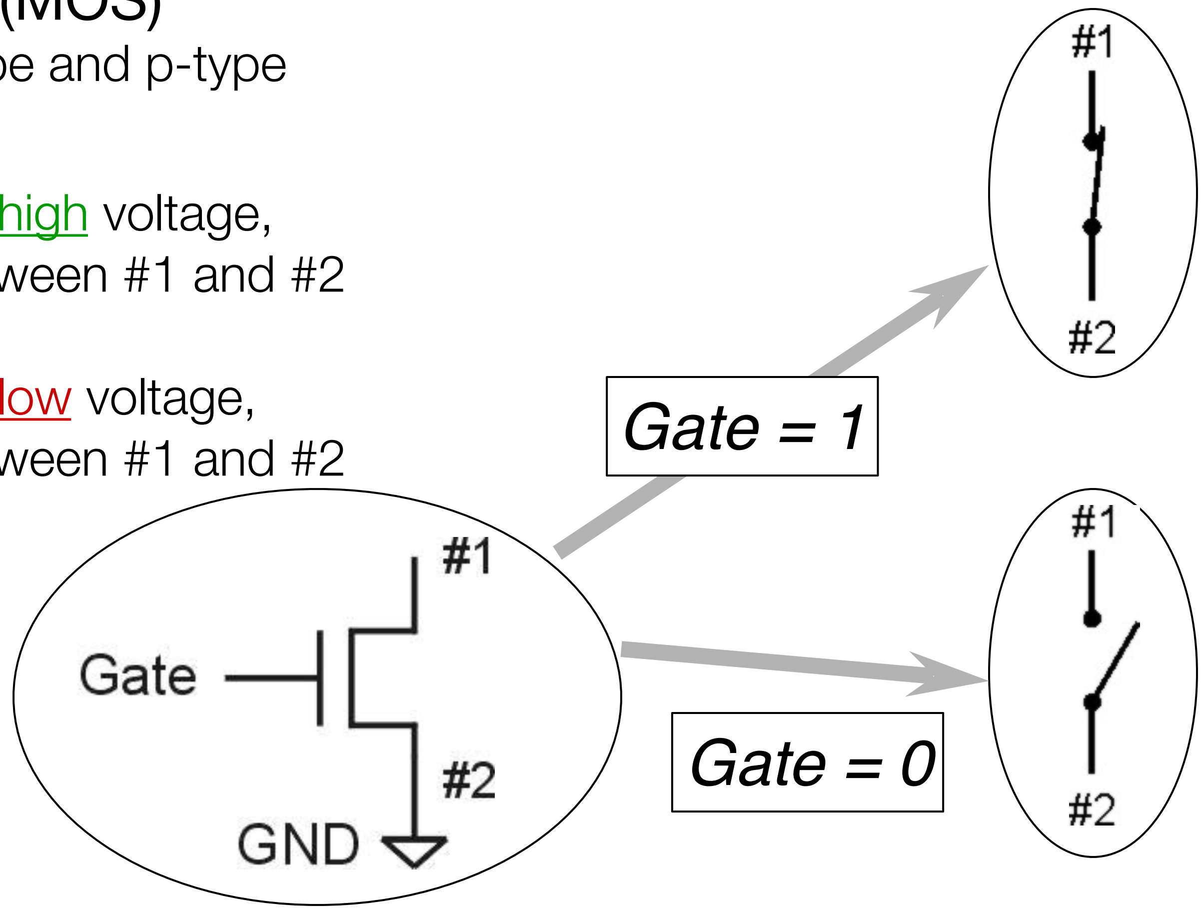
Why Bits?

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)

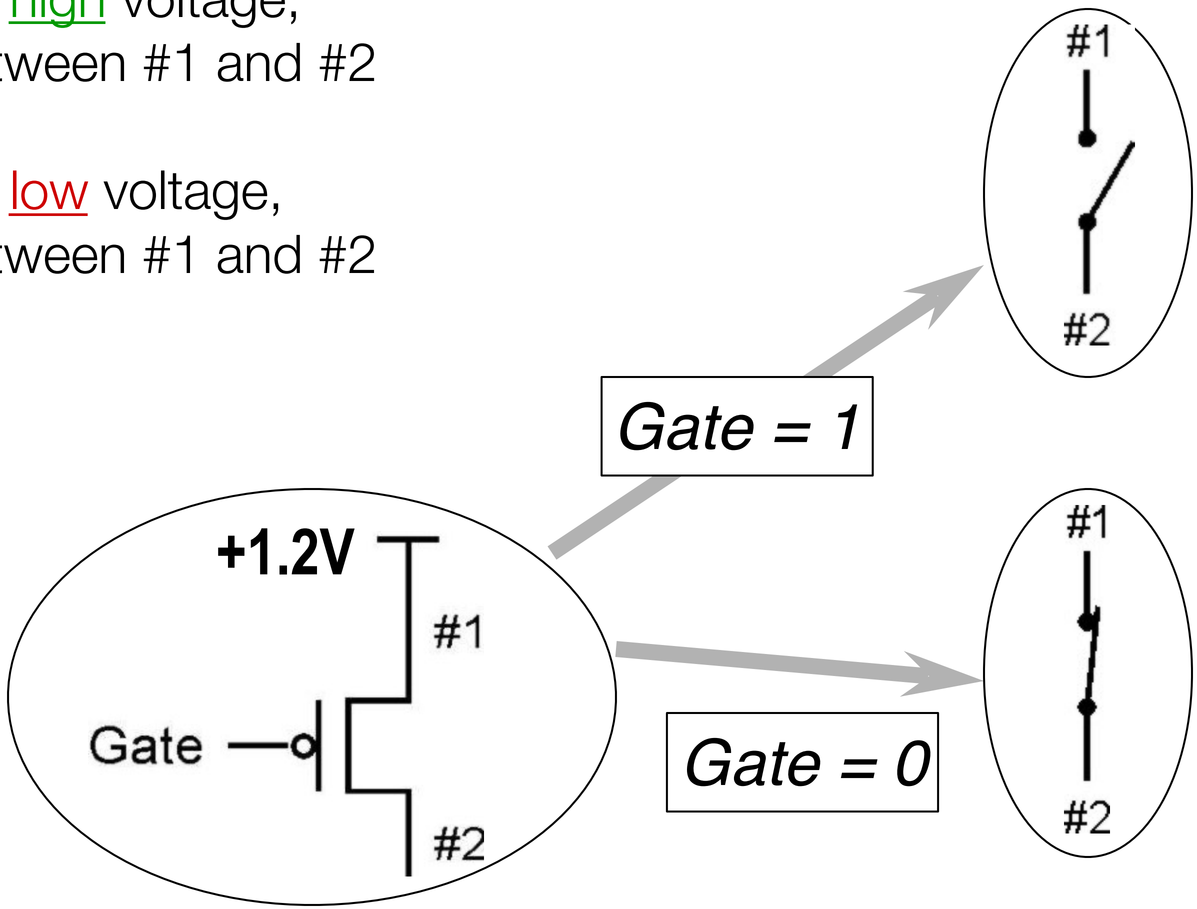


Terminal #2 must be connected to GND (0V).

Why Bits?

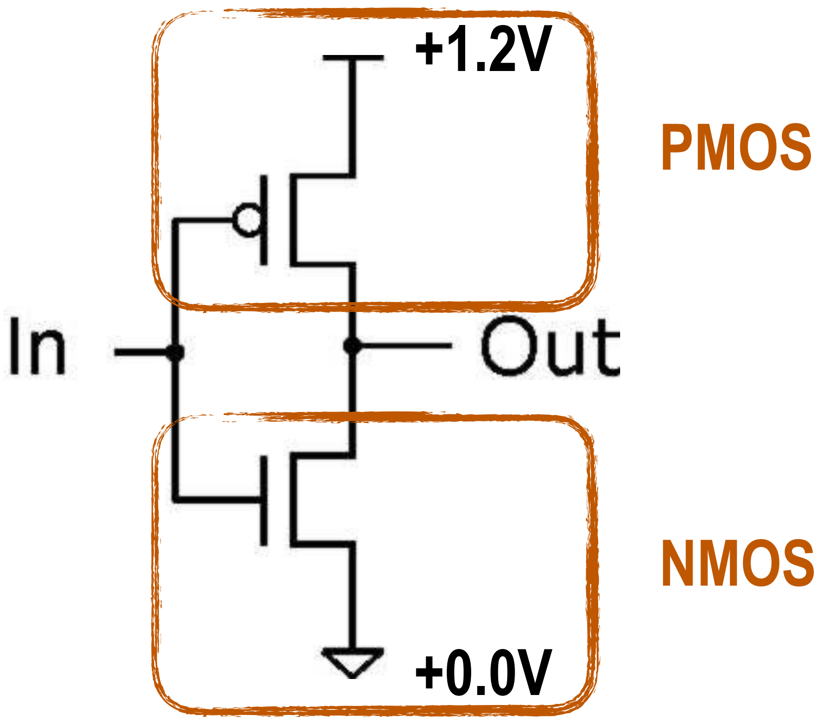
p-type is *complementary* to n-type (PMOS)

- 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)

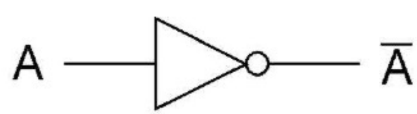


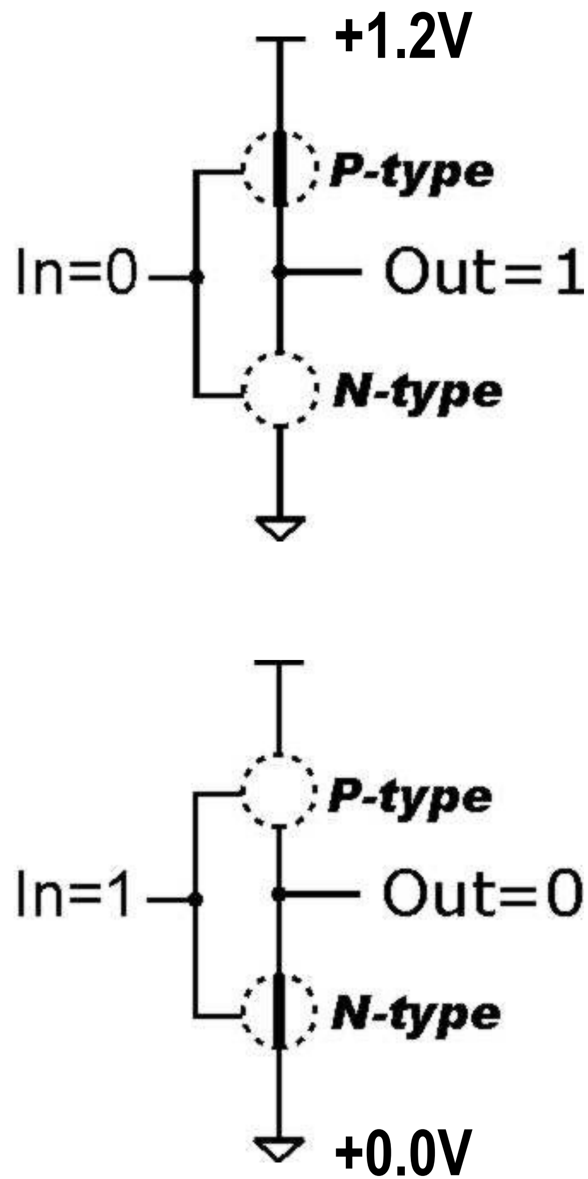
Terminal #1 must be connected to +1.2V

Inverter

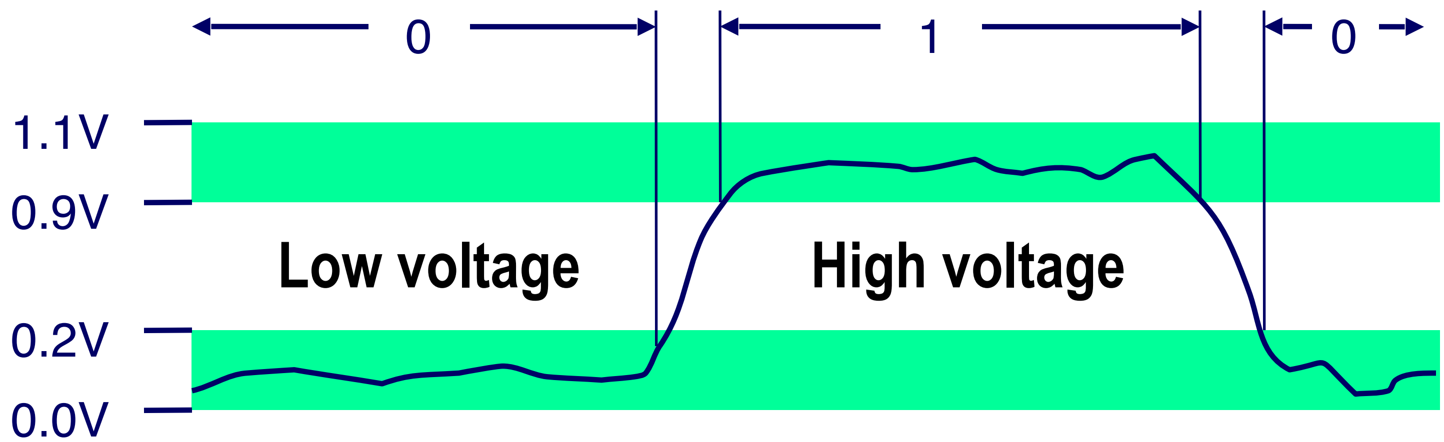


In	Out
0	1
1	0

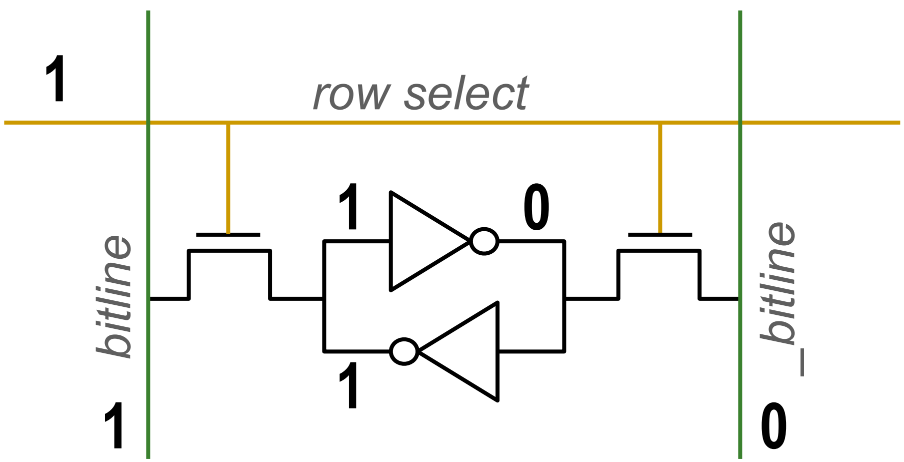




Store/Access Data

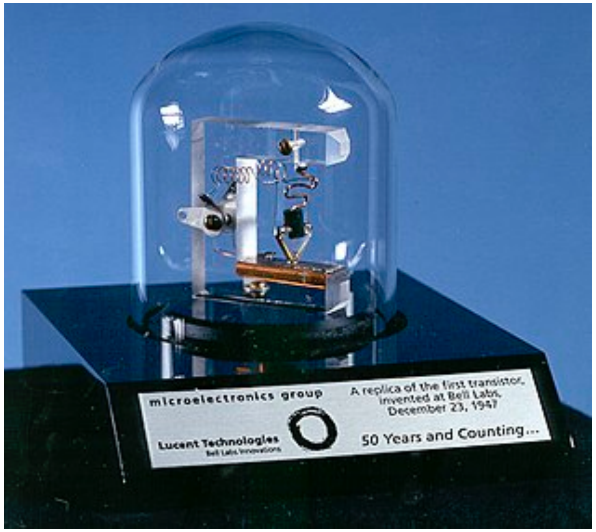


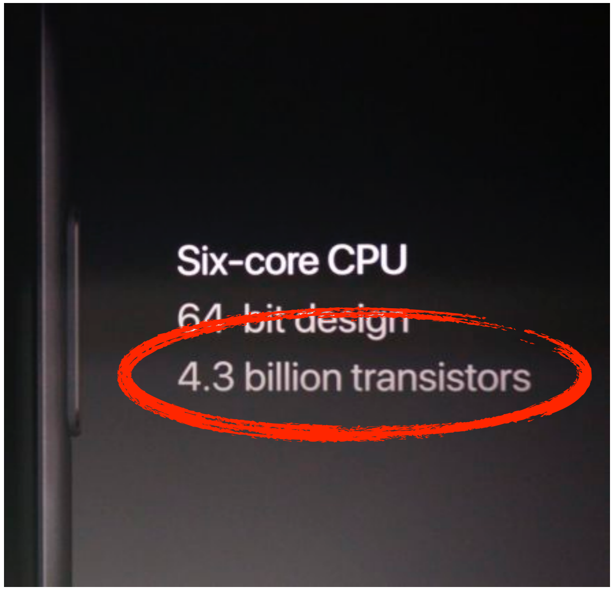
- Two cross coupled inverters store a single bit
  - Feedback path persists the value in the “cell”
  - 4 transistors for storage
  - 2 transistors for access
  - A “6T” cell



Transistors

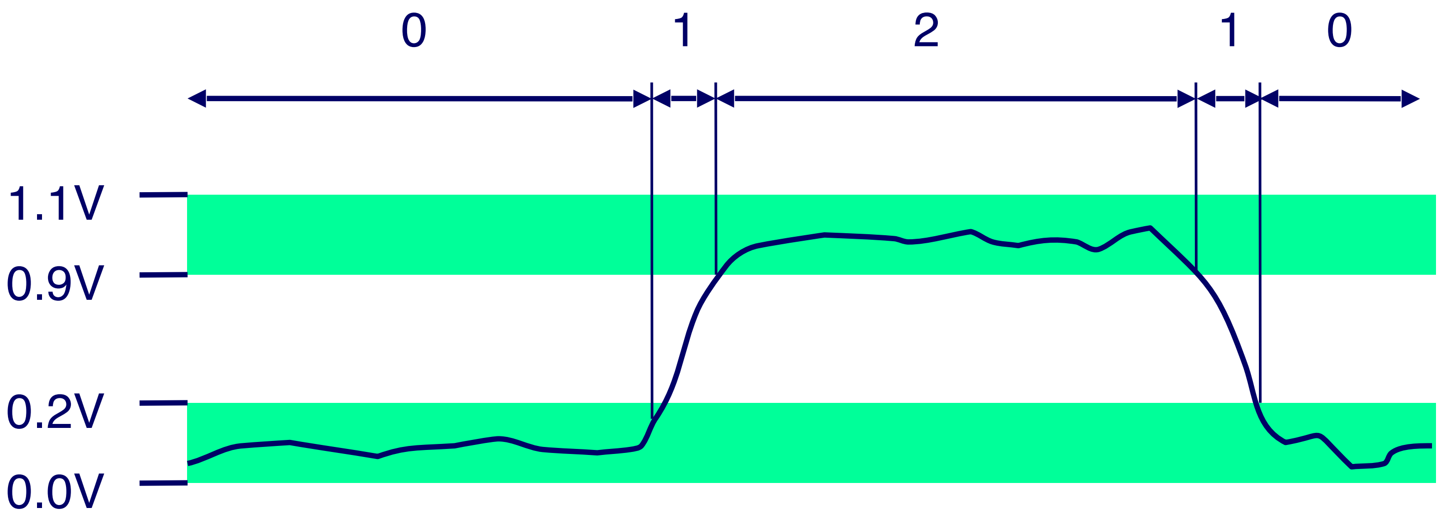
- Computers are made of transistors
- Transistors have become smaller over the years
    - Not so much anymore…





Why Limit Ourselves Only to Binary?

- Voltage is continuous. Why interpret it only as 0s and 1s?
- Answer: Noise



Binary Notation

- Base 2 Number Representation (Binary)
- C.f., Base 10 number representation (Decimal)
- $21_{10} = 1*10^0 + 2*10^1 = 21$
- 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

Hexdecimal (Hex) Notation

- Base 16 Number Representation
  - Use characters ‘0’ to ‘9’ and ‘A’ to ‘F’
  - Four bits per Hex digit
  - $11111110_2 = FE_{16}$
- Write $FA1D37B_{16}$ in C as
  - 0xFA1D37B
  - 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

Bit, Byte, Word

- 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)

10110111

MSb **LSb**

- Word = 4 Bytes (32-bit machine) / 8 Bytes (64-bit machine)
  - Least Significant Byte (LSB) vs. Most Significant Byte (MSB)

Today: Representing Information in Binary

- Why Binary (bits)?
- Bit-level manipulations
- Integers
  - Representation: unsigned and signed
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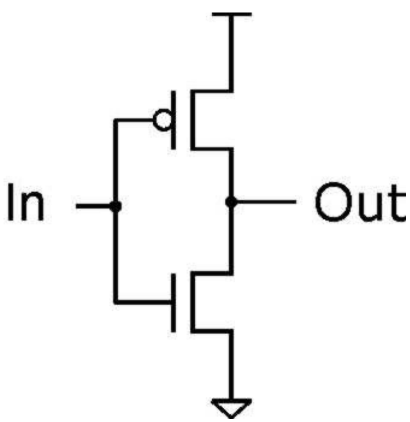
Bit-level manipulations

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

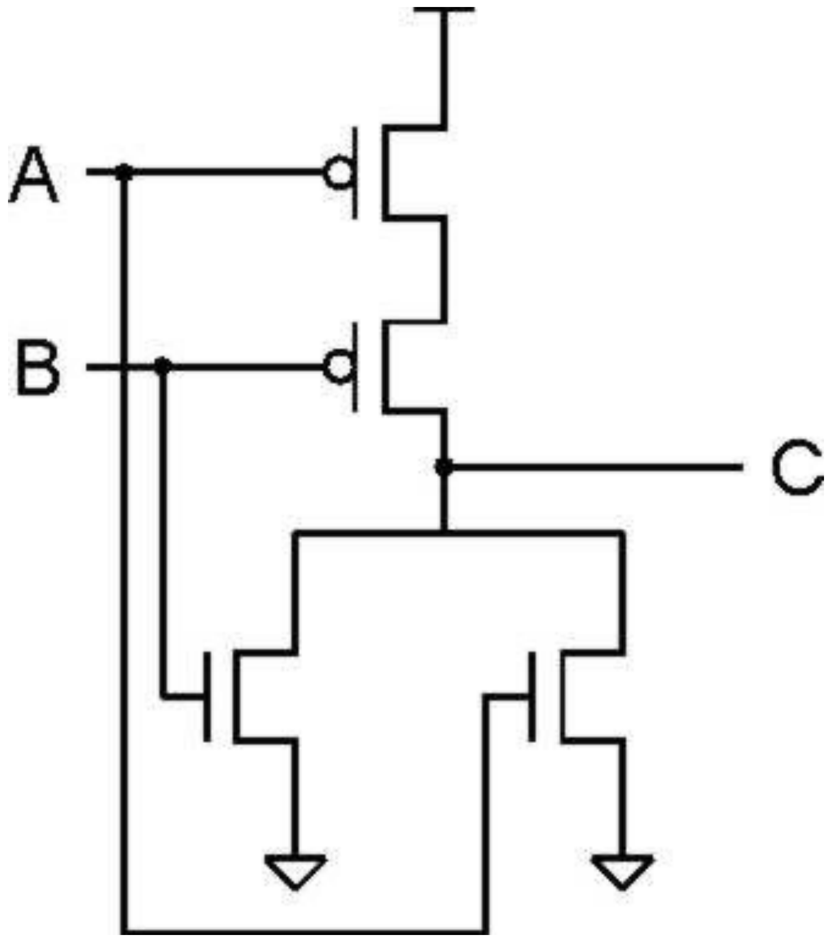
&	0	1
0	0	0
1	0	1

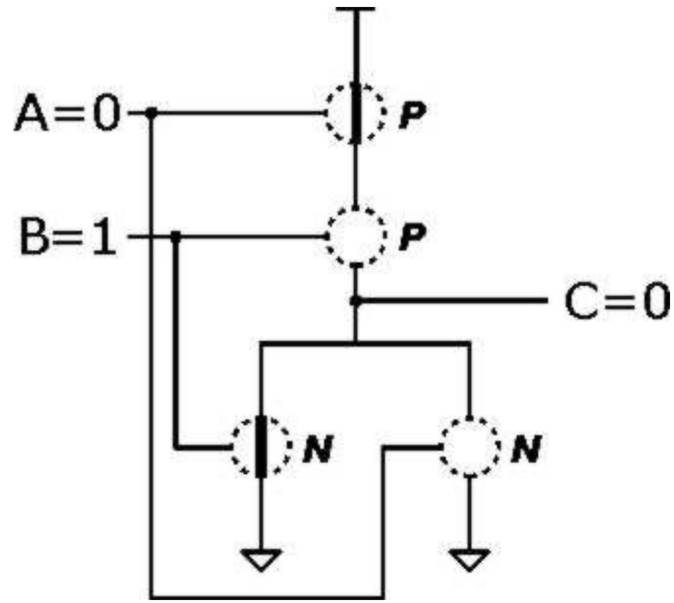
Exclusive-Or (Xor)

- 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

```
  01101001      01101001      01101001
& 01010101    | 01010101    ^ 01010101    ~ 01010101
  --------      --------      --------      --------
  01000001      01111101      00111100      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`
    - $01101001_2 \mid 01010101_2 \rightarrow 01111101_2$

Aside: Logic Operations in C

- Contrast to Logical Operators
  - `&&`, `||`, `!`
    - 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`
  - `p && *p` (avoids null pointer access)

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
  - Arithmetic shift
    - Replicate most significant bit on left
- Undefined Behavior
  - Shift amount < 0 or ≥ total amount of bits

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

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

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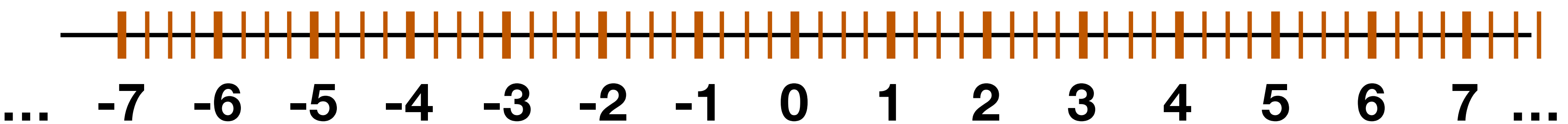
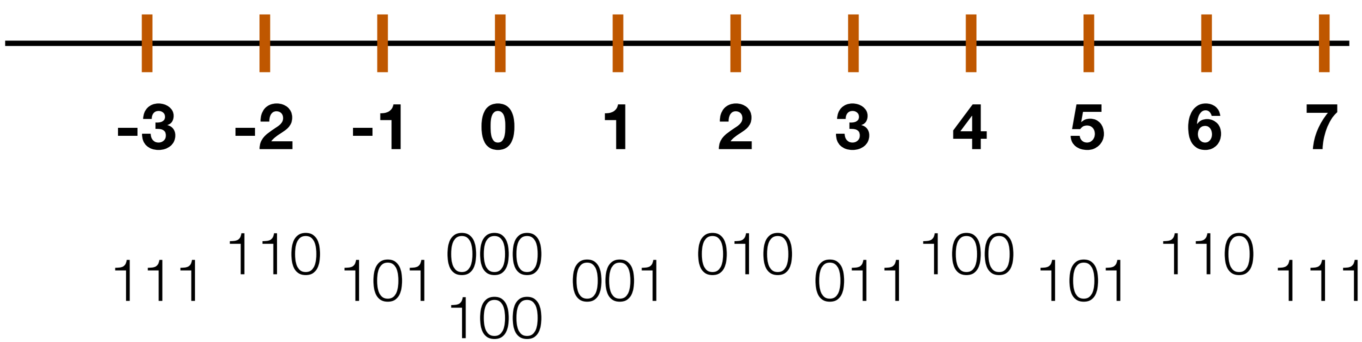
Representing Numbers in Binary

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



Encoding Negative Numbers

- So far we have been discussing non-negative numbers: so called unsigned. How about negative numbers?
- Solution 1: Sign-magnitude
  - First bit represents sign; 0 for positive; 1 for negative
  - The rest represents magnitude



Sign-Magnitude Implications

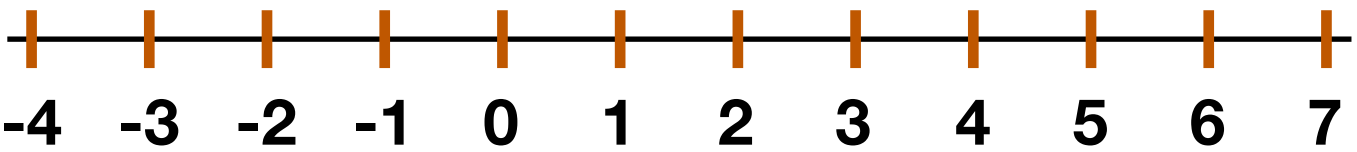
- Bits have different semantics
  - Two zeros…
  - Normal arithmetic doesn't work
  - Make hardware design harder

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

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

Encoding Negative Numbers

- Solution 2: Two's Complement



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

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

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

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-Complement Implications

- Only 1 zero
- Usual arithmetic still works
- There is a bit that represents 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
+)  101
-------
    111
```

```
      2
+)   -3
-------
     -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
- Other Values
  - Minus 1
    111…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
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`int`	4	4
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- C Language
  - `#include <limits.h>`
  - Declares constants, e.g.,
    - `ULONG_MAX`
    - `LONG_MAX`
    - `LONG_MIN`
  - Values platform specific