

CSC 252: Computer Organization

Spring 2020: Lecture 2

Instructor: Yuhao Zhu

Department of Computer Science
University of Rochester

Action Items:

- **Programming Assignment 1 is out**

Announcement

- Programming Assignment 1 is out
 - Details: <https://www.cs.rochester.edu/courses/252/spring2020/labs/assignment1.html>
 - Due on Jan. 31, 11:59 PM
 - You have 3 slip days

19	20	21 Today	22	23	24	25
26	27	28	29	30	31 Due	Feb 1

Announcement

- TA office hours are all posted. Start from this week.
- Programming assignment 1 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

Program

Instruction Set
Architecture (ISA)

Microarchitecture

Circuit

Previously in 252...

Problem

Algorithm

Program

Instruction Set
Architecture (ISA)

ISA is the contract
between software and
hardware.

Microarchitecture

Circuit

Previously in 252...

Problem

Algorithm

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

Circuit

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e and

Previously in 252...

Problem

Algorithm

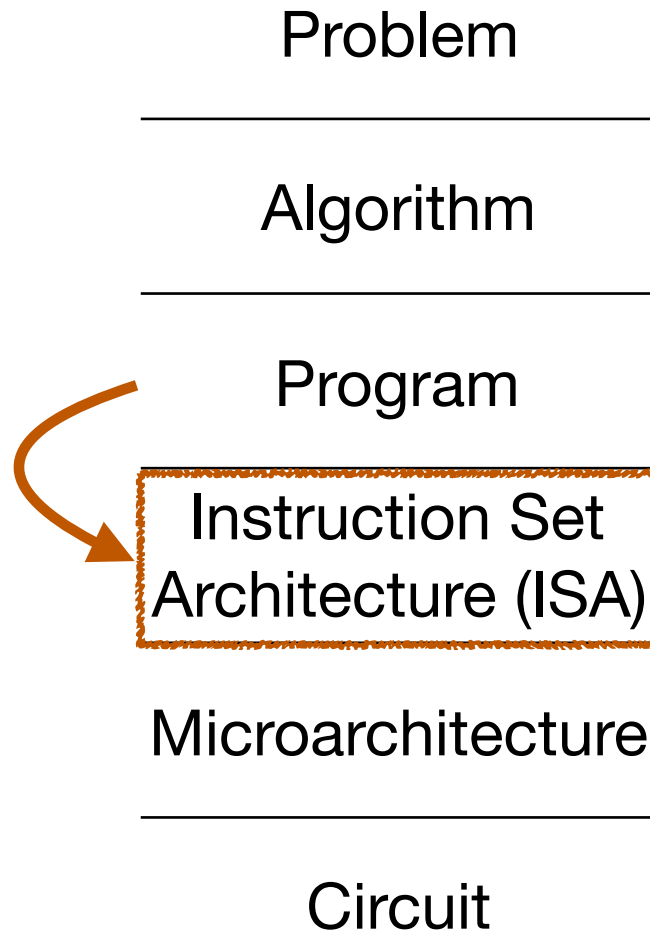
	Renting	Computing
Service provider	Landlord	Hardware
Service receiver	YOU	Software
Contract	Lease	Assembly Program
Contract's language	Natural language (e.g., English)	ISA

Circuit

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Previously in 252...

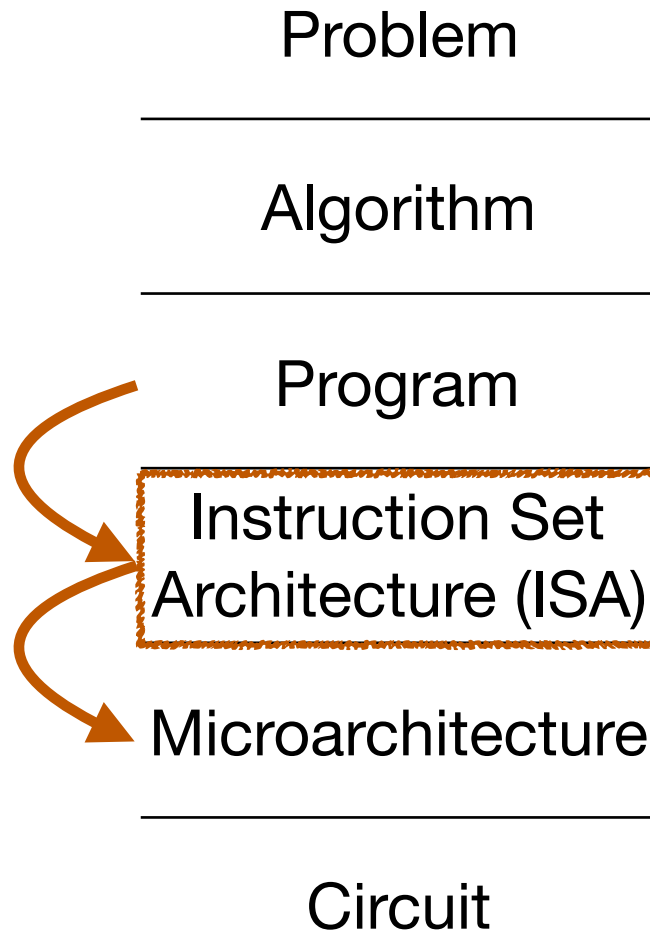
- How is a human-readable program translated to a representation that computers can understand?



ISA is the contract between software and hardware.

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?

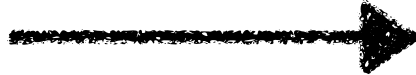


ISA is the contract between software and hardware.

Previously in 252...

C Program

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



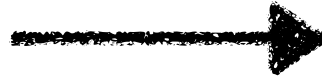
Assembly program

```
movl    $1, -4(%rbp)  
movl    $2, -8(%rbp)  
movl    -4(%rbp), %eax  
addl    -8(%rbp), %eax
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Previously in 252...

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Executable Binary

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00011001 ...
01101010 ...
11010101 ...
01110001 ...
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Previously in 252...

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Executable Binary

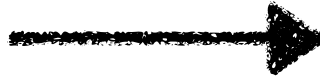
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- What's the difference between an assembly program and an executable binary?
 - They refer to the same thing — a list of instructions that the software asks the hardware to perform
 - They are just different representations
- **Instruction = Operator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

Previously in 252...

Assembly program

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Executable Binary

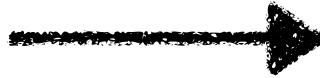
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- Instruction = Operator + Operand(s)

Today: Representing Information in Binary

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

Everything is bits

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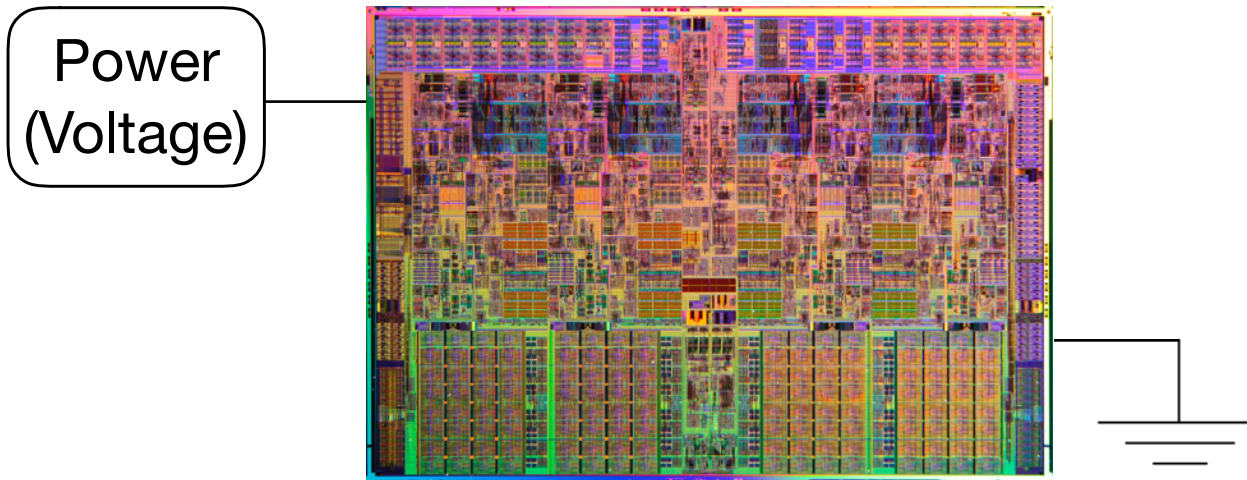
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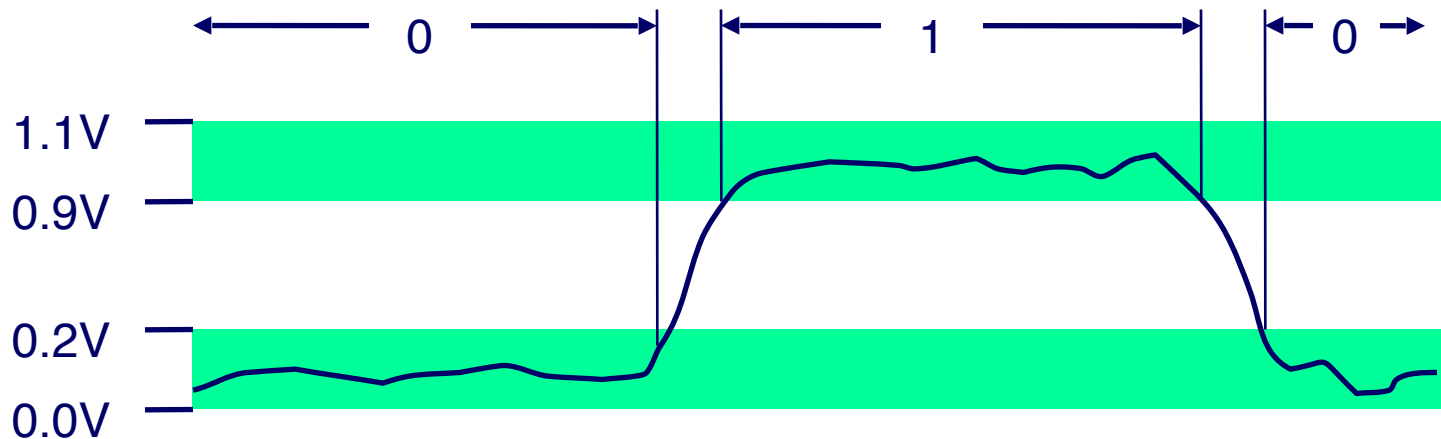
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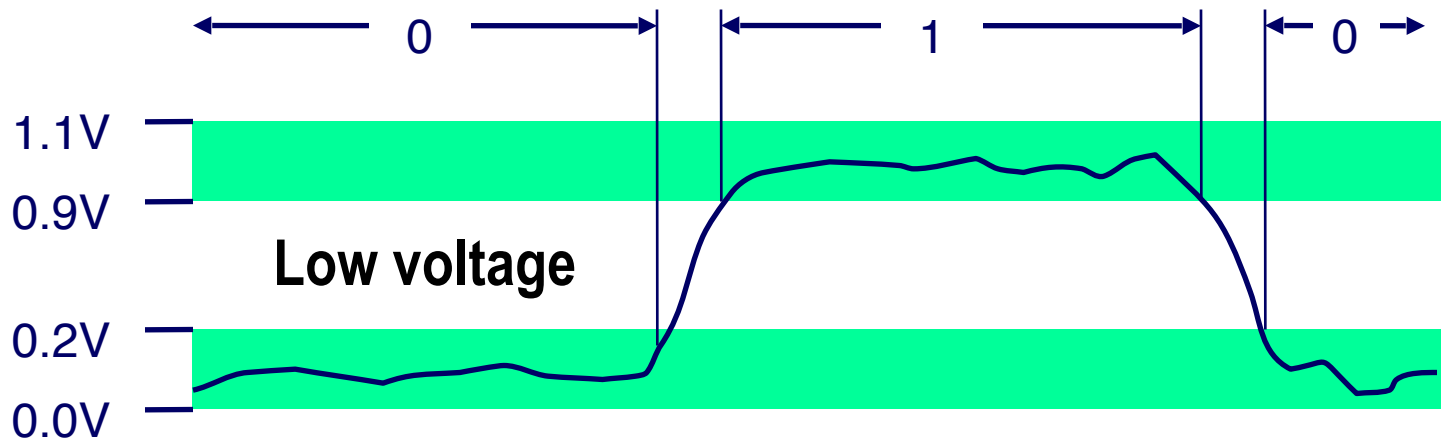
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 - Use high voltage to represent 1
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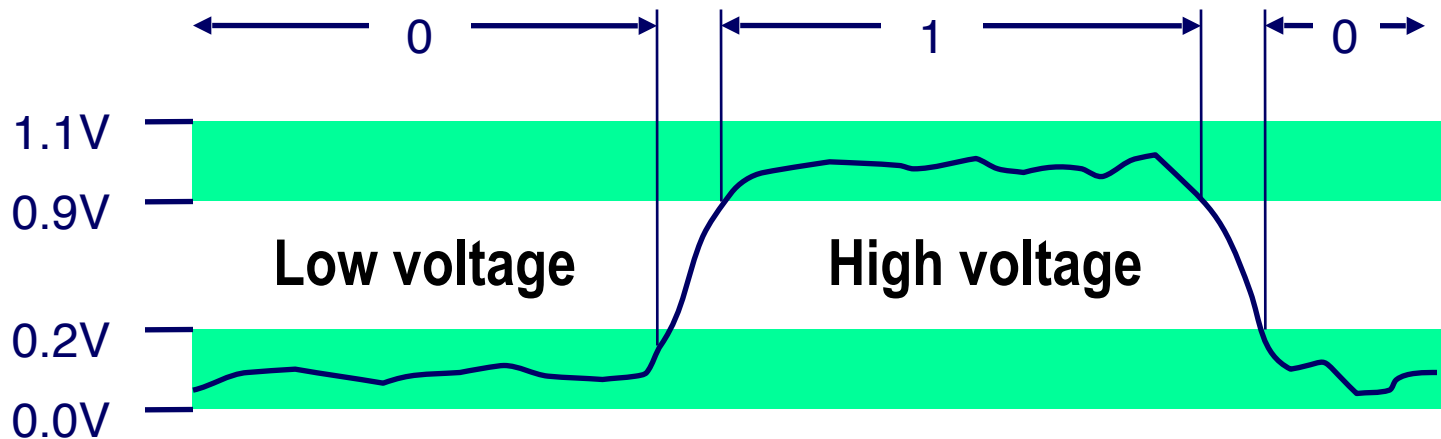
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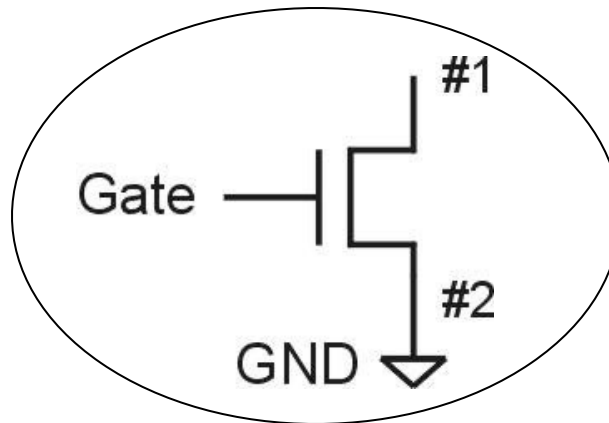
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Why Bits?

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

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n-type (NMOS)



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

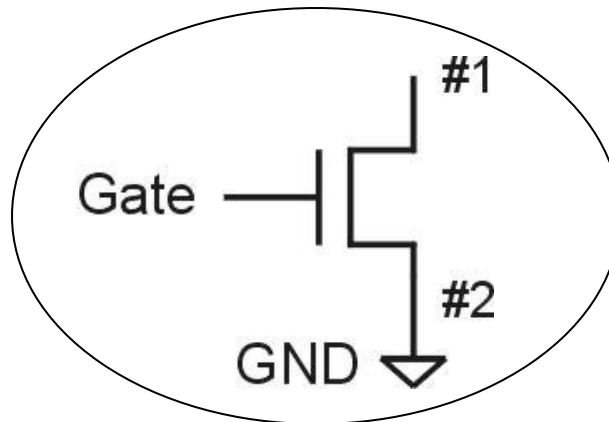
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n-type (NMOS)

- when Gate has high voltage,
short circuit between #1 and #2
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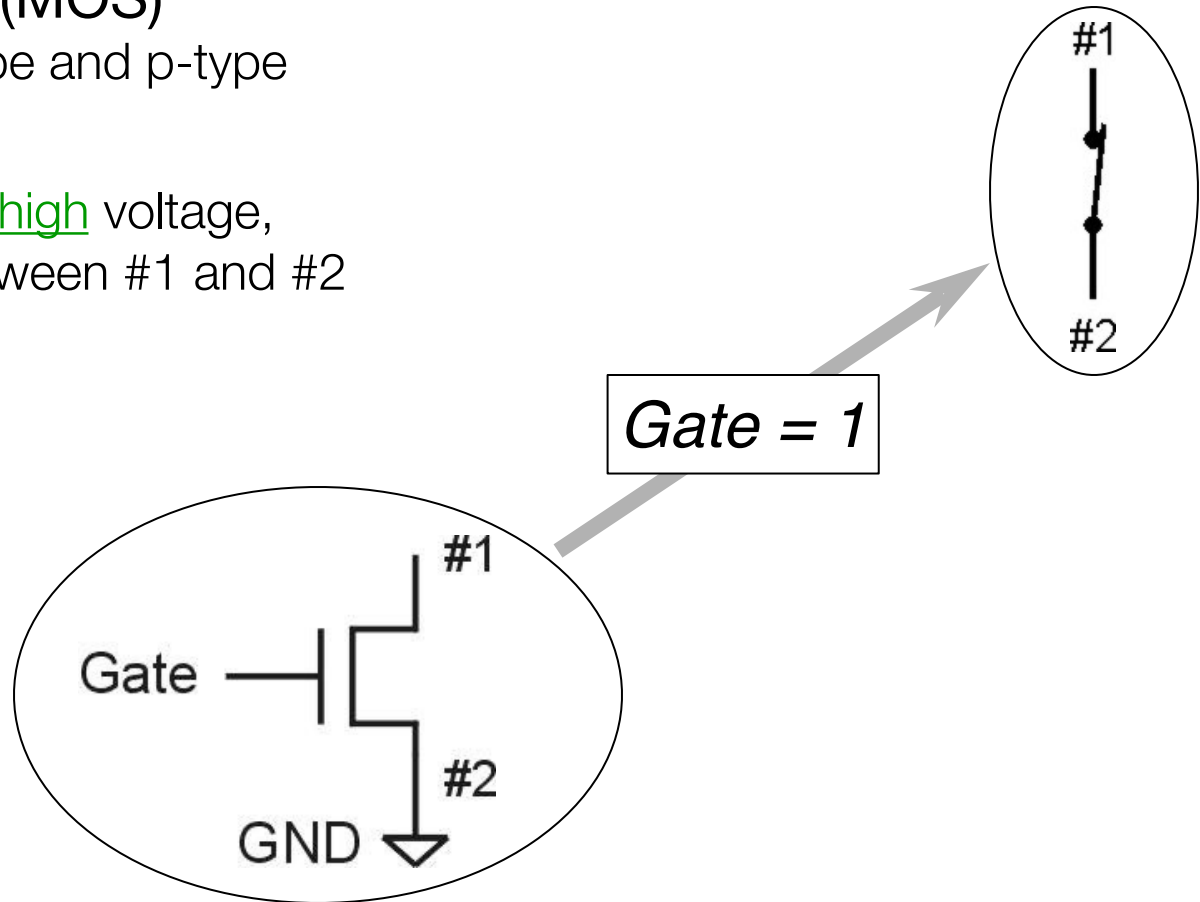
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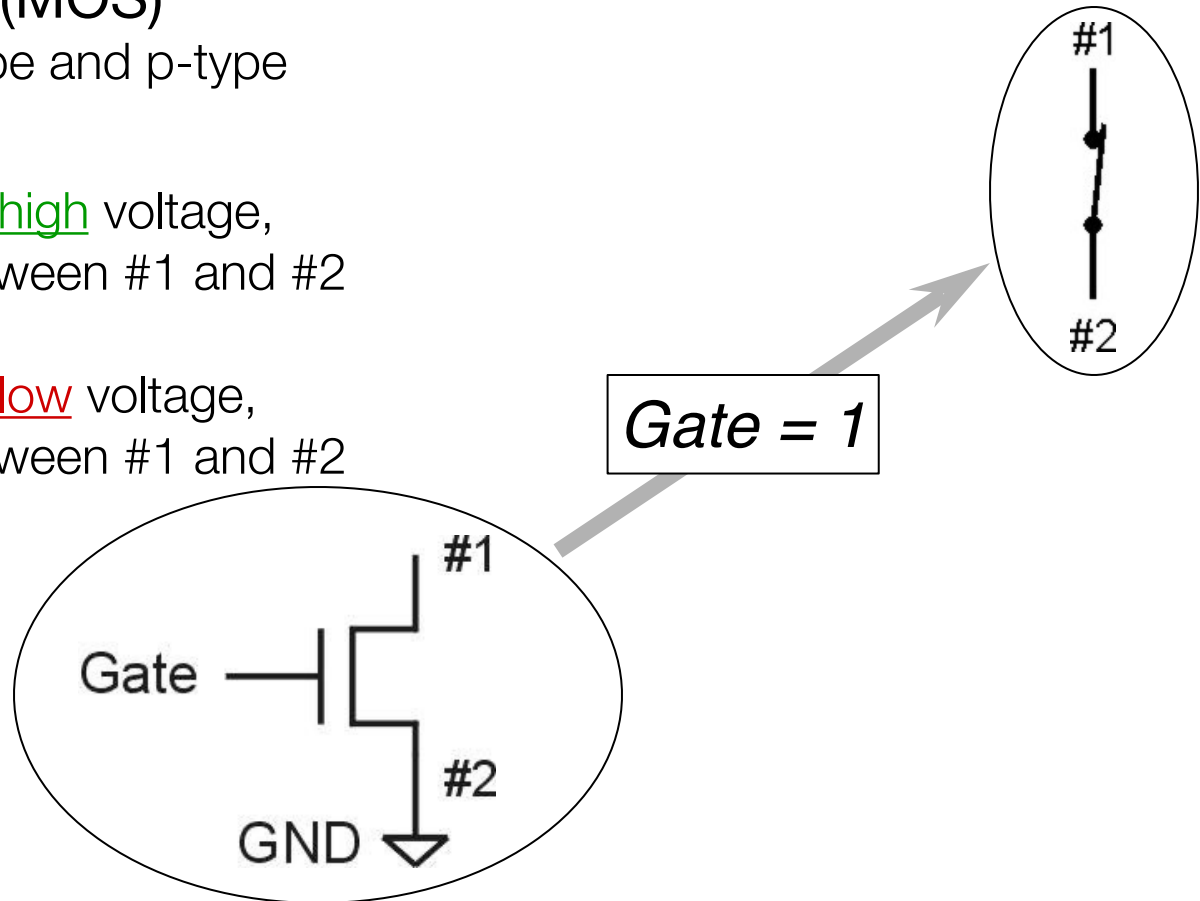
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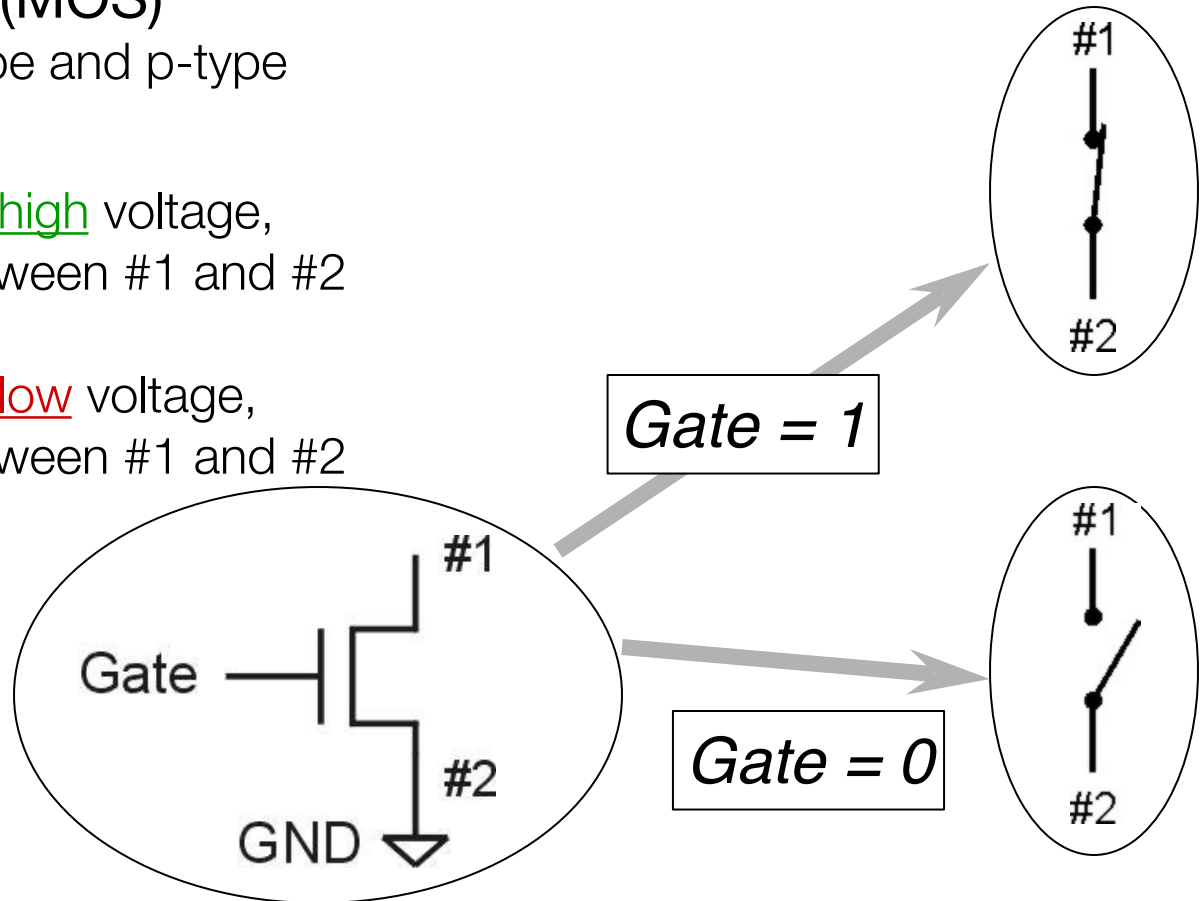
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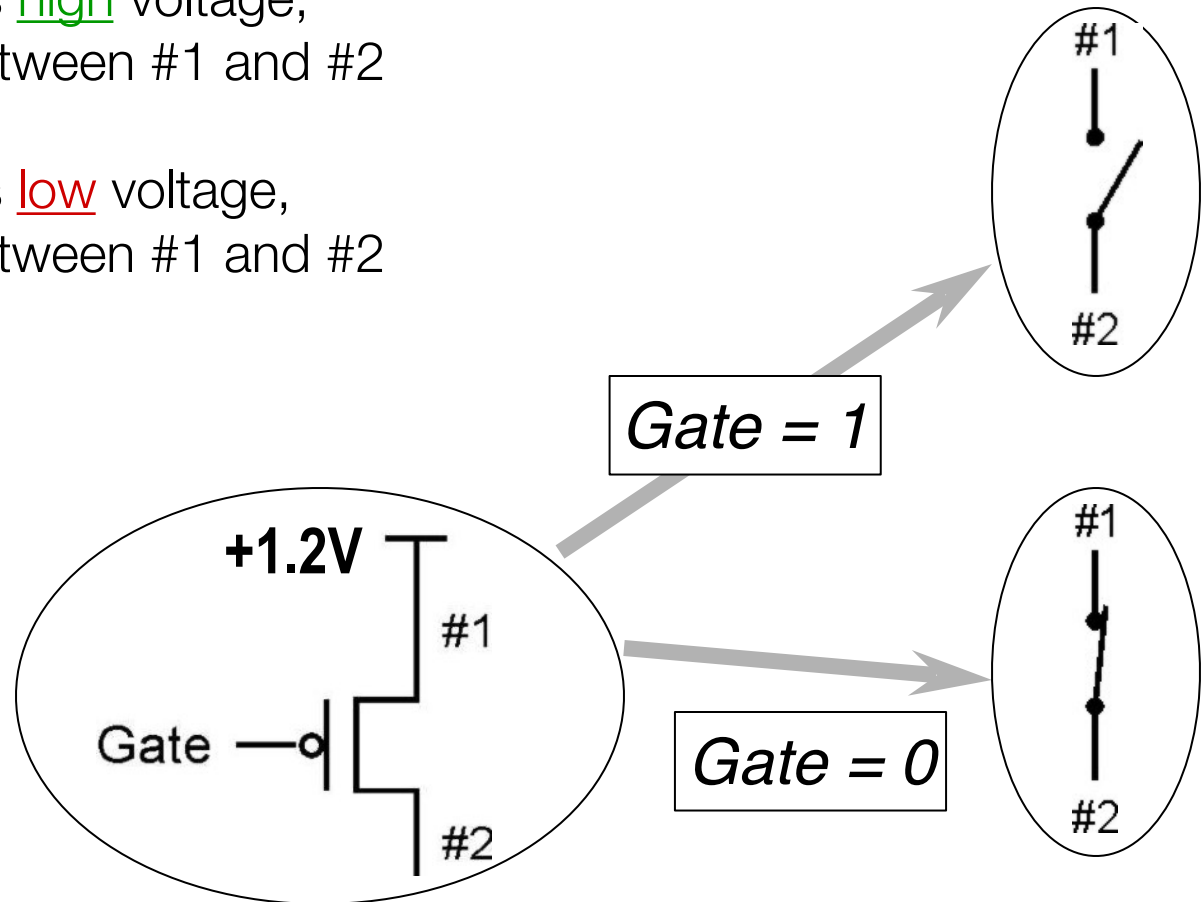


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Why Bits?

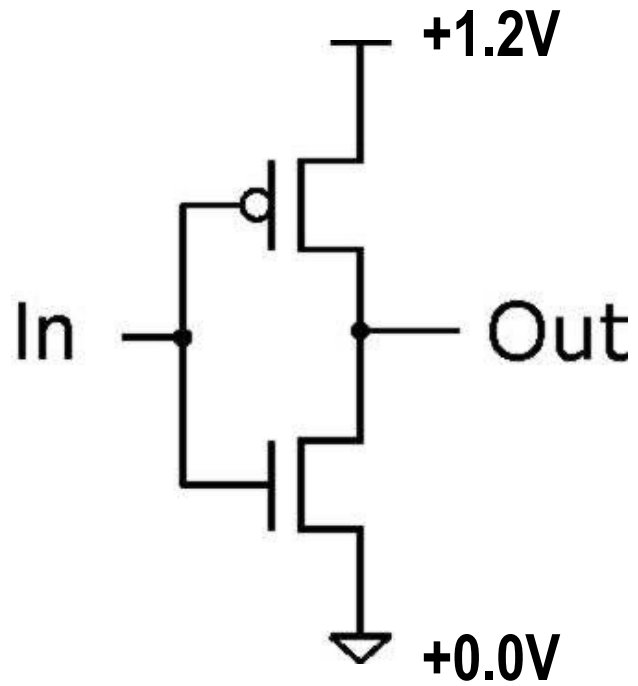
p-type is *complementary* to n-type (**PMOS**)

- 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)

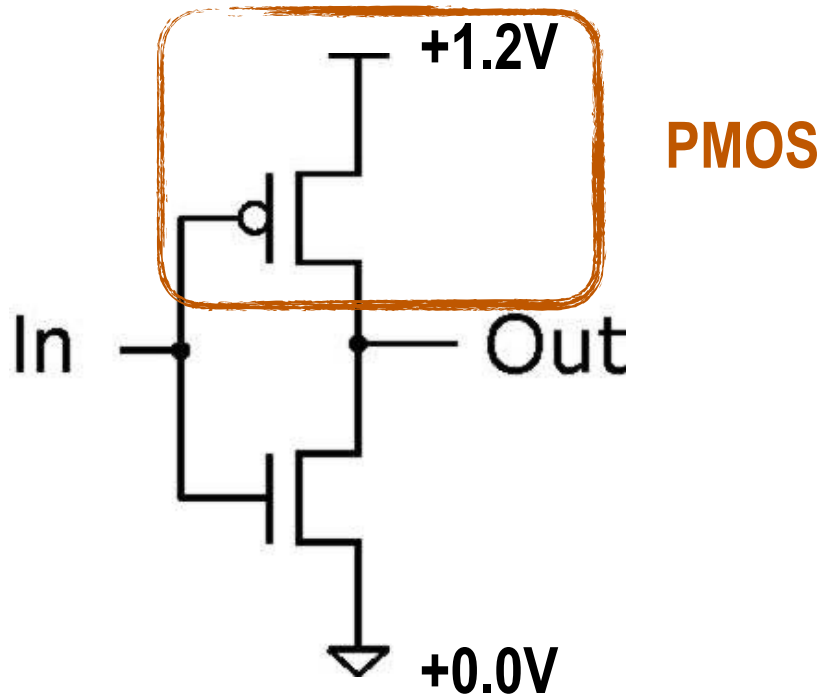


Terminal #1 must be connected to +1.2V

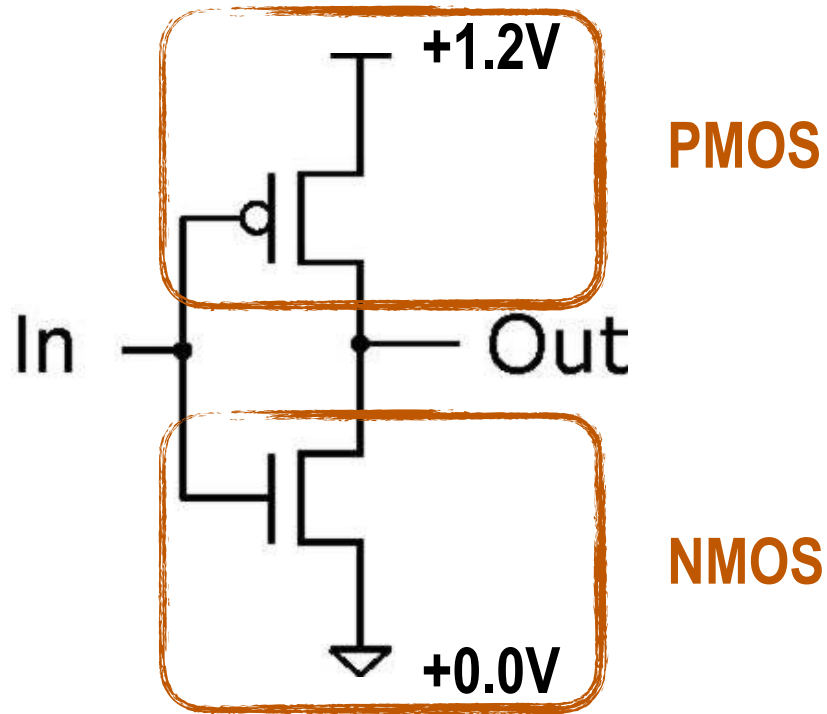
Inverter



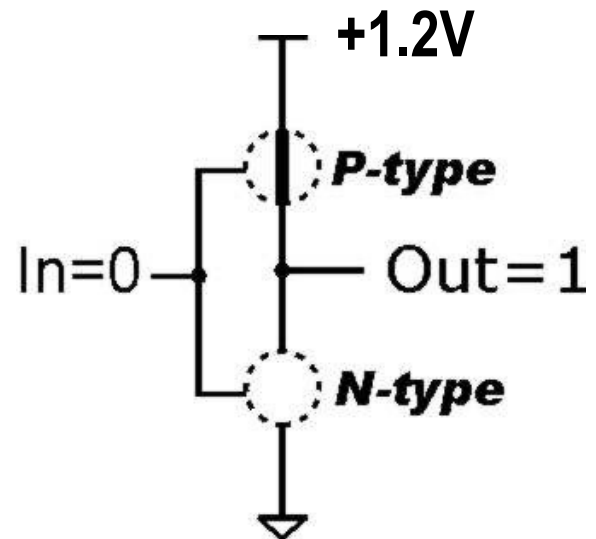
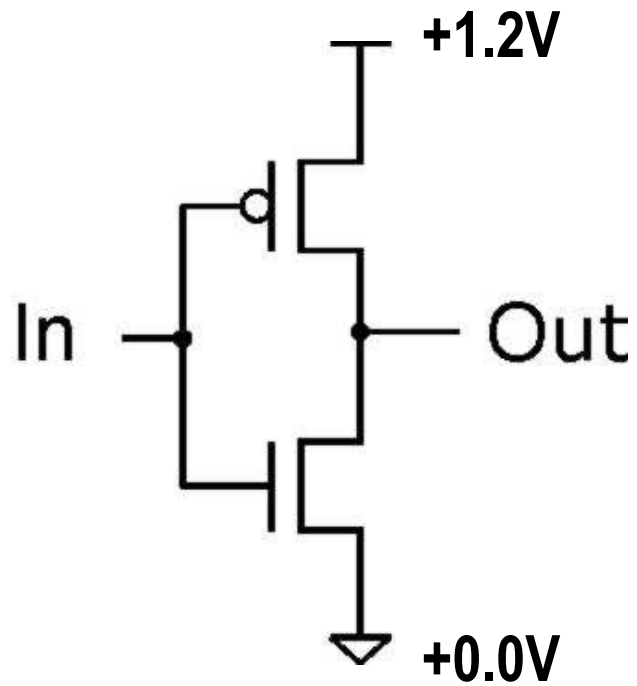
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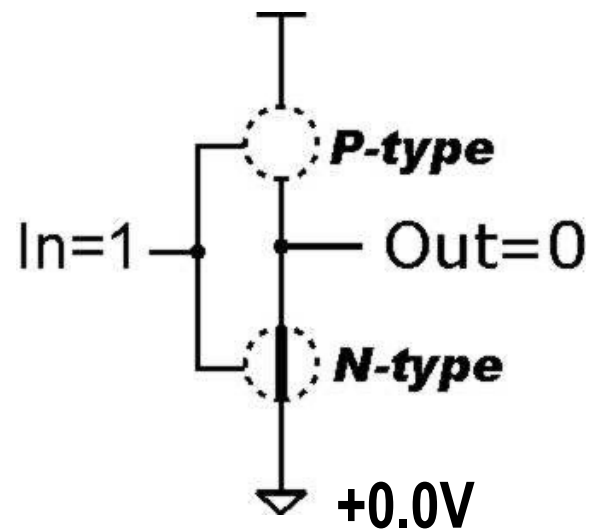
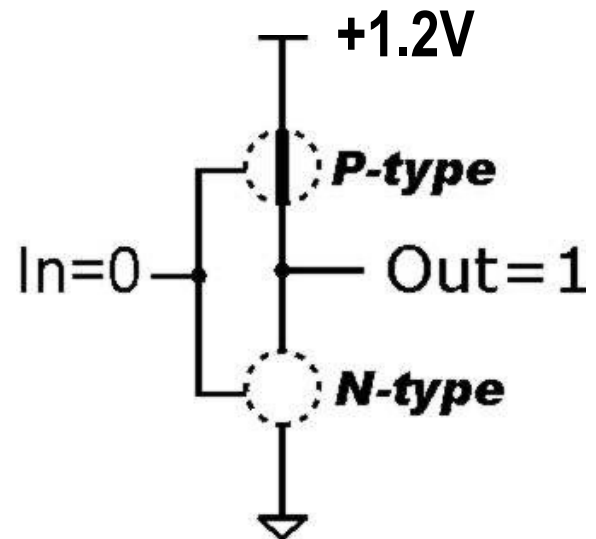
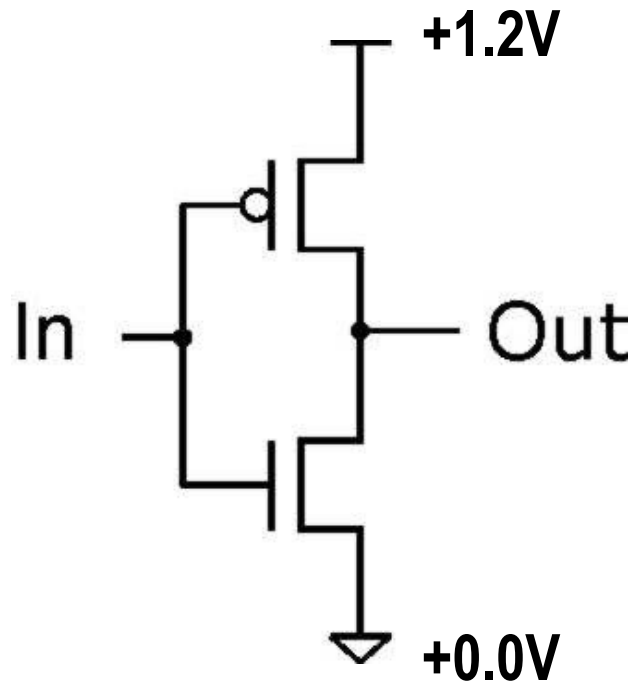
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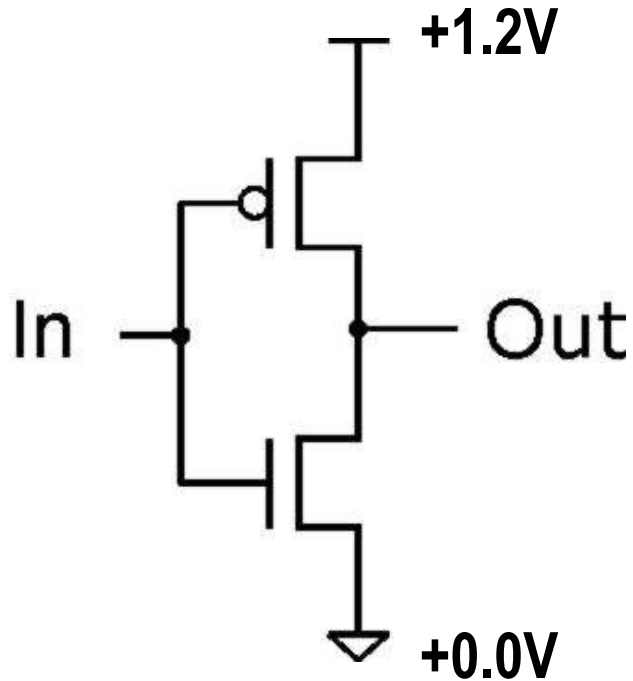
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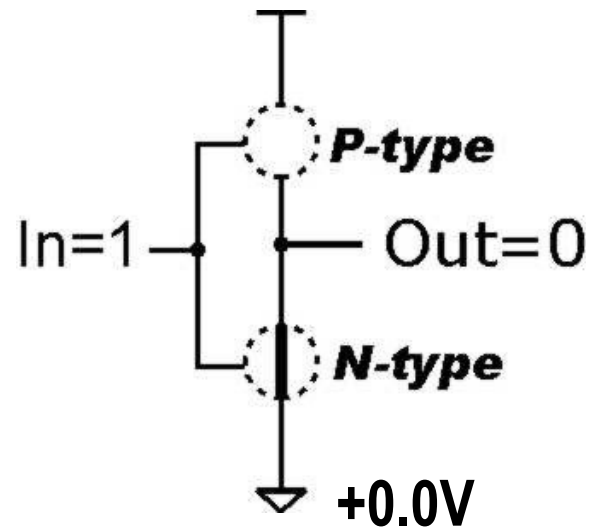
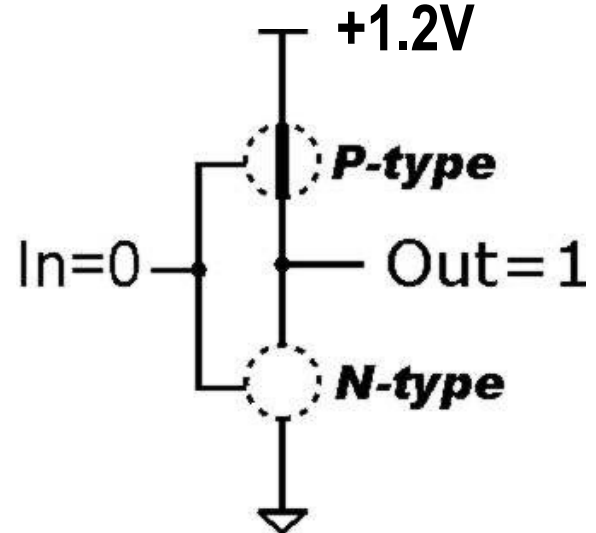
Inverter



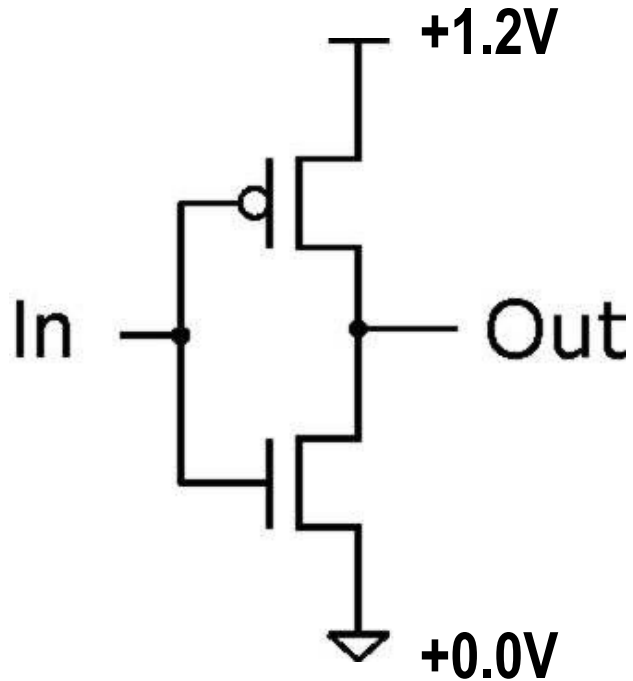
Inverter



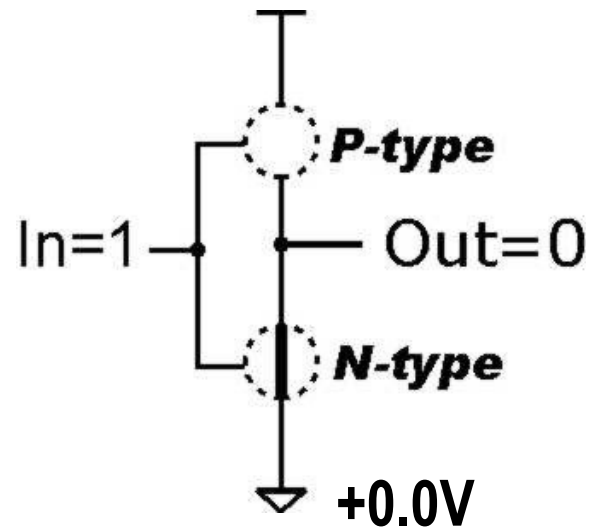
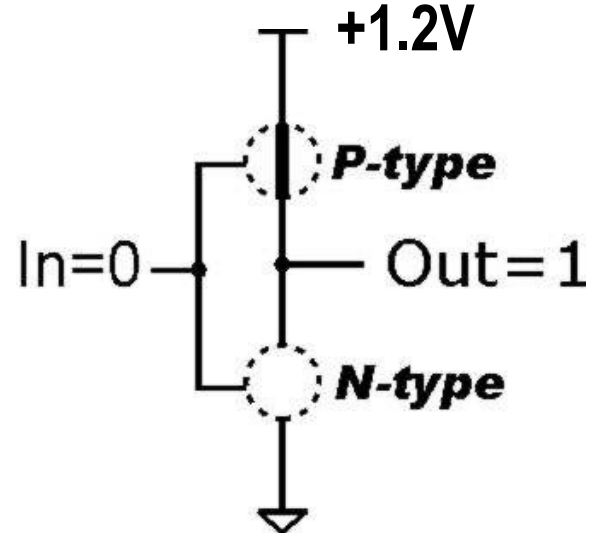
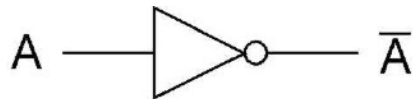
In	Out
0	1
1	0



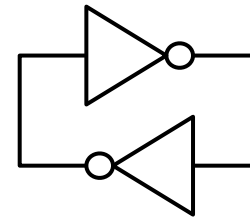
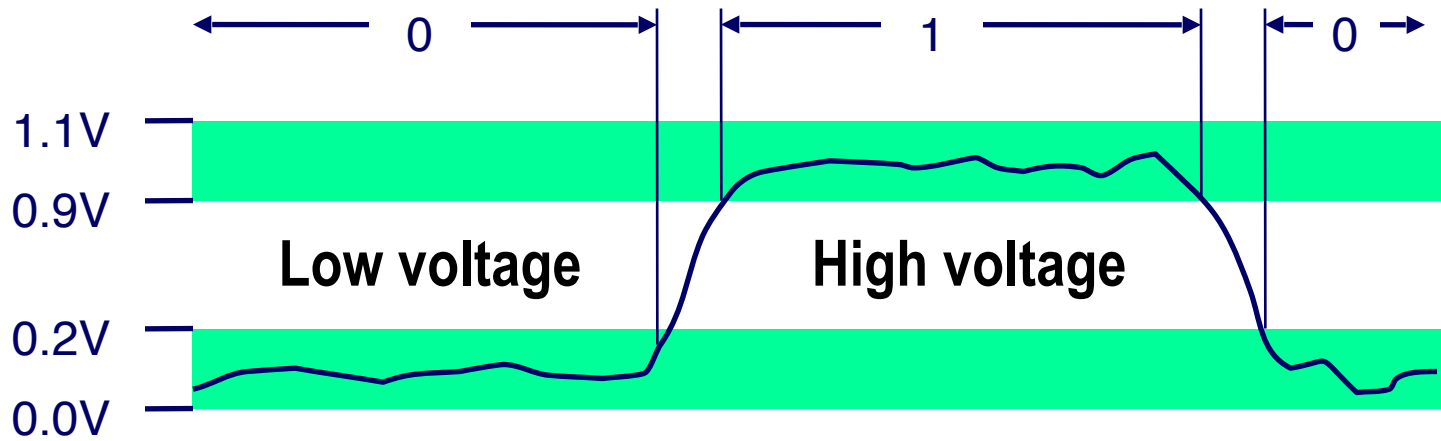
Inverter



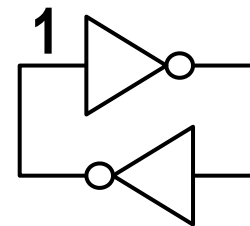
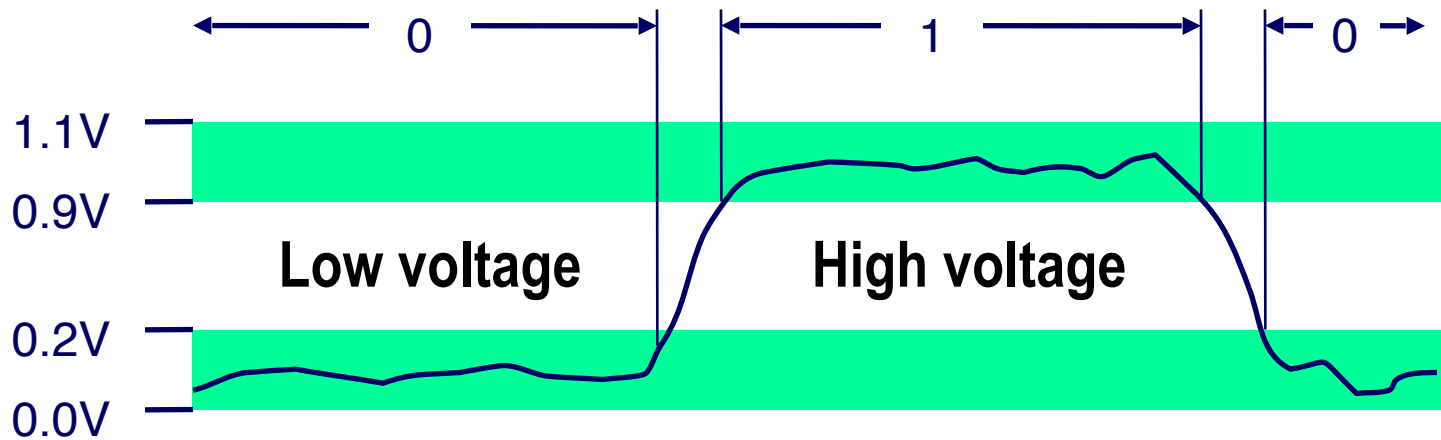
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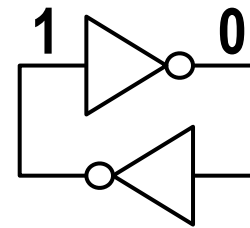
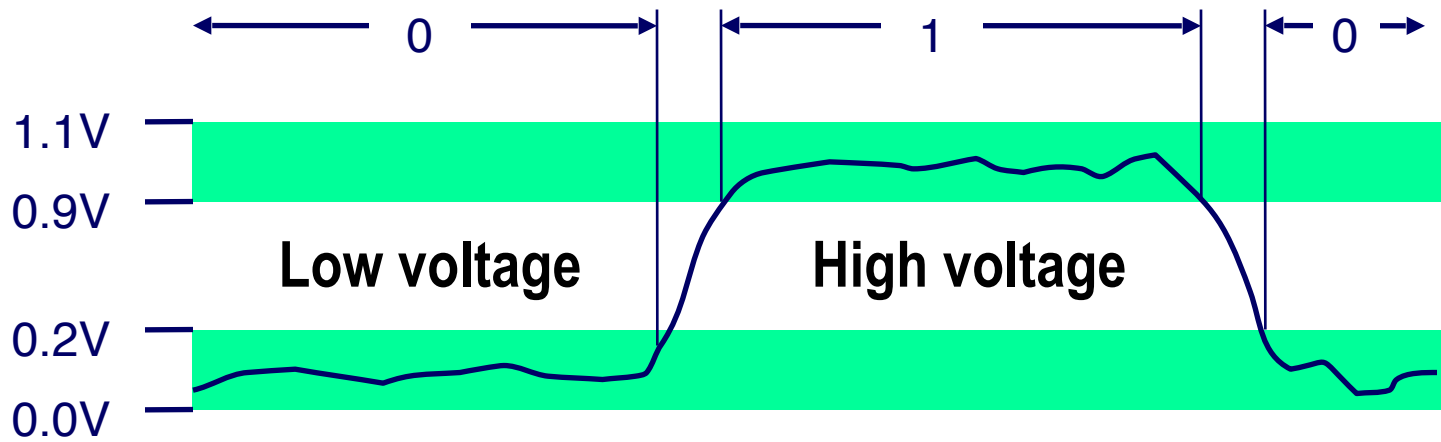
Store/Access Data



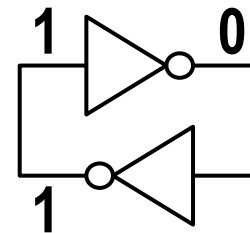
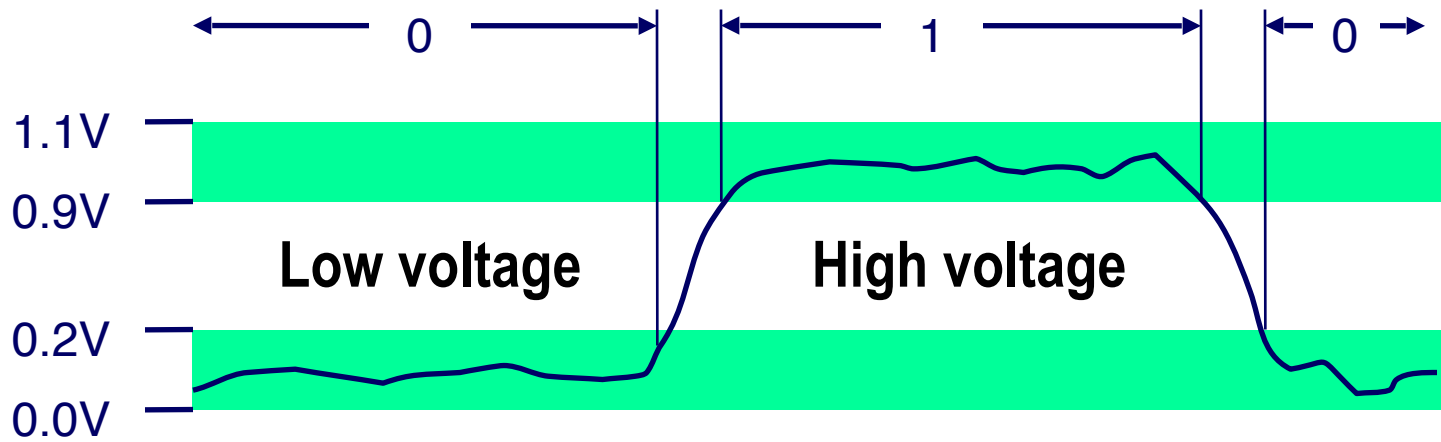
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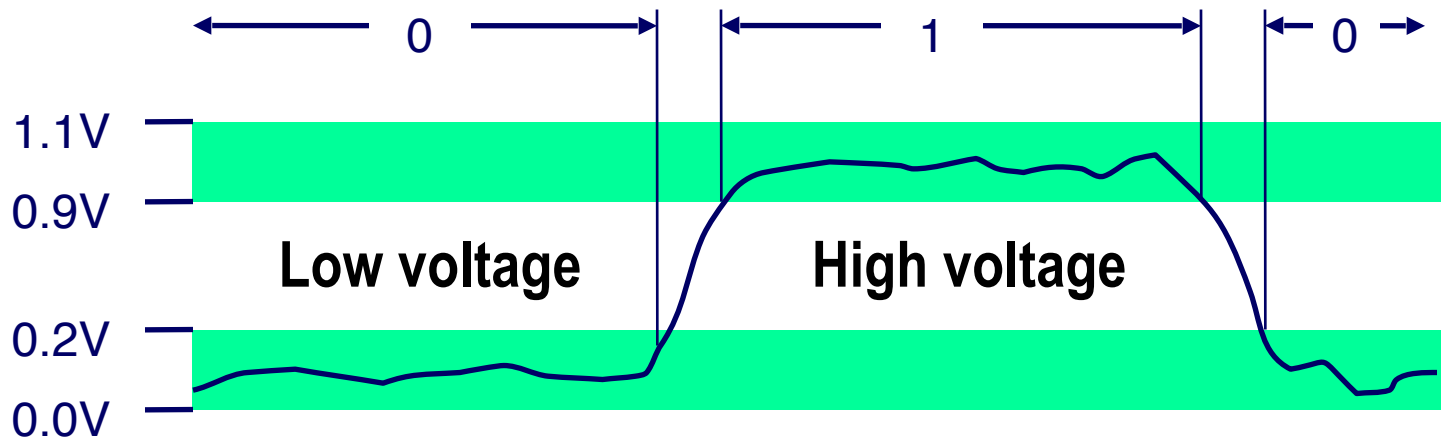
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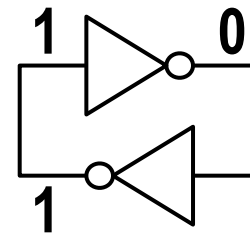
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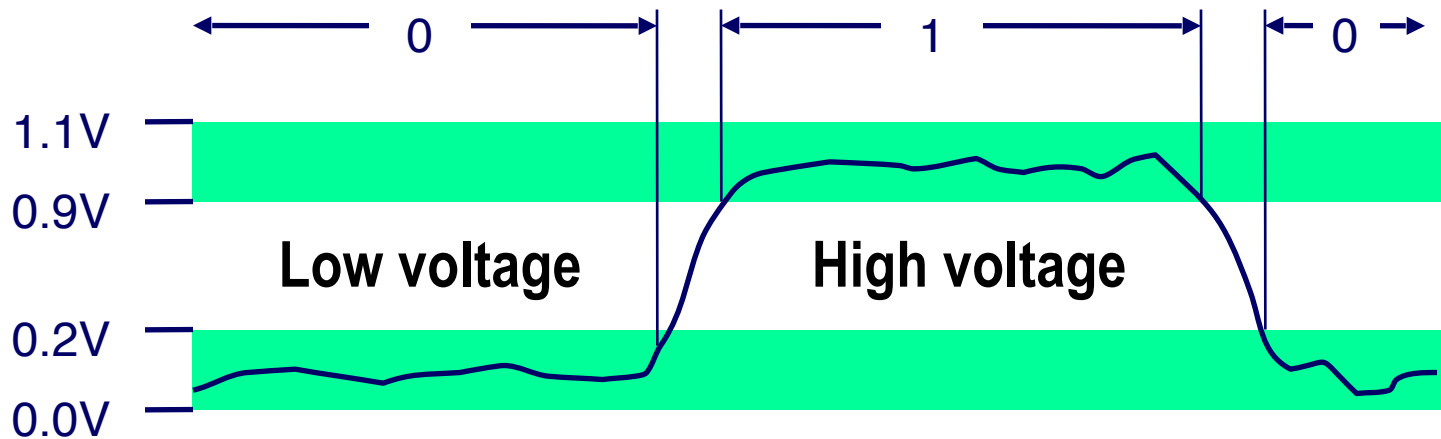
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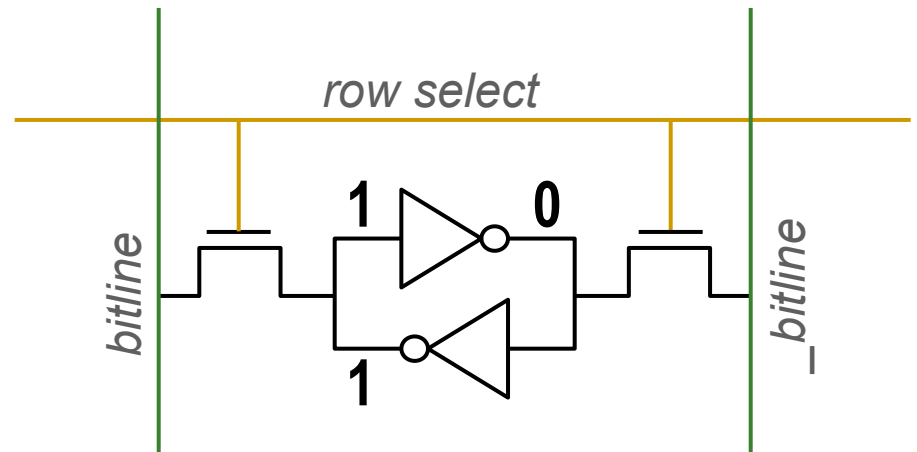
- Two cross coupled inverters store a single bit
 - Feedback path persists the value in the “cell”



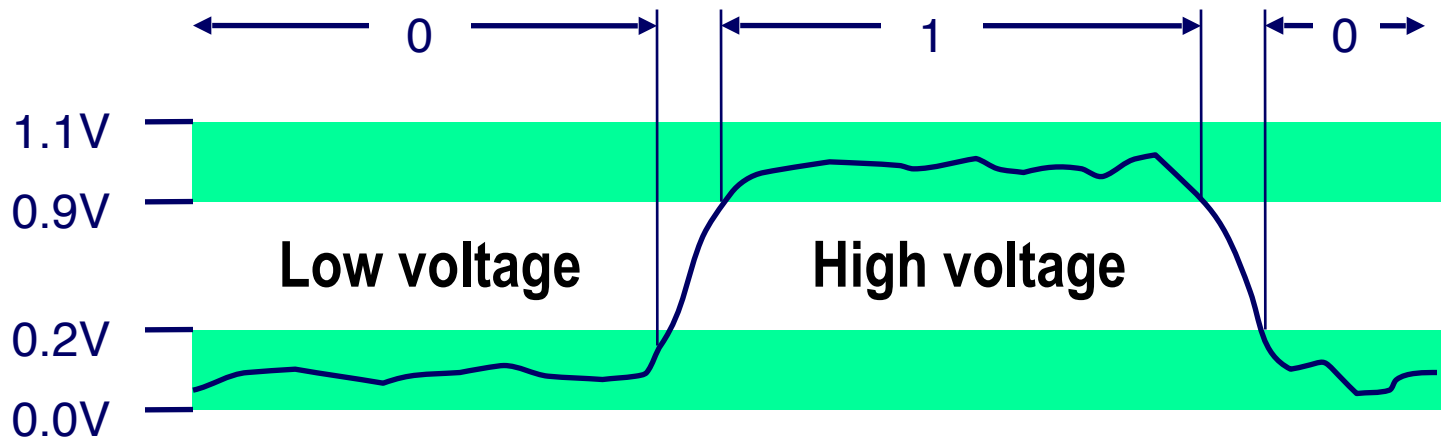
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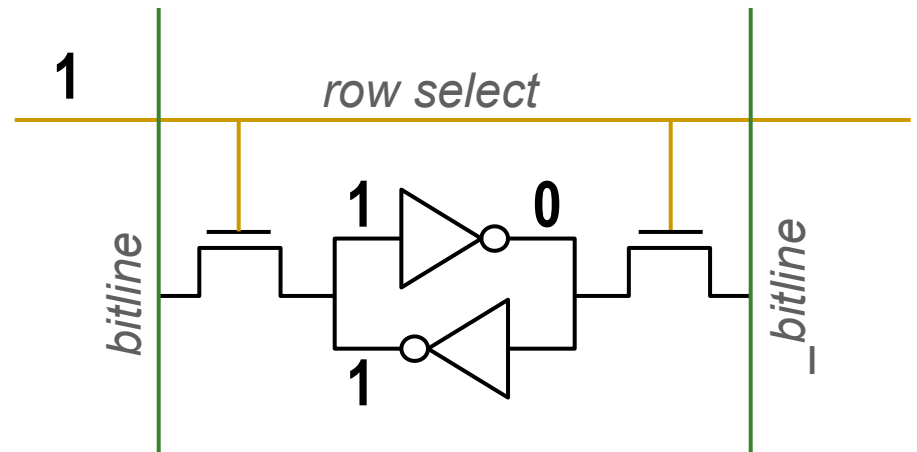
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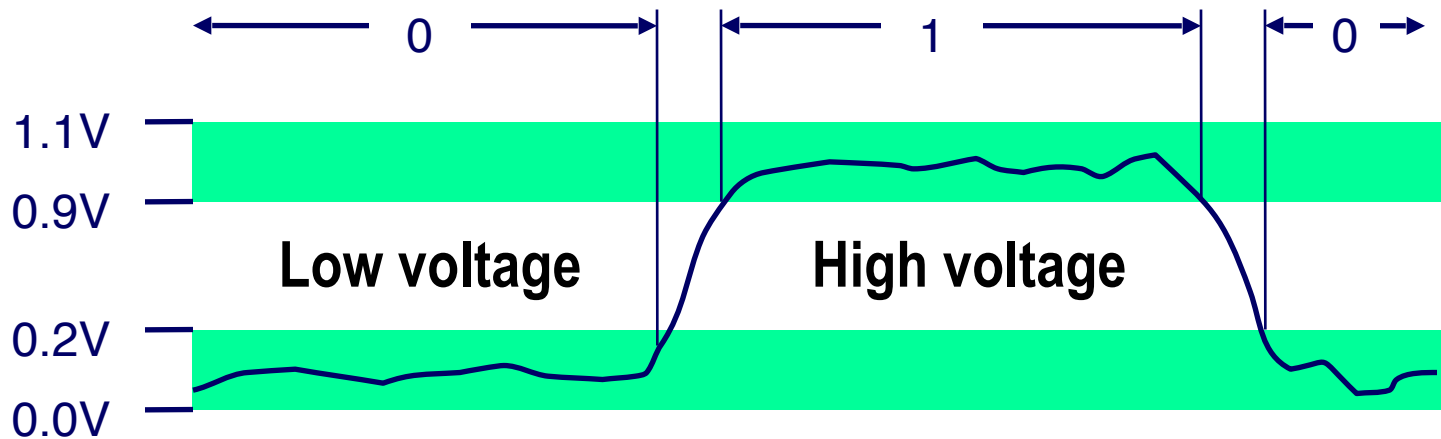
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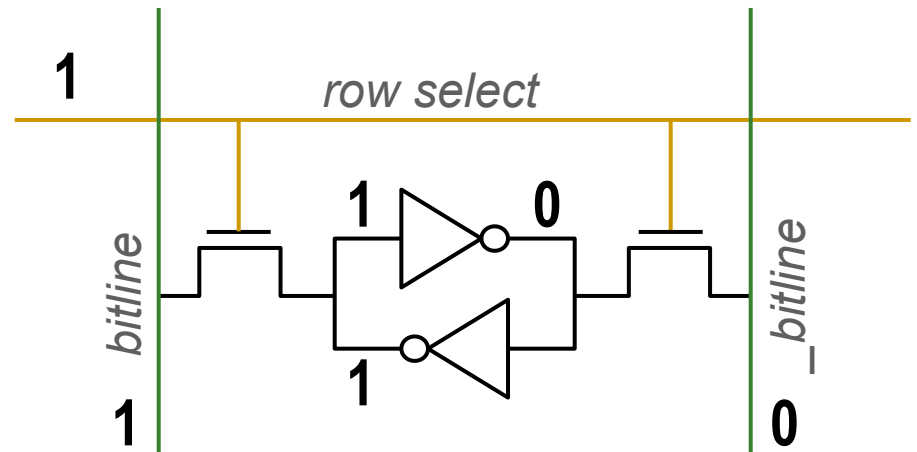
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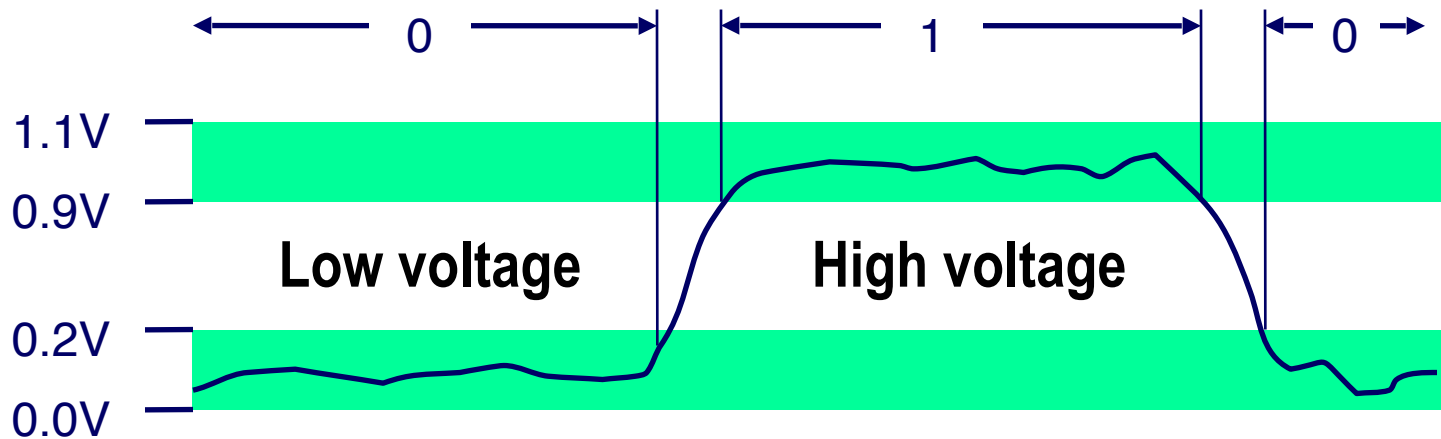
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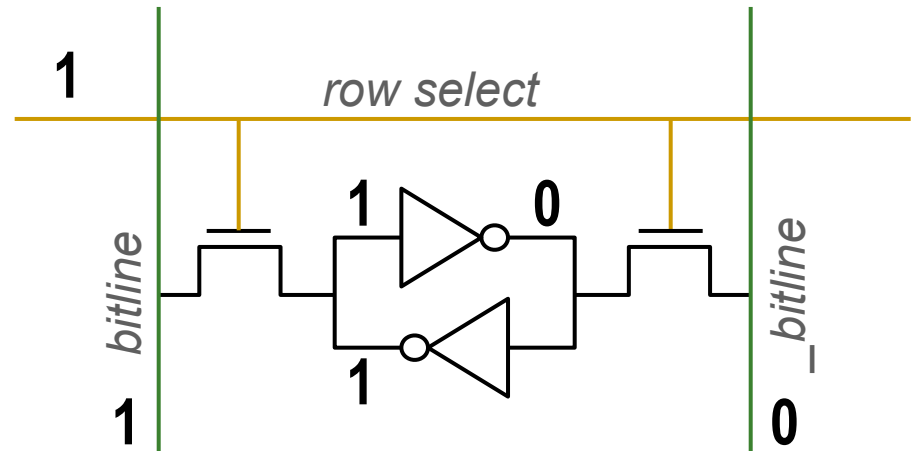
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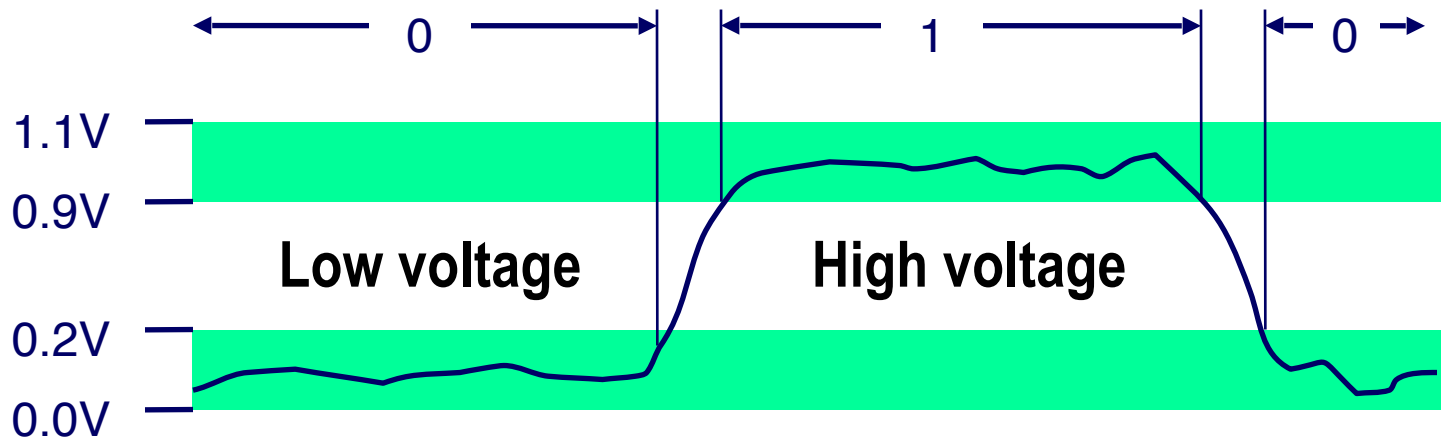
Store/Access Data



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 - Feedback path persists the value in the “cell”
 - 4 transistors for storage

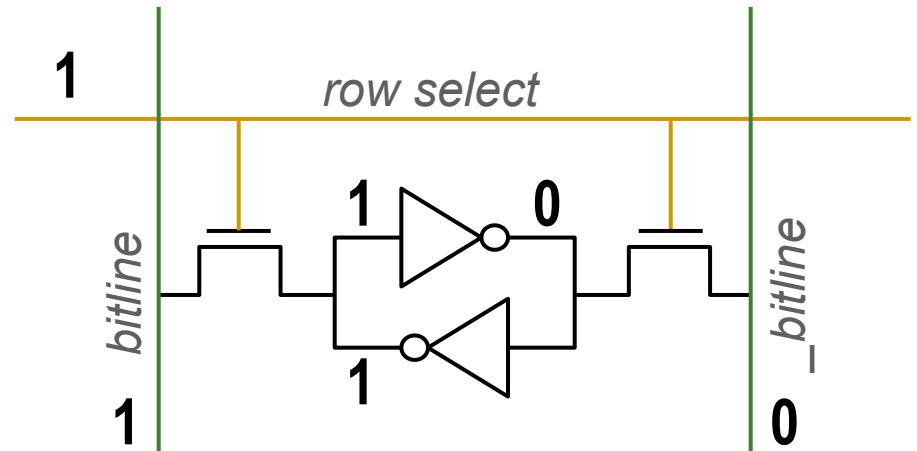


Store/Access Data

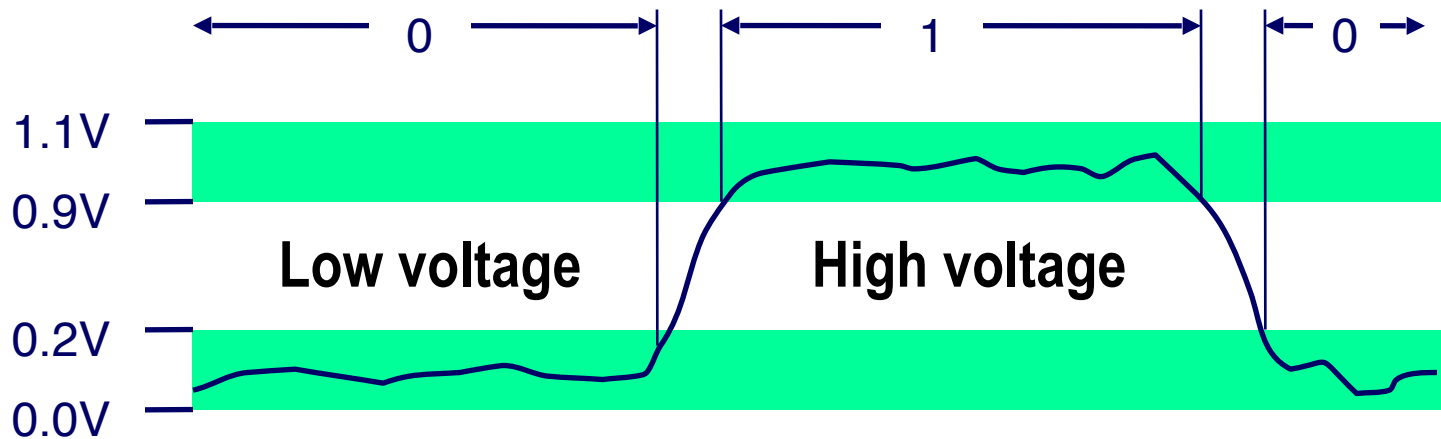


- Two cross coupled inverters store a single bit

- Feedback path persists the value in the “cell”
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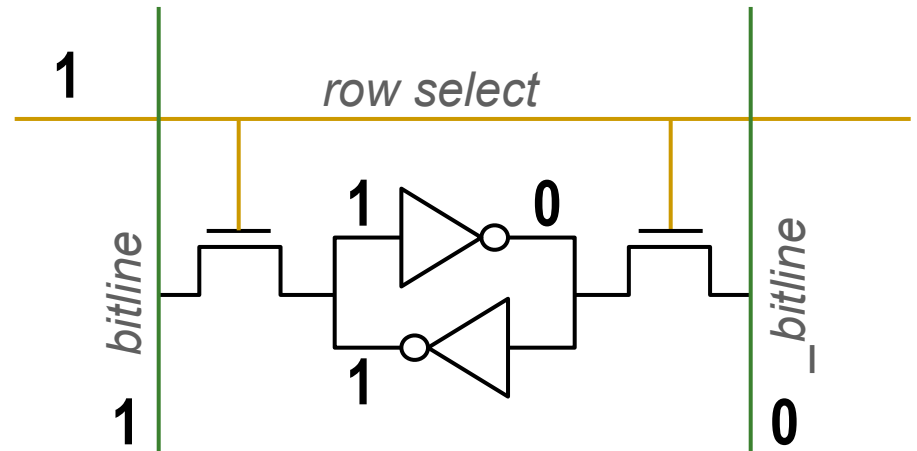


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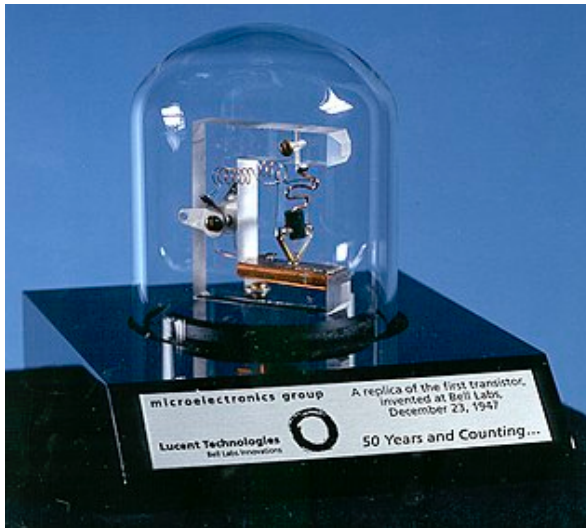
- Two cross coupled inverters store a single bit

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



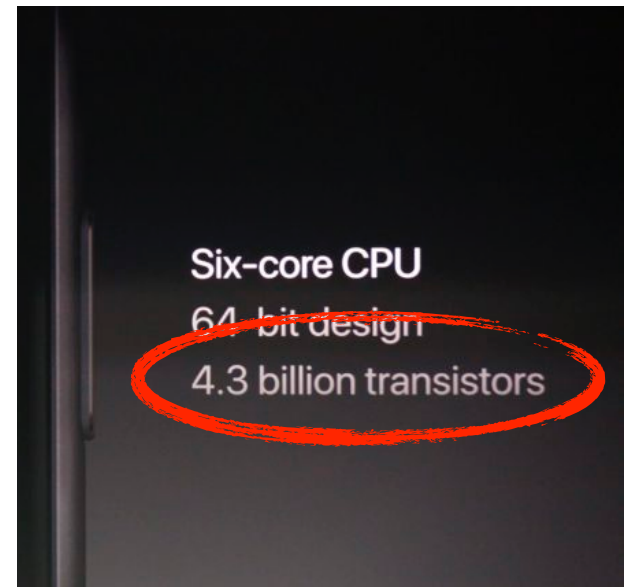
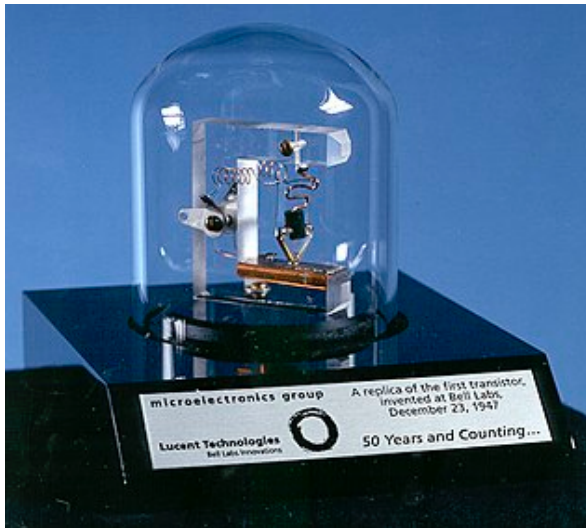
Transistors

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



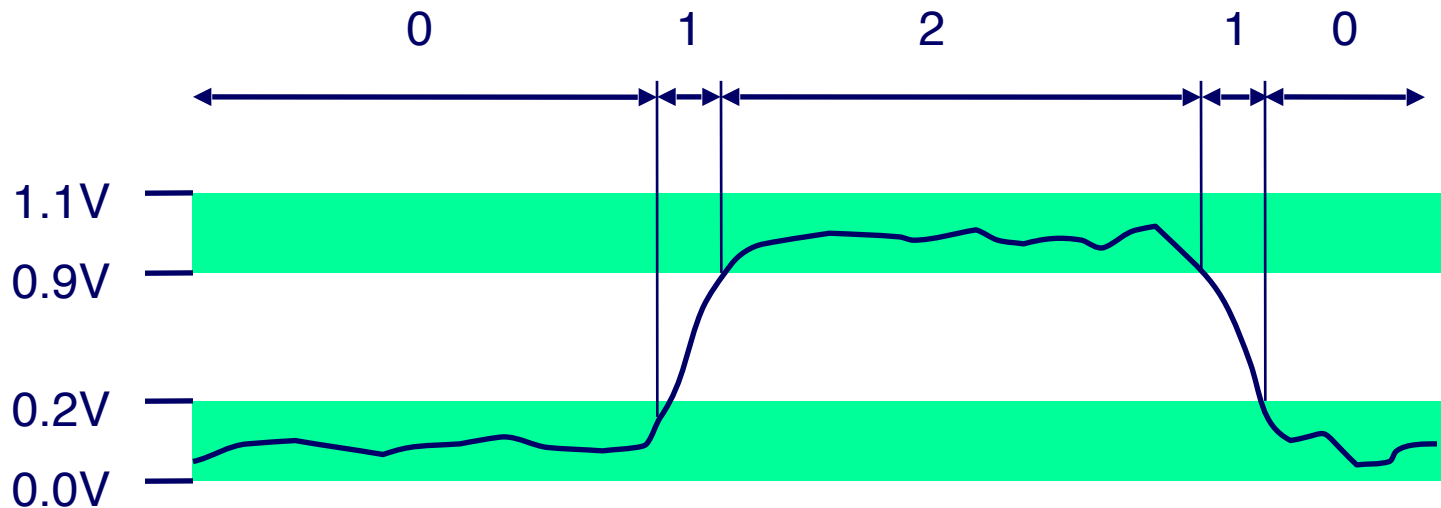
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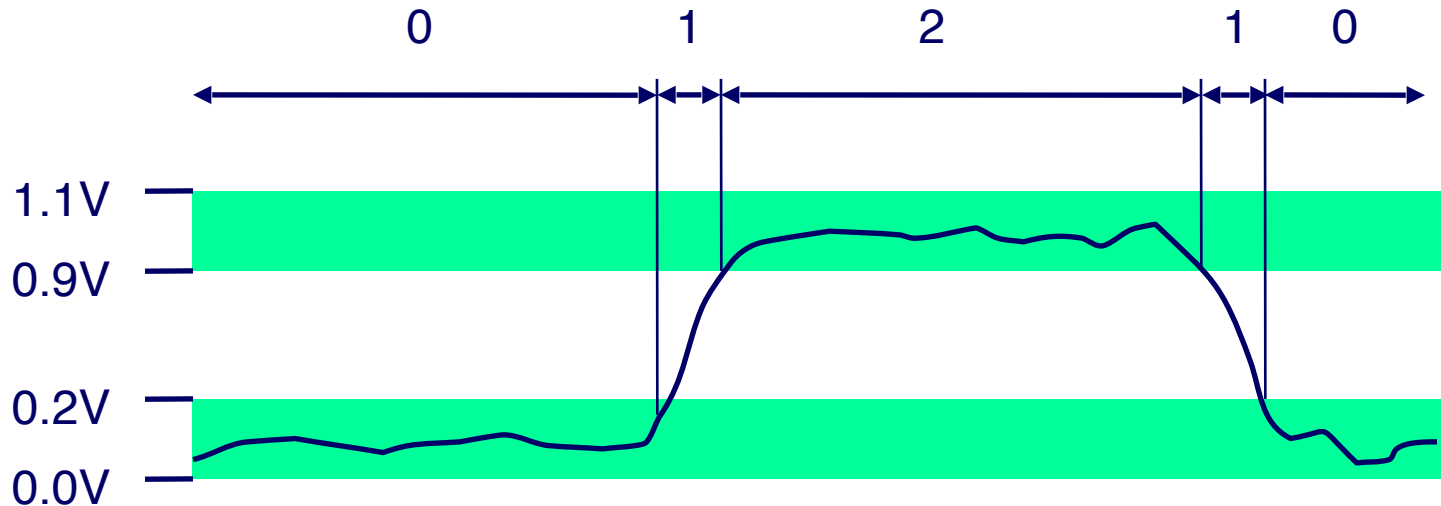
Why Limit Ourselves Only to Binary?

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



Why Limit Ourselves Only to Binary?

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

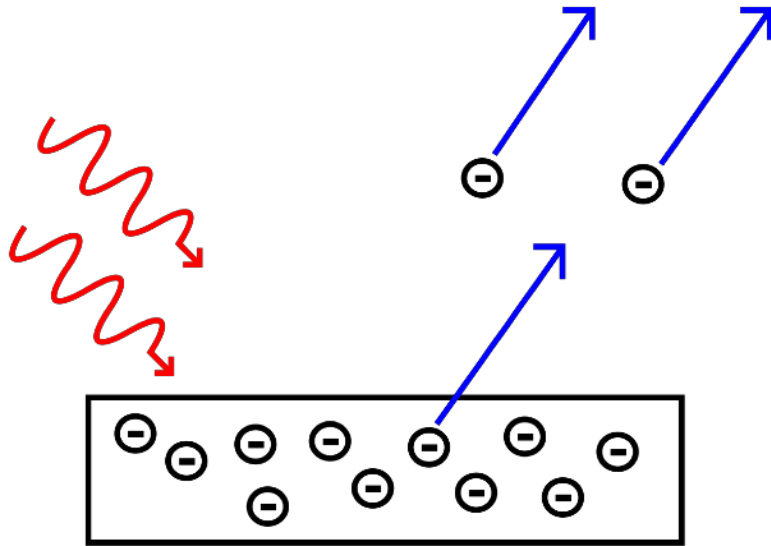


Why Limit Ourselves Only to Binary?

- But, there are applications that can tolerate noise

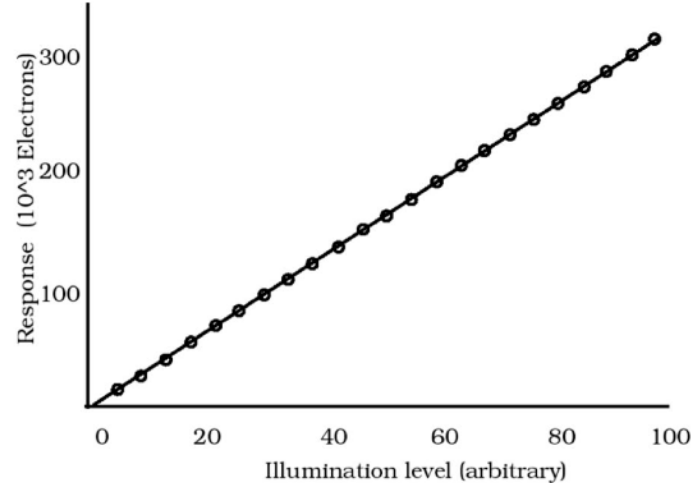
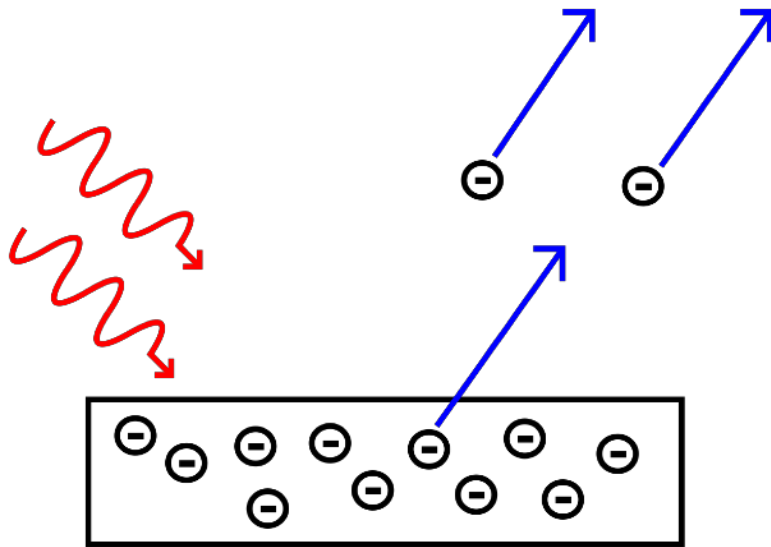
Why Limit Ourselves Only to Binary?

- But, there are applications that can tolerate noise
- Classic Example: Camera Sensor
 - Photoelectric Effect



Why Limit Ourselves Only to Binary?

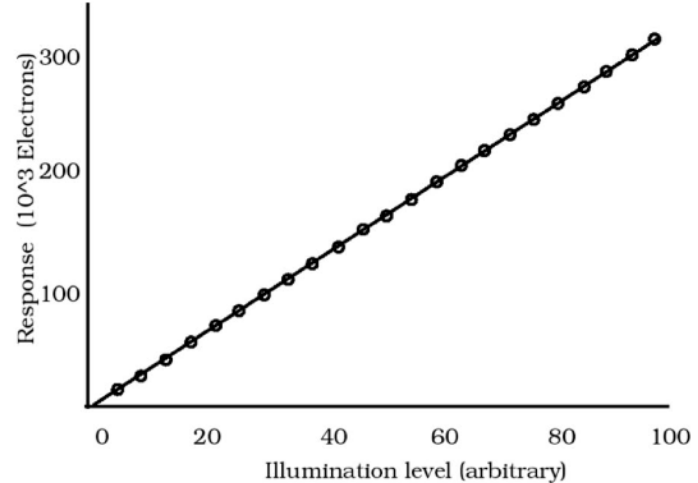
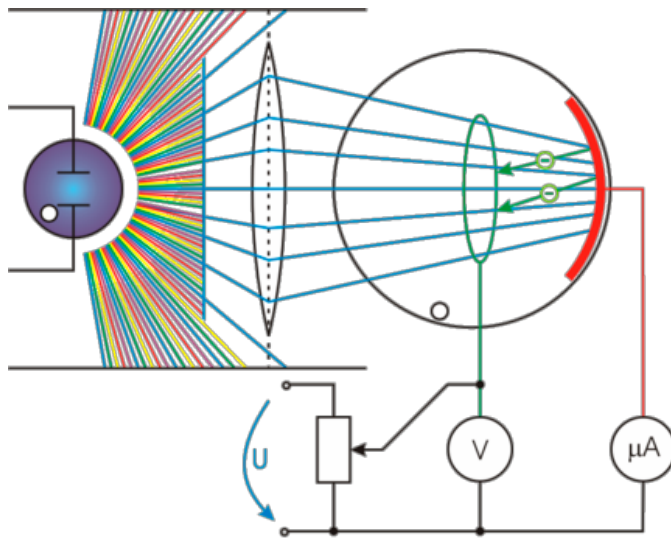
- But, there are applications that can tolerate noise
- Classic Example: Camera Sensor
 - Photoelectric Effect



(Epperson, P.M. et al. Electro-optical characterization of the Tektronix TK5 ..., Opt Eng., 25, 1987)

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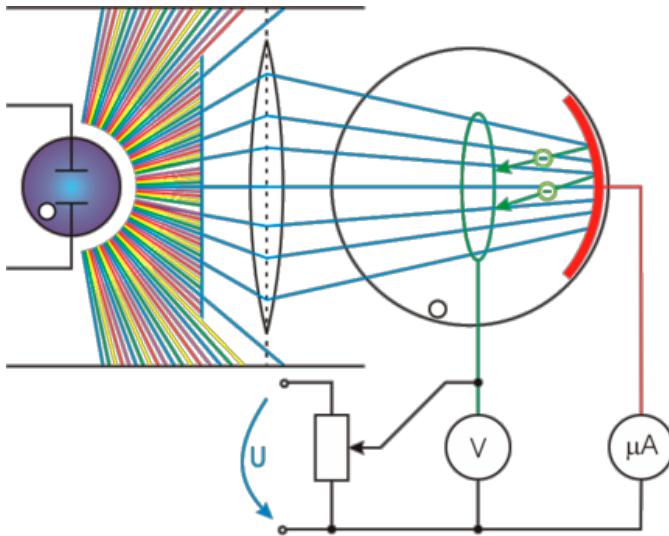
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Binary Notation

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- Base 2 Number Representation (Binary)

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- C.f., Base 10 number representation (Decimal)

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 - Each bit has a weight depending on its position

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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

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$$\begin{array}{r} 0110 \\ + 0101 \\ \hline 1011 \end{array}$$

Decimal	Binary
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1	0001
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$$\begin{array}{r} 0110 \\ + 0101 \\ \hline 1011 \end{array}$$

$$\begin{array}{r} 6 \\ + 5 \\ \hline 11 \end{array}$$

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
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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

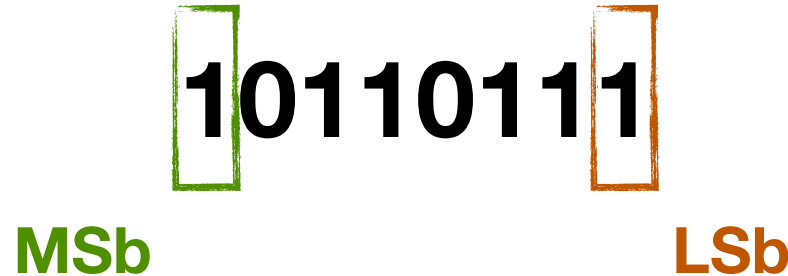
Bit, Byte, Word

- 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**

The diagram shows the binary sequence '10110111'. The first bit '1' is enclosed in a green rectangular box, and the last bit '1' is enclosed in an orange rectangular box. Below the green box is the label 'MSb' in green text, and below the orange box is the label 'LSb' in orange text.

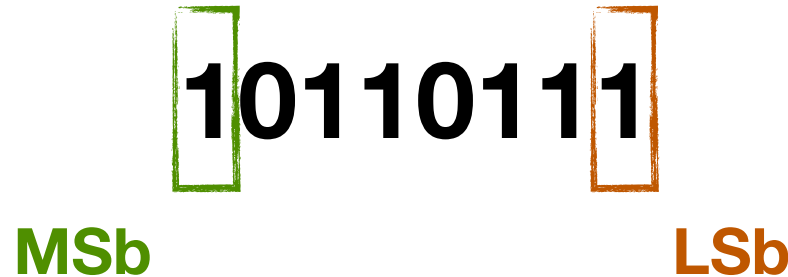
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- Word = 4 Bytes (32-bit machine) / 8 Bytes (64-bit machine)
- Least Significant Byte (LSB) vs. Most Significant Byte (MSB)

Today: Representing Information in Binary

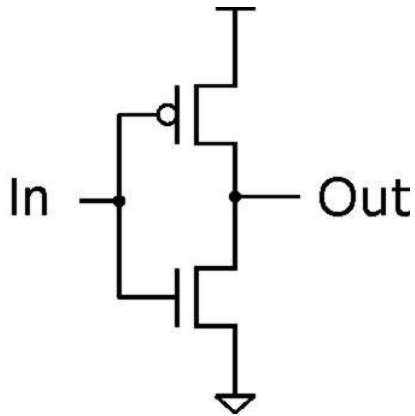
- Why Binary (bits)?
- Bit-level manipulations
- Integers
 - Representation: unsigned and signed
 - Conversion, casting
 - Expanding, truncating
 - Addition, negation, multiplication, shifting
 - Summary
- Representations in memory, pointers, strings

Bit-level manipulations

Not

- $\sim A = 1$ when $A=0$

\sim	
0	1
1	0



Bit-level manipulations

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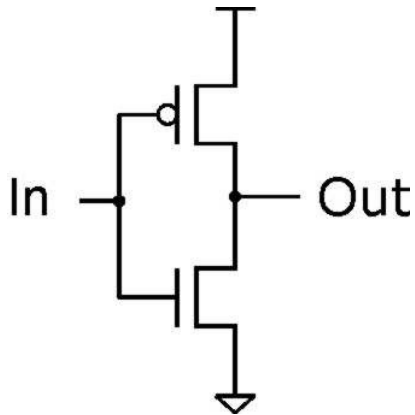
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Or

- $A \vee B = 1$ when either $A=1$ or $B=1$

	0	1
0	0	1
1	1	1



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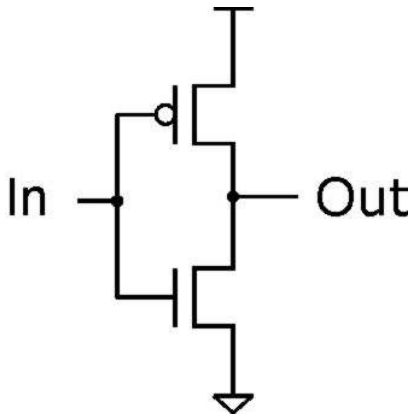
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And

- $A \wedge B = 1$ when both $A=1$ and $B=1$

	0	1
0	0	1
1	1	1

	0	1
0	0	0
1	0	1

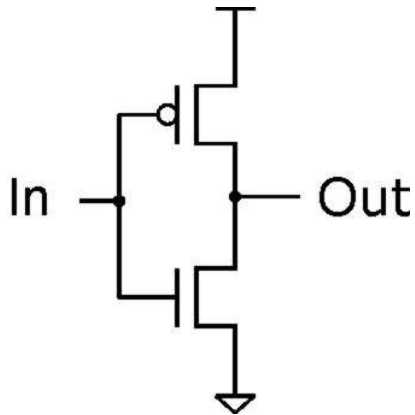


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And

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Exclusive-Or (Xor)

- $A \oplus B = 1$ when either $A=1$ or $B=1$, but not both

\vee	0	1
0	0	1
1	1	1

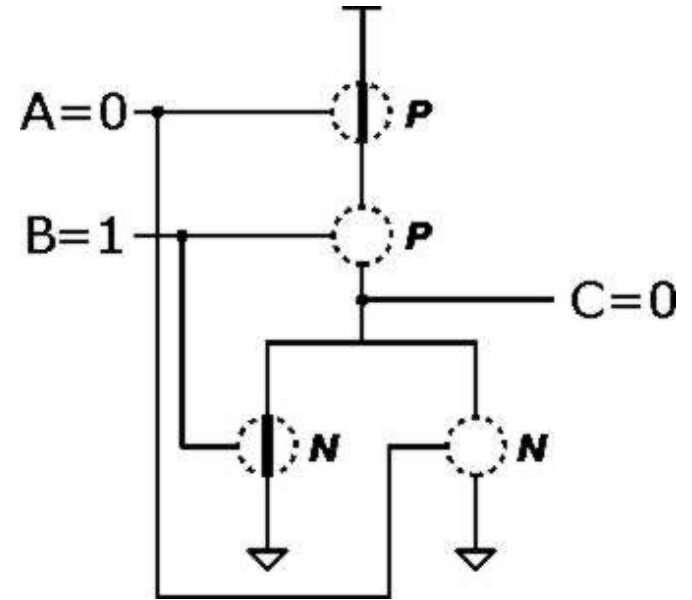
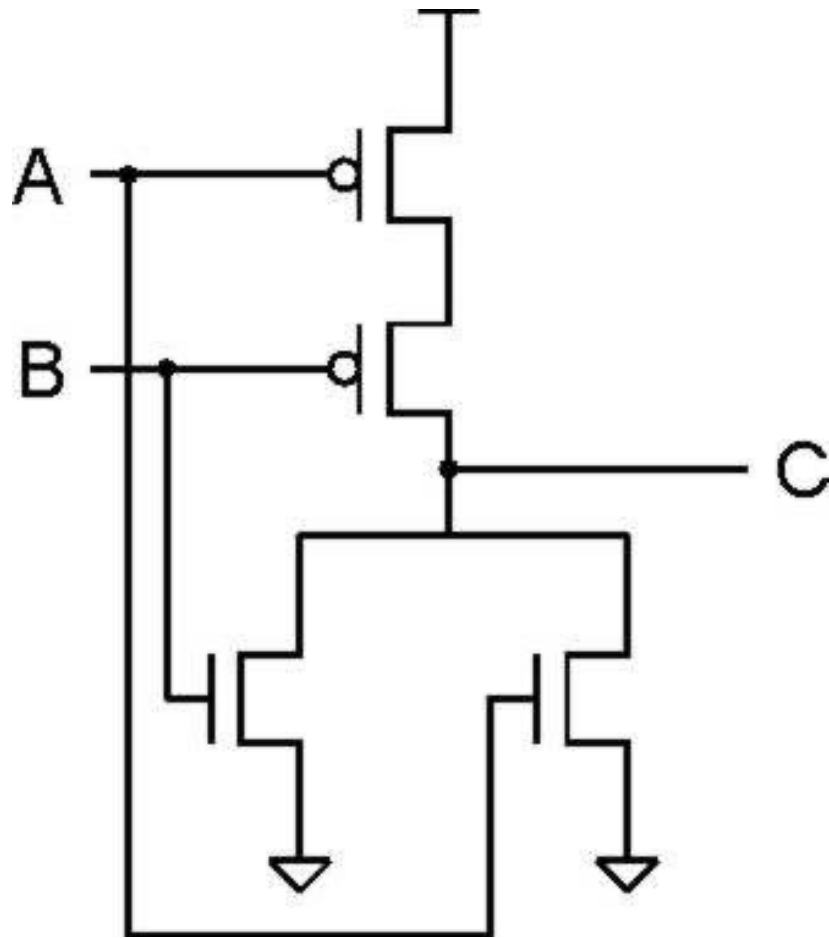
\wedge	0	1
0	0	0
1	0	1

\oplus	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

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
<u> </u>	<u> </u>	<u> </u>	<u> </u>

Bit Vector Operations

- Operate on Bit Vectors
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$$\begin{array}{r} 01101001 \\ \& 01010101 \\ \hline 01000001 \end{array} \quad \begin{array}{r} 01101001 \\ | 01010101 \\ \hline \end{array} \quad \begin{array}{r} 01101001 \\ ^ 01010101 \\ \hline \end{array} \quad \begin{array}{r} \sim 01010101 \\ \hline \end{array}$$

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$$\begin{array}{r} 01101001 \\ \wedge 01010101 \\ \hline 00111100 \end{array}$$

$$\begin{array}{r} \sim 01010101 \\ \hline 10101010 \end{array}$$

Bit-Level Operations in C

- Operations $\&$, $|$, \sim , \wedge 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)
 - $\sim 0x41 \rightarrow 0xBE$
 - $\sim 01000001_2 \rightarrow 10111110_2$
 - $\sim 0x00 \rightarrow 0xFF$
 - $\sim 00000000_2 \rightarrow 11111111_2$
 - $0x69 \& 0x55 \rightarrow 0x41$
 - $01101001_2 \& 01010101_2 \rightarrow 01000001_2$
 - $0x69 | 0x55 \rightarrow 0x7D$
 - $01101001_2 | 01010101_2 \rightarrow 01111101_2$

Contrast: 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

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 - Shift bit-vector x left y positions
 - Throw away extra bits on left
 - Fill with 0's on right
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 - Arithmetic shift
 - Replicate most significant bit on left
- Undefined Behavior
 - Shift amount < 0 or \geq word size

Argument x	01100010
$\ll 3$	
Log. $\gg 2$	
Arith. $\gg 2$	

Argument x	10100010
$\ll 3$	
Log. $\gg 2$	
Arith. $\gg 2$	

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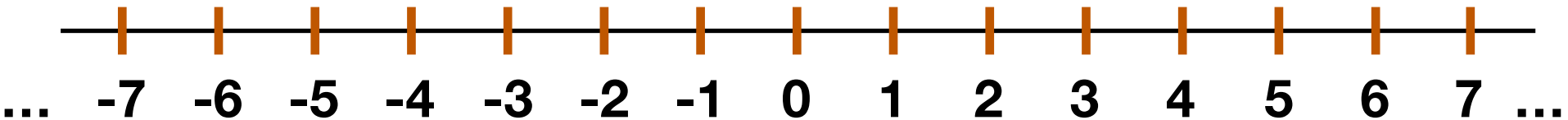
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\ll 3	00010000
Log. \gg 2	00101000
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Today: Representing Information in Binary

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

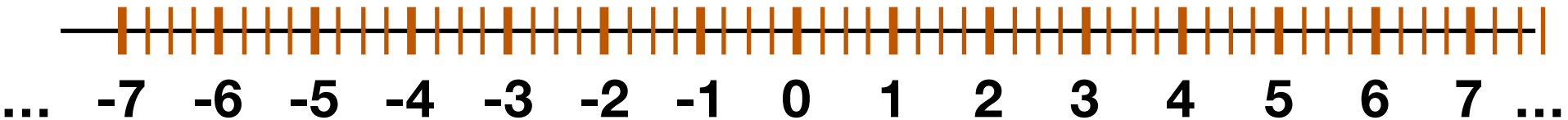
Representing Numbers in Binary

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



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Encoding Negative Numbers

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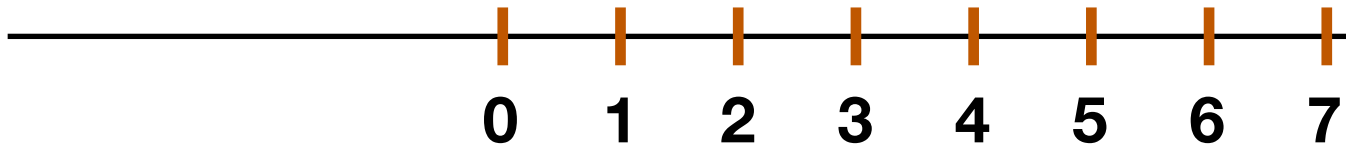
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 - First bit represents sign; 0 for positive; 1 for negative
 - The rest represents magnitude

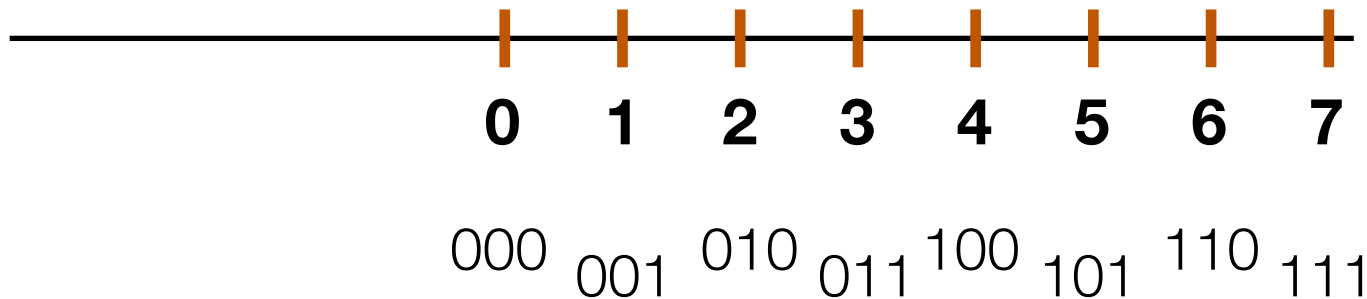
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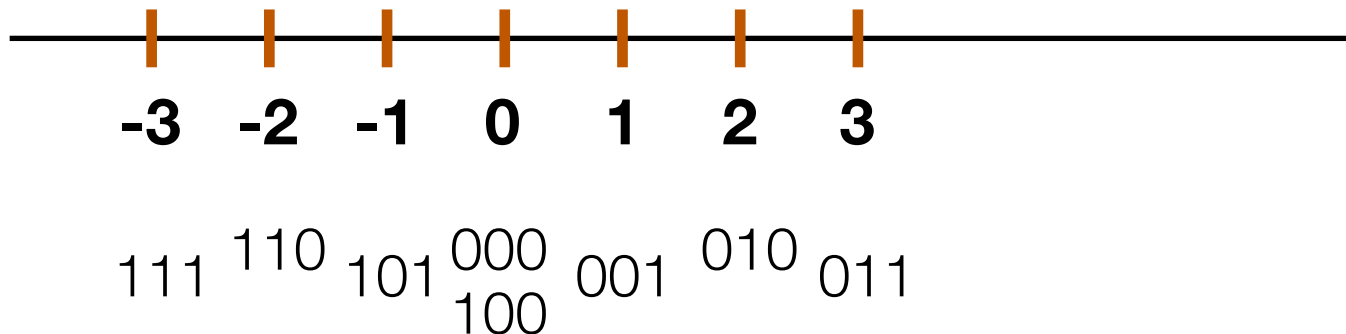
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- Solution 1: Sign-magnitude
 - First bit represents sign; 0 for positive; 1 for negative
 - The rest represents magnitude



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

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$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$

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The diagram shows two arithmetic operations, each crossed out with a large red 'X'. On the left, the operation is
$$\begin{array}{r} 010 \\ +) 101 \\ \hline 111 \end{array}$$
 with the result 111 written in red below the line. On the right, the operation is
$$\begin{array}{r} 2 \\ +) -1 \\ \hline -3 \end{array}$$
 with the result -3 written in red below the line. The red 'X' is drawn over both operations, indicating that such standard arithmetic is invalid in sign-magnitude representation.

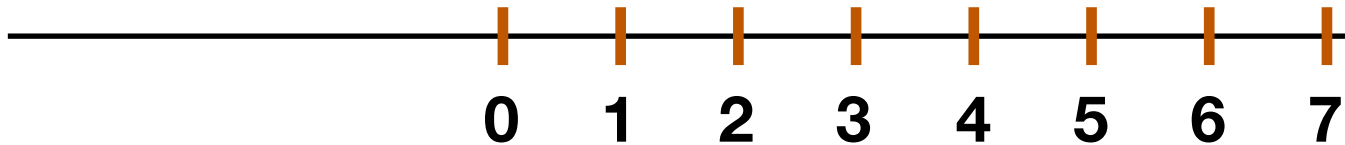
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1	001
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Encoding Negative Numbers

- Solution 2: Two's Complement

Encoding Negative Numbers

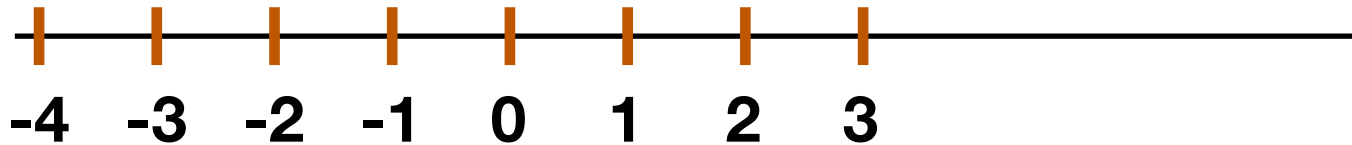
- Solution 2: Two's Complement



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

Encoding Negative Numbers

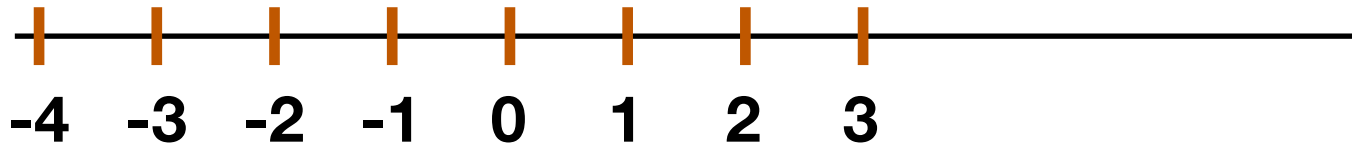
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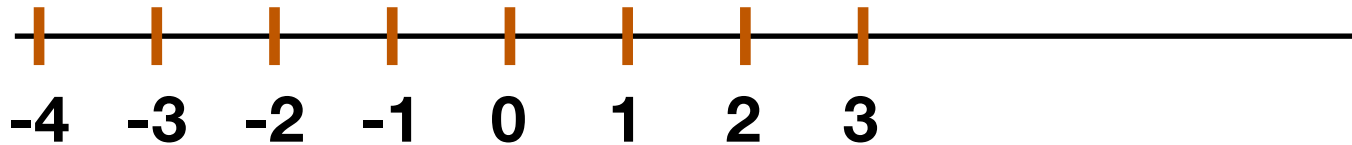
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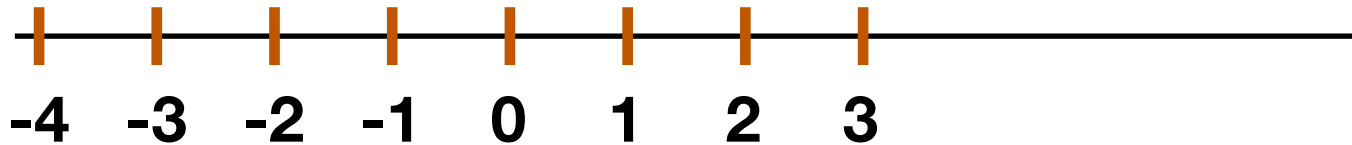


Signed Weight	Unsigned Weight	Bit Position
2^0	2^0	0
2^1	2^1	1
-2^2	2^2	2

Signed	Unsigned	Binary
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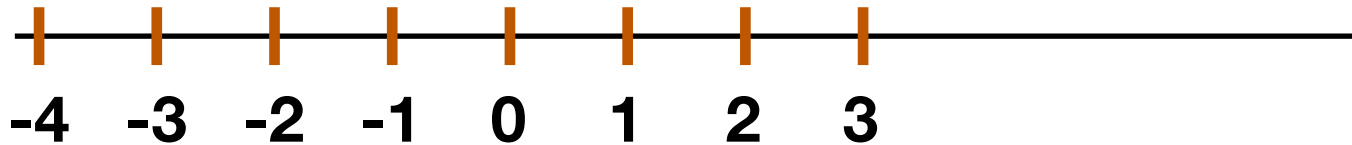


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$$101_2 = 1 \cdot 2^0 + 0 \cdot 2^1 - 1 \cdot 2^2 = -3_{10}$$

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 sign!
- Most widely used in today's machines

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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

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- Other Values

- Minus 1
111...1

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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
<code>char</code>	1	1
<code>short</code>	2	2
<code>int</code>	4	4
<code>long</code>	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

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- C Language

- `#include <limits.h>`
- Declares constants, e.g.,
 - `ULONG_MAX`
 - `LONG_MAX`
 - `LONG_MIN`
- Values platform specific

Can We Represent Fractions in Binary?

- What does 10.01_2 mean?
- C.f., Decimal
 - $12.45 = 1*10^1 + 2*10^0 + 4*10^{-1} + 5*10^{-2}$
- $10.01_2 = 1*2^1 + 0*2^0 + 0*2^{-1} + 1*2^{-2} = 2.25_{10}$

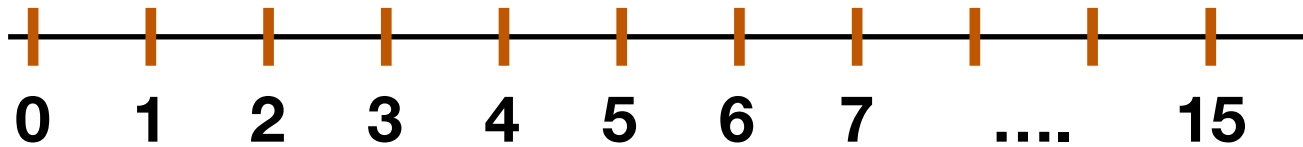
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Decimal	Binary
0	00.00
0.25	00.01
0.5	00.10
0.75	00.11
1	01.00
1.25	01.01
1.5	01.10
1.75	01.11
2	10.00
2.25	10.01
2.5	10.10
2.75	10.11
3	11.00
3.25	11.01
3.5	11.10
3.75	11.11

Can We Represent Fractions in Binary?

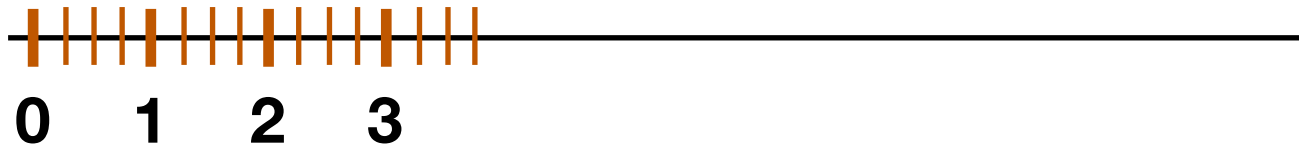
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0.75	00.11
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1.5	01.10
1.75	01.11
2	10.00
2.25	10.01
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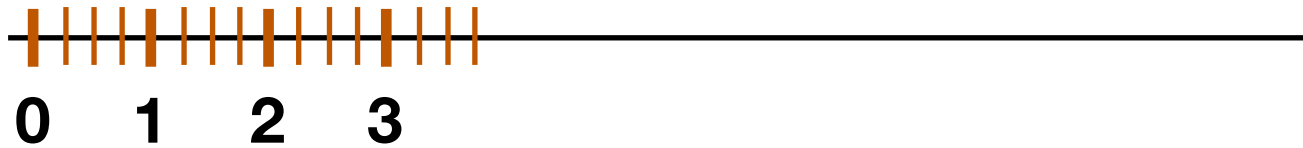
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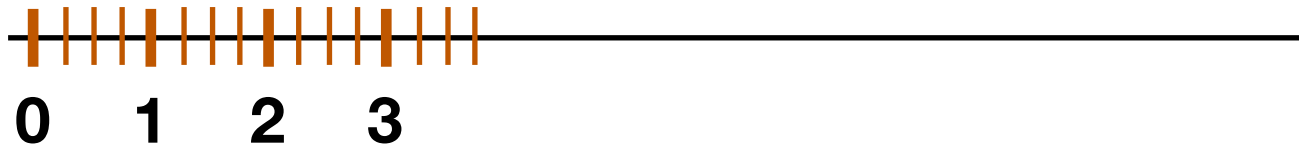
$$\begin{array}{r}
 01.10 \\
 + 01.01 \\
 \hline
 10.11
 \end{array}$$

$$\begin{array}{r}
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 \hline
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Integer Arithmetic Still Works!

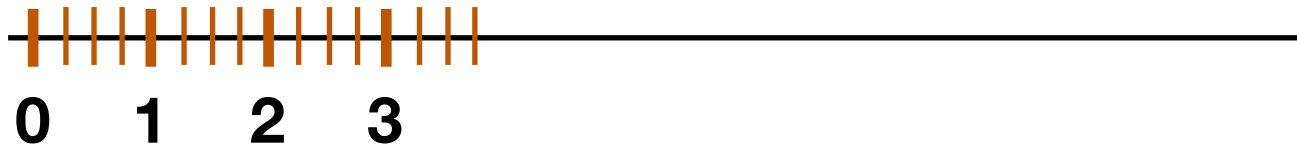
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Fixed-Point Representation

- Fixed interval between two representable numbers as long as the **binary point stays fixed**
 - Each bit represents 0.25_{10}
- **Fixed-point** representation of numbers
 - Integer is one special case of fixed-point



$$\begin{array}{r} 01.10 \\ + 01.01 \\ \hline 10.11 \end{array}$$

$$\begin{array}{r} 1.50 \\ + 1.25 \\ \hline 2.75 \end{array}$$

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