CS222: Computer Architecture

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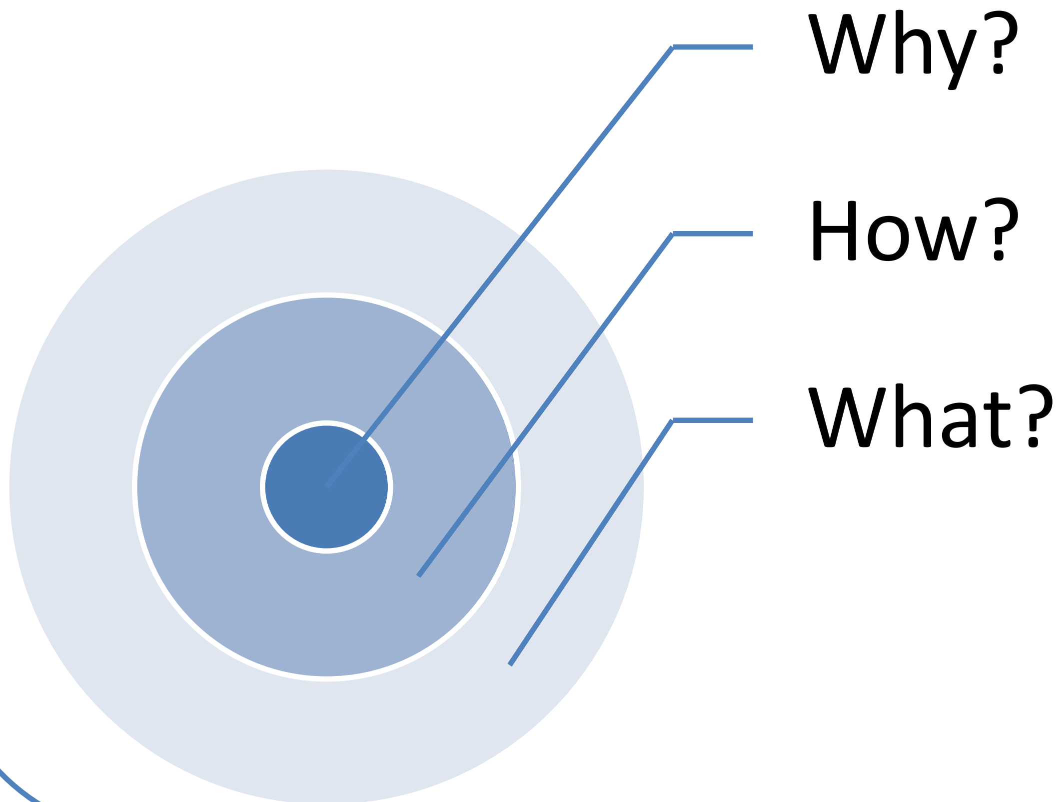
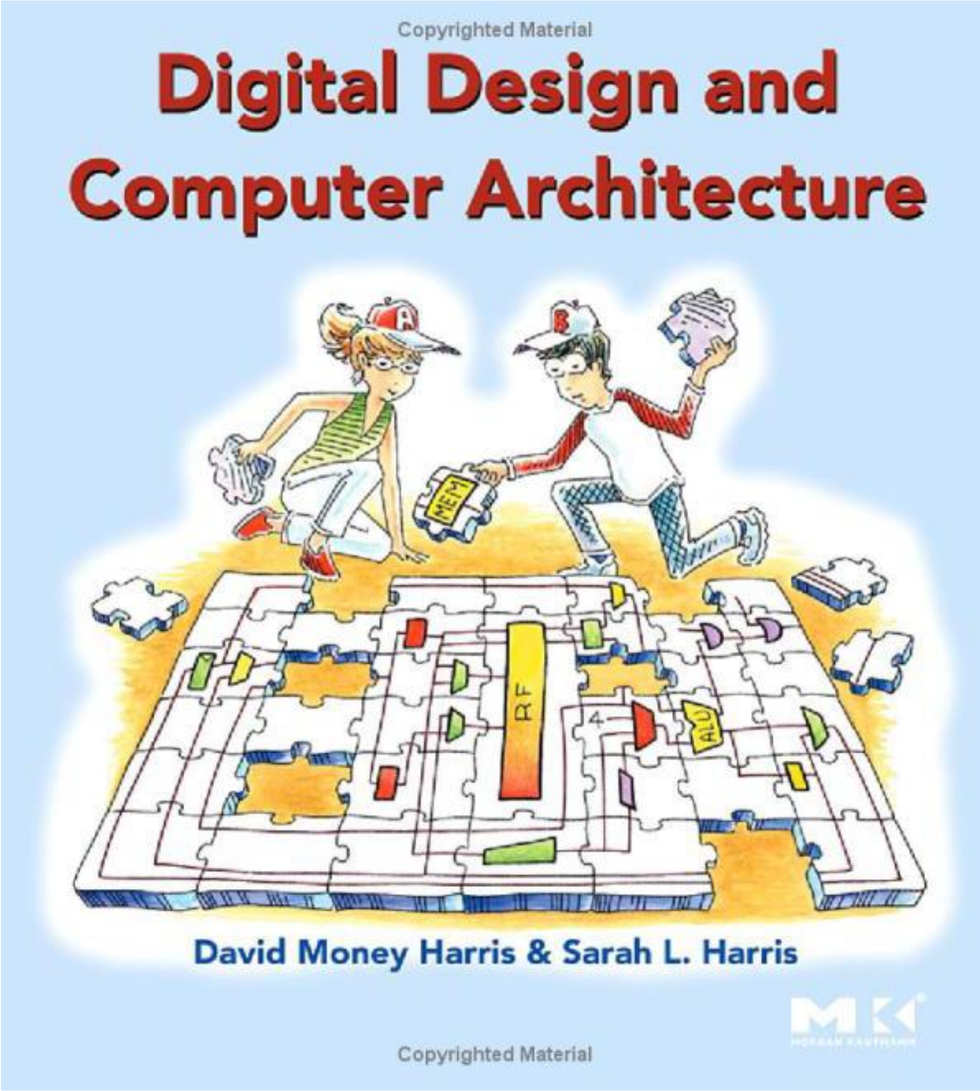
Study: CS222: Computer Architecture



What ? Computer Architecture

- **computer architecture** defines how to command a processor.
- **computer architecture** is a set of rules and methods that describe the functionality, organization, and implementation of computer system.

How ? Course Book



How ? Course Content

Lec #	Subject	Week #
Lec 1	Chapter 1: From Zero to One	Week #1
Lec 2	Chapter 2: Combinational Logic Design	Week #2
Lec 3	Chapter 3: Sequential Logic Design	Week #3
Lec 4	Chapter 3 Continue	Week #4
Lec 5	Chapter 5: Digital Building Blocks	Week #5
Lec 6	Chapter 5 Continue	Week #6
Lec 7	Chapter 6: Computer Architecture	Week #7
	Midterm Exam	Week #8
Lec 8	Chapter 6 : Continue	Week #9
Lec 9	Chapter 7: Microarchitecture	Week #10
Lec 10	Chapter 7 Continue	Week #11
Lec 11	Chapter 7 Continue	Week #12
Lec 12	General Revision	Week #13

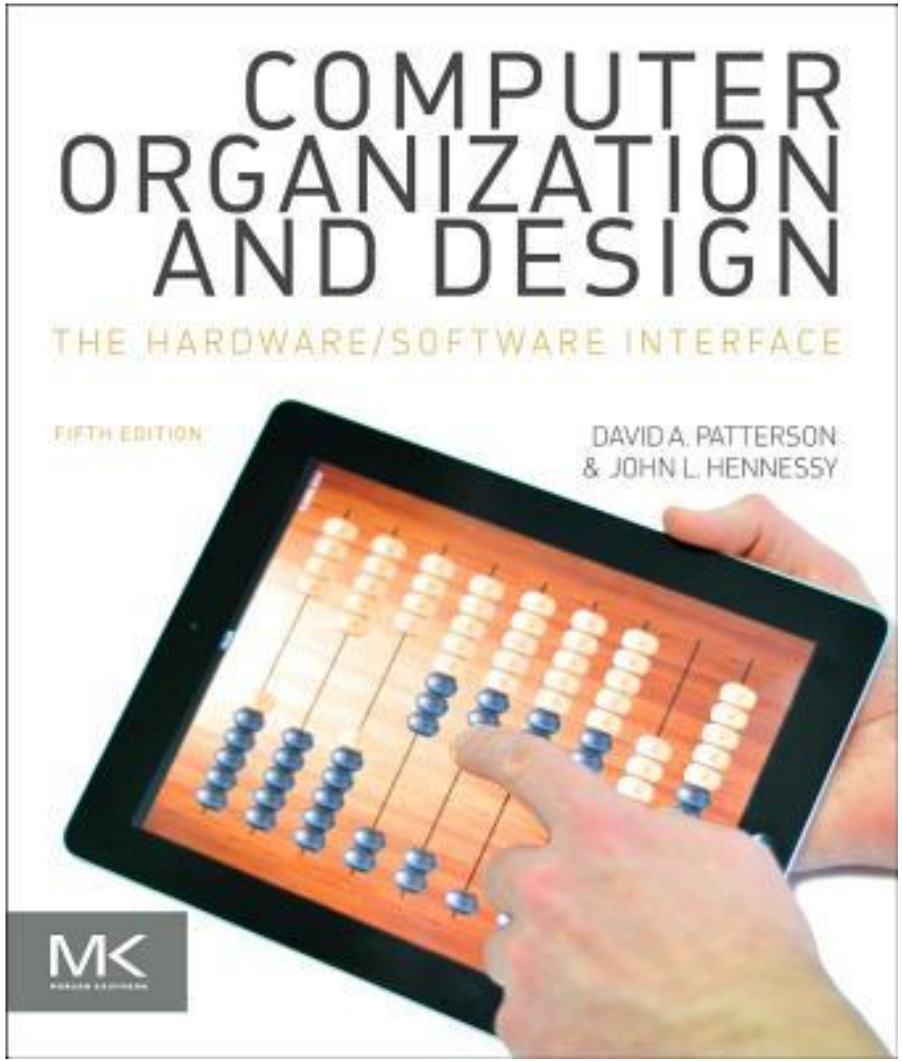
Assessment

Final-Term Exam 50

Mid-Term Exam + lab Exam + Oral Exam + Projects

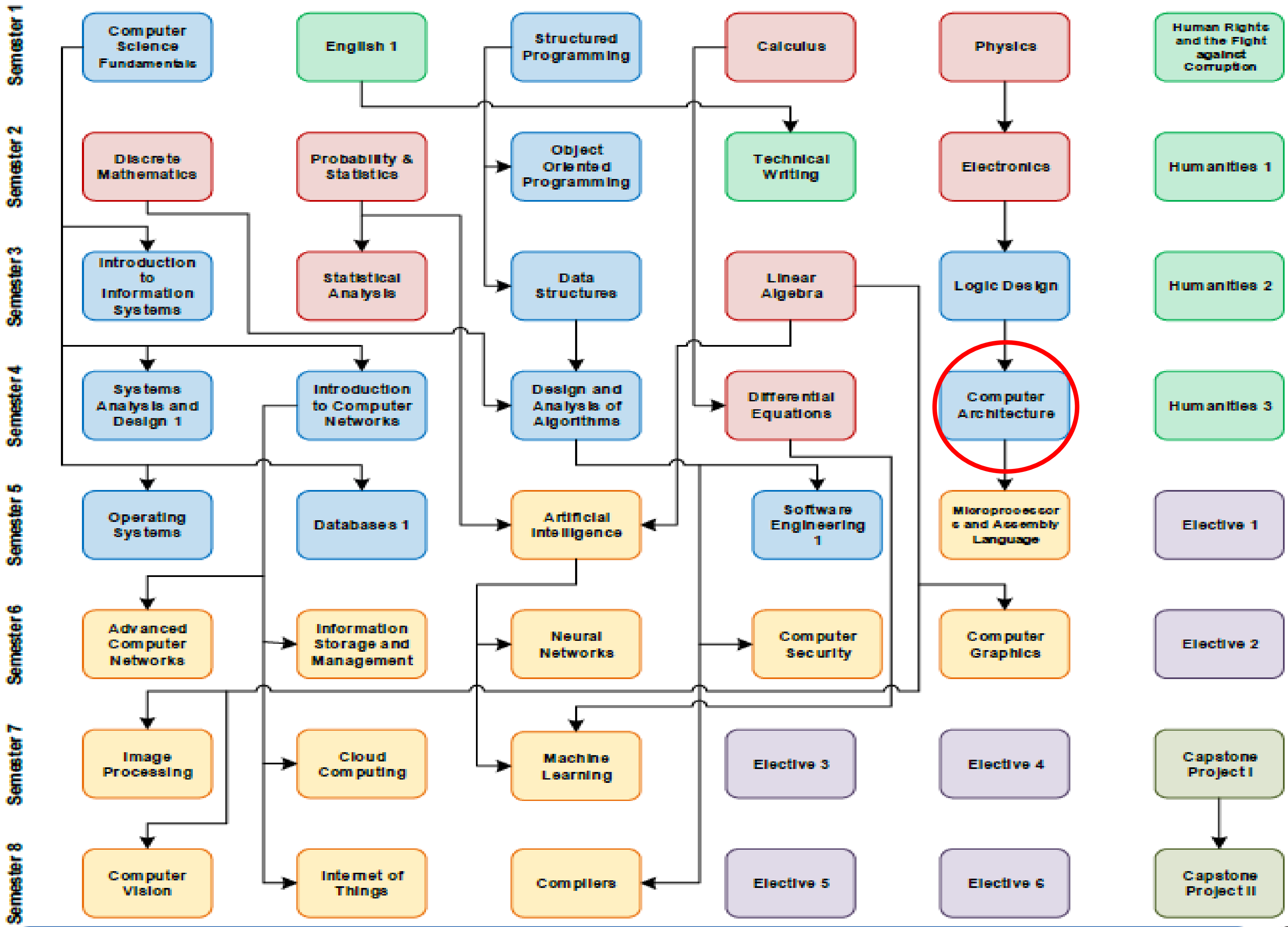
- logic design Project in Verilog – the week after midterm (Lab)
- final project -> lab exam 50

Reference Book



Why ? Computer Architecture

Computer Architecture



Chapter 1

Digital Design and Computer Architecture, 2nd Edition

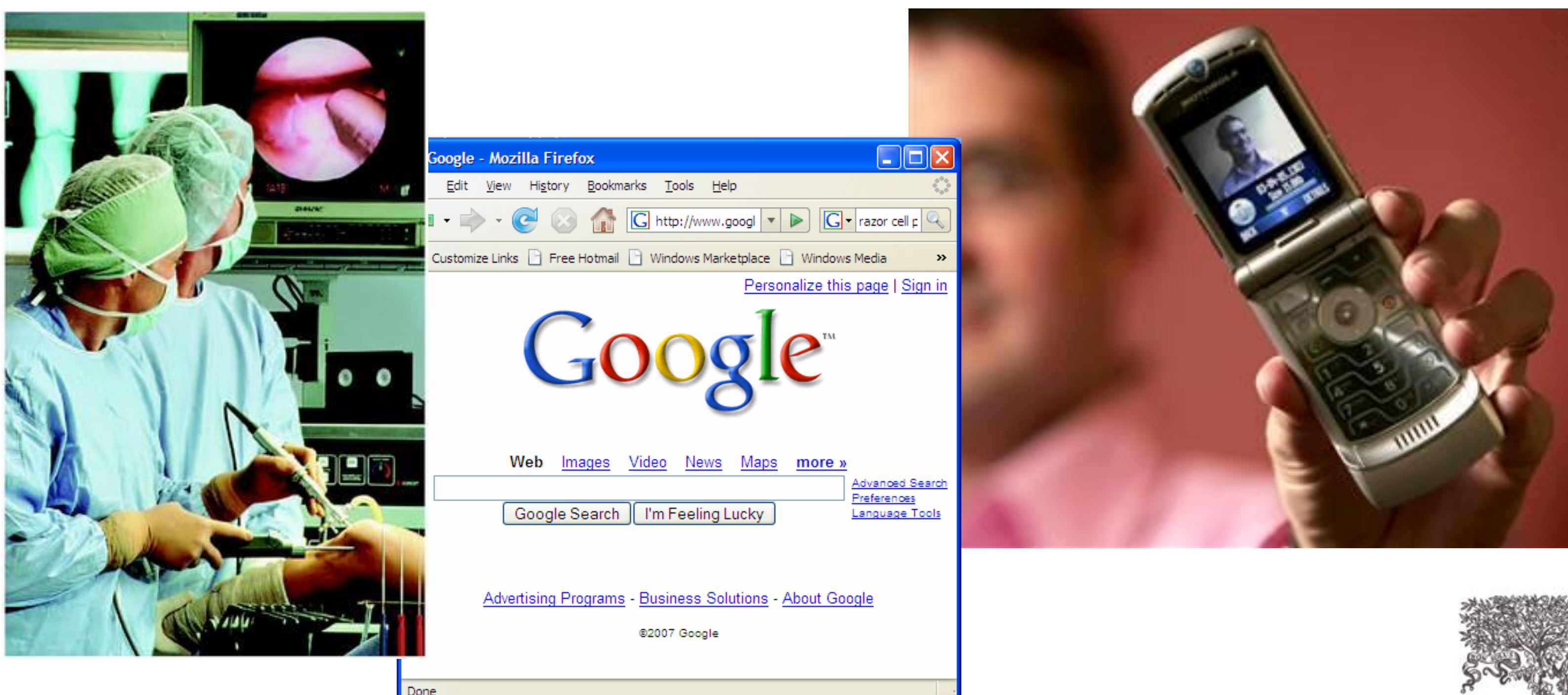
David Money Harris and Sarah L. Harris

Chapter 1 :: Topics

- **Background**
- **The Game Plan**
- **The Art of Managing Complexity**
- **The Digital Abstraction**
- **Number Systems**
- **Logic Gates**
- **Logic Levels**
- **CMOS Transistors**
- **Power Consumption**

Background

- Microprocessors have revolutionized our world
  - Cell phones, Internet, rapid advances in medicine, etc.
- The semiconductor industry has grown from $21 billion in 1985 to $300 billion in 2011



The Game Plan

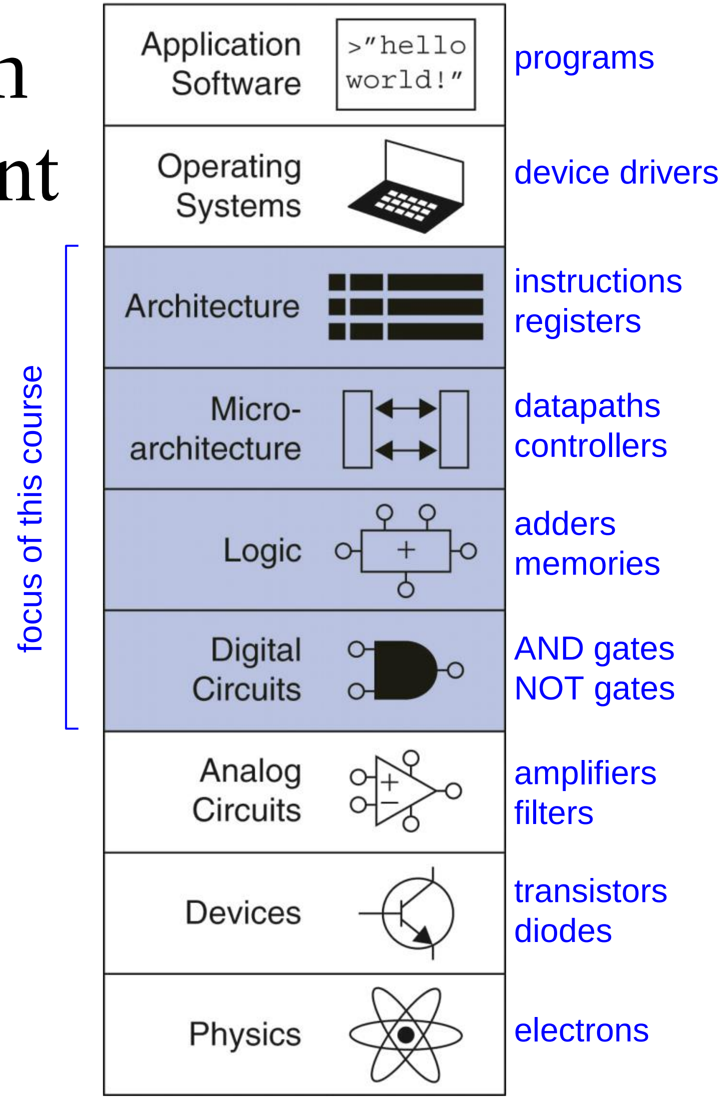
- Purpose of the course:
  - Understand what’s under the hood of a computer
  - Learn the principles of digital design
  - Design and build a microprocessor

The Art of Managing Complexity

- Abstraction
- Discipline
- The Three –y's
  - Hierarch**y**
  - Modularit**y**
  - Regularit**y**

Abstraction

- Hiding details when they aren't important



Discipline

- Intentionally restrict design choices
- Example: Digital discipline
  - Discrete voltages instead of continuous
  - Simpler to design than analog circuits – can build more sophisticated systems
  - Digital systems replacing analog predecessors:
    - i.e., digital cameras, digital television, cell phones, CDs

The Three -y's

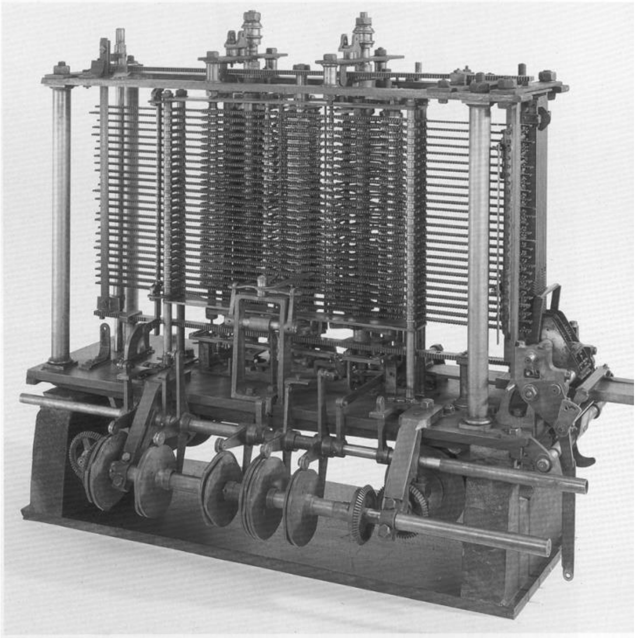
- **Hierarchy**
  - A system divided into modules and submodules
- **Modularity**
  - Having well-defined functions and interfaces
- **Regularity**
  - Encouraging uniformity, so modules can be easily reused

The Digital Abstraction

- Most physical variables are **continuous**
  - Voltage on a wire
  - Frequency of an oscillation
  - Position of a mass
- Digital abstraction considers **discrete subset** of values

The Analytical Engine

- Designed by Charles Babbage from 1834 – 1871
- Considered to be the first digital computer
- Built from mechanical gears, where each gear represented a discrete value (0-9)
- Babbage died before it was finished

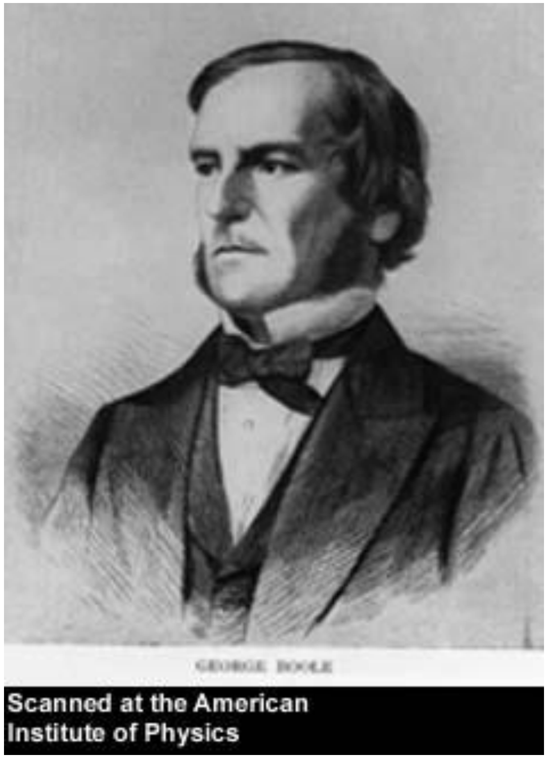


Digital Discipline: Binary Values

- **Two discrete values:**
  - 1's and 0's
  - 1, TRUE, HIGH
  - 0, FALSE, LOW
- **1 and 0:** voltage levels, rotating gears, fluid levels, etc.
- Digital circuits use **voltage** levels to represent 1 and 0
- ***Bit***: *B*inary dig*it*

George Boole, 1815-1864

- Born to working class parents
- Taught himself mathematics and joined the faculty of Queen’s College in Ireland
- Wrote *An Investigation of the Laws of Thought* (1854)
- Introduced binary variables
- Introduced the three fundamental logic operations: AND, OR, and NOT



FROM ZERO TO ONE

Number Systems

- Decimal numbers

1000's column
100's column
10's column
1's column

$$5374_{10} = 5 \times 10^3 + 3 \times 10^2 + 7 \times 10^1 + 4 \times 10^0$$

five thousands · three hundreds · seven tens · four ones

- Binary numbers

8's column
4's column
2's column
1's column

$$1101_2 = 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 13_{10}$$

one eight · one four · no two · one one

Powers of Two

- $2^0 = 1$
- $2^1 = 2$
- $2^2 = 4$
- $2^3 = 8$
- $2^4 = 16$
- $2^5 = 32$
- $2^6 = 64$
- $2^7 = 128$
- $2^8 = 256$
- $2^9 = 512$
- $2^{10} = 1024$
- $2^{11} = 2048$
- $2^{12} = 4096$
- $2^{13} = 8192$
- $2^{14} = 16384$
- $2^{15} = 32768$
- Handy to memorize up to 2^9

Number Conversion

- Decimal to binary conversion:
  - Convert 10011_2 to decimal
  - $16\times1 + 8\times0 + 4\times0 + 2\times1 + 1\times1 = 19_{10}$

- Decimal to binary conversion:
  - Convert 47_{10} to binary
  - $32\times1 + 16\times0 + 8\times1 + 4\times1 + 2\times1 + 1\times1 = 101111_2$

Binary Values and Range

- *N*-digit decimal number
  - How many values? 10^N
  - Range? $[0, 10^N - 1]$
  - Example: 3-digit decimal number:
    - $10^3 = 1000$ possible values
    - Range: [0, 999]
- *N*-bit binary number
  - How many values? 2^N
  - Range: $[0, 2^N - 1]$
  - Example: 3-digit binary number:
    - $2^3 = 8$ possible values
    - Range: $[0, 7] = [000_2 \text{ to } 111_2]$

Hexadecimal Numbers

Hex Digit	Decimal Equivalent	Binary Equivalent
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

Hexadecimal Numbers

- Base 16
- Shorthand for binary

Hexadecimal to Binary Conversion

- Hexadecimal to binary conversion:
  - Convert $4AF_{16}$ (also written 0x4AF) to binary
  - $0100\ 1010\ 1111_2$

- Hexadecimal to decimal conversion:
  - Convert $4AF_{16}$ to decimal
  - $16^2 \times 4 + 16^1 \times 10 + 16^0 \times 15 = 1199_{10}$

FROM ZERO TO ONE

Bits, Bytes, Nibbles…

- Bits

10010110

most significant bit — least significant bit

- Bytes & Nibbles

byte

10010110

nibble

- Bytes

CEBF9AD7

most significant byte — least significant byte

Large Powers of Two

- 2^{10} = 1 kilo ≈ 1000 (1024)
- 2^{20} = 1 mega ≈ 1 million (1,048,576)
- 2^{30} = 1 giga ≈ 1 billion (1,073,741,824)

Addition

- Decimal

```
   11  ← carries
   3734
 + 5168
 ------
   8902
```

- Binary

```
   11  ← carries
   1011
 + 0011
 ------
   1110
```

Binary Addition Examples

- Add the following 4-bit binary numbers

```
   1
  1001
+ 0101
------
  1110
```

- Add the following 4-bit binary numbers

```
 111
  1011
+ 0110
------
 10001
```

Overflow!

Overflow

- Digital systems operate on a **fixed number of bits**
- Overflow: when the result is too big to fit in the available number of bits
- See the previous example of 11 + 6

Signed Binary Numbers

- Sign/Magnitude Numbers
- Two's Complement Numbers

Sign/Magnitude Numbers

- 1 sign bit, *N*-1 magnitude bits
- Sign bit is the most significant (left-most) bit
  - Positive number: sign bit = 0
  - Negative number: sign bit = 1

$$A : \{a_{N-1}, a_{N-2}, \cdots a_2, a_1, a_0\}$$

$$A = (-1)^{a_{n-1}} \sum_{i=0}^{n-2} a_i 2^i$$

- Example, 4-bit sign/mag representations of ± 6:

  +6 = **0110**

  - 6 = **1110**

- Range of an *N*-bit sign/magnitude number:

  $[-(2^{N-1}-1), 2^{N-1}-1]$

Sign/Magnitude Numbers

- Problems:
  - Addition doesn't work, for example -6 + 6:

```
   1110
 + 0110
 ------
  10100 (wrong!)
```

  - Two representations of 0 (± 0):

```
   1000
   0000
```

Two's Complement Numbers

- Don't have same problems as sign/magnitude numbers:
  - Addition works
  - Single representation for 0

Two's Complement Numbers

- Msb has value of -2^{N-1}

$$A = a_{n-1}\left(-2^{n-1}\right) + \sum_{i=0}^{n-2} a_i 2^i$$

- Most positive 4-bit number:
- Most negative 4-bit number:
- The most significant bit still indicates the sign (1 = negative, 0 = positive)
- Range of an *N*-bit two's comp number:

Two's Complement Numbers

- Msb has value of -2^{N-1}

$$A = a_{n-1}\left(-2^{n-1}\right) + \sum_{i=0}^{n-2} a_i 2^i$$

- Most positive 4-bit number: **0111**
- Most negative 4-bit number: **1000**
- The most significant bit still indicates the sign (1 = negative, 0 = positive)
- Range of an *N*-bit two's comp number:

$[-(2^{N-1}), 2^{N-1}-1]$

"Taking the Two's Complement"

- Flip the sign of a two's complement number
- Method:
    1. Invert the bits
    2. Add 1
- Example: Flip the sign of $3_{10} = 0011_2$
    1. **1100**
    2. **+ 1**

$1101 = -3_{10}$

Two's Complement Examples

- Take the two's complement of $6_{10} = 0110_2$
  1. 1001
  2. \+ 1

  $1010_2 = -6_{10}$

- What is the decimal value of the two's complement number 1001_2?
  1. 0110
  2. \+ 1

  $0111_2 = 7_{10}$, so $1001_2 = -7_{10}$

Two's Complement Addition

- Add 6 + (-6) using two's complement numbers

```
   111
    0110
+   1010
--------
   10000
```

- Add -2 + 3 using two's complement numbers

```
   111
    1110
+   0011
--------
   10001
```

Increasing Bit Width

- **Extend number from *N* to *M* bits (*M* > *N*) :**
  - Sign-extension
  - Zero-extension

Sign-Extension

- Sign bit copied to msb's
- Number value is same

- **Example 1:**
  - 4-bit representation of 3 = 0011
  - 8-bit sign-extended value: 00000011
- **Example 2:**
  - 4-bit representation of -5 = 1011
  - 8-bit sign-extended value: 11111011

Zero-Extension

- Zeros copied to msb's
- Value changes for negative numbers

- **Example 1:**
  - 4-bit value = $0011_2 = 3_{10}$
  - 8-bit zero-extended value: $00000011 = 3_{10}$
- **Example 2:**
  - 4-bit value = $1011 = -5_{10}$
  - 8-bit zero-extended value: $00001011 = 11_{10}$

Number System Comparison

Number System	Range
Unsigned	$[0, 2^N-1]$
Sign/Magnitude	$[-(2^{N-1}-1), 2^{N-1}-1]$
Two's Complement	$[-2^{N-1}, 2^{N-1}-1]$

For example, 4-bit representation:

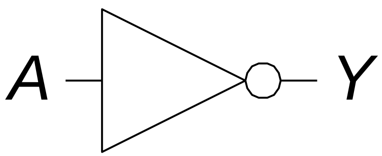
	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Unsigned									0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
Two's Complement	1000	1001	1010	1011	1100	1101	1110	1111	0000	0001	0010	0011	0100	0101	0110	0111								
Sign/Magnitude		1111	1110	1101	1100	1011	1010	1001	0000 1000	0001	0010	0011	0100	0101	0110	0111								

Logic Gates

- **Perform logic functions:**
  - inversion (NOT), AND, OR, NAND, NOR, etc.
- **Single-input:**
  - NOT gate, buffer
- **Two-input:**
  - AND, OR, XOR, NAND, NOR, XNOR
- **Multiple-input**

Single-Input Logic Gates

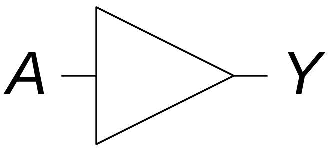
NOT



$$Y = \overline{A}$$

A	Y
0	1
1	0

BUF

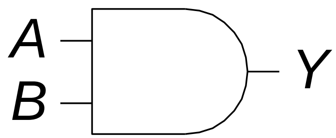


$$Y = A$$

A	Y
0	0
1	1

Two-Input Logic Gates

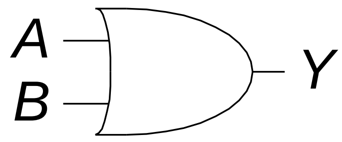
AND



$Y = AB$

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

OR

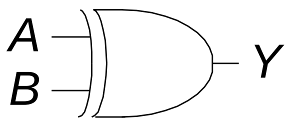


$Y = A + B$

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

More Two-Input Logic Gates

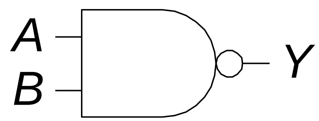
XOR



$Y = A \oplus B$

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

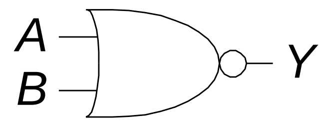
NAND



$Y = \overline{AB}$

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

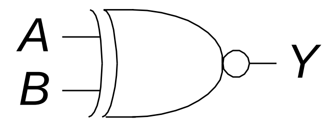
NOR



$Y = \overline{A + B}$

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

XNOR

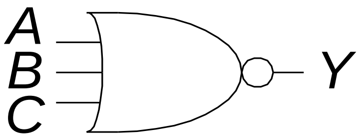


$Y = \overline{A \oplus B}$

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

Multiple-Input Logic Gates

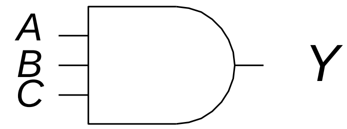
NOR3



$$Y = \overline{A+B+C}$$

A	B	C	Y
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

AND3



$$Y = ABC$$

A	B	C	Y
0	0	0	0
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	1

- Multi-input XOR: Odd parity

Logic Levels

- Discrete voltages represent 1 and 0
- For example:
  - 0 = *ground* (GND) or 0 volts
  - 1 = V_{DD} or 5 volts
- What about 4.99 volts? Is that a 0 or a 1?
- What about 3.2 volts?

Logic Levels

- *Range* of voltages for 1 and 0
- Different ranges for inputs and outputs to allow for *noise*

V_{DD} Scaling

- In 1970's and 1980's, V_{DD} = 5 V
- V_{DD} has dropped
  - Avoid frying tiny transistors
  - Save power
- 3.3 V, 2.5 V, 1.8 V, 1.5 V, 1.2 V, 1.0 V, …
- Be careful connecting chips with different supply voltages

Chips operate because they contain magic smoke

Proof:

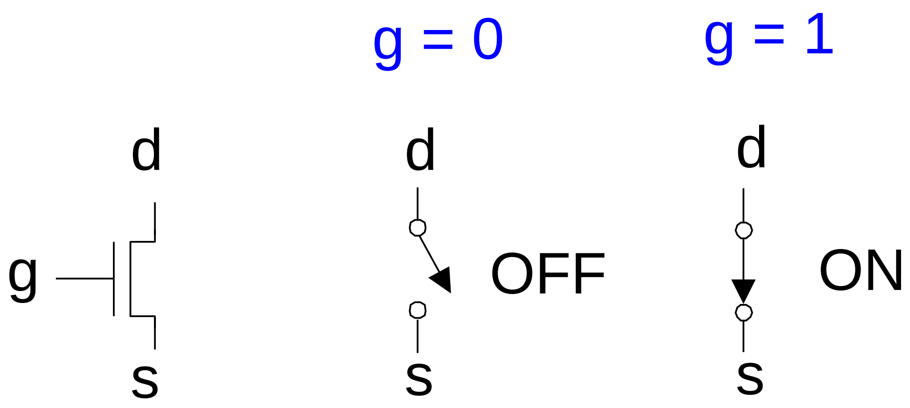
- if the magic smoke is let out, the chip stops working

Logic Family Examples

Logic Family	V_{DD}	V_{IL}	V_{IH}	V_{OL}	V_{OH}
TTL	5 (4.75 - 5.25)	0.8	2.0	0.4	2.4
CMOS	5 (4.5 - 6)	1.35	3.15	0.33	3.84
LVTTL	3.3 (3 - 3.6)	0.8	2.0	0.4	2.4
LVCMOS	3.3 (3 - 3.6)	0.9	1.8	0.36	2.7

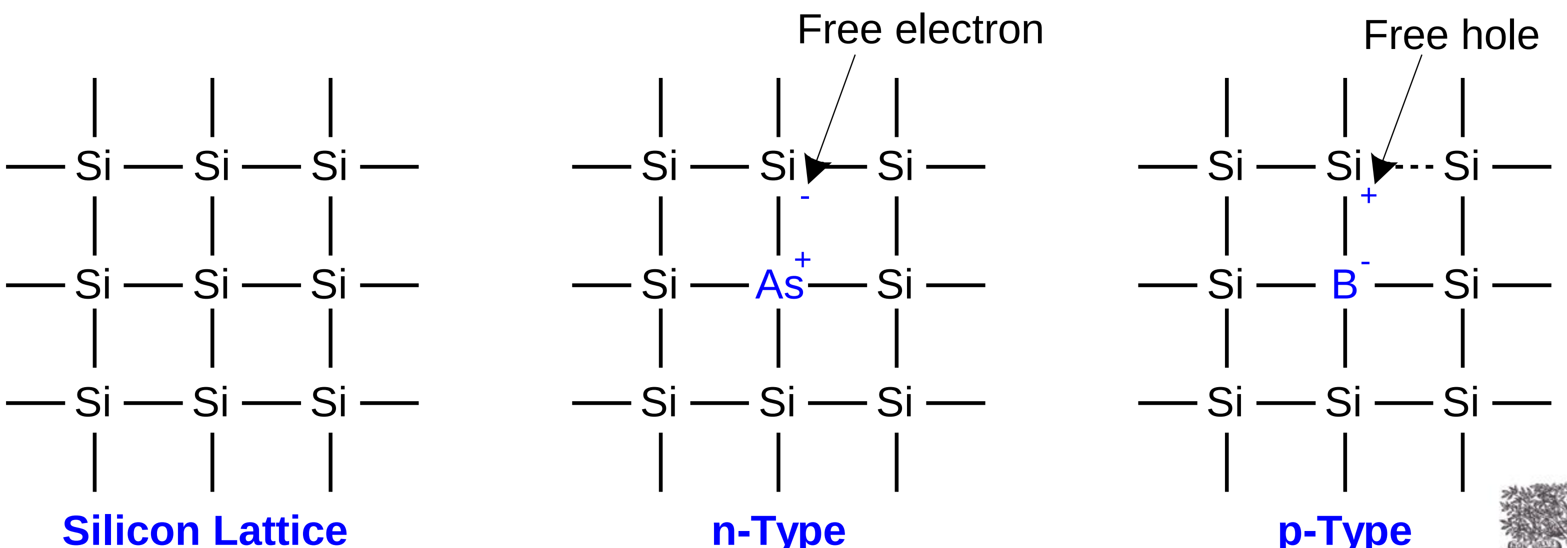
Transistors

- Logic gates built from transistors
- 3-ported voltage-controlled switch
  - 2 ports connected depending on voltage of 3rd
  - d and s are connected (ON) when g is 1



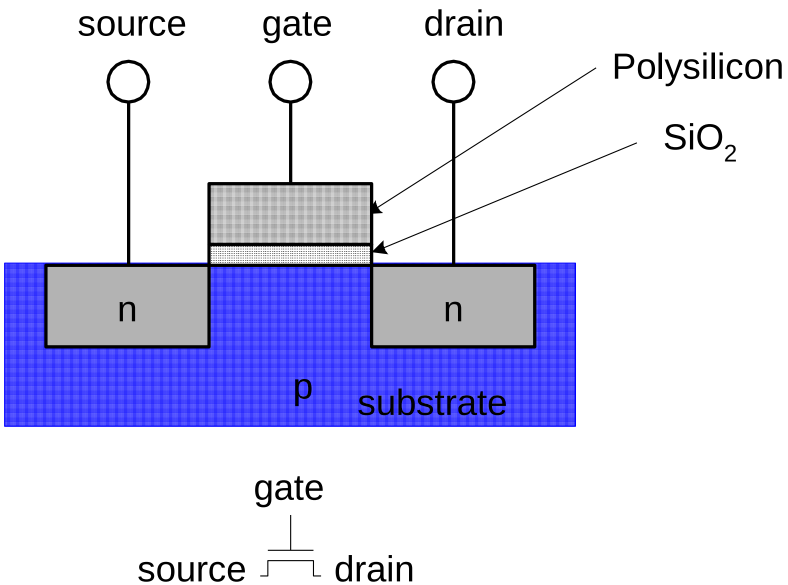
Silicon

- Transistors built from silicon, a semiconductor
- Pure silicon is a poor conductor (no free charges)
- Doped silicon is a good conductor (free charges)
  - n-type (free *n*egative charges, electrons)
  - p-type (free *p*ositive charges, holes)



MOS Transistors

- **Metal oxide silicon (MOS) transistors:**
  - Polysilicon (used to be **metal**) gate
  - **Oxide** (silicon dioxide) insulator
  - Doped **silicon**

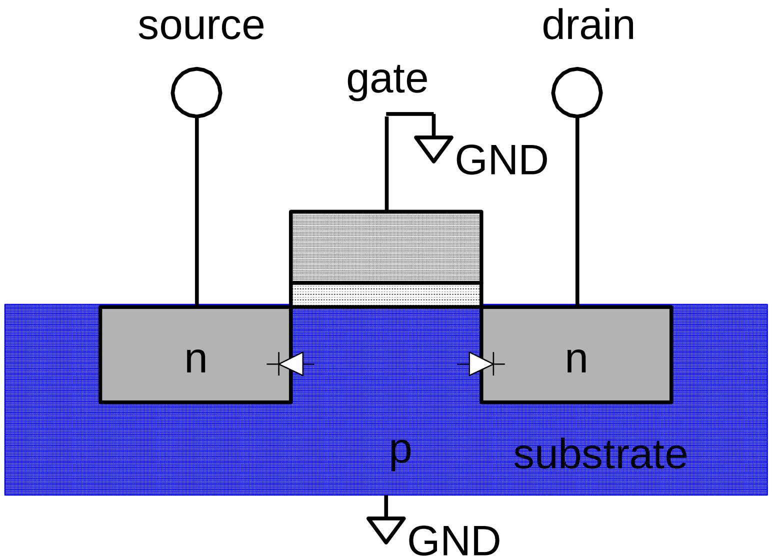


nMOS

Transistors: nMOS

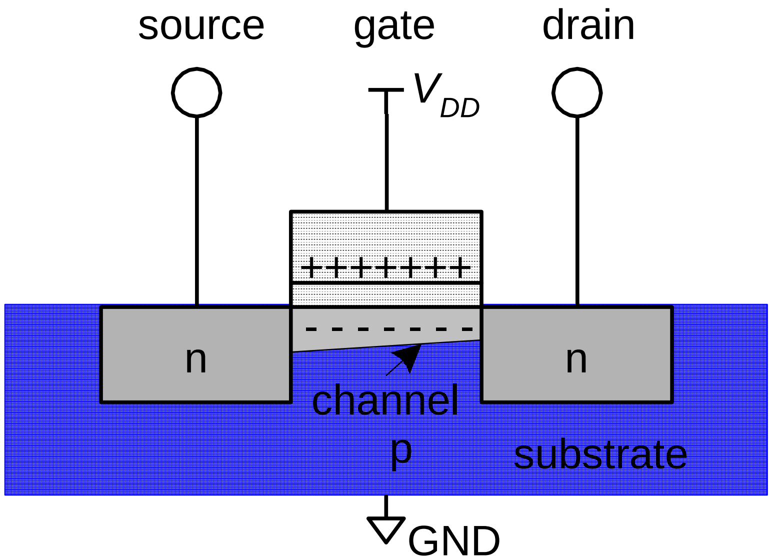
Gate = 0

OFF (no connection between source and drain)



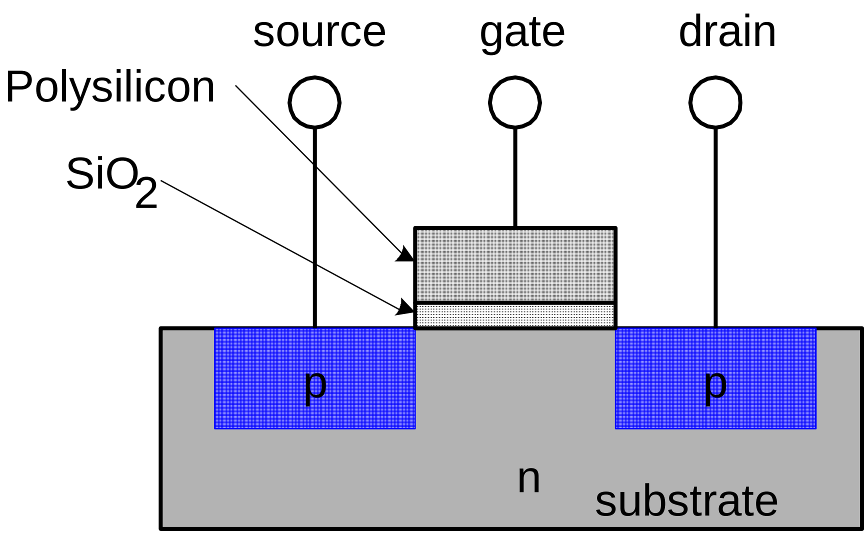
Gate = 1

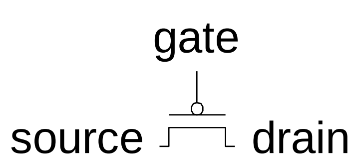
ON (channel between source and drain)



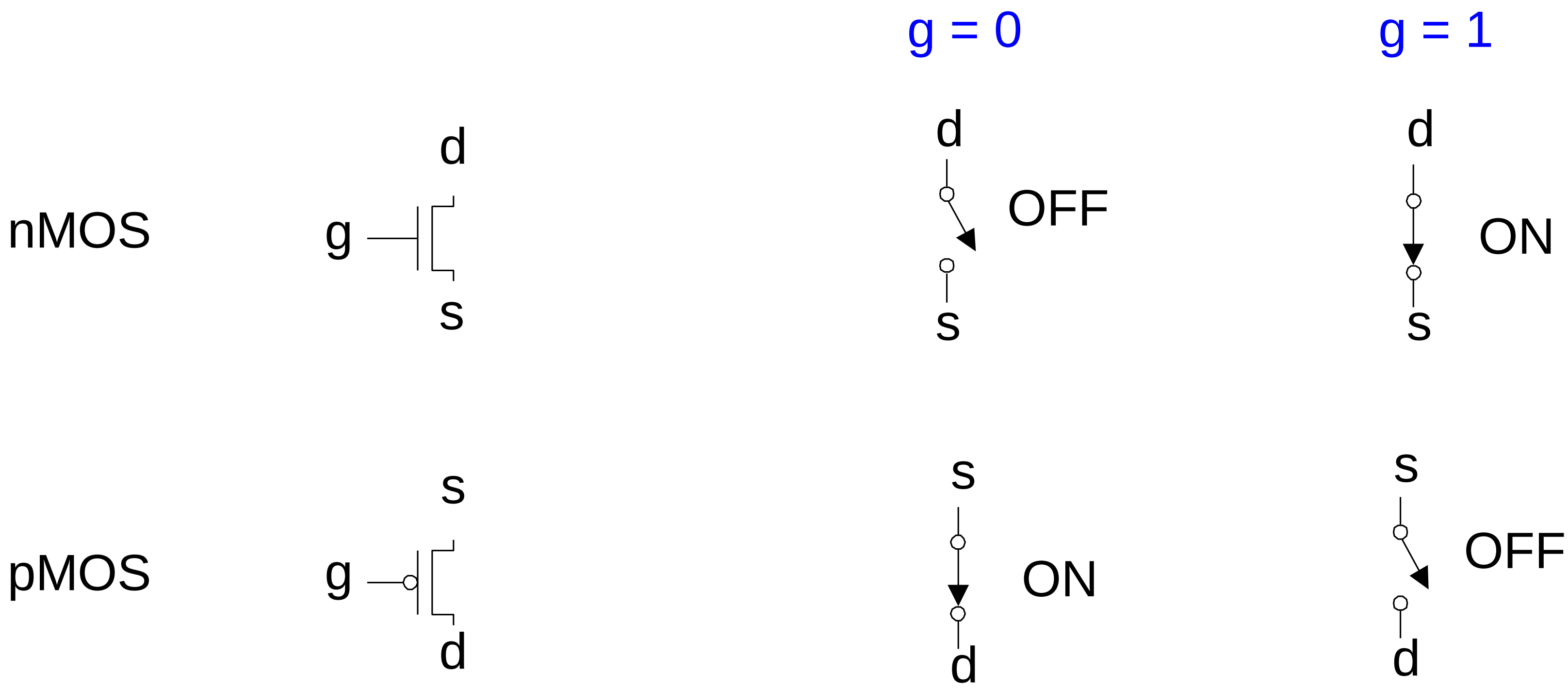
Transistors: pMOS

- pMOS transistor is opposite
  - ON when Gate = 0
  - OFF when Gate = 1



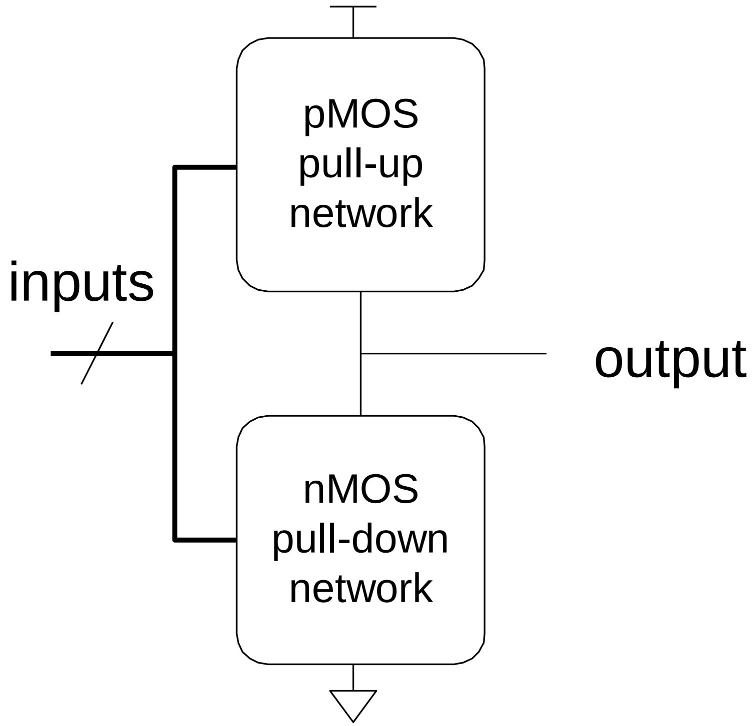


Transistor Function

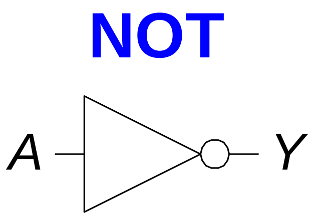


Transistor Function

- **nMOS:** pass good 0's, so connect source to GND
- **pMOS:** pass good 1's, so connect source to V_{DD}

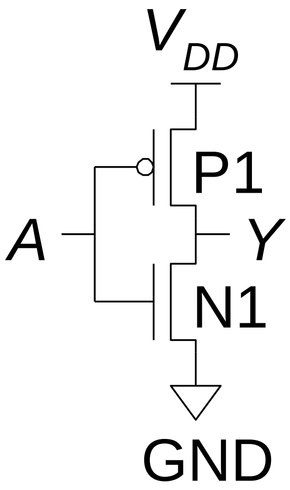


CMOS Gates: NOT Gate



$$Y = \overline{A}$$

A	Y
0	1
1	0

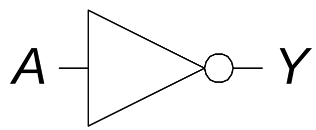


A	P1	N1	*Y*
0			
1			

FROM ZERO TO ONE

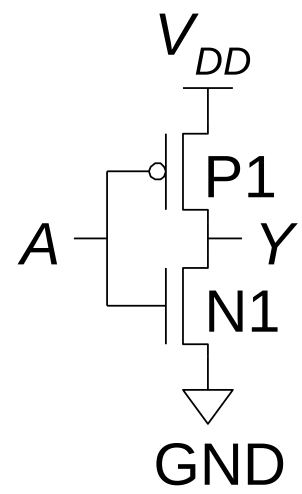
CMOS Gates: NOT Gate

NOT



$Y = \overline{A}$

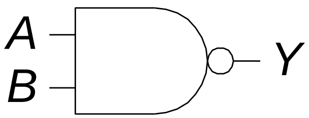
A	Y
0	1
1	0



A	P1	N1	*Y*
0	ON	OFF	1
1	OFF	ON	0

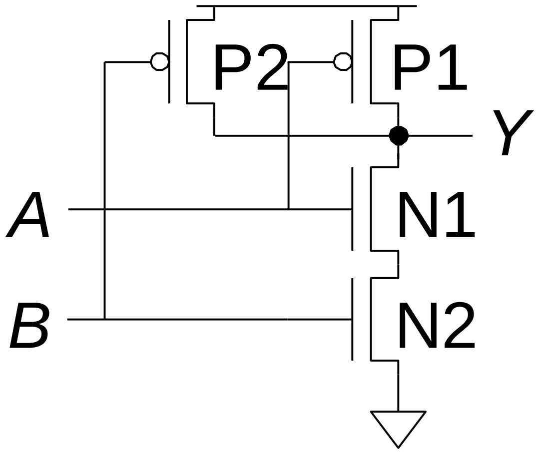
CMOS Gates: NAND Gate

NAND



$Y = \overline{AB}$

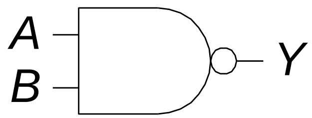
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0



A	*B*	P1	P2	N1	N2	*Y*
0	0					
0	1					
1	0					
1	1					

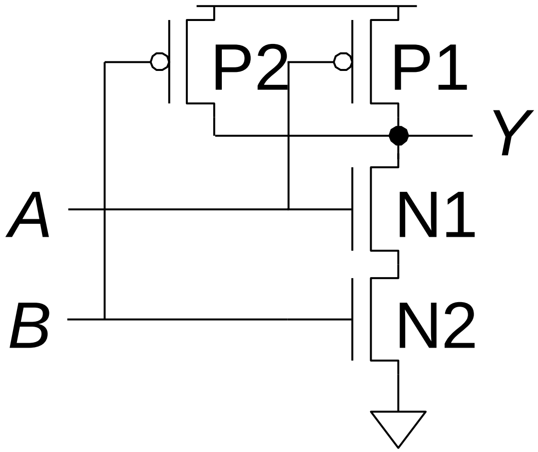
CMOS Gates: NAND Gate

NAND



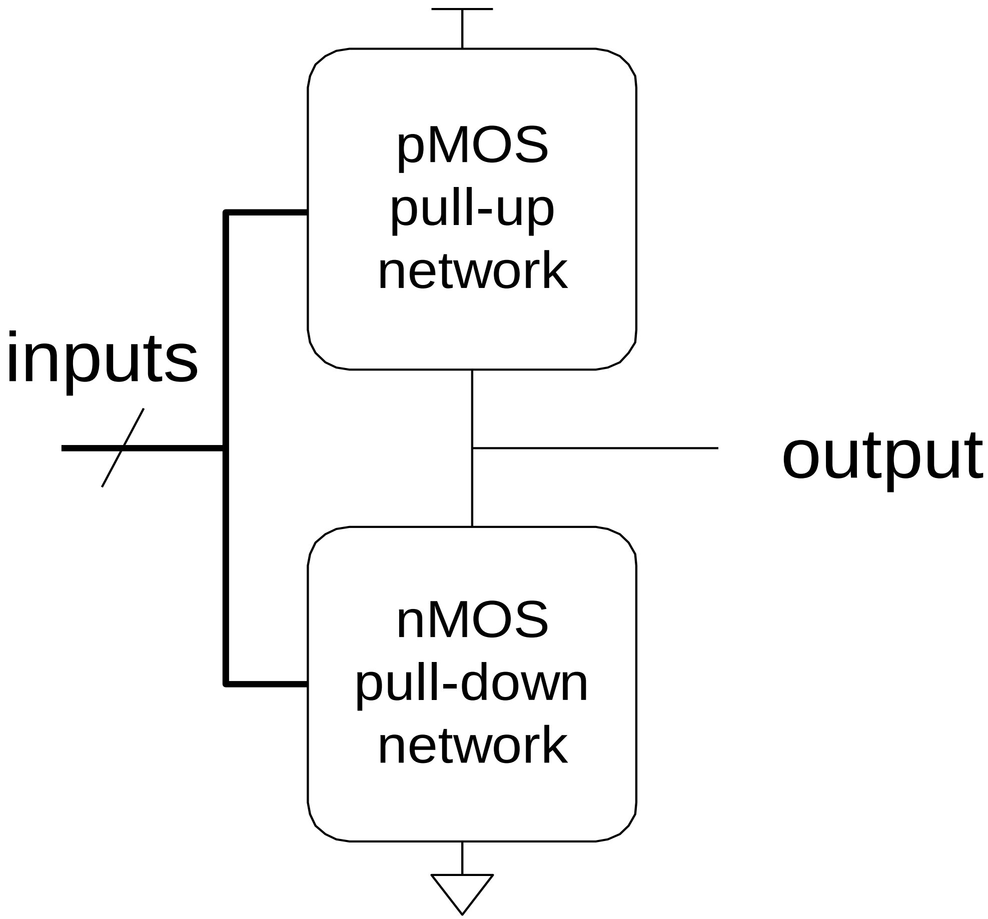
$$Y = \overline{AB}$$

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0



A	*B*	P1	P2	N1	N2	*Y*
0	0	ON	ON	OFF	OFF	1
0	1	ON	OFF	OFF	ON	1
1	0	OFF	ON	ON	OFF	1
1	1	OFF	OFF	ON	ON	0

CMOS Gate Structure

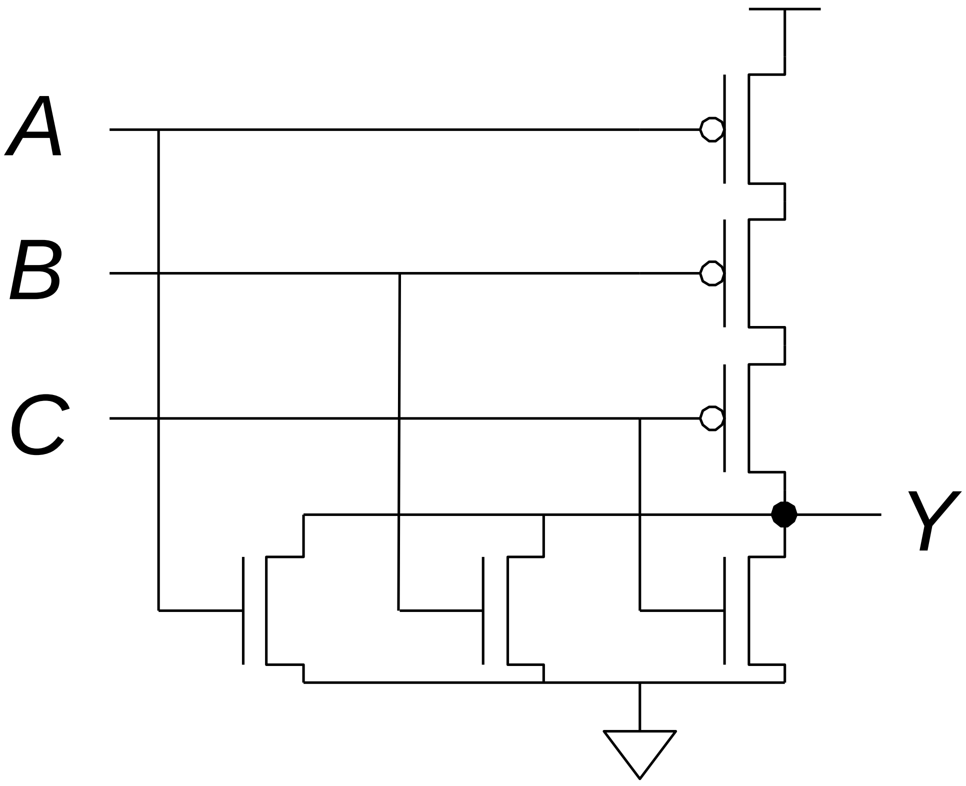


Silicon Run 1 2nd Edition.rm

NOR Gate

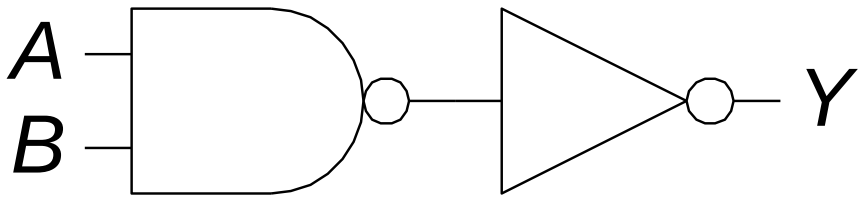
How do you build a three-input NOR gate?

NOR3 Gate



Other CMOS Gates

How do you build a two-input AND gate?



FROM ZERO TO ONE

Chapter 1 :: Topics

- **Background**
- **The Game Plan**
- **The Art of Managing Complexity**
- **The Digital Abstraction**
- **Number Systems**
- **Logic Gates**
- **Logic Levels**
- **CMOS Transistors**

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