



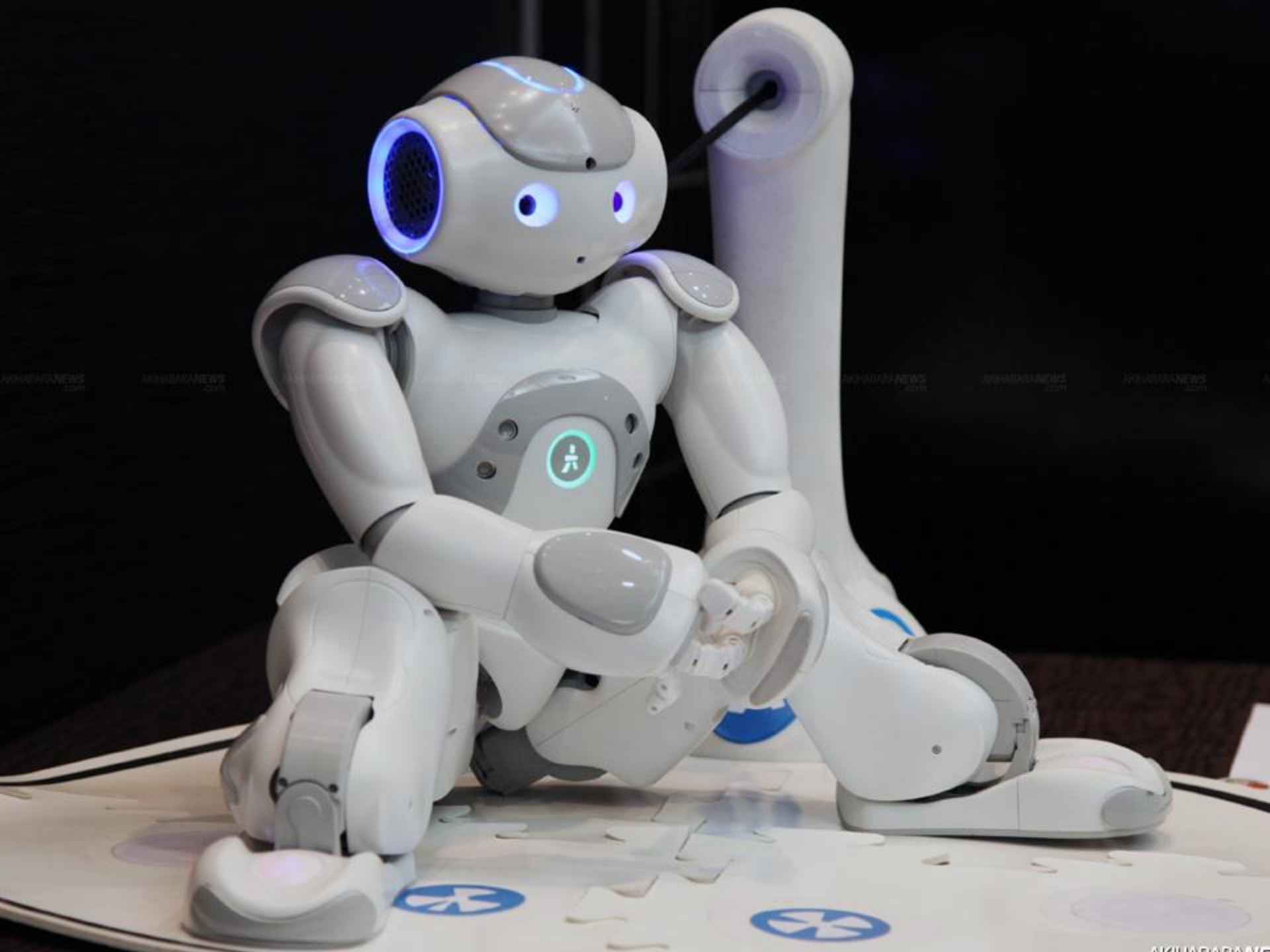
# innopolis UNIVERSITY

## Computer Architecture

Nikolaos Mavridis, PhD Massachusetts Institute of Technology

Professor, Innopolis University; Director, IRML Lab;

Head of Robotics Institute, Innopolis



# MY BACKGROUND



**PhD from MIT Media Lab**

**Born in Thessaloniki, Greece**





**Grounded  
Situation Models:  
Where words and  
percepts meet**

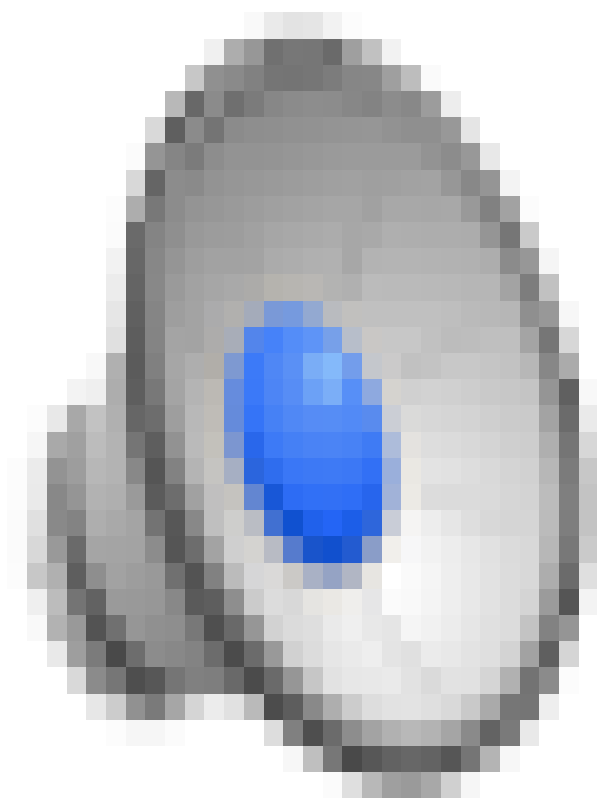


BBC  
NEWS



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# Nikolaos Mavridis

- Education

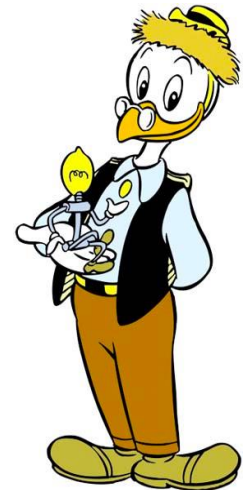
- *PhD – Massachusetts Institute of Tech (MIT)*
- *MS – University of California Los Angeles (UCLA)*
- *5-Yr Dipl. Eng. – Aristotle Uni of Thessaloniki*
- “Coder” and “Maker” since 10 years old! + online

- Experience

- Professor and Lab Director – 7 years
- Graduate Researcher – 7 years
- Fields: Interactive and Social Robotics, Applied Computer Vision & Machine Learning, Cognitive Systems
- Leadership, Consultancy & Volunteering Positions

- Academic Bases

- Massachusetts Institute of Technology (USA)
- ITI & NCSR-Demokritos (GREECE)



# MS-RO: 2-Year Robotics Masters @ Innopolis

- Program Objectives

- 1) Create future leaders for industry, entrepreneurship and government
- 2) Students for PhD programs in various Robotics-related disciplines
- 3) Interdisciplinary thinkers with advanced collaboration skills
- 4) Competitive in national and international job markets
- 5) Provide strong basis for just-in-time and life-long learning

- Emphasis on

- Hands-on experience with all the latest tools, in an ideal mix with deep interdisciplinary understanding that enables rapid adaptation
- Very strong synergistic connectivity with local & global ecosystem

- Some of our Resources

- Labs, Advanced Curriculum, World-class Faculty, Selected Students



# If you want:

- A cool interdisciplinary field, where everything you will want to explore in your life will somehow be connected with your work!
- A way to help humanity improve its present condition
- Exciting teamwork and many employment and startup opportunities
- The possibility to really deeply self-reflect about cognition, perception, emotion, beliefs, goals, interaction...

..and to Know Thyself

## THEN, BECOME A ROBOTICIST!



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# Chapter 1

## ***Digital Design and Computer Architecture, 2<sup>nd</sup> Edition***

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David Money Harris and Sarah L. Harris

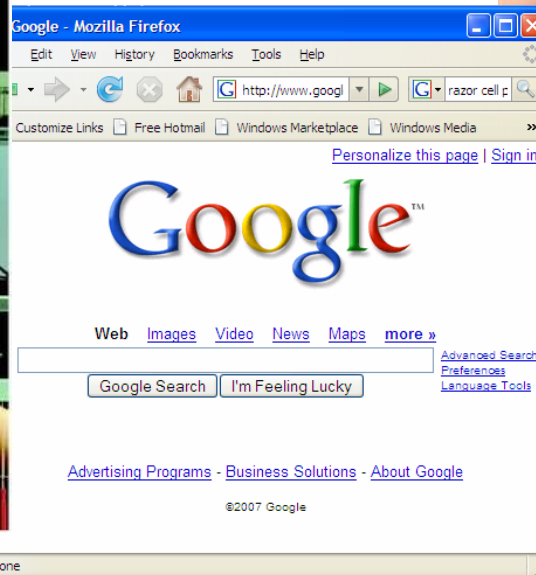
Or... How we will go all the way from Sand....  
...through your Laptops....  
....to the Collective Intelligence of the Earth

# 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 course:
  - Understand what's under the hood of a computer
  - Learn the principles of digital design
  - Learn to systematically debug increasingly complex designs
  - Design and build a microprocessor



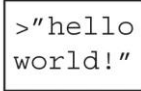

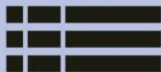
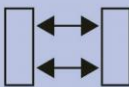
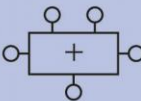
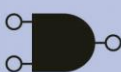
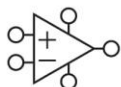


# The Art of Managing Complexity

- Abstraction
- Discipline
- The Three –y's
  - Hierarchy
  - Modularity
  - Regularity

# Abstraction

- Hiding details when they aren't important

focus of this course

Application Software		programs
Operating Systems		device drivers
Architecture		instructions registers
Micro-architecture		datapaths controllers
Logic		adders memories
Digital Circuits		AND gates NOT gates
Analog Circuits		amplifiers filters
Devices		transistors diodes
Physics		electrons

# 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**
- **Modularity**
- **Regularity**

# 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

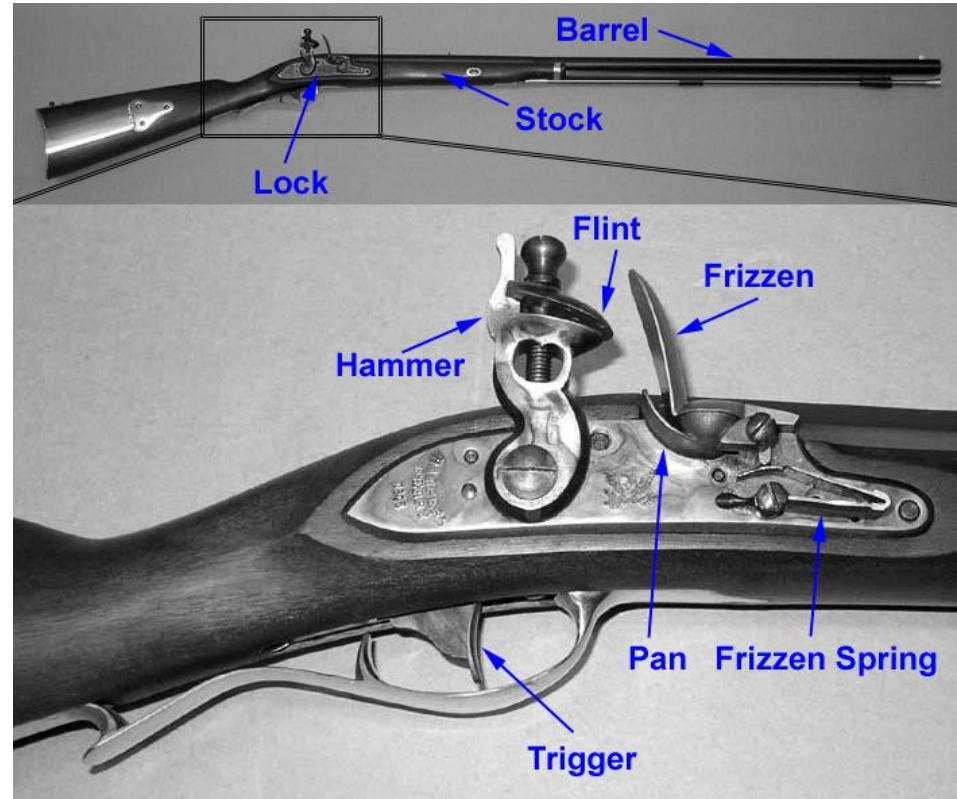




# Example: The Flintlock Rifle

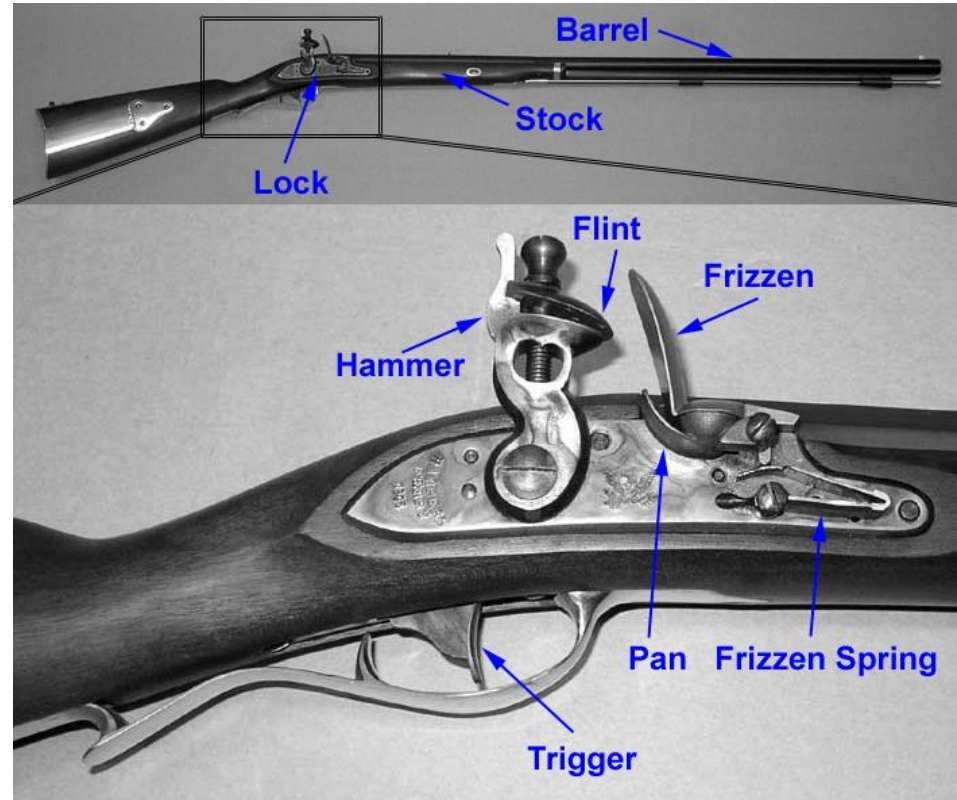
- **Hierarchy**

- **Three main modules:** lock, stock, and barrel
- **Submodules of lock:** hammer, flint, frizzen, etc.



# Example: The Flintlock Rifle

- **Modularity**
  - **Function of stock:** mount barrel and lock
  - **Interface of stock:** length and location of mounting pins
- **Regularity**
  - Interchangeable parts

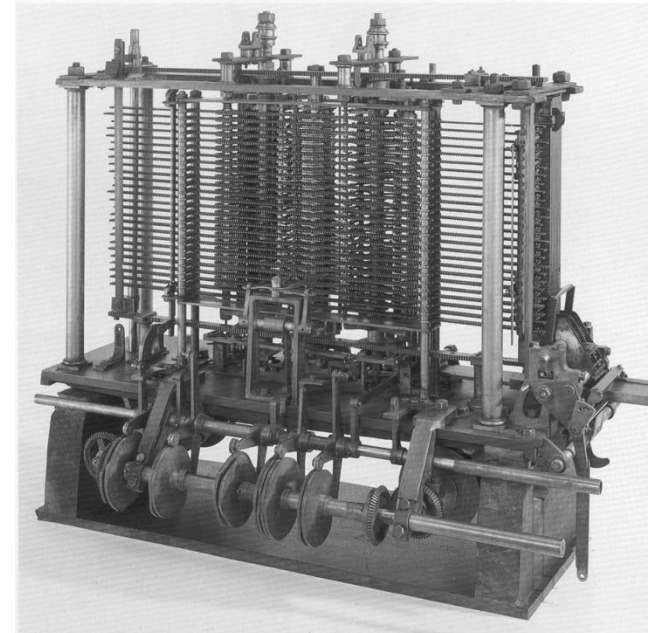


# The Digital Abstraction

- 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:*** Binary digit



# 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



# Number Systems

- Decimal numbers

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

$$5374_{10} =$$

- Binary numbers

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

$$1101_2 =$$

# Number Systems

- Decimal numbers

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

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

five                      three                      seven                      four  
thousands              hundreds              tens                      ones

- Binary numbers

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

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

one                      one                      no                      one  
eight                      four                      two                      one



# Powers of Two

- $2^0 =$

- $2^1 =$

- $2^2 =$

- $2^3 =$

- $2^4 =$

- $2^5 =$

- $2^6 =$

- $2^7 =$

- $2^8 =$

- $2^9 =$

- $2^{10} =$

- $2^{11} =$

- $2^{12} =$

- $2^{13} =$

- $2^{14} =$

- $2^{15} =$

# 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
- Decimal to binary conversion:
  - Convert  $47_{10}$  to binary

# Number Conversion

- Decimal to binary conversion:
  - Convert  $10011_2$  to decimal
  - $16 \times 1 + 8 \times 0 + 4 \times 0 + 2 \times 1 + 1 \times 1 = 19_{10}$
- Decimal to binary conversion:
  - Convert  $47_{10}$  to binary
  - $32 \times 1 + 16 \times 0 + 8 \times 1 + 4 \times 1 + 2 \times 1 + 1 \times 1 = 101111_2$

# Binary Values and Range

- $N$ -digit decimal number
  - How many values?
  - Range?
  - Example: 3-digit decimal number:
- $N$ -bit binary number
  - How many values?
  - Range:
  - Example: 3-digit binary number:

# 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	
1	1	
2	2	
3	3	
4	4	
5	5	
6	6	
7	7	
8	8	
9	9	
A	10	
B	11	
C	12	
D	13	
E	14	
F	15	

# 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
- Hexadecimal to decimal conversion:
  - Convert 0x4AF to decimal



# 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
  - $16^2 \times 4 + 16^1 \times 10 + 16^0 \times 15 = 1199_{10}$



# 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

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

# Estimating Powers of Two

- What is the value of  $2^{24}$ ?
- How many values can a 32-bit variable represent?





# Estimating Powers of Two

- What is the value of  $2^{24}$ ?

$$2^4 \times 2^{20} \approx 16 \text{ million}$$

- How many values can a 32-bit variable represent?

$$2^2 \times 2^{30} \approx 4 \text{ billion}$$



# Addition

- Decimal

$$\begin{array}{r} 3734 \\ + 5168 \\ \hline \end{array}$$

- Binary

$$\begin{array}{r} 1011 \\ + 0011 \\ \hline \end{array}$$

# Addition

- Decimal

$$\begin{array}{r} 11 \leftarrow \text{carries} \\ 3734 \\ + 5168 \\ \hline 8902 \end{array}$$

- Binary

$$\begin{array}{r} 11 \leftarrow \text{carries} \\ 1011 \\ + 0011 \\ \hline 1110 \end{array}$$

# Binary Addition Examples

- Add the following 4-bit binary numbers

$$\begin{array}{r} 1001 \\ + 0101 \\ \hline \end{array}$$

- Add the following 4-bit binary numbers

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

# Binary Addition Examples

- Add the following 4-bit binary numbers

$$\begin{array}{r} 1 \\ 1001 \\ + 0101 \\ \hline 1110 \end{array}$$

- Add the following 4-bit binary numbers

$$\begin{array}{r} 111 \\ 1011 \\ + 0110 \\ \hline 10001 \end{array}$$

Overflow!

# Overflow

- Digital systems operate on a **fixed number of bits**
- Overflow: when result is too big to fit in the available number of bits
- See 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     $A : \{a_{N-1}, a_{N-2}, \dots, a_2, a_1, a_0\}$
  - Negative number: sign bit = 1    
$$A = (-1)^{a_{n-1}} \sum_{i=0}^{n-2} a_i 2^i$$
- Example, 4-bit sign/mag representations of  $\pm 6$ :
  - +6 =
  - 6 =
- Range of an  $N$ -bit sign/magnitude number:

# Sign/Magnitude Numbers

- 1 sign bit,  $N-1$  magnitude bits
- Sign bit is the most significant (left-most) bit
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  - Negative number: sign bit = 1    
$$A = (-1)^{a_{n-1}} \sum_{i=0}^{n-2} a_i 2^i$$
- Example, 4-bit sign/mag representations of  $\pm 6$ :
  - +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  $-6 + 6$ :

$$\begin{array}{r} 1110 \\ + 0110 \\ \hline 10100 \text{ (wrong!)} \end{array}$$

- Two representations of 0 ( $\pm 0$ ):

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  $3_{10} = 0011_2$

# “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.  $\begin{array}{r} + \quad 1 \\ \hline \end{array}$

1101 =  $-3_{10}$

# Two's Complement Examples

- Take the two's complement of  $6_{10} = 0110_2$
- What is the decimal value of  $1001_2$ ?

# Two's Complement Examples

- Take the two's complement of  $6_{10} = 0110_2$

1. 1001

2.  $\begin{array}{r} + 1 \\ \hline \end{array}$

$1010_2 = -6_{10}$

- What is the decimal value of the two's complement number  $1001_2$ ?

1. 0110

2.  $\begin{array}{r} + 1 \\ \hline \end{array}$

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



# Two's Complement Addition

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

$$\begin{array}{r} 0110 \\ + 1010 \\ \hline \end{array}$$

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

$$\begin{array}{r} 1110 \\ + 0011 \\ \hline \end{array}$$

# Two's Complement Addition

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

$$\begin{array}{r} 111 \\ 0110 \\ + 1010 \\ \hline 10000 \end{array}$$

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

$$\begin{array}{r} 111 \\ 1110 \\ + 0011 \\ \hline 10001 \end{array}$$

# 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:**

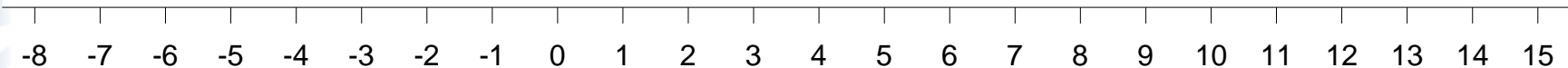
- 4-bit value =  $1011 = -5_{10}$
- 8-bit zero-extended value:  $00001011 = 11_{10}$



# 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:



Unsigned

0000 0001 0010 0011 0100 0101 0110 0111 1000 1001 1010 1011 1100 1101 1110 1111

1000 1001 1010 1011 1100 1101 1110 1111 0000 0001 0010 0011 0100 0101 0110 0111

Two's Complement

1111 1110 1101 1100 1011 1010 1001 0000  
1000 0001 0010 0011 0100 0101 0110 0111

Sign/Magnitude

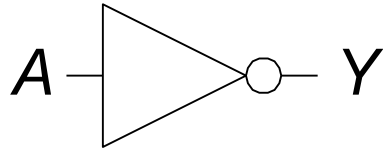


# Logic Gates

- **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

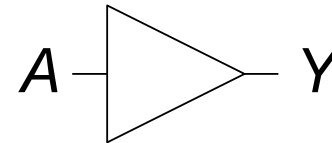
## NOT



$$Y = \overline{A}$$

A	Y
0	1
1	0

## BUF

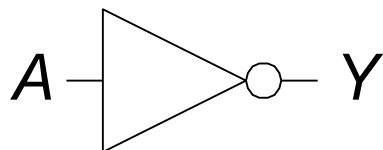


$$Y = A$$

A	Y
0	0
1	1

# Single-Input Logic Gates

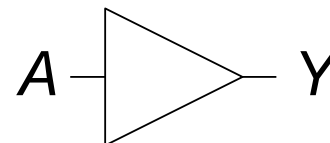
## NOT



$$Y = \overline{A}$$

A	Y
0	1
1	0

## BUF

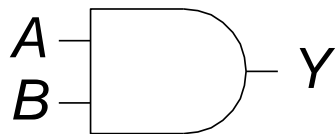


$$Y = A$$

A	Y
0	0
1	1

# Two-Input Logic Gates

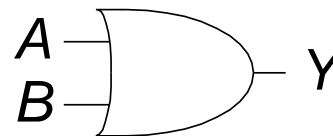
## AND



$$Y = AB$$

A	B	Y
0	0	
0	1	
1	0	
1	1	

## OR

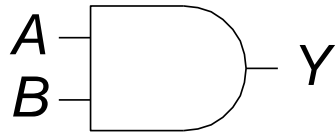


$$Y = A + B$$

A	B	Y
0	0	
0	1	
1	0	
1	1	

# Two-Input Logic Gates

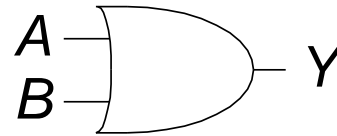
## AND



$$Y = AB$$

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

## OR

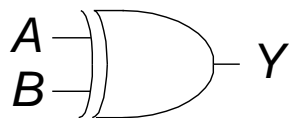


$$Y = A + B$$

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

# More Two-Input Logic Gates

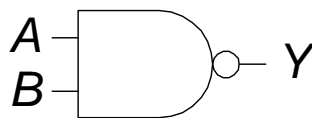
## XOR



$$Y = A \oplus B$$

A	B	Y
0	0	
0	1	
1	0	
1	1	

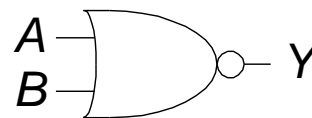
## NAND



$$Y = \overline{AB}$$

A	B	Y
0	0	
0	1	
1	0	
1	1	

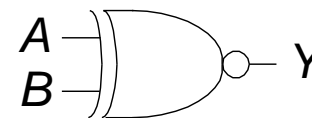
## NOR



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

A	B	Y
0	0	
0	1	
1	0	
1	1	

## XNOR



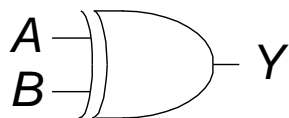
$$Y = \overline{A \oplus B}$$

A	B	Y
0	0	
0	1	
1	0	
1	1	



# More Two-Input Logic Gates

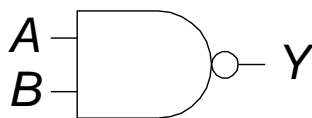
## XOR



$$Y = A \oplus B$$

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

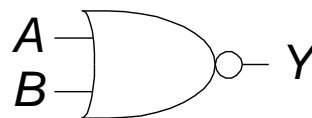
## NAND



$$Y = \overline{AB}$$

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

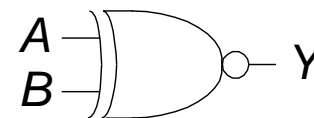
## NOR



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

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

## XNOR

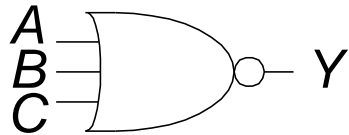


$$Y = \overline{A \oplus B}$$

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

# Multiple-Input Logic Gates

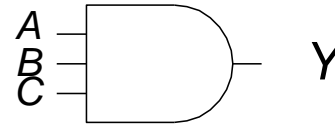
## NOR3



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

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

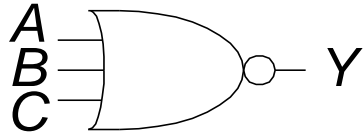


$$Y = ABC$$

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

# Multiple-Input Logic Gates

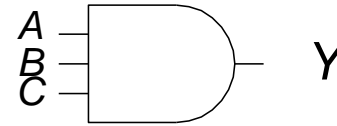
## NOR3



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

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?

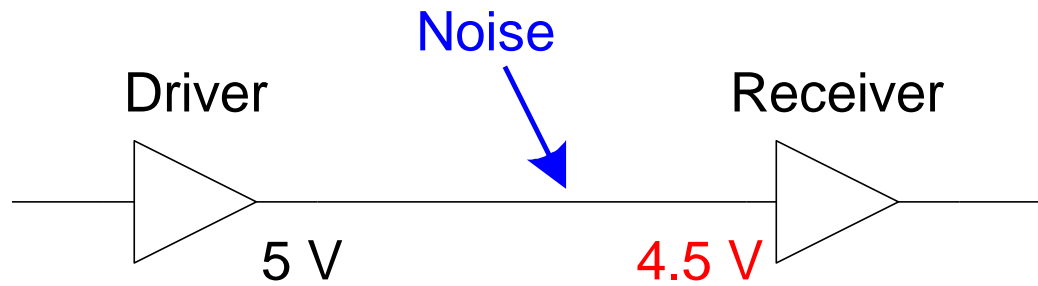
# Logic Levels

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

# What is Noise?

# What is Noise?

- **Anything that degrades the signal**
  - E.g., resistance, power supply noise, coupling to neighboring wires, etc.
- **Example:** a gate (driver) outputs 5 V but, because of resistance in a long wire, receiver gets 4.5 V

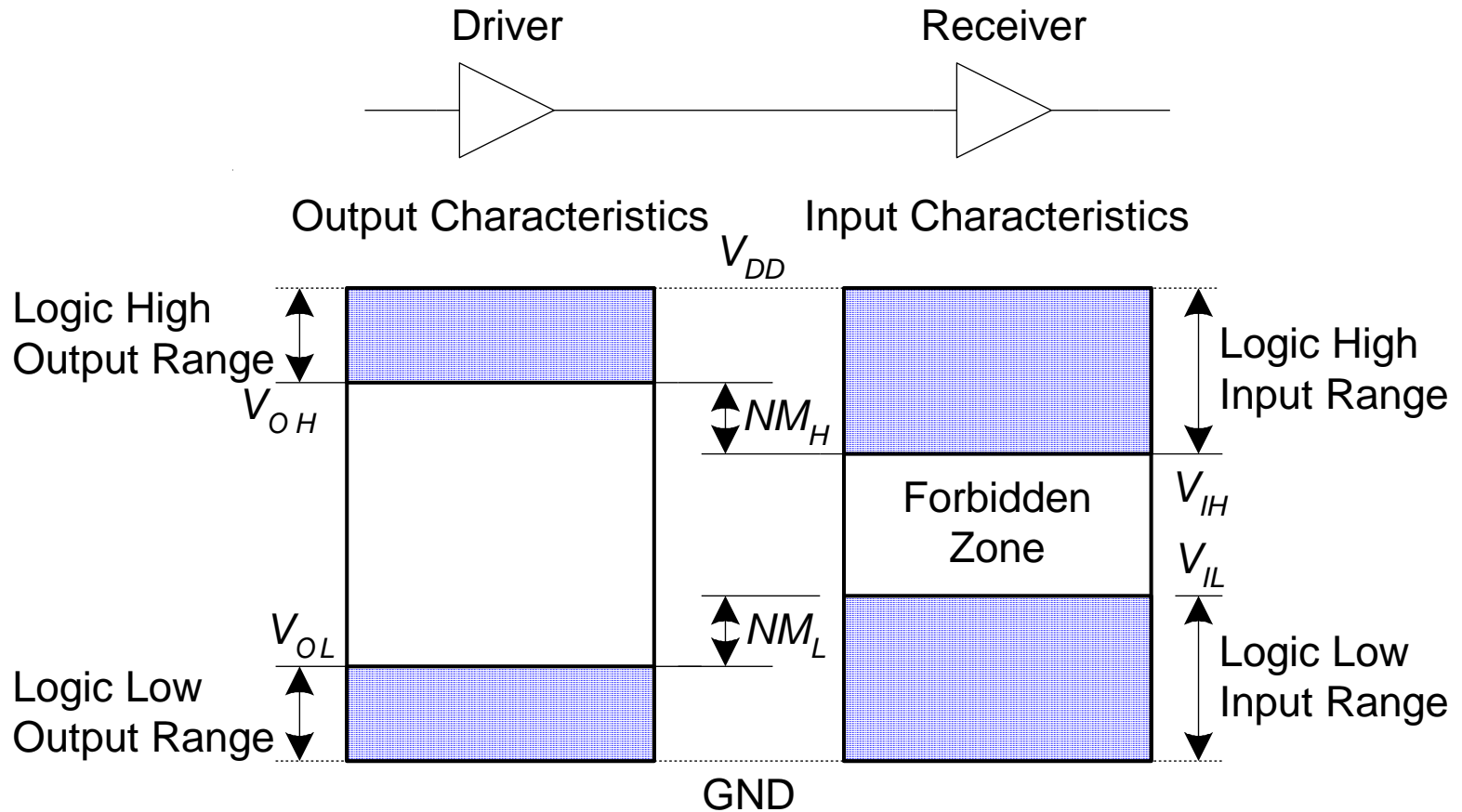


# The Static Discipline

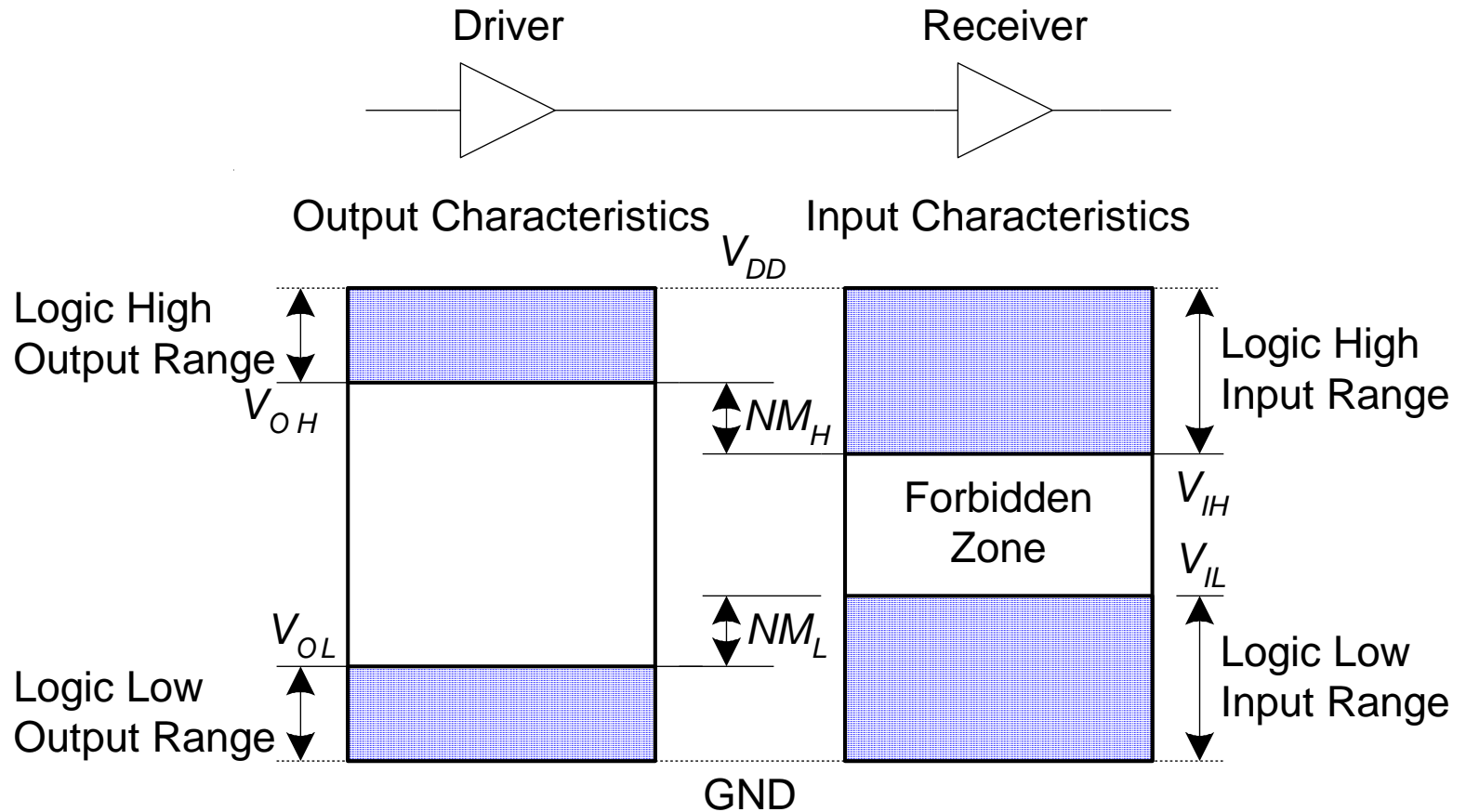
- With logically valid inputs, every circuit element must produce logically valid outputs
- Use limited ranges of voltages to represent discrete values



# Logic Levels



# Noise Margins

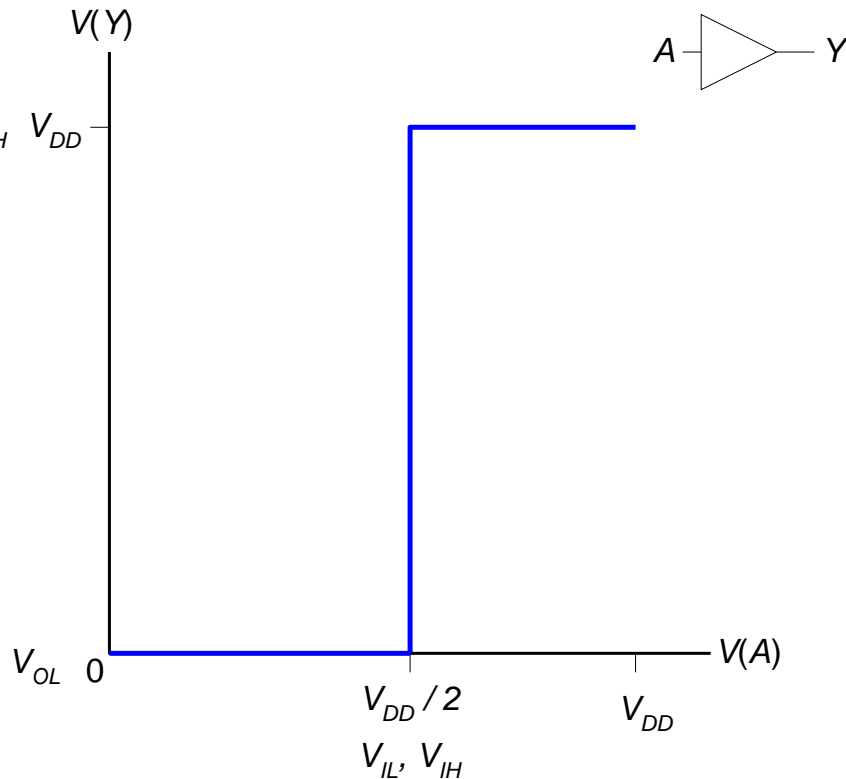


$$NM_H = V_{OH} - V_{IH}$$

$$NM_L = V_{IL} - V_{OL}$$

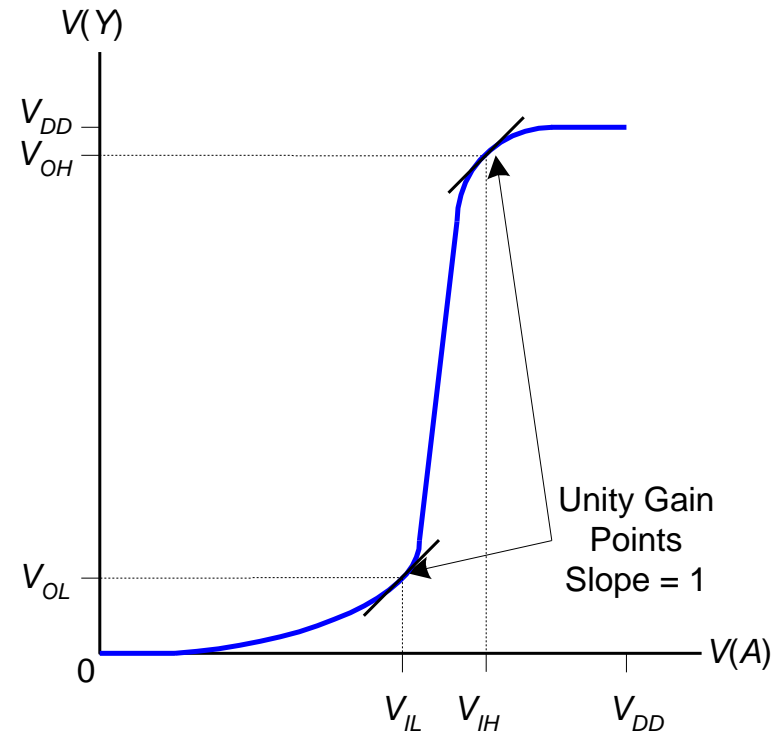
# DC Transfer Characteristics

Ideal Buffer:



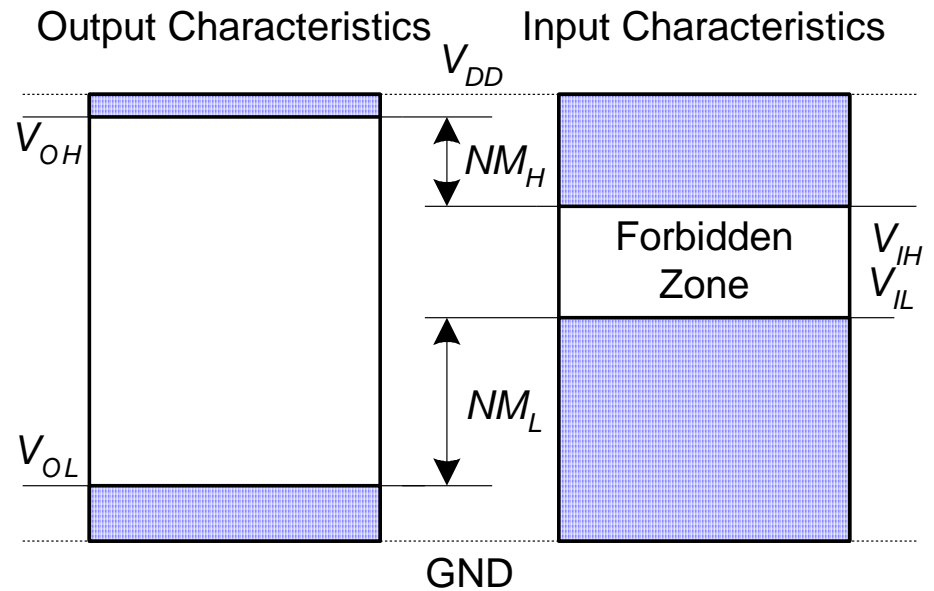
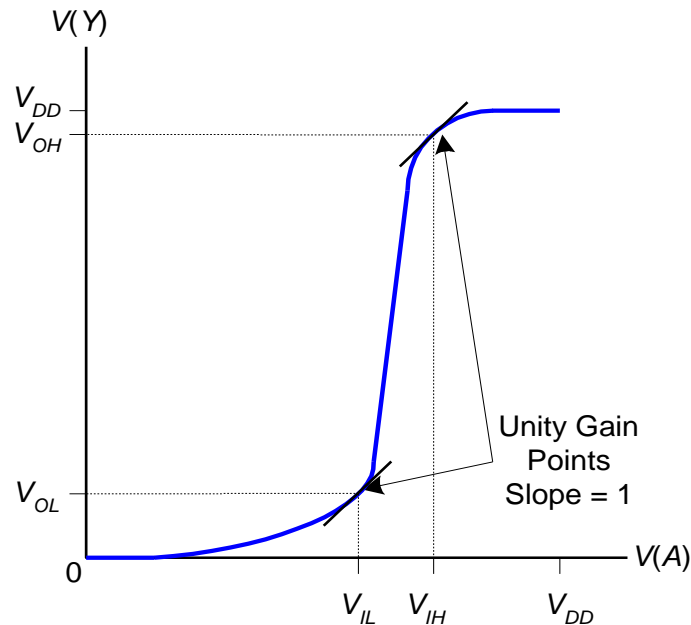
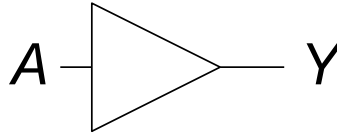
$$NM_H = NM_L = V_{DD}/2$$

Real Buffer:



$$NM_H, NM_L < V_{DD}/2$$

# DC Transfer Characteristics



# $V_{DD}$ Scaling

- In 1970's and 1980's,  $V_{DD} = 5\text{ V}$
- $V_{DD}$  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

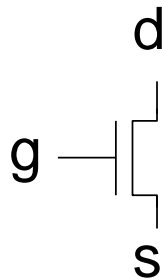


# Logic Family Examples

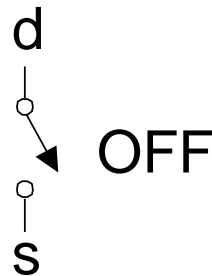
Logic Family	$V_{DD}$	$V_{IL}$	$V_{IH}$	$V_{OL}$	$V_{OH}$
TTL	5 (4.75 - 5.25)	0.8	2.0	0.4	2.4
CMOS	5 (4.5 - 6)	1.35	3.15	0.33	3.84
LVTTL	3.3 (3 - 3.6)	0.8	2.0	0.4	2.4
LVC MOS	3.3 (3 - 3.6)	0.9	1.8	0.36	2.7

# Transistors

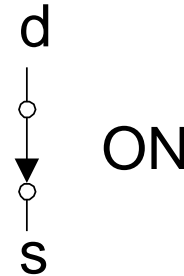
- Logic gates built from transistors
- 3-ported voltage-controlled switch
  - 2 ports connected depending on voltage of 3rd
  - d and s are connected (ON) when g is 1



$g = 0$

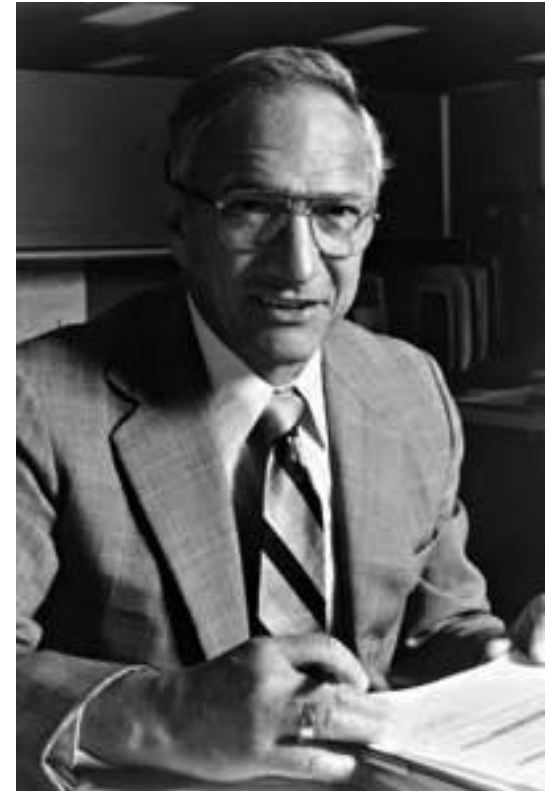


$g = 1$



# Robert Noyce, 1927-1990

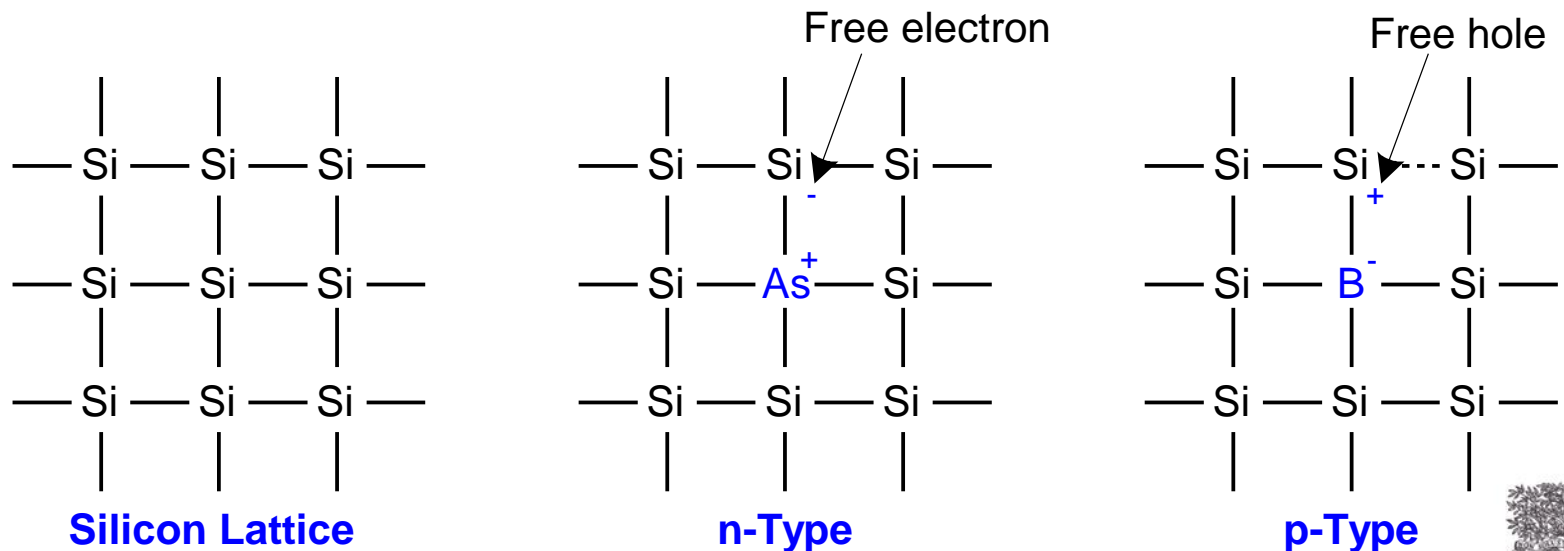
- Nicknamed “Mayor of Silicon Valley”
- Co-founded Fairchild Semiconductor in 1957
- Co-founded Intel in 1968
- Co-invented the integrated circuit





# Silicon

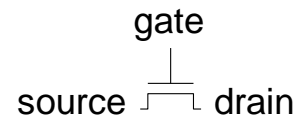
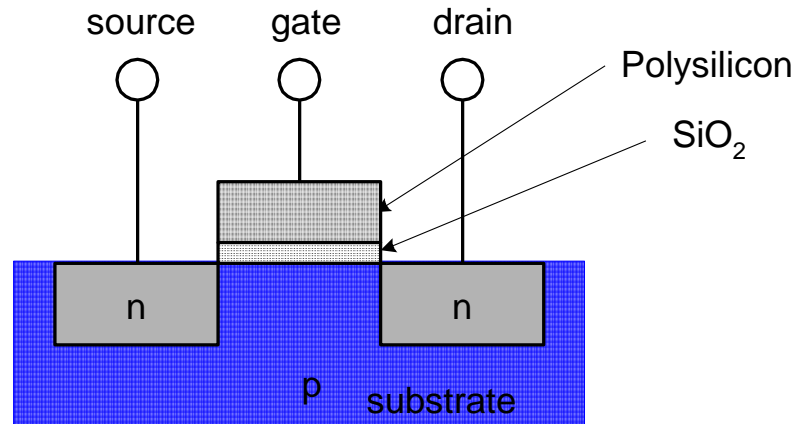
- Transistors built from silicon, a semiconductor
- Pure silicon is a poor conductor (no free charges)
- Doped silicon is a good conductor (free charges)
  - n-type (free *negative* charges, electrons)
  - p-type (free *positive* charges, holes)



# MOS Transistors

- **Metal oxide silicon (MOS) transistors:**

- Polysilicon (used to be **metal**) gate
- **Oxide** (silicon dioxide) insulator
- Doped **silicon**

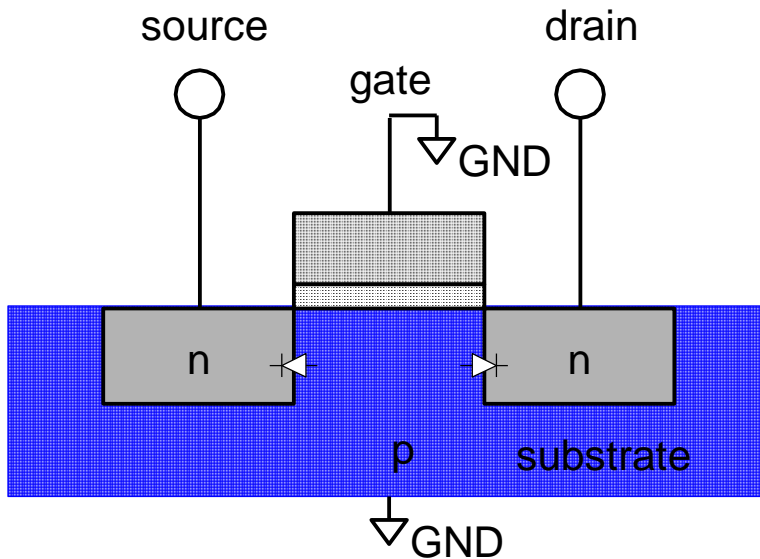


nMOS

# Transistors: nMOS

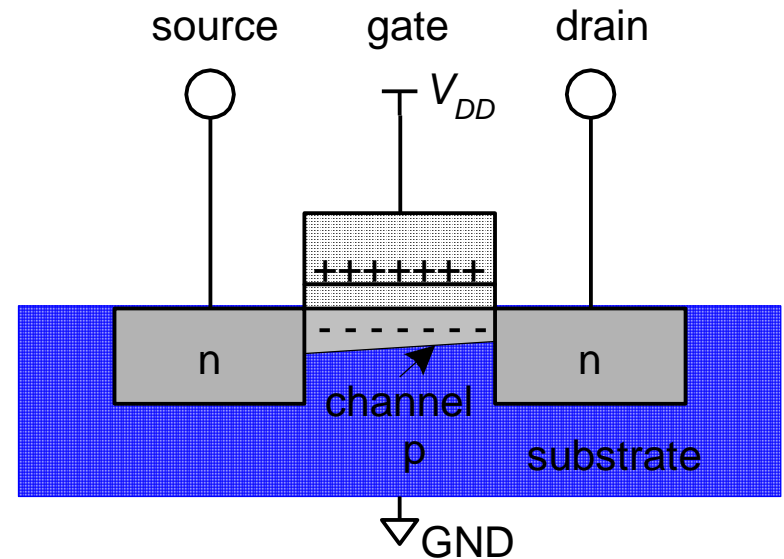
Gate = 0

OFF (no connection between source and drain)



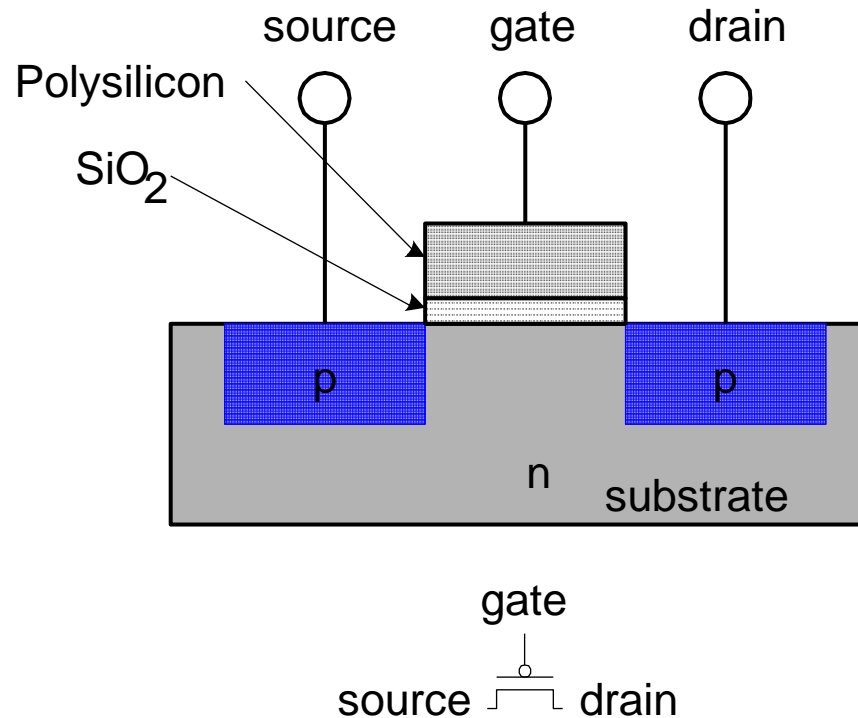
Gate = 1

ON (channel between source and drain)



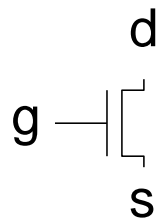
# Transistors: pMOS

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

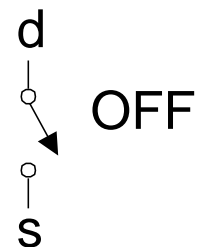


# Transistor Function

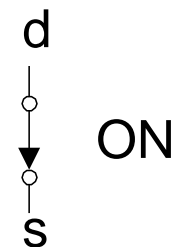
nMOS



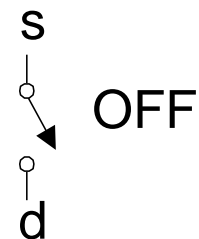
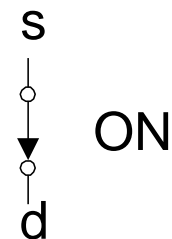
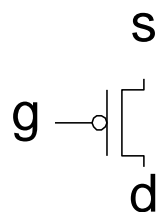
$g = 0$



$g = 1$

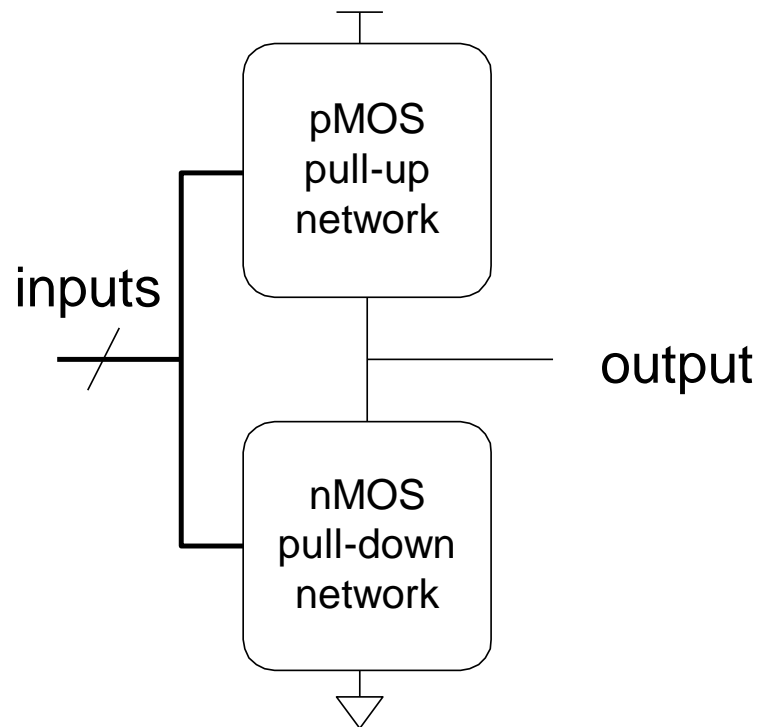


pMOS



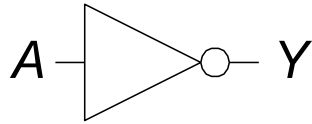
# Transistor Function

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



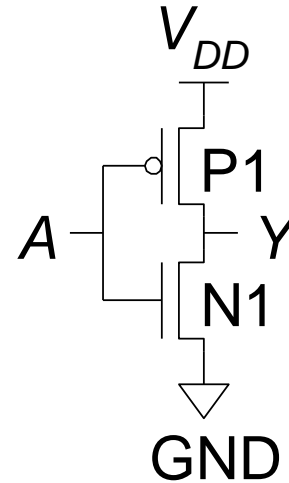
# CMOS Gates: NOT Gate

**NOT**



$$Y = \overline{A}$$

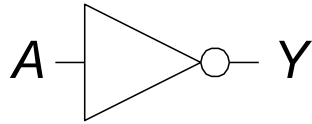
A	Y
0	1
1	0



A	P1	N1	Y
0			
1			

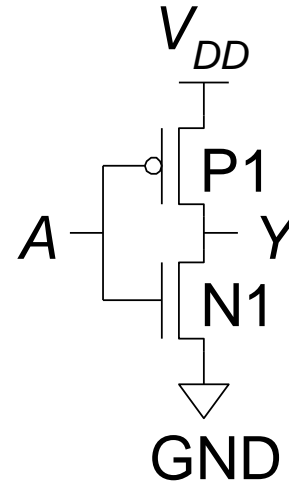
# CMOS Gates: NOT Gate

**NOT**



$$Y = \overline{A}$$

A	Y
0	1
1	0

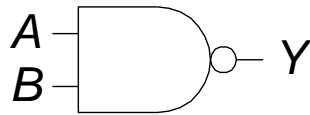


A	P1	N1	Y
0	ON	OFF	1
1	OFF	ON	0



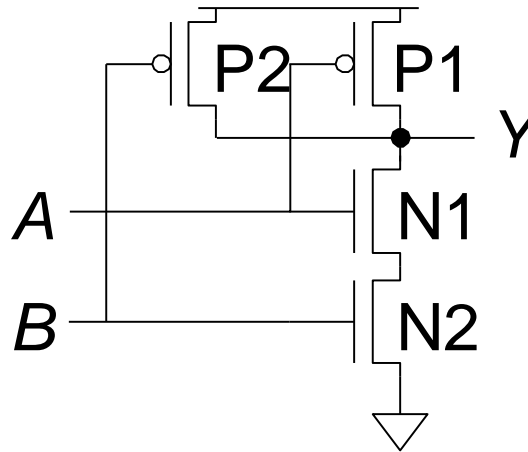
# CMOS Gates: NAND Gate

## NAND



$$Y = \overline{AB}$$

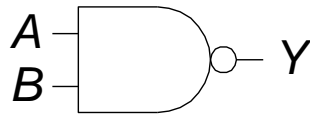
A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0



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

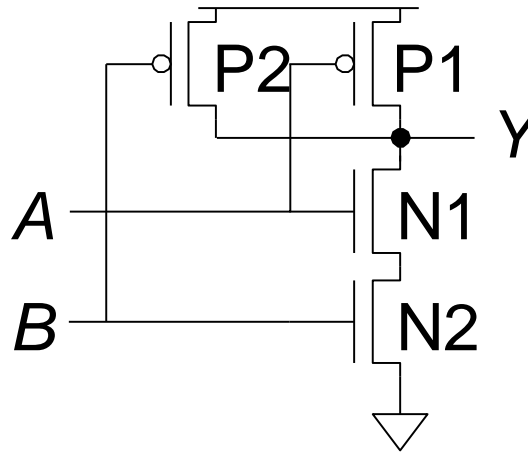
# CMOS Gates: NAND Gate

## NAND



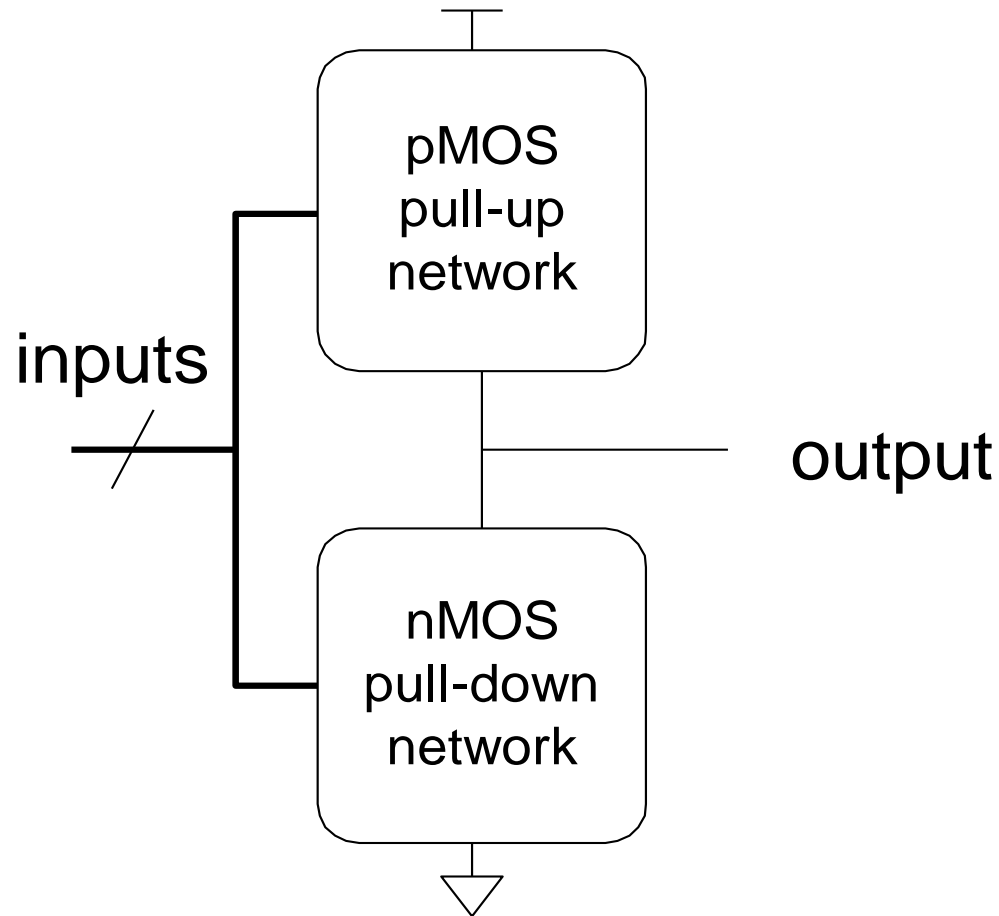
$$Y = \overline{AB}$$

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

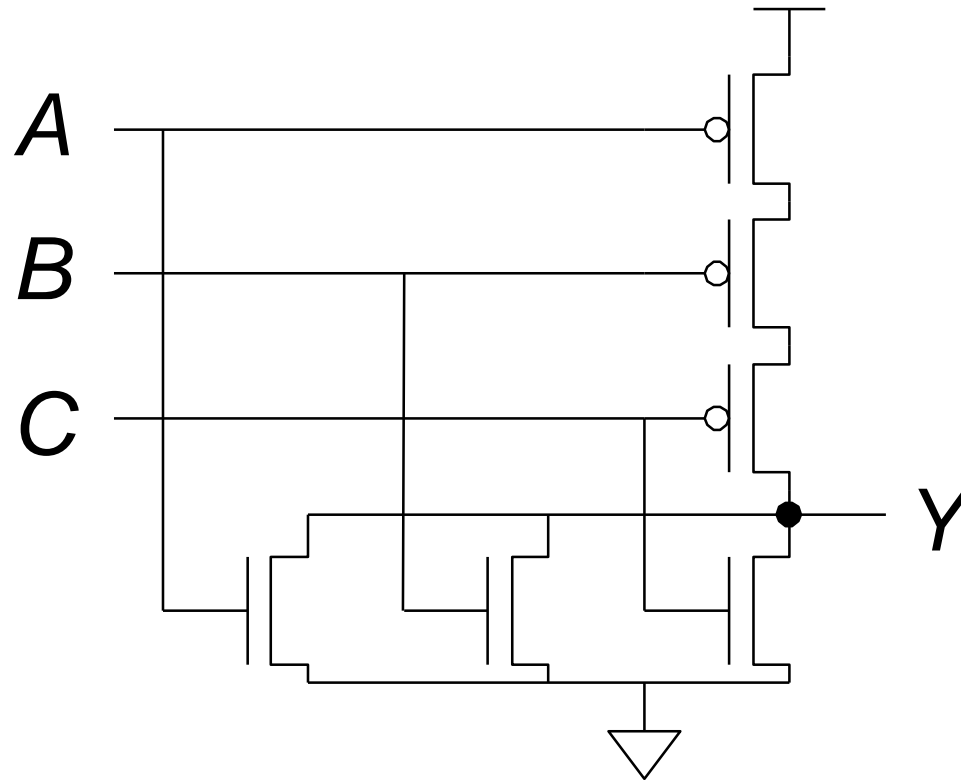
# CMOS Gate Structure



# NOR Gate

How do you build a three-input NOR gate?

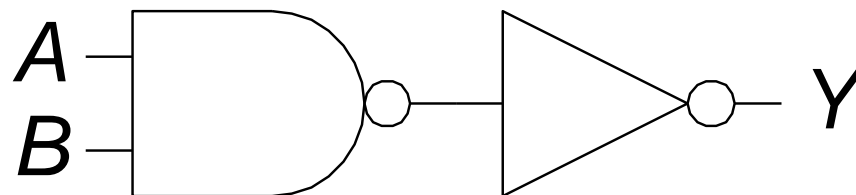
# NOR3 Gate



# Other CMOS Gates

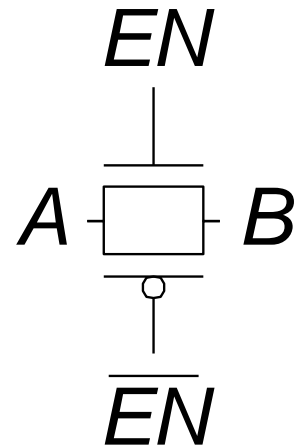
How do you build a two-input AND gate?

# AND2 Gate



# Transmission Gates

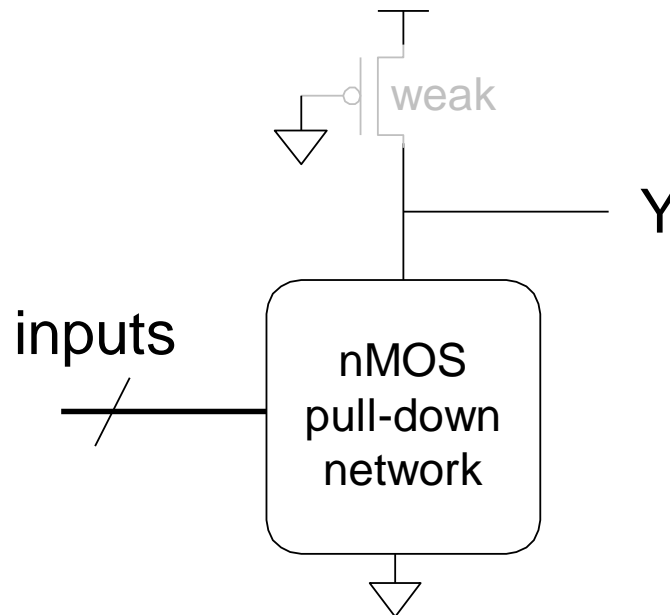
- nMOS pass 1's poorly
- pMOS pass 0's poorly
- Transmission gate is a better switch
  - passes both 0 and 1 well
- When  $EN = 1$ , the switch is ON:
  - $EN = 0$  and  $A$  is connected to  $B$
- When  $EN = 0$ , the switch is OFF:
  - $A$  is not connected to  $B$





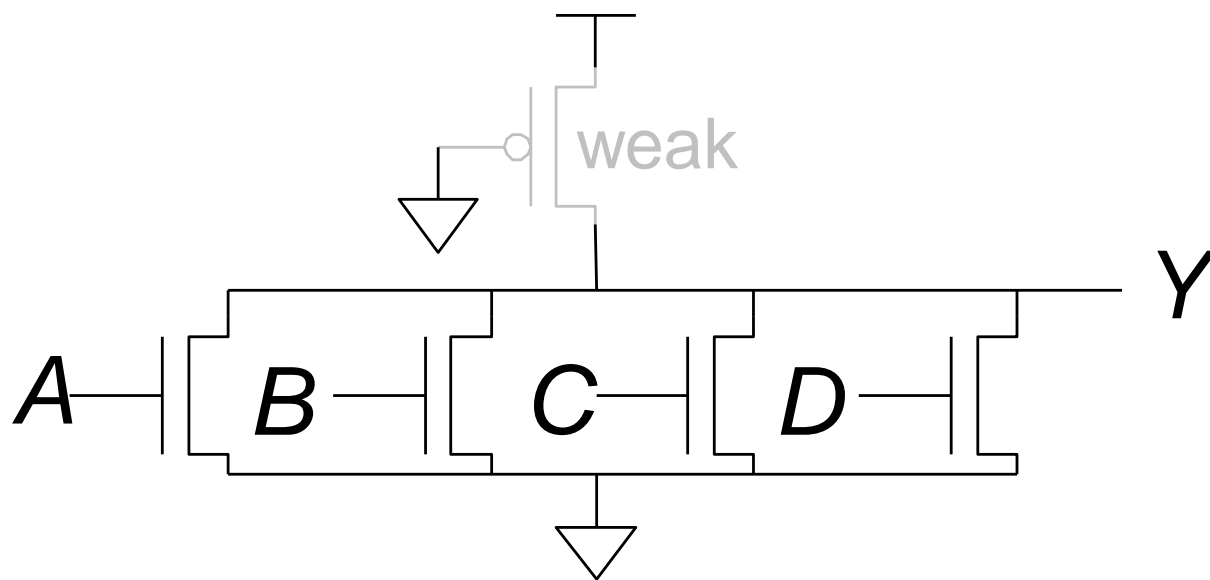
# Pseudo-nMOS Gates

- Replace pull-up network with *weak* pMOS transistor that is always on
- pMOS transistor: pulls output HIGH *only* when nMOS network not pulling it LOW



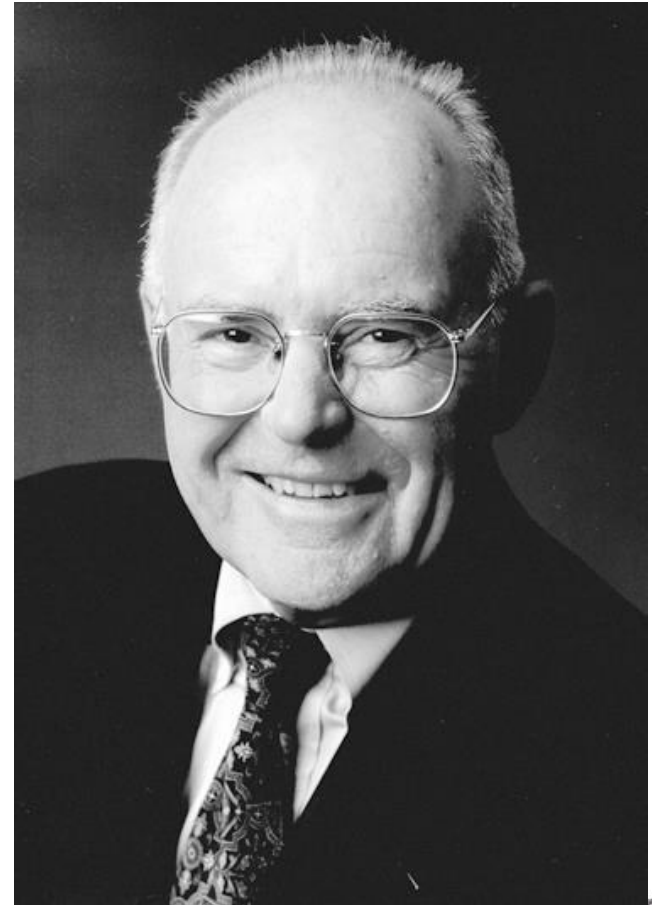
# Pseudo-nMOS Example

## Pseudo-nMOS **NOR4**

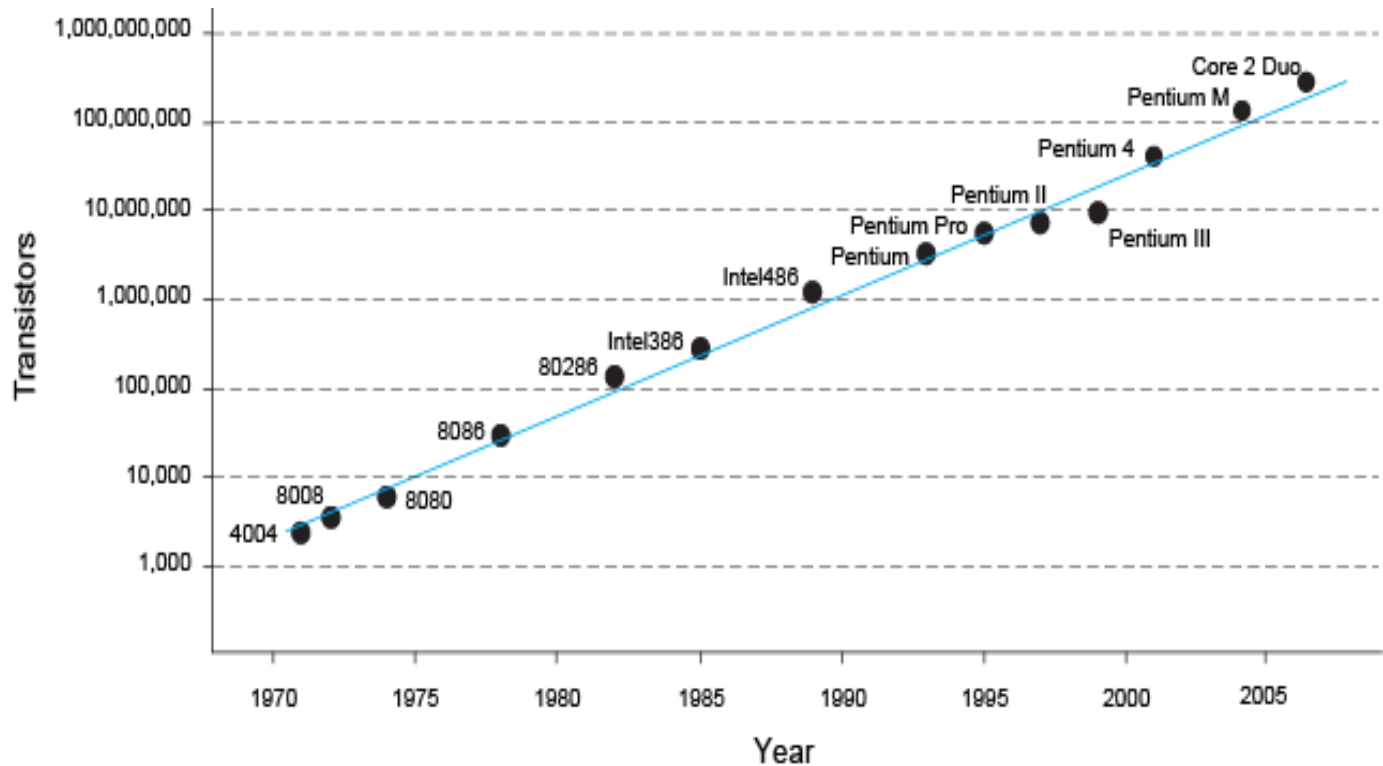


# Gordon Moore, 1929-

- Cofounded Intel in 1968 with Robert Noyce.
- **Moore's Law:** number of transistors on a computer chip doubles every year (observed in 1965)
- Since 1975, transistor counts have doubled every two years.



# Moore's Law



- *“If the automobile had followed the same development cycle as the computer, a Rolls-Royce would today cost \$100, get one million miles to the gallon, and explode once a year . . .”*

– Robert Cringley

# Power Consumption

- Power = Energy consumed per unit time
  - Dynamic power consumption
  - Static power consumption

# Dynamic Power Consumption

- **Power to charge transistor gate capacitances**
  - Energy required to charge a capacitance,  $C$ , to  $V_{DD}$  is  $CV_{DD}^2$
  - Circuit running at frequency  $f$ : transistors switch (from 1 to 0 or vice versa) at that frequency
  - Capacitor is charged  $f/2$  times per second (discharging from 1 to 0 is free)
- Dynamic power consumption:

$$P_{dynamic} = \frac{1}{2}CV_{DD}^2f$$

# Static Power Consumption

- Power consumed when no gates are switching
- Caused by the *quiescent supply current*,  $I_{DD}$  (also called the *leakage current*)
- Static power consumption:

$$P_{static} = I_{DD}V_{DD}$$

# Power Consumption Example

- Estimate the power consumption of a wireless handheld computer
  - $V_{DD} = 1.2 \text{ V}$
  - $C = 20 \text{ nF}$
  - $f = 1 \text{ GHz}$
  - $I_{DD} = 20 \text{ mA}$



# Power Consumption Example

- Estimate the power consumption of a wireless handheld computer
  - $V_{DD} = 1.2 \text{ V}$
  - $C = 20 \text{ nF}$
  - $f = 1 \text{ GHz}$
  - $I_{DD} = 20 \text{ mA}$

$$\begin{aligned} P &= \frac{1}{2} C V_{DD}^2 f + I_{DD} V_{DD} \\ &= \frac{1}{2} (20 \text{ nF}) (1.2 \text{ V})^2 (1 \text{ GHz}) + \\ &\quad (20 \text{ mA}) (1.2 \text{ V}) \\ &= (14.4 + 0.024) \text{ W} \approx 14.4 \text{ W} \end{aligned}$$