Lecture1:
Introduction to Embedded Systems and System Design

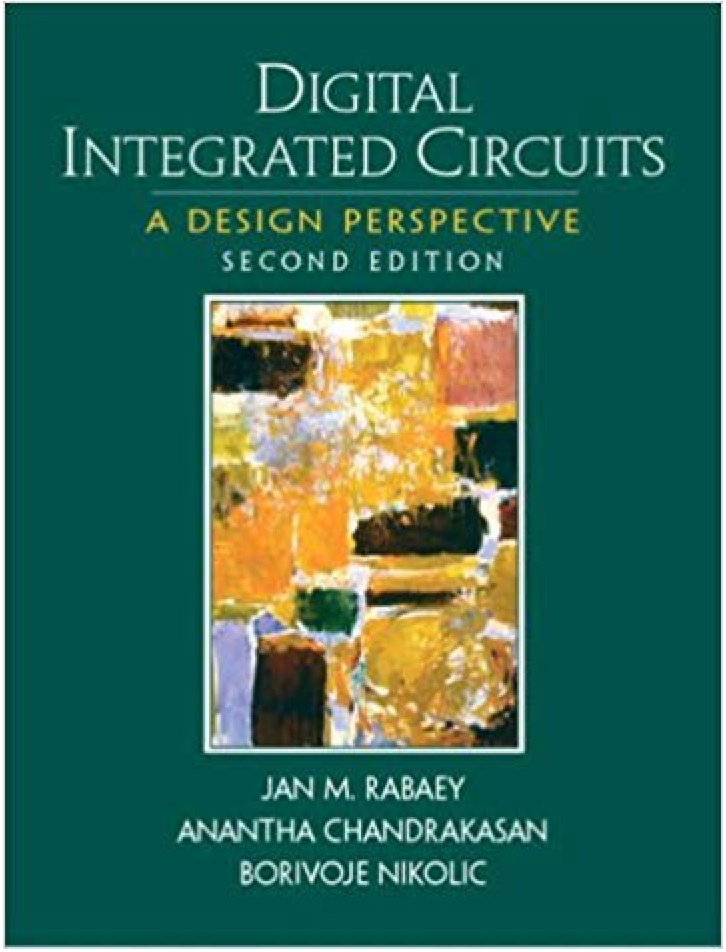
Book1: Chapter 1 &

Notes 2025.pdf

Emad Samuel Malki Ebeid

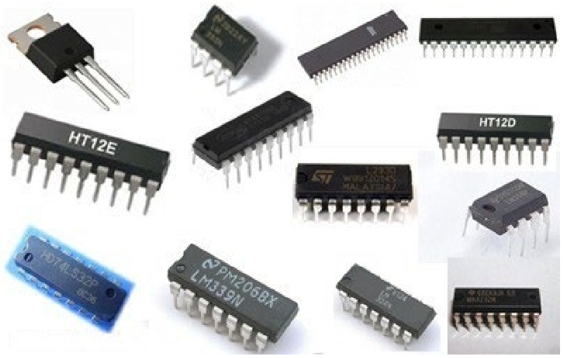
Book 1

- Digital Integrated Circuits. A Design Perspective. 2nd Edition. Jan M. Rabaey, Anantha Chandrakasan, and Borivoje Nikolic



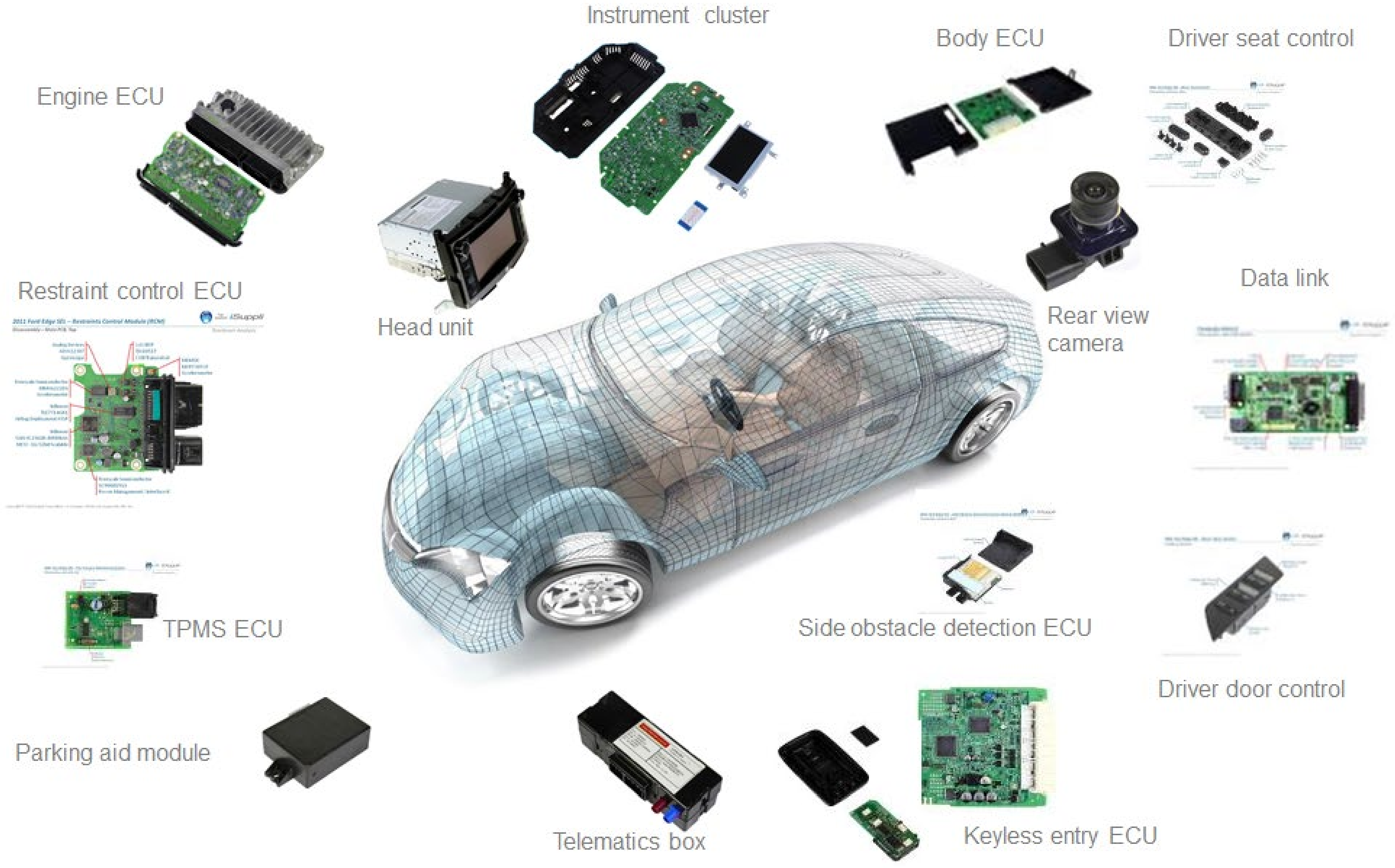
What is an Integrated Circuit/Embedded System?

- Integrated Circuit (IC) is a micro chip that can function as an amplifier, oscillator, timer, microprocessor, or computer memory.
- IC can hold anywhere from hundreds to millions of transistors, resistors, and capacitors.
- It can perform calculations and store data using either digital or analog technology
- Embedded system is a combination of computer hardware and software designed for functions within a larger system or for a specific function.



Embedded Systems Applications

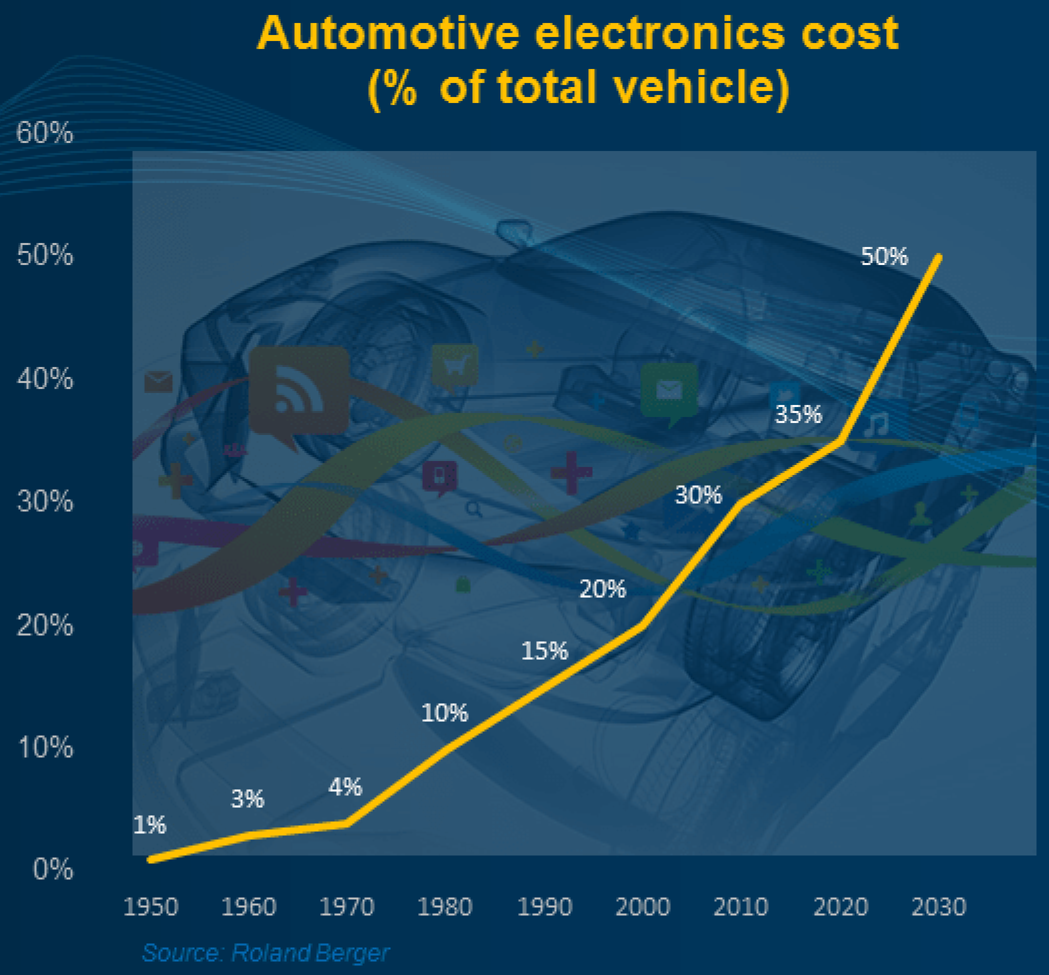
- Advanced Driver Assistance System



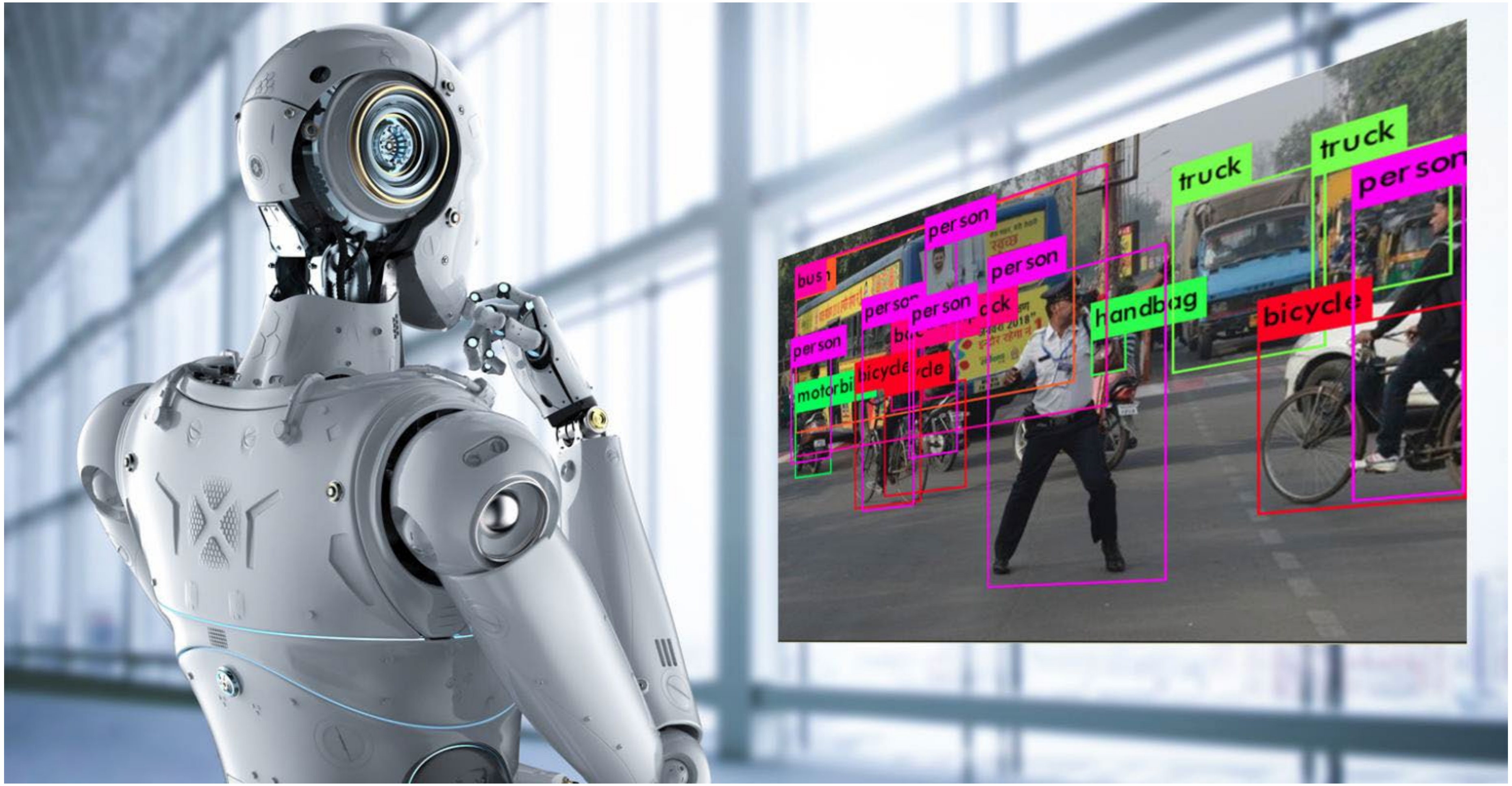
Automotive Market

"High-end cars will contain more than ***$6,000*** *worth of electronics in five years, driving a* ***$160 billion*** *automotive electronics market in 2022"*

Luca De Ambroggi
Principal analyst Automotive electronics
IHS Markit



Self-learing robots



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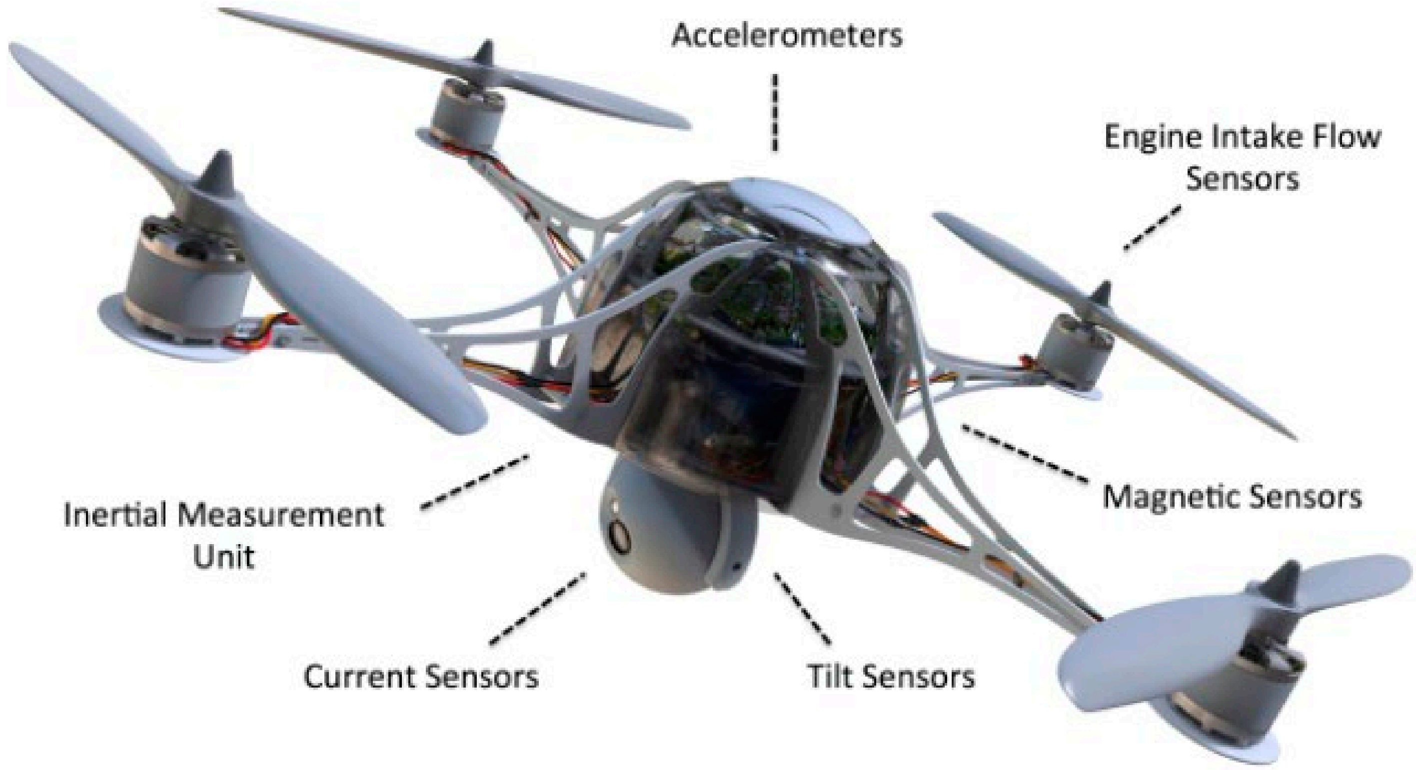
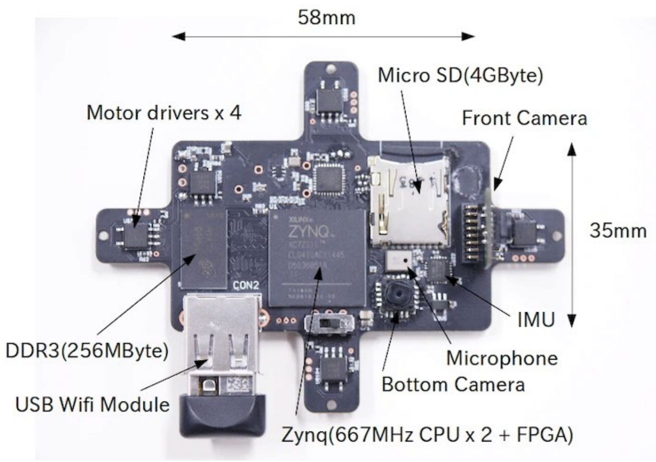
Autonomous drones





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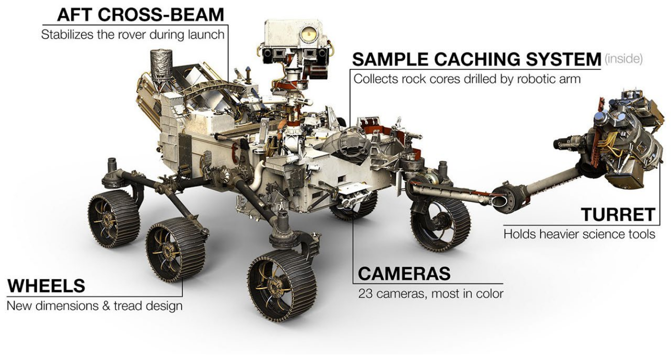
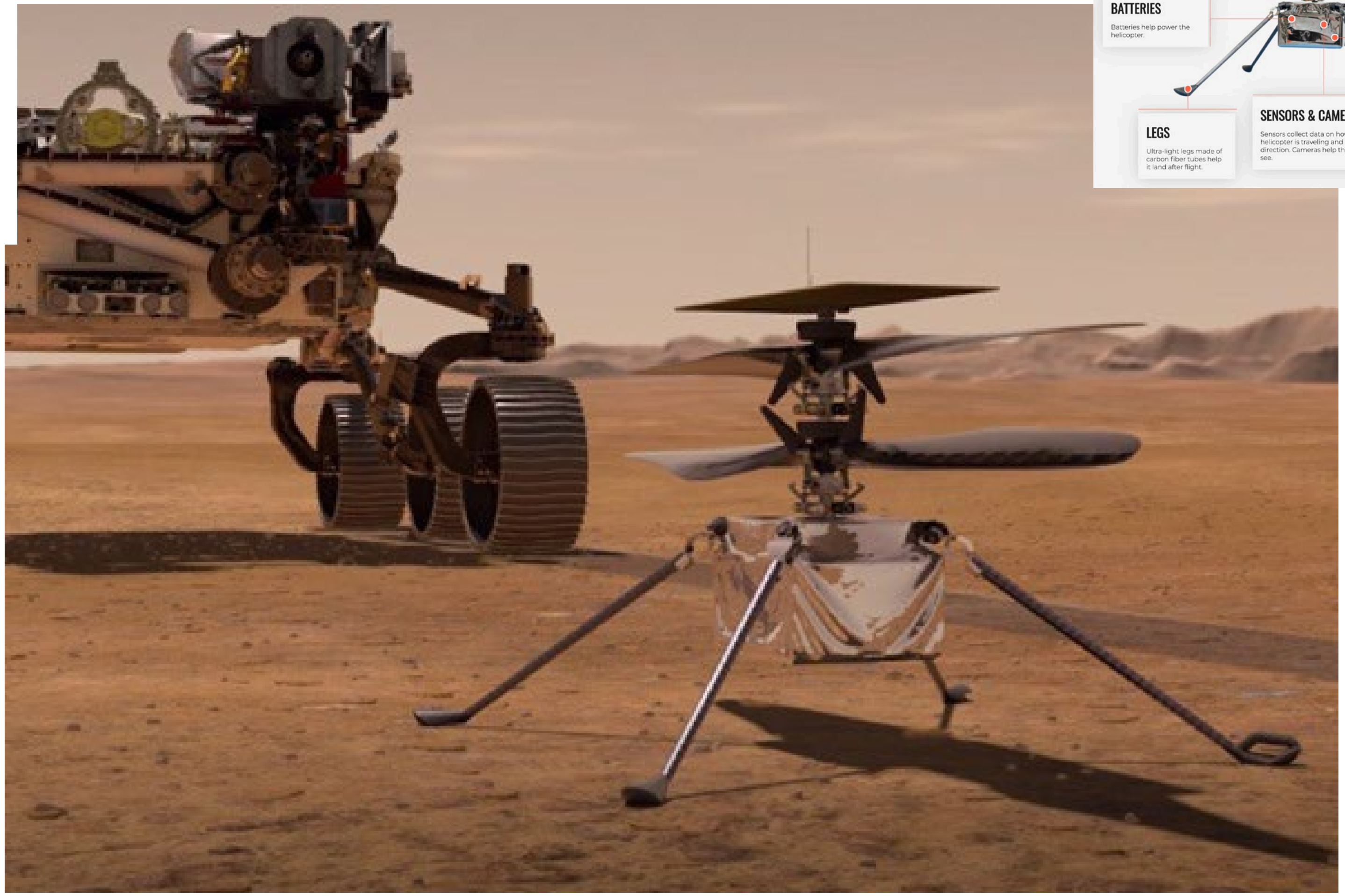
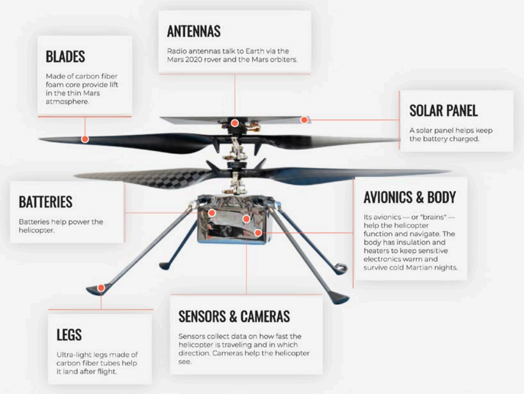
Drone Powered by Xilinx

https://www.youtube.com/watch?v=y9CvI7-e74U

In Space







https://mars.nasa.gov/

FPGA onboard!

Solutions Products Support XILINX

Community Forums › Blogs › Xclusive Blog › Touchdown! NASA's Perseverance Rover Lands on Mars...

Touchdown! NASA's Perseverance Rover Lands on Mars with Xilinx FPGAs On Board

xilinx-blog
Xilinx Employee

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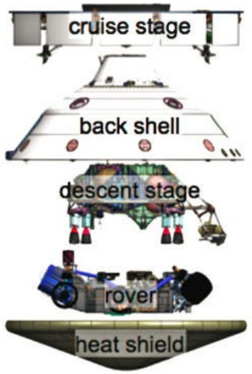
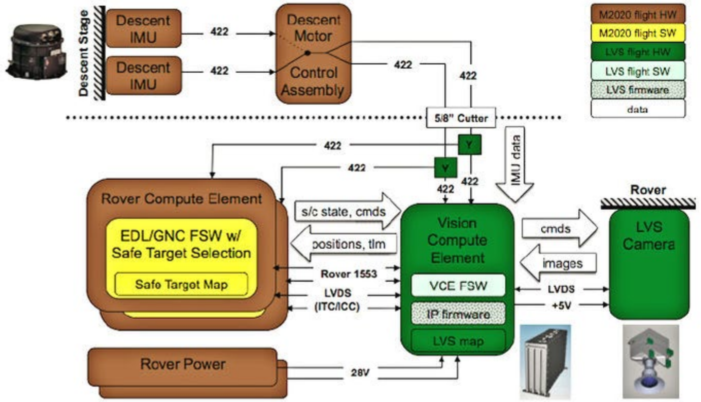
Hello MARS...Congratulations to the amazing engineers and scientists at NASA and Jet Propulsion Labs (JPL) for a successful touchdown on the Mars Jezero Crater on February 18, 2021! We are so proud to be part of this mission with Xilinx FPGAs in the lander rover and instruments, including the vision processor to perform image processing optimization for the historic first images.

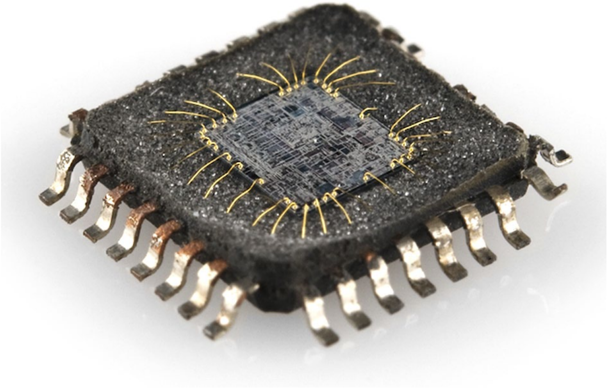


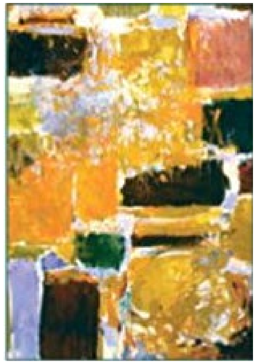


https://forums.xilinx.com/t5/Xilinx-Xclusive-Blog/Touchdown-NASA-s-Perseverance-Rover-Lands-on-Mars-with-Xilinx/ba-p/1209732

Introduction to Digital Integrated Circuits

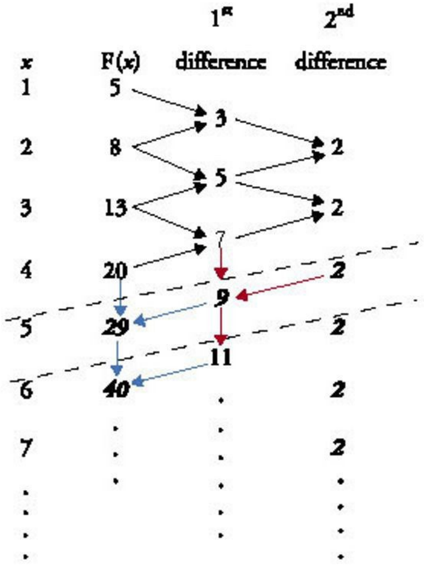
- Why is designing digital integrated circuits different today than it was before?
- Will it change in the future?





The first computer

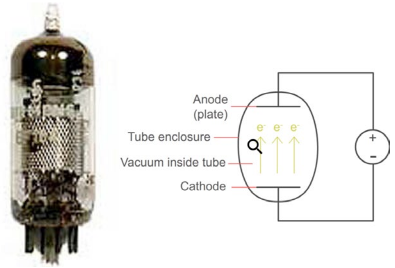
- Charles Babbage: difference engine (1834), a large-scale mechanical computing device.
- It allows the values of a polynomial function (e.g., $x^2 + 4$) to be calculated using simple **addition** only.
- 25000 parts
- Cost £17,470 in 1834!

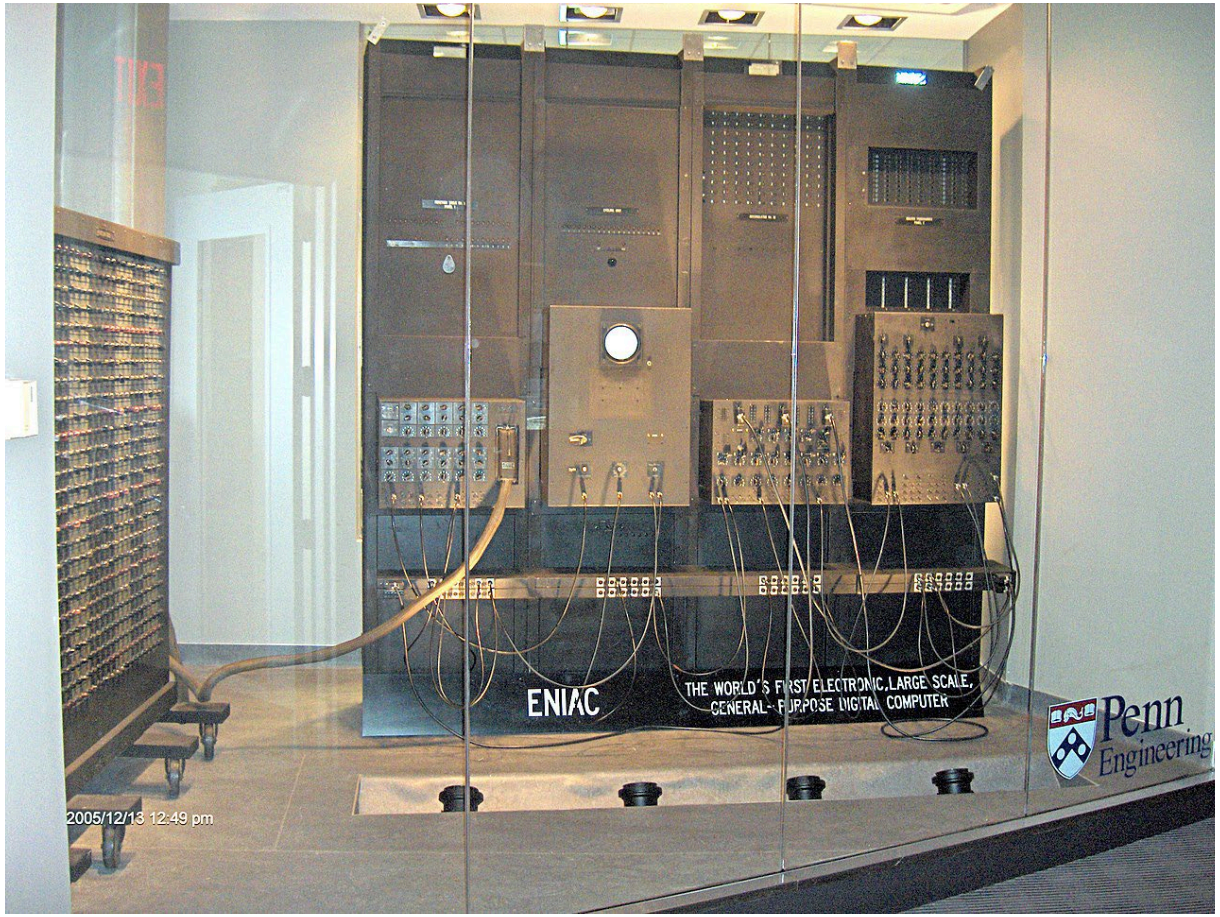


$F(x) = x^2 + 4$

Electronic Numerical Integrator and Computer (ENIAC)

- The first electronic general-purpose computer (1946).
- It has
  - 18,000 vacuum tubes
  - several miles of wiring
  - 40 black eight-foot panels
  - weigh 30 tons
  - occupying the 50-by-30-foot basement of the Moore School of Electrical Engineering at the U Penn.
  - ENIAC could execute up to 5,000 additions per second

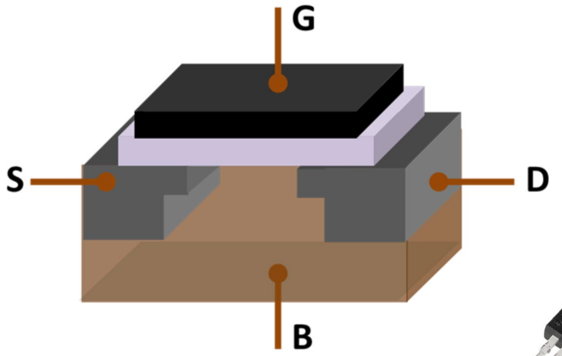


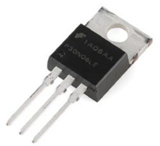


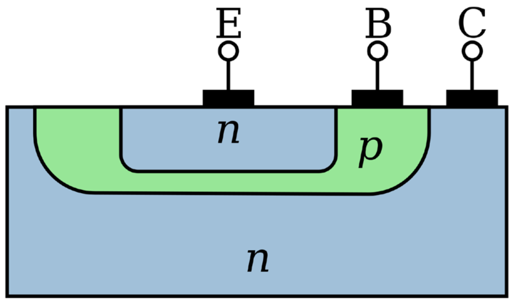
Paul W Shaffer, University of Pennsylvania

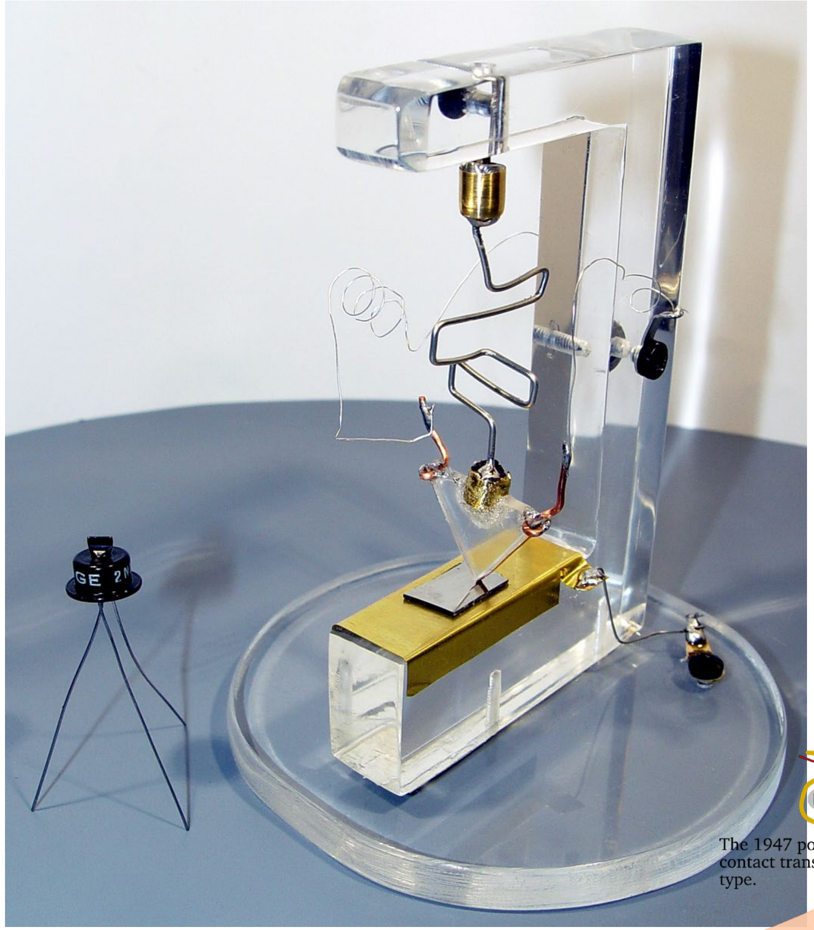
The transistor revolution

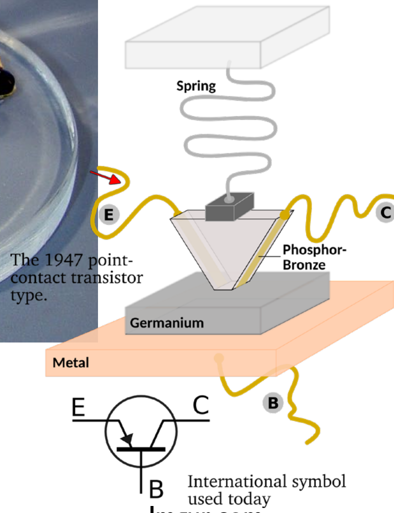
- First transistor developed at Bell Labs (started by Alexander Graham Bell and now is Nokia Bell Lab) in 1947.
  - A point contact transistor
- Bipolar junction transistor in 1948
- MOSFET in 1959









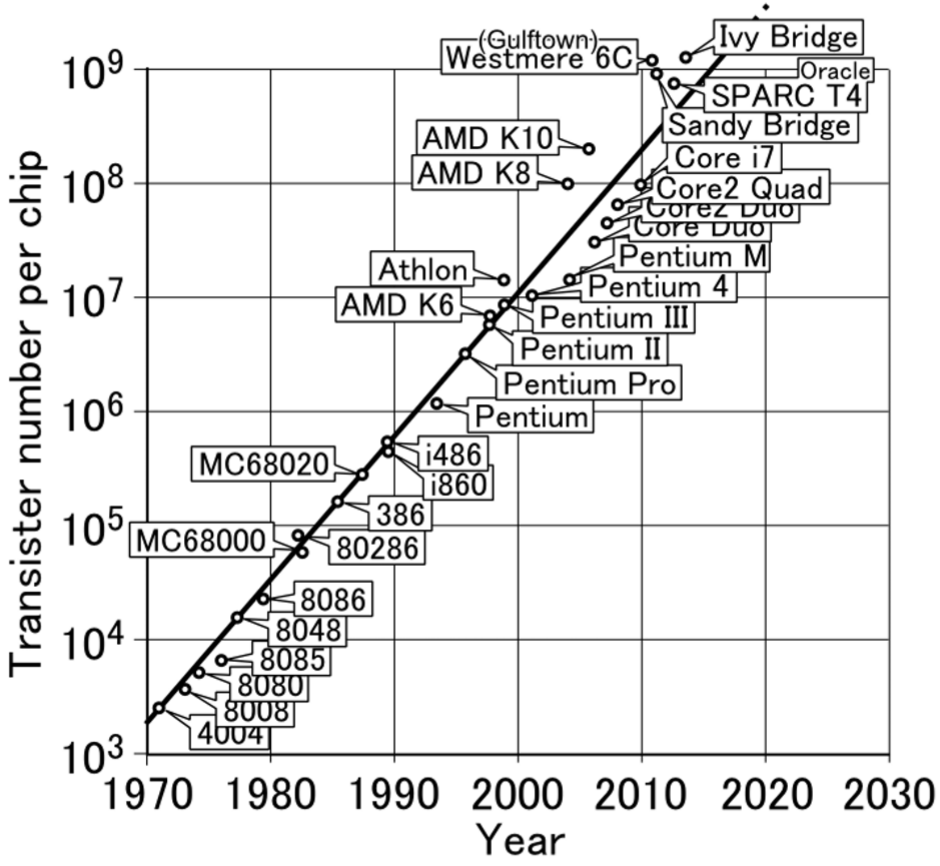


Imgur.com

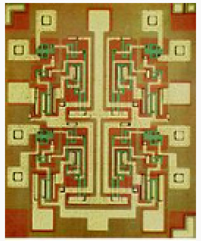
Transistor evolution

- Gordon Moore, Fairchild Semiconductor, 1965 (Intel cofounder in 1968)

(Intel.com, 2018)



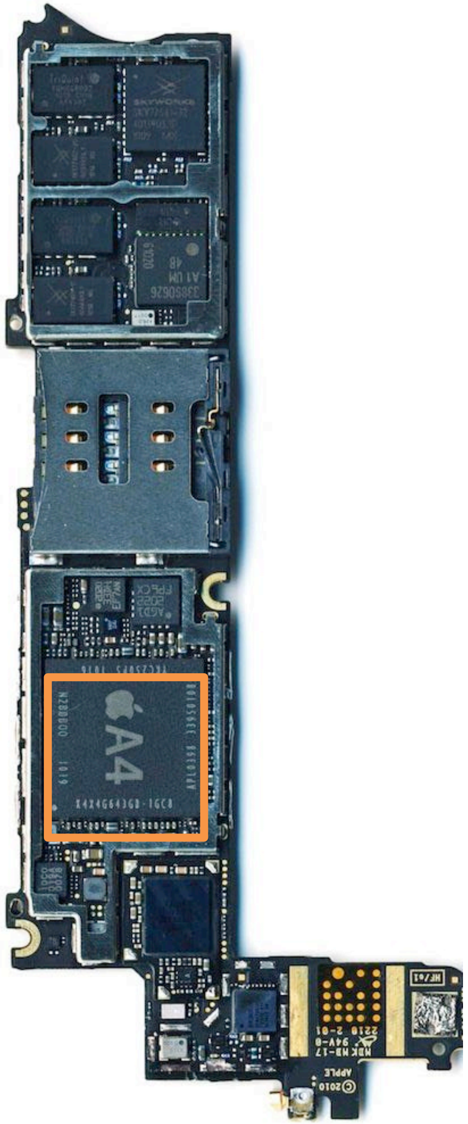
Semiconductor manufacturing processes

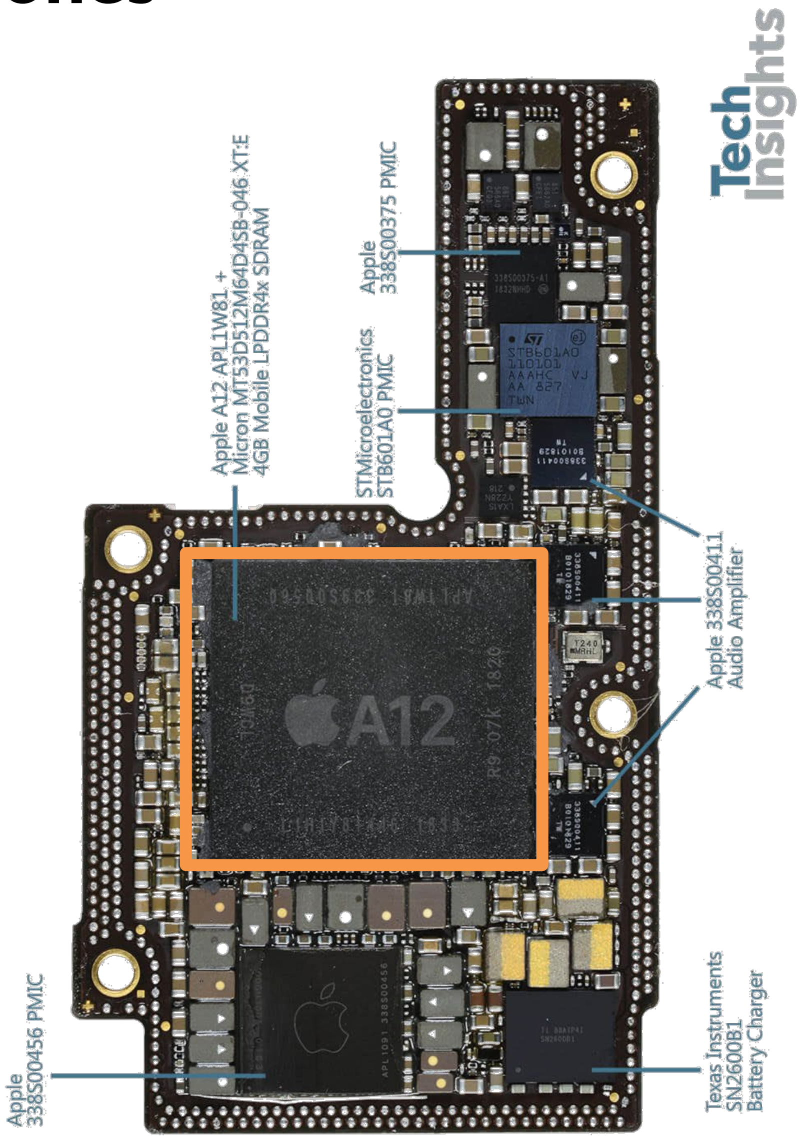


10 µm – 1971
6 µm – 1974
3 µm – 1977
1.5 µm – 1981
1 µm – 1984
800 nm – 1987
600 nm – 1990
350 nm – 1994
250 nm – 1996
180 nm – 1999
130 nm – 2001
90 nm – 2003
65 nm – 2005
45 nm – 2007
32 nm – 2009
22 nm – 2012
14 nm – 2014
10 nm – 2016
7 nm – 2018
5 nm – 2019
3 nm – *~2021*

Smartphones

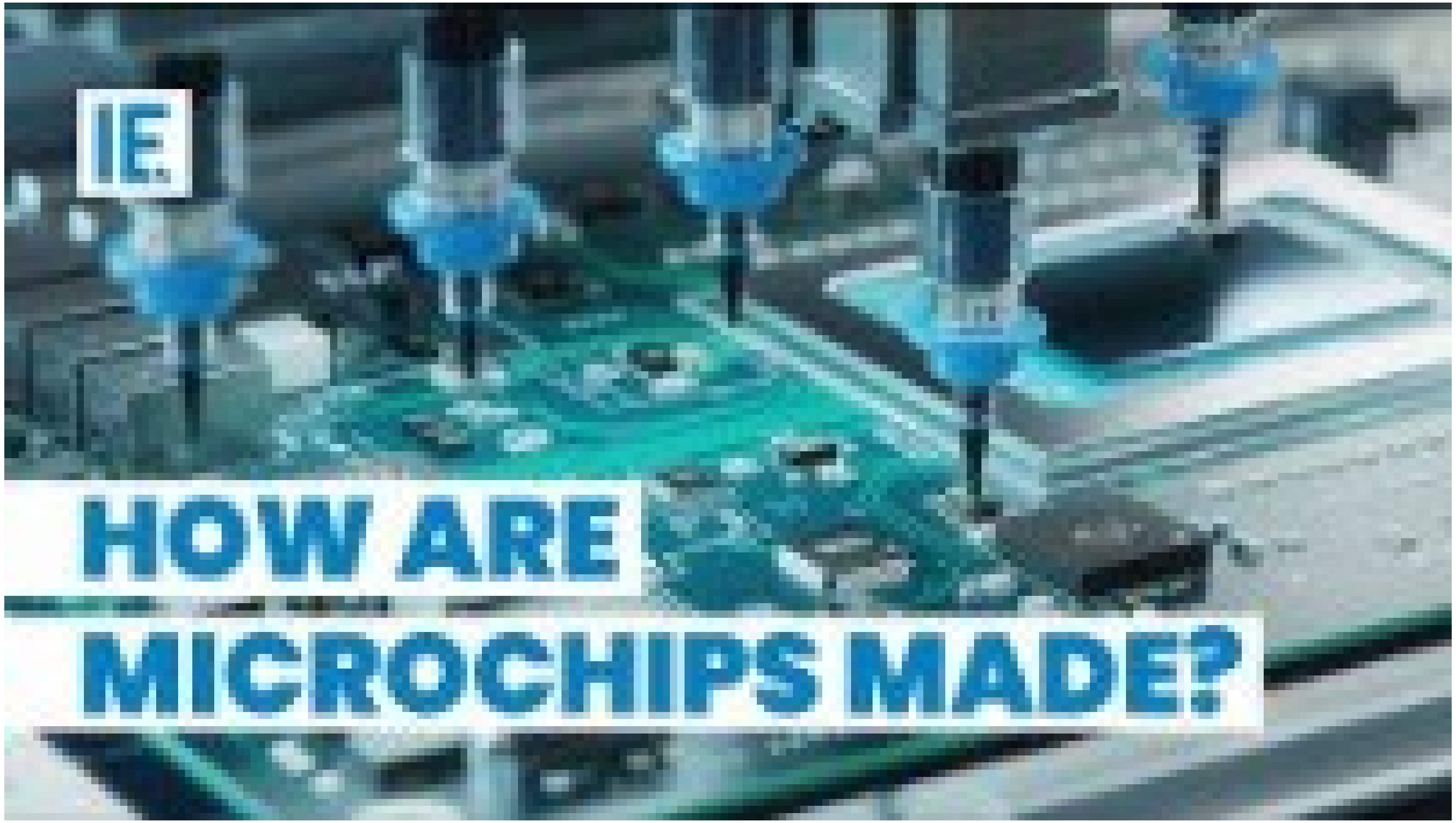
iPhone 4 (2010)
45nm/800MHz





iPhone XS (2018)
7nm/2.49GHz

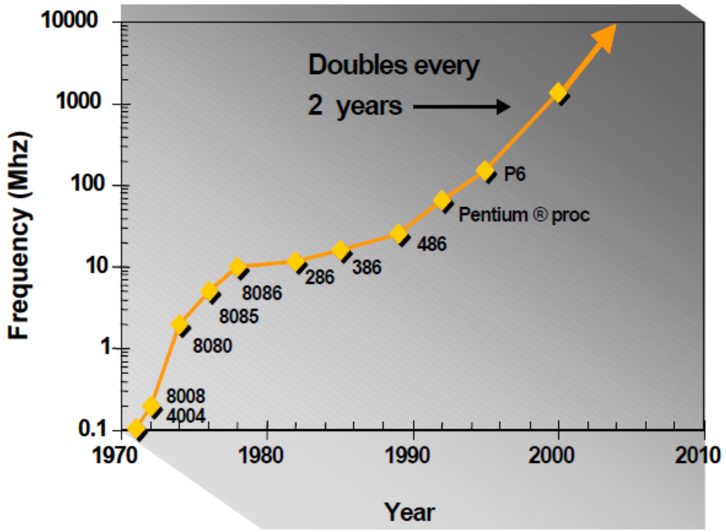
Chip design and fabrication



https://www.youtube.com/watch?v=g8Qav3vIv9s

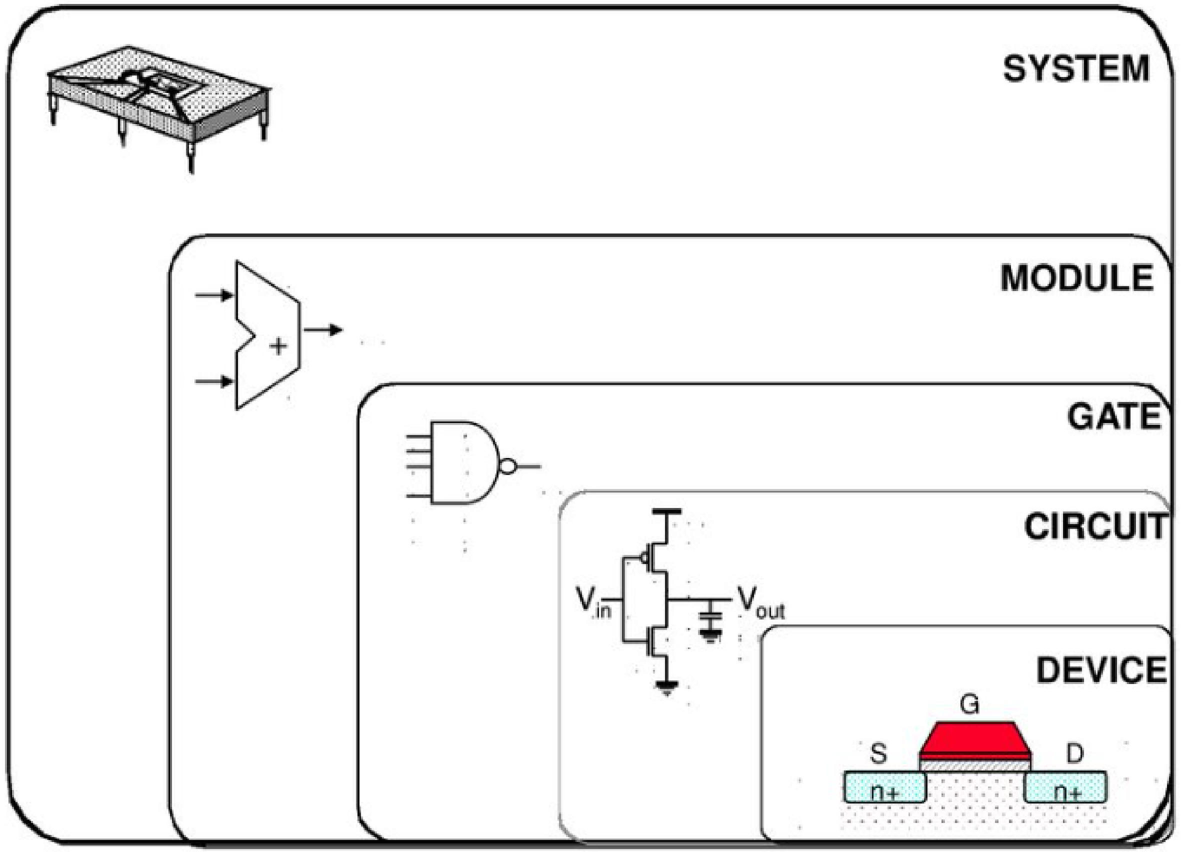
Moore's law

- Number of transistors doubles every two years
- Frequency doubles every two years
- With every generation can integrate 2x more functions per chip; chip cost does not increase significantly
  - Cost of a function decreases by 2x
- But …
  - How to design chips with more and more functions?
  - Design engineering population does not double every two years…
- Hence, a need for more efficient design methods
  - Exploit different levels of abstraction



Abstraction

- Abstraction is to deal with the design complexity
- *Computer-aided design* (CAD) frameworks for digital integrated circuits
  - without it the current design complexity would not have been achievable.
- Design tools include simulation at the various complexity levels, design verification, layout generation, and design synthesis.



Issues in Digital Integrated Circuit Design

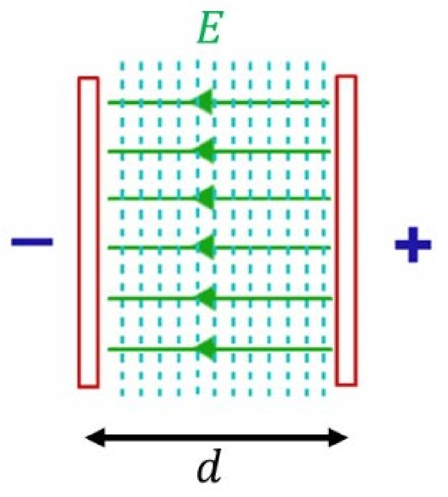
Microscopic Problems

- Power Dissipation & distribution
- Clock distribution
- Noise
- Crosstalk
- Reliability
- Manufacturability

Macroscopic Issues

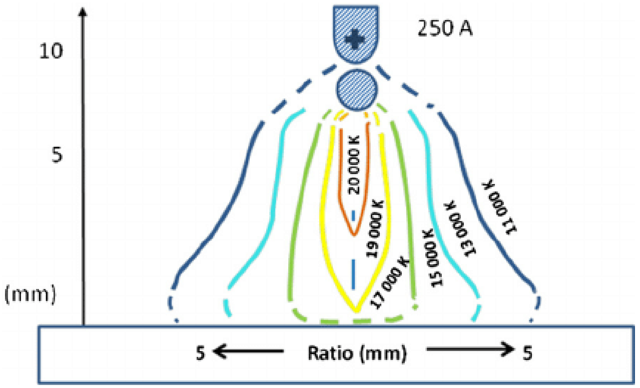
- Time-to-Market
- Millions of Gates
- High-Level Abstractions
- Reuse & IP: Portability
- Predictability
- etc.

Power dissipation



- Power dissipation is a f(speed, area, technology).

- $E = \dfrac{V}{d}$

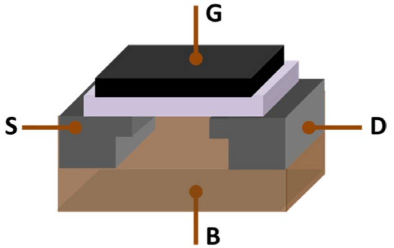


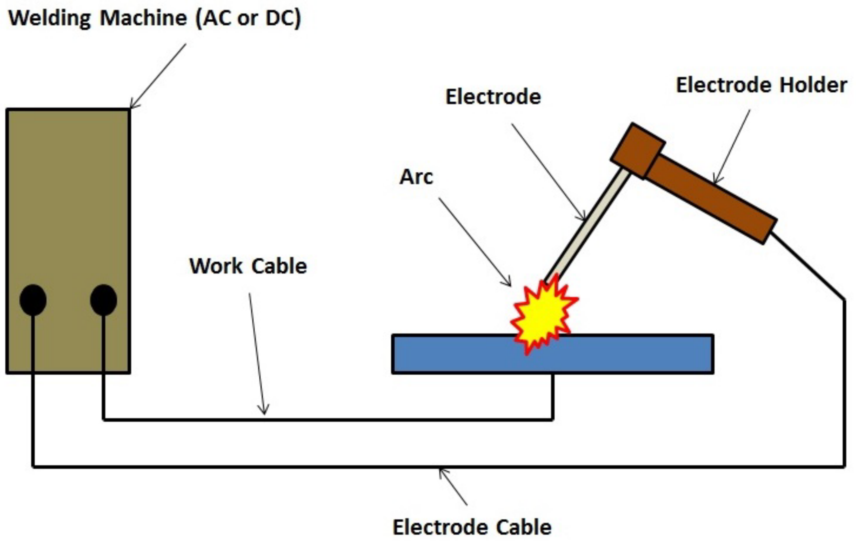
- Examples:
  - For welding:

    $$E = \frac{5000\ V}{5000\ \mu m} = 1\ V/\mu\, m$$

  - Inside the transistor:

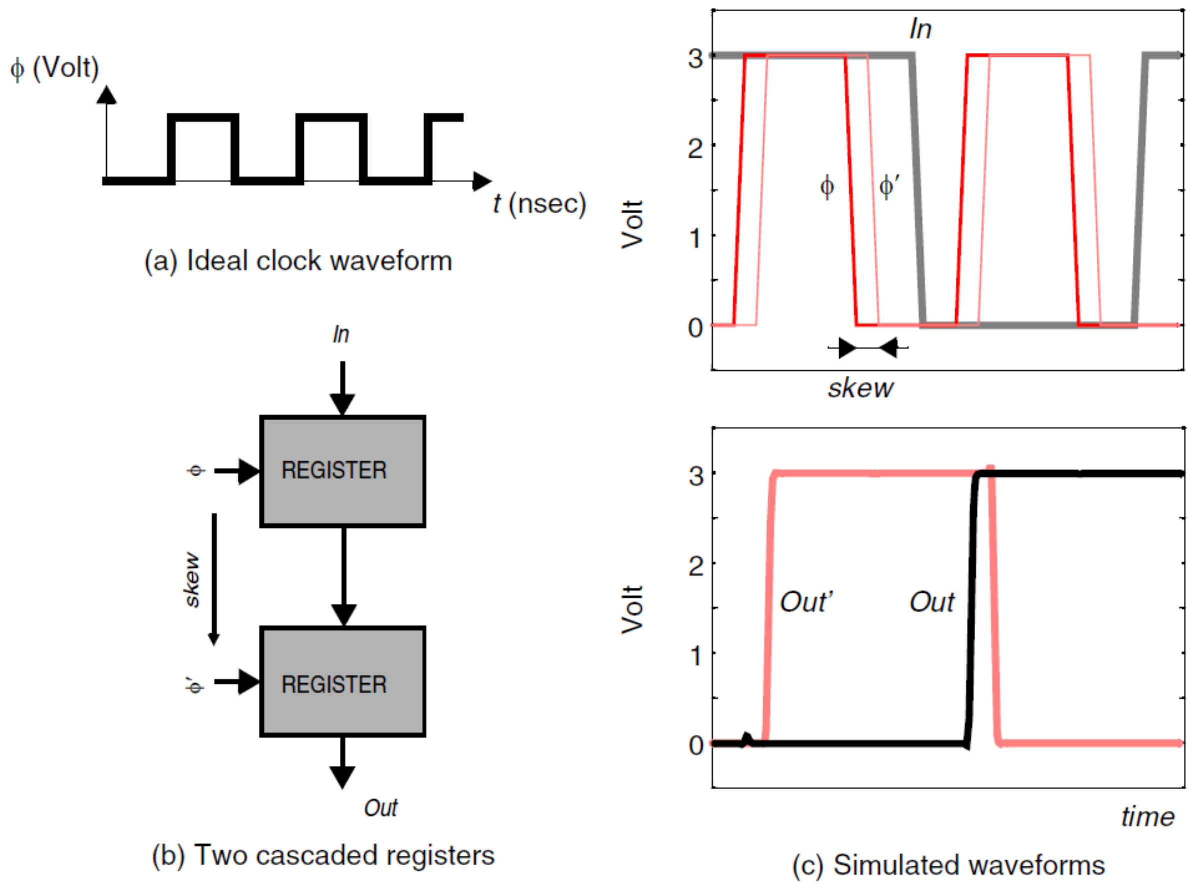
    $$E = \frac{0.6\ V}{0.06\ \mu m} = 10\ V/\mu\, m\ !!!$$





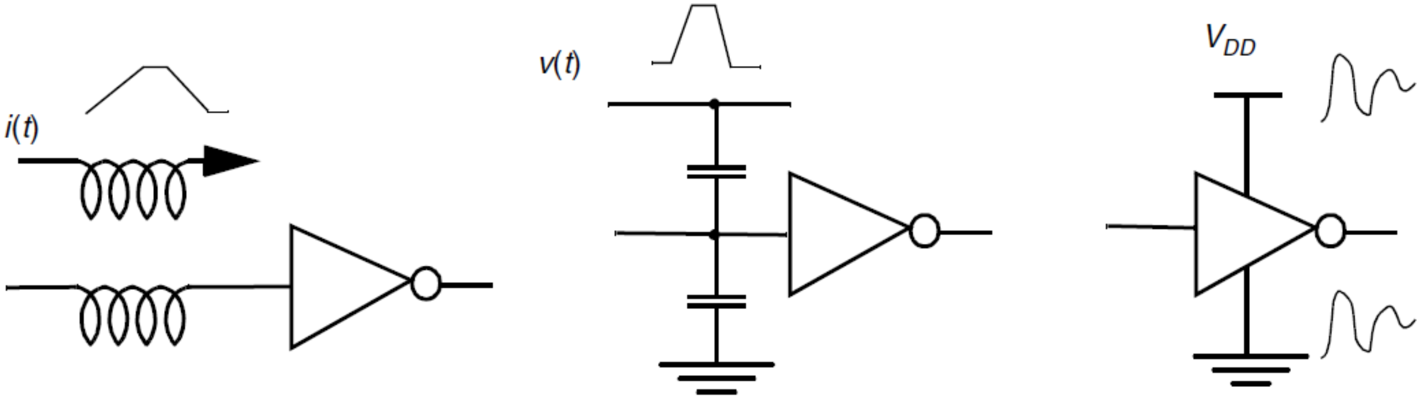
Clock distrubtion

- Due to delays associated with routing the clock wires, it may happen that the clocks become misaligned with respect to each other; clock delay or skew



Functionality and Robustness

- Noise in digital circuits means *“unwanted variations of voltages and currents at the logic nodes.”*
- *Noise sources in digital circuits:*



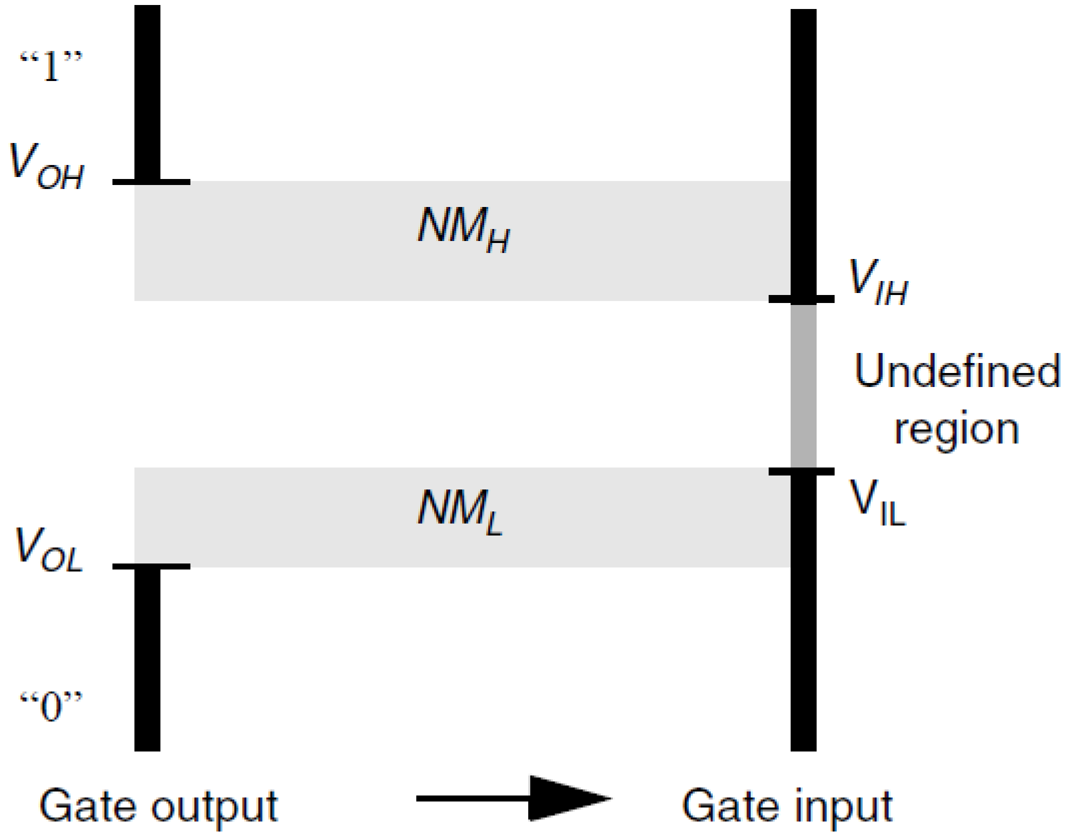
(a) Inductive coupling (b) Capacitive coupling (c) Power and ground noise

Noise Margins

- Digital circuits (DC) perform operations on *logical* (or *Boolean*) variables (0 or 1) that are abstract representation of the real values.
- But phyiscally not
  - $1 \leftrightarrow V_{OH}\ and\ 0 \leftrightarrow V_{OL}$

Noise Margin is how much noise can be added to the logic level and still these level unchanged.

- $NM_H = V_{OH} - V_{IH}$
- $NM_L = V_{IL} - V_{OL}$
- $NM = \min(NM_H, NM_L)$



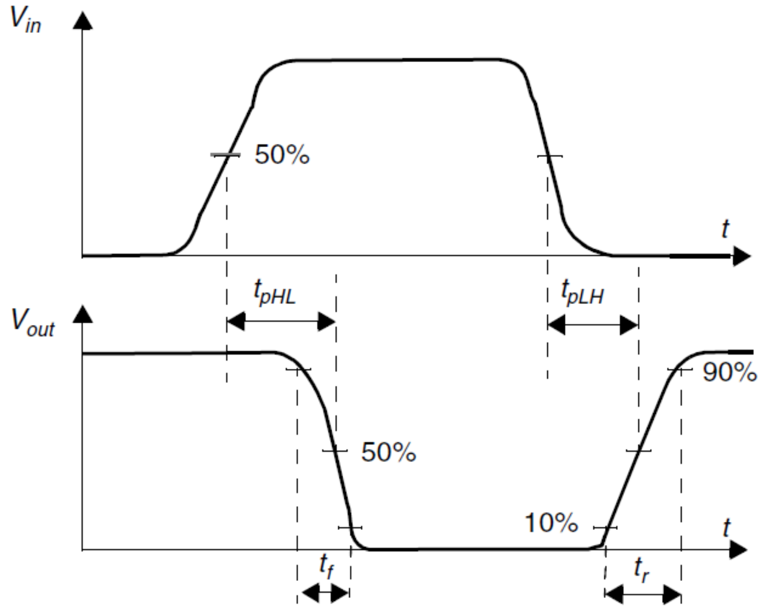
Performance

- The performance of a digital circuit expresses the computational load that the circuit can manage.
  - the duration of the clock period (*clock cycle time)* or clock rate (*clock frequency*)
- For instance, a microprocessor is often characterized by the number of instructions it can execute per second.
- Circuit performance depends on the architecture of the processor (the number of instructions it can execute in parallel) and the *actual design of logic circuitry*.

Propagation delay

- The *propagation delay tp* of a gate defines how quickly it responds to a change at its input(s)

- $t_p = \frac{t_{pLH}+t_{pHL}}{2}$
- Oscillation period (*T*) =
  $$2 \ * \ t_p \ * N \ \ (only\ valide\ if\ T \gg \ t_f + t_r)$$
  - Typically, a ring oscillator needs a least five stages to be operational
- *Clock Frequency* = $\frac{1}{T}$
  - *If T = 2ns -> F = 0.5GHz*



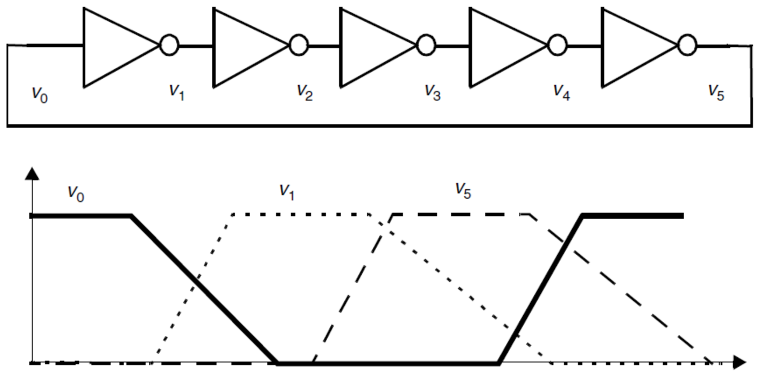
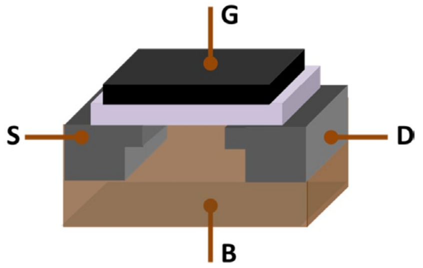
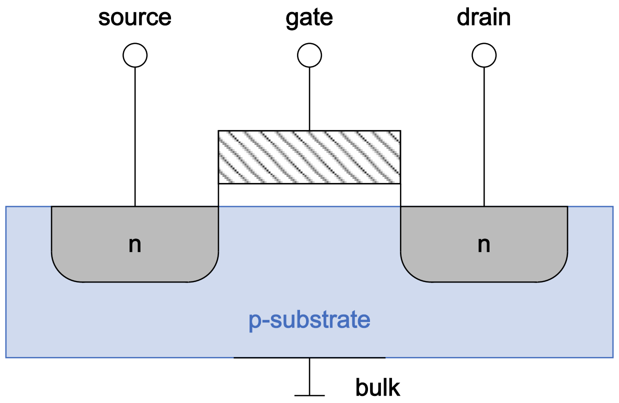


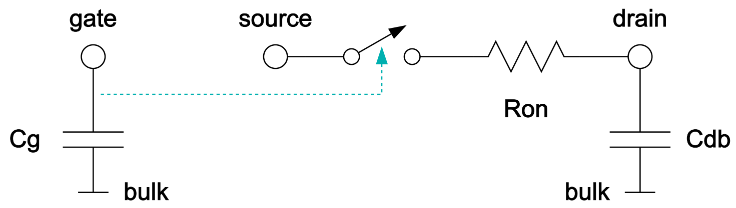
Figure 1.20 Ring oscillator circuit for propagation-delay measurement.

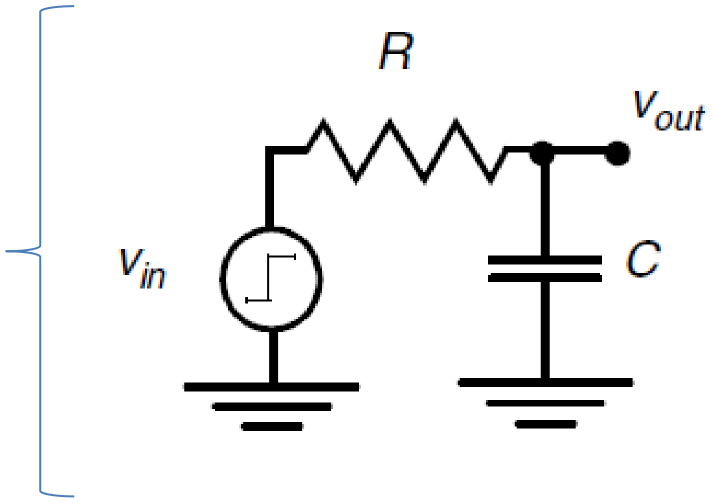


Propagation delay of the first-order *RC* networks

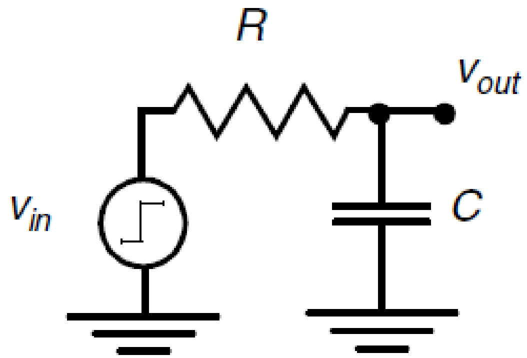
- The RC step response is a fundamental behavior of all digital circuits and thus digital circuits are often modeled as first-order *RC* networks.
- The propagation delay of the circuit is of considerable interest.







Propagation delay



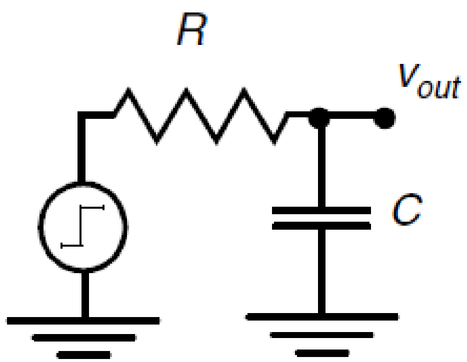
First order RC network

- $V_{in} = R * i(t) + v_{out}(t)$
- $v_{out}(t) = v_c(t) = \frac{1}{C}\int_0^t \boldsymbol{i(t)}dt$
- Hence, $V_{in} = R * \boldsymbol{i(t)} + \frac{1}{C}\int_0^t i(t)dt$

To calculate i(t), take the derivative

- $0 = R\frac{di(t)}{dt} + \frac{1}{C}\, i(t) \Rightarrow \frac{di(t)}{dt} + \frac{1}{RC}\, i(t) = 0$ (solve the diff. Equations)
- $i(t) = I_0 e^{-\frac{t}{RC}}$ $\&\, when\ t = 0, I_0 = \frac{V_{in}}{R}$
- $v_{out}(t) = \frac{1}{C}\int_0^t \frac{V_{in}}{R} e^{-\frac{t}{RC}}dt = V_{in}\left(1 - e^{-\frac{t}{RC}}\right) = V_{in}(1 - e^{-\frac{t}{\tau}})$ $\quad where\ \tau = RC\ (time\ constant)$

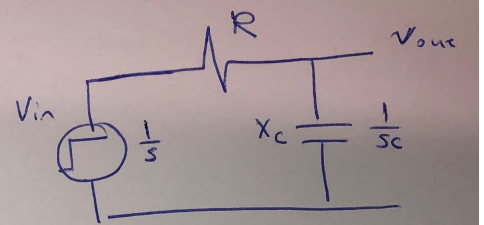
Propagation delay



First order RC network (another solution)

s domain

$$V_{out} = V_{in}\frac{X_c}{R+X_c} = \frac{1}{s}\,\frac{\frac{1}{sC}}{R+\frac{1}{sC}} = \frac{1}{s}\cdot\frac{1}{sRC+1}$$



$$= \frac{A}{s} + \frac{B}{sRC+1} \quad \Leftarrow \text{Partial fraction}$$

$$A\Big|_{s=0} = 1 \qquad B\Big|_{s=-\frac{1}{RC}} = -RC$$

$$= \frac{1}{s} + \frac{-RC}{sRC+1} = \frac{1}{s} - \frac{1}{s+\frac{1}{RC}}$$

$$V_{out} = \left(1 - e^{-\frac{t}{RC}}\right)V_{in}$$

Laplace transform:

$$u(t) = \frac{1}{s}$$

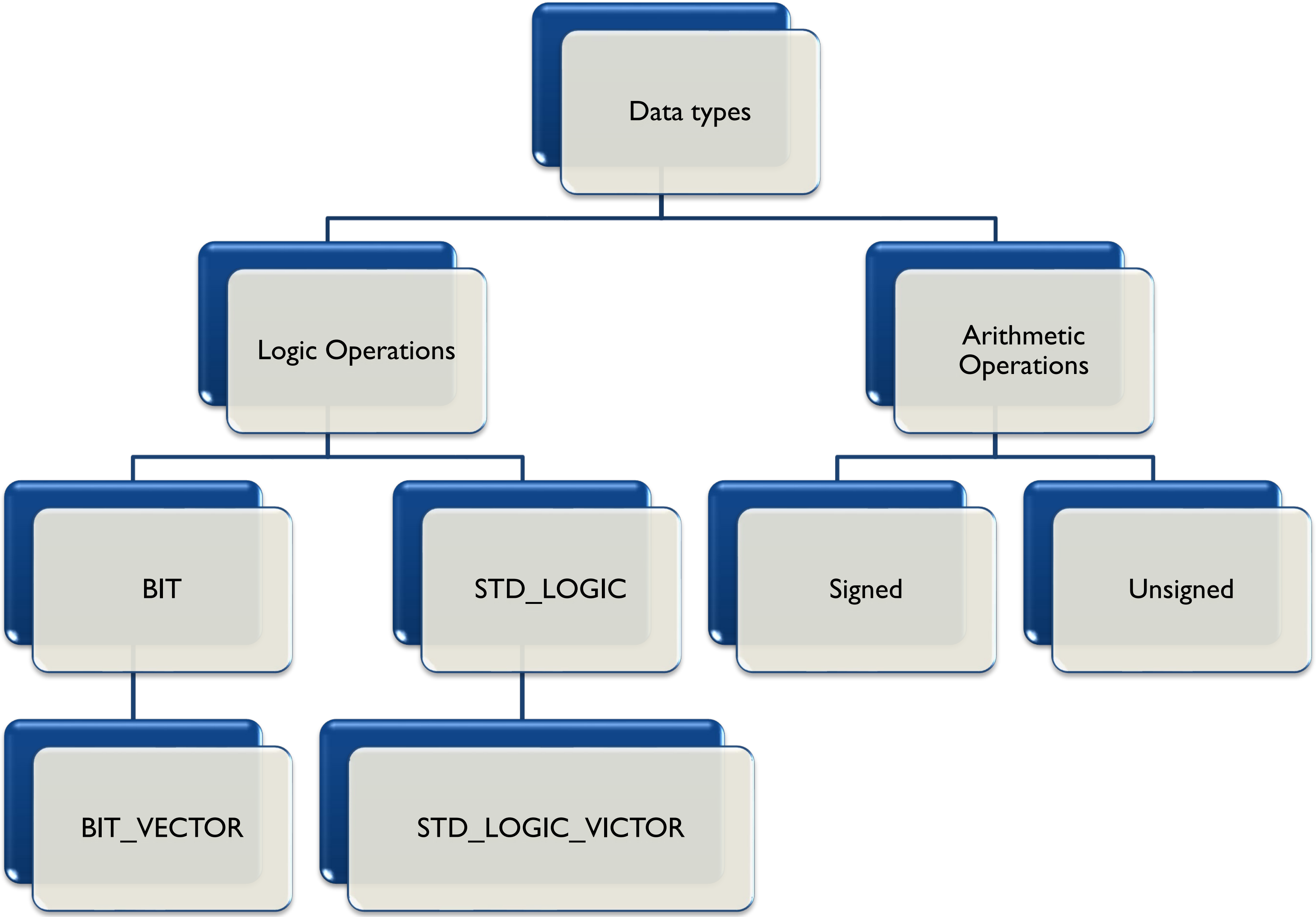
$$e^{-\alpha t}u(t) = \frac{1}{s+\alpha}$$

Digital system design (VHDL examples)

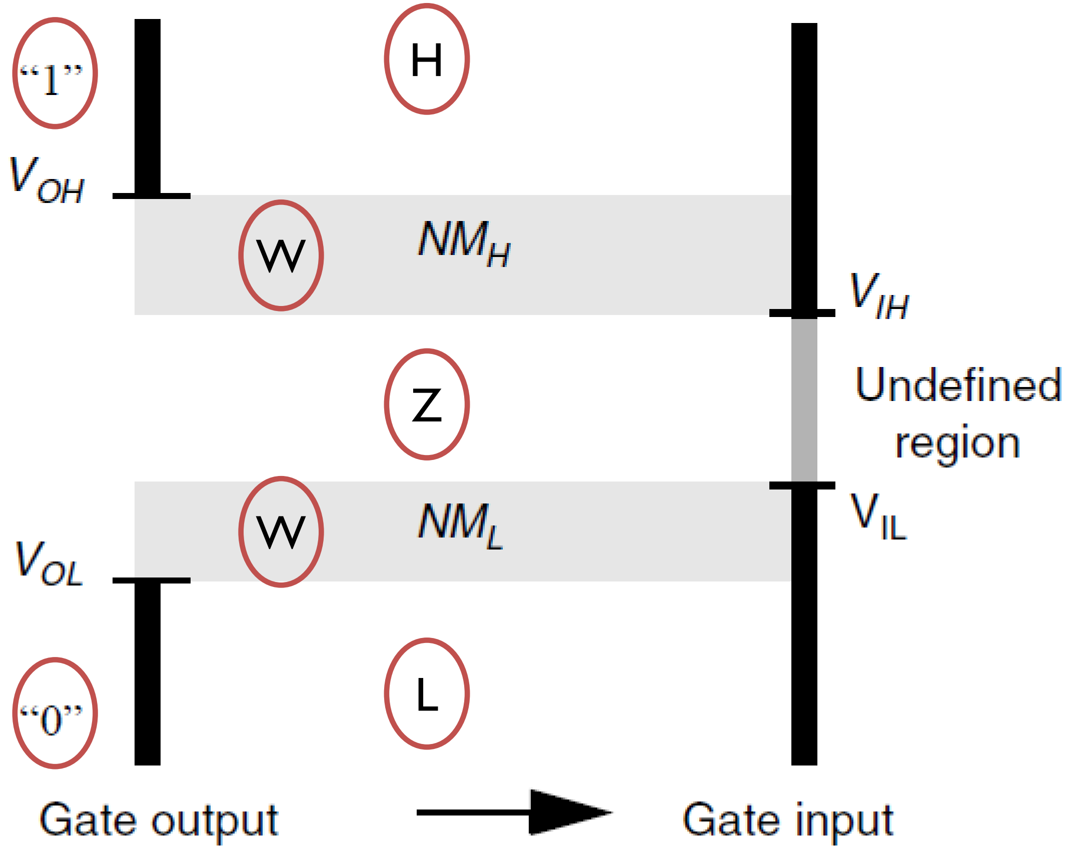
VHDL

- *Very high speed integrated circuit Hardware Description Language* (VHDL) is a programming language that has been designed and optimized for describing the behavior of digital systems.
- 1980: The USA department of defense (DOD) wanted to make circuit design self documenting.
- 1983: The development of VHDL began with a joint effort by IBM, Texas Instruments and Intermetrics.
- 1987: The institute of Electrical and Electronics Engineers (IEEE) was presented with a proposal to standardize the language.
- 1993: The VHDL language was revised to IEEE 1076-1993. IEEE published 1164 standards that describes the definitions of logic values to be used.
- 1996: A VHDL package for use with synthesis tools become part of the IEEE 1076 standard, specifically it is 1076.3. This greatly improved the portability of designs between different synthesis vendor tools.

Character	Value
'U'	uninitialized
'X'	strong drive, unknown logic value
'0'	strong drive, logic zero
'1'	strong drive, logic one
'Z'	high impedance
'W'	weak drive, unknown logic value
'L'	weak drive, logic zero
'H'	weak drive, logic one
'-'	don't care


Data types
Logic Operations
Arithmetic Operations
BIT
STD_LOGIC
Signed
Unsigned
BIT_VECTOR
STD_LOGIC_VICTOR

STD_LOGIC

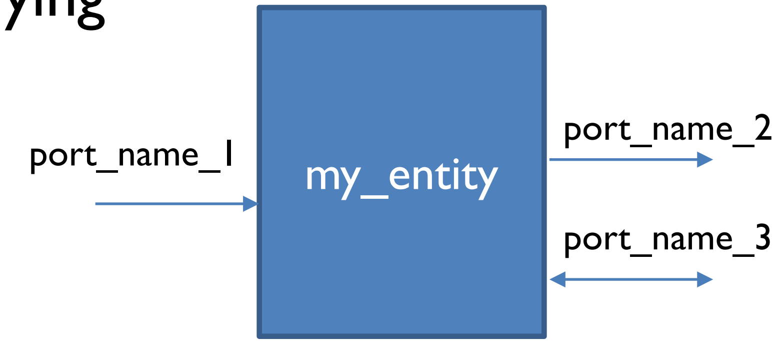


Character	Value
'U'	uninitialized
'X'	strong drive, unknown logic value
'0'	strong drive, logic zero
'1'	strong drive, logic one
'Z'	high impedance
'W'	weak drive, unknown logic value
'L'	weak drive, logic zero
'H'	weak drive, logic one
'-'	don't care

VHDL Design Units

Entity

- The VHDL entity describes how the unit interfaces with the outside world.
- The entity lists the various inputs and outputs of the underlying circuitry.




```
entity my_entity is
port(
     port_name_1 : in    std_logic ;
     port_name_2 : out   std_logic;
     port_name_3 : inout std_logic ); --do not forget the semicolon
end my_entity; -- do not forget this semicolon either
```

VHDL Design Units

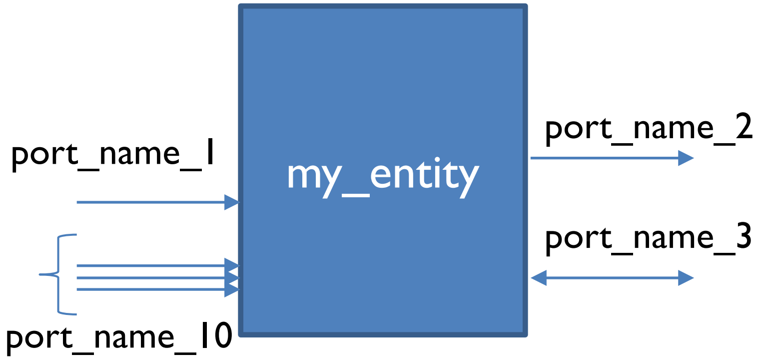
Vector (bus)

A set of similar signals.

port_name_10: in std_logic_vector(2 downto 0);

OR

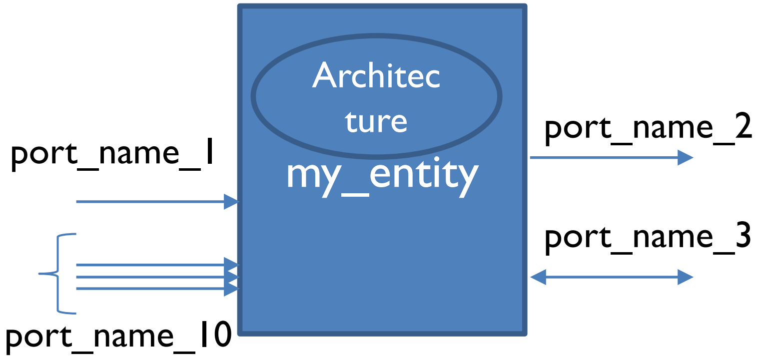
port_name_10: in std_logic_vector(0 to 2);



VHDL Design Units

Architecture:

- The architecture describes what the circuit actually does. In other words, the VHDL architecture describes the internal implementation of the associated entity.
- There is the **data-flow** model, the **behavioral** model, the **structural** model and the **hybrid** models.



Digital circuit designs in VHDL

Combinational circuits

They are defined as the *time independent circuits* which do not depends upon previous inputs to generate any output are termed as combinational circuits.

Examples – Encoder, Decoder, Multiplexer, Demultiplexer, etc.

Sequential circuits

They are those which are *dependent on clock cycles* and depends on present as well as past inputs to generate any output.

Examples – Flip-flops, Counters, Registers, etc.