

Lecture I:

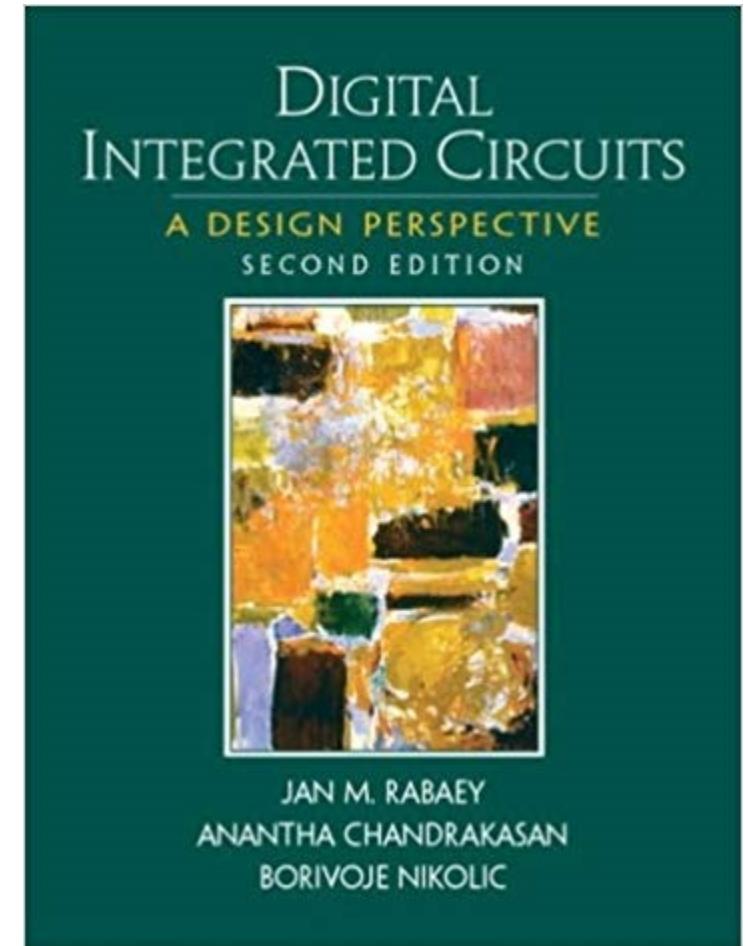
Introduction to Integrated Circuits and Embedded Systems

Chapter I (Book I)

Emad Samuel Malki Ebeid

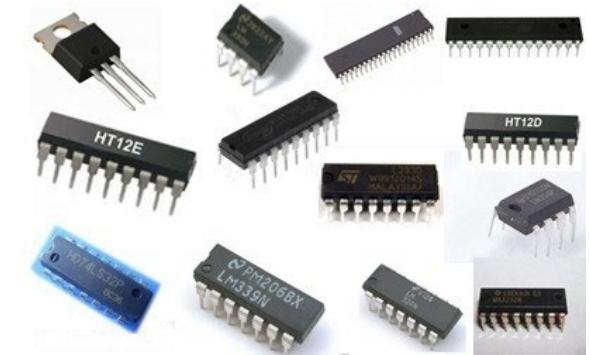
Book I

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



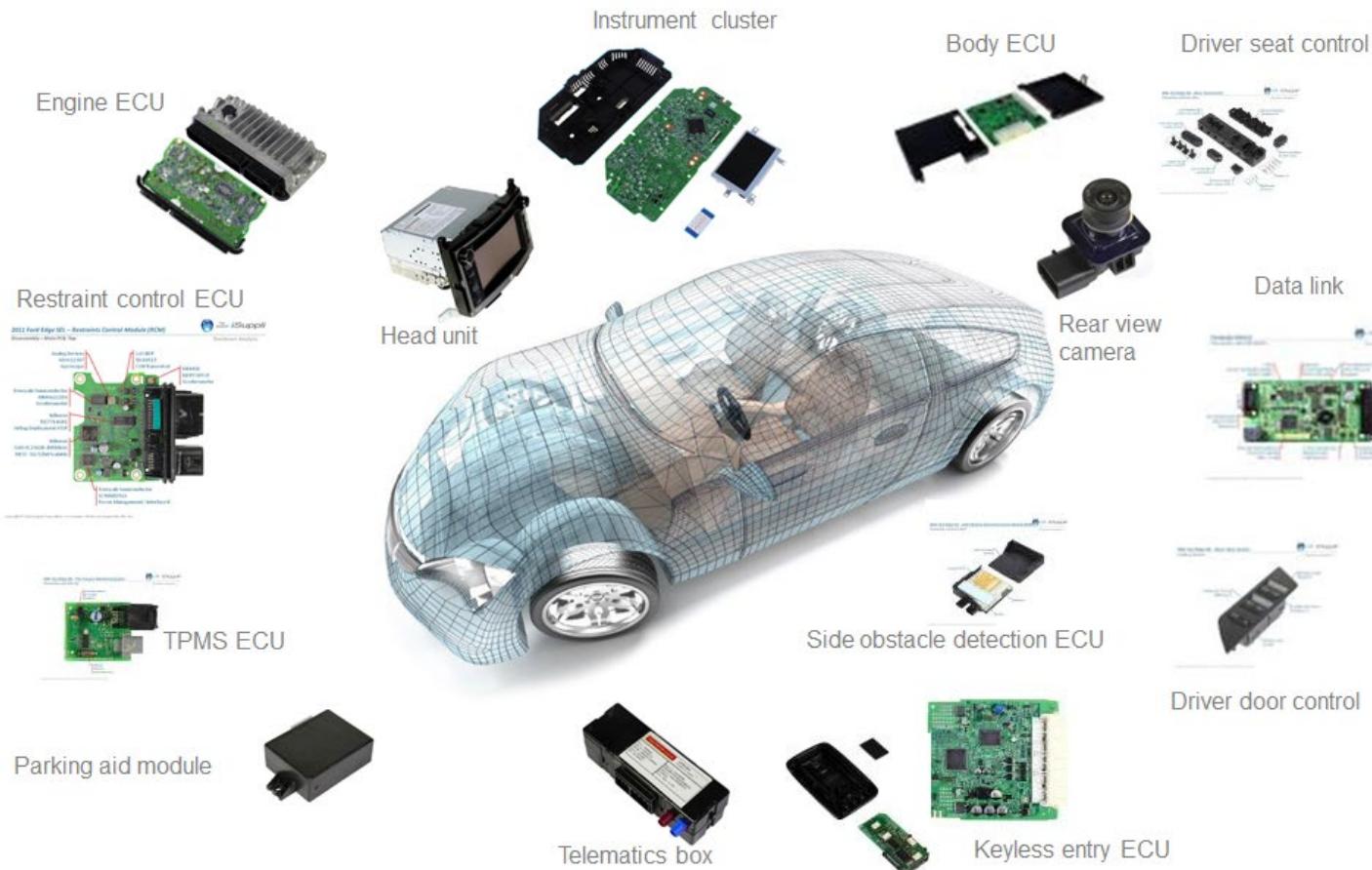
What is an Integrated Circuit/Embedded System?

- 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

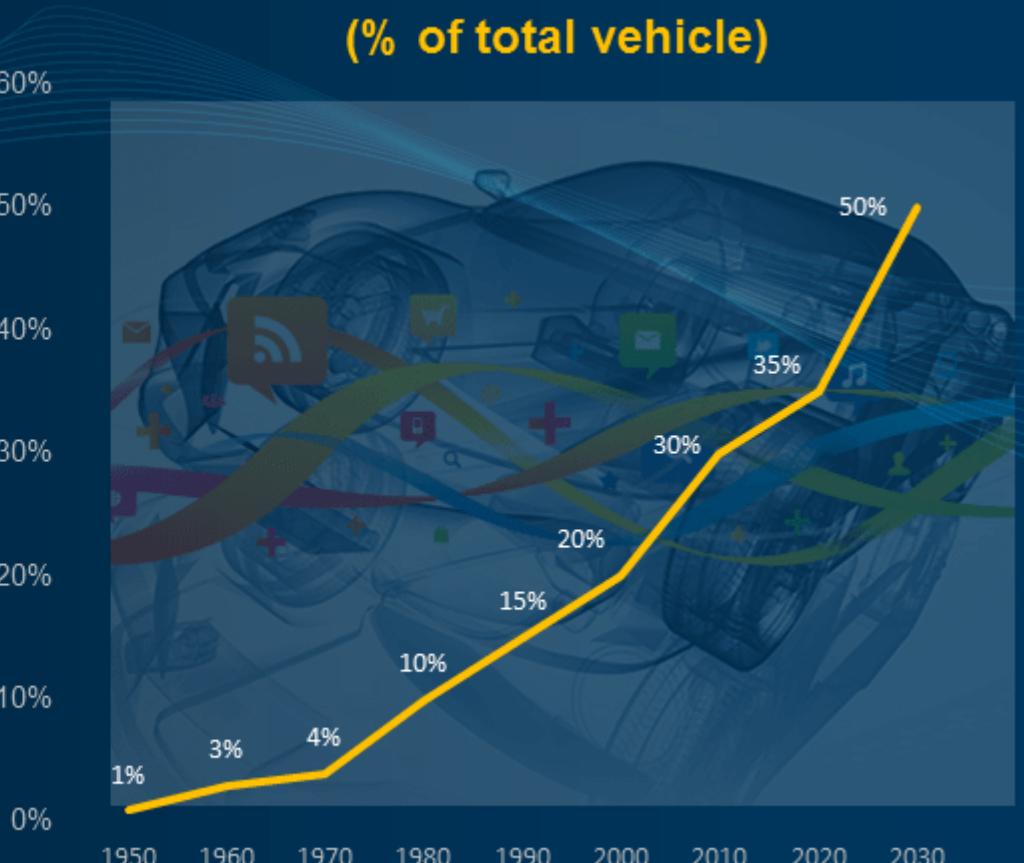


Automotive Market

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

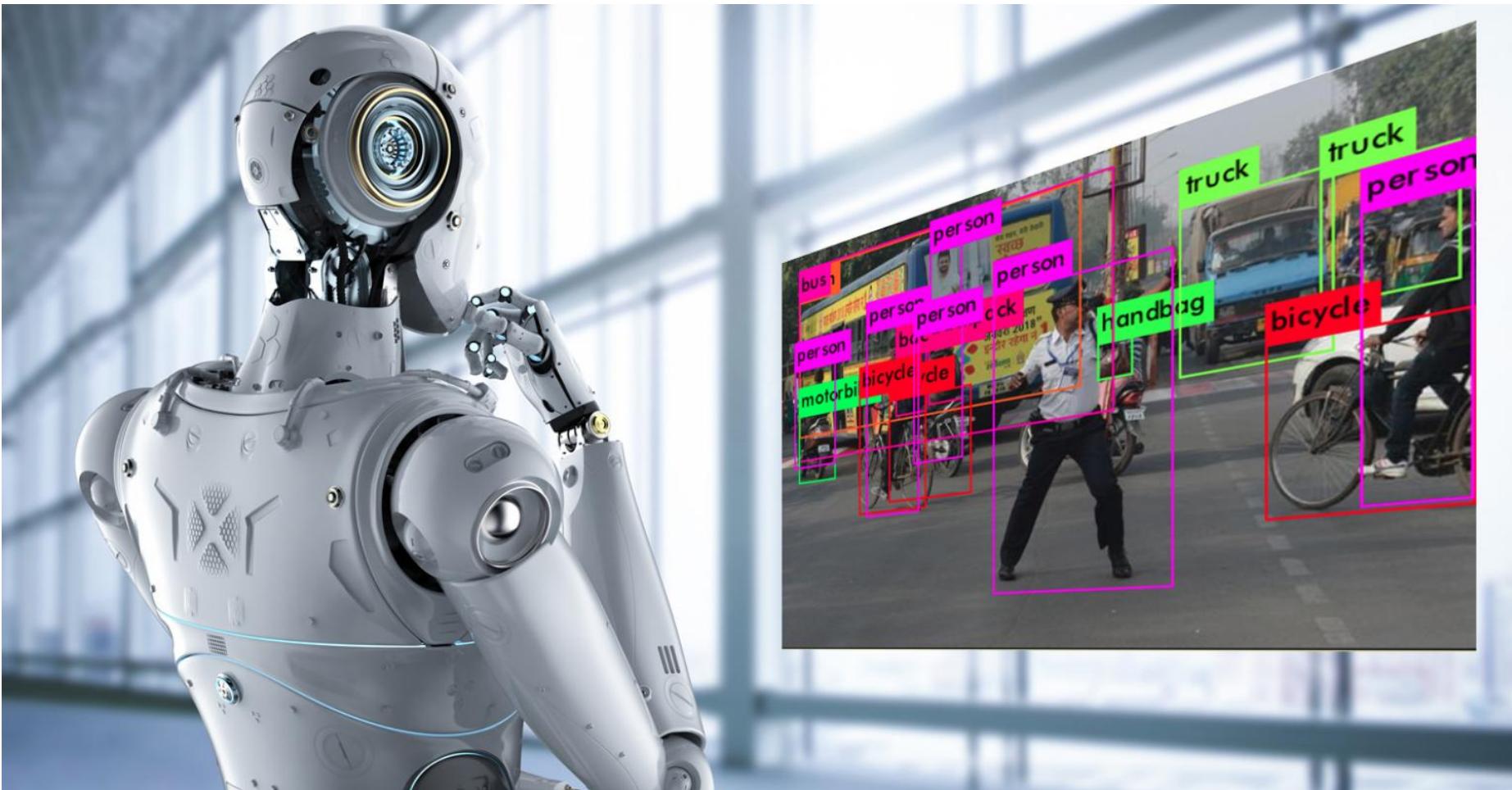
Luca De Ambroggi
Principal analyst Automotive electronics
IHS Markit

Automotive electronics cost
(% of total vehicle)



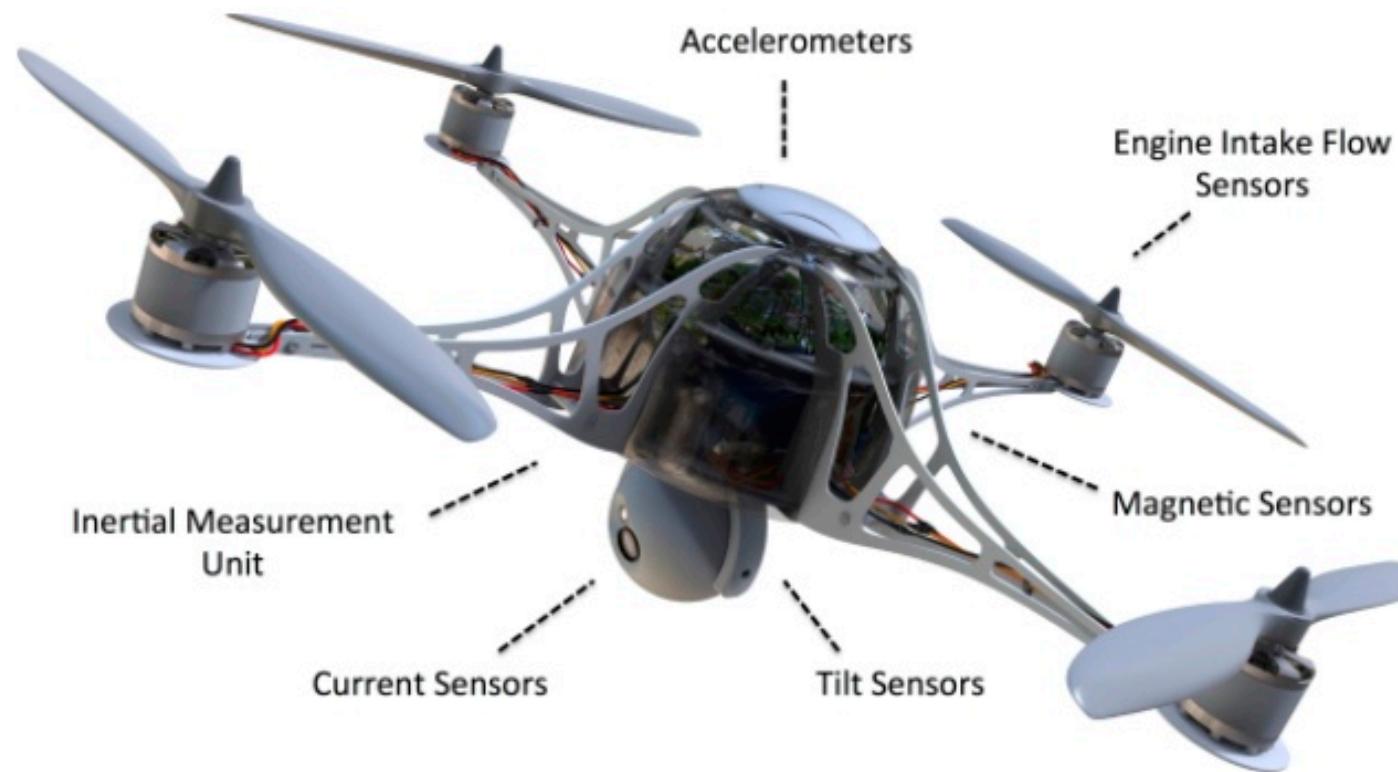
Source: Roland Berger

Self-learning robots



electronicdesign.com

Autonomous drones



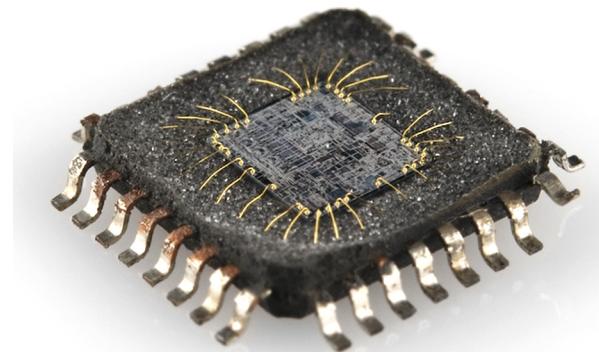
Drone Powered by Xilinx



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

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!

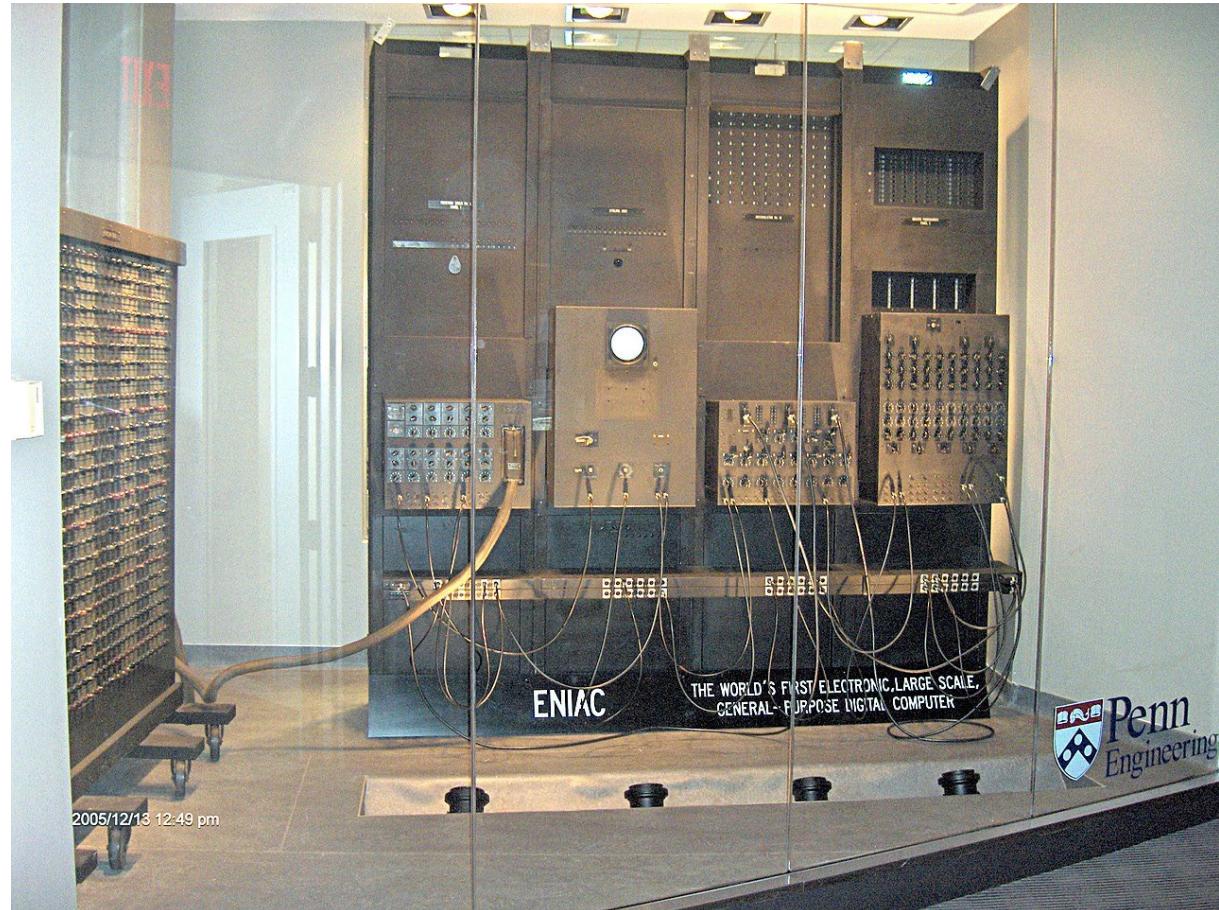
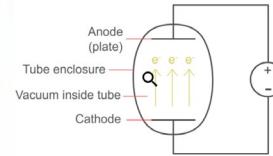
x	F(x)	1 st	2 nd
		difference	difference
1	5		
2	8	3	2
3	13	5	2
4	20	7	2
5	29	9	2
6	40	11	2
7	:	:	2
:	:	:	:
:	:	:	:
:	:	:	:

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



Electronic Numerical Integrator and Computer (ENIAC)

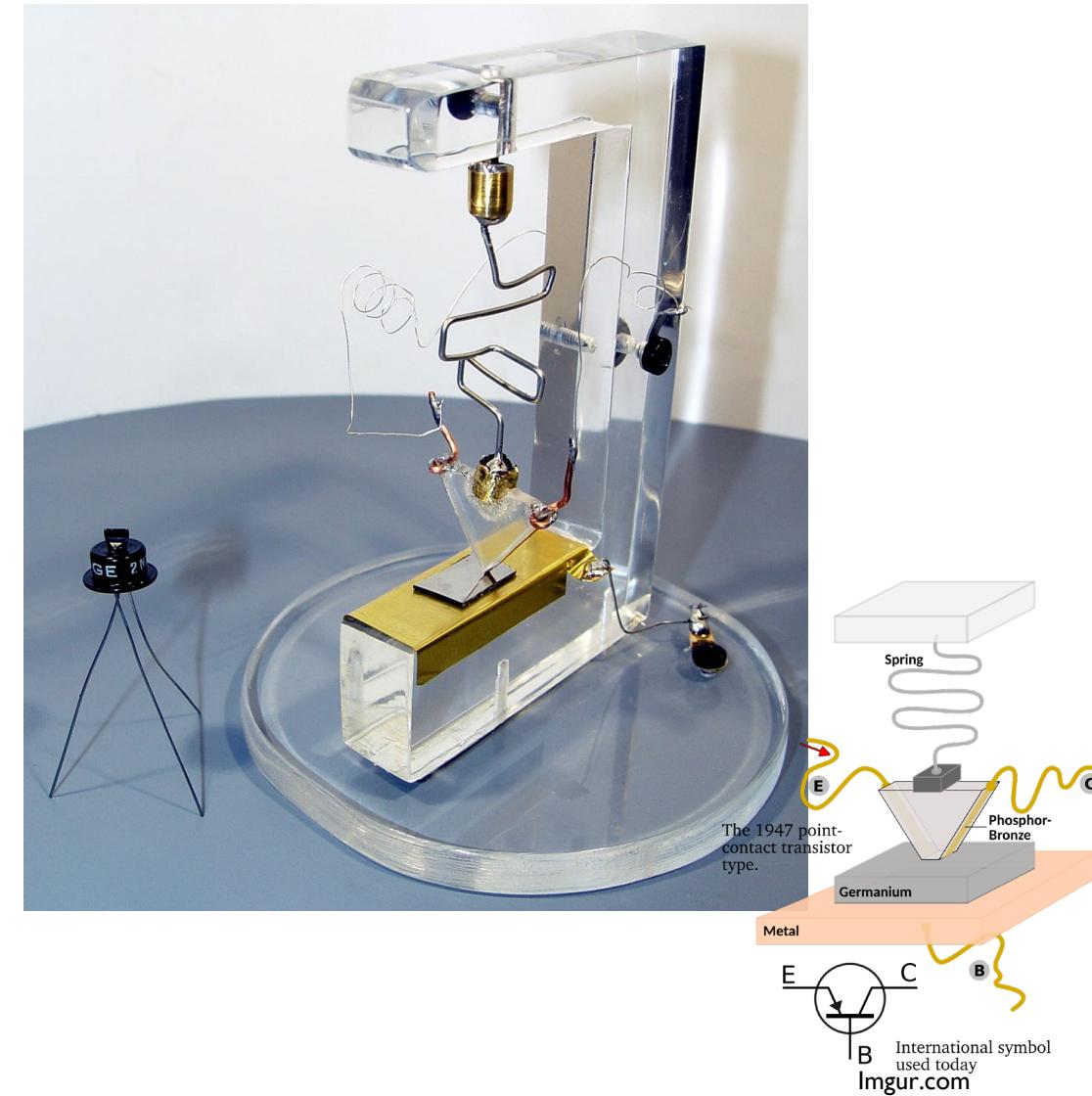
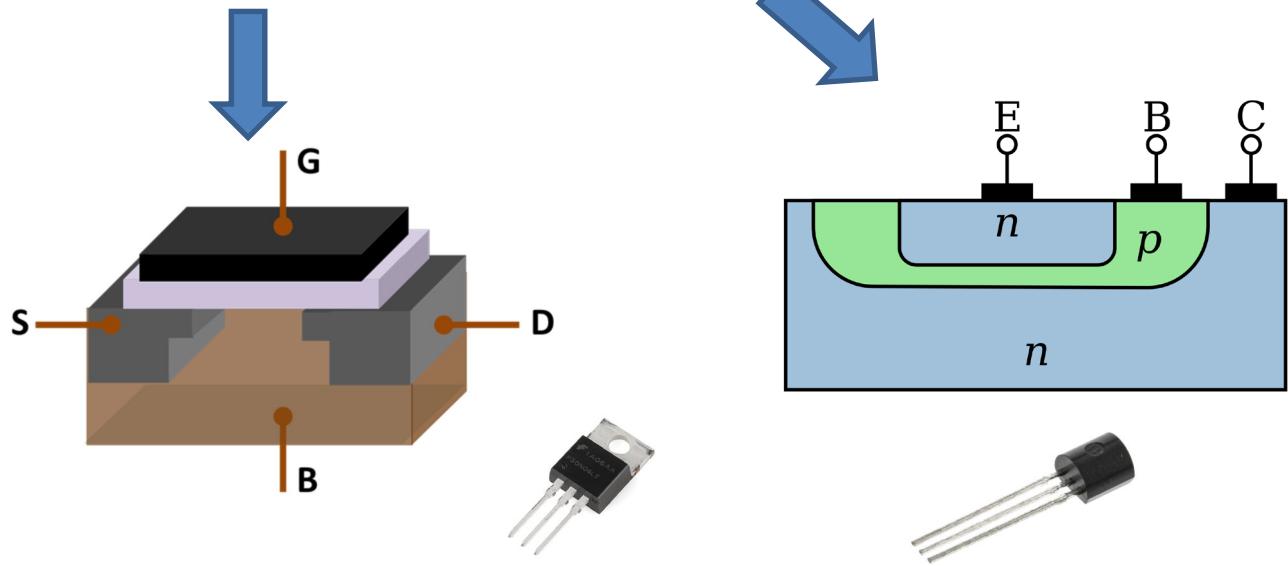
- The first electronic general-purpose computer (1946).
- It has
 - 18,000 vacuum tubes
 - several miles of wiring
 - 40 black eight-foot panels
 - weigh 30 tons
 - occupying the 50-by-30-foot basement of the Moore School of Electrical Engineering at the U Penn.
 - ENIAC could execute up to 5,000 additions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

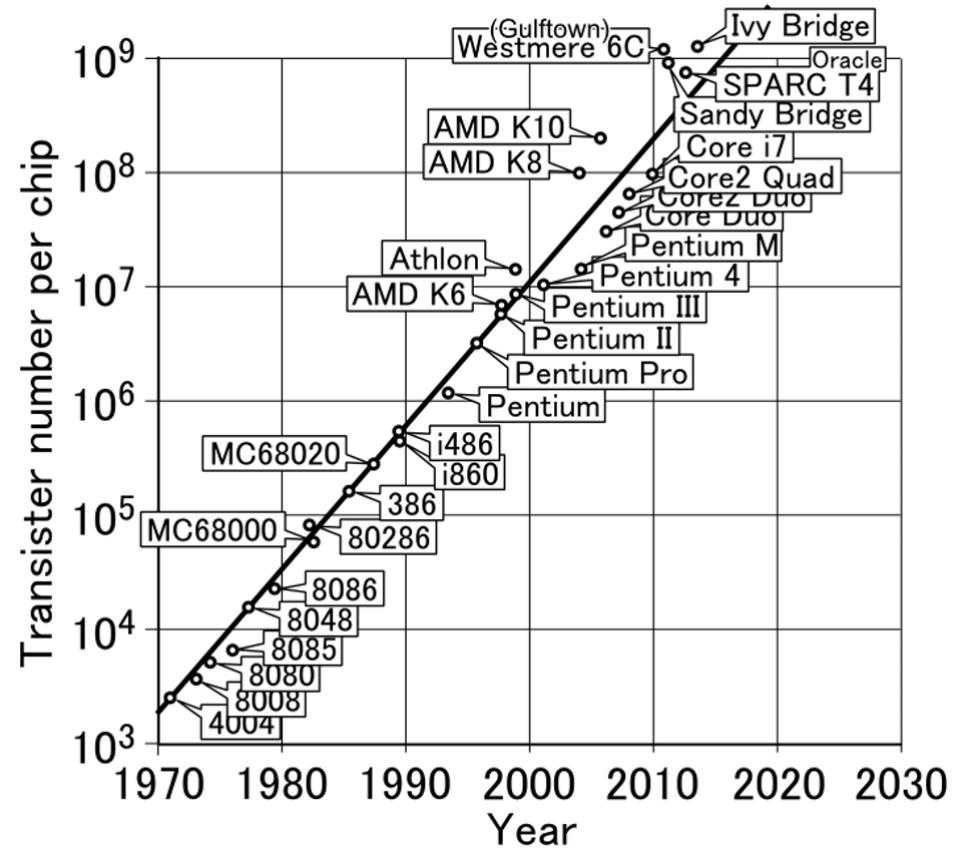


Transistor evolution

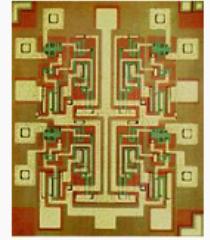
- Gordon Moore, Fairchild Semiconductor, 1965 (Intel cofounder in 1968)



(Intel.com, 2018)



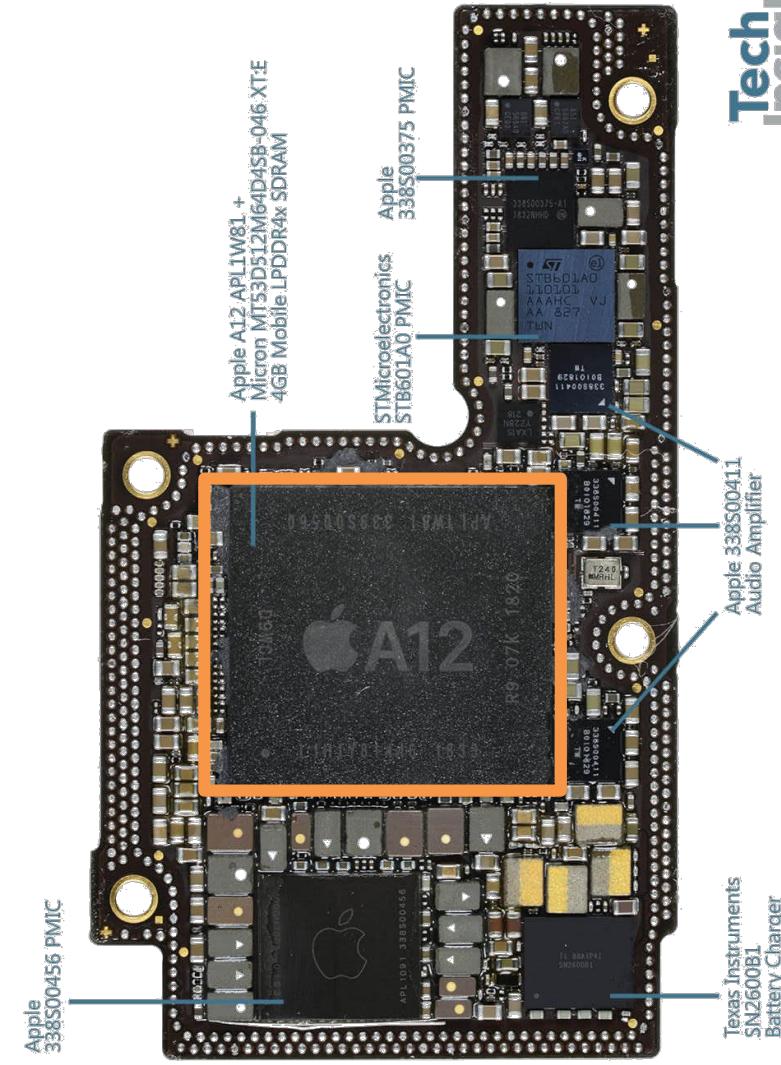
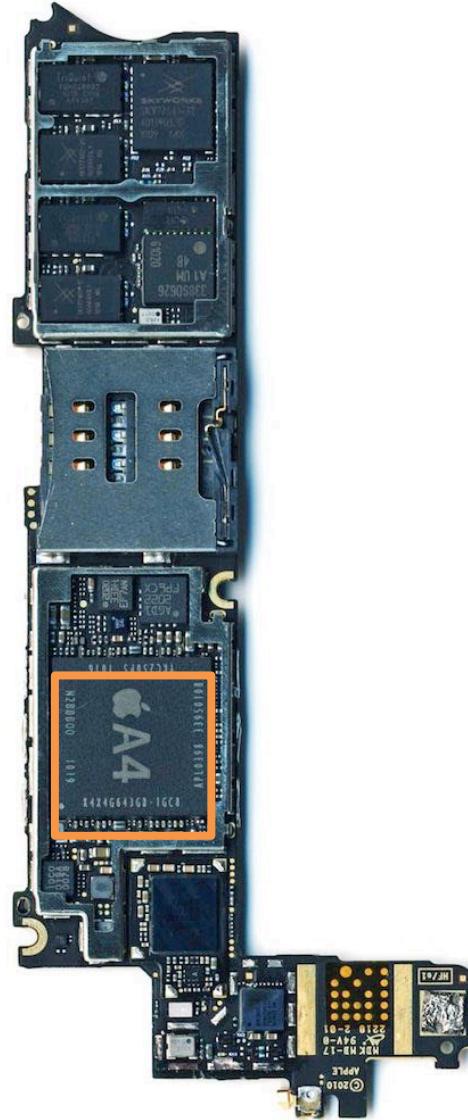
Semiconductor manufacturing processes



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

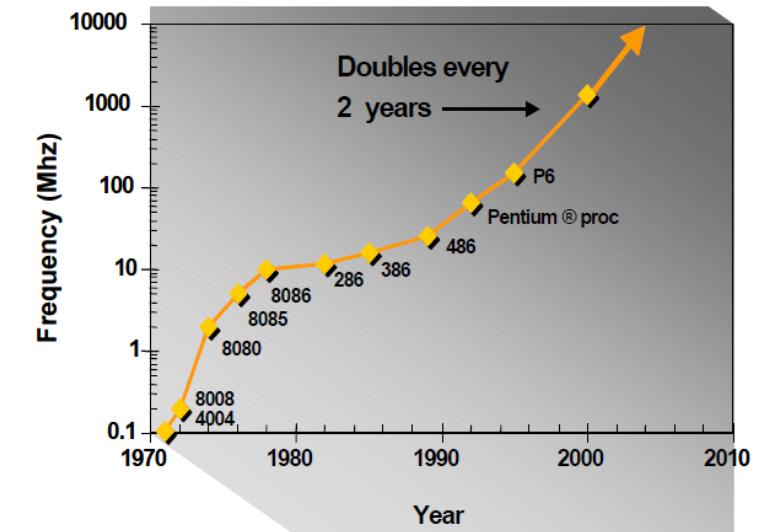


Tech Insights

iPhone XS (2018)
7nm/2.49GHz

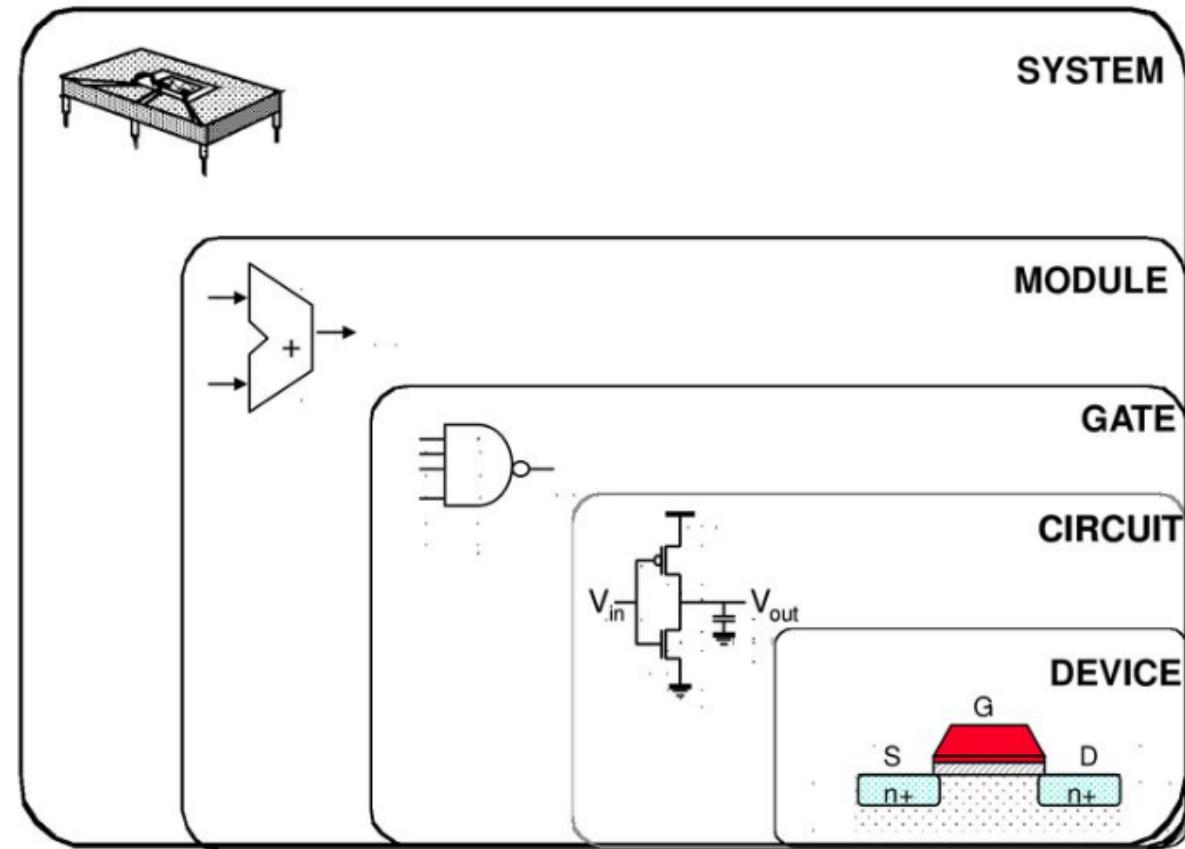
Moore's law

- 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).

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

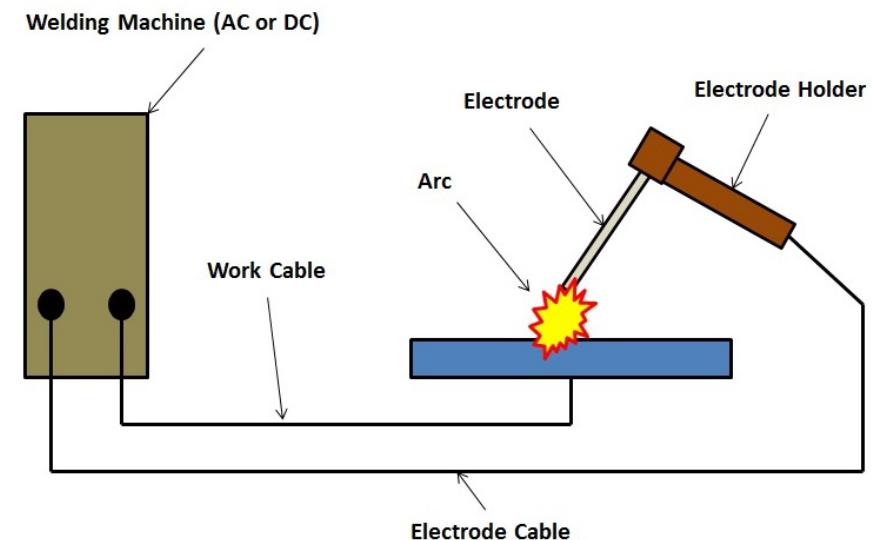
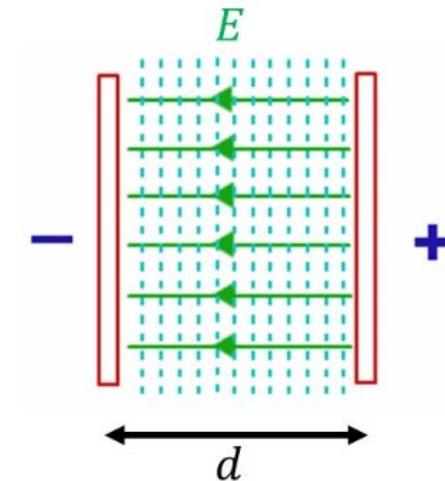
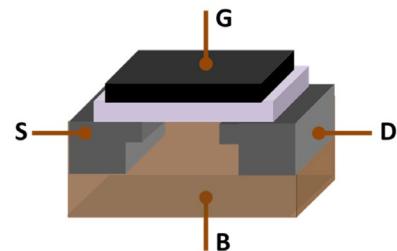
- Examples:

- For welding:

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

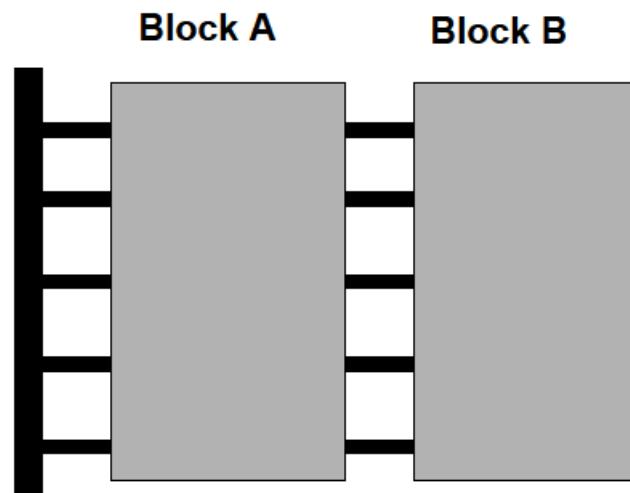
- Inside the transistor:

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

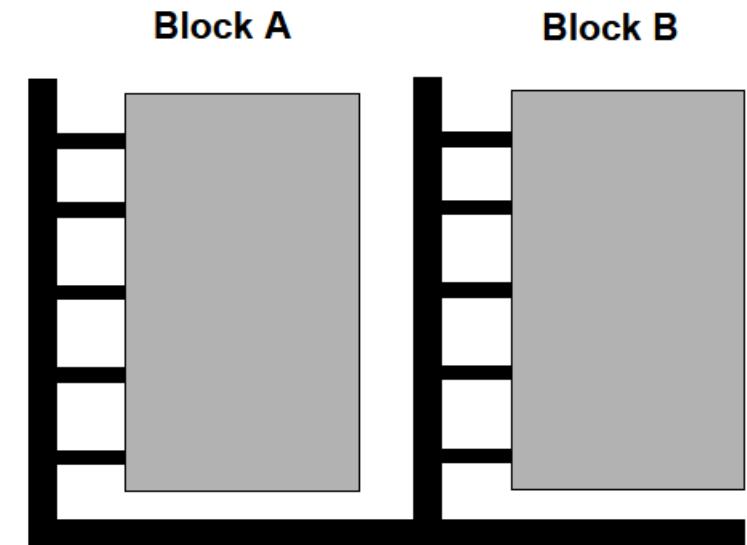


Power distribution

- A) voltage drop in block A
- B) easy to distribute power but needs more area to implement



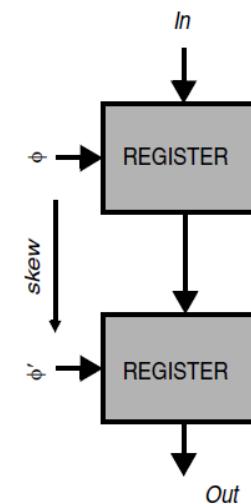
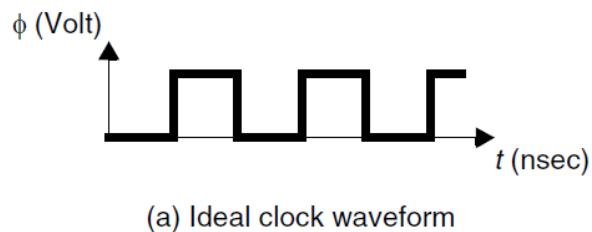
(a) Routing through the block



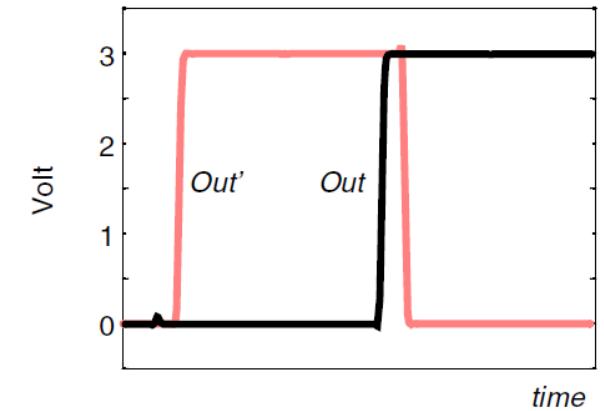
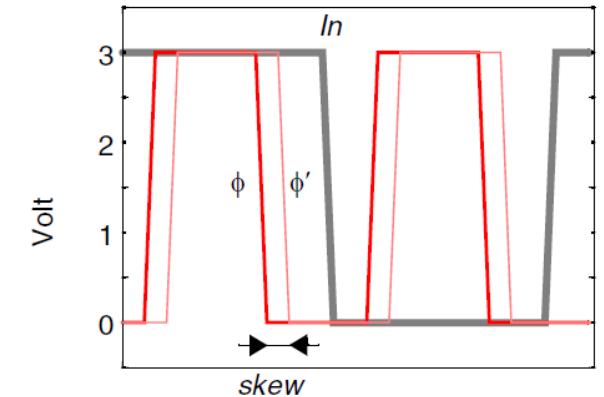
(b) Routing around the block

Clock distribution

- 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



(b) Two cascaded registers



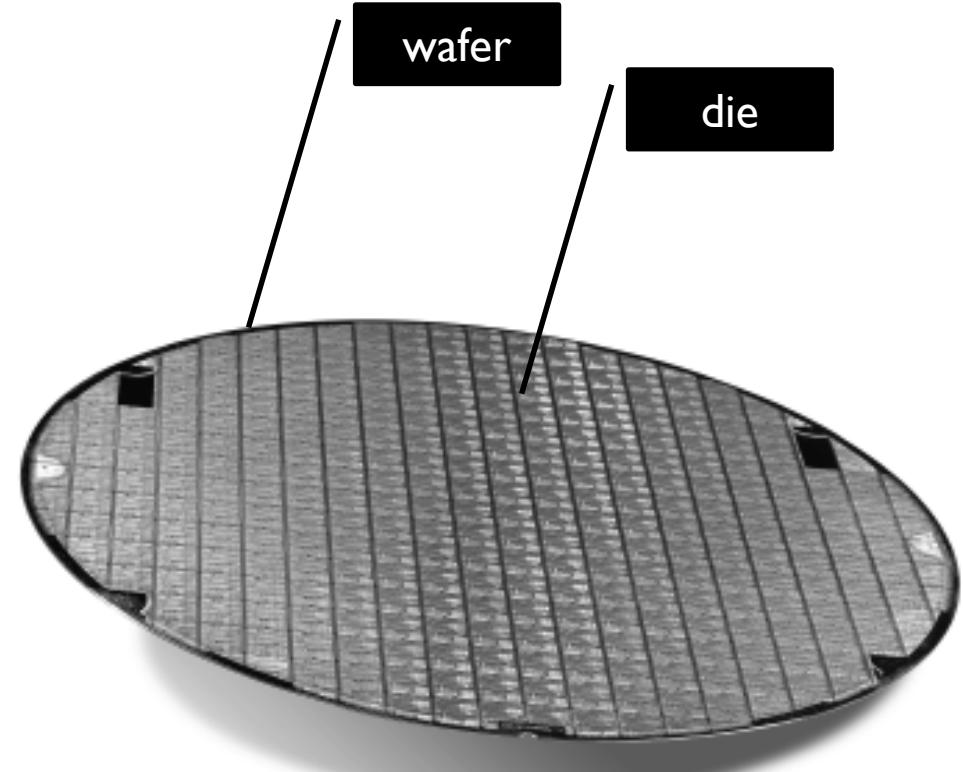
(c) Simulated waveforms

Cost of an Integrated Circuit

- **Cost per IC = variable cost per IC + (fixed cost/volume)**

Where:

- *Variable costs include the costs of the parts used in the product, assembly costs, and testing costs.*
- *Fixed costs are the effort in time and manpower it takes to produce the design + R&D, manufacturing equipment, marketing, sales, and building infrastructure*



AMD Duron™ microprocessor

Die cost

- Die cost = cost of wafer / (dies per wafer * die yield)

Where:

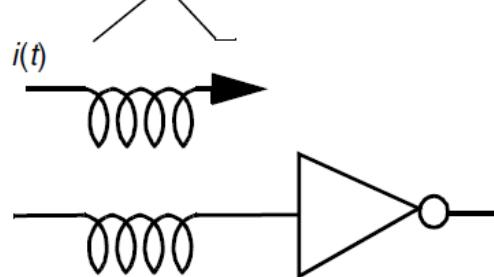
$$\text{die yield} = \frac{\text{number of good dies per wafer}}{\text{total number of dies per wafer}} * 100 (\%)$$

- Defects: 1 defect/cm²
 - For example: pure sand has 10^6 silicon atoms and one unknown atom.

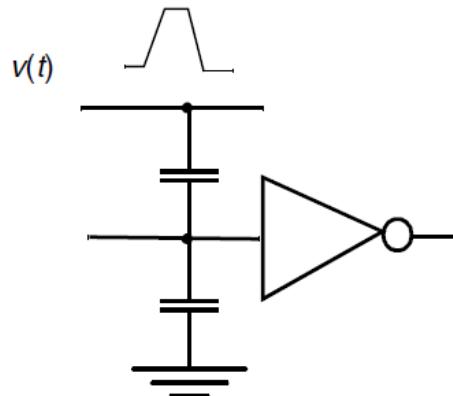


Functionality and Robustness

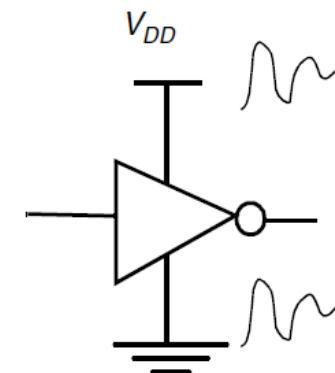
- Noise in digital circuits means “*unwanted variations of voltages and currents at the logic nodes.*”
- Noise sources in digital circuits:



(a) Inductive coupling



(b) Capacitive coupling



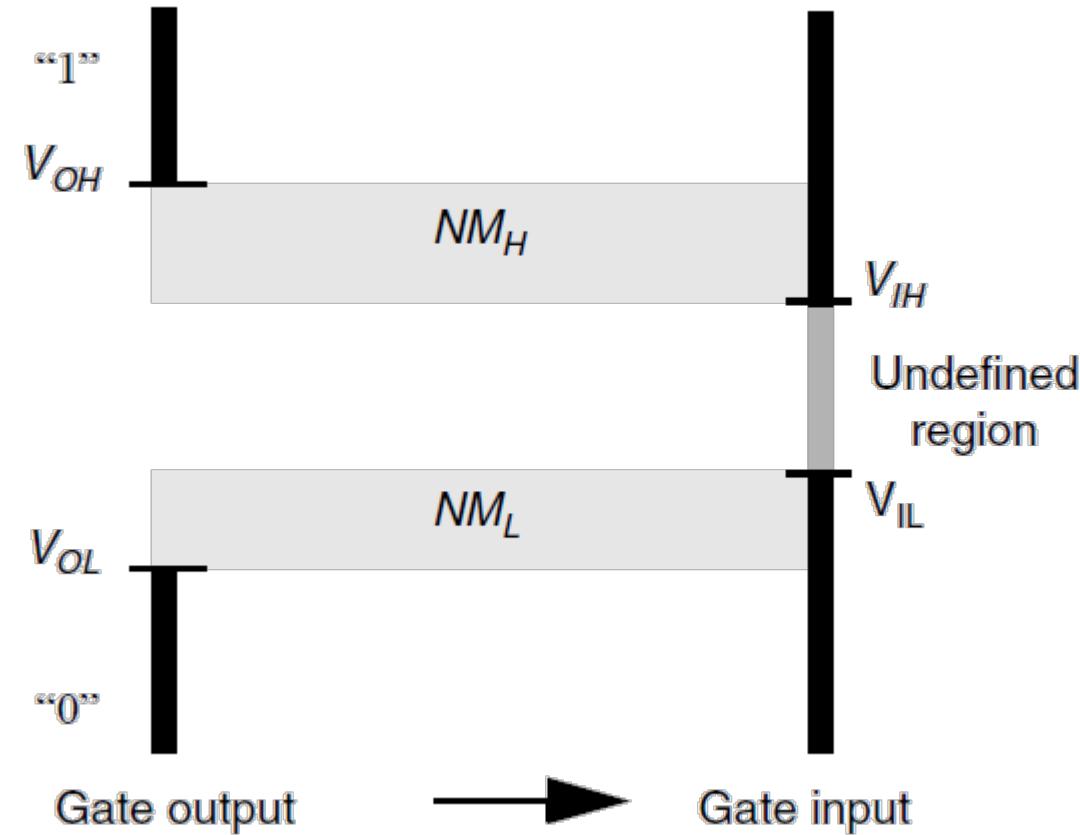
(c) Power and ground noise

Noise Margins

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

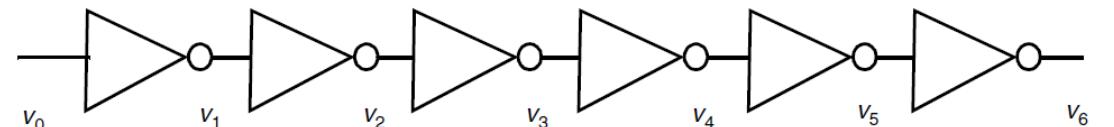
Noise Margin is how much noise can be added to the logic level and still these level unchanged.

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

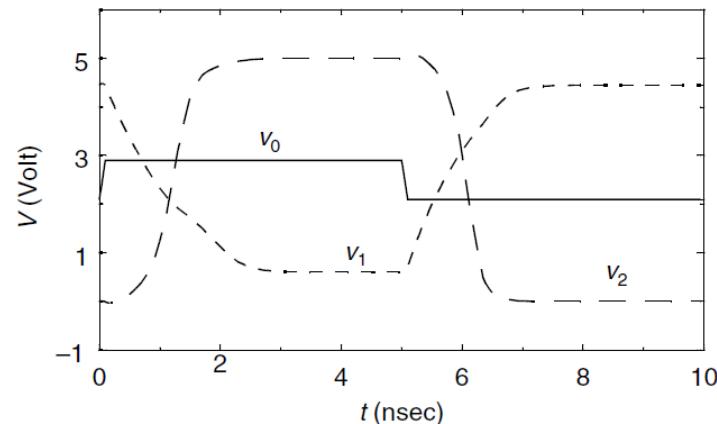


Regenerative Property

- Regenerative circuit **does not allow** different noise sources to accumulate and eventually force a signal level into the undefined region.
- Degenerative circuit **does allow** ...
- **Regenerative example:**
- **Noise immunity:** how immune the circuit to noise



(a) A chain of inverters



(b) Simulated response of chain of MOS inverters

Fan-In and Fan-Out

- **Fan-out** how much logic gates can be driven by any logic gate.
- Fan-in is the *number of inputs* to the gate.

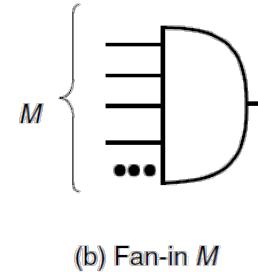
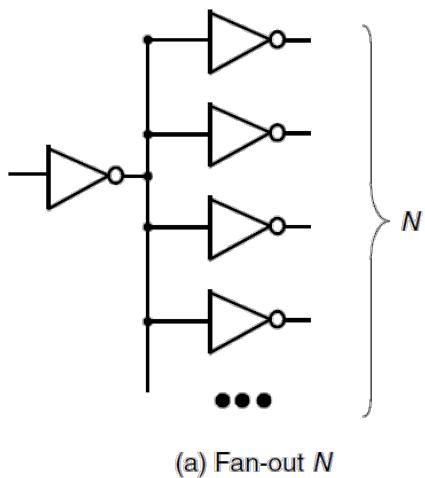
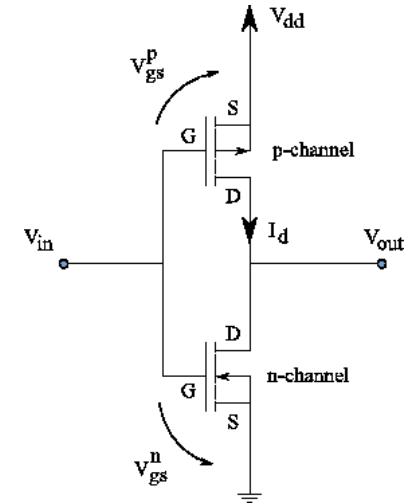


Figure 1.16 Definition of fan-out and fan-in of a digital gate.



- Example: Fan-out = 10 and Fan-in = 2 => can lead up to 5 gates.

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

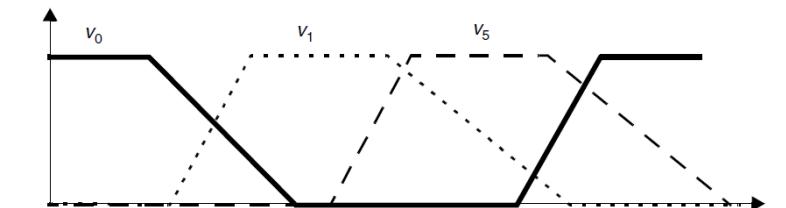
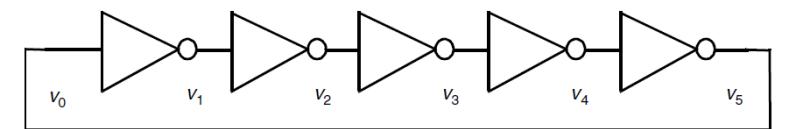
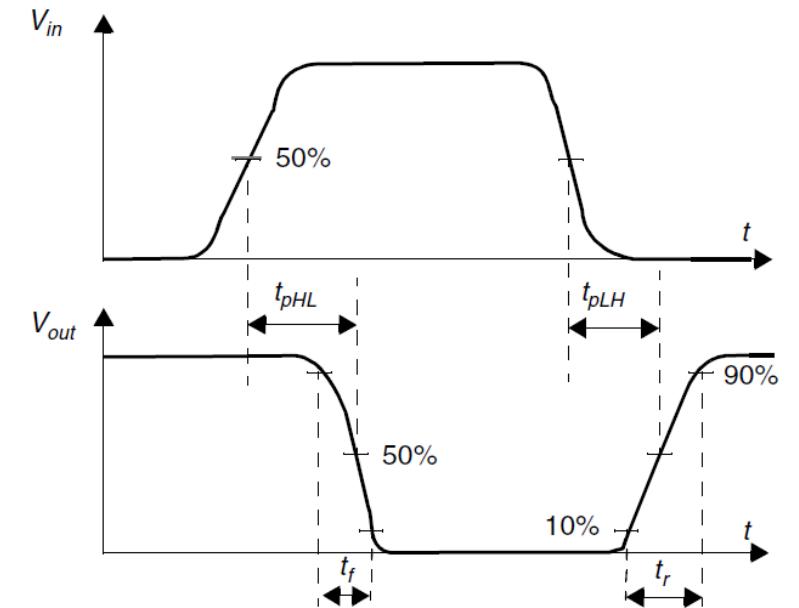
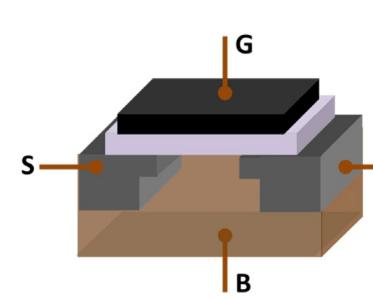
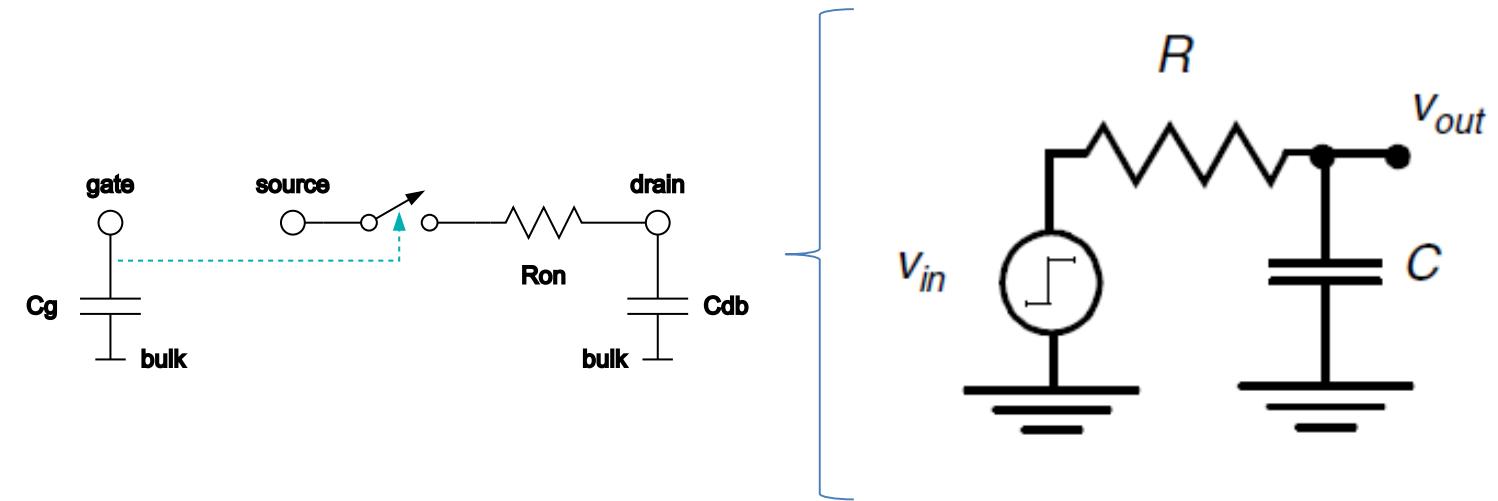
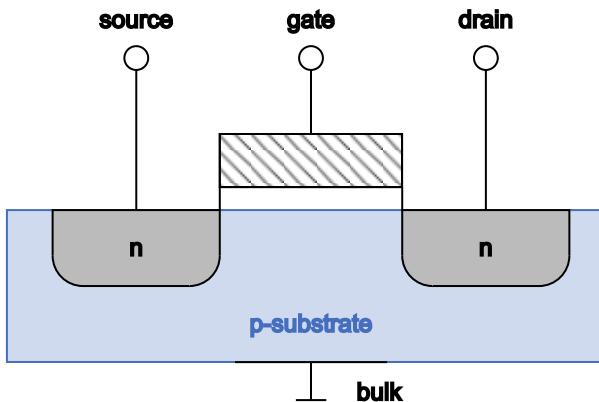


Figure 1.20 Ring oscillator circuit for propagation-delay measurement.



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.



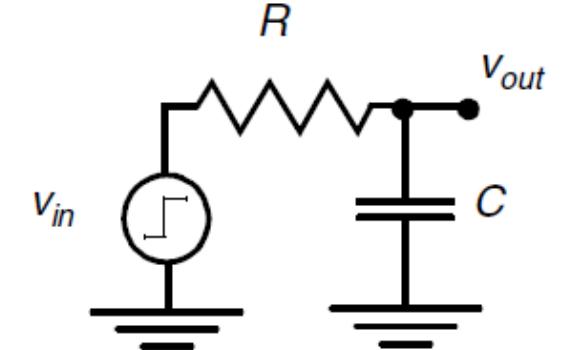
Propagation delay

First order RC network

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

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 $t = 0, I_0 = \frac{V_{in}}{R}$
- $v_{out}(t) = \frac{1}{C} \int_0^t \frac{V_{in}}{R} e^{-\frac{t}{RC}} dt = V_{in} \left(1 - e^{-\frac{t}{RC}}\right) = V_{in} \left(1 - e^{-\frac{t}{\tau}}\right)$ where $\tau = RC$ (time constant)



Propagation delay

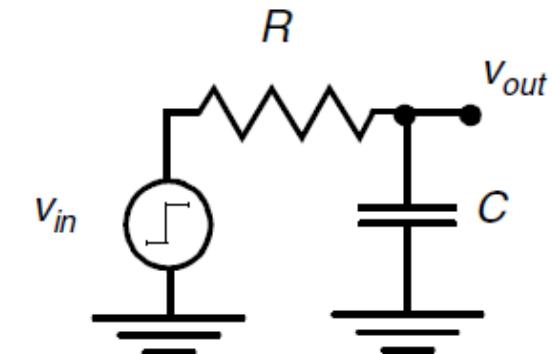
First order RC network (another solution)

$$\begin{aligned}
 V_{out} &= V_{in} \cdot \frac{x_c}{R + x_c} \xrightarrow{\text{S-domain}} \frac{\frac{1}{sc}}{R + \frac{1}{sc}} = \frac{1}{s} \cdot \frac{1}{sRC + 1} \\
 &= \frac{A}{s} + \frac{B}{sRC + 1} \quad \leftarrow \text{Partial fraction} \\
 A|_{s=0} &= 1 \quad B|_{s=\frac{-1}{RC}} = -RC \\
 &= \frac{1}{s} + \frac{-RC}{sRC + 1} = \frac{1}{s} - \frac{1}{s + \frac{1}{RC}} \\
 V_{out} &= \left(1 - e^{-\frac{t}{RC}}\right) V_{in}
 \end{aligned}$$

Laplace transform:-

$$U(s) = \frac{1}{s}$$

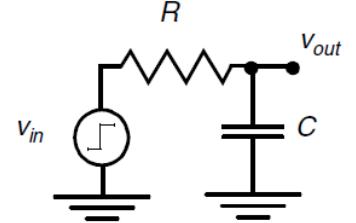
$$e^{-xt} = \frac{1}{s+x}$$



Power and Energy Consumption

- It determines how much energy is consumed per operation and heat the circuit dissipates.
- Design decisions depends on:
 - power-supply capacity
 - battery lifetime
 - supply-line
 - sizing
 - packaging
 - cooling

Power and Energy Consumption



- Dissipation measures:

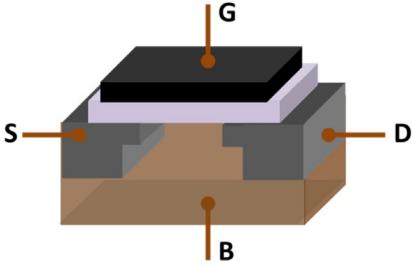
$$P_{peak} = i_{peak} V_{supply} = \max[p(t)]$$

$$P_{av} = \frac{1}{T} \int_0^T p(t) dt = \frac{V_{supply}}{T} \int_0^T i_{supply}(t) dt$$

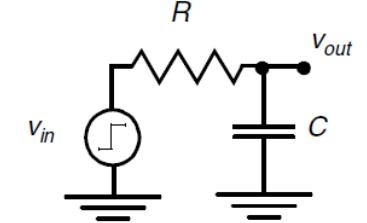
Where:

- $p(t)$ is the instantaneous power
- i_{supply} is current being drawn from the supply voltage V_{supply}
- *higher the number of switching events, the higher the dynamic power consumption.*

PDP (power-delay product): energy consumed by the gate per switching event



Energy Dissipation of First-Order RC Network



- Total energy delivered by the source

$$E_{in} = \int_0^{\infty} i_{in}(t)v_{in}(t)dt = V \int_0^{\infty} C \frac{dv_{out}}{dt} dt = (CV) \int_0^V dv_{out} = CV^2$$

- Energy stored in the capacitor

$$E_C = \int_0^{\infty} i_C(t)v_{out}(t)dt = \int_0^{\infty} C \frac{dv_{out}}{dt} v_{out} dt = C \int_0^V v_{out} dv_{out} = \frac{CV^2}{2}$$

- Where is the other half?

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.

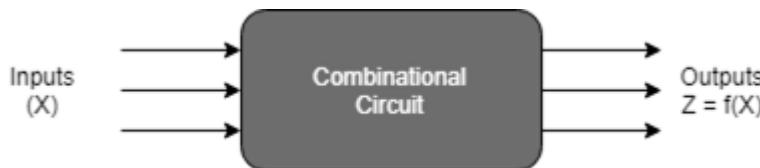
Character	Value
'U'	uninitialized
'X'	strong drive, unknown logic value
'0'	strong drive, logic zero
'1'	strong drive, logic one
'Z'	high impedance
'W'	weak drive, unknown logic value
'L'	weak drive, logic zero
'H'	weak drive, logic one
'-'	don't care

Digital circuit designs in VHDL

Combinational circuits

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

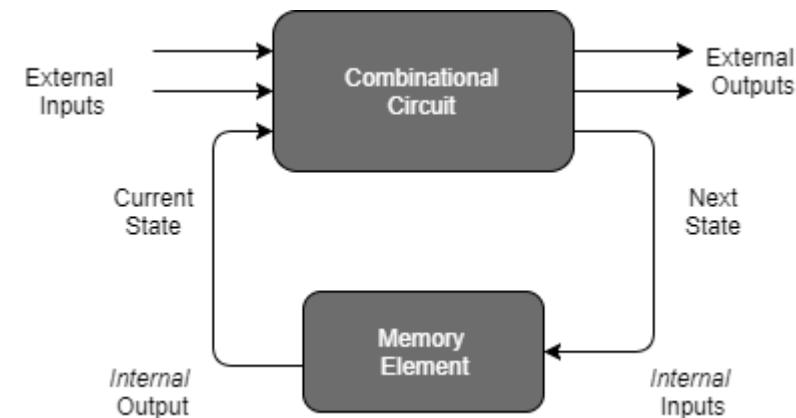
Examples – Encoder, Decoder, Multiplexer, Demultiplexer, etc.



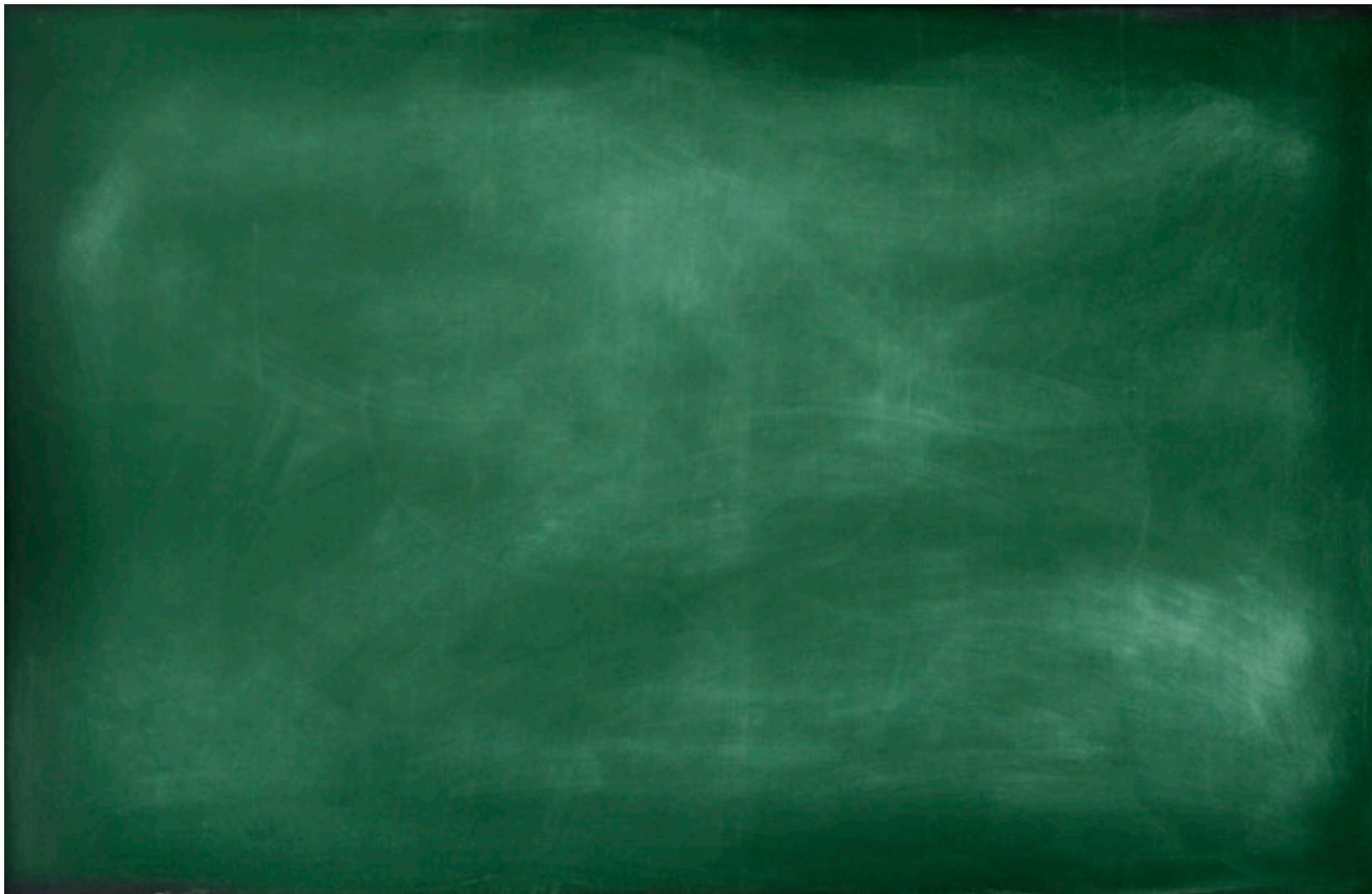
Sequential circuits

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.



Look to the black board notes





Next time:

- Install Vivado
- Think about how to build a keypad interface to read a pressed key.

