8 June 2020 وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا 16 شوال 1441

Analog IC Design

Lecture 01
Introduction

Dr. Hesham A. Omran

Integrated Circuits Laboratory (ICL)
Electronics and Communications Eng. Dept.
Faculty of Engineering
Ain Shams University

10 November 2019

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13 ربيع الأول 1441

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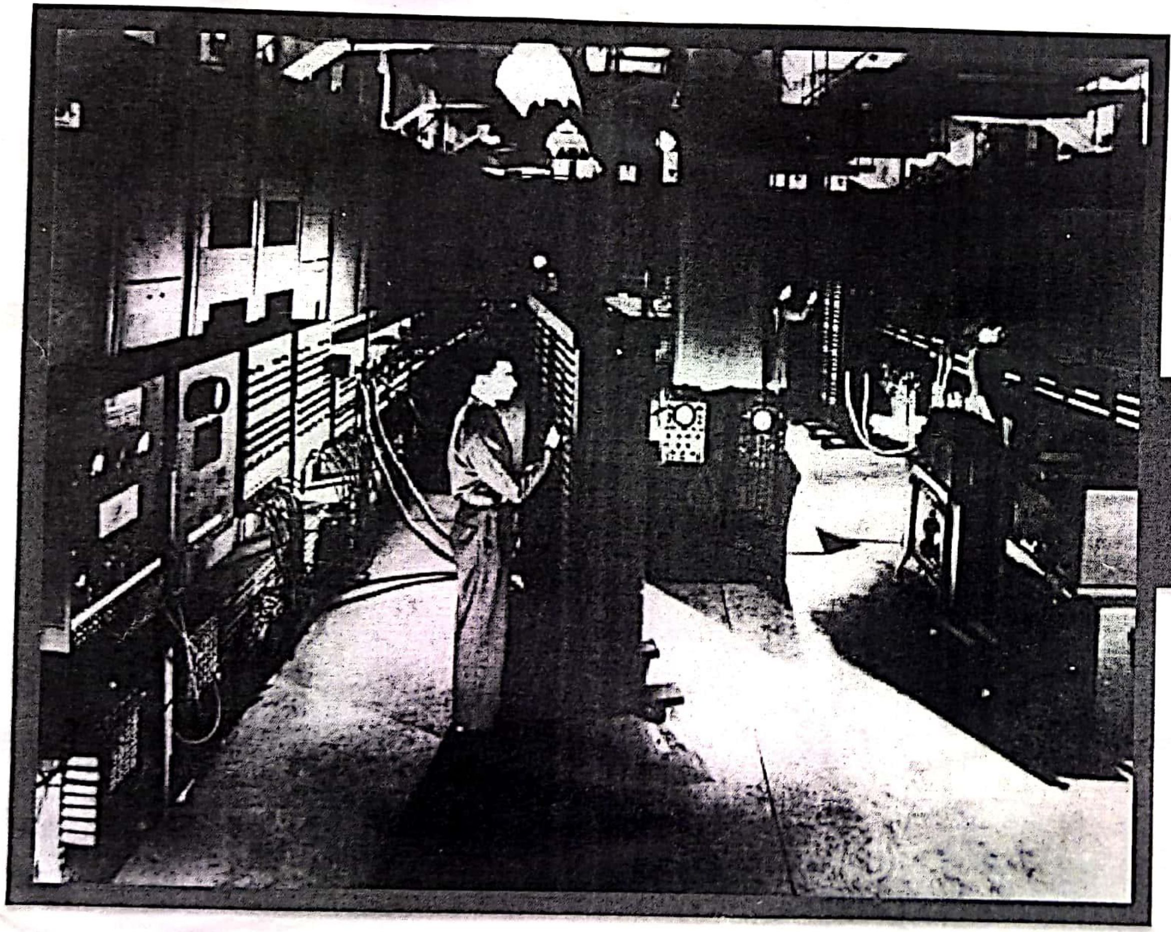
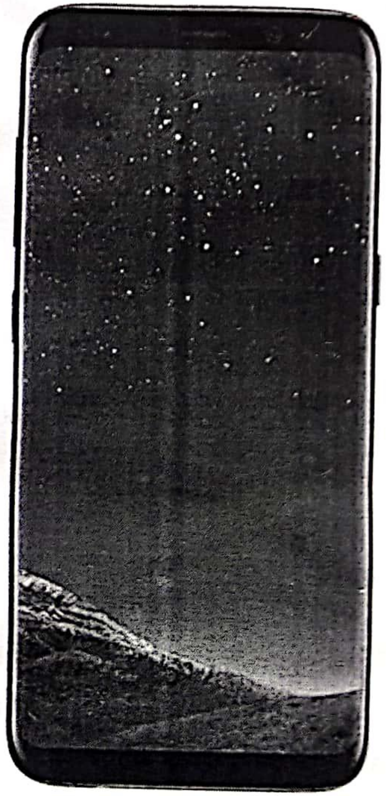
Introduction

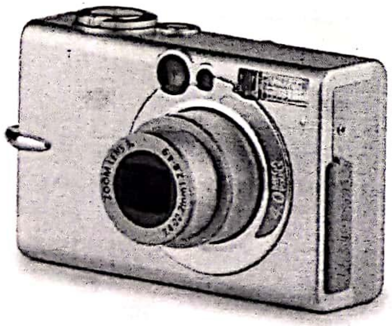


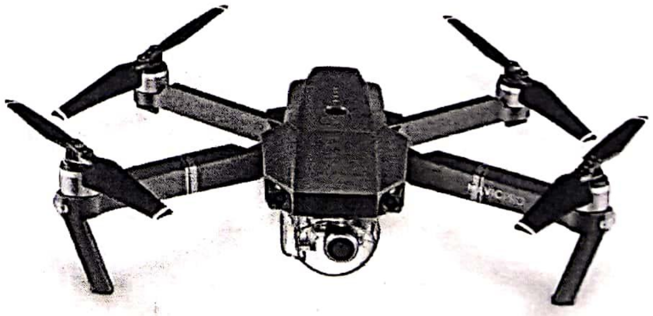
ENIAC, U.S. Army, 1946
Size → Large hall (> $150m^2$)
Power Consumption ≈ 150kW



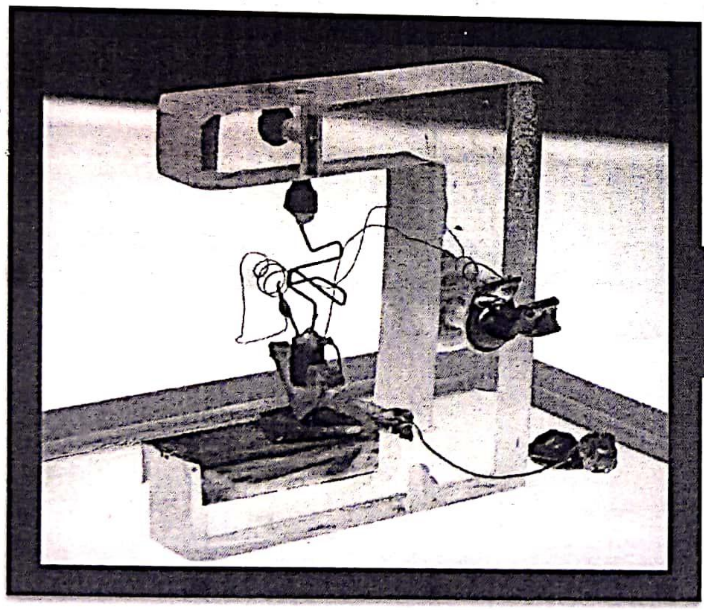
Smart phone, 2017
Size → Your pocket
Power consumption < 1W

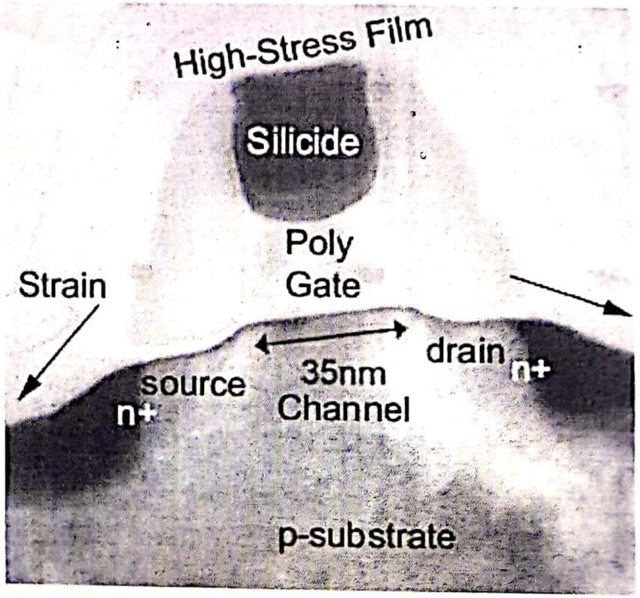
Electronics All Around Us





Transistor Evolution



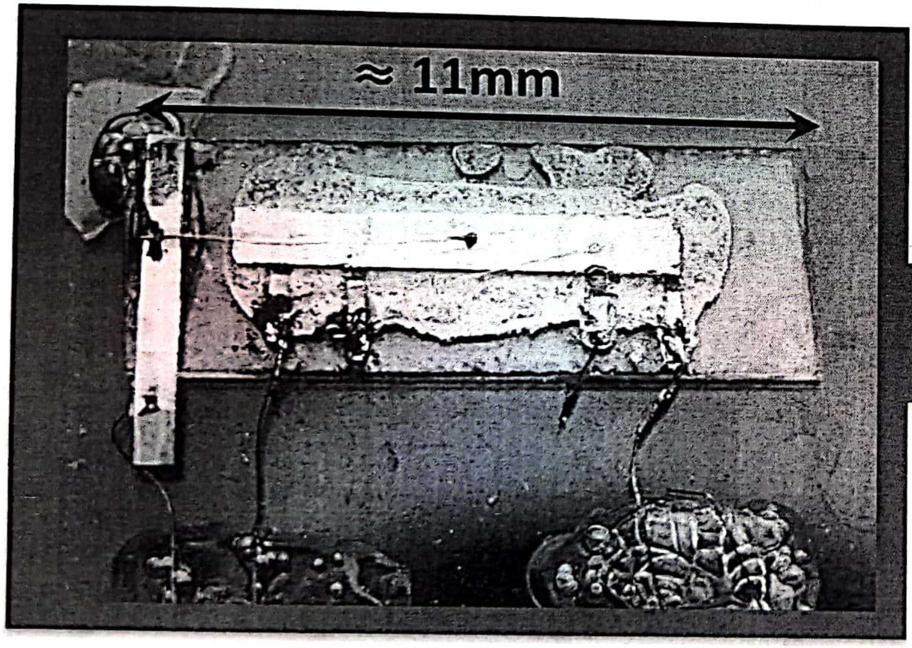


First transistor
Emitter and Collector contacts
separation ≈ 100µm
Bell Labs, 1947

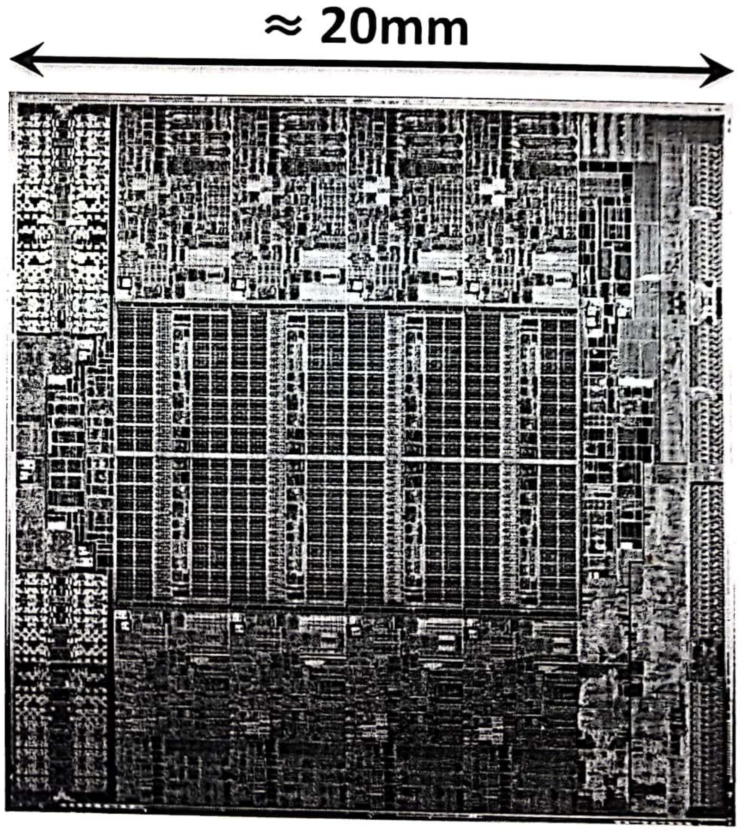
Modern MOSFET
Effective channel
length ≈ 35nm
Intel, 2006

[Weste and Harris, 2010]

Integrated Circuit Evolution

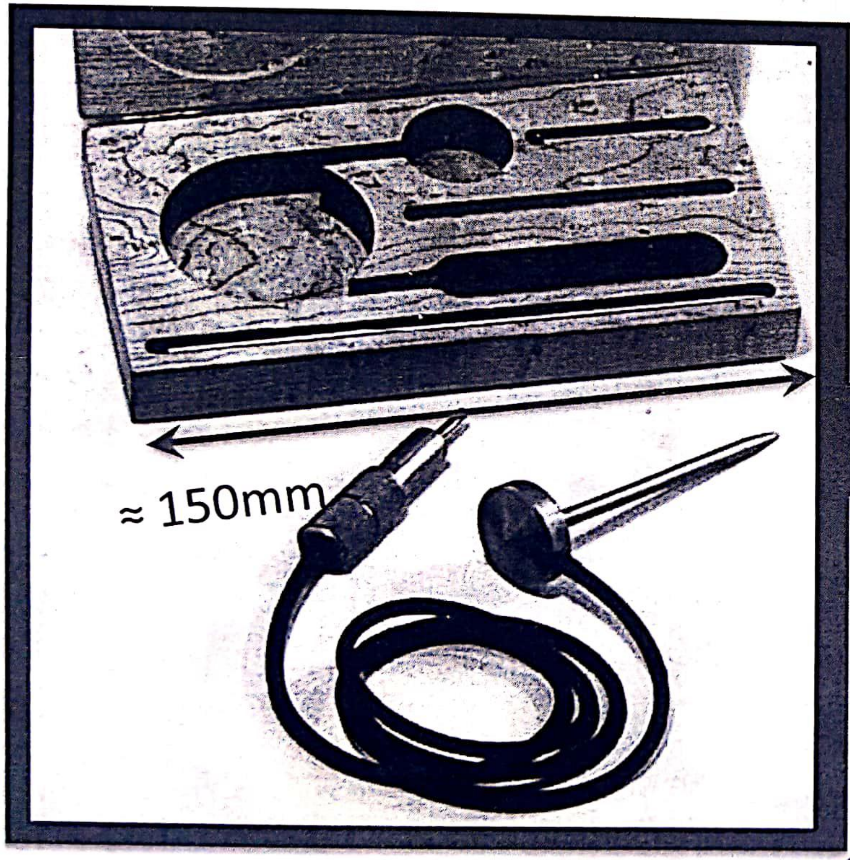


First IC
Only one transistor (+ R + C)!
Texas Instruments (TI), 1958



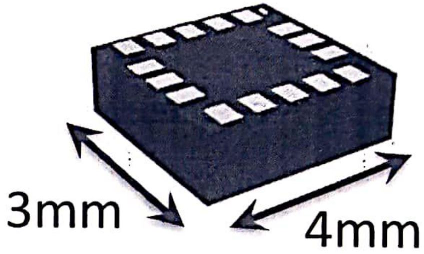
Xeon E5 Microprocessor
2.26 billion transistors!
Intel, 2012

Sensing Microsystems



First accelerometer
B&K, 1940s
Simple bulky transducer
Acceleration → Voltage

measure acceleration "converts it into electric signal"



★one of the most basic applications of the accelerometer is the auto-rotation property in cell phones by measuring gravity.

ADXL350
Analog Devices, 2012

★It also used in car air bags by measuring or detecting sharp deceleration.

Complete system on a tiny chip

- 3-axis MEMS* accelerometer
- Interface electronics
- Analog-to-digital conversion
- Memory
- Control logic
- Power management
- Digital interface

*MEMS = Micro-Electro-Mechanical Systems

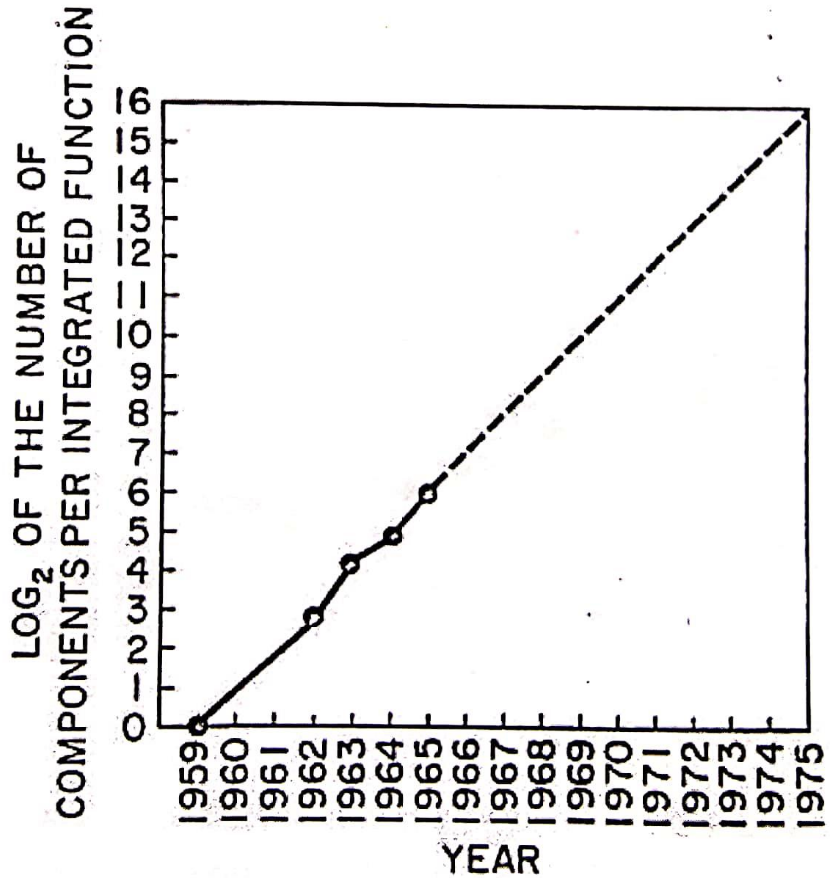
Moore's Law

- Moore's law [1965]: Transistor count doubles every year

↳ co-founder (intel company)

in electronics magazine

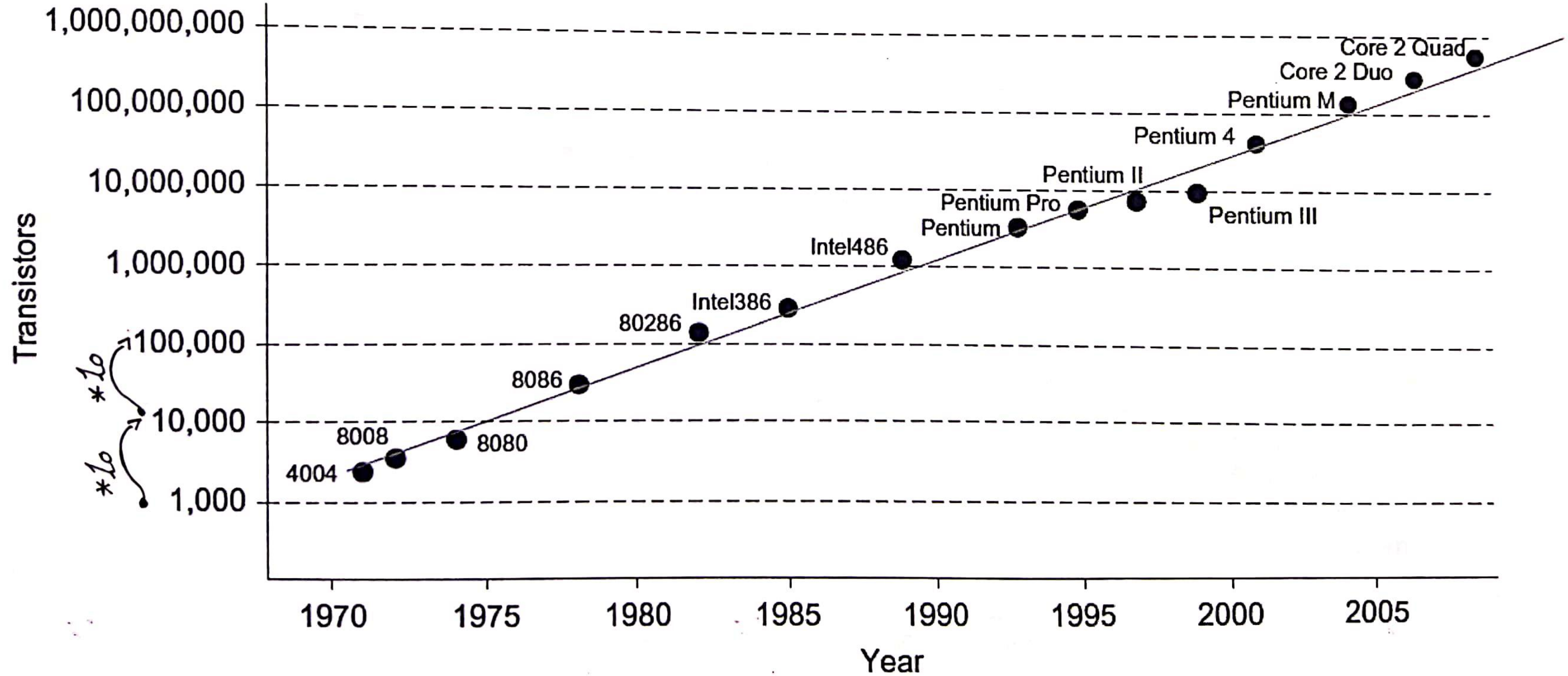
★ This scale is a log scale so it increases "exponentially"



[Electronics magazine article, 1965]

Moore's Law

- Moore's law [1965]: Transistor count doubles every year
- Practically: It doubled every 2-3 years since the 4004 [1970s]
- At the end of the day: It is exponential!



[Weste and Harris, 2010]

Technology Minimum Feature Size

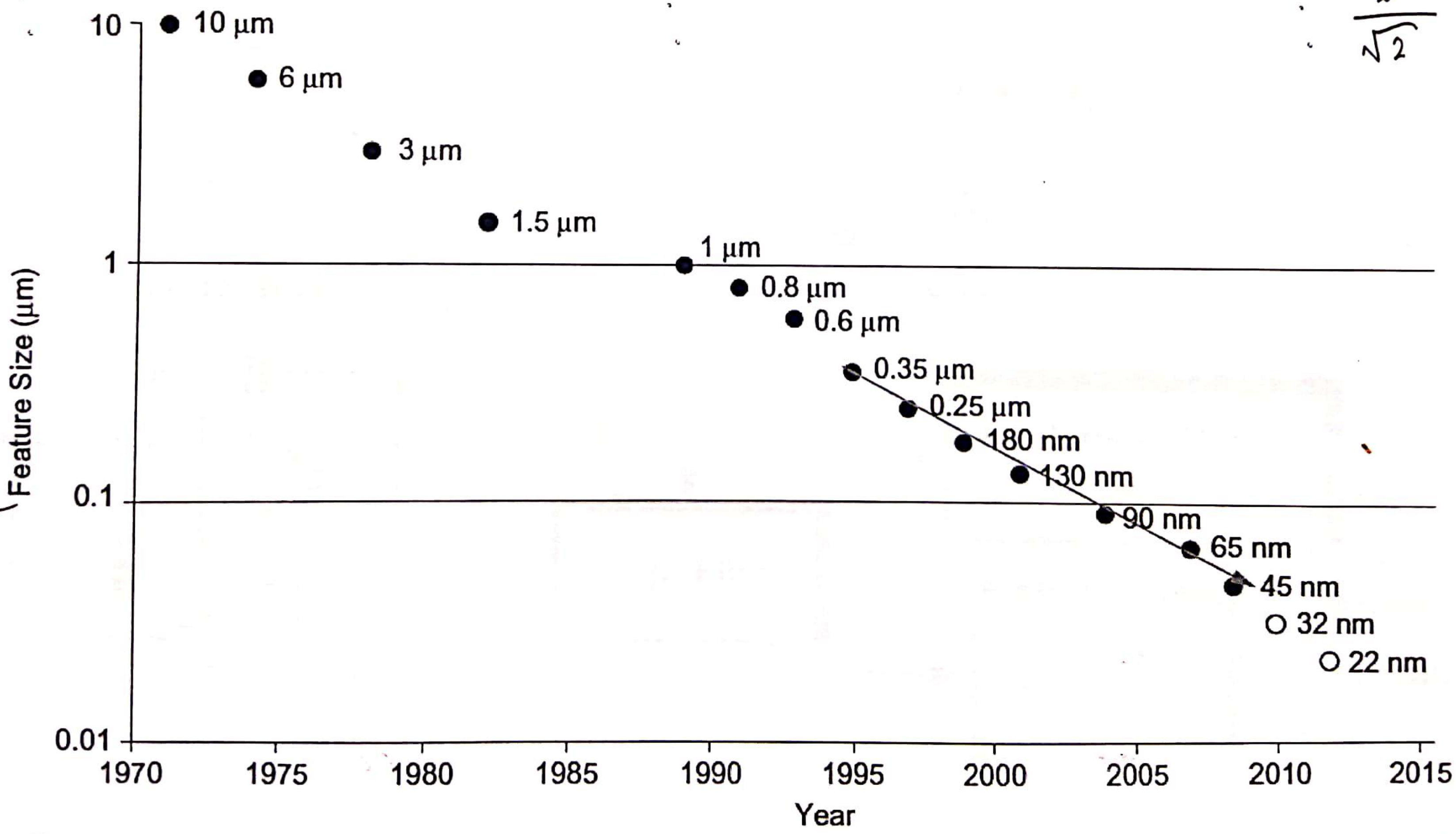
- Minimum feature size shrinking 30% ($\approx 1/\sqrt{2}$) every 2-3 years
  - Transistor **area and cost** are reduced by a factor of 2
- Device scaling brings new challenges in circuit design

d

d A

$\frac{1}{\sqrt{2}}$ $\frac{1}{2}$

The smallest dimension we can manufacture on a chip.



7 nm 2020

5→3 nm 2022

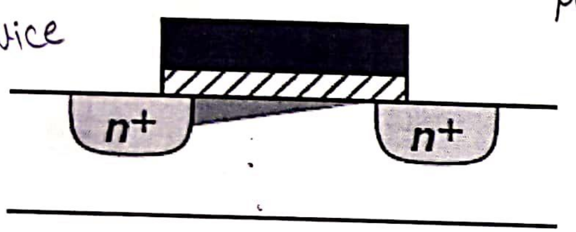
20B$ TSMC are developing

[Weste and Harris, 2010]

Levels of Abstraction

• modeling Device
• fabrication Device
• characterization of the device

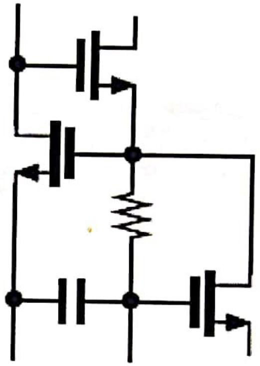
Device



(a)

circuit Model

Circuit

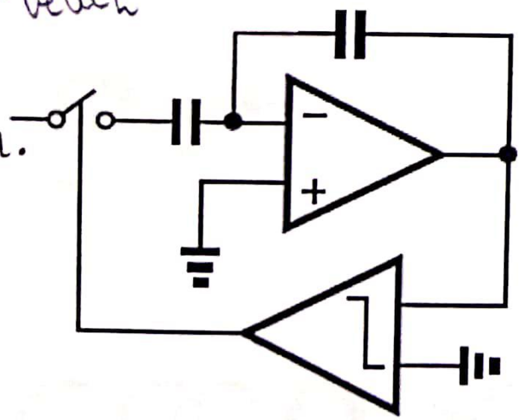


(b)

→ op-amp ★
→ comparator

• Circuit @ a higher level of : abstraction.

Architecture

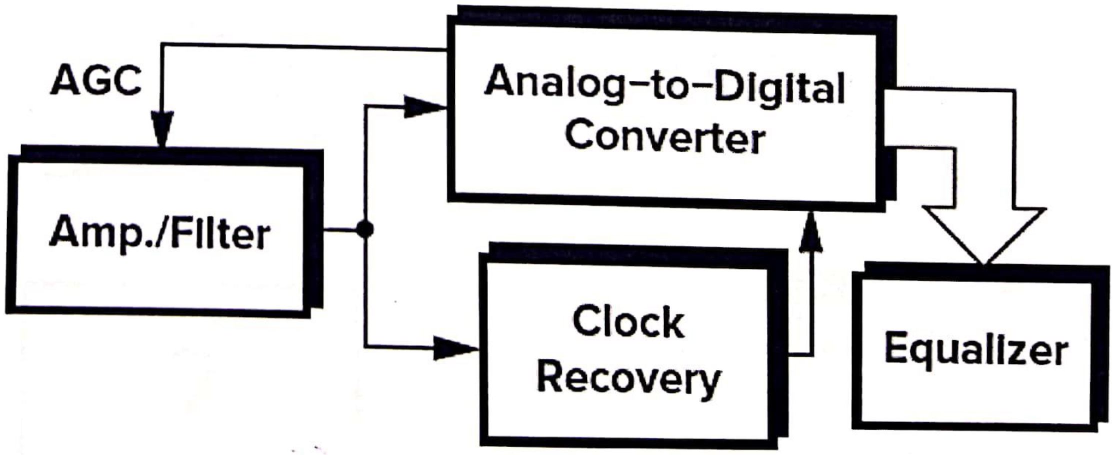


(c)

→ ADC
→ filter

System

• USB
• wireless system



(d)

[Razavi, 2017]

IC Industry in Egypt

*FABLESS Companies.

* Fabrication X
* Design ✓
  - circuit
  - Architecture
  - system

- QualComm
  - SoC
  - (Design)
  - TSMC
- Mediatech
  - SoC

Egyptian

Foreigner

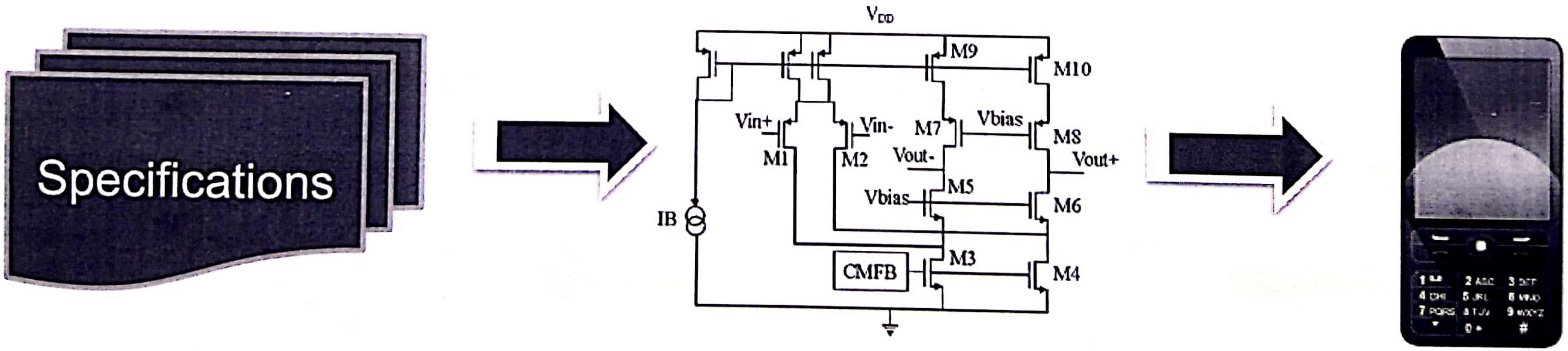
Foreigner

?

*These companies need:
-> Deep technical knowledge
-> work is strongly related to your study in college.

Course Objective

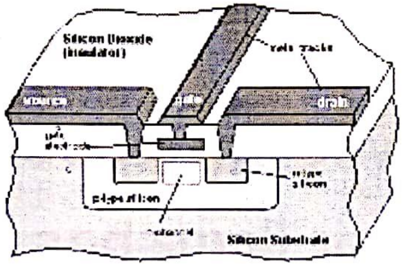
- To teach the basic knowledge required for:
  - Analog IC analysis and design using CMOS technology
  - Moving from specifications (specs) to block design
  - **Simulating analog ICs using professional CAD tools**



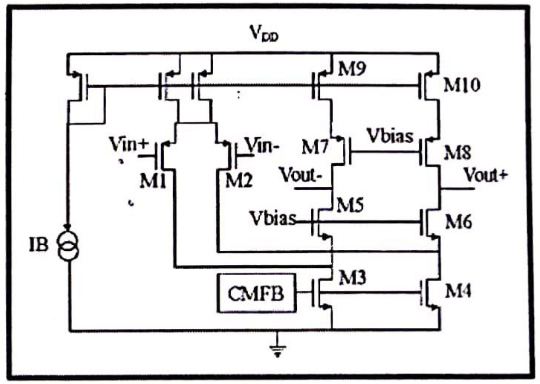
Your Learning Journey

Material

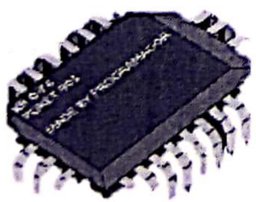
Devices



Circuits

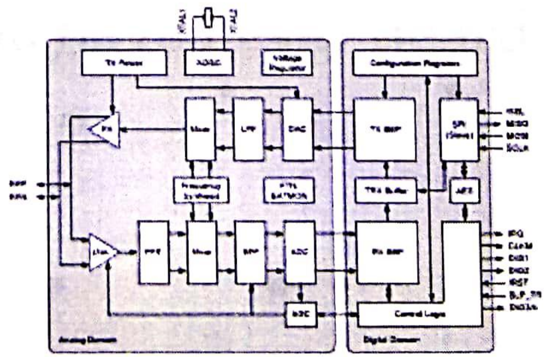


Product



*Graduation Project

System



Course Prerequisites

- You should be familiar with:
  - Analysis of electrical circuits
  - Basic semiconductor physics
  - Basic MOSFET operation and physics
  - MOSFT large signal and small signal models
  - Basic analysis of transistor amplifiers
- A review will be provided for the above topics
  - But you will struggle if you have never heard about these topics before

References

- Textbook
  - B. **Razavi**, "Design of analog CMOS integrated circuits," 2nd ed., McGraw-Hill Ed., 2017.

- References for beginners
  - Before Razavi
  - A. **Sedra** and K. **Smith**, "Microelectronic circuits," 7th ed., Oxford University Press, 2015.
  - T. **Floyd,** "Electronics Fundamentals, Circuits, Devices, and Applications," 8th ed., Pearson, 2014.
  - B. **Razavi**, "Fundamentals of microelectronics," 2nd ed., Wiley, 2014.

References

- References for professionals
  - T. C. **Carusone**, D. **Johns**, and K. W. **Martin,** "Analog integrated circuit design," 2nd ed., Wiley, 2012.
  - P. **Gray**, P. Hurst, S. Lewis, and R. **Meyer**, "Analysis and design of analog integrated circuits," 5th ed., Wiley, 2009.
  - P. **Jespers** and B. **Murmann**, Systematic Design of Analog CMOS Circuits Using Pre-Computed Lookup Tables, Cambridge University Press, 2017.
  - D. Stefanovic and M. **Kayal**, Structured Analog CMOS Design Springer, 2008.
  - R. J. **Baker**, "CMOS circuit design," 3rd ed., Wiley, 2010.
  - W. **Sansen**, "Analog design essentials," Springer, 2006.

Canvas

- ❑ Canvas is a learning management system (LMS) used in many universities in the US and around the world
- ❑ We will use Canvas for
  - Posting lectures, notes, etc.
  - Questions and answers
  - Announcements and discussions
  - Quizzes
  - Submitting and grading assignments, reports, etc.
- ❑ **Everyone must register at Canvas today!**

Feedback

- ❑ Don't hesitate to send me feedback to improve the course quality.
- ❑ Avoid two common misconceptions
  1. Feedback should NOT wait to the end of the course!
     - It will be too late to improve anything!
     - But anyway, you may still help next generations ☺
  2. Feedback should NOT be always negative!
     - Too much negative feedback leads to zero output!
     - Too much positive feedback causes oscillation!
     - Be balanced!

What Students Say About this Course

“The training was amazing. It wasn't easy but I enjoyed it. I strongly recommend attending this training for future analog designers.”

“It was an excellent course with a lot of benefits that changed my thinking and understanding towards circuits and analysis ... thanks :)”

“This course is a great experience that you will never have alone.”

“Very great course and very helpful for those who will work in this field in the future.”

“I got a great experience from this course and I applied it practically. My interest in the electronics field became greater than before. I deeply recommend my friends to get it.”

What Students Say About this Course

"One of the greatest courses I have took since I started college."

"I recommend this course to every student in Communication department."

"It was definitely a rewarding experience that's worth recommending."

"I would like to thank you for one of the most important courses that I took so far in college. It has guided my thoughts to continue my career in analog ICs. I really understood and enjoyed everything that I took in this course."

What Students Say About This Course

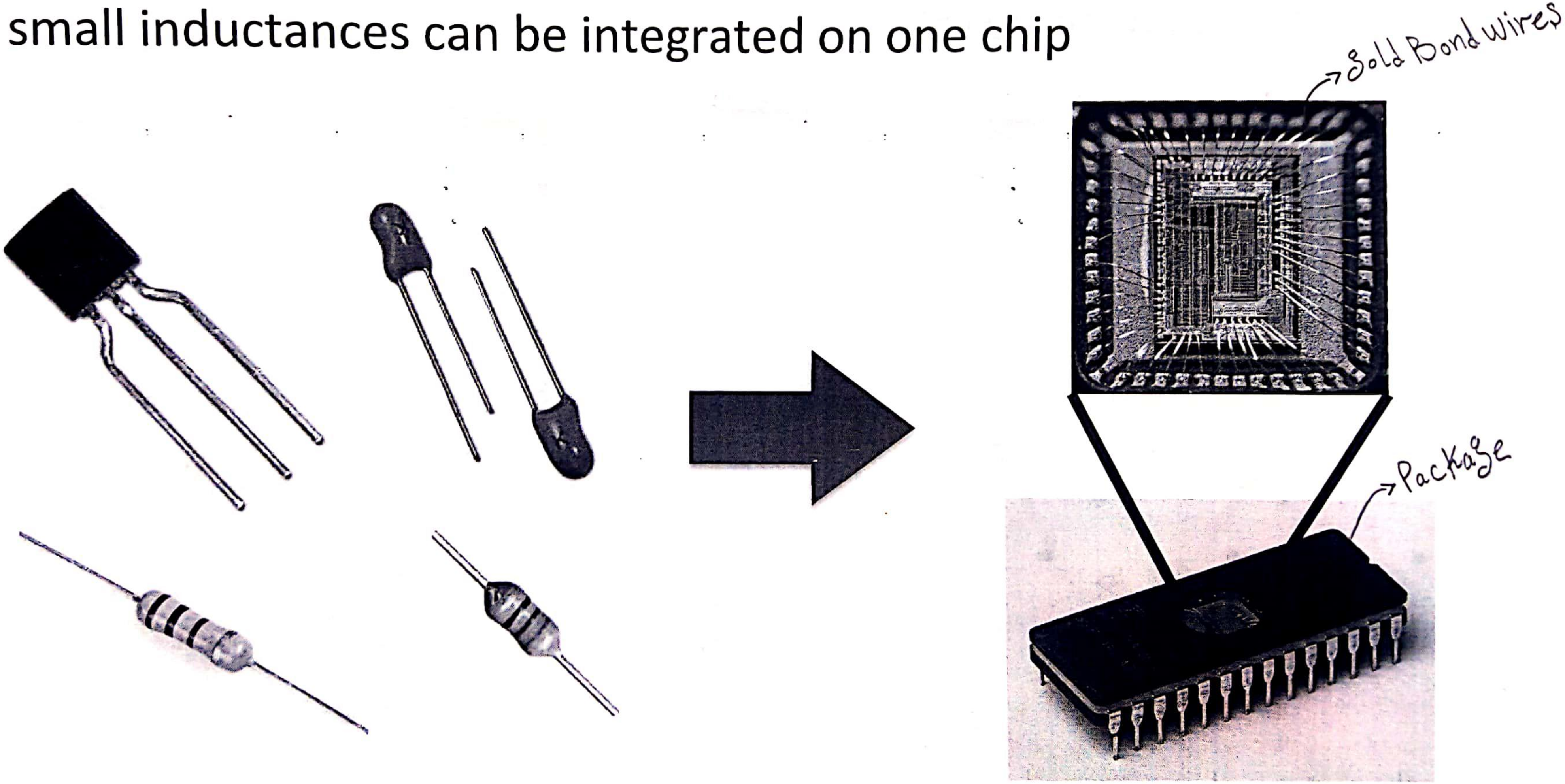
"It was an awesome course . It has a lot of interesting topics, and a lot of knowledge and experience."

"Amazing mind opener for those interested in electronics."

"The staff was amazing, and the videos were excellent. The whole course exceeded my expectations. I enjoyed the design and the labs and everything about the course."

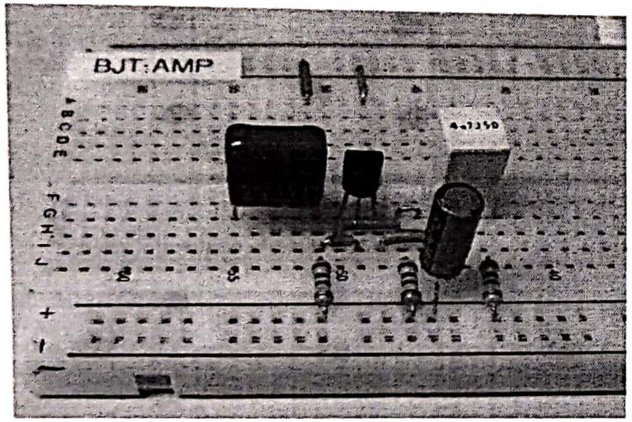
What is an Integrated Circuit (IC)?

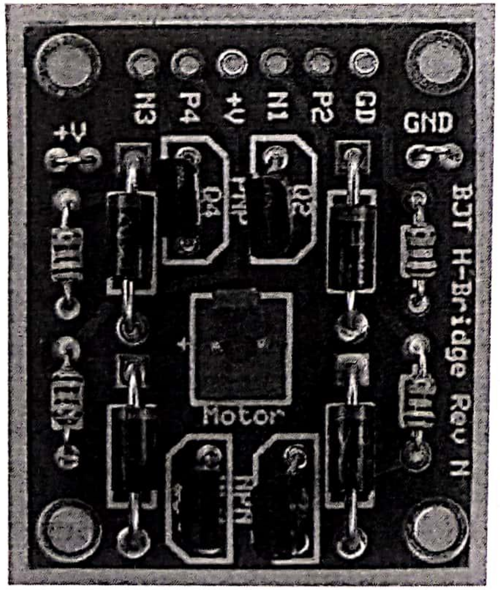
- Various circuit elements: transistors, capacitors, resistors, and even small inductances can be integrated on one chip

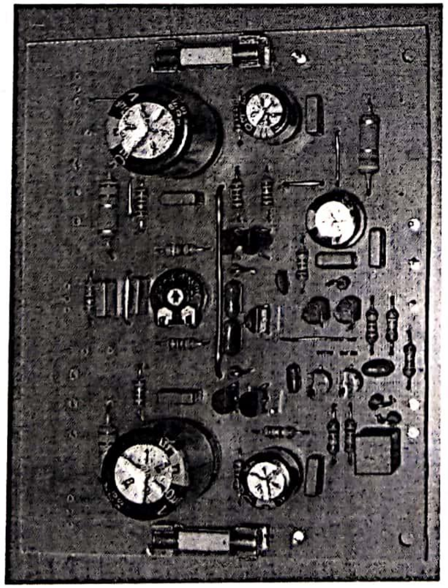


Discrete vs. Integrated Electronics

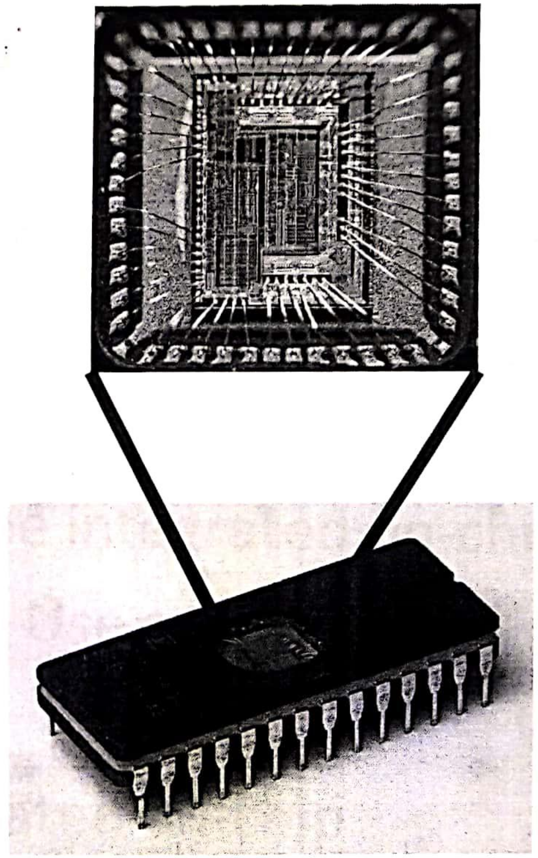
Circuits using discrete components







Integrated circuit



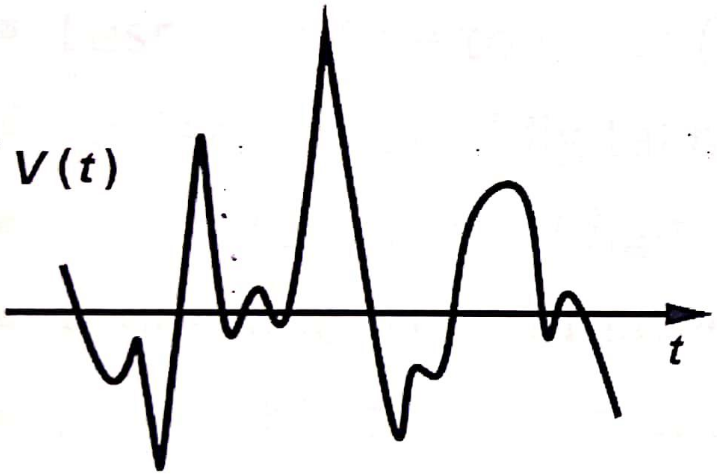
Integrated Circuit Components

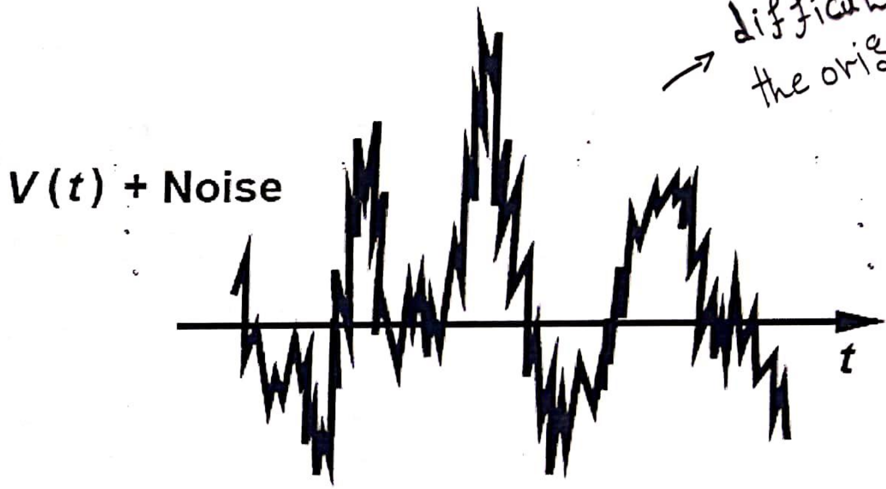
- Transistors: ★The large scale integeration of transistors is due to: transistors performance parameters doesn't depend on absolute dimensions but it depends on the ratio between two dimensions. $I_D \propto \frac{W\downarrow}{L\downarrow}$ increase or const.
  - Billions of tiny transistors can be integrated on the same chip
  - Very Large Scale Integration (VLSI): > 10,000 transistors
- Capacitors: ★ also > Billion transistor is VLSI, or ULSI (ultra large scale integration)
  - Capacitors as large as 100s of pF can be integrated on-chip
  - But they consume a lot of chip area → Use sparingly $\downarrow C = \epsilon \frac{A \to dim^2 \downarrow}{d \to dim}$
- Resistors: ★our Problem in Resistors are the Properties → good Properties need more space on chip.
  - Resistors as large as few MOhms can be integrated on-chip
  - But they consume a lot of chip area → Use sparingly ★cross section of wire is ↓↓↓ ∴ R↑↑↑
- Inductors: "The worst": Due to the selenoid shape ∴ Q < 10 Quality factor
  - Small inductors (few nH) can be integrated on-chip
  - But they consume a lot of area with relatively poor performance → Use sparingly: Only in high frequency circuits (e.g., RFICs)

Analog vs Digital Signals

- Analog: continuous in time and amplitude

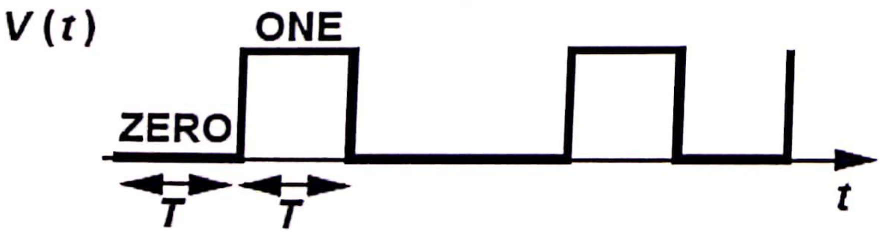
difficult to restore the original signal.

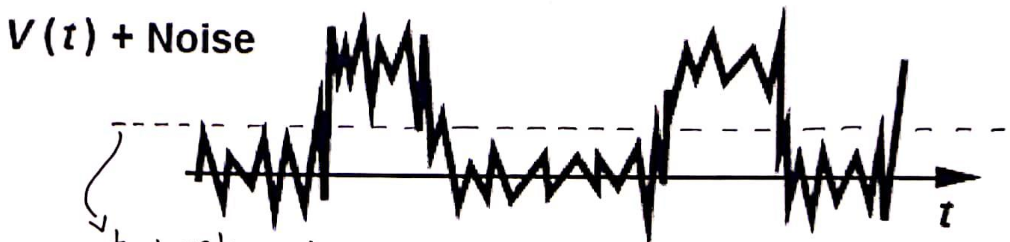




- Digital: discrete in time and amplitude

changes in specific instance of time and carries only two values of amplitude.





to restore the original signal you can easily put or make a threshold if I am below so I have zero and if I am above the threshold so I have one.

[Razavi, 2014]

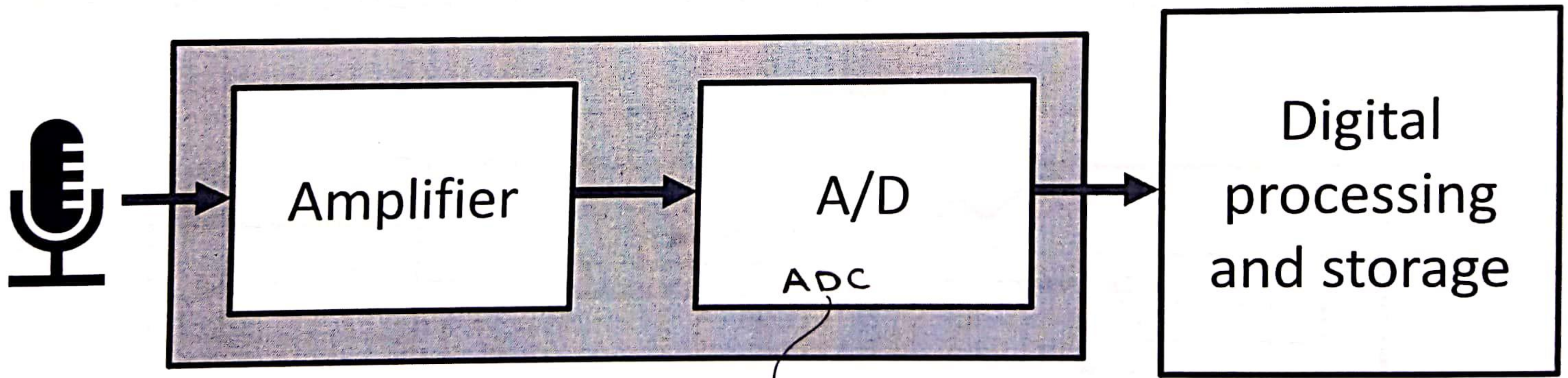
Why Digital?

- Digital circuits are
  - Less sensitive to noise (robust)
  - Easier to store (digital memories)
  - Easier to process (digital signal processing: DSP)
  - Amenable to automated design
  - Amenable to automated testing

    As we are dealing with a high level of abstraction as we mainly deal with "Code" like FPGA or HDL.
  - Direct beneficiary of Moore's law (down-scaling)

Why Analog?

- All the physical signals in the world around us are analog
  - Voice, light, temperature, pressure, etc.
- We (will) always need an "analog" interface circuit to connect between our physical world and our digital electronics
- There will always be jobs for analog/mixed-Signal/RF designers ☺



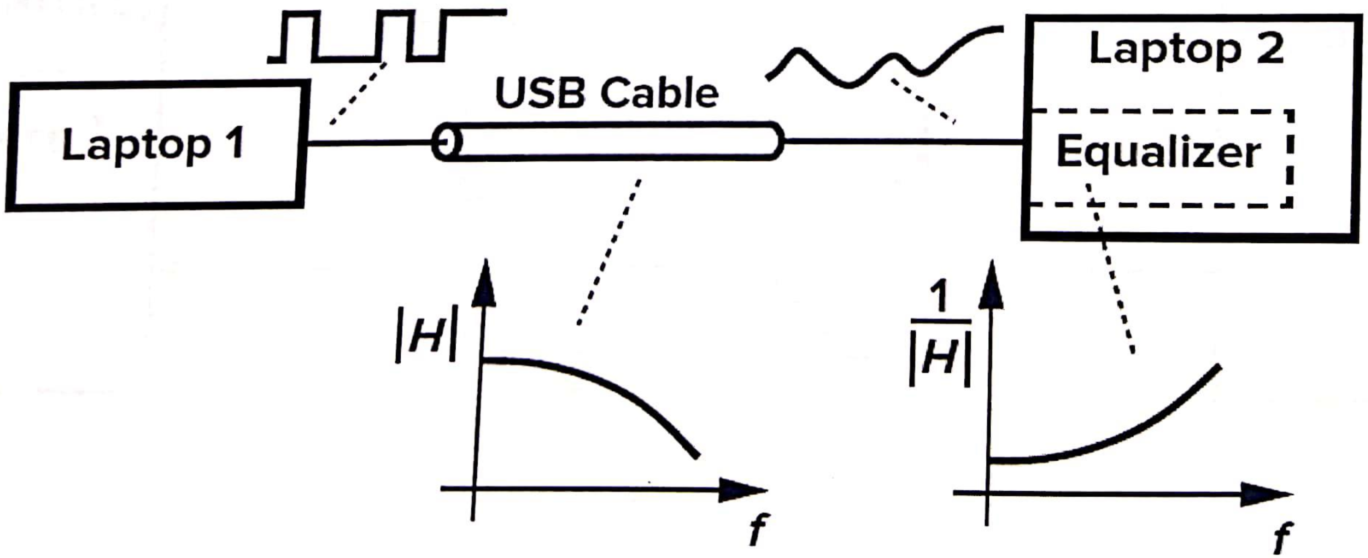
Analog to Digital converter is designed by:
"Analog Mixed-Signal Designer"

Why Analog?

- High speed digital design is actually analog design!
- At low speeds, we may directly digitize the signal and perform the signal processing in the digital domain.
- At high speeds, signal processing in the analog domain is much more energy efficient.
- The boundary between high and low speed has risen over time.

USB
1. 12MbPs
2. 480MbPs
3. 5GbPs

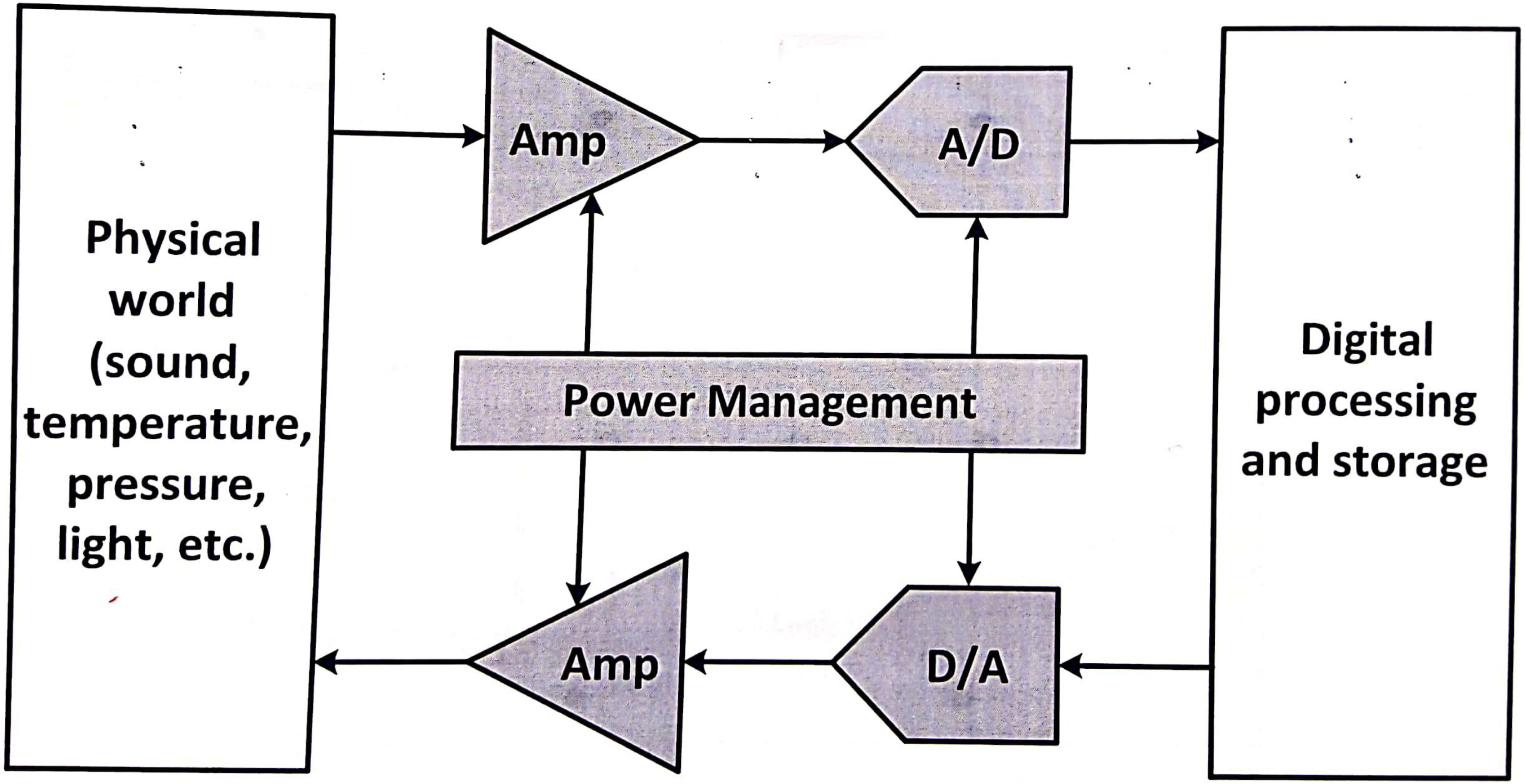
★Serial Link circuits



[Razavi, 2017]

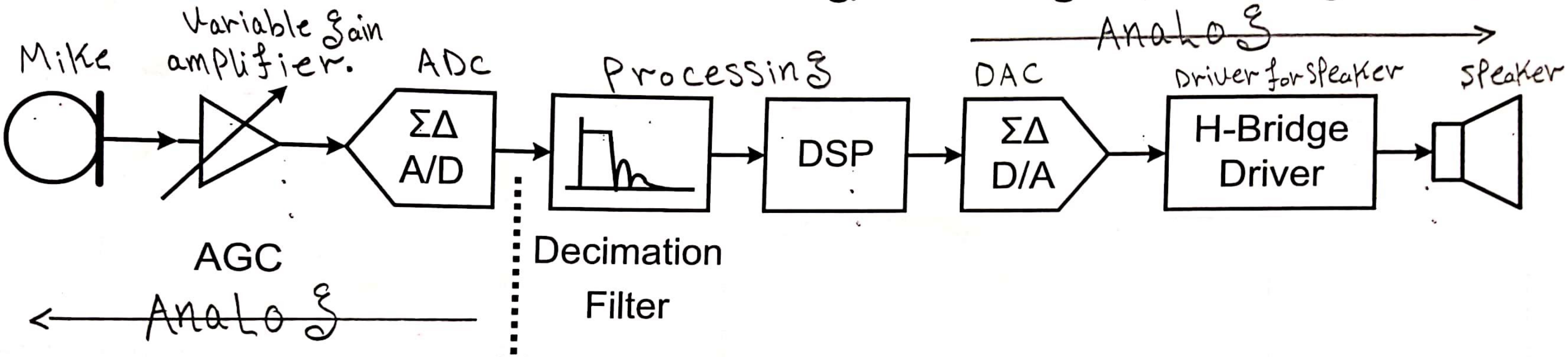
Signal Processing Chain

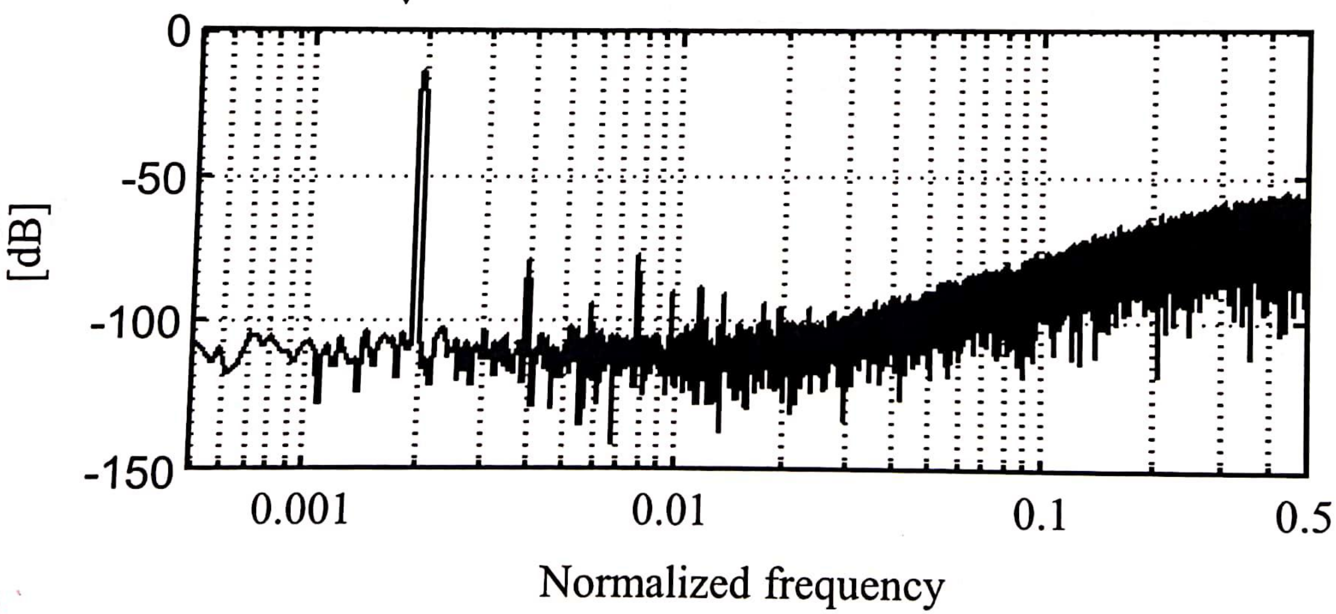
- ❑ There will always be jobs for analog/mixed-signal/RF designers ☺



Example: Mixed-Signal Hearing Aid

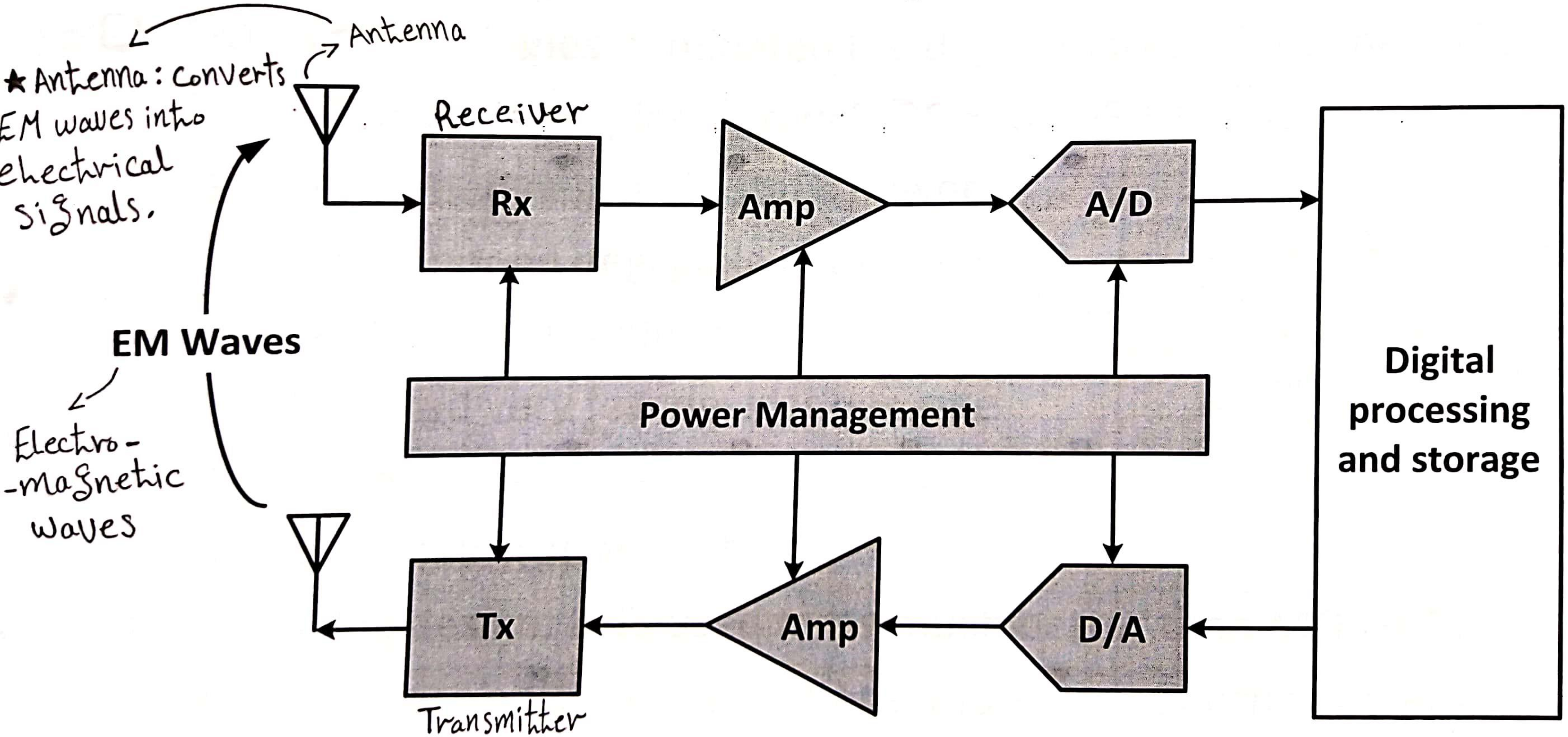
- There will always be jobs for analog/mixed-signal/RF designers ☺





Wireless Signal Processing Chain

- ☐ There will always be jobs for analog/mixed-signal/RF designers ☺



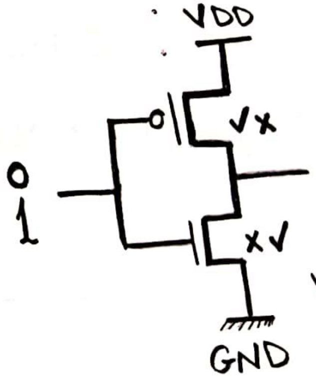
Why CMOS?

- Early integrated circuits primarily used bipolar transistors (BJTs)
- CMOS technologies dominated the digital market since the 1980s

  → CMOS = Complementary MOS = NMOS + PMOS

  1. Consumed negligible static power
     - Was indeed negligible in the past
     - But not negligible any more...
  2. Required very few devices per gate
  3. Can be scaled down more easily
  4. Lower fabrication cost

* Because of the leakage accompanies down scalling Process.



CMOS Inverter

* No Direct Pass between VDD and the Ground, So Less "static" Power Consumption.

- For analog design, BJTs used to be much better than MOSFETs
  - Faster, less noisy, less variations, more energy efficient, more gain.
- Then why analog CMOS?

Why Analog CMOS?

mainly digital but only have a small analog.

- ❑ ICs market is driven primarily by memories and microprocessors
  - The analog designer needs to survive in a digital driven market
- ❑ We want to integrate analog and digital on the same chip
  - Mixed-signal design and system-on-a-chip (SOC) {Analog + Digital on one chip}
- ❑ BJTs used to be faster, but with continuous scaling, MOSFET speed exceeded BJT (MOSFET is faster than BJT in nowadays very large down scalling)
- ❑ MOSFET can operate with lower supply voltage

in MOS we can dec. "VDD" by dec. "V_{TH}"

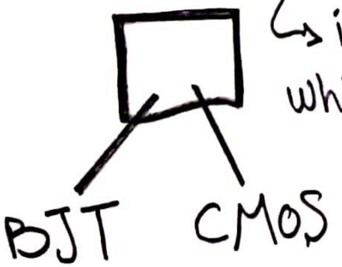
{12V ⟶ < 1V

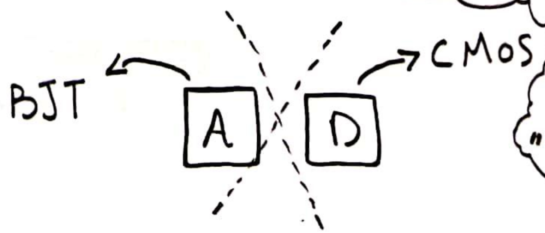
$\mathcal{E} = \frac{V}{d}\downarrow$

★ while down scalling for "d" if not scalling "V" as well a large electric field will cause "Break Down"}

★ Power Consumption decreases quadratically by decreasing "VDD"

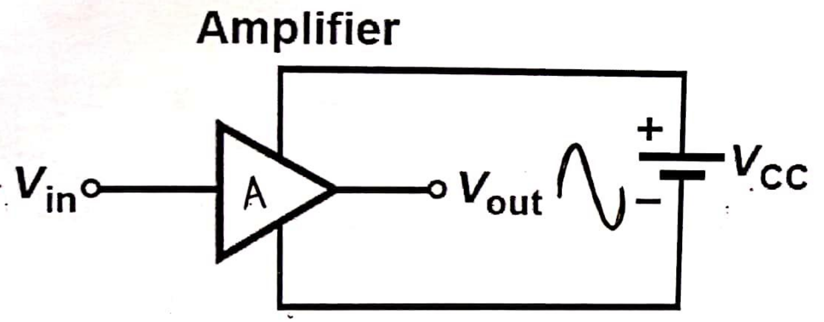
"BiCMOS": was very Popular in 90's but it failed due to its cost.
↳ it nowadays used in some specialized applications which aren't cost sensitive.
- → medical
- → military
- → aerospace

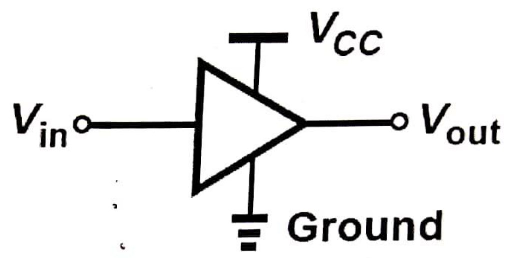


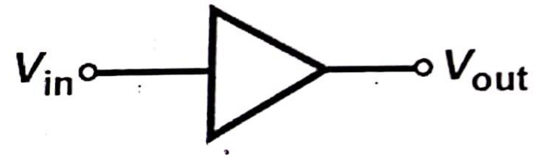


★ Designing two different chips one for analog and the other on for digital is not a better choice, as it will double the cost, the size and the weight.

Analog Amplifier

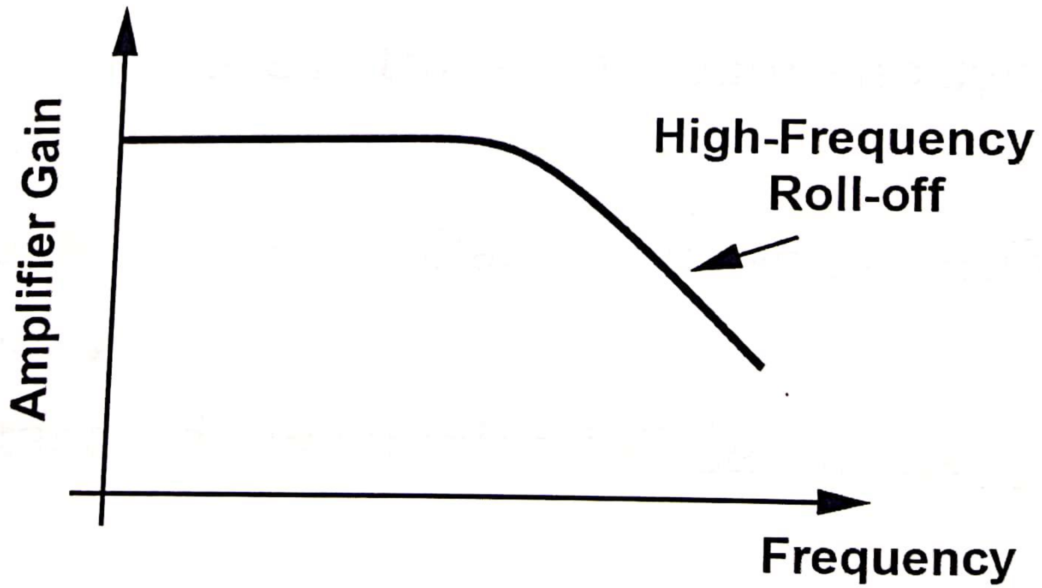






- The amplifier has finite gain ($A_v = \frac{v_{out}}{v_{in}}$) and finite bandwidth (speed) (speed)

frequency response



[Razavi, 2014]

Analog Design Challenges

- Device scaling
  - Transistors become faster, but the gain declines
- Supply voltage scaling
  - From 12V in 1970s to less than 1V nowadays
- Low power consumption
  - Increase battery lifetime, decrease cost and heat emissions
- Complexity
  - Continuous increase in transistor count and system complexity
- PVT variations
  - Tolerate large process, voltage, and temperature variations
- New applications
  - Wireless standards, wearables, IoT, serial links (e.g., USB), ...

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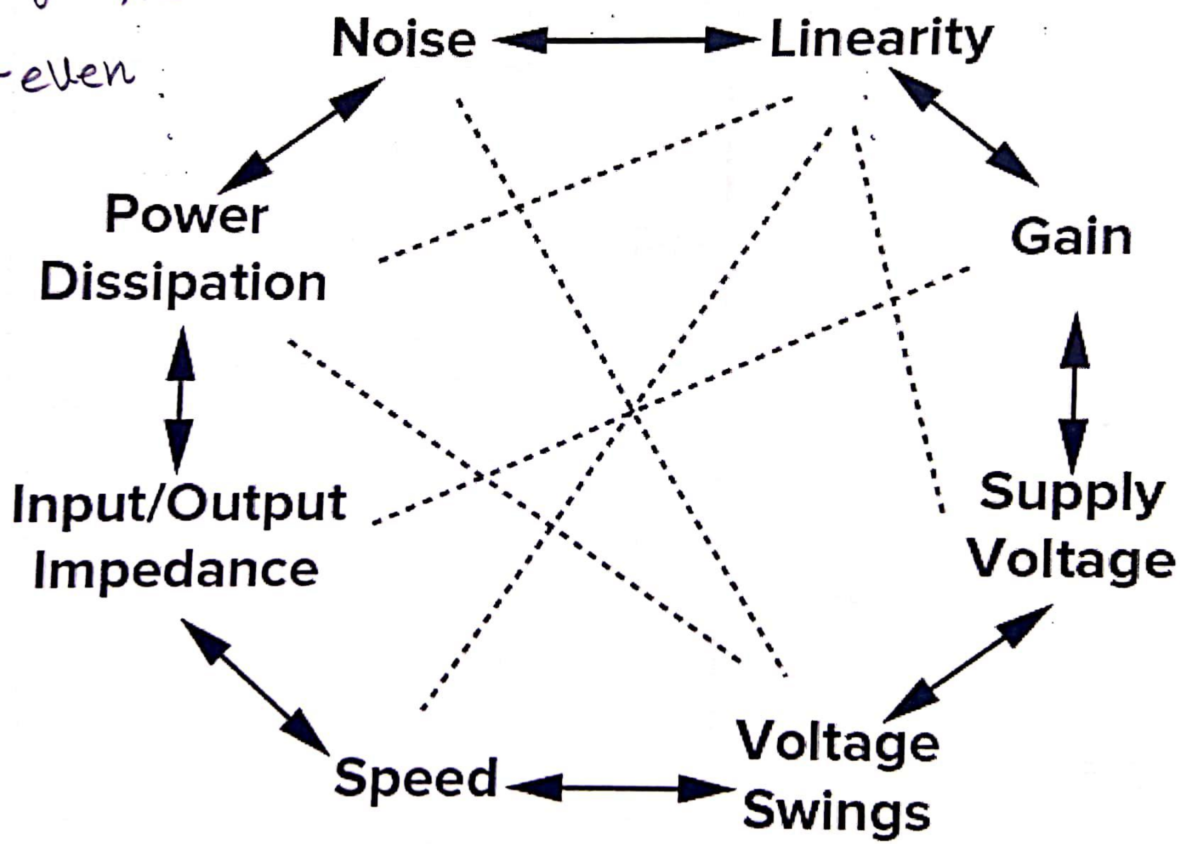
Analog Design Challenges

- Analog design automation is a difficult task

★ Research effort for analog design automation are from 30 years, and it still an active research whill Probably lasts for another 20, 30 or even 40 more years.



★ for Digital:

1

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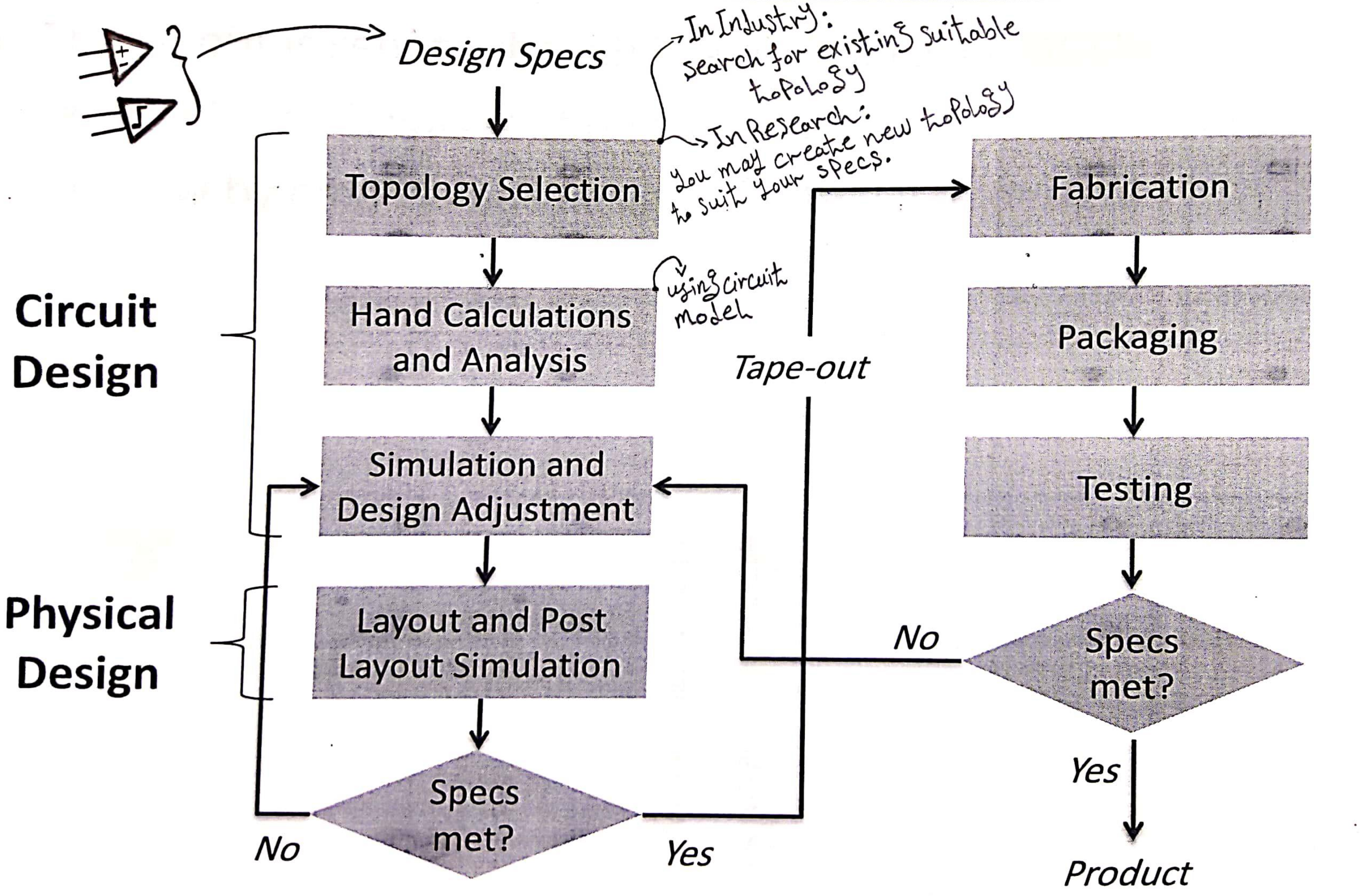
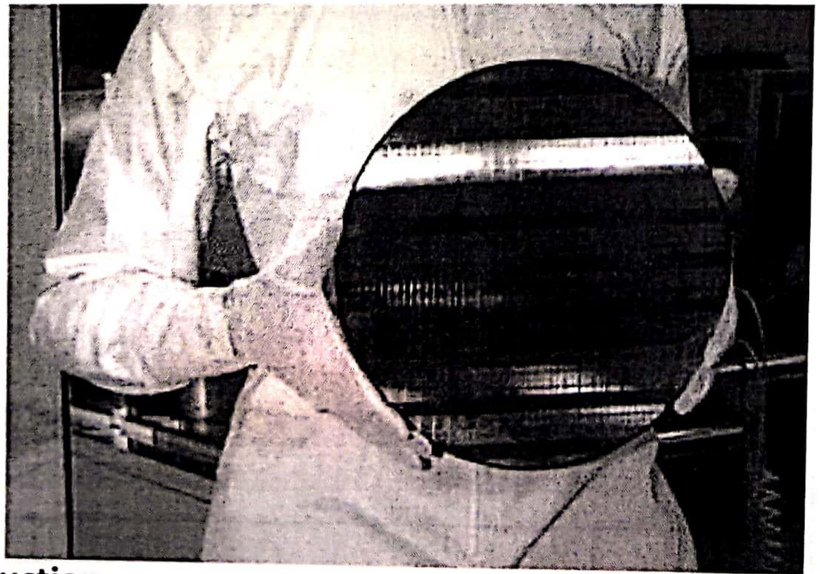
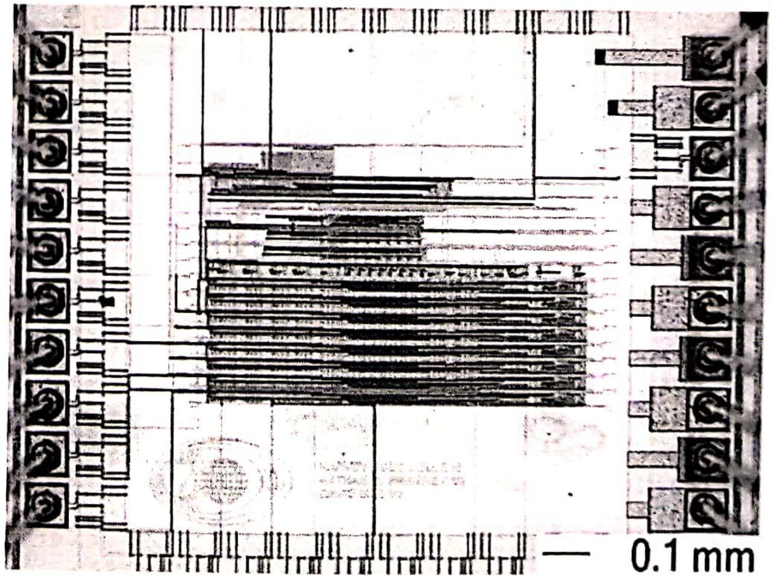
Analog IC Design Flow (Simplified)



Tape-Out → Process of fabrication

- The layout is sent to the fab in a format called GDS II
  - Previously it was sent on a magnetic tape → tape-out
  - Now by email (small design) or FTP (large design)





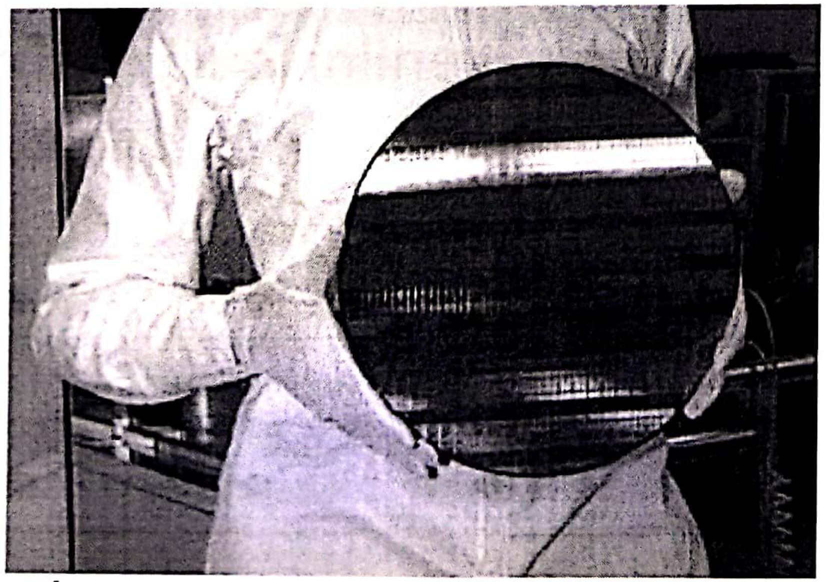
[Weste and Harris, 2010]

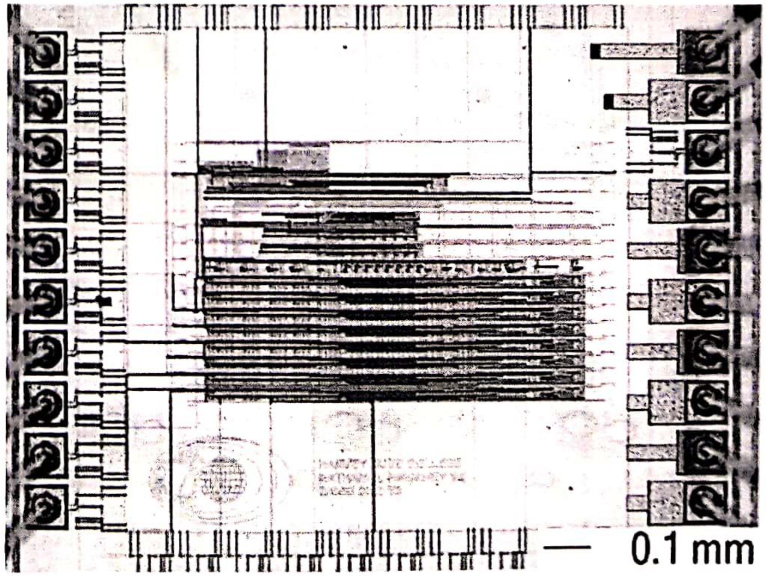
MPW

Tape-Out

→ next page is missing

- ICs are fabricated on silicon wafers
  - Turnaround time ~ 3months
- A fabrication run in 65nm process costs about $3 million
  - Cost sharing using MPW (multi-project wafer)
    - US: MOSIS
    - Europe and MENA: Europractice





[Weste and Harris, 2010]

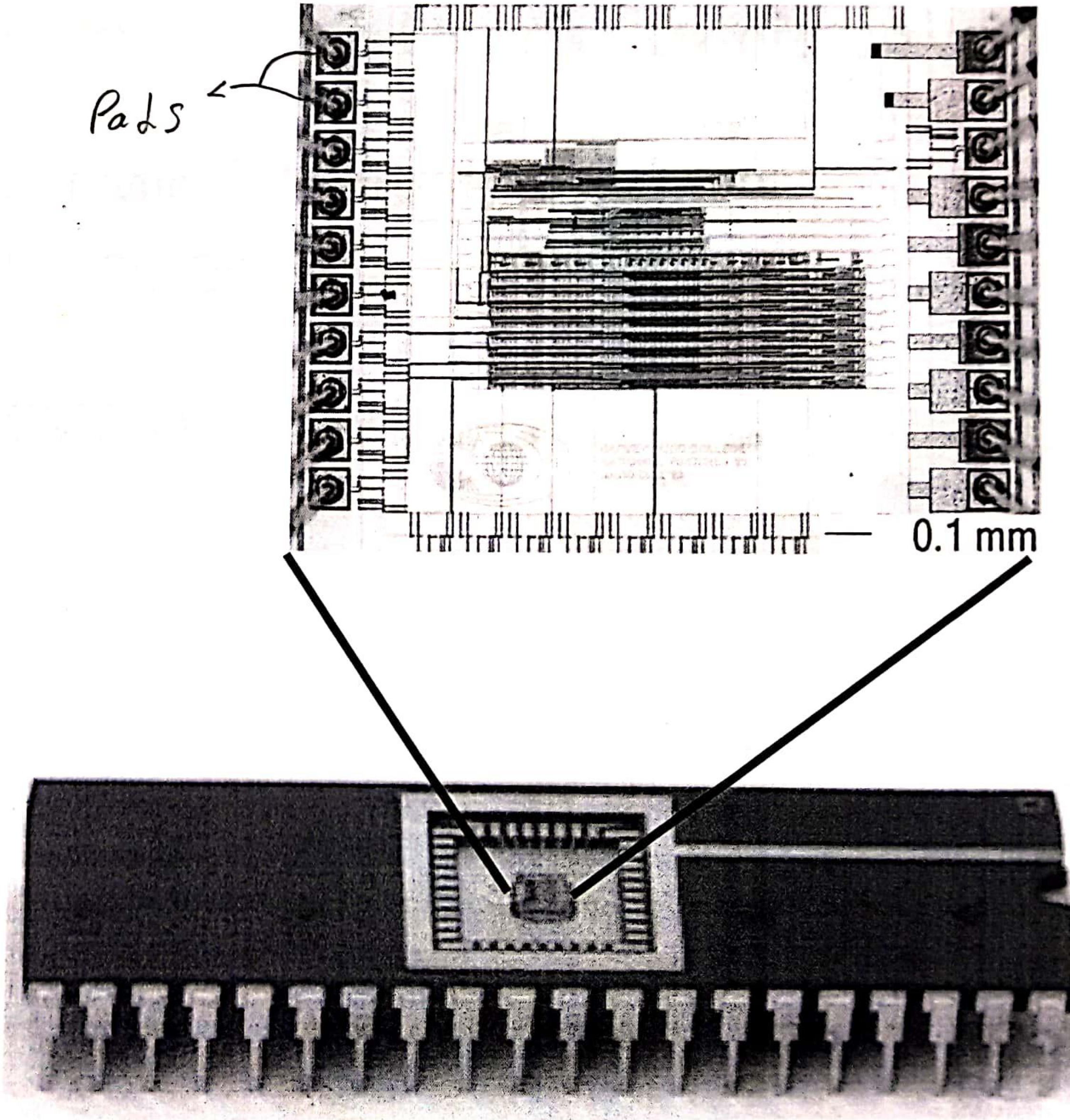
Packaging and Testing

- Wafer diced into dies
- Gold bond wires from die I/O pads to package
- Packaging is now much more advanced than the simple DIP

  → DIP: Dual inline package

missing pic.

Pads



[Weste and Harris, 2010]

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- B. Razavi, "Fundamentals of Microelectronics," Wiley, 2nd ed., 2014
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- N. Weste and D. Harris, "CMOS VLSI Design," Pearson, 4th ed., 2010

Thank you!

Modern "Moore" Concepts

- **More Moore**
  - Further miniaturization of transistor as per Moore's law
  - New materials for performance enhancement (HK, SOI, III-V)
  - We are approaching the "physical limits" of the transistor
- **More than Moore**
  - Adding functionalities **not** associated with transistor scaling to increase device value (sensors, MEMS, bio, passives, etc.)
  - 3D integrated circuits
- **Beyond Moore (Beyond CMOS)**
  - Exploring new device architectures
  - Gate-all-around transistors, nanowires (NW-FET), nanotubes (CNT), memristors, spin electronics, graphene, etc.

IC Technology Generations

- Early integrated circuits primarily used bipolar transistors (BJTs)
- 1960s: MOS ICs became attractive for their low cost
  - MOS transistor occupied less area
  - The fabrication process was simpler
  - Early commercial processes used only PMOS transistors and suffered from poor performance, yield, and reliability
- 1970s: Processes using only NMOS transistors became common
- Digital circuits in all the previous technologies have quiescent power
  - Power is dissipated when the circuit is idle, i.e., not switching
  - This limits the maximum number of transistors that can be integrated on one die

IC Technology Generations (Cont'd)

- 1980s: The VLSI era
  - Power consumption became a major issue
  - CMOS processes were widely adopted and replaced NMOS and bipolar processes for nearly all digital logic applications

    → CMOS = Complementary MOS = NMOS + PMOS
  - A key advantage for "digital" CMOS is that it has negligible idle (static) power consumption
- Nowadays:
  - With aggressive scaling and billions of transistors, CMOS idle leakage current is not negligible any more
  - But no better technology is available yet...

How to Design a Billion Transistor Chip?

1. Abstraction
   - Hiding details until they become necessary
2. Structured design
   - Hierarchy: Block, sub-blocks, … → Tree structure (from root to leaf cells)
   - Regularity: Min no. of different blocks → Block reuse (e.g., standard cells)
   - Modularity: Blocks are black boxes that have well-defined interfaces → Combine to build larger system without surprises!
3. CAD Tools
   - Automation, automation, automation!
   - Analog automation is way behind digital automation

CAD/EDA

- **Analog design**
  - **Design entry (schematic), simulation, layout**
  - **Verification (LVS: layout vs schematic, DRC: layout design rule check, parasitic extraction, post-layout simulation)**
- Digital design
  - Design entry (e.g., HDL) and simulation
  - Automated synthesis (from HDL to gates)
  - Automated place and route (from gates to transistor layout)
  - Verification
- System design
  - Behavioral modeling and high level simulation/verification
- EM simulation, process simulation, device simulation, etc.

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Allah almighty said in the Qur'an :
“and you ⌜O humanity⌝ have been given but little knowledge.”

لو أن الناس كلما استصعبوا أمرًا تركوه ما قام للناس دنيا ولا دين

The Muslim Caliph Umar ibn Abdulaziz, May Allah have mercy on him, Said:
“If every time people found something difficult, they abandoned it, then neither worldly affairs nor religion would have ever been established for people.”

- All Credits for these lectures go to **Dr. Hesham Omran**, Associate Professor at Ain Shams University and CTO at Master Micro, May Allah bless Dr. Hesham for these Lectures.

  https://www.master-micro.com/professional-courses/analog-ic-design

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- These Notes were made by: **Fady Sabry Negm** and any success or guidance is from Allah, and any mistake or lapse is from me and Satan.