وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Analog IC Design

Lecture 01
Introduction

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Faculty of Engineering
Ain Shams University

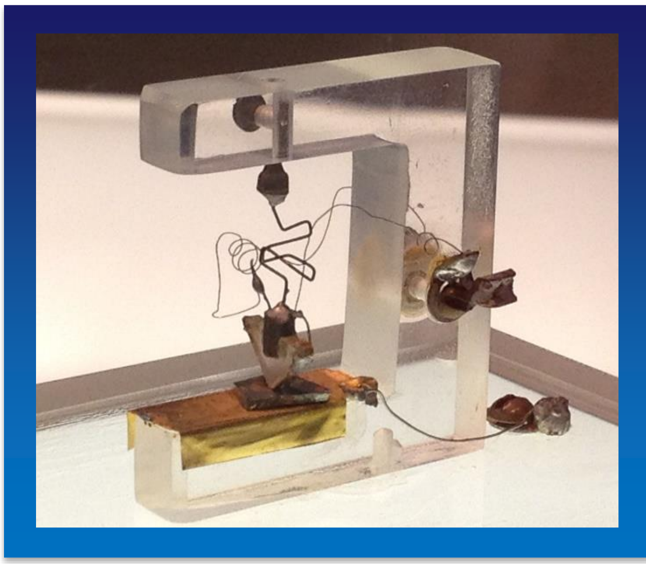
Introduction

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

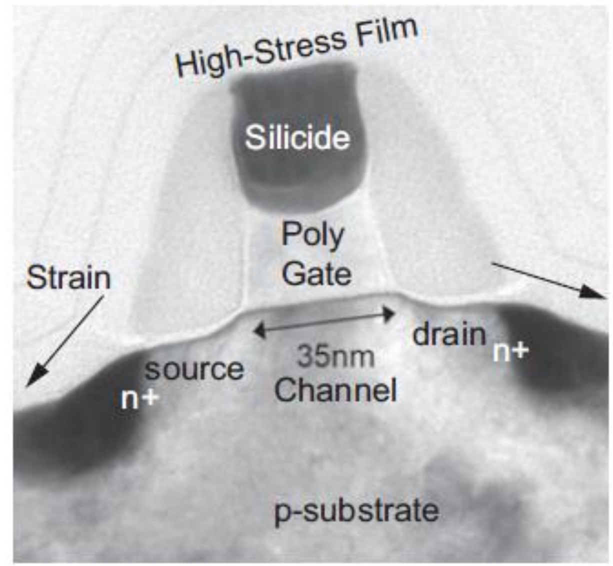
Smart phone, 2017
Size → Your pocket
Power consumption < 1W

Electronics All Around Us

Transistor Evolution



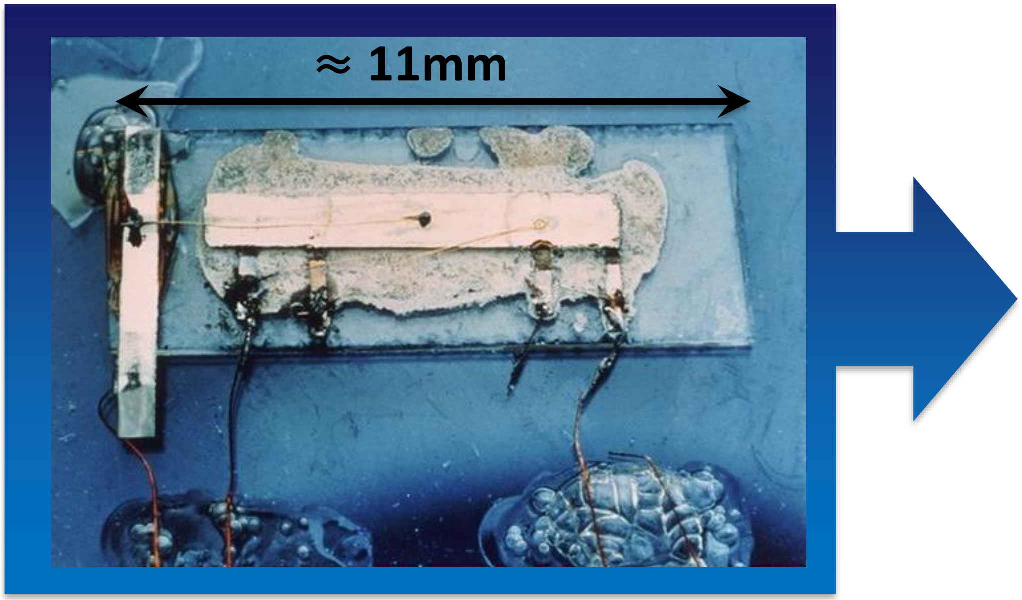
First transistor
Emitter and Collector contacts
separation ≈ 100µm
Bell Labs, 1947

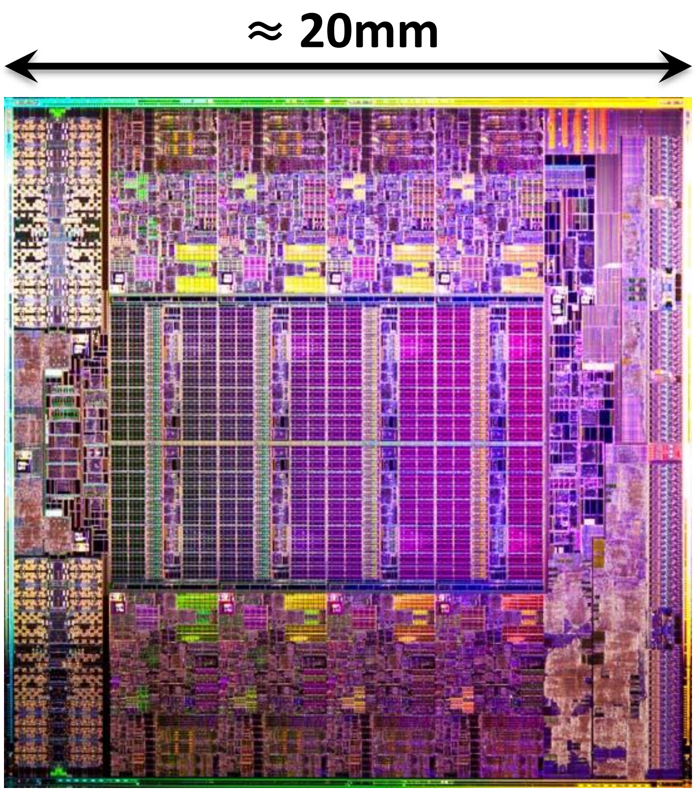


Modern MOSFET
Effective channel
length ≈ 35nm
Intel, 2006

[Weste and Harris, 2010]

Integrated Circuit Evolution

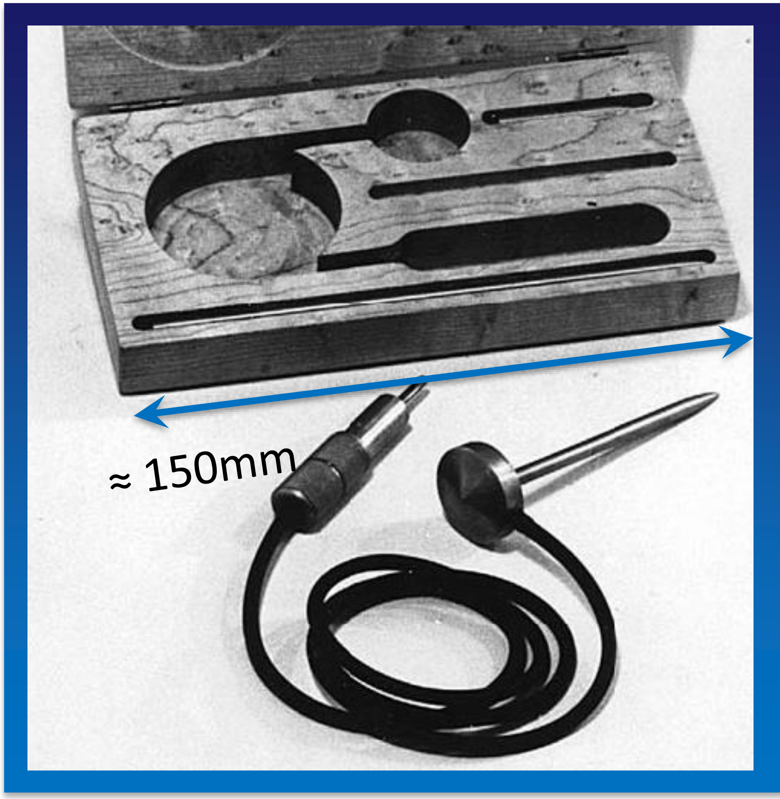




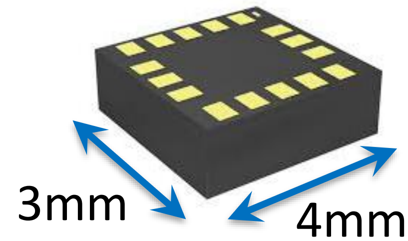
First IC
Only one transistor (+ R + C)!
Texas Instruments (TI), 1958

Xeon E5 Microprocessor
2.26 billion transistors!
Intel, 2012

Sensing Microsystems



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



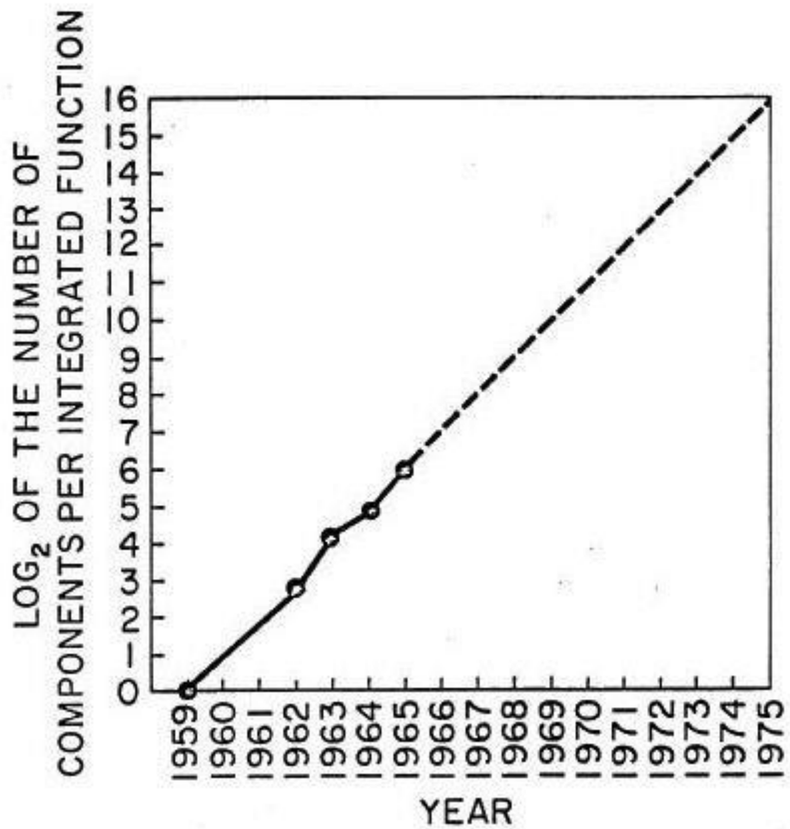
ADXL350
Analog Devices, 2012
Complete system on a tiny chip

- 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

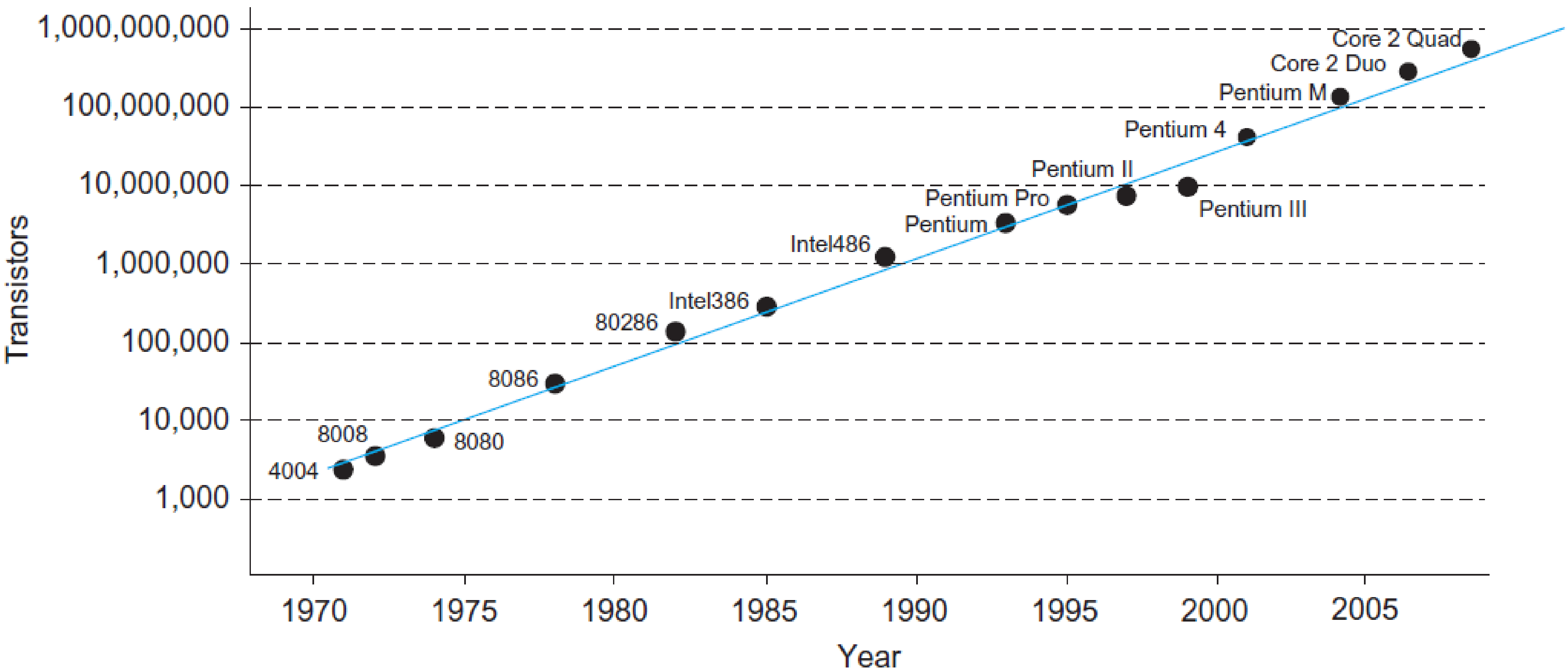
- Moore’s law [1965]: Transistor count doubles every year



[Electronics magazine article, 1965]

Moore's Law

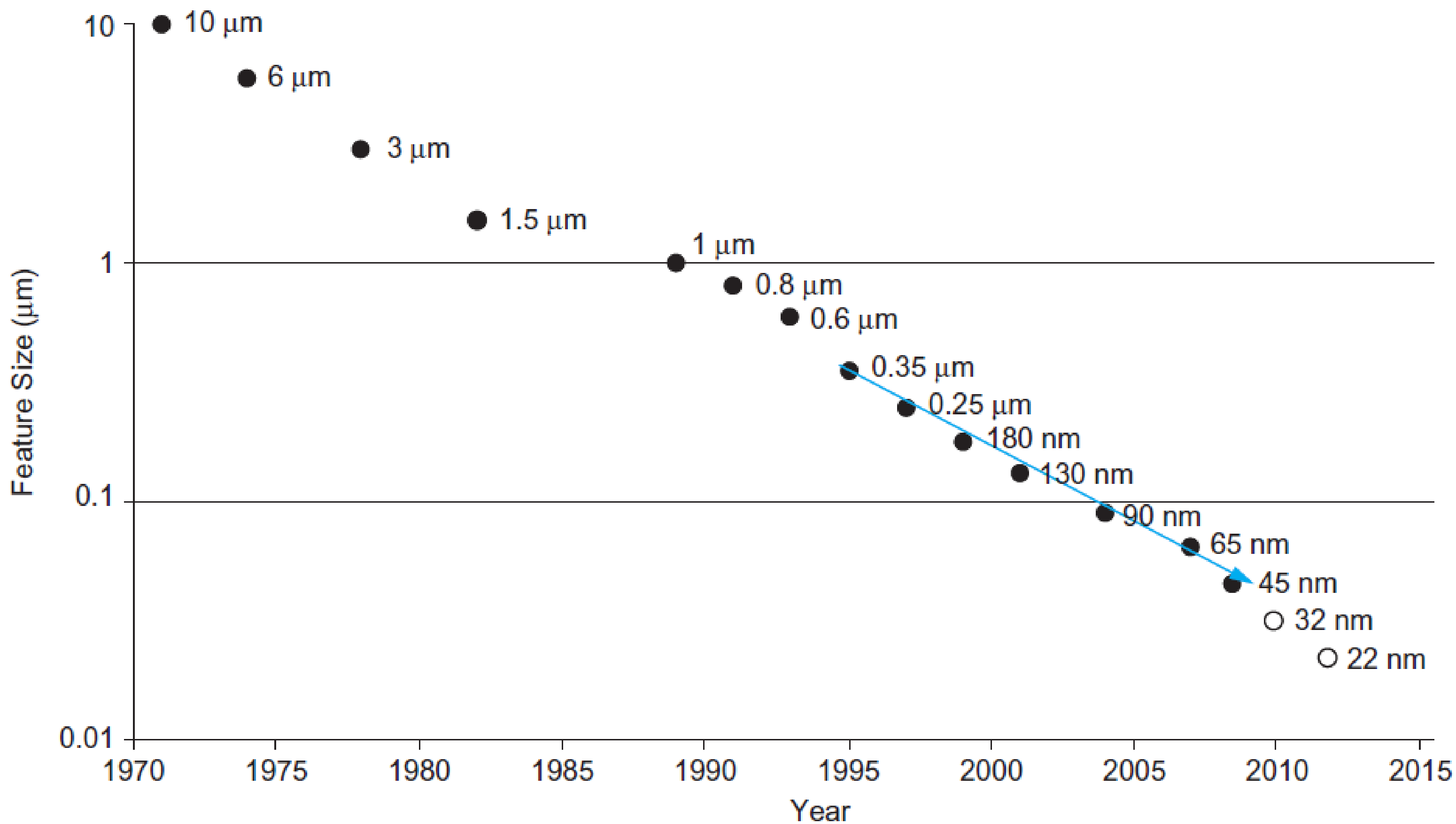
- Moore's law [1965]: Transistor count doubles every year
- Practically: It doubled every 2-3 years since the 4004 [1970s]
- At the end of the day: It is exponential!



[Weste and Harris, 2010]

Technology Minimum Feature Size

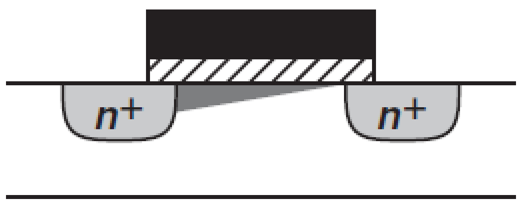
- Minimum feature size shrinking 30% ($\approx 1/\sqrt{2}$) every 2-3 years
  - Transistor **area and cost** are reduced by a factor of 2
- Device scaling brings new challenges in circuit design



[Weste and Harris, 2010]

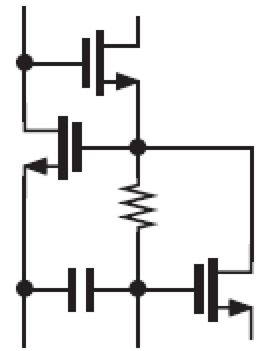
Levels of Abstraction

Device



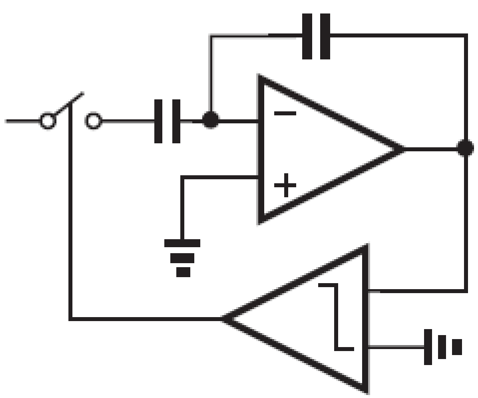
(a)

Circuit



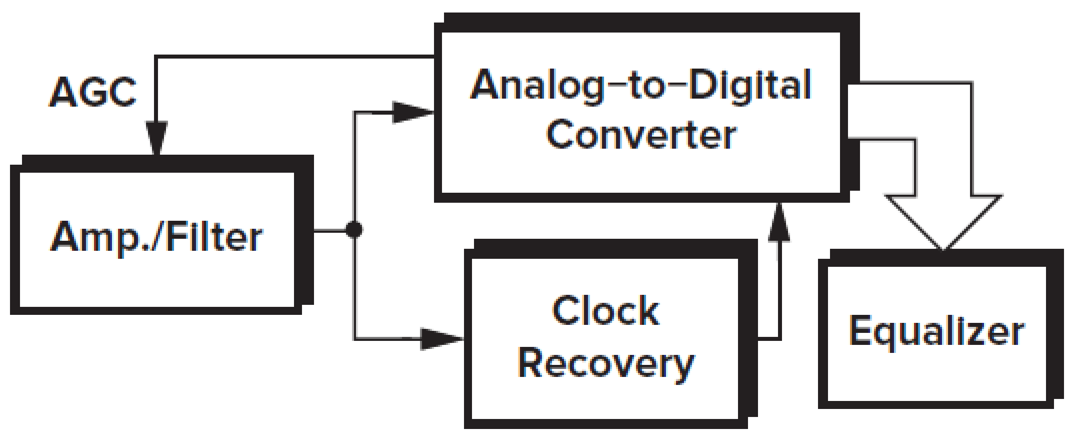
(b)

Architecture



(c)

System



(d)

[Razavi, 2017]

IC Industry in Egypt

Si-Ware Systems

Silicon Vision
Innovative IC Solutions

Mentor Graphics®

Analog Devices

Wasiela

Axxcelera
Broadband Wireless

mipex
Mixed-Signal IP Excellence

MEMS Vision

ICpedia

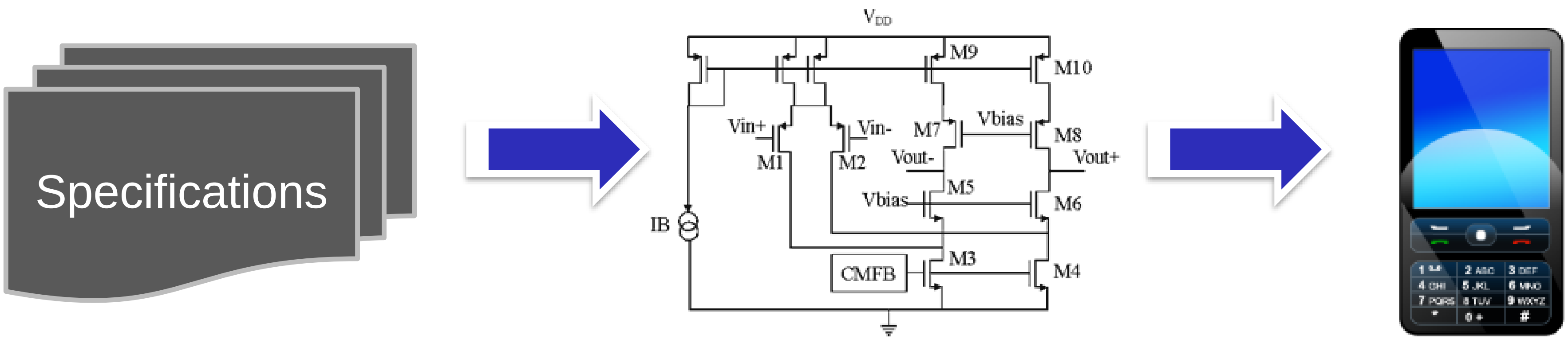
GOODiX

?

vidatronic
egypt

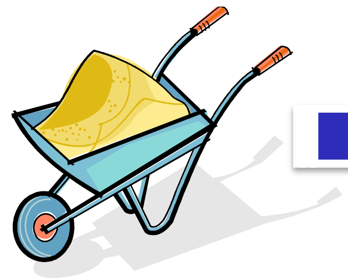
Course Objective

- 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**

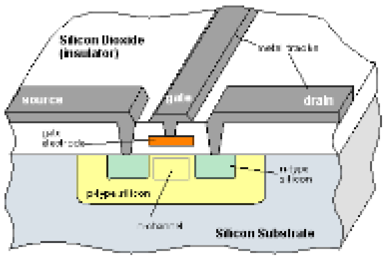


Your Learning Journey

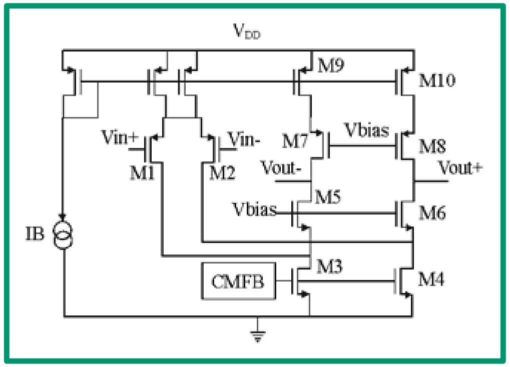
Material



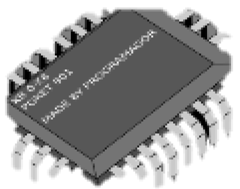
Devices



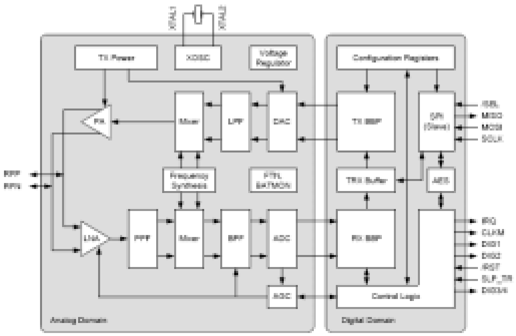
Circuits



Product



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
  - 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

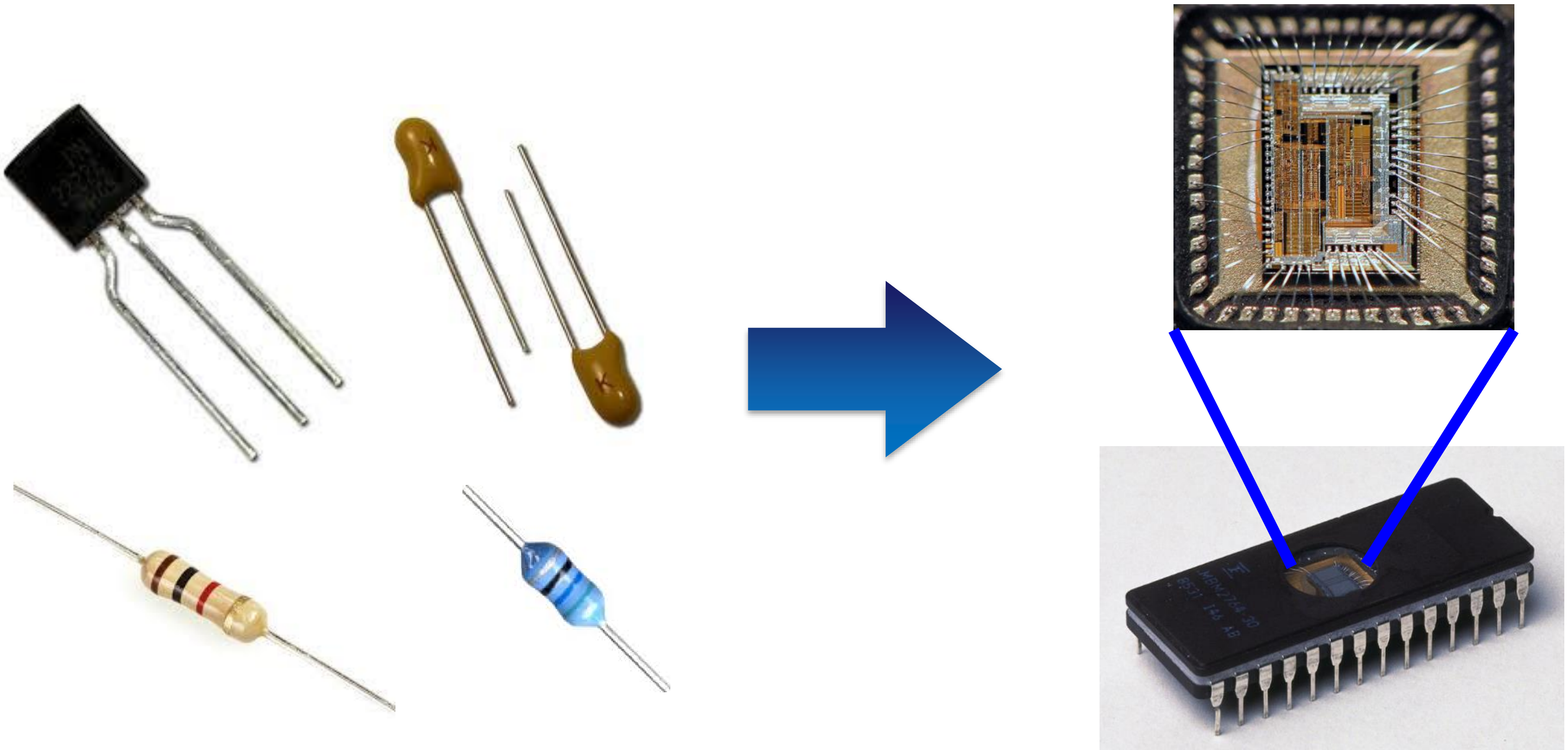
"It was an awesome course . It has a lot of interesting topics, and a lot of knowledge and experience."

"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."

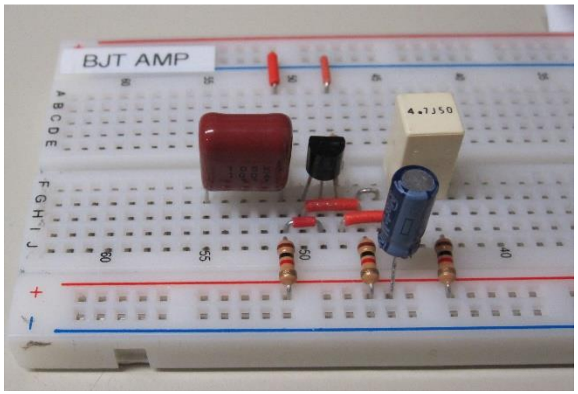
What is an Integrated Circuit (IC)?

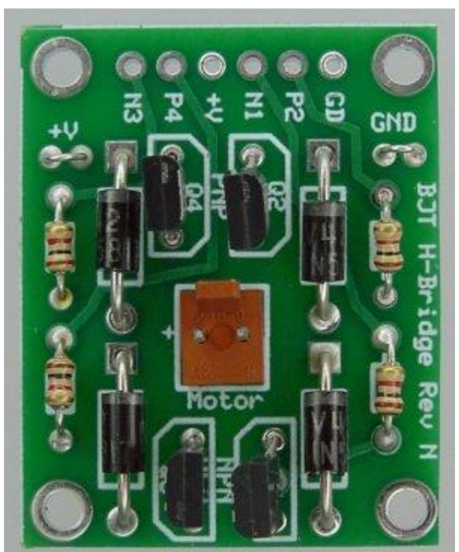
- Various circuit elements: transistors, capacitors, resistors, and even small inductances can be integrated on one chip

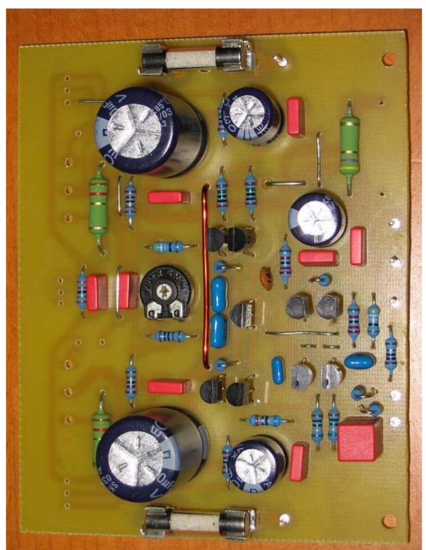


Discrete vs. Integrated Electronics

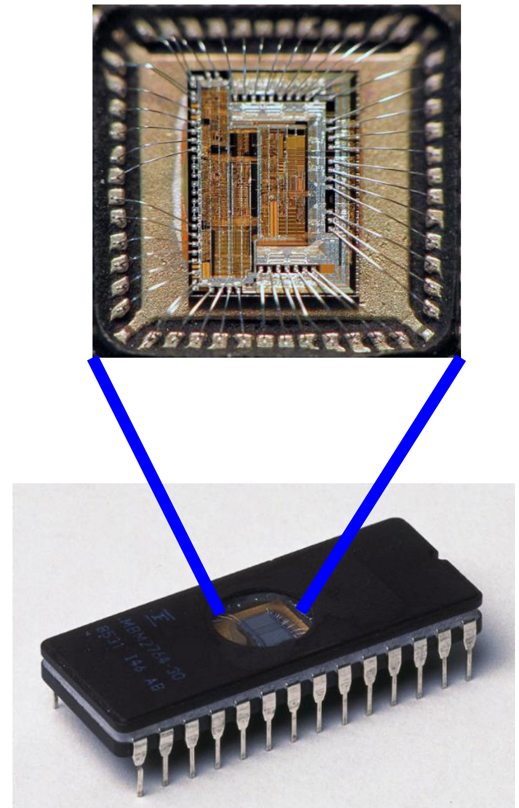
Circuits using discrete components







Integrated circuit

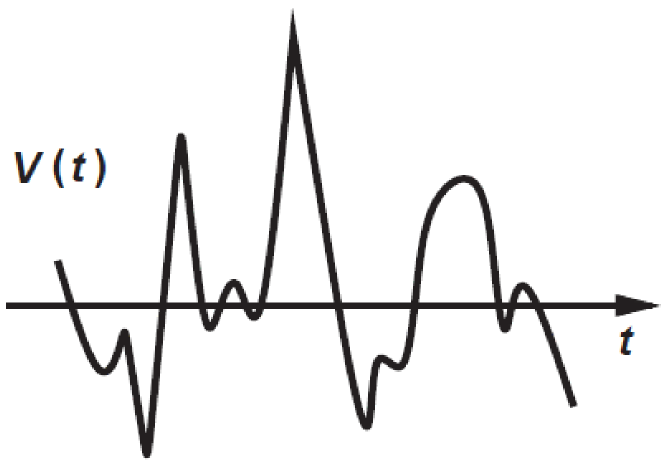


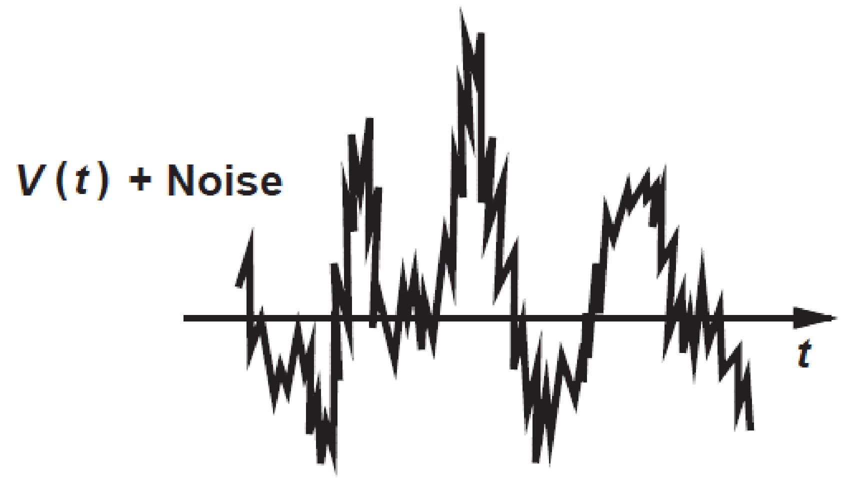
Integrated Circuit Components

- Transistors:
  - Billions of tiny transistors can be integrated on the same chip
  - Very Large Scale Integration (VLSI): > 10,000 transistors
- Capacitors:
  - Capacitors as large as 100s of pF can be integrated on-chip
  - But they consume a lot of chip area → Use sparingly
- Resistors:
  - Resistors as large as few MOhms can be integrated on-chip
  - But they consume a lot of chip area → Use sparingly
- Inductors:
  - 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)

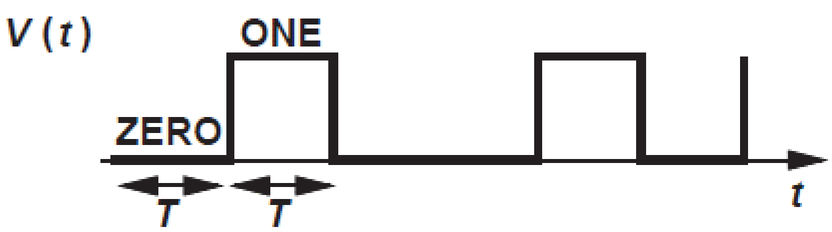
Analog vs Digital Signals

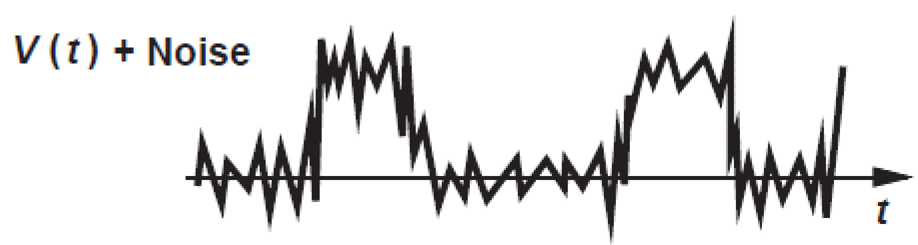
- Analog: continuous in time and amplitude





- Digital: discrete in time and amplitude





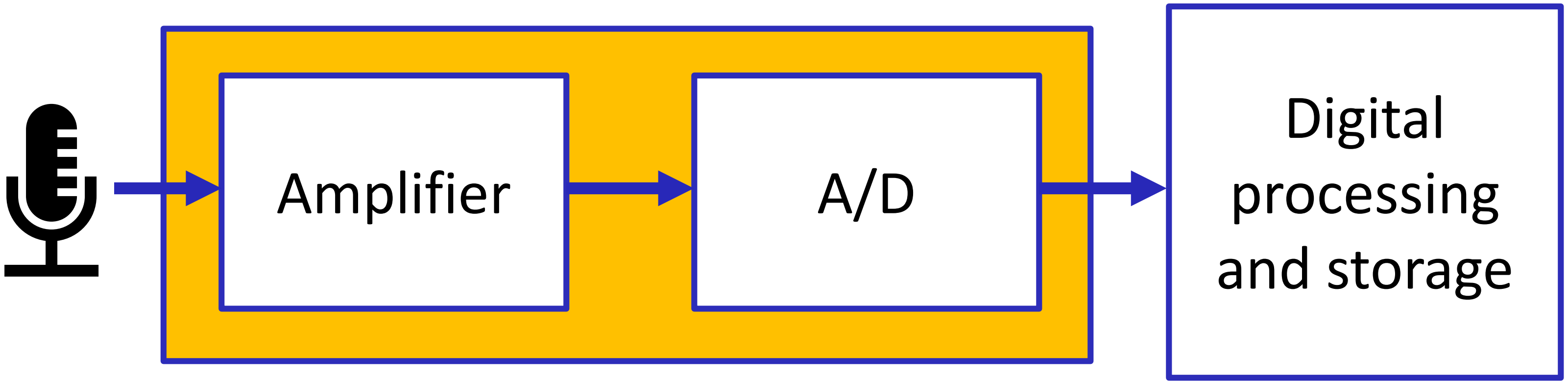
 [Razavi, 2014]

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
  - Direct beneficiary of Moore's law (down-scaling)

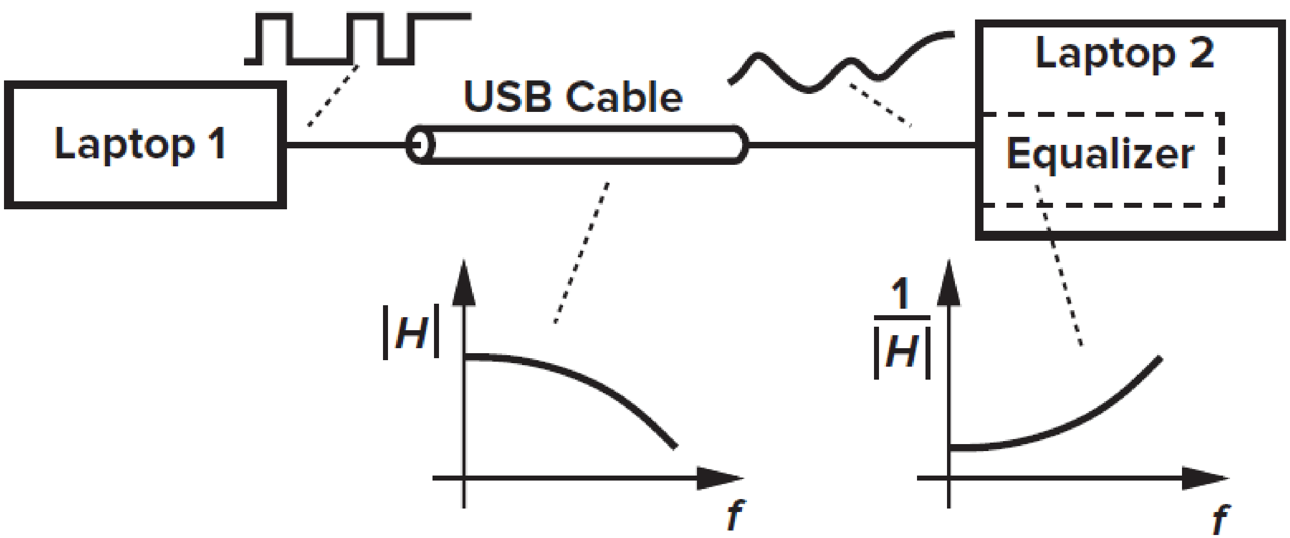
Why Analog?

- 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



Why Analog?

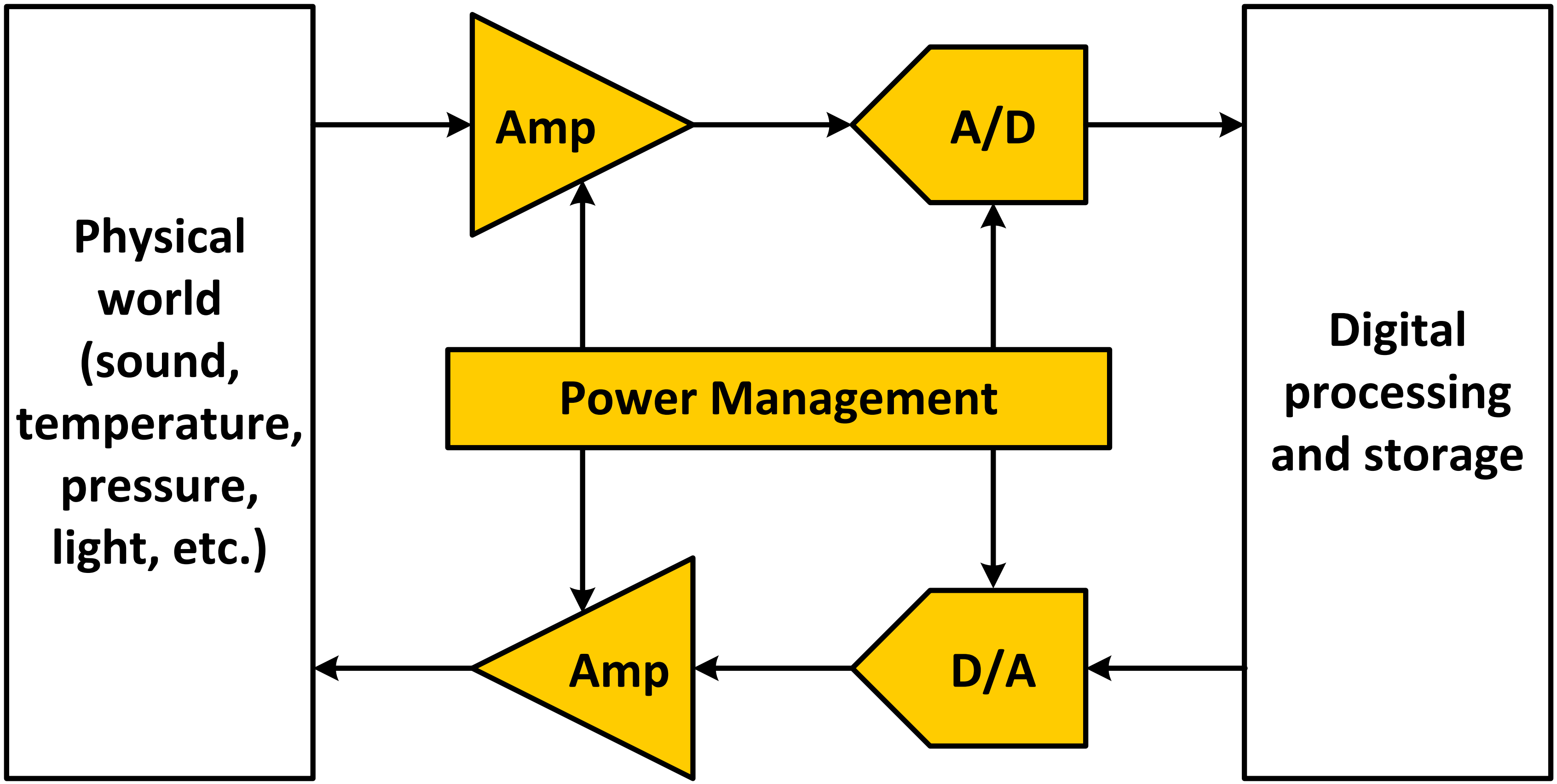
- High speed digital design is actually analog design!
- At low speeds, we may directly digitize the signal and perform the signal processing in the digital domain.
- At high speeds, signal processing in the analog domain is much more energy efficient.
- The boundary between high and low speed has risen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



[Razavi, 2017]

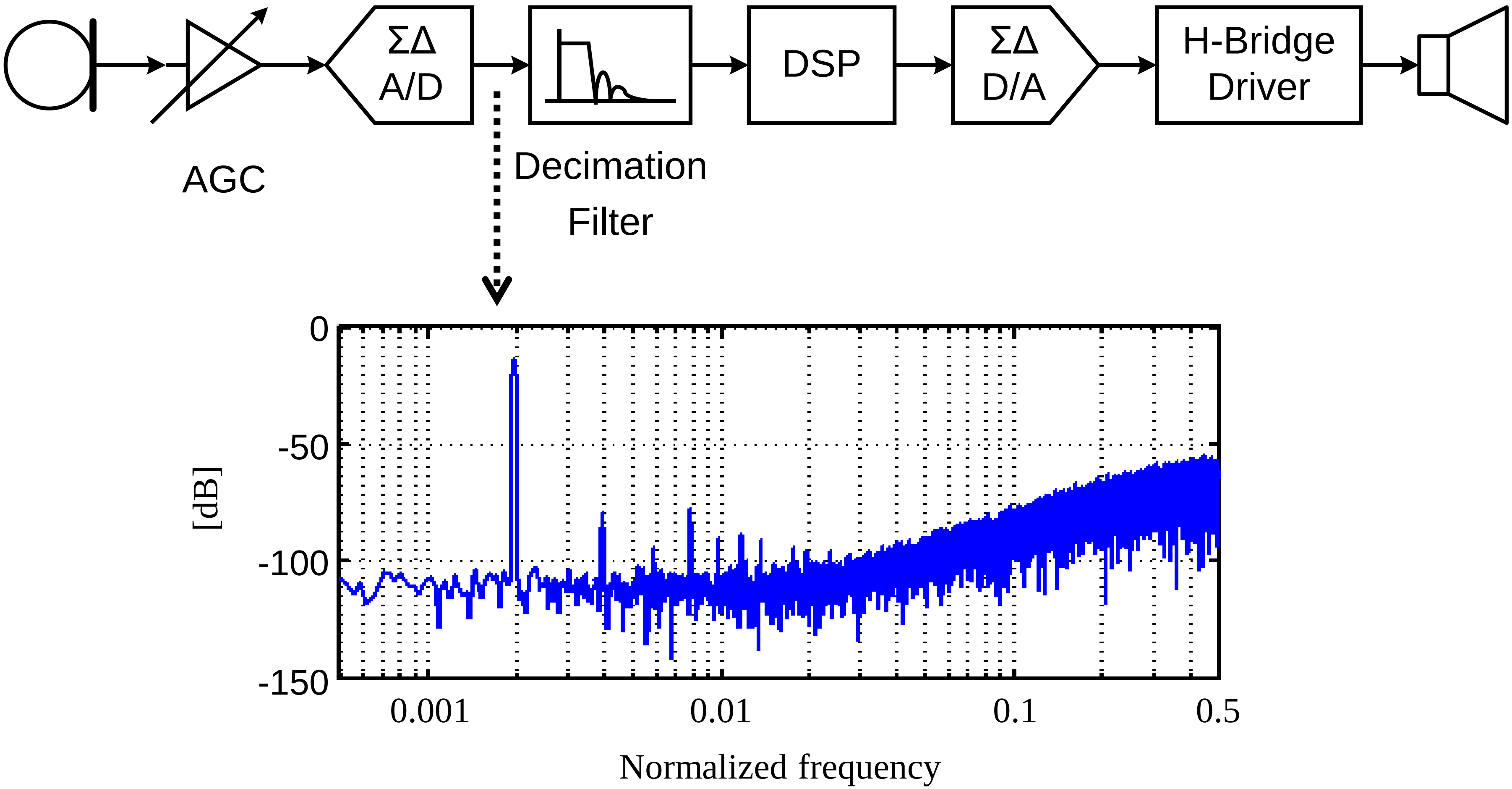
Signal Processing Chain

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



Example: Mixed-Signal Hearing Aid

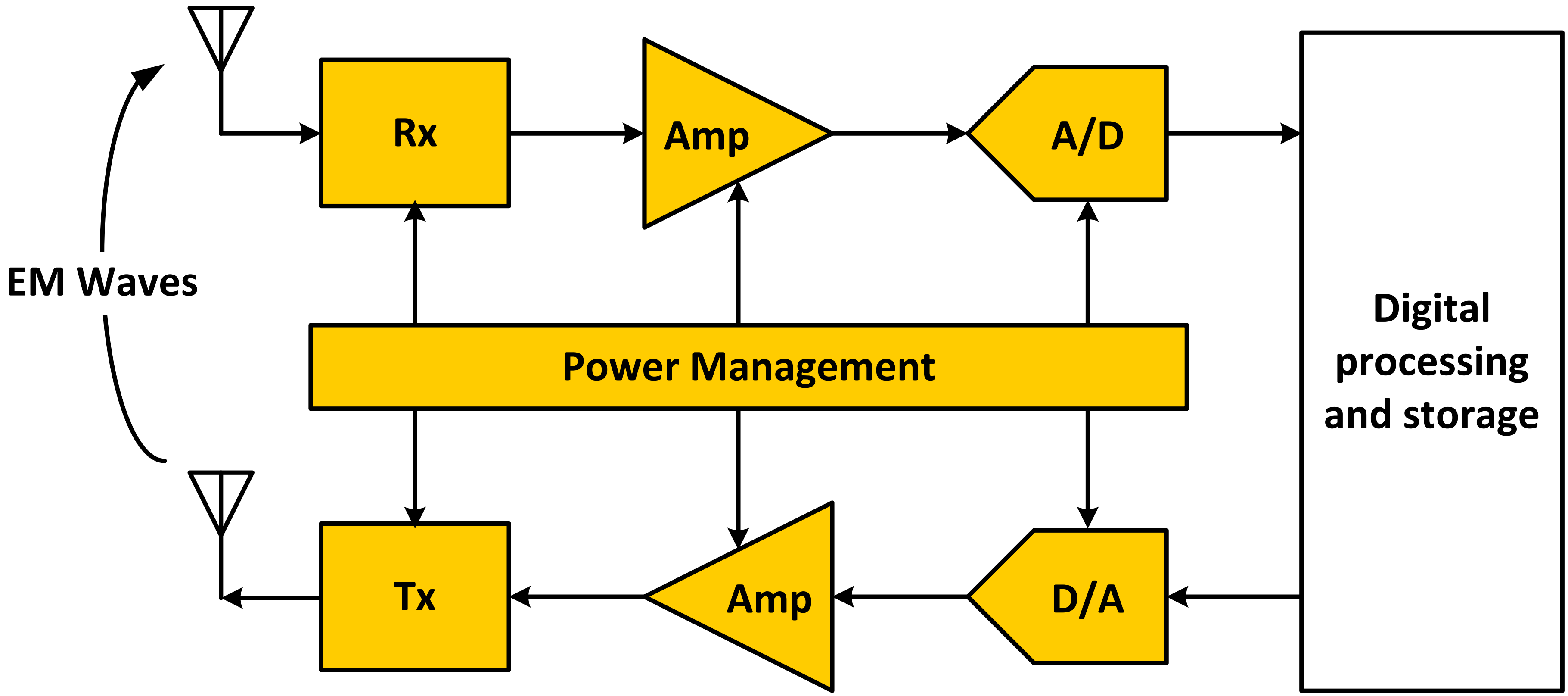
- ❑ There will always be jobs for analog/mixed-signal/RF designers ☺



[Y. Chiu, EECT 7327, UTD]

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

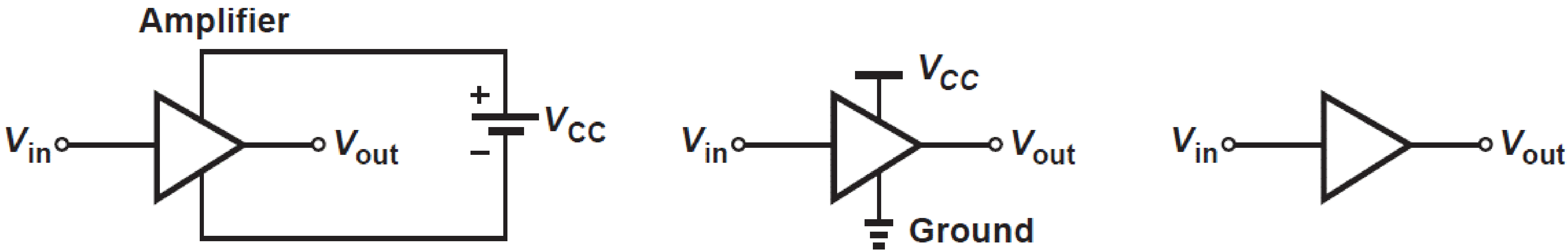
  → CMOS = Complementary MOS = NMOS + PMOS

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

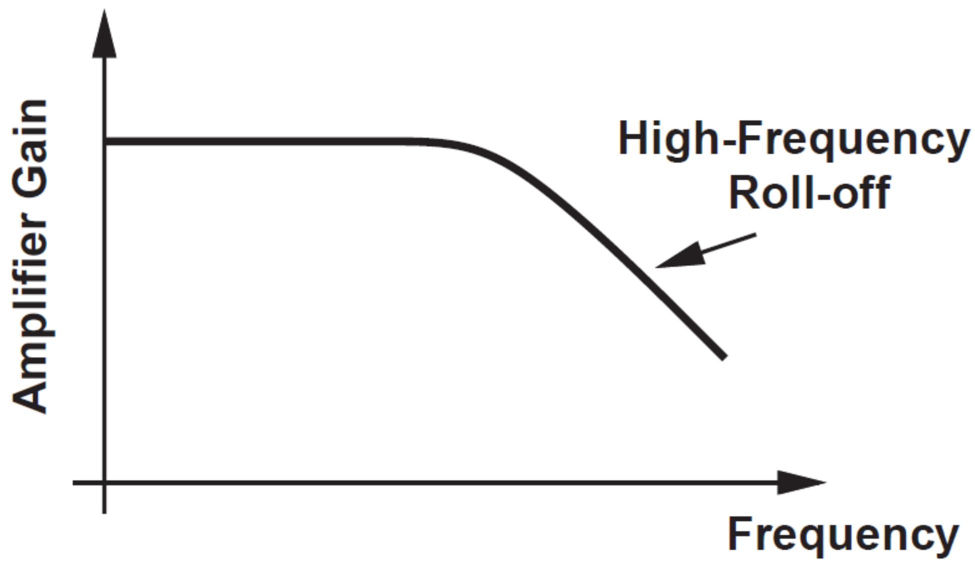
Why Analog CMOS?

- 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
- BJTs used to be faster, but with continuous scaling, MOSFET speed exceeded BJT
- MOSFET can operate with lower supply voltage

Analog Amplifier



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



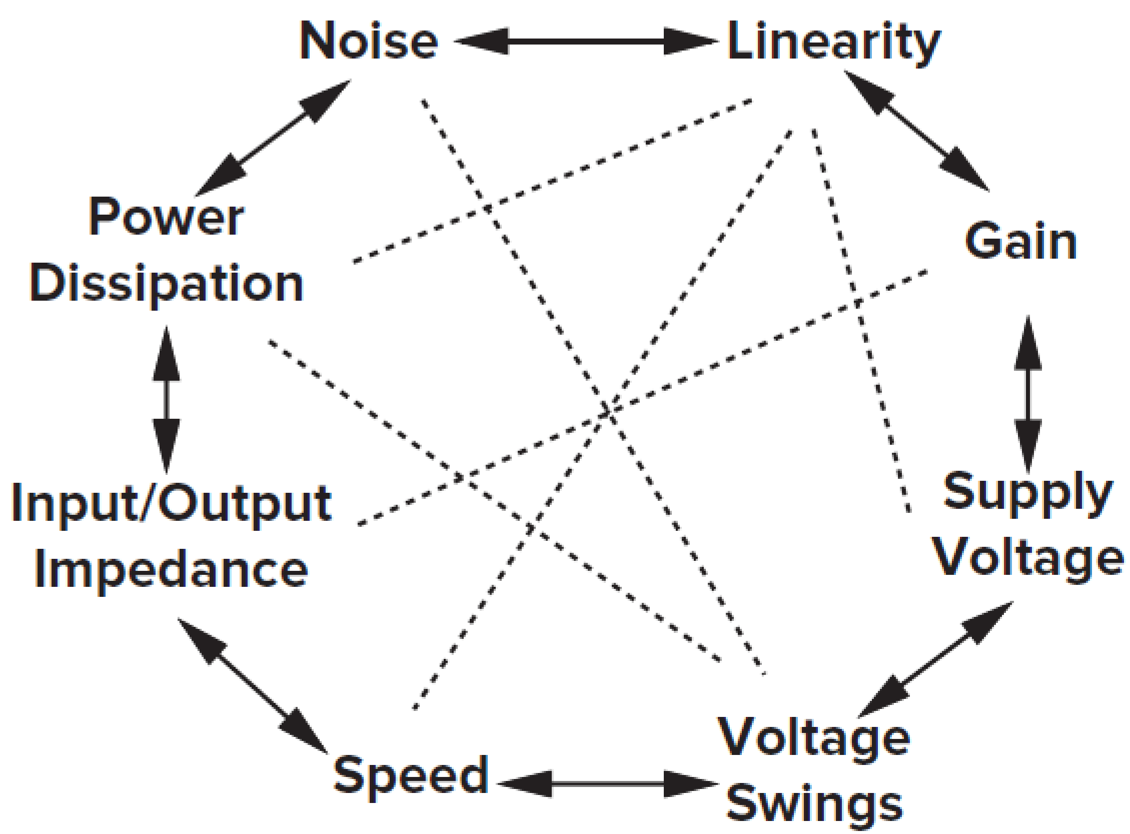
[Razavi, 2014]

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), …

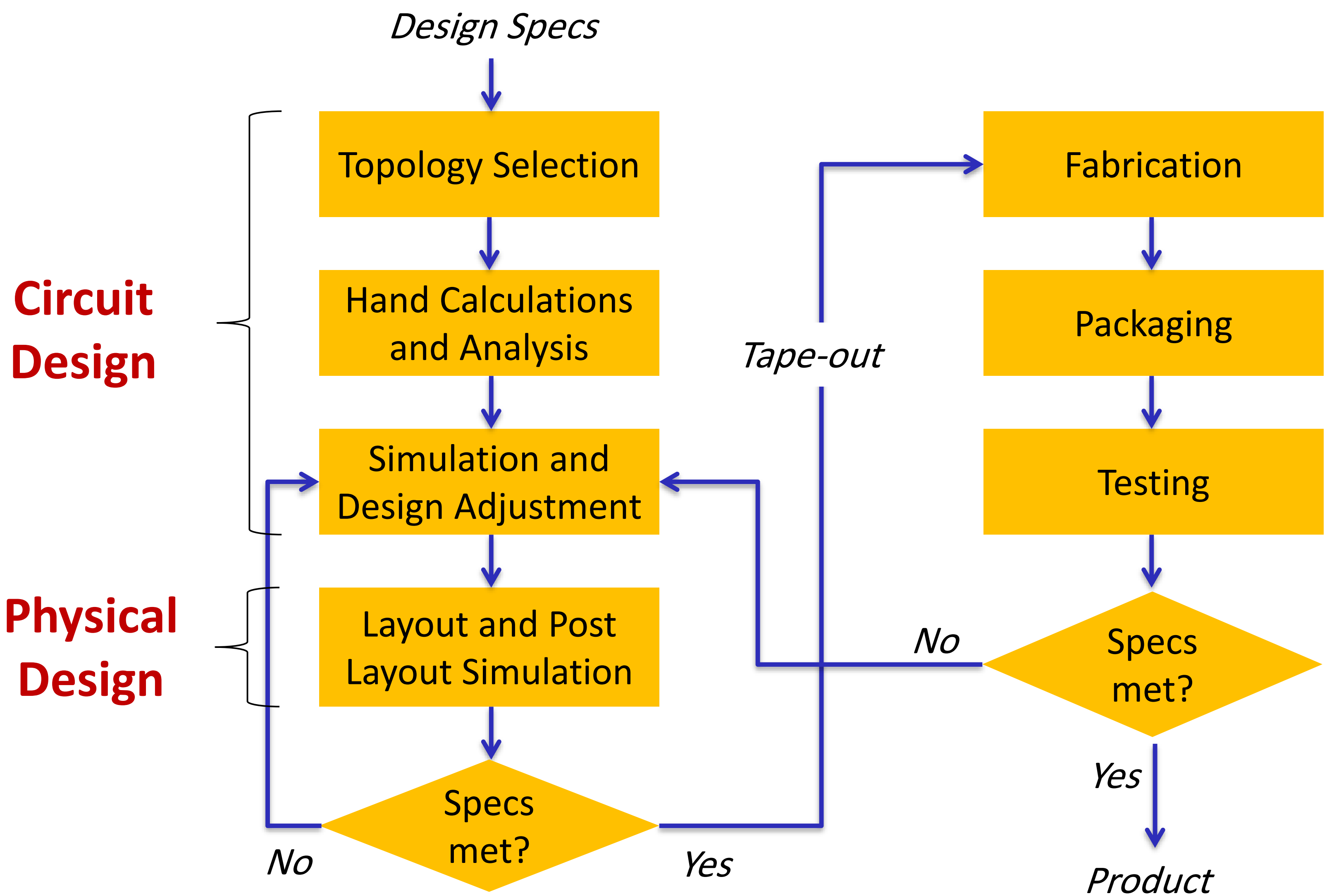
Analog Design Challenges

- Analog design automation is a difficult task



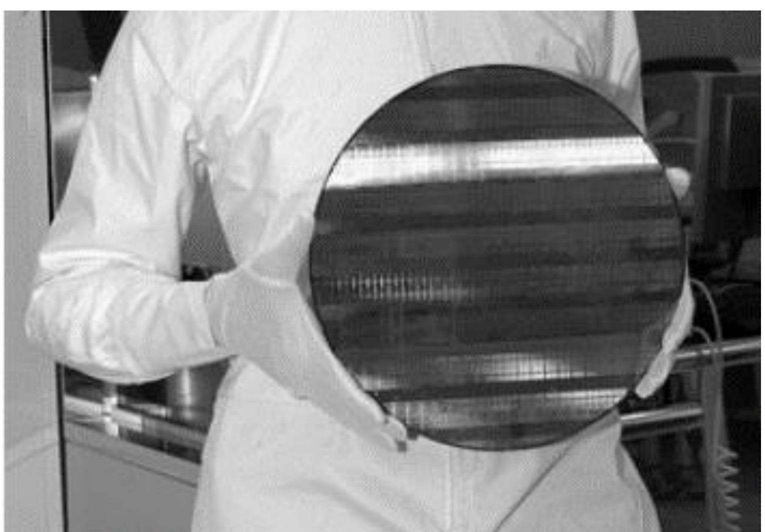
[Razavi, 2017]

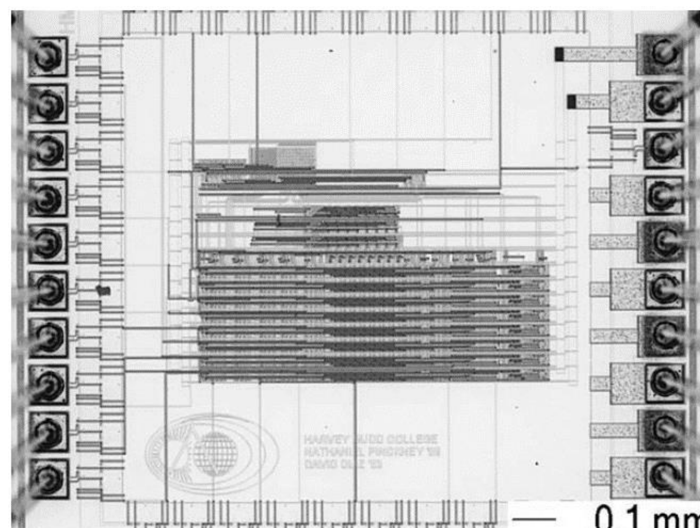
Analog IC Design Flow (Simplified)



Tape-Out

- 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)

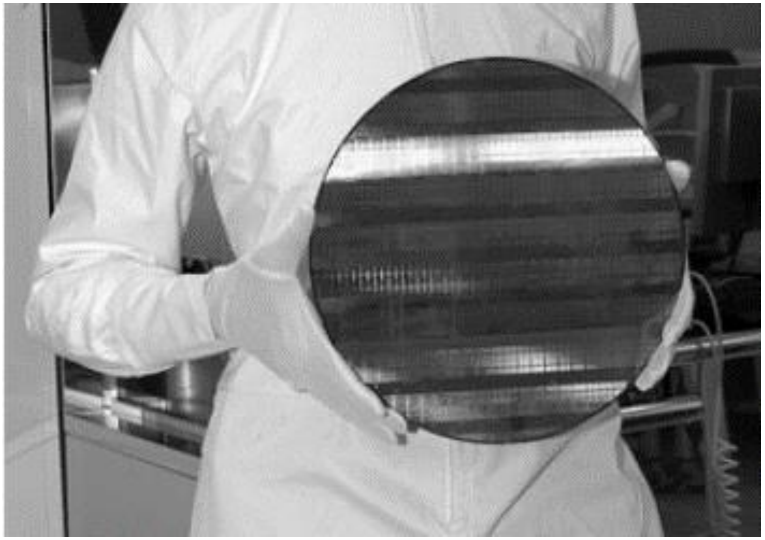


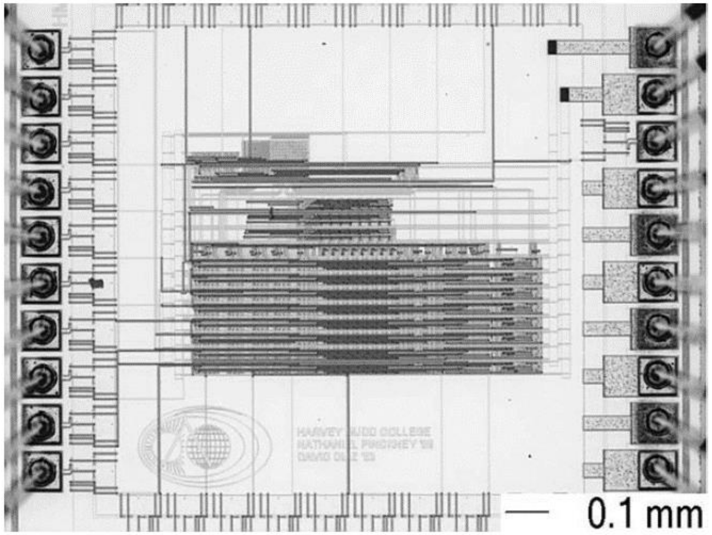


[Weste and Harris, 2010]

Tape-Out

- 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



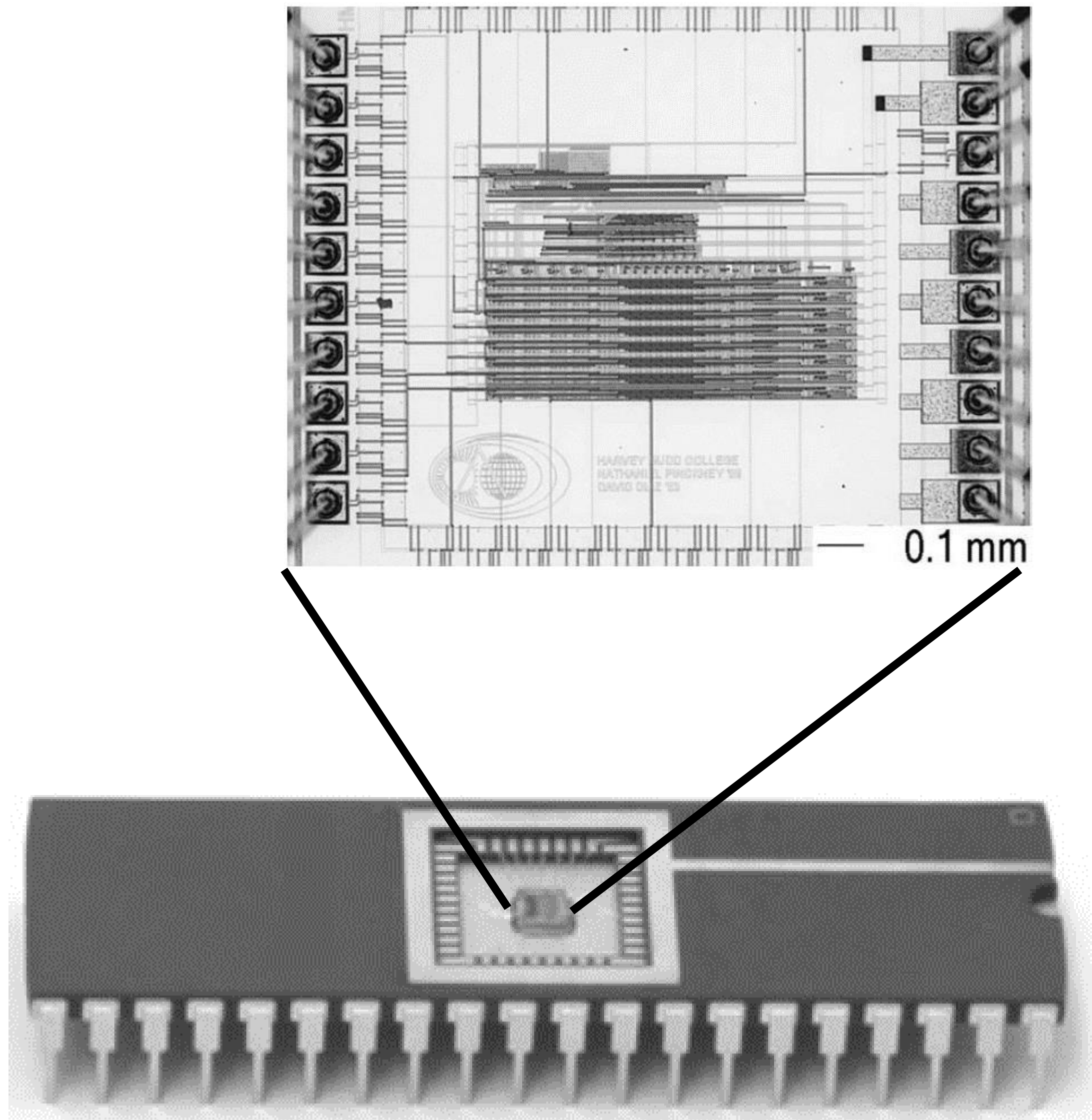


[Weste and Harris, 2010]

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



[Weste and Harris, 2010]

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- A. Sedra and K. Smith, "Microelectronic Circuits," Oxford University Press, 7th ed., 2015
- B. Razavi, "Fundamentals of Microelectronics," Wiley, 2nd ed., 2014
- B. Razavi, "Design of Analog CMOS Integrated Circuits," McGraw-Hill, 2nd ed., 2017
- 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.