EE 332: Devices and Circuits II

Lecture 1: Integrated Circuits & Analog Electronics

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Autumn 2022

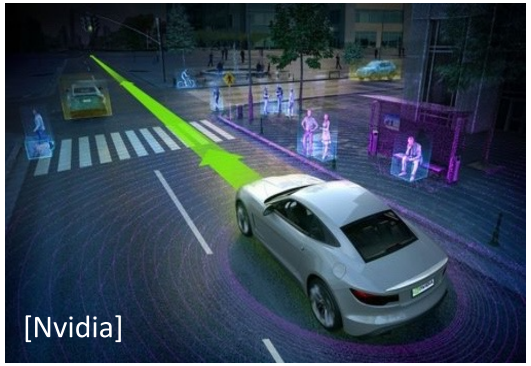
Today's Integrated Systems

Internet of Things (IoT)

Machine Learning & AI

5G Wireless

AR/VR



Autonomous Vehicles

Integrated circuits & systems are key enablers of todays major technologies!!!

Chips are crucial … sometimes behind the scene!

The ongoing chip shortage is expected to cost the auto industry $110 billion this year, almost double analysts' estimate from January

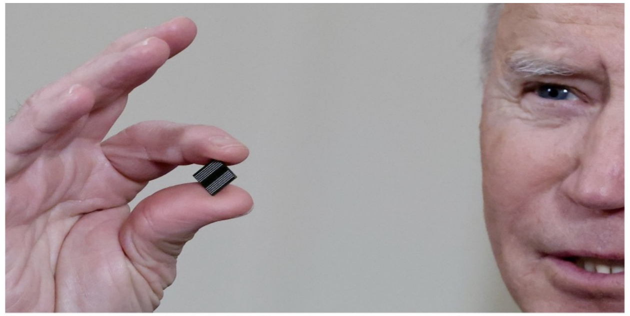
Dominick Reuter May 14, 2021, 11:22 AM

Workers build Ford F-150 trucks at one of the automaker's assembly plants. Associated Press

The New York Times

Biden Administration Releases Plan for $50 Billion Investment in Chips

The Commerce Department issued guidelines for companies angling to receive federal funding aimed at bolstering the domestic semiconductor industry.



President Biden, here with a semiconductor chip in February, has sought a broad supply-chain review as chips have become scarce.
PHOTO: JONATHAN ERNST/REUTERS

Integrated systems have an enormous impact on society and economy – it's growing every year.

Shortage of Skilled workforce?

Best time to become a circuit designer ☺

ELECTRICAL & COMPUTER ENGINEERING

Integrated Systems: Enablers of future technologies

…

Nanotechnology Initiative (2000)

Renewable Energy (ARPA-E) (2011)

Brain Initiative (2014)

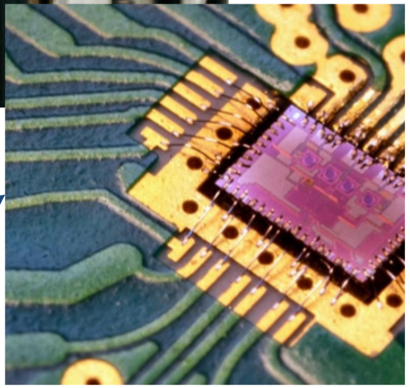
AI Initiative (2018)

Quantum Initiative (2018)

…

[NeuraLink]

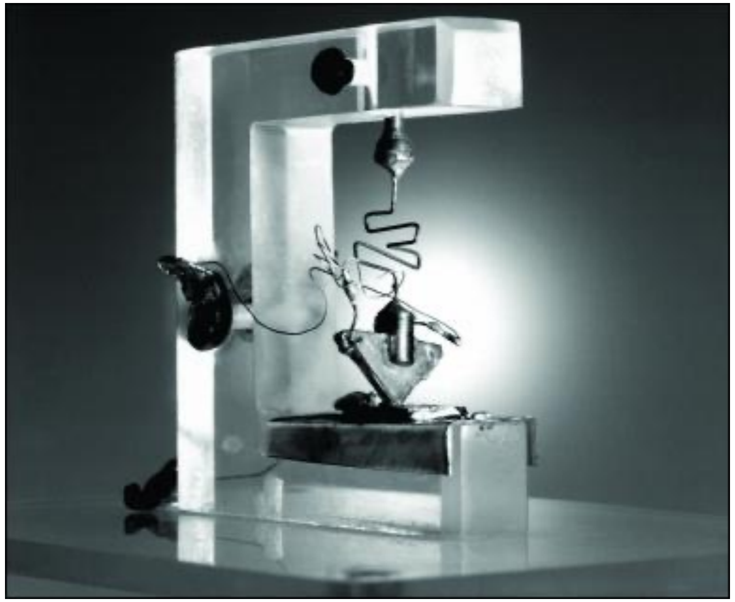
[Nvidia]



[Google]

Research Initiatives by governments and national agencies

Invention of Transistors (1947)

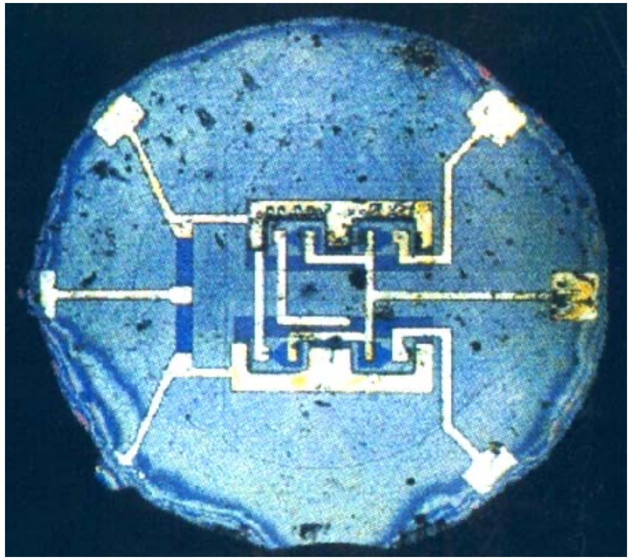


- Bardeen, Shockley, and Brattain at Bell Labs
- Invented first transistor in 1947
- Nobel prize in 1956
- Shockley sometimes credited as “the man who brought silicon to Silicon Valley”

Point contact transistor
(in Germanium)

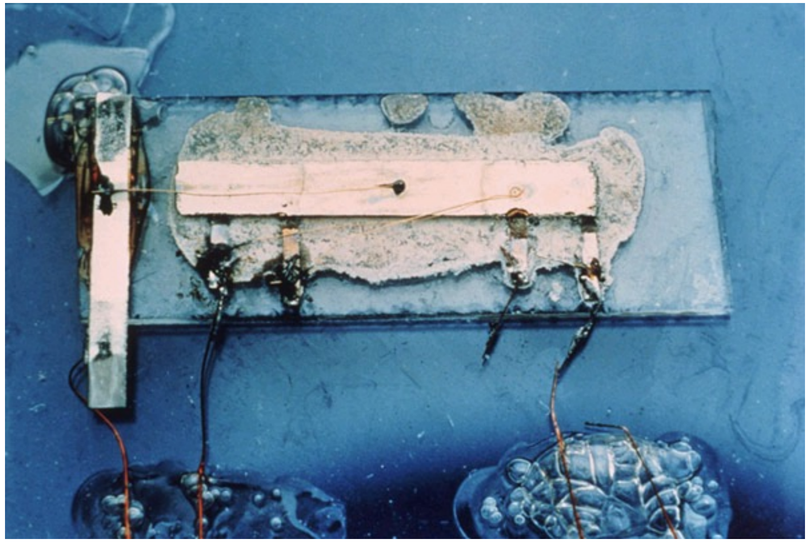
Later in 1948 Shockley showed the first bipolar junction transistor (BJT)!

The First Integrated Circuits (1958)



R. N. Noyce
Fairchild Semiconductor
Co-Founder of both
Fairchild and Intel
(deceased 1990)

"Unitary Circuit" made of Si



Jack Kilby
Texas Instruments
Invented IC during his first year at TI

(Nobel Prize 2000)

"Solid Circuit" made of Ge

Moore's Paper (1965)

Cramming more components onto integrated circuits

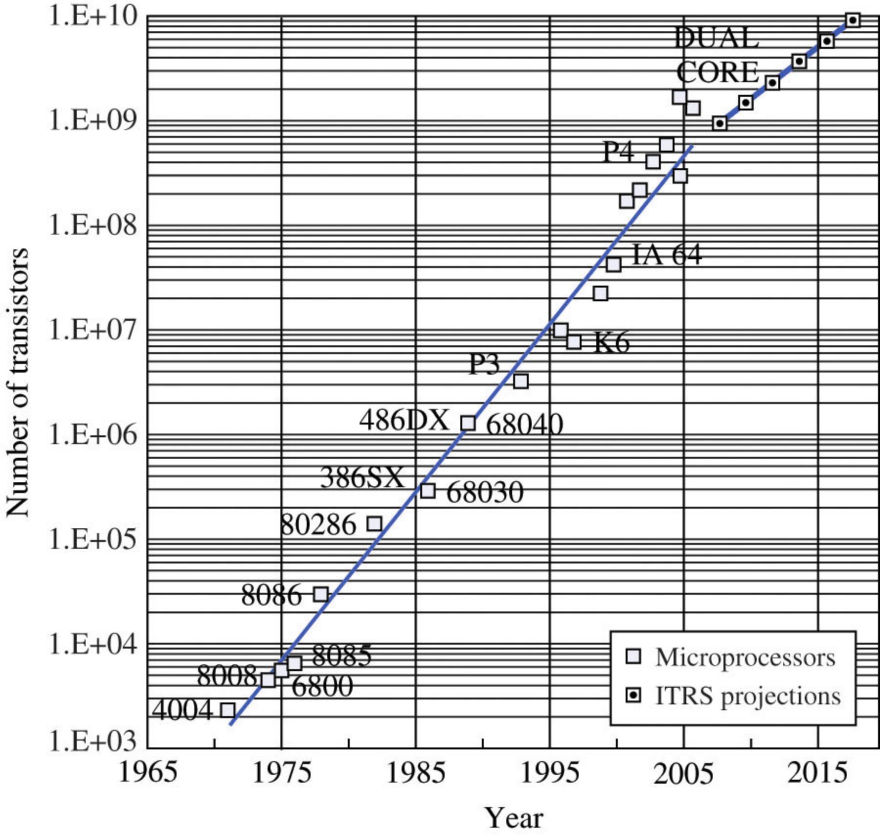
With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

The number of transistors in integrated circuits doubles every two years!

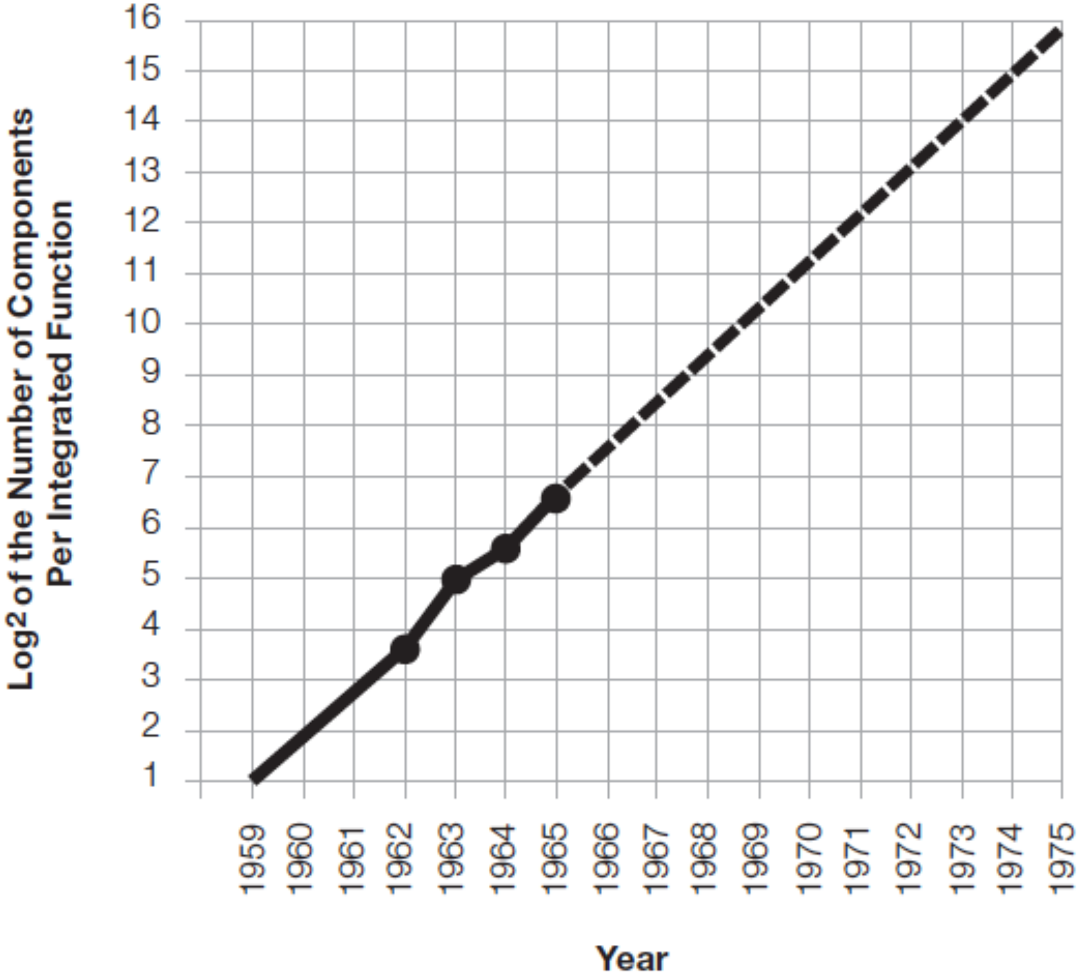
Microprocessor complexity versus time

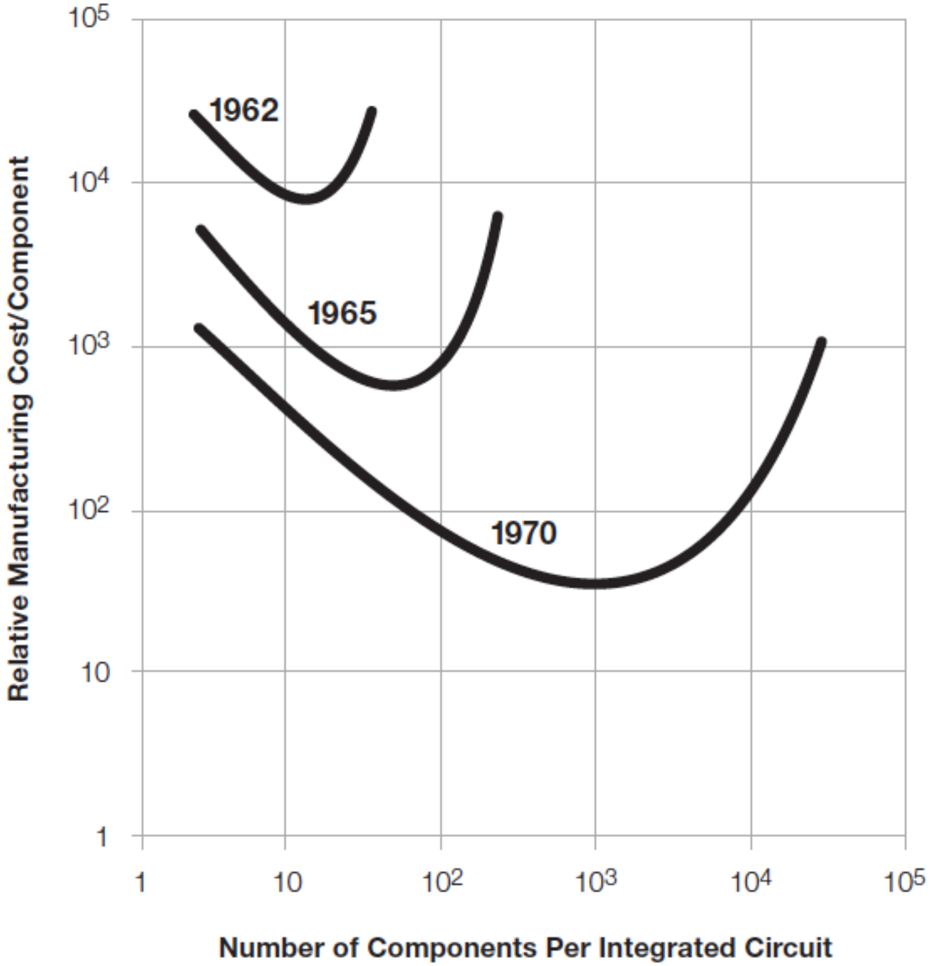


Short video on Gordon Moore's story … https://vimeo.com/70293585

Moore’s Law in 1965

More Transistors → Cheaper $/Transistor



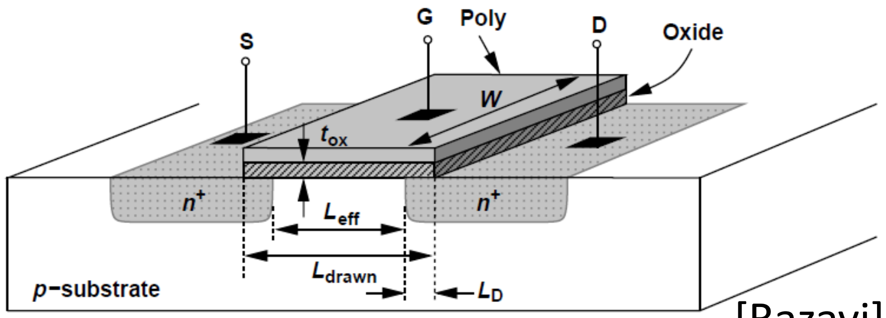


Dennard Scaling (1974)

Design of Ion-Implanted MOSFET's with Very Small Physical Dimensions

ROBERT H. DENNARD, MEMBER, IEEE, FRITZ H. GAENSSLEN, HWA-NIEN YU, MEMBER, IEEE, V. LEO RIDEOUT, MEMBER, IEEE, ERNEST BASSOUS, AND ANDRE R. LEBLANC, MEMBER, IEEE

Classic Paper



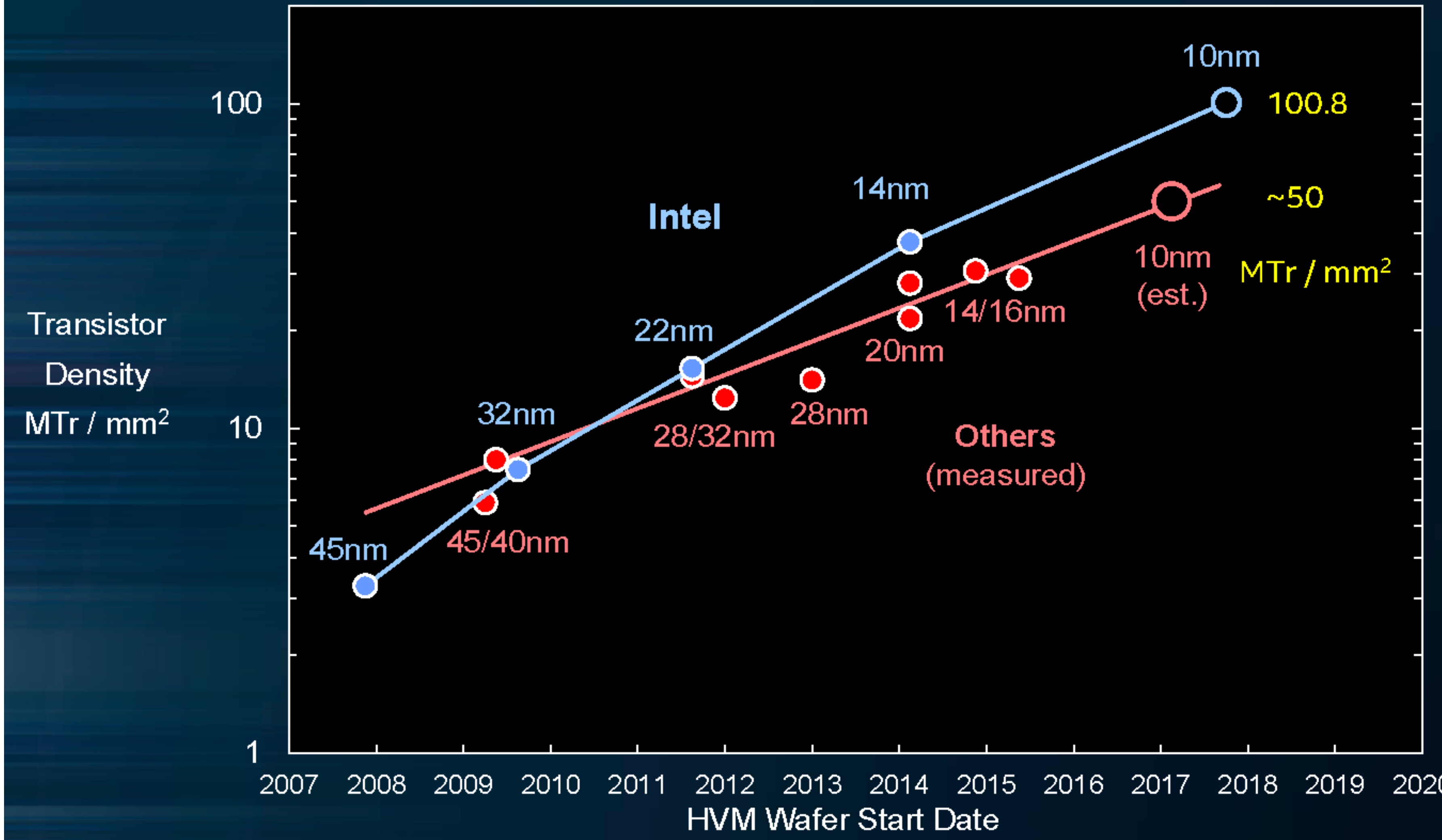
[Razavi]

Scaling down all dimensions by 0.7x → **Scaling down supply by 0.7x (Constant Field)** → **Speed goes up by 1.4x Power down by 0.5x**

We will look into this more closely in homework 1 !

ELECTRICAL & COMPUTER ENGINEERING

LOGIC TRANSISTOR DENSITY



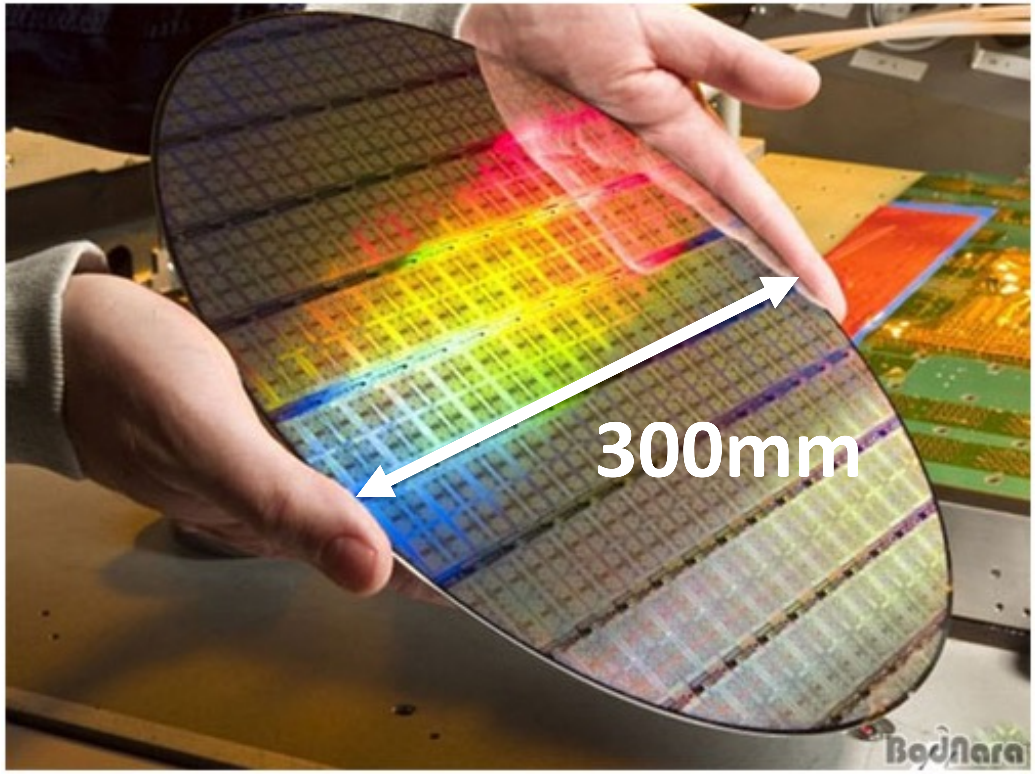
[intel]

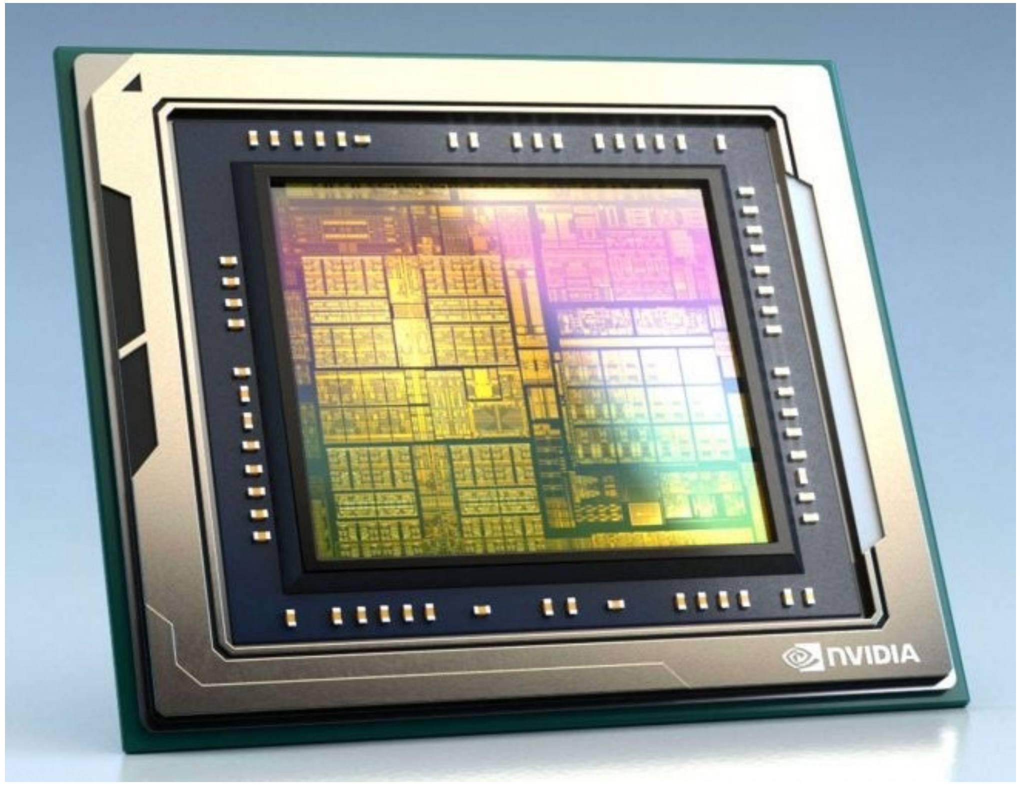
7nm Transistors by TSMC (2020)

Nvidia A100 GPU (7nm TSMC)

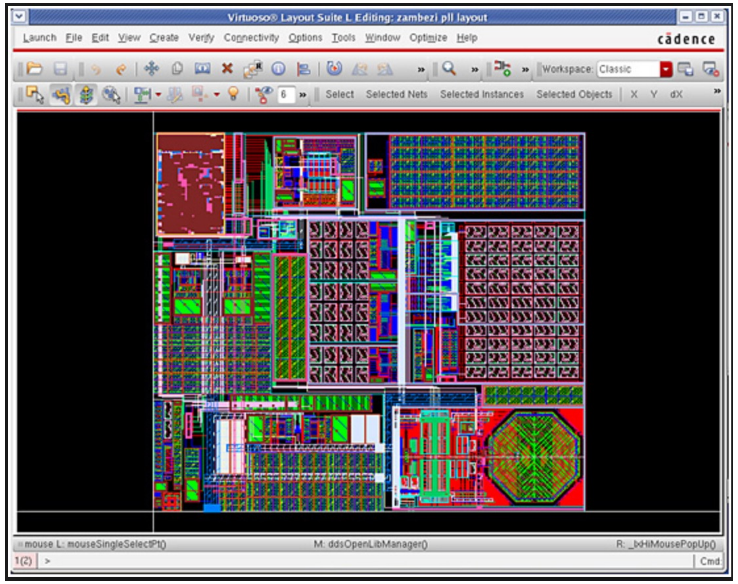
56 billion Transistors!

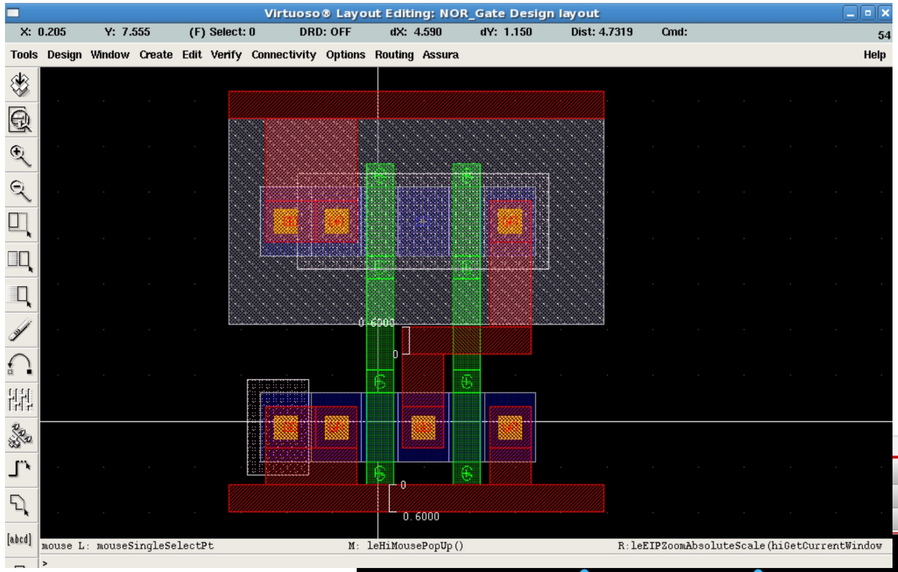
in 826mm^2

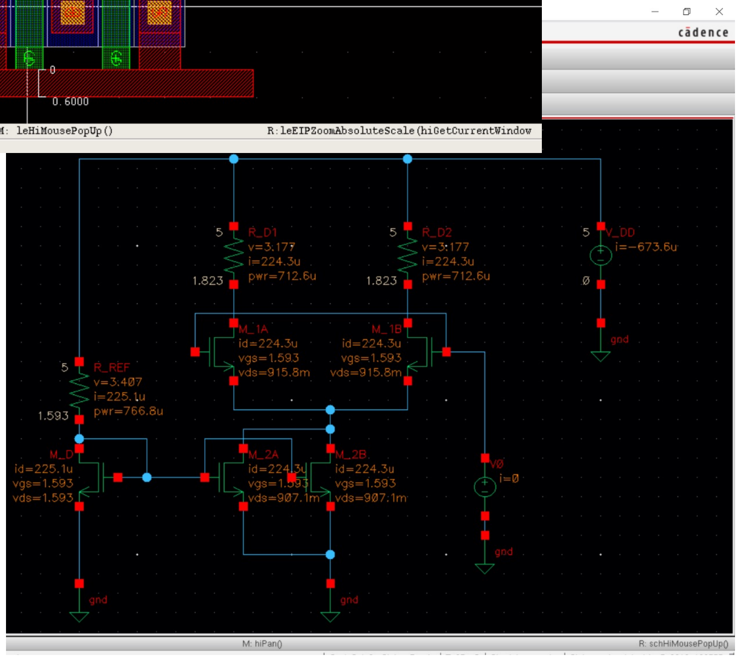




Cadence EDA/CAD Tools





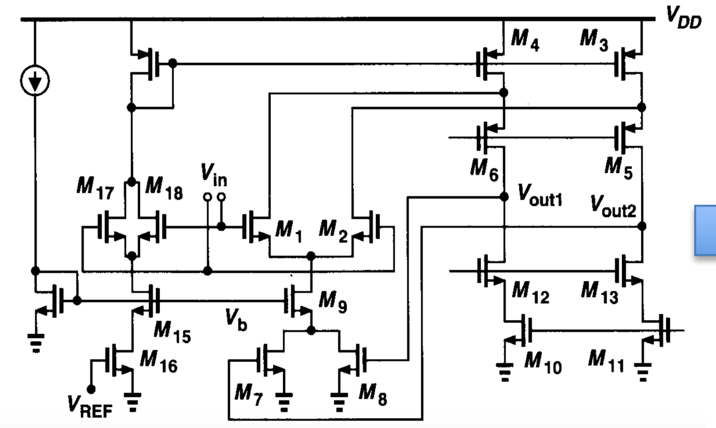


- Demand for automated design and simulation flows
- A collection of hundreds of tools for doing analog, digital mixed-signal, and RF design.
- You will learn how to use Cadence Virtuoso in this course ☺

Cadence EDA/CAD Tools

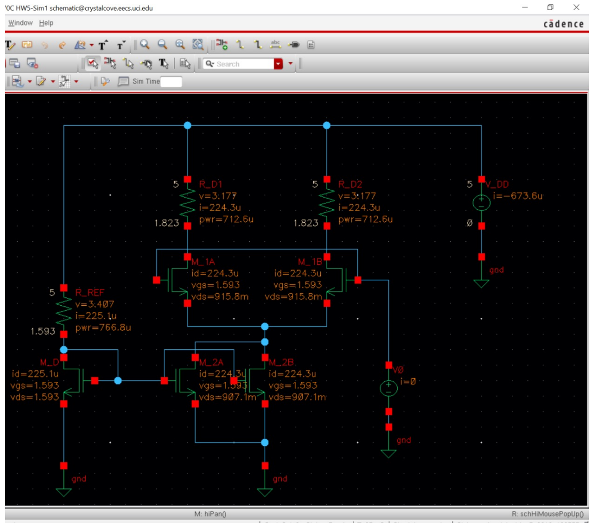
- ***Process Design Kit (PDK)*** provided by a foundry (TSMC, Intel, etc.)

Circuit Topology



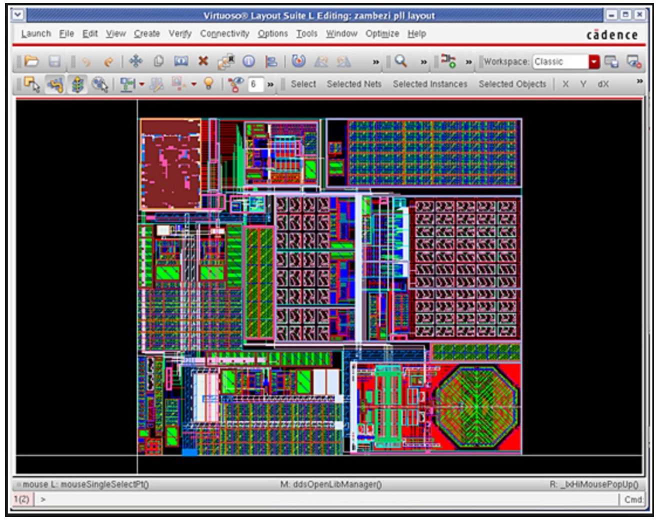
Example: Amplifier, filter, transmitter, receiver, …

Schematic



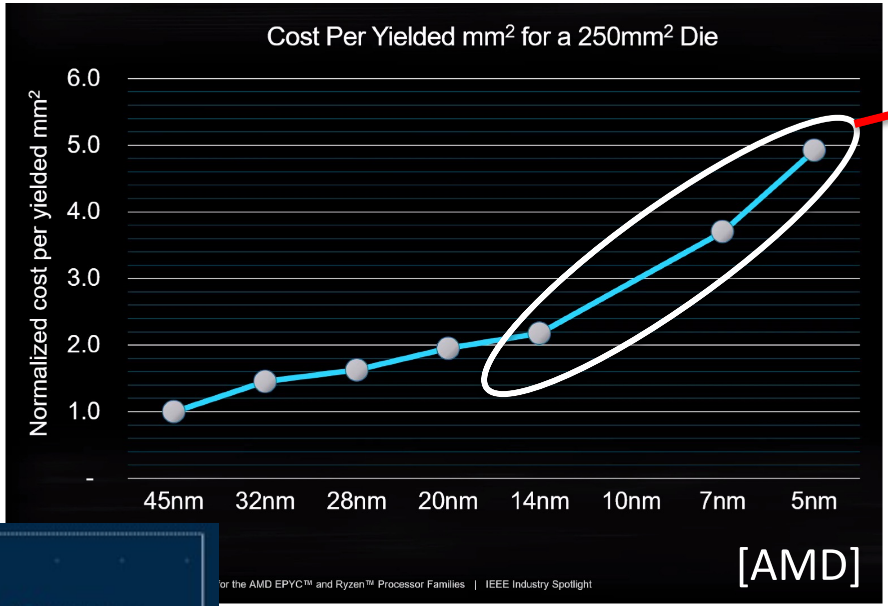
Check Bias Point
Simulations: AC, DC, …

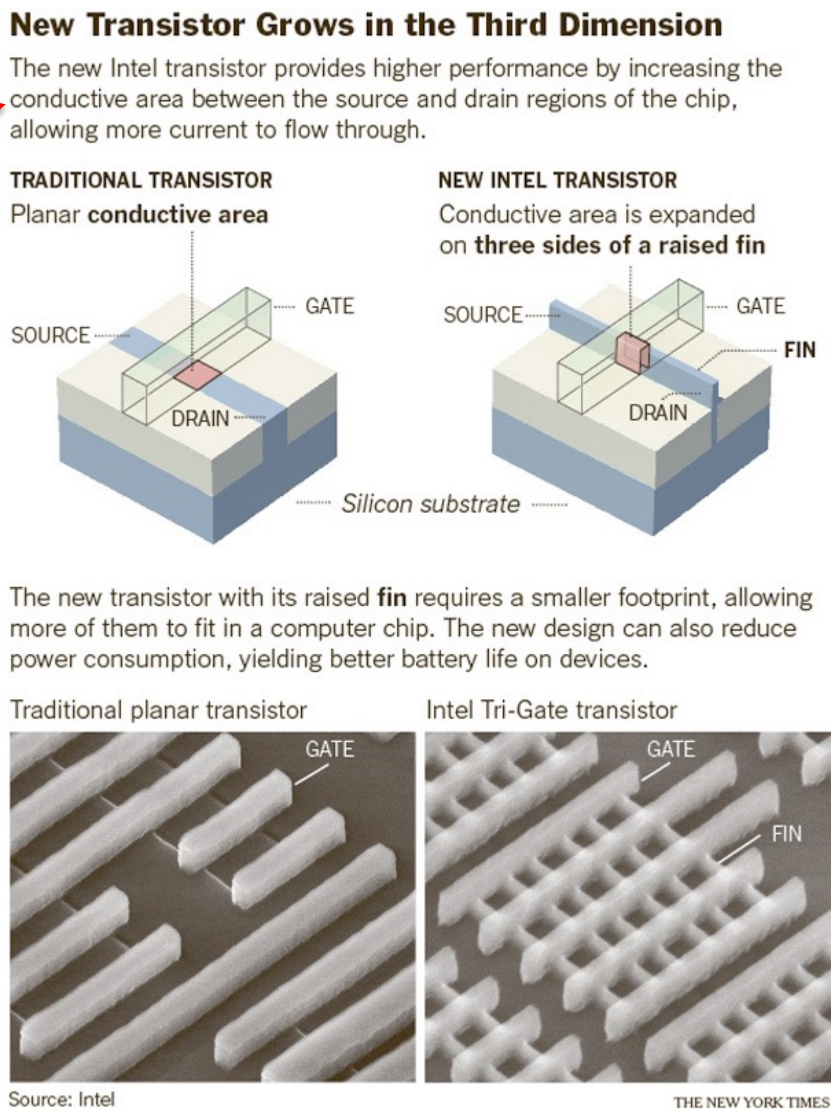
Layout



Layout vs. Schematic (LVS)
Design Rule Check (DRC)
Parasitic Extraction (PEX)
…

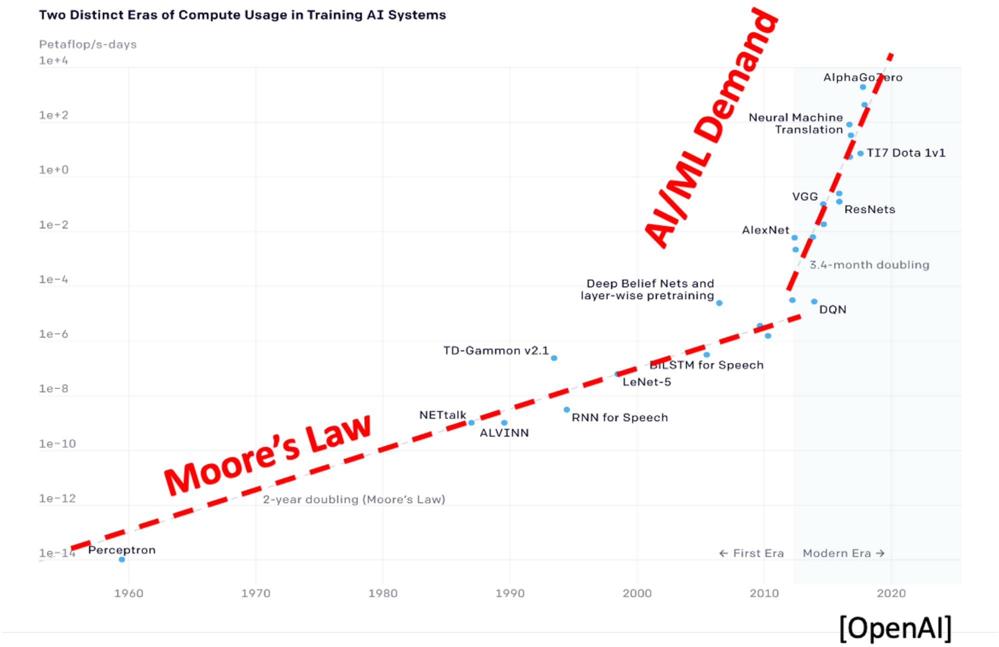
Moore's law slowing down!

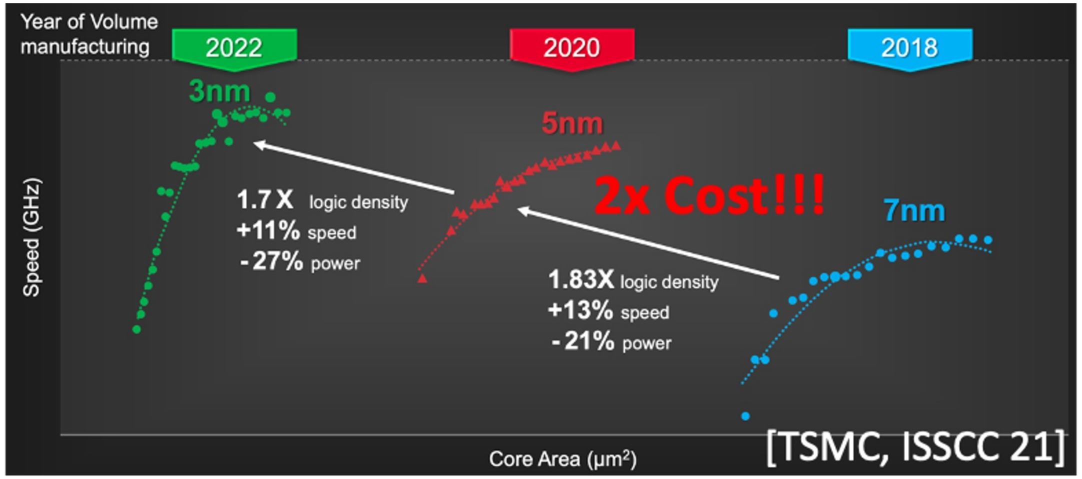




Beginning of a New Era in Circuit Design!

An inflection point in computing: The demand for performance has exploded….

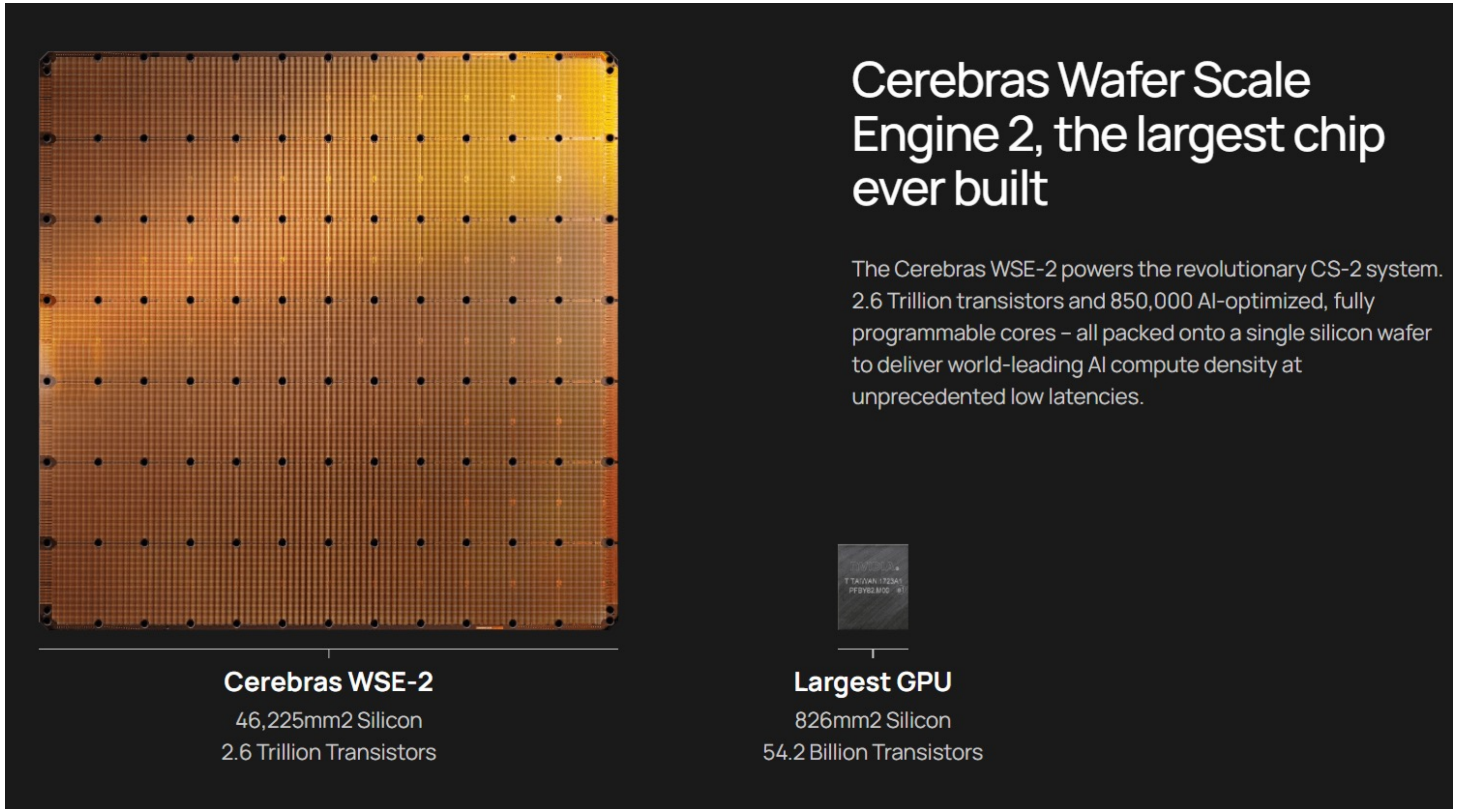


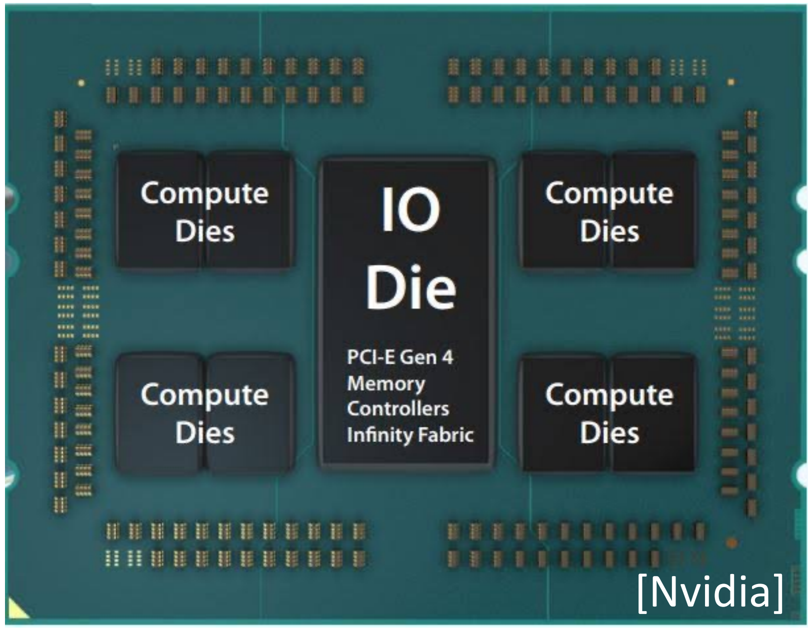


… and technology will no longer deliver alone

Novel paradigms in IC design/VLSI needed now more than ever before

New Trends in Chip Manufacturing



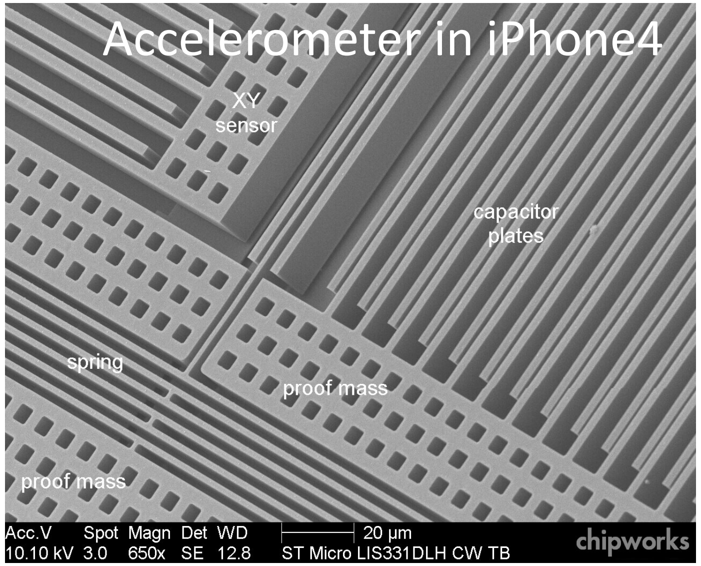


Chiplets, 3D stacking, Wafer-size chips, …

More-than-Moore Perspective

Enhanced CMOS enables new applications!

MEMS (Micro-Electro-Mechanical Systems)

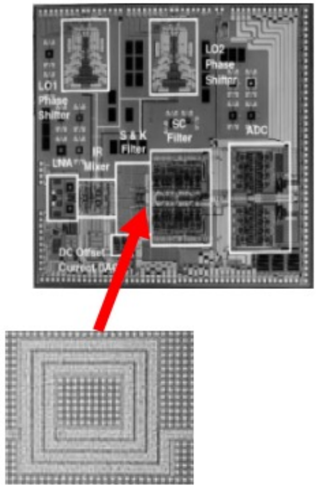


Accelerometers, pressure, chemical, gyroscopes, microphones, resonators, filters

mm-Waves & Photonics

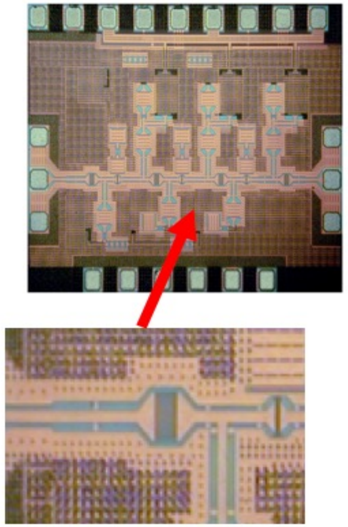
CMOS Radios

Rudell & Gray (1997)



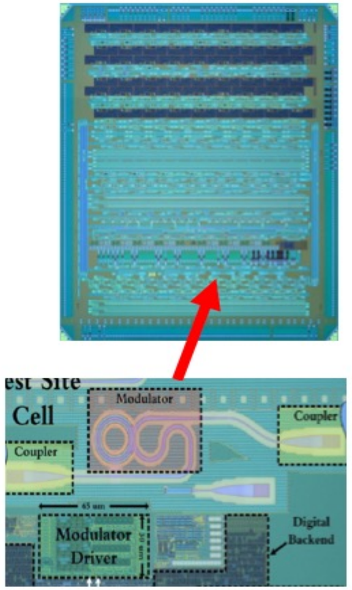
***mm*Wave CMOS Amplifier**

Niknejad & Brodersen (2004)

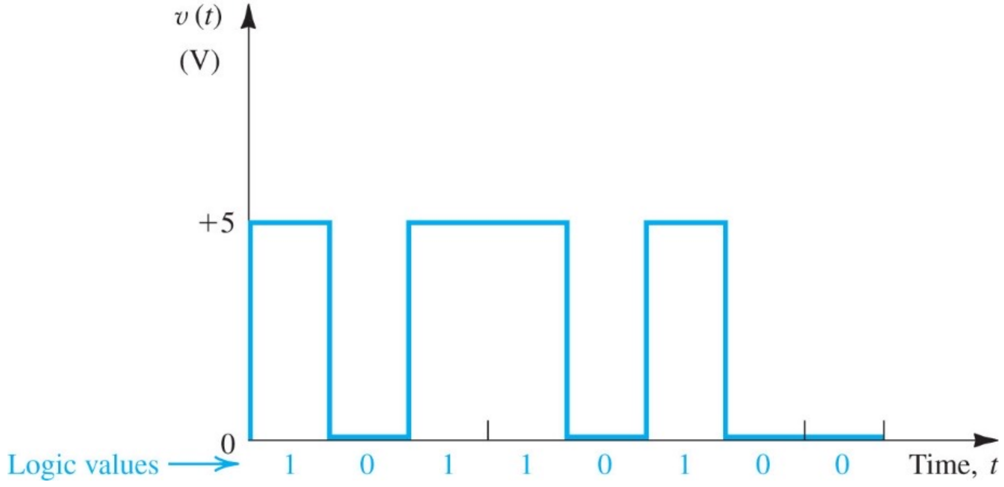


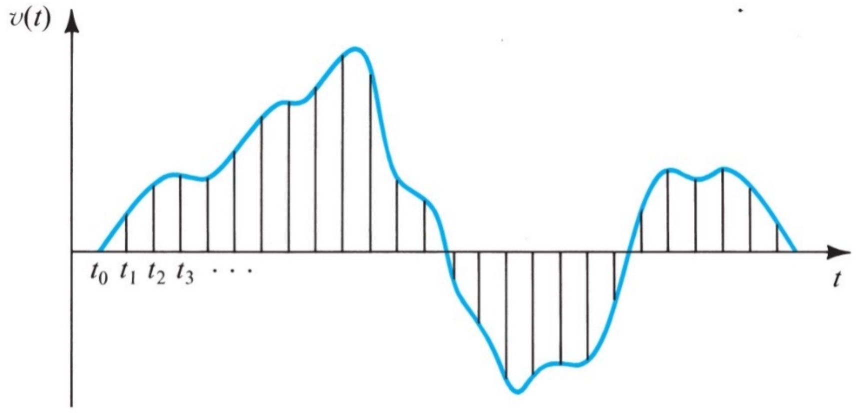
Optical Transmitters in CMOS

Stojanovic, Popovic, Ram (2012)



Digital vs. Analog





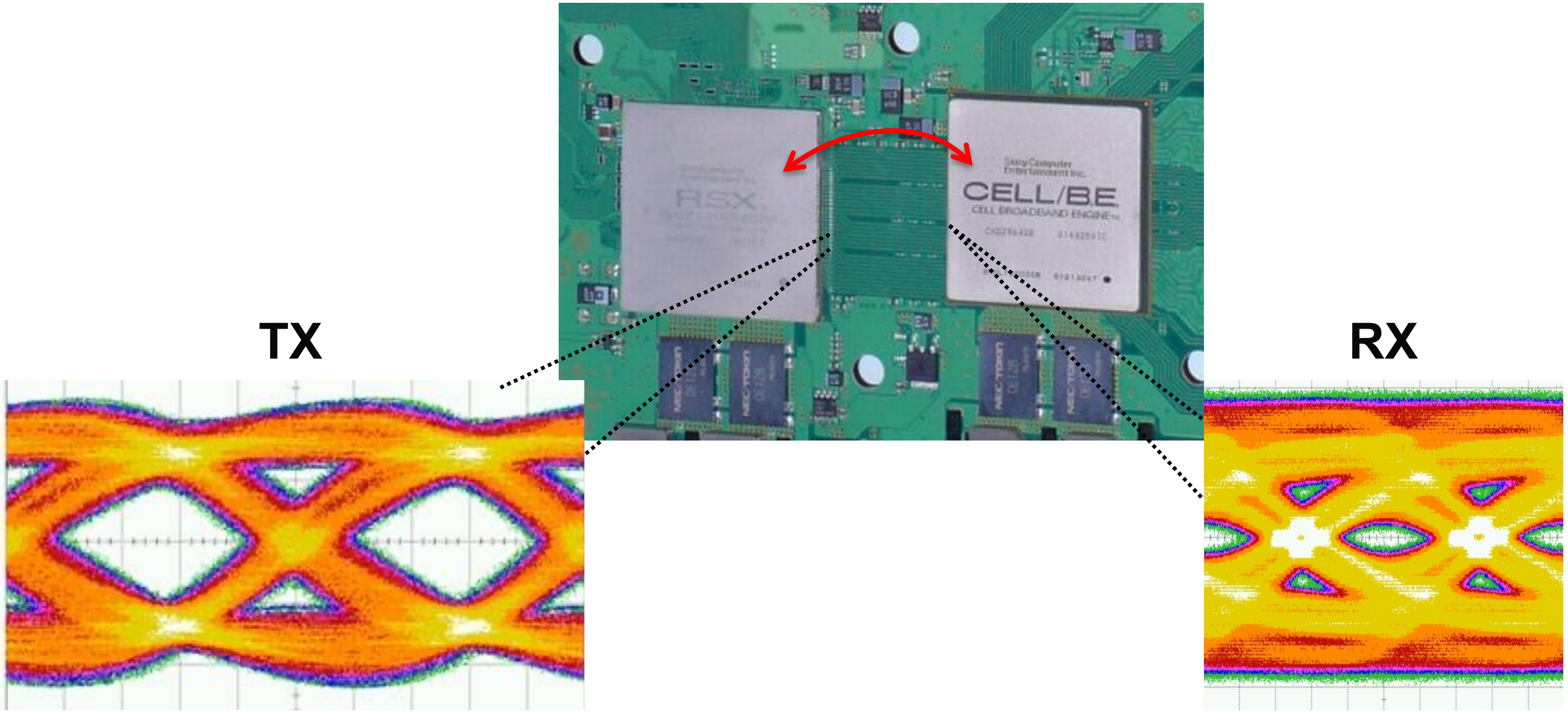
(a)

- Digital signals appear at discrete levels. Usually we use binary signals with two levels
- One level is referred to as logical 1 and logical 0 is assigned to the other level

- Analog electrical signals take on continuous values

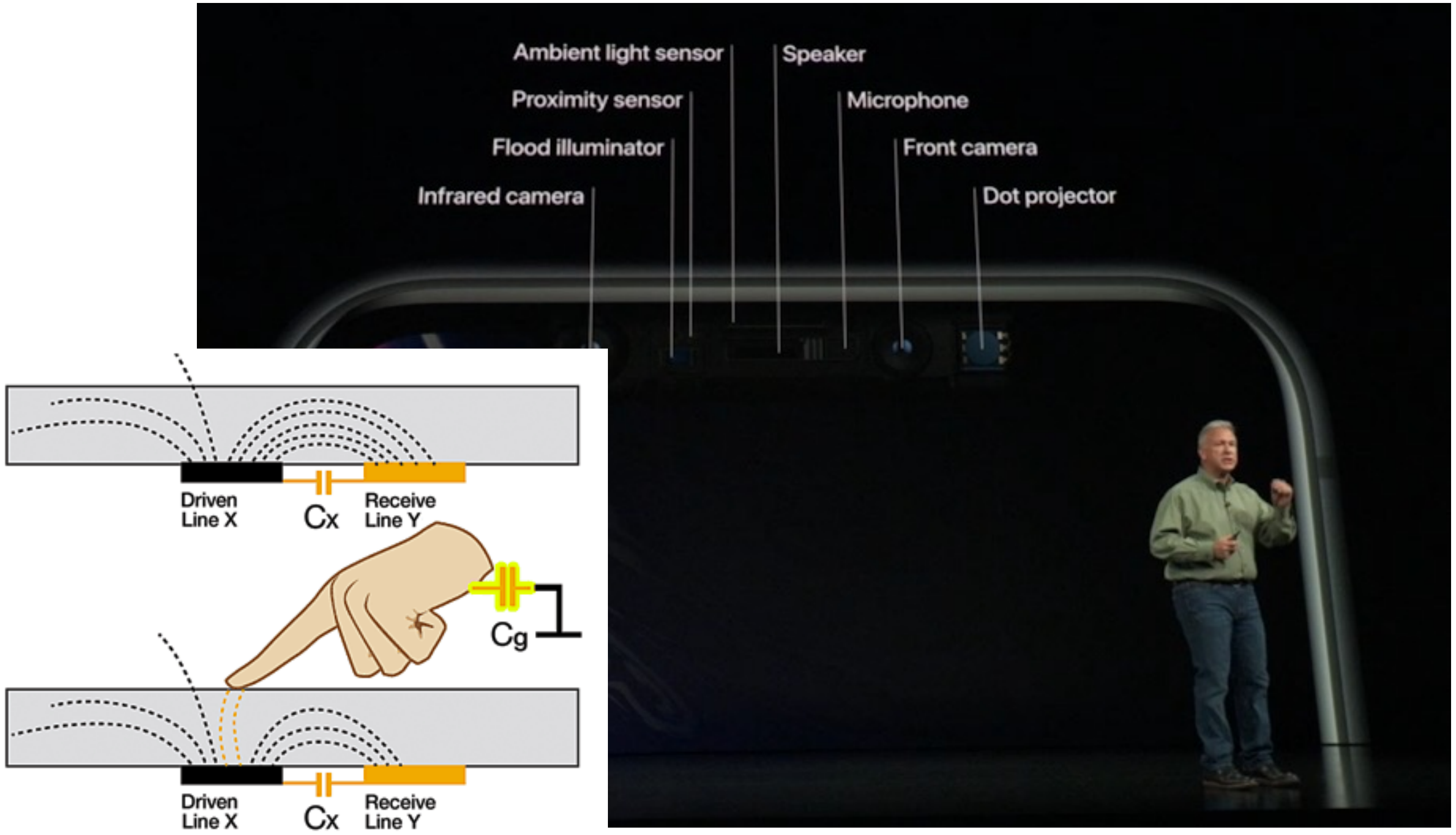
Why Analog?

- The "real" world is analog
  - Analog is required to interface to just about anything
  - Even to get two digital chips to talk to each other:



(Elad Alon)

Sensing



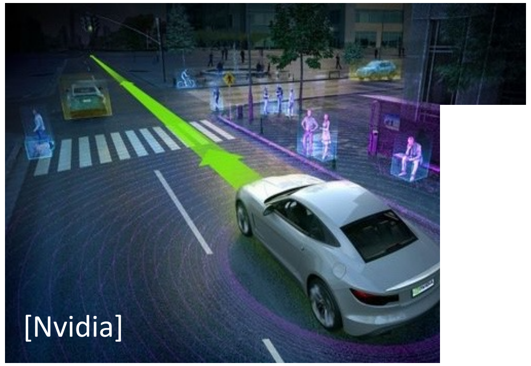
Similar to communications – analog needed for signal conditioning!

Sensors in a smartphone:

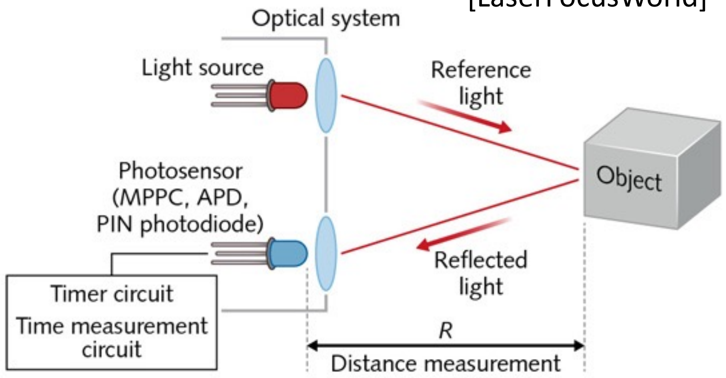
- 4 cameras!!!
- 9DoF motion sensing,
  - 3 axis accelerometer
  - 3 axis gyroscope
  - 3 axis compass
- 3 microphones,
- 2 image sensors,
- ambient light and proximity sensors,
- Touch screen sensor
- Finger print sensor
- Face recognition (IR camera)

Photonics

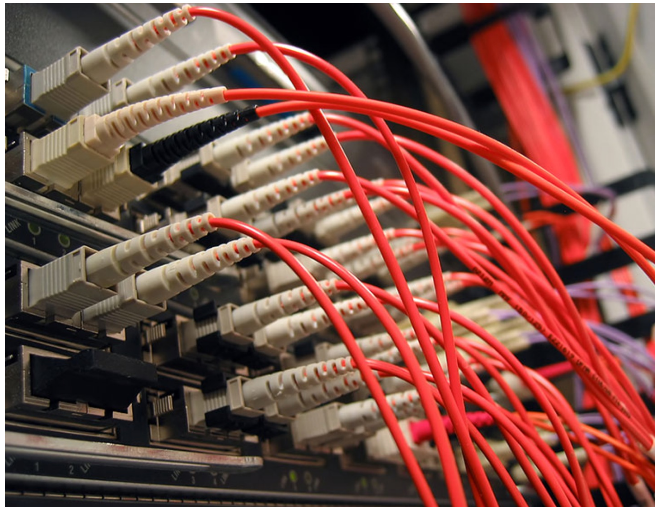
Ranging and Sensing (e.g. for self-driving cars)



[LaserFocusWorld]



Fiber optics (for Data-centers & Supercomputers)



- Photonic applications are becoming imminent everywhere
- Basis of photonics is similar to electronics (pn-junctions, Si-based devices, etc.)
- Analog electronics are essential for photonics: TIA, amplifiers, PLL, etc.
  - This is also true for a variety of new emerging devices like Ultrasound transducers, Memristors, etc. (interface is always analog!)

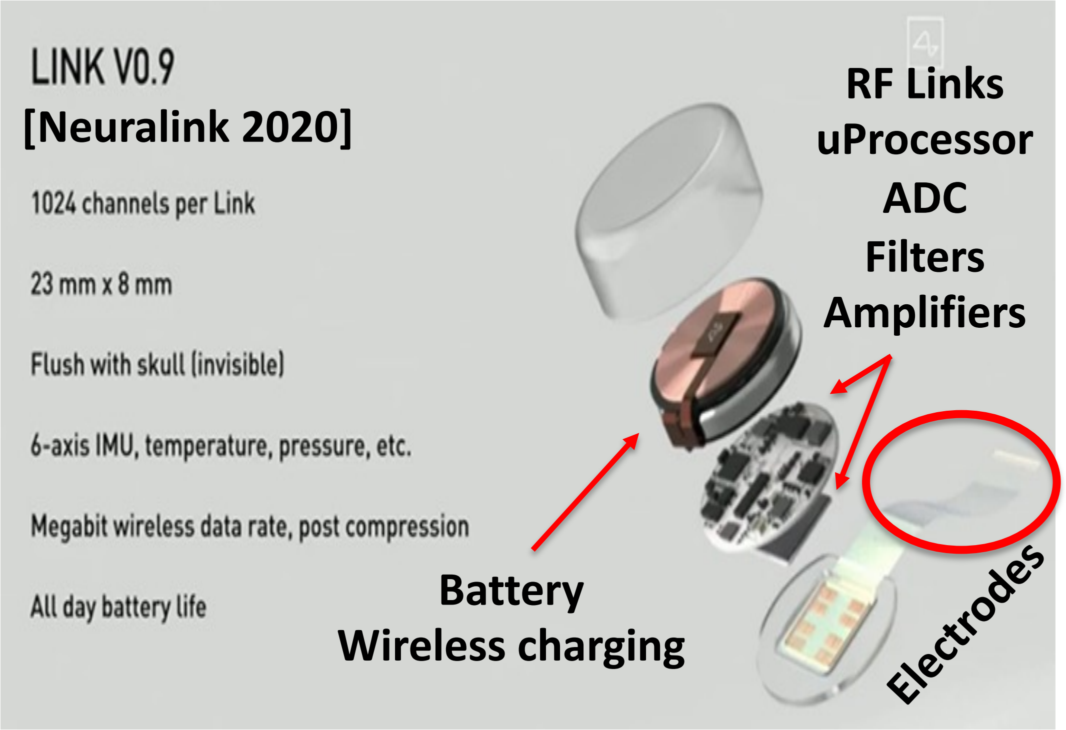
Medical Electronics

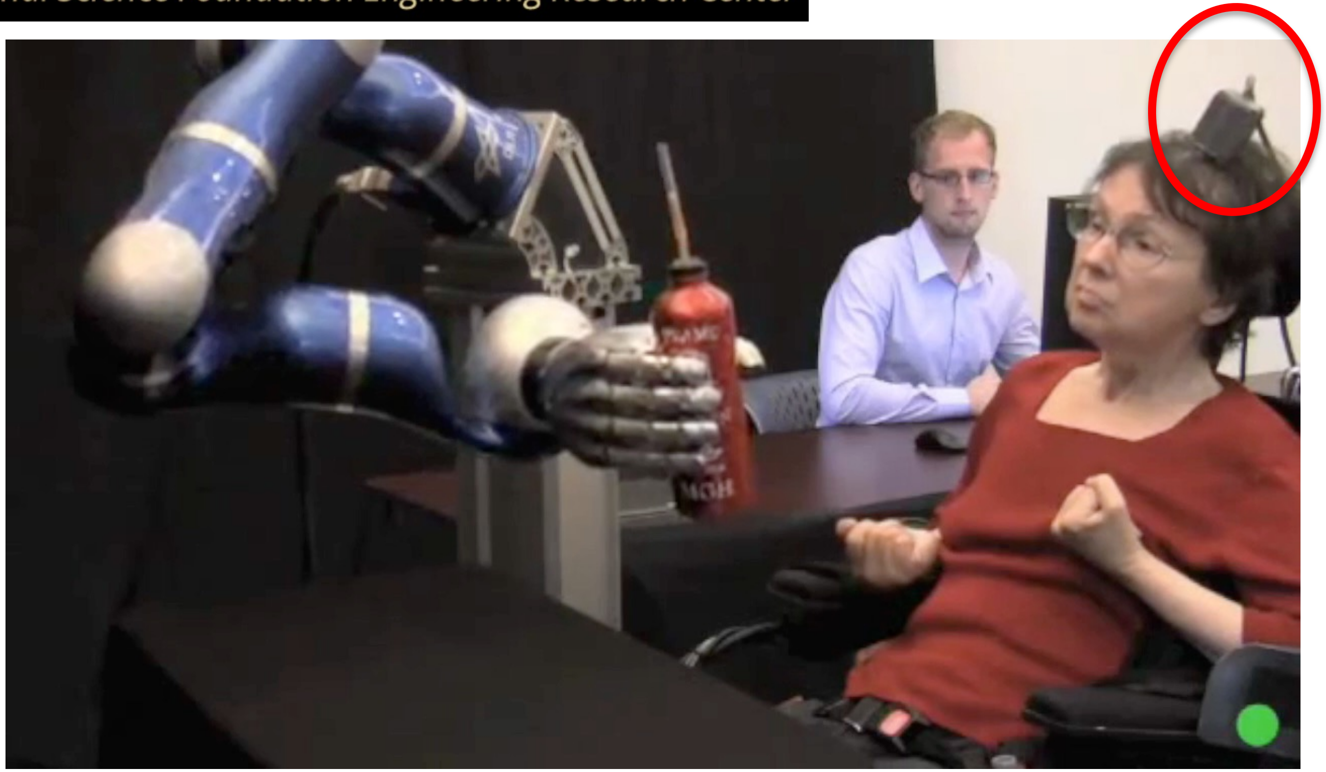
- Two commonly used devices to monitor patient health are Electrocardiogram (ECG) and Blood Oximetry (SpO2) sensors
- ECG uses a bunch of op-amps to amplify a weak signal that can be used to diagnose the health of the heart
- SpO2 uses light / infrared diodes and photosensors + interface electronics to measure blood oxygen levels

ELECTRICAL & COMPUTER ENGINEERING

Brain-Machine Interfaces

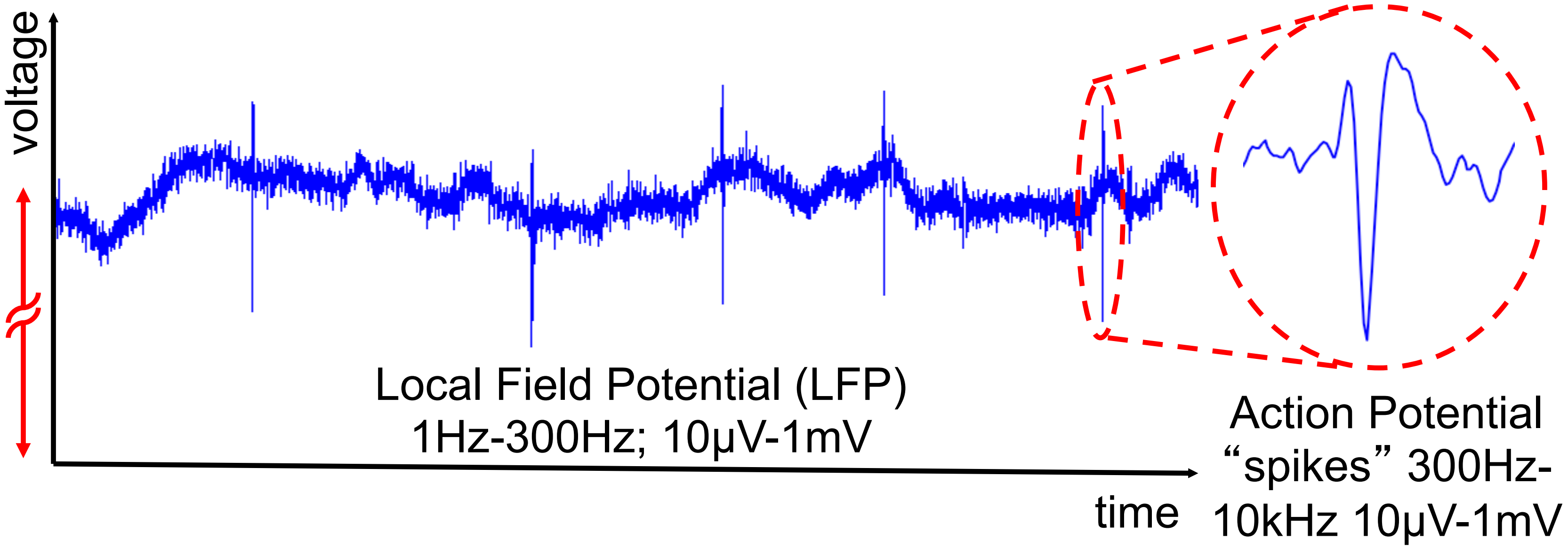
CENTER *for*
NEUROTECHNOLOGY
a National Science Foundation Engineering Research Center





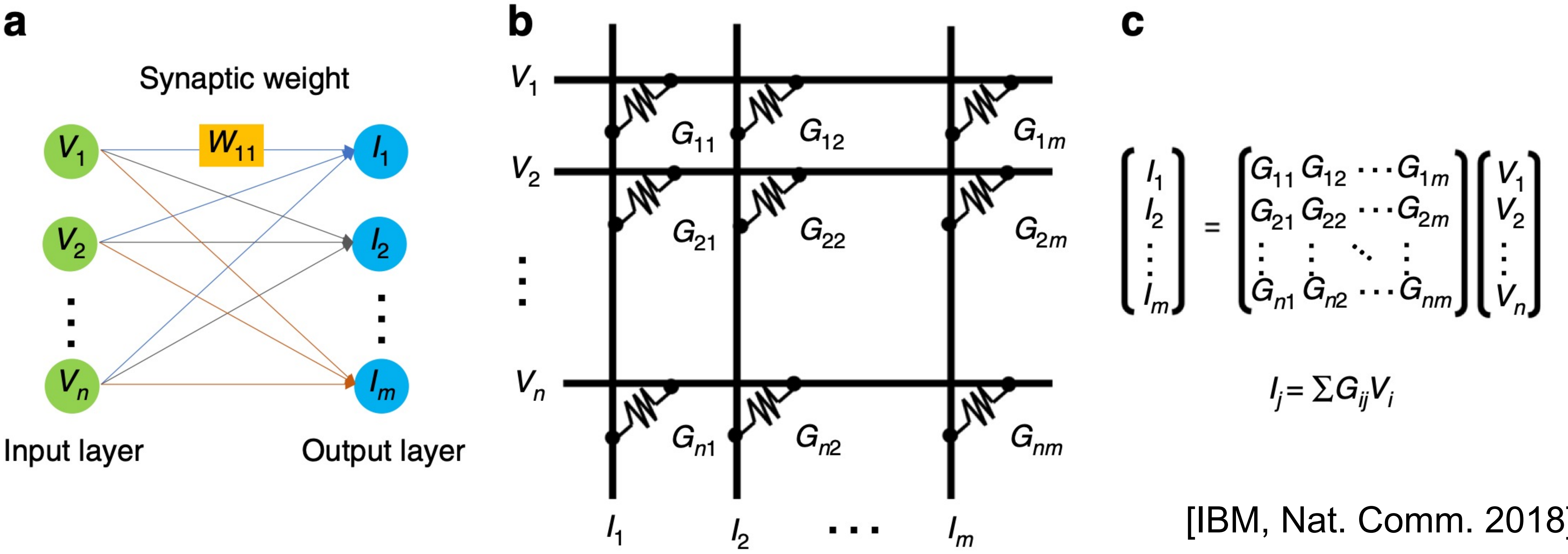
Source: Hochberg et al., *Nature* ‘12

Brain-Machine Interfaces



- Similar to ECG, the goal of a brain-machine interface is to record the small-amplitude neural signals and pick out the meaningful signals from the “noise”.
- These signals are then decoded to create trajectories, movements, and speeds for controlling prostheses, computers, etc.

Neuromorphic Analog Computing



[IBM, Nat. Comm. 2018]

- Using Ohm's law and current summation for Matrix-Vector Multiplication!
- Memristor-based Cross-bar: MRAM, RRAM, SRAM, "Analog-cells", …
- Energy-efficient but low-speed and low-precision (for edge-computing)

What You Learned in EE 331

- Semiconductors
  - P/N Doping
  - Drift/Diffusion Currents
- PN Junctions
- Diode circuits (e.g. Rectifier, etc.)
- MOSCAPs & MOSFETs
  - NMOS & PMOS Basics
- CMOS Logic
  - Noise margin
  - Dynamic Power
  - NOT/NAND/NOR

Device Physics

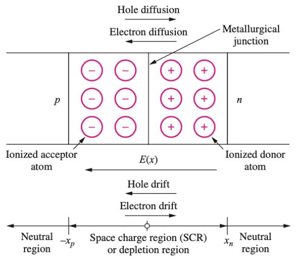


Figure 3.4 Space charge region formation near the metallurgical junction.

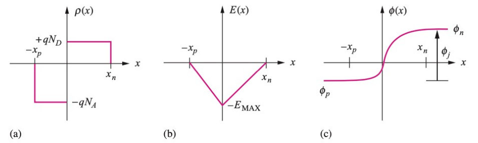
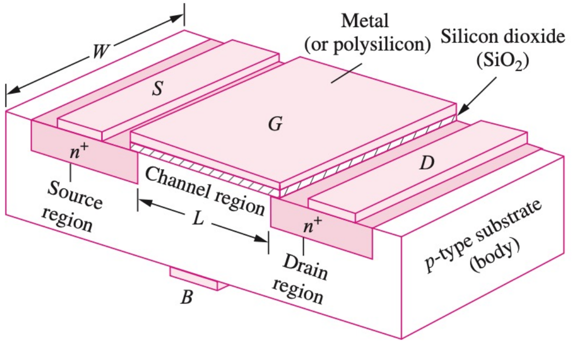


Figure 3.5 (a) Charge density (C/cm^3), (b) electric field (V/cm), and (c) electrostatic potential (V) in the space charge region of a *pn* junction.



Circuits & Systems

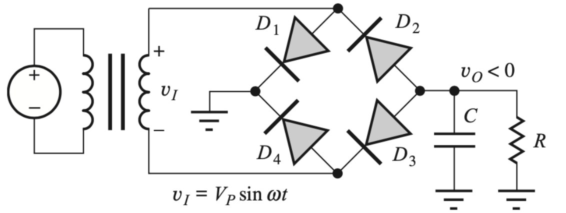
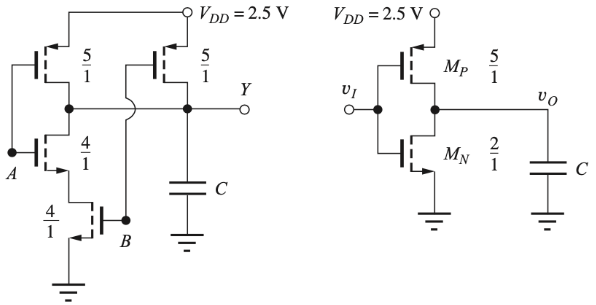


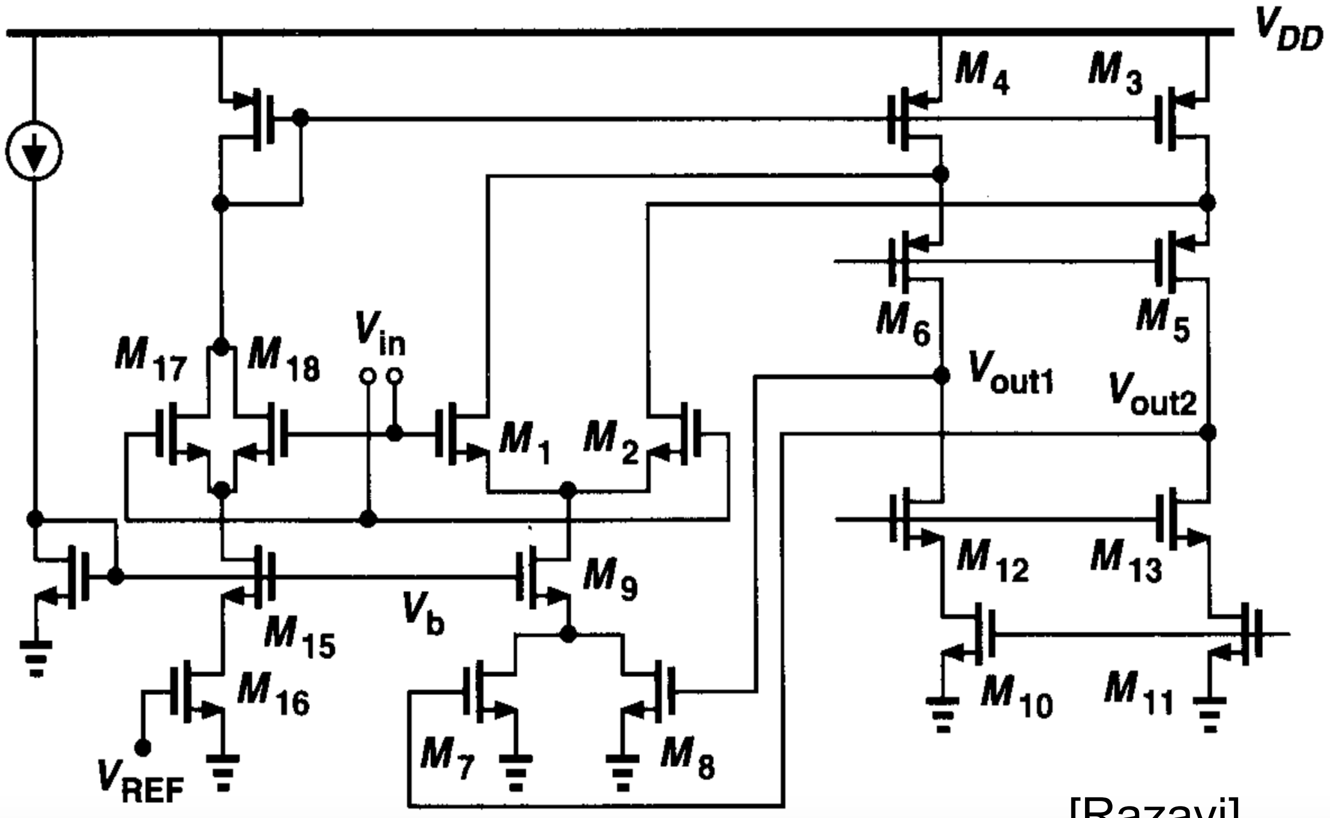
Figure 3.66 Full-wave bridge rectifier circuit with $v_O < 0$.



[From Jaeger's textbook]

What You Will Learn in EE 332

- MOS basics and modeling
- Single-stage Amp
- Frequency response
- Differential Signaling
- Noise
- Feedback
- OpAmps
- + Cadence software



[Razavi]

Although we focus on amplifiers mostly, methods and techniques are the foundations for any integrated circuit/system design!

ELECTRICAL & COMPUTER ENGINEERING