23. Future Directions

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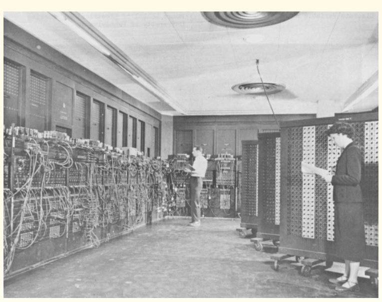
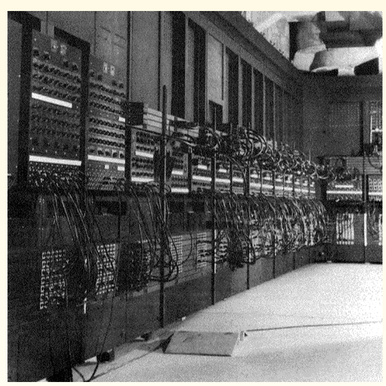
VLSI Design
Fall 2020

November 19, 2020

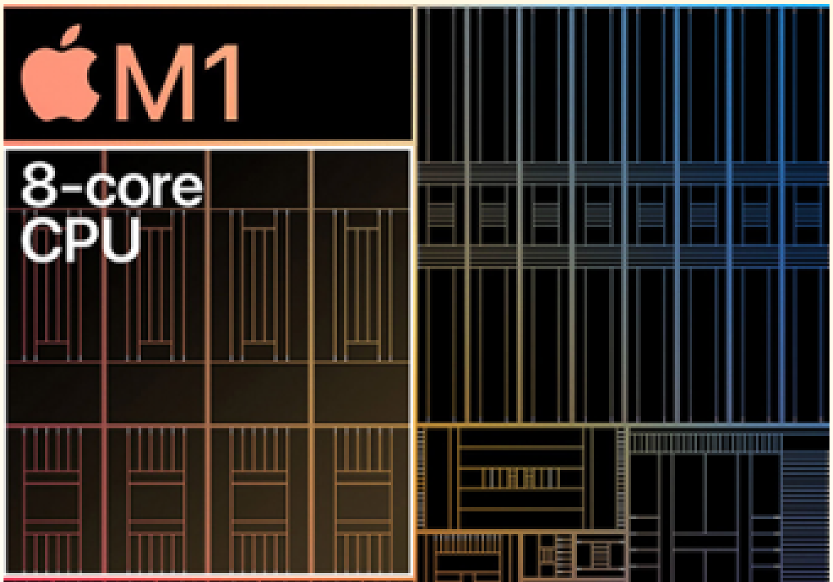
From (Physically) BIG Computers . . .

ENIAC

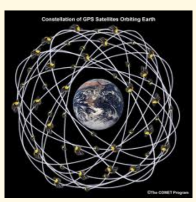




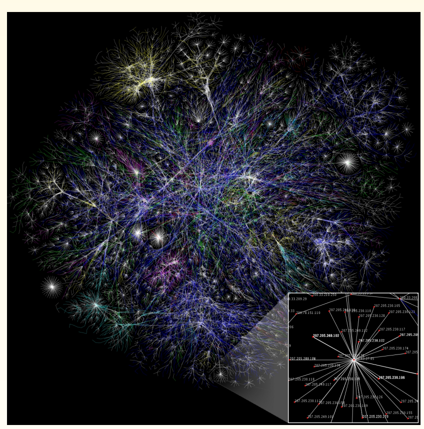
. . . to Multicore Chips



Integrated Circuits are Everywhere



Orbits of GPS satellites
(source: http://www.eumetsat.int/)



Internet map
(source: Wikipedia)

Embedded Systems

Myriad of Intelligent systems

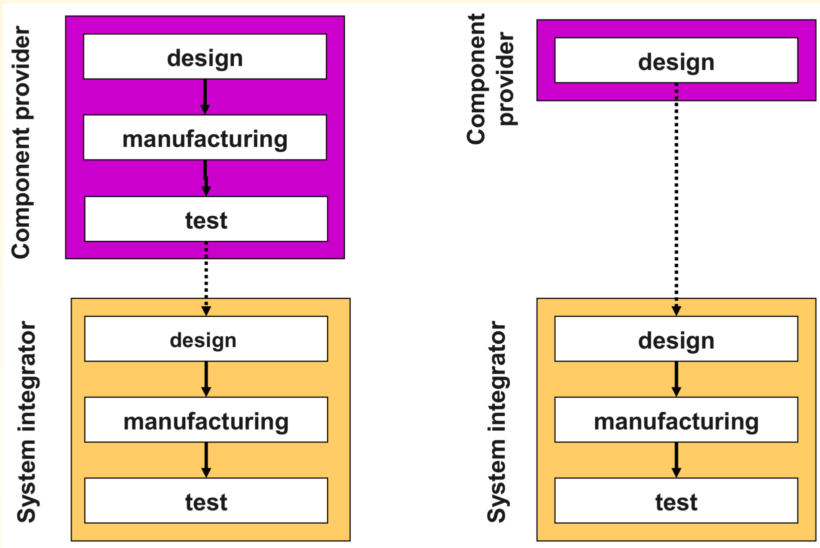
- Cost, power consumption constraints
- In critical applications, **resiliency** is very important

Example: self-driving cars

- 100 Million lines of code for software, sensing and actuation
- 64 TOPS for cognition and control functions

Smart Homes

System-in-Package (SiP) vs. System-on-Chip (SoC)



SiP SoC

Developing a System-on-Chip

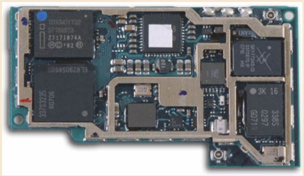
- Application requirements
- Software, hardware (function) partitions
- Select processor cores
  - ARM, MIPS, Tensilica, DSP
- Memory and interfaces
  - DRAM, SRAM, Flash, Rambus, etc.
- System interfaces
  - USB, PCI, PCMCIA, Ethernet, 802.11, Firewire, Bluetooth, etc.
- Glue ASICs

Characteristics of Building Blocks

- VLSI design involves the implementation of complex functions using simple building blocks
  - Logic building blocks
  - Analog transfer characteristics
  - Composition
- **We should be able to deal with other types of building blocks**
  - **For example, the theory developed for relay computers is applicable to CMOS transistors**

Hierarchically compose building blocks

- Systems include hardware and software



Apple iPhone board

Test and Verification are Still Problems

State-space explosion

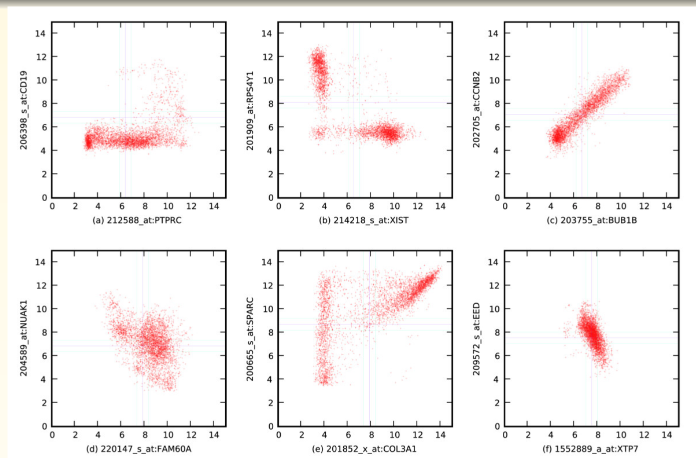
- Need to check a very large number of states to find a system-level test or to uncover a bug
- Even combinational equivalence checking NP-complete

Problem: the number of protons in the universe is around 10^{80}, which is less than the number of states for a system with 300 storage elements!

Hubble photo of Coma Cluster:

thousands of galaxies in a spherical shape 20 million light years across

Application of Verification Engine: Finding "Implications" in DNA Sequences

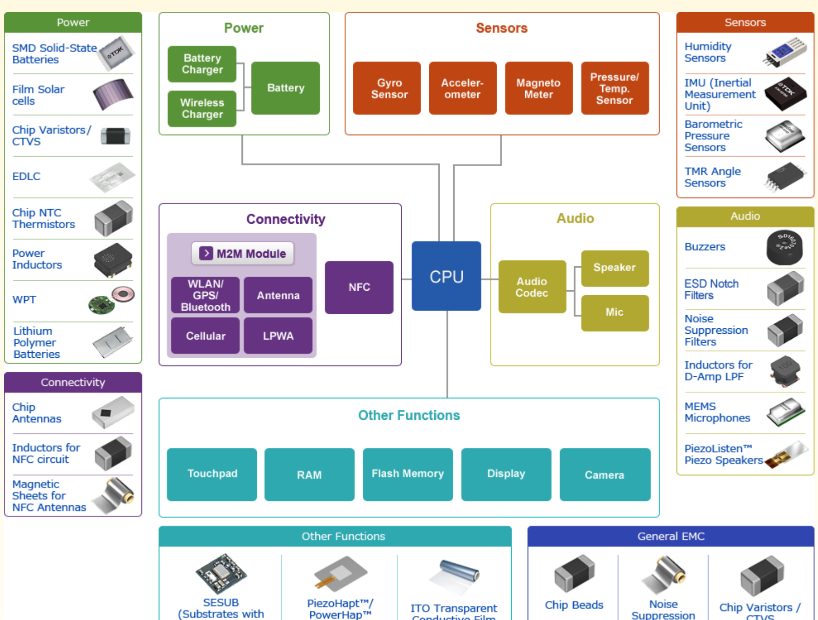


Six different types of Boolean relationships between pairs of genes taken from the Affymetrix U133 Plus 2.0 human dataset

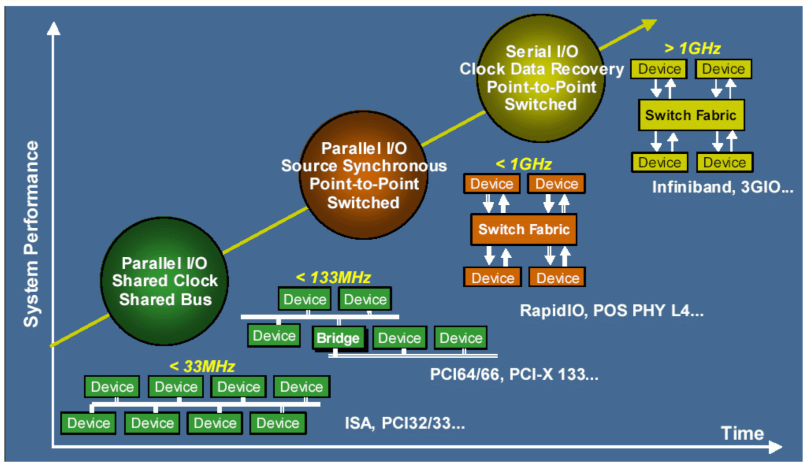
The two axes correspond to the expression levels of two genes

Source: Sahoo et al., Genome Biology 2008

Internet of Things (IOT)



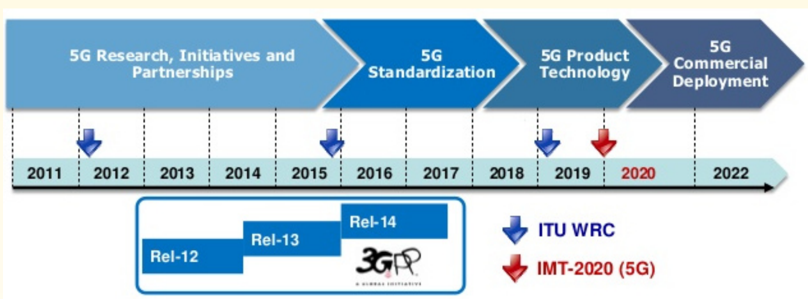
Serial Connectivity Trends



Source: Xilinx

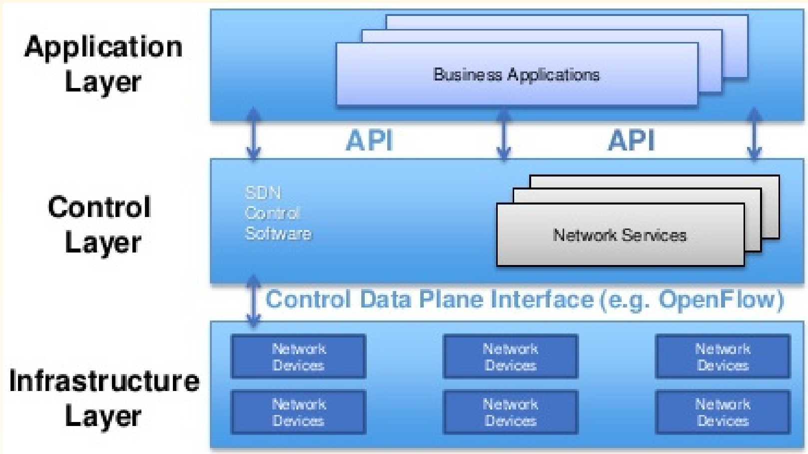
Communications Technology

5G Expected Timeline



Source: cpqd.com

Software Defined Networks (SDN)



Source: Citrix

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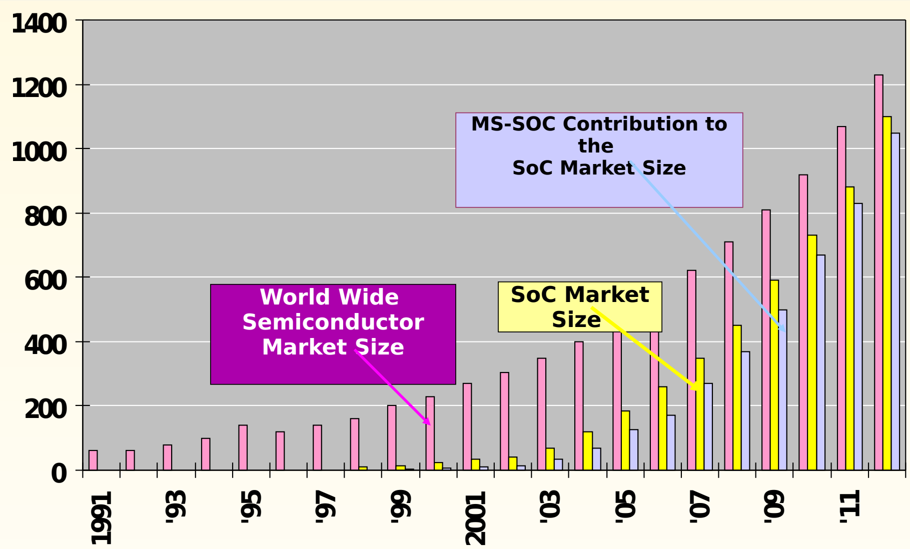
The World is not all Digital: System-on-Chip Market Size ($ Billions)



SONY Corp & Market Estimates

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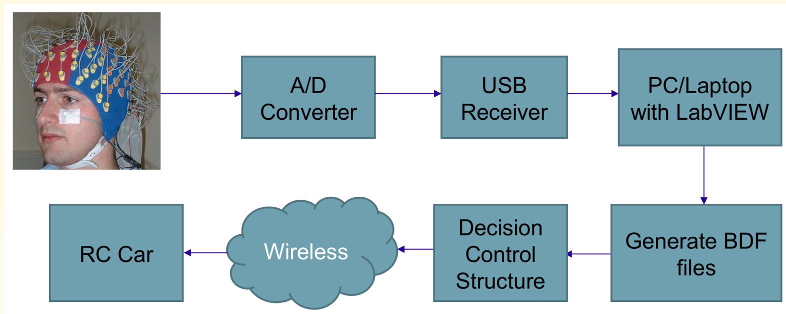
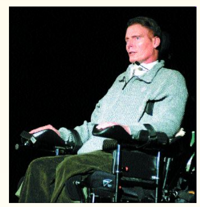
Thought Control





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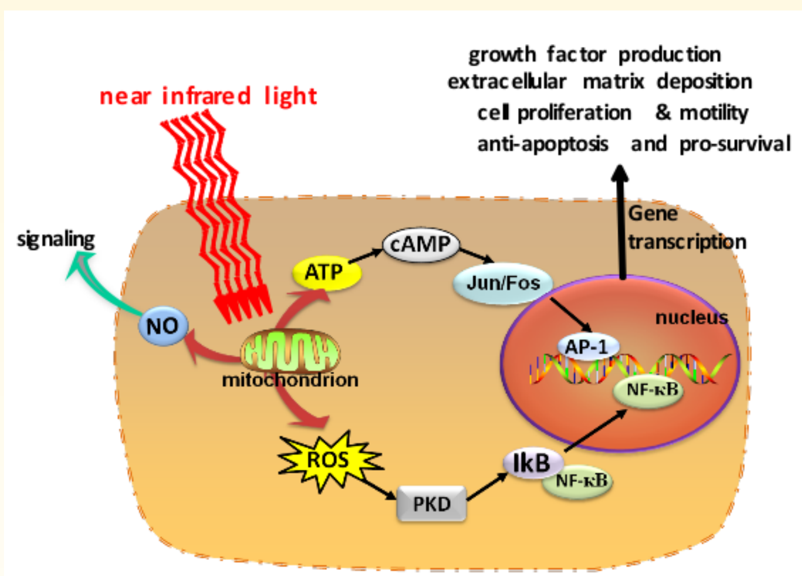
Near-Infrared Light (NIR) and Cellular Pathways



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In-Vivo Transcranial Laser Stimulation

Laser Impact on the Brain

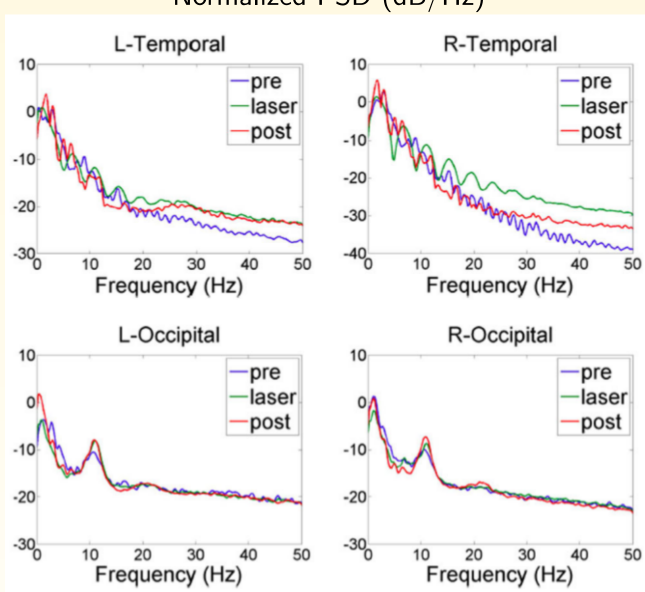
- Monochromatic light in the near-infrared wavelengths
- Modulates brain function
- Produces neurotherapeutic effects in a non-destructive and non-thermal manner

Mechanism of Low-Level Light Therapy (LLLT or 3LT

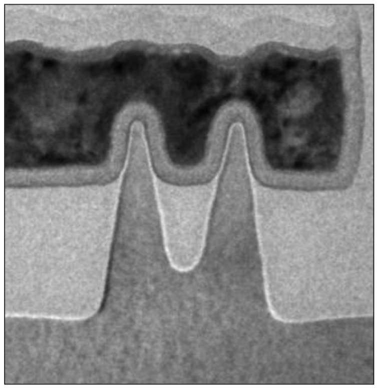
- Based on bioenegertics (fundamentally different from electric or magnetic stimulation
- LLLT modulates the function of neurons
- Involves the absorption of photons by specific molecules in neurons
- Part of the mitochondrial respiratory enzyme *cytochrome oxidase*

Effect of Stimulation on EEG Power Spectral Density

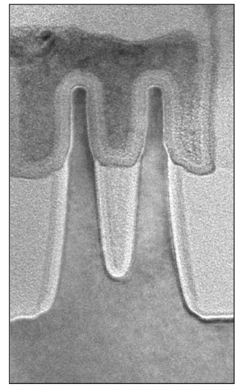
Normalized PSD (dB/Hz)



Second Generation FinFET (Tri-Gate) Transistors



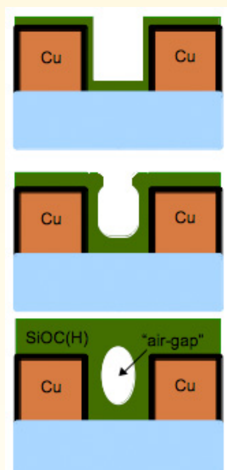
22 nm 1st Generation Tri-gate Transistor



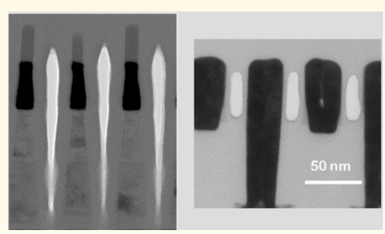
14 nm 2nd Generation Tri-gate Transistor

Source: Intel

Air Gaps in Low-K Dielectric Materials



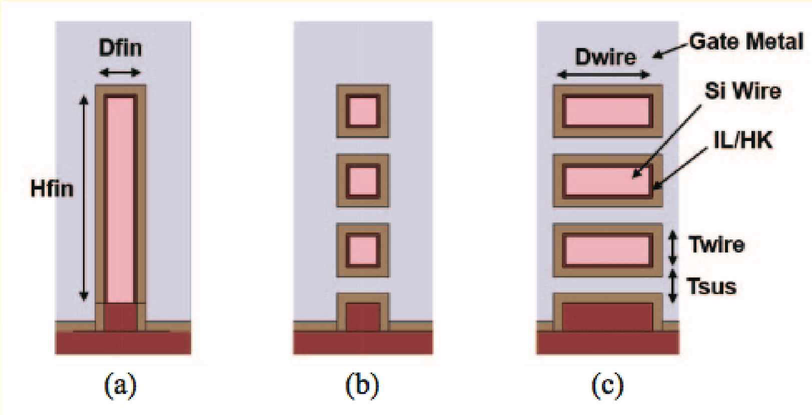
Intel 22nm Transistor



Intel/Micron 25nm NAND Flash technology

Source: Intel/Micron

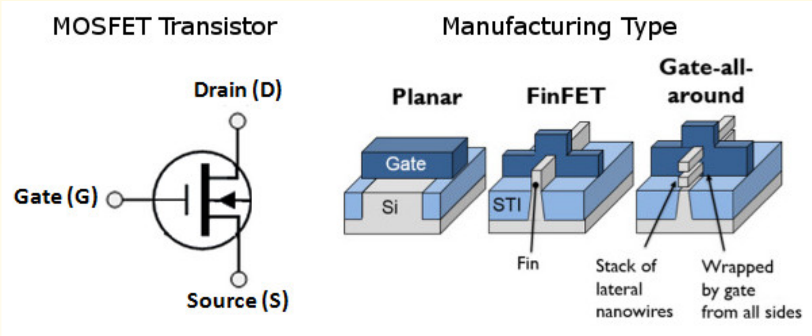
Possible Future Transistors



(a) FinFET (b) Nanowire (c) Nanosheet

Source: IBM

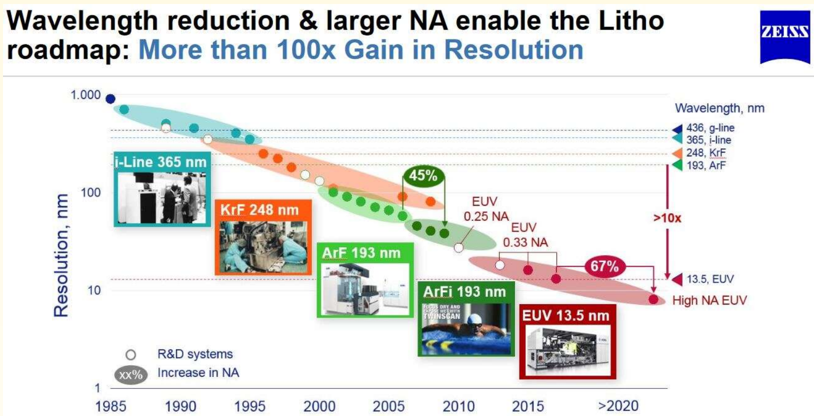
Gate All Around (GAA) Transistors



(STI: Shallow Trench Isolation)

Source: androidauthority.com

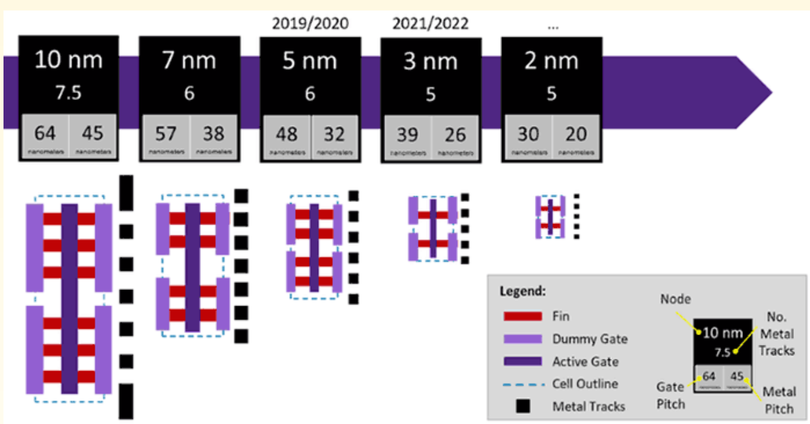
Next Generation Manufacturing – Extreme Ultra-Violet Lithography



(NA: Numerical Aperture)

Source: Zeiss

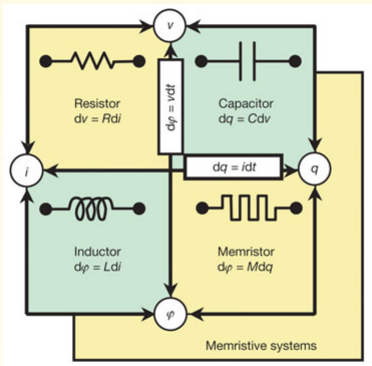
Projected Technology Nodes (TSMC)

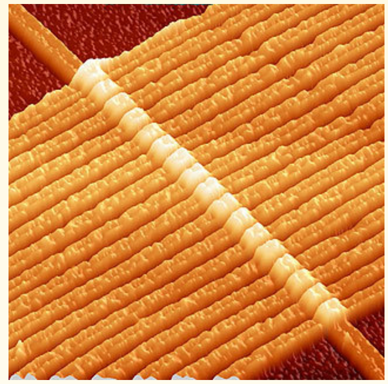


TSMC plans on using FinFET transistors for its 3nm mode before switching to GAAFET (gate all around) for 2nm chips (A. Friedman, Oct. 2020)

Source (figure): M. Tyson, Hexus, June 13, 2019

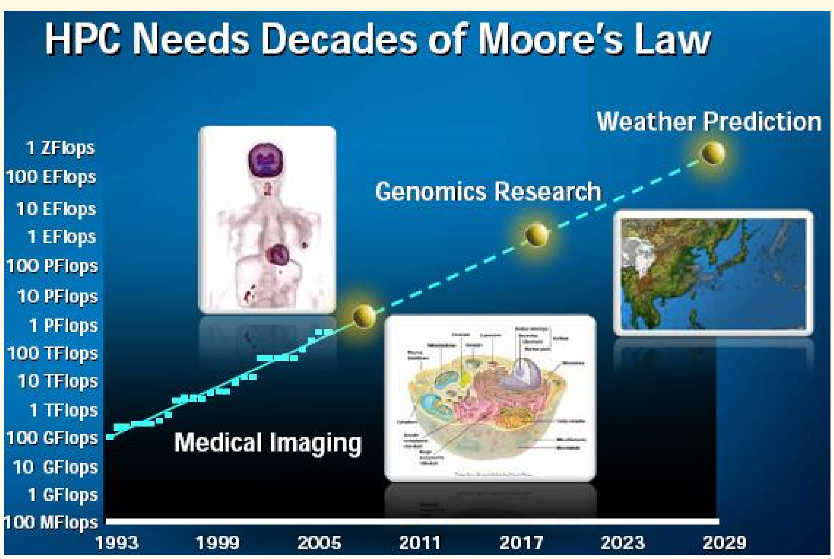
Resistive RAM – RRAM (Memristors)



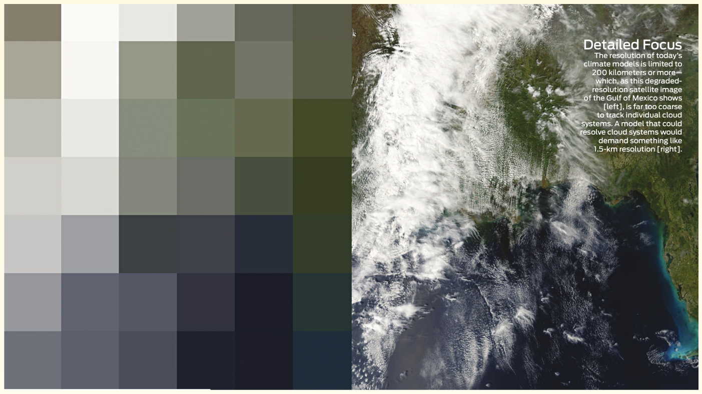


Atomic force microscope images of 17 HP Labs non-linear devices in a row, each a pair of oxide layers between the single bottom wire and one of the top wires

Applications Which Will Require Bigger Computers



Climate Modeling Requirements

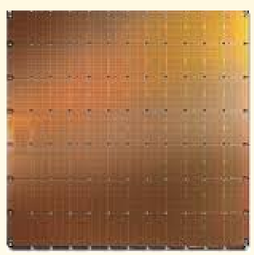


Resolution: 200 km Resolution: 1.5 km

Source: Wehner et al., IEEE Spectrum, October 2009

Processor	Clock Speed	GFlops/Core	Cores	Power
AMD Opteron	2.8 GHz	5.6	1,700,000	179MW
Tensilica LX2	500MHz	1	10,000,000	3MW

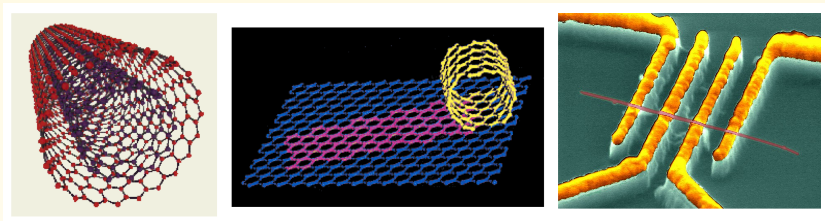
Wafer-Scale AI Chip – Cerebras



Physical Dimensions: limited by 300 mm wafer

- TSMC 7 nm technology
- 1.2 Trillion transistors (redundancy to deal with defects)
- 400,000 AI compute cores
- As a comparison, Joule supercomputer has 84000 CPU cores, and consumes 450 KW of power
- Cerebras CS-1 uses 20 KW of power

Carbon Nanotubes

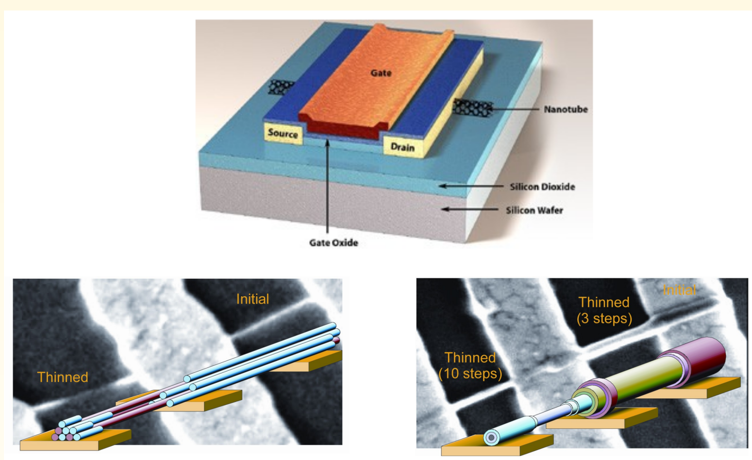


Carbon nanotubes are around 1 nm in diameter

Much stronger than steel, flexible

Can possibly conduct 10^9 A/cm^2

Carbon Nanotube Transistor

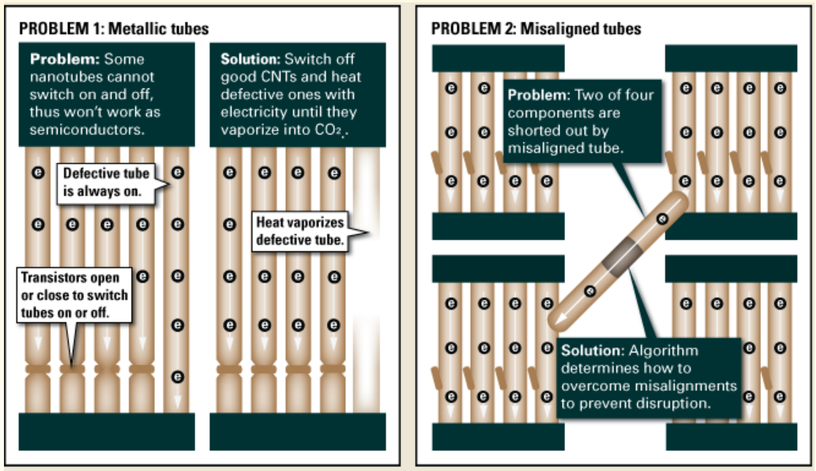


Source: IBM

Self-assembly techniques (proposals include use of DNA)

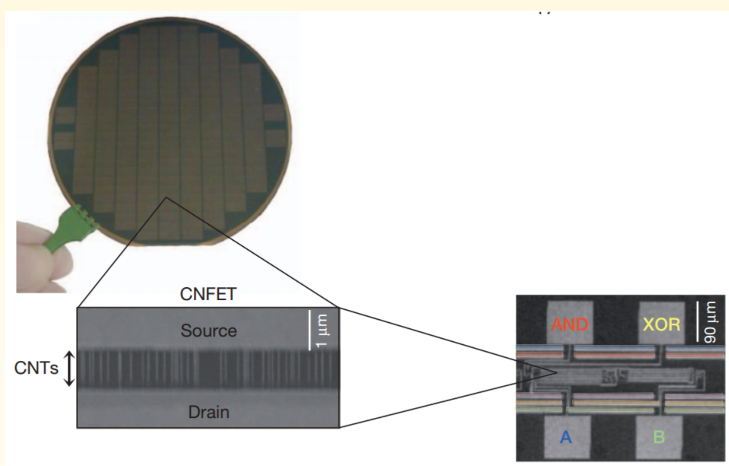
Good success with liftoff techniques

Implementing Robust Carbon Nanotube Structures



SOURCE: Stanford Electrical Engineering/Computer Science, Max Shulaker

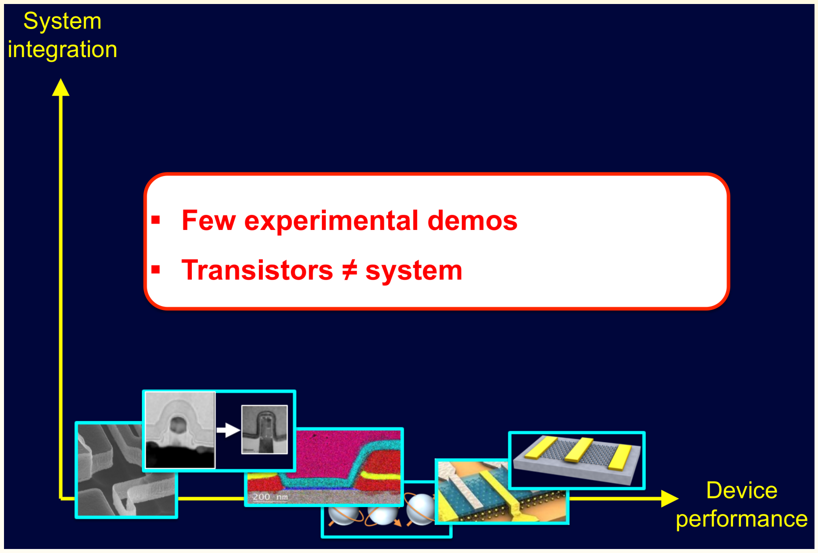
First Carbon Nanotube Computer



Max Shulaker et al, Nature, 2013

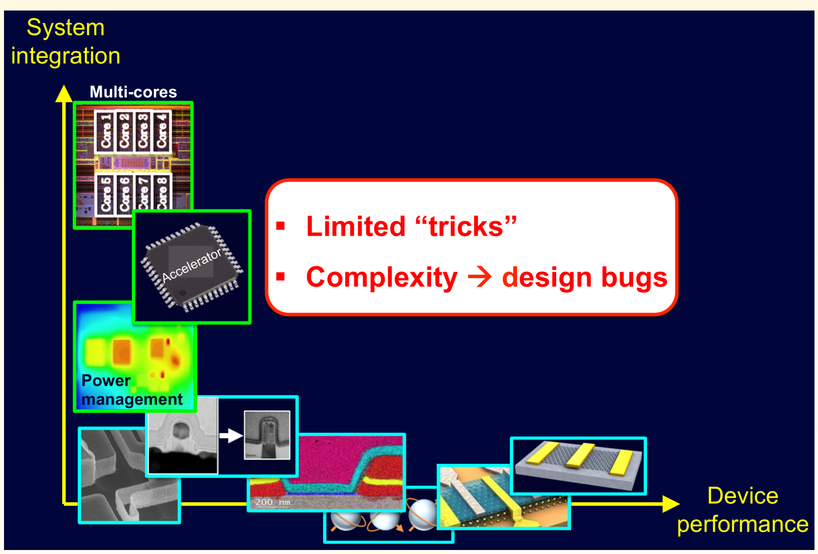
One instruction computer (SUBNEG – subtract and branch if negative (Turing complete))

Improving Computing Performance: Better Transistors?

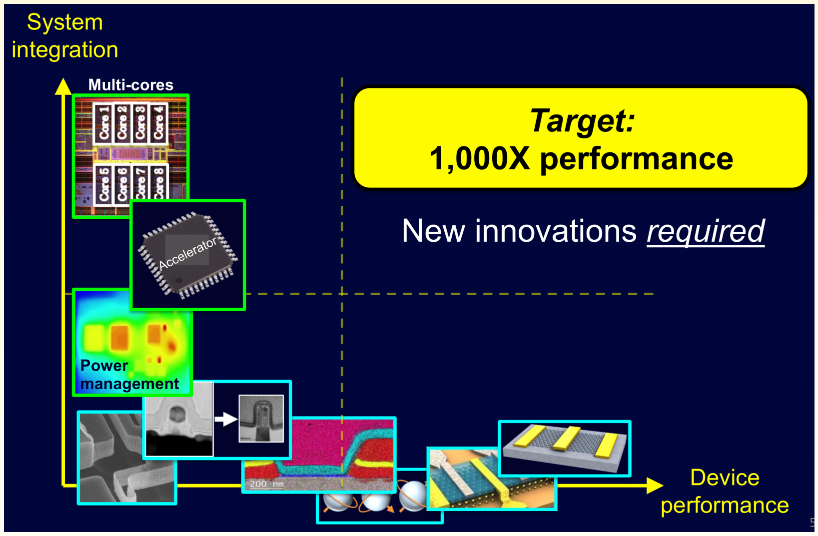


Source: S. Mitra *et al.*, Stanford University

Improving Computing Performance: Architecture and Design Tricks?



Improving Computing Performance: New Innovations



Source: S. Mitra *et al.*, Stanford University

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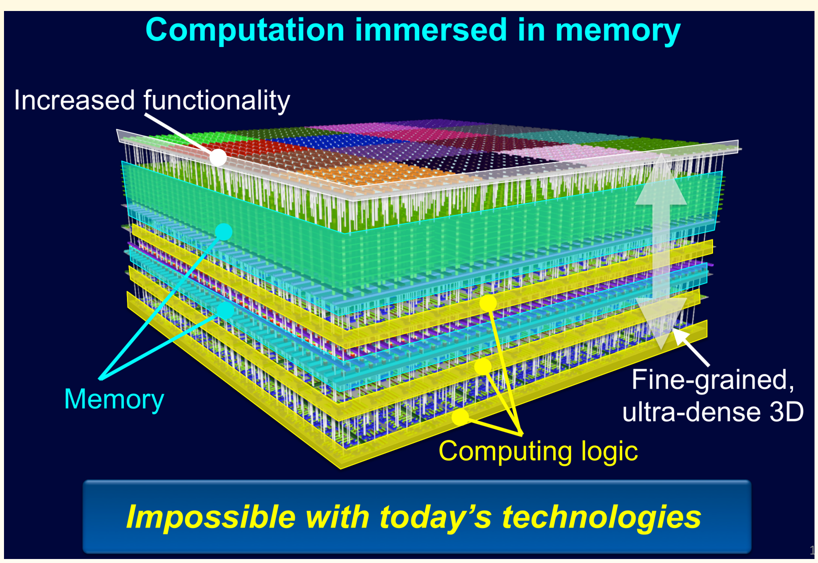
Nanosystems (Stanford Univ. N3XT Project)



Source: S. Mitra *et al.*, Stanford University

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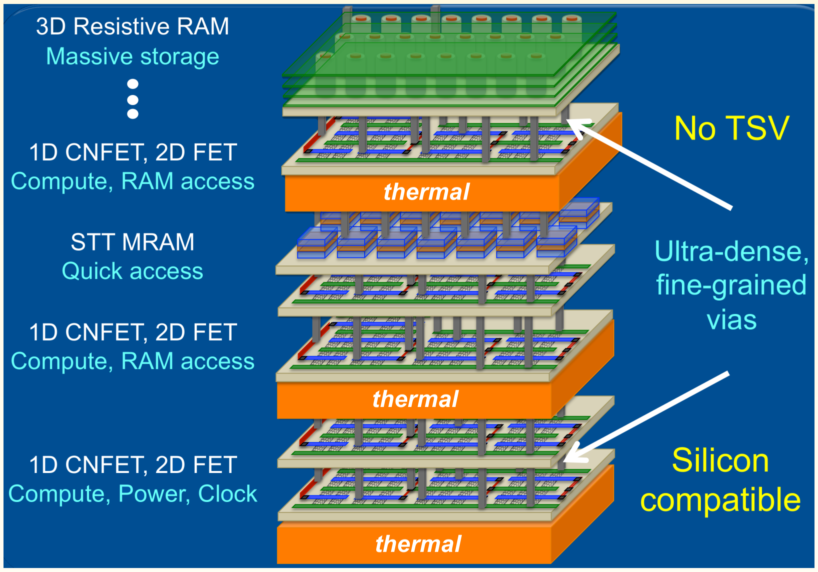
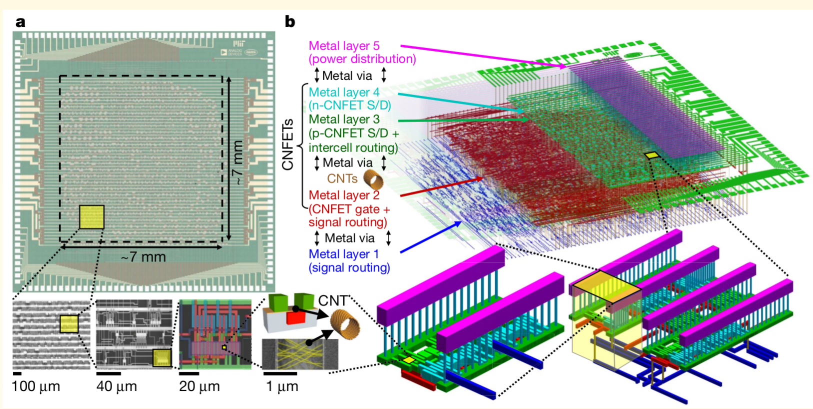
N3XT Computation Immersed in Memory



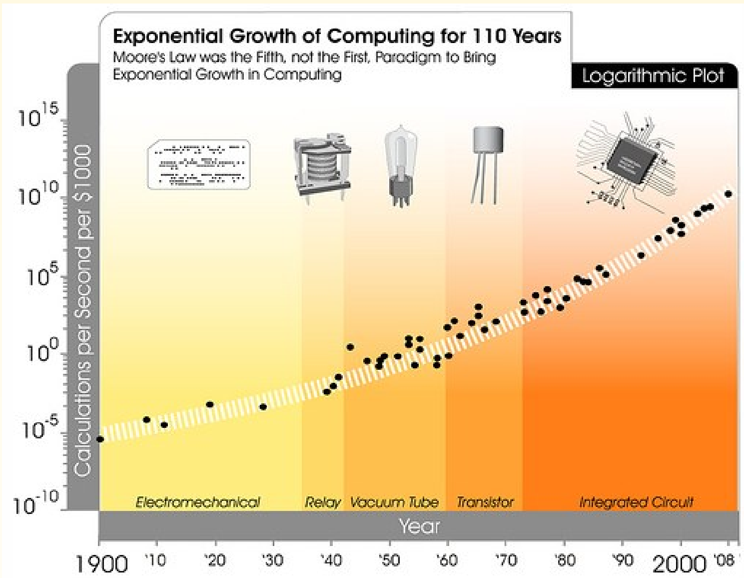
Source: S. Mitra *et al.*, Stanford University

RISC-V Micpcoressor (RV 16X-NANO) Built With Complementary Carbon Nanotube Transistors



(a) Fabricated chip
(b) 3-D schematic of layout; CNFETs are physically located in the middle of the stack, with metal routing both above and below
Source: G. Hills, *Nature*, 2019

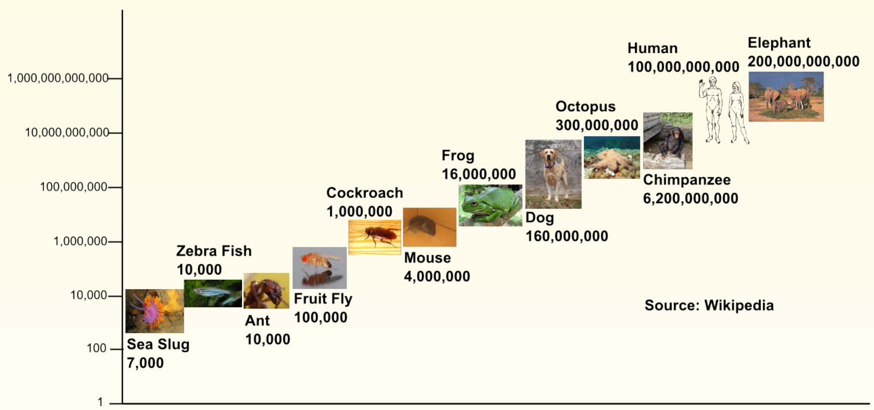
Are Things Really Changing Compared to the Past?



Source: Kurzweil, updated by Jurvetson

Are We Making Good Use of the Transistors We Have?

Look at the number of neurons (in the cerebral cortex for mammals) in different species



Can't We Make VLSI Chips Smarter?