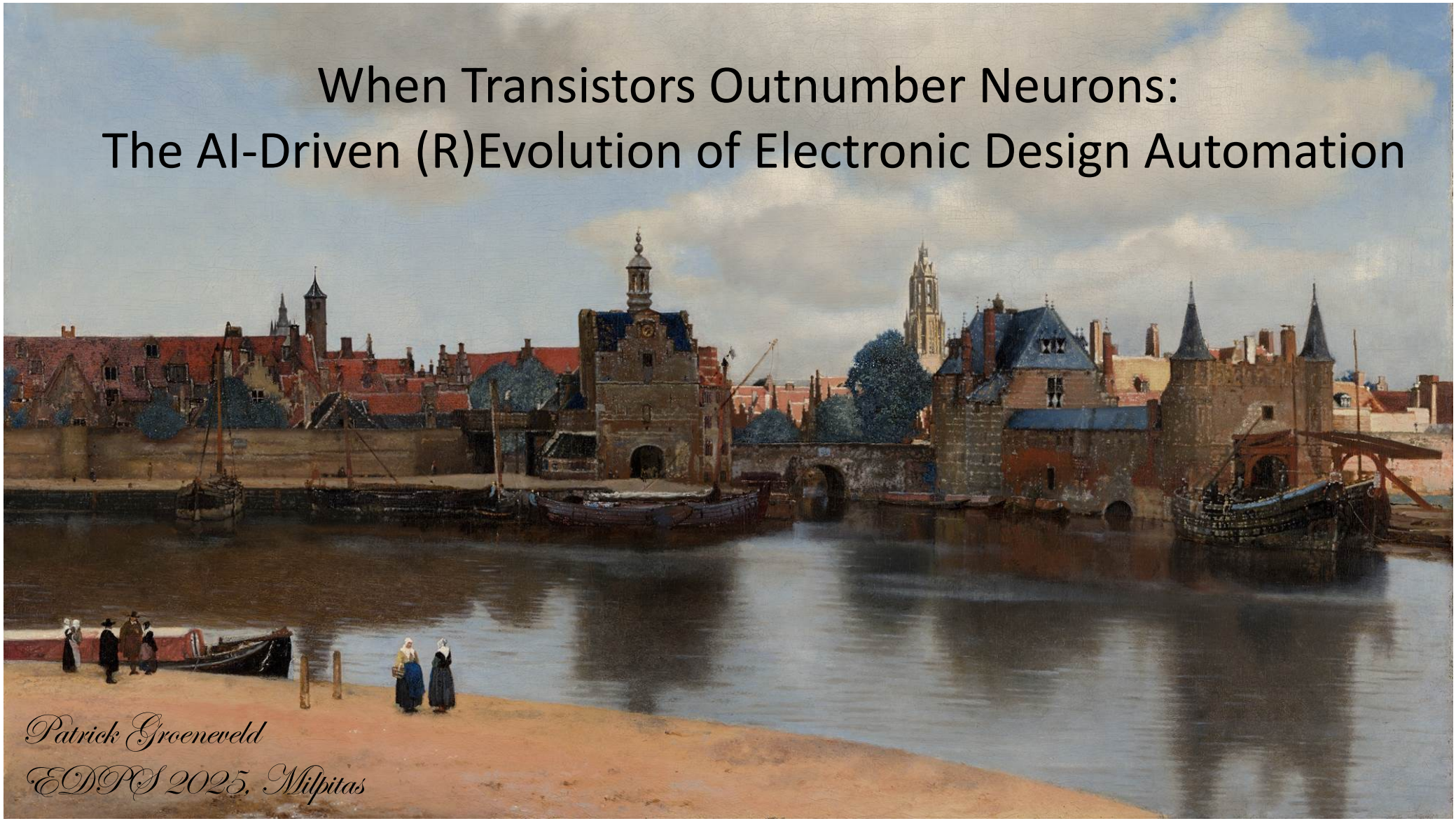
# When Transistors Outnumber Neurons: The AI-Driven (R)Evolution of Electronic Design Automation



*Patrick Groeneveld*

*EDPS 2025, Milpitas*


Johannes Vermeer. View of Delft 1660


TU/e

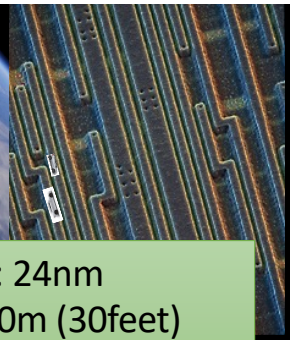

MAGMA
Timing Is Everything
MAGMA


TECHNISCHE UNIVERSITEIT DELFT
MDCCCXLII


A
MAGMA

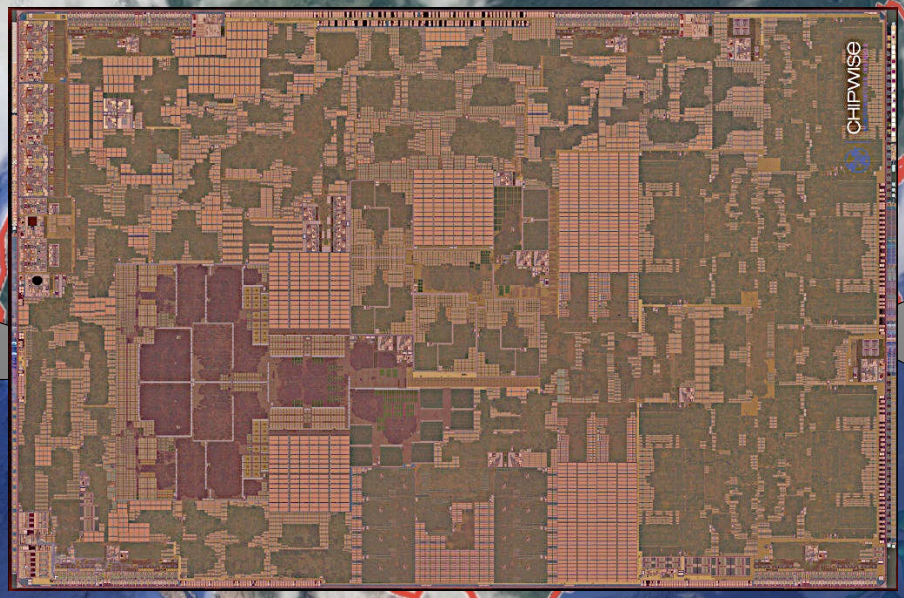

Stanford University
Groeneveld, Patrick
009627607
Faculty/Staff
Issued 04/17/2018

# Imagine:
# If the Wires on a 3nm Mobile SoC were as wide as 2-lane Roads…



IC Wire pitch at 3nm: 24nm
2-lane Road width: 10m (30feet)
Scaling factor = 435Million

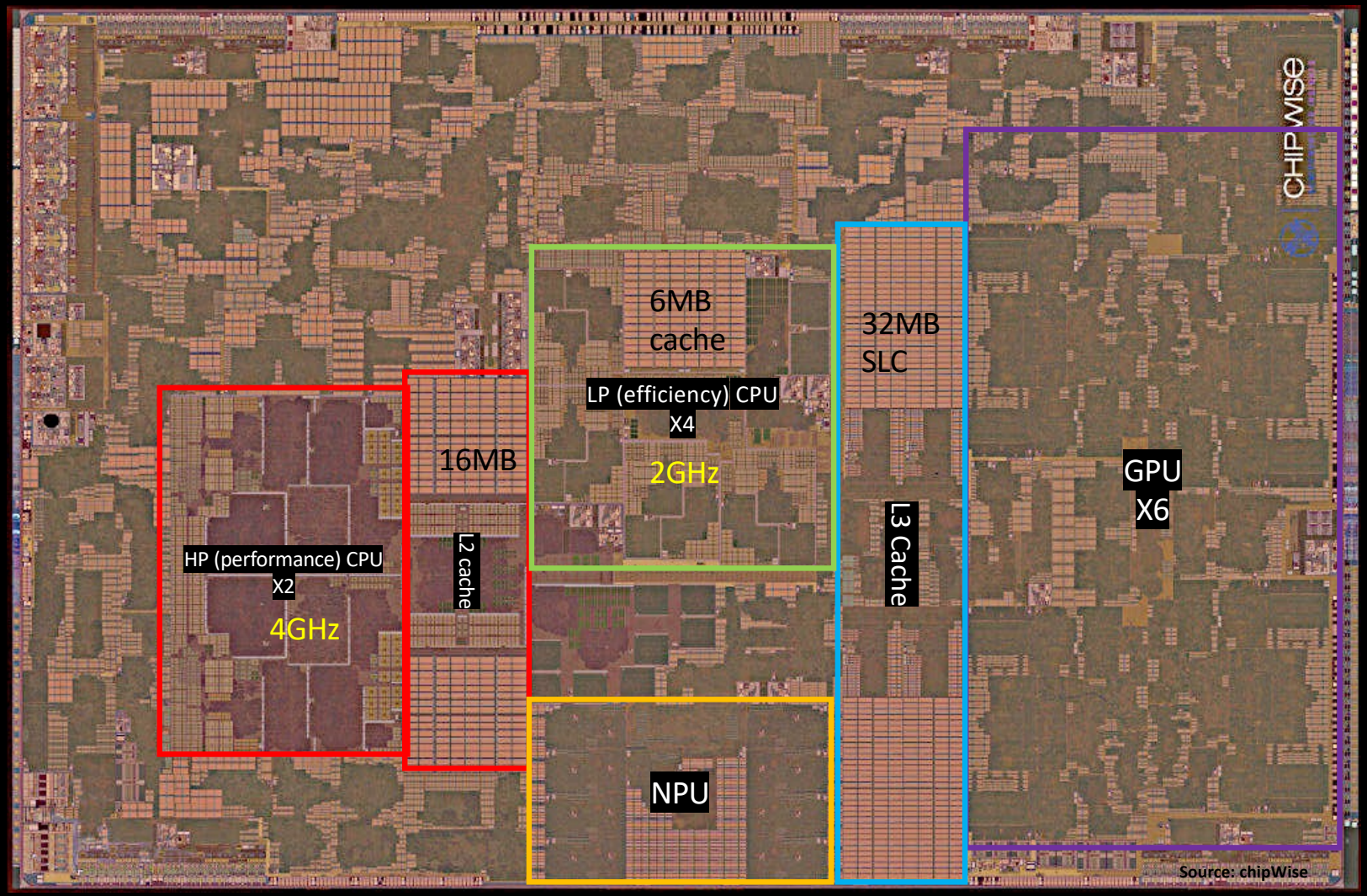
Scaled up, the wire is a road.
The **A19 Pro Chip (iPhone 17)** contains:
~18 million miles wires in 12 layers.
Connecting
~20 Billion transistors
~1.2 Billion standard cells
Consumes ~2 GigaWatt




**2700miles/4350km**

The **USA** contains
2.7 million miles of paved roads in 1 layer.
Connecting
0.31 Billion people
0.26 Billion cars
0.14 Billion homes
Consumes ~400 GigaWatt

# Apple A19 SoC in iPhone 17 September 2025



# Moore's Law Ending?


MIT Technology Review

Intelligent Machines

**The End of Moore's Law?**

The current economic boom is likely due to increases in computing speed and decreases in price. Now there are some good reasons to think that the party may be ending.

by Charles C. Mann May 1, 2000

The New York Times

SCIENCE

***Incredible Shrinking Transistor Nears Its Ultimate Limit: The Laws of Physics***

By WILLIAM J. BROAD FEB. 4, 1997

nature International weekly journal of sci

nature news home | news archive | specials | opinion | features | news blog

comments on this story

Published online 24 June 1999 | Nature | doi:10.1038/news990624-1

News

**The end of the road for silicon?**

Philip Ball

The writing is on the wall for silicon chips, according to research published in the 24 June issue of Nature. By the year 2012, miniaturization of microelectronics will have reached its limit, and computer power will be unable to increase any further without drastically rethinking the whole basis of silicon electronics.

Stories by subject

- Technology
- Chemistry

MIT Technology Review

Topics+ The D

Intelligent Machines

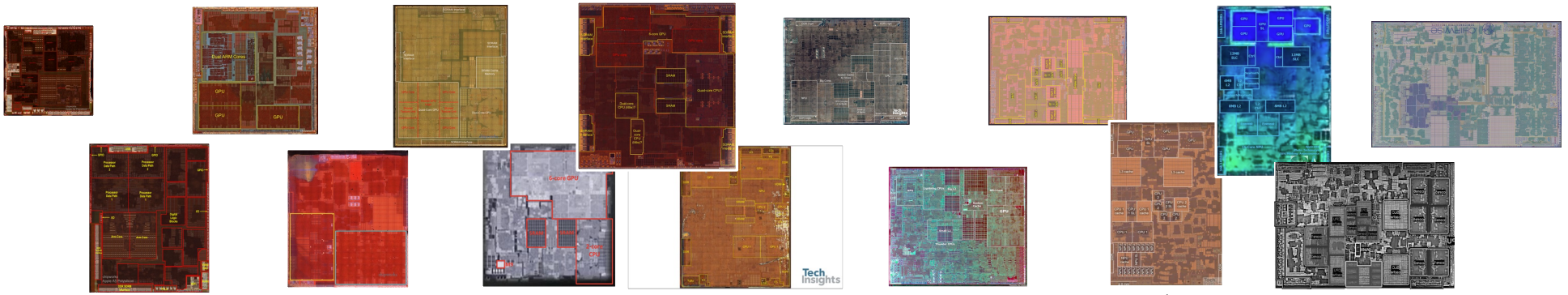
**Moore's Law Is Dead. Now What?**

Shrinking transistors have powered 50 years of advances in computing—but now other ways must be found to make computers more capable.

by Tom Simonite May 13, 2016

# 15 Generations of Apple Mobile System-on-Chips

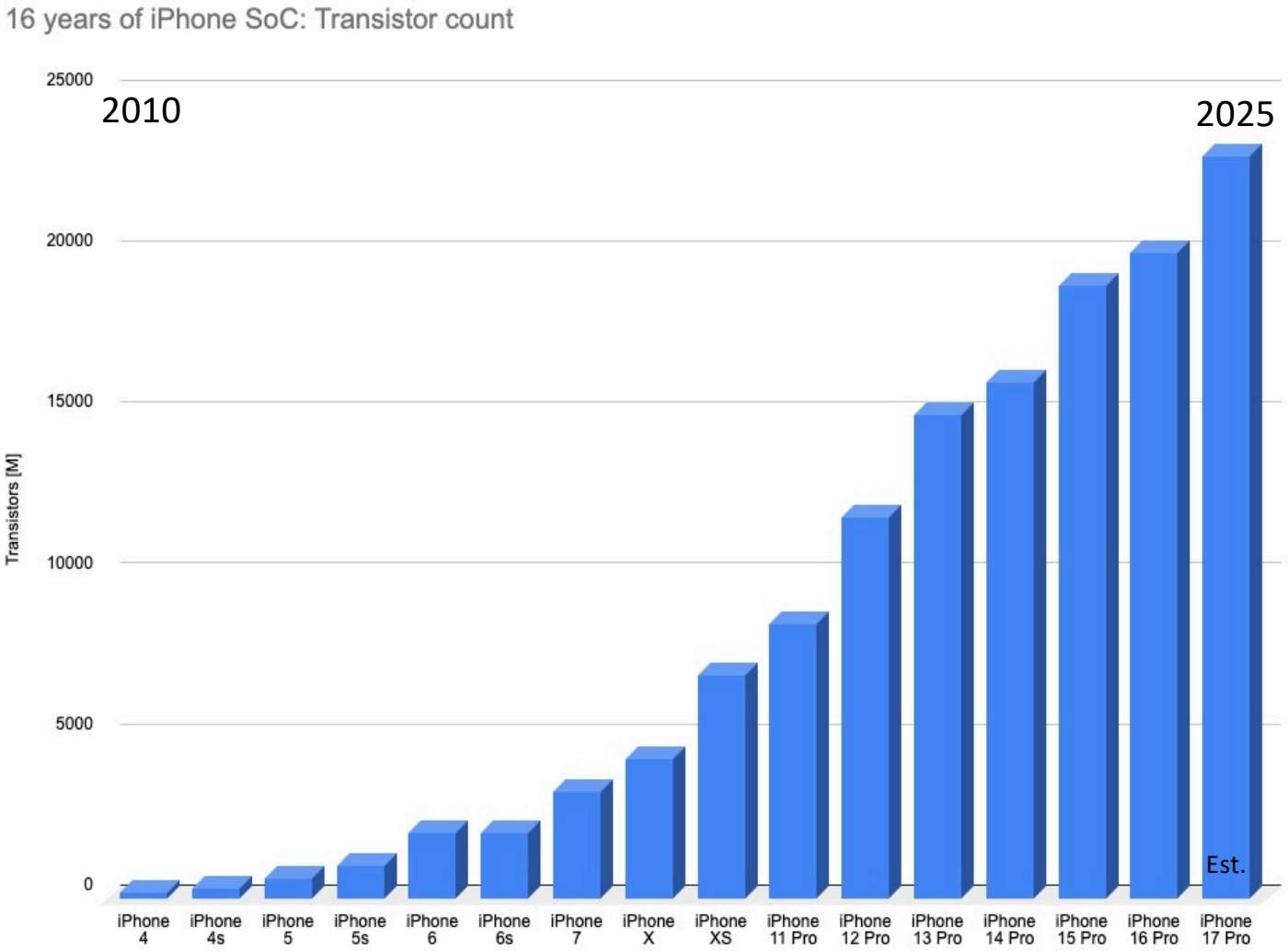
| Chip | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 | A17 | A18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
| **Device** | iPhone 4 | iPhone 4s | iPhone 5 | iPhone 5s | iPhone 6 | iPhone 6s | iPhone 7 | iPhone 8 & X | iPhone Xs | iPhone 11 | iPhone 12 | iPhone 13 | iPhone 14 | iPhone 15 | iPhone 16 |
| **Node** | 45nm Samsung | 45nm Samsung | 32nm Samsung | 28nm Samsung | 20nm TSMC | 16nm TSMC | 16nm TSMC | 10nm TSMC | '7'nm TSMC | 7nm TSMC | 5nm TSMC | 5nm TSMC | 4nm TSMC | 3nm TSMC | 3nm TSMC |
| **Area [cm2]** | 0.52 | 1.25 | 0.96 | 1.03 | 0.89 | 1.05 | 1.25 | 0.88 | 0.83 | 0.98 | 0.88 | 1.08 | 1.14 | 1.03 | 1.05 |



Die photos:
chipworks/TechInsights/Angstonomics

Data source: wikipedia

# iPhone SoC scale

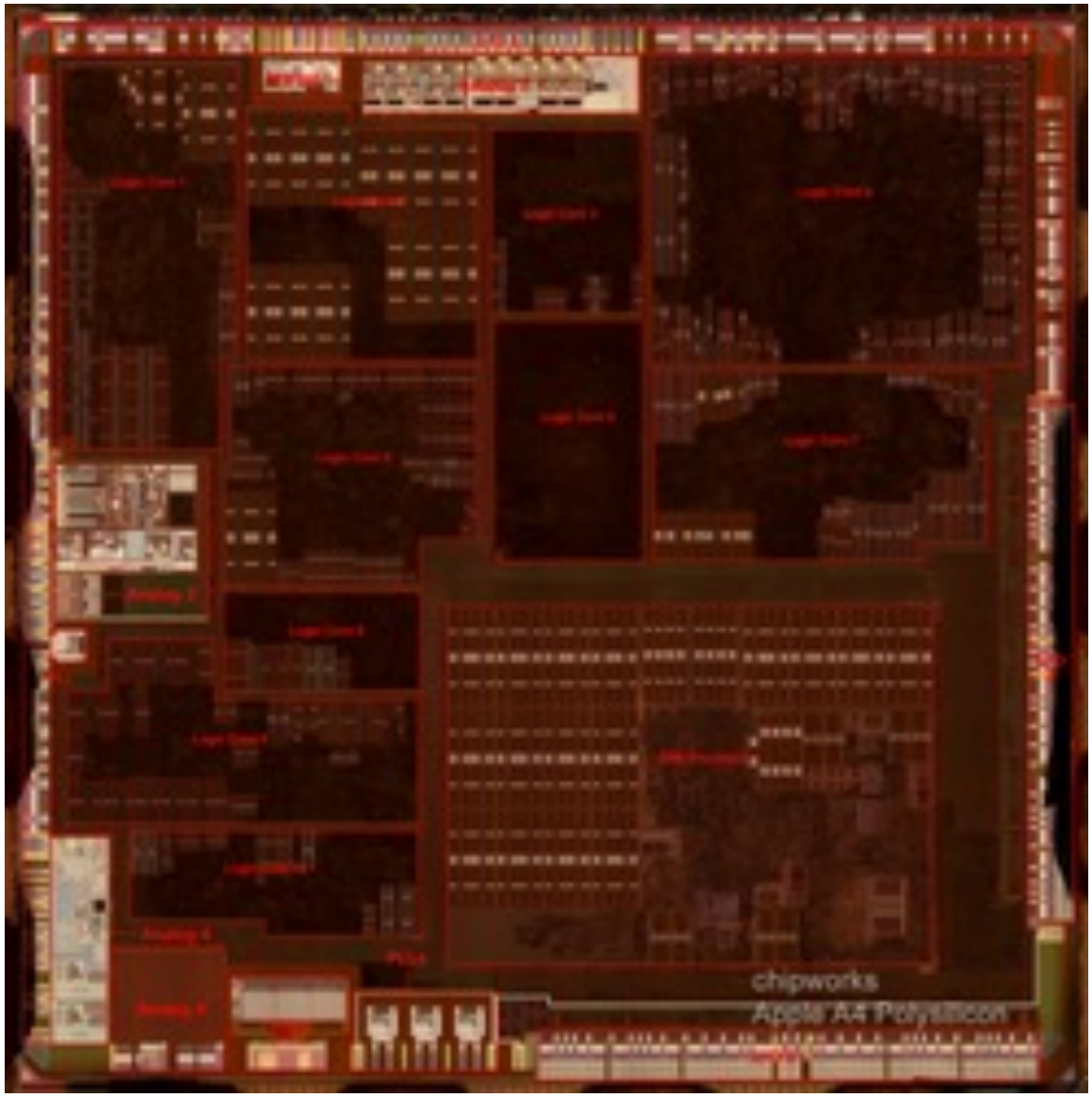


2010

iPhone 4

45nm Samsung

A4 SoC



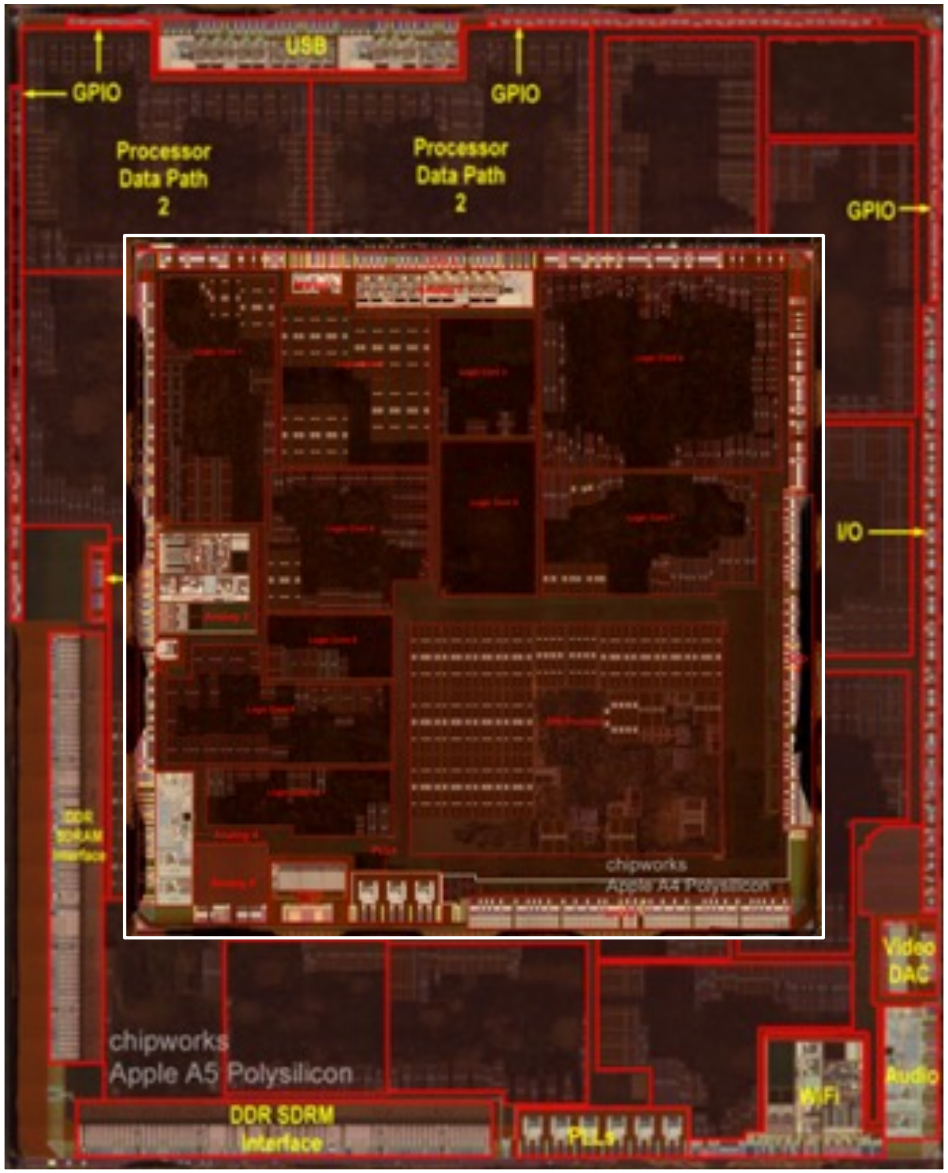

Die photos:
chipworks/TechInsights/Angstonomics
Data source: wikipedia

2011

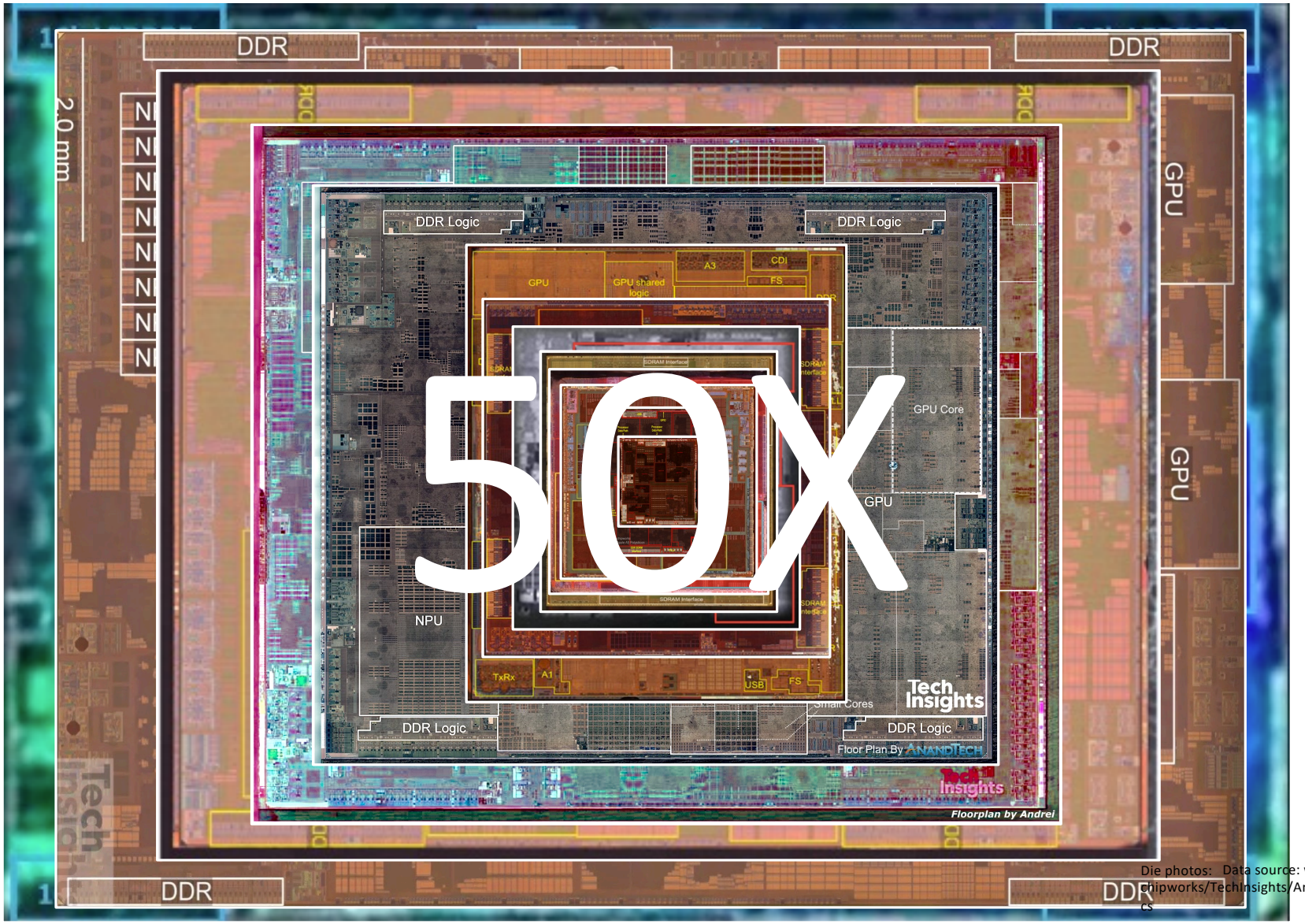
iPhone 4s

45nm Samsung

A5 SoC




Die photos:
chipworks/TechInsights/Angstonomics
Data source: wikipedia

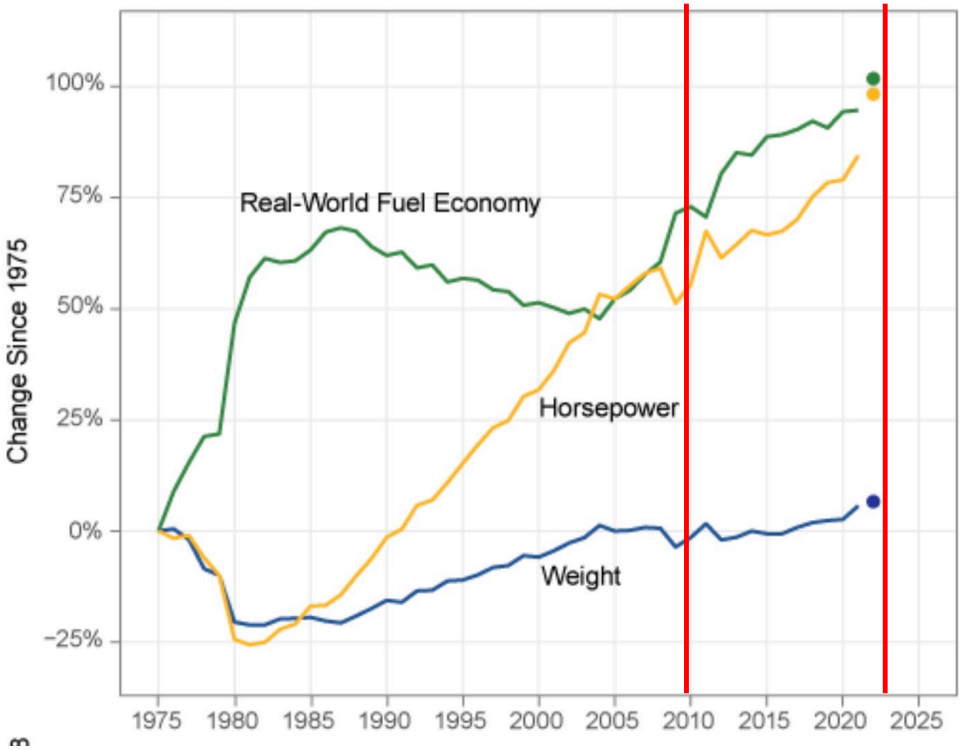



Die photos: Data source: wikipedia Chipworks/TechInsights/Angstonomics

# Automotive Progress vs SoC Progress, Same Period

1.2X

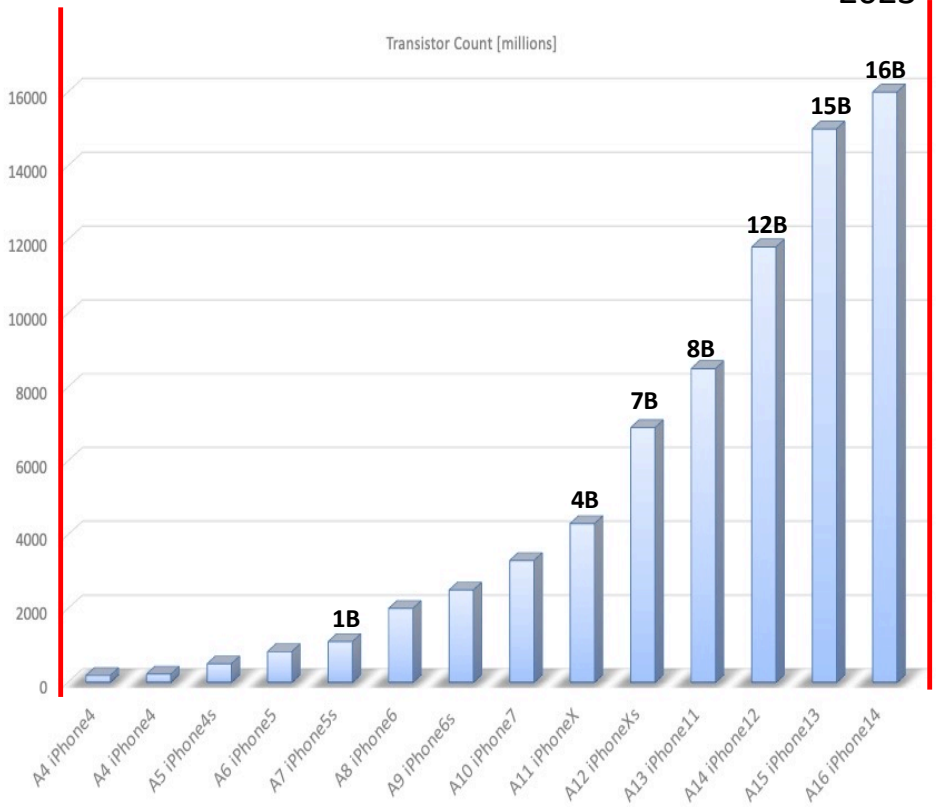
2010 2023



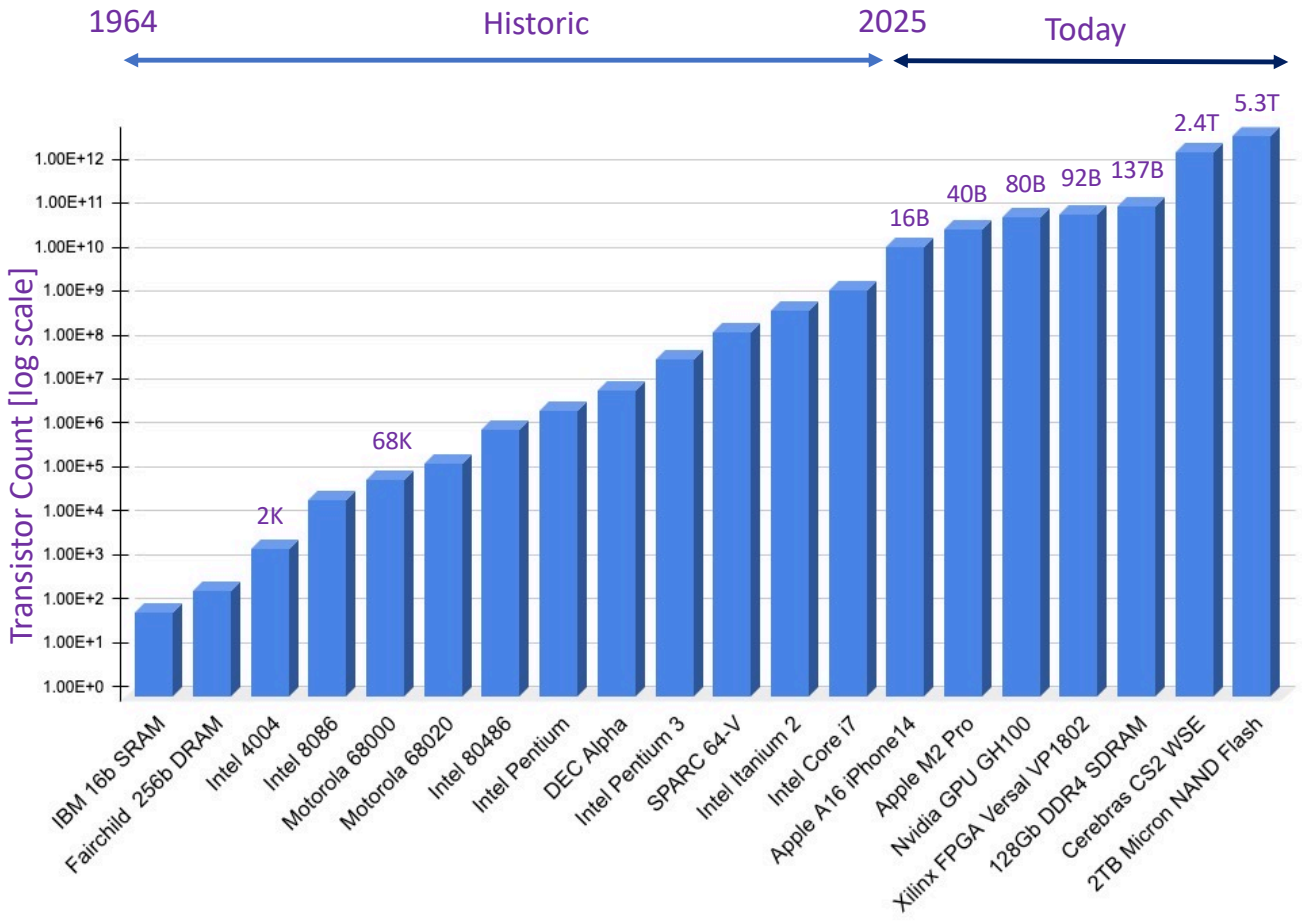

2010

50X

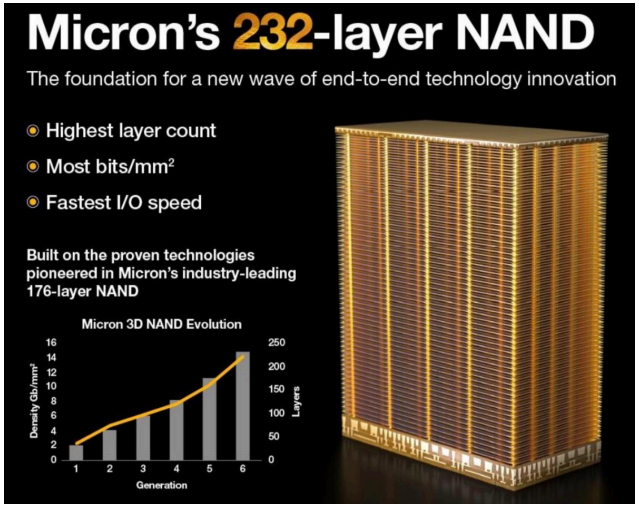
2023



# 60 Years of Relentless Scaling

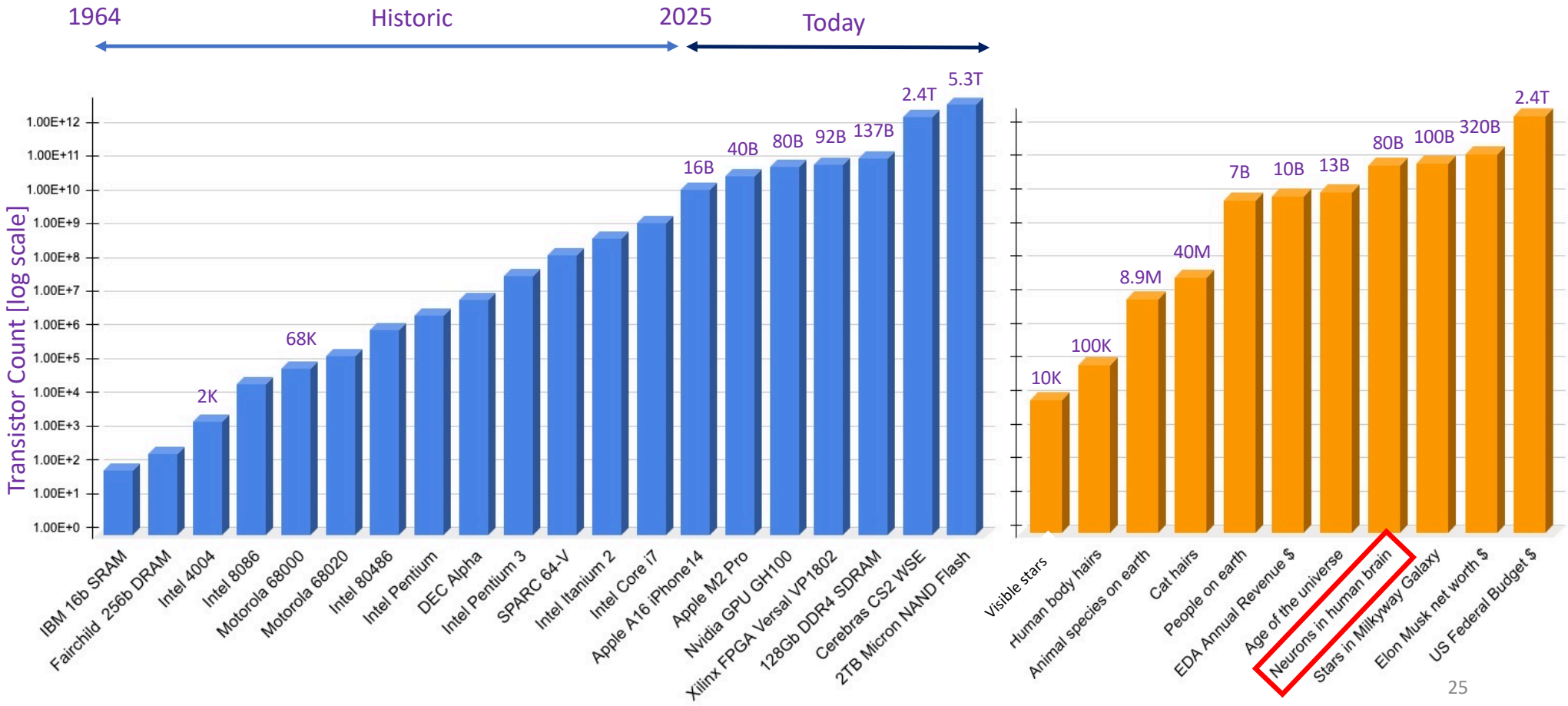



Cerebras CS-2: 2.4T




Largest Flash: 5.3T

# Microelectronics: Mindboggling Scale

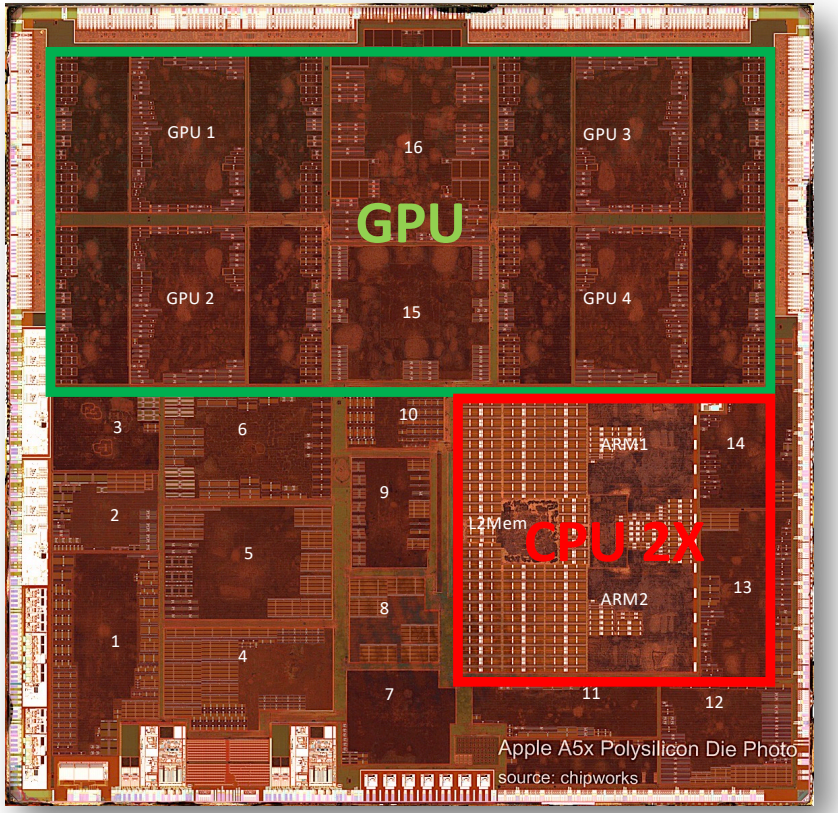


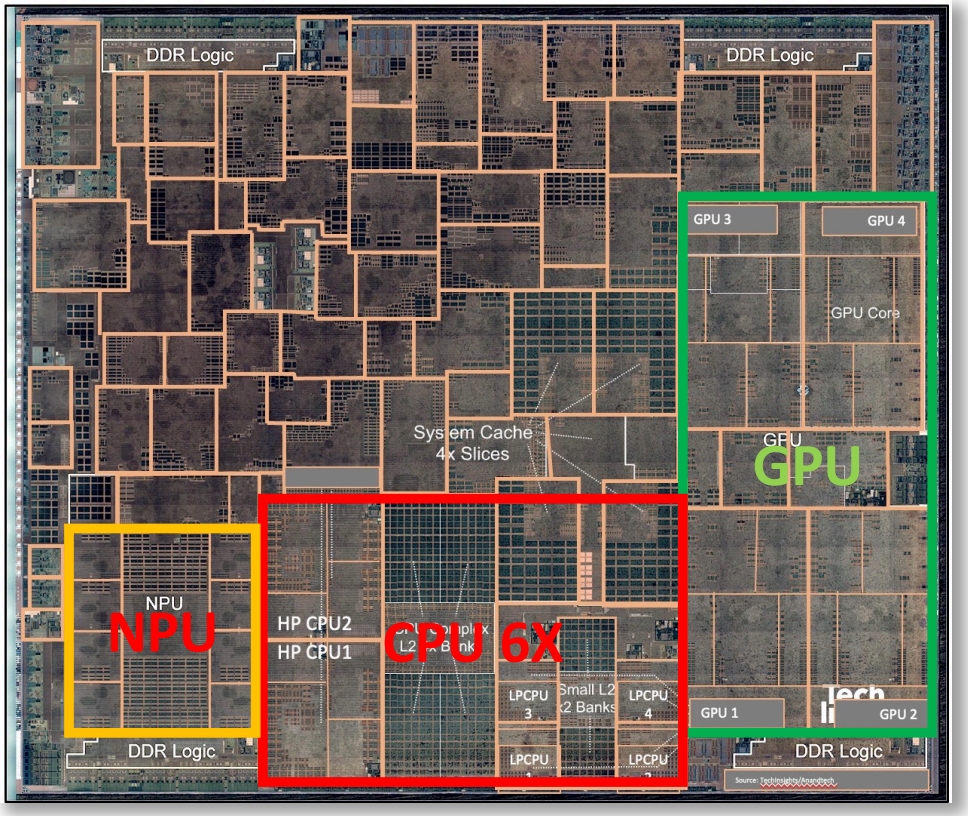
# How was “Moore’s Dividend” Reinvested?

2012: A5 SoC (0.7B Transistors)

10X

2018: A12 SoC (7B Transistors)



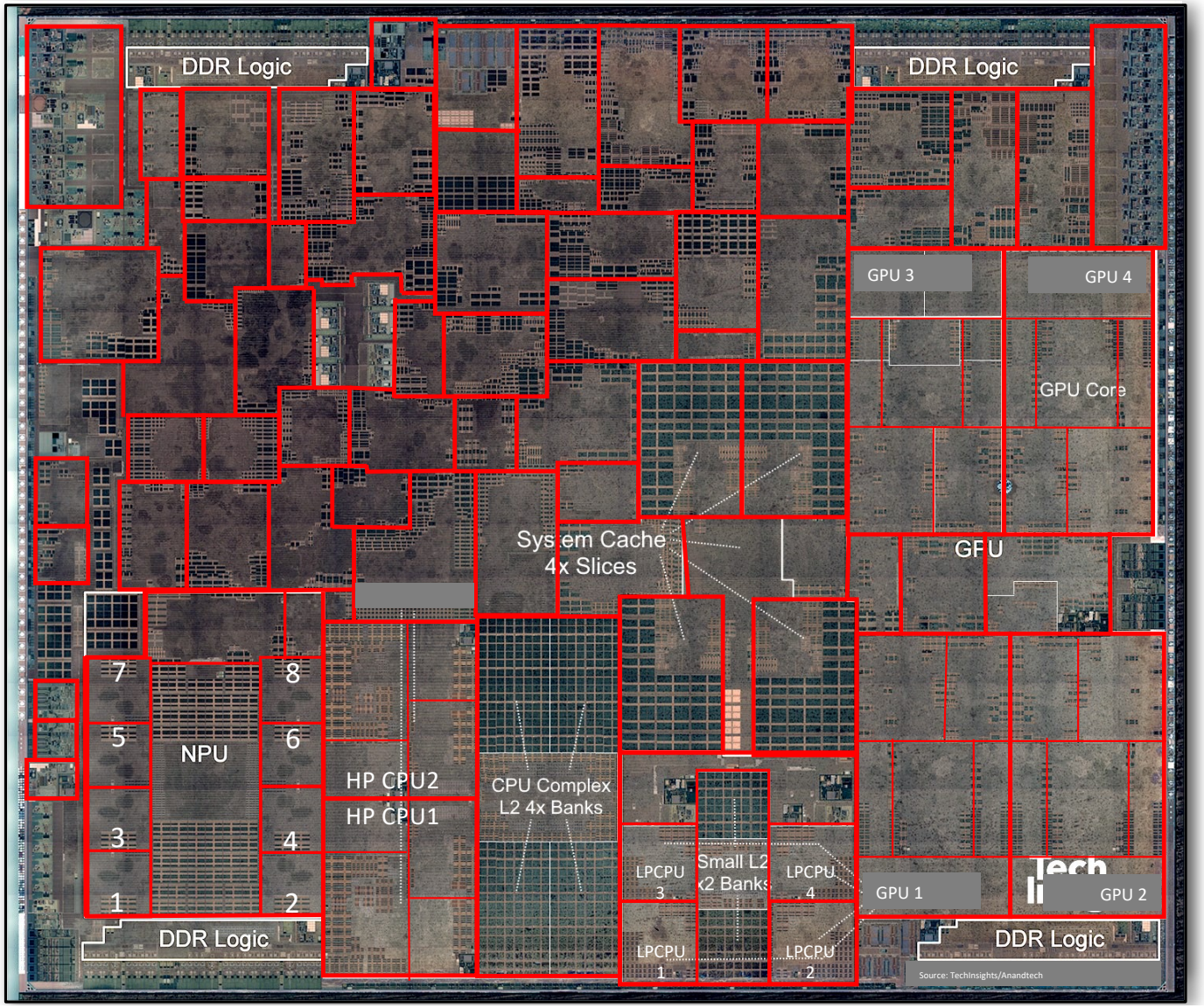




http://www.chipworks.com/media/wpmu/uploads/blogs.dir/4/files/2012/03/apple-a5x-big.jpg

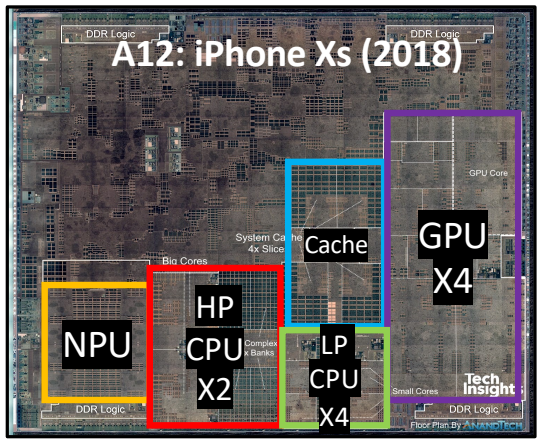
# Apple A12

- 7nm TSMC FinFet
- 9.89 x 8.42 = 83.27 mm2
- 6.9 Billion transistors
- 4 **GPU** cores (~18%): 9 Blocks
- 6 **CPU** cores (~14%):  13 Blocks
  - 4 ‘Tempest’ Low Power CPU cores
  - 2 ‘Vortex’ High Performance CPU cores
  - L2 & L3 caches
- 8 **NPU/TPU** cores (~7%) 4 Blocks
- DDR (~3%) 1 block
- Misc (~57%): 50 Unique Blocks

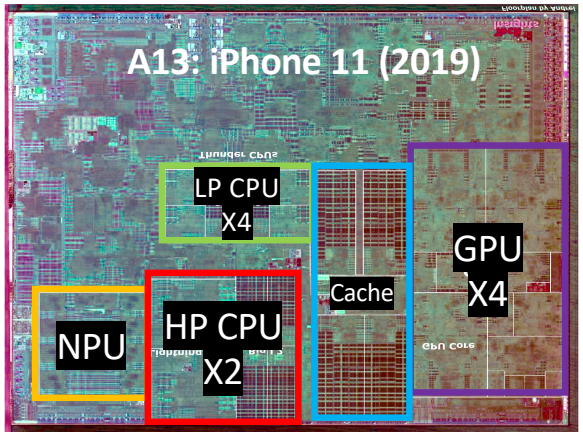
- Total: ~75 unique blocks
- ~5 Watt peak



# Tracking the changes 2018-2025

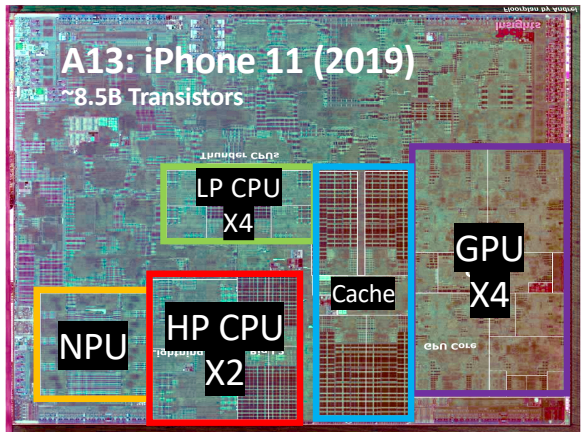


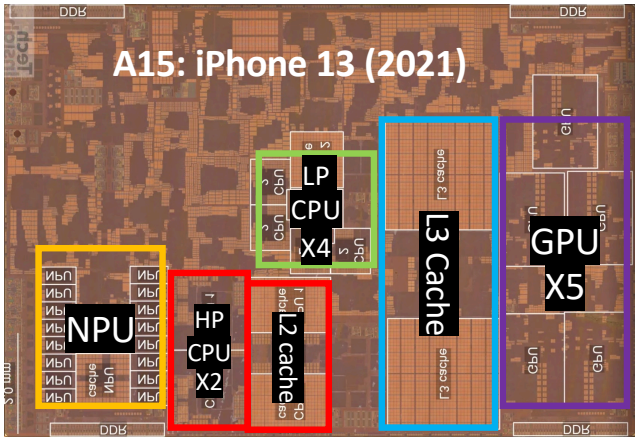

7B transistors

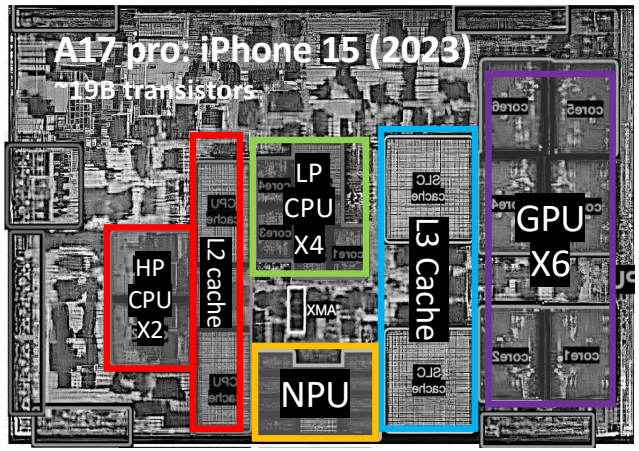


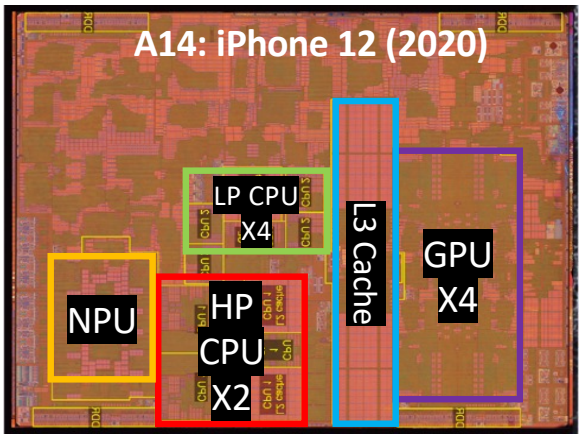

Sources: TechInsights/Anandtech/Angstronomics

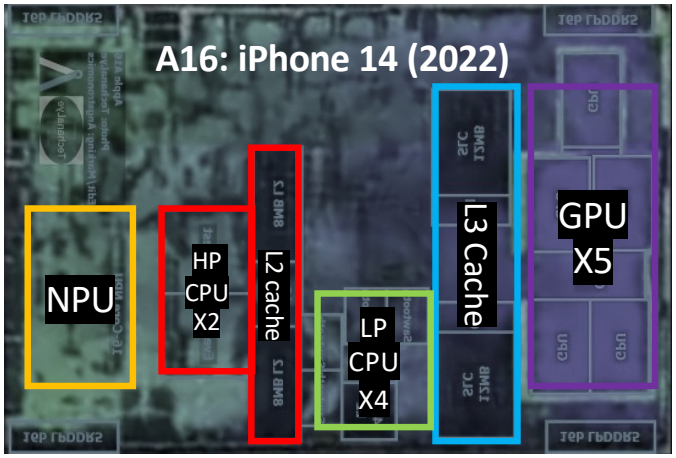
# The Past 6 Years of Apple Mobile SoCs

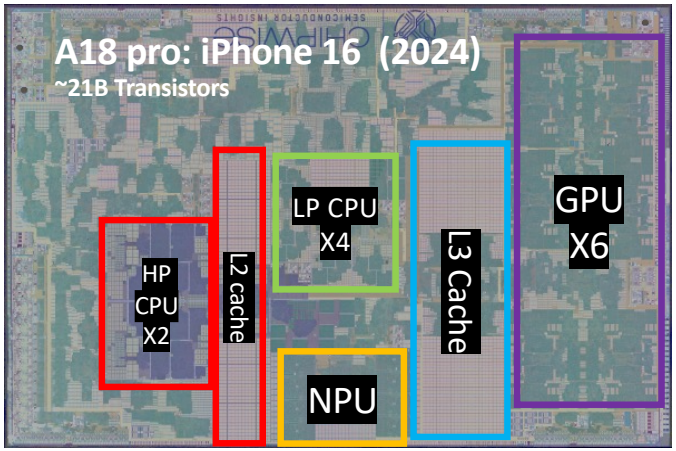


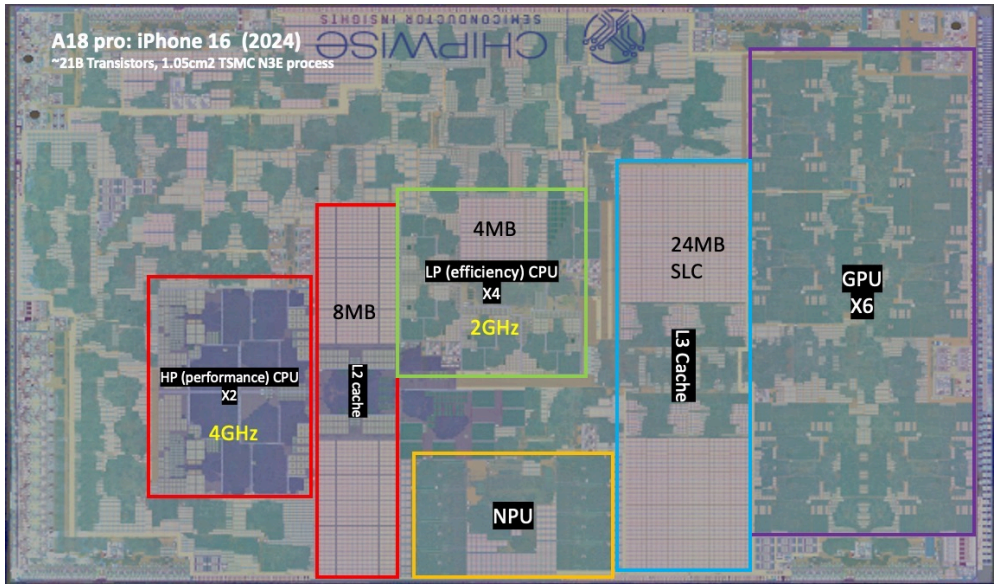



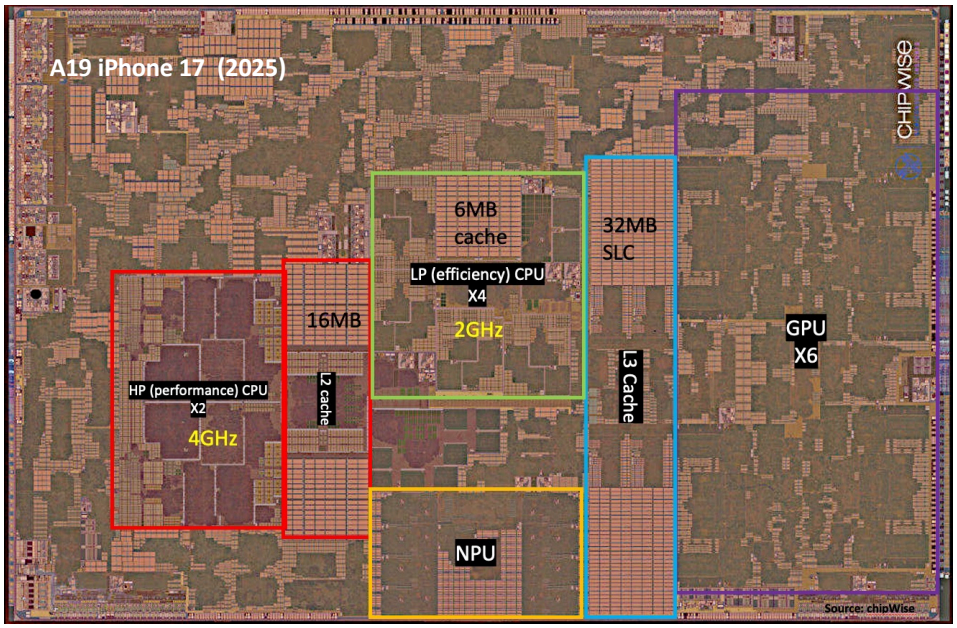




Sources: TechInsights/Anandtech/Angstronomics/chipWise

# iPhone 16 vs iPhone 17: incremental

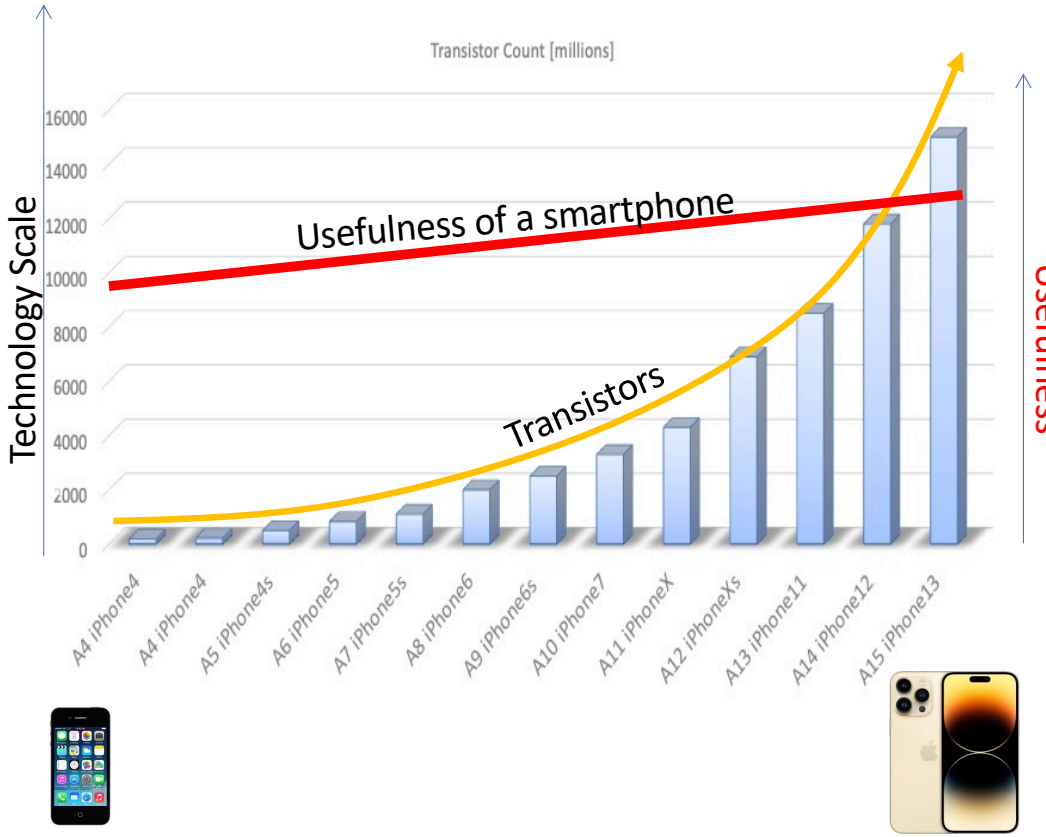


# Claasen's Law

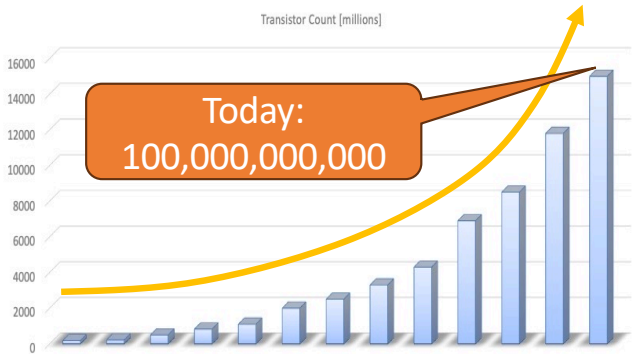
**"The Perceived Usefulness of a new product is an underlying technology's logarithmic function"**

**Theo Claasen, Philips Semiconductor (now: NXP), 1999**



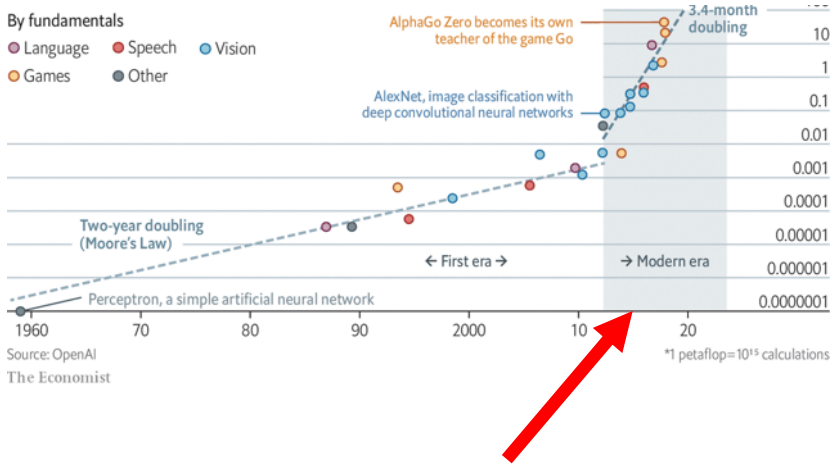
# AI hardware needs "More than Moore"

Moore's Law Transistor Supply:
transistors doubling every ~**24 months**




Computational Demand from AI / Machine Learning
doubling every ~**5-7 months**

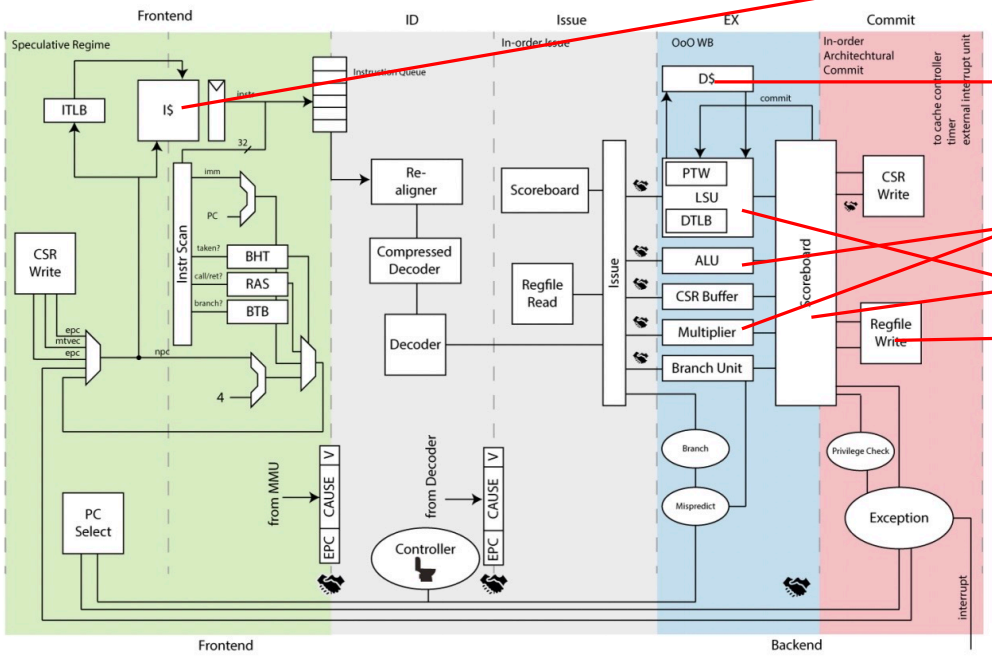
LLMs




Mid-2010's:
Unleashes Machine Learning / AI
Based on brute force
Floating-point multiply-add

Beyond CMOS: Analog, Optical, Carbon Nanotube?

# EDA: From Concept to Chip, *Fully* Automated



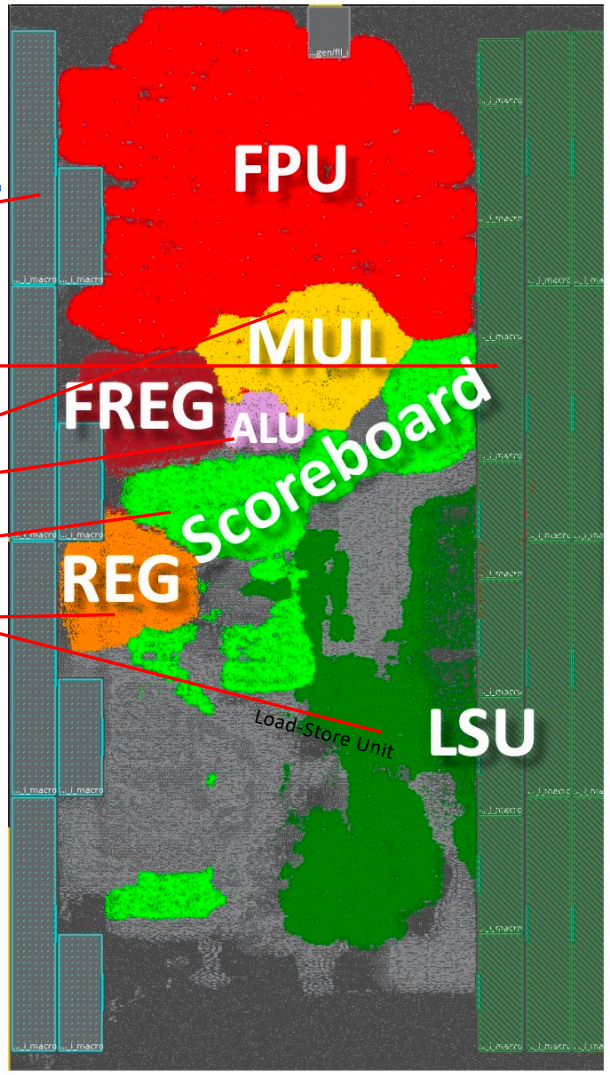

Block Diagram of a RISC-V processor

Source: Florian Zaruba, ETH Zürich
https://riscv.org/wp-content/uploads/2018/05/14.15-14.40-FlorianZaruba_riscv_workshop-1.pdf

Instruction cache

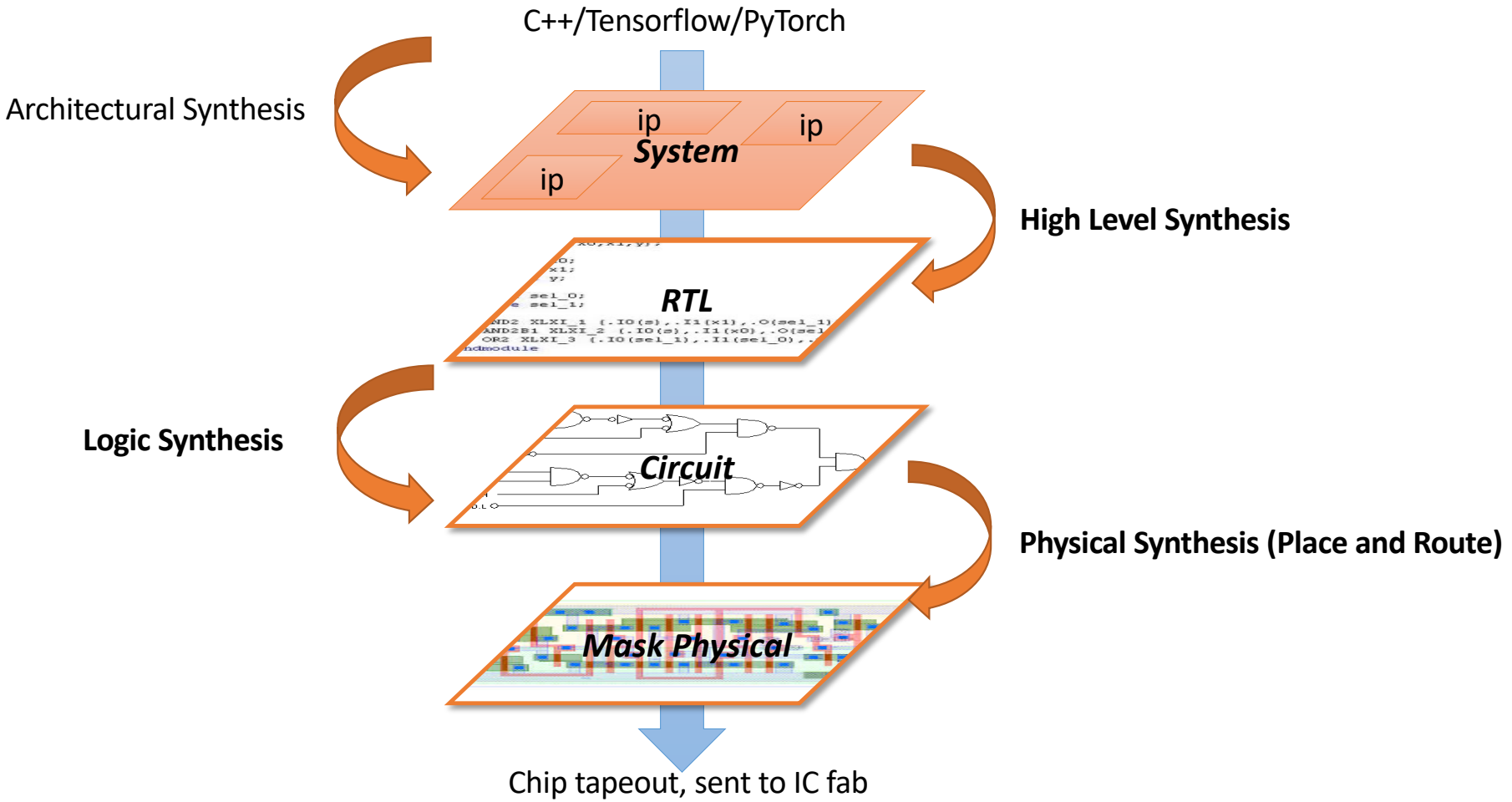
Data cache

EDA flow

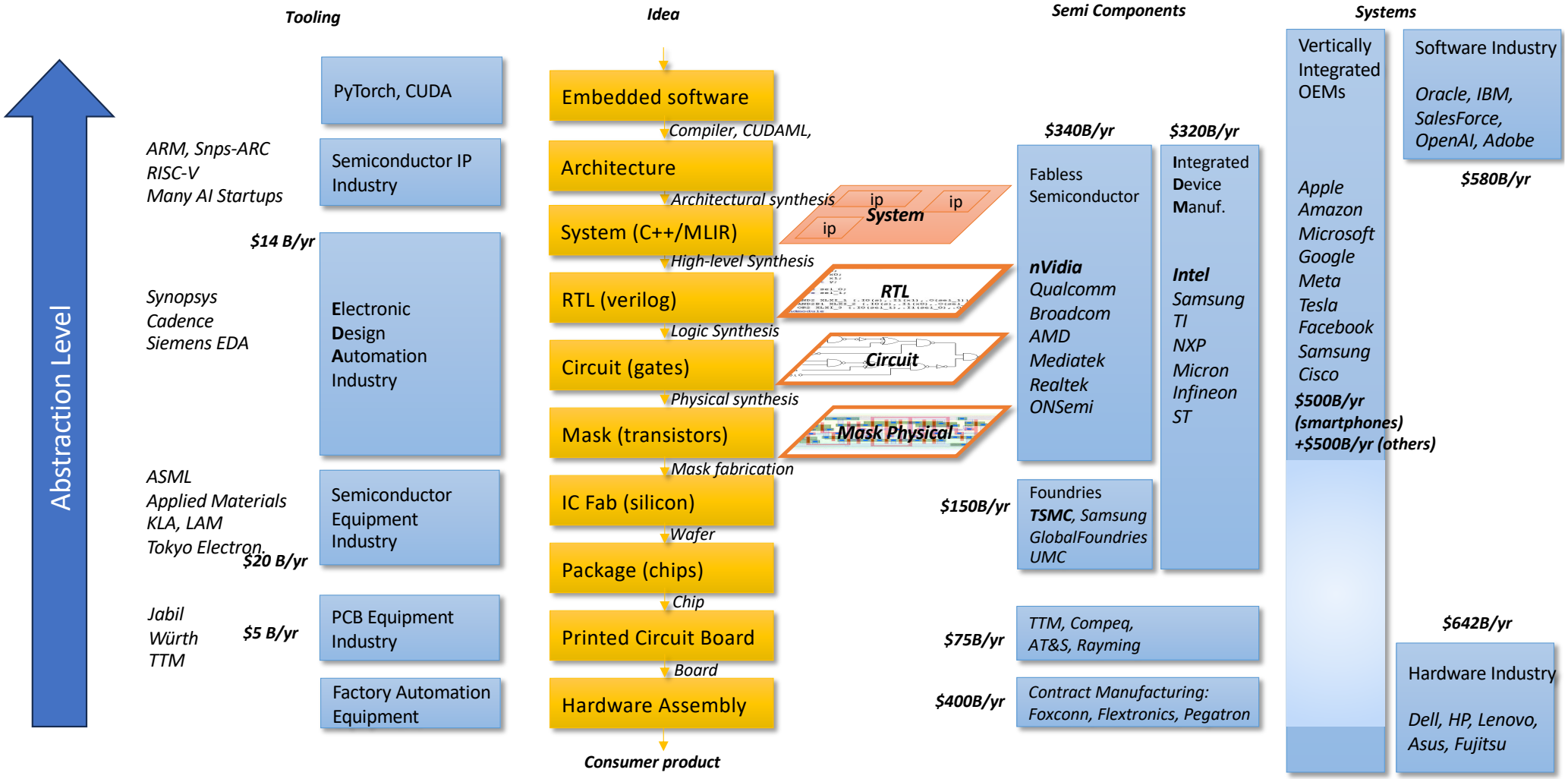



ASIC Layout

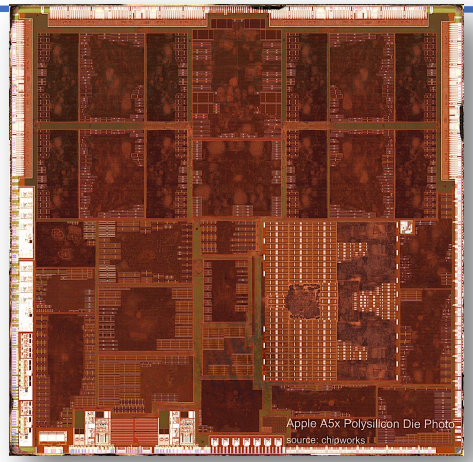
# Major Abstraction Levels in Microelectronic Design



# The Semiconductor Hardware Ecosystem



# What Electronic Design Automation can do (..and Mechanical Design Automation can't)

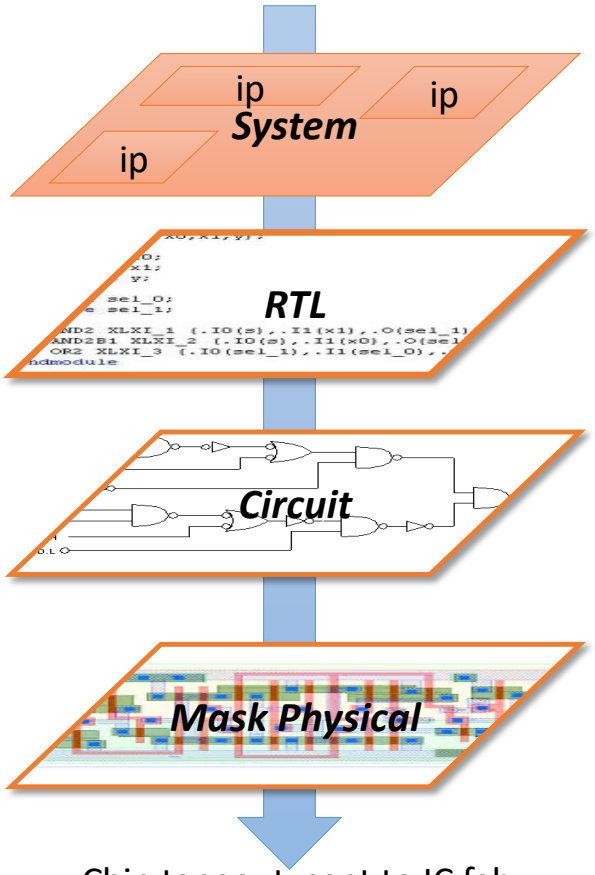


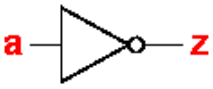

- 10,000,000,000 transistors
- Development cost: $50M
- Development time: < 1 year
- Development team size: 100
- EDA software: ~$14B/year

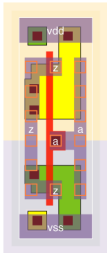

| | |
|---|---|
| • 4,000,000 parts | 0.0005x |
| • Development cost: $20B | 400x |
| • Development time: 10 years | 10x |
| • Development team size: 10,000 | 100x |
| • MCAD software: ~$12B/year | |

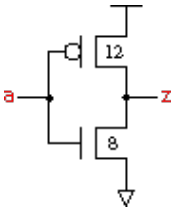
# Standard cells enable a reliable flow!

C++/Tensorflow/PyTorch



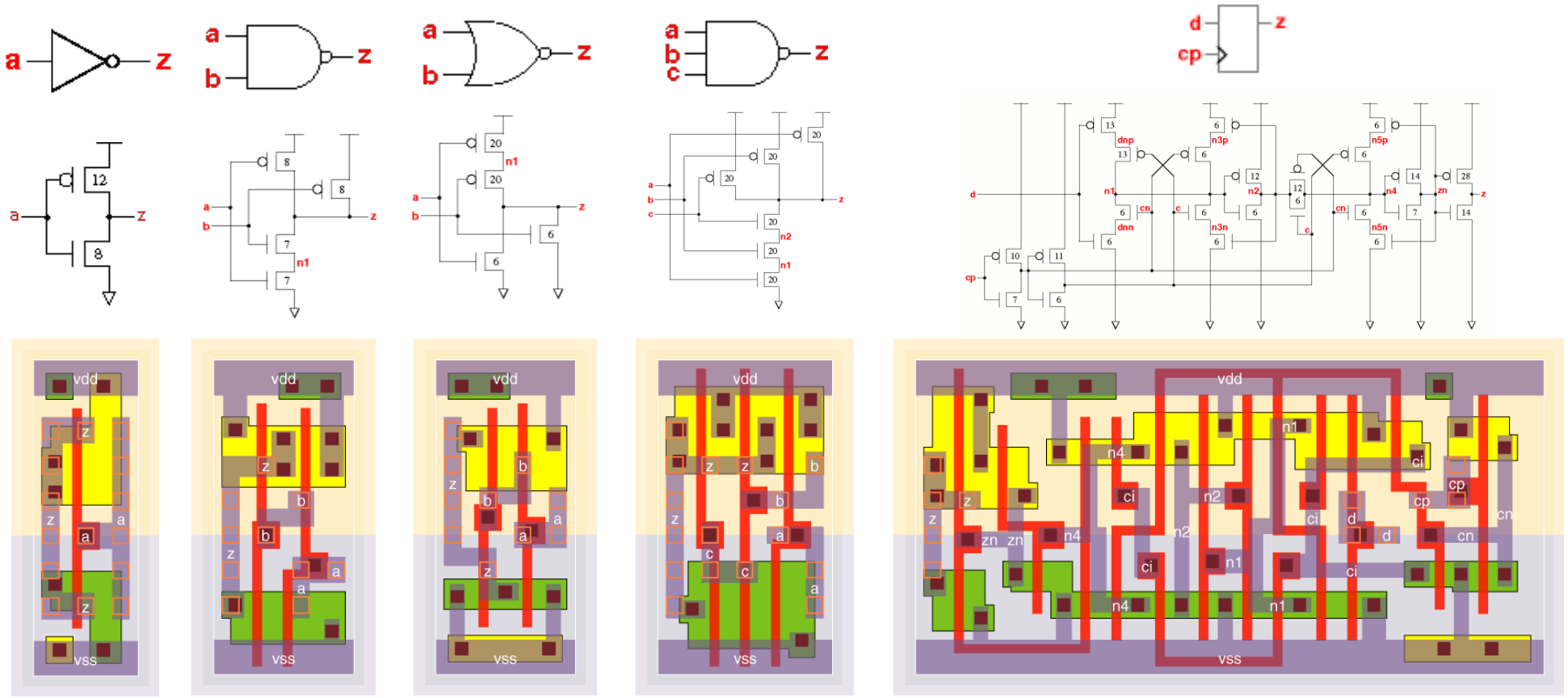






Chip tapeout, sent to IC fab

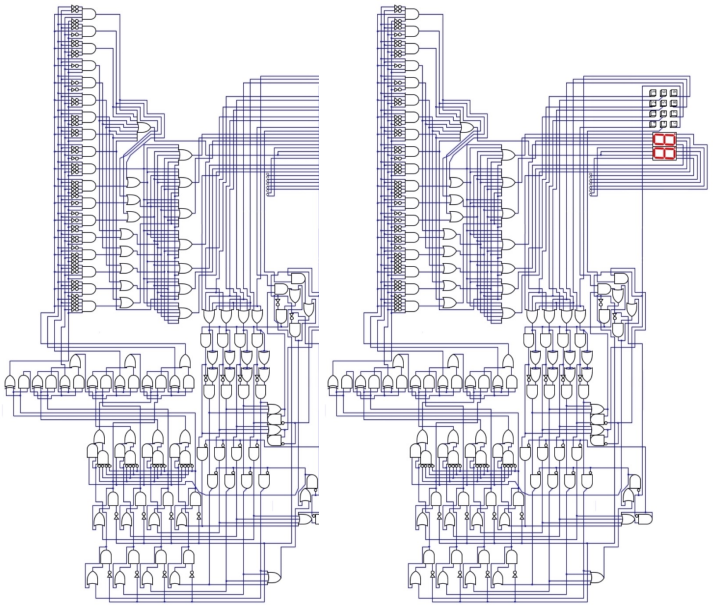
# Standard Cell Library: ~100 different types

inverter nand2 nor2 nand3 flipflop

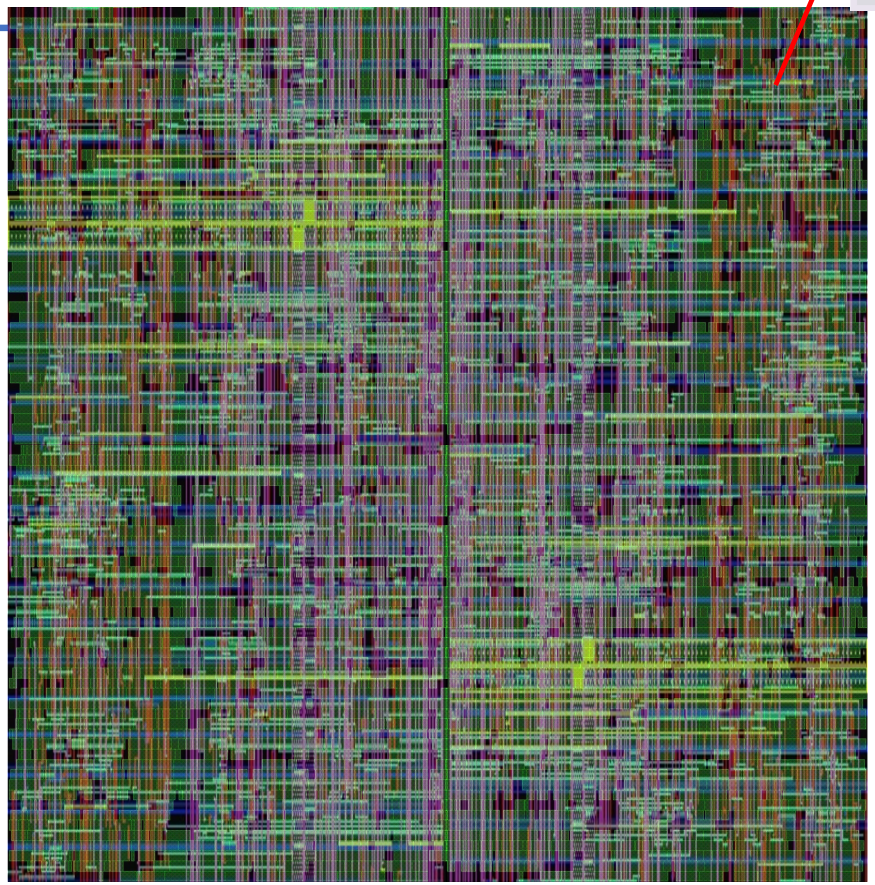



vlsitechnology.org /vsclib

# Logic Gates to Placed Standard Cells

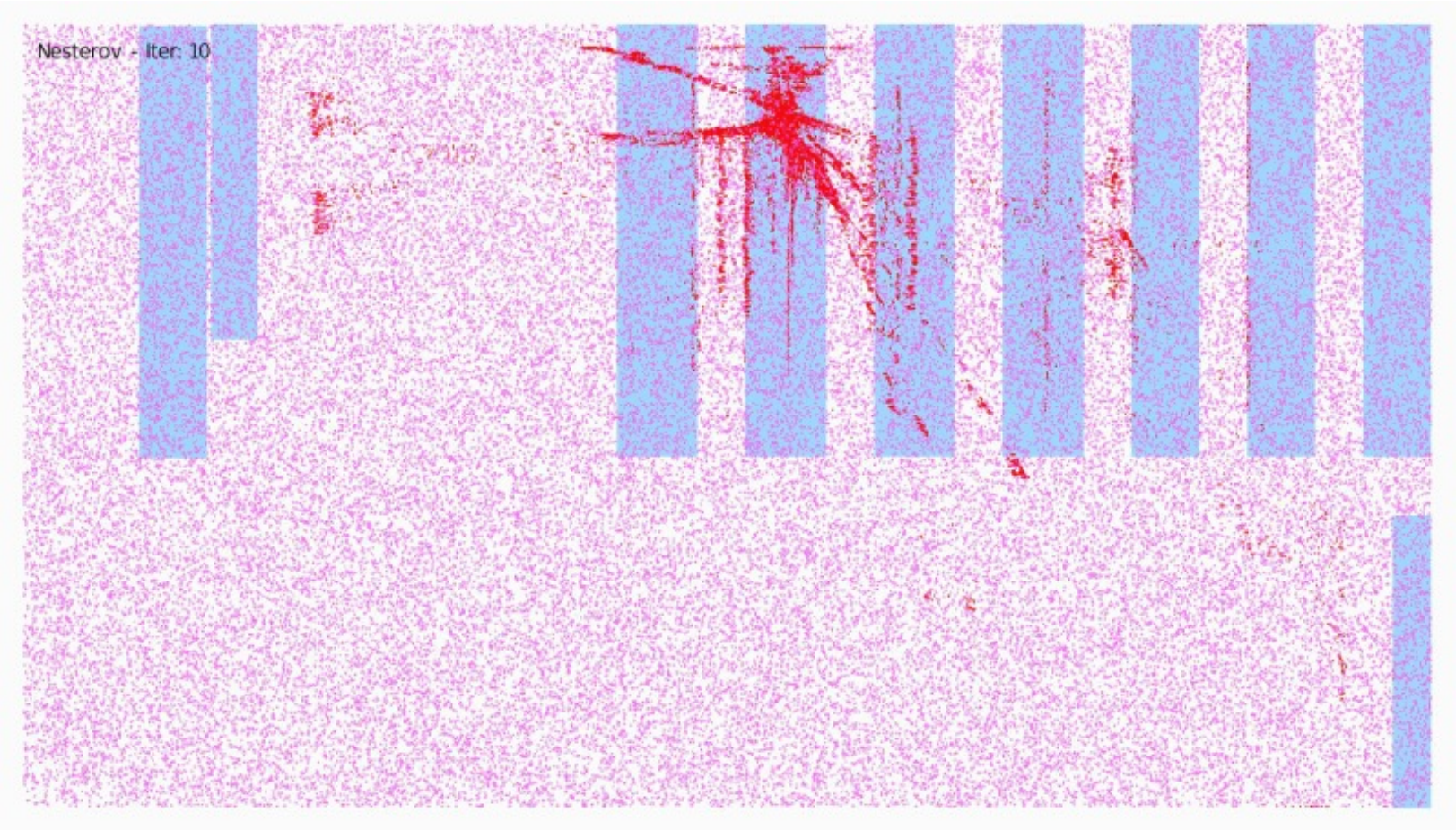


Netlist of logic gates



Layout Mask

# Placing Standard Cells

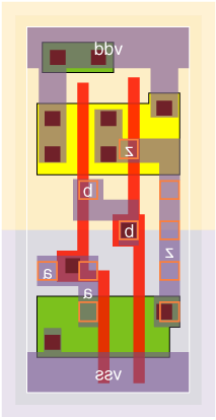



Chung-Kuan Cheng, Andrew B. Kahng,, Ilgweon Kang, and Lutong Wang, "**RePlAce: Advancing Solution Quality and Routability Validation in Global Placement**", IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 2018

# 3 Levels of Physical Hierarchy!

Hides complex Physics and Lithography

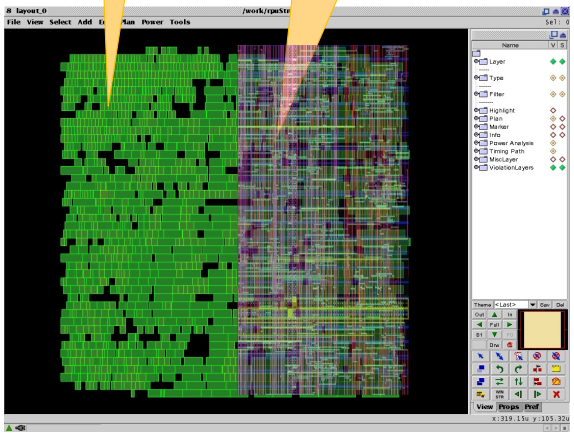
**Standard Cell**:
4 transistors




Millions of homogenous standard cells.

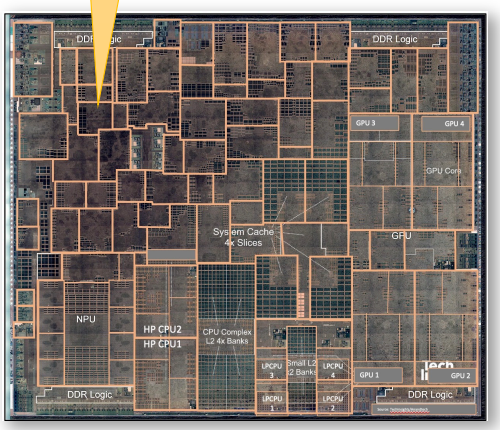
Millions of homogenous wires

**Block**:
10,000,000 transistors

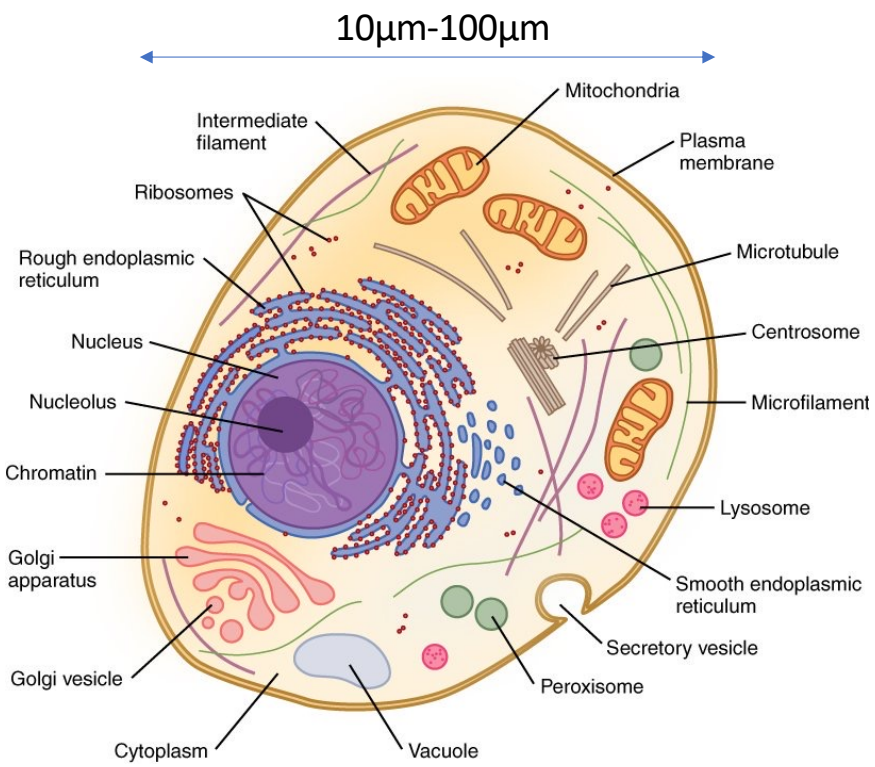


Floorplan with a few dozen different-sized blocks at top level

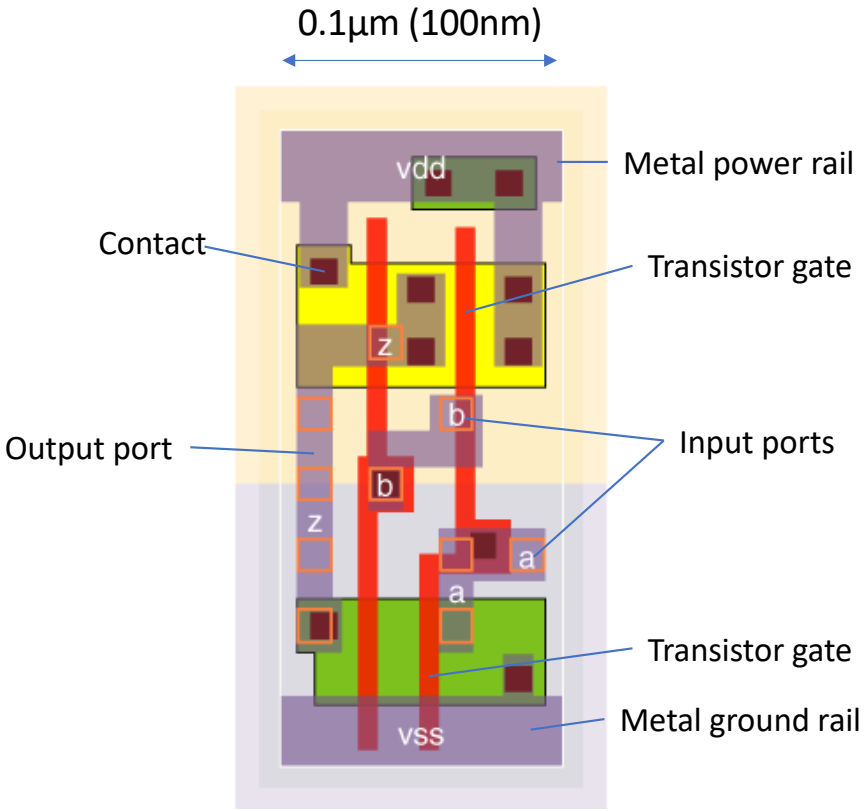
**Chip**:
10,000,000,000 tr



# Biological Cell, Compared to a Standard Cell

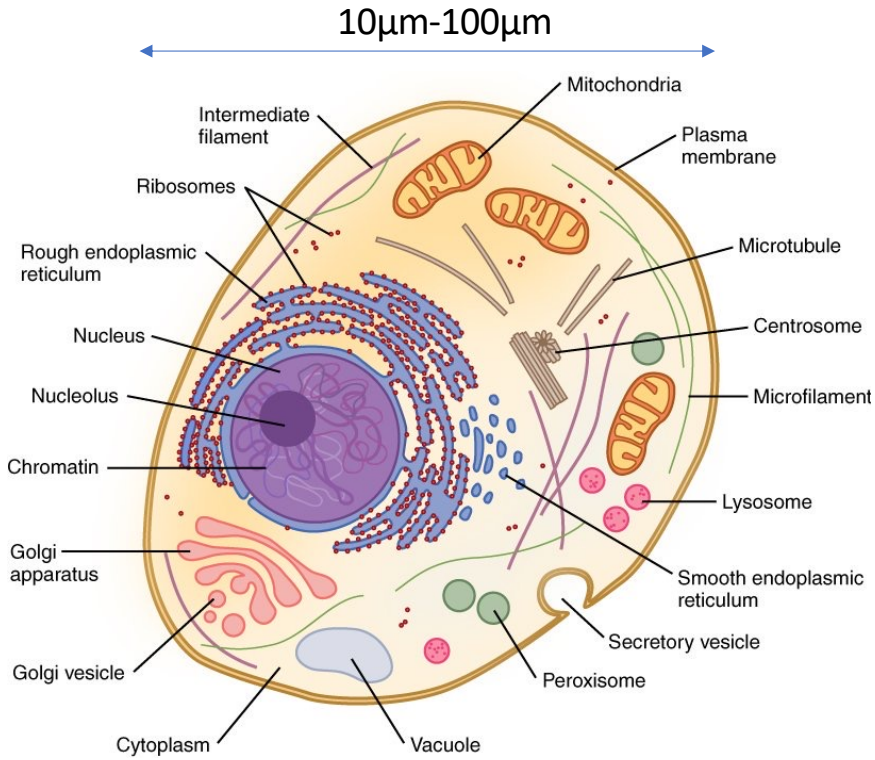


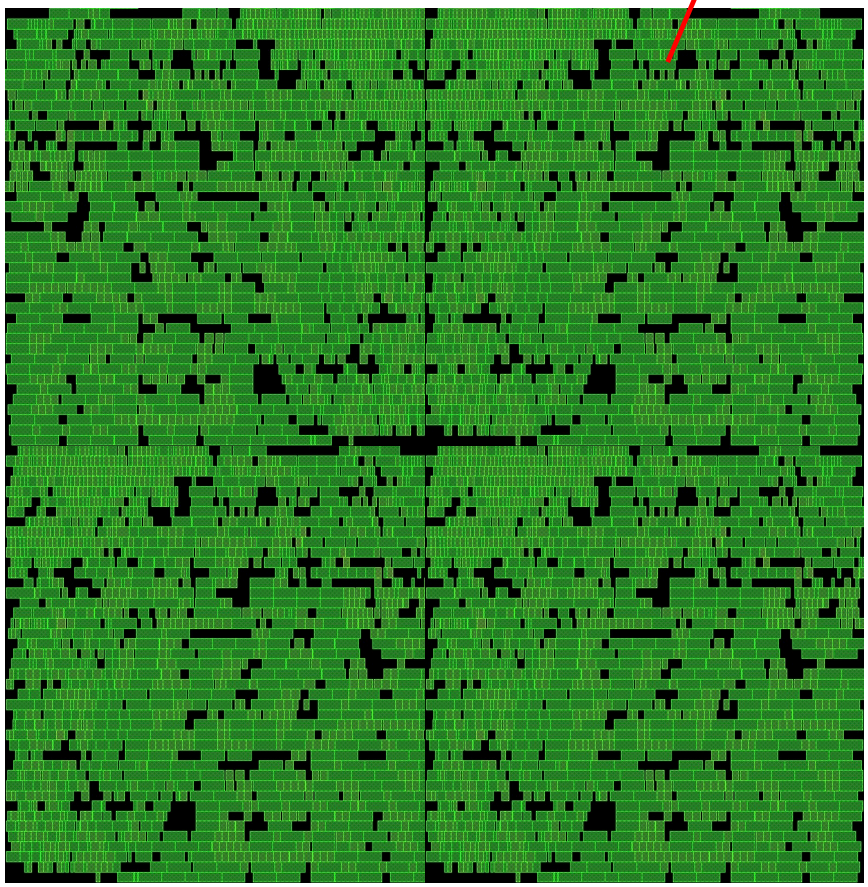

Dominant Elements: C H O P and N
Energy supply: Glucose




Dominant Elements: Si O Cu Al
Electric energy supply via power rails

# Biological Cell, Compared to a Standard Cell

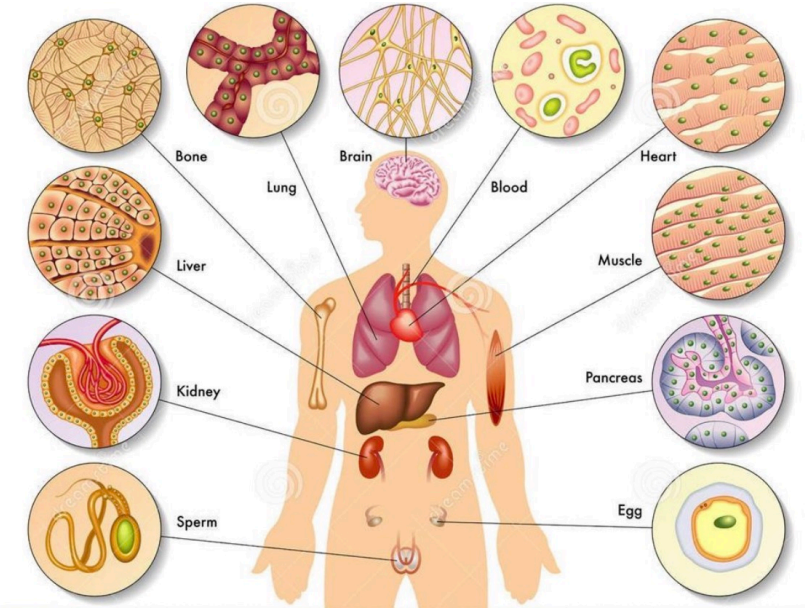


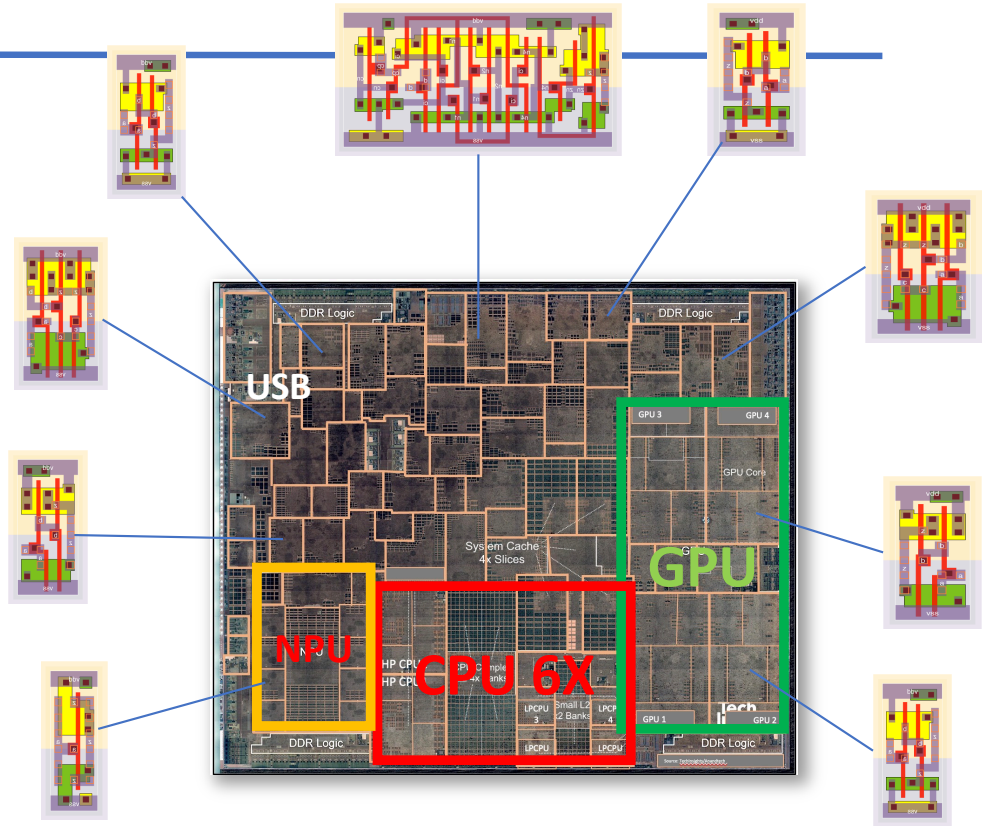
Biological cell is ~300X larger

But uses ~10,000X less energy

# Human vs SoC: Anatomical Similarities

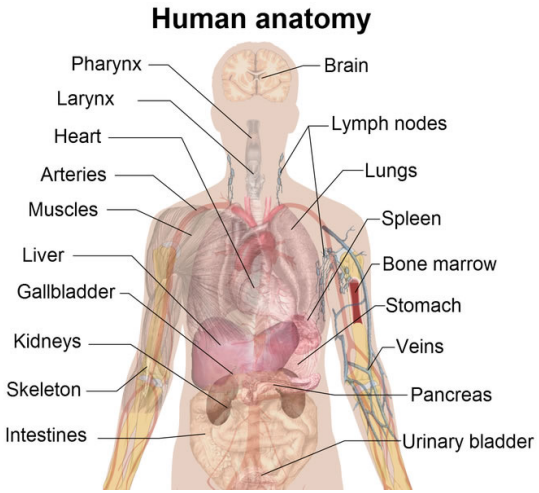


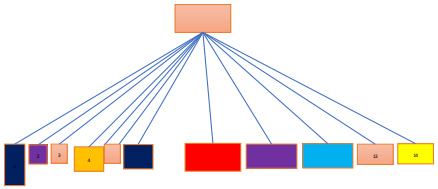

~200 different cell types
78 organs
400 Watt

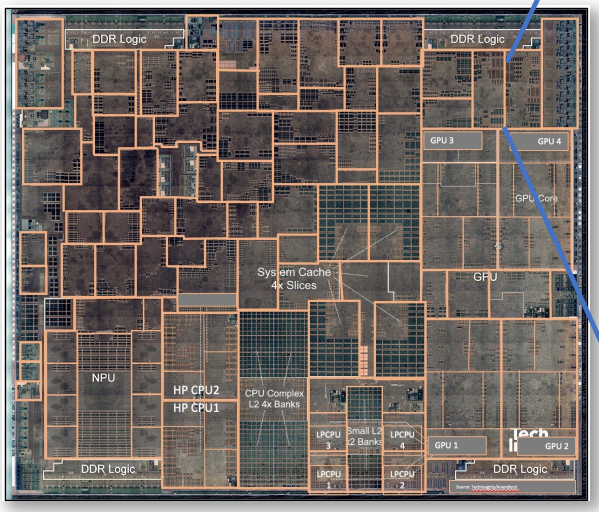


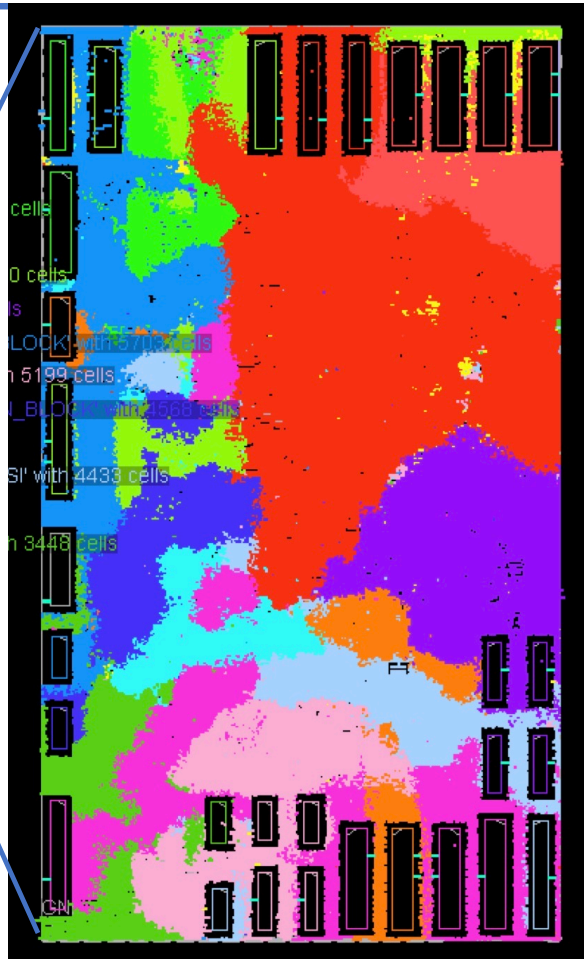

~200 different cell types
~75 blocks
400 Watt (max)

# ‘Flatter’ 3-Level Physical Hierarchy





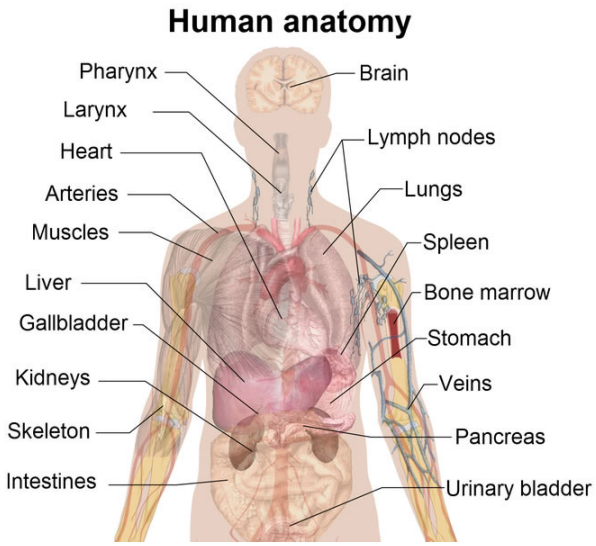



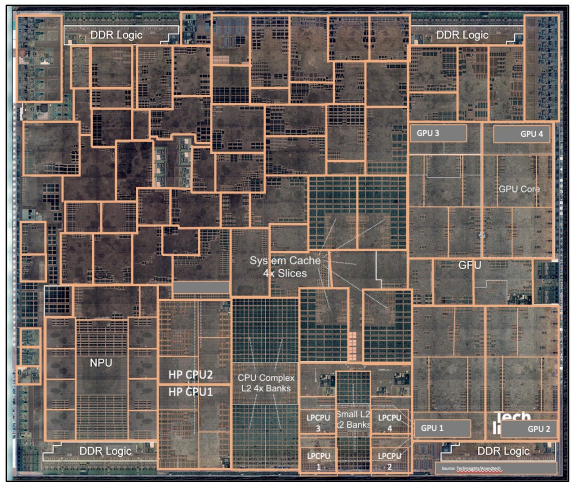
# Human Cells vs Standard Cells

| | Human Cell/human body | Standard Cell/chip |
|---|---|---|
| **Cell Library size** | ~200 | ~200 |
| **Cell components** | Nucleus, Ribosomes, membranes, DNA, Golgi, etc. | 2-20 transistors, vias, wires |
| **Number of cells** | 37,000,000,000,000 | 20,000,000,000 |
| **Main elements** | C, H, O, N, P | Si, O, Cu, Al |
| **Design** | Bottom-up evolution through natural selection, M-years | Top-down creation using EDA tools, months |
| **(re-) production** | Division, self-assembly | Lithography |
| **Power** | 400W | 400W |
| **Power per cell** | 0.001nW | 70nW |
| **Infrastructure** | Blood vessels, nerves | Power Wires, Clock network |
| **MTBF/lifetime** | 8 years (cell) /80 years (person) | 3 years (econ.)/ 10+ years |
| **Error resilience** | Self-healing | None |
| **Failure mechanisms** | Cancer, heart disease, infections | Electromigration, heat, ESD |
| **Disposal** | 100% recycled | 84% Landfill, <1% recycled |

# Key Similarities between Biological Systems and Electrical System

- **Cells are similarly sized**, with minor variation in types
- Cells use **uniform plumbing** for energy supply
- Cells are **composable into organs** (IP blocks) to perform a wild variety of functions
- An organism (or SoC) is built from several such organs blocks
- Somehow, arrangements of billions of cells become ‘intelligent’




**SoC Anatomy**

# Numerous as Sand on the Beach…

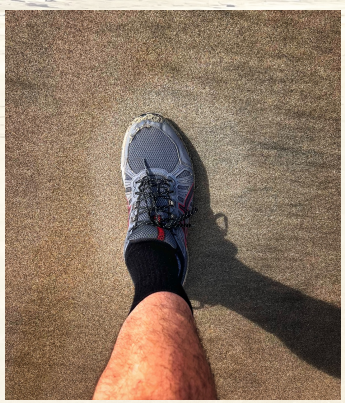
1000 BCE / Bible, Genesis 22 verse 17:
*I will surely bless you and make your descendants as numerous as* ***the stars in the sky*** *and as* ***the sand on the seashore***

1980 CE / Carl Sagan, Cosmos:
*There are* ***more stars in the universe*** *than there are* ***grains of sand on all the beaches of Earth***

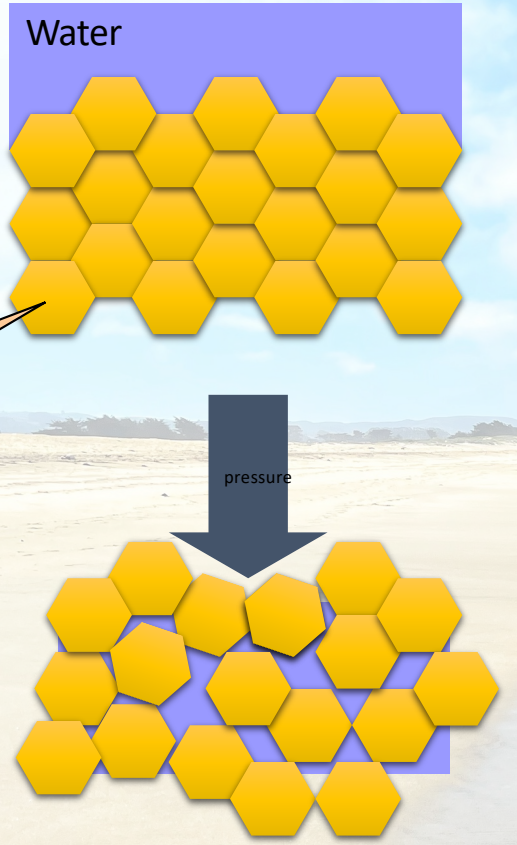
2024 CE / Some dude (Brady Booch) on Twitter:
*There are* ***more transistors on earth*** *than* ***grains of sand on all the beaches of Earth***

# Sand as a Parable for MOS Transistors

# Sand as a Parable for MOS Transistors

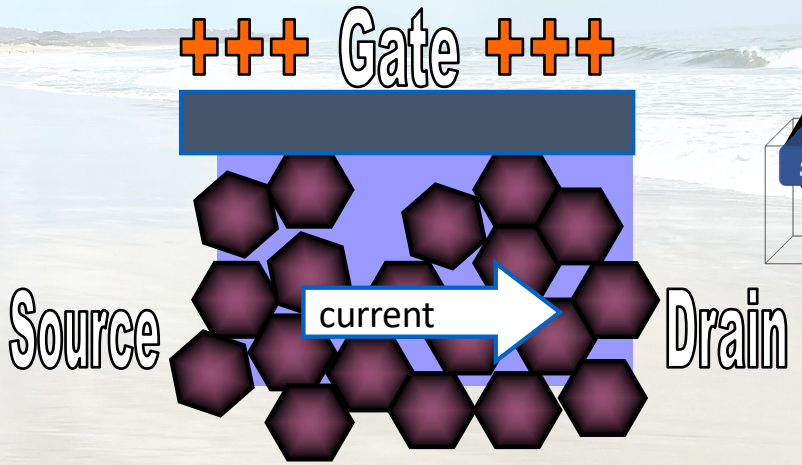


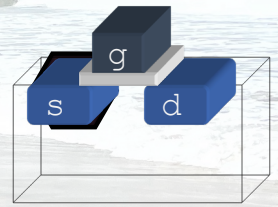
Grain of sand



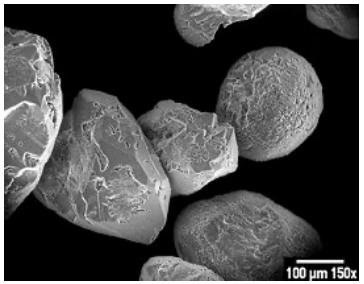




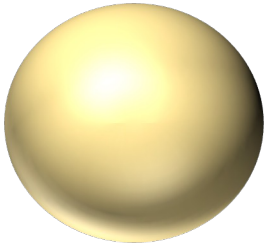



# Beach Sand or Stars: Which is Greater?



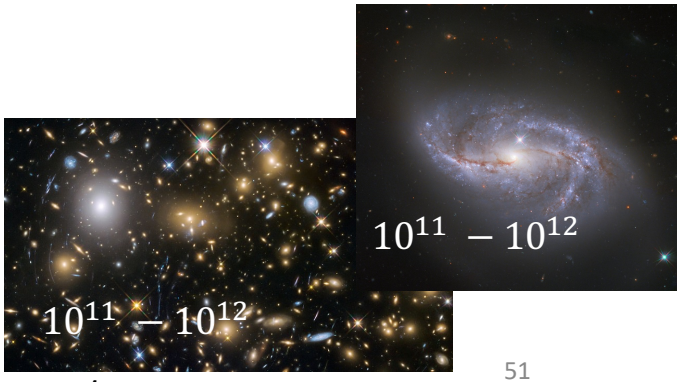

- There are ~ $\mathbf{6 * 10^{21}}$ (6 sextillion) grains of sand on beaches
  - Sand is grains of mainly $SiO_2$ , typically 0.5mm diameter.
    -> a cubic meter of sand contains ~8B grains
  - Assuming a beach is 200 meter wide and sand layer is 20 meters deep, then one km of beach has 1000 * 200 * 20 * 8B grains = $3.2 * 10^{16}$ grains per km of beach.
  - The world has 620,000 km of coastline, of which 31% is sandy (Source: NASA)
- There are between $\mathbf{10^{22}}$ and $\mathbf{10^{24}}$ stars in the universe
  - Between $10^{11}$ (100B) and $10^{12}$ (1T) stars per galaxy
  - Between $10^{11}$ and $10^{12}$ galaxies in the universe (source: ESA)



0.19mm2

0.5mm

Room for ~39,000,000 Transistors in 5nm



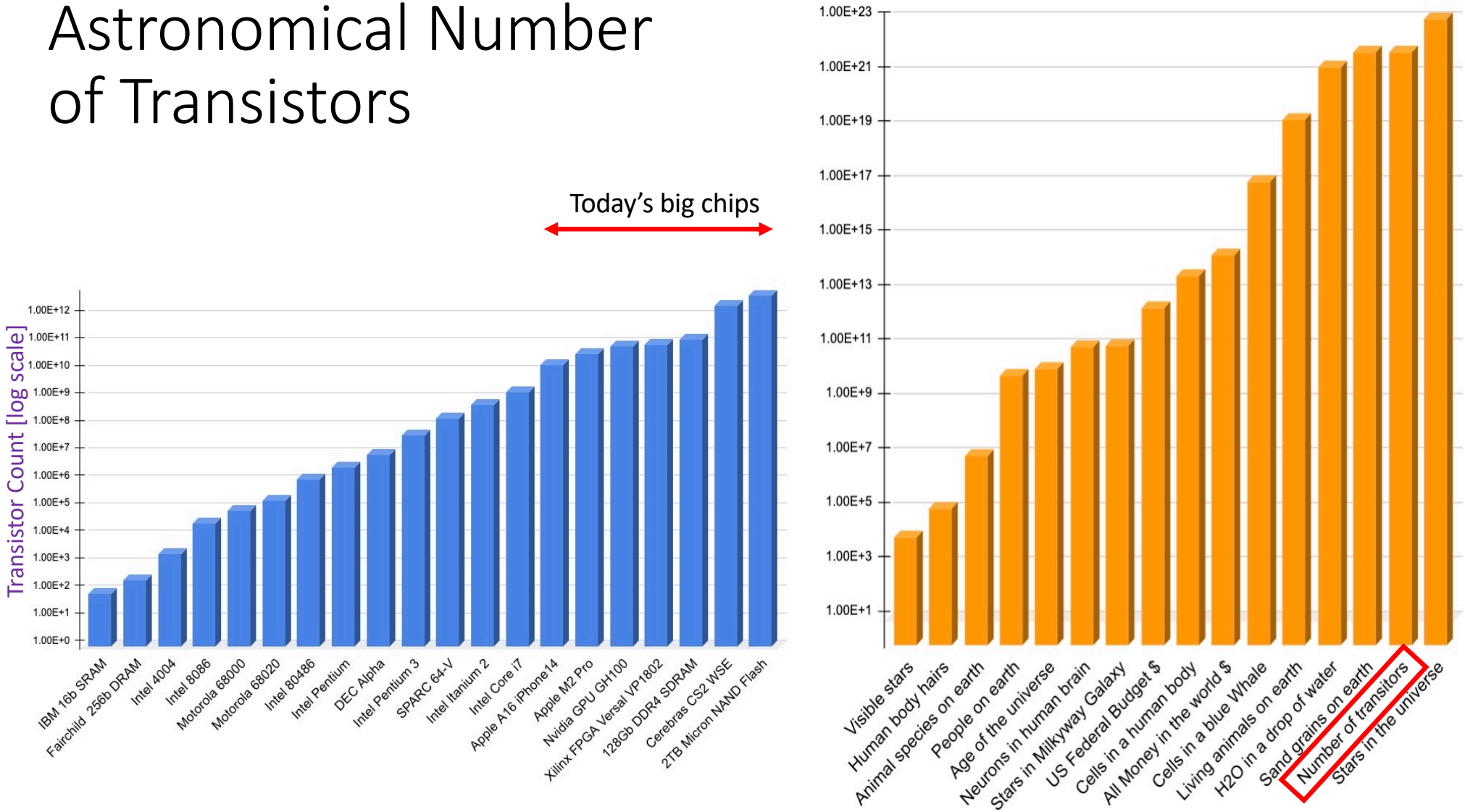

NASA/Hubble

# How many Transistors are “Alive” in the World?

- Approx. $8 * 10^{19}$ in 2024 based on number of 12” wafers :
  - TSMC made 13M wafers, most in dense technologies of ~3T transistors/wafer = $2.9 * 10^{19}$. They have ~40% of the market.
  - Approx. 72M raw 12-inch wafers were produced in 2023 @ ~1T transistors per wafer
- Approx. $1.8 * 10^{21}$ in 2024 alone based on NAND FLASH memory market data:
  - Flash memory market was ~$70B in 2024
  - at $100/Terabyte means that ~700M TB were produced = $1.8 * 10^{21}$ Transistors (assuming $2.6 * 10^{12}$ transistors per TB = 6 bits per cell)
- With average product life of 3 years, we have $\mathbf{6 * 10^{21}}$ transistors running, most of them as memory

- Conclusions:
  - There are approximately **as many transistors as grains of sand** on all beaches in the world
  - There are **still more stars than transistors** in the universe

# Astronomical Number of Transistors



# Electronic Design Automation at Astronomical Scale

- EDA design methodologies pull it off , somehow
- How?
  - Successful algorithms
  - Gradual transition through abstraction level
  - Strict verification
- Next steps:
  - Harness Machine Learning .. And gen-AI