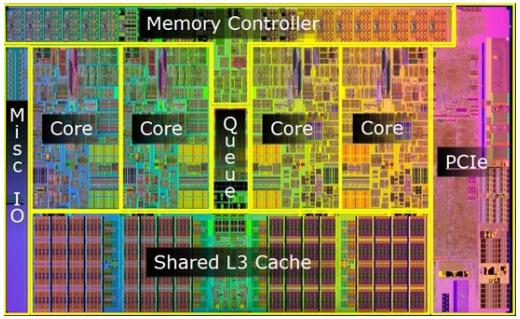

088949 – ADVANCED COMPUTER ARCHITECTURES COURSE OVERVIEW

Second Semester 2024/2025

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Prof. Cristina Silvano
email: cristina.silvano@polimi.it
Politecnico di Milano

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What are the Advanced Computer Architectures?

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ACA Course Objectives

- Main goal is to understand the major concepts used in **modern microprocessor architectures** by the end of the semester and main techniques on **how to improve performance.**

- The course will cover **different forms of parallelism:**
  - **instruction-level**
  - **data-level**
  - **thread-level**
  - **core-level**

- The course discusses how these forms of parallelism can be exploited by **parallel processor architectures.**

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Parallel Architectures

- Parallel Superscalar Processors
- Multicore and Manycore Processors
- Multithreading Processors
- Data Parallel Vector Processors
- Neural and Neuromorphic Processors
- Reconfigurable Architectures
- Heterogeneous Architectures

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Systems based on Parallel Computing Architectures

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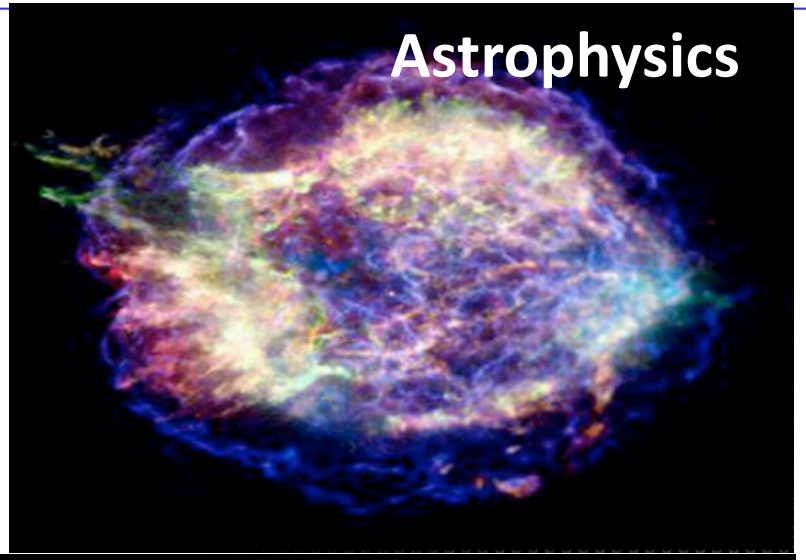
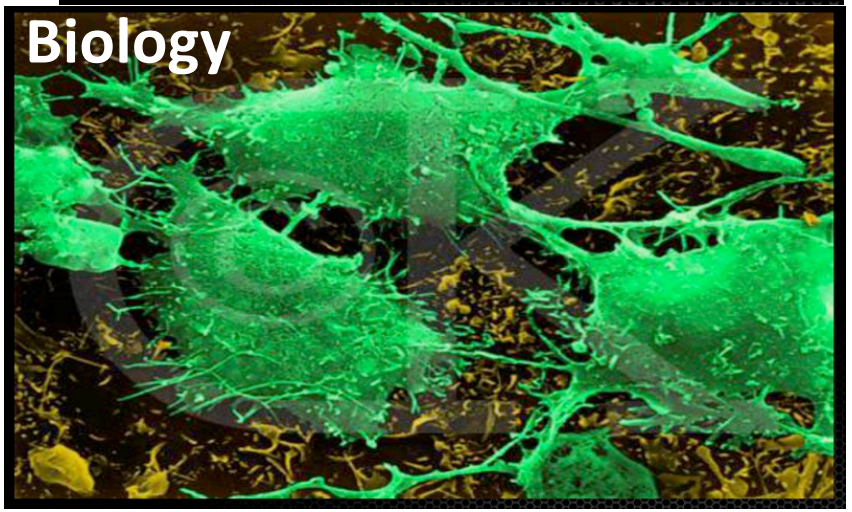
Applications driving the demand for more computing performance and big data





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TOP500 List

- The **TOP500 list** is ranking the world's most powerful supercomputers.
- The TOP500 list is updated twice a year: in June and in November.
- The **LINPACK Benchmark** (introduced by Jack Dongarra) is used to measure the system's floating point computing power.
- LINPACK measures how fast a computer solves a dense ***n*** by ***n*** system of linear equations ***A x = b,*** which is a common task in engineering.

TOP500 The List.

www.top500.org

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How to measure performance?

Flop/s, Floating Point Operations per Second

Name	Flop/s
ExaFlop/s	10^{18}
PetaFlop/s	10^{15}
TeraFlop/s	10^{12}
GigaFlop/s	10^{9}
MegaFlop/s	10^{6}
KiloFlop/s	10^{3}
Flop/s	1

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High Performance Computing

- First supercomputer reaching the **Petascale** (10^{15} Flops) performance: IBM Roadrunner installed in **2008** at Los Alamos National Lab (New Mexico, USA).
- Research on supercomputing has pushed to the ***Exascale era of billions of billions (10^{18}) FLOPS reached in 2022.***

In 2022, TOP500 announced Frontier as the first Exascale machine up to 1.102 ExaFlop/s.

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Top500 (November 2024)

#1 El Capitan (USA) reached 1.742 ExaFlop/s with 11M combined CPU and GPU cores based on AMD 4th gen. EPYC processors with 24 cores at 1.8GHz and AMD Instinct MI300A. Energy efficiency of 58.89 GigaFlops/Watt.
Site: Lawrence Livermore National Laboratory in California, USA.

Top500 (November 2024)

#2 Frontier (USA): In June 2022, first Exascale supercomputer with 1,2 ExaFlop/s on Linpack.
In Nov. 2024, it reached 1.35 Exaflop/s (2024) with 9 M cores and 24.6 MW.
Based on HPE Cray EX235a architecture, AMD EPYC 64C 2GHz processor and AMD Instinct MI 250X.

Site: Dept. of Energy's, Oak Ridge National Lab., Tennessee (USA).

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Where is Italy placed in the worldwide ranking?

#5 in Top500 and #1 in Europe: HPC6

Same architecture as Frontier, but only 3 M cores.

Pre-Exascale system with 477.90 PFlop/s and 8.5 MW power dissipation.

Site: ENI center in Ferrera Erbognone (PV), Italy.

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Where is Italy placed in the worldwide ranking?

#9 in Top500 and #4 in Europe: Leonardo

Pre-Exascale with 241 PetaFlop/s on Linpack benchmark with 1.8M cores and Atos BullSequana XH2000 system based on Xeon Platinum 8358 32C 2.6 GHz, NVIDIA A100 SXM 4 64GB.

Site: CINECA, Bologna (Italy).
Co-funding 240 Meuro EuroHPC & Italian Ministry of Univ. and Research.

Leonardo entered as **#4** in Top500 in Nov. 2022.

HPC vs Laptop: Performance comparison

2024

#1 Frontier 1.2 ExaFlop/s

10^6x

2024

Laptop at 4 GHz 3.6 TeraFlop/s

HPC vs. Smartphone: Performance comparison

2004

IBM BlueGene 2004: 9.1 TeraFlop/s

≈

2024

Apple iPhone 15 Ultra: 2.5 TeraFlop/s

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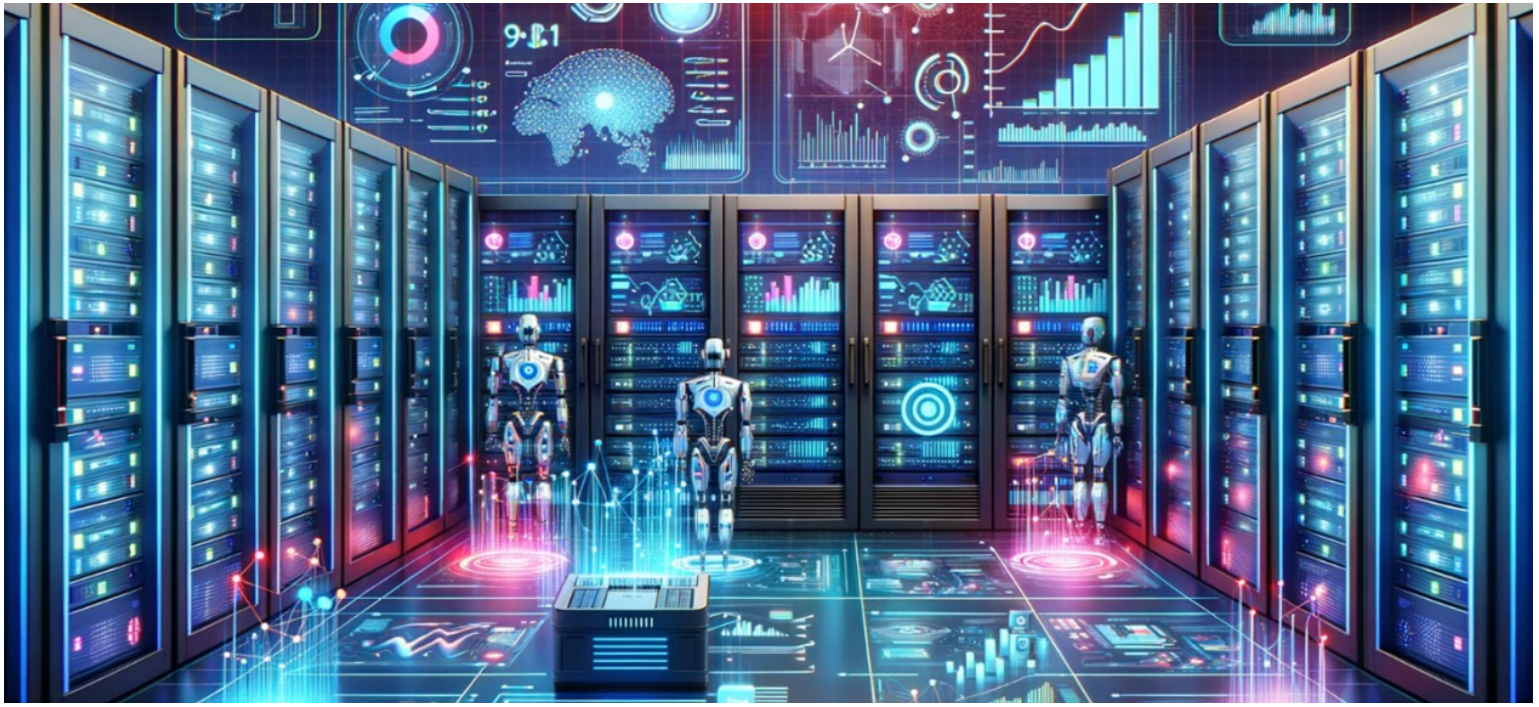
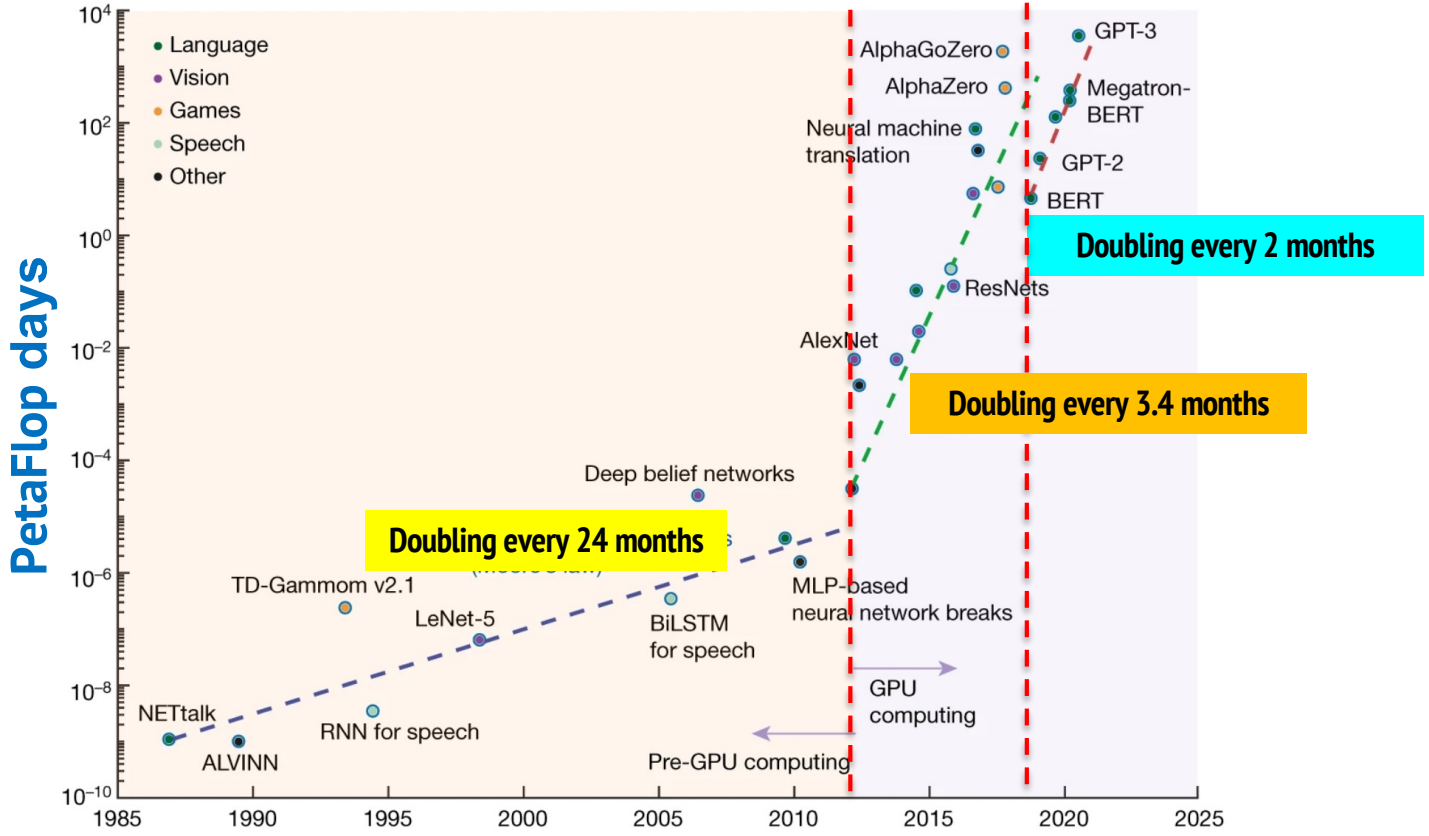
HPC and Artificial Intelligence: Some trends



1) Computing power demands for AI applications



Mehonic and Kenyon, Brain-inspired computing needs a master plan, Nature, 2022

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2) Generative AI workloads are energy hungry

- ChatGPT-3 training required thousands of GPUs for about one month with **more than 200 MWh.**
- Estimating a family consumes on average **10 MWh per year** => GPT-3 training corresponds to the average energy consumed by a family in *20 years!*
- A single request to ChatGPT-3 requires about ten times more energy (**2.9 Wh**) than a search on Google (**0,3 Wh**).

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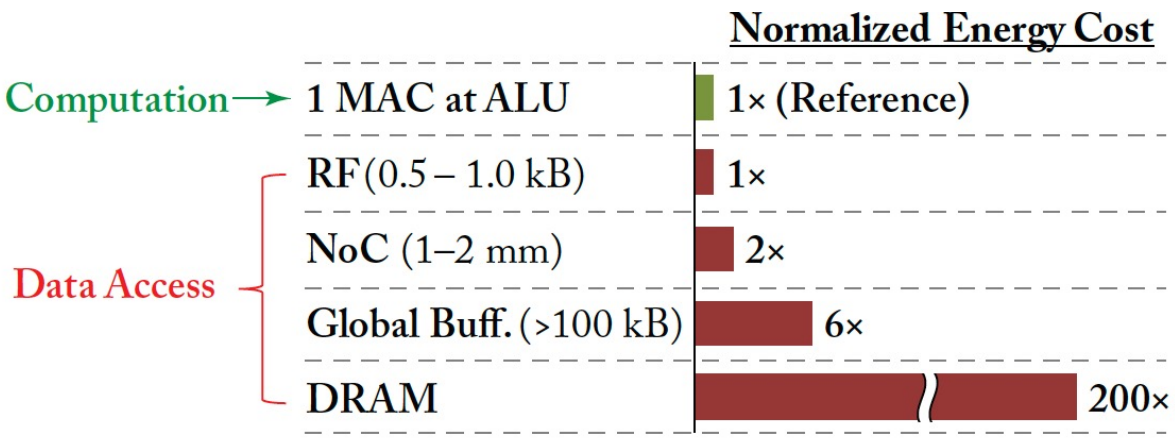
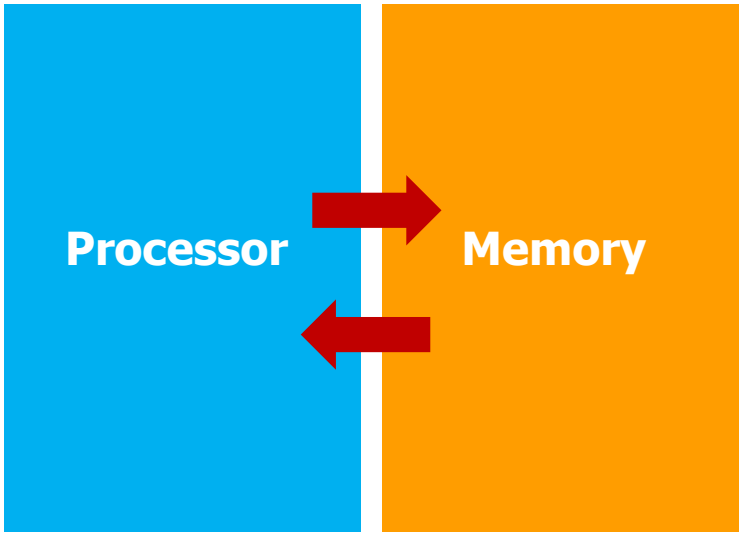
3) Data transfer dominates energy consumption





Most of the energy consumption is spent to move data.

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4) Brain-inspired or Neuromorphic Computing

- To take inspiration from **biology,** where data storage is not separate from processing.
- In the **human brain,** neurons and synapses perform both functions in massively parallel and adaptable structures with extreme energy efficiency.
- Neuromorphic Computing systems transform the way of processing signals and data by **co-locating memory and processing.**

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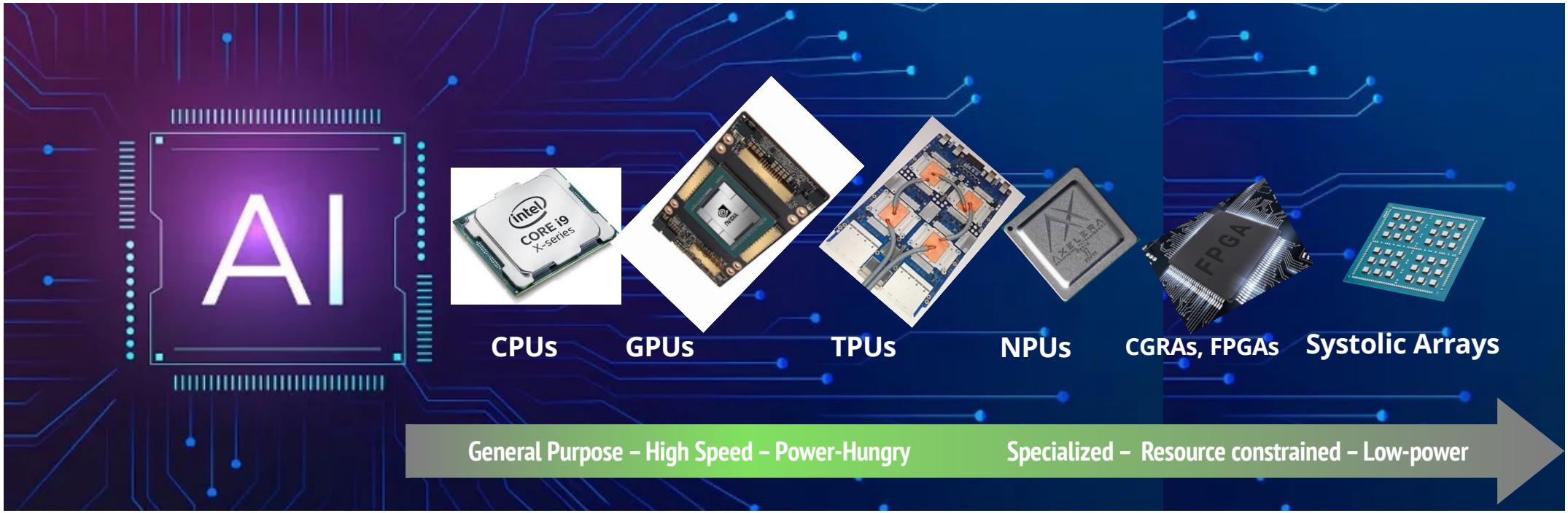
AI Accelerators from HPC to the Edge



D. Garisto, "Accelerating AI: The cutting-edge chips powering the computing revolution", Nature, News Feature, Vol.630, June 2024.

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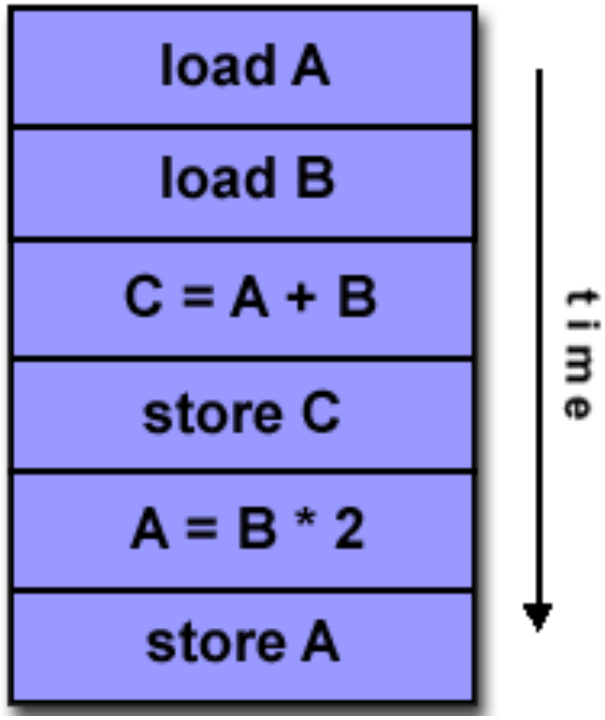
How did we get here?

- *Technology?*
- *Parallelism?*
- *Which kind of parallelism?*

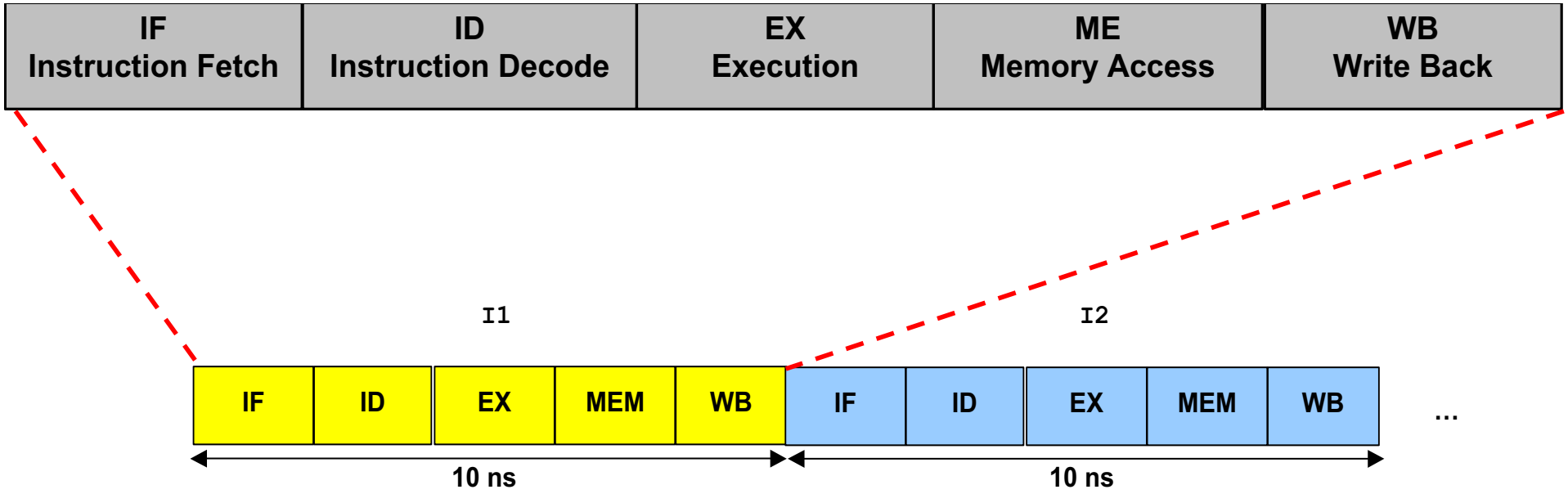
SISD: Single Instruction Single Data

- A serial (non-parallel) computer
- **Single instruction:** only one instruction stream is executed by the CPU
- **Single data:** only one data stream is being used as input
- Each instruction is executed by the CPU during each clock cycle



Instruction execution into phases

Each instruction is executed in **5 clock cycles (phases)**



Sequential execution

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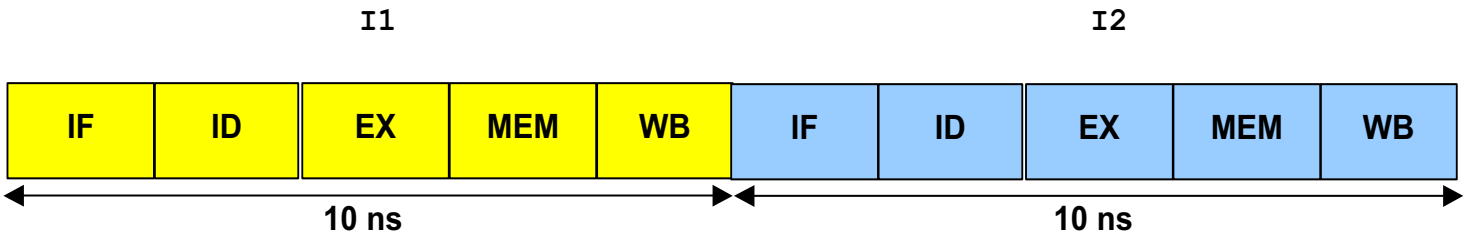
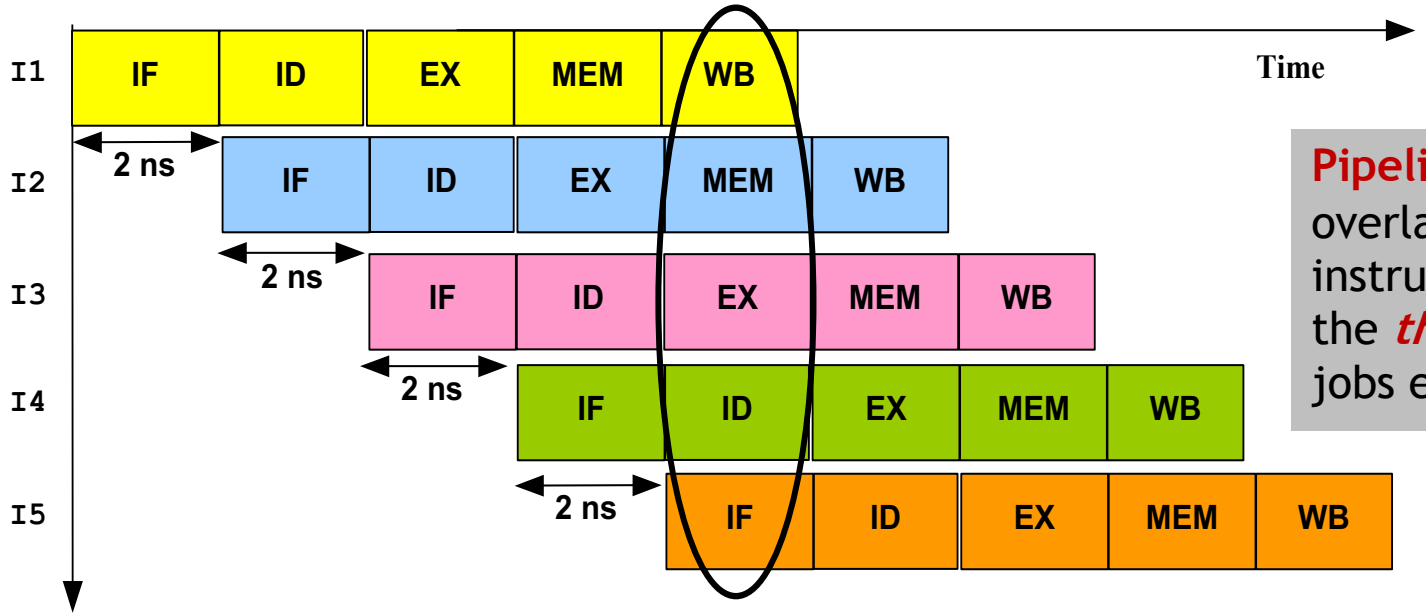
Sequential vs. Pipelining Execution: Instruction Level Parallelism

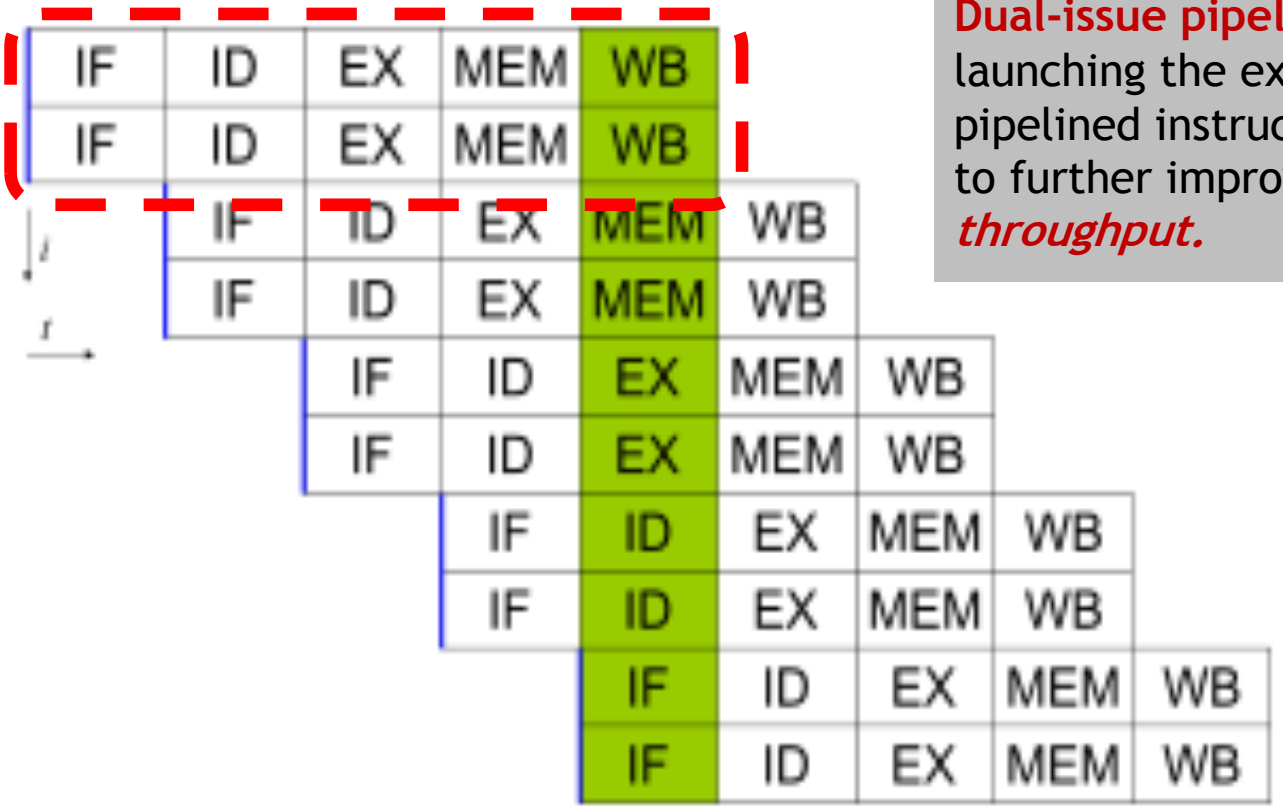


Sequential execution of instruction stages.



Pipelined execution: overlapping execution of instruction stages to improve the ***throughput:*** number of jobs executed per time unit

Multiple-issue pipeline to double the throughput



Dual-issue pipeline:
launching the execution of two pipelined instructions per cycle to further improve the ***throughput.***

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Pallelism? Which kind?

- *Instruction Level Parallelism: Pipelining, Multiple Issue*
- *What's next? Multiprocessing*

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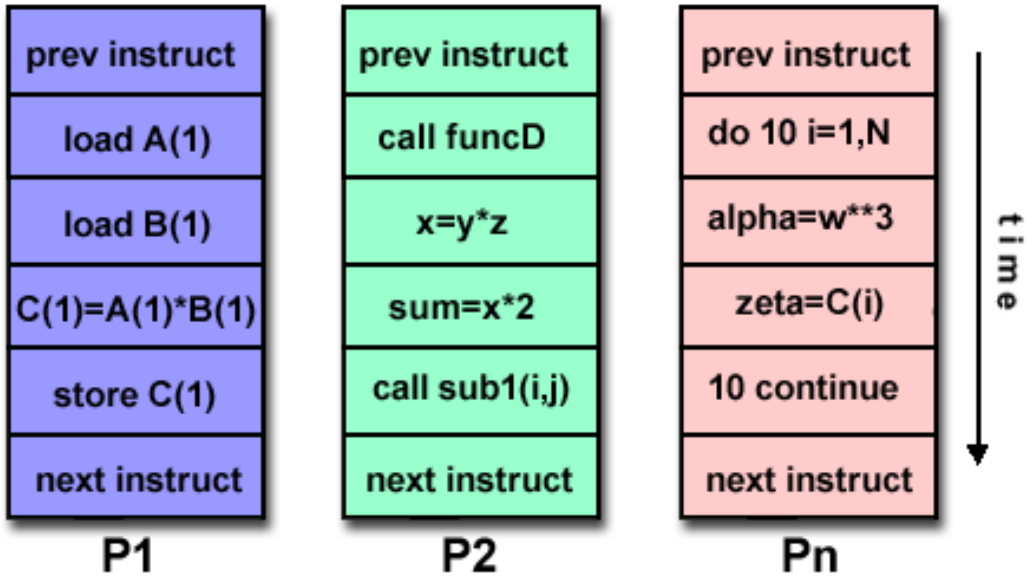
MIMD: Multiple Instruction Multiple Data

- **Multiple Instruction:** every processor may be executing a different instruction stream
- **Multiple Data:** every processor may be working with a different data stream



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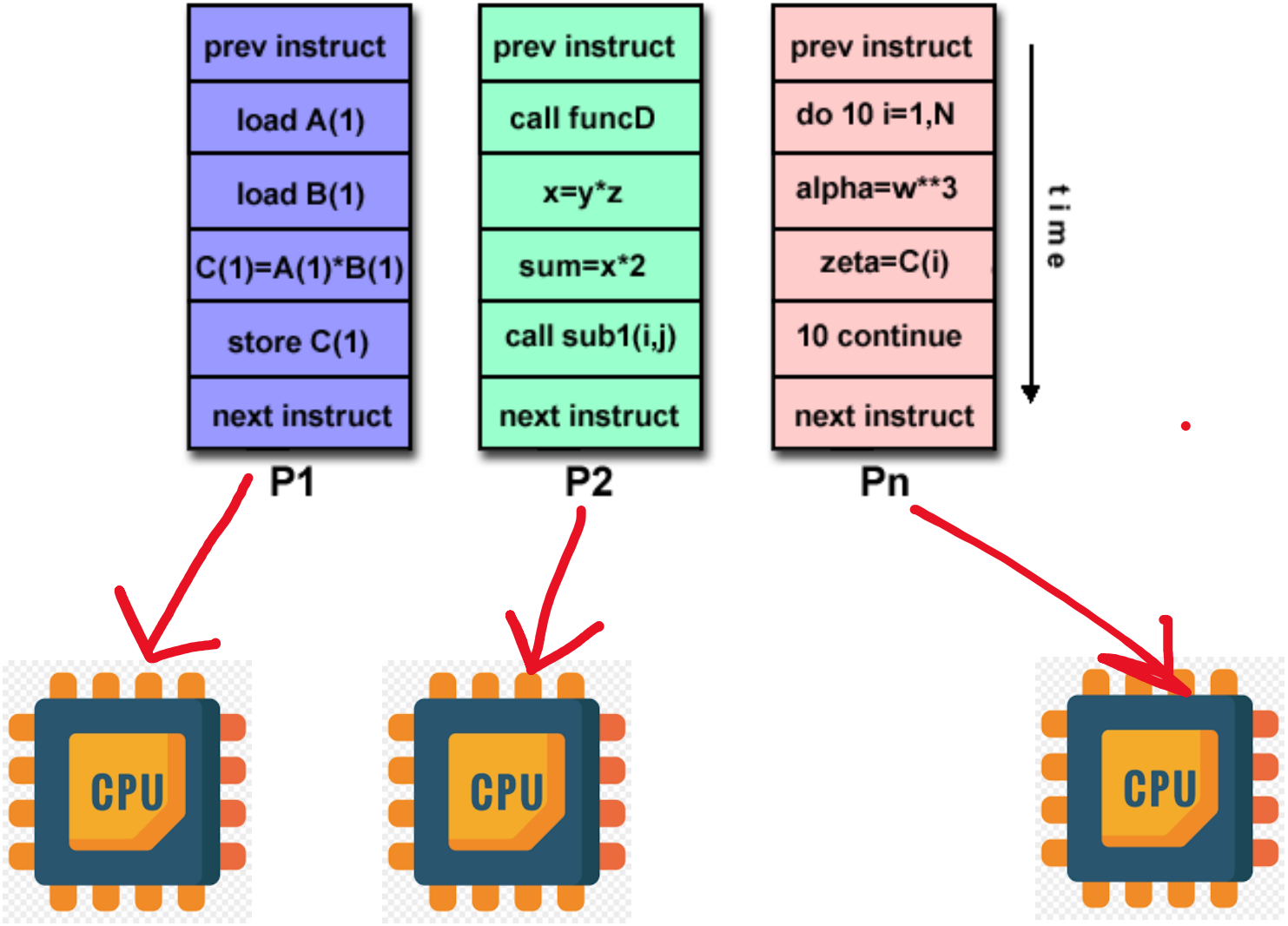
MIMD: Multiprocessors



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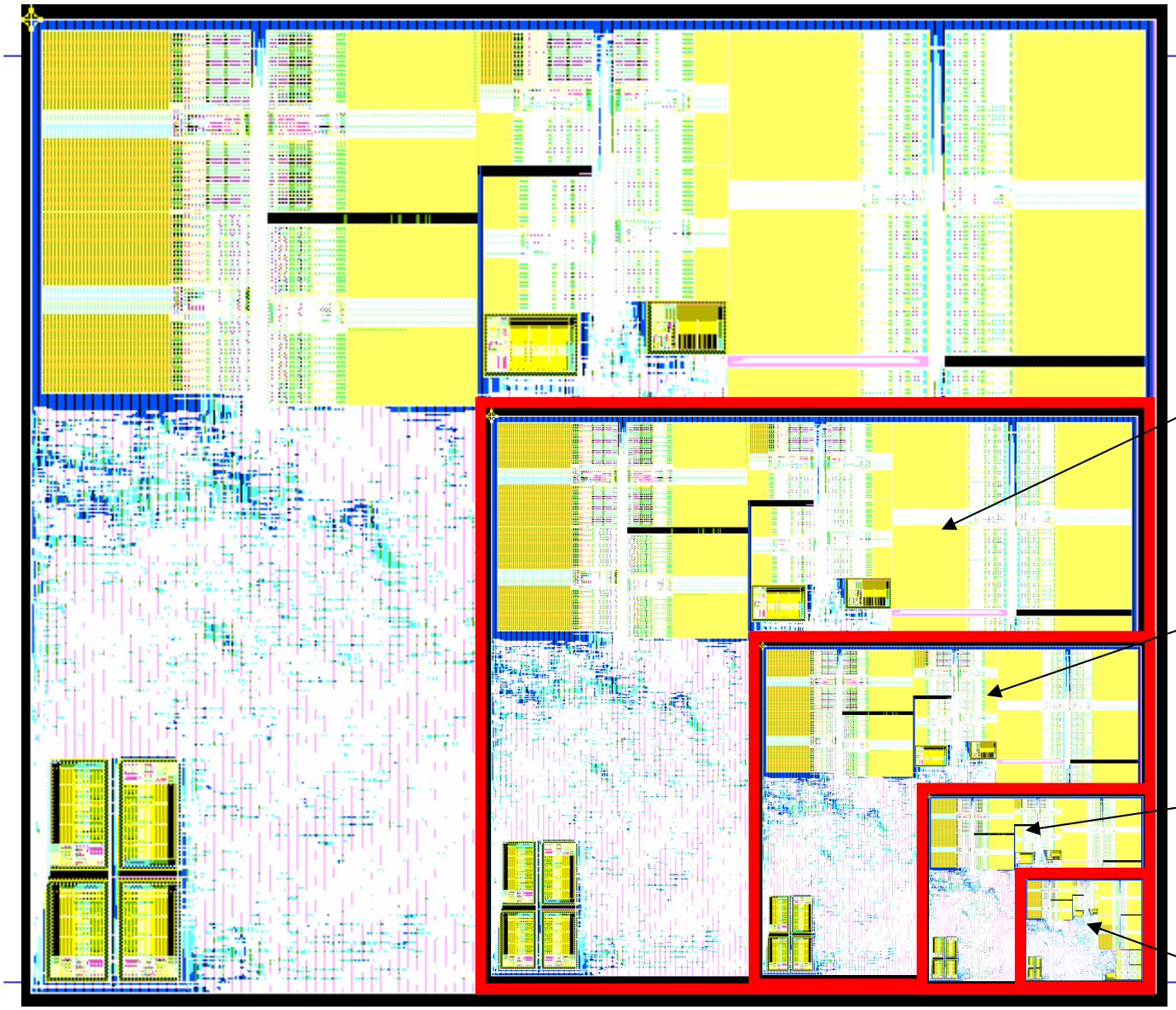
Squeezing of computing cores



2005
65 nm
1.4 mm²

Source:
ARM9 STMicroelectronics

2007
45 nm

2009
32 nm

2011
22 nm

2013
14 nm

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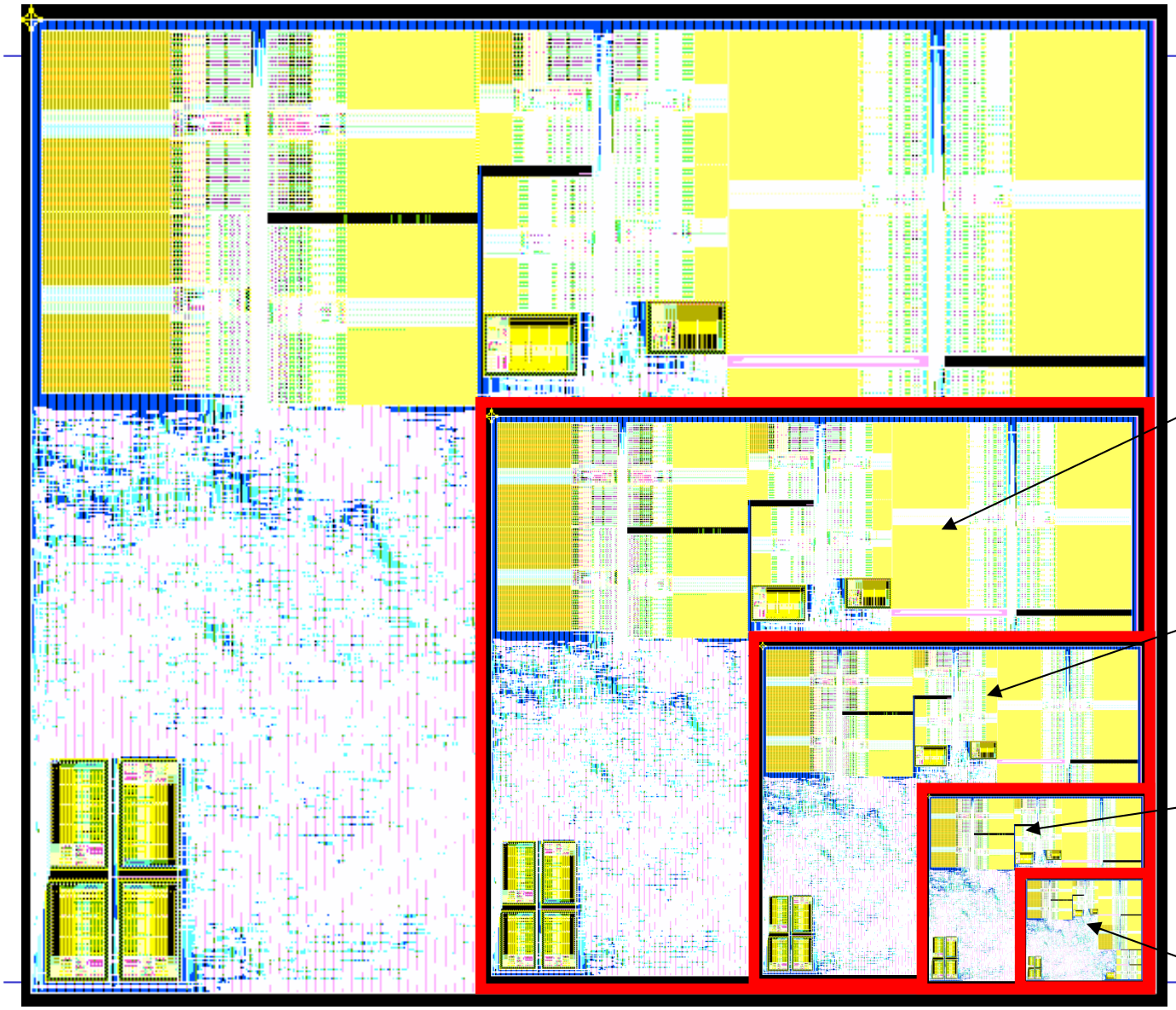
… entering the multi/many-core era



2005
65 nm
1.4 mm²

Source:
ARM9 STmicroelectronics

2007
45 nm

2009
32 nm

2011
22 nm

2013
14 nm

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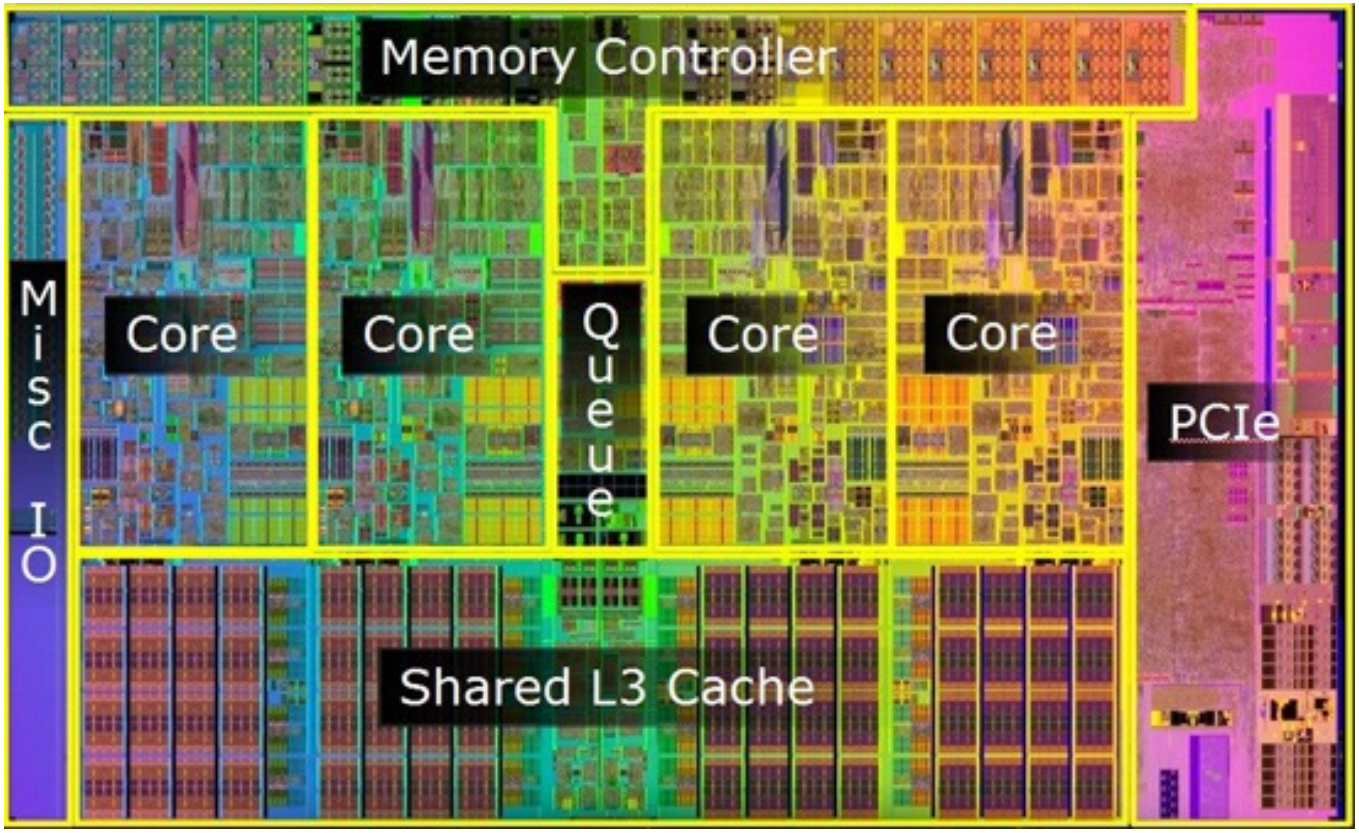
Multicore: Multiprocessor on a single-chip



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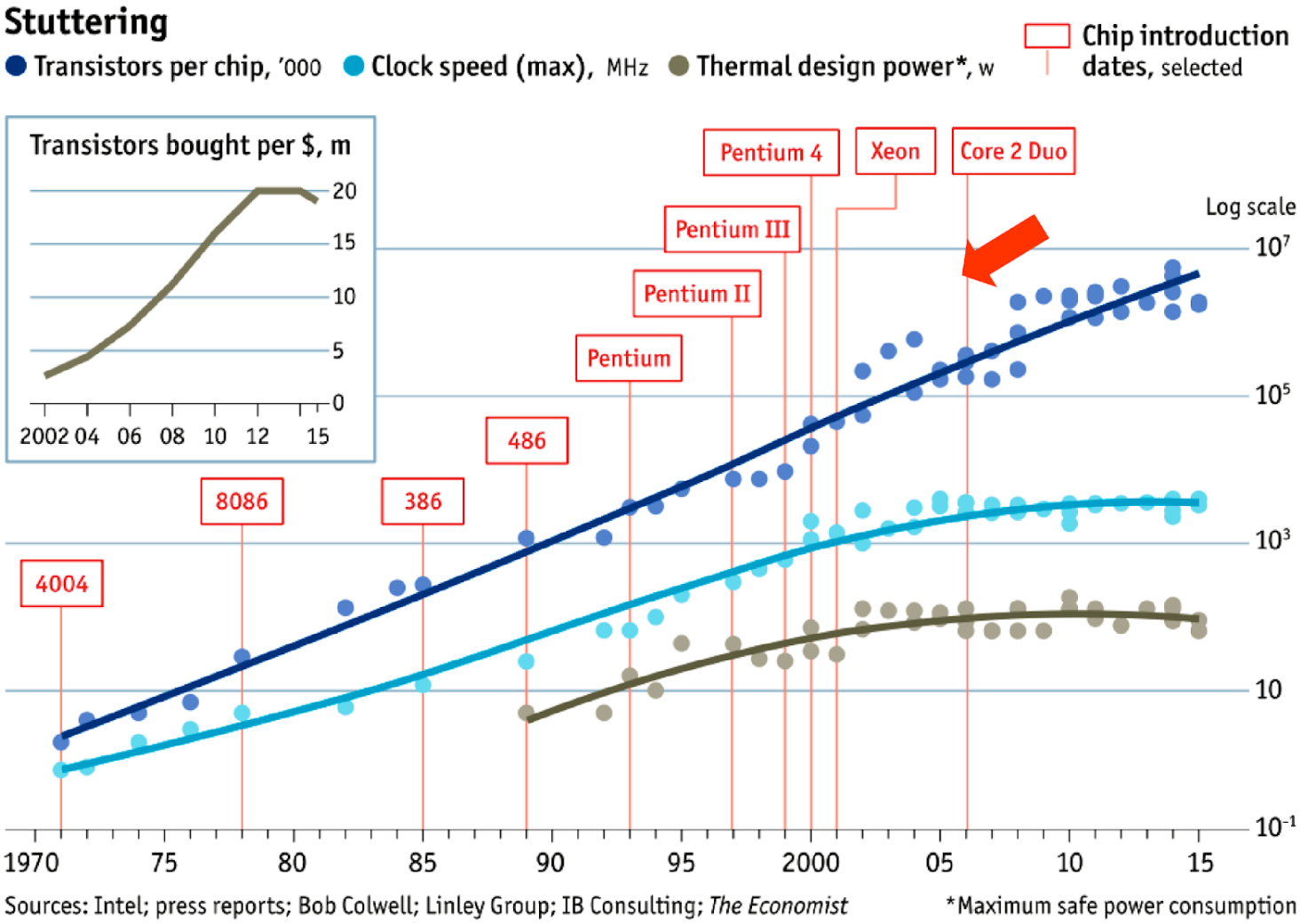
Technology Trends



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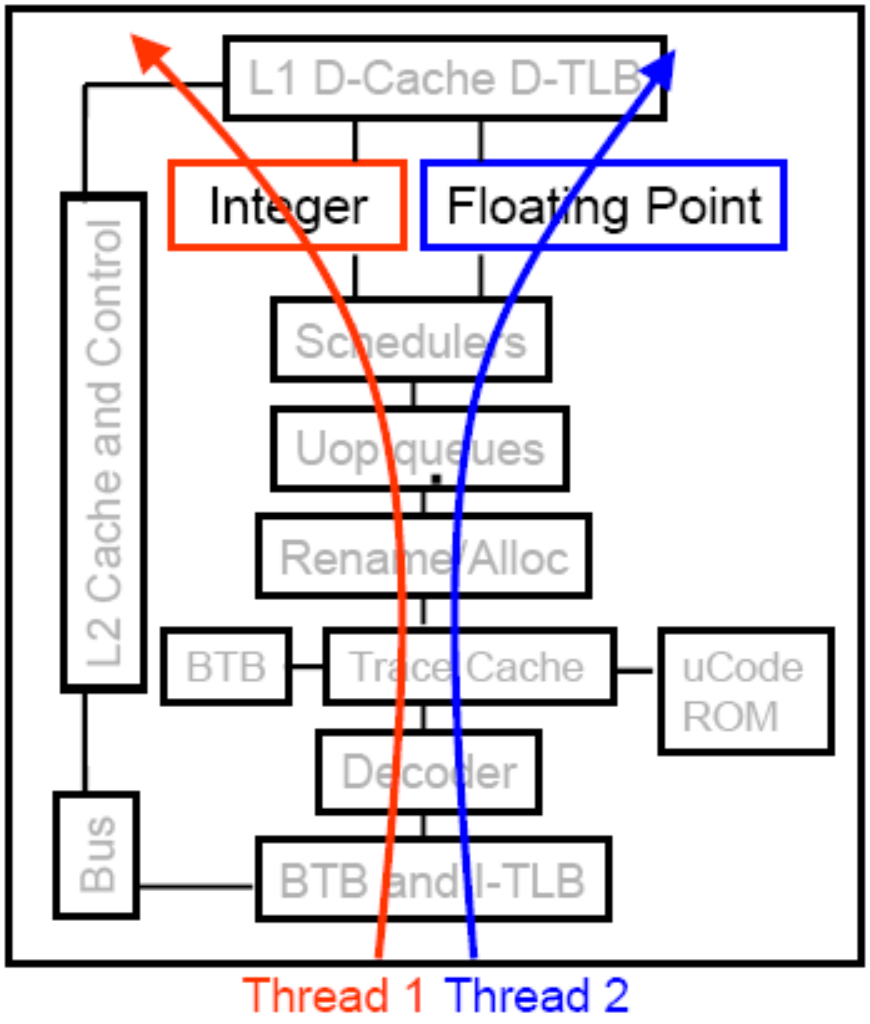
Pallelism? Which kind?

- ILP: Pipelining, Multiple Issue (SISD)
- Multiprocessing and Multicores (MIMD)
- *What's next?*
  - *Multithreading*

Two threads per processor core



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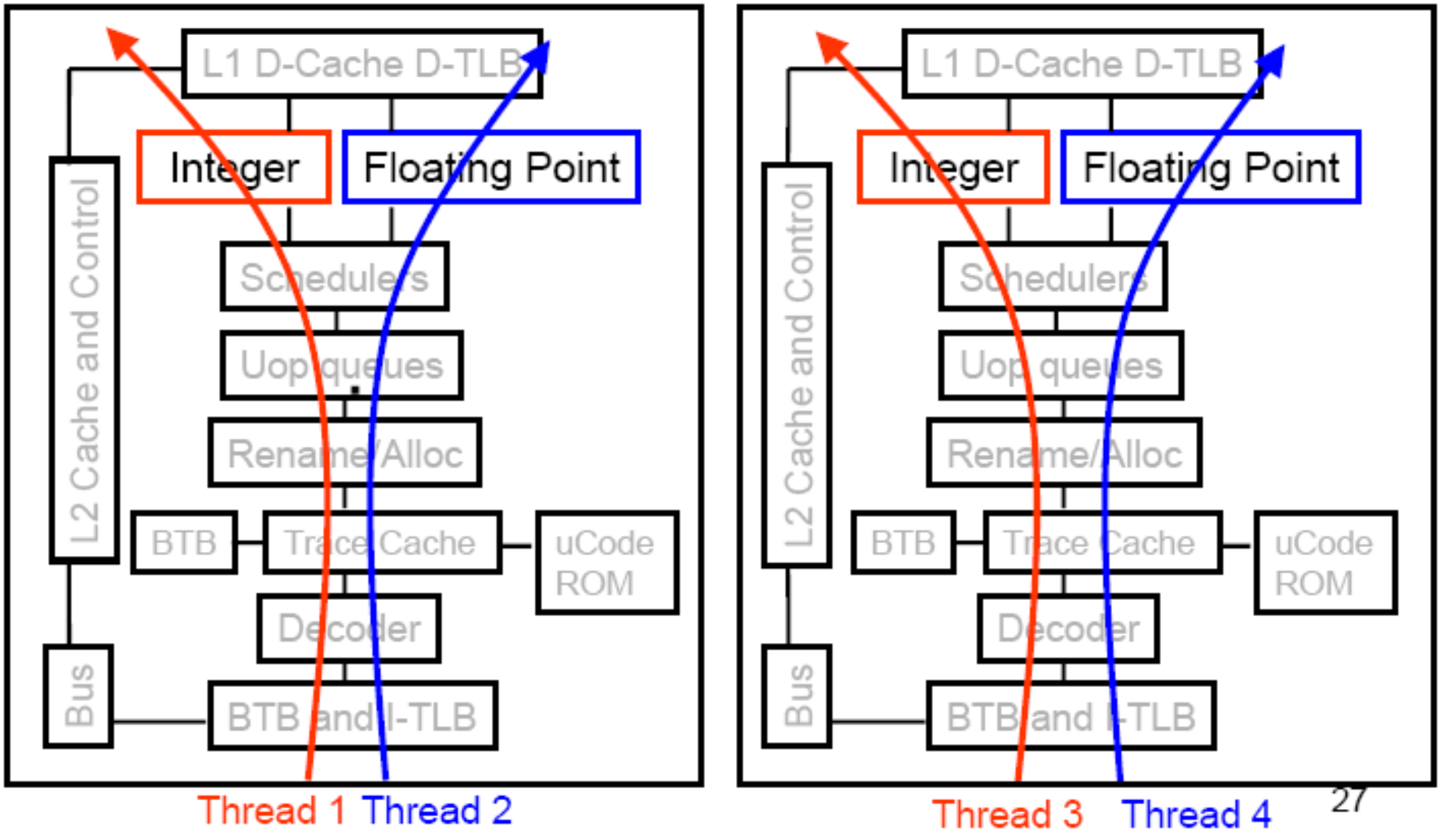
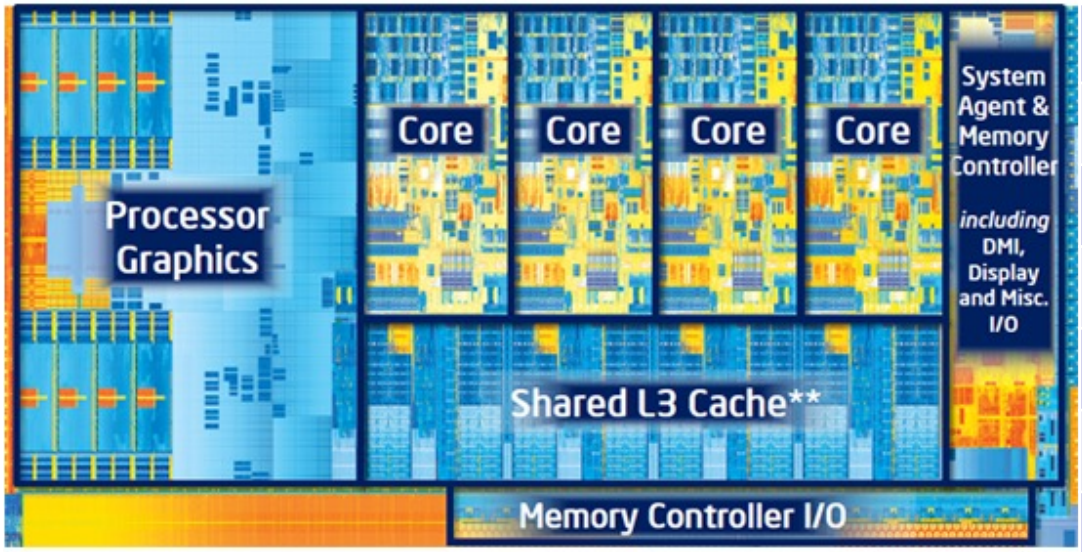
Dual-core processor with 2 threads per core



Intel® Core™ i7-3770T Hyperthreading Processor



- First generation launched in 2008.
- Next generations: Broadwell, Skylake, Kaby Lake at 14nm (2014); Cannonlake at 10nm (2H 2017); Ice Lake 10nm (2018).

# of Cores	4
# of Threads	8
Clock Speed	2.5 GHz
Max Turbo Frequency	3.7 GHz
Intel® Smart Cache	8 MB
Instruction Set	64-bit
Instruction Set Extensions	SSE4.1/4.2, AVX
Number of transistors	1.4 B transistors
Lithography	22 nm
Max TDP	45 W
Recomm. Customer Price	TRAY: $294.00
Max Memory Size	32 GB
Memory Types	DDR3-1333/1600
# of Memory Channels	2
Max Memory Bandwidth	25.6 GB/s

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Pallelism? Which kind?

- ILP: Pipelining, Multiple Issue (SISD)
- Multiprocessing and Multicores (MIMD)
- Multithreading
- *What's next? Data-Level Parallelism (SIMD)*

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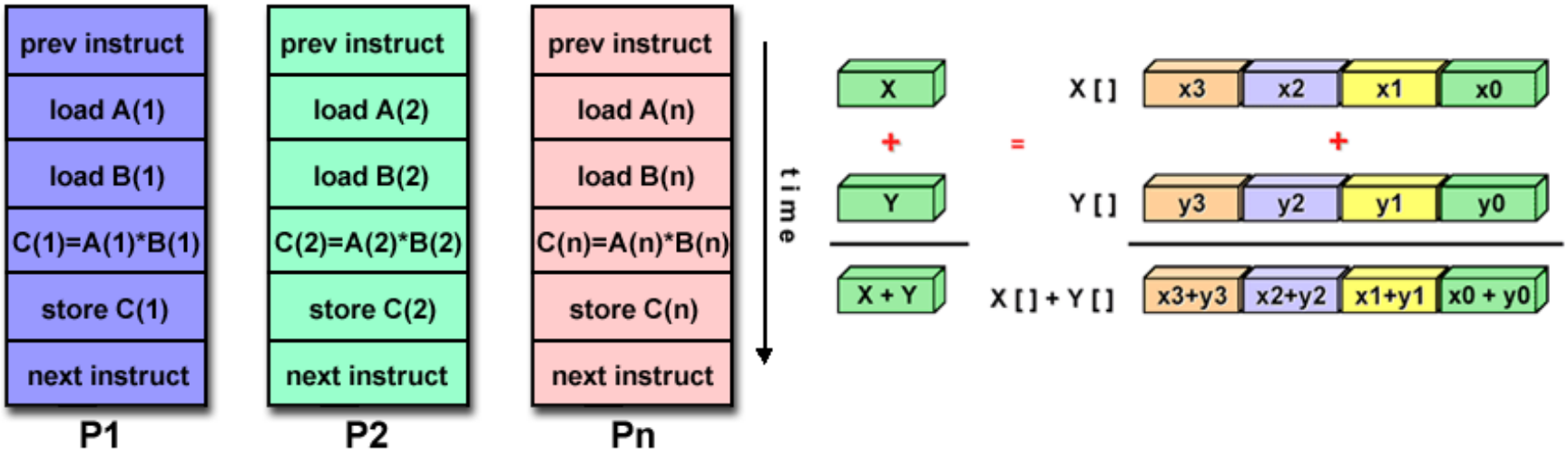
SIMD: Single Instruction Multiple Data

- **Single instruction:** all processing units execute the same instruction at any given clock cycle
- **Multiple data:** each processing unit can operate on a different data element



- Suitable for specialized problems managing vectors

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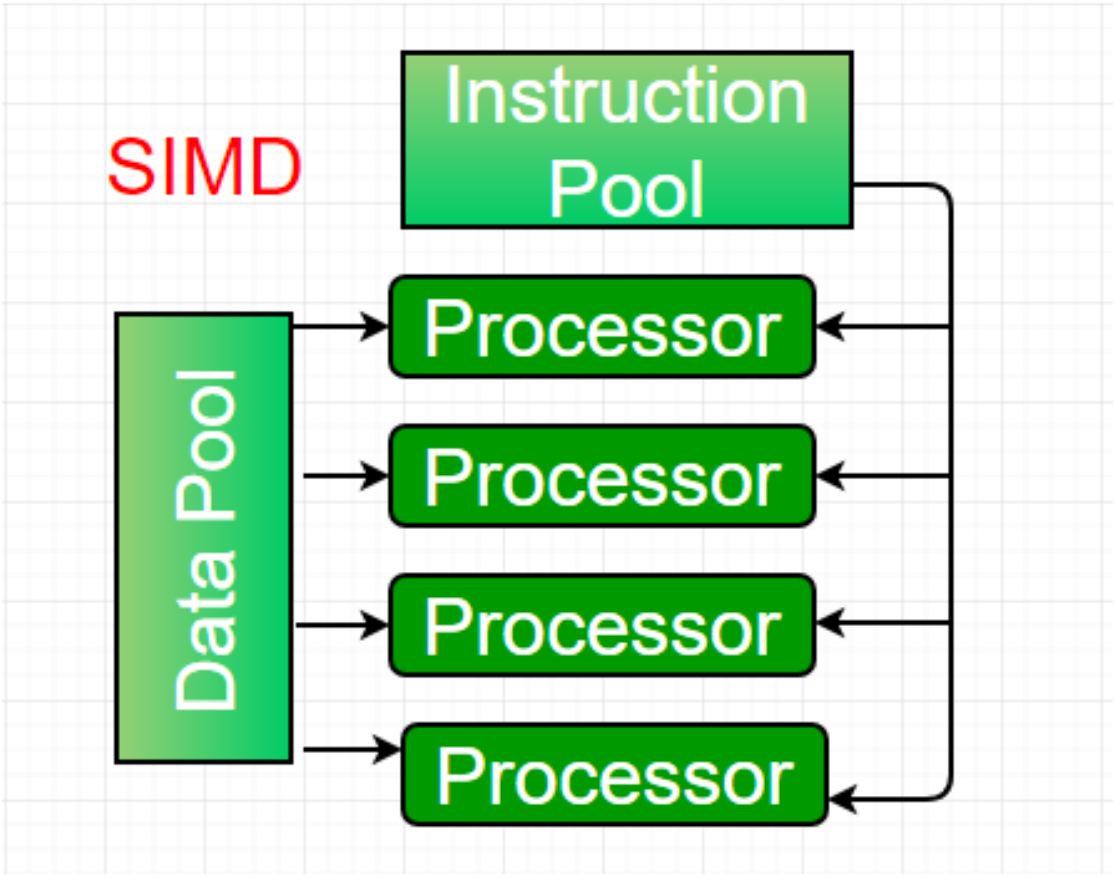
SIMD: Single Instruction Multiple Data



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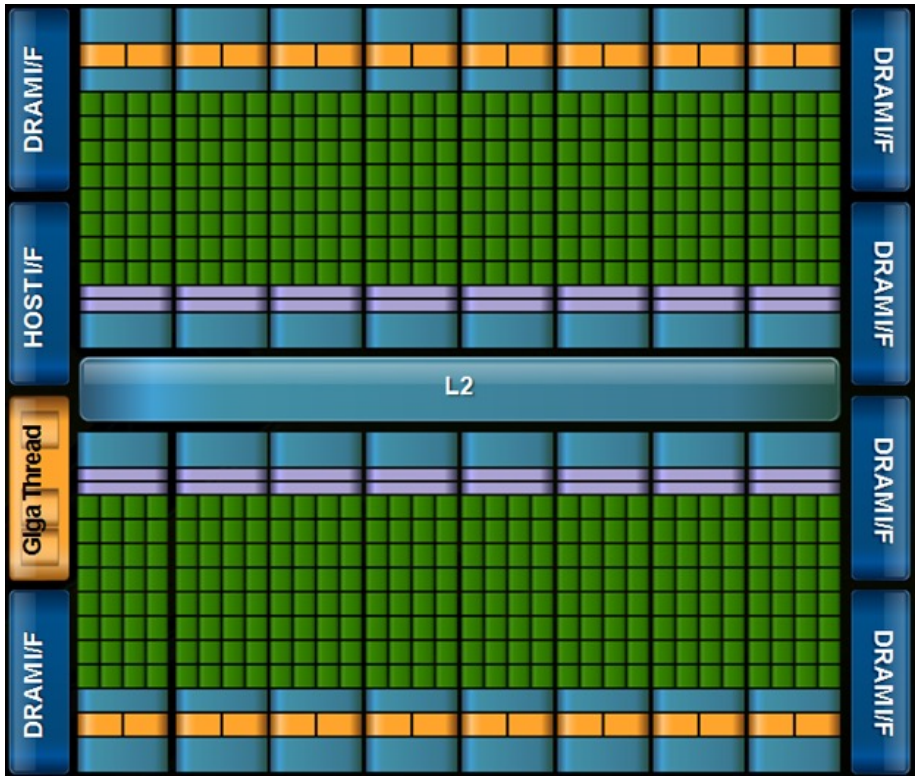
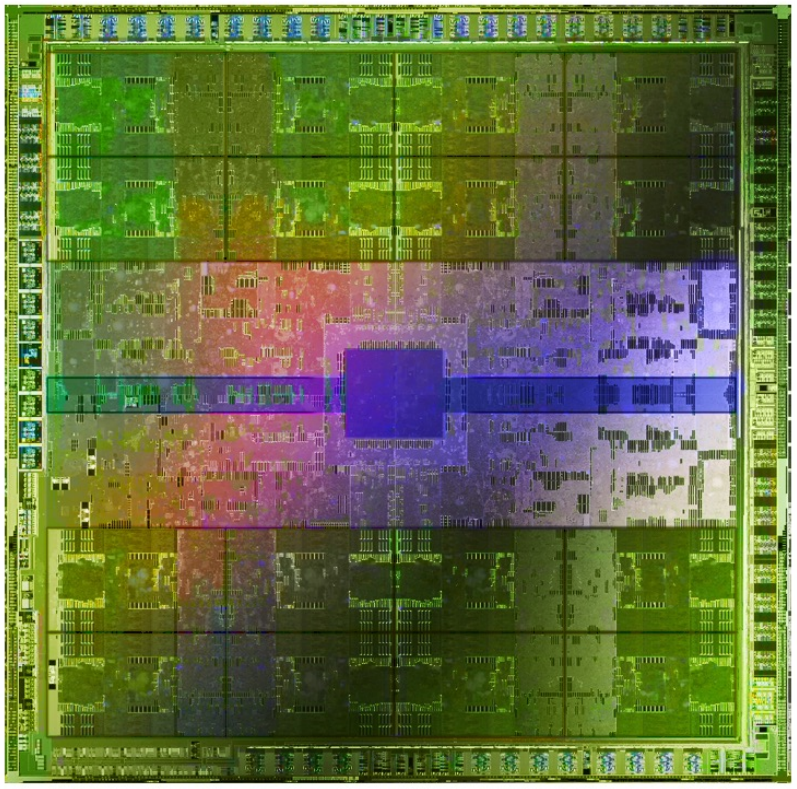
NVIDIA Fermi GPU (2010)





16 Streaming Multiprocessors with 32 cores each => 512 cores and 3B transistors

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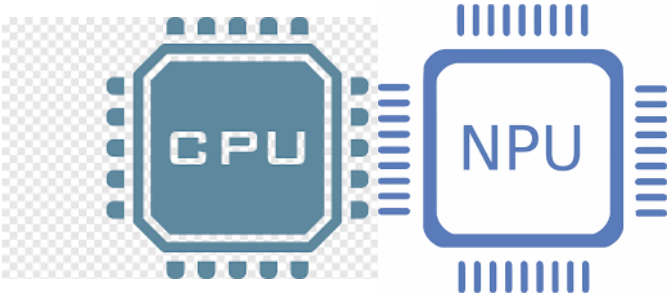
Pallelism? Which kind?

- ILP: Pipelining, Multiple Issue (SISD)
- Multiprocessing and Multicores (MIMD)
- Multithreading (MT)
- Data-Level Parallelism: SIMD and Vector Processors
- ***What's next?***
  - ***Heterogeneity:*** *Processors + Accelerators such as* ***Neural Processing Unit*** *and* ***Tensor Cores*** *for machine learning and deep learning*



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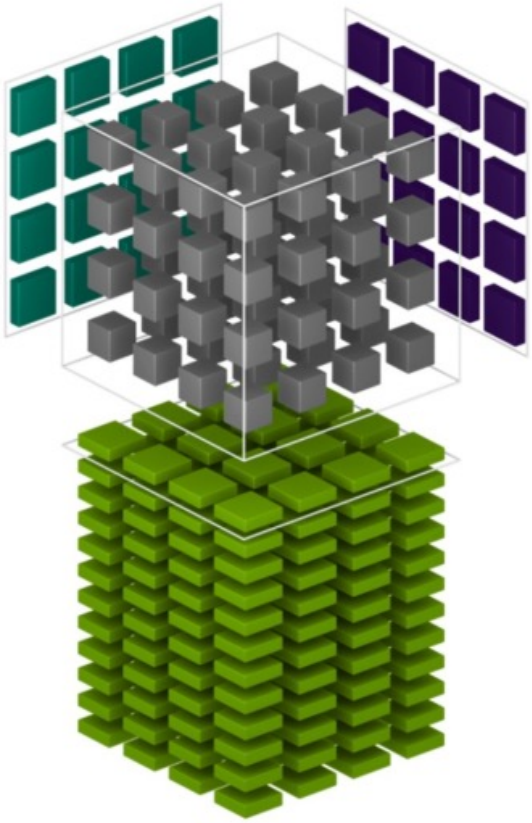
NVIDIA Tensor Cores



$$D = \underset{\text{FP16 or FP32}}{\begin{pmatrix} A_{0,0} & A_{0,1} & A_{0,2} & A_{0,3} \\ A_{1,0} & A_{1,1} & A_{1,2} & A_{1,3} \\ A_{2,0} & A_{2,1} & A_{2,2} & A_{2,3} \\ A_{3,0} & A_{3,1} & A_{3,2} & A_{3,3} \end{pmatrix}}_{\text{FP16}} \underbrace{\begin{pmatrix} B_{0,0} & B_{0,1} & B_{0,2} & B_{0,3} \\ B_{1,0} & B_{1,1} & B_{1,2} & B_{1,3} \\ B_{2,0} & B_{2,1} & B_{2,2} & B_{2,3} \\ B_{3,0} & B_{3,1} & B_{3,2} & B_{3,3} \end{pmatrix}}_{\text{FP16}} + \underbrace{\begin{pmatrix} C_{0,0} & C_{0,1} & C_{0,2} & C_{0,3} \\ C_{1,0} & C_{1,1} & C_{1,2} & C_{1,3} \\ C_{2,0} & C_{2,1} & C_{2,2} & C_{2,3} \\ C_{3,0} & C_{3,1} & C_{3,2} & C_{3,3} \end{pmatrix}}_{\text{FP16 or FP32}}$$

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NVIDIA Volta GV100 with 84 SMs (2017)

Full GV100 GPU with 84 Streaming Multiprocessors, for a total of 5376 FP32 cores, 5376 INT32 cores, 2688 FP64 cores, 672 Tensor Cores, and 336 texture units.

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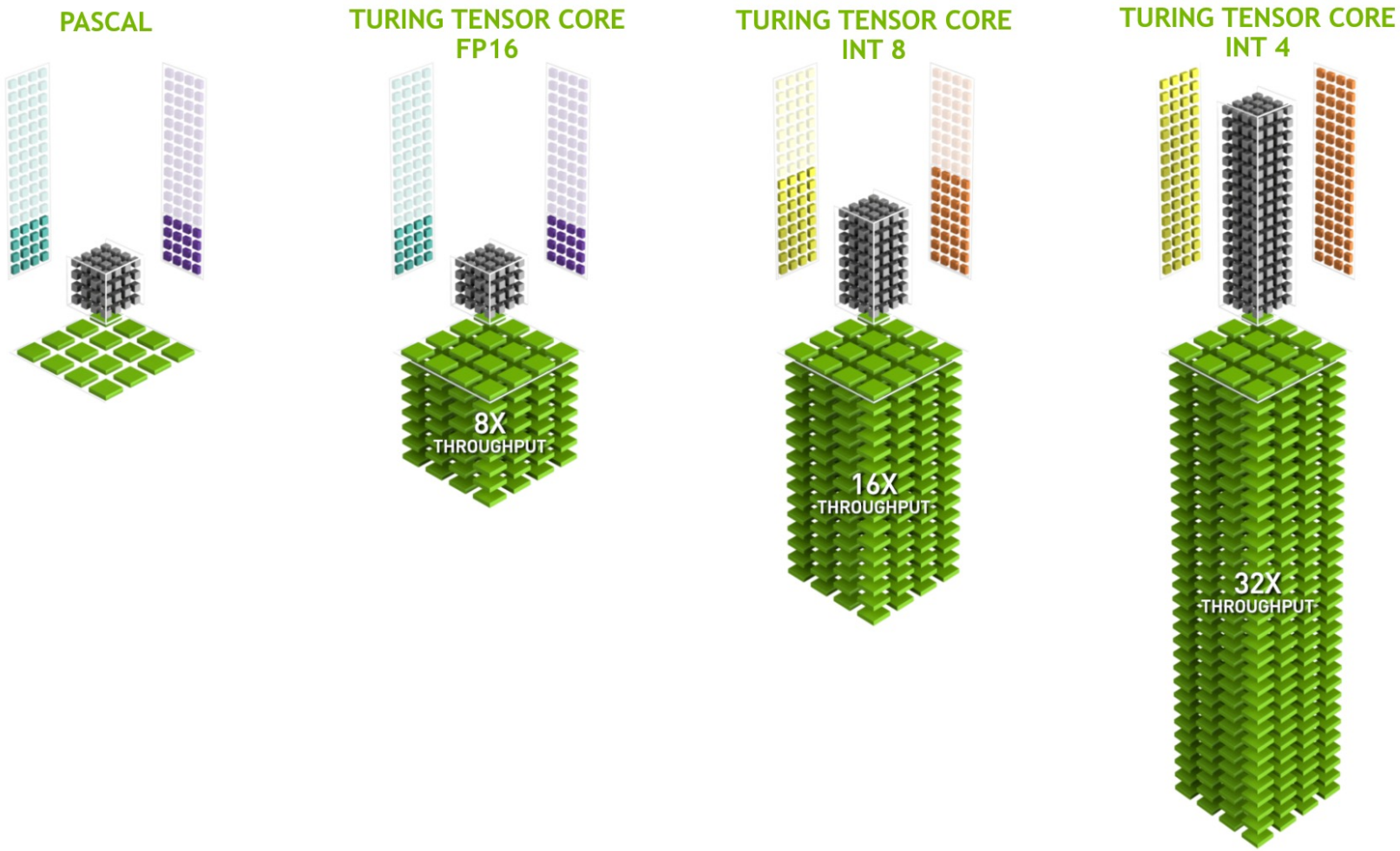
Volta GV100 SM

- NVIDIA Volta GV100 Streaming Multiprocessor
- NVIDIA's first chip to feature Tensor Cores to accelerate Deep Learning

NVIDIA Tensor Cores Evolution



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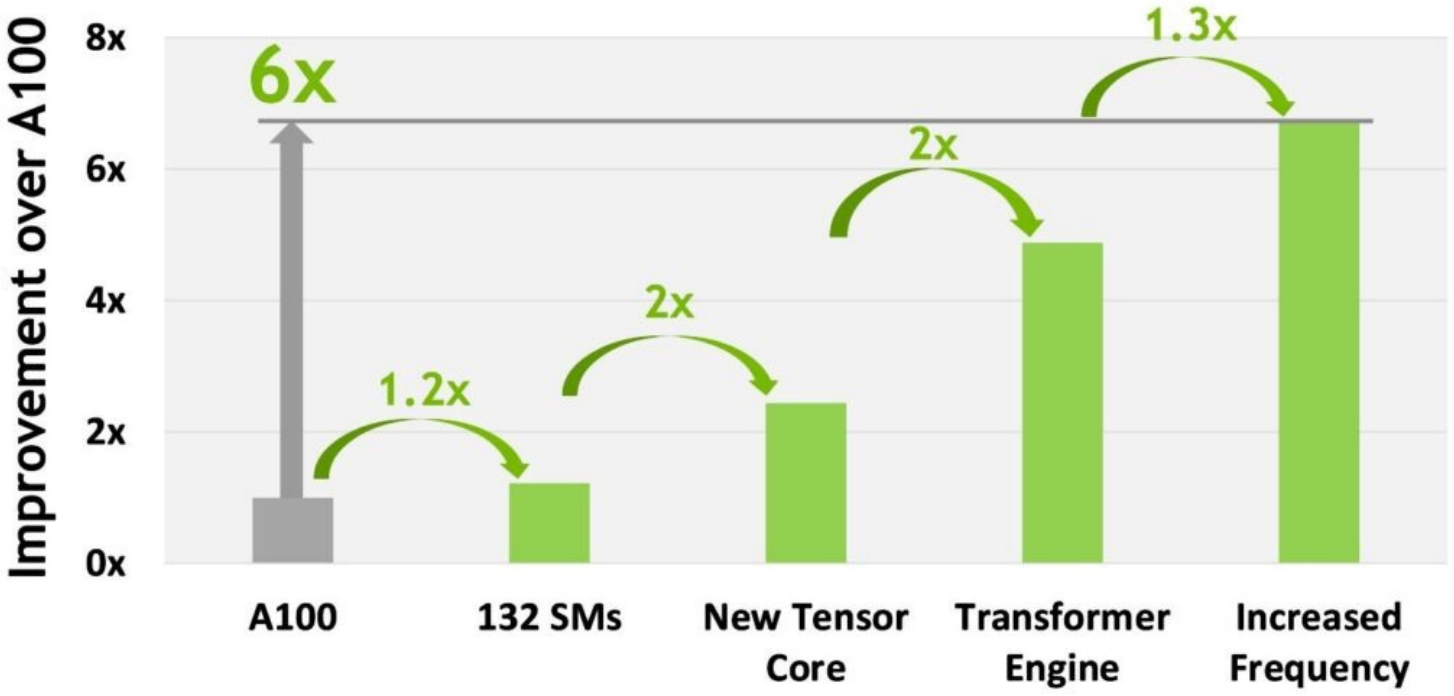
NVIDIA AMPERE GA100 Tensor Core GPU with 128 SMs and 54.2 billion trans. (20x faster than Volta)

NVIDIA Hopper H100

- **Next generation:** NVIDIA Hopper H100 with 144 Streaming Multiprocessors and 80 billion transistors with 4nm TSMC technology process



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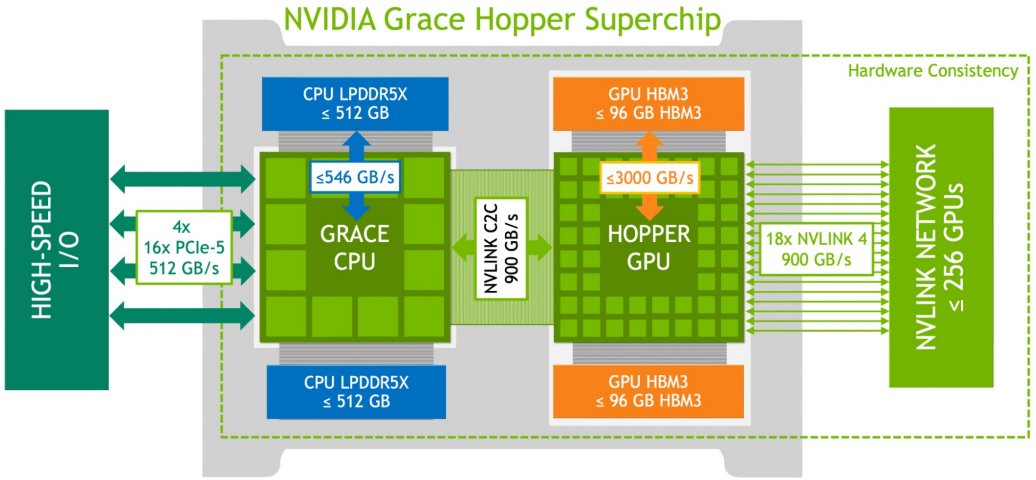
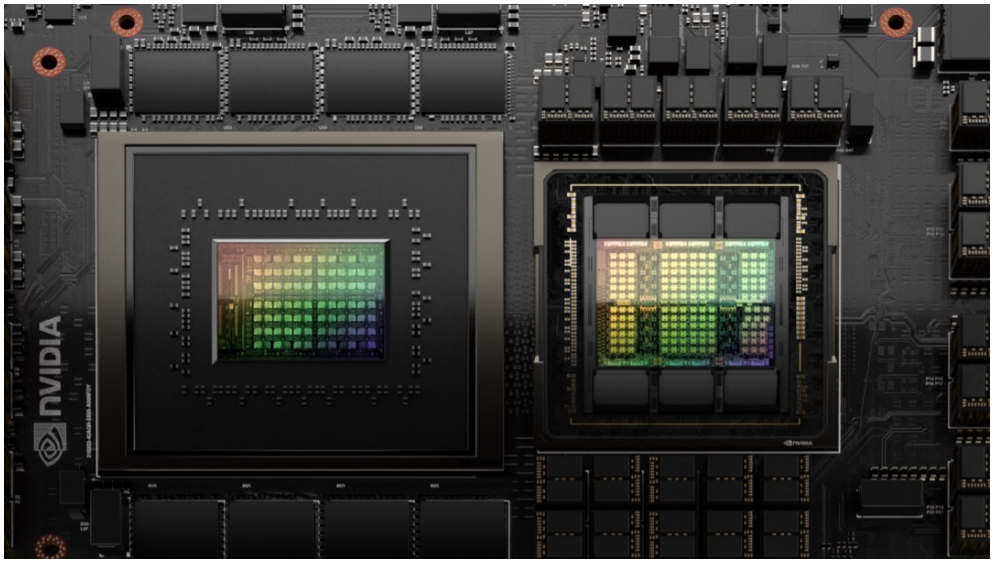
NVIDIA Grace Hopper Superchip (2024)





https://developer.nvidia.com/blog/nvidia-grace-hopper-superchip-architecture-in-depth/

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Putting all together ….

- *ILP: Pipelining, Multiple Issue (SISD)*
- *Multiprocessing and Multicores (MIMD)*
- *Multithreading (MT)*
- *Data-Level Parallelism: SIMD and Vector Processors*
- *Heterogeneity*

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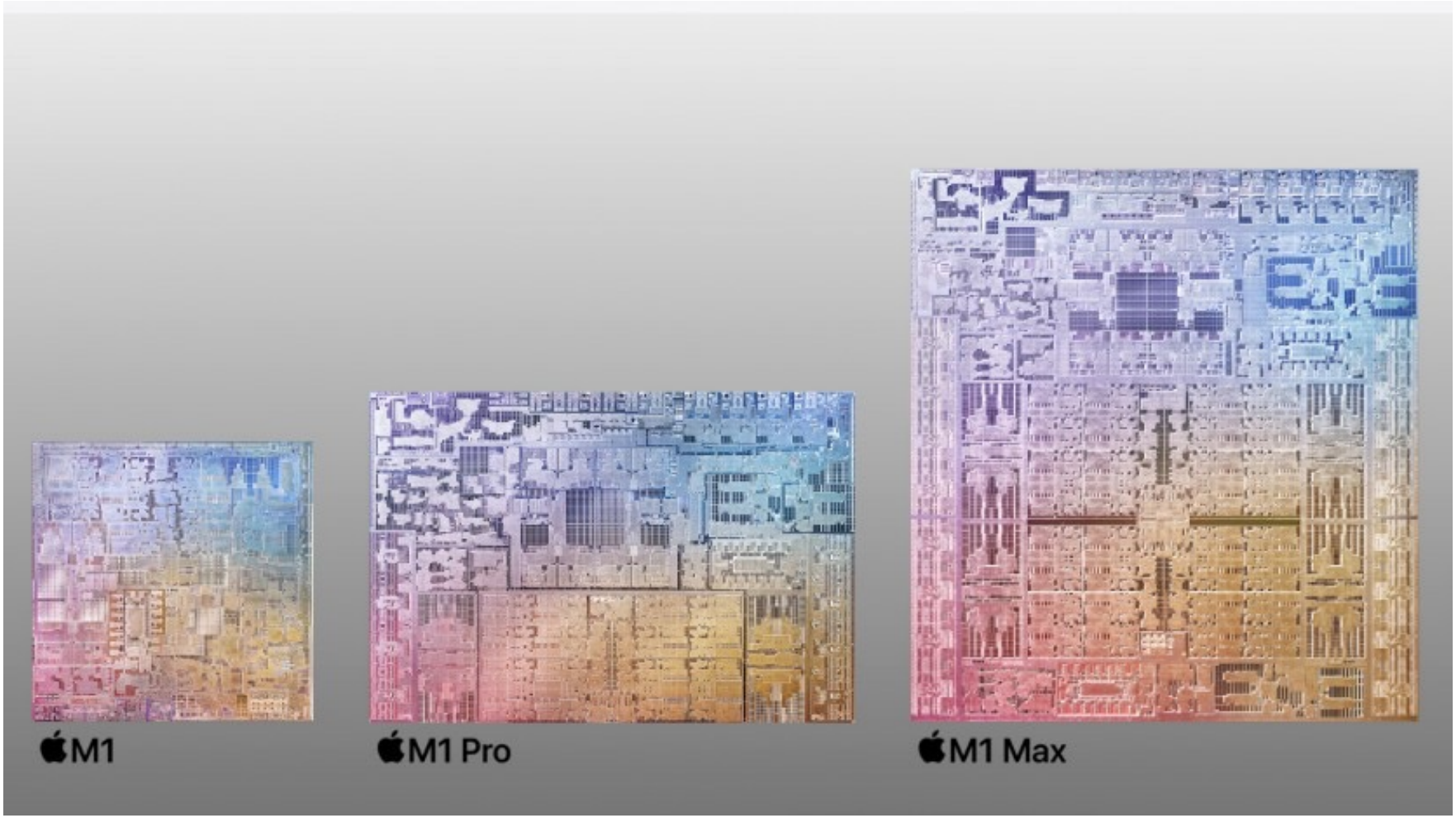
Apple M1, M1 Pro and M1 Max (2020-2021)



Source: https://www.golem.de/news/m1-pro-max-dieses-apple-silicon-ist-gigantisch-2110-160415.html

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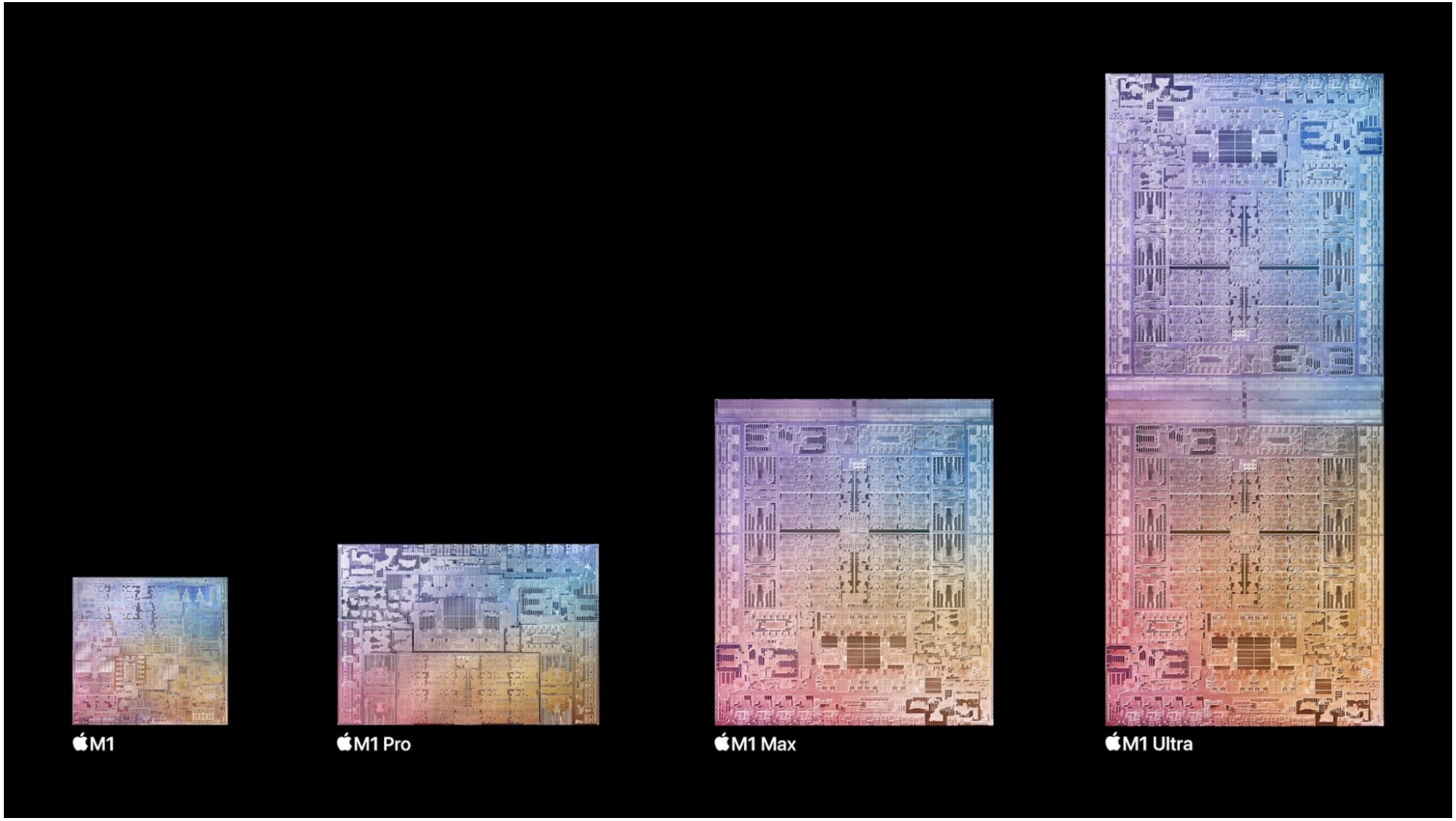
Up to Apple M1 Ultra (2022)



https://www.theverge.com/2022/3/9/22968611/apple-m1-ultra-gpu-nvidia-rtx-3090-comparison

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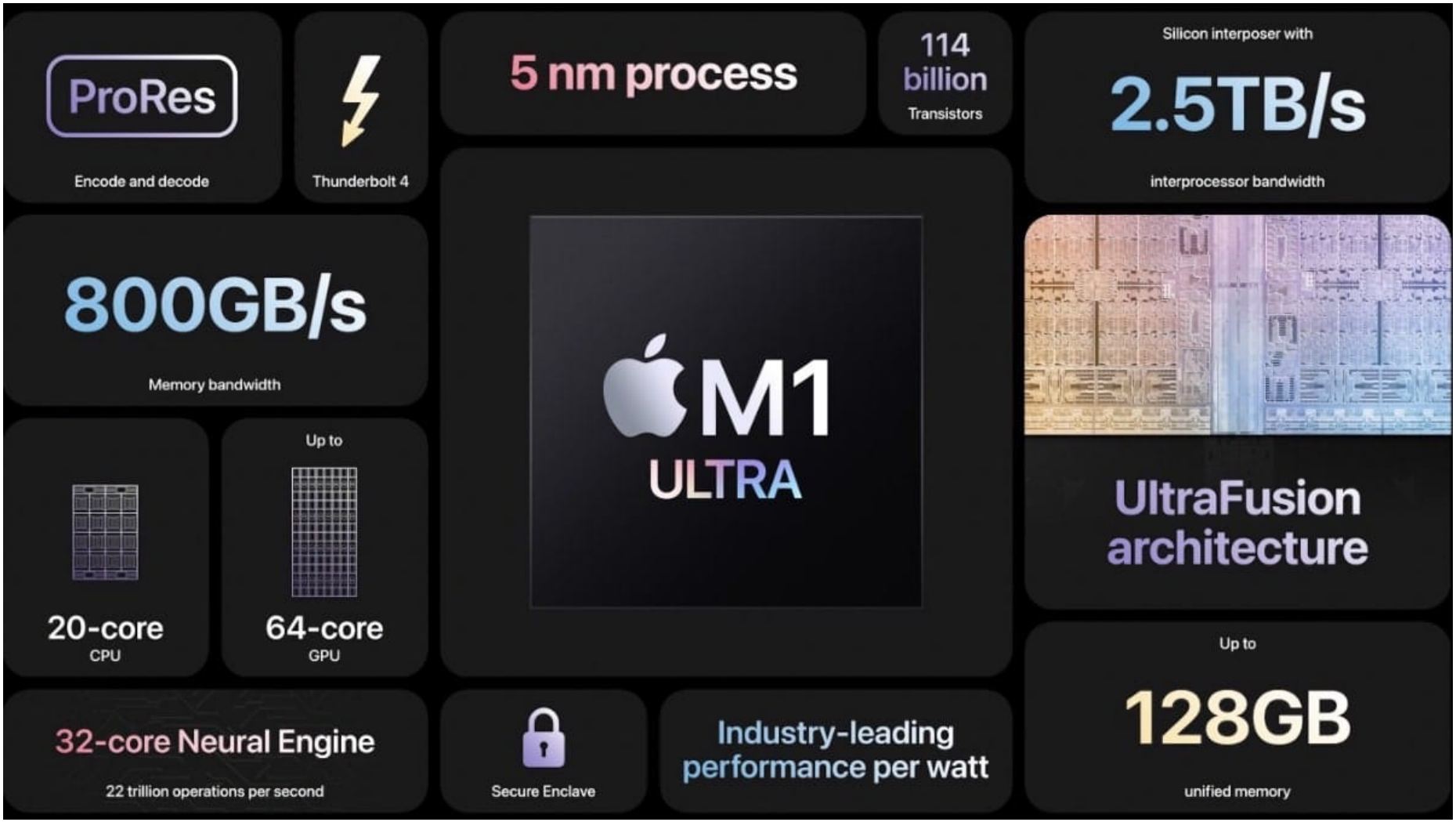
Apple M1 Ultra (2022)



https://stadt-bremerhaven.de/apple-neuer-m1-ultra-chip-ist-offiziell/

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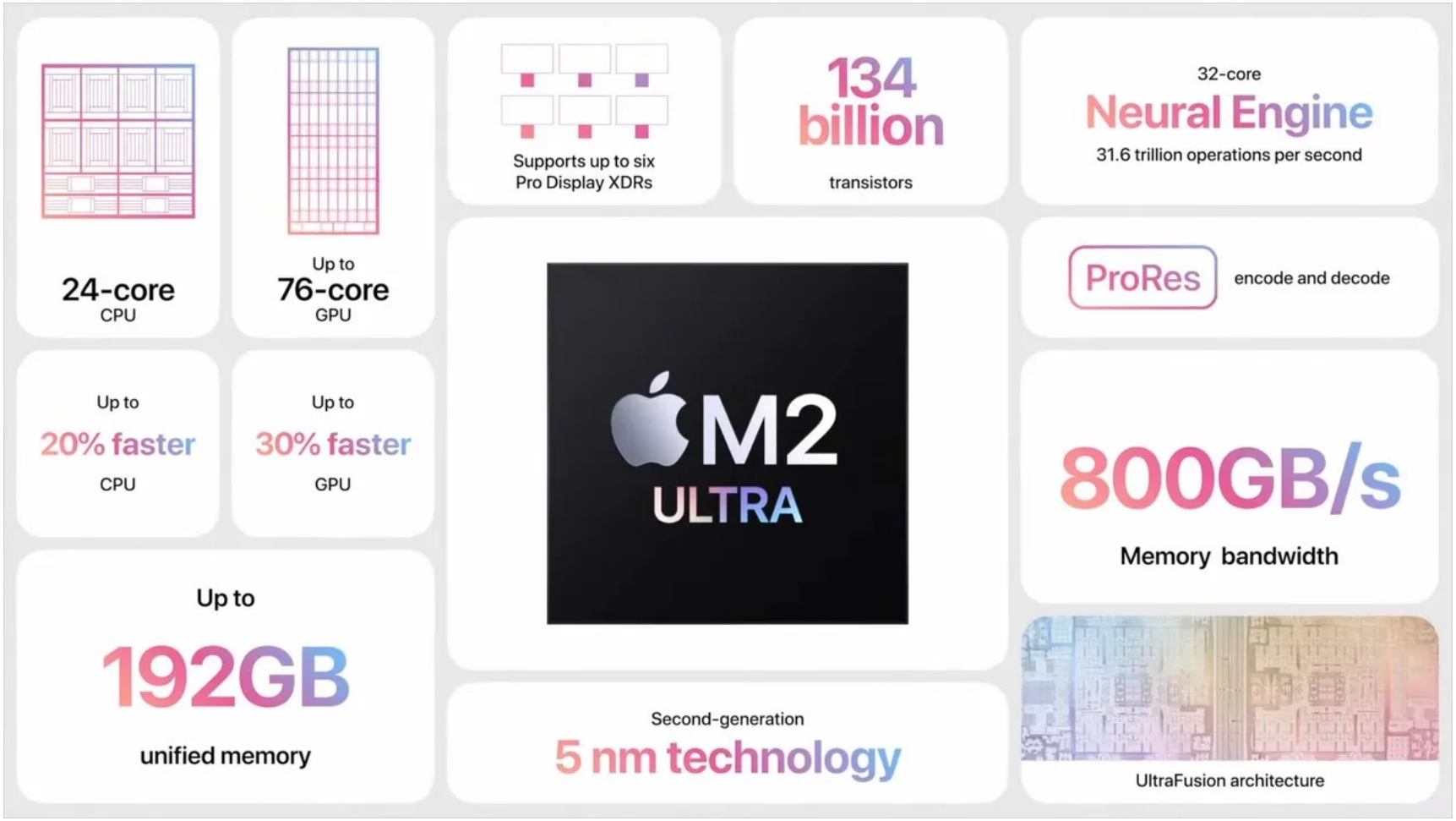
Apple M2 Ultra (2023)



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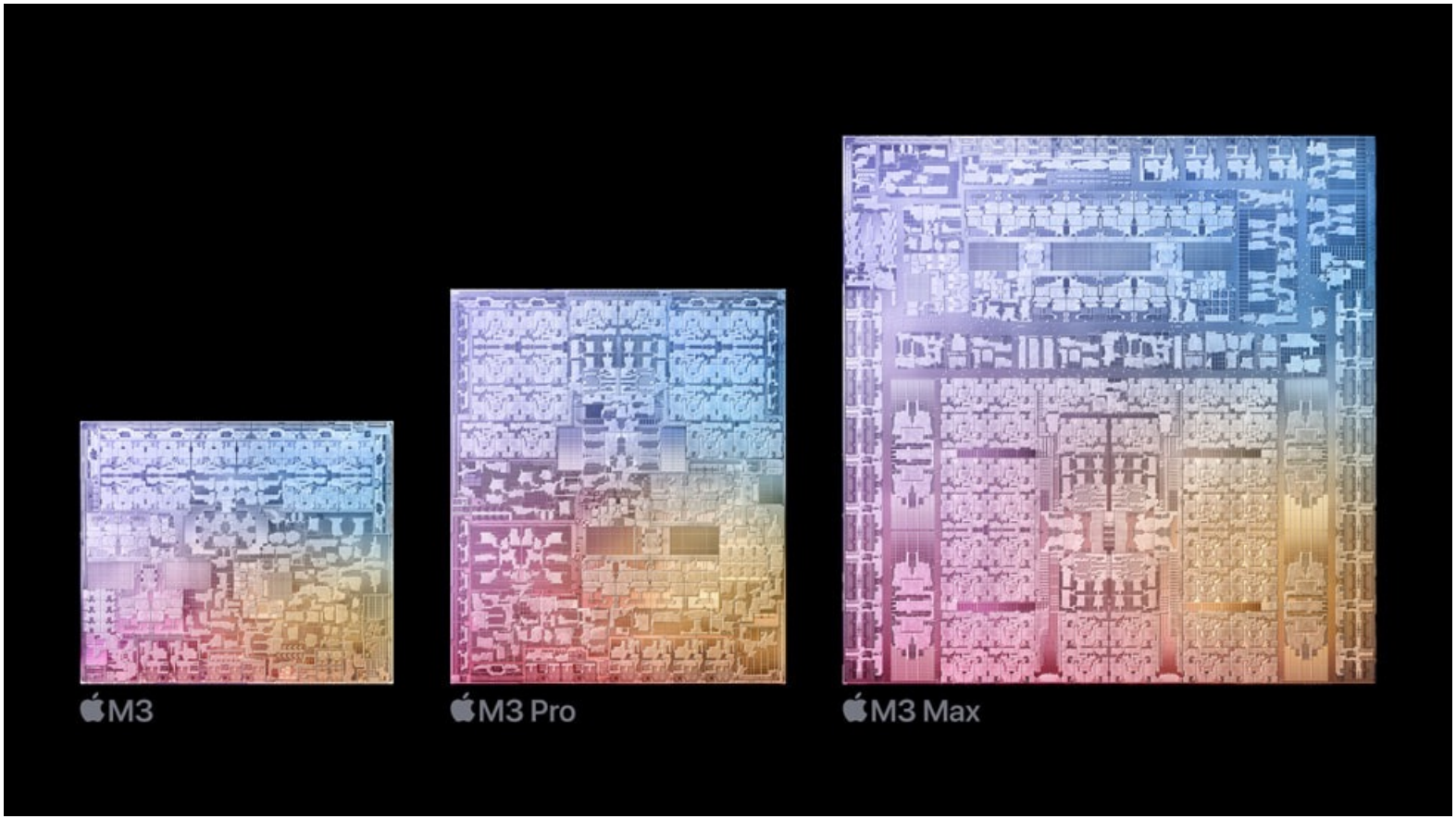
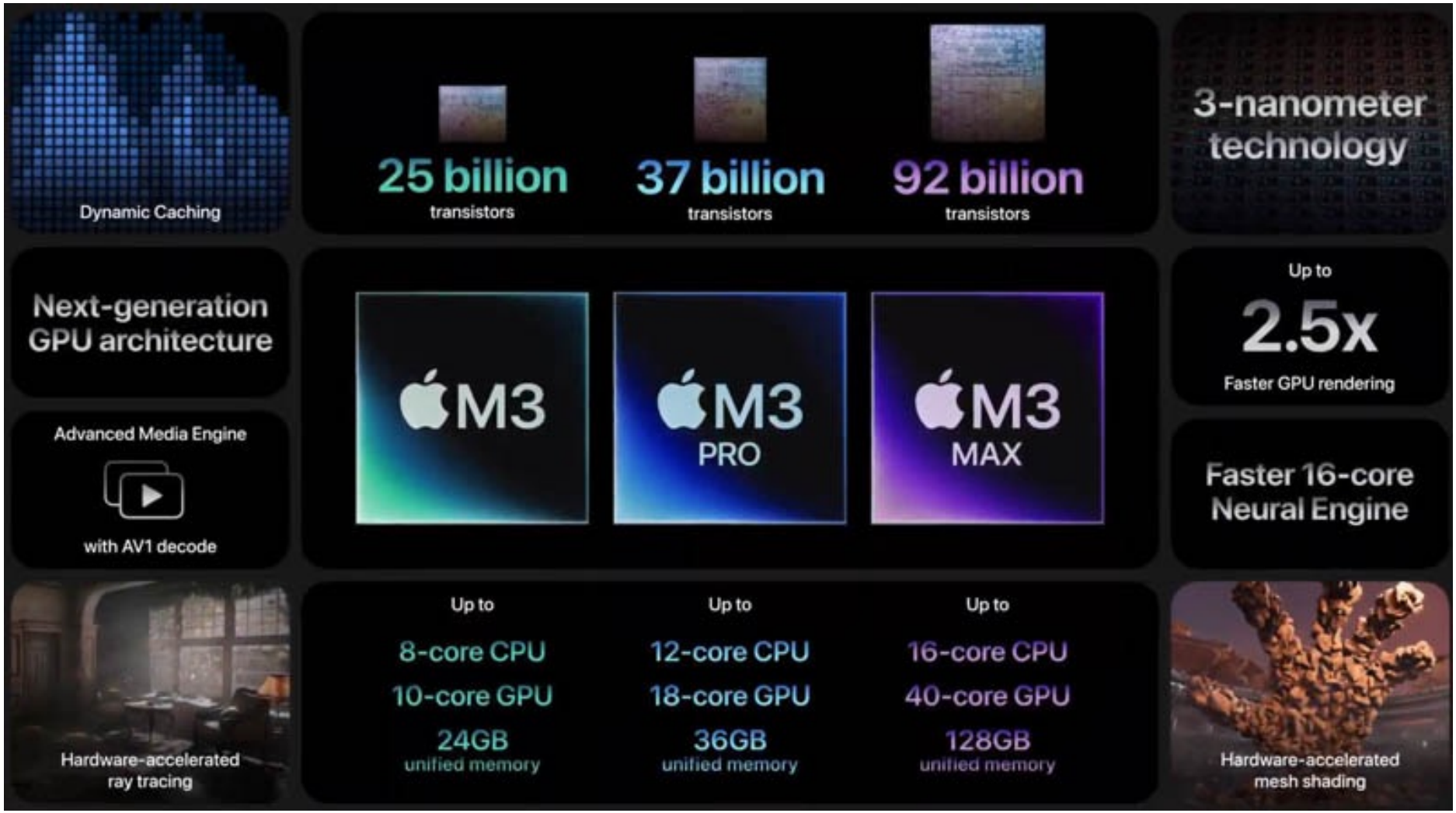
Apple M3, M3 Pro and M3 Max (2023)



Apple M3, M3 Pro and M3 Max (2023)



Apple M4 announced in May 2024

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Apple M4 Pro and M4 Max announced in Oct. 2024