CS5120 VLSI System Design, Spring 2025

Introduction

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Lecture 01

聲明

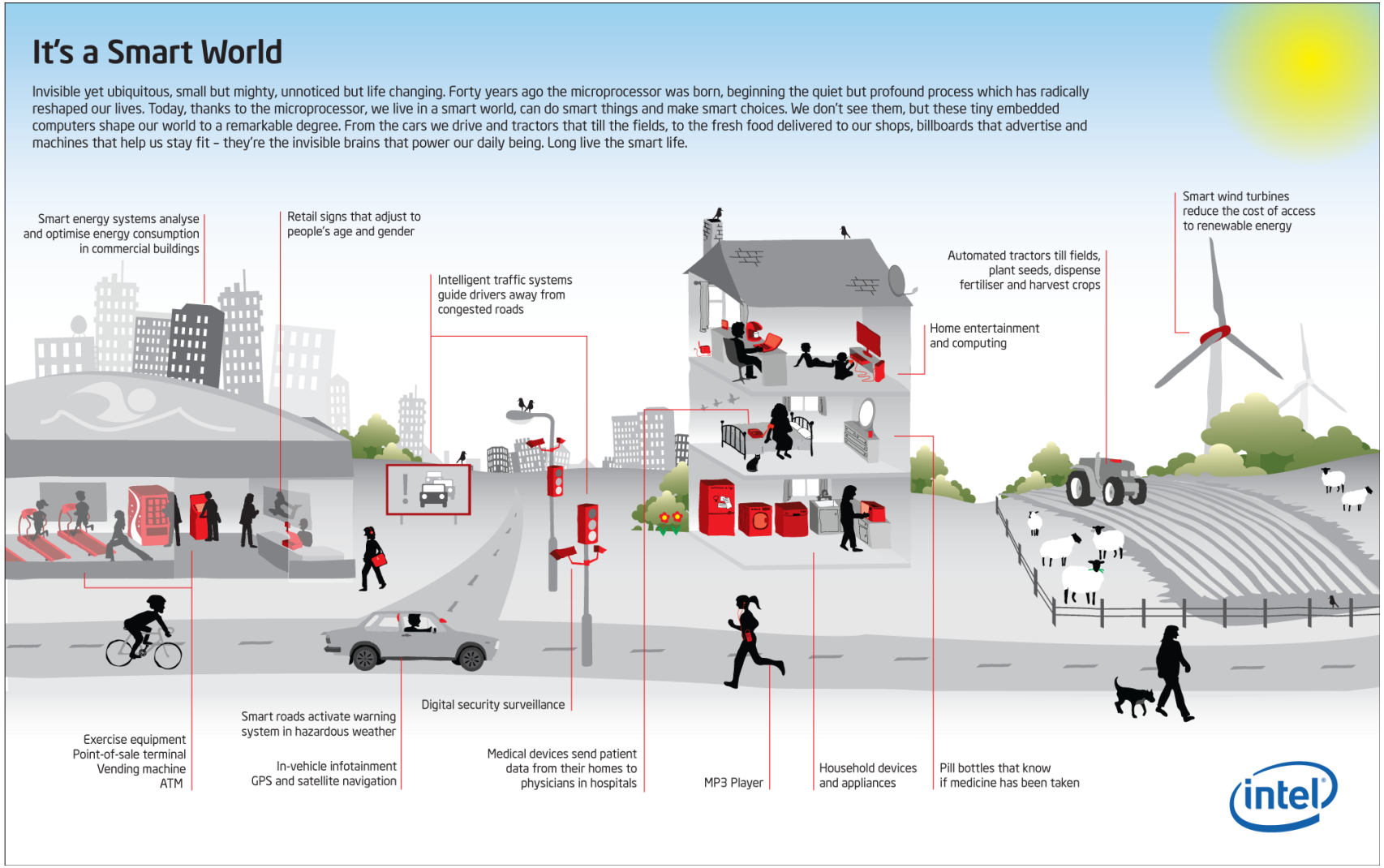
- 本課程之內容 (包括但不限於教材、影片、圖片、檔案資料等)，僅供修課學生個人合理使用，非經授課教師同意，不得以任何形式轉載、重製、散布、公開播送、出版或發行本影片內容 (例如將課程內容放置公開平台上，如 Facebook, Instagram, YouTube, Twitter, Google Drive, Dropbox 等等)。如有侵權行為，需自負法律責任。

The Future of Computing Is Exascale

- Scaling application domains
  - Security
  - Scientific discovery
  - Economic & manufacturing
  - Internet & cloud
  - Healthcare & biology
- New architecture and computing paradigms
  - Advanced process nodes
  - Heterogeneous computing with accelerators
  - Innovative memory hierarchy

Smart World: Ubiquitous Computing

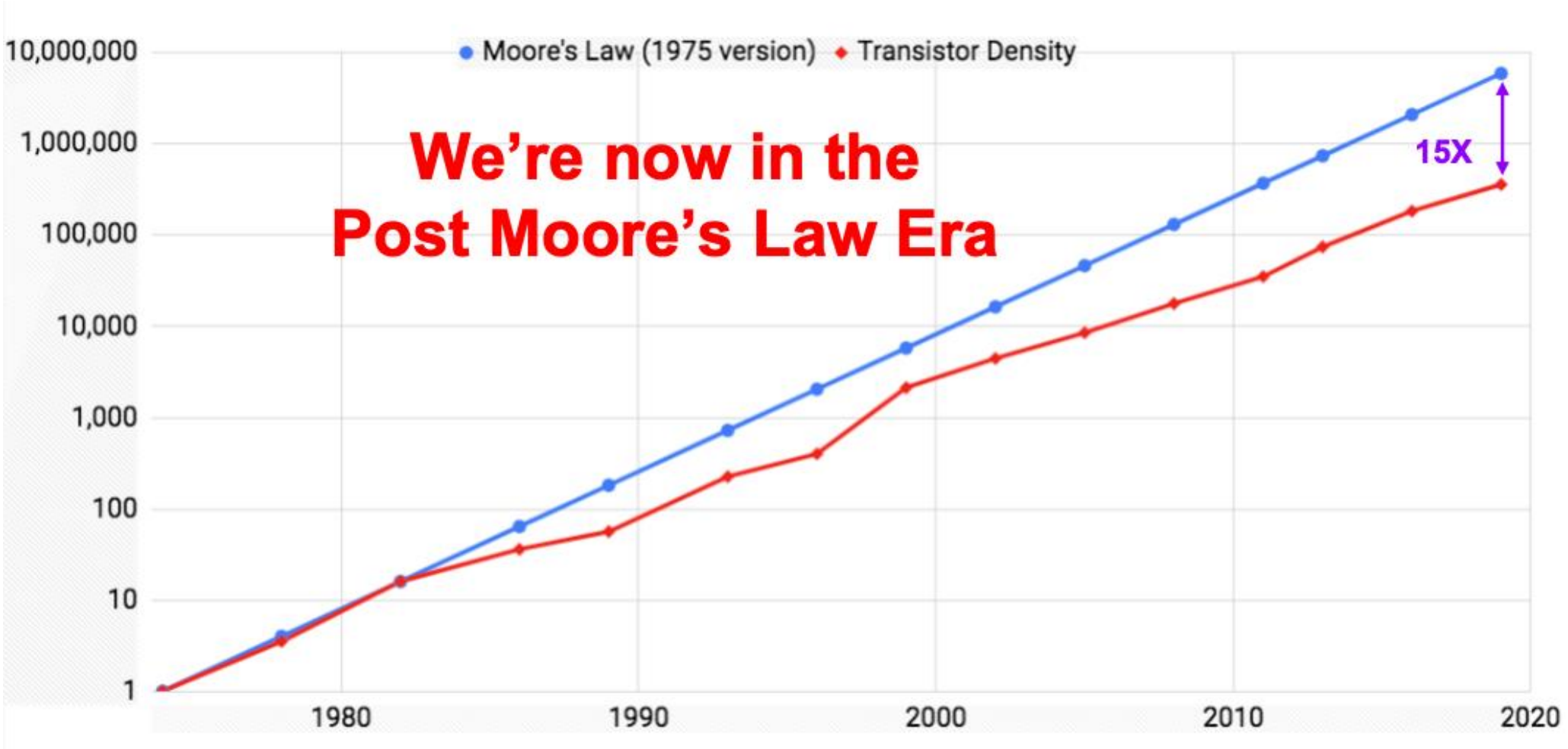
- Diversified, customized computing nodes
  - Cloud
  - Edge
  - End devices



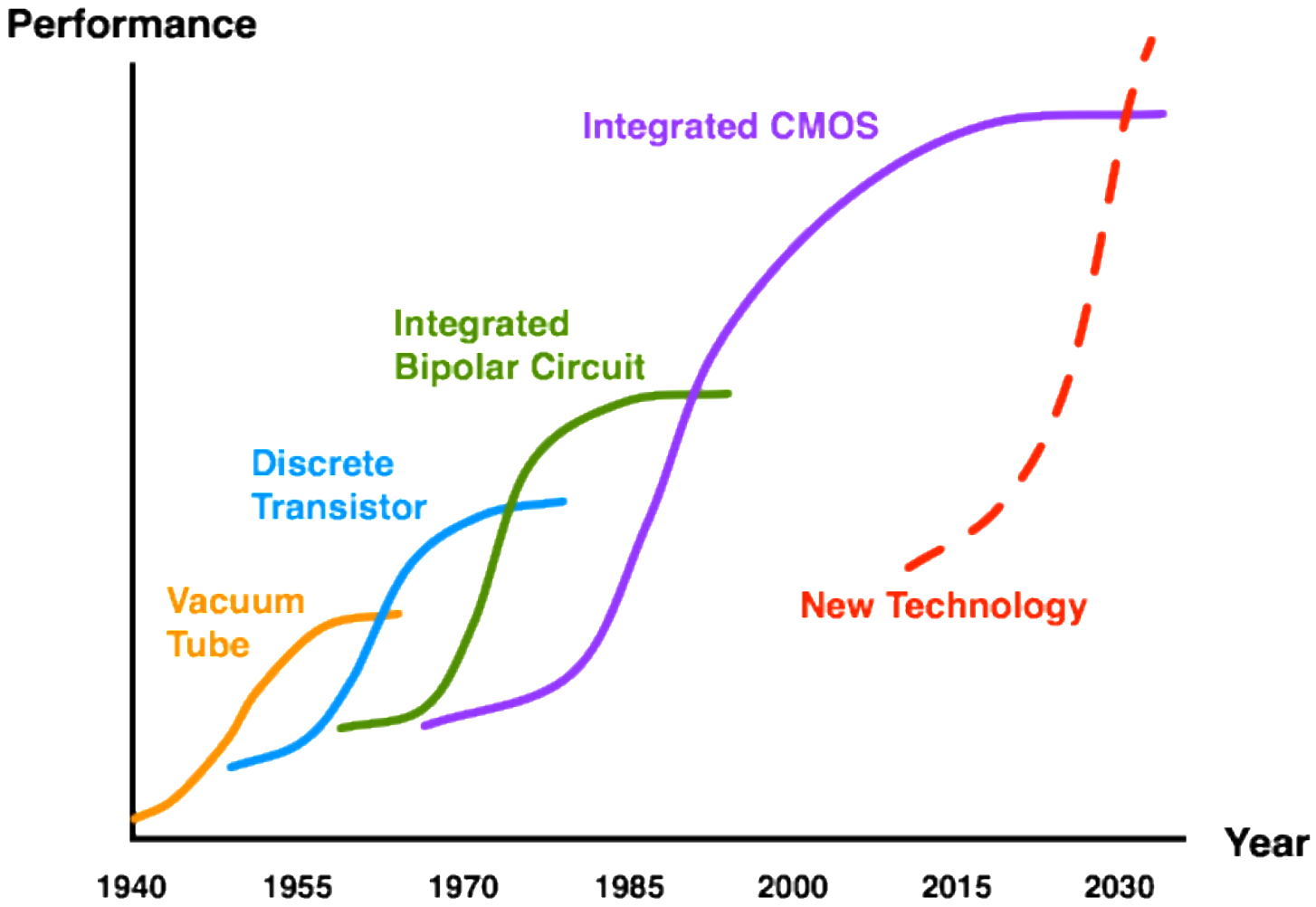
https://visual.ly/community/Infographics/technology/its-smart-world

No More Moore's Law?

Gordon Moore in 1965 that the number of transistors per silicon chip doubles every year.

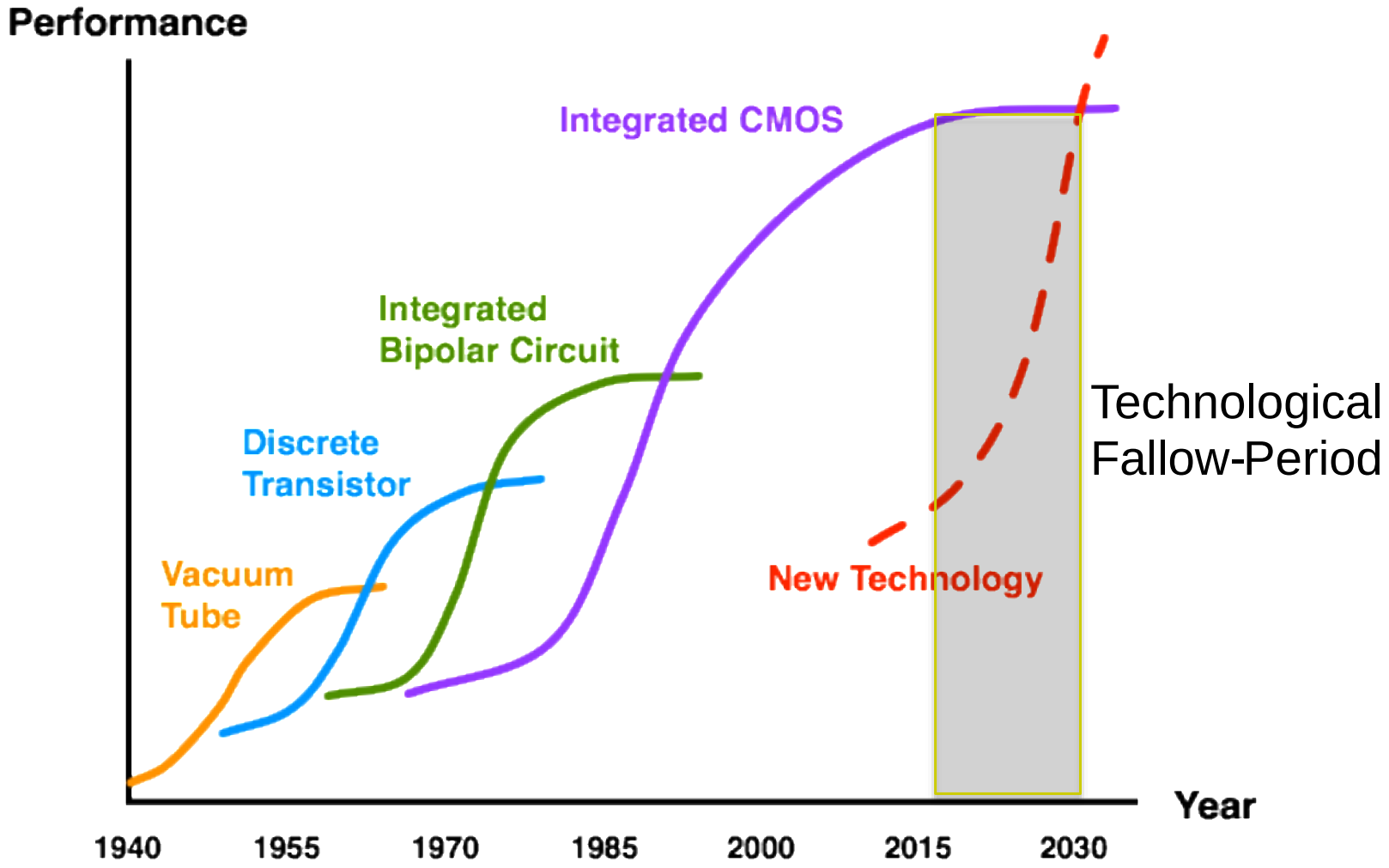


CMOS Technology Scaling



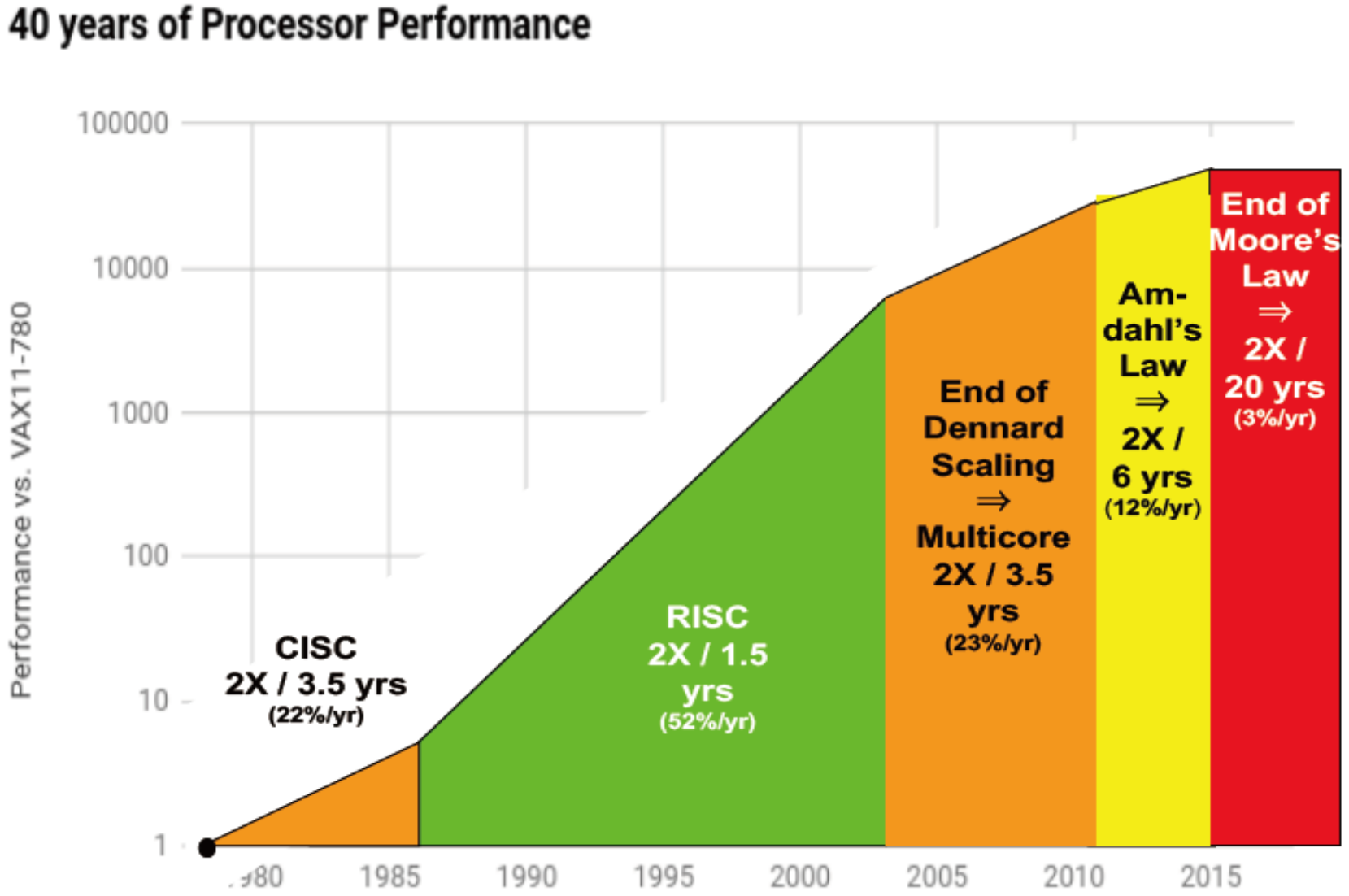
[Source: Prof. David Brooks, Harvard Univ.]

Technological Fallow Period?



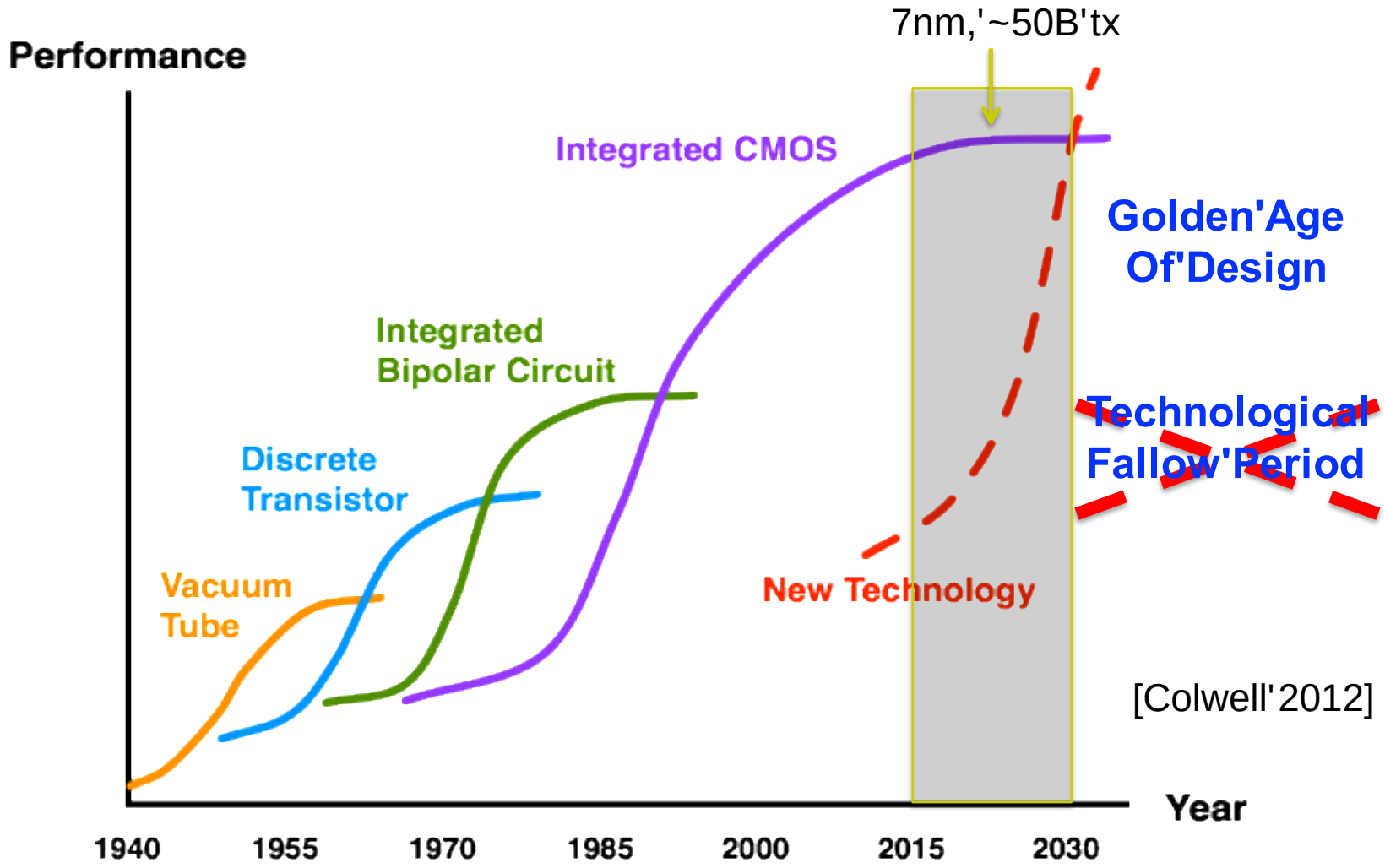
[Source: Prof. David Brooks, Harvard Univ.]

End of Moore's Law!
End of Growth of Performance?



[Source: Prof. David Patterson]

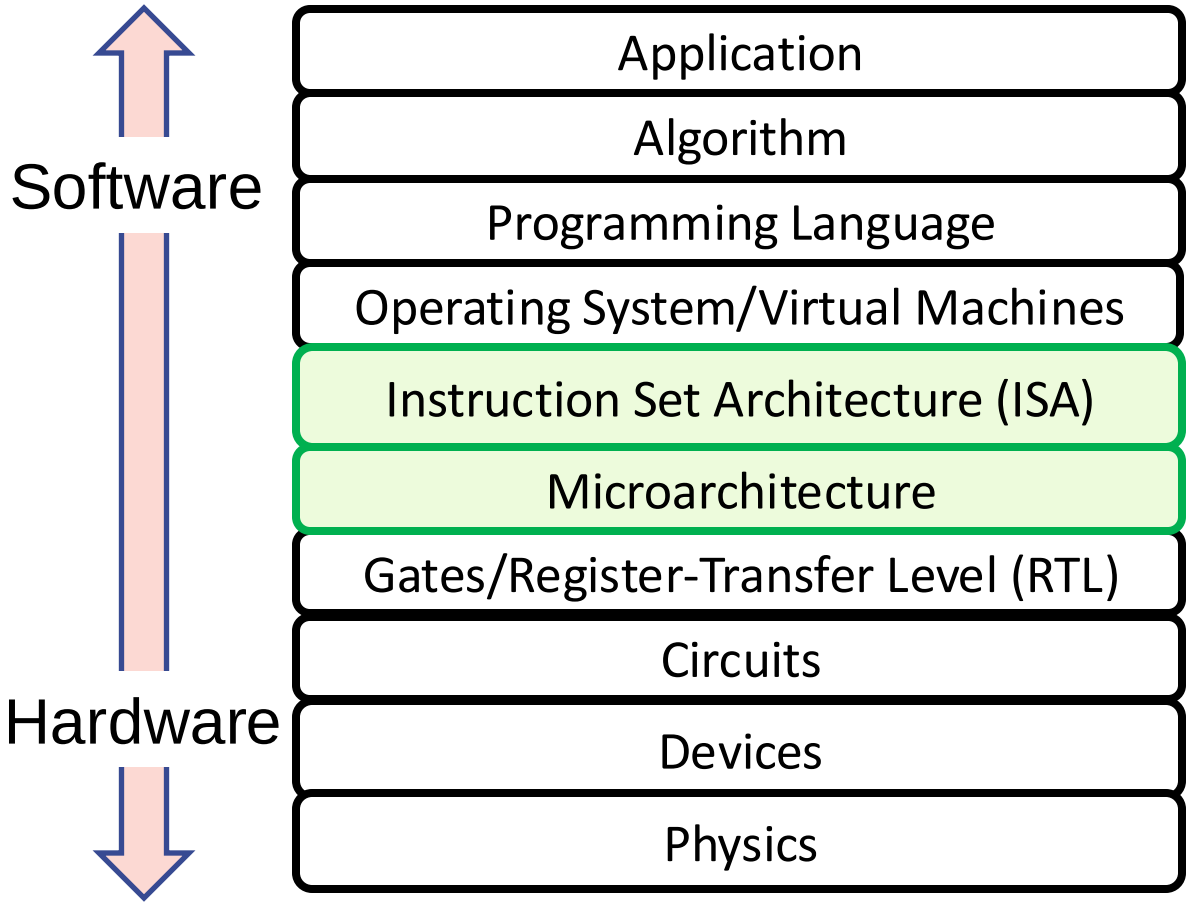
It Comes The Golden Age of Design!



[Source: Prof. David Brooks, Harvard Univ.]

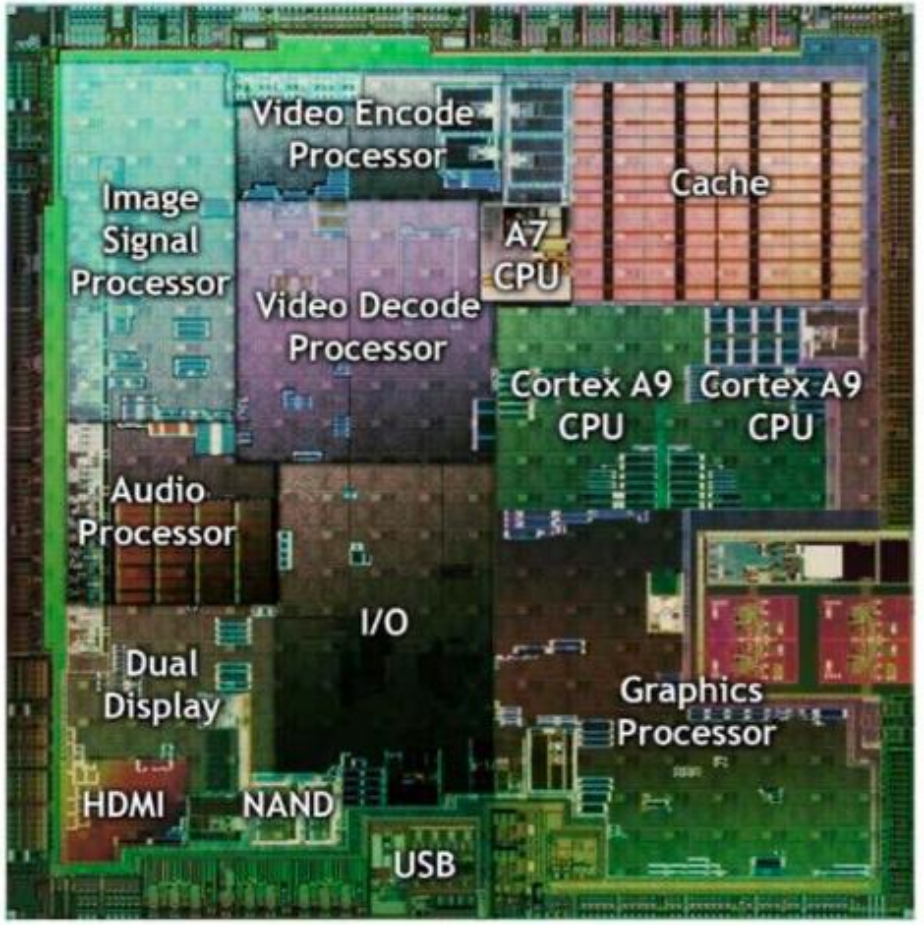
Abstraction Layers in Traditional Computer Systems

- *Design of the abstraction layers* that allow us to implement information processing applications efficiently using available manufacturing technologies.
- Computer architecture acts as the intermediate between programmers and devices (e.g., VLSI)



Today, Many ISAs on One SoC (System-on-Chip)

- Applications processor (usually ARM)
- Graphics processors
- Image processors
- Radio DSPs (Digital Signal Processors)
- Audio DSPs
- Security processors
- Power-management processor
- > dozen ISAs on some SoCs – each with unique software stack
- Why?
  - Apps processor ISA too big, inflexible for accelerators
  - IP bought from different places, each proprietary ISA
  - Engineers build home-grown ISA cores

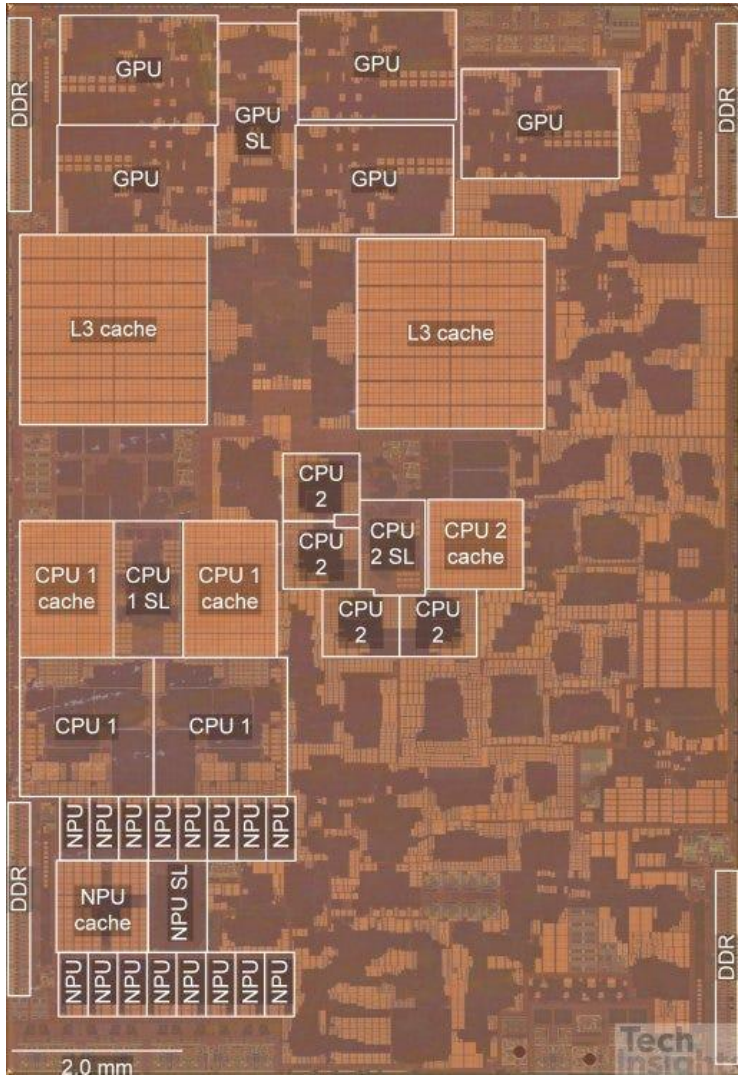


NVIDIA Tegra SoC

Source: NVIDIA

Domain-Specific Accelerators Dominate SoC

- Apple A15 Bionic Processor (2021)
  - Application Processor (AP)
  - TSMC 5nm technology
  - Die size: 107.68 mm^2
  - 15 billion transistors
  - 6-core CPU
  - 4- or 5-core GPU
  - 16-core Neural Engine
    - 15.8 trillion ops/s
  - Image processor
  - Video codec

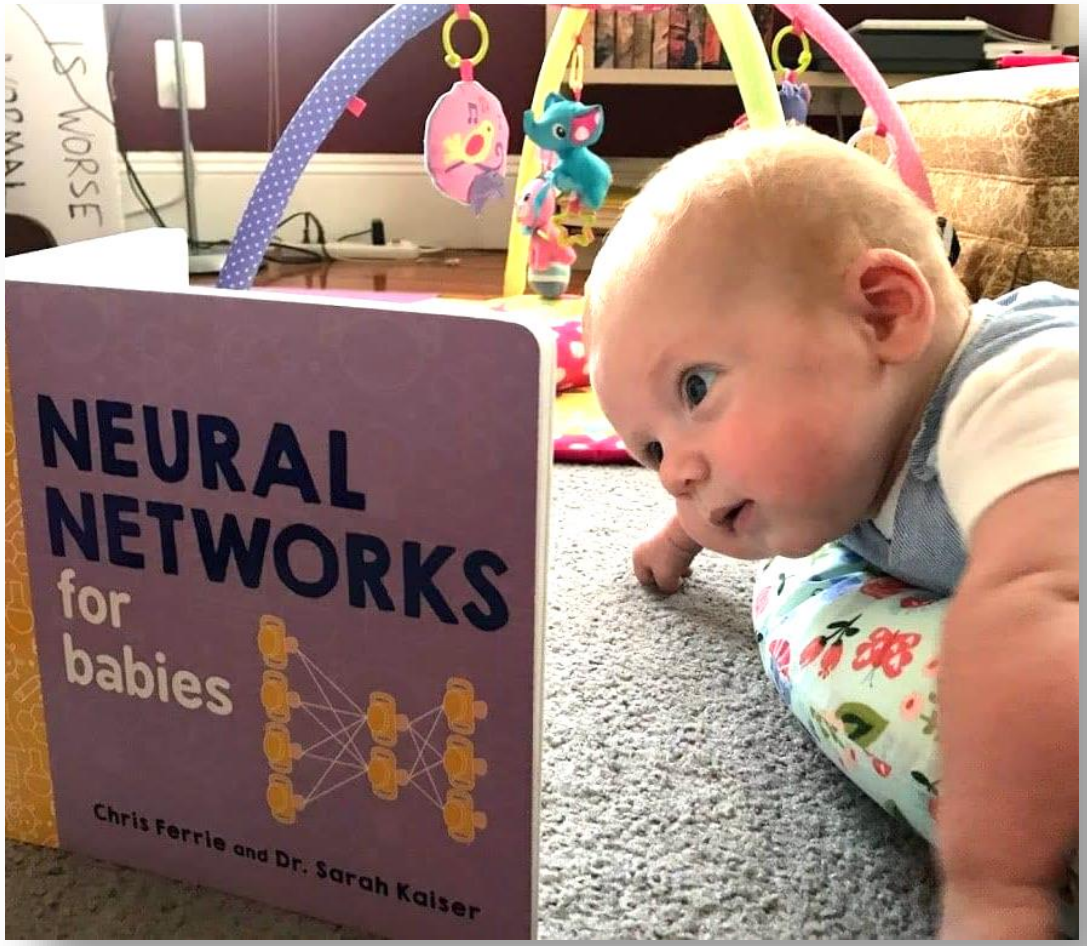


[Source: semianalysis.com]

Which specific domain are we going to discuss about?

AI! Of course!

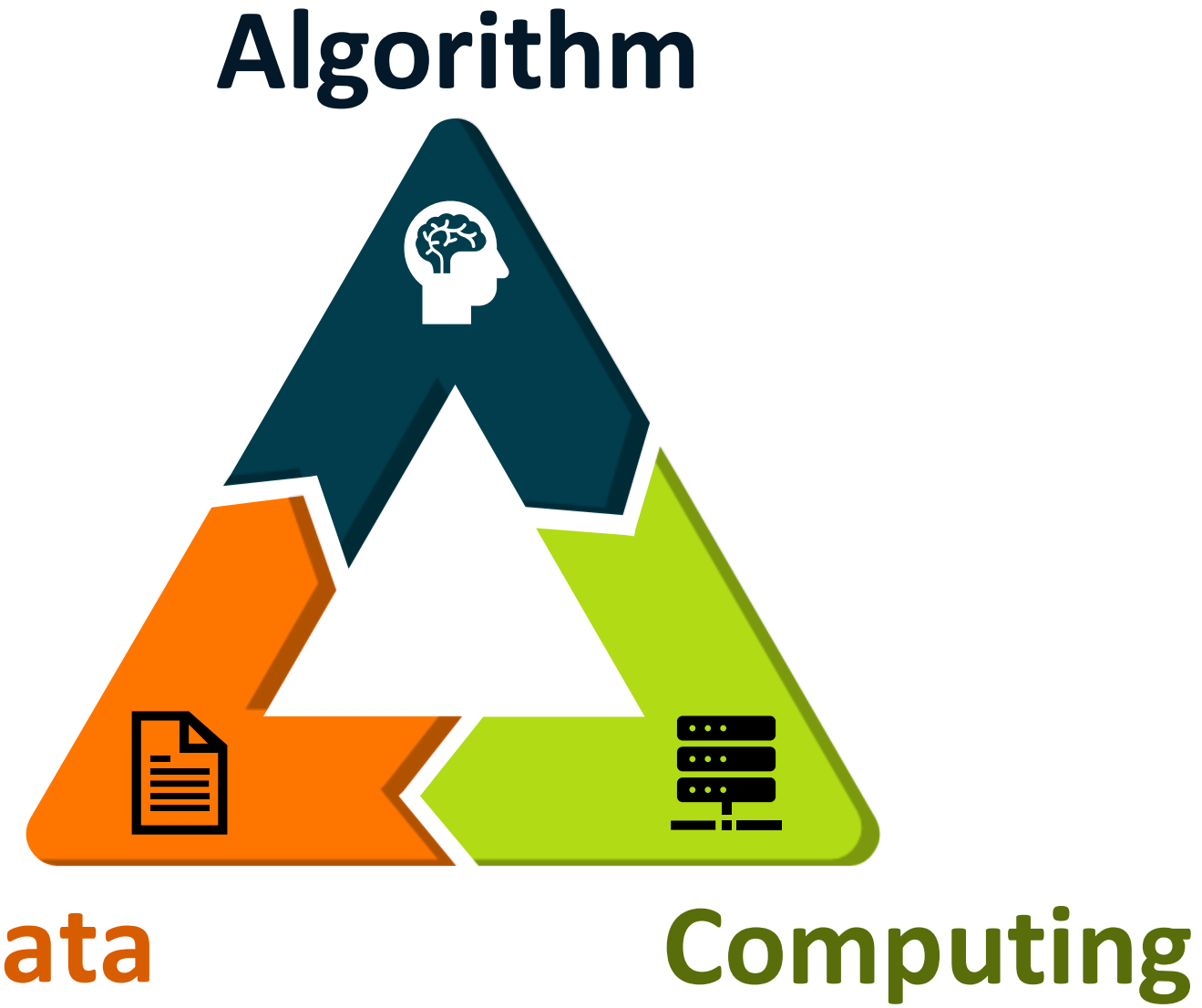
從小和AI做朋友？



https://market.cloud.edu.tw/list/ai.jsp
https://www.amazon.com/Neural-Networks-Babies-Baby-University/dp/1492671207

ABC of AI

- A: Algorithms
  - Improved learning techniques
- B: Big data
  - Significantly larger amounts of digital data
- C: Computing
  - Relatively inexpensive massively parallel computational capabilities

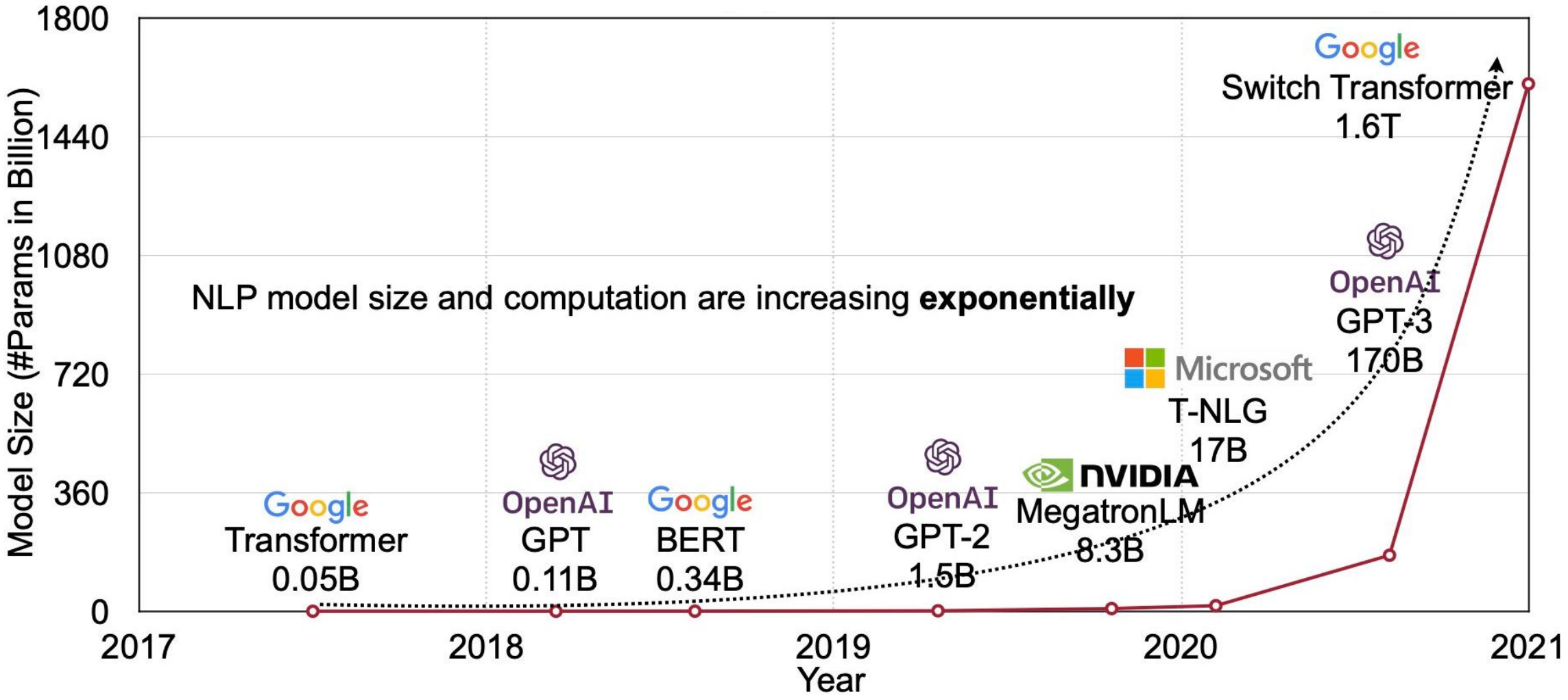


Lately, Software Giants Are Building Their Own AI Chips…

- Accelerators for Deep Learning
  - Google: Tensor Processing Unit (TPU)
    - Google Translate, image search
  - Microsoft: FPGA-based AI supercomputer (Intel/Altera)
  - Facebook: AI chip by Nvidia
  - Amazon: Inferentia
  - Tesla: Full-Self-Driving (FSD) chip
  - Qualcomm/ARM: creating chips to work with TPU
    - Qualcomm Neural Processing Engine for Snapdragon
  - Intel: creating chips optimized for Google's Tensor Flow software (machine learning and neural networks)
- Conventional von Neumann computer architecture is energy inefficient for AI
  - Datacenter: ~2-5 KW
  - 900-core systems: ~100 W
  - Digital hardware accelerator: ~100 mW
  - Neuromorphic processor: 1 mW

NLP's Moore's Law:

Model size increases by 10X every year



Source: MIT Han Lab

CPU vs. GPU

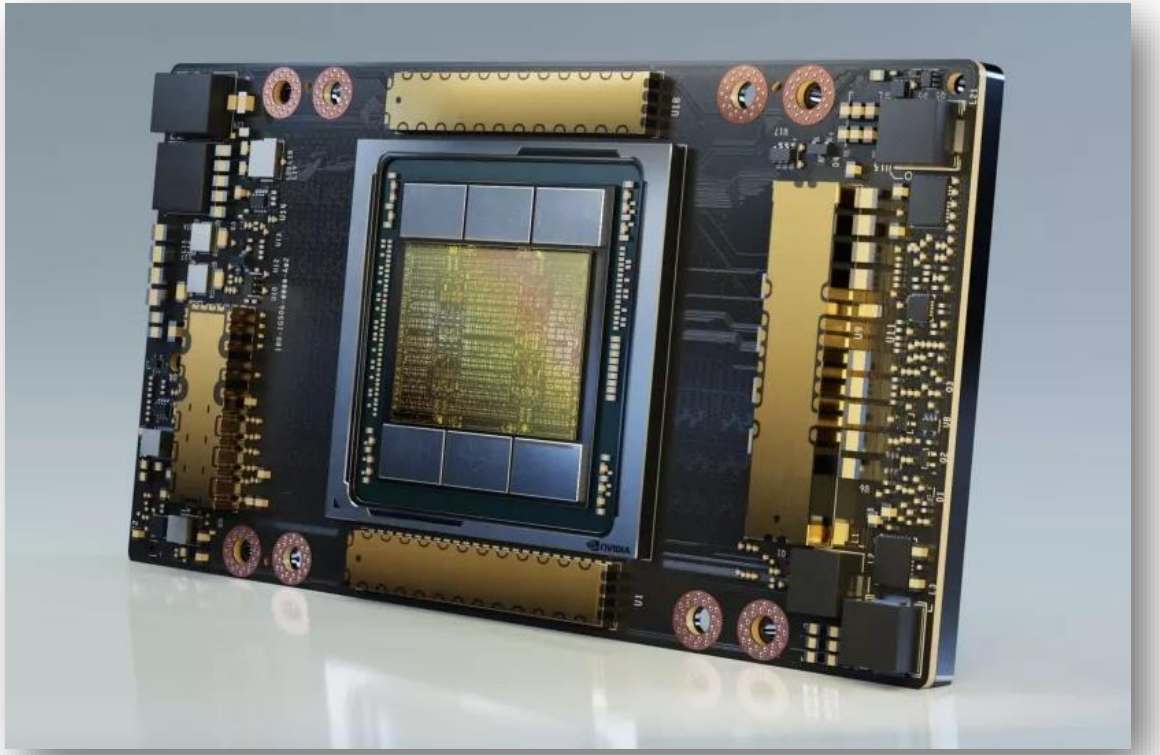
	Cores	Clock Speed	Memory (DRAM)	Price	Throughput
CPU (Intel Core i7 7700k)	4	4.2 GHz	DDR4	$385	~540 GFLOPs
GPU (Nvidia RTX 3090 Ti)	10496	1.7 GHz	DDR6 24GB	$1499	36 TFLOPs

6.7X

- CPU: a small number of complex cores
  - Clock speed of each core is high
  - Good for sequential, dynamic tasks
- GPU: a large number of simple cores
  - Clock speed of each core is low
  - Good for parallel, deterministic tasks

NVIDIA A100 GPU

- Ampere architecture
- TSMC 7 nm FinFET
- 54 billion transistors
- Die size 826 mm^2
- Stream multiprocessors: 108
- CUDA cores: 6,912
- Tensor cores: 432
- GPU memory: 80 GB HBM2
- GPU memory bandwidth: 2.39 TB/s
- Bus width: 5120
- FP32: 19.5 TFLOPS
- Tensor FP16 (sparsity): 312 (624) TFLOPS
- Max Thermal Design Power (TDP): 400W
- Launch date: May 2020
- Launch price:
  $199K for DXG A100 (with 8xA100)

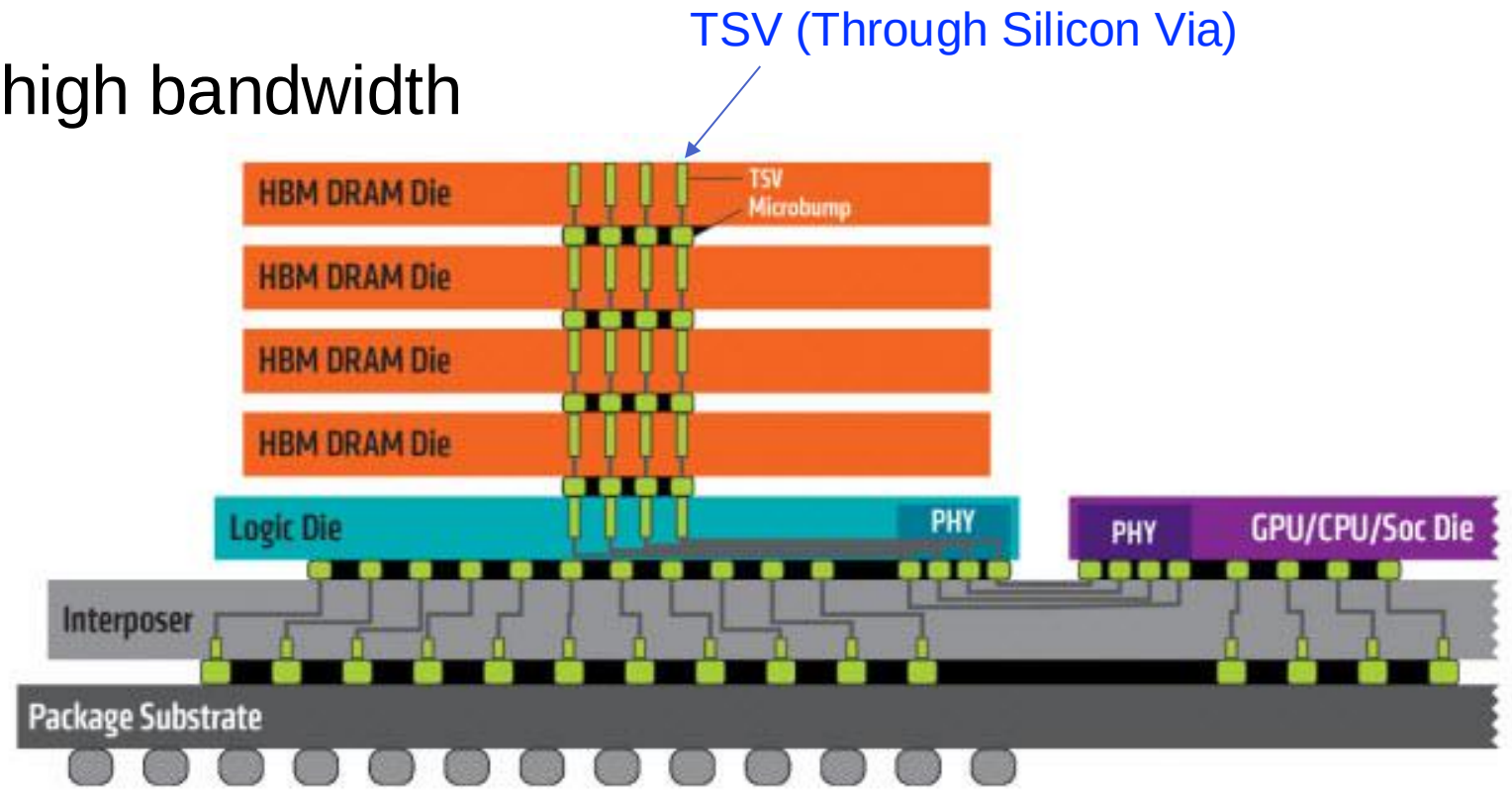


[Source: NVIDIA]

High-Performance Graphics Memory

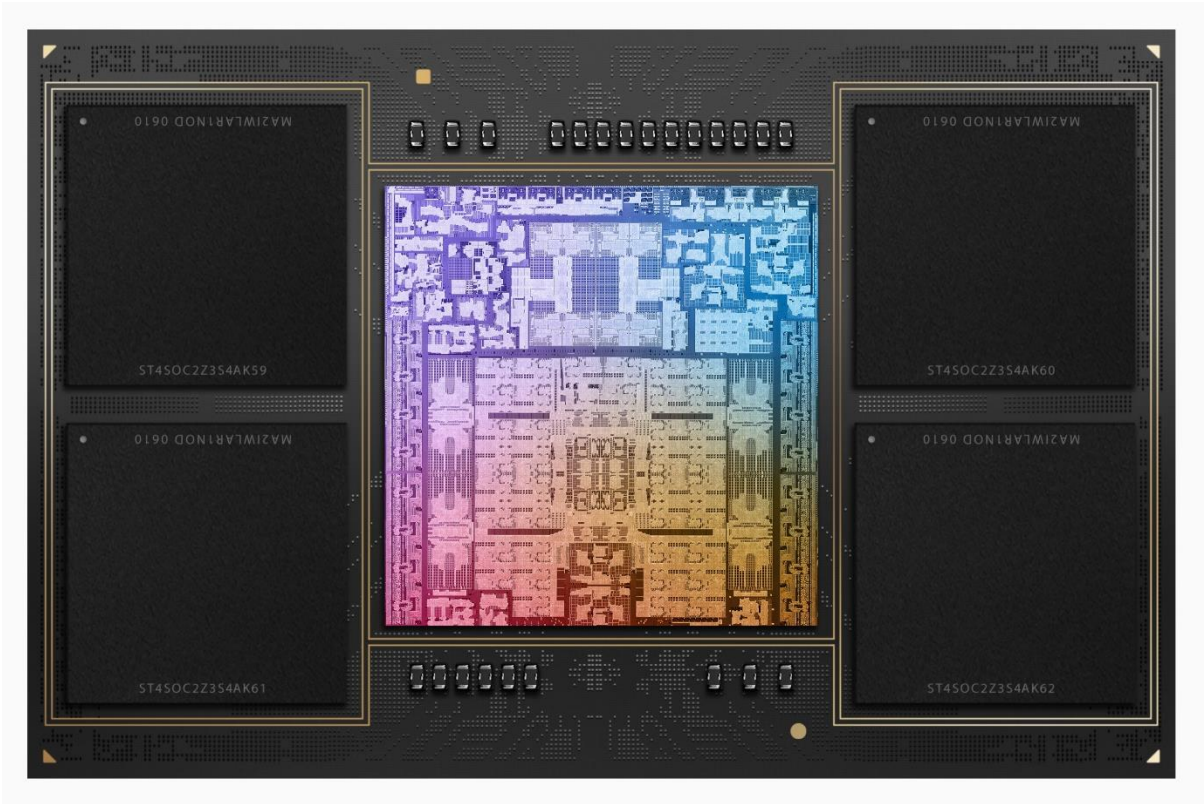
- Modern GPUs even employing 3D-stacked memory via silicon interposer
  - Very wide bus, very high bandwidth
  - E.g., HBM2 in Volta

    (High Bandwidth Memory)



Graphics Card Hub, “GDDR5 vs GDDR5X vs HBM vs HBM2 vs GDDR6 Memory Comparison,” 2019

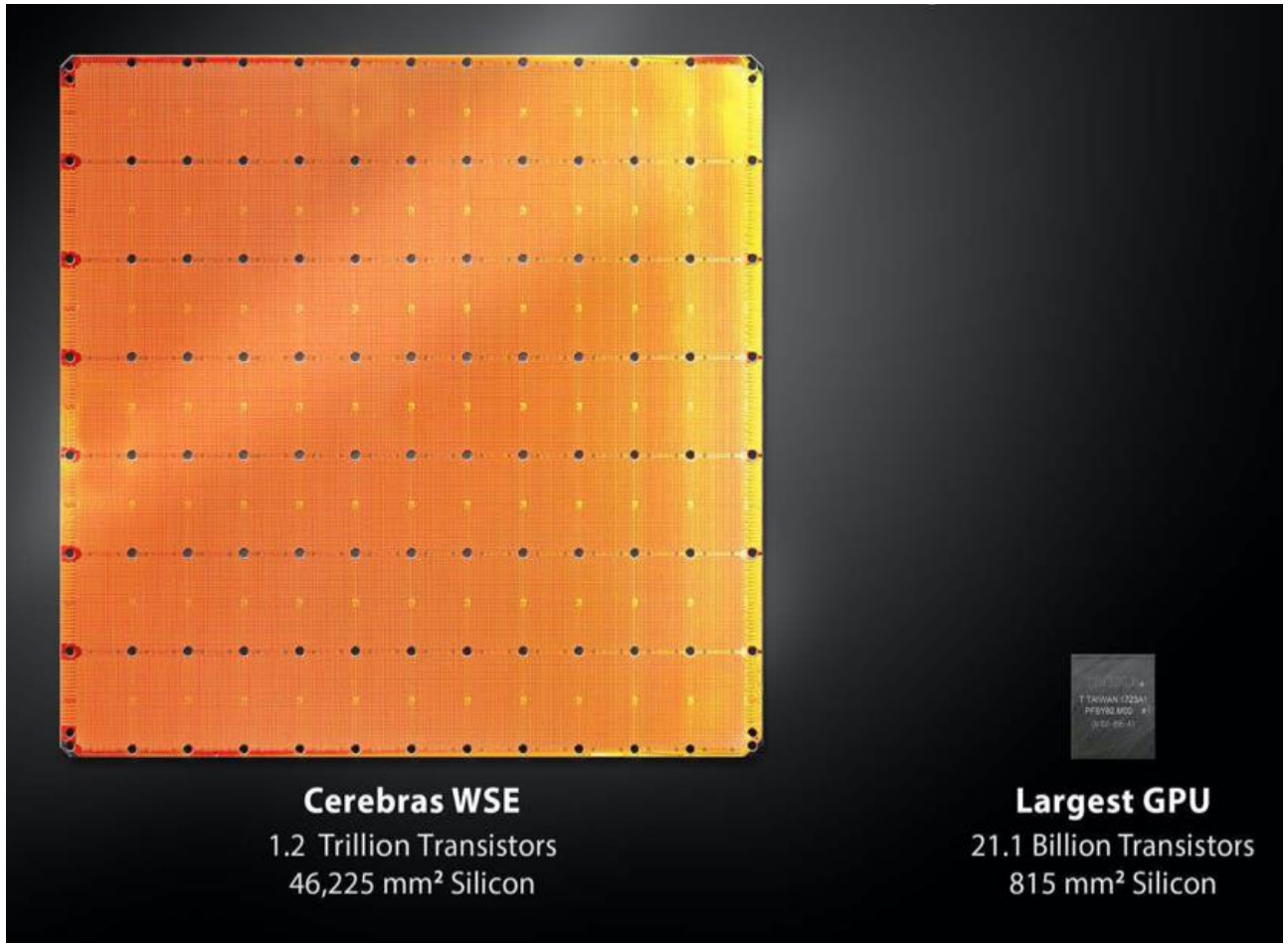
Apple M2 MAX



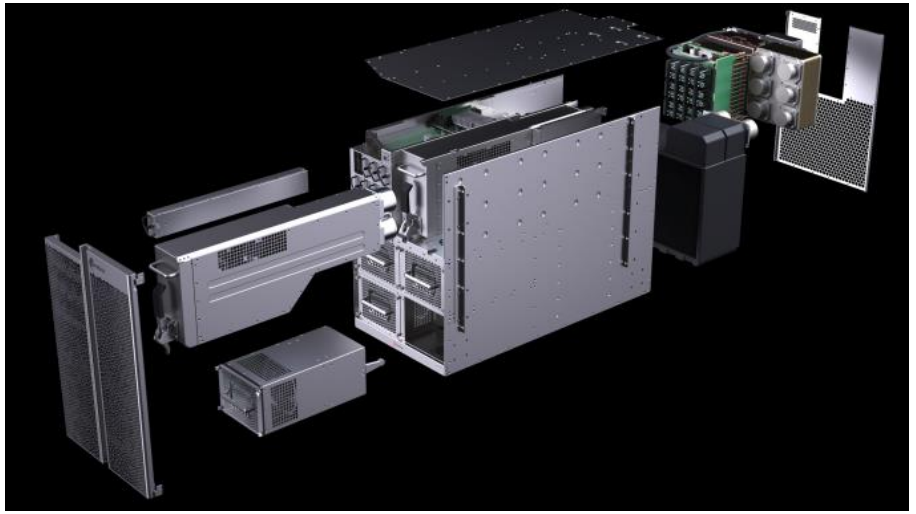
[Source: Apple]

- 5nm technology
- 67 billion transistors
- 12-core CPU
- 38-core GPU
- 16-core Neural engine
  - 15.8 trillion ops/s
- 96GB unified memory
  - LPDDR5
  - Memory bandwidth: 400GB/s

Largest Chip Ever Built: Cerebras Wafer Scale AI Engine



- 46,225 mm^2 silicon
- 1.2 trillion transistors
- 400,000 AI optimized cores
- 18 Gigabytes of On-chip Memory
- 9 PByte/s memory bandwidth
- 100 Pbit/s fabric bandwidth
- TSMC 16nm FinFET process

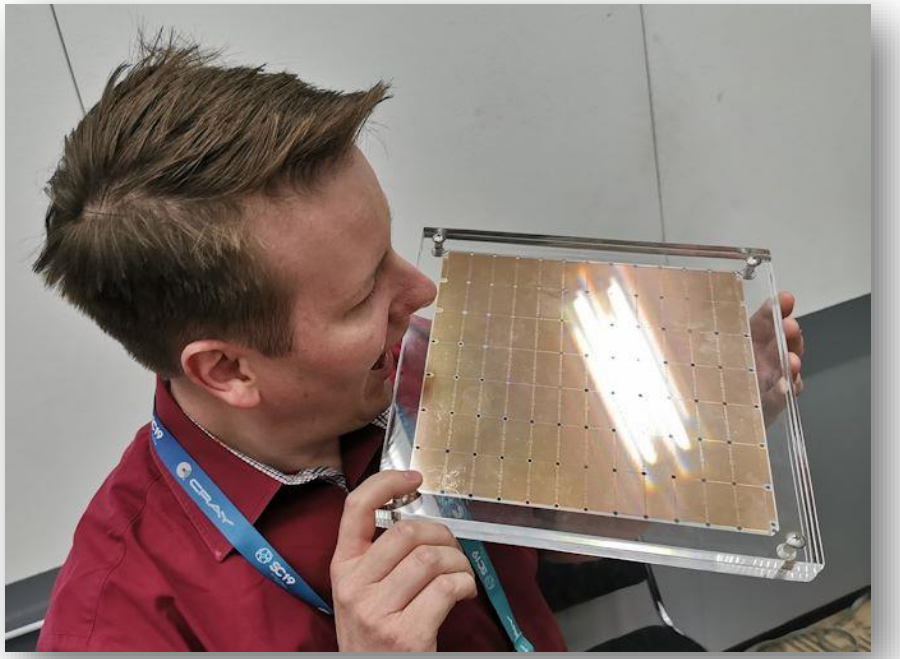


[Source: Cerebras]

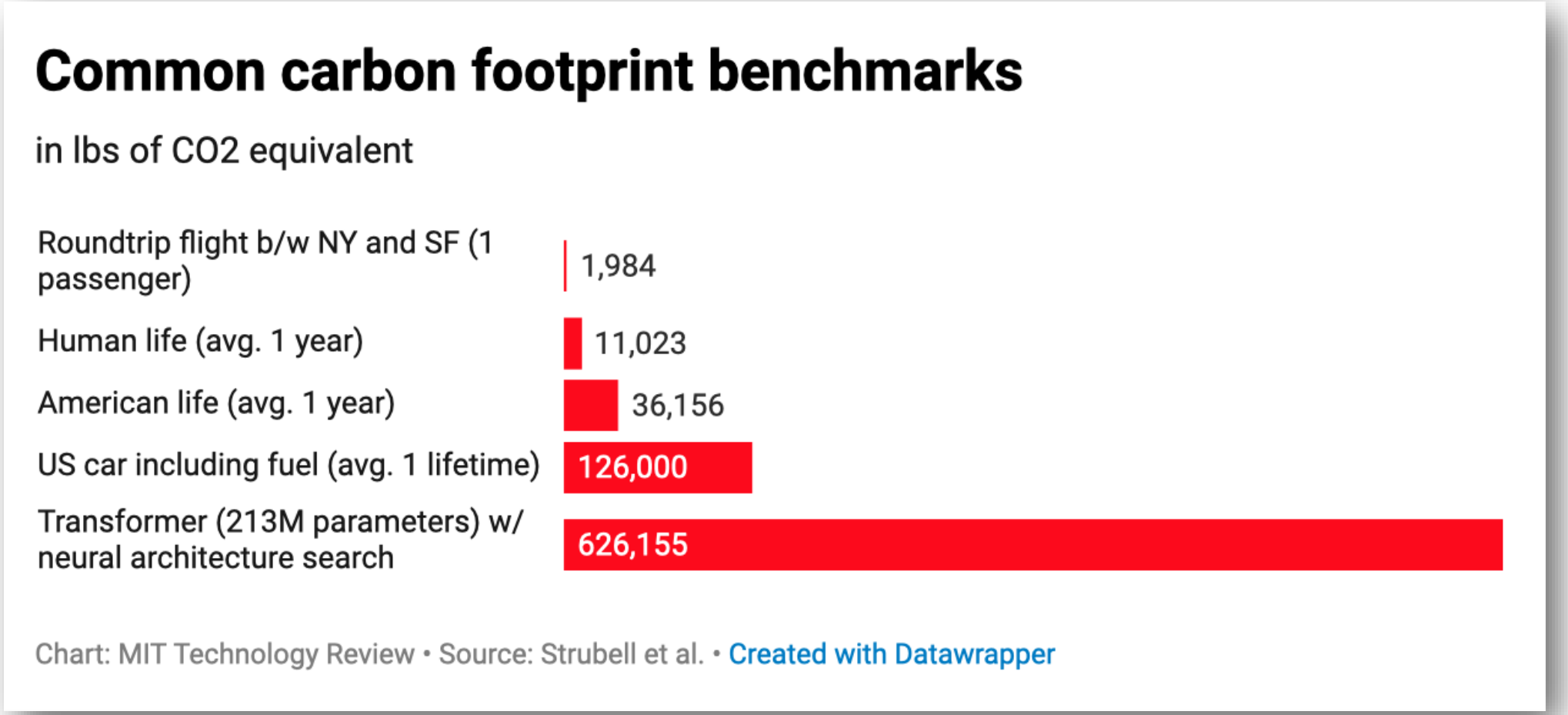
Cerebras Wafer Scale Engine

- Cerebras' Wafer Scale Engine Scores a Sale:
  $5M Buys Two for the Pittsburgh Supercomputing Center
  [AnandTech, June 9, 2020]

https://www.anandtech.com/show/15838/cerebras-wafer-scale-engine-scores-a-sale-5m-buys-two-for-the-pittsburgh-supercomputing-center



AI Consumes Too Much Energy!!!

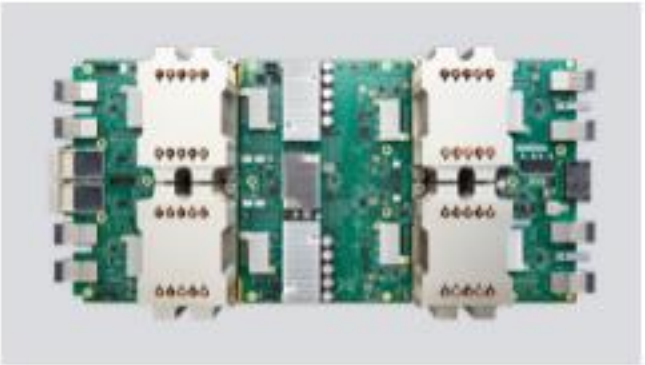


Global Shortage of Energy Supply

- In 2014, cloud data centers consumed about 1.62% of global energy
- CNBC interviewed David Patterson
  [www.cnbc.com, 5/6/2017]
  - “Four years ago, Google worried that if every Android user had 3 minutes of conversation translated a day using machine learning, they'd have to double their data centers.”
  - Alphabet spend about $10B each year on Google data center equipment
    - New data centers or improved equipment
  - Google TPU outperforms CPU by 15-30X
    - 30-80X in energy efficiency

Google TPU (Tensor Processing Unit)

- Systolic MAC array
  - V1: 8-bit Inference
  - V2: Training with bfloat
  - V3: 2x powerful over V2
  - AlphaGo V1 to V3
    - 1000X lower power
- Edge TPU
  - Coral Dev Board
  - 4 TOPS
  - 2 TOPS/Watt
  - Supports TensorFlow Lite



Cloud TPU v2

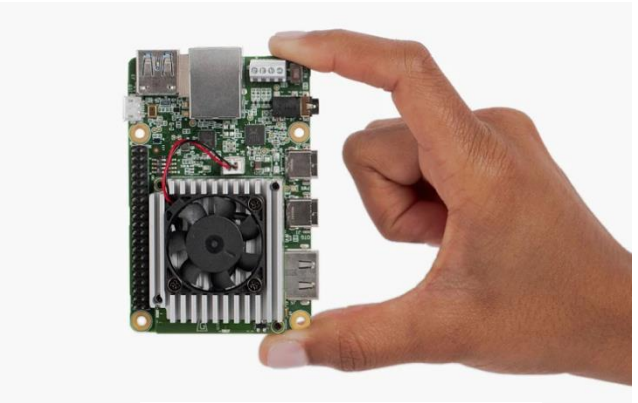
180 teraflops

64 GB High Bandwidth Memory (HBM)

Cloud TPU v3

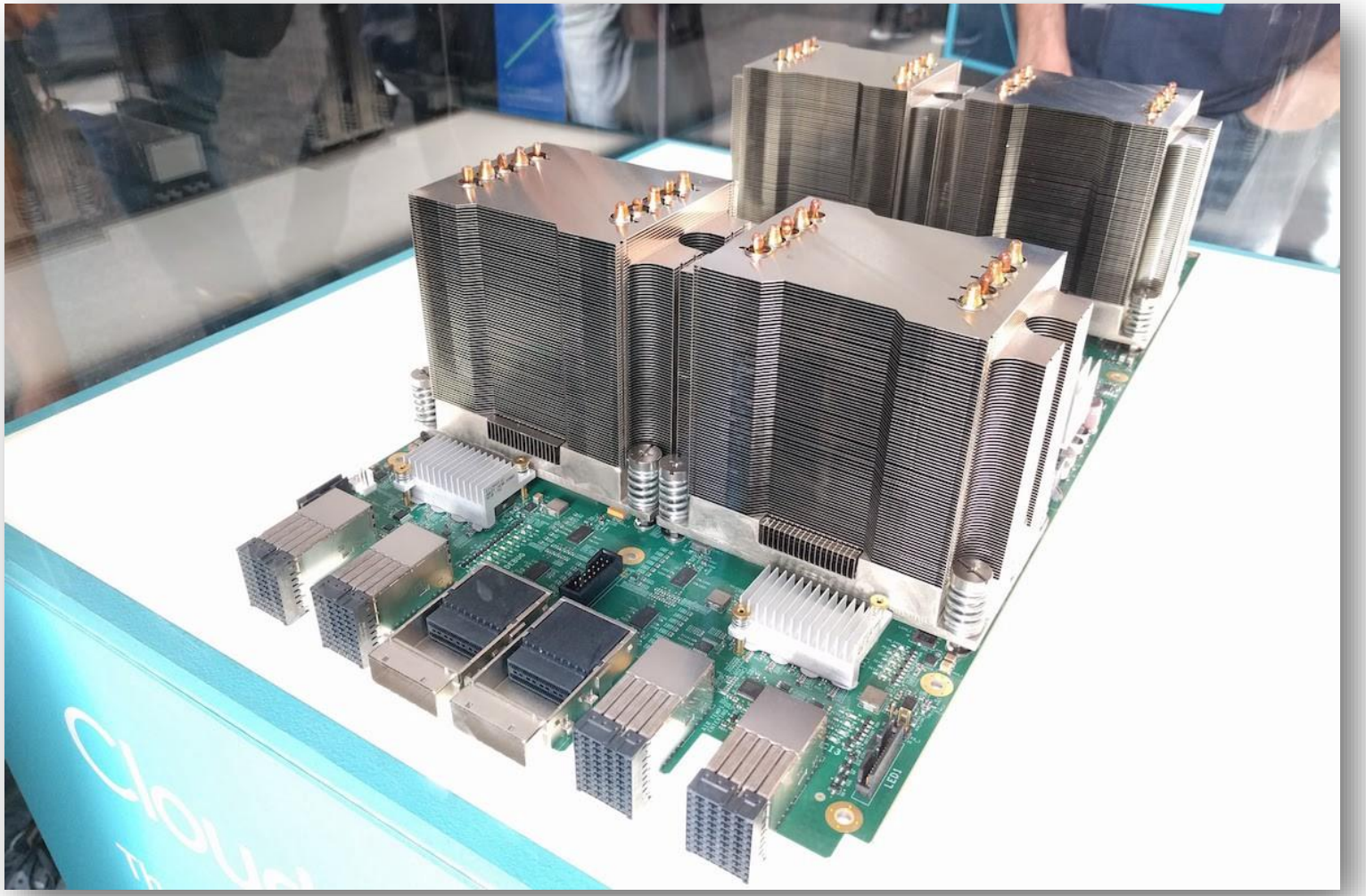
420 teraflops

128 GB HBM



[Source: Google]

A Closer View of Google TPU V2

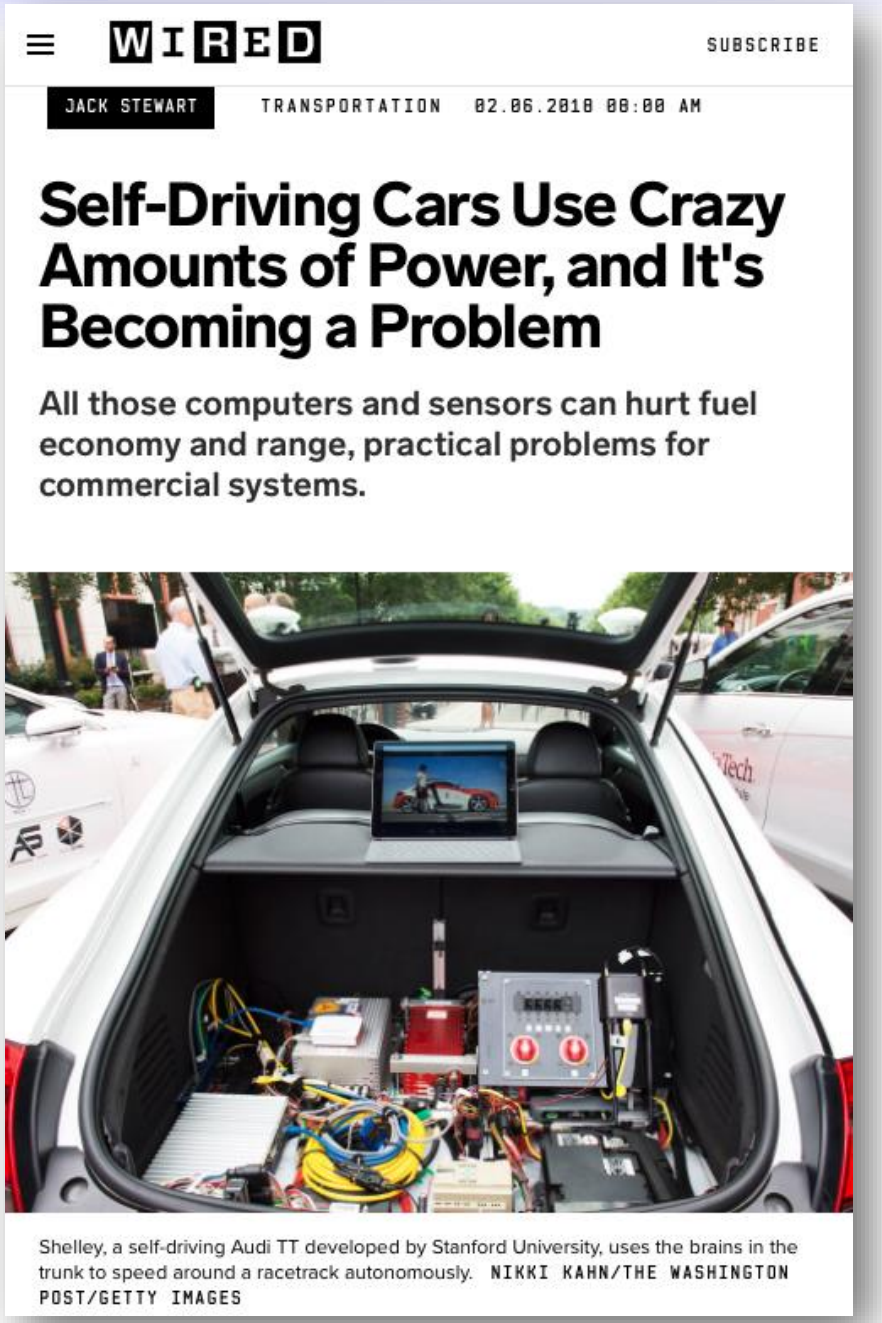


Source: https://medium.com/@antonpaquin/whats-inside-a-tpu-c013eb51973e

AI Consumes Too Much Energy!!!

WIRED [Feb 2018]

- Cameras/radar generate about **6 gigabytes** of data **every 30 seconds**.
- Self-driving car prototypes use approximately **2,500 watts** of computing power!



WIRED SUBSCRIBE

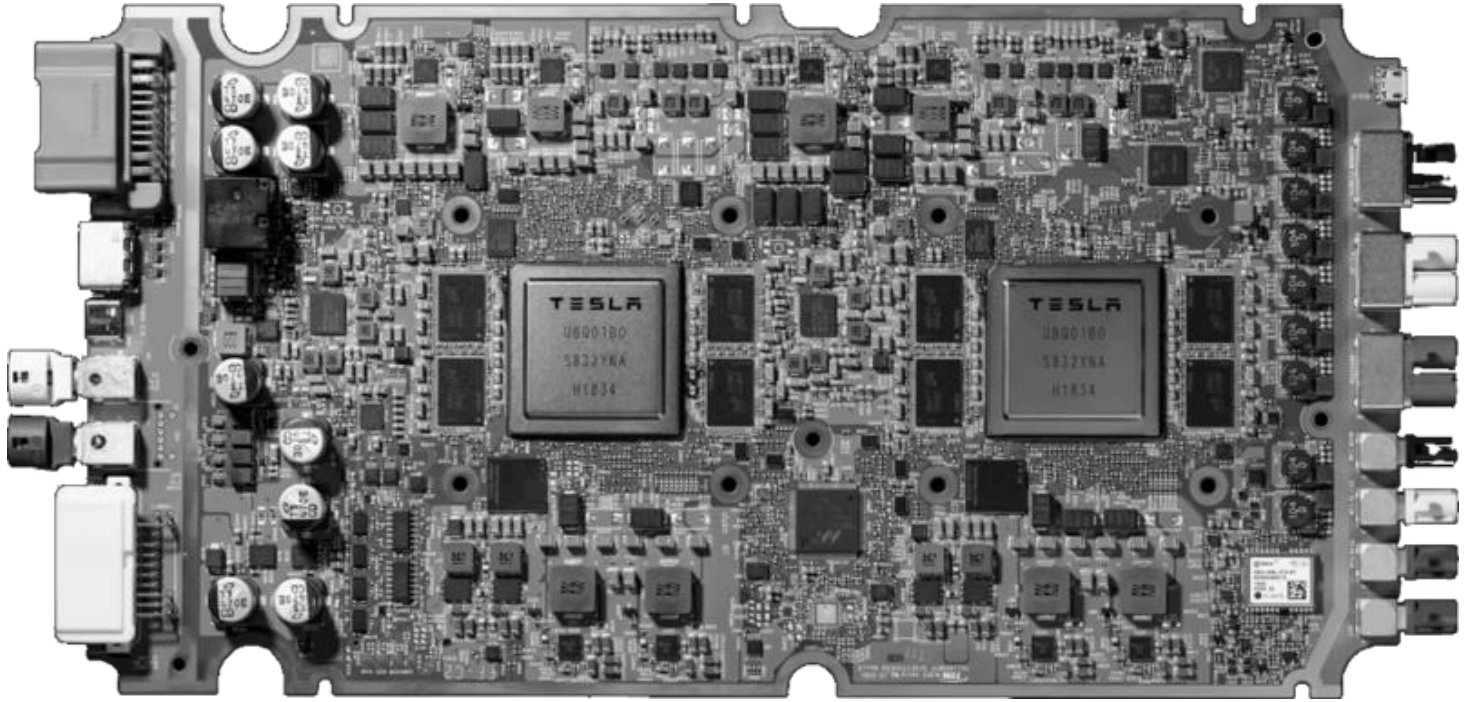
JACK STEWART TRANSPORTATION 02.06.2018 08:00 AM

Self-Driving Cars Use Crazy Amounts of Power, and It's Becoming a Problem

All those computers and sensors can hurt fuel economy and range, practical problems for commercial systems.

Shelley, a self-driving Audi TT developed by Stanford University, uses the brains in the trunk to speed around a racetrack autonomously. NIKKI KAHN/THE WASHINGTON POST/GETTY IMAGES

Tesla Full Self-Driving Computer



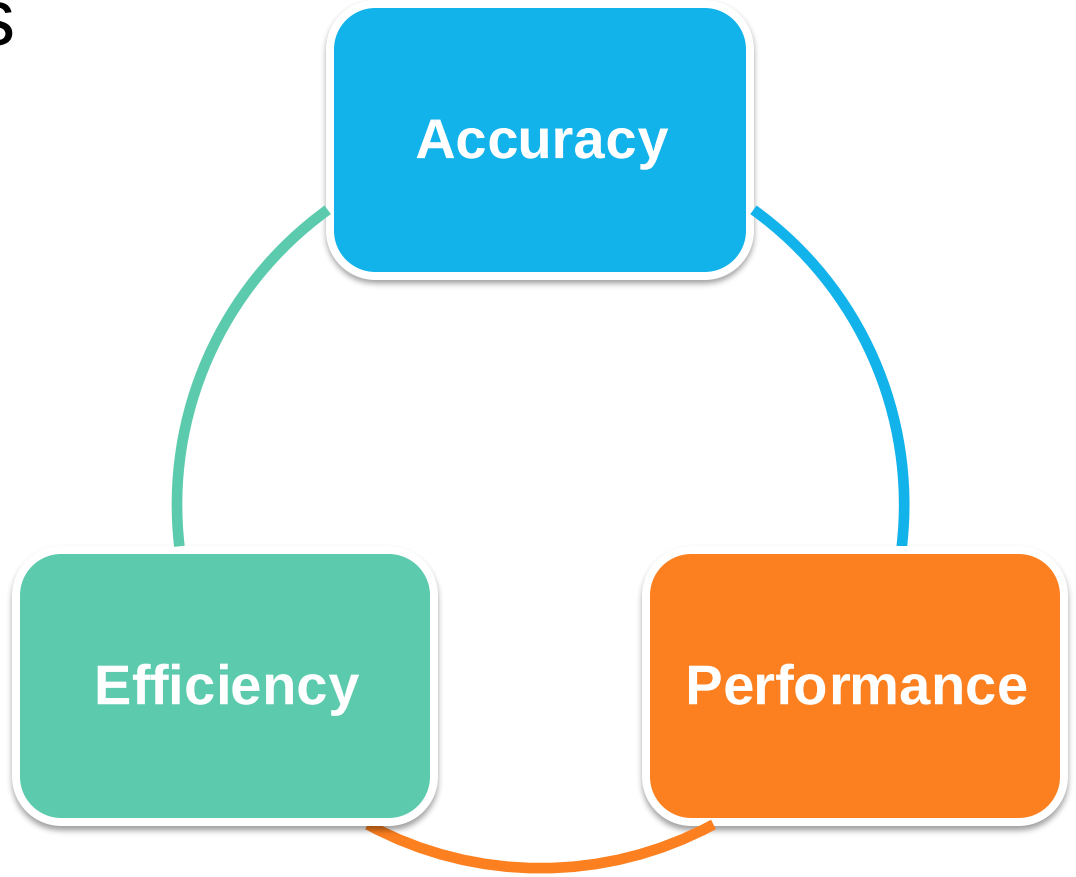
[Source: Tesla]

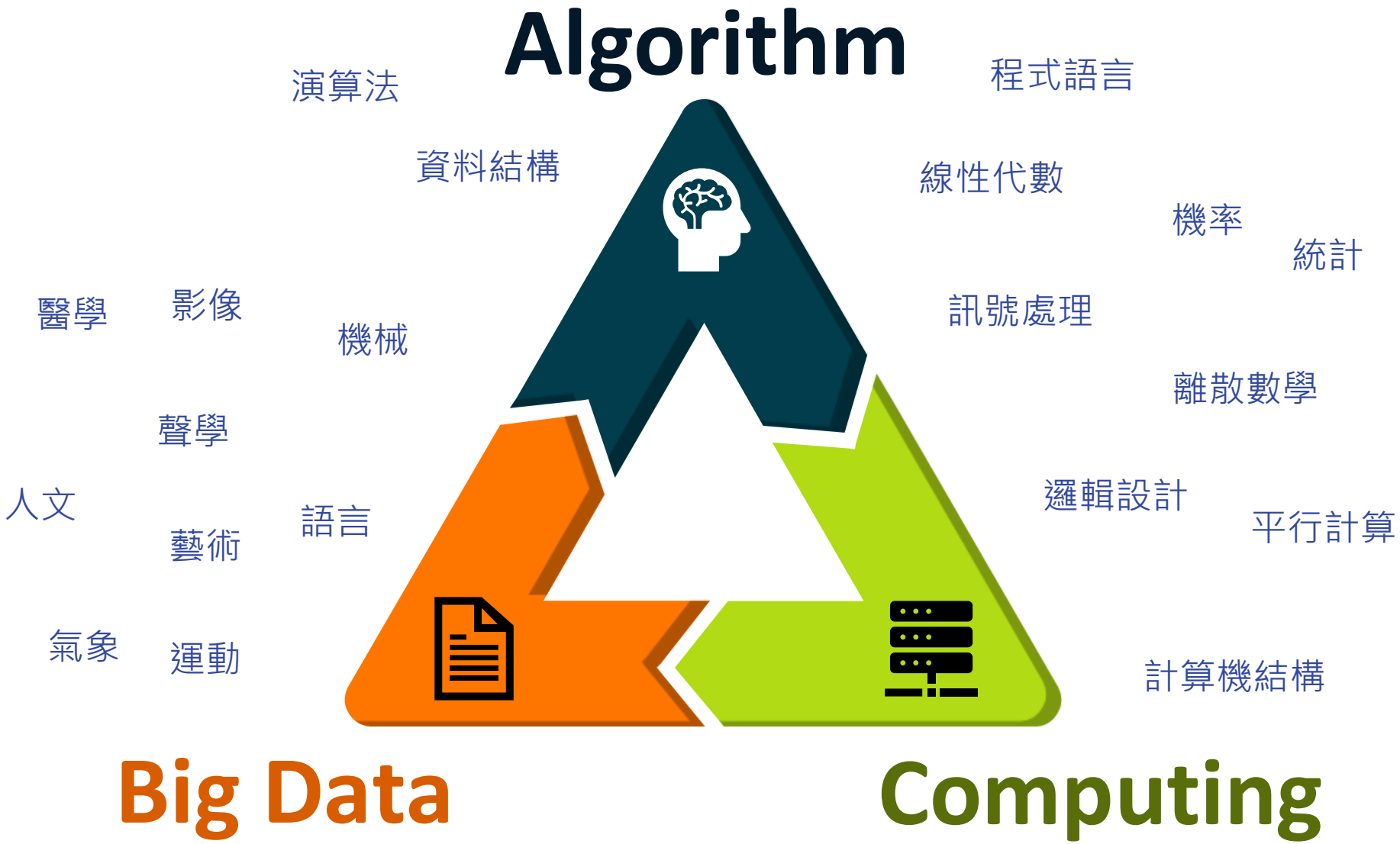
Tesla FSD chip
- ~74 TOPS
- 36 Watts

NVIDIA DGX-1
- 130-170 TFLOPS
- 3200 Watts

Efficient System Design for Deep Learning

- How do we identify the hot spots of the problem?
  - Profiling the bottleneck
- How do we optimize the system
  - Hardware/software co-design
  - Trade-off among
    - Accuracy
    - Performance
    - Efficiency




Algorithm
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資料結構
程式語言
線性代數
機率
統計
訊號處理
離散數學
邏輯設計
平行計算
計算機結構
醫學
影像
機械
聲學
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藝術
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Algorithm
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多領域的專家
必須具備紮實
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Computing
醫學
影像
聲學
人文
藝術
氣象
運動
機率
統計
離散數學
設計
平行計算
計算機結構

“People who are really serious about software should make their own hardware.”

– Alan Kay

“Design is not just what it looks like and feels like. Design is how it works.”

– Steve Jobs

“We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard.”

– JFK, 1962