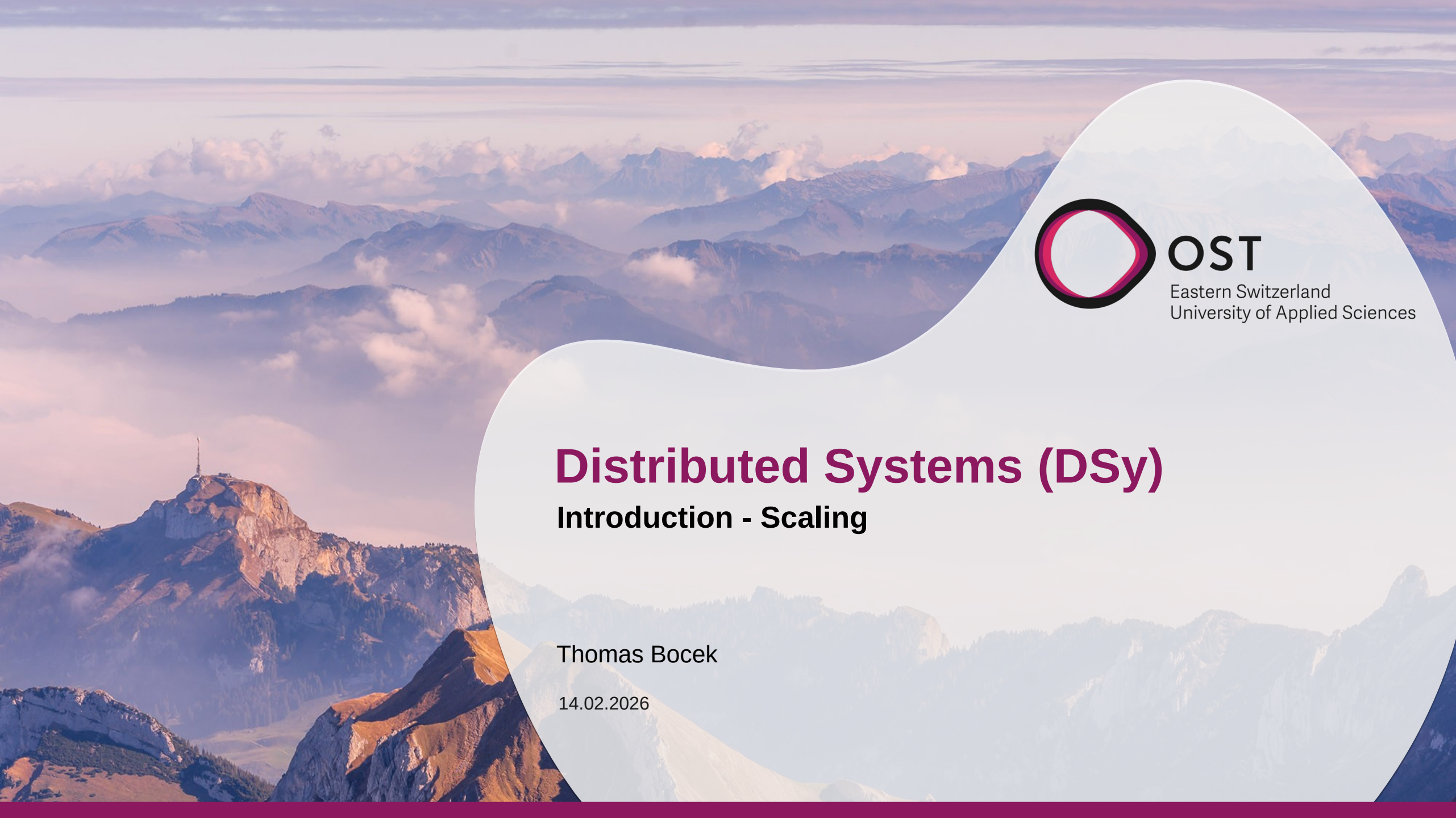

OST
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Distributed Systems (DSy)

Introduction - Scaling

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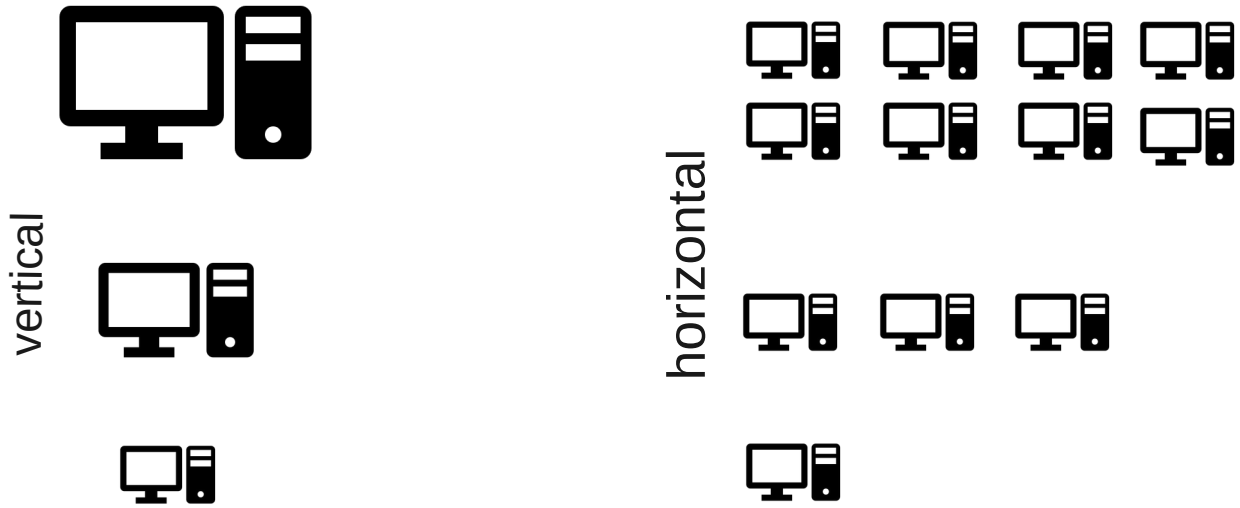
14.02.2026

Learning Goals

- Distributed systems add complexity. Avoid complexity!
- Why do we need distributed systems?
  1) Scaling (if one machine is not enough)
  2) Location (to move closer to the user)
  3) Fault-tolerance (HW will fail eventually)

Distributed Systems Motivation

- Why Distributed Systems
  - Scaling
    - Vertical (scale up), more memory, faster CPU
    - Horizontal (scale out), more machines
    - 2025, Google: largest known Kubernetes cluster, with 130,000 nodes [source] [source]



- Scaling Vertical
  - Single Core
    - Cinebench R23:
      - 1700X: 981 (2017) [link]
      - 3900X: 1302 (2019) [link]
      - 5950X: 1644 (2020)
      - 9950X: 2202 (2024) [link]
  - In 7 years, more than 2x as fast

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Sigle Core – Mulit Core

- Amdahl's Law (Gene Amdahl, 1967)
  - S = 1 / ((1 - P) + P/N)
  - S = Speedup, P = parallelizable fraction (0–1), N = number of parallel units
- Parallelization applies at every level
  - Cores
  - CPUs
  - Servers
  - Clusters
  - Datacenters
- Example: P = 95%
  - Max speedup = 20x (even with ∞ processors)
    - 10 processors → 6.9x
    - 100 → 16.8x
    - 1000 → 19.6x
- The sequential part is always the bottleneck
- Real-world: DB locks limit throughput regardless of server count

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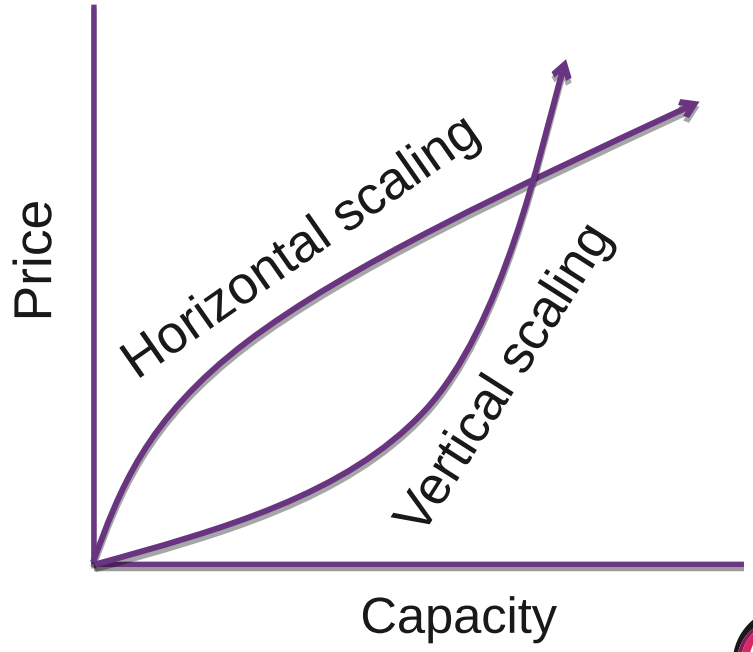
Distributed Systems Motivation

- Machine Learning
  - Current trend: scale horizontally
  - NVIDIA Blackwell GPU [link], 192GB, NVL72
  - AMD Instinct MI350X Accelerators [link], 288GB, MI400X announced with 432GB.
  - High param LLM with large context size
  - ML with vertical scaling is not (yet) feasible
- Economics
  - Initially scaling vertically cheaper, until max out HW
  - Current RAM prices, increasing
  - Current servers are fast: Rasperry Pi4 [link]
  - Raspberry Pi5 with llama.cpp / llama 3.2 [link] [link]



Distributed Systems Motivation

Horizontal Scaling

+ Lower cost with massive scale

+ Easier to add fault-tolerance

+ Higher availability

- Adaption of software required

- More complex system, more components involved

Vertical Scaling

+ Lower cost with small scale

+ No adaption of software required

+ Less complexity

- HW limits for scaling

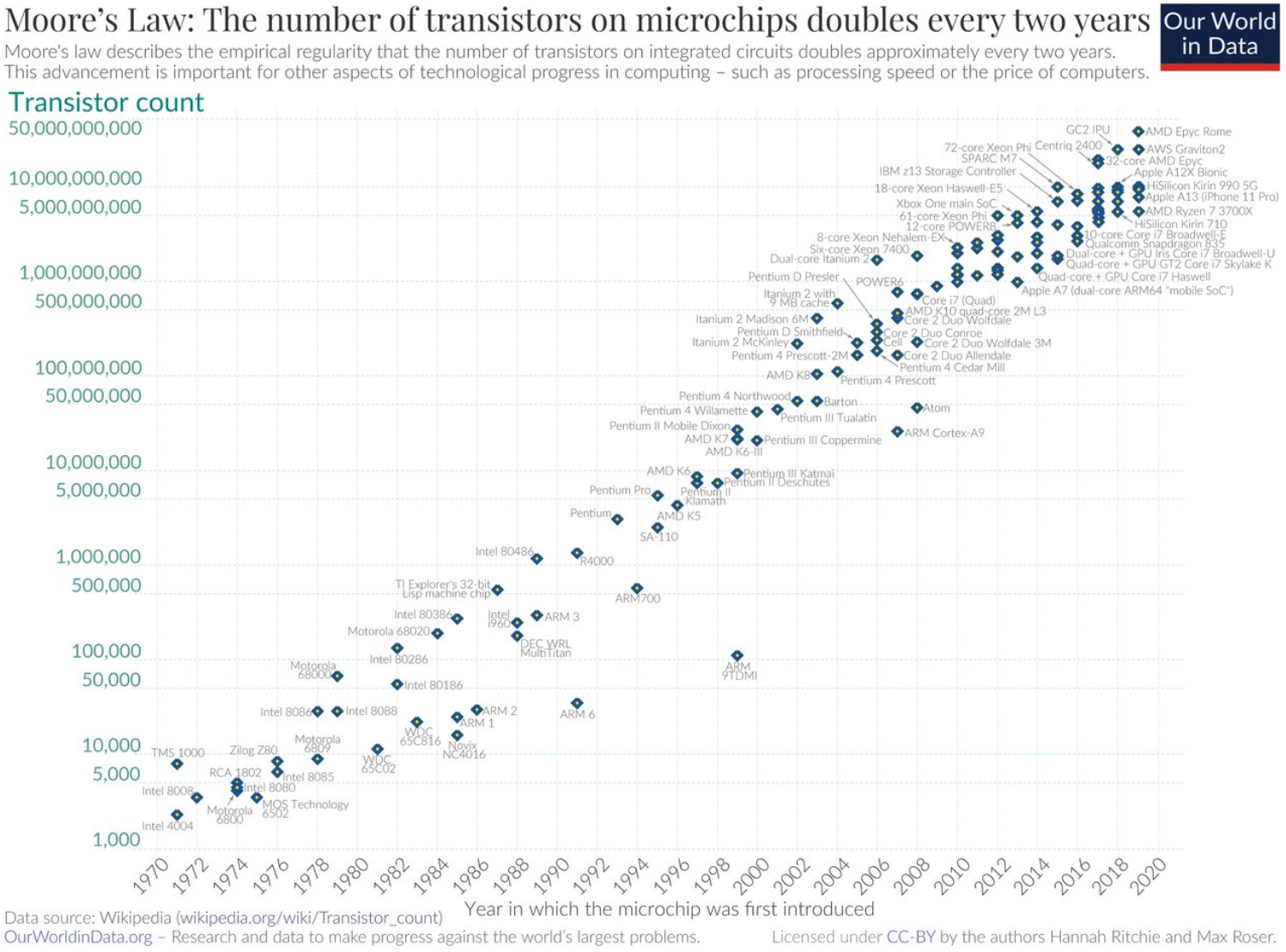
- Risk of HW failure causing outage

- More difficult to add fault-tolerance

Vertical Scaling Performance

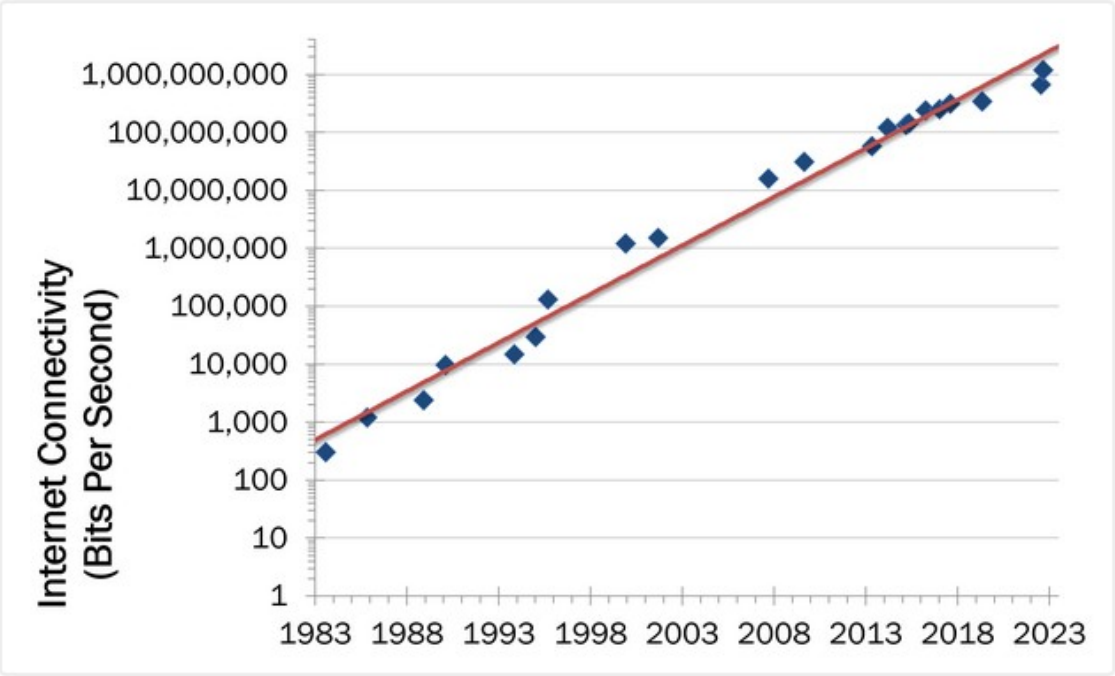
- Moore's Law – nr. of transistors doubles every 2 years (other predictions (D. House), doubling chip performance every 18 month)
- Dead in 2025?
- Forbes 1995: "The price per transistor will bottom out sometime between 2003 and 2005. From that point on, there will be no economic point to making transistors smaller. So Moore's Law ends in seven years."

  AMD EPYC, 192 cores, 2socket server → 768 threads
- Apple M3 Ultra ~184b (208b GB200)



Vertical Scaling Performance

- Nielsen's Law: a high-end user's connection speed grows by 50% per year
- Bandwidth grows slower than computer power
  - Telecoms companies are conservative
  - Users are reluctant to spend much money on bandwidth
  - The user base is getting broader
- Optimize for bandwidth not for CPU
- Zmap complete scan of the IPv4 address space in under 5 minutes
- Init7: Fiber7-X2 25/25 Gbit ~64CHF/month



https://www.nngroup.com/articles/law-of-bandwidth/

		Annualized Growth Rate	Compound Growth Over 10 Years
Nielsen's law	Internet bandwidth	50%	57×
Moore's law	Computer power	60%	100×

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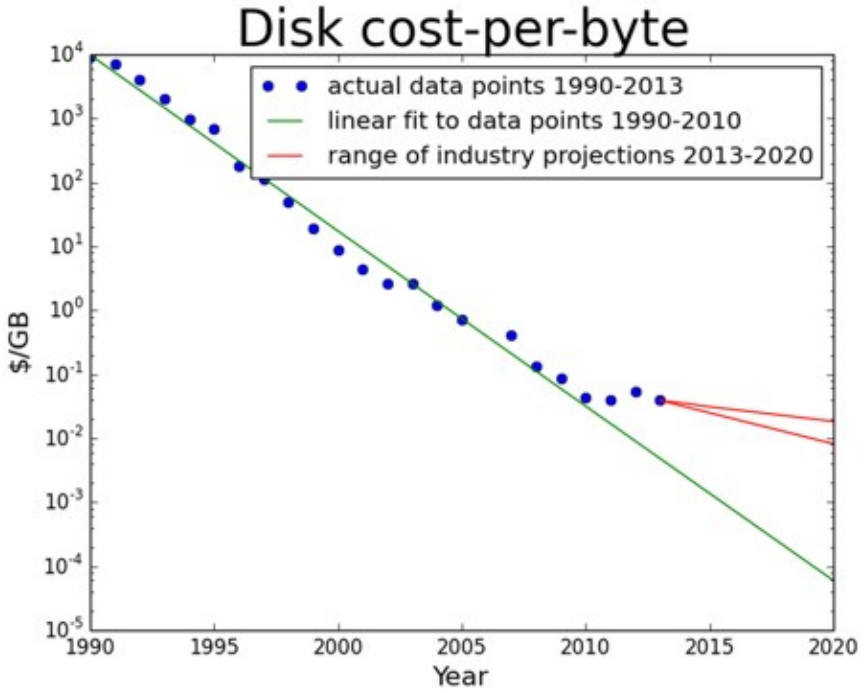
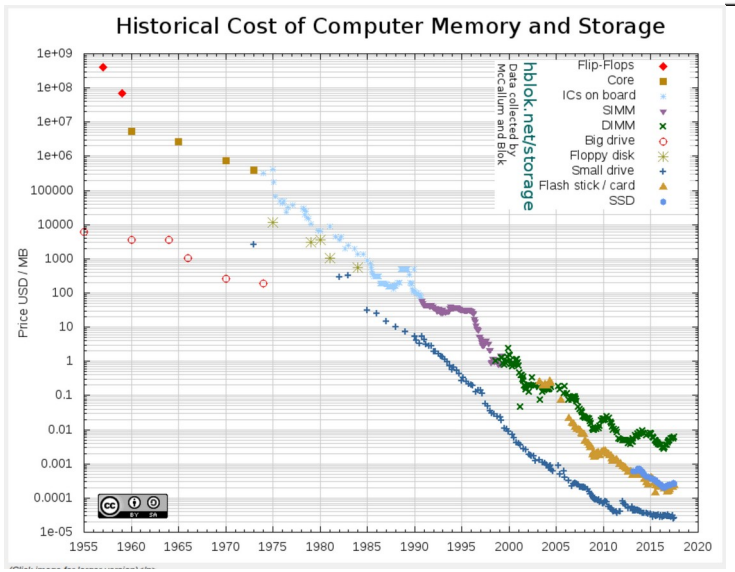
Vertical Scaling Performance

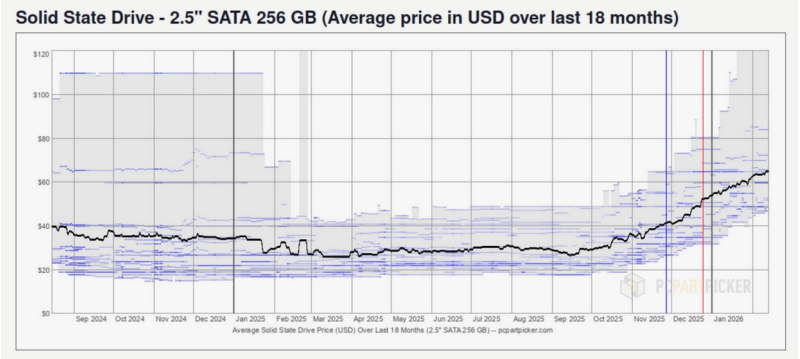
- Kryder's Law: disk density doubling every 13 month
- «Soon hard drives will migrate into phones, still cameras, PDAs, cars and everyday appliances» https://www.scientificamerican.com/article/kryders-law/ , Aug. 2005
- User behavior changed
  - SSD, speed is important
- Cloud – Dropbox, Spotify
  - Streaming





Source: https://hblok.net/blog/storage/

http://blog.dshr.org/2016/05/the-future-of-storage.html



Source: https://pcpartpicker.com/trends/price/internal-hard-drive/

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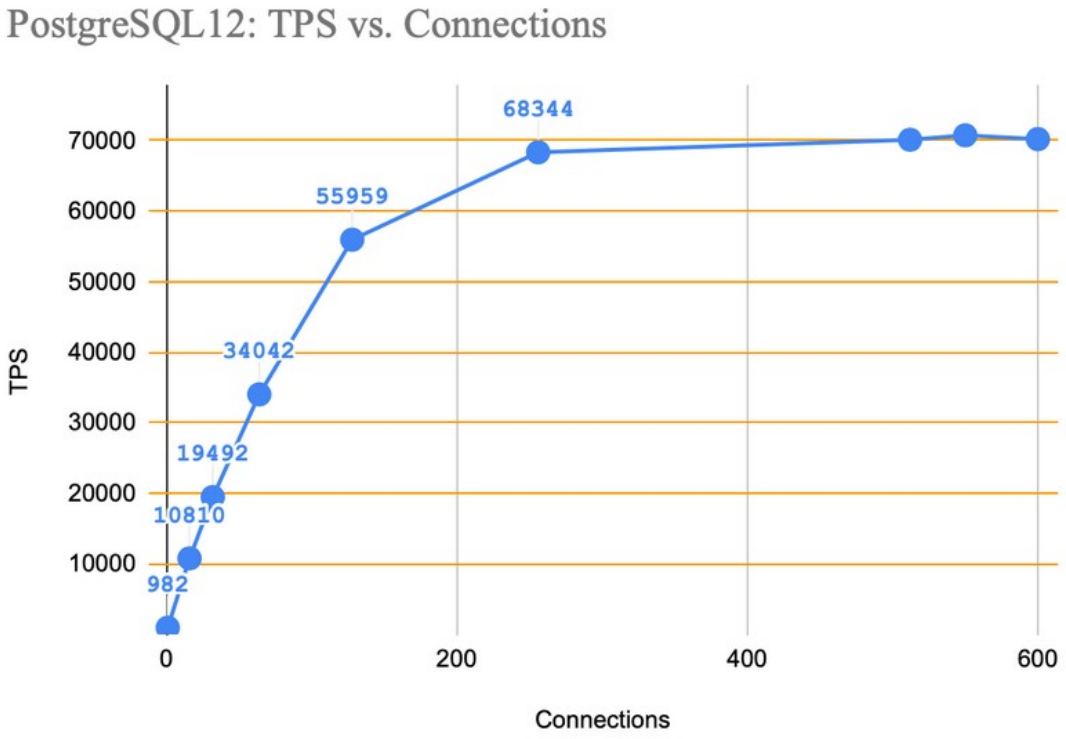
Vertical Scaling Performance

- Vertical scaling
  - HW today is fast!
    - Database benchmark with a fast machine in 2020 (96 cores, 384GB RAM, 4 x NVMe SSD)
    - 70k TPS
- Best principle for small and simple applications!
- RPi 4 [link]
- Simple website with a few DB calls is not HW intensive



https://www.enterprisedb.com/blog/pgbench-performance-benchmark-postgresql-12-and-edb-advanced-server-12

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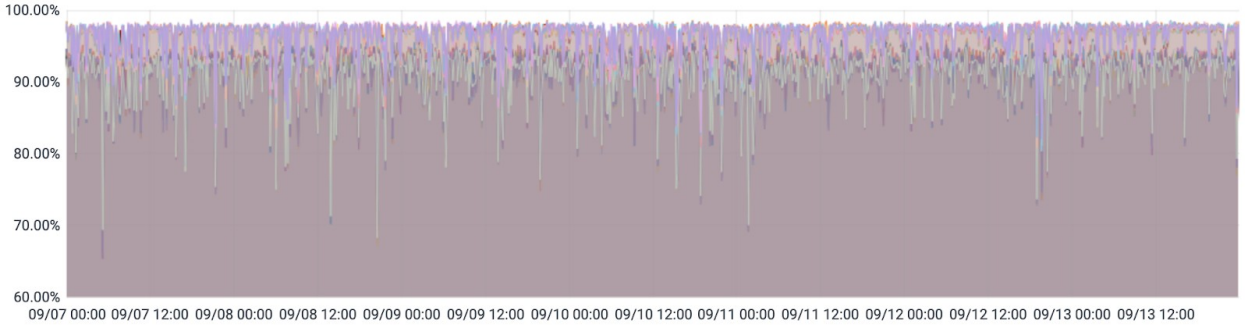
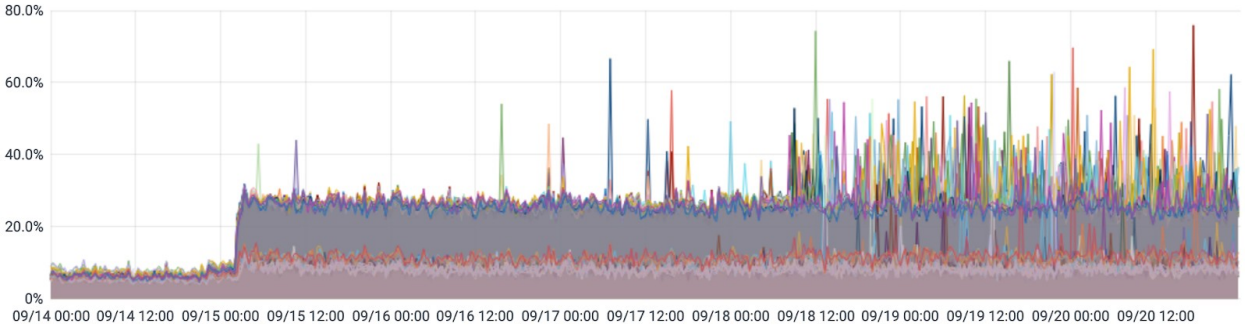
Vertical Scaling Performance

- Example: Let's Encrypt
- 21.01.2021: The Next Gen Database Servers Powering Let's Encrypt [link]
  - Providing certificates for 275m websites
  - “A database is at the heart of how Let’s Encrypt manages certificate issuance” - 1 single MariaDB
  - “We run the CA against a single database in order to minimize complexity” – Some read operations at replicas, one server for writes
  - 2x Xeon 24-cores running at 90%
  - Upgrade to 2x64 Epyc, on 15.09, running at 25%
    - Query 3 times faster
    - SATA → NVMe - IO from 500MB/s to 3 GB/s





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Wirth's law (1995)

- "Software is getting slower more rapidly than hardware becomes faster." [link]
- Hardware get faster (e.g., Moore's Law)
- Software complexity and resource demands grow even faster - while widely observed, this is not scientifically measured like Moore's Law (On Bloat)
- Result: Modern software often feels slower despite running on much faster hardware - this is anecdotal experience many developers share

- Examples of bloat: Modern web pages often larger than the original DOOM game, electron apps consuming gigabytes of RAM
- Will it run DOOM? [link]
  - Doom Ledger Application [link]

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Energy: The New Scaling Constraint

- Global data center power: ~415 TWh (2024), projected 945 TWh by 2030 [source]
- AI-optimized servers: 21% of DC power (2025), 44% by 2030, growing 5× faster than conventional [source]
- US data centers: 183 TWh ~4% of national electricity [source]
- One GB200 NVL72 rack = 120 kW ≈ 40 households [source]
- Bitcoin network: ~204 Twh/year [source]
- AI-specific hardware will surpass Bitcoin soon
- ChatGPT query: ~0.3 Wh, Google Gemini: 0.24 Wh [source, source]

  + 100 queries/day = 30 Wh < 0.3% Swiss household consumption ≈ 15 min Netflix

  + Efficiency improving

  + Time savings, indirect energy savings

  - Rebound effect, OpenAI ~2.5B queries/day

  - Infrastructure needs to be built anyway

  - Recommendation: Use consciously and targeted