Computing Performance 2021

What's On the Horizon

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YOW!

NETFLIX

Disclaimers: About this talk

This is

- **a performance engineer's views about industry-wide server performance**

This isn't

- necessarily about my employer, or my employer’s views
- an endorsement of any company/product or sponsored by anyone
- professional market predictions (various companies sell such reports)
- based on confidential materials
- necessarily correct or fit for any purpose

My predictions may be wrong! They will be thought-provoking.

Agenda

1. Processors
2. Memory
3. Disks
4. Networking
5. Runtimes
6. Kernels
7. Hypervisors
8. Observability

Slides are online and include extra details as fine print

Slides: http://www.brendangregg.com/Slides/YOW2021_ComputingPerformance.pdf

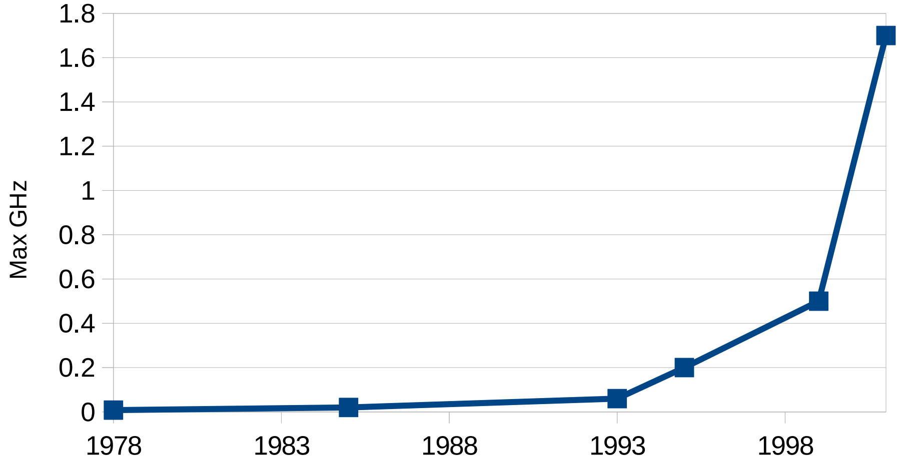
Not covering: Databases, file systems, front-end, mobile, desktop.

1. Processors

Clock rate

Early Intel Processors

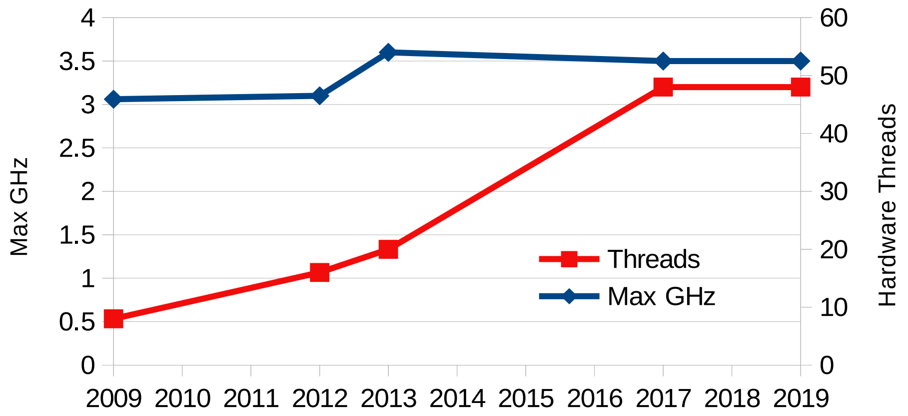
Year	Processor	GHz
1978	Intel 8086	0.008
1985	Intel 386 DX	0.02
1993	Intel Pentium	0.06
1995	Pentium Pro	0.20
1999	Pentium III	0.50
2001	Intel Xeon	1.70



Clock rate

Server Processor Examples (AWS EC2)

Year	Processor	Cores/T.	Max GHz
2009	Xeon X5550	4/8	3.06
2012	Xeon E5-2665 0	8/16	3.10
2013	Xeon E5-2680 v2	10/20	3.60
2017	Platinum 8175M	24/48	3.50
2019	Platinum 8259CL	24/48	3.50



Increase has leveled off due to power/efficiency

- Workstation processors higher; E.g., 2020 Xeon W-1270P @ **5.1 GHz**

Horizontal scaling instead

- More CPU cores, hardware threads, and server instances

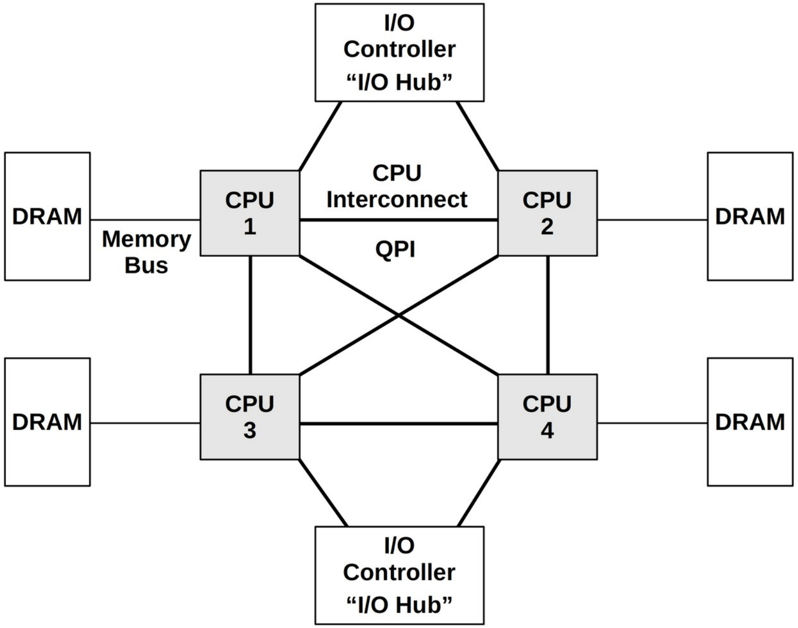
Interconnects

Year	CPU Interconnect	Bandwidth Gbytes/s
2007	Intel FSB	12.8
2008	Intel QPI	25.6
2017	Intel UPI	41.6

10 years:

- 6x core count
- 3.25x bus rate

Memory bus (covered later) also lagging



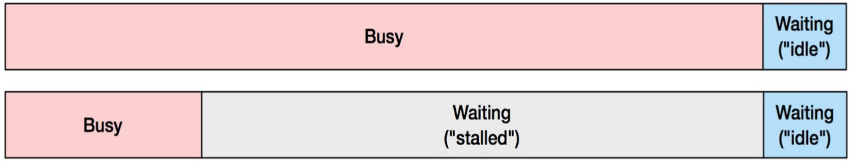
Source: Systems Performance 2nd Edition Figure 6.10 [Gregg 20]

CPU utilization is wrong

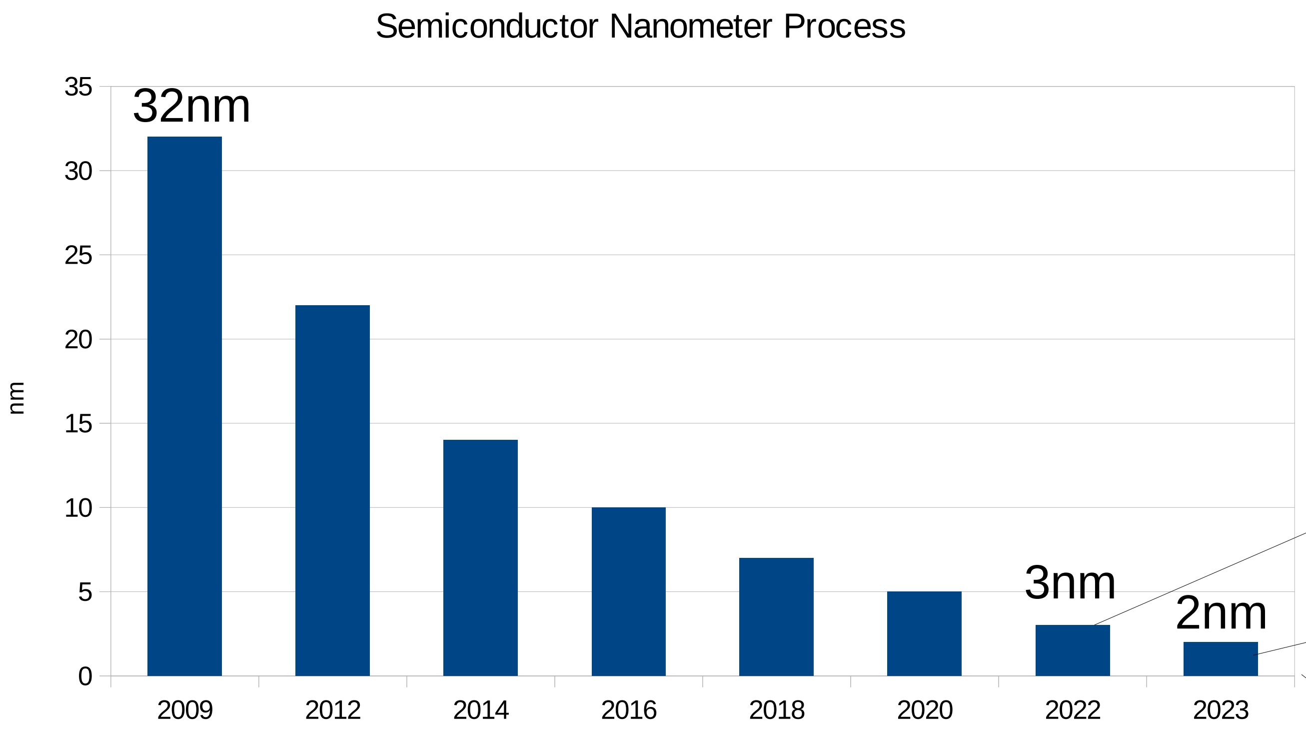
- Often mostly memory/interconnect stalls

90% CPU

...may mean:



Lithography



Source: Semiconductor device fabrication [Wikipedia 21a]

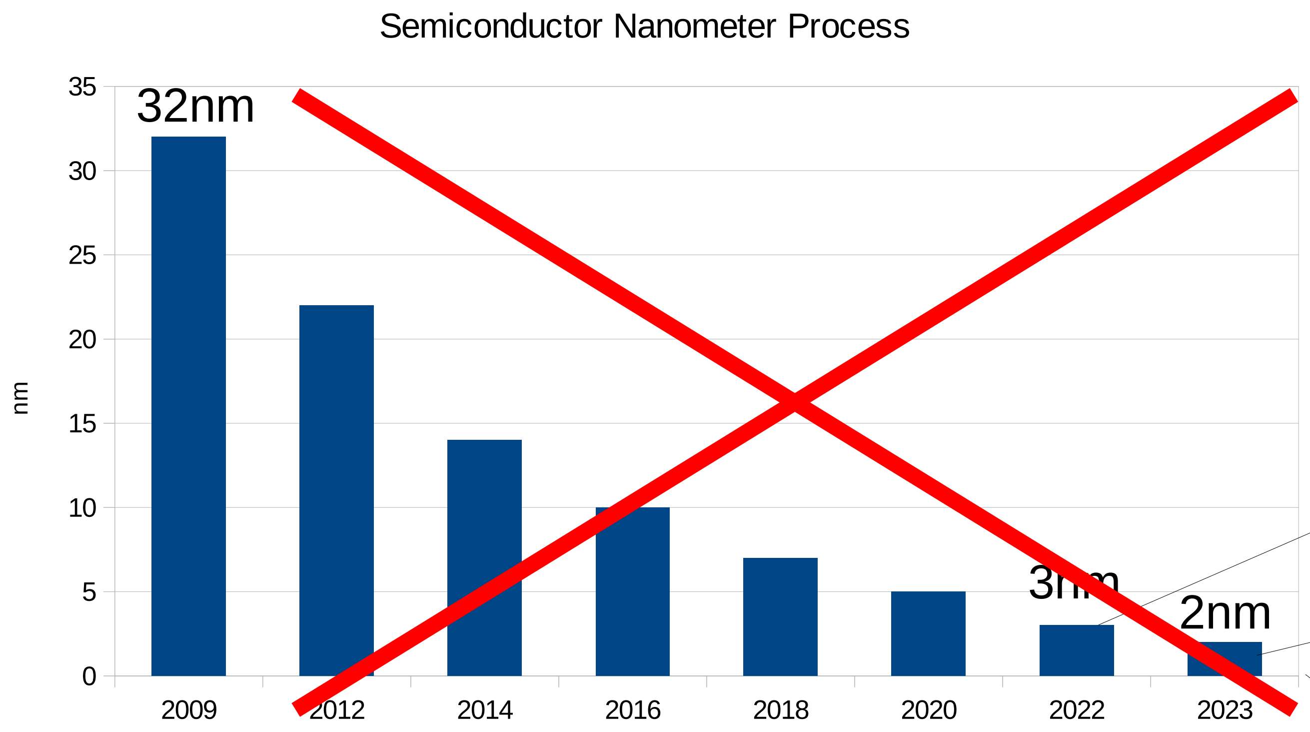
TSMC expects volume production of 3nm in 2022 [Quach 21a]

IBM has already built one [Quach 21b]

Lithography limits expected to be reached by 2029, switching to stacked CPUs. [Moore 20]

BTW: Silicon atom diameter ~0.2 nm [Wikipedia 21b]

Lithography



Source: Semiconductor device fabrication [Wikipedia 21a]

BTW: Silicon atom diameter ~0.2 nm [Wikipedia 21b]

"Nanometer process" since 2010 should be considered a marketing term

New terms proposed include:

- **GMT** (gate pitch, metal pitch, tiers)
- **LMC** (logic, memory, interconnects)

[Moore 20]

TSMC expects volume production of 3nm in 2022 [Quach 21a]

IBM has already built one [Quach 21b] (it has 12nm gate length)

Lithography limits expected to be reached by 2029, switching to stacked CPUs. [Moore 20]

Other processor scaling

Special instructions

- E.g., AVX-512 Vector Neural Network Instructions (VNNI)

Connected chiplets

- Using embedded multi-die interconnect bridge (EMIB) [Alcorn 17]

3D stacking

- E.g., Intel HBM, AMD Vcache [Cutress 21]

Hybrid core architecture

- ARM big.LITTLE; Intel Alder Lake pcores/ecores [Alcorn 21]

Recent server processor examples

Vendor	Processor	Process	Clock	Cores/T.	LLC Mbytes	Date
Intel	Xeon Platinum 8380 (Ice Lake)	"10nm"	2.3 - 3.4	40/80	60	Apr 2021
AMD	EPYC 7713P	"7nm"	2.0 - 3.675	64/128	256	Mar 2021
ARM-based	Ampere Altra Q80-33	"7nm"	3.3	80/80	32	Dec 2020

Intel Alder Lake for server (Sapphire Rapids) coming soon?
Other server processors: IBM Z, RISC-V

Coming soon to a datacenter near you

Although there is a **TSMC chip shortage** that may last through to 2022/2023 [Quatch 21][Ridley 21]

Cloud chip race

Amazon ARM/Graviton2

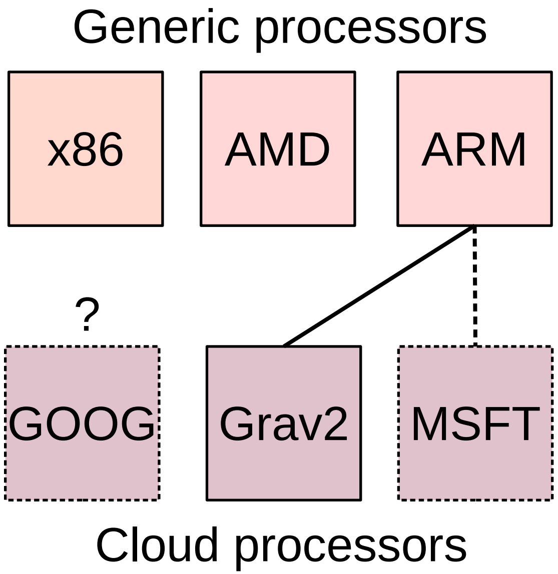
- ARM Neoverse N1, 64 core, 2.5 GHz
- Promising microbenchmark results in a test environment

Microsoft ARM

- ARM-based something coming soon [Warren 20]

Google SoC

- Systems-on-Chip (SoC) coming soon [Vahdat 21]



Accelerators

GPUs

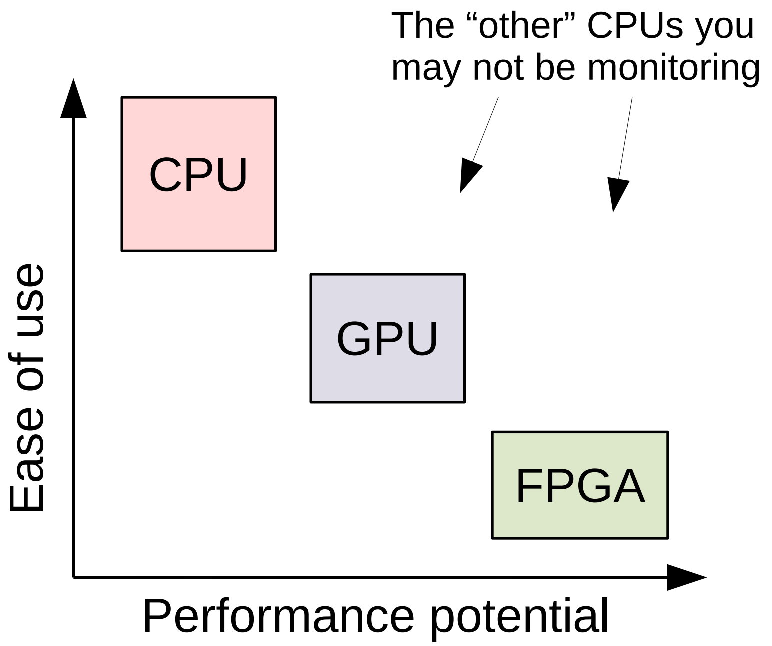
- Parallel workloads, thousands of GPU cores. Widespread adoption in machine learning.

FPGAs

- Reprogrammable semiconductors
- Great potential, but needs specialists to program
- Good for algorithms: compression, cryptocurrency, video encoding, genomics, search, etc.
- Microsoft FPGA-based configurable cloud [Russinovich 17]

Also IPUs, TPUs

- Infrastructure processing units [Kummrow 21]
- Tensor processing units [Google 21]



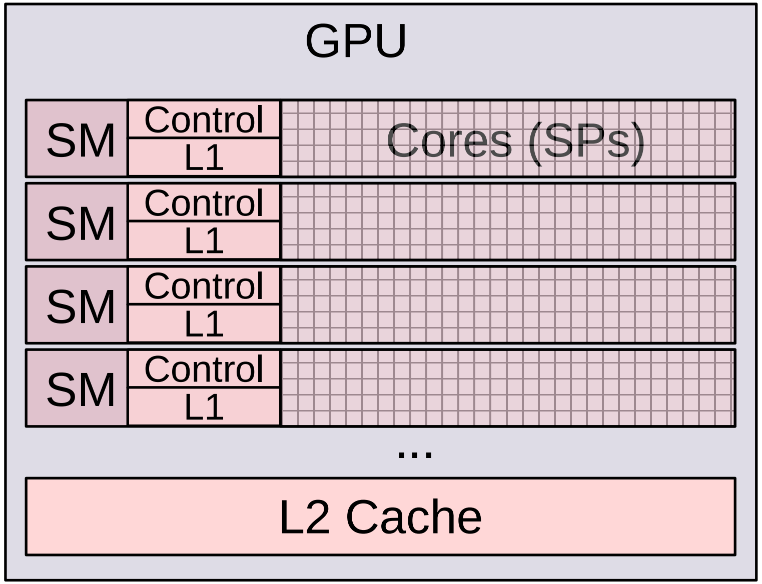
Latest GPU examples

NVIDIA GeForce RTX 3090: **10,496 CUDA cores**, 2020

- [Burnes 20]

Cerebras Gen2 WSE: **850,000 AI-optimized cores**, 2021

- Use most of the silicon wafer for one chip.
  2.6 trillion transistors, 23 kW. [Trader 21]
- Previous version was already the “Largest chip ever built,” and US$2M. [insideHPC 20]



SM: Streaming multiprocessor

SP: Streaming processor

Latest FPGA examples

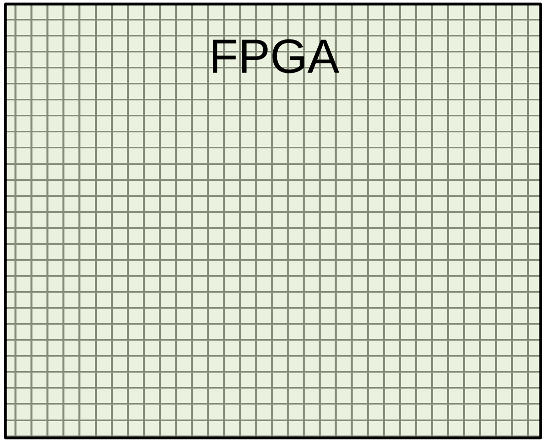
Xilinx Virtex UltraScale+ VU19P, **8,938,000 logic cells**, 2019

- Using 35B transistors. Also has 4.5 Tbit/s transceiver bandwidth (bidir), and 1.5 Tbit/sec DDR4 bandwidth [Cutress 19]

Xilinx Virtex UltraScale+ VU9P, **2,586,000 logic cells**, 2016

- Deploy right now: AWS EC2 F1 instance type (up to 8 of these FPGAs per instance)

AMD is acquiring Xilinx



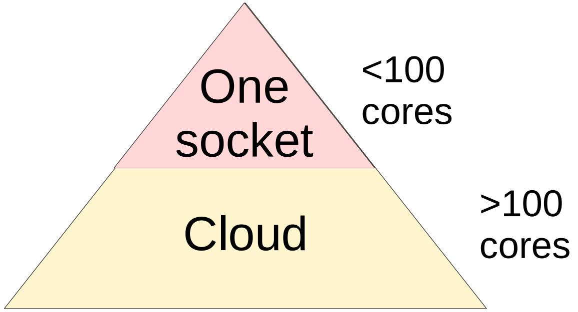
BPF (covered later) already in FPGAs

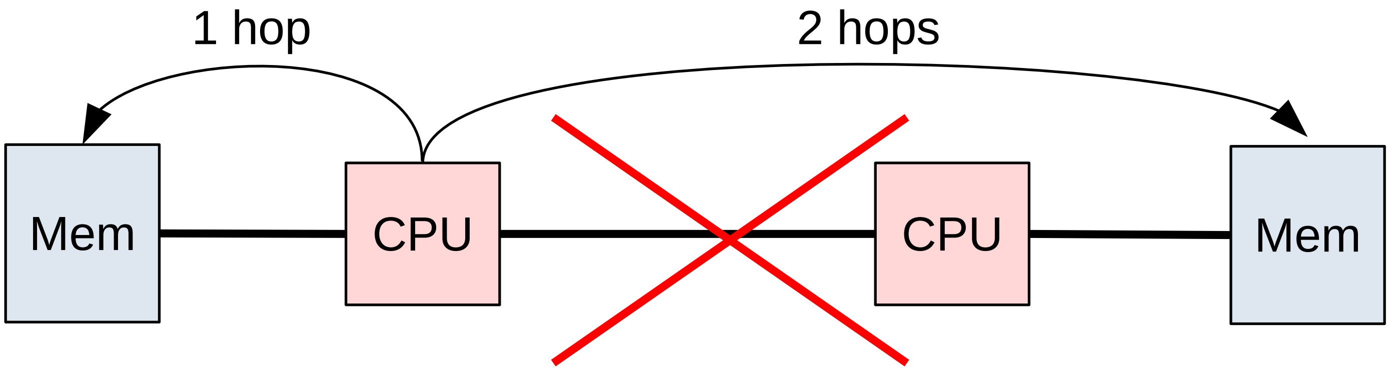
- E.g., 400 Gbit/s packet filter FFShark [Vega 20]

My Predictions

My Prediction: Multi-socket is doomed

- Single socket is getting big enough (cores)
- Already scaling horizontally (cloud)
  - And in datacenters, via “blades” or “microservers”
- Why pay NUMA costs?
  - Two single-socket instances should out-perform one two-socket instance





Multi-socket future is mixed: one socket for cores, one GPU socket, one FPGA socket, etc. EMIB connected.

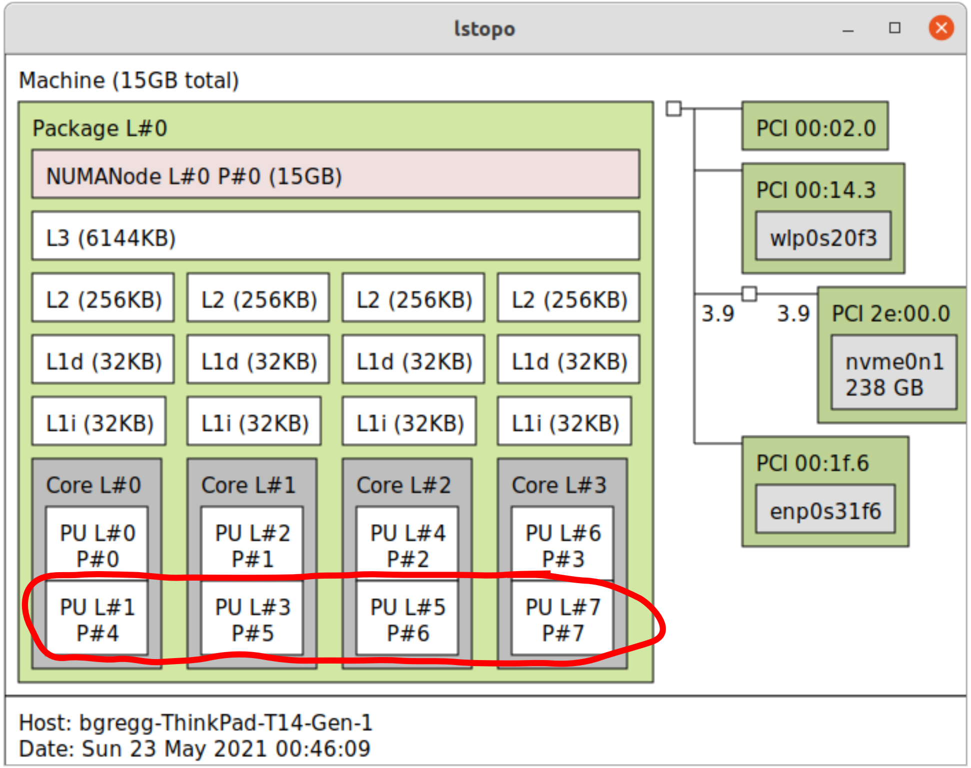
My Prediction: SMT future unclear

Simultaneous multithreading (SMT) == hardware threads

- Performance variation
- ARM cores competitive
- Post meltdown/spectre
  - Some people turn them off

Possibilities:

- SMT becomes "free"
  - Processor feature, not a cost basis
  - Turn "oh no! hardware threads" into "great! bonus hardware threads!"
- No more hardware threads
  - Future investment elsewhere



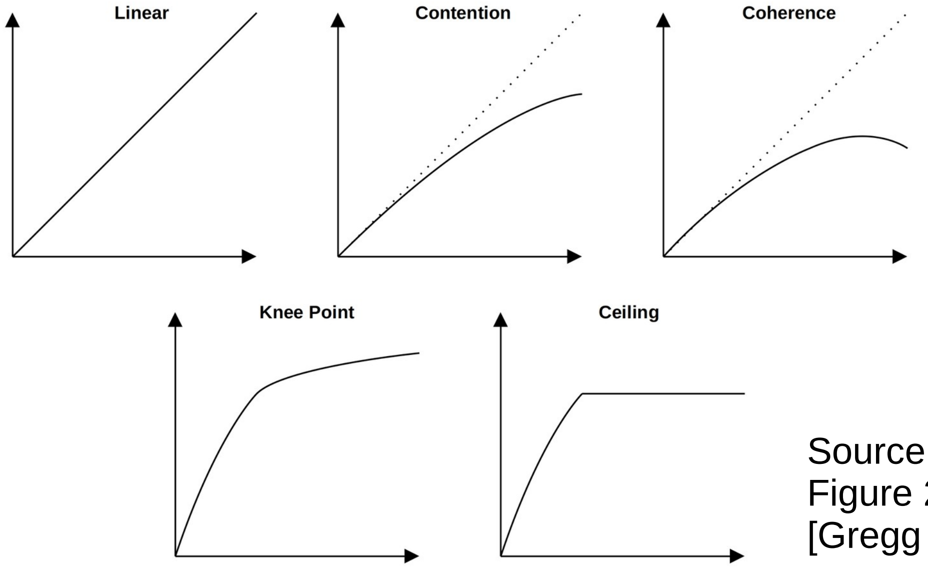
My Prediction: Core count limits

Imagine an 850,000-core server processor in today's systems...

My Prediction: Core count limits

Worsening problems:

- Memory-bound workloads
- Kernel/app lock contention
- False sharing
- Power consumption
- Core connectivity overheads
- etc.



Source: Figure 2.16 [Gregg 20]

General-purpose computing will hit a **practical core limit**

- For a given memory subsystem & kernel, and running multiple applications
- E.g., 1024 cores (except GPUs/ML/AI); Esperanto RISC-V is already reaching “kilocore” scale [Kostovic 21]
- Apps themselves will hit an even smaller practical limit (some already have by design, e.g., Node.js and 2 CPUs)

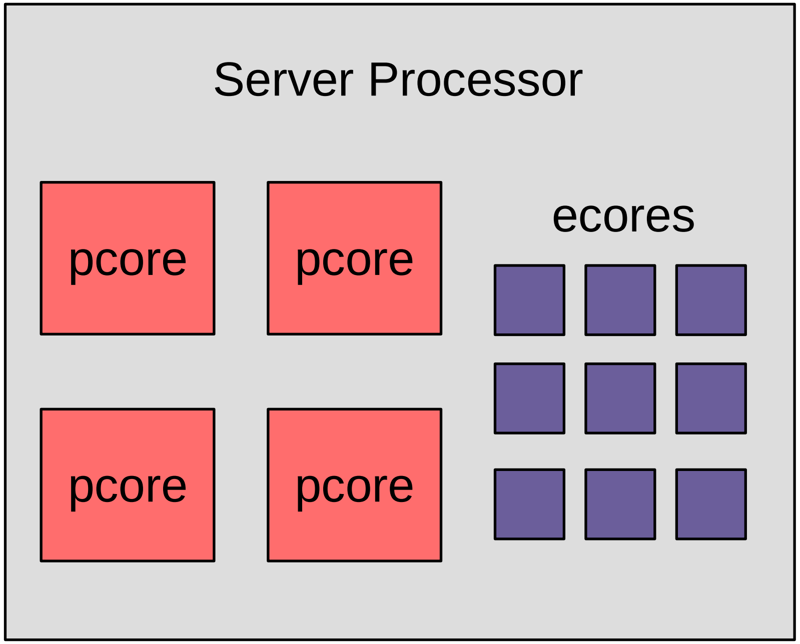
My Prediction: pcores & ecores

Intel Alder Lake (desktop) has performance and efficiency cores

This will come to server

Efficiency core tasks:

- Garbage collection
- NUMA rebalancing
- FS writeback compression & flushing
- Backups
- Security scanning
- etc.



My Prediction: 3 Eras of processor scaling

Delivered processor characteristics:

Era 1: Clock frequency

Era 2: Core/thread count

Era 3: Cache size & policy

My Prediction: 3 Eras of processor scaling

	Practical server limits:
Era 1: Clock frequency	→ **already reached by ~2005 (3.5 GHz)**
Era 2: Core/thread count	→ **limited by mid 2030s (e.g., 1024)**
Era 3: Cache size & policy	→ **limited by end of 2030s**

Mid-century will need an entirely new computer hardware architecture, kernel memory architecture, or logic gate technology, to progress further.

- E.g., use of graphine, carbon nanotubes [Hruska 12]
- This is after moving more to stacked processors

My Prediction: More processor vendors

ARM licensed or RISC-V

- Including Apple M1 for servers

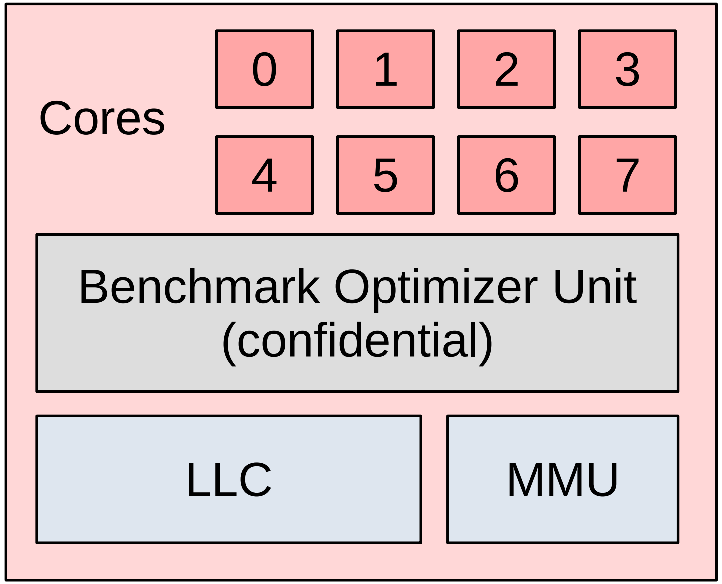
Era of CPU choice

Beware: “optimizing for the benchmark”

- Don’t believe microbenchmarks without doing “active benchmarking”: Root-cause perf analysis while the benchmark is still running.

Intel back to innovating & competing

- Pat Gelsinger now CEO



DogeCPU “+AggressiveOpts” processor

My Prediction: Cloud CPU advantage

Large cloud vendors can analyze >100,000 workloads *directly*

- Via PMCs and other processor features.

Vast real-world detail to aid processor design

- More detail than traditional processor vendors have, and detail available immediately whenever they want.
- Will processor vendors offer their own clouds just to get the same data?

Machine-learning aided processor design

- Based on the vast detail. Please point it at real-world workloads and not microbenchmarks.

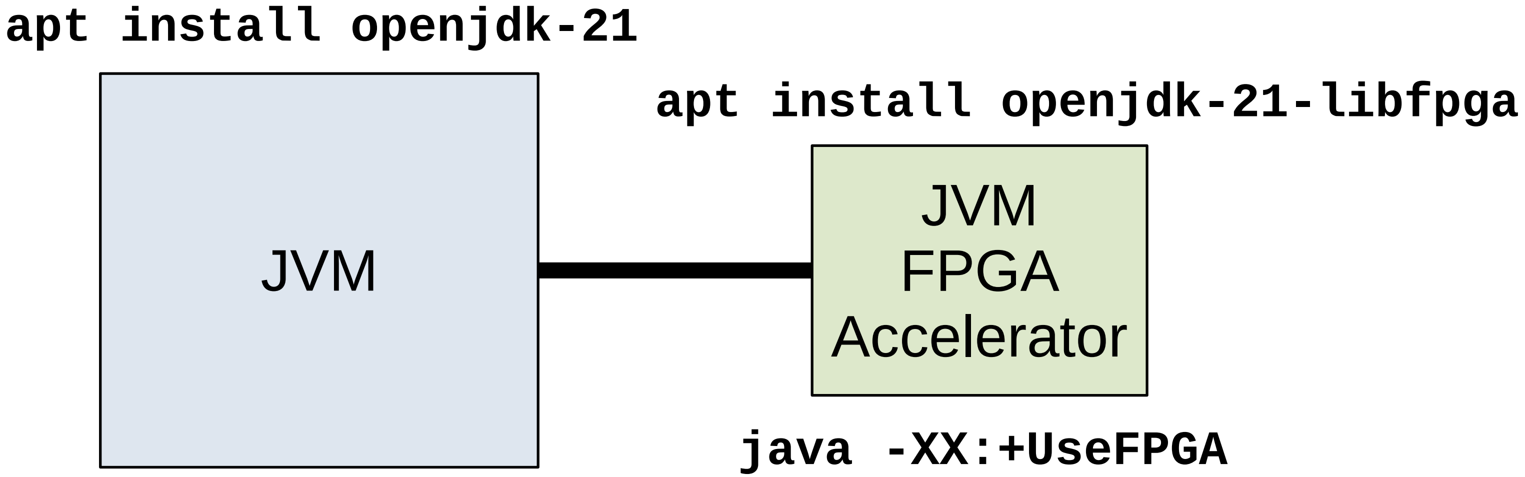
Vast detail example: processor trace showing timestamped instructions:

```
# perf script --insn-trace --xed
date 31979 [003] 653971.670163672: ... (/lib/x86_64-linux-gnu/ld-2.27.so) mov %rsp, %rdi
date 31979 [003] 653971.670163672: ... (/lib/x86_64-linux-gnu/ld-2.27.so) callq 0x7f3bfbf4dea0
date 31979 [003] 653971.670163672: ... (/lib/x86_64-linux-gnu/ld-2.27.so) pushq %rbp
[...]
```

My Prediction: FPGA turning point

Little adoption (outside cryptocurrency) until major app support

- Solves the ease of use issue: Developers just configure the app (which may fetch and deploy an FMI)
- BPF use cases are welcome, but still specialized/narrow
- Needs runtime support, e.g., the JVM. Already work in this area (e.g., [TornadoVM 21]).



(none of this is real, yet)

2. Memory

Many workloads memory I/O bound

```
# ./pmcarch 1
K_CYCLES   K_INSTR      IPC BR_RETIRED   BR_MISPRED  BMR% LLCREF      LLCMISS     LLC%
334937819  141680781   0.42 25744860335  536087729   2.08 1611987169  366692918  77.25
329721327  140928522   0.43 25760806599  525951093   2.04 1504594986  350931770  76.68
330388918  141393325   0.43 25821331202  484397356   1.88 1535130691  350629915  77.16
329889409  142876183   0.43 26506966225  510492279   1.93 1501785676  354458409  76.40
[...]
```

```
# ./pmcarch 1
K_CYCLES   K_INSTR      IPC BR_RETIRED   BR_MISPRED  BMR% LLCREF      LLCMISS     LLC%
38222881   25412094    0.66 4692322525   91505748    1.95 780435112   117058225  85.00
40754208   26308406    0.65 5286747667   95879771    1.81 751335355   123725560  83.53
35222264   24681830    0.70 4616980753   86190754    1.87 709841242   113254573  84.05
38176994   26317856    0.69 5055959631   92760370    1.83 787333902   119976728  84.76
[...]
```

```
# ./pmcarch
K_CYCLES   K_INSTR      IPC BR_RETIRED   BR_MISPRED  BMR% LLCREF      LLCMISS     LLC%
122697727  13892225    0.11 2604221808   40692664    1.56 419652590   93646793   77.68
144881903  17918325    0.12 3240599094   48088436    1.48 489936685   104672186  78.64
95561140   13815722    0.14 2722513072   42575763    1.56 401658252   94214458   76.54
99311699   15034220    0.15 2815805820   41802209    1.48 386979370   84139624   78.26
[...]
```

DDR5 has better bandwidth

DDR5 has a faster bus

- But not width

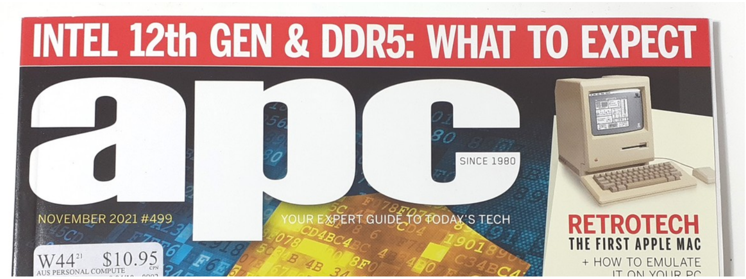
Needs processor support

- E.g., Intel Alder Lake / Sapphire Rapids

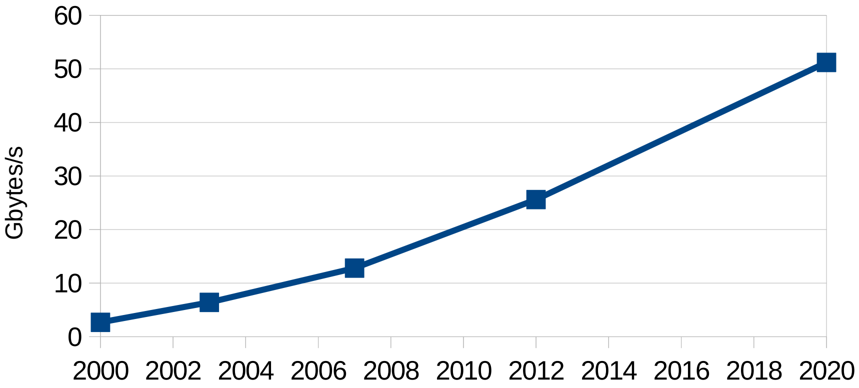
512GB DDR5 DIMMs

- Already released by Samsung [Shilov 21]

Desktop/Gamers already know about it:

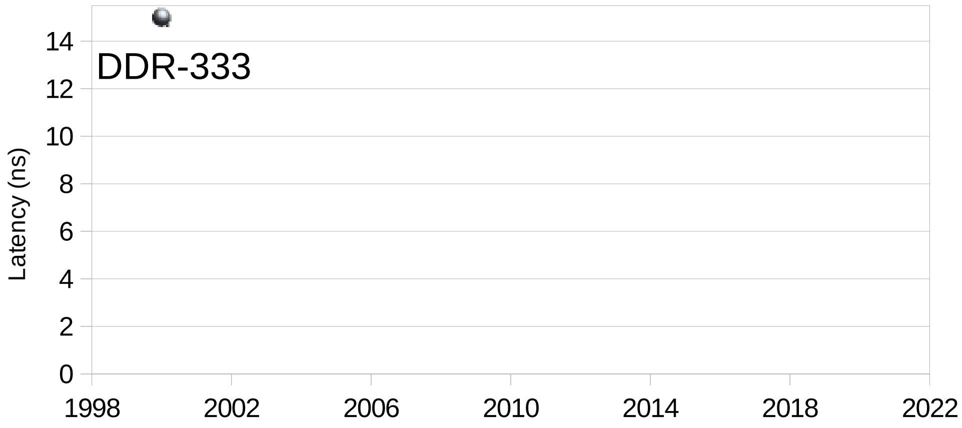


Year	Memory	Peak Bandwidth Gbytes/s
2000	DDR-333	2.67
2003	DDR2-800	6.4
2007	DDR3-1600	12.8
2012	DDR4-3200	25.6
2020	DDR5-6400	51.2



DDR latency

Year	Memory	Latency (ns)
2000	DDR-333	15



DDR latency

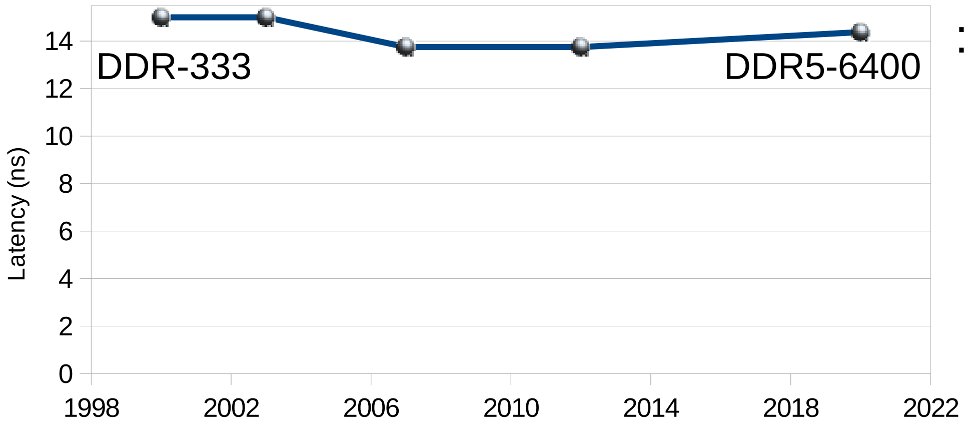
Hasn't changed in 20 years

- This is single access latency
- Same memory clock (200 MHz) [Greenberg 11]
- Also see [Cutress 20][Goering 11]

Low-latency DDR does exist

- Reduced Latency DRAM (RLDRAM) by Infineon and Micron: lower latency but lower density
- Not seeing widespread server use (I've seen it marketed towards HFT)

Year	Memory	Latency (ns)
2000	DDR-333	15
2003	DDR2-800	15
2007	DDR3-1600	13.75
2012	DDR4-3200	13.75
2020	DDR5-6400	14.38



:-(

HBM

High bandwidth memory, 3D stacking

- Target uses cases include high performance computing, and virtual reality graphical processing [Macri 15]

GPUs already use it

Can be provided on-package

- Intel Sapphire Rapids rumored to include 64 Gbyte HBM2E [Shilov 21d]

Server DRAM size

SuperMicro SuperServer B12SPE-CPU-25G

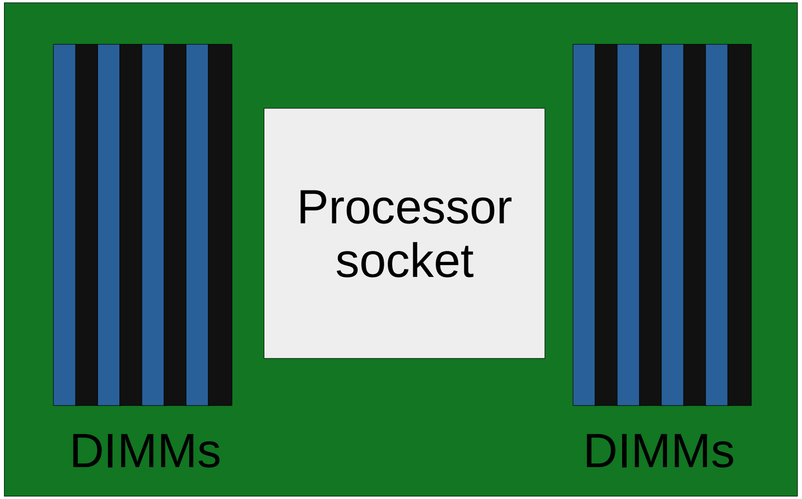
- Single Socket (see earlier slides)
- 16 DIMM slots
- **4 TB DDR-4**

[SuperMicro 21]

Facebook Delta Lake (1S) OCP

- 6 DIMM slots
- **96 Gbytes DDR-4**
- Price/optimal for a typical WSS?

[Haken 21]

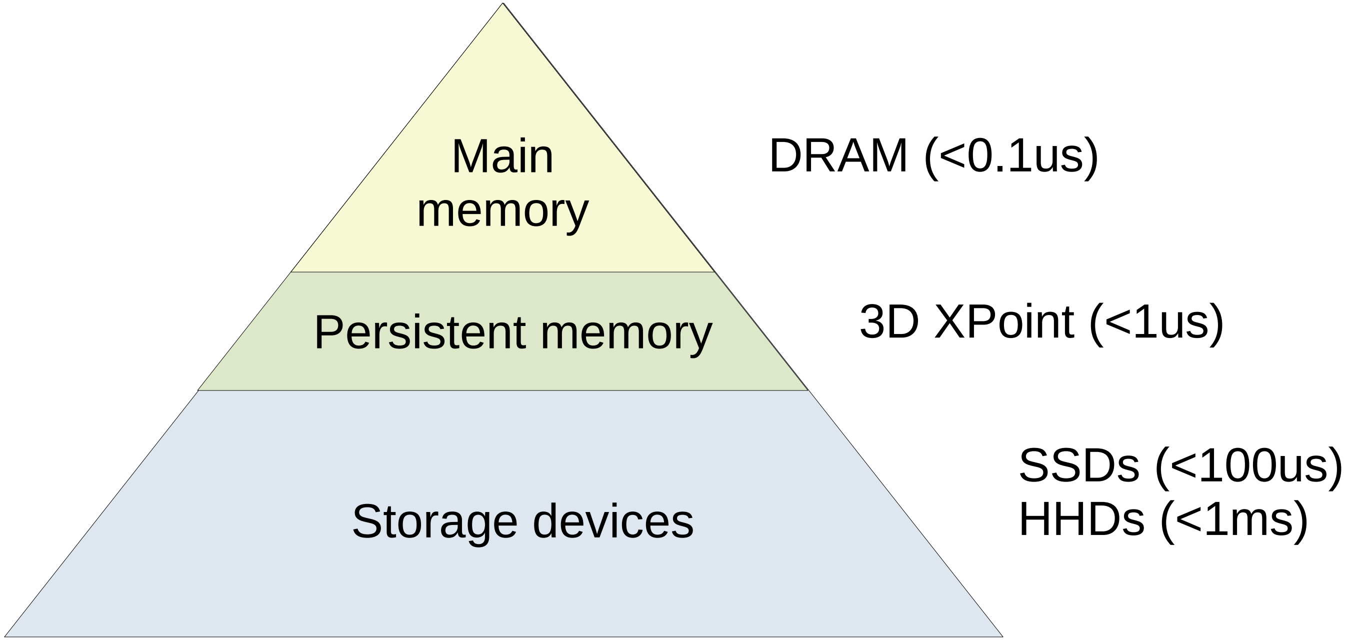


B12SPE-CPU-25G

Additional memory tier

3D XPoint (next section) memory mode:

- Can also operate in application direct mode and storage mode [Intel 21]



My Prediction: Extrapolation

Not a JEDEC announcement

Assumes miraculous engineering work

- For various challenges see [Peterson 20]

But will single-access latency drop in DDR-6?

- I'd guess not, DDR internals are already at their cost-sweet-spot, leaving low-latency for other memory technologies

Year	Memory	Peak Bandwidth Gbytes/s
2000	DDR-333	2.67
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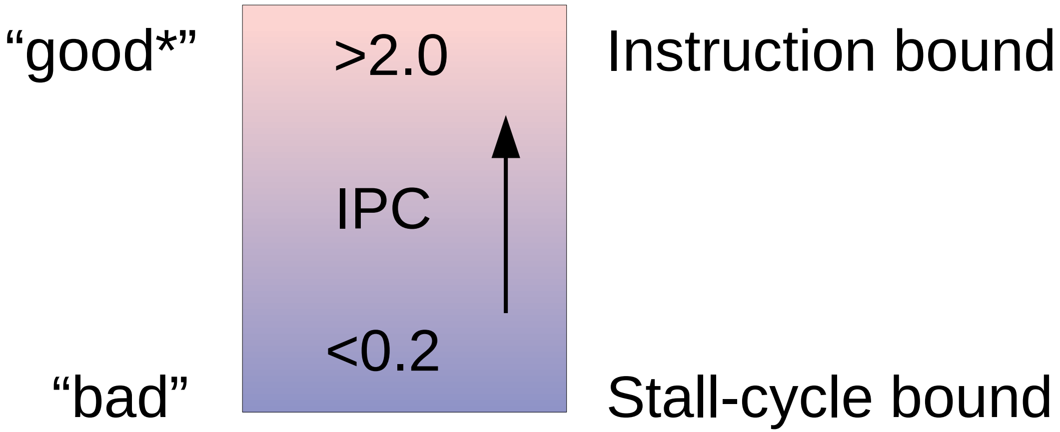
2007	DDR3-1600	12.8
2012	DDR4-3200	25.6
2020	DDR5-6400	51.2
2028	**DDR6-12800**	**102.4**
2036	**DDR7-25600**	**204.8**
2044	**DDR8-51200**	**409.6**

doubling

My Prediction: DDR5 “up to 2x” Wins

E.g., IPC 0.1 → ~0.2 for *bandwidth*-bound workloads



* probably; exceptions include spin locks

If DDR-6 gets a latency drop, more frequent wins

My Prediction: HBM-only servers

Clouds offering “high bandwidth memory” HBM-only instances

- HBM on-processor
- Finally helping memory catch up to core scaling

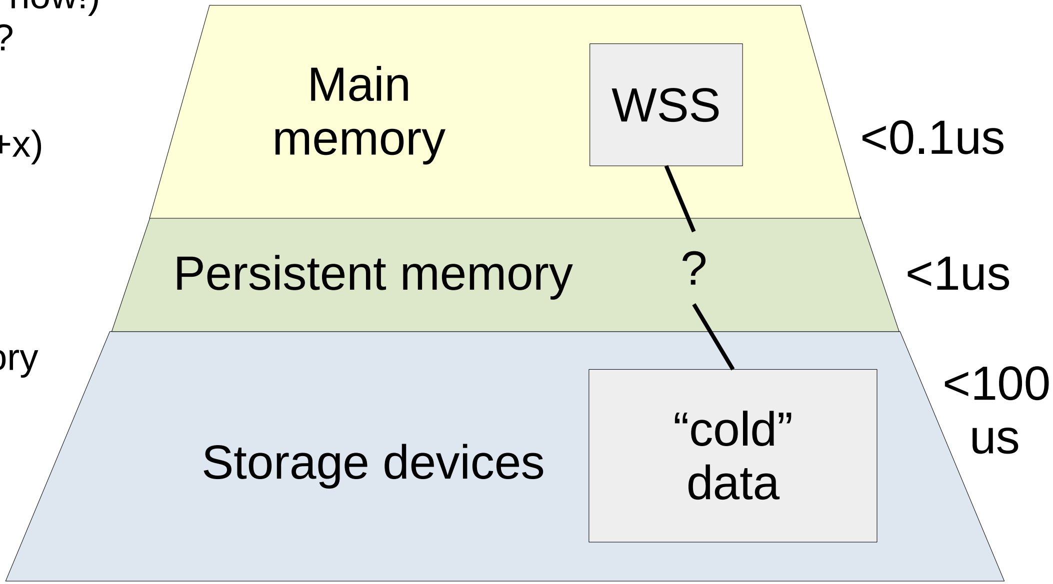
RLDRAM on-package as another option?

- “Low latency memory” instance

My Prediction: Extra tier too late

Competition isn't disks, it's Tbytes of DRAM

- SuperMicro's single socket should hit 8 Tbytes DDR-5
- AWS EC2 p4.24xl has 1.1 Tbytes of DRAM (deploy now!)
  How often does your working set size (WSS) not fit?
  Across several of these for redundancy?
- Next tier needs to get much bigger than DRAM (10+x) and much cheaper to find an extra-tier use case (e.g., cost based).
- Meanwhile, DRAM is still getting bigger and faster
- I developed the first cache tier between main memory and disks to see widespread use:
  the ZFS L2ARC [Gregg 08]



It's more like a trapezoid

3. Disks

Recent timeline for rotational disks

2005: Perpendicular magnetic recording (PMR)

- Writes vertically using a shaped magnetic field for higher density

2013: Shingled magnetic recording (SMR)

- (next slide)

2019: Multi-actuator technology (MAT)

- Two sets of heads and actuators; like 2-drive RAID 0 [Alcorn 17].

2020: Energy-assisted magnetic recording (EAMR)

- Western Digital 18TB & 20TB [Salter 20]

2021: Heat-assisted magnetic recording (HAMR)

- Seagate 20TB HAMR drives [Shilov 21b]

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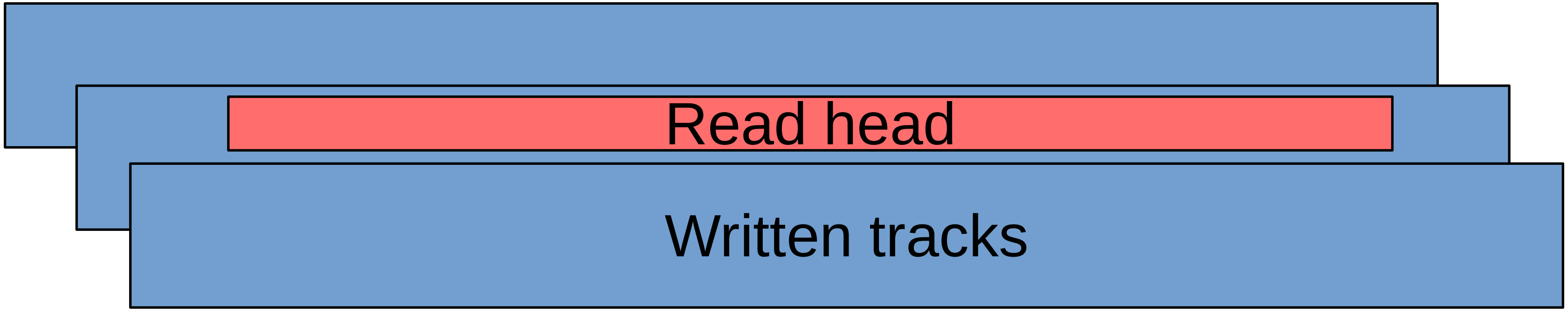
- Seagate 20TB HAMR drives [Shilov 21b]

I don't know their perf characteristics yet

SMR

11-25% more storage, worse performance

- Writes tracks in an overlapping way, like shingles on a roof. [Shimpi 13]
- Overwritten data must be rewritten. Suited for archival (write once) workloads.



Look out for 18TB/20TB-with-SMR drive releases

Flash memory-based disks

Single-Level Cell (SLC)

Multi-Level Cell (MLC)

Enterprise MLC (eMLC)

2009: Tri-Level Cell (TLC)

2009: Quad-Level Cell (QLC)

- QLC is only rated for around 1,000 block-erase cycles [Liu 20].

2013: 3D NAND / Vertical NAND (V-NAND)

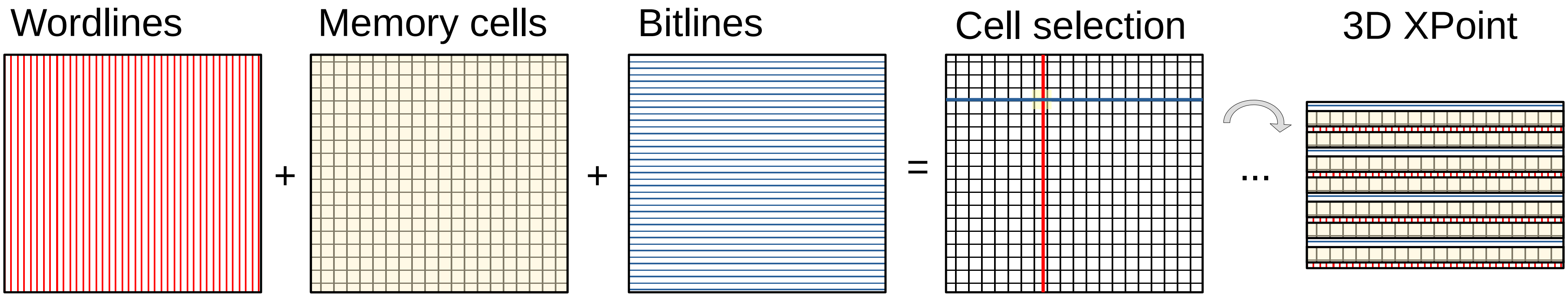
- SK Hynix envisions 600-Layer 3D NAND [Shilov 21c]. Should be multi-Tbyte.

SSD performance pathologies: latency from aging, wear-leveling, fragmentation, internal compression, etc.

Persistent memory-based disks

2017: 3D XPoint (Intel/Micron) Optane

- Low and consistent latency (e.g., 14 us access latency) [Hady 18]
- App-direct mode, memory mode, and as storage



DRAM: Trapped electrons in a capacitor, requires refreshing

3D XPoint: Resistance change; layers of wordlines+cells+bitlines keep stacking vertically

Latest storage device example

2021: Intel Optane memory H20

- QLC 3D NAND storage (512 Gbytes / 1 Tbyte) +
- 3D XPoint as an accelerator (32 Gbytes)
- Currently M.2 2280 form factor (laptops)
- (Announced while I was developing these slides)

Storage Interconnects

SAS-4 cards in development

- (Storage attached SCSI)

PCIe 5.0 coming soon

- (Peripheral Component Interconnect Express)
- Intel already demoed on Sapphire Rapids [Hruska 20]

NVMe 1.4 latest

- (Non-Volatile Memory Express)
- Storage over PCIe bus
- Support zoned namespace SSDs (ZNS) [ZonedStorage 21]
- Bandwidth bounded by PCIe bus

These have features other than speed

- Reliability, power management, virtualization support, etc.

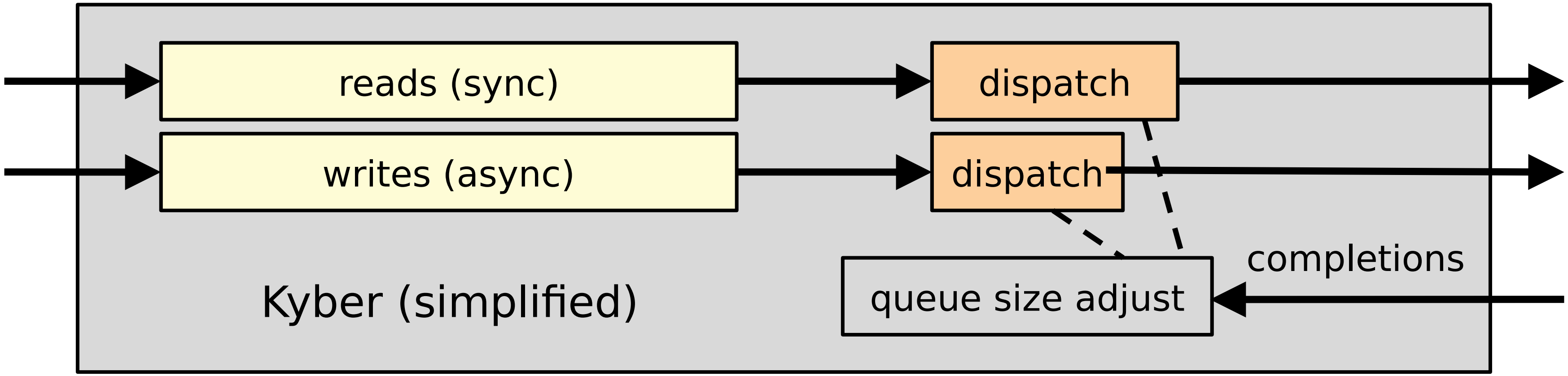
Year Specified	Interface	Bandwidth Gbit/s
2003	SAS-1	3
2009	SAS-2	6
2012	SAS-3	12
2017	SAS-4	22.5
202?	**SAS-5**	**45**

Year Specified	Interface	Bandwidth 16 lane Gbyte/s
2003	PCIe 1	4
2007	PCIe 2	8
2010	PCIe 3	16
2017	PCIe 4	31.5
2019	**PCIe 5**	**63**

Linux Kyber I/O scheduler

Multi-queue, target read & write latency

- Up to 300x lower 99th percentile latencies [Gregg 18]
- Linux 4.12 [Corbet 17]



My Prediction: Slower rotational

Archive focus

- There’s ever-increasing demand for storage (incl. social video today; social VR tomorrow?)
- Needed for archives
- More “weird” pathologies. SMR is just the start.
- Even less tolerant to shouting

Bigger, slower, and weirder

My Prediction: 3D XPoint

As a rotational disk accelerator

As petabyte storage

- Layers keep stacking
- 3D NAND could get to petabytes too, but consumes more power
- 1 Pbyte = ~700M 3.5inch floppies!

And not really as a memory tier (DRAM too good) or widespread application direct (too much work when 3D XPoint storage accelerators exist so apps can get benefits without changing anything)

My Prediction: More flash pathologies

- Worse internal lifetime
- More wear-leveling & logic
- More latency outliers

Bigger, *faster*, and weirder

We need more observability of flash drive internals

4. Networking

Latest Hardware

400 Gbit/s in use

- E.g., 400 Gbit/s switches/routers by Cisco and Juniper, tranceivers by Arista and Intel
- AWS EC2 P4 instance type (deploy now!)
- On PCI, needs PCIe 5

800 Gbit/s next

- [Charlene 20]
- Terabit Ethernet (1 Tbit/s) not far away

More NIC features

- E.g., inline kTLS (TLS offload to the NIC), e.g., Mellanox ConnectX-6-Dx [Gallatin 19]

Protocols

QUIC / HTTP/3

- TCP-like sessions over (fast) UDP.
- 0-RTT connection handshakes. For clients that have previously communicated.

MP-TCP

- Multipath TCP. Use multiple paths in parallel to improve throughput and reliability. RFC-8684 [Ford 20]
- Linux support starting in 5.6.

Linux TCP Congestion Control Algorithms

DCTCP

- Data Center TCP. Linux 3.18. [Borkmann 14]

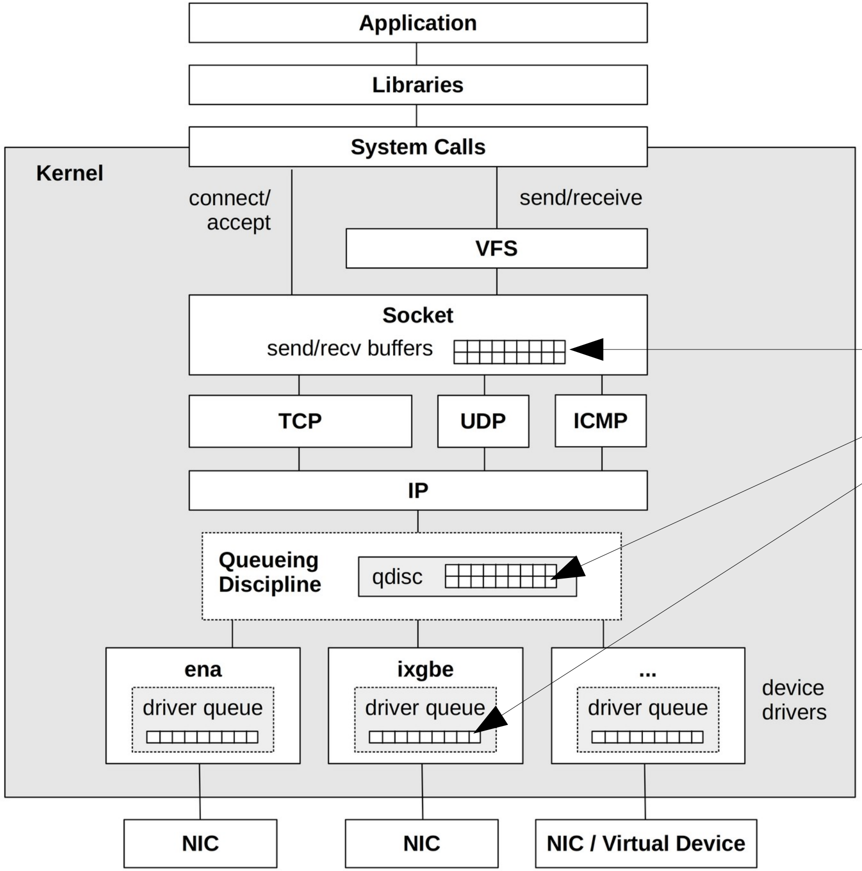
TCP NV

- New Vegas. Linux 4.8

TCP BBR

- Bottleneck Bandwidth and RTT (BBR) improves performance on packet loss networks [Cardwell 16]
- With 1% packet loss, Netflix sees 3x better throughput [Gregg 18]

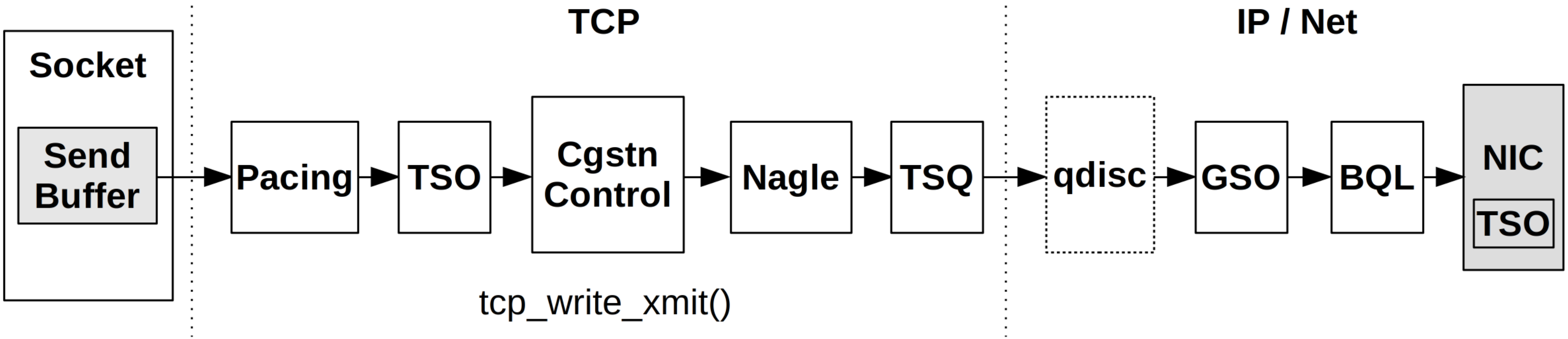
Linux Network Stack



Queues/
Tuning

Source: Systems Performance 2nd Edition, Figure 10.8 [Gregg 20]

Linux TCP send path



Keeps adding performance features

Source: Systems Performance 2nd Edition, Figure 10.11 [Gregg 20]

Software

eXpress Data Path (XDP) (uses eBPF)

- Programmable fast lane for networking. In the Linux kernel.
- A role previously served by DPDK and kernel bypass.

My Prediction: BPF in FPGAs/IPUs

Massive I/O tranceiver capabilities

Netronome already did BPF in hardware

My Prediction: Cheap BPF routers

Linux + BPF + 400 GbE NIC

- Cheap == commodity hardware
- Use case from the beginning of eBPF (PLUMgrid)

My Prediction: More demand for network perf

Apps increasingly network

Netflix 4K content

Remote work & video conferencing

World of sensors

VR tourism

Facebook VR multiverse

5. Runtimes

Latest Java

Sep 2018: Java 11 (LTS)

- JEP 333 ZGC A Scalable Low-Latency Garbage Collector
- JEP 331 Low-Overhead Heap Profiling
- GC adaptive thread scaling

Sep 2021: Java 17 (LTS)

- JEP 338: Vector API (JDK16)
- Parallel GC improvements (JDK14)
- Various other perf improvements (JDK12-17)

Java 11 includes JMH JDK microbenchmarks

[Redestad 19]

My Predictions: Runtime features

FPGA as a compiler target

- E.g., JVM c2 or Graal adding it as a compiler target, and becoming a compiler “killer” feature.

io_uring I/O libraries

- Massively accelerate some I/O-bound workloads by switching libraries.

Adaptive runtime internals

- I don’t want to pick between c2 and Graal. Let the runtime do both and pick fastest methods; ditto for testing GC algorithms.
  - Not unlike the ZFS ARC shadow-testing different cache algorithms.

1000-core scalability support

- Runtime/library/model support to help programmers write code to scale to hundreds of cores

6. Kernels

Latest Kernels/OSes

Apr 2021: FreeBSD 13.0

Oct 2021: Linux 5.15 (LTS)

Nov 2021: Windows 10.0.22000.318

Recent Linux perf features

2021: Syscall user dispatch (5.11)

2020: Static calls to improve Spectre-fix (5.10)

2020: BPF on socket lookups (5.9)

2020: Thermal pressure (5.7)

2020: MultiPath TCP (5.6)

2019: MADV_COLD, MADV_PAGEOUT (5.4)

2019: io_uring (5.1)

2019: UDP GRO (5.0)

2019: Multi-queue I/O default (5.0)

2018: TCP EDT (4.20)

2018: PSI (4.20)

For 2016-2018, see my summary: [Gregg 18].
Includes CPU schedulers (thermal, topology);
Block I/O qdiscs; Kyber scheduler (earlier slide);
TCP congestion control algoritms (earlier slide); etc.

Recent Linux perf features

2021: Syscall user dispatch (5.11)

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Block I/O qdiscs; Kyber scheduler (earlier slide);
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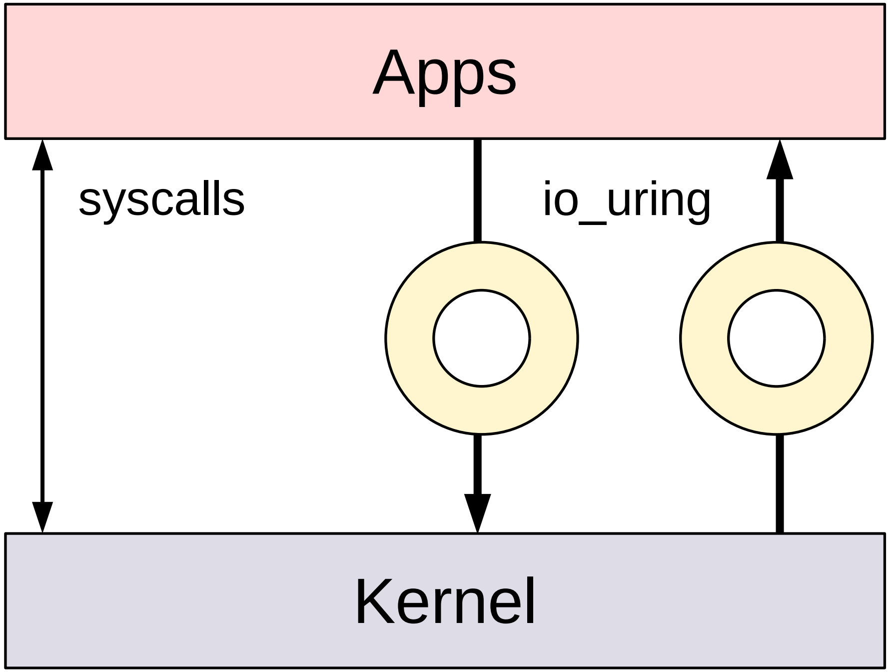
io_uring

Faster syscalls using shared ring buffers

- Send and completion ring buffers
- Allows I/O to be batched and async
- Primary use cases network and disk I/O



eBPF Everywhere

Microsoft Microsoft 365 Azure Office 365 Dynamics 365 Power Platform Windows 10

Microsoft Open Source Blog

Making eBPF work on Windows

May 10, 2021

Share

Dave Thaler

Partner Software Engineer, Microsoft

Poorna Gaddehosur

Principal Software Engineer Lead, Microsoft

eBPF is a well-known but revolutionary technology—providing programmability,
extensibility, and agility. eBPF has been applied to use cases such as denial-of-service

[Thaler 21]

Plus eBPF for BSD projects already started.

eBPF == BPF

2015:

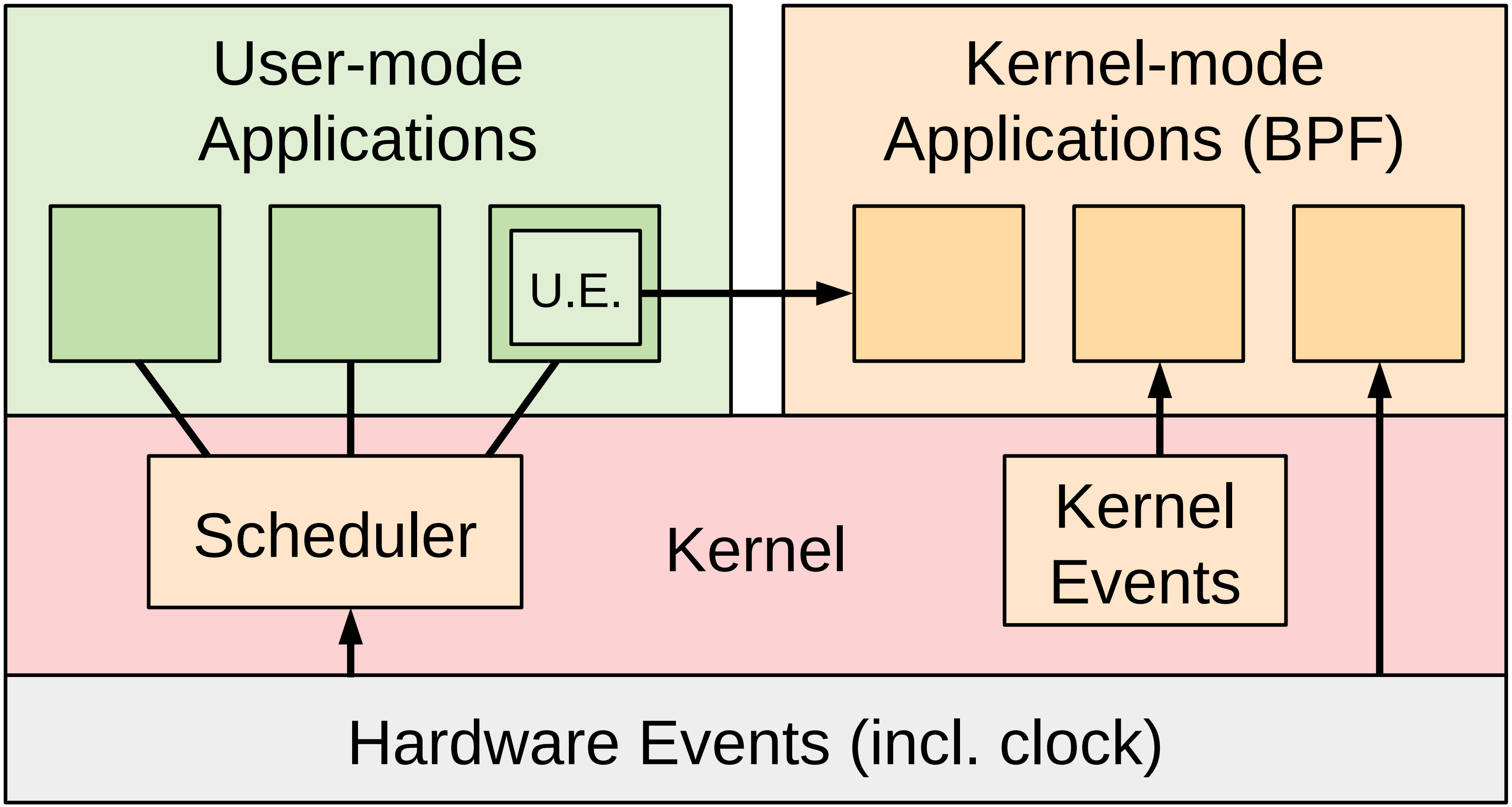
- BPF: Berkeley Packet Filter
- eBPF: extended BPF

2021:

- “Classic BPF”: Berkeley Packet Filter
- BPF: A technology name (aka eBPF)
  - Kernel engineers like to use “BPF”; companies “eBPF”.

This is what happens when you don’t have marketing professionals help name your product

BPF Future: Event-based Applications



https://twitter.com/srostedt/status/1177147373283418112

Emerging BPF uses

Observability agents

Security agents

TCP congestion control algorithms

Kernel drivers

My Prediction: Future BPF Uses

File system buffering/readahead policies

CPU scheduler policies

Lightweight I/O-bound applications (e.g., proxies)

- Or such apps can go to io_uring or FPGAs. “Three buses arrived at once.”
  - When I did engineering at University: “people ride buses and electrons ride busses.” Unfortunately that usage has gone out of fashion, otherwise it would have been clear which bus I was referring to!

My Prediction: Kernels become JITed

PGO/AutoFDO shows ~10% wins, but hard to manage

- Performance-guided optimization (PGO) / Auto feedback-directed optimization (AutoFDO)
- Some companies already do kernel PGO (Google [Tolvanen 20], Microsoft [Bearman 20])
- We can't leave 10% on the table forever

Kernels PGO/JIT support by default, so it “just works.”

My Prediction: Kernel emulation often slow

I can run <kernel> apps under <other kernel> by emulating <a bare-minimal set of> syscalls!

Cool project, but:

- Missing latest kernel and perf features (E.g., Linux's BPF, io_uring, WireGuard, etc. Plus certain syscall flags return ENOTSUP. So it's like a weird old fork of Linux.)
  - Some exceptions: E.g., another kernel may have better hardware support, which may benefit apps more than the loss of kernel capabilities.
- Debugging and security challenges. Better ROI with lightweight VMs.

In other words, WSL2 >> WSL1

My Prediction: OS performance

Linux: increasing complexity & worse perf defaults

- Becomes so complex that it takes an OS team to make it perform well. This assumes that the defaults rot, because no perf teams are running the defaults anymore to notice (e.g., high-speed network engineers configure XDP and QUIC, and aren't looking at defaults with TCP). A bit more room for a lightweight kernel (e.g., BSD) with better perf defaults to compete. Similarities: Oracle DB vs MySQL; MULTICS vs UNIX.

BSD: high perf for narrow uses

- Still serving some companies (including Netflix) very well thanks to tuned performance (see footnote on p124 of [Gregg 20]). Path to growth is better EC2/Azure performance support, but it may take years before a big customer (with a perf team) migrates and gets everything fixed. There are over a dozen of perf engineers working on Linux on EC2; BSD needs at least one *full time* senior EC2 (not metal) perf engineer.

Windows: community perf improvements

- BPF tracing support allows outsiders to root cause kernel problems like never before (beyond ETW/Xperf). Will have a wave of finding "low hanging fruit" to begin with, improving perf and reliability.

My Prediction: Unikernels

Finally gets *one* compelling published use case

"2x perf for X"

But few people run X

- Needs to be really kernel heavy, and not many workloads are. And there's already a lot of competition for reducing kernel overhead (BPF, io_uring, FPGAs, DPDK, etc.)
- Once one use case is found, it may form a valuable community around X and Unikernels. But it needs the published use case to start, preferably from a FAANG.
- Does need to be 2x or more, not 20%, to overcome the cost of retooling everything, redoing all observability metrics, profilers, etc. It's not impossible, but not easy [Gregg 16].
- More OS-research-style wins found from hybrid- and micro-kernels.

7. Hypervisors

Containers

Cgroup v2 rollout

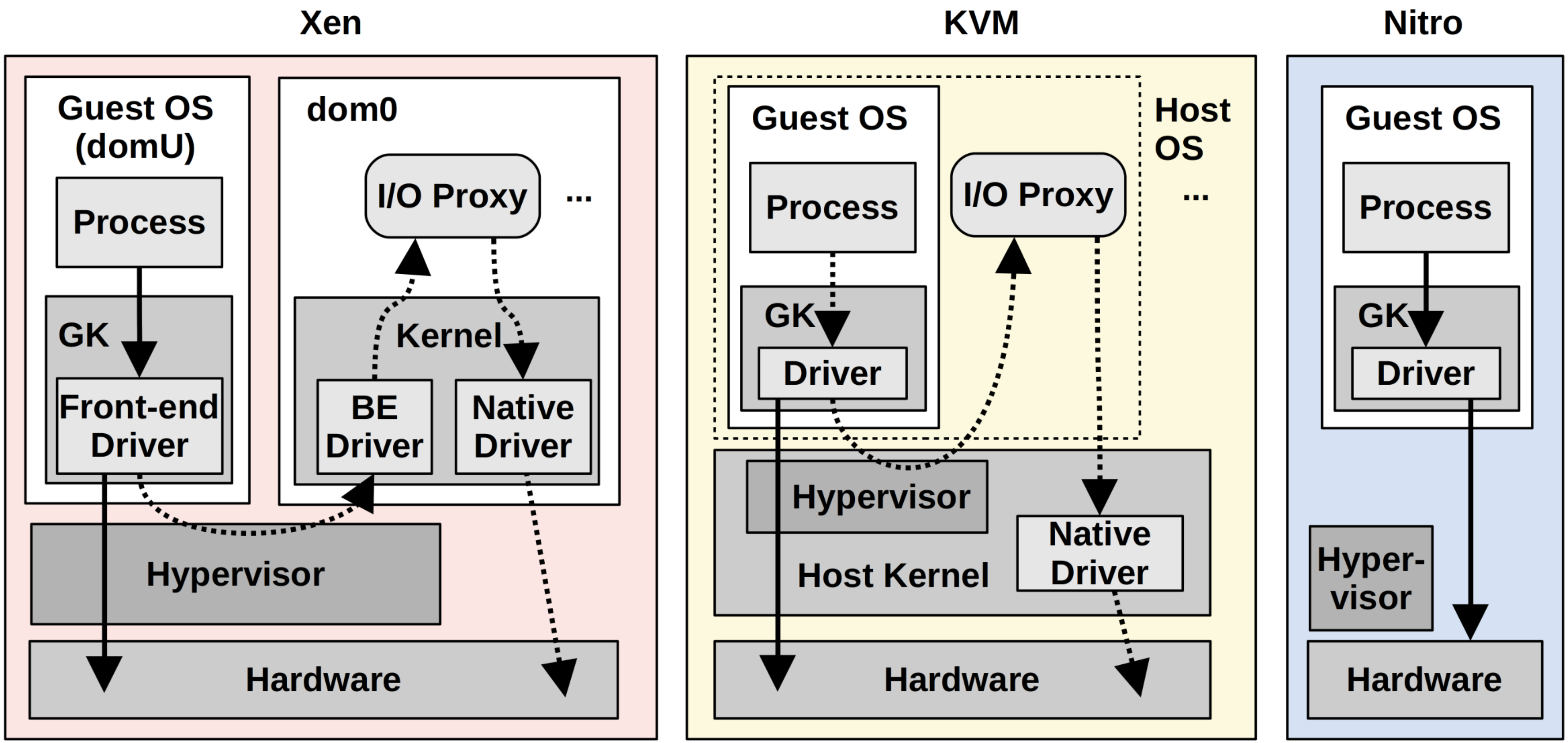
Container scheduler adoption

- Kubernetes, OpenStack, and more
- Netflix develops its own called “Titus” [Joshi 18]
- Price/performance gains: “Tetris packing” workloads without too much interference (clever scheduler)

Many perf tools still not “container aware”

- Usage in a container not restricted to the container, or not permitted by default (needs CAP_PERFMON CAP_SYS_PTRACE, CAP_SYS_ADMIN)

Hardware Hypervisors



Source: Systems Performance 2nd Edition, Figure 11.17 [Gregg 20]

VM Improvements

- Bare-metal performance
- Near-metal performance
- Optimized performance
- Poor performance

Importance: Most → Least

	#	Tech	Type	With	CPU, Memory	Network I/O	Local Storage I/O	Remote Storage I/O	Interrupts, Timers	Motherboard, Boot
	1	VM	Fully Emulated		VS	VS	VS	VS	VS	VS
Old	2	VM	Xen PV 3.0	PV drivers	P	P	P	P	VS	VS
	3	VM	Xen HVM 3.0	PV drivers	VH	P	P	P	VS	VS
	4	VM	Xen HVM 4.0.1	PVHVM drivers	VH	P	P	P	P	VS
	5	VM	Xen AWS 2013	PVHVM + SR-IOV(net)	VH	VH	P	P	P	VS
	6	VM	Xen AWS 2017	PVHVM + SR-IOV(net, stor.)	VH	VH	VH	P	P	VS
	7	VM	AWS Nitro 2017		VH	VH	VH	VH	VH	VS
New	8	HW	AWS Bare Metal 2017		H	H	H	H	H	H
			Bare Metal		H	H	H	H	H	H

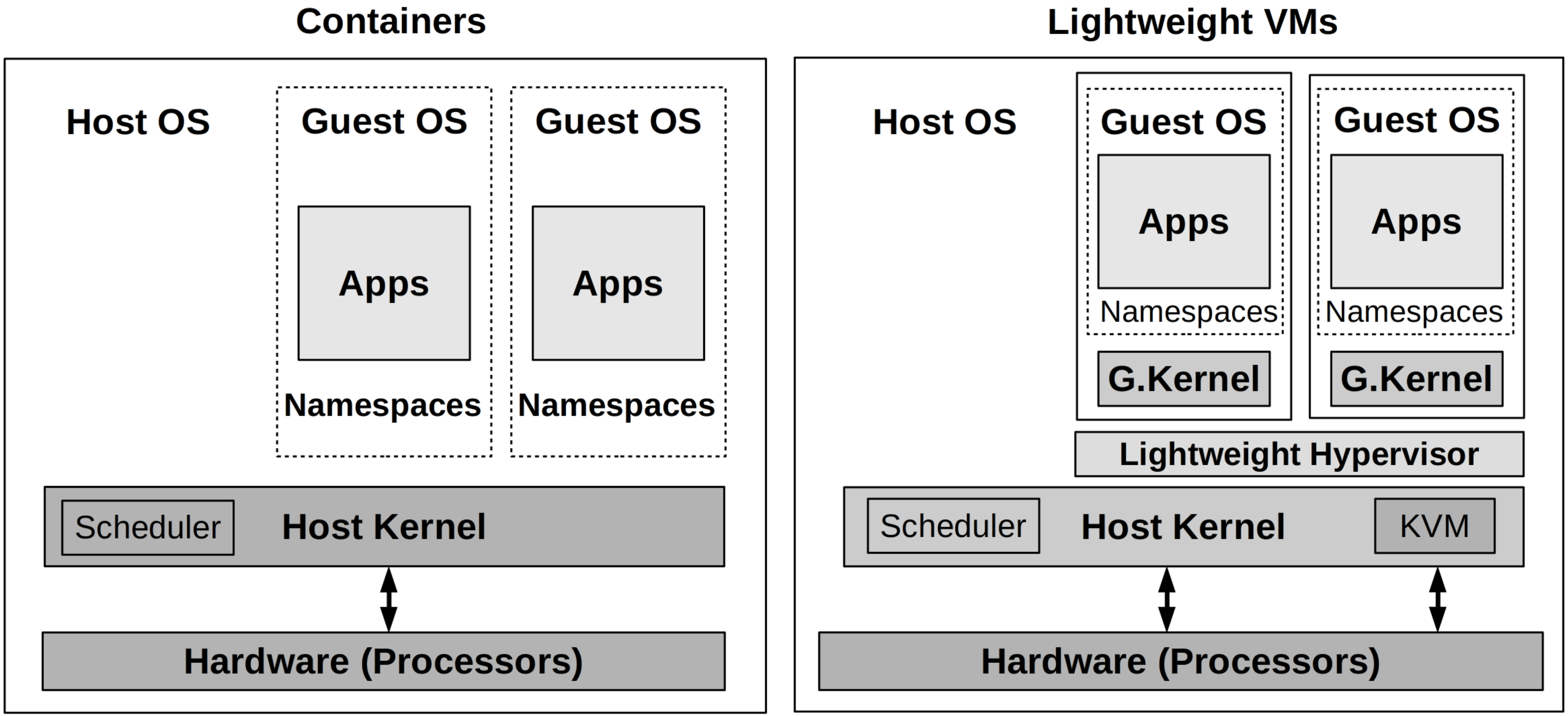
VM: Virtual Machine. HW: Hardware.
VS: Virt. in software. VH: Virt. in hardware. P: Paravirt. Not all combinations shown.
SR-IOV(net): ixgbe/ena driver. SR-IOV(storage): nvme driver.

http://www.brendangregg.com/blog/2017-11-29/aws-ec2-virtualization-2017.html

Source: [Gregg 17]

Lightweight VMs

E.g., AWS “Firecracker”



Source: Systems Performance 2nd Edition, Figure 11.4 [Gregg 20]

My Prediction: Containers

Perf tools take several years to be fully “container aware”

- Includes non-root BPF work.
- It’s a lot of work, and not enough engineers are working on it. We’ll use workarounds in the meantime (e.g., Kyle Anderson and Sargun Dhillon have made perf tools work in containers at Netflix).
- Was the same with Solaris Zones (long slow process).

My Prediction: Landscape

Short term:

- Containers everywhere

Long term:

- More containers than VMs
- More lightweight VM cores than container cores
  - Hottest workloads switch to dedicated kernels (no kernel resource sharing, no seccomp overhead, no overlay overhead, full perf tool access, PGO kernels, etc.)

My Prediction: Evolution

1. FaaS
2. Container
3. Lightweight VM
4. Metal

Light workload

Heavy workload

Many apps aren't heavy
Metal can also mean single container on metal

My Prediction: Cloud Computing

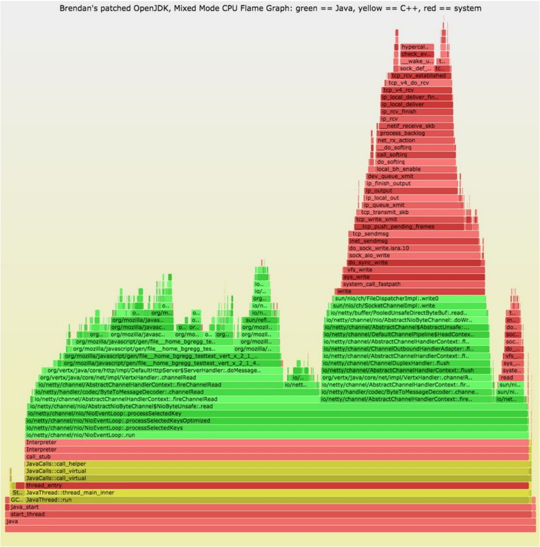
Microservice IPC cost drives need for:

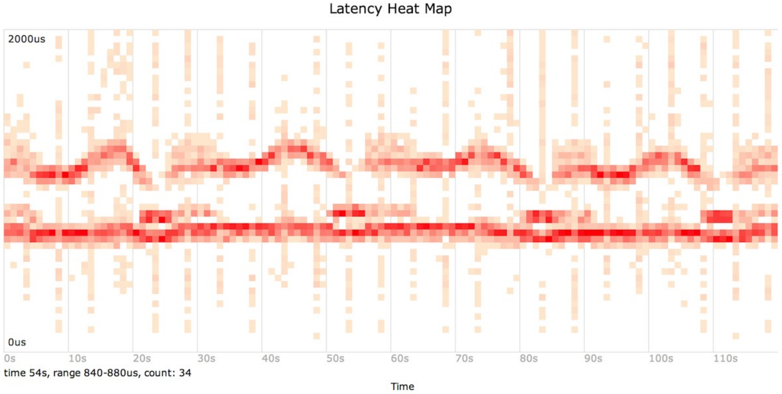
- Container schedulers co-locating chatty services
  - With BPF-based accelerated networking between them (e.g., Cilium)
- Cloud-wide runtime schedulers co-locating apps
  - Multiple apps under one JVM roof and process address space

8. Observability

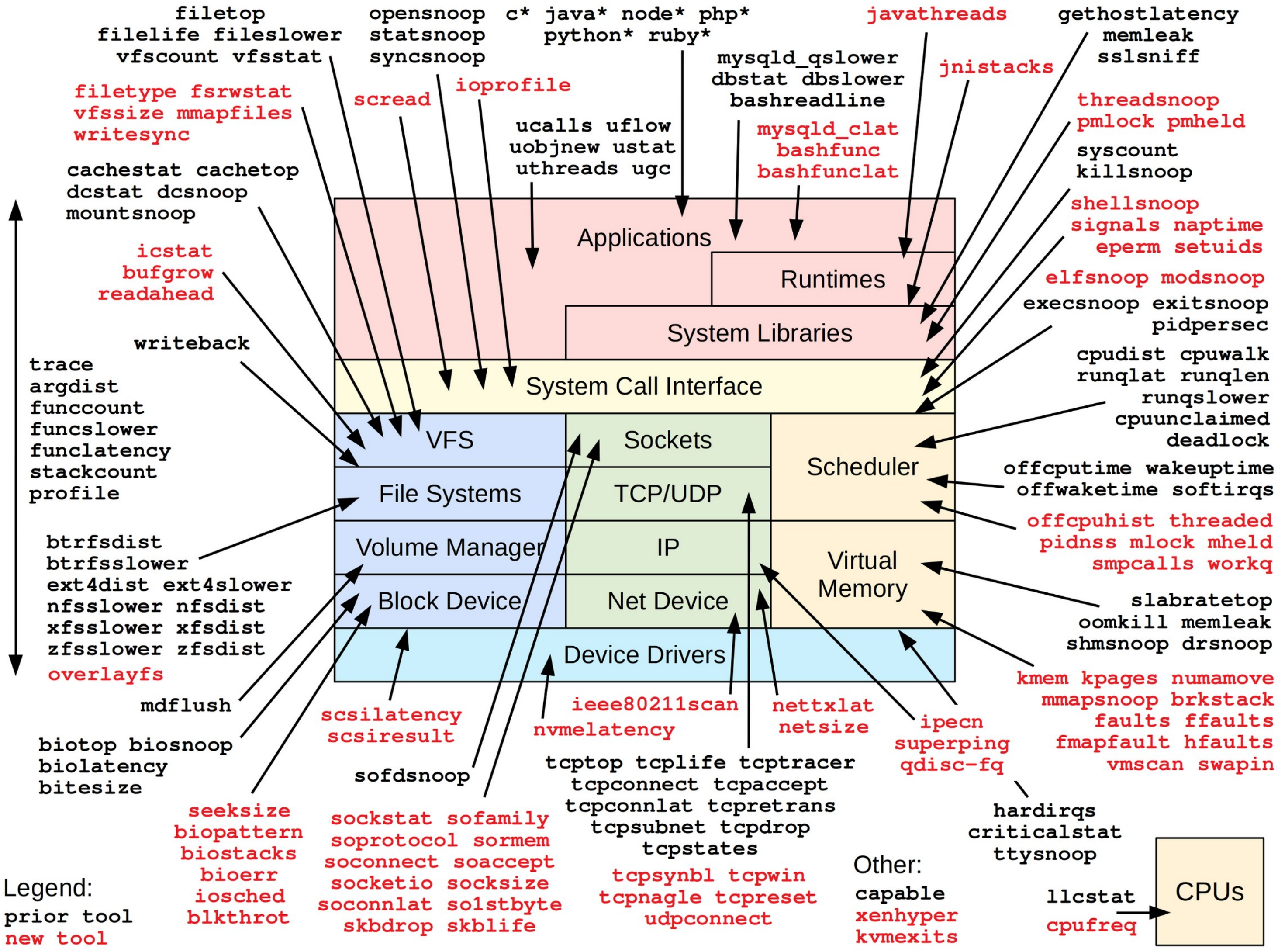
2021: Age of Seeing

- Flame graphs everywhere
- Latency heat maps
- eBPF & bpftrace
- PMCs in the cloud





More info: flame graphs [Gregg 13], heat maps [Gregg 10], and eBPF [Gregg 16b]


filetop
filelife fileslower
vfscount vfsstat
filetype fsrwstat
vfssize mmapfiles
writesync
cachestat cachetop
dcstat dcsnoop
mountsnoop
icstat
bufgrow
readahead
writeback
trace
argdist
funccount
funcslower
funclatency
stackcount
profile
btrfsdist
btrfsslower
ext4dist ext4slower
nfsslower nfsdist
xfsslower xfsdist
zfsslower zfsdist
overlayfs
mdflush
biotop biosnoop
biolatency
bitesize
seeksize
biopattern
biostacks
bioerr
iosched
blkthrot
Legend:
prior tool
new tool
opensnoop
statsnoop
syncsnoop
scread
ioprofile
scsilatency
scsiresult
sofdsnoop
sockstat sofamily
soprotocol sormem
soconnect soaccept
socketio socksize
soconnlat so1stbyte
skbdrop skblife
c* java* node* php*
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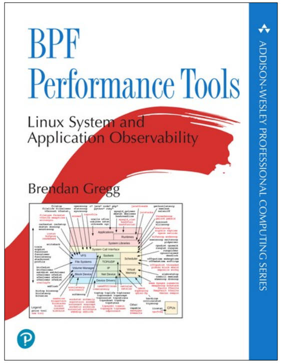
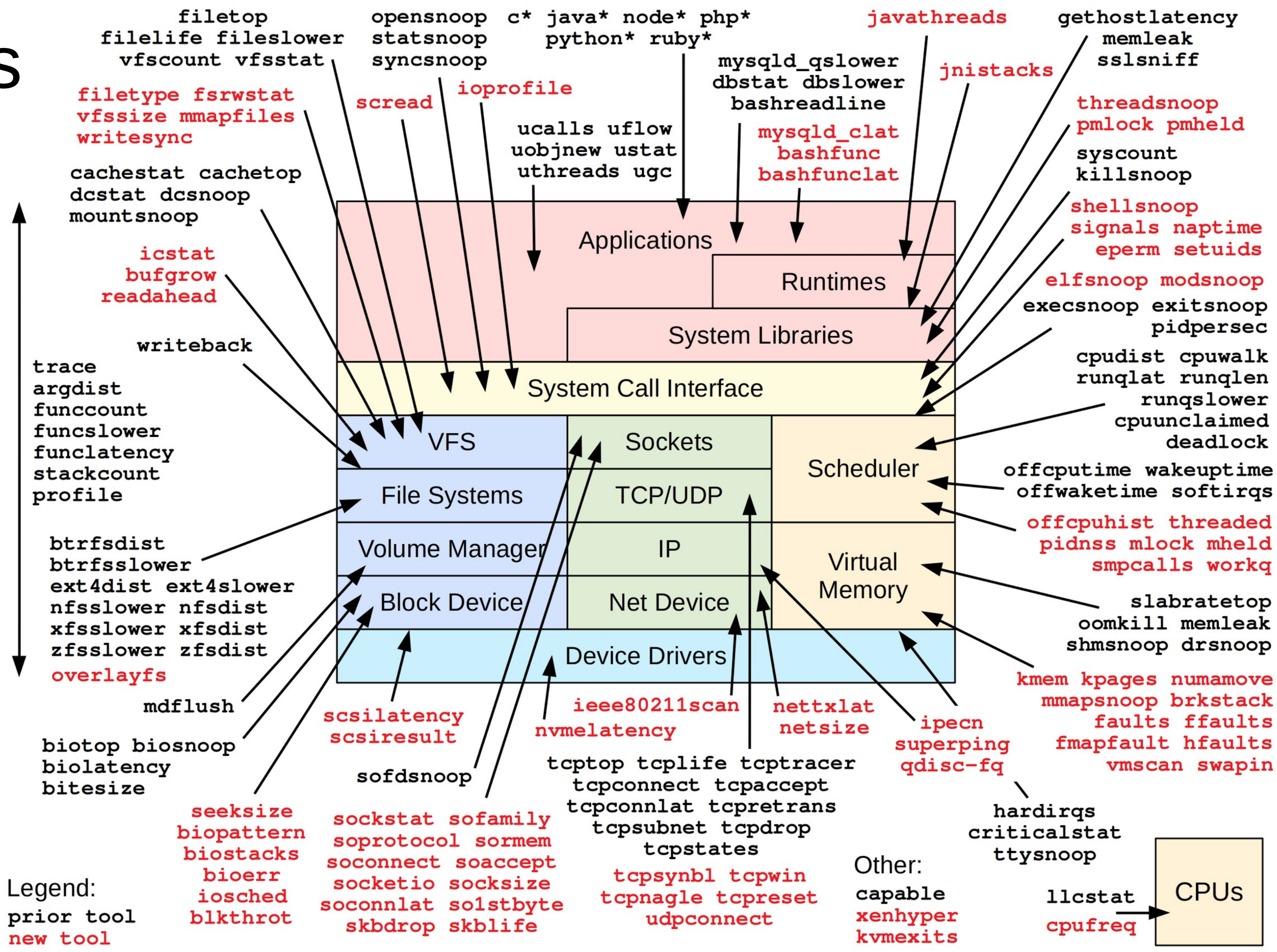
uobjnew ustat
uthreads ugc
mysqld_qslower
dbstat dbslower
bashreadline
mysqld_clat
bashfunc
bashfunclat
javathreads
jnistacks
Applications
Runtimes
System Libraries
System Call Interface
VFS
Sockets
Scheduler
File Systems
TCP/UDP
Volume Manager
IP
Virtual Memory
Block Device
Net Device
Device Drivers
ieee80211scan
nvmelatency
nettxlat
netsize
tcptop tcplife tcptracer
tcpconnect tcpaccept
tcpconnlat tcpretrans
tcpsubnet tcpdrop
tcpstates
tcpsynbl tcpwin
tcpnagle tcpreset
udpconnect
ipecn
superping
qdisc-fq
Other:
capable
xenhyper
kvmexits
gethostlatency
memleak
sslsniff
threadsnoop
pmlock pmheld
syscount
killsnoop
shellsnoop
signals naptime
eperm setuids
elfsnoop modsnoop
execsnoop exitsnoop
pidpersec
cpudist cpuwalk
runqlat runqlen
runqslower
cpuunclaimed
deadlock
offcputime wakeuptime
offwaketime softirqs
offcpuhist threaded
pidnss mlock mheld
smpcalls workq
slabratetop
oomkill memleak
shmsnoop drsnoop
kmem kpages numamove
mmapsnoop brkstack
faults ffaults
fmapfault hfaults
vmscan swapin
hardirqs
criticalstat
ttysnoop
llcstat
cpufreq
CPUs

BPF Perf Tools

(In red are the new open source tools I developed for the BPF book)





Example BPF tool

```
# execsnoop.py -T
TIME(s) PCOMM            PID    PPID   RET ARGS
0.506   run              8745   1828     0 ./run
0.507   bash             8745   1828     0 /bin/bash
0.511   svstat           8747   8746     0 /command/svstat /service/httpd
0.511   perl             8748   8746     0 /usr/bin/perl -e $l=<>;$l=~/(\d+) sec/;p...
0.514   ps               8750   8749     0 /bin/ps --ppid 1 -o pid,cmd,args
0.514   grep             8751   8749     0 /bin/grep org.apache.catalina
0.514   sed              8752   8749     0 /bin/sed s/^ *//;
0.515   xargs            8754   8749     0 /usr/bin/xargs
0.515   cut              8753   8749     0 /usr/bin/cut -d  -f 1
0.523   echo             8755   8754     0 /bin/echo
0.524   mkdir            8756   8745     0 /bin/mkdir -v -p /data/tomcat
[...]
1.528   run              8785   1828     0 ./run
1.529   bash             8785   1828     0 /bin/bash
1.533   svstat           8787   8786     0 /command/svstat /service/httpd
1.533   perl             8788   8786     0 /usr/bin/perl -e $l=<>;$l=~/(\d+) sec/;p...
[...]
```

Example bpftrace one-liner

```
# bpftrace -e 't:block:block_rq_issue { @[args->rwbs] = count(); }'
Attaching 1 probe...
^C

@[R]: 1
@[RM]: 1
@[WFS]: 2
@[FF]: 3
@[WSM]: 9
@[RA]: 10
@[WM]: 12
@[WS]: 29
@[R]: 107
```

libbpf-tools

```
# ./opensnoop
PID    COMM              FD ERR PATH
27974  opensnoop         28   0 /etc/localtime
1482   redis-server       7   0 /proc/1482/stat
[…]

# ldd opensnoop
    linux-vdso.so.1 (0x00007ffddf3f1000)
    libelf.so.1 => /usr/lib/x86_64-linux-gnu/libelf.so.1 (0x00007f9fb7836000)
    libz.so.1 => /lib/x86_64-linux-gnu/libz.so.1 (0x00007f9fb7619000)
    libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f9fb7228000)
    /lib64/ld-linux-x86-64.so.2 (0x00007f9fb7c76000)

# ls -lh opensnoop opensnoop.stripped
-rwxr-xr-x 1 root root 645K Feb 28 23:18 opensnoop
-rwxr-xr-x 1 root root 151K Feb 28 23:33 opensnoop.stripped
```

- 151 Kbytes for a stand-alone BPF program!
- (Note: A static bpftrace/BTF + scripts will also have a small average tool size)

Modern Observability Stack

OpenTelemetry

- Standard for monitoring and tracing

Prometheus

- Monitoring database

Grafana

- UI with dashboards

Grafana

Source: Figure 1.4 [Gregg 20]

My Prediction: BPF tool front-ends

bpftrace

- For one-liners and to hack up new tools
- When you want to spend an afternoon developing some custom BPF tracing

libbpf-tools

- For packaged BPF binary tools and BPF products
- When you want to spend weeks developing BPF

My Prediction: Too many BPF tools

(I'm partly to blame)

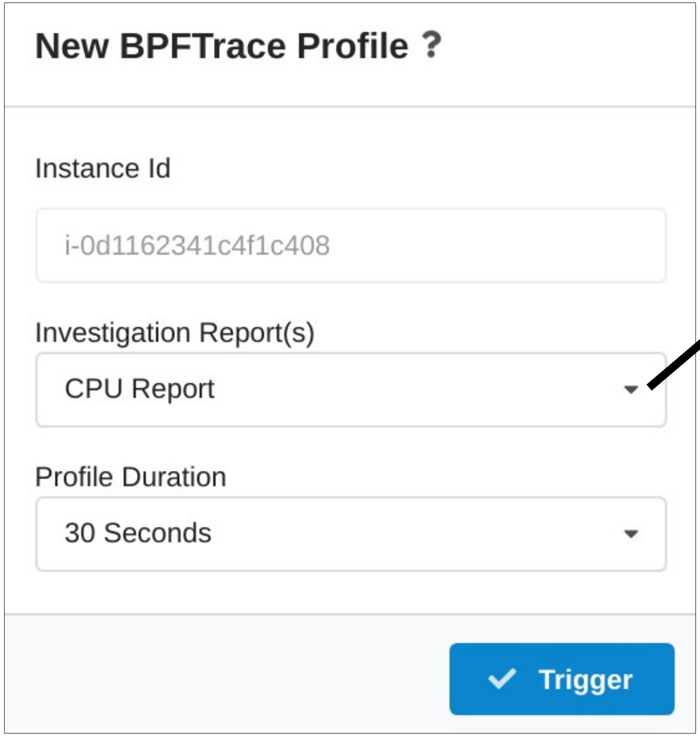
2014: I have **no tools** for this problem

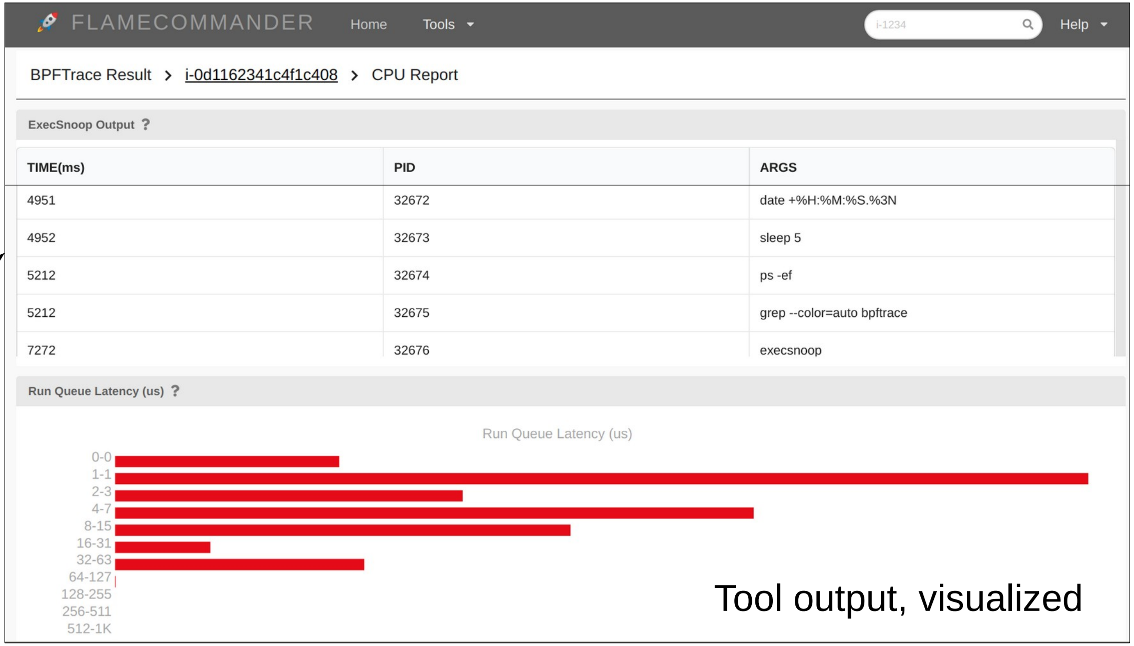
20**24**: I have **too many tools** for this problem

Tool creators: Focus on solving something no other tool can. Necessity is the mother of good BPF tools.

My Prediction: BPF perf tool future

GUIs, not CLI tools





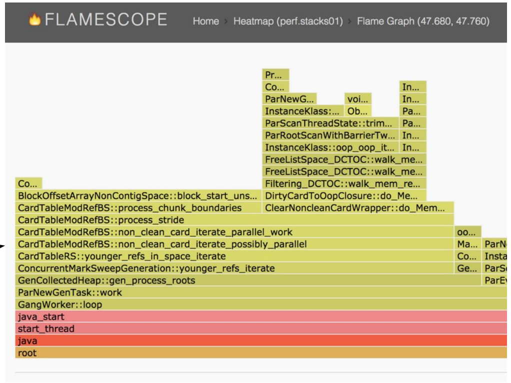
This GUI is in development by Susie Xia, Netflix

The end user may not even know it's using BPF

My Prediction: Flame scope adoption

Analyze variance, perturbations:

Subsecond-offset heat map



Flame graph

[Spier 20]

Recap

1. Processors
2. Memory
3. Disks
4. Networking
5. Runtimes
6. Kernels
7. Hypervisors
8. Observability

Performance engineering is getting more complex

1. Processors: **CPUs, GPUs, FPGAs, TPUs**
2. Memory: **DRAM, RLDRAM, HBM, 3D XPoint**
3. Disks: **PMR, SMR, MAT, EAMR, HAMR, SLC, MLC, ...**
4. Networking: **QUIC, MP-TCP, XDP, qdiscs, pacing, BQL, ...**
5. Runtimes: **Choice of JVM, GC, c2/Graal**
6. Kernels: **BPF, io_uring, PGO, Linux complexity**
7. Hypervisors: **VMs, Containers, LightweightVMs**
8. Observability: **BPF, PMCs, heat maps, flame graphs, OpenTelemetry, Prometheus, Grafana**

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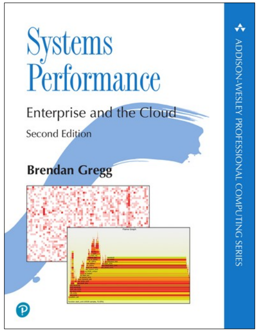

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Thanks

Thanks for watching!

Slides: http://www.brendangregg.com

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