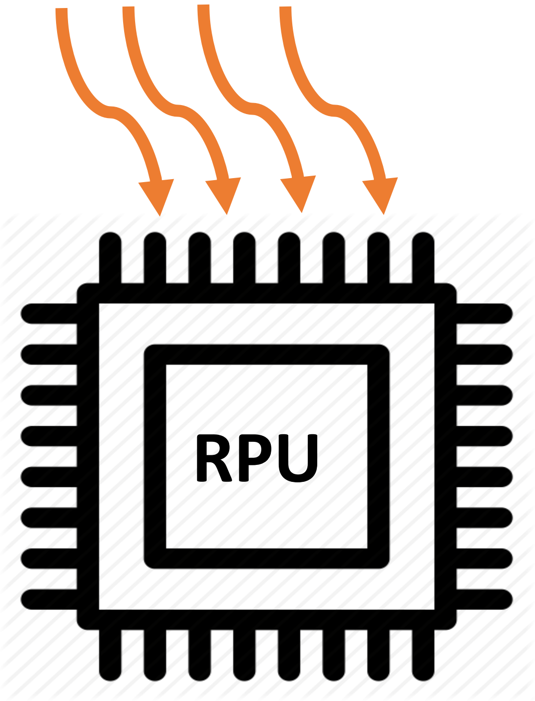
MICRO 2022



SIMR: Single Instruction Multiple Request Processing for Energy-Efficient Data Center Microservices

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FAQs, Concerns and Pitfalls

I have presented this work multiple times, and this slides contain most of the questions and concerns I received along with my answers. If you do not find your question here, feel free to contact us.

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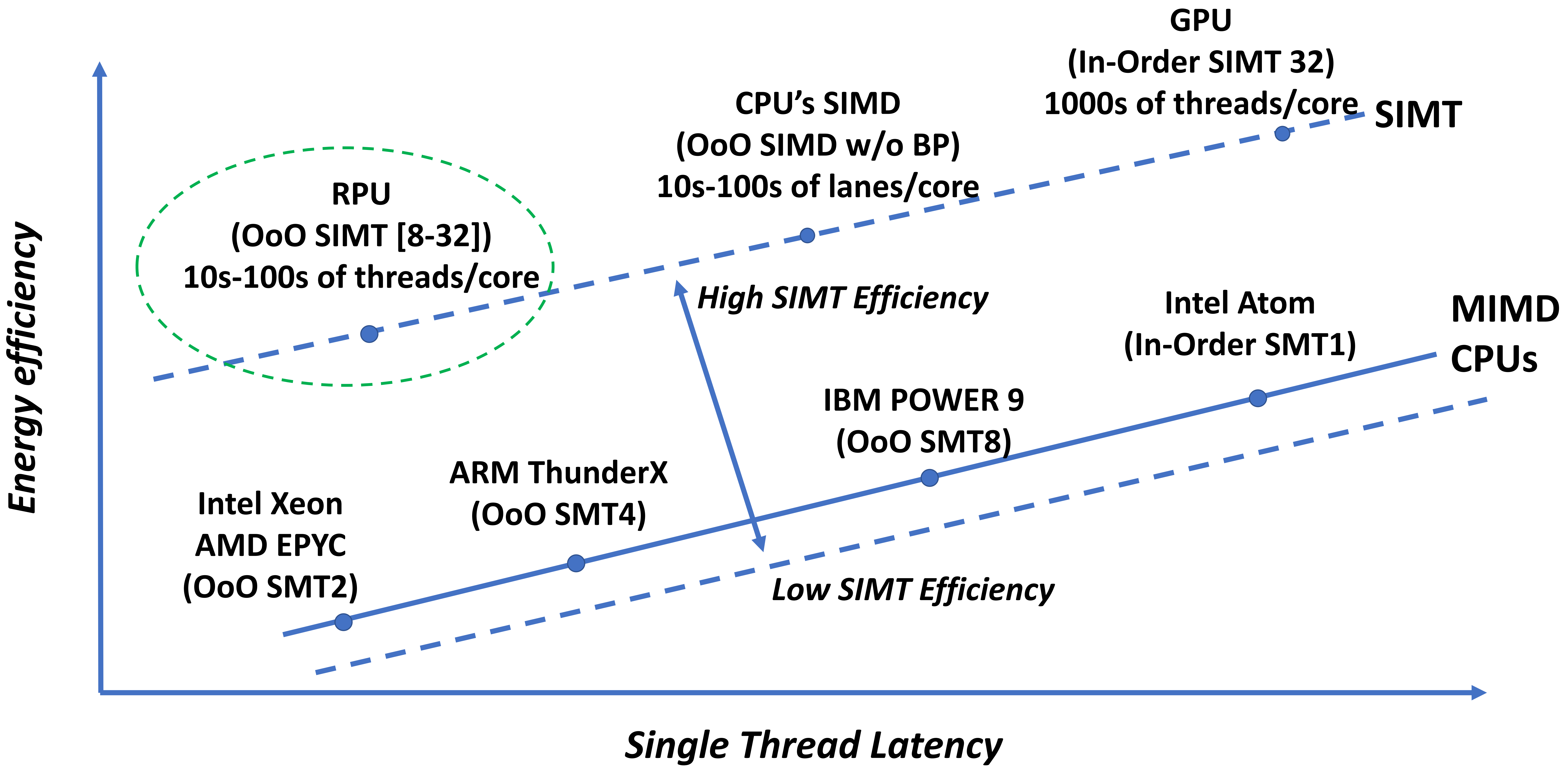
Question: There have been many CPU solutions that increase throughput and improve energy efficiency, e.g. Sun’s Niagara, Intel Atom, ARM Cortex, and others. How much is your RPU solution different from those?

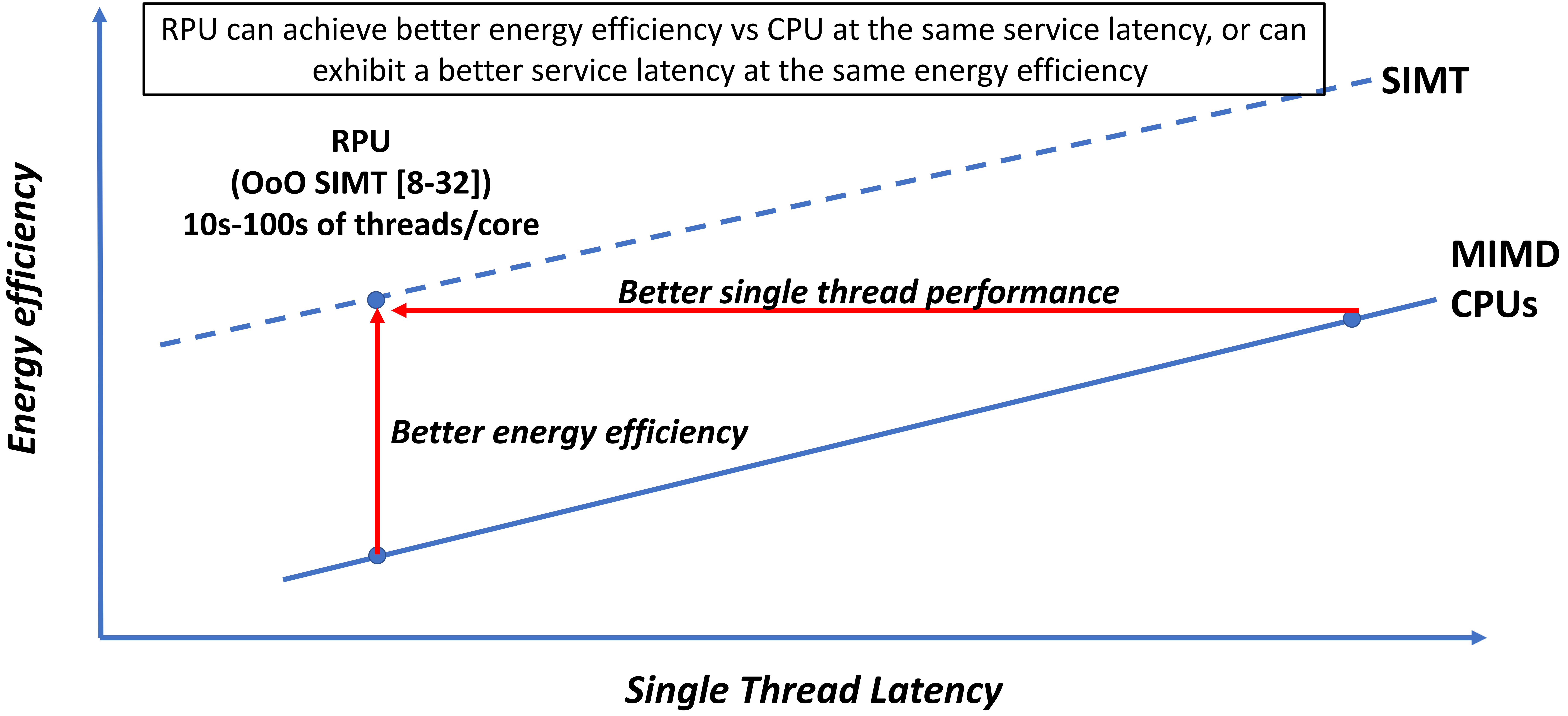
Answer: RPU is better in single-thread latency. Compared to wimpy CPUs, RPU will be better in either energy efficiency or single-thread latency or both, thanks to SIMT efficiency.

See next slides.

Latency & Energy-Efficiency Tradeoff



Latency & Energy-Efficiency Tradeoff



RPU can achieve better energy efficiency vs CPU at the same service latency, or can exhibit a better service latency at the same energy efficiency

SIMT

RPU
(OoO SIMT [8-32])
10s-100s of threads/core

MIMD
CPUs

Better single thread performance

Better energy efficiency

Energy efficiency

Single Thread Latency

Question: In RPU, you increase single thread latency by 1.44x, how much CPU’s energy efficiency you can get from 1.44x higher latency? This should be your baseline

Answer: Good Question! You can relax CPU’s freq to 0.7x to get 1.44x higher latency. Typically, CPU power decreases by approximately O(k^2) when CPU frequency decreases by k. Thus, this will lead to 2x power efficiency.

But, we care about energy efficiency not power, energy = power x time. So, energy = 0.5 * 1.44 = 0.72. Then, energy efficiency = 1/0.72 = 1.38x only. However, RPU achieves 5.7x energy efficiency.

➔ Then, RPU’s energy efficiency = 5.77/1.38 = 4.1x better than CPU at the same service latency.
This comparison is missing in the original paper, but we plan to add it in our extended version of our paper.

Hölzle, Urs. "Brawny cores still beat wimpy cores, most of the time." (2010).

Question: Similarly, how is wimpy CPU's latency you can get at the same RPU's energy efficiency?

Answer: Intel Atom can get 10x less power at 3x higher latency vs high end brawny core. This means 3.3x energy efficiency (energy = power * time). But, to achieve 5.7x energy as RPU, this means we need to scale latency to 5x down.

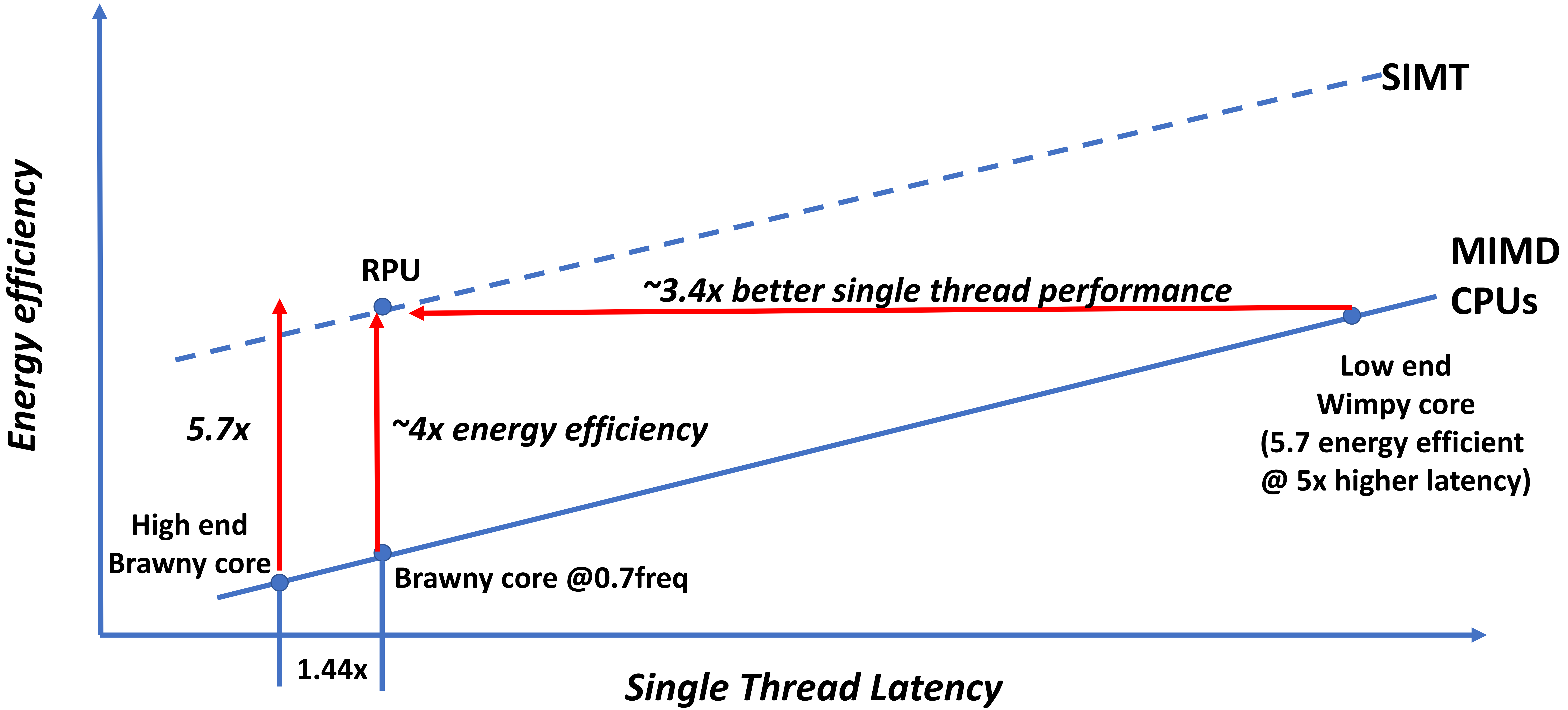
➔ Then, RPU is = 5/1.44 = 3.4x better single thread latency than CPU at the same energy efficiency.

Recall: power efficiency is easy to get, but energy efficiency is hard.

Note: this is a very high level analysis, further simulation-based analysis is needed to prove our claim.

https://www.anandtech.com/show/8357/exploring-the-low-end-and-micro-server-platforms/9

Latency & Energy-Efficiency Tradeoff

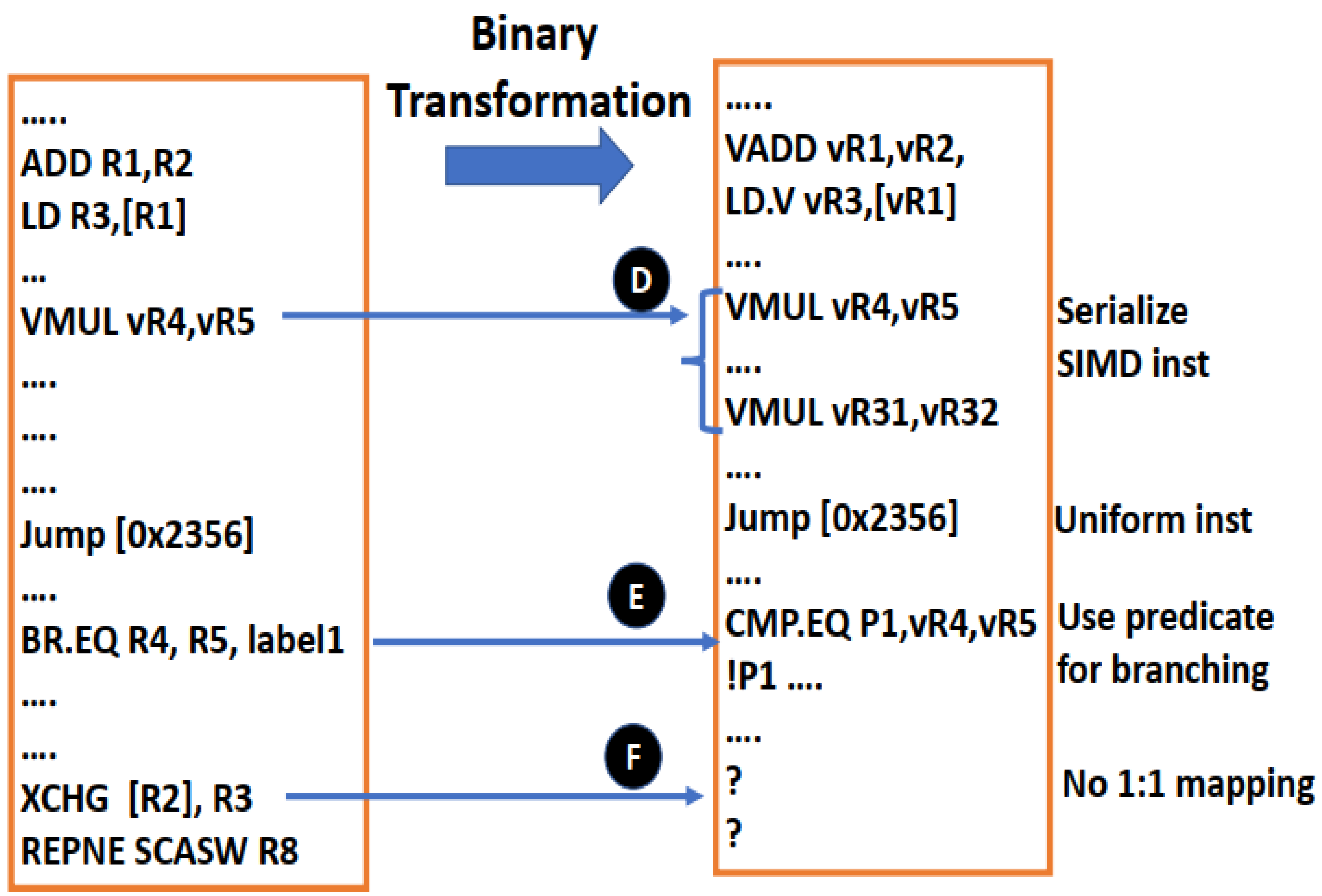


Question: What about CPU’s SIMD? Can we use SIMD instead of RPU?

Answer: Let’s recall what was SIMD designed for: CPU’s SIMD was designed to accelerate data-parallel portion of the code (i.e., loops). It was not intended to execute the entire application (including system calls, initialization, heavily branching and function calls). Therefore, there are many hurdles that SIMD is facing to execute microservices. See next slide.

What about CPU’s SIMD?

- Recall: CPU’s SIMD was designed to accelerate data-parallel portion (i.e., loops), not to execute the serial portion
- Therefore, many existing scalar instructions lack a 1:1 mapping with any vector instruction
  - For example, x86 AVX instructions only cover 27% of the scalar ISA
- Even if the ISA barriers is resolved, two more issues still exist:
  - Non transparency: recompilation/transformation for the entire SW stack (user code, libs & OS system calls)
  - Limited service latency:
    - Running coarse-grain threads in fine grain lane context. What if the scalar code already contains SIMD insts?
    - SIMD relies heavily on predicates for conditional branches, limited support for per-lane branch prediction



```
.....
ADD R1,R2
LD R3,[R1]
...
VMUL vR4,vR5
....
....
....
Jump [0x2356]
....
BR.EQ R4, R5, label1
....
....
XCHG  [R2], R3
REPNE SCASW R8
```

Original scalar
x86 or ARM

```
.....
VADD vR1,vR2,
LD.V vR3,[vR1]
....
VMUL vR4,vR5
....
VMUL vR31,vR32
....
Jump [0x2356]
....
CMP.EQ P1,vR4,vR5
!P1 ....
....
?
?
```

Vectorized x86 AVX-512
or ARM SVE

Concern: Batching Overhead?

Answer:
1- At a very high traffic (with billion-scale services), batching overhead is amortized

2- Batching is already applied in today’s data centers widely (see Google TPUv4*) with batch sizes of range 8-200 requests. So, the data centers are able to deal with batching overhead already.

3- The user can set a time-out per service to ensure the request meets the QoS

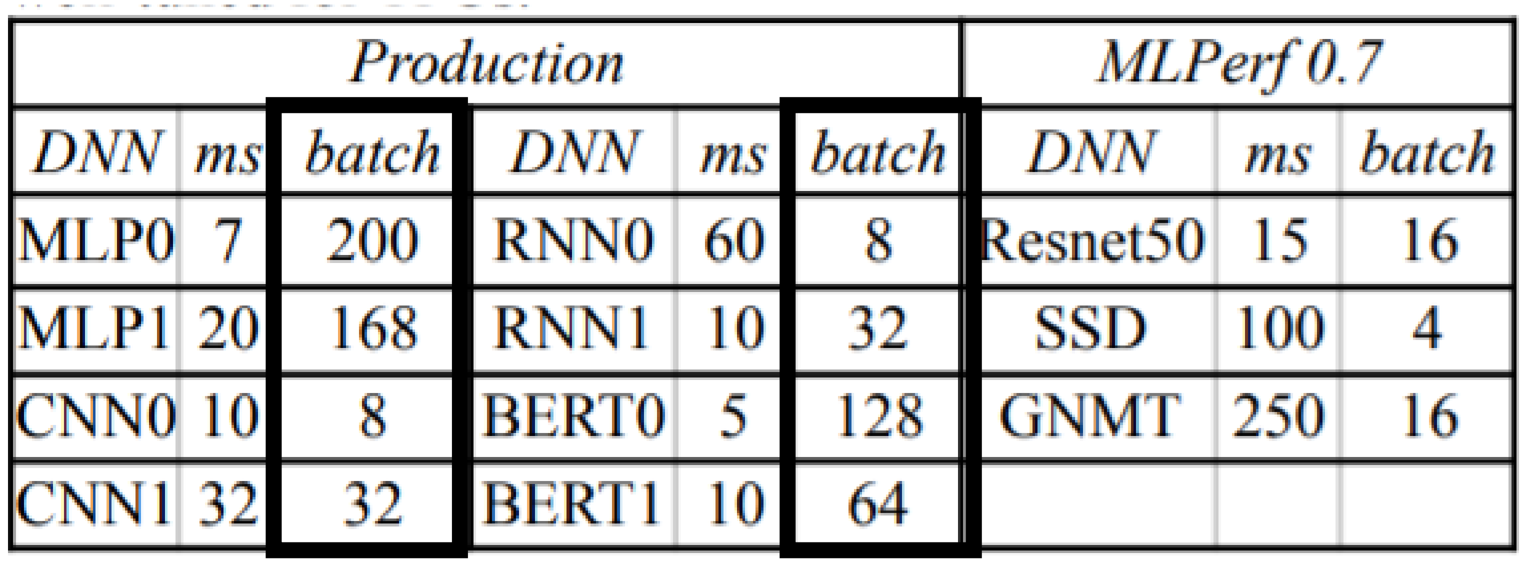
See next slides.

In general, if the service cannot tolerate batching of any size (we support as small as 8 request batch) or shows low SIMT efficiency, then they can be executed on the CPUs at lower throughput

* Jouppi, Norman P., et al. "Ten lessons from three generations shaped Google’s TPUv4i: Industrial product." *ISCA 2021*

Batching Optimization

From Google's Production DL Inference

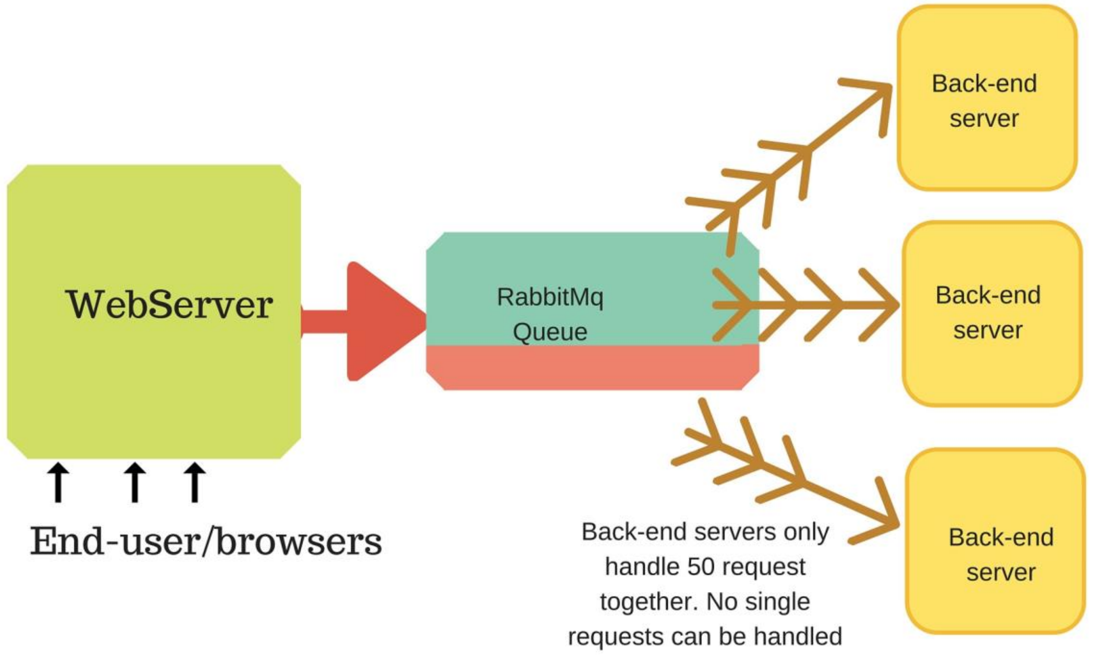


Production						*MLPerf 0.7*		
DNN	*ms*	*batch*	*DNN*	*ms*	*batch*	*DNN*	*ms*	*batch*
MLP0	7	200	RNN0	60	8	Resnet50	15	16
MLP1	20	168	RNN1	10	32	SSD	100	4
CNN0	10	8	BERT0	5	128	GNMT	250	16
CNN1	32	32	BERT1	10	64			

Table 5. Latency limit in ms and batch size picked for TPUv4i.

DL Inference Batching

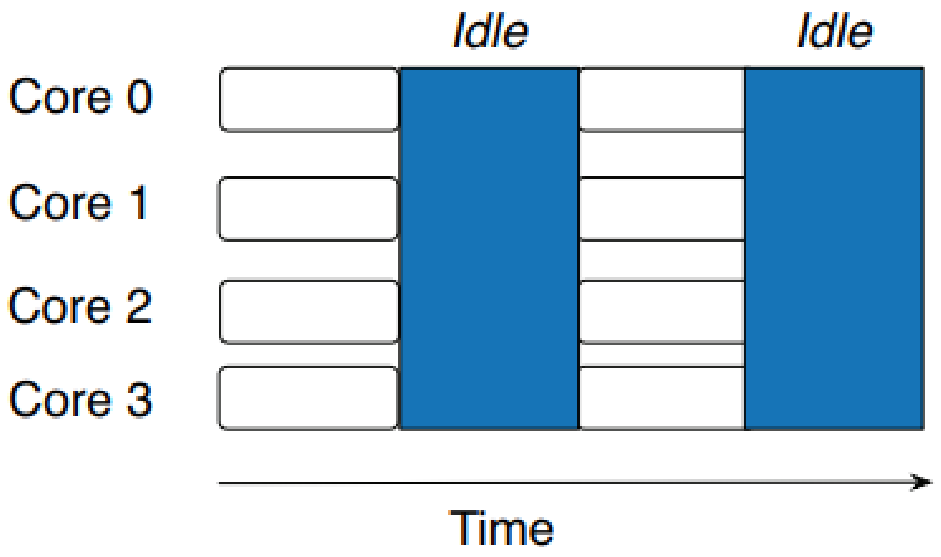
Memcached servers



Back-end servers only handle 50 request together. No single requests can be handled

Network Batching

Power management

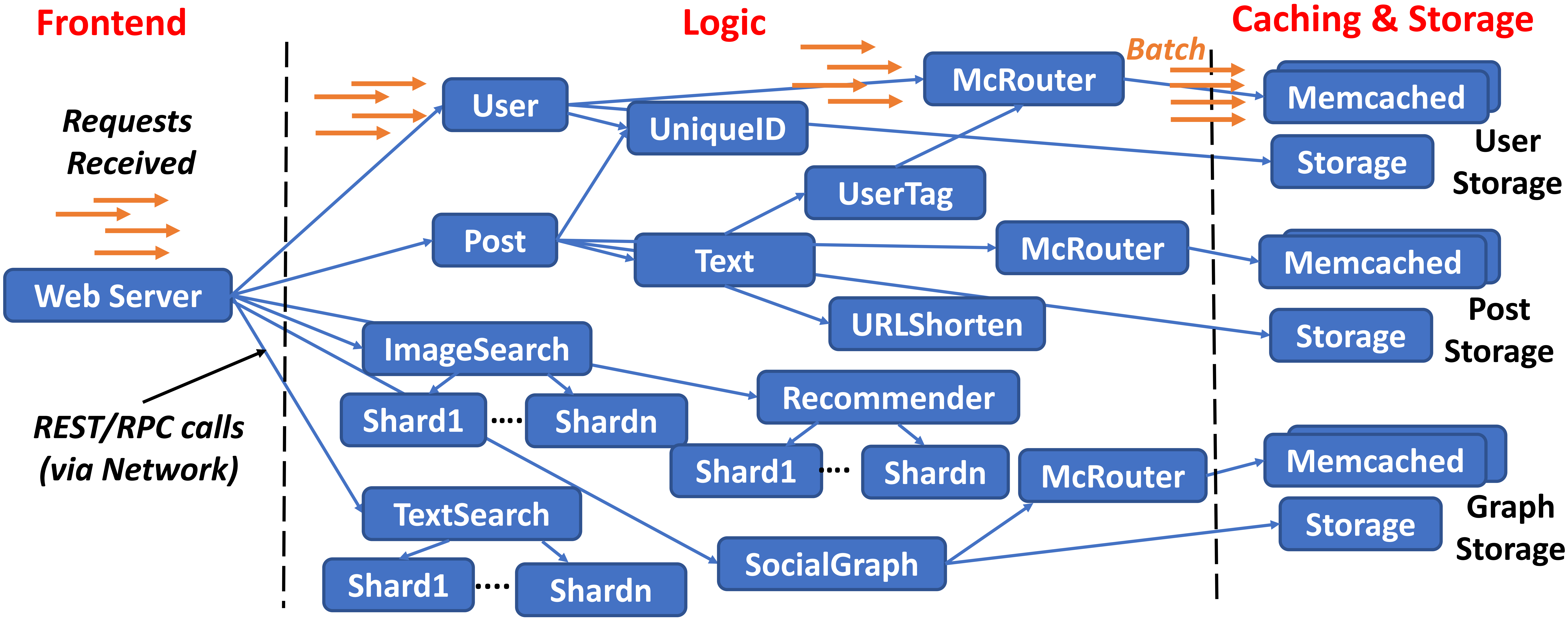


Batching for deep sleep

<span style="color:red">Key Observation:</span> Modern data centers already rely on request batching heavily

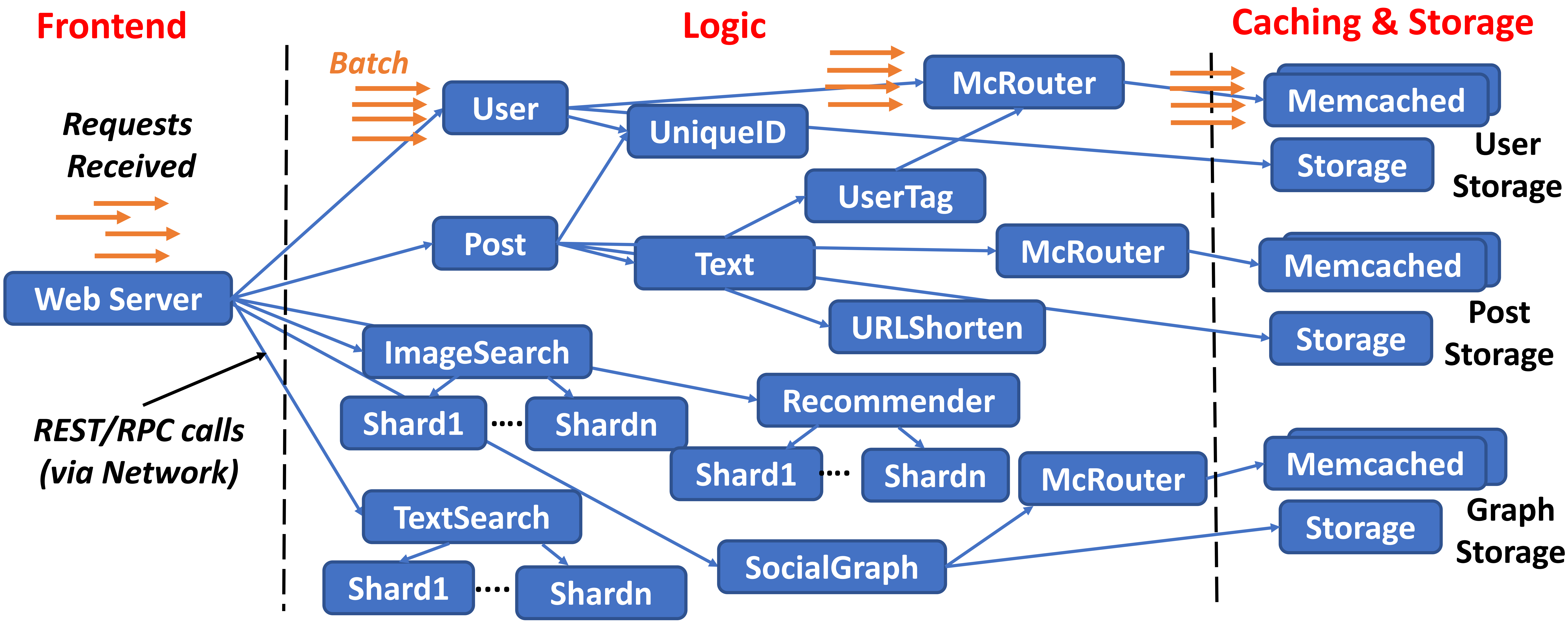
Jouppi, Norman P., et al. "Ten Lessons From Three Generations Shaped Google's TPUv4i: Industrial Product." *2021 ISCA*
https://memcached.org/blog/nvm-multidisk/
Meisner, David, and Thomas F. Wenisch. "Dreamweaver: architectural support for deep sleep." *ASPLOS 2012*

Current System: Selective Batching



Key Observation: Batching is heavily employed in the data center (DL inference, Memcached, ..)

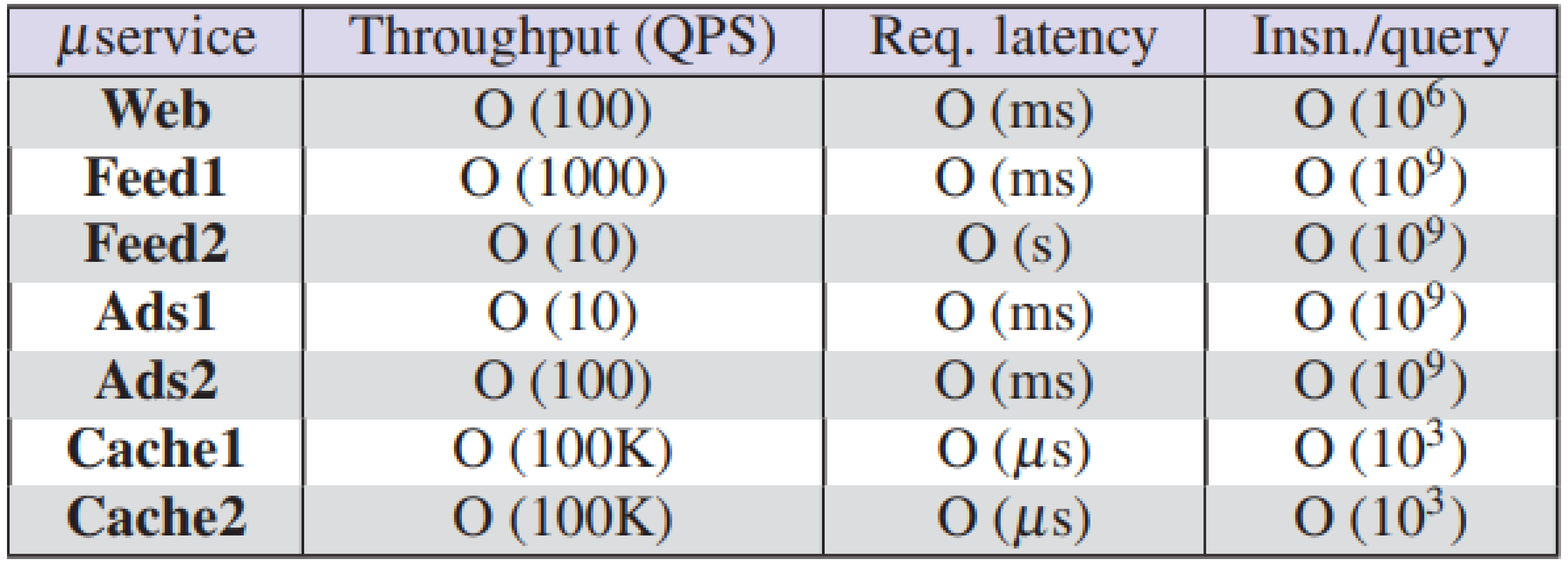
Our Proposed System-Level Batching



Key Observation: Batching is heavily employed in the data center (DL inference, Memcached, ..)
→ Instead of batching individual microservices, we propose batching in all microservices in the graph

Batching Opportunity for Facebook Services

- To amortize batching overhead, you either need:
  - (1) High service latency, with low traffic so service latency will amortize batching **OR**
  - (2) High traffic, with low service latency so high traffic will amortize batching **OR**
  - (3) High traffic and high service latency (ideal case)
- Let’s take a look at Facebook in-production services:



μservice	Throughput (QPS)	Req. latency	Insn./query
Web	O (100)	O (ms)	O (10^6)
Feed1	O (1000)	O (ms)	O (10^9)
Feed2	O (10)	O (s)	O (10^9)
Ads1	O (10)	O (ms)	O (10^9)
Ads2	O (100)	O (ms)	O (10^9)
Cache1	O (100K)	O (μs)	O (10^3)
Cache2	O (100K)	O (μs)	O (10^3)

Low traffic but high latency

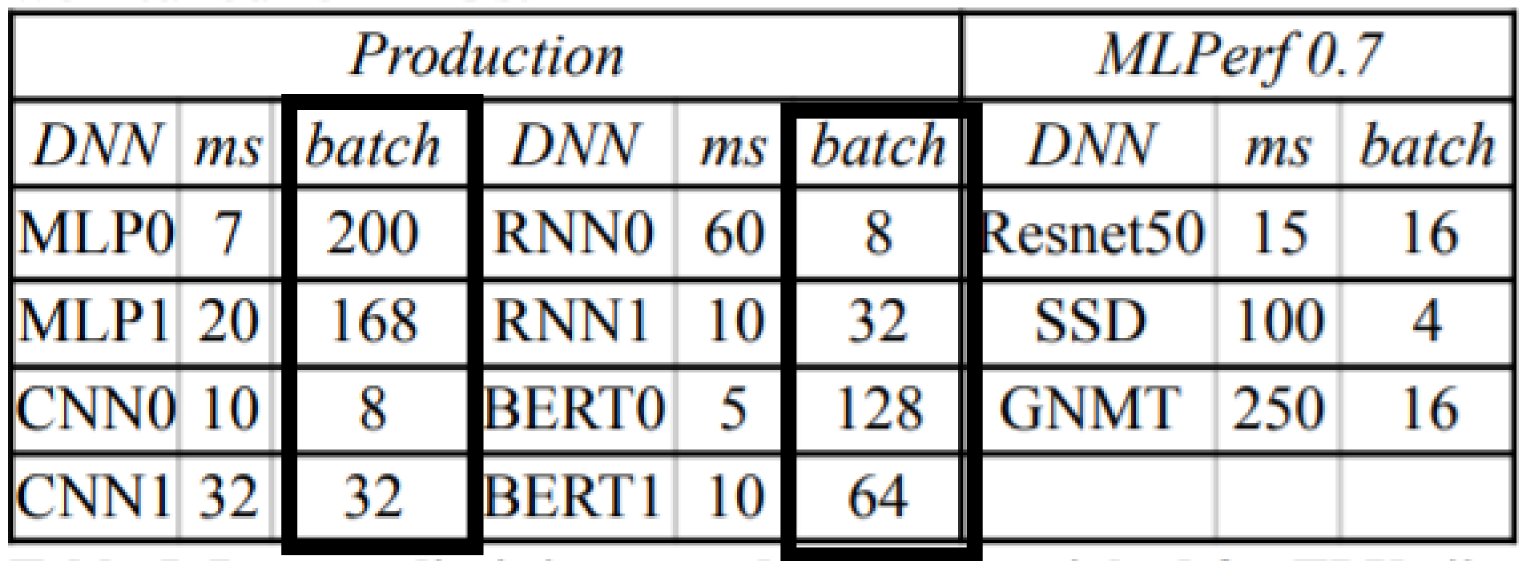
Low latency but high traffic

Note: I was not able to calculate the exact batching overhead as the exact numbers are not shown and SLA (P99 latency) is not specified.

Sriraman, Akshitha, Abhishek Dhanotia, and Thomas F. Wenisch. "Softsku: Optimizing server architectures for microservice diversity@ scale.“ASPLOS 2019

Batching Opportunity for Google Services

- (1) from Google in-production ML inference services:
  - Batching is widely used for DL inference with size = 8-200 reqs based on traffic and latency



Production						*MLPerf 0.7*		
DNN	*ms*	*batch*	*DNN*	*ms*	*batch*	*DNN*	*ms*	*batch*
MLP0	7	200	RNN0	60	8	Resnet50	15	16
MLP1	20	168	RNN1	10	32	SSD	100	4
CNN0	10	8	BERT0	5	128	GNMT	250	16
CNN1	32	32	BERT1	10	64			

Table 5. Latency limit in ms and batch size picked for TPUv4i.

Quoted: “Clearly, datacenter applications limit latency, not batch size. Future DSAs should take advantage of larger batch sizes”

- (2) Further, Google search service has a high service latency (~10s ms) and high traffic (~100K QPS), so they are a good candidate for batching

Jouppi, Norman P., et al. "Ten Lessons From Three Generations Shaped Google’s TPUv4i: Industrial Product." *2021 ISCA*

Concern: Batching already has an overhead and batching per-argument size as you proposed makes the overhead even worse?

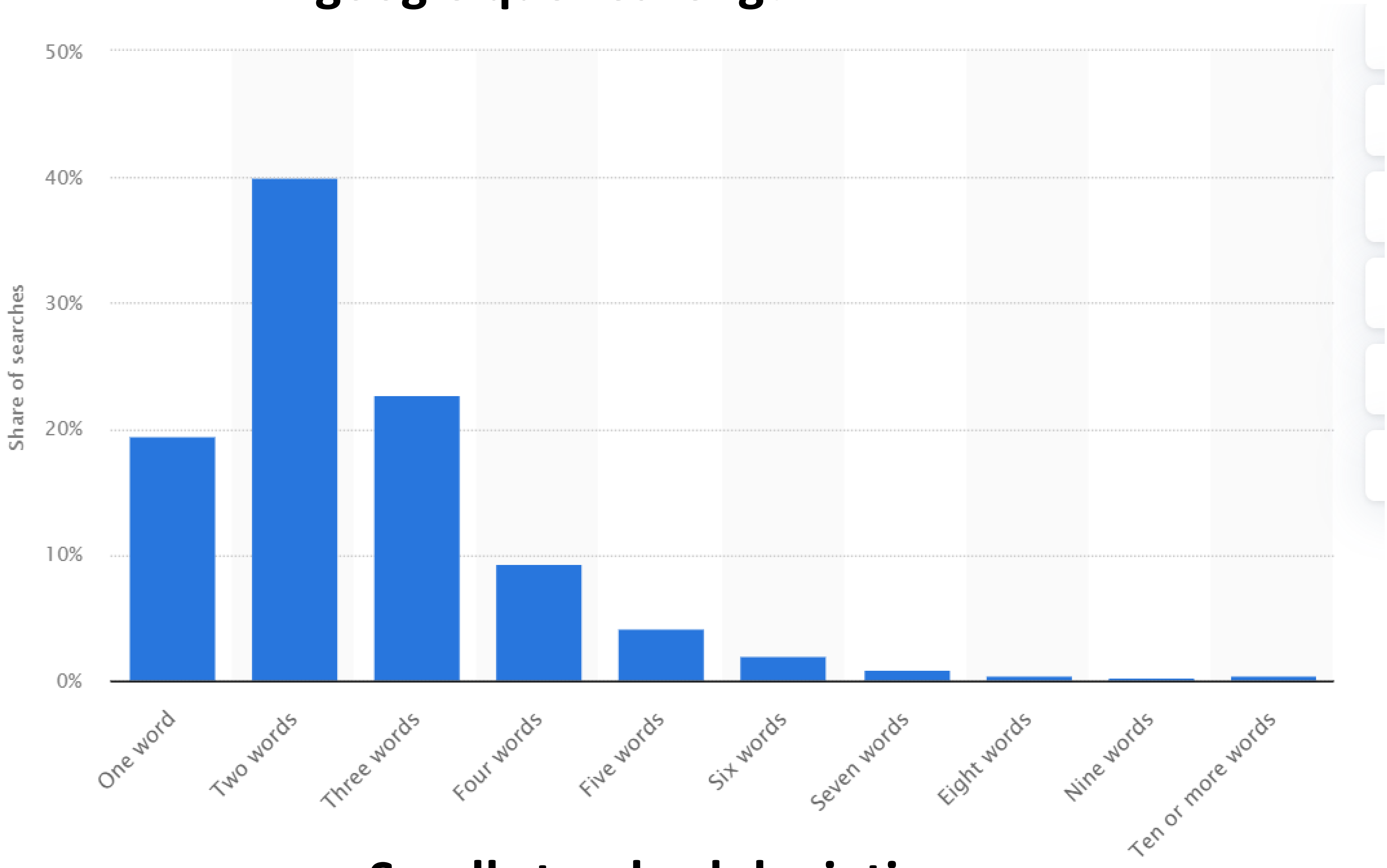
Answer: In real world scenarios, most of the arguments/queries length is within a very small standard deviation.
For example, 90% of Google search queries are 1-5 words.

Small standard deviation query length + high traffic will make the chance of formulating a batch of similar size very high.

Here, we make an assumption the query length is an indication for the query service time, If not (in the rare cases), apply batch split technique when needed.

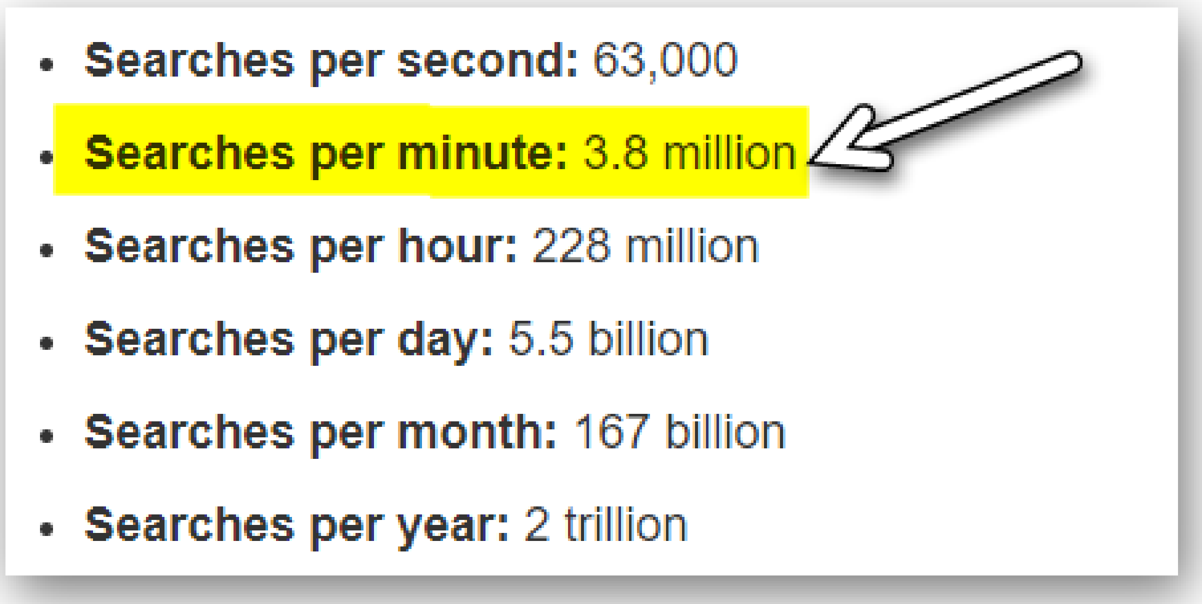
Online search queries statistics

google queries length



Small standard deviation

google queries frequency (2018)



- **Searches per second:** 63,000
- **Searches per minute:** 3.8 million
- **Searches per hour:** 228 million
- **Searches per day:** 5.5 billion
- **Searches per month:** 167 billion
- **Searches per year:** 2 trillion

Very High Traffic

https://backlinko.com/google-keyword-study
https://www.oberlo.com/blog/google-search-statistics#:~:text=The%20latest%20data%20shows%20that,Internet%20Live%20Stats%2C%202022)

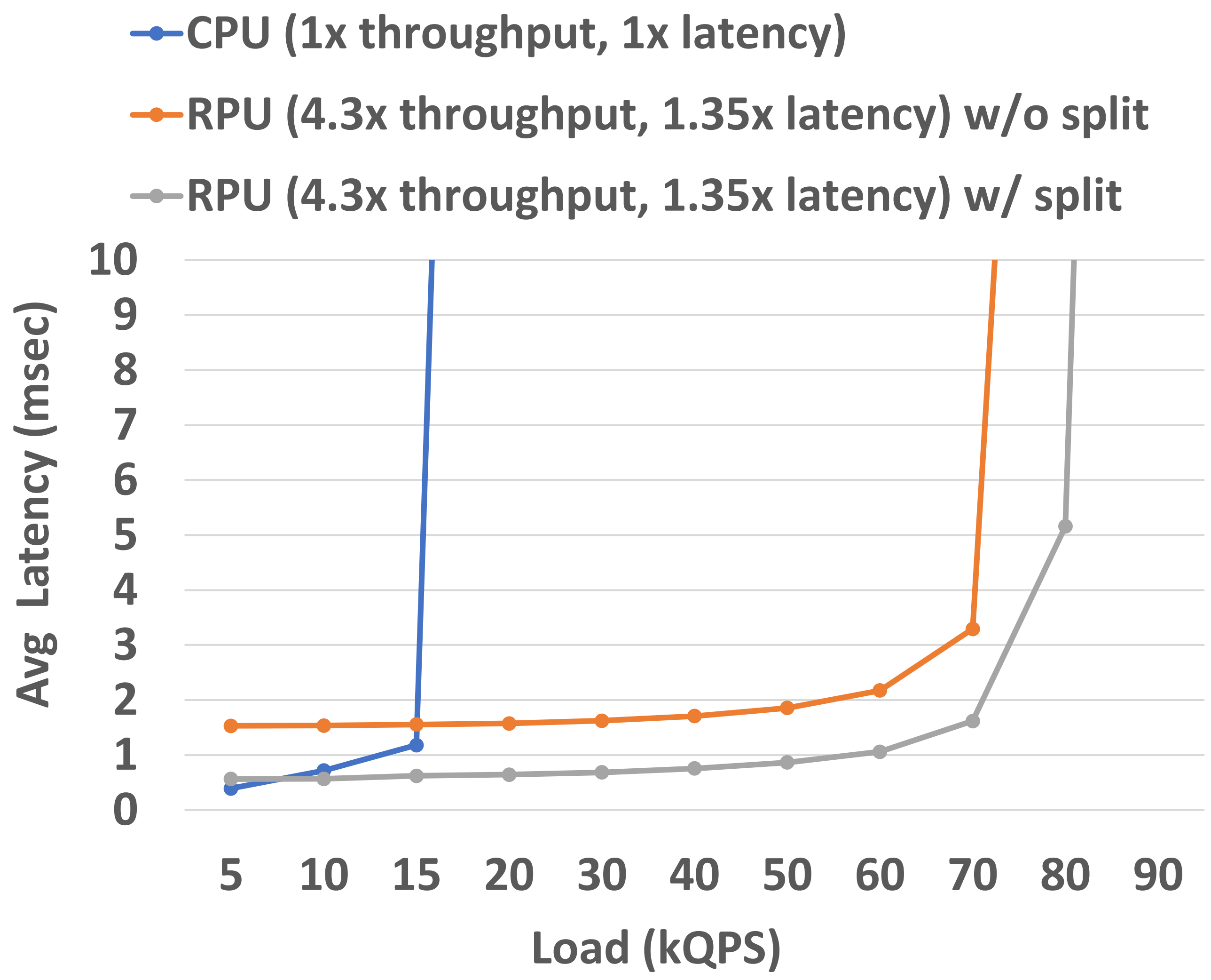
Concern: How can you get high SIMT efficiency on data dependent code? Batching per length will help on some cases, but what if there is IF condition based on the query value itself?

Answer: In fact, this is what the 8% control divergence is about. We do not claim 100% efficiency, we achieve 92%. We do have some divergence occurring. For example, B+ tree traversal, data compression in zlib library, and others, all of these are dependent on data values and report high control divergence in our traces.

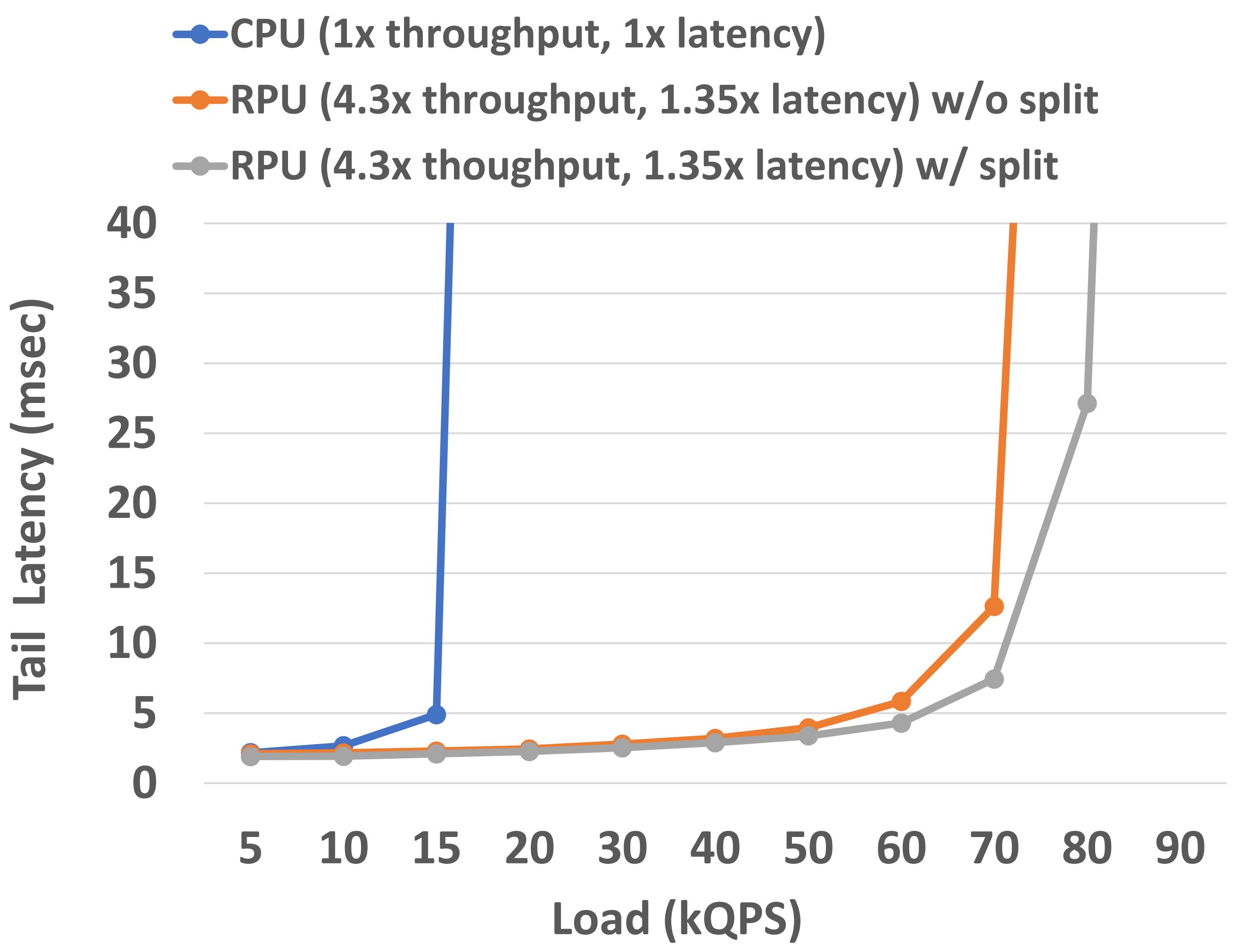
Question: How much does the 1.44x higher latency affect your end-to-end average and tail latency?

Answer: We run our experiments to study the service latency increase effect on system scale. Requests typically spend 50% of time in networking and 50% in processing. So, If the processing time (i.e., RPU service latency) increases be 44%, then this will lead to end-to-end latency increase by 22% as networking time remains the same. With further tunning and throttling, we can maintain the almost same latency as CPU systems on system level.

System-Level Results (uQsim Simulator)



Average latency



99% tail latency

→ RUP's batching overhead is amortized at low and high loads

→ Batch split technique achieves almost the same average and tail latency as CPU system at 4x higher throughput

→ Without the batch split technique, we are still able to get a good tail latency

Notes: assume 90% hit rate of Memcached, storage latency = 1 ms & network latency = 60 nsec

Question: What would the threshold be for latency increase that can be tolerated by data centers?

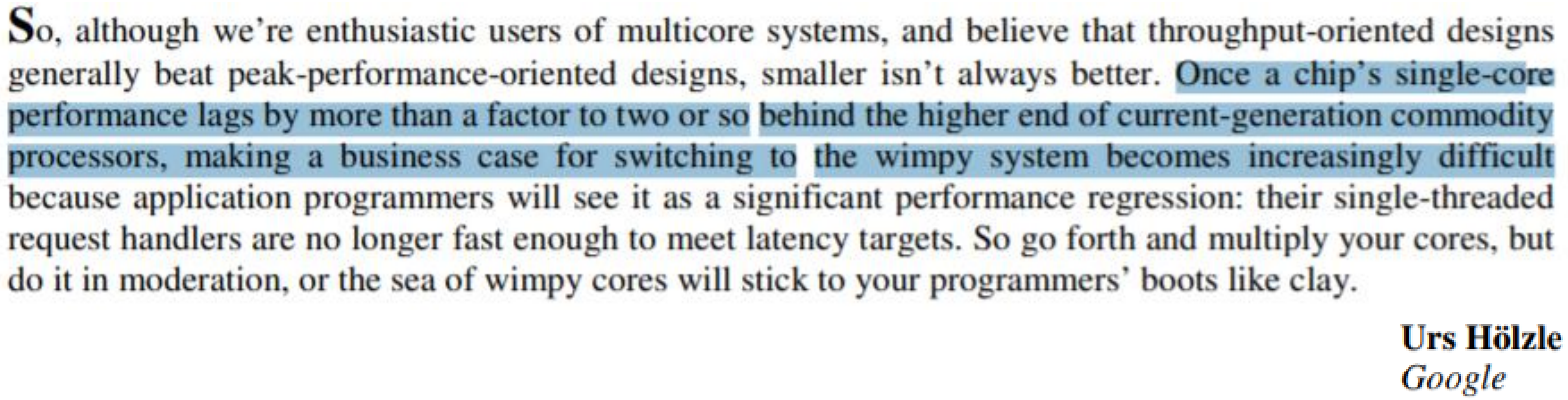
Answer: Up to 2x slower latency should be tolerated by data center providers. So, for example, see the high-end CPU in the market (e.g. Intel Xeon or AMD EPYC) and ensure your proposed energy-efficiency CPU design is not behind by more than 2x of single thread performance. See Hölzle [MICRO’10].

Hölzle, Urs. "Brawny cores still beat wimpy cores, most of the time." (2010).

Maximum Tolerated Latency

Up to 2x slower latency should be tolerated by data center providers

Quoted:



So, although we're enthusiastic users of multicore systems, and believe that throughput-oriented designs generally beat peak-performance-oriented designs, smaller isn't always better. Once a chip's single-core performance lags by more than a factor to two or so behind the higher end of current-generation commodity processors, making a business case for switching to the wimpy system becomes increasingly difficult because application programmers will see it as a significant performance regression: their single-threaded request handlers are no longer fast enough to meet latency targets. So go forth and multiply your cores, but do it in moderation, or the sea of wimpy cores will stick to your programmers' boots like clay.

Urs Hölzle
Google

Hölzle, Urs. "Brawny cores still beat wimpy cores, most of the time." (2010).

Question: Scaling the threads will be limited by lock contention & critical section?

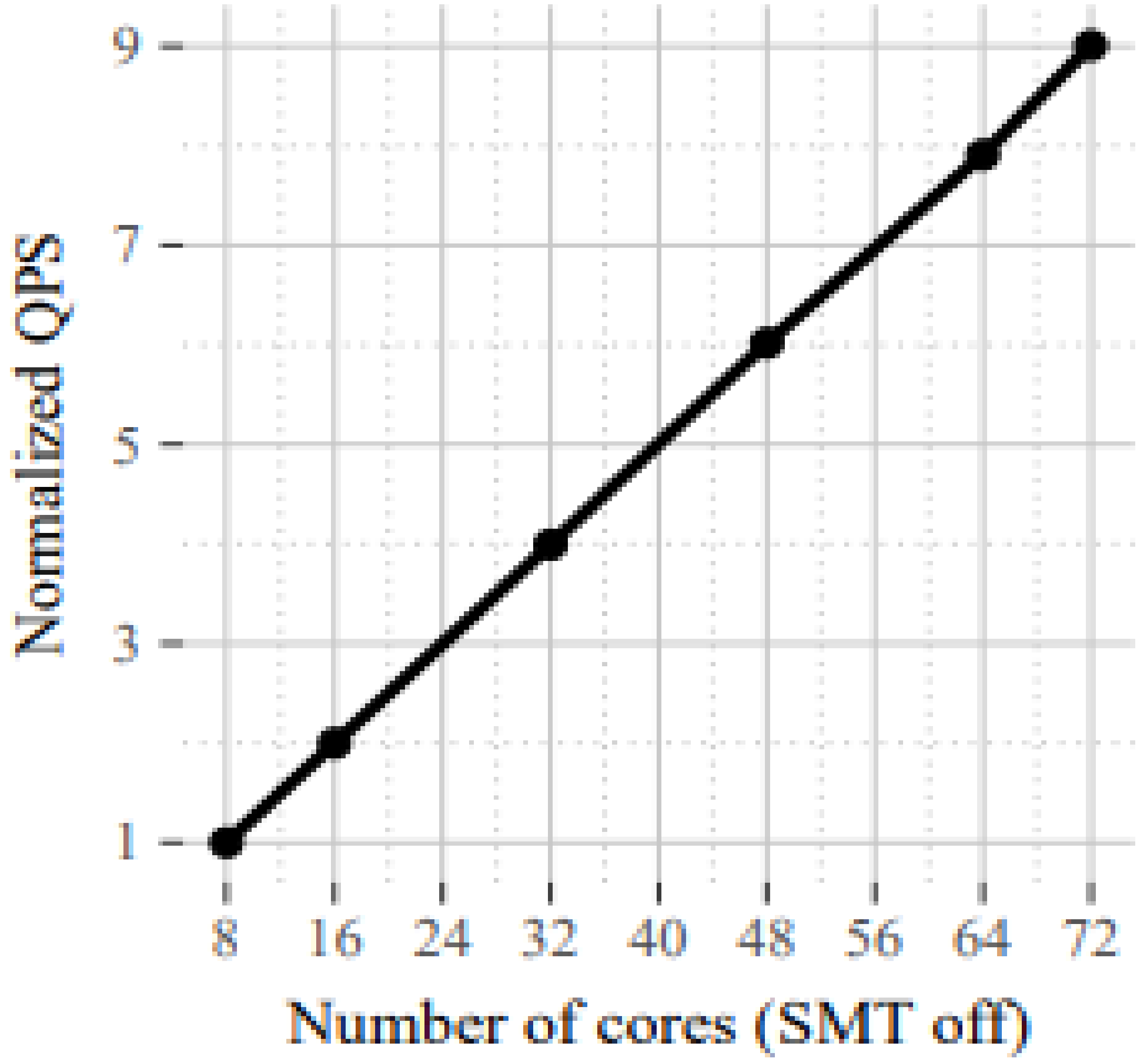
Answer: Real-world data center workloads are highly optimized to reduce lock contention by employing lock-free data structure, highly-concurrent memory allocator and fine-grain locking. See next slides.

Note that: this is not just a scalability issue for RPU, it is also an issue for multi-core CPU designs too.

Perfect Scaling in Real-world Server Workloads (I)

- From Google in-production Search service

9x more cores = 9x more QPS!



Multi Threaded Servers

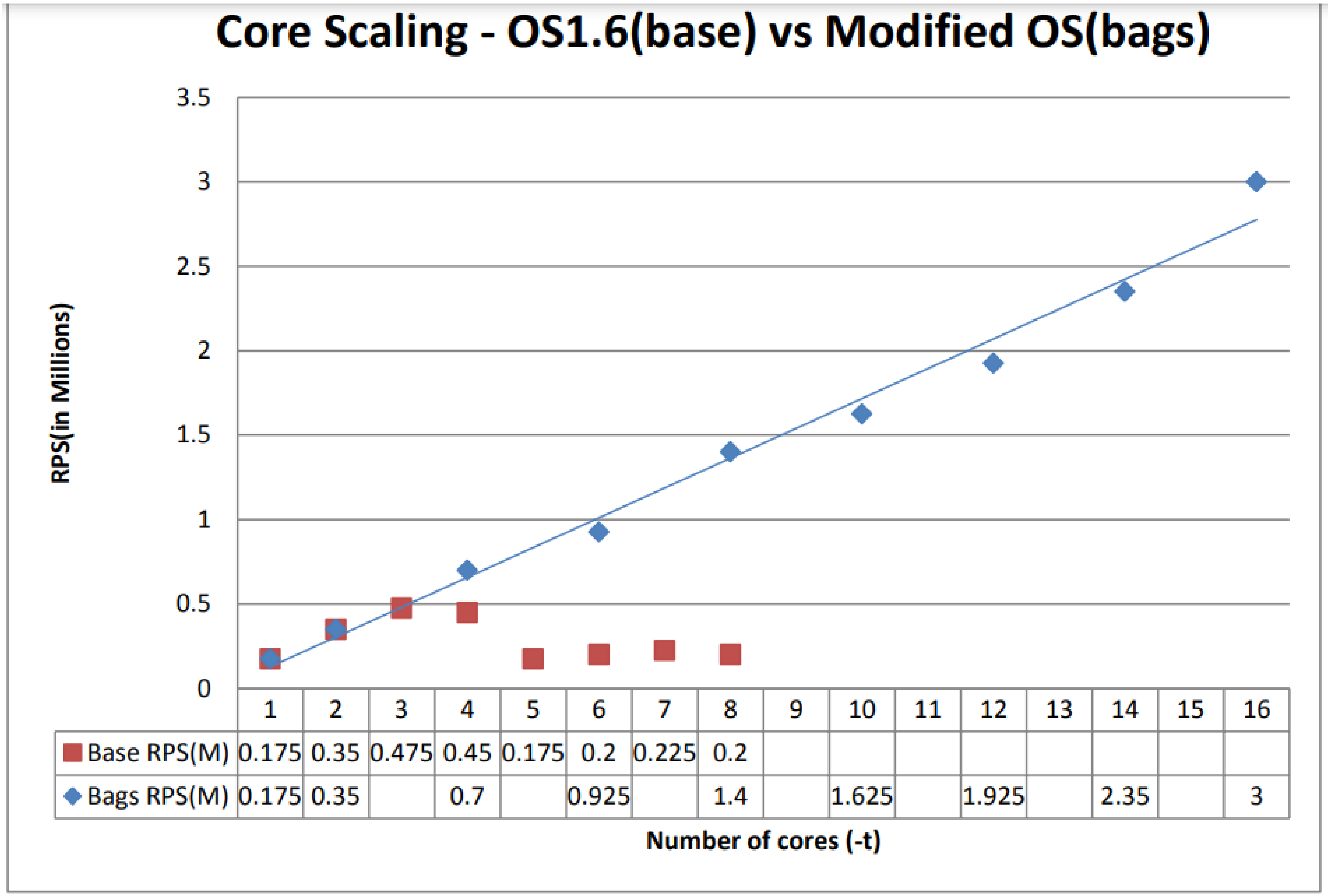
Quoted: “The near-perfect scaling implies that search has a limited amount of read/write sharing or locking in the memory system”

Ayers, Grant, et al. "Memory hierarchy for web search." *HPCA 2018*

Perfect Scaling in Real-world Server Workloads (II)

Another example: Multi-threaded Memcached

4x more cores = 4x more RPS



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
🟥 Base RPS(M)	0.175	0.35	0.475	0.45	0.175	0.2	0.225	0.2								
◆ Bags RPS(M)	0.175	0.35		0.7		0.925		1.4		1.625		1.925		2.35		3

Figure 14 - Maximum throughput with a median RTT < 1ms SLA as core counts increase

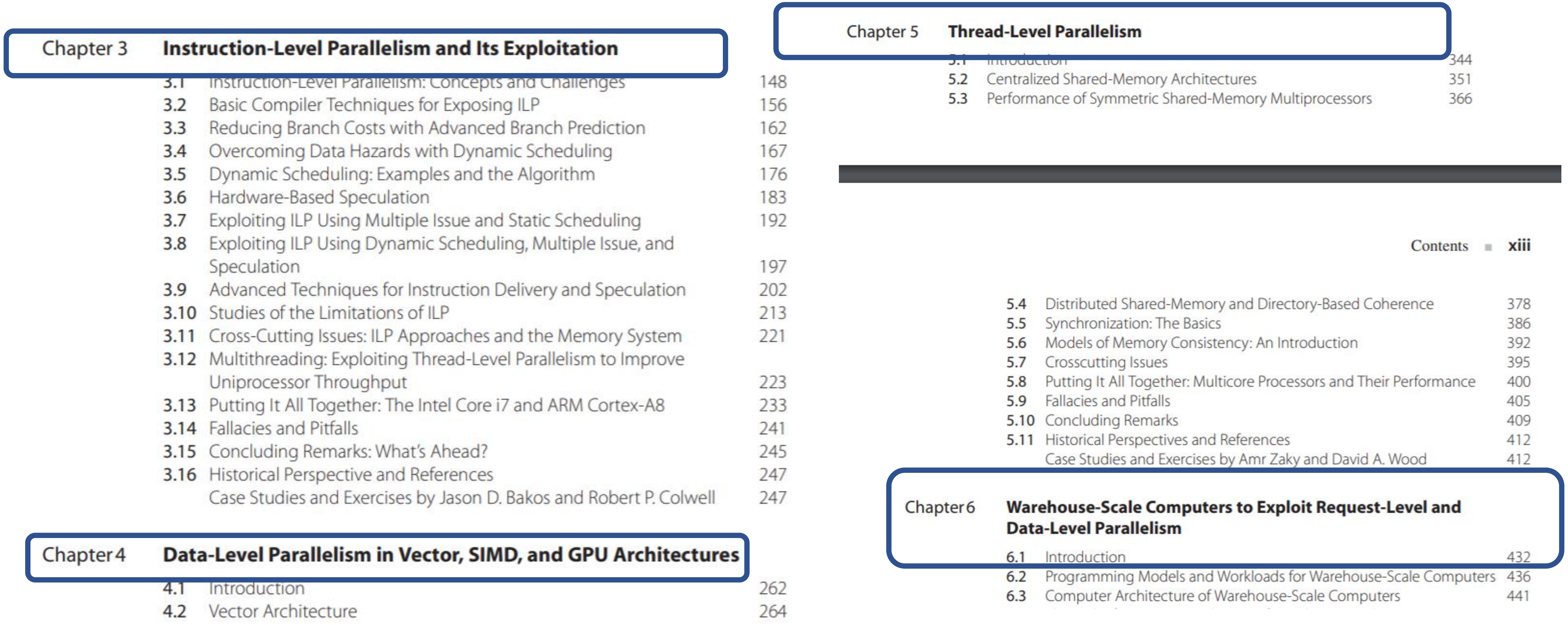
Quoted: "The approach employs Concurrent data structures and a modified cache replacement strategy to improve scalability. These data structures enable concurrent lockless item retrieval and provide striped lock capability for hash table updates"

Wiggins, Alex, and Jimmy Langston. "Enhancing the scalability of memcached." *Intel document,* (2012)

Question: Why do you call it RPU?

Answer: An Accerlator to exploit thread similarity and Request level parallelism
→ Request Processing Unit (RPU)

In Literature, RLP is different than TLP



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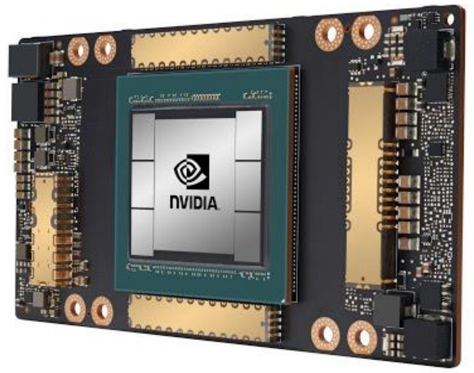
Computer Architecture: A Quantitative Approach 5th edition (Table of Contents)

Instruction level parallelism (ILP) &
Thread level parallelism (TLP)

Data level parallelism (DLP)

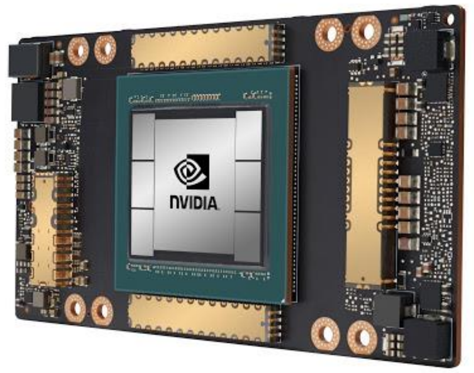


Request level parallelism (RLP)

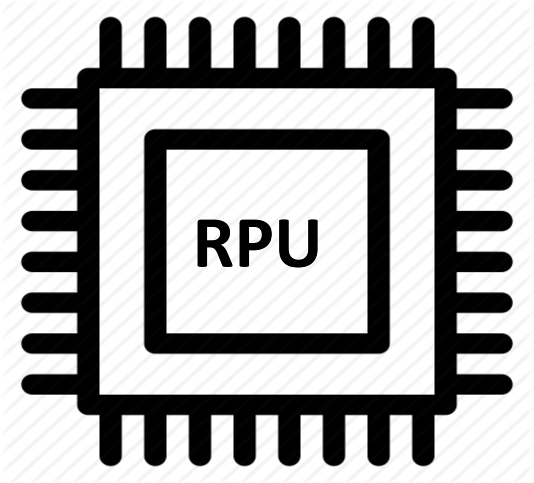
??

Instruction level parallelism (ILP) &
Thread level parallelism (TLP)

Data level parallelism (DLP)



Request level parallelism (RLP)



Question: How latency is only increased by 44%?
4x higher instruction latency, 2x higher L1 access latency and sub batch interleaving should lead to more than that

Answer: As shown in previous studies, data center workloads exhibit a limited IPC and retire rate as they are bounded by memory latency. See next slides

Sriraman, Akshitha, et al. "Softsku: Optimizing server architectures for microservice diversity@ scale.“ ISCA 2019
Kanev, Svilen, et al. "Profiling a warehouse-scale computer." ISCA 2015

Low IPC in Data Center

Facebook (SMT is On)

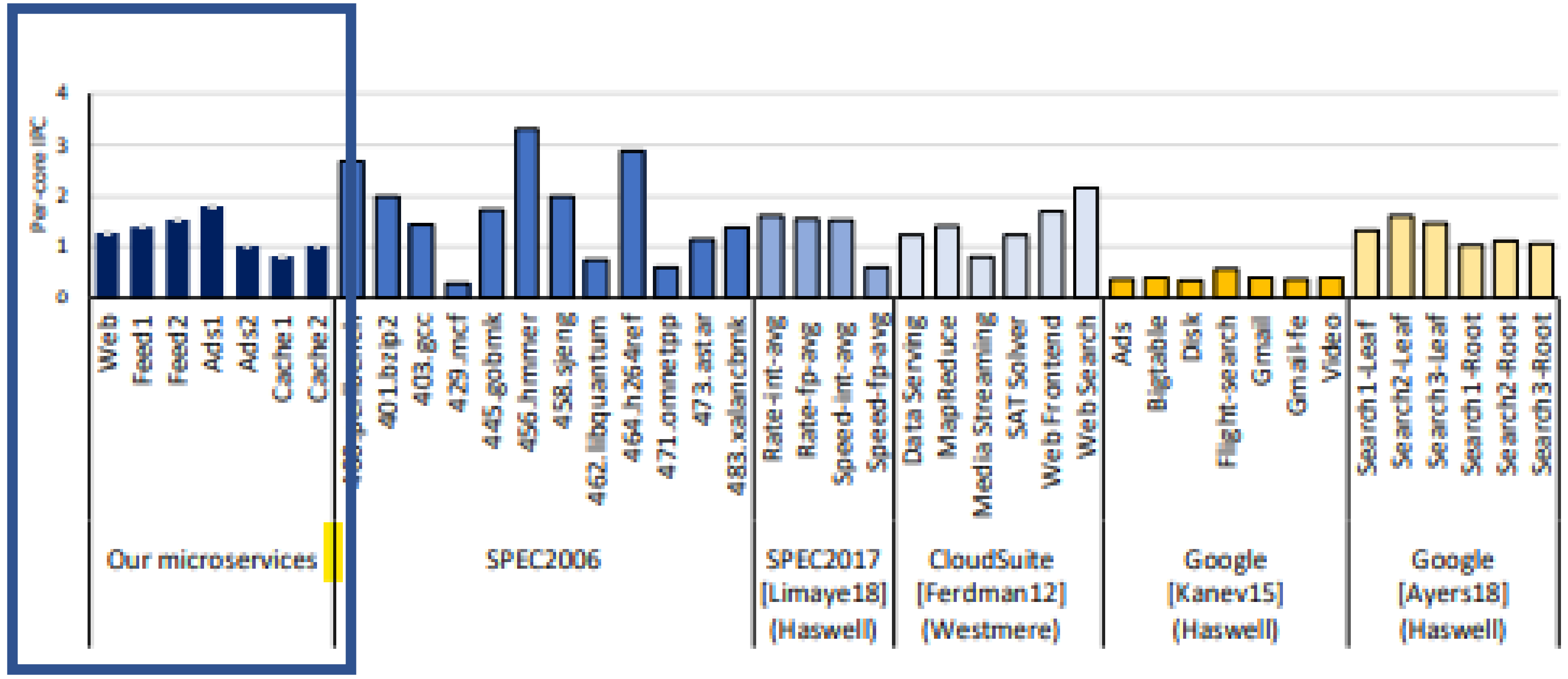


Figure 6: Per-core IPC across our μservices & prior work (IPC measured on other platforms): our μservices have a high IPC diversity.

For FB, SMT is on, so divide the IPC per 2 to get IPC per thread approximately

Google (SMT is off)

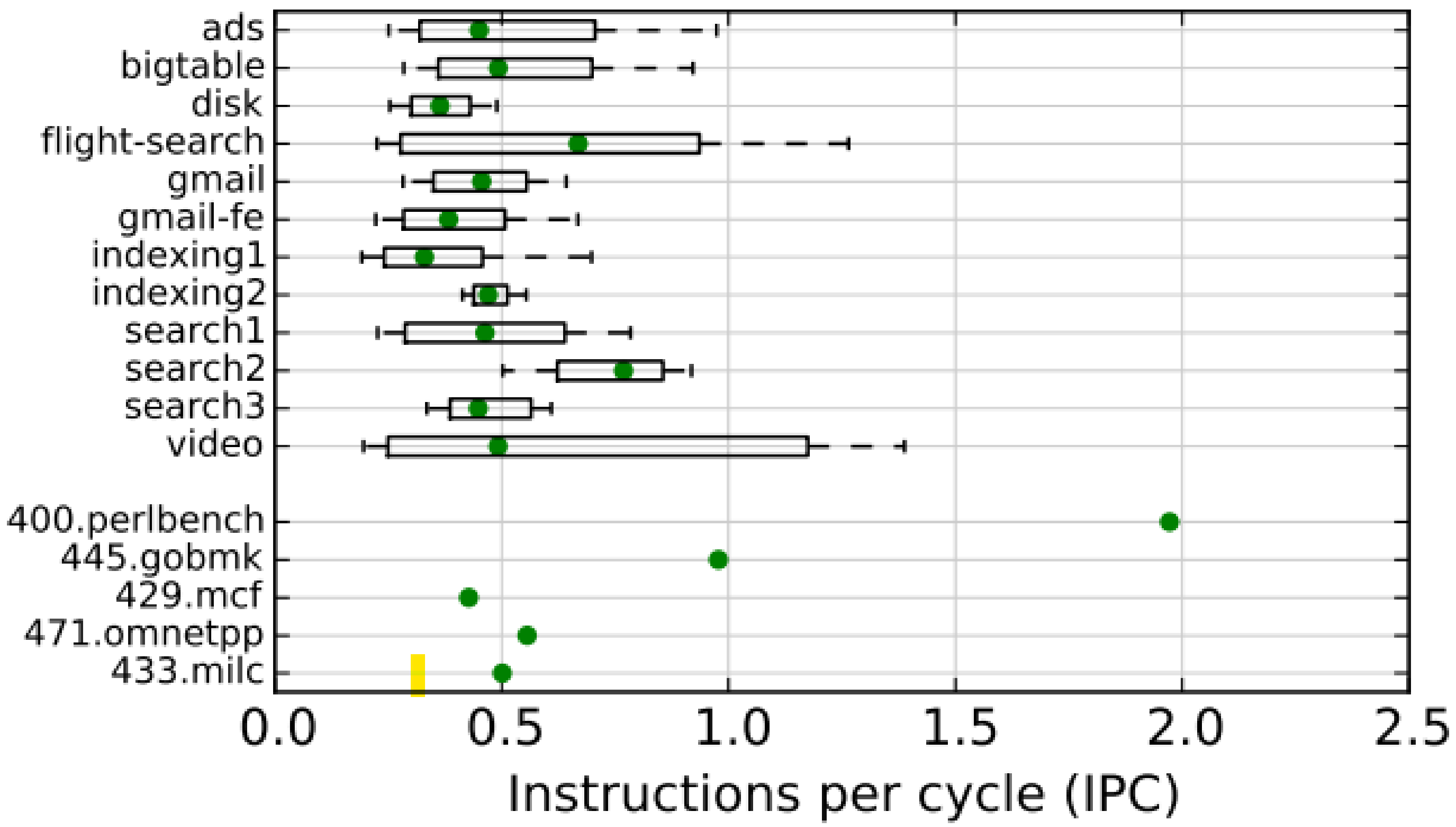


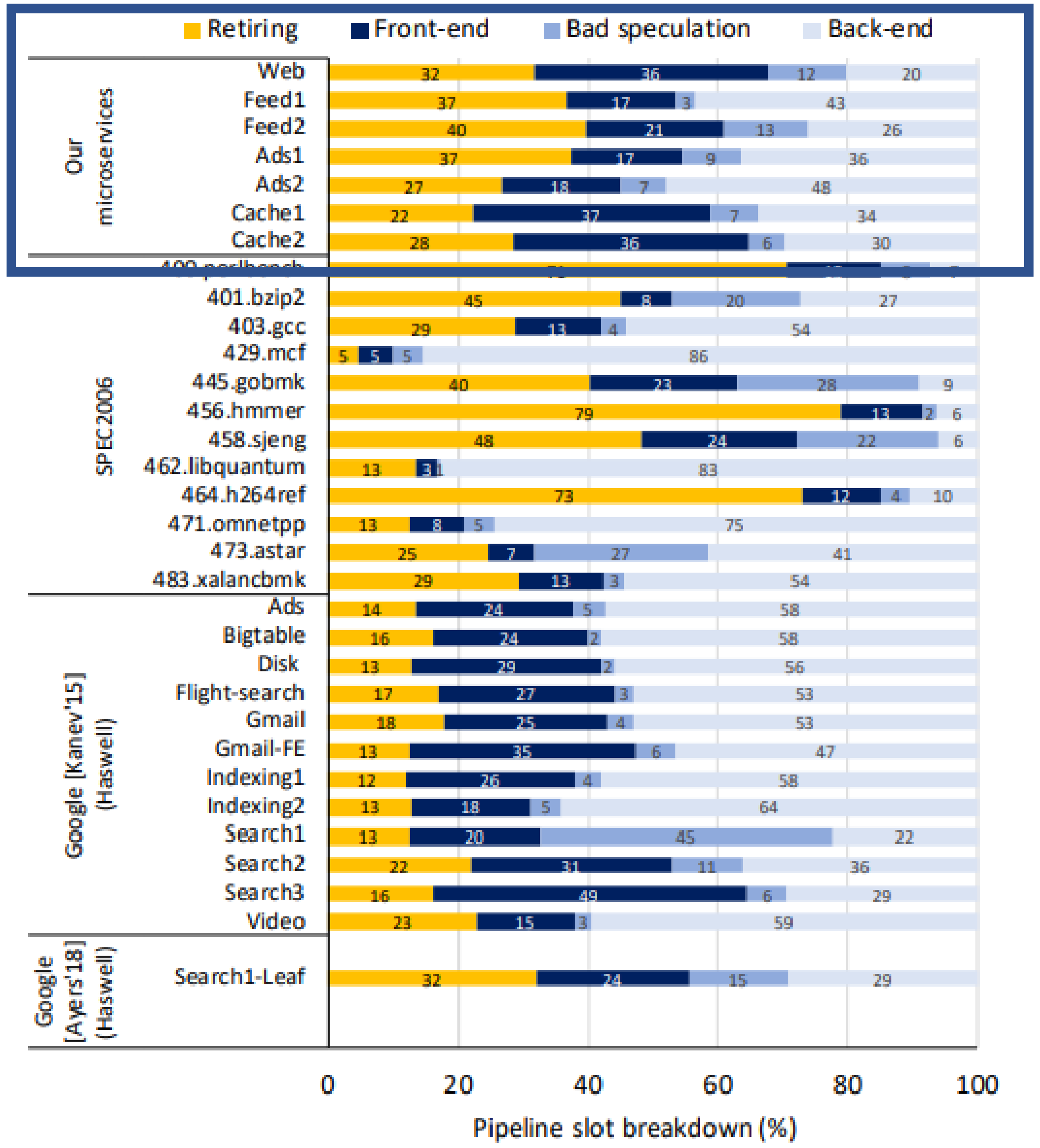
Figure 10: IPC is universally low.

IPC per thread = 0.5-1

Sriraman, Akshitha, et al. "Softsku: Optimizing server architectures for microservice diversity@ scale." ISCA 2019
Kanev, Svilen, et al. "Profiling a warehouse-scale computer." ISCA 2015

Low Retirement Rate in Data Center

Facebook (SMT is On)



Google (SMT is off)

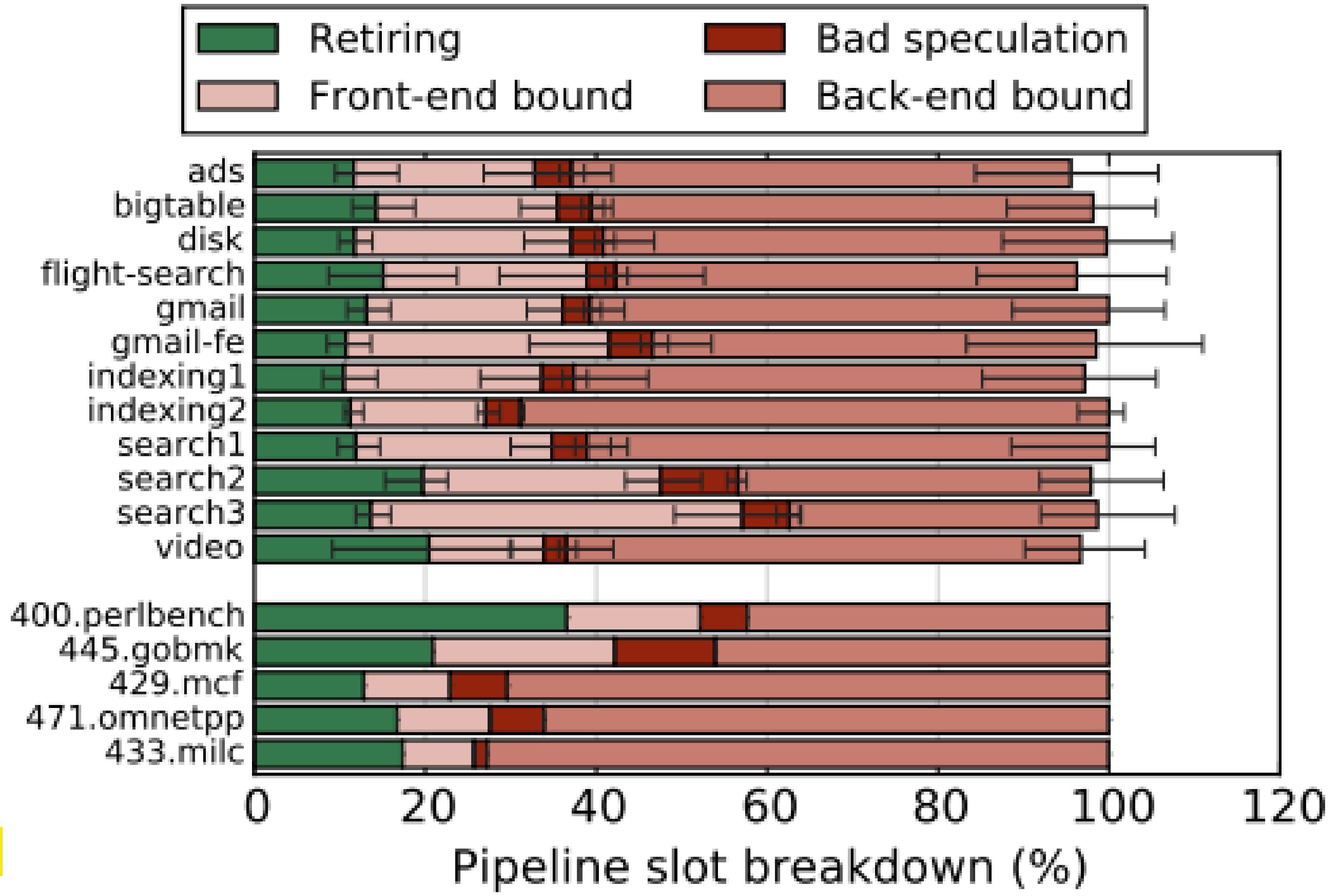
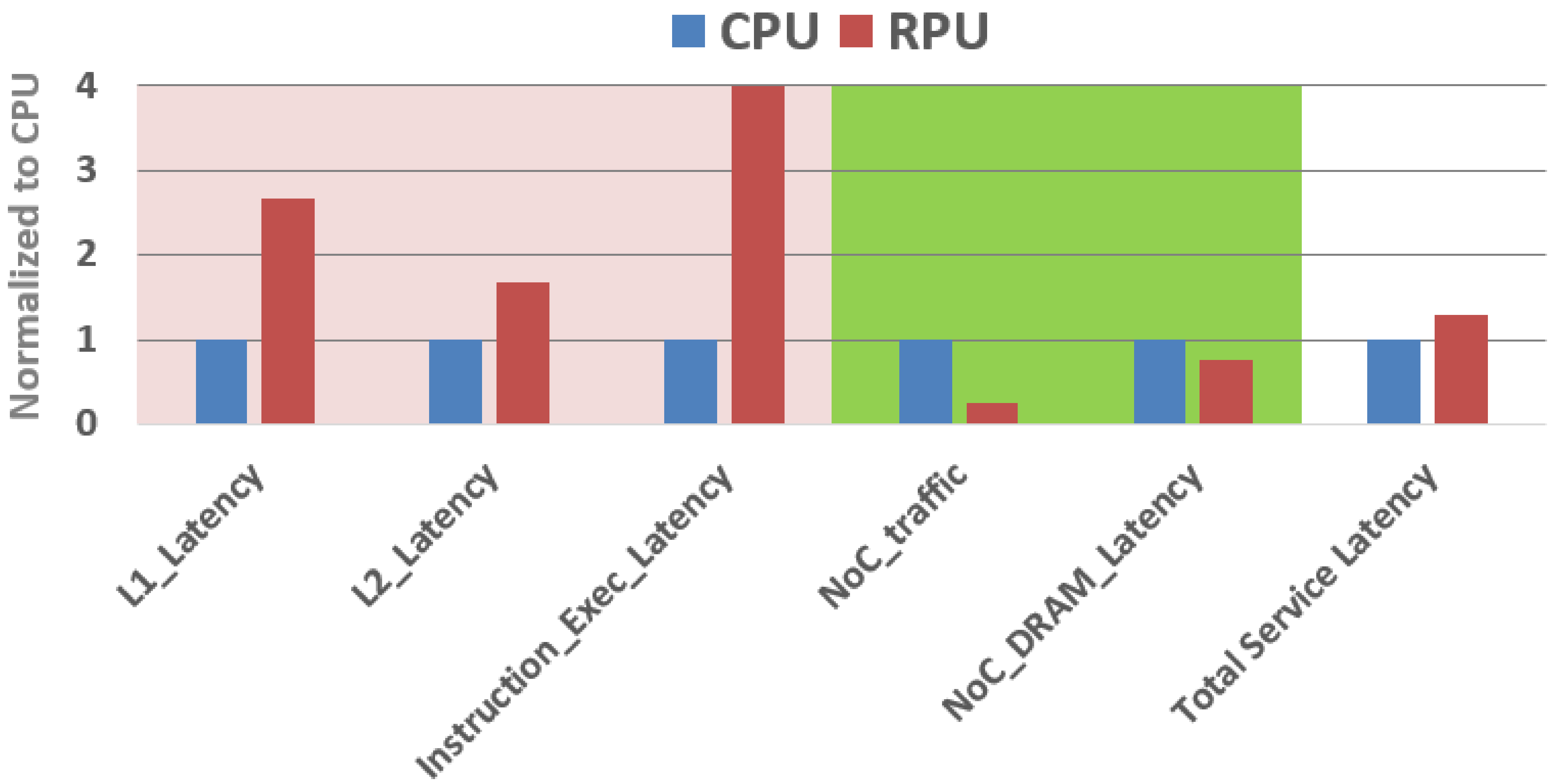


Figure 6: Top-level bottleneck breakdown. SPEC CPU2006 benchmarks do not exhibit the combination of low retirement rates and high front-end boundedness of WSC ones.

Retire rate = 10-25% per thread

Sriraman, Akshitha, et al. "Softsku: Optimizing server architectures for microservice diversity@ scale." ISCA 2019
Kanev, Svilen, et al. "Profiling a warehouse-scale computer." ISCA 2015

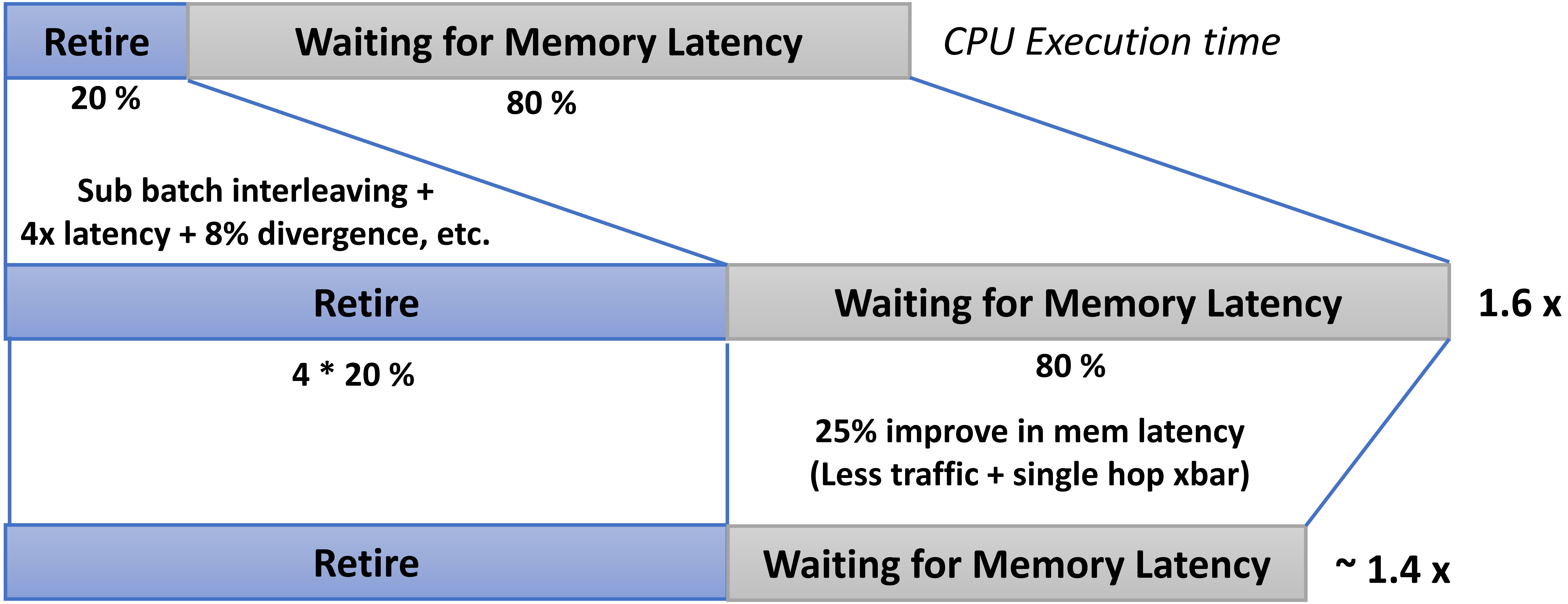
Memory Latency Improvement



Metrics that contribute to total service latency

→ Memory Latency improvement (due to less traffic and crossbar) helps to offset the latency increases in instructions and cache hits

High-Level Service Latency Analysis



Retire
Waiting for Memory Latency
CPU Execution time
20 %
80 %
Sub batch interleaving +
4x latency + 8% divergence, etc.
Retire
Waiting for Memory Latency
1.6 x
4 * 20 %
80 %
25% improve in mem latency
(Less traffic + single hop xbar)
Retire
Waiting for Memory Latency
~ 1.4 x

Concern: Weak consistency + NMCA model is hard to program in multi-threaded applications?

Answer: But, the data center workloads by nature does not need strong consistency model nor MCA

Weak Consistency + NMCA

- Important lesson learned from the GPU space:
  - Traditional coherence/consistency model (MOESI/TSO) does not efficiently scale beyond 100/1K threads
  - You need to relax your consistency model to continue thread scaling
- Good news: (key observations)

  (1) Data Center workloads rarely communicate and exhibit low locks, read-write sharing and overall low coherence traffic

  (2) Multiple copy atomicity (MCA) is not required by most of the data center applications. As <u>eventual consistency</u> is widely adopted

  - Example: For facebook, It is okay for a friend to see the post update before others

So, lets apply more-scalable weak consistency with non multi copy atomicity model (NMCA)

Ferdman, Michael, et al. "Clearing the clouds: a study of emerging scale-out workloads on modern hardware.“ ASPLOS 2012
Ayers, Grant, et al. "Memory hierarchy for web search." *HPCA 201*

RPU’s Consistency Model

- Weak Consistency + NMCA. What does this mean?
  - Private caches are only guaranteed to be coherent and consistent at barriers & fences
    - Move atomics to L3 cache → negligible performance impact as we have low locks
  - A simple, relaxed, directory-based coherence protocol with no-transient states or invalidation acknowledgments → only ack at barrier (see HMG [HPCA’20])
  - Multiple threads can share the same store queue per core

This relaxed memory model allows RPU to scale the number of threads efficiently, improving thread density by an order of magnitude

- Other good news: some CPU ISAs, like ARMv7 and IBM POWER, already support a weak consistency model with NMCA

Ren, Xiaowei, et al. "Hmg: Extending cache coherence protocols across modern hierarchical multi-gpu systems.“ HPCA 2020

Concern: RPU’s 5.7x energy efficiency is a big number? Be realistic!

Answer: There has been previous work showing that they can get 8x energy efficiency from vectorizing data parallel workloads, like PARSEC and Rodinia, on real HW CPUs (if the workload is SIMD-friendly). See next slide.

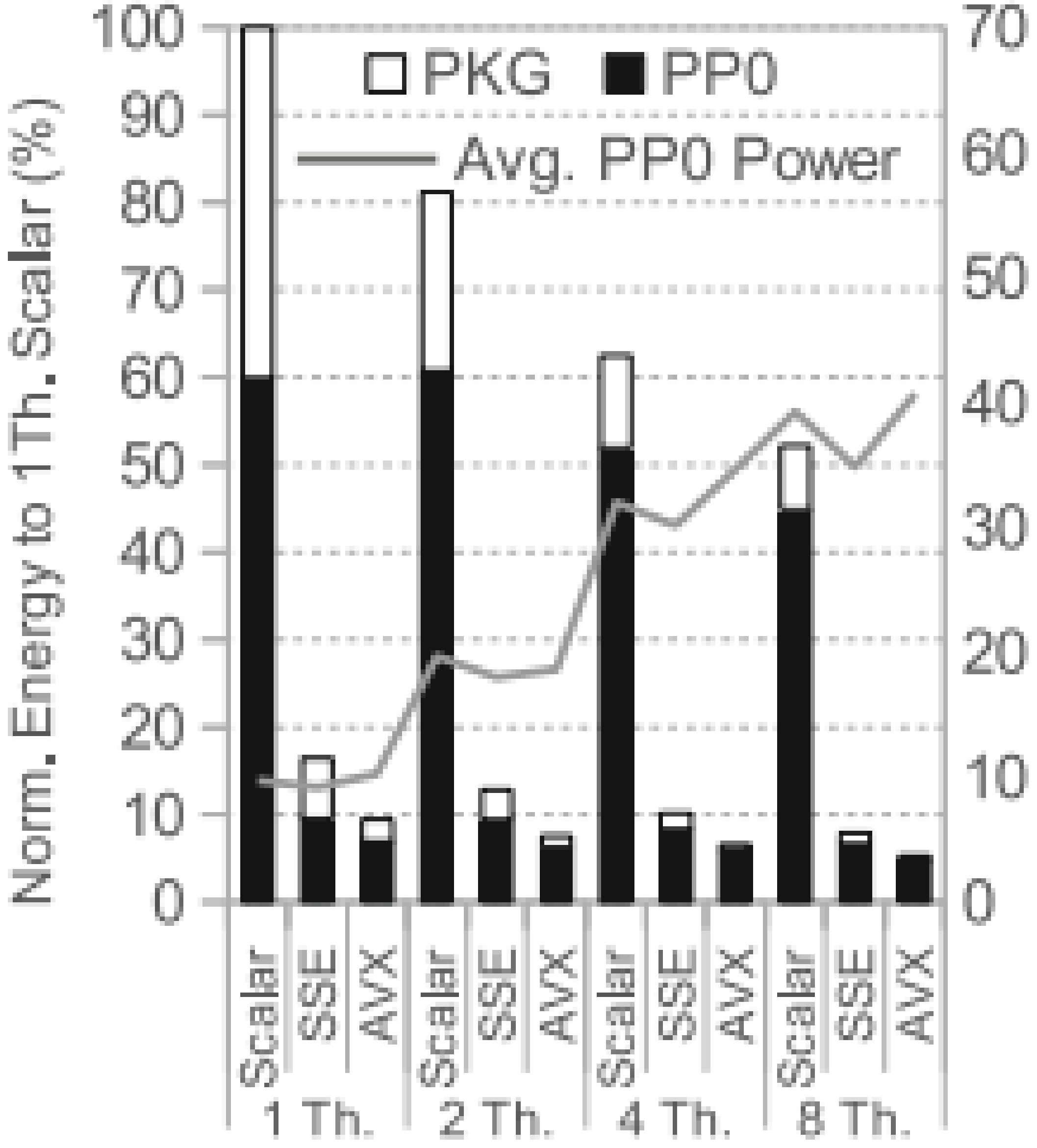
So, my question is: If we can get 8x energy efficiency from vectorizing data parallel workloads, why we cannot get similar energy efficiency from vectorizing microservices?! Since both have the same concept: amortize the frontend+OoO.

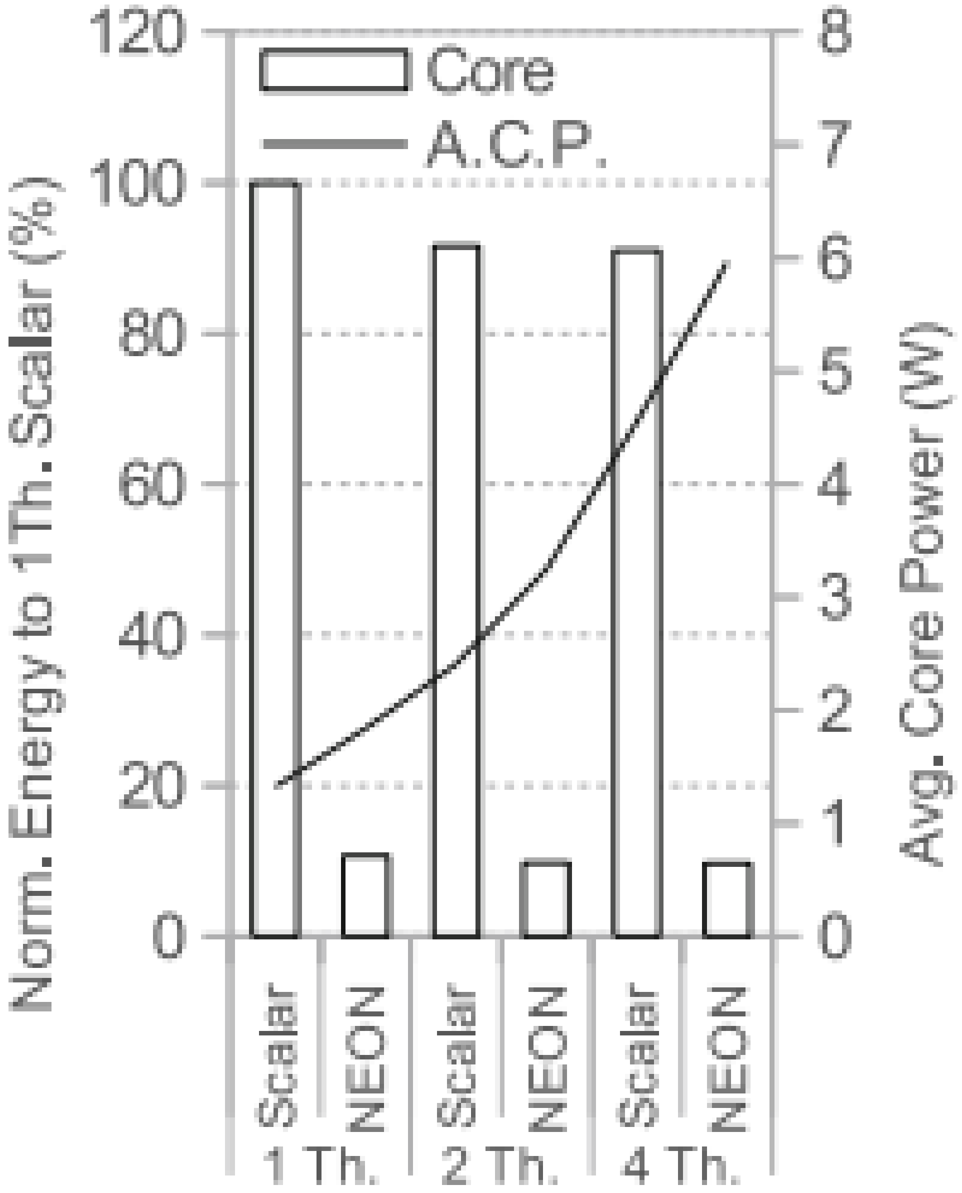
I showed that frontend+OoO in serial workloads are 75% and we can also amortize up to 15% of the memory and static energy, this increases our amortization factor to 90%, apply Amdahl's law, then up to 10x energy efficiency is achievable.

Cebrian, Juan M., Magnus Jahre, and Lasse Natvig. "ParVec: vectorizing the PARSEC benchmark suite." *Computing* 97.11 (2015): 1077-1100.

https://link.springer.com/content/pdf/10.1007/s00607-015-0444-y.pdf

Example: Vectorizing Blackscholes

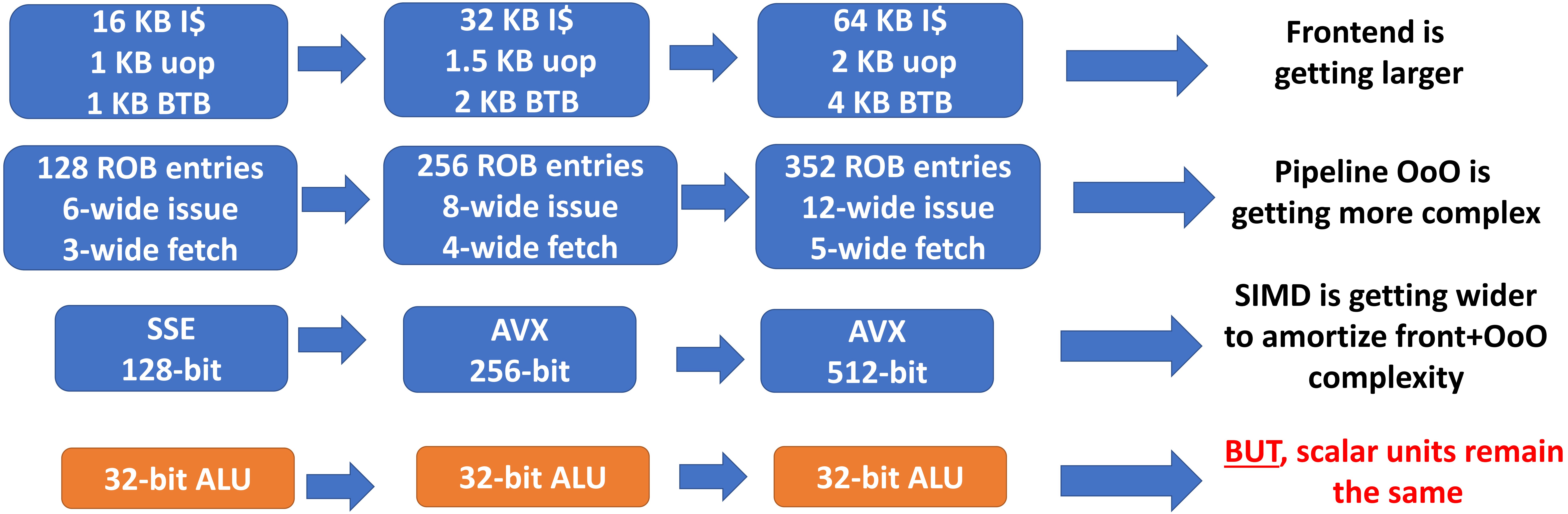




Up to 10x energy efficiency from vectorizing on real HW Intel and ARM CPUs

Cebrian, Juan M., Magnus Jahre, and Lasse Natvig. "ParVec: vectorizing the PARSEC benchmark suite." *Computing* 97.11 (2015): 1077-1100.

Frontend+OoO Overhead is Increasing



16 KB I$
1 KB uop
1 KB BTB

32 KB I$
1.5 KB uop
2 KB BTB

64 KB I$
2 KB uop
4 KB BTB

Frontend is getting larger

128 ROB entries
6-wide issue
3-wide fetch

256 ROB entries
8-wide issue
4-wide fetch

352 ROB entries
12-wide issue
5-wide fetch

Pipeline OoO is getting more complex

SSE
128-bit

AVX
256-bit

AVX
512-bit

SIMD is getting wider to amortize front+OoO complexity

32-bit ALU

32-bit ALU

32-bit ALU

BUT, scalar units remain the same

As we move forward, the frontend+OoO overhead is getting larger compared to the scalar units

Question: As you increase the core and caches size, the energy of cache access and data wiring will increase, the bigger the core the large energy you consume, how do you still get 5.7x energy after that?

Answer: We show in our paper that the dynamic energy per L1 access and L2 access in RPU is higher by a factor of 1.72x and 1.82x respectively than in CPU, due to the larger cache size. However, the generated traffic reduction and other energy savings in the frontend will outweigh this energy increase as detailed in our experimental results.

Energy Efficiency of CPU vs RPU

$$\frac{\boldsymbol{CPU\ Energy}}{\boldsymbol{RPU\ Energy}} = \frac{\boldsymbol{Execution\ Energy\ + Memory\ system\ Energy + Front\_OoO\ Energy +\ Static\ Energy}}{\boldsymbol{Execution\ Energy + \ (1-r)\ (Memory\ system\ Energy) + \frac{1}{n\ * eff}\ \underbrace{[\,Front\_OoO\ Energy +\ r * Memory\ system\ Energy + Static\ Energy]}\ + SIMT\_Overhead}}$$

Amortized factors = 50-90%

batch size (n) = 8-32

SIMT Efficiency=92%

Larger L1/L2 Caches, etc.

→At high SIMT efficiency, the energy savings from the amortized metrics greatly outweigh the SIMT management overhead

Concern: Do you batch on TCP/IP processing? Batching on TCP/IP will cause a negative interaction with TCP congestion avoidance protocol, hurting network RTT and throughput?

To mitigate this issue, we can bypass batching on the web server (or at least its TCP/IP processing) to send acknowledgments to the end users as soon as possible. However, we assume TCP/IP batching after that as the data center provider has full control of the network stack within the data center so they can tune/adapt the TCP congestion protocol parameters (timeout and congestion window) along with the batching timeout/size to ensure there is no negative effect on the network throughput. We did not study this in detail as it is beyond the scope of the paper. We leave this study for future work.

Other solution: we can apply batching on network traffic too. So, the RPU driver SW (with or without HW support) can detect if all the requests are sent to the same microservice in the graph (i.e., same server IP/socket). If so, send only one network request. See the below patent: https://patentimages.storage.googleapis.com/69/ee/89/f8fc1838fefeed/US20220050707A1.pdf

Concern: Large paper scope, superficial discussion and evaluation? Many details are missing, especially at system-scale?

Answer: We agree that the scope of the paper is large. We believe that the paper opens up a wide number of interesting research directions in a relatively unexplored space. However, to prove that the space is worth exploring, an initial paper must detail a feasible full-system solution, where each technical contribution is afforded less space for discussion.

Concern: Why SMT_8 shows poor performance and exhibit high latency in your results (5x higher than single thread performance)?

Answer: Recall, SMT works very well when the threads exhibit dissimilarity during execution. For example, one thread is compute bound and the other is memory-bound. In our evaluation, all the threads are running the same program/microservice (SPMD), so dissimilarity is very rare. Even more, we launch the threads at the same time making dissimilarity is even harder to exist.

In recent study from Google about in-production search service (ref is below), they show that enabling SMT_2 on Intel Haswell CPU has led to barely 1.37x higher throughput (QPS), which indicates service latency has increased by 1.45x. Scale this number to SMT_8 (8 threads), then service latency is expected to increase to 4.4x for SMT_8, close to the number that I have in the paper. In fact, IBM POWER SMT_8 scales better but I do not have enough details about IBM architecture.

Ayers, Grant, et al. "Memory hierarchy for web search." *HPCA 2018*

Question: In figure 11, why did select 75 batches (2400 requests) for per-argument batching? This number looks weird.

Answer: We select this number based on the following assumptions:
Assume an online search service with 120 ms latency and receive about 100K QPS (see refs below)
Now, assume a batch overhead is 20% (close to previous work assuming batching for power management)

So, batching window = 0.2 * 120 ms = 24 ms
100K QPS means 100 reqs per 1 ms
So reqs received per batching window = 24 * 100 = 2400 reqs

https://www.barroso.org/publications/TheTailAtScale.pdf
https://www.oberlo.com/blog/google-search-statistics#:~:text=But%20how%20many%20is%20that,searches%20per%20year%20have%20progressed.

Question: Why did you use Accel-Sim not gem5? Where did you get your CPU configuration from. Your CPU configuration looks impractical?

Answer: We select the simulation tools that we are familiar and more productive with. In academia, the researcher is free to select his own simulation infrastructure. After all, the industry does not trust open-source simulators.

We configure our CPU to be similar to previous work and close enough to industrial designs.

Question: The rise of serverless computing has made multi-process and containerized-based microservices more commo. How do you handle multi-process services in this case?

Answer: In multi-process services, the separate virtual address spaces can cause both control flow and memory divergence. We believe that with user-orchestrated inter-process data sharing and some modifications to the RPU's virtual memory these effects can be mitigated. However, since the contemporary services we study are all multi-threaded, we leave such a study as future work.

Concern: Security Implications? The grouping of concurrent requests for SIMT execution may enable new vulnerabilities

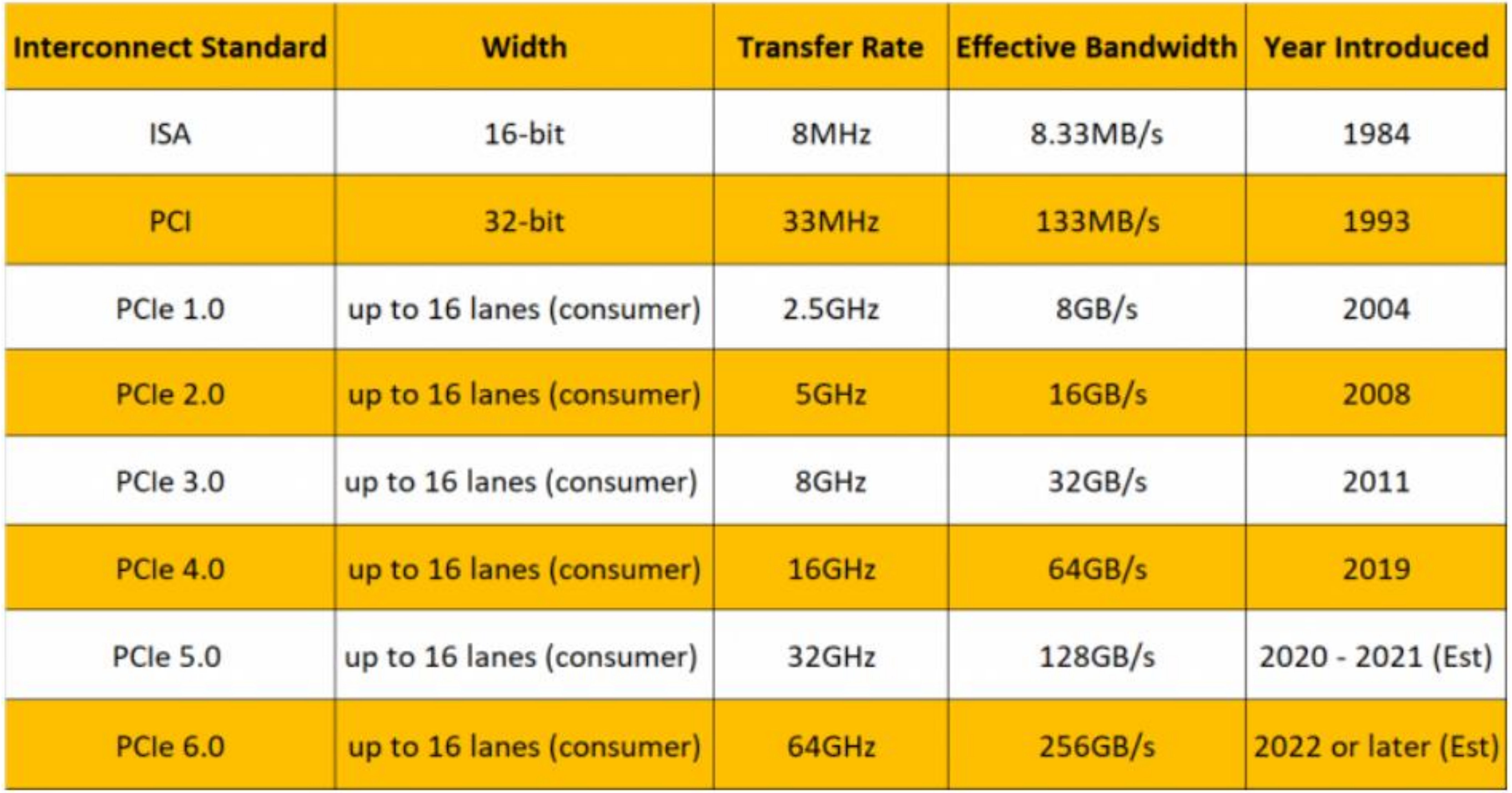
Answer: Two security breaches may exist:
(1) a malicious user may generate a very long query that could affect the QoS of other short requests. Such attacks can be mitigated in our input size-aware batching software by detecting and isolating maliciously long requests. If this does not work, our run-time batch split technique can be used as needed

(2) Another security vulnerability is the potential for parallel threads to access each other's stack data (exploiting the fact that threads' stack data are adjacent in the physical space). However, as described in Section III-B2, the RPU's address generation unit is able to identify inter-thread stack accesses and throw an exception if such sharing is not permitted.

Pitfall: The RPU can be bottlenecked by I/O throughput

Answer: we demonstrate that the off-chip memory bandwidth will dramatically scale in future years with the introduction of DRR5, DDR6, and HBM in the data center. We observe similar trends for I/O standards like PCIe5 and PCIe6 [137]. 128x PCIe6 lanes per single socket can provide 2 TB/sec of bidirectional I/O bandwidth. Ethernet 400/800 Gb/sec and recent NVMe interface advances will enable substantial network and storage throughput improvements.

PCIe I/O Scaling



Interconnect Standard	Width	Transfer Rate	Effective Bandwidth	Year Introduced
ISA	16-bit	8MHz	8.33MB/s	1984
PCI	32-bit	33MHz	133MB/s	1993
PCIe 1.0	up to 16 lanes (consumer)	2.5GHz	8GB/s	2004
PCIe 2.0	up to 16 lanes (consumer)	5GHz	16GB/s	2008
PCIe 3.0	up to 16 lanes (consumer)	8GHz	32GB/s	2011
PCIe 4.0	up to 16 lanes (consumer)	16GHz	64GB/s	2019
PCIe 5.0	up to 16 lanes (consumer)	32GHz	128GB/s	2020 - 2021 (Est)
PCIe 6.0	up to 16 lanes (consumer)	64GHz	256GB/s	2022 or later (Est)

https://www.extremetech.com/computing/293451-pci-express-6-0-with-256gb-s-coming-in-2022

Pitfall: SIMR requires a lot of changes

Answer: We design the SIMR system so that the SW stack changes are as minimal as possible. Only the HTTP server, HW and some OS system calls are required to change in the software stack while we keep the programming interface, compiler, runtime, and ISA unaltered. In fact, data center providers adopted DL accelerators [9], [46] and changed the entire software stack for similar outcomes and efficiency.

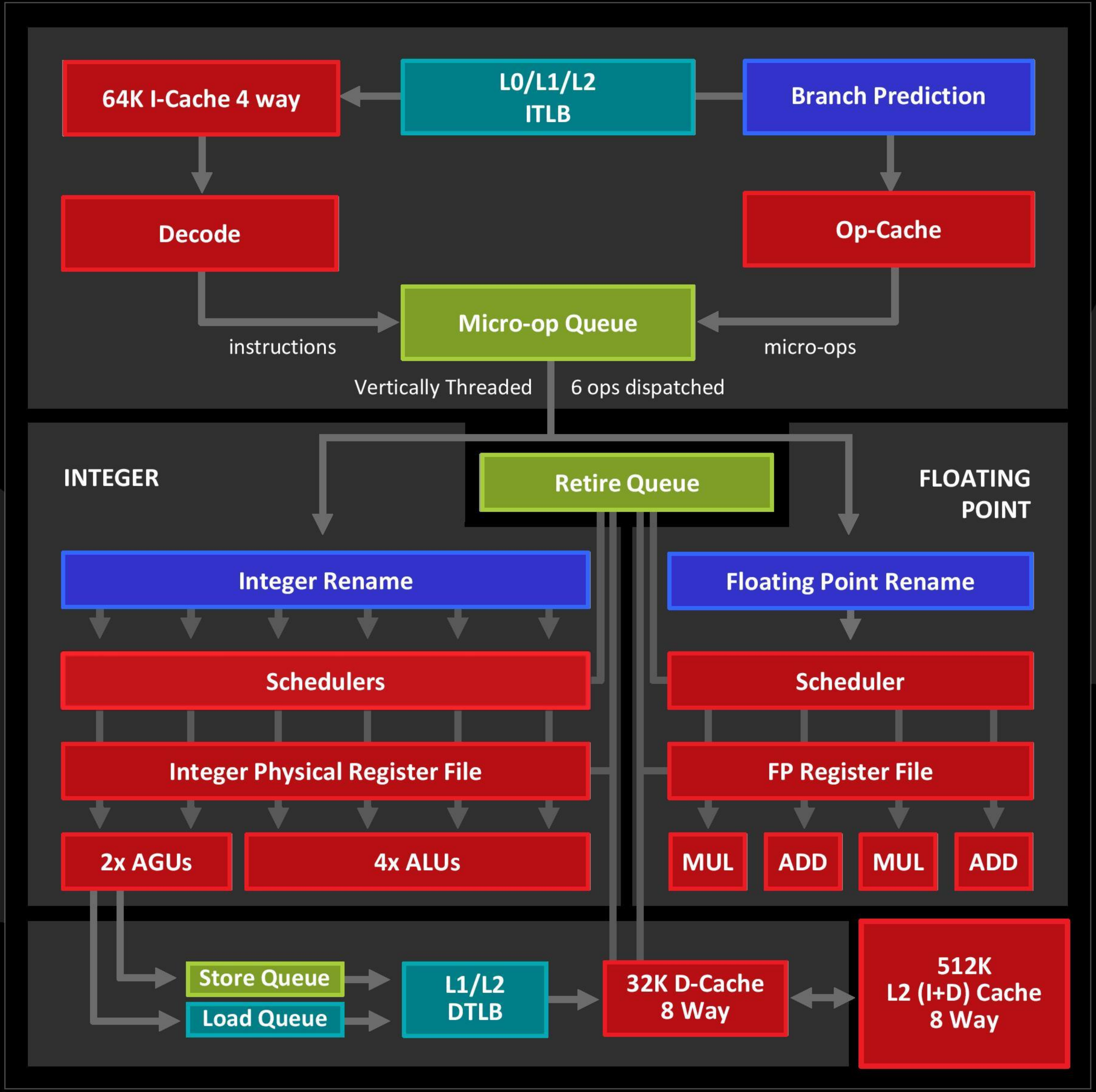
Question: SIMT vs SMT vs SIMD

Answer: In SMT, the entire CPU pipeline is partitioned among the simultaneous threads. Threads on the same core are executed independently, which fails to exploit thread similarity and increases single thread latency. SIMT avoids all of these issues exploiting the fact that threads are running the same instruction stream and allocate the entire pipeline resources for the same task.

In SIMD, It is up to the programmer/compiler to express the data parallelism in SIMD vector ISA. However, in SIMT, the programmer can still write the programs in scalar ISA and the HW will detect convergence opportunities and handle control and memory divergence transparently.

See next slides.

https://yosefk.com/blog/simd-simt-smt-parallelism-in-nvidia-gpus.html



SMT OVERVIEW

- All structures fully available in 1T mode
- Front End Queues are round robin with priority overrides
- Increased throughput from SMT

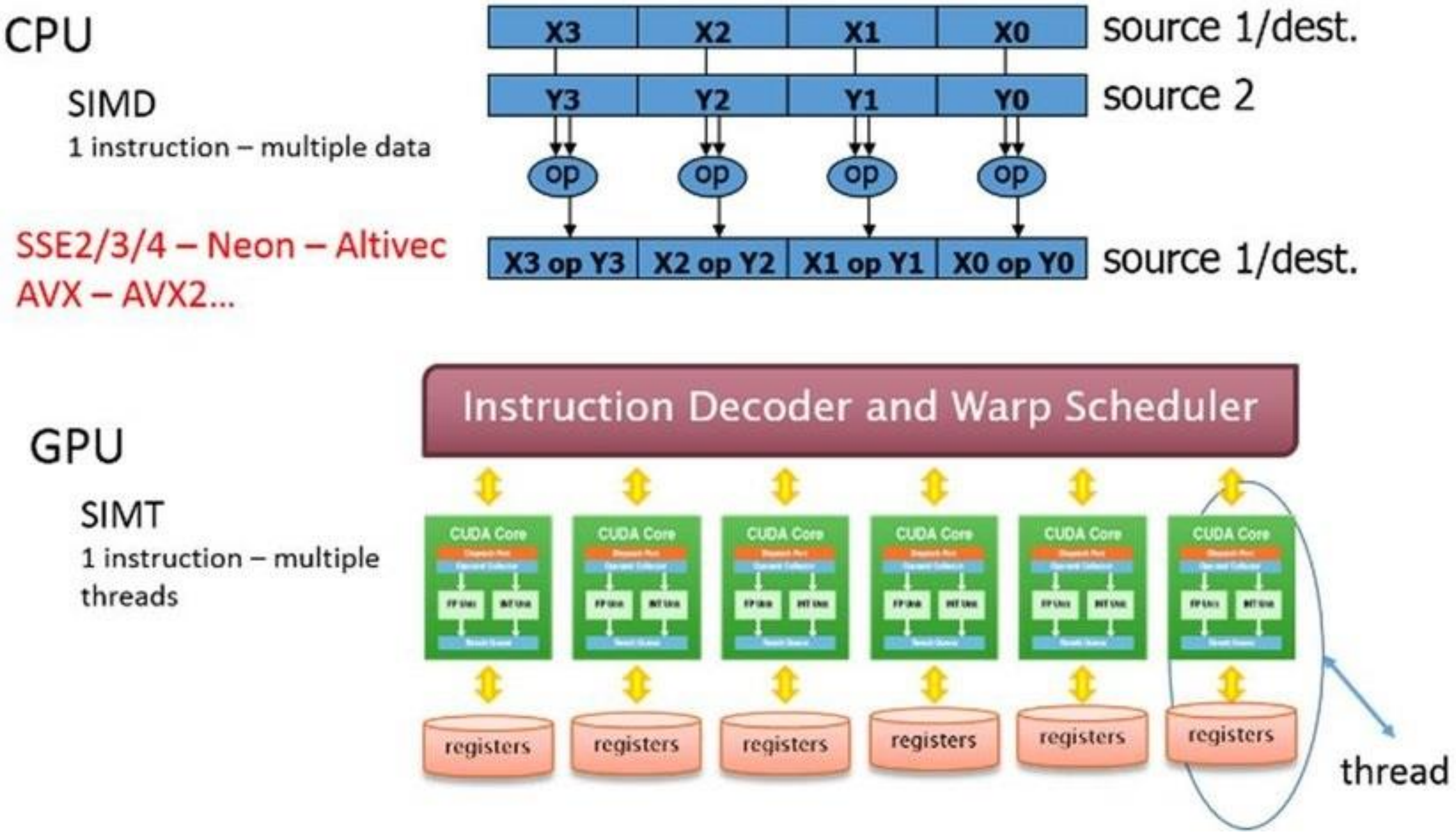
🟥 Competitively shared structures

🟦 Competitively shared and SMT Tagged

🟦 Competitively shared with Algorithmic Priority

🟩 Statically Partitioned

SIMD vs SIMT



CPU

SIMD
1 instruction – multiple data

SSE2/3/4 – Neon – Altivec
AVX – AVX2...

GPU

SIMT
1 instruction – multiple threads

Thank You!

If you do not find your question here, feel free to contact us.