Attack of the Killer Microseconds and The Tail at Scale

Yang Zhou

Sep 25, 2025

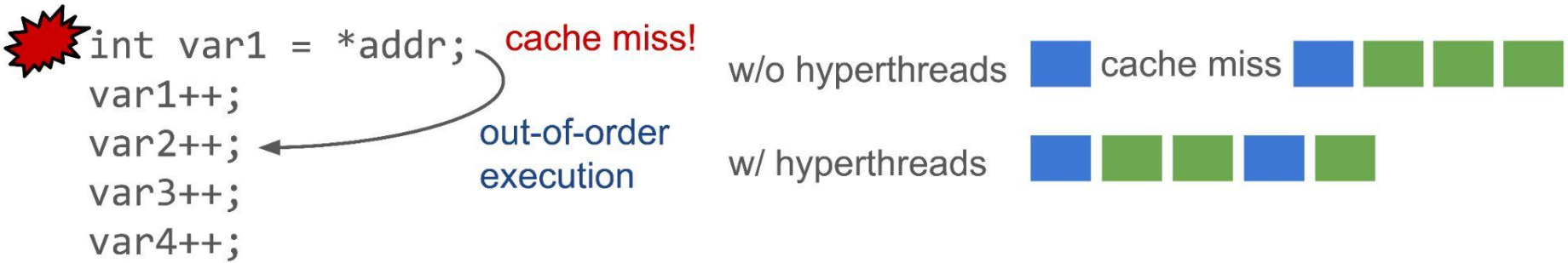
With slides from Prof. Amanda Raybuck last-year offering

Latency numbers every programmer should know

L1 Cache Reference	0.5 ns			
Branch Mispredict	5 ns			
L2 Cache Reference	7 ns			14x L1 cache
Mutex Lock/Unlock	25 ns			
Main Memory Reference	100 ns			20x L2 cache, 200x L1 cache
Compress 1K Bytes with Zippy	3,000 ns	3 µs		
Send 1K Bytes over 1 Gbps Network	10,000 ns	10 µs		
Read 4K Randomly from an SSD	150,000 ns	150 µs		~1GB/s SSD
Read 1MB Sequentially from Memory	250,000 ns	250 µs		
Round Trip within Same Datacenter	500,000 ns	500 µs		
Read 1MB Sequentially from SSD	1,000,000 ns	1,000 µs	1 ms	~1GB/s SSD, 4X memory
Disk Seek	10,000,000 ns	10,000 µs	10 ms	20x datacenter roundtrip
Read 1MB Sequentially from Disk	20,000,000 ns	20,000 µs	20 ms	80x memory, 20x SSD
Send Packet CA->Netherlands->CA	150,000,000 ns	150,000 µs	150 ms	

Handling nanosecond-scale events

- Hardware can efficiently handle nanosecond-scale events (e.g., cache misses, ~100 ns)
  - Out of order execution,
  - Hyperthreads, Simultaneous Multithreading (SMT)
  - Prefetching
- Programmers don't have to think about this



Handling millisecond-scale events

- Millisecond-scale events
  - Disk reads – 10s of ms
  - Wide-area network traffic – 10s of ms
  - Low-end flash – a few ms
- Software can efficiently mask these
  - OS can context switch to a different thread (microseconds)
- Programmers can use convenient synchronous (blocking) programming models

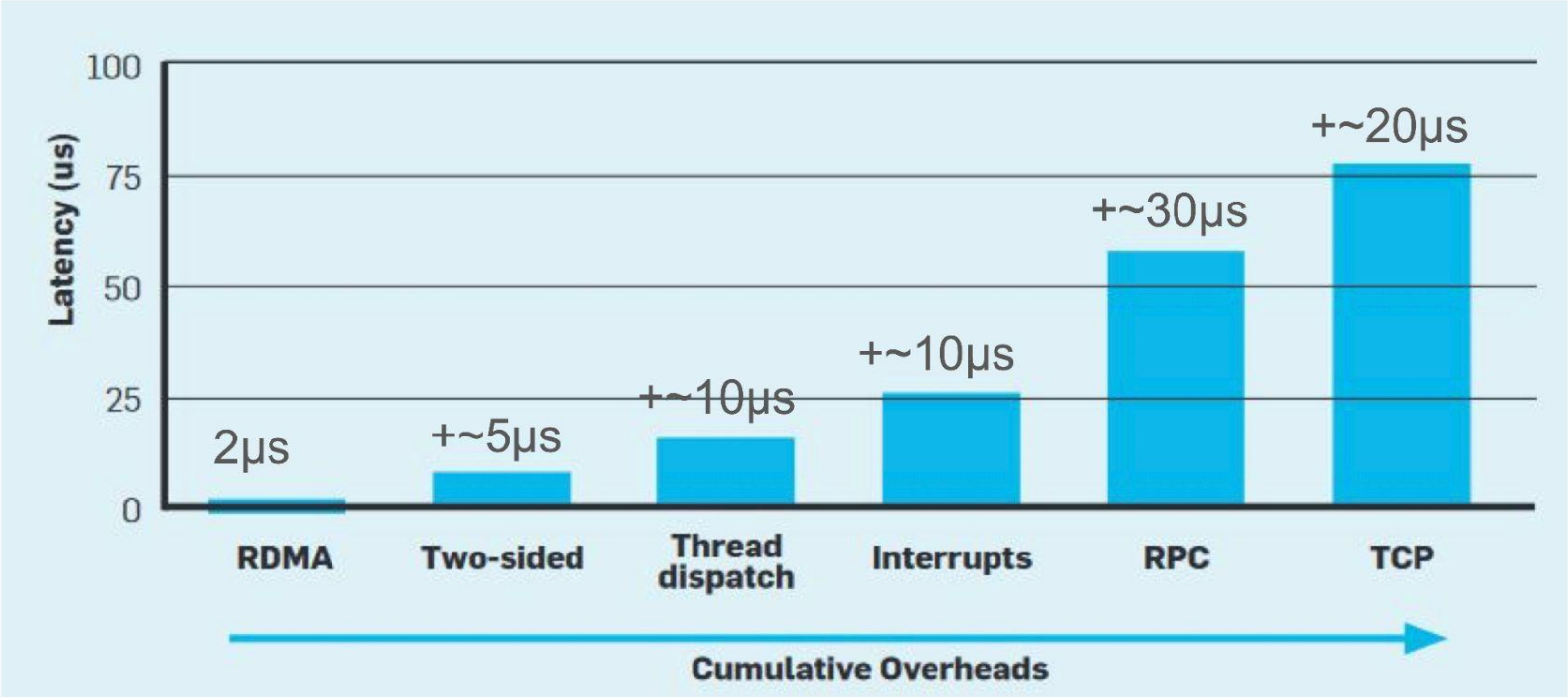
The challenges of microsecond-scale events

- But microsecond-scale events remain challenging
  - Datacenter RTT - a few µs
  - High-end flash – tens of µs
  - GPU/accelerator - tens of µs
- Hardware techniques do not scale well
  - Not enough independent instructions to fill pipelines for µs
  - Not enough hyperthreads to hide µs
- Software techniques have too high of overhead
  - Context switch time dominates microsecond-scale events
  - These are the killer microseconds!

Can asynchronous programming models help?

- Asynchronous model: program sends a request to a device
  - Continues to run other tasks while waiting
  - Must periodically poll or use interrupts to figure out when request is complete
- Can be complex to implement at scale
  - Case study: Google datacenter applications with multiple interacting systems in multiple languages touched by thousands of devs
  - Changing a Google DC app from an async to sync model resulted in:
    - Improved performance
    - Simpler and easier to understand code

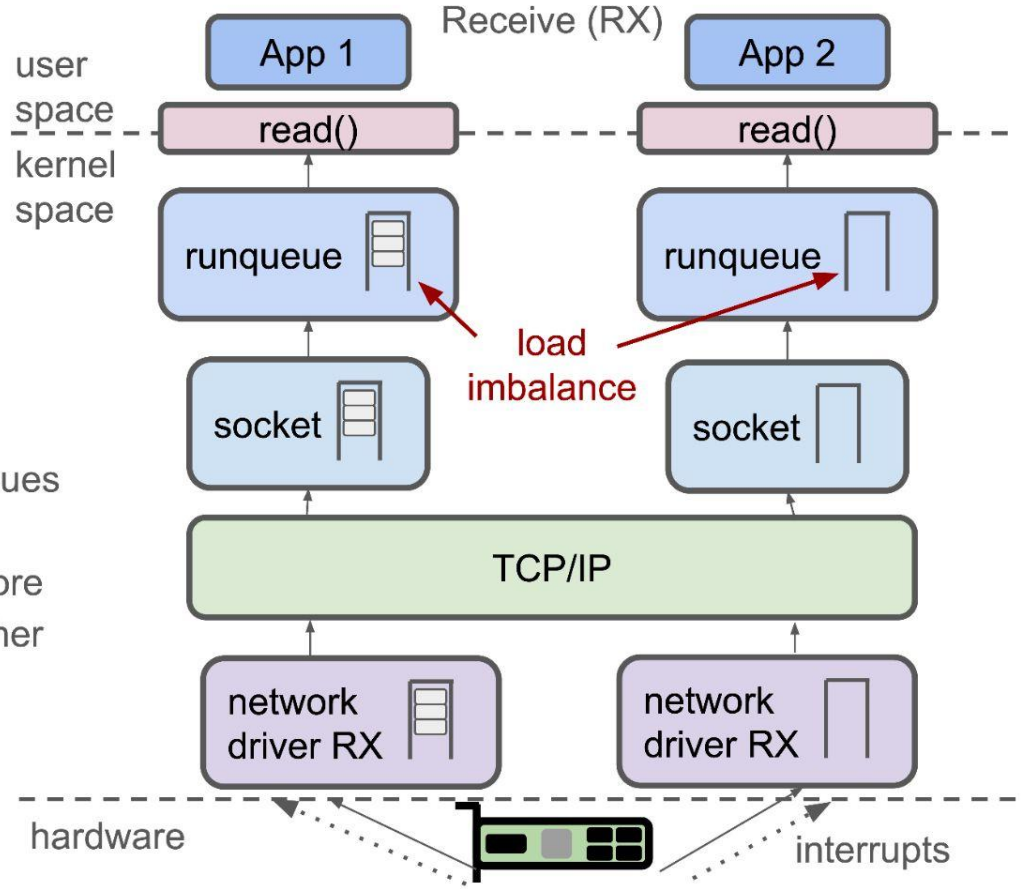
How to waste a fancy, expensive NIC



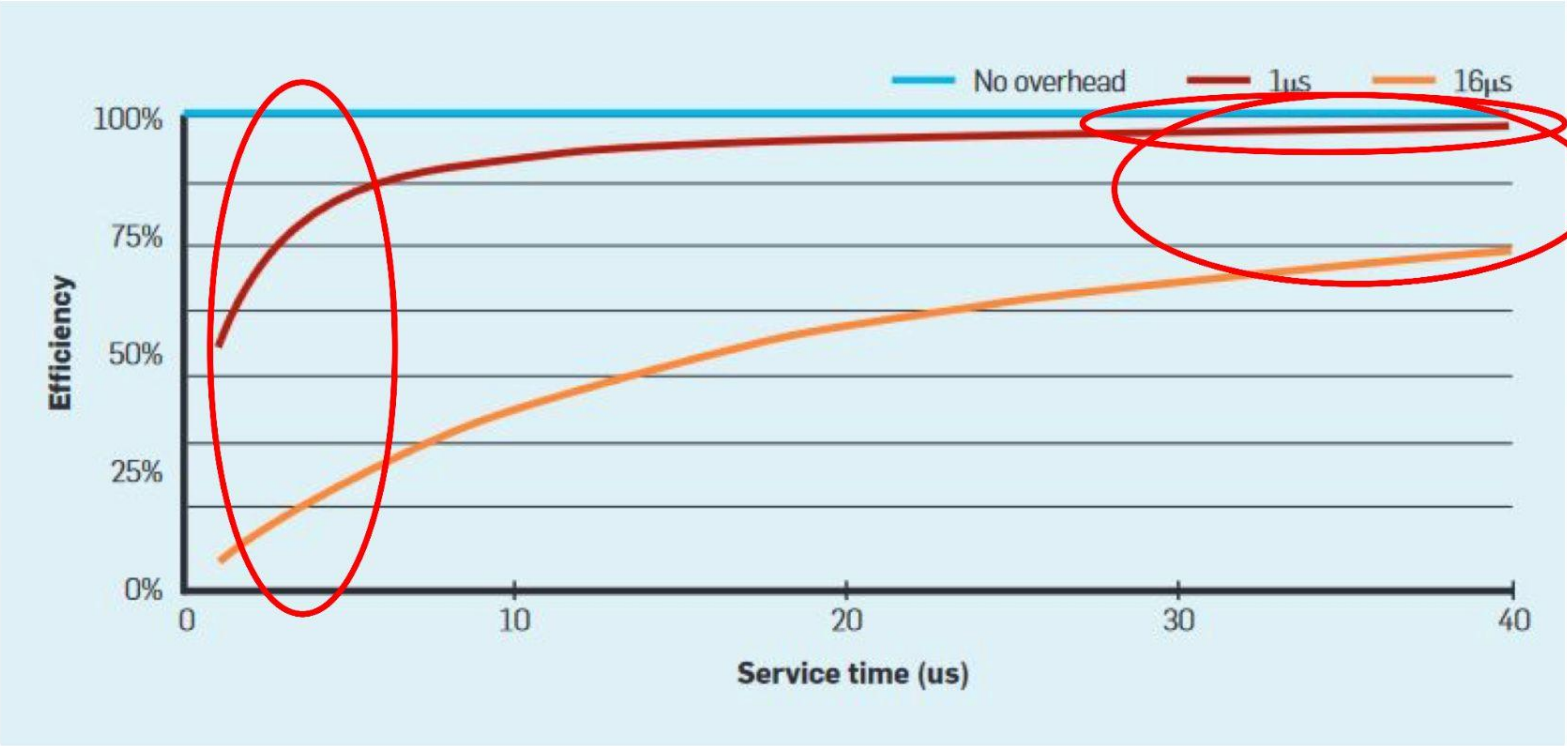
How does the OS add so much overhead?

Focus on the receive path

- Multicore example
- Sources of overhead:
  - Context switches
  - Lots of queueing
  - Copies
  - Load imbalance (balances runqueues every 4 ms)
  - Packets can arrive at the wrong core
  - Applications can interrupt each other



Does this really matter?



Yet another source of overhead

- **“Datacenter Tax”**: Tasks that result in computation that must span machines
  - Serialization/Deserialization of data
  - Memory allocation and deallocation
  - Network stack costs
  - Compression
  - Encryption
- Between 20-25% of processor cycles are spent on these tasks

OK, so what do we do?

- Offload to dedicated accelerators?
  - IO tends to be fine-grained, closely coupled with main work at single-digit us latencies
- Look to HPC world
  - But techniques are not directly applicable to WSCs – different workloads, smaller dev teams
  - Focus on pure performance vs. performance-per-TCO
- “Microsecond aware” systems stacks
  - Reduce lock contention & synch, low overhead interrupts, better scheduling, HW offload
- New HW optimizations for sync blocking, thread level parallelism, context switches, pending IO handling, queue management, scheduling
  - Better cache awareness, QoS support

Another problem for datacenters: Tail latency

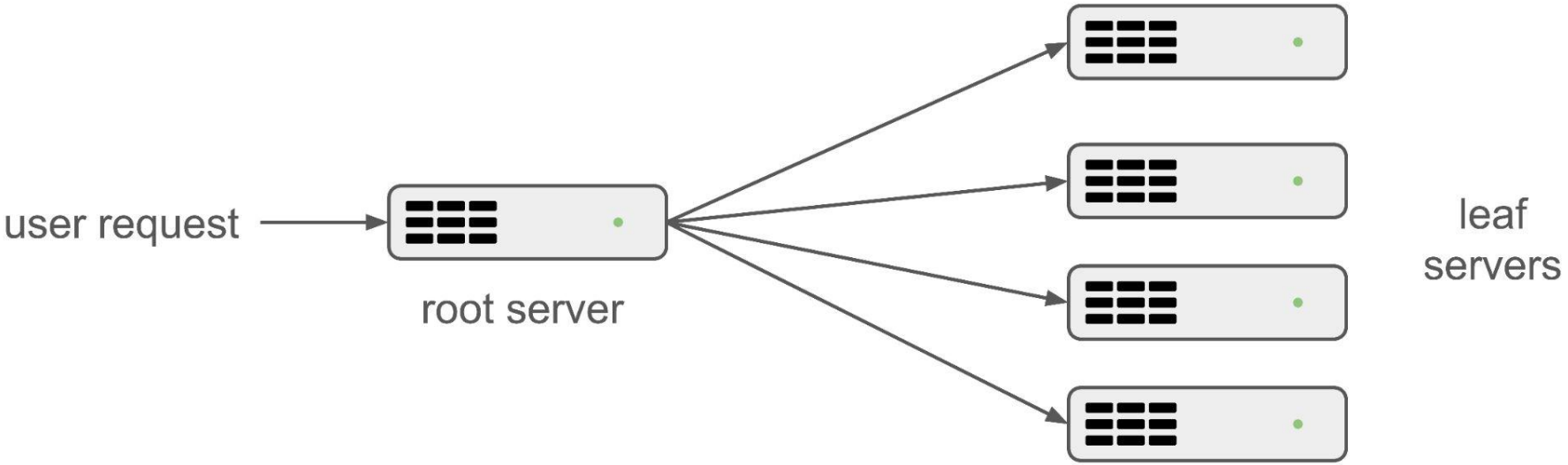
- Datacenter applications should appear fast and interactive
  - E.g., search auto-completion, snappy search results
- Temporary high latency episodes can degrade responsiveness at large scale
- Rare spikes in latency can affect a significant portion of requests
  - Why/how?

What causes latency variability?

- Shared resources leading to contention
  - And global resource sharing (e.g., network switches, shared FS)
- Background daemons and maintenance activities (e.g., garbage collection)
- Queueing at many layers
- Power limits and energy management

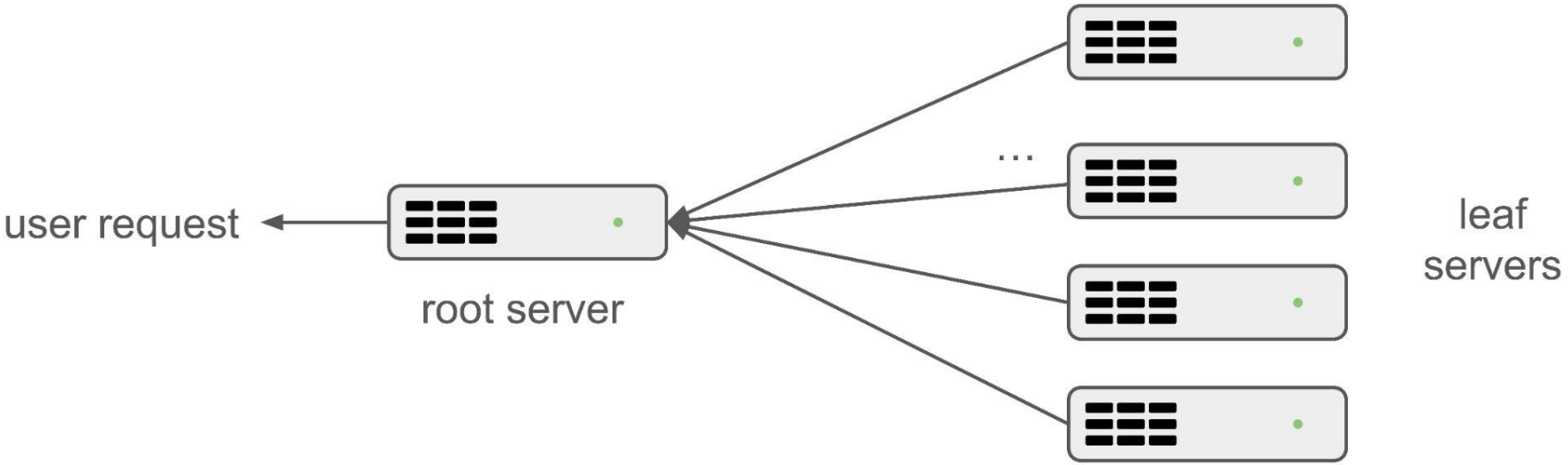
Parallelization to reduce latency

- Break a user request into parallelizable sub-operations
- Fan out requests from root server to leaf servers
- Leaf servers perform task, respond back to root server



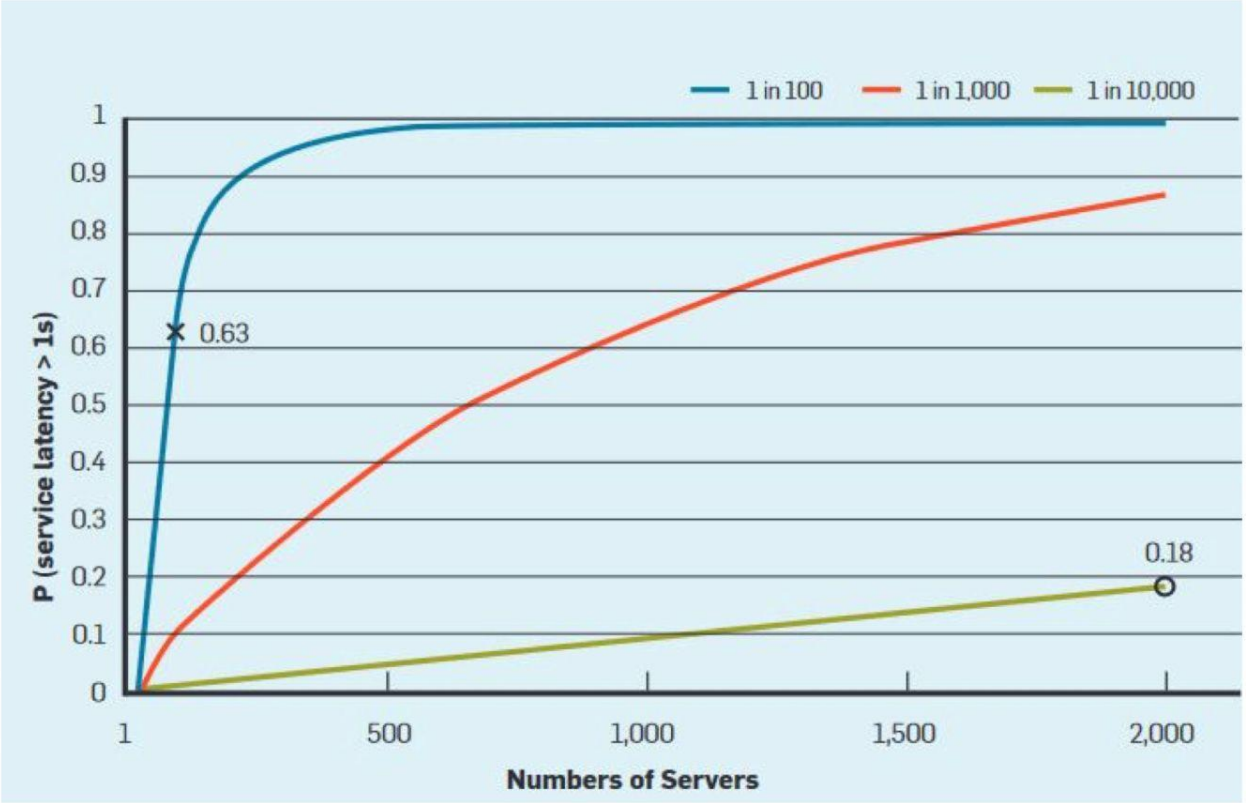
Parallelization to reduce latency

- Break a user request into parallelizable sub-operations
- Fan out requests from root server to leaf servers
- Leaf servers perform task, respond back to root server



Effects of latency variability

- Large fanouts exacerbate degraded latency from slow servers
- Significant lower perf for a large portion of user requests



How to reduce latency variability

- Separate service classes
  - Separate latency-critical tasks from latency-insensitive/batch tasks
- Reduce head-of-line blocking
  - Break longer requests into shorter requests, time-slice between them
- Manage background activity
  - Careful scheduling of background tasks to reduce interference
- But it’s infeasible to eliminate all sources of latency variability…

Short term adaptations to latency variability

- Take advantage of techniques from fault tolerance (e.g., replication)
- **Hedged requests:** Send out request to multiple servers, use first reply
  - Cancel outstanding requests once first result is received
  - What if multiple servers execute the same request simultaneously & unnecessarily?
  - Must be careful to avoid adding unacceptable extra load – be smart at sending 2nd request
- **Tied requests:** A main source of latency in lagged requests is queueing
  - Allow a client to choose a server based on queue lengths
  - Enqueue copies of a request at multiple servers simultaneously, allow servers to communicate status to one another
  - What about message delays?

Longer term adaptations to latency variability

- Deal with coarser-grained phenomena like load imbalance, service variation
- **Micropartitions:** # partitions >> # machines
  - Dynamic assignment and load balance of partitions among machines – finer grained
- **Selective replication:** More replication for popular items
  - Spread the load among more replicas
- **Latency-induced Probation:** Don’t send requests to slow machines
  - Keep probing machine to figure out when it is no longer suffering from slowdowns

Other considerations

- Large information retrieval
  - “Good enough” results: Don’t wait for every last response, send reply when enough have responded to achieve a “good enough” result
  - Canary queries: Don’t send a potentially dangerous query to everyone at the same time. Send to one and observe behavior; if safe, send to everyone else
- Mutations
  - Latency variation in state updates is usually not much of a concern
  - Updates are infrequent, off the critical path, and already latency tolerant
- Hardware trends
  - Hardware variability is likely to increase
  - Device heterogeneity and increasing scale make software tolerance even more important
  - Better hardware can also make latency tolerance cheaper

Performance in datacenters is hard

- Faster hardware increases the importance of low-overhead techniques
  - We don’t want software wasting our fancy new hardware
  - Need to redesign software stacks with microsecond-scale in mind
- Latency variation can lead to unacceptable violations in performance
  - Fan-out techniques common in datacenters exacerbate this
  - Can take advantage of smart techniques to make applications latency tolerant