An OS for the Data Center

- Server I/O performance matters
  - Key-value stores, web & file servers, lock managers, …
- **Can we … are?**
- Example …

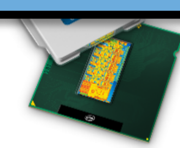
Today's I/O devices are fast

Intel X520
10G NIC
2 us / 1KB packet

\+

Intel RS3 RAID
1GB flash-backed cache
25 us / 1KB write

\+



Sandy Bridge CPU
6 cores, 2.2 GHz

= **$1,200**

Can’t we just use Linux?

Linux I/O Performance

% OF 1KB REQUEST TIME SPENT

Redis

GET | HW 18% | Kernel 62% | App 20% | **9 us**

us

Kernel mediation is too heavyweight

Kernel

I/O Processing

Copying

Protection

Data Path

10G NIC
2 us / 1KB packet

RAID Storage
25 us / 1KB write

Arrakis Goals

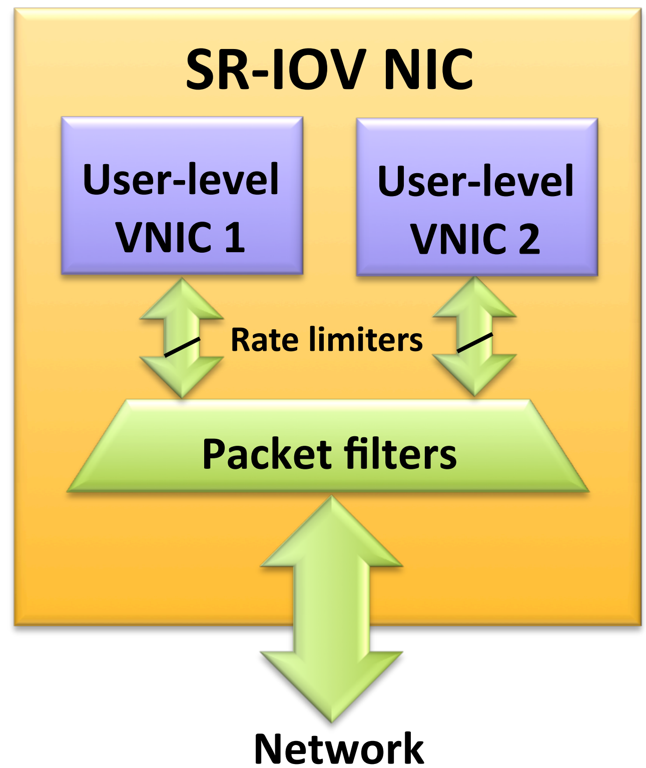
- Skip kernel & deliver I/O directly to applications
  - Reduce OS overhead

- Keep classical server OS features
  - Process protection
  - Resource limits
  - I/O protocol flexibility
  - Global naming

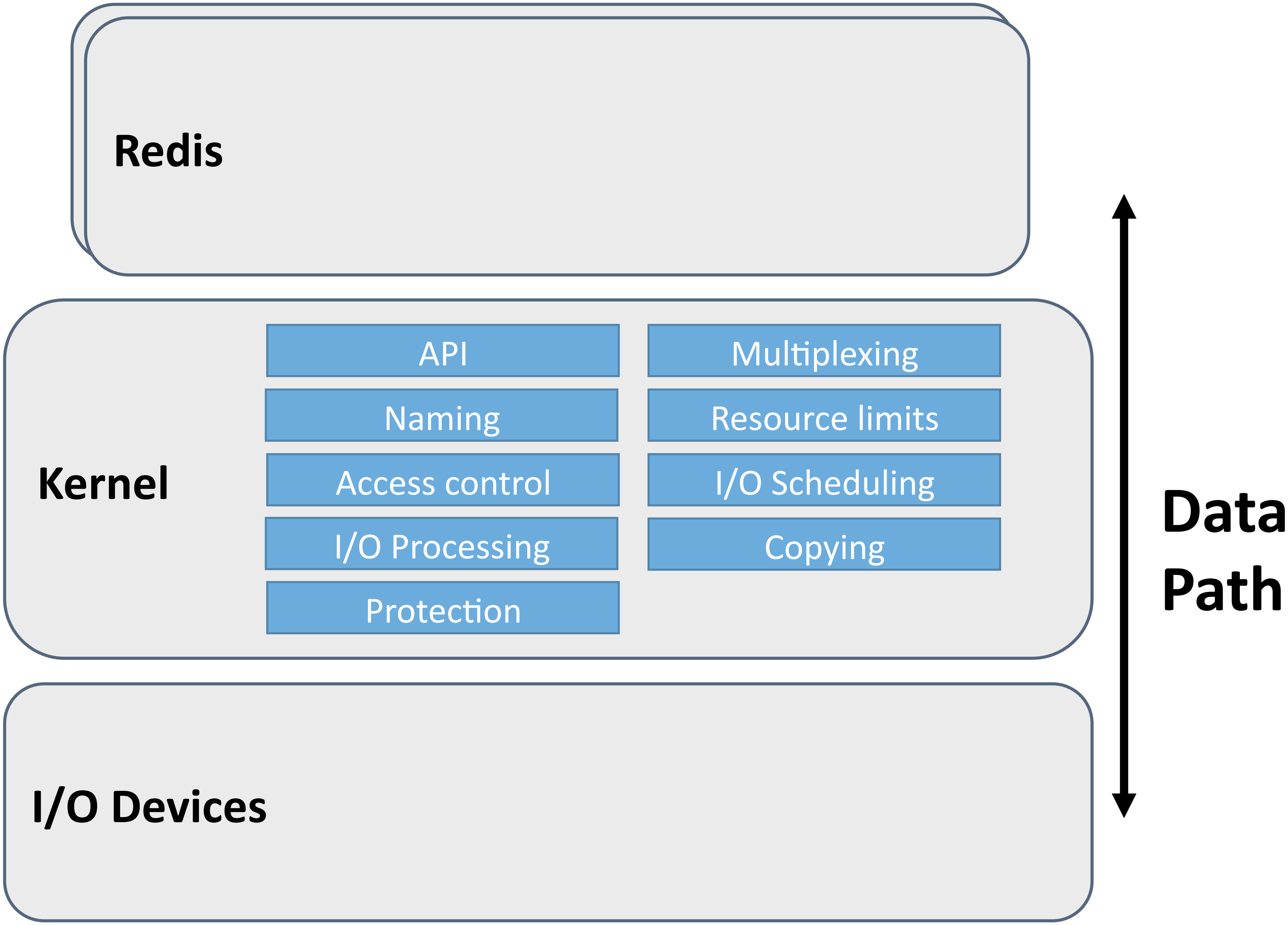
- The hardware can help us…

Hardware I/O Virtualization

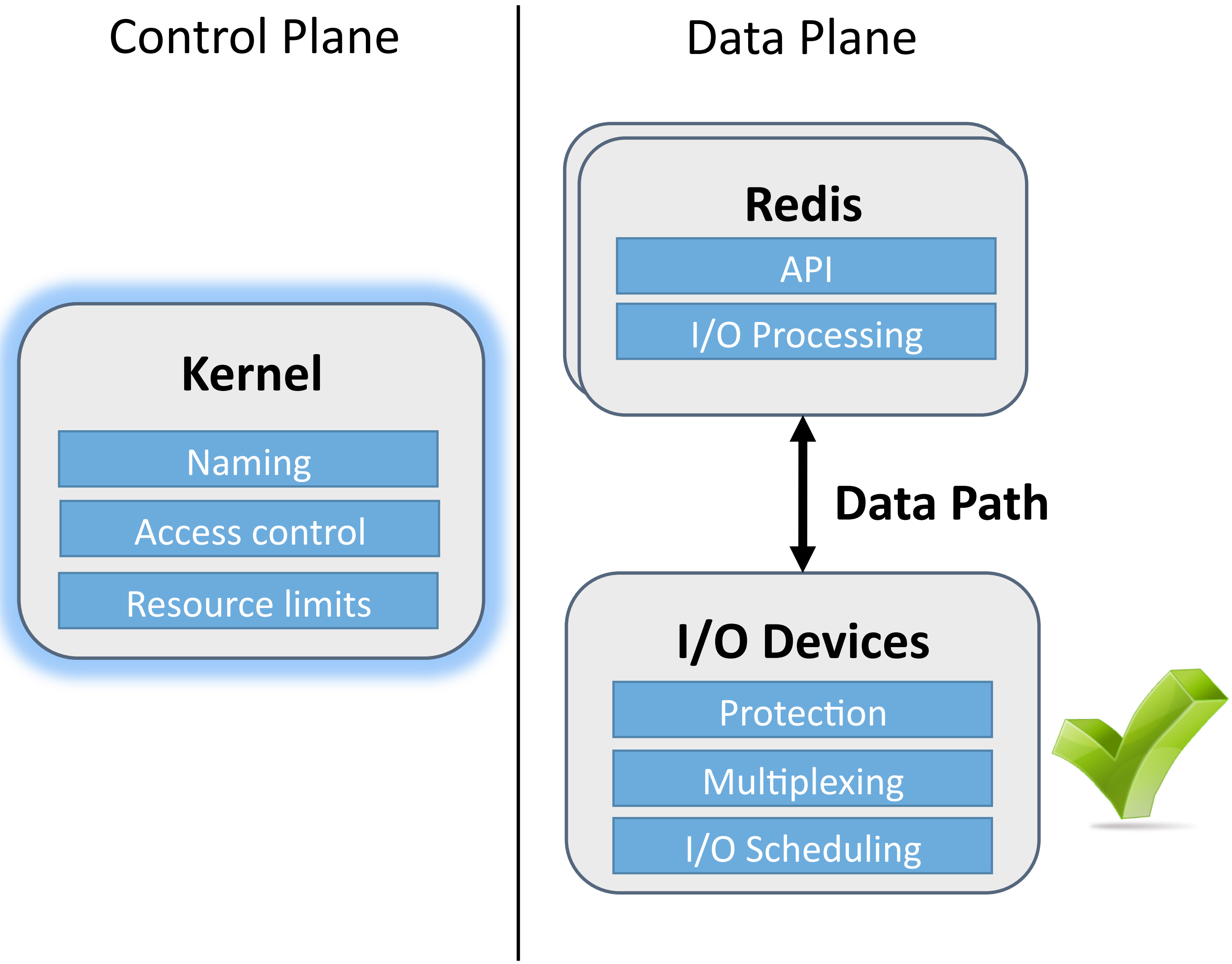
- Standard on NIC, emerging on RAID
- Multiplexing
  - **SR-IOV**: Virtual PCI devices w/ own registers, queues, INTs
- Protection
  - **IOMMU**: Devices use app virtual memory
  - **Packet filters**, **logical disks**: Only allow eligible I/O
- I/O Scheduling
  - NIC **rate limiter**, **packet schedulers**



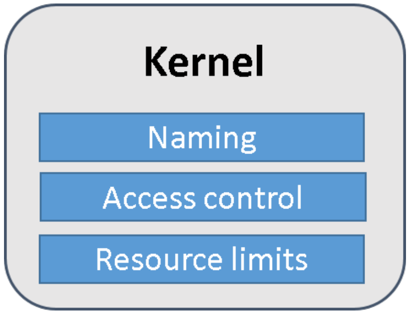
How to skip the kernel?



Arrakis I/O Architecture

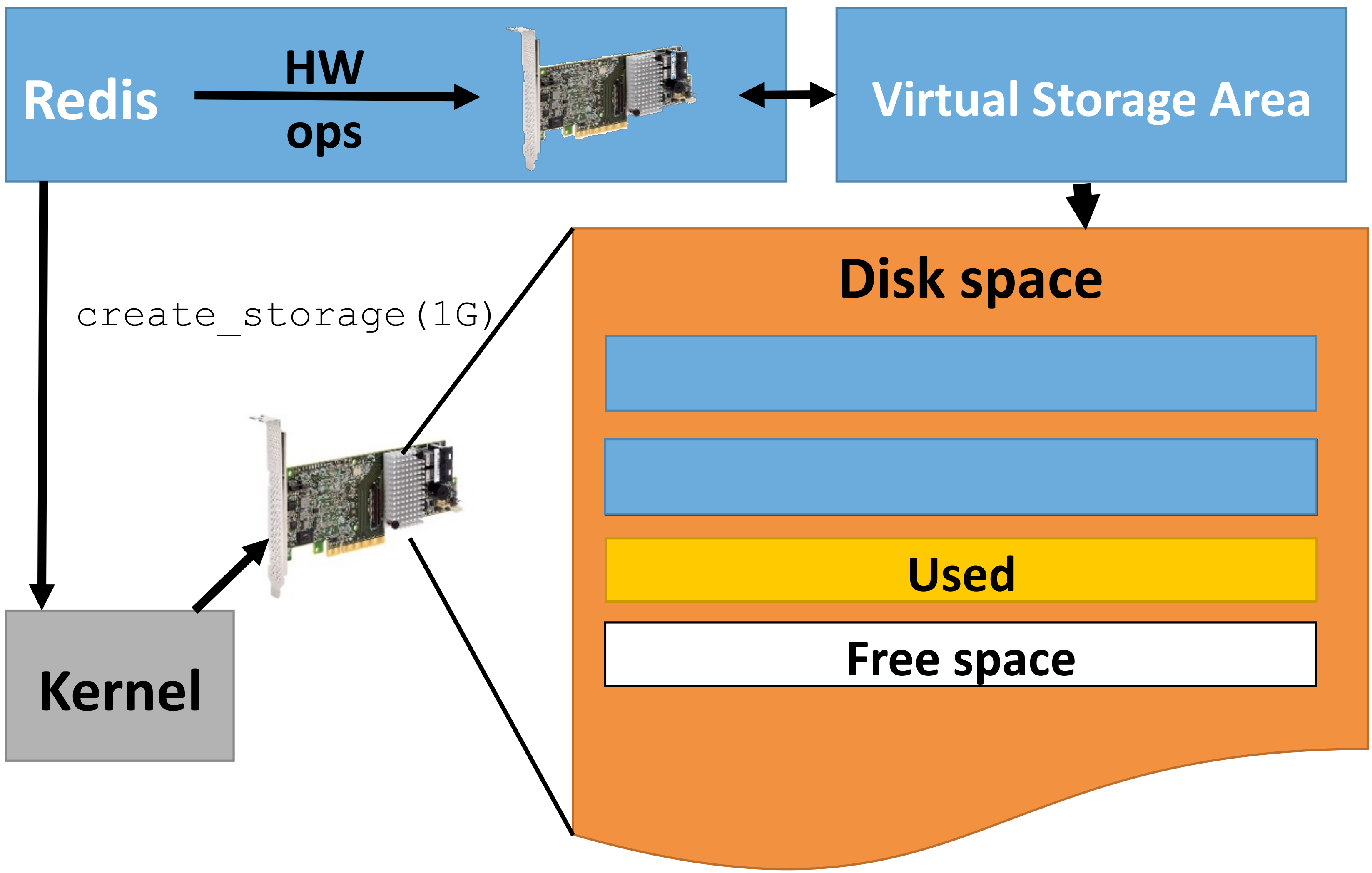


Arrakis Control Plane

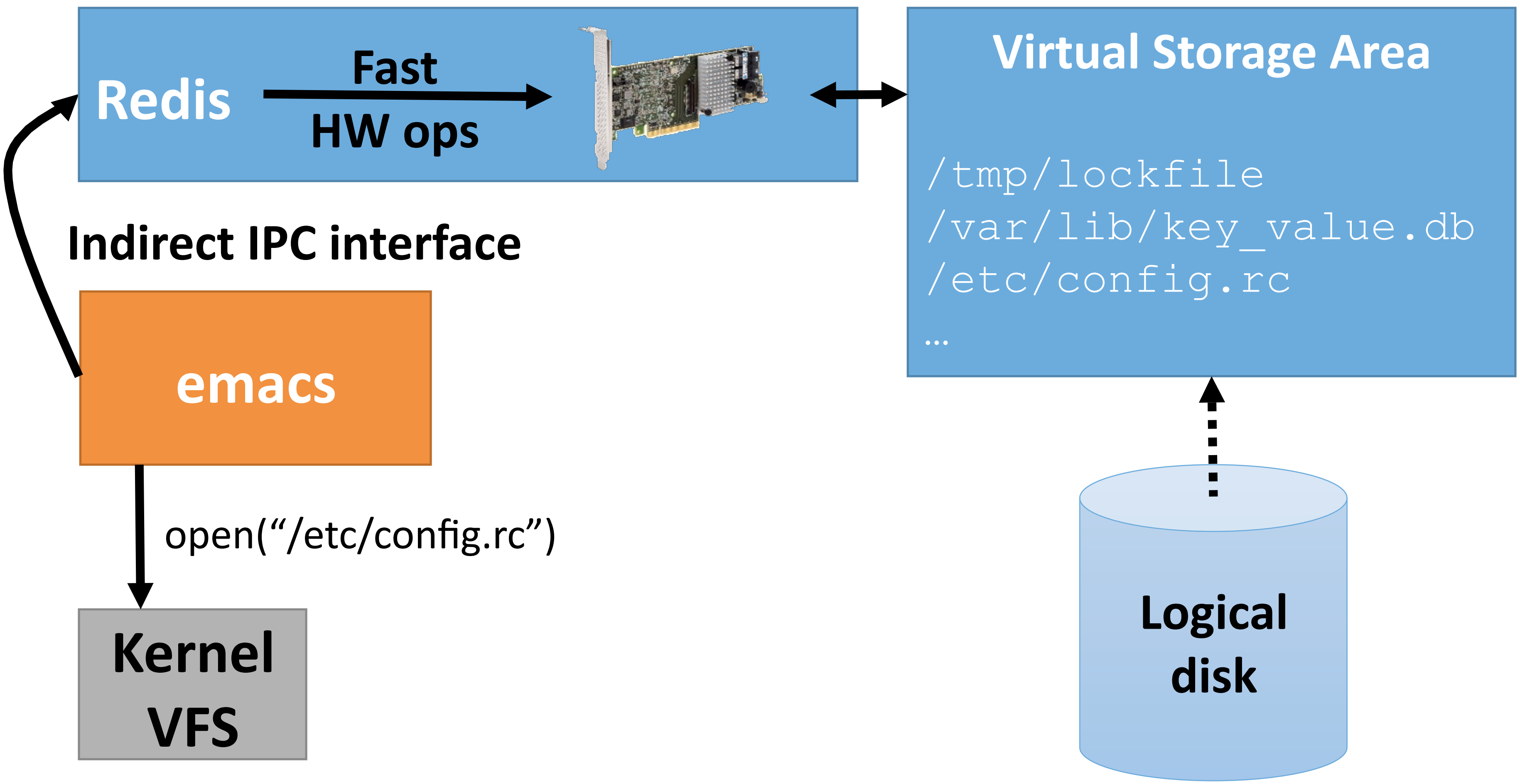


- Access control
  - Do once when configuring data plane
  - Enforced via NIC filters, logical disks
- Resource limits
  - Program hardware I/O schedulers
- Global naming
  - Virtual file system still in kernel
  - Storage implementation in applications

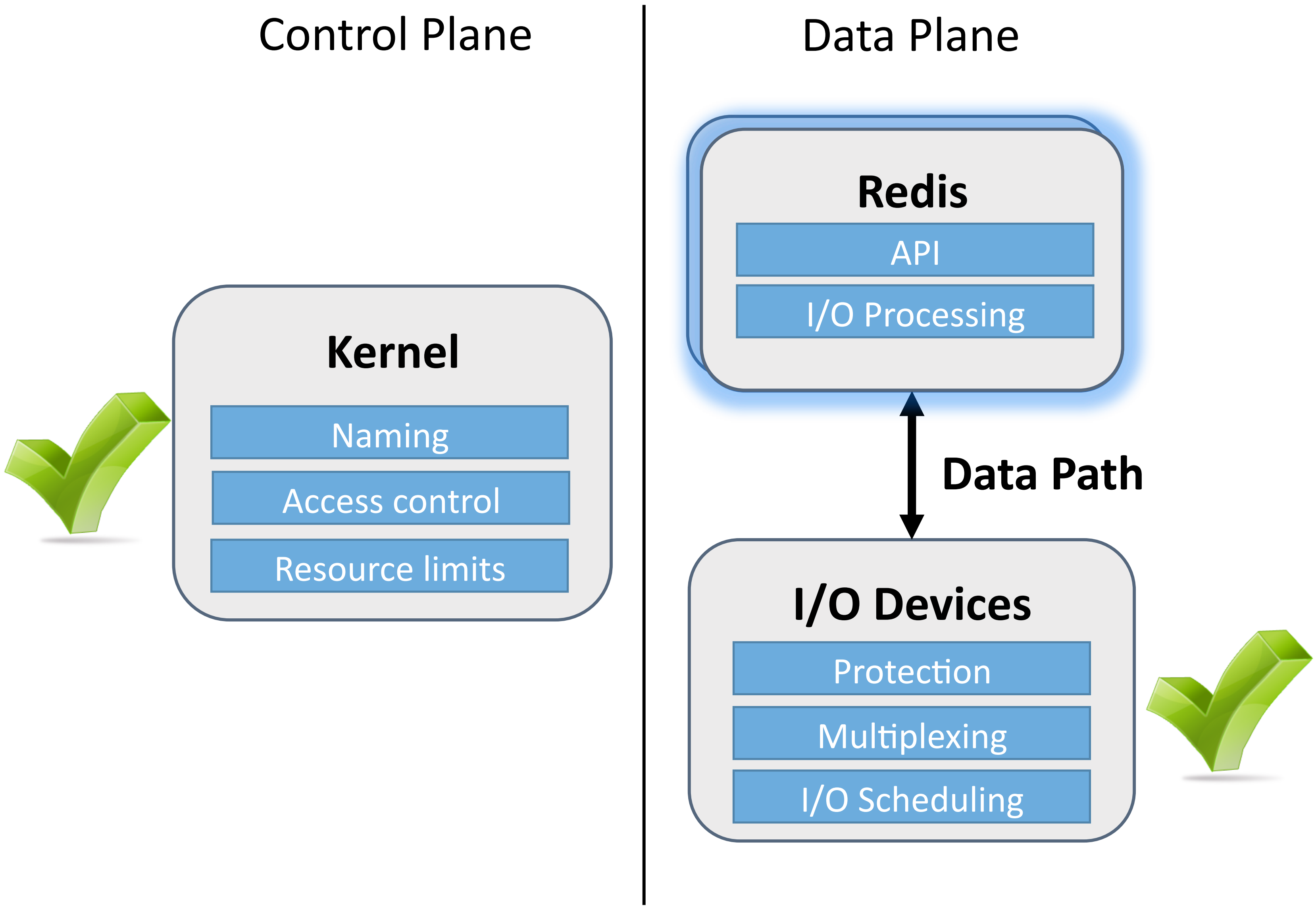
Storage Space Allocation



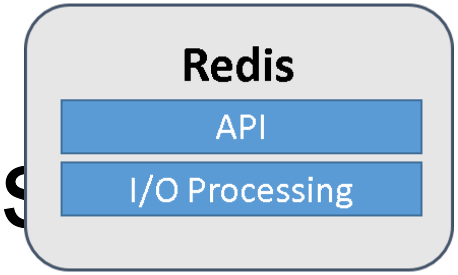
Separate Naming From Implementation



Arrakis I/O Architecture



Storage Data Plane: Persistent Data Structures



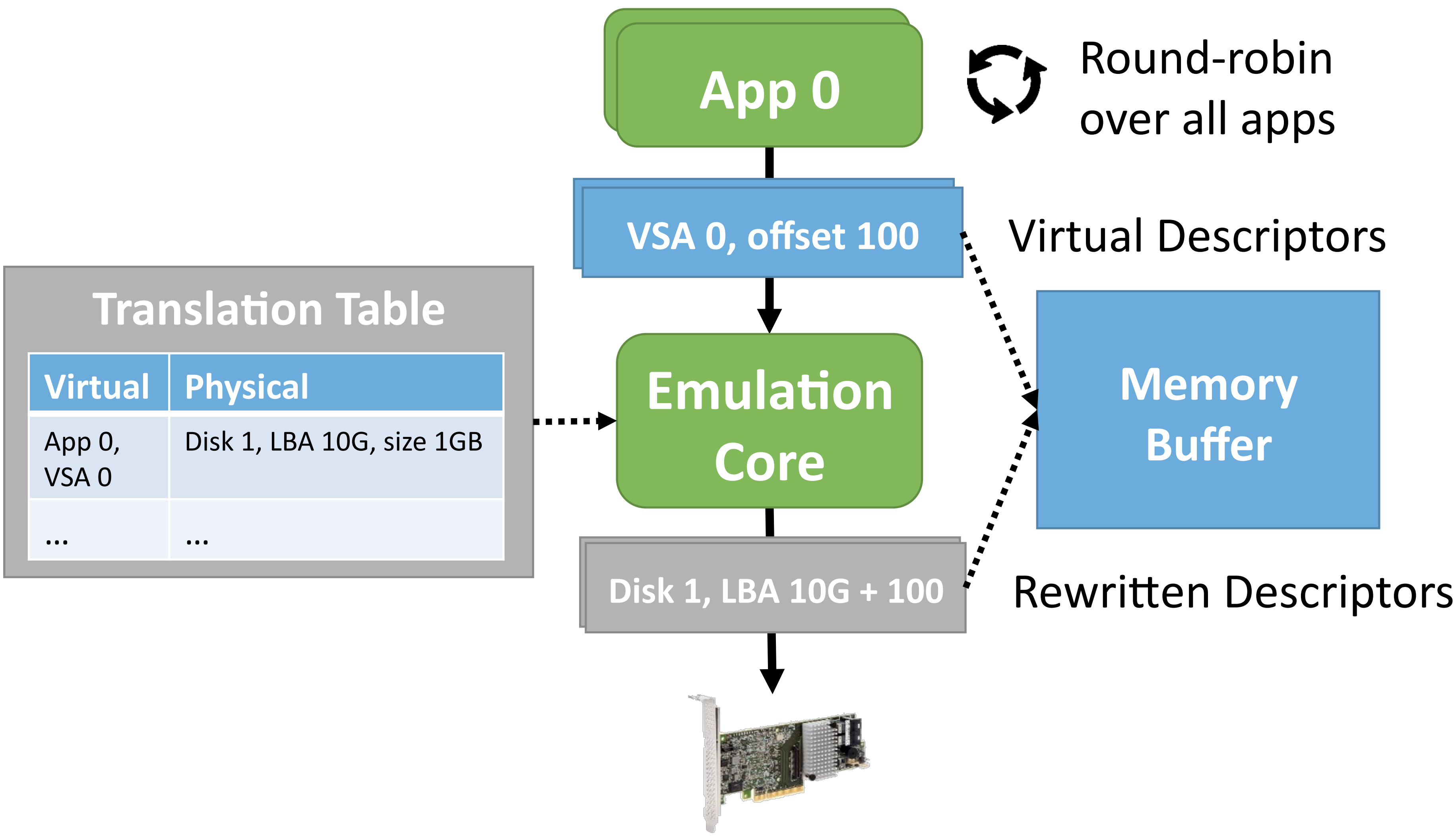
- Examples: **log, queue**
- Operations immediately persistent on disk

Benefits:

- In-memory = on-disk layout
  - Eliminates marshaling
- Metadata in data structure
  - Early allocation
  - Spatial locality
- Data structure specific caching/prefetching

- Modified Redis to use **persistent log**: **109 LOC** changed

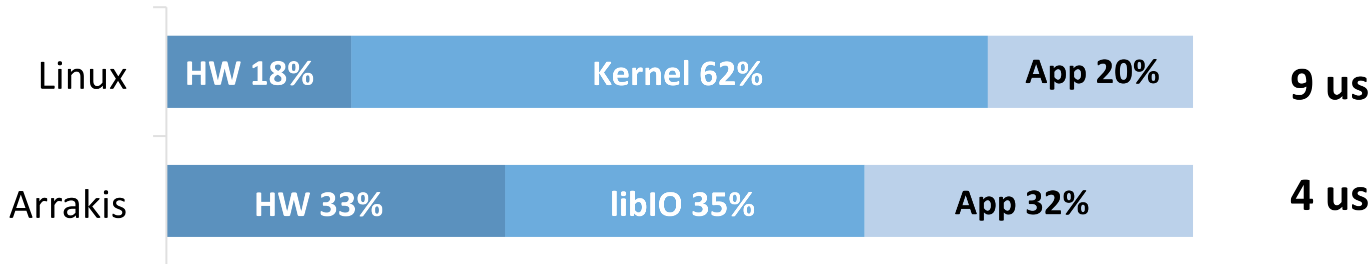
Arrakis Device Emulation



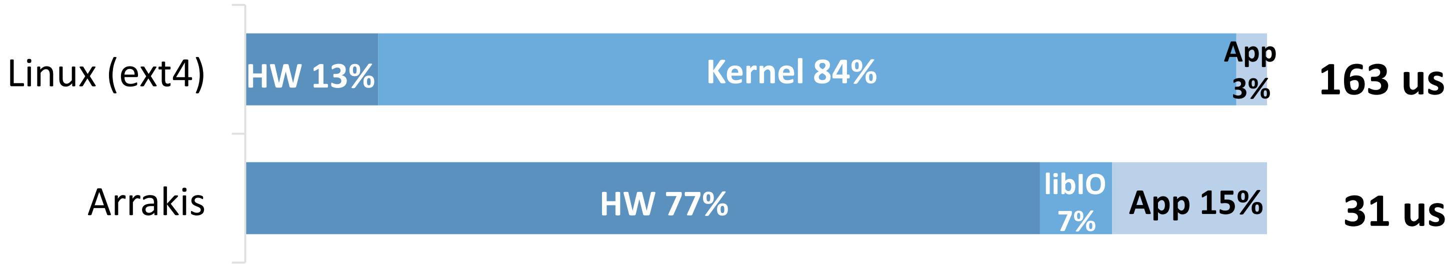
Evaluation

Redis Latency

- Reduced (in-memory) GET latency by **65%**



- Reduced (persistent) SET latency by **81%**

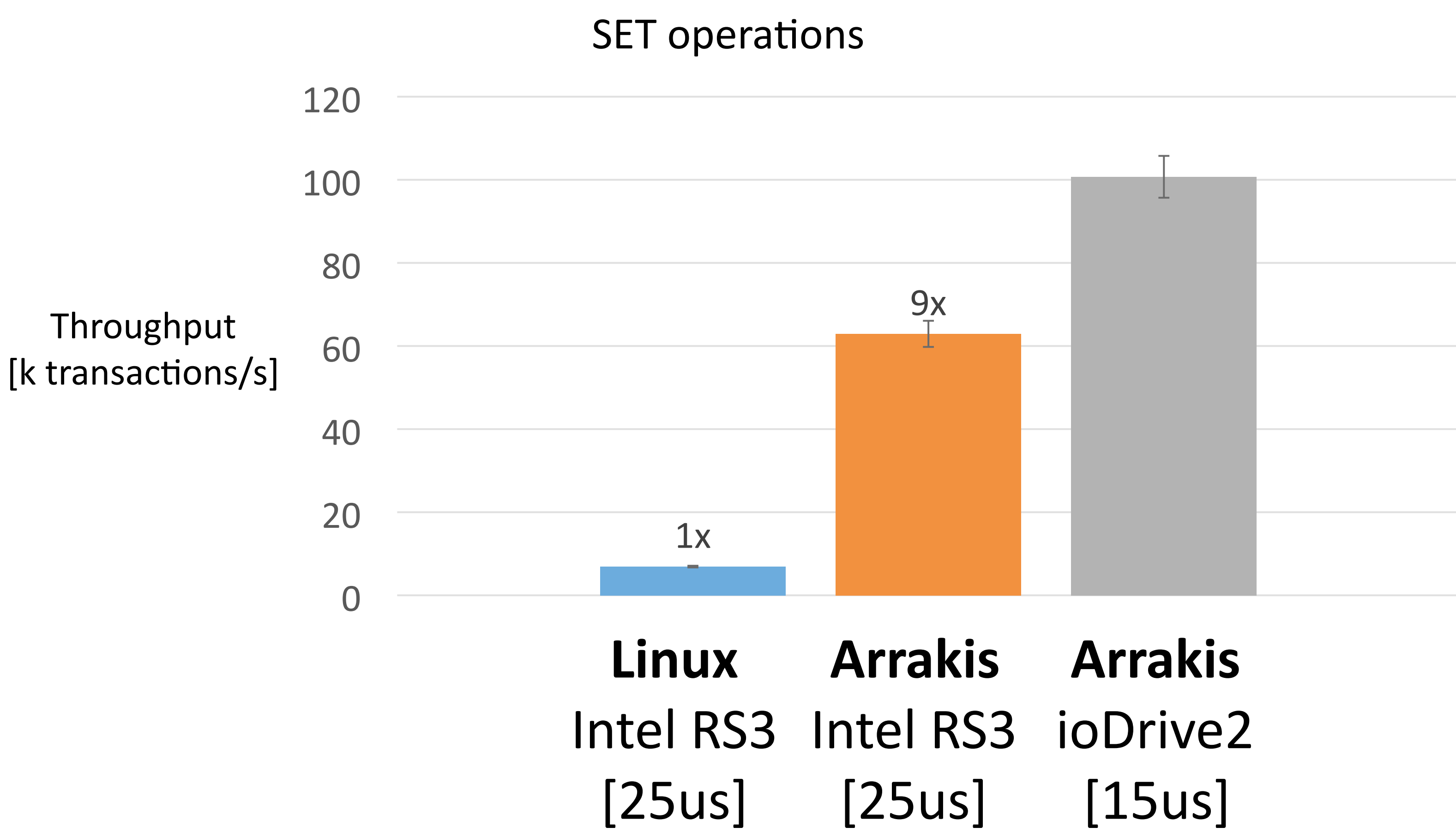


Redis Throughput

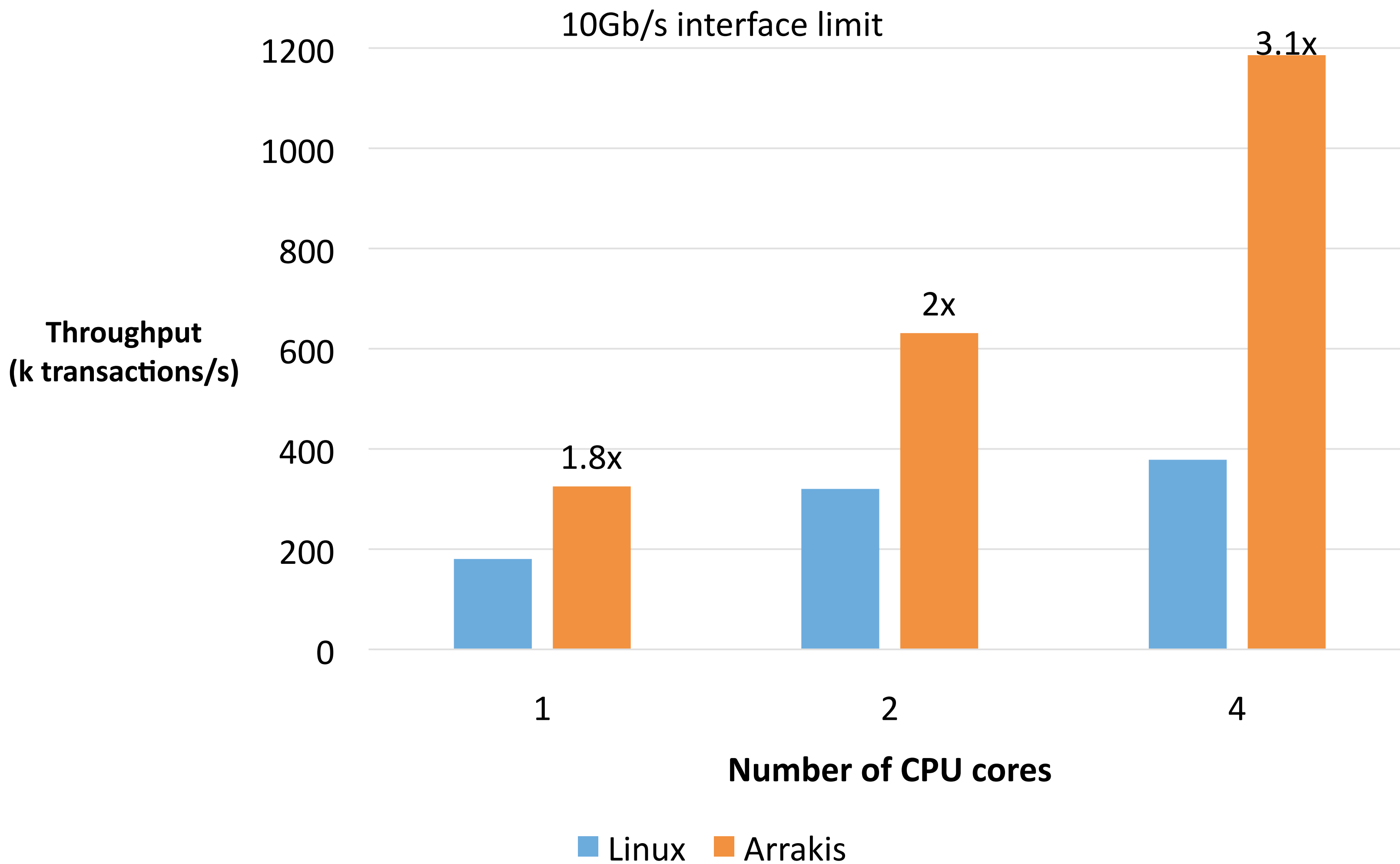
- Improved GET throughput by **1.75x**
  - Linux: **143k** transactions/s
  - Arrakis: **250k** transactions/s

- Improved SET throughput by **9x**
  - Linux: **7k** transactions/s
  - Arrakis: **63k** transactions/s

Redis Throughput



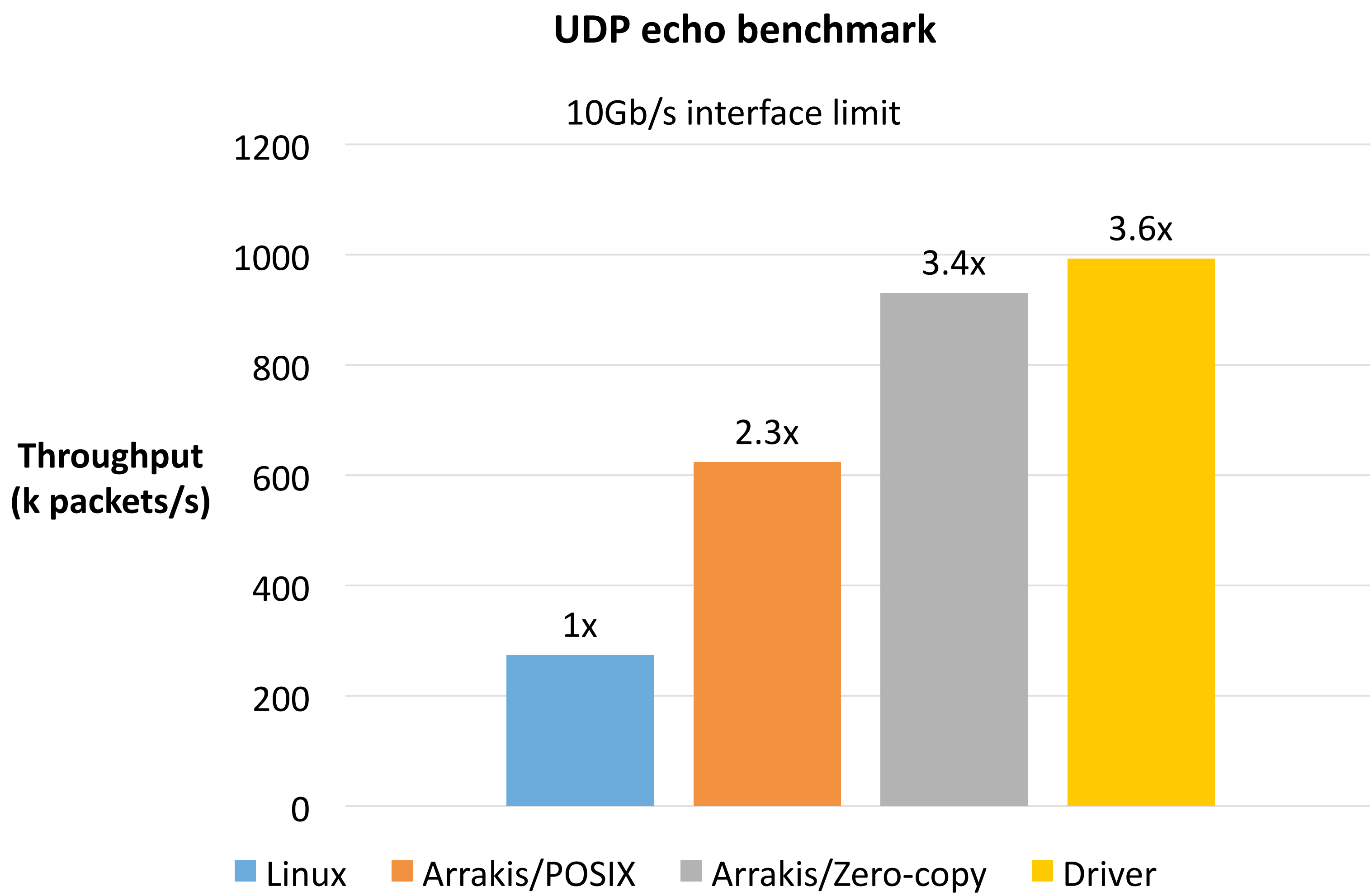
memcached Scalability



Getting even more performance…

- POSIX requires data copy for buffering
  - send(): Synchronous packet transmission
  - recv(): User specifies receive location
- Arrakis/Zero Copy
  - Modify send() so that libOS returns buffer when done
  - Modify recv() so that libOS specifies buffer to use
- Port of memcached to Arrakis/Zero Copy
  - TX: 63 LOC changed, 10% better latency
  - RX: 11 LOC changed, 9% better latency

Single-core Performance



Implication

We’re all OS developers now.

Future Directions: Devices

- I/O hardware-application co-design
  - At 40 Gbps, even a single cache miss is too expensive
- Application needs fine-grained control (aka OpenFlow)
  - How arriving packets are routed to cores
  - Where in memory or cache to put the packet (or portion of packet)
  - Under control of the sender or receiver, or both
- Similar control needed for persistent memory controllers
- Opportunity to rethink the device driver interface
  - Application-level safe sandboxing of third party drivers
  - Rethink the POSIX API for fast data processing

Future Directions: Storage

- Fast persistent storage is here
  - DRAM+flash, or memristors, or phase change memory
- Rethink distributed systems when networking and persistent memory are both very fast
  - Ex: many data centers observe a non-trivial number of hardware faults
  - On Arrakis, Byzantine fault tolerance protocols that run much faster than today's Paxos or primary/backup replication
- Application-specific storage system design
  - LFS, WAFL, write-ahead logging, …
  - Application management of caching, prefetching, and the storage hierarchy

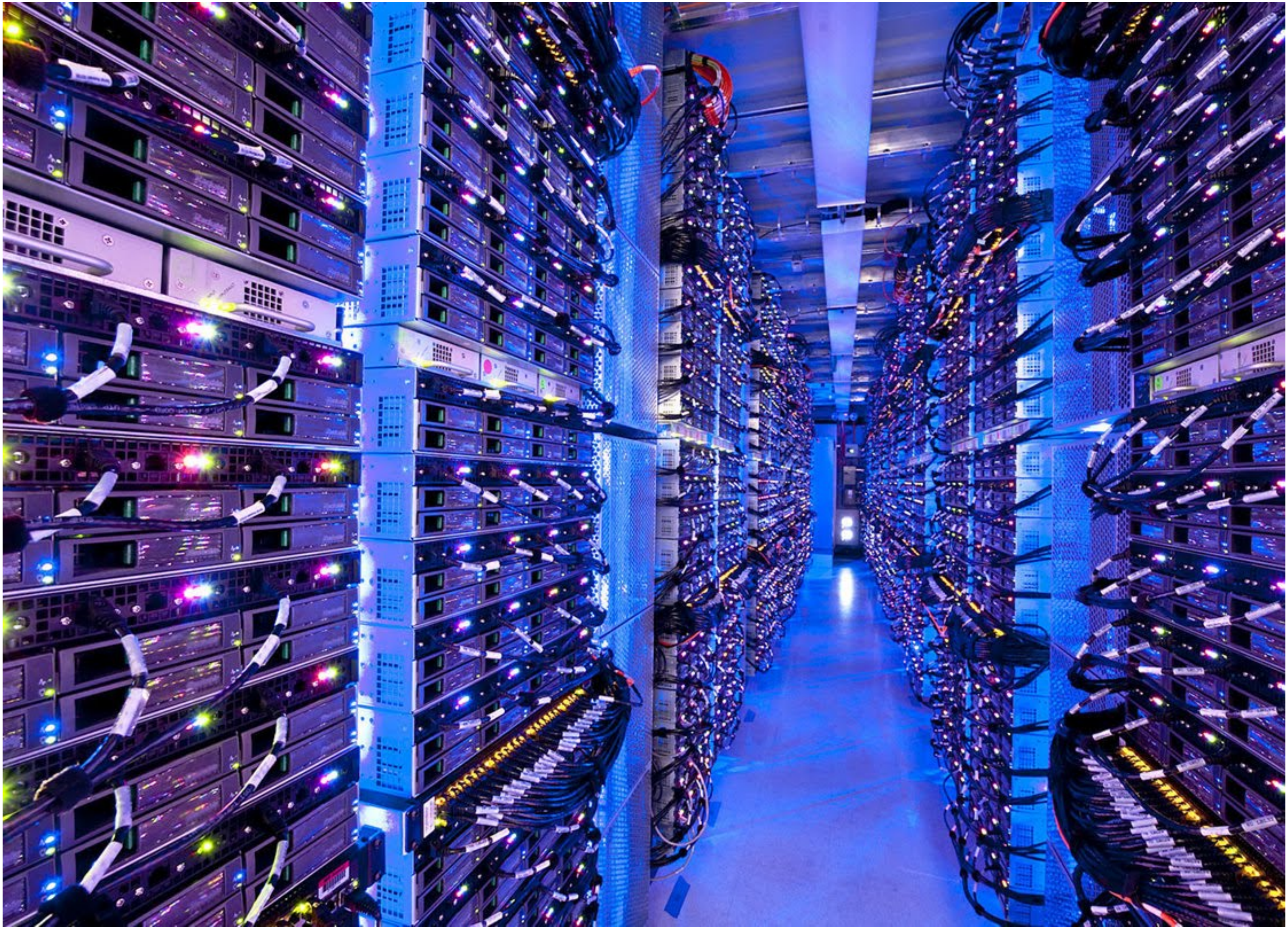
Future Directions: Networking

- Opportunity to rethink congestion control/resource allocation in the data center network
  - TCP mechanics no longer enforced in the OS kernel
  - For multi-gigabit networks, packet loss is a terrible way to signal congestion
- Dynamic negotiation of application-specific network protocols
  - Beyond TCP: PCP, SPDY, QUIC, ...
- Lower OS overhead => more network traffic
  - Network is already a bottleneck

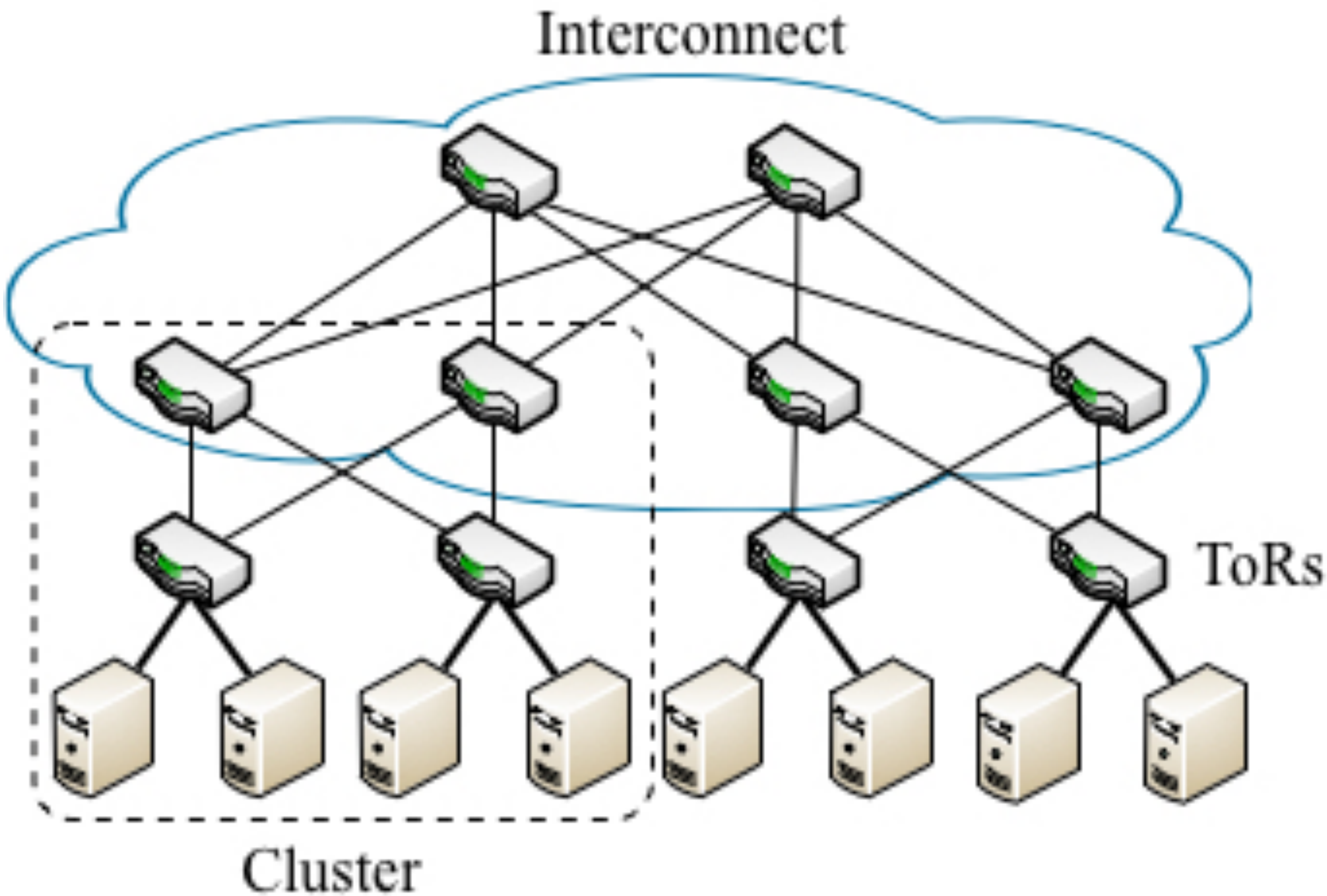
Arrakis Summary

- OS is becoming an I/O bottleneck
  - Globally shared I/O stacks are slow on data path
- **Arrakis:** Split OS into control/data plane
  - Direct application I/O on data path
  - Specialized I/O libaries
- Application-level I/O stacks deliver great performance
  - **Redis:** up to **9x** throughput, **81%** speedup
  - Memcached **scales linearly** to **3x** throughput

Source code: ***http://arrakis.cs.washington.edu***



Today's Data Center Networks



Cost vs. Capacity

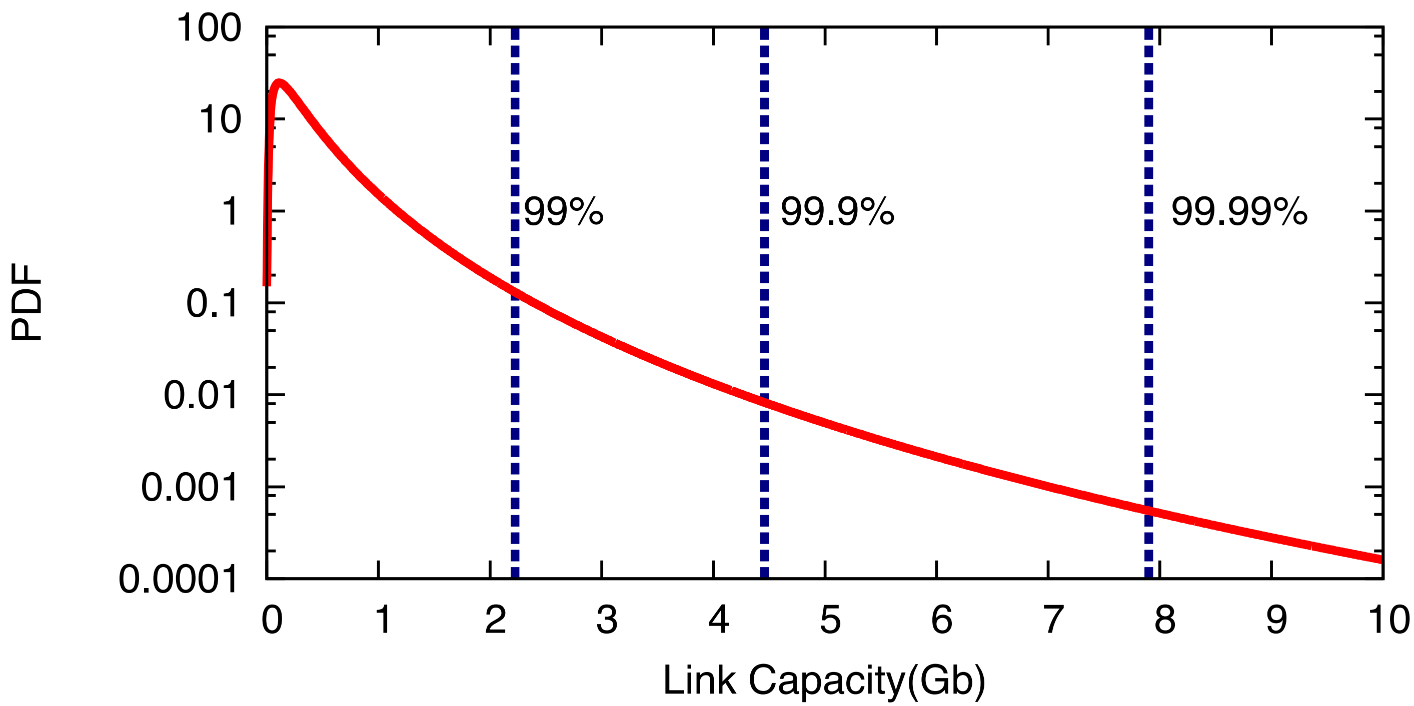
- Tension between high cost of network equipment and performance impact of congestion
  - Under-provisioned aggregation/core switches
  - High bandwidth/less congestion within a rack

- Above ToR switches, average link utilization is only 25% at best
- Over a 5 min period, 2.3% of links experience loss

Statistics from Benson ’09 & ’10

Why Is This Happening?

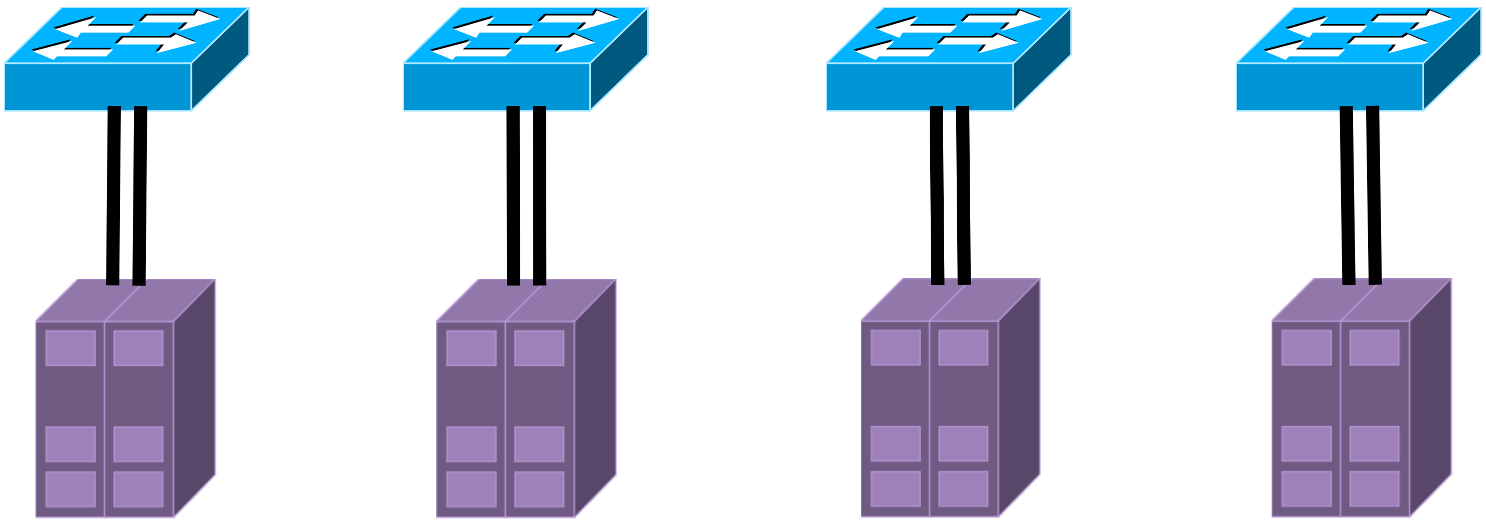
- Rack-level traffic is bursty/long-tailed



This is often a result of **good** job placement, not bad!

Subways

A family of data center architectures
that use multiple ports per server



Subways

A family of data center architectures
that use multiple ports per server

We do this with edge-only modification and with no additional hardware

- Less traffic in the ToR interconnect
- Remaining traffic is spread more evenly

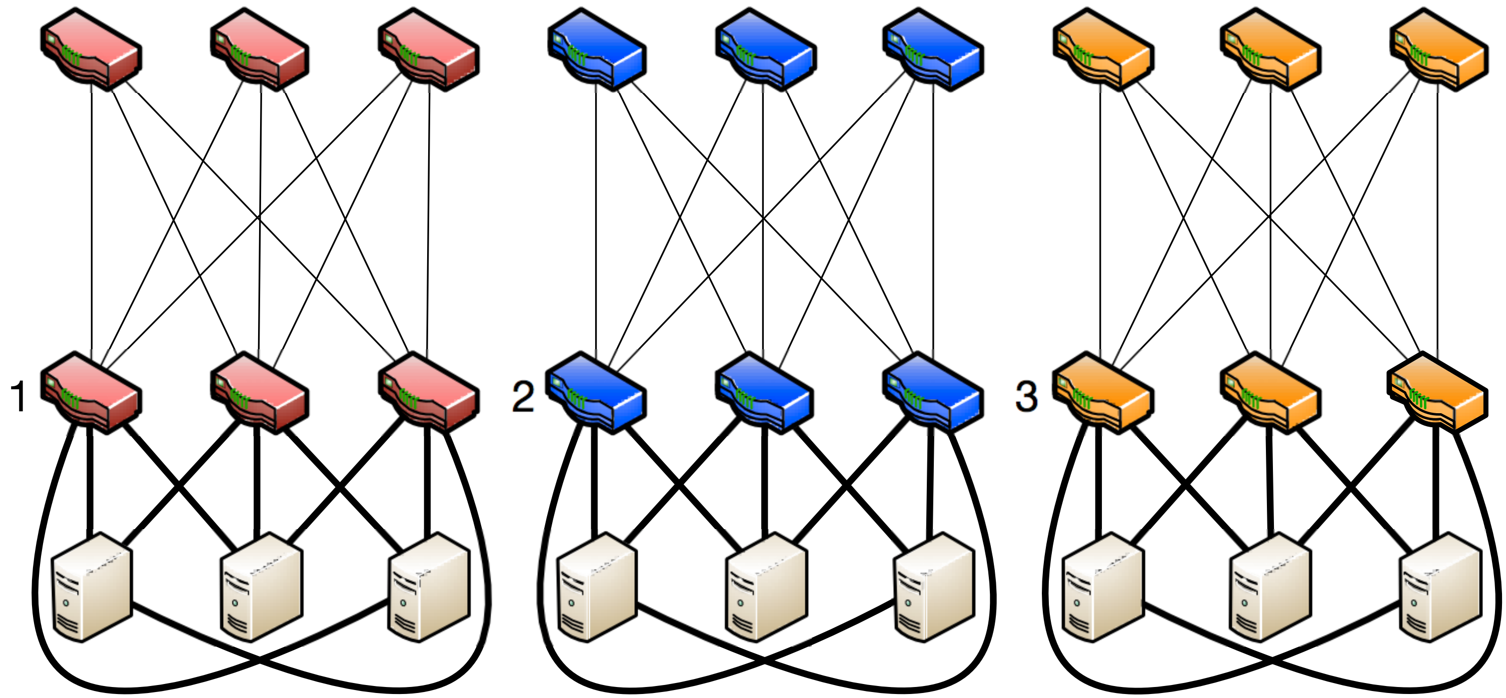
Wiring

Load Balancing	Single ToR per rack	Shared ToRs w/in a cluster	Cross-cluster loops
Uniform random	Level-0	Level-1	Level-2
Adaptive load balancing		Level-3	Level-4
Detours		Level-5	Level-6

Wiring

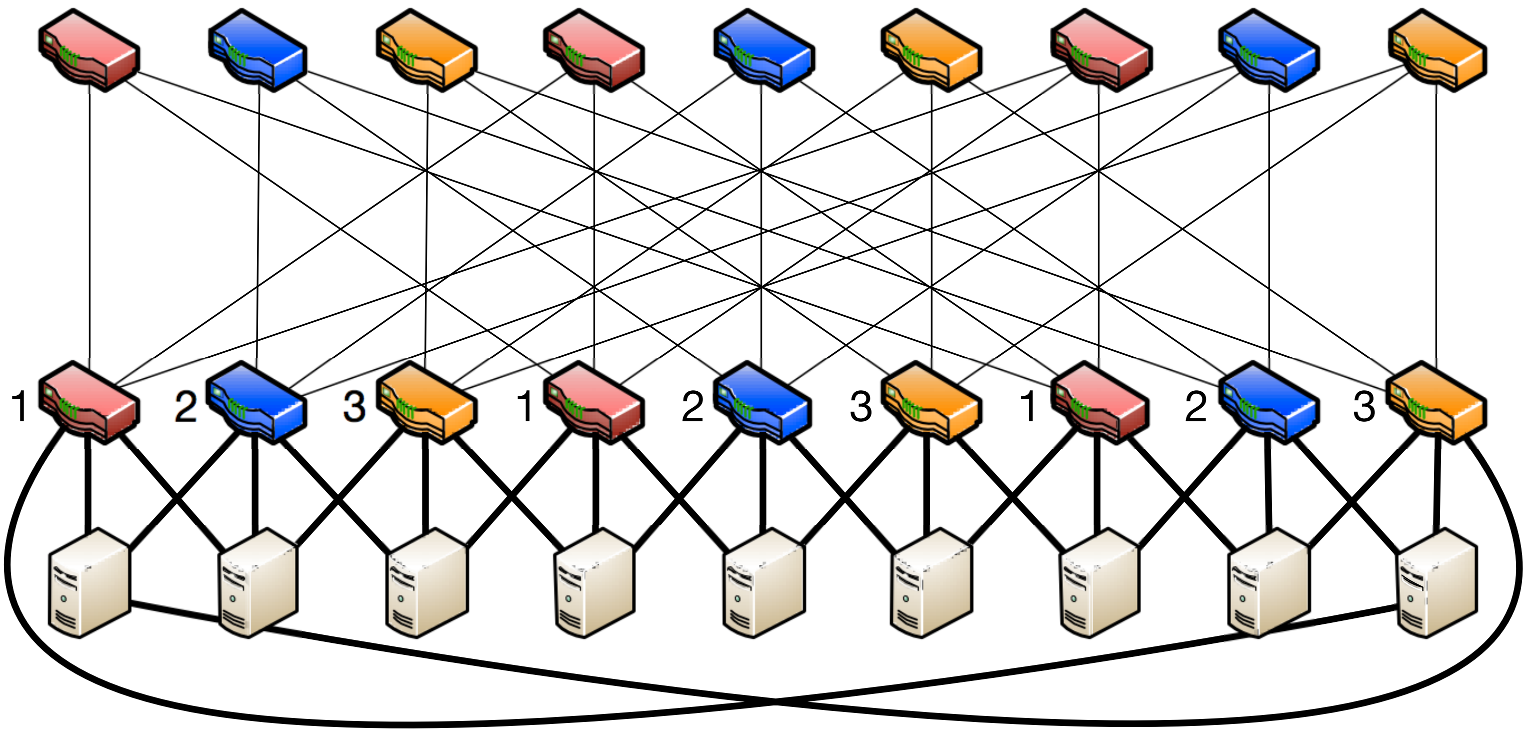
Load Balancing	Single ToR per rack	Shared ToRs w/in a cluster	Cross-cluster loops
Uniform random	Level-0	***Level-1***	***Level-2***
Adaptive load balancing		Level-3	Level-4
Detours		Level-5	Level-6

Level-1: Shared ToRs w/in a cluster



- Less traffic in the ToR interconnect
- Remaining traffic is spread more evenly
- No changes to routing

Level-2: Cross-cluster Loops

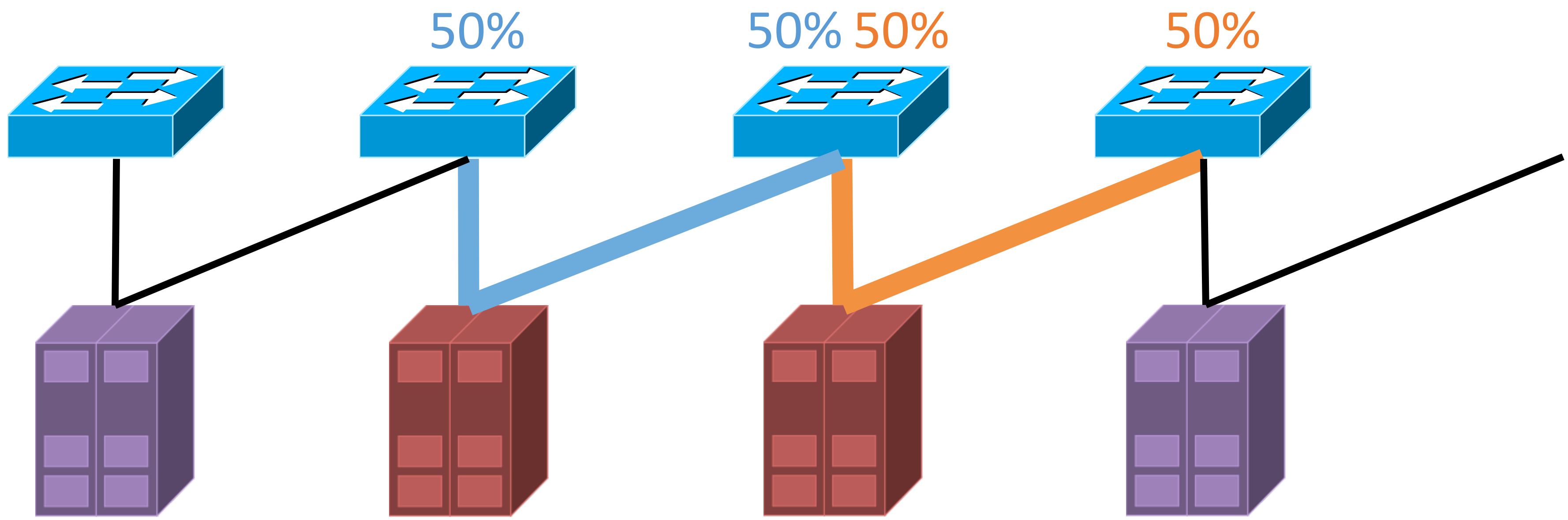


- Load balancing across both racks and clusters
- More shortcuts -> Decreased load on network core

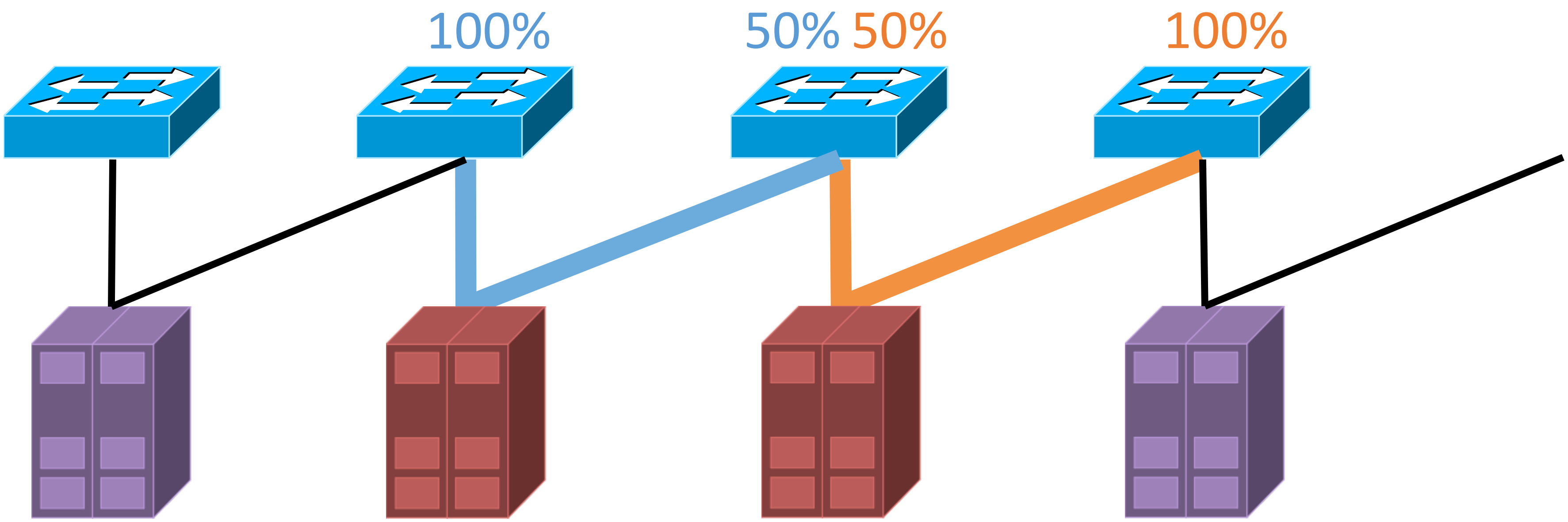
Wiring

Load Balancing	Single ToR per rack	Shared ToRs w/in a cluster	Cross-cluster loops
Uniform random	Level-0	Level-1	Level-2
Adaptive load balancing		Level-3	Level-4
Detours		Level-5	Level-6

Uniform Random

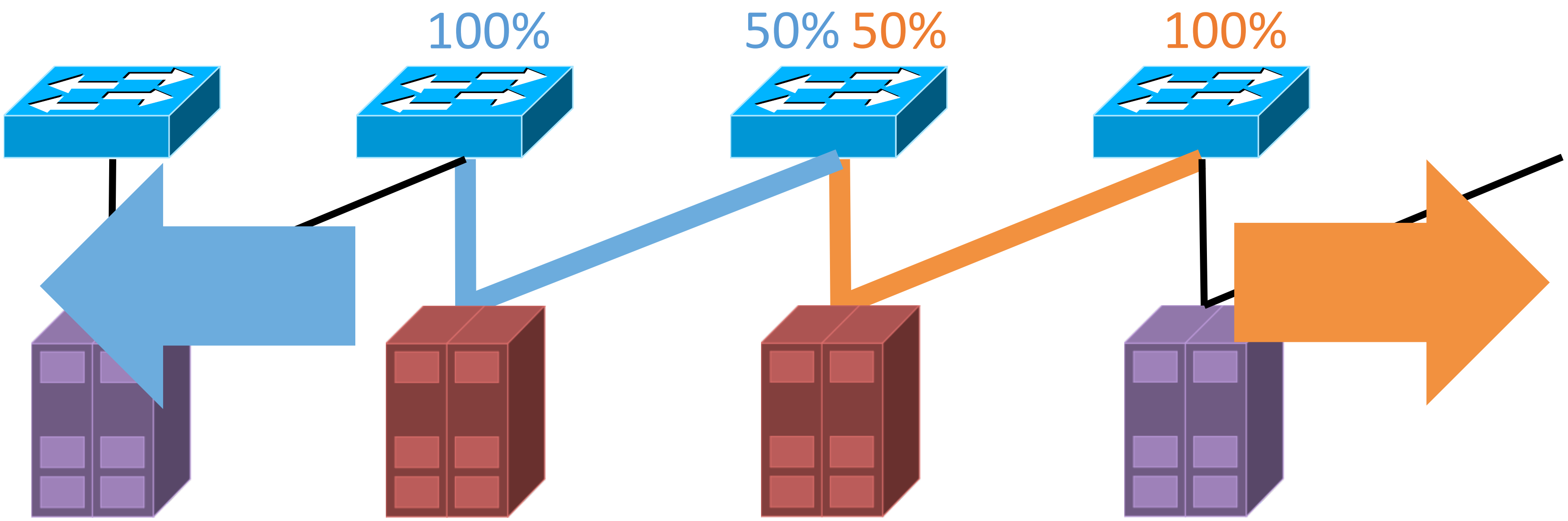


Adaptive Load Balancing



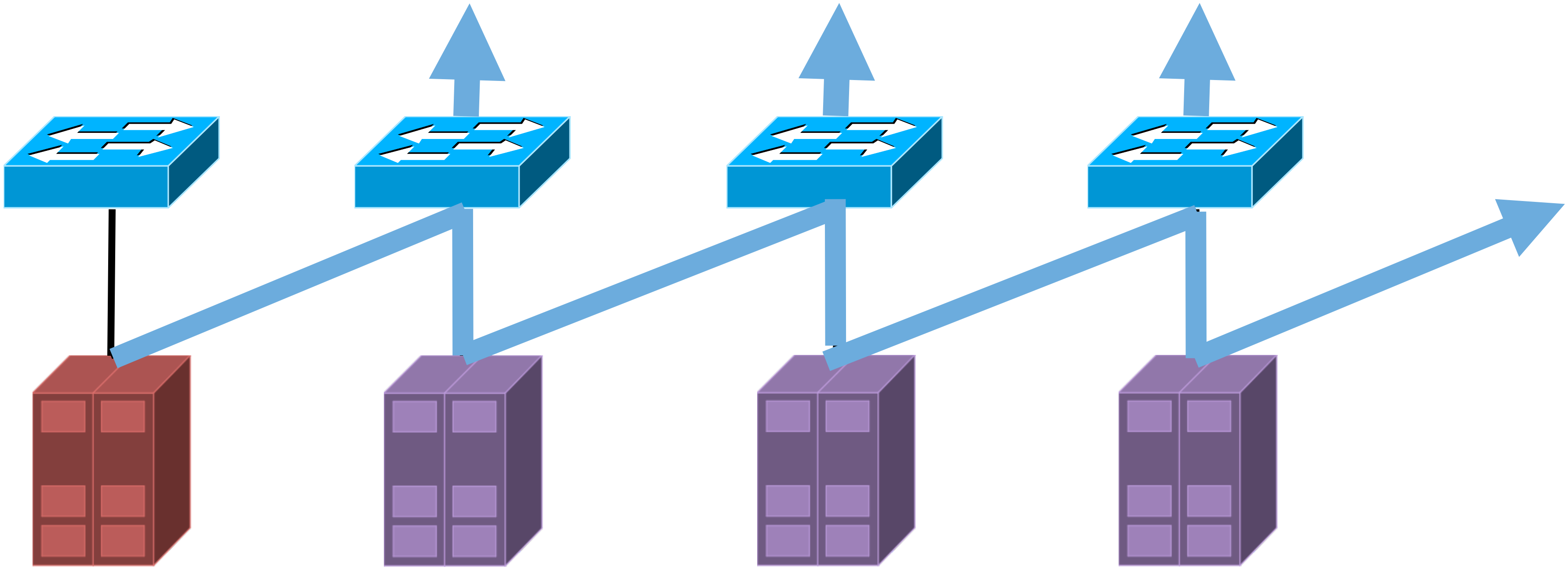
- Using either MPTCP or Weighted-ECMP
- Better tail latency/less congestion

Detours



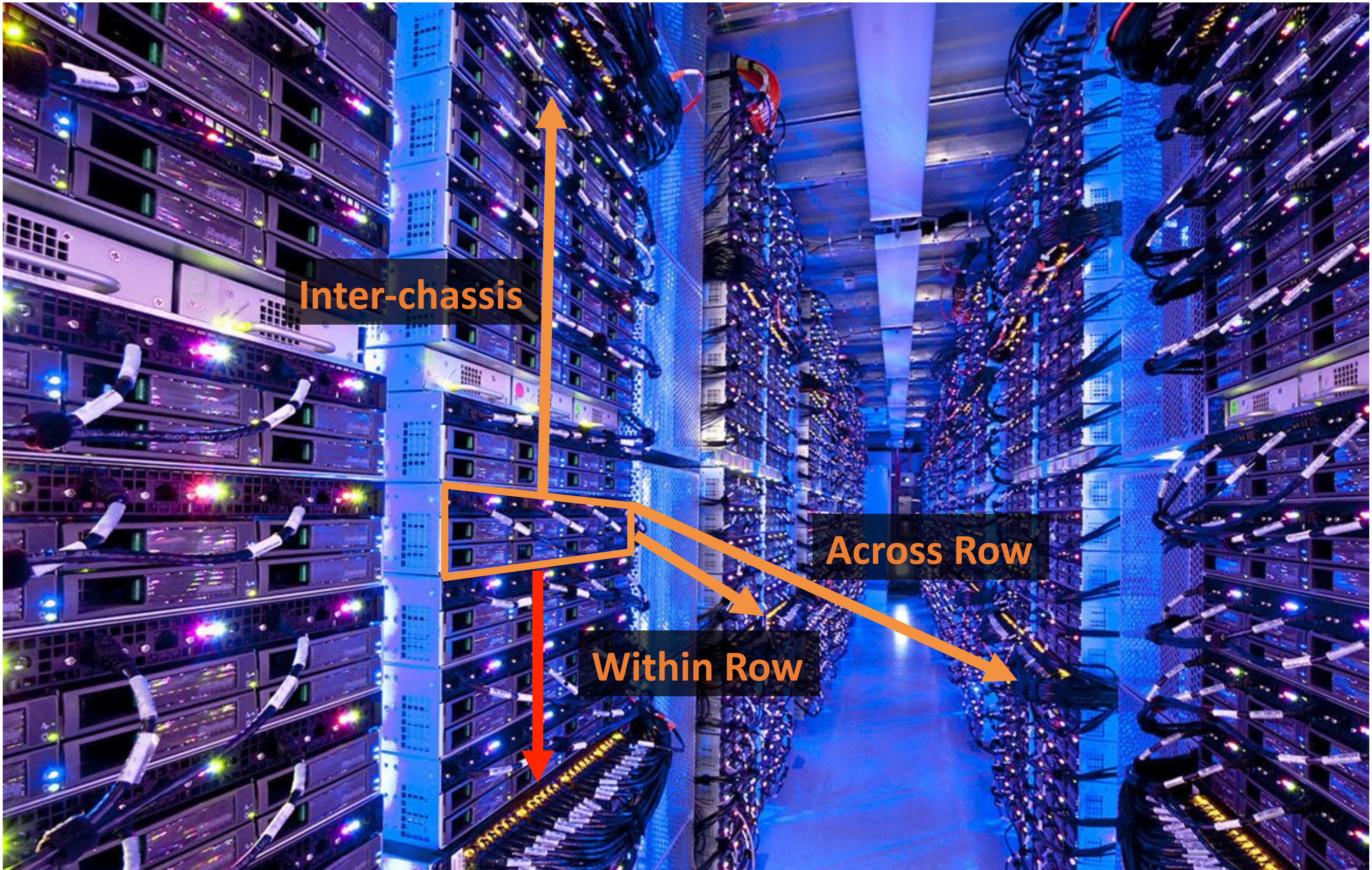
- Offload traffic to nearby ToRs

Detours



- Offload traffic to nearby ToRs
- For a single rack, provides full burst bandwidth *regardless* of oversubscription ratio

Physical Design Considerations

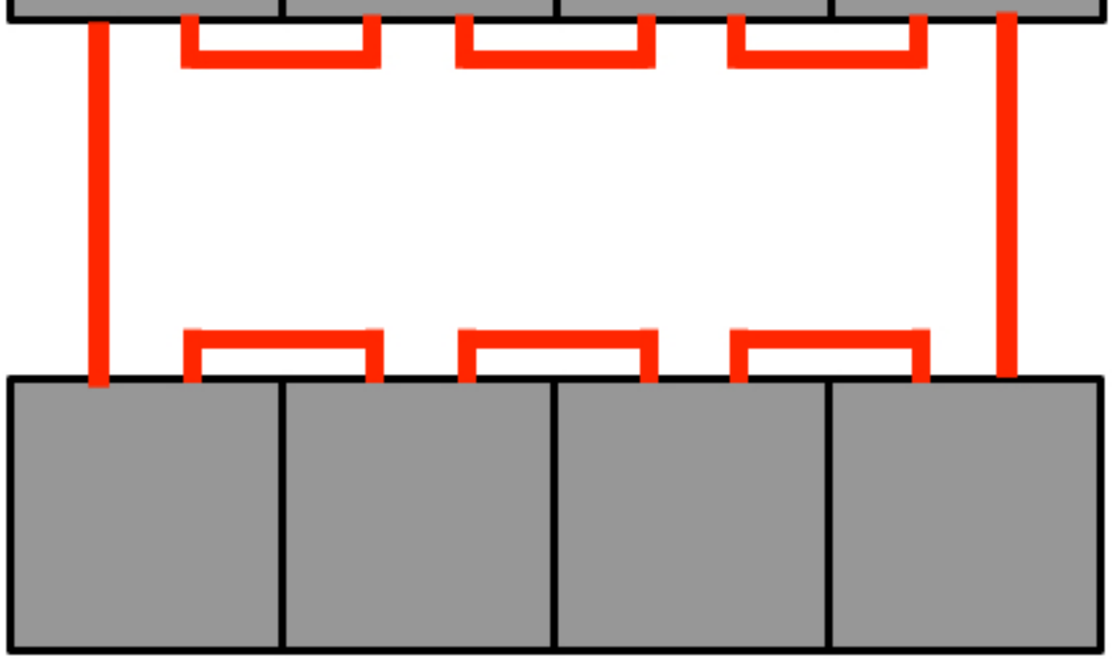


How might we wire a subways loop?

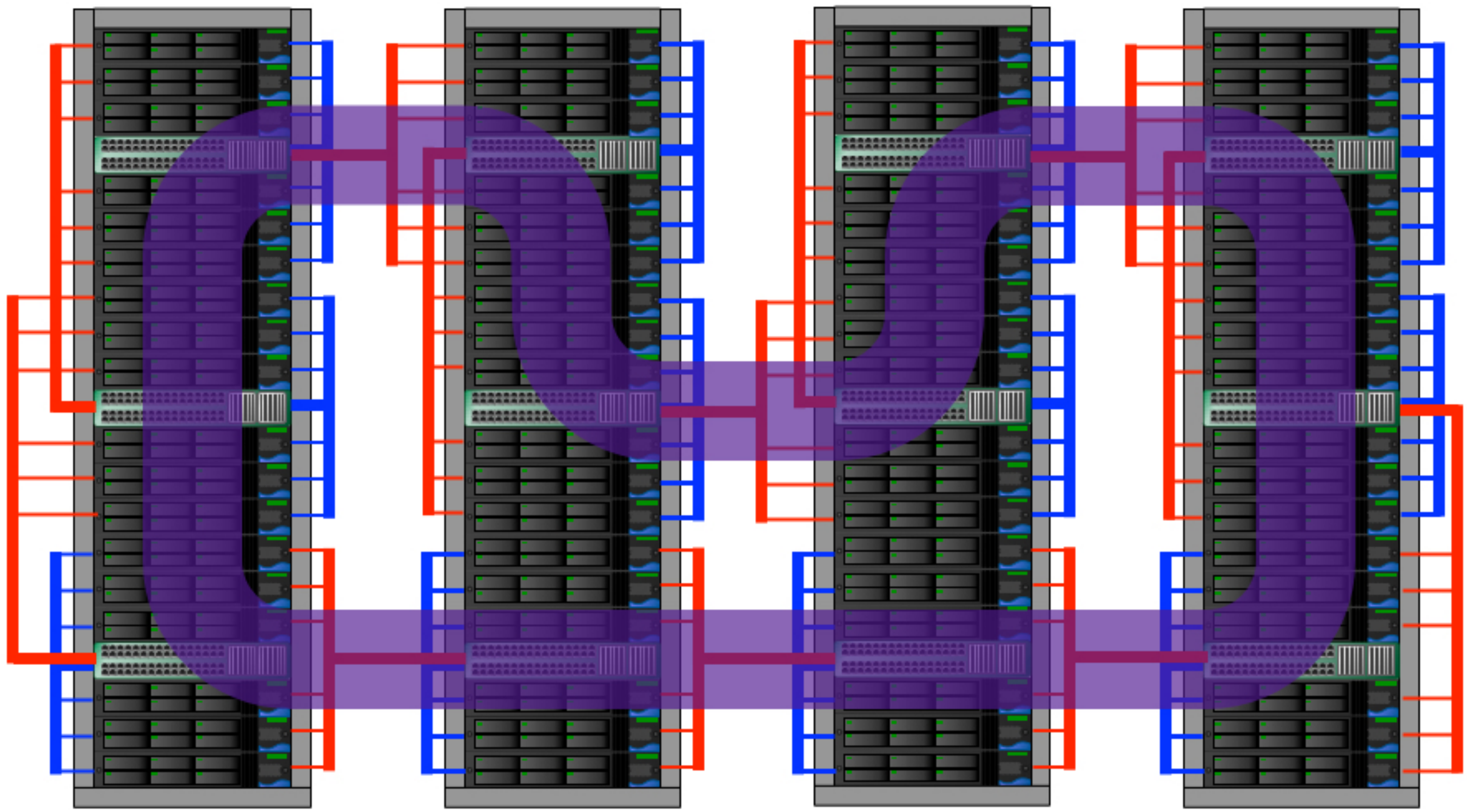
Within Row

Across Row

Bird's-eye view

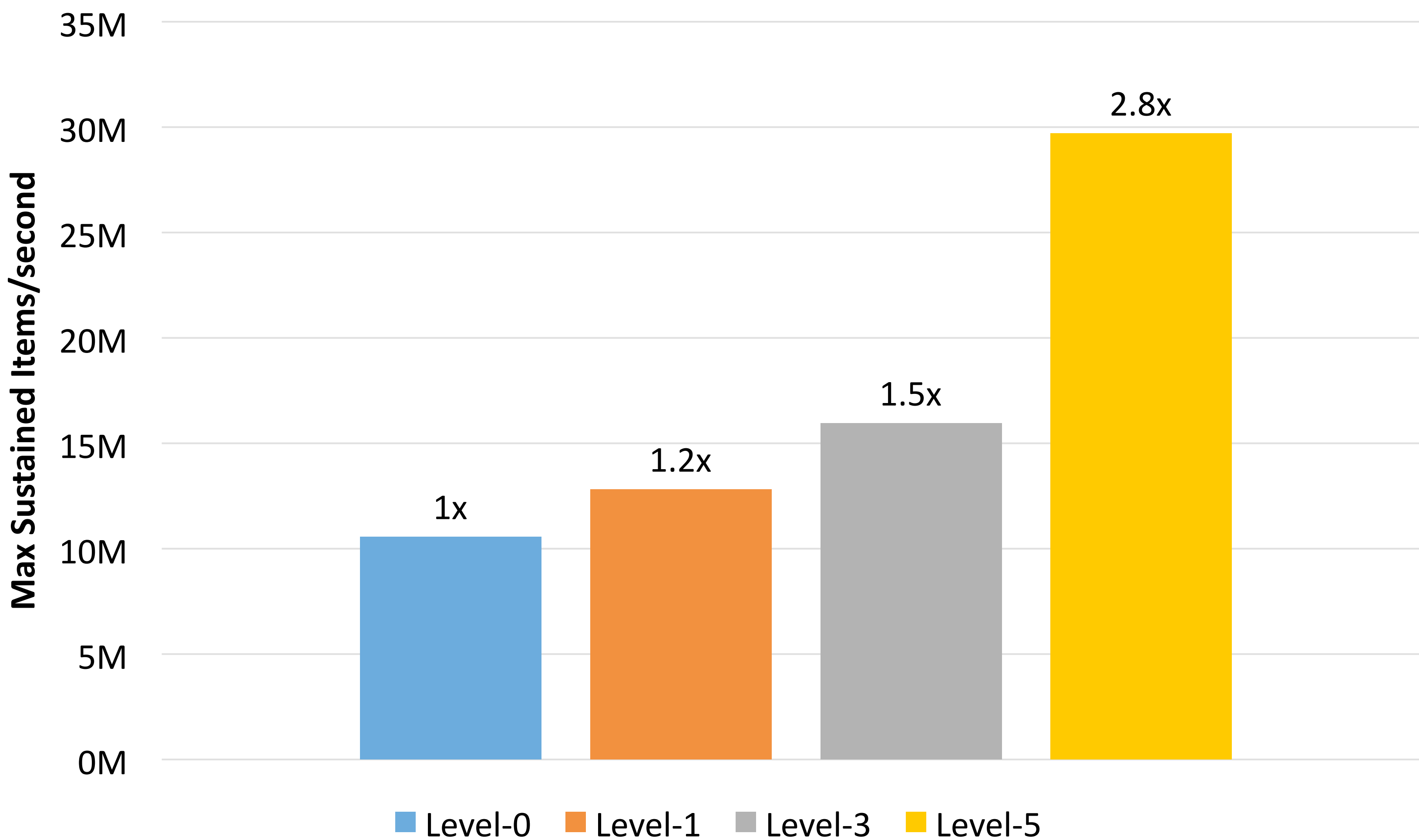


How Might We Wire a Subways Loop?

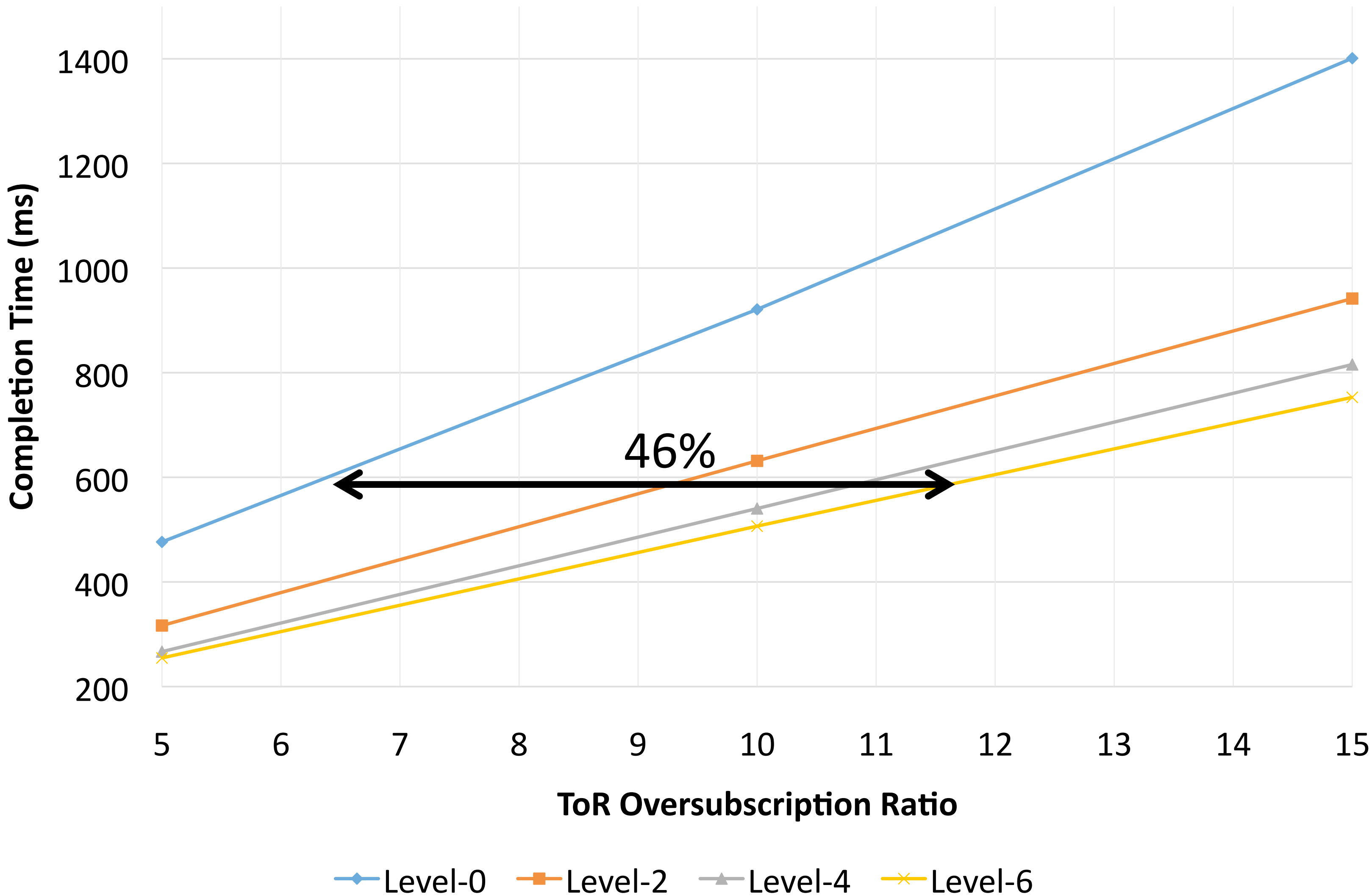


Evaluation

Improving Memcache Throughput



Faster MapReduce with Less Hardware



Subways Summary

- Data center network is becoming bottleneck
  - Above ToR, network is *both* congested and under-utilized
- **Subways:** Wire multiple NICs per server into adjacent racks
  - Cross-rack, cross-cluster, aisle-wide dynamic load balancing
- Benefits to application performance/system cost
  - **Memcache:** up to **2.8x** better throughput
  - **MapReduce:** equal performance with **1.9x** less bandwidth in data center aggregation network

Biography

- College: physics -> psychology -> philosophy
  - Took three CS classes as a senior
- After college: developed an OS for a z80
  - After project shipped, project got cancelled
  - So I applied to grad school; seven out of eight turned me down
- Grad school
  - Learned a lot
  - Dissertation had zero commercial impact for decades
- Post-grad
  - Pick topics where I get to learn a lot
  - Work with people from whom I can learn a lot