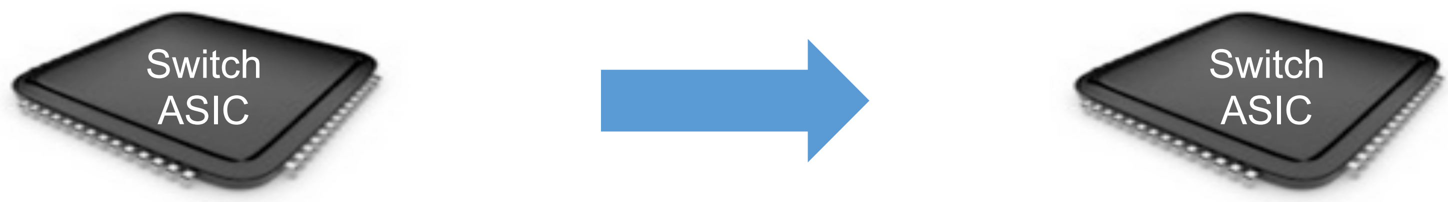
PISA-Based Application Acceleration for IO-Intensive Workloads

Xin Jin

Johns Hopkins University

Joint work with Xiaozhou Li, Haoyu Zhang, Nate Foster, Jeongkeun Lee, Robert Soulé, Changhoon Kim, and Ion Stoica

The revolution in networking

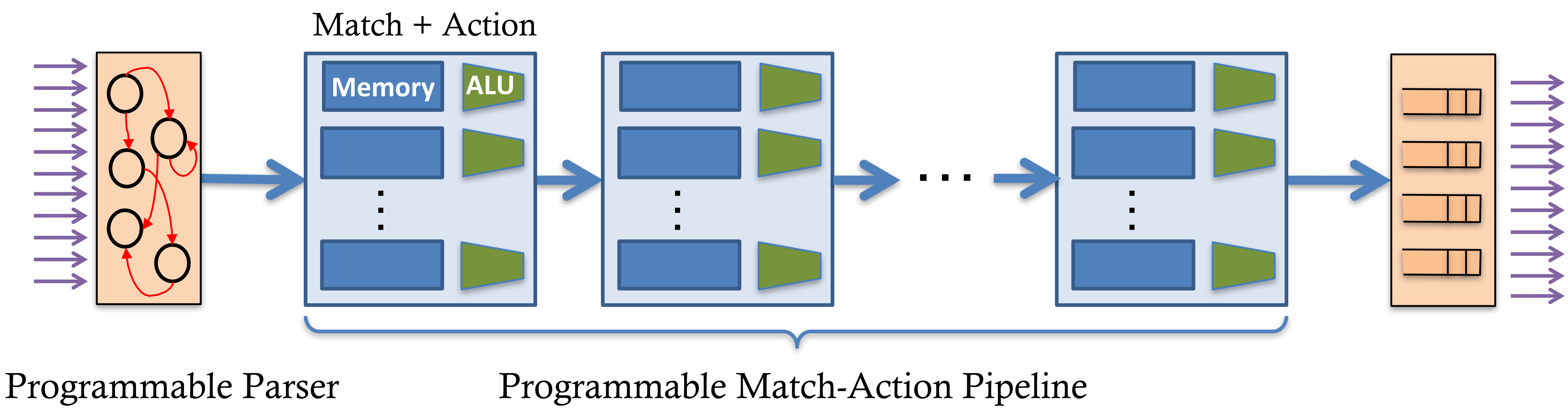


Fixed-function switch

Programmable switch

PISA: Protocol Independent Switch Architecture

- Programmable Parser
  - Convert packet data into metadata
- Programmable Mach-Action Pipeline
  - Operate on metadata and update memory state



Programmable switch data planes enable many innovations

Sonata [SIGCOMM'18]
Network Telemetry

Dapper [SOSR'17]
TCP Diagnosis

SilkRoad [SIGCOMM'17]
Layer 4 Load Balancing

HULA [SOSR'16]
Adaptive Multipath Routing

The ending of the Moore's Law, and the rise of domain specific processors…

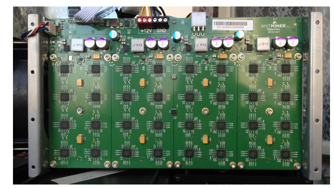
GPU

Graphics
Machine learning

TPU

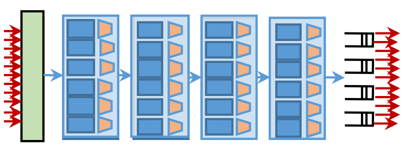
Machine learning

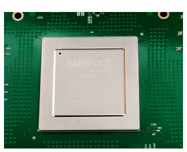
Antminer ASIC



Cryptocurrency

PISA





Traditional Packet Processing

Sonata [SIGCOMM'18]
Network Telemetry

Dapper [SOSR'17]
TCP Diagnosis

SilkRoad [SIGCOMM'17]
Layer 4 Load Balancing

HULA [SOSR'16]
Adaptive Multipath Routing

PISA-Based Accelerator
IO-Intensive Workloads

PISA switches as domain specific accelerators for IO-intensive workloads

- **NetCache** [SOSP'17]: balancing key-value stores with PISA-based caching

- **NetChain** [NSDI'18, best paper award]: fast coordination with PISA-based chain replication

Joint work with Xiaozhou Li, Haoyu Zhang, Nate Foster, Jeongkeun Lee, Robert Soulé, Changhoon Kim, and Ion Stoica

NetCache is a **rack-scale key-value store** that leverages **PISA-based caching** to achieve

billions QPS throughput & **~10 μs latency**

even under

highly-skewed & **rapidly-changing**

workloads.

Goal: fast and cost-efficient rack-scale key-value storage

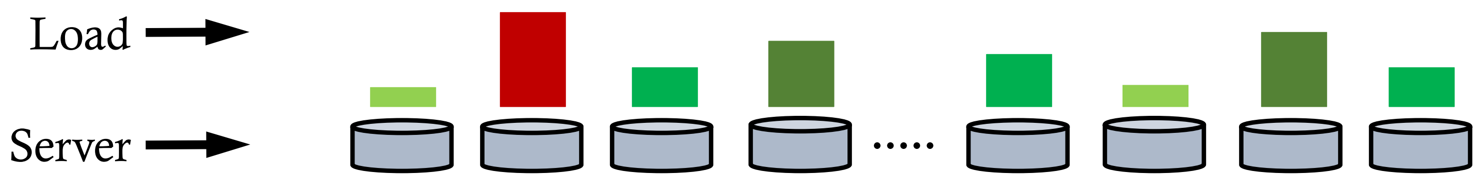
- Store, retrieve, manage key-value objects
  - Critical building block for large-scale cloud services

    …
  - Need to **meet aggressive latency and throughput objectives efficiently**

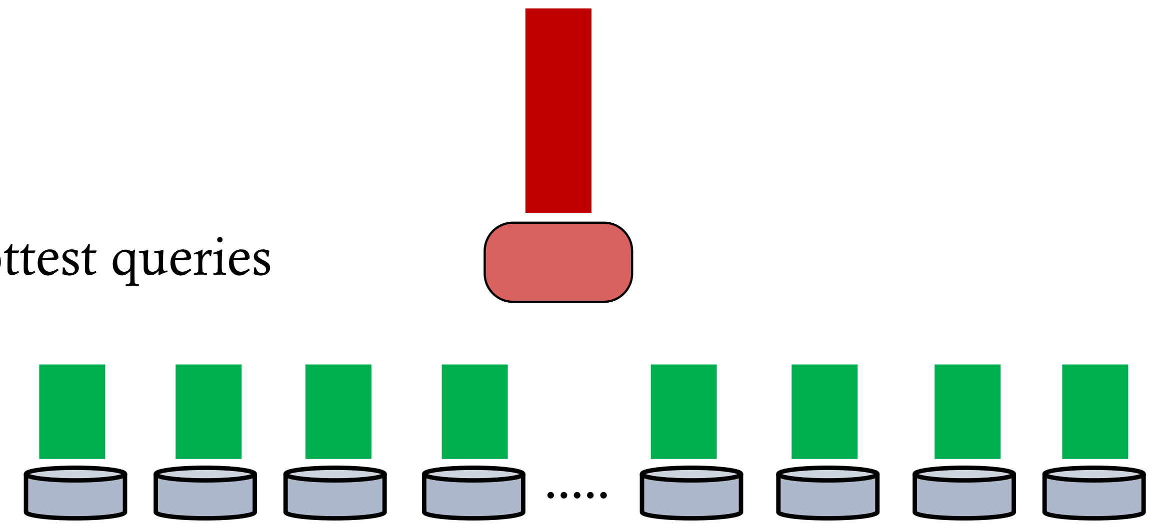
- **Target workloads**
  - Small objects
  - Read intensive
  - **Highly skewed and dynamic key popularity**

Key challenge: highly-skewed and rapidly-changing workloads

low throughput & high tail latency



Opportunity: fast, small cache for load balancing



Cache absorbs hottest queries

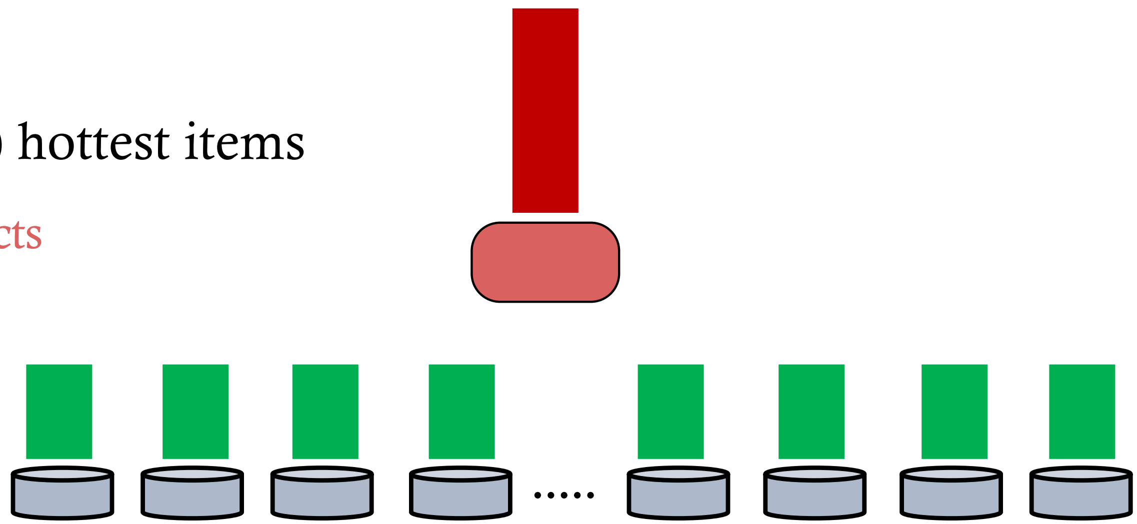
Balanced load

Opportunity: fast, small cache for load balancing

[B. Fan et al. **SoCC'11**, X. Li et al. **NSDI'16**]

Cache **O(*N* log *N*)** hottest items

E.g., 10,000 hot objects



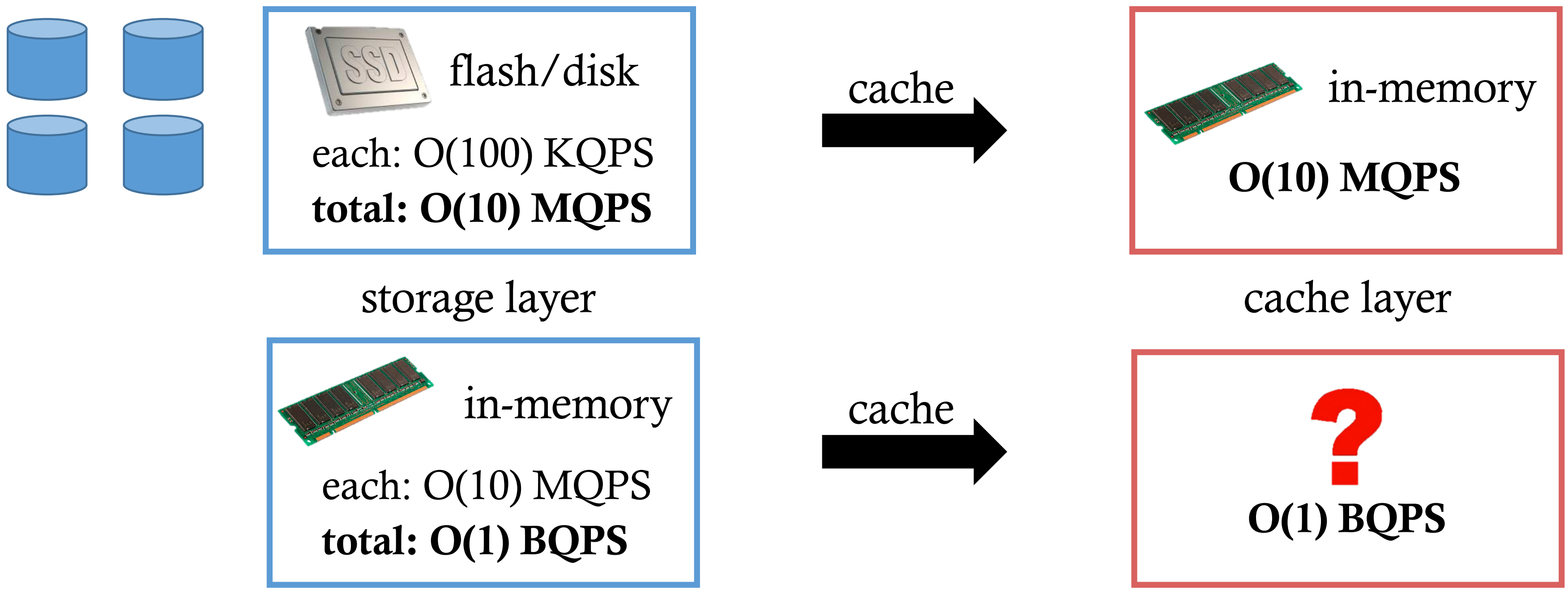
N: # of servers

E.g., 100 backends with 100 billions items

Requirement: cache throughput ≥ backend aggregate throughput

NetCache: towards billions QPS key-value storage rack

Cache needs to provide the **aggregate** throughput of the storage layer



NetCache: towards billions QPS key-value storage rack

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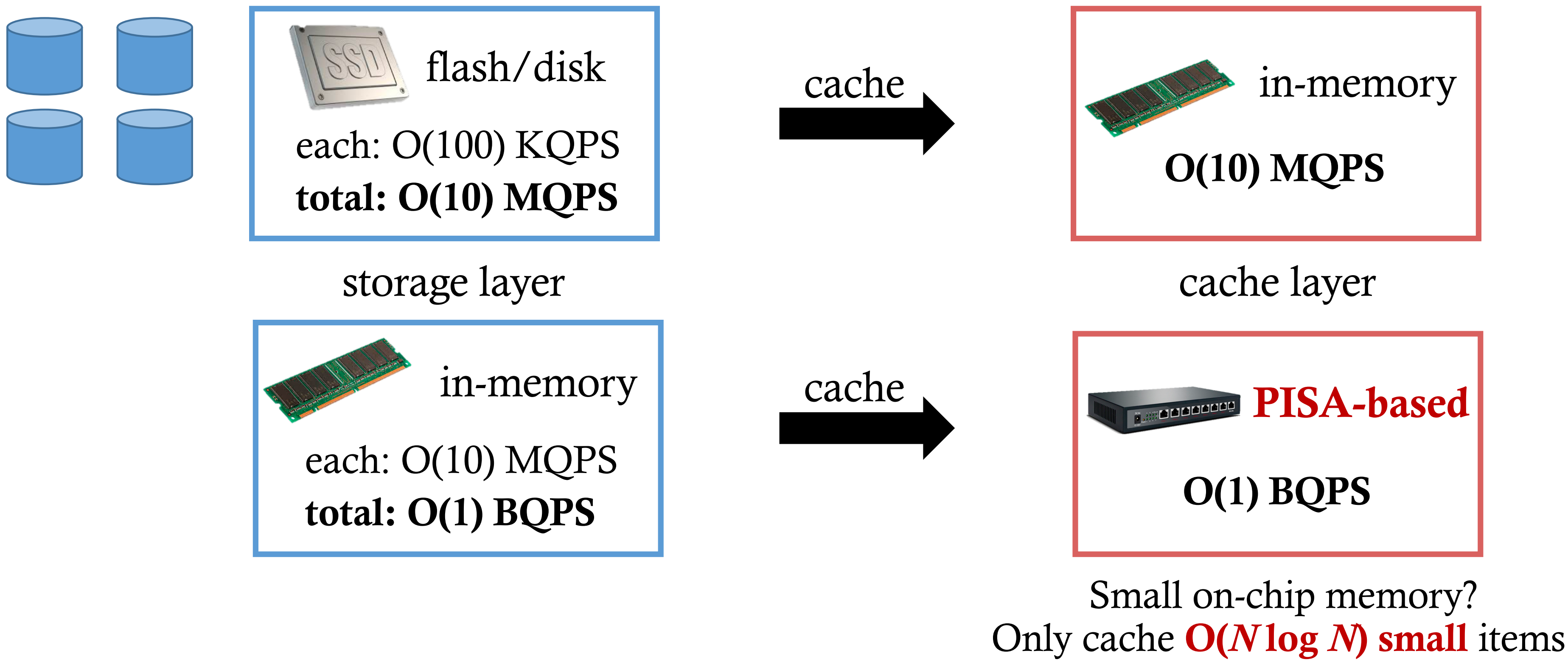
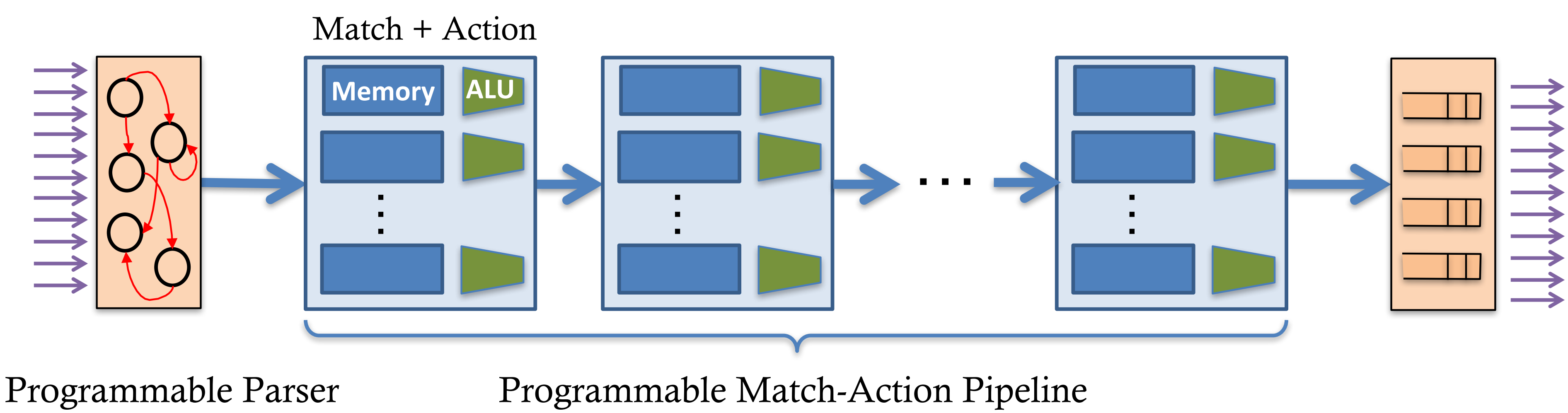


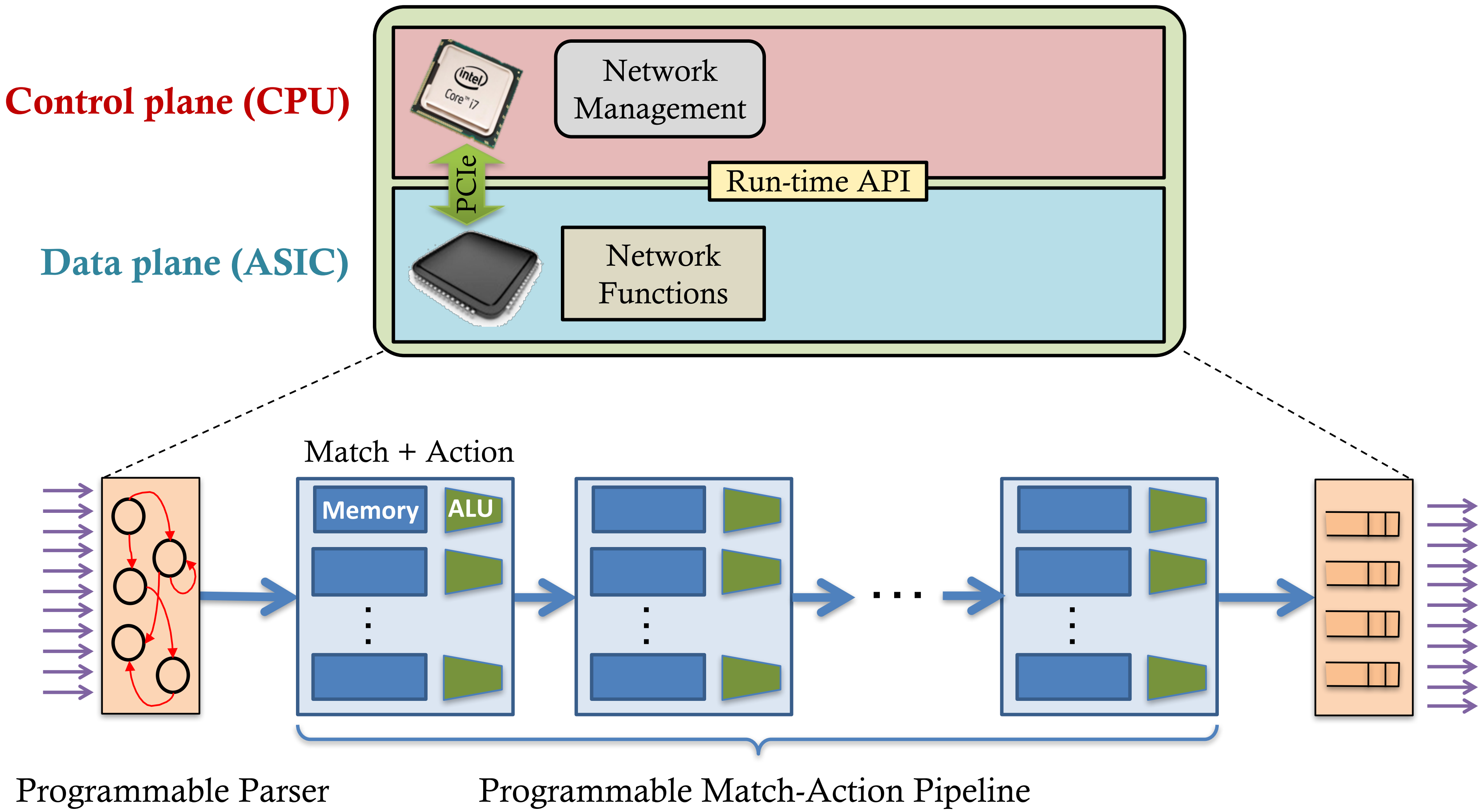
Key-value caching in network ASIC at line rate ?!

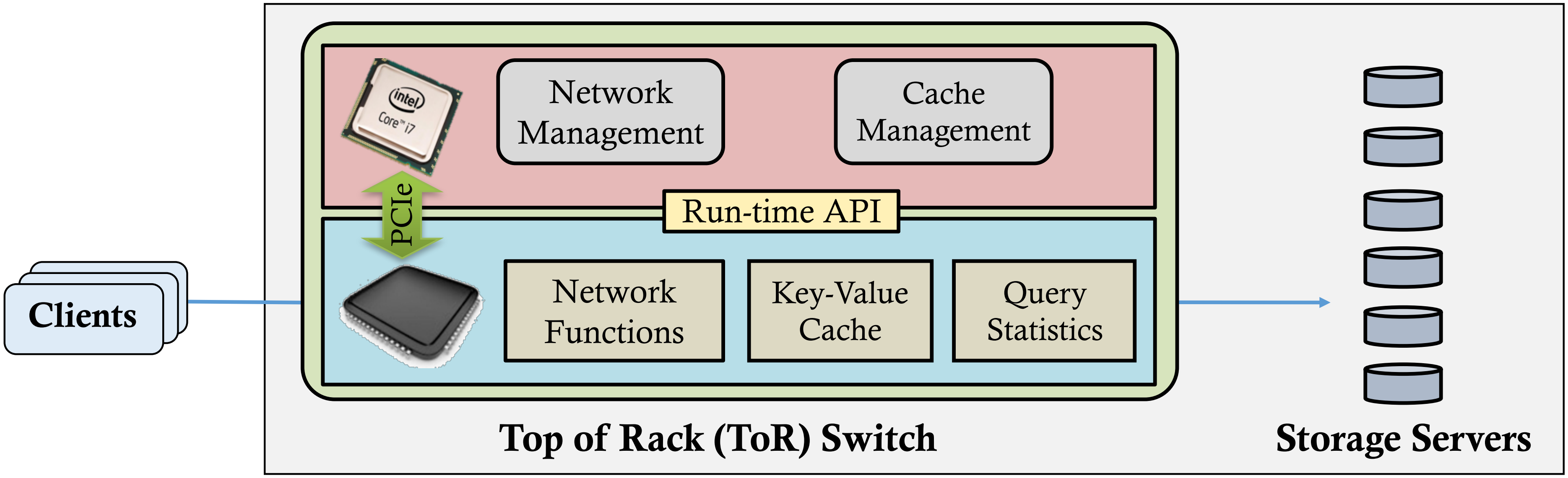
- How to identify application-level packet fields ?
- How to store and serve variable-length data ?
- How to efficiently keep the cache up-to-date ?

PISA: Protocol Independent Switch Architecture

- Programmable Parser
  - Parse custom key-value fields in the packet
- Programmable Mach-Action Pipeline
  - Read and update key-value data
  - Provide query statistics for cache update




Control plane (CPU)
Data plane (ASIC)
Network Management
Run-time API
PCIe
Network Functions
Match + Action
Memory
ALU
Programmable Parser
Programmable Match-Action Pipeline

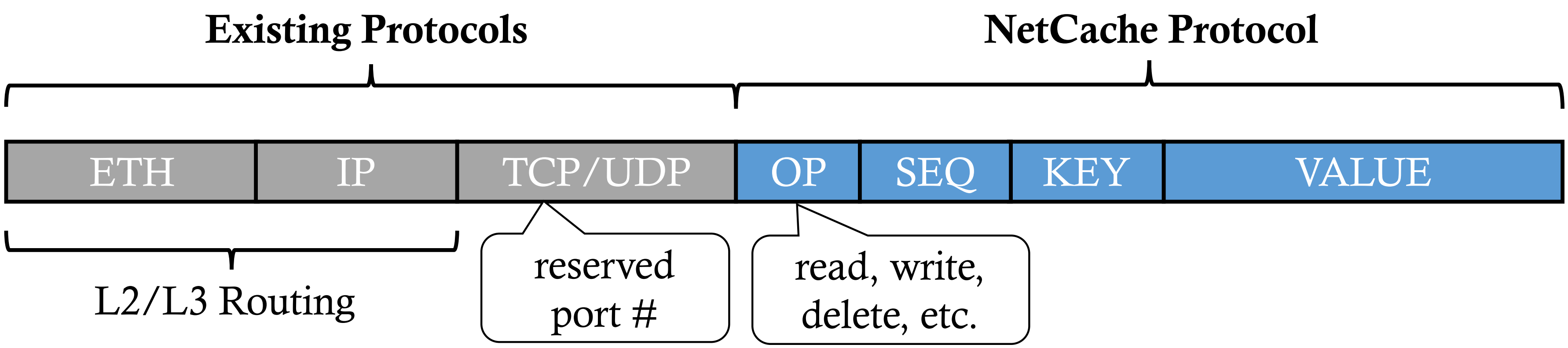


- **Switch data plane**
  - Key-value store to serve queries for cached keys
  - Query statistics to enable efficient cache updates
- **Switch control plane**
  - Insert hot items into the cache and evict less popular items
  - Manage memory allocation for on-chip key-value store

Key-value caching in network ASIC at line rate

- ❑ How to identify application-level packet fields ?
- ❑ How to store and serve variable-length data ?
- ❑ How to efficiently keep the cache up-to-date ?

NetCache Packet Format



- Application-layer protocol: compatible with existing L2-L4 layers
- Only the top of rack switch needs to parse NetCache fields

Key-value caching in network ASIC at line rate

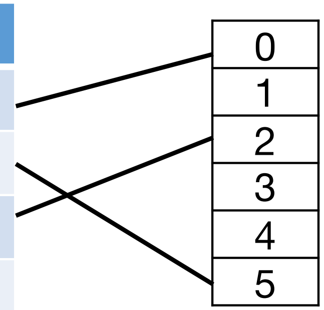
- How to identify application-level packet fields ?
- How to store and serve variable-length data ?
- How to efficiently keep the cache up-to-date ?

Key-value store using register arrays

Match-Action Table

Match	Action
Key = X	Read RA[0]
Key = Y	Read RA[5]
Key = Z	Read RA[2]
Default	Drop()

Register Array (RA)



Key Challenges:

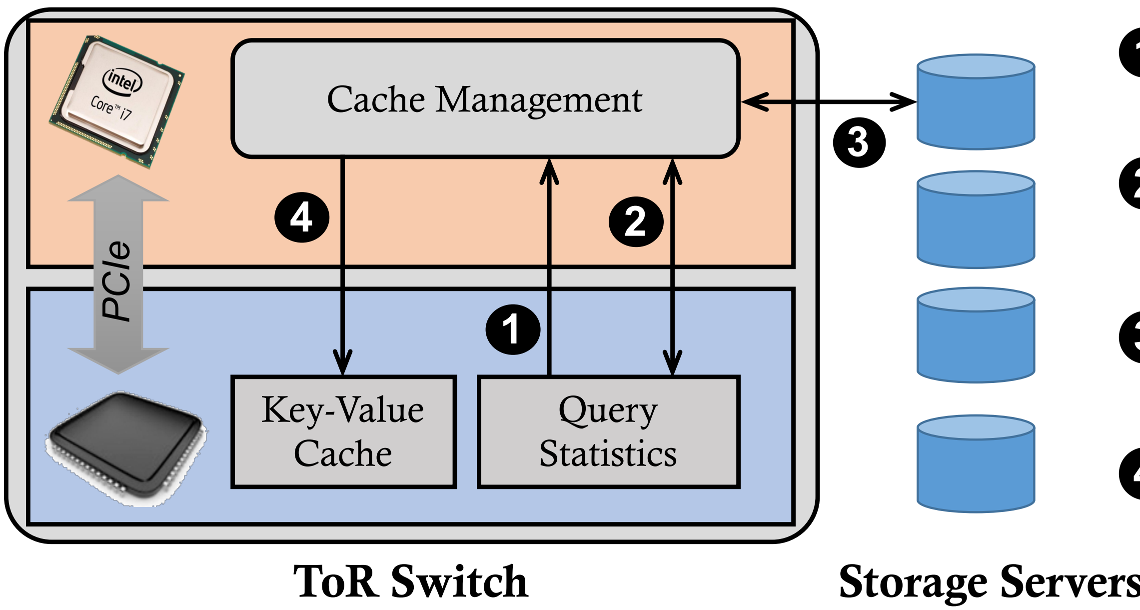
- No loop or string due to strict timing requirements
- Need to minimize hardware resources consumption
  - Number of table entries
  - Size of action data from each entry
  - Size of intermediate metadata across tables

Key-value caching in network ASIC at line rate

- How to identify application-level packet fields ?
- How to store and serve variable-length data ?
- How to efficiently keep the cache up-to-date ?

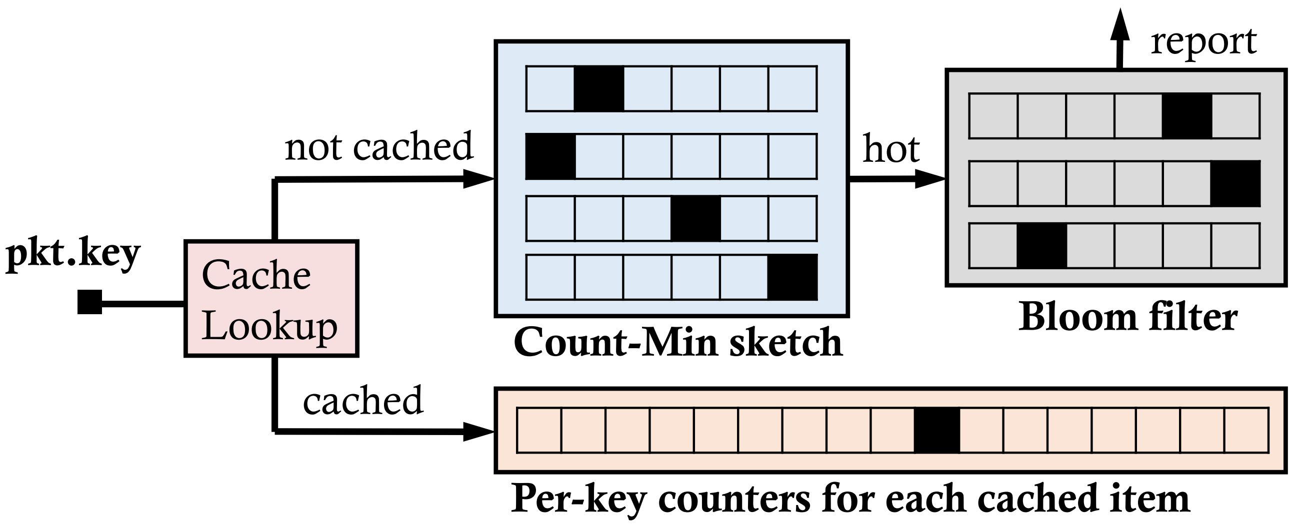
Cache insertion and eviction

- Challenge: cache the hottest O($N \log N$) items with **limited insertion rate**
- Goal: react quickly and effectively to workload changes with **minimal updates**



1. Data plane reports hot keys
2. Control plane compares loads of new hot and sampled cached keys
3. Control plane fetches values for keys to be inserted to the cache
4. Control plane inserts and evicts keys

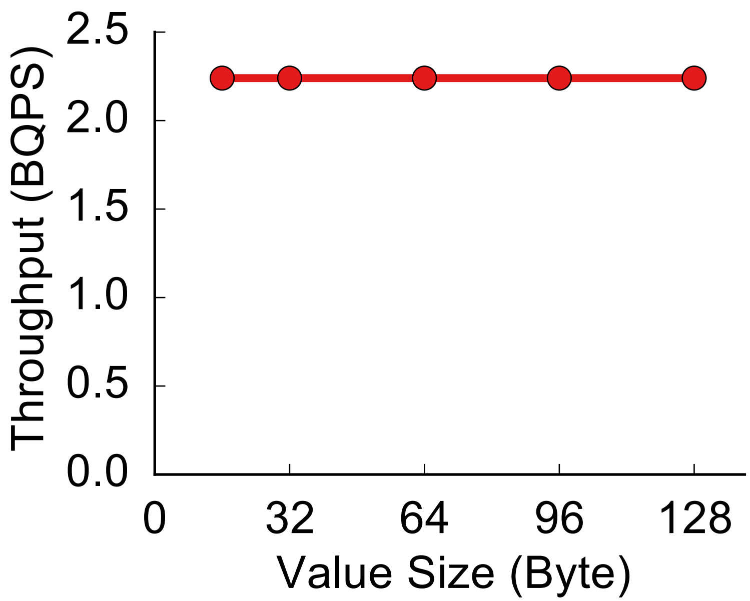
Query statistics in the data plane

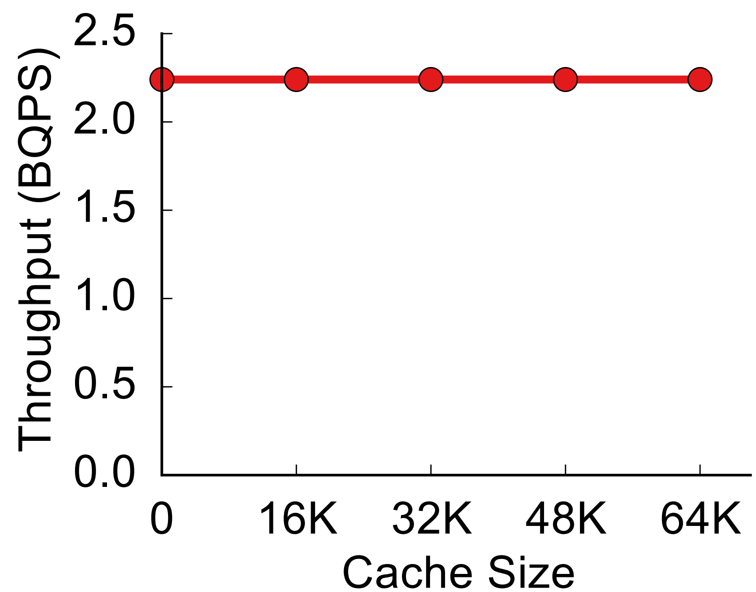


- Cached key: per-key counter array
- Uncached key
  - Count-Min sketch: report new hot keys
  - Bloom filter: remove duplicated hot key reports

The “boring life” of a NetCache switch

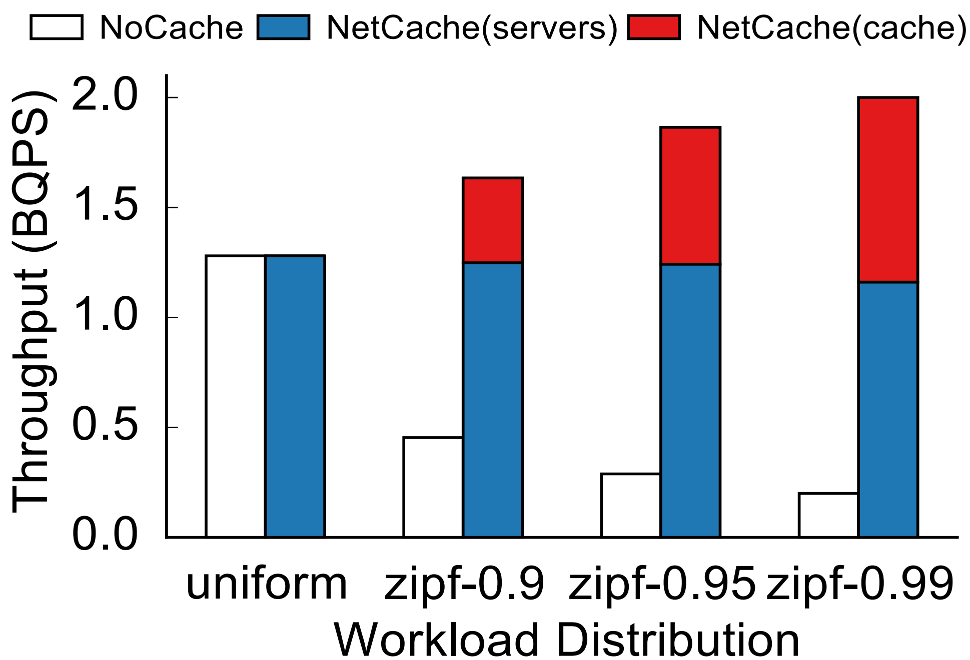
Single switch benchmark





And its “not so boring” benefits

1 switch + 128 storage servers



3-10x throughput improvements

NetCache is a **rack-scale key-value store** that leverages **PISA-based caching** to achieve

billions QPS throughput & **~10 μs latency**

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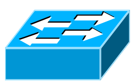
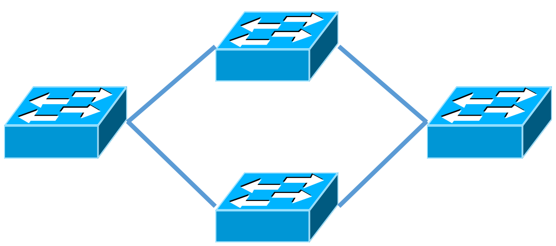


NetCache: lighting fast key-value cache enabled by PISA switches



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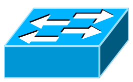

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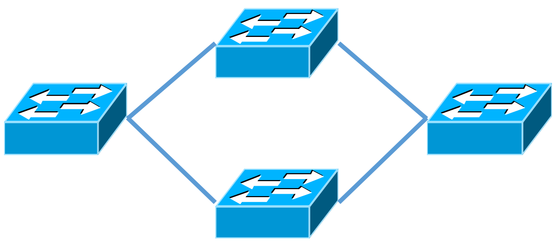
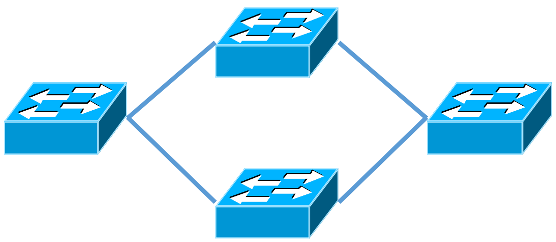


NetChain: lightning fast coordination enabled by PISA switches

Conventional wisdom: avoid coordination



NetChain: lightning fast coordination enabled by PISA switches

Open the door to rethink distributed systems design

Coordination services: fundamental building block of the cloud

Applications

hadoop | APACHE Spark | APACHE kafka | MESOS

Coordination Service

Google Chubby | Apache Zookeeper | etcd

Provide critical coordination functionalities

Applications

Coordination Service

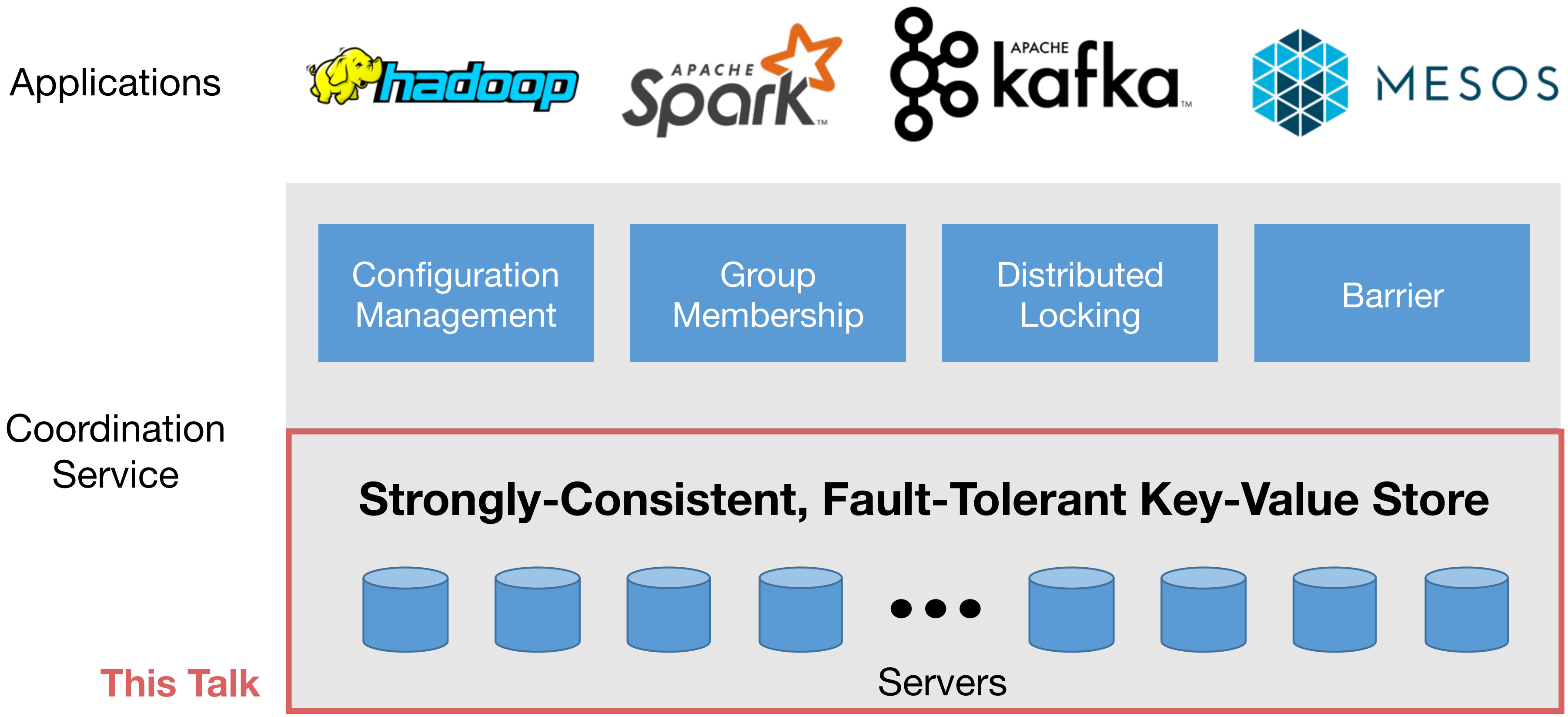
Configuration Management

Group Membership

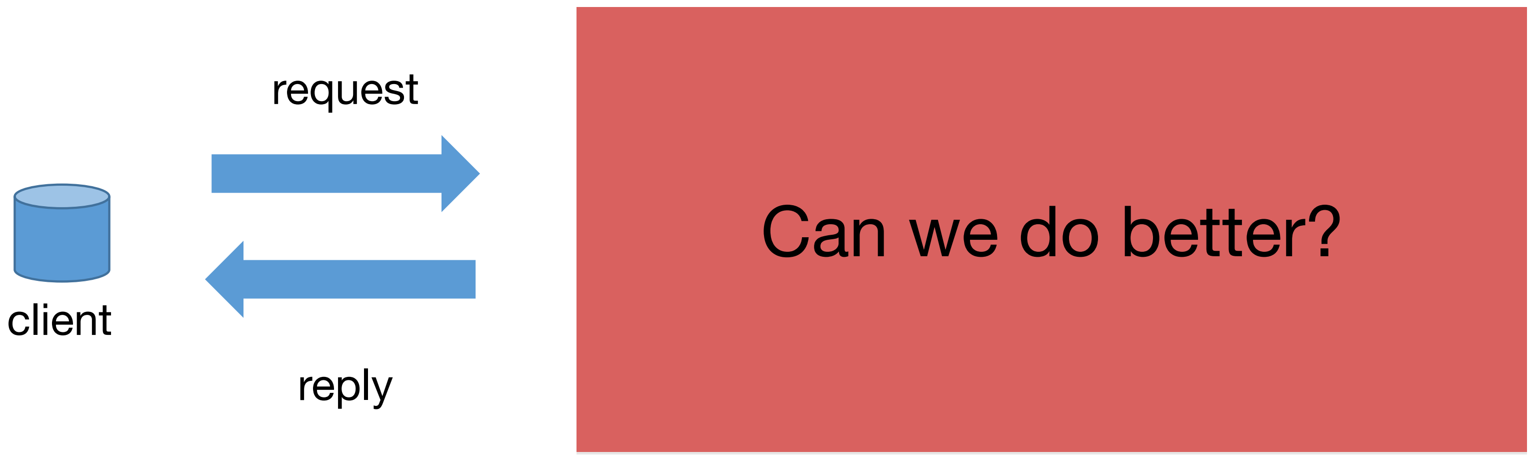
Distributed Locking

Barrier

The core is a strongly-consistent, fault-tolerant key-value store

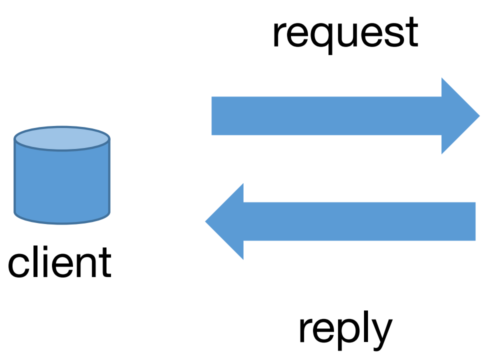


Workflow of coordination services



- ➢ Throughput: at most server NIC throughput
- ➢ Latency: at least one RTT, typically a few RTTs

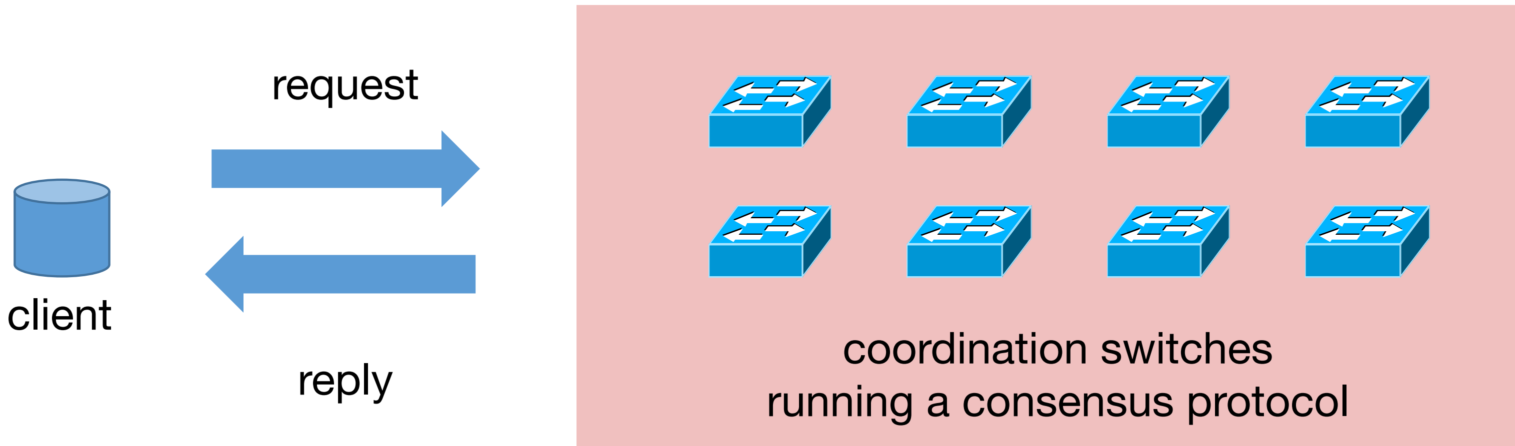
Opportunity: PISA-based coordination



Distributed coordination is
IO-intensive,
not computation-intensive.

	Server	Switch
Example	[NetBricks, OSDI'16]	**Barefoot Tofino**
Packets per second	30 million	**A few billion**
Bandwidth	10-100 Gbps	**6.5 Tbps**
Processing delay	10-100 us	**< 1 us**

Opportunity: PISA-based coordination



- Throughput: switch throughput
- Latency: half of an RTT

Design goals for coordination services

- High throughput
- Low latency
- Strong consistency
- Fault tolerance

Directly from
high-performance switches

How?

Design goals for coordination services

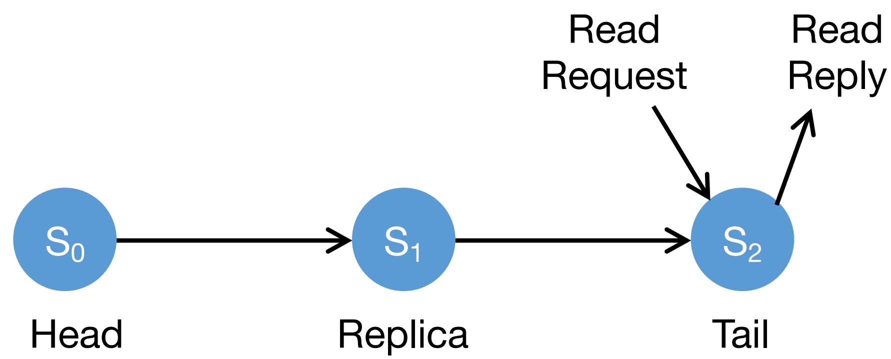
- High throughput
- Low latency

Directly from
high-performance switches

- Strong consistency
- Fault tolerance

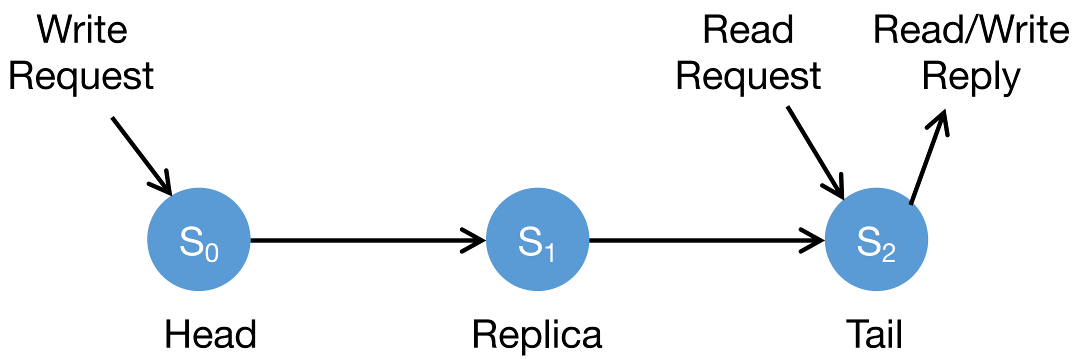
Chain replication with PISA switches

What is chain replication



- Storage nodes are organized in a chain structure
- Handle operations
  - Read from the tail

What is chain replication

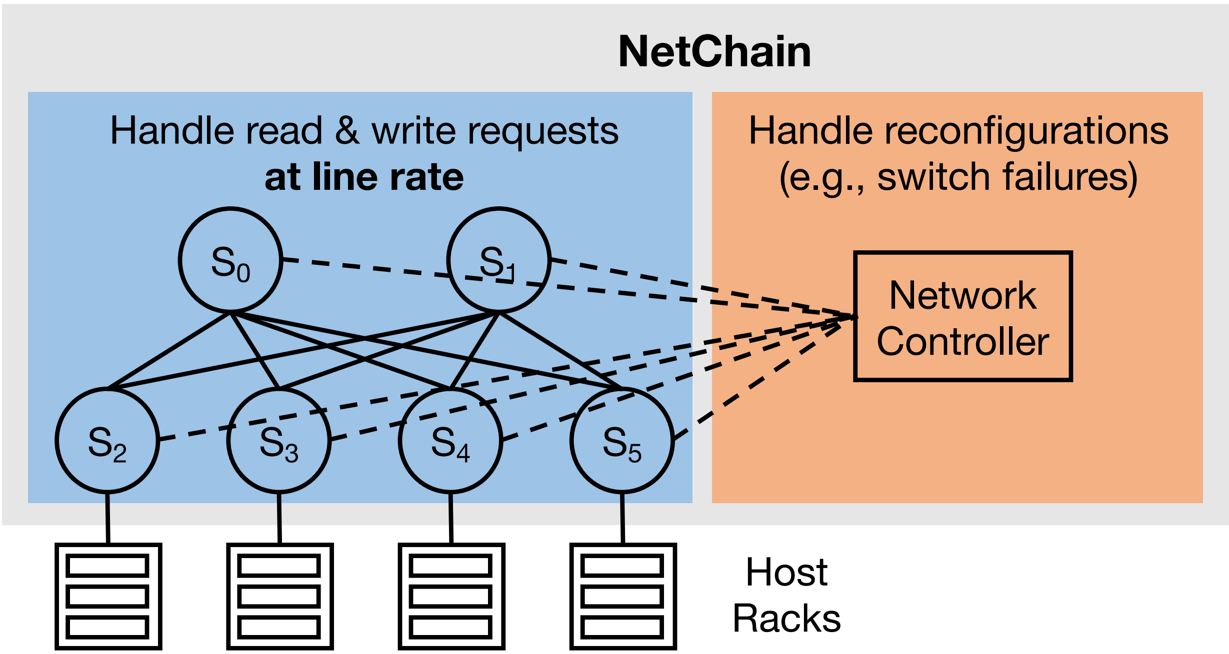


- Storage nodes are organized in a chain structure
- Handle operations
  - Read from the tail
  - Write from head to tail
- Provide strong consistency and fault tolerance
  - Tolerate f failures with f+1 nodes

Division of labor in chain replication: a perfect match to network architecture

Chain Replication	**Storage Nodes** • Optimize for high-performance to handle read & write requests • Provide strong consistency	**Auxiliary Master** • Handle less frequent reconfiguration • Provide fault tolerance
	⬍	⬍
Network Architecture	**Network Data Plane** • Handle packets at line rate	**Network Control Plane** • Handle network reconfiguration

NetChain overview



How to build a strongly-consistent, fault-tolerant, PISA-based key-value store

- How to store and serve key-value items?
- How to route queries according to chain structure?
- How to handle out-of-order delivery in network?
- How to handle switch failures?

Data Plane

Control Plane

How to build a strongly-consistent, fault-tolerant, PISA-based key-value store

- How to store and serve key-value items?
  NetCache ☺
- How to route queries according to chain structure?
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Data Plane

- How to handle switch failures?

Control Plane

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Data Plane

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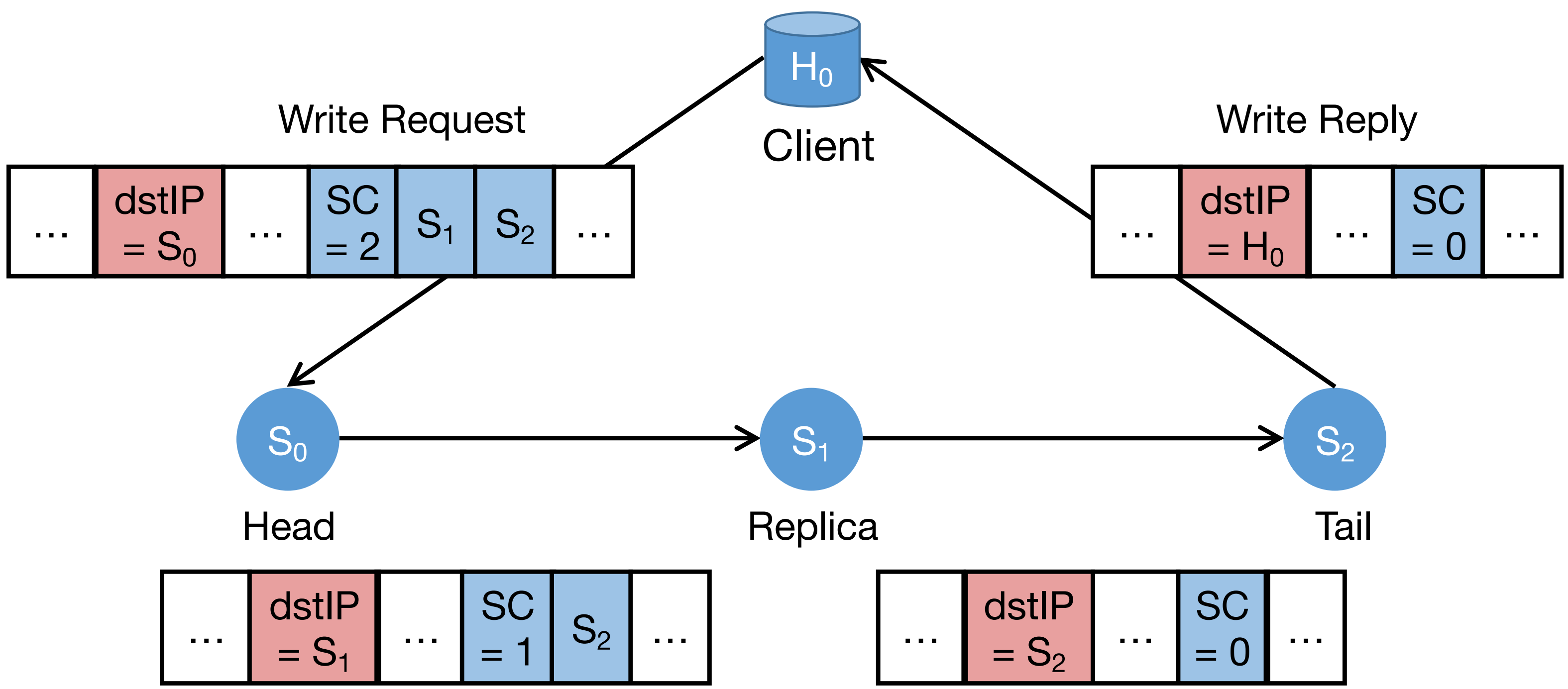
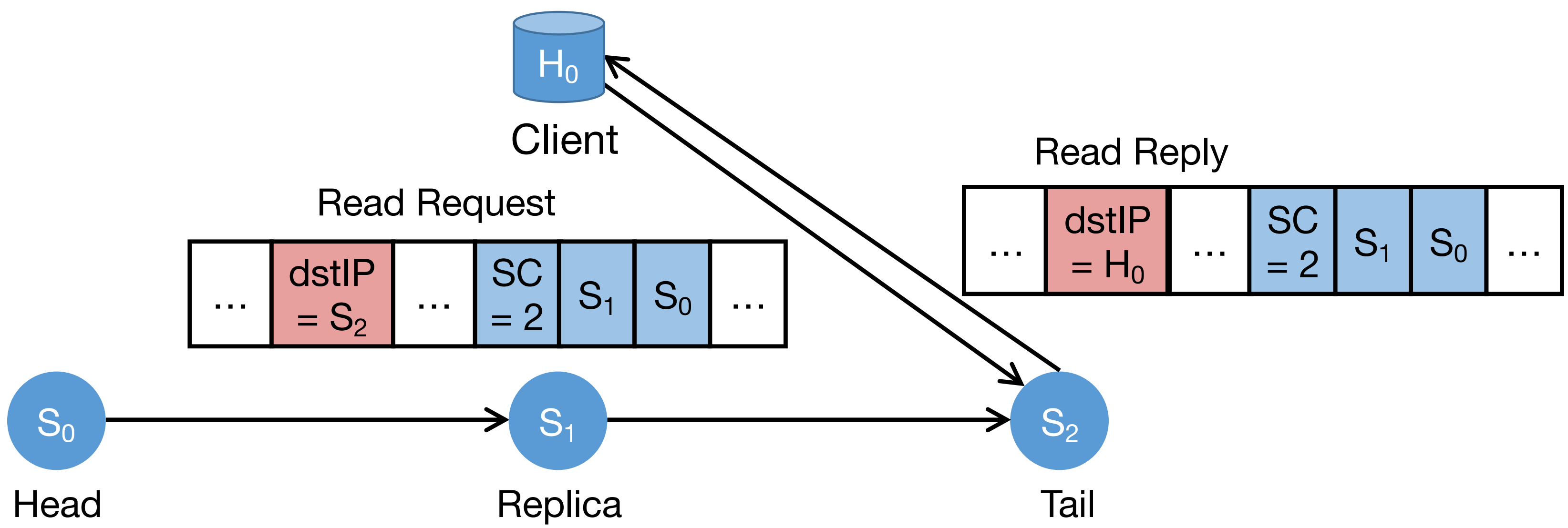
Control Plane

NetChain routing: segment routing according to chain structure



NetChain routing: segment routing according to chain structure



How to build a strongly-consistent, fault-tolerant, PISA-based key-value store

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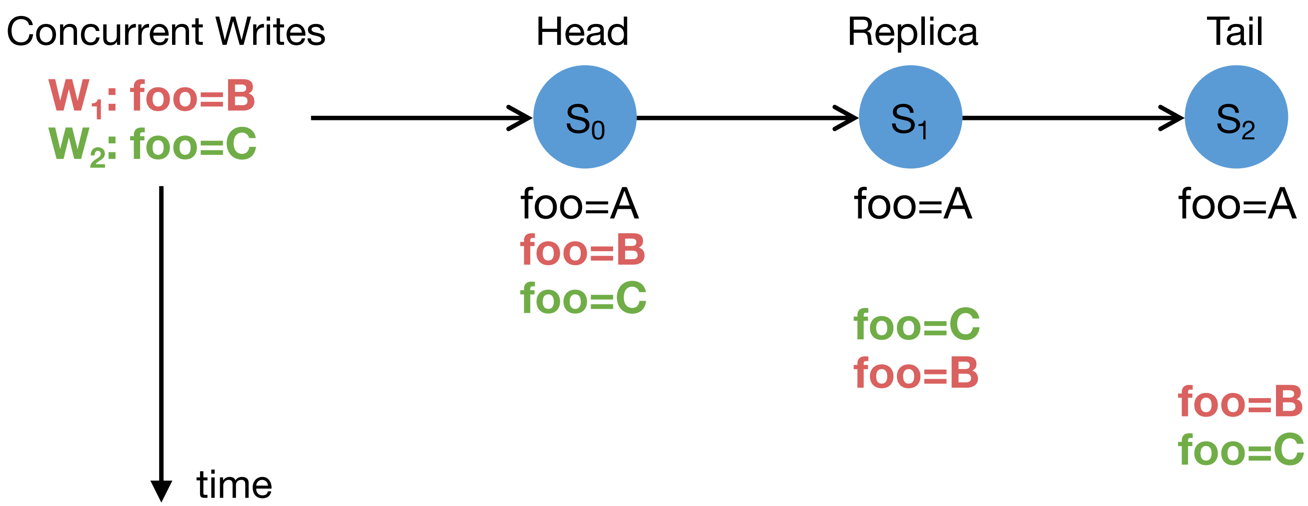
- ➢ How to handle switch failures?

Data Plane

Control Plane

Problem of out-of-order delivery



Serialization with sequence number

How to build a strongly-consistent, fault-tolerant, PISA-based key-value store

- How to store and serve key-value items?
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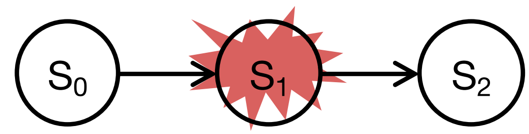
Data Plane

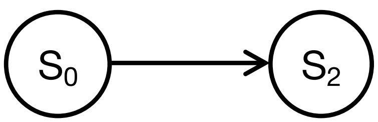
Control Plane

Handle a switch failure

Before failure: tolerate f failures with f+1 nodes

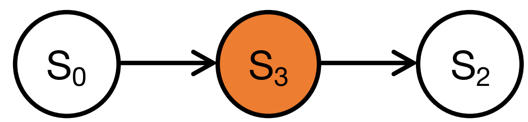


Fast Failover



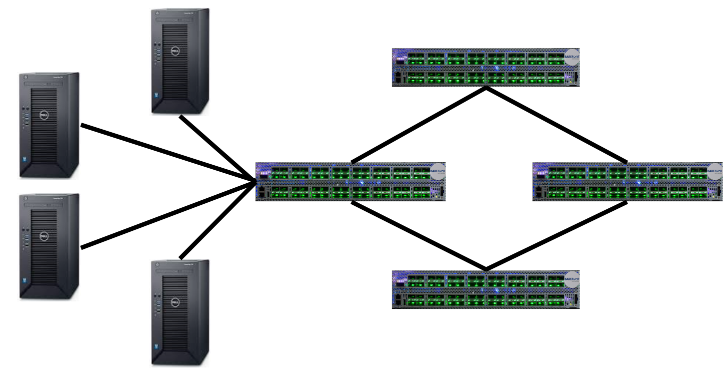
- Failover to remaining f nodes
- Tolerate f-1 failures
- Efficiency: only need to update neighbor switches of failed switch

Failure Recovery



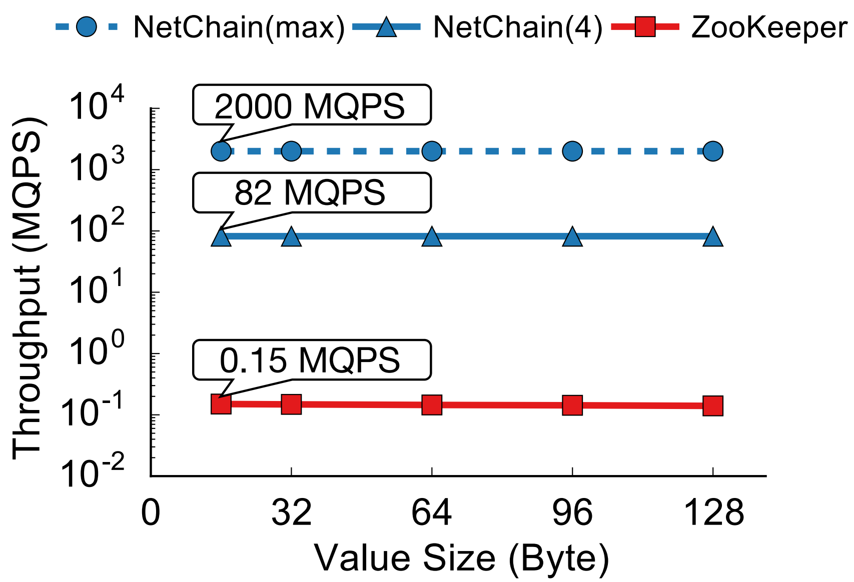
- Add another switch
- Tolerate f failures again
- Consistency: two-phase atomic switching
- Minimize disruption: virtual groups

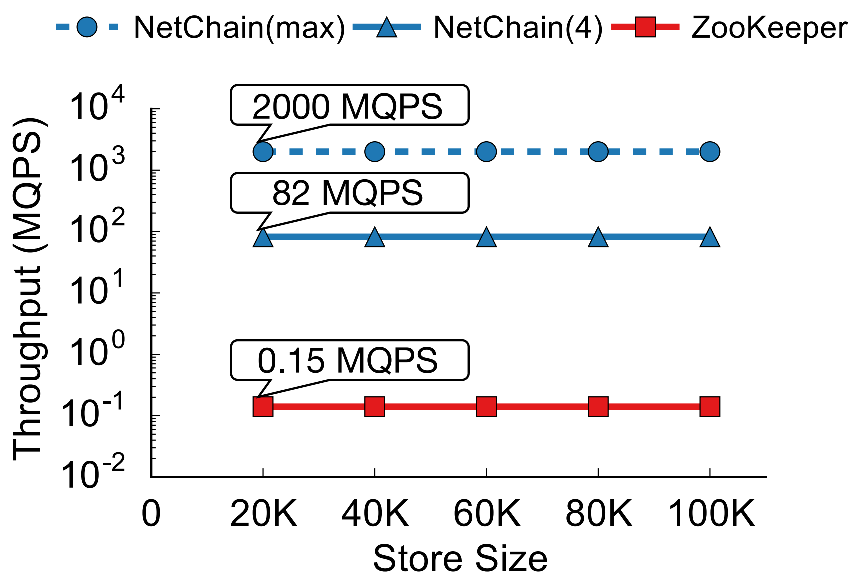
Implementation



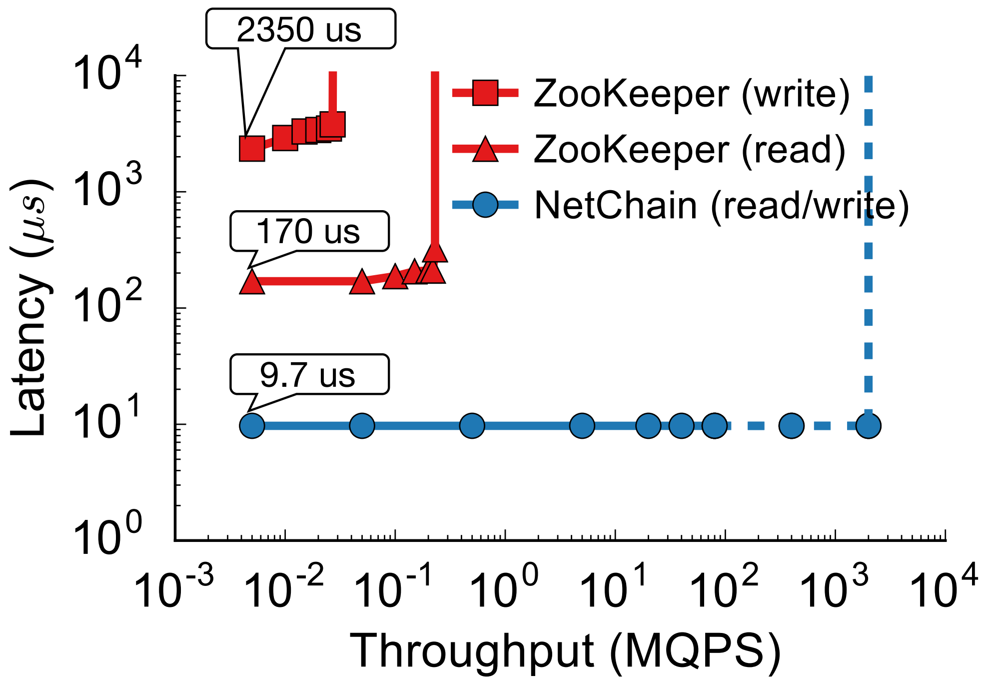
- **Testbed**
  - 4 Barefoot Tofino switches and 4 commodity servers
- **Switch**
  - P4 program on 6.5 Tbps Barefoot Tofino
  - Routing: basic L2/L3 routing
  - Key-value store: up to 100K items, up to 128-byte values
- **Server**
  - 16-core Intel Xeon E5-2630, 128 GB memory, 25/40 Gbps Intel NICs
  - Intel DPDK to generate query traffic: up to 20.5 MQPS per server

Orders of magnitude higher throughput





Orders of magnitude lower latency



Conclusion

- **Moore's law** is ending…
  - **Specialized** processors for **domain-specific** workloads: GPU servers, FPGA servers, TPU servers…

- **PISA servers**: new generation of ultra-high performance systems for **IO-intensive workloads** enabled by PISA switches
  - NetCache: fast key-value caching built with PISA switches
  - NetChain: fast coordination built with PISA switches

Thanks!