The Impact of Thread-Per-Core Architecture on Application Tail Latency

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Introduction

- Thread-per-core architecture has emerged to eliminate overheads in traditional multi-threaded architectures in server applications.
- Partitioning of hardware resources can improve parallelism, but there are various trade-offs applications need to consider.
- Takeaway: *Request steering* and *OS interfaces* are holding back the thread-per-core architecture.

Outline

- Overview of thread-per-core
- A key-value store
- Impact on tail latency
- Problems in the approach
- Future directions

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What is thread-per-core?

- Thread-per-core = no multiplexing of a CPU core at OS level
- Eliminates thread context switching overhead [Qin 2019; Seastar]
- Enables elimination of thread synchronization by partitioning [Seastar]
- Eliminates thread scheduling delays [Ousterhout, 2019]

Ousterhout et al. 2019. Shenango: Achieving High CPU Efficiency for Latency-sensitive Datacenter Workloads. NSDI ’19.
Qin et al. 2018. Arachne: Core-Aware Thread Management. OSDI ’18.
Seastar framework for high-performance server applications on modern hardware. http://seastar.io/

Interrupt isolation for thread-per-core

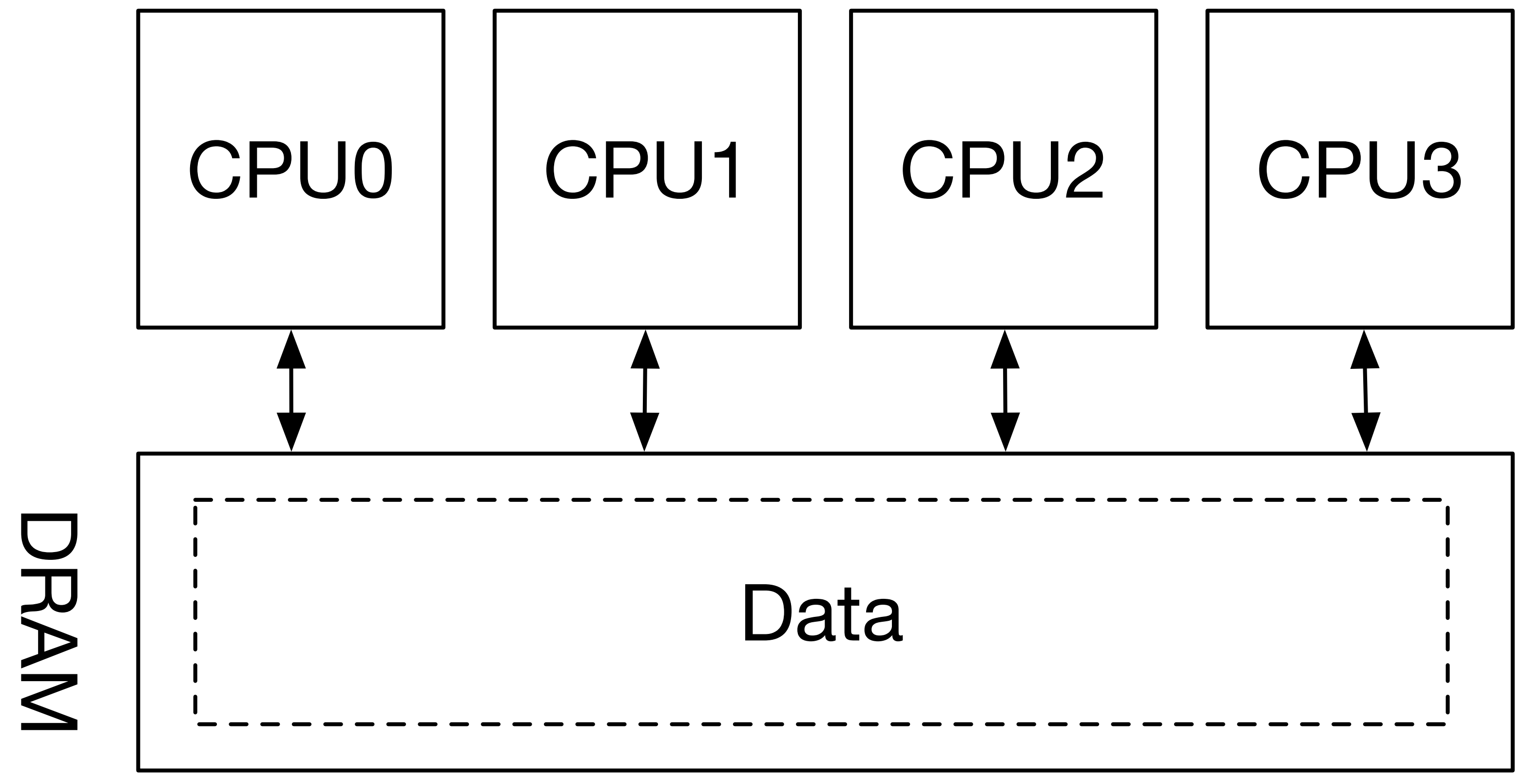
- The in-kernel network stack runs in kernel threads, which interfere with application threads.
- Network stack processing must be isolated to CPU cores not running application thread.
- Interrupt isolation can be done with IRQ affinity and IRQ balancing configuration changes.
- NIC receive side-steering (RSS) configuration needs to align with IRQ affinity configuration.

Li *et al*. 2014. Tales of the Tail: Hardware, OS, and Application-level Sources of Tail Latency. SOCC '14

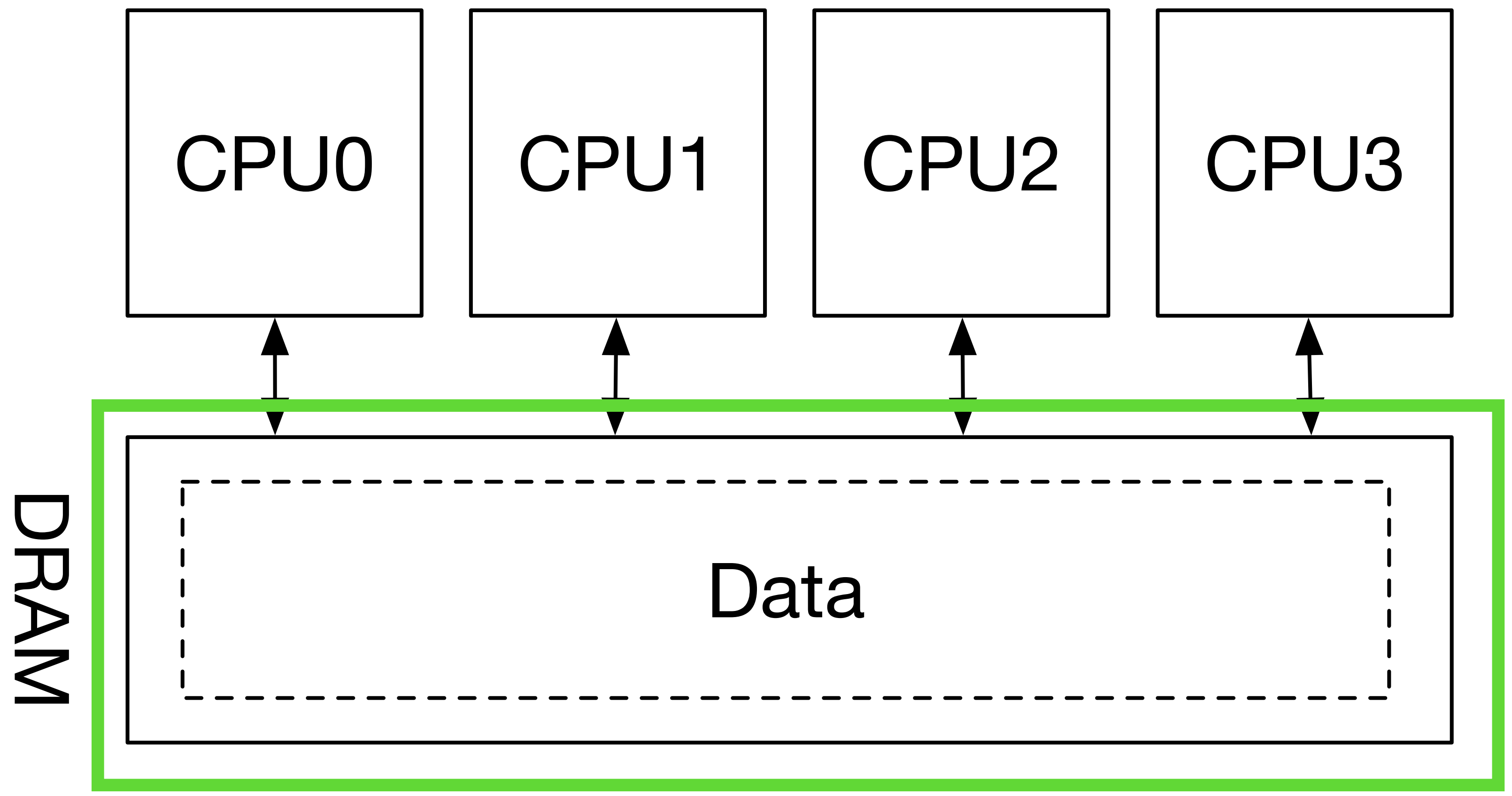
Partitioning in thread-per-core

- Partitioning of hardware resources (such as NIC and DRAM) can improve parallelism, by eliminating thread synchronization.
- Different ways of partitioning resources:
  - Shared-everything, shared-nothing, and shared-something.

Shared-everything

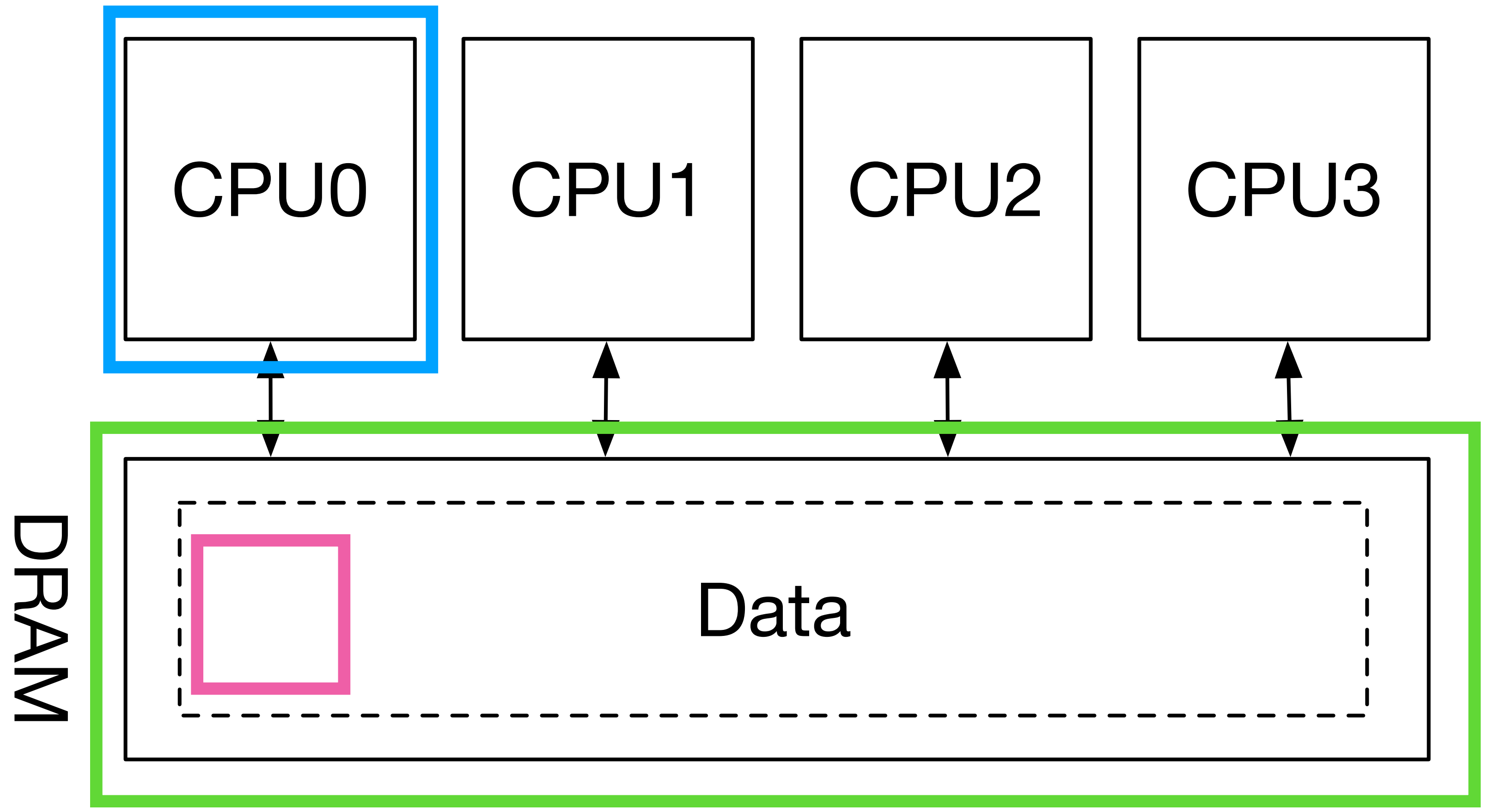


Shared-everything



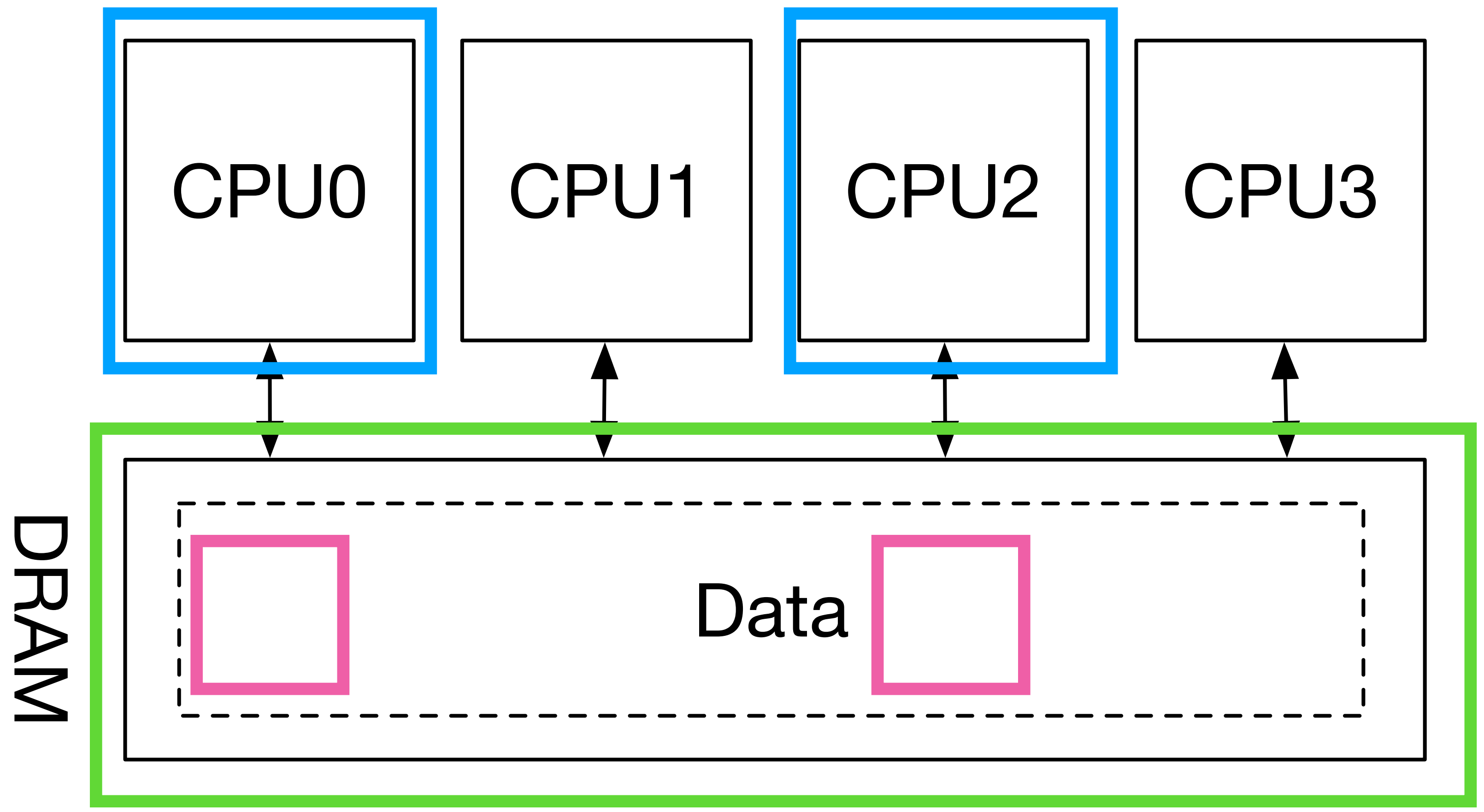
Hardware resources are shared between all CPU cores.

Shared-everything



Every request can be processed on any CPU core.

Shared-everything



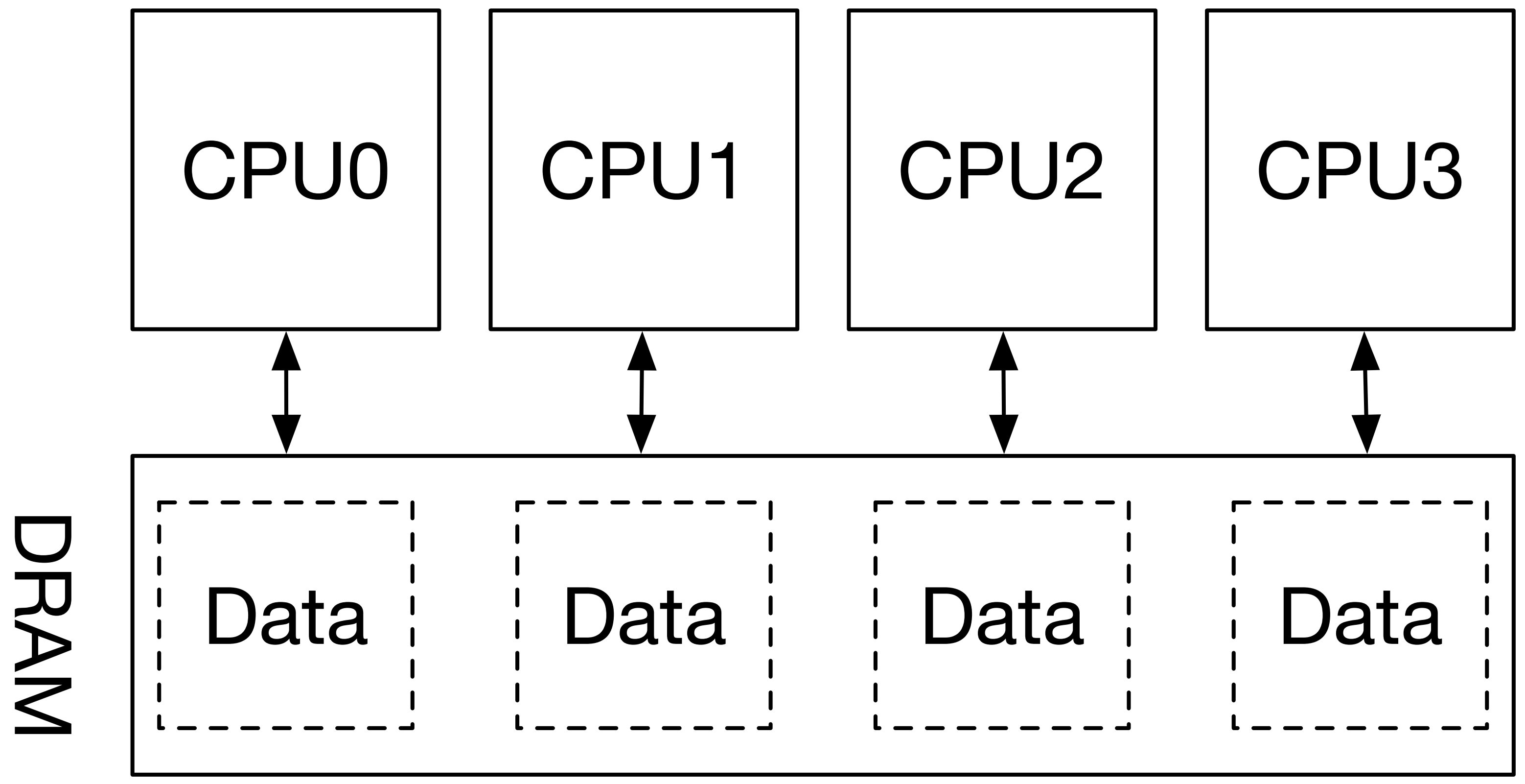
Data access must be synchronized.

Shared-everything

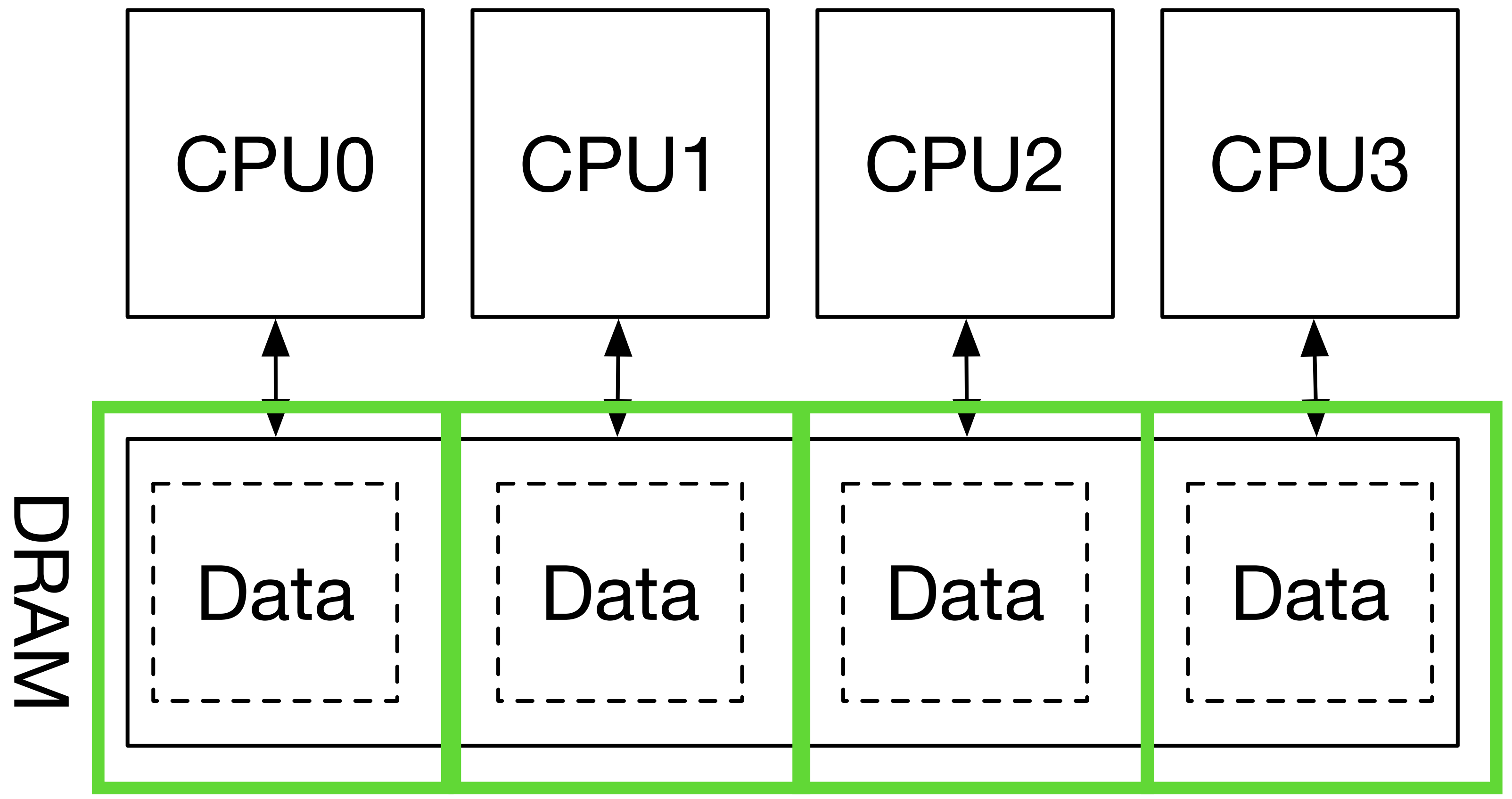
- Advantages:
    - Every request can be processed on any CPU core.
    - No request steering needed.
- Disadvantages:
    - Shared-memory scales badly on multicore [Holland, 2011]
- Examples:
    - Memcached (when thread pool size equals CPU core count)

Holland *et al*. 2011. Multicore OSes: Looking Forward from 1991, Er, 2011. HotOS ‘11

Shared-nothing

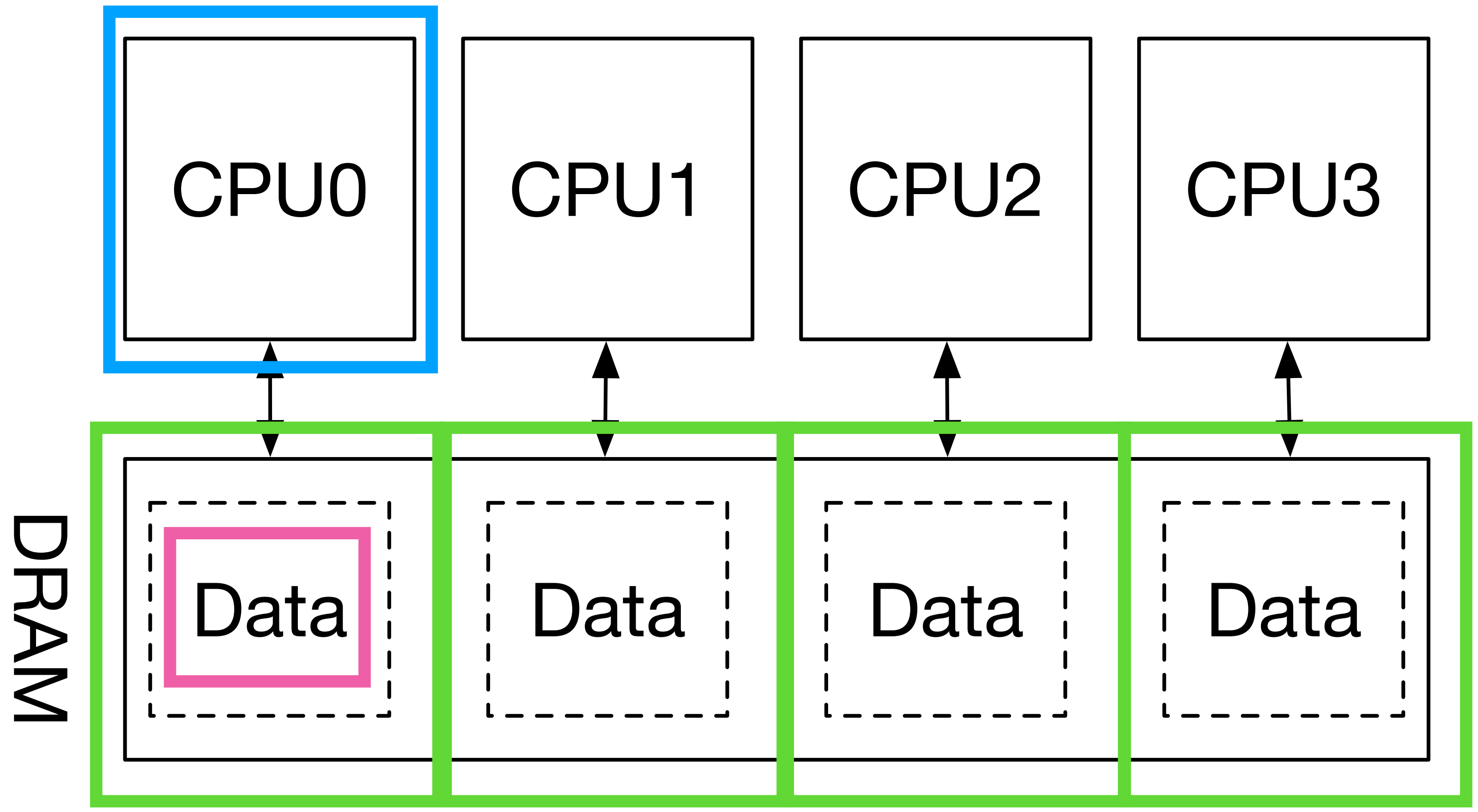


Shared-nothing



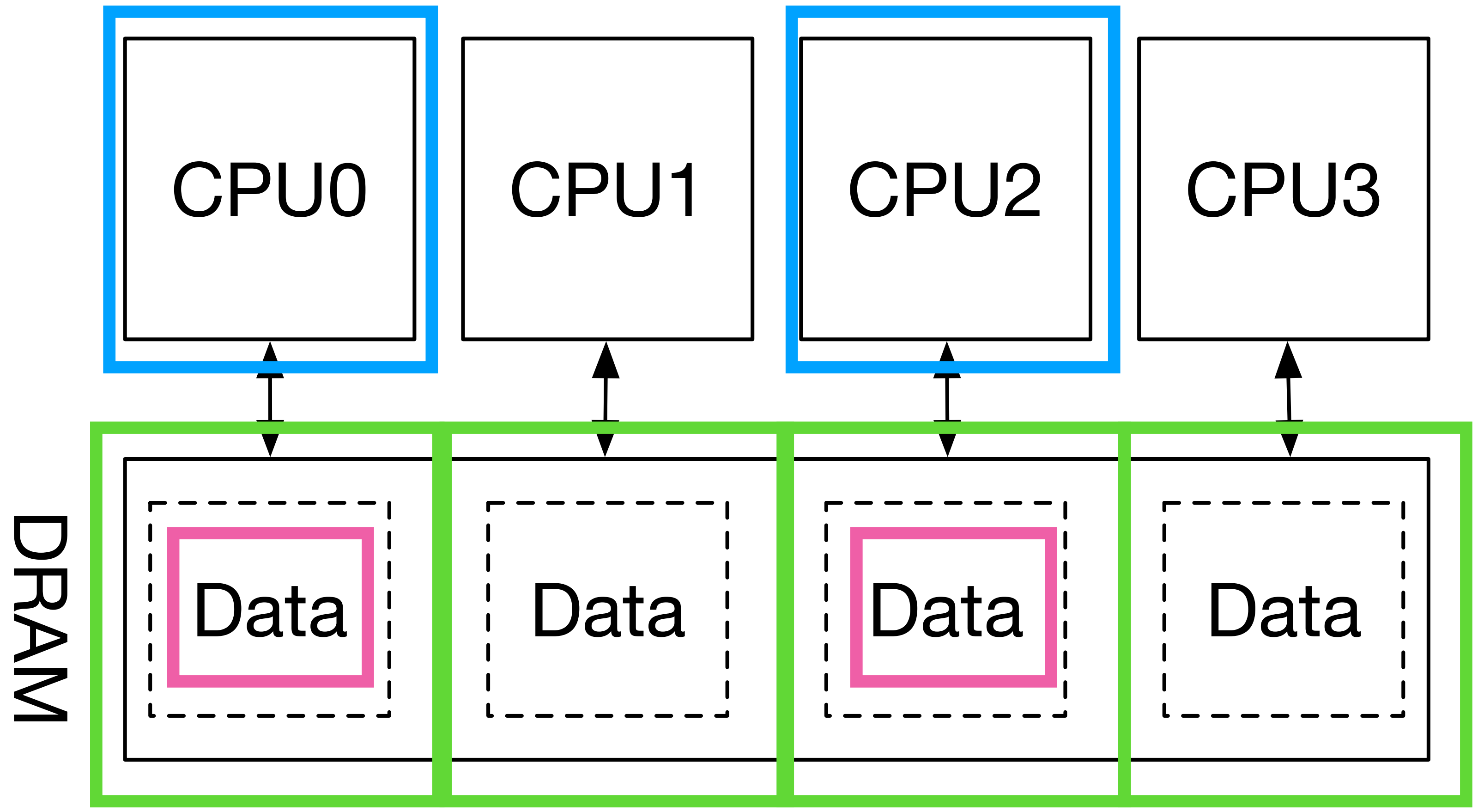
Hardware resources are partitioned between CPU cores.

Shared-nothing



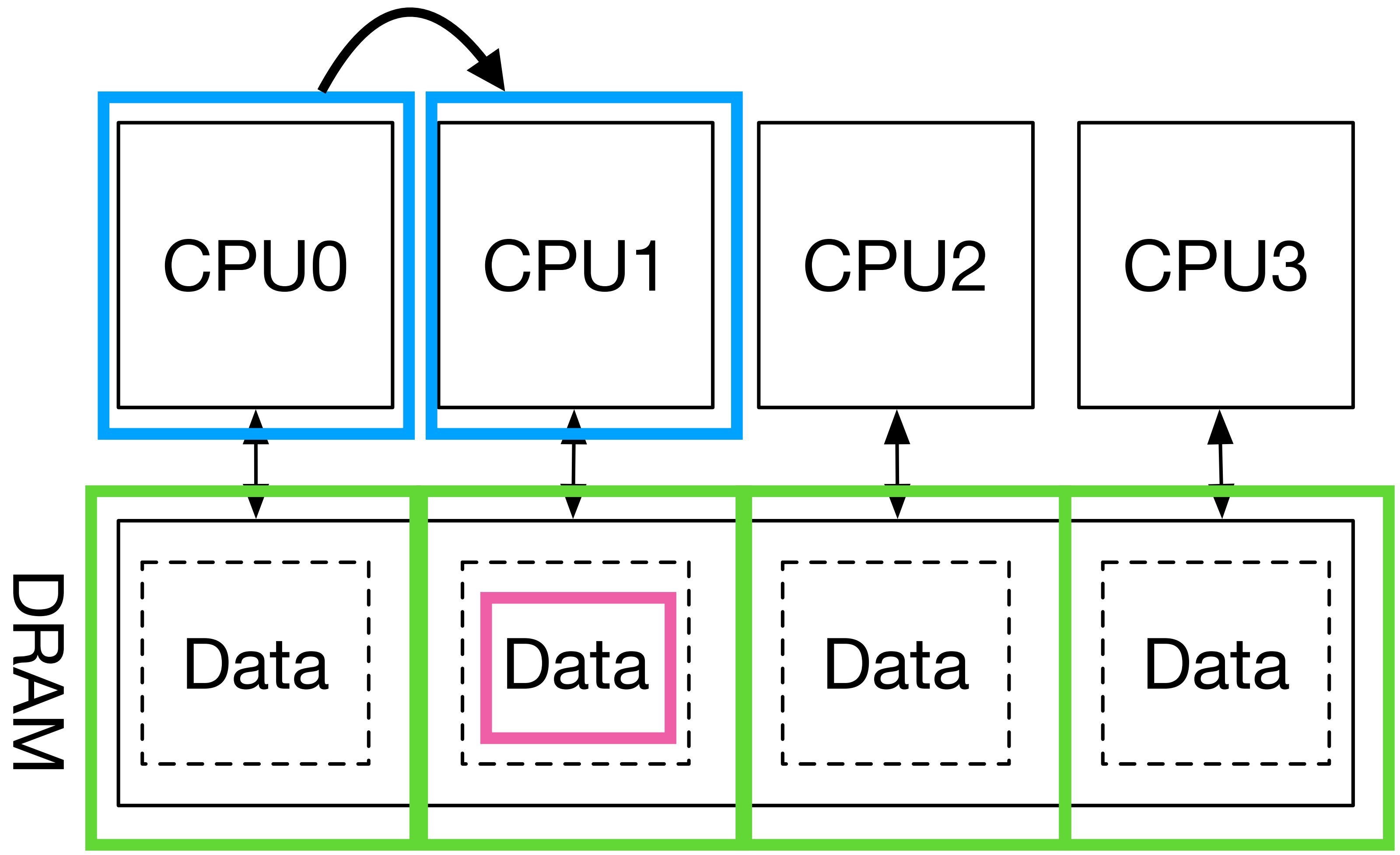
Request can be processed on one specific CPU core.

Shared-nothing



Data access does not require synchronization.

Shared-nothing



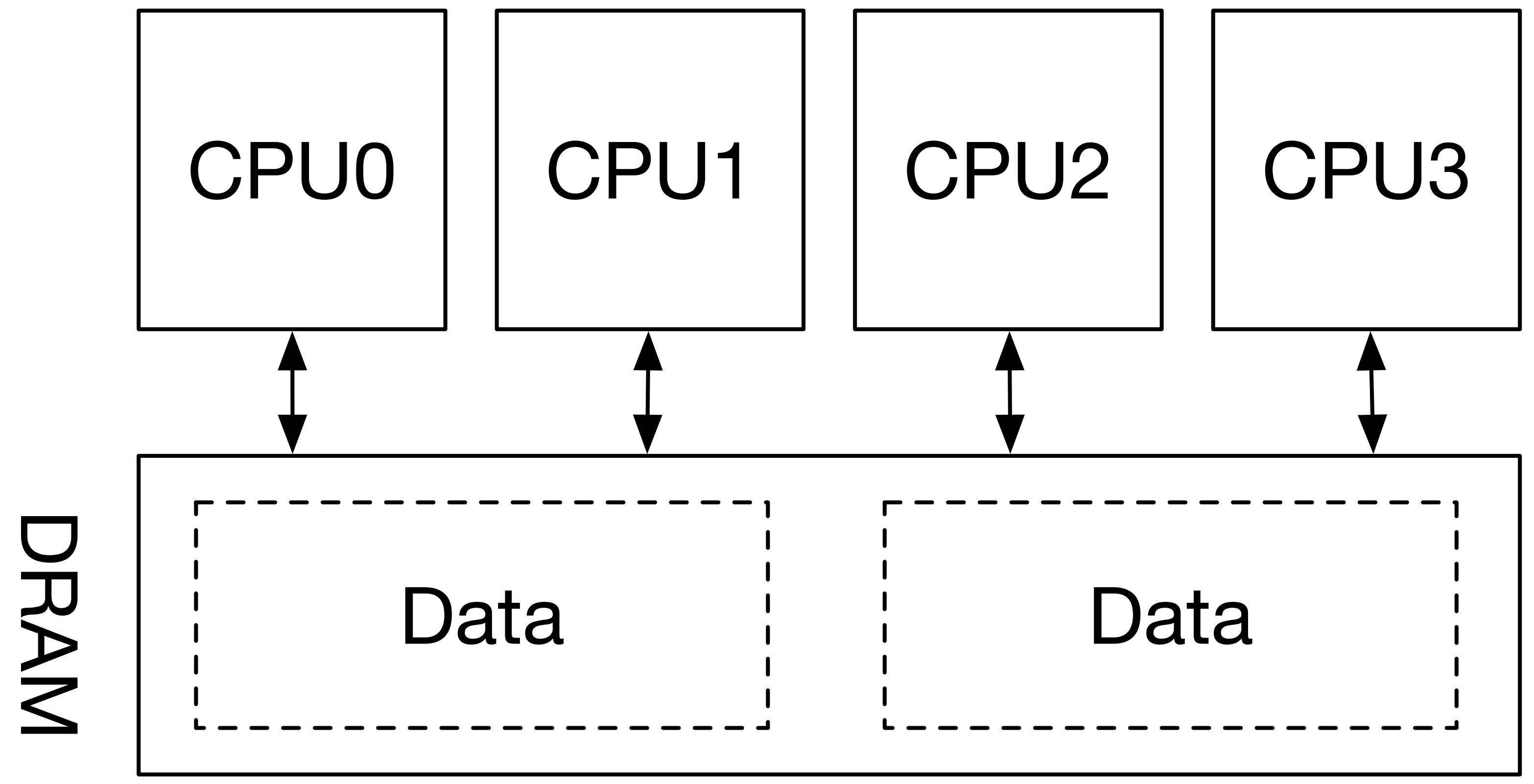
Requests need to be steered.

Shared-nothing

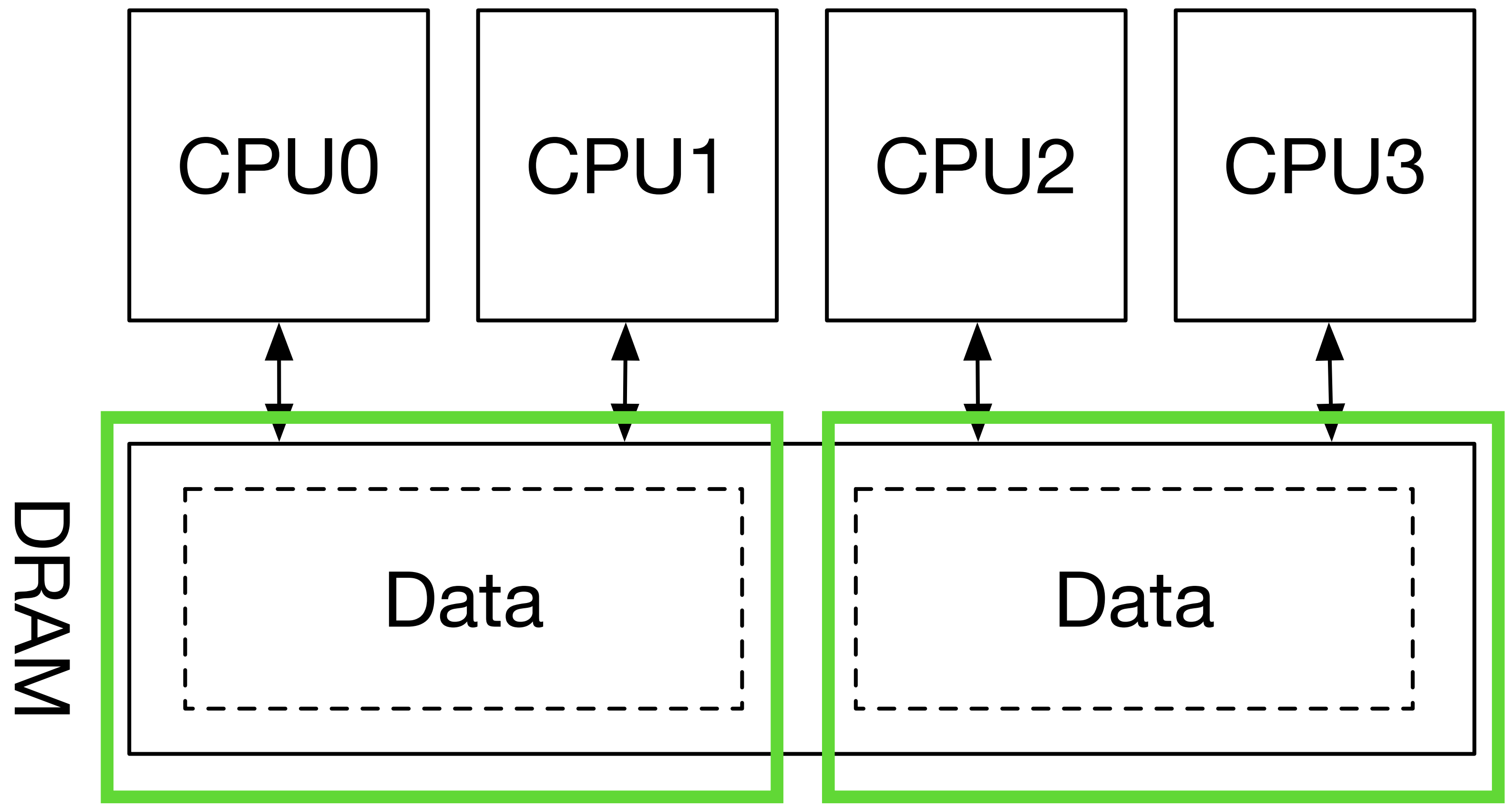
- Advantages:
    - Data access does not require synchronization.
- Disadvantages:
    - Request steering is needed [Lim, 2014; Didona, 2019]
    - CPU utilisation imbalance if data is not distributed well ("hot partition")
    - Sensitive to skewed workloads
- Examples:
    - Seastar framework and MICA key-value store

Didona *et al*. 2019. Sharding for Improving Tail Latencies in In-memory Key-value Stores. NSDI '19
Lim *et al*. 2014. MICA: A Holistic Approach to Fast In-memory Key-value. NSDI '14

Shared-something

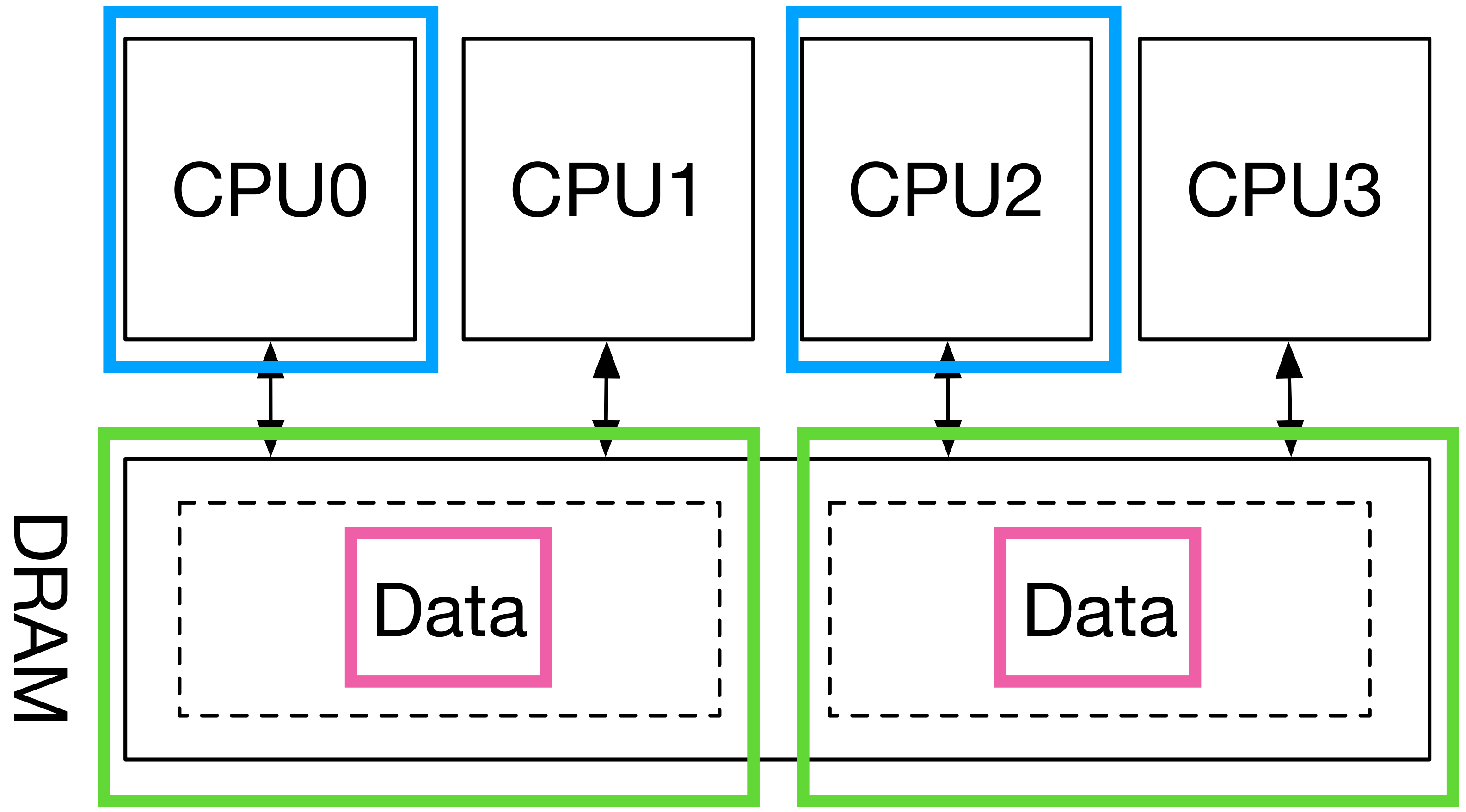


Shared-something



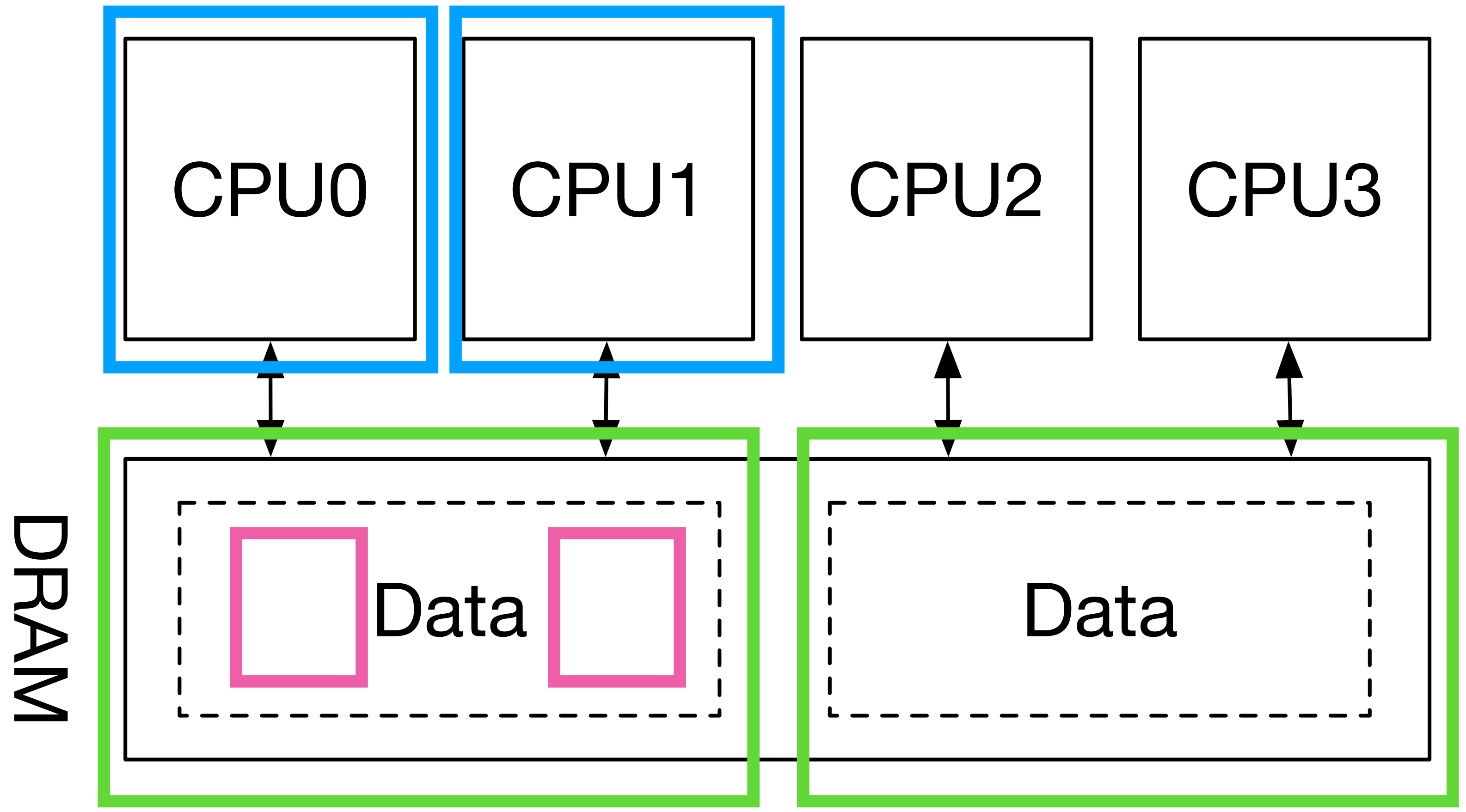
Hardware resources are partitioned between *CPU core clusters*.

Shared-something



No synchronization needed for data access on *different* CPU clusters.

Shared-something



Data access needs to be synchronised within the *same* CPU core cluster.

Shared-something

- Advantages:
  - Request can be processed on many cores
  - Shared-memory scales on *small core counts* [Holland, 2011].
  - Improved hardware-level parallelism?
    - For example, partitioning around sub-NUMA clustering could improve memory controller utilization.
- Disadvantages:
  - Request steering becomes more complex.

Holland *et al*. 2011. Multicore OSes: Looking Forward from 1991, Er, 2011. HotOS '11

Takeaways

- Partitioning improves parallelism, but there are trade-offs applications need to consider.
- Isolation of the in-kernel network stack is needed to avoid interference with application threads.

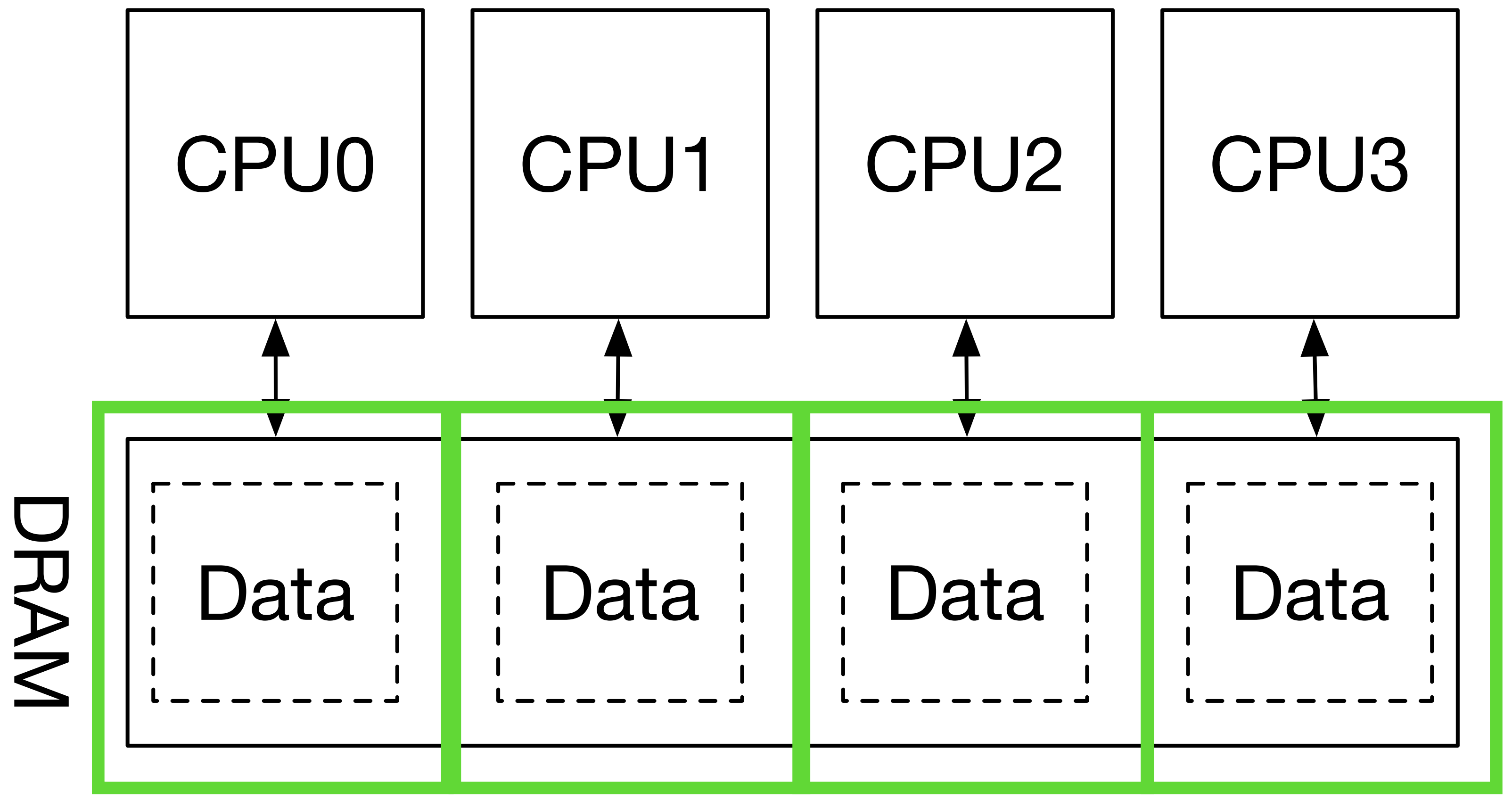
Outline

- Overview of thread-per-core
- **A key-value store**
- Impact on tail latency
- Problems in the approach
- Future directions

A shared-nothing, key-value store

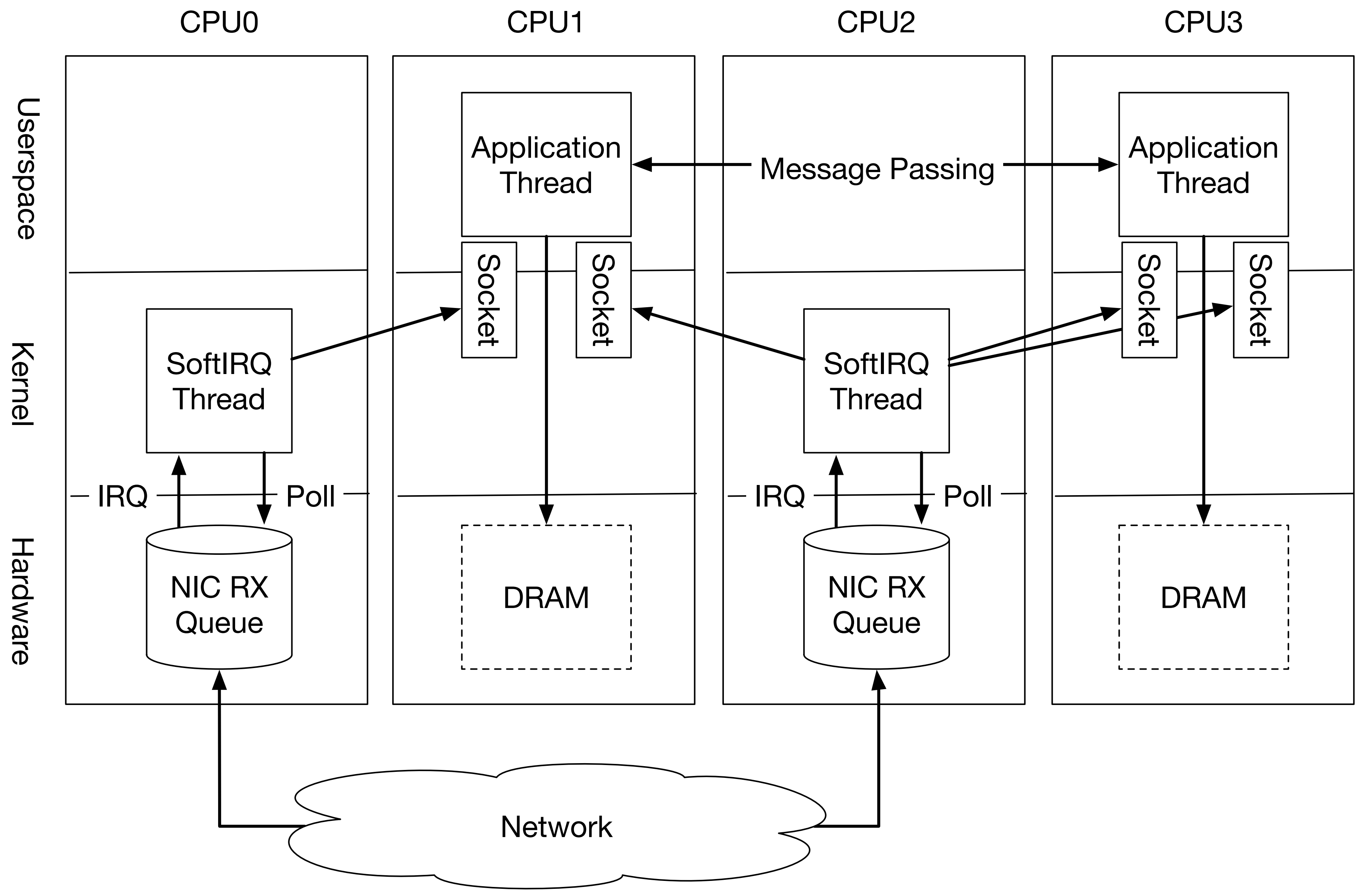
- To measure the impact of thread-per-core on tail latency, we designed a shared-nothing key-value store.
- Memcached wire-protocol compatible for easier evaluation.
- Software-based request steering with message passing between threads.
  - Lockless, single-producer, single-consumer (SPSC) queue per thread.

Shared-nothing



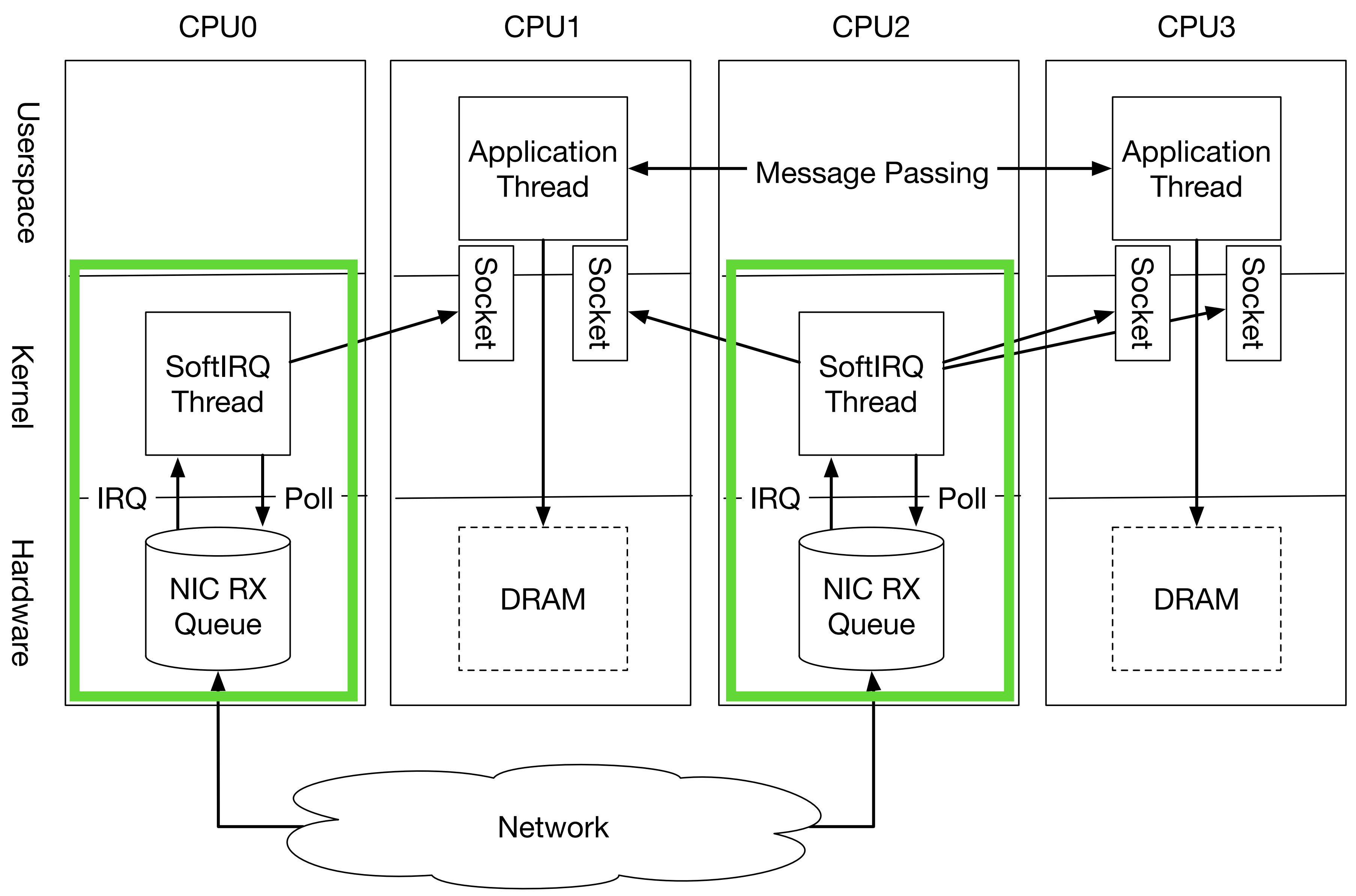
Taking the shared-nothing model…

KV store design



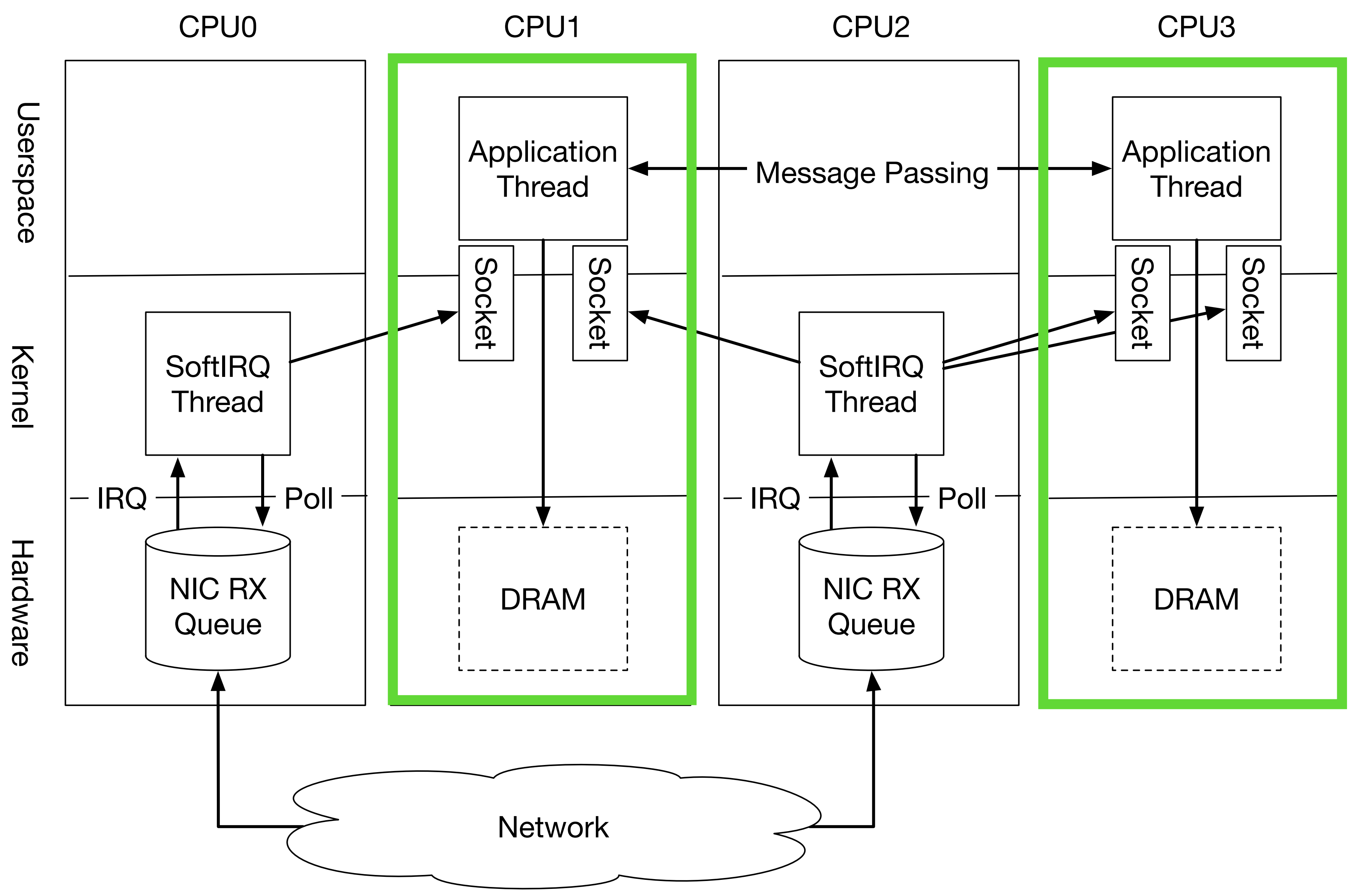
…and implementing it on Linux.

KV store design



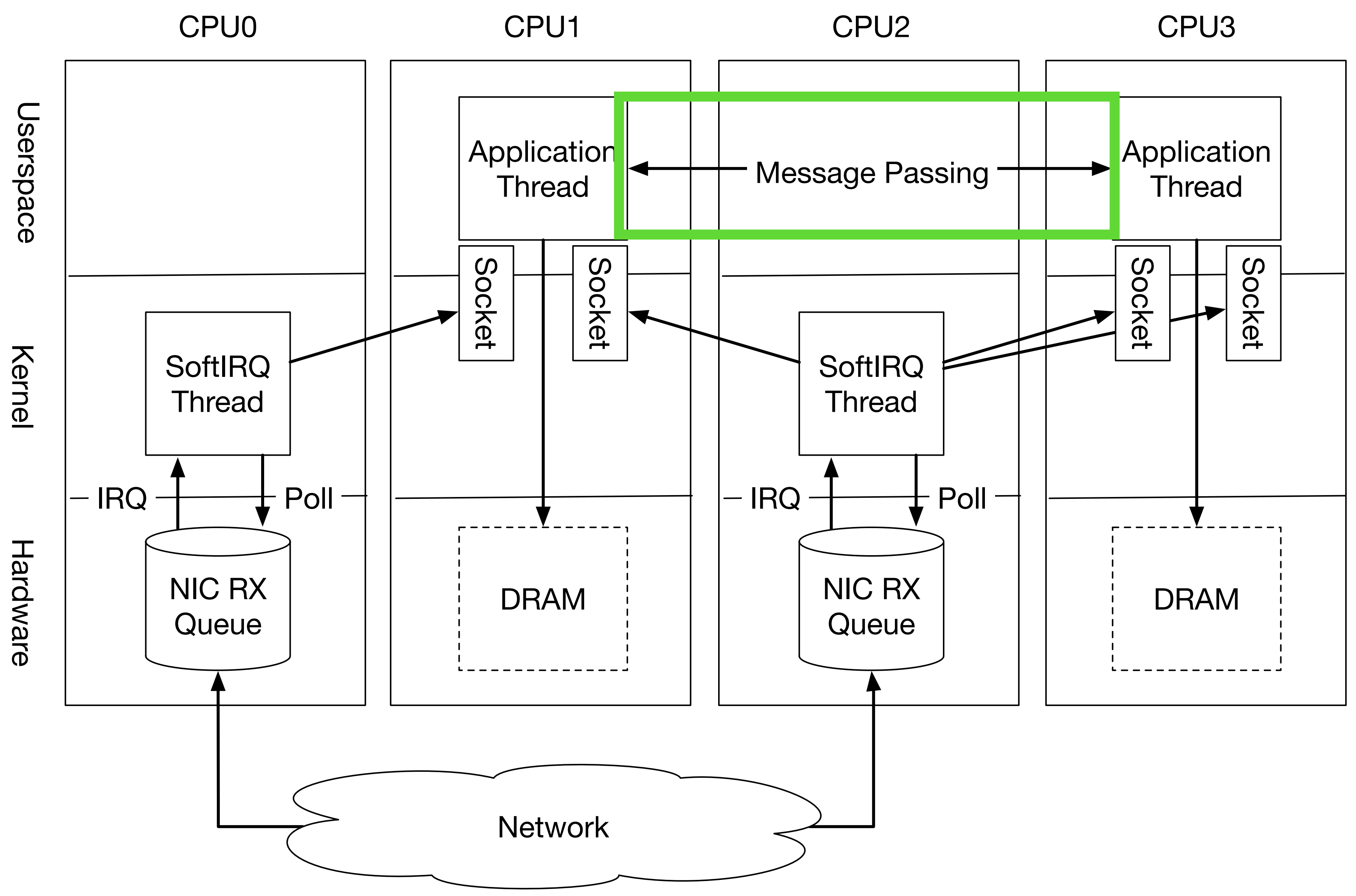
In-kernel network stack isolated on its own CPU cores.

KV store design



Application threads are running on their own CPU cores.

KV store design



Message passing between the application threads.

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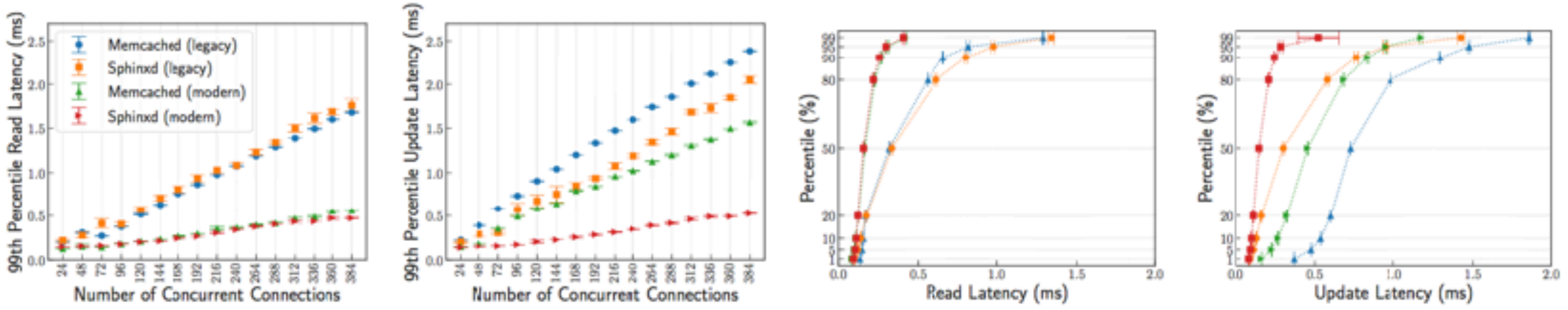
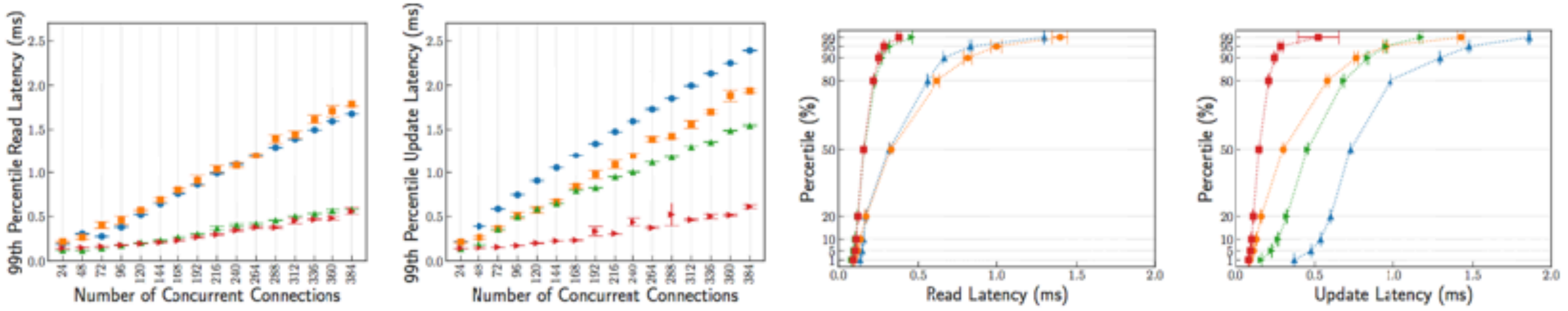
Impact on tail latency

- Comparison of Memcached (*shared-everything*) and Sphinx (*shared-nothing*)
- Measured read and update latency with the Mutilate tool
- Testbed servers (Intel Xeon):
    - 24 CPU cores, Intel 82599ES NIC (*modern*)
    - 8 CPU cores, Broadcom NetXtreme II (*legacy*)
- Varied IRQ isolation configurations.

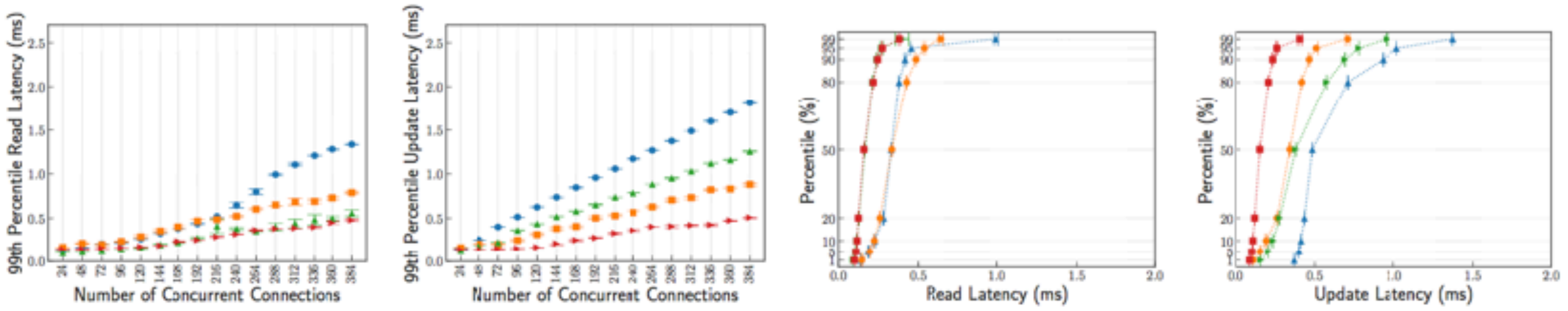
Impact on tail latency



(a) IRQ affinity not configured, and IRQ balance enabled.

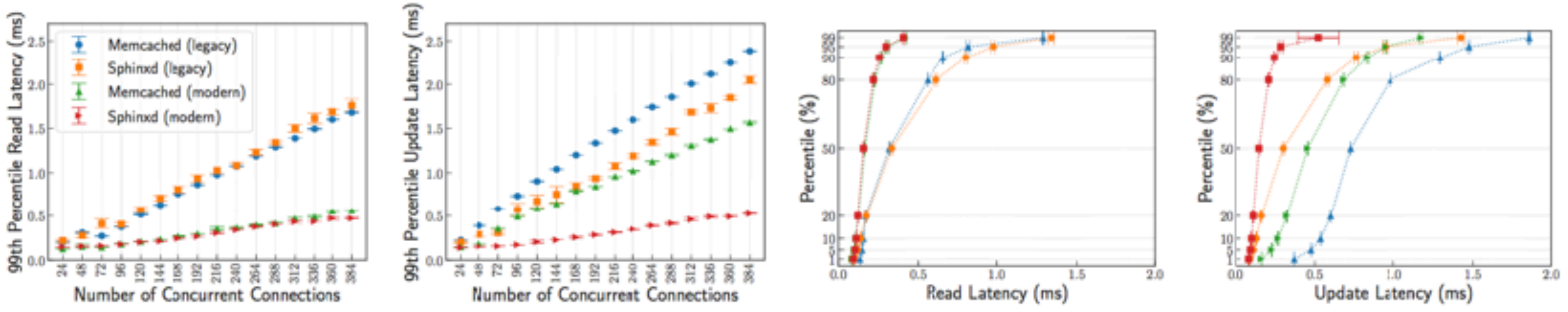


(b) IRQ affinity not configured, and IRQ balance disabled.



(c) IRQ affinity configured, and IRQ balance disabled.

Impact on tail latency



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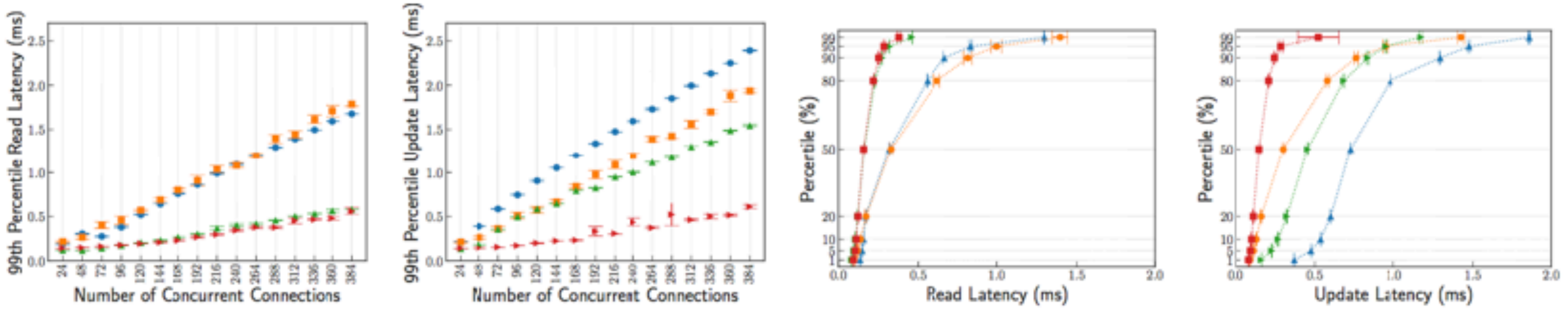

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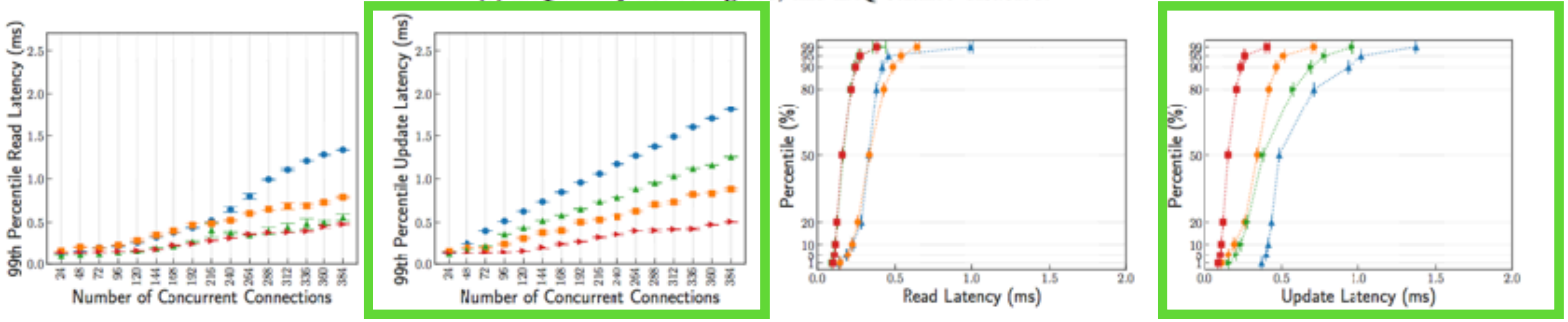
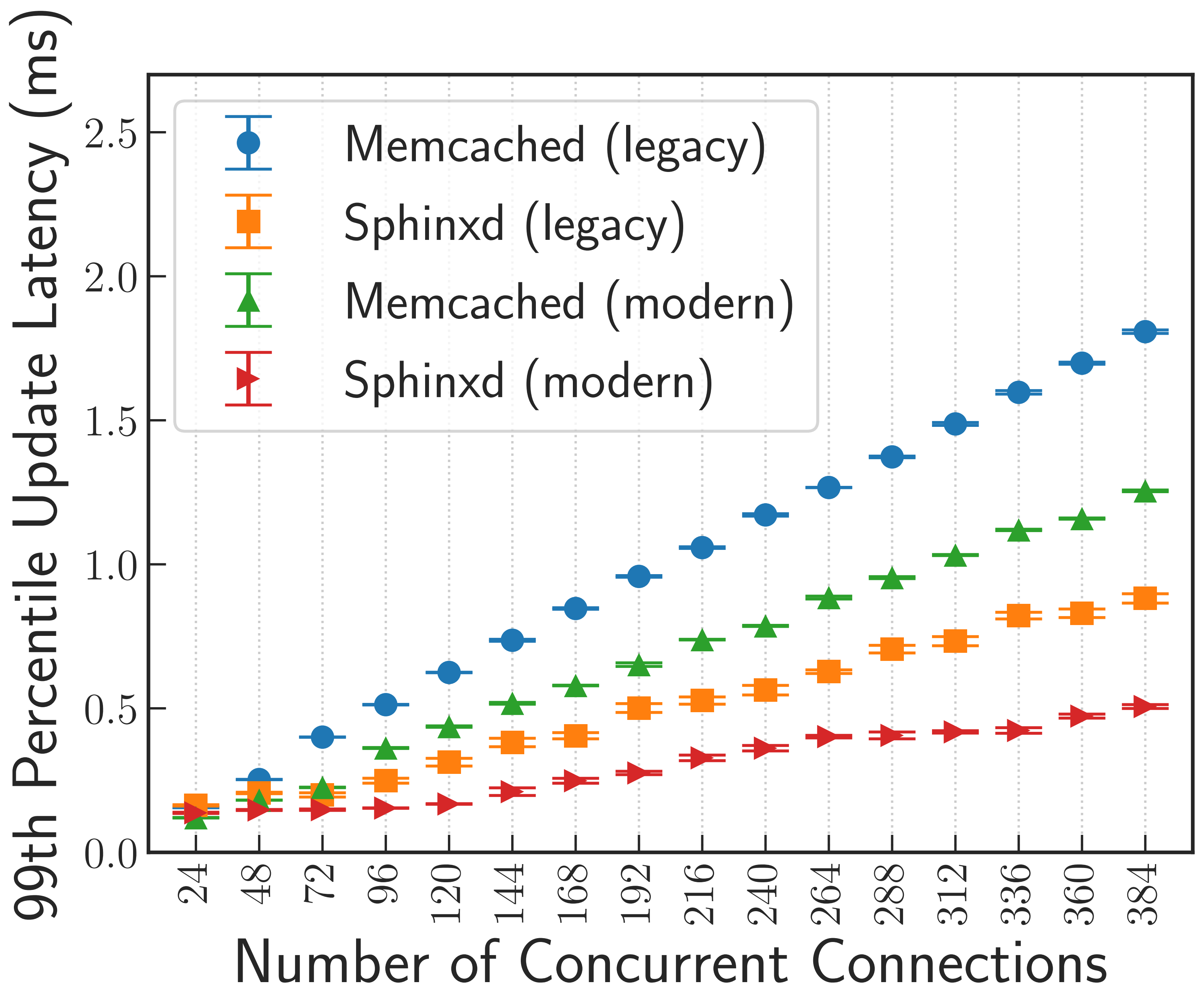
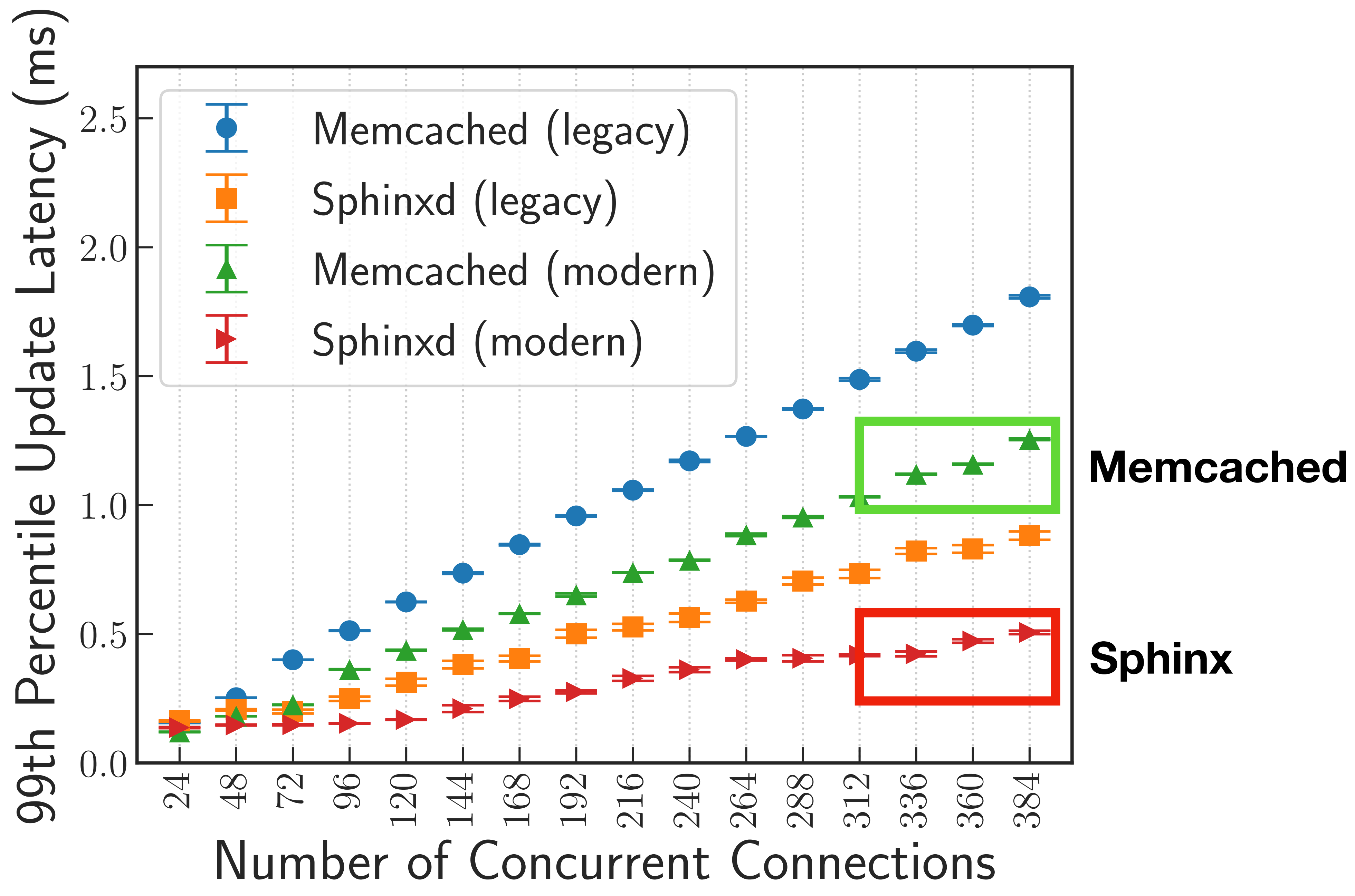


(c) IRQ affinity configured, and IRQ balance disabled.

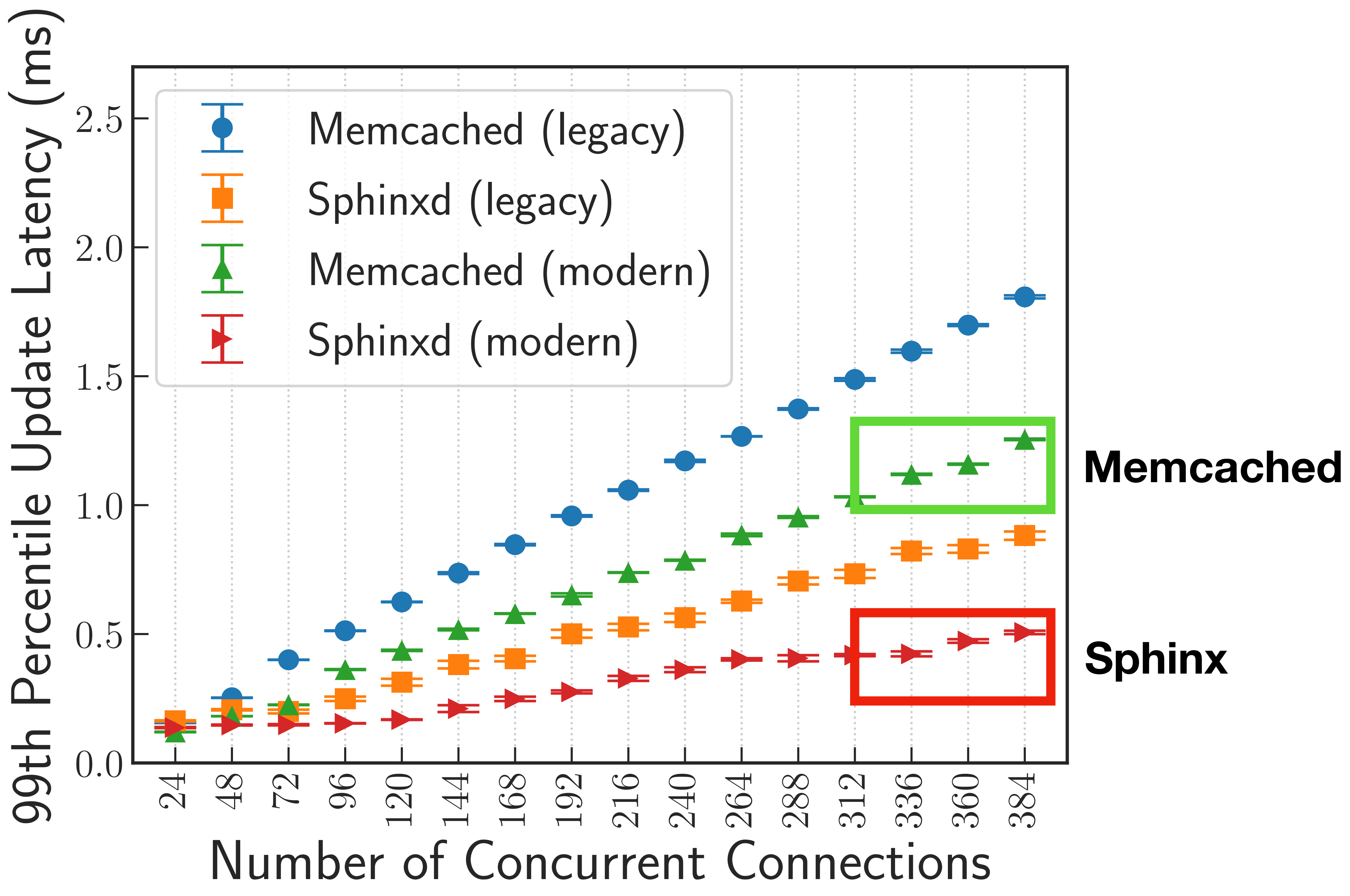
99th percentile latency over concurrency for updates



99th percentile latency over concurrency for updates

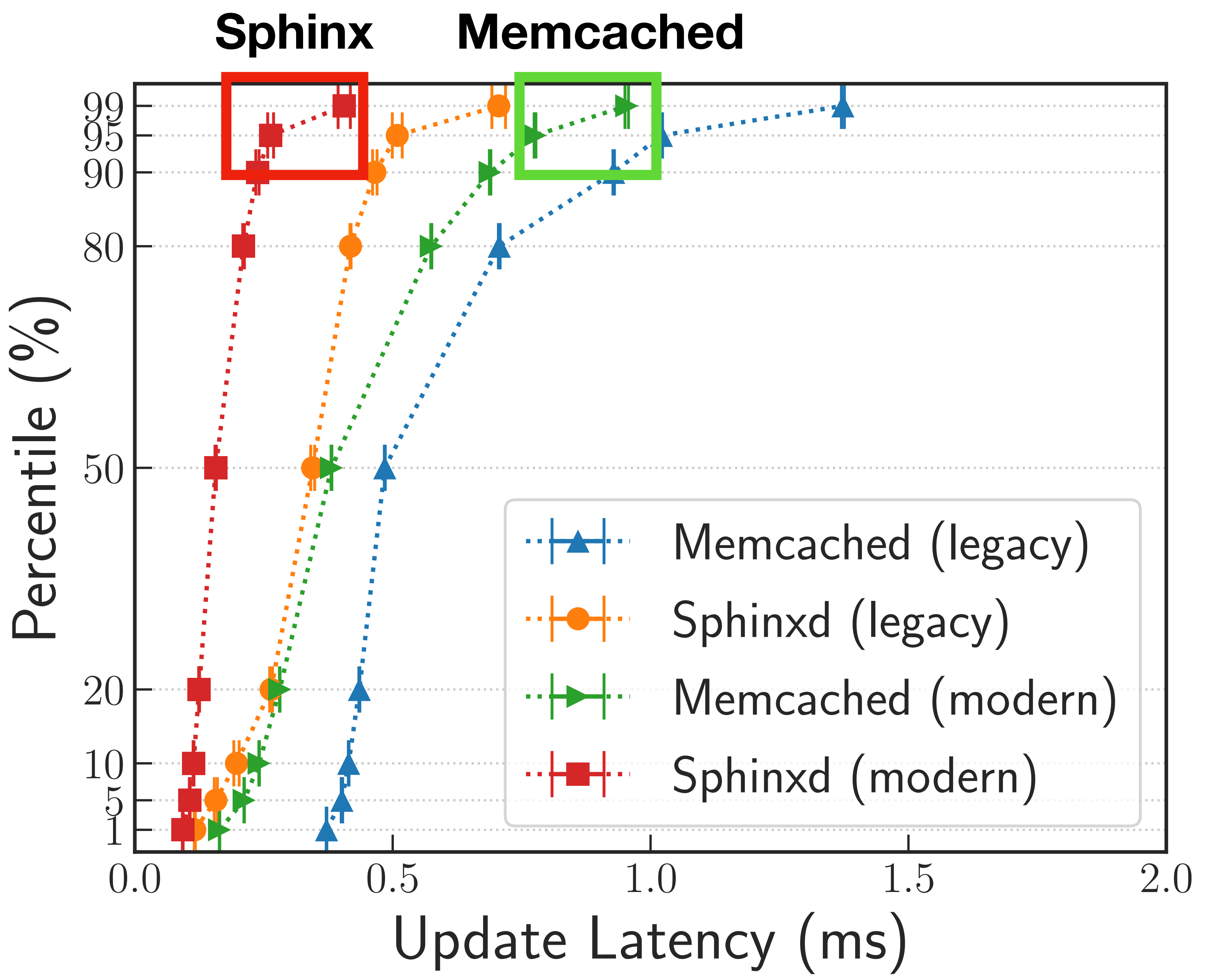


99th percentile latency over concurrency for updates



No locking, better CPU cache utilization.

Latency percentiles for updates



Takeaways

- **Shared-nothing** model **reduces tail latency** for update requests, because partitioning **eliminates locking**.
- More results in the paper:
  - **Interrupt isolation reduces latency** for **both** shared-everything and shared-nothing.
  - No difference for read requests between shared-nothing and shared-something (no locking in either case).

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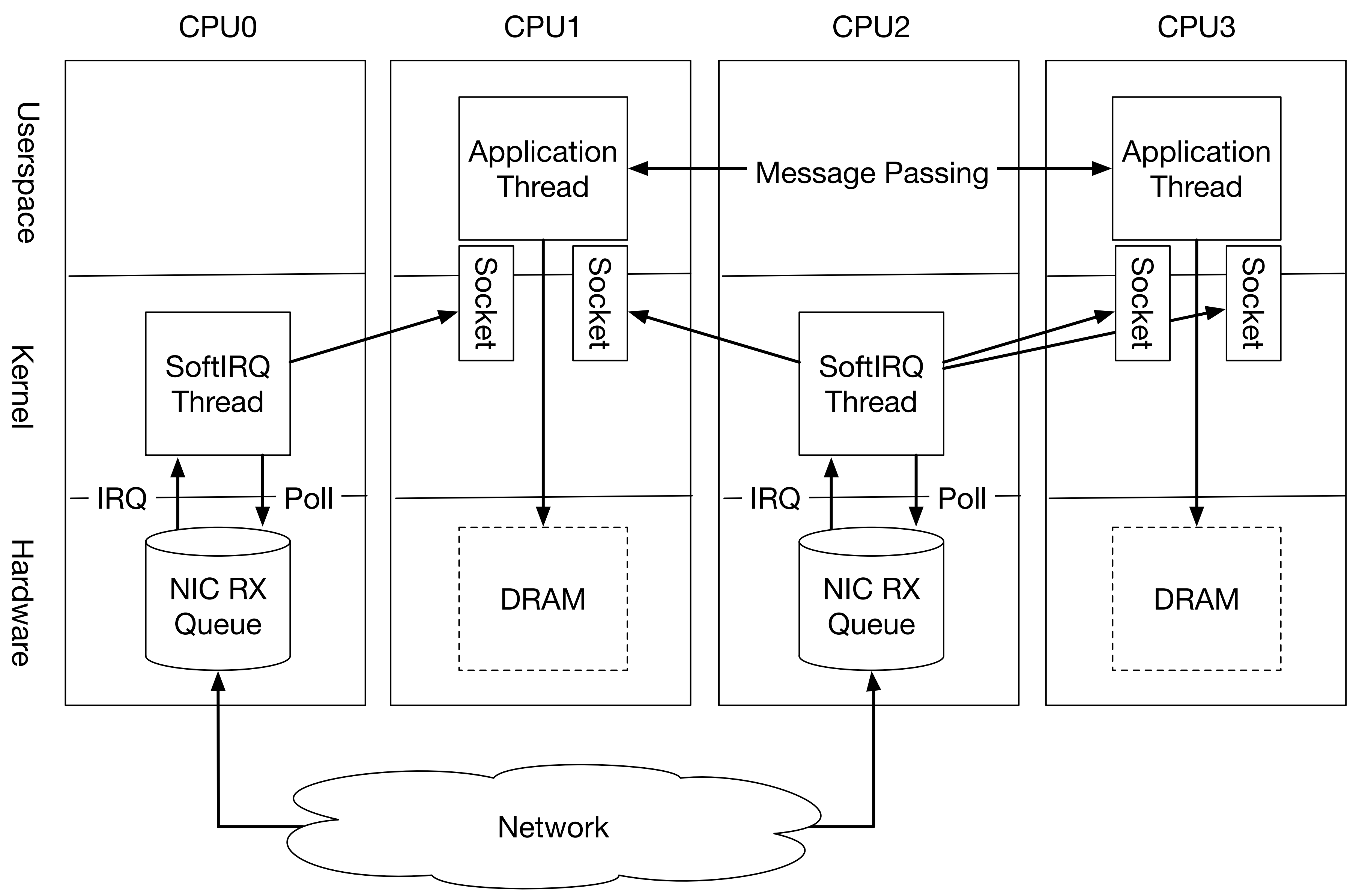
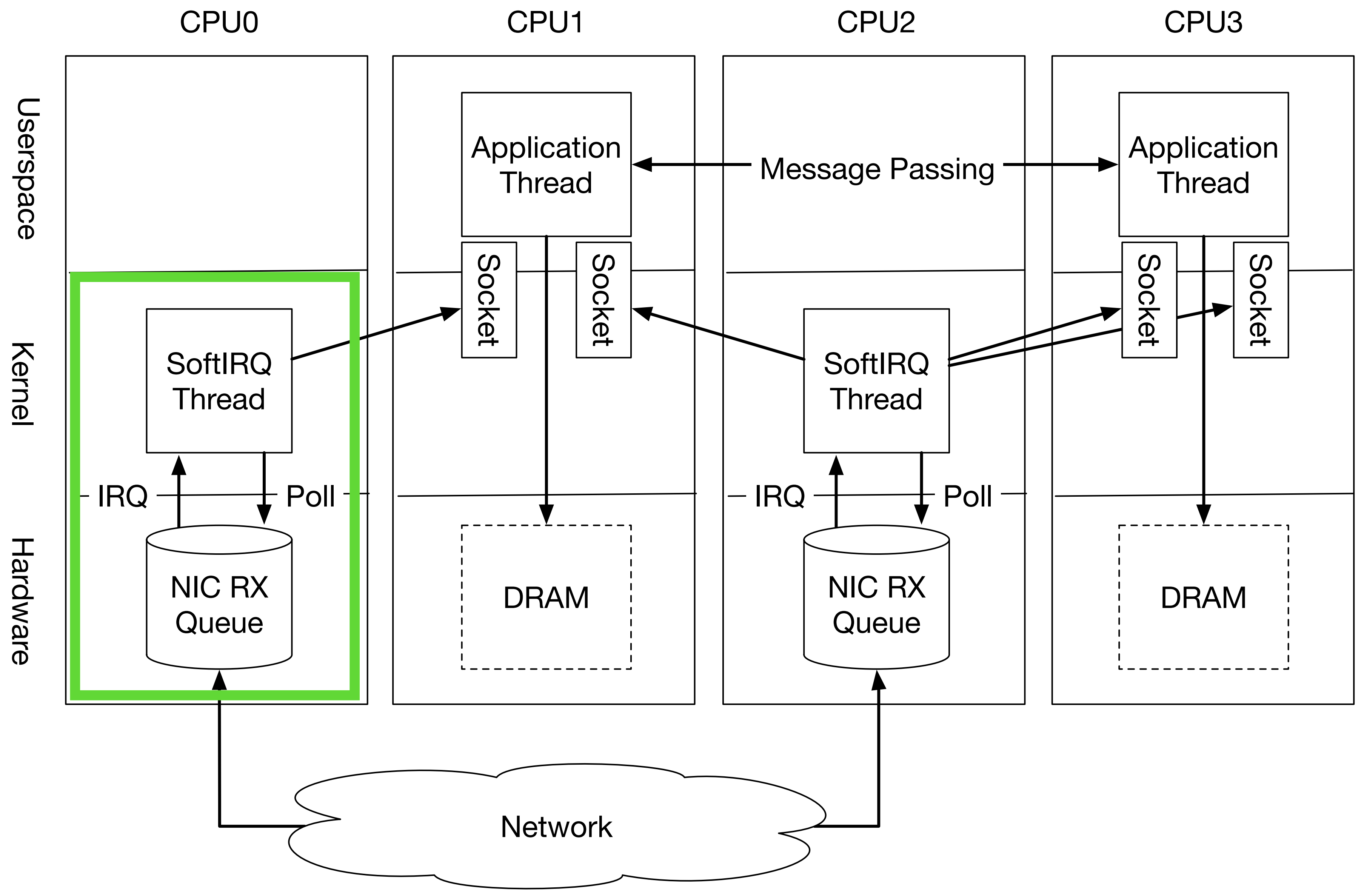
Packet movement between CPU cores

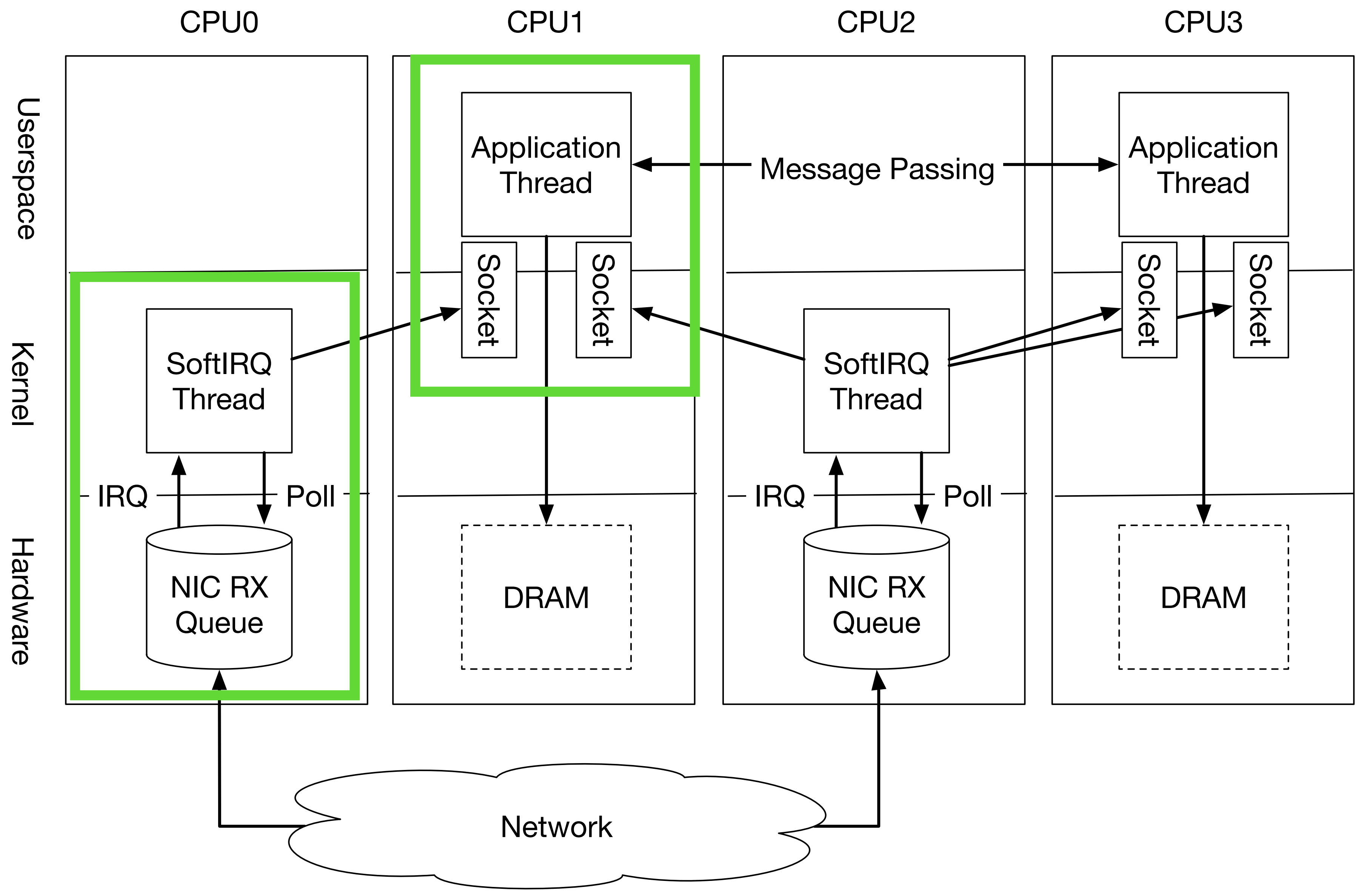


Packet movement between CPU cores



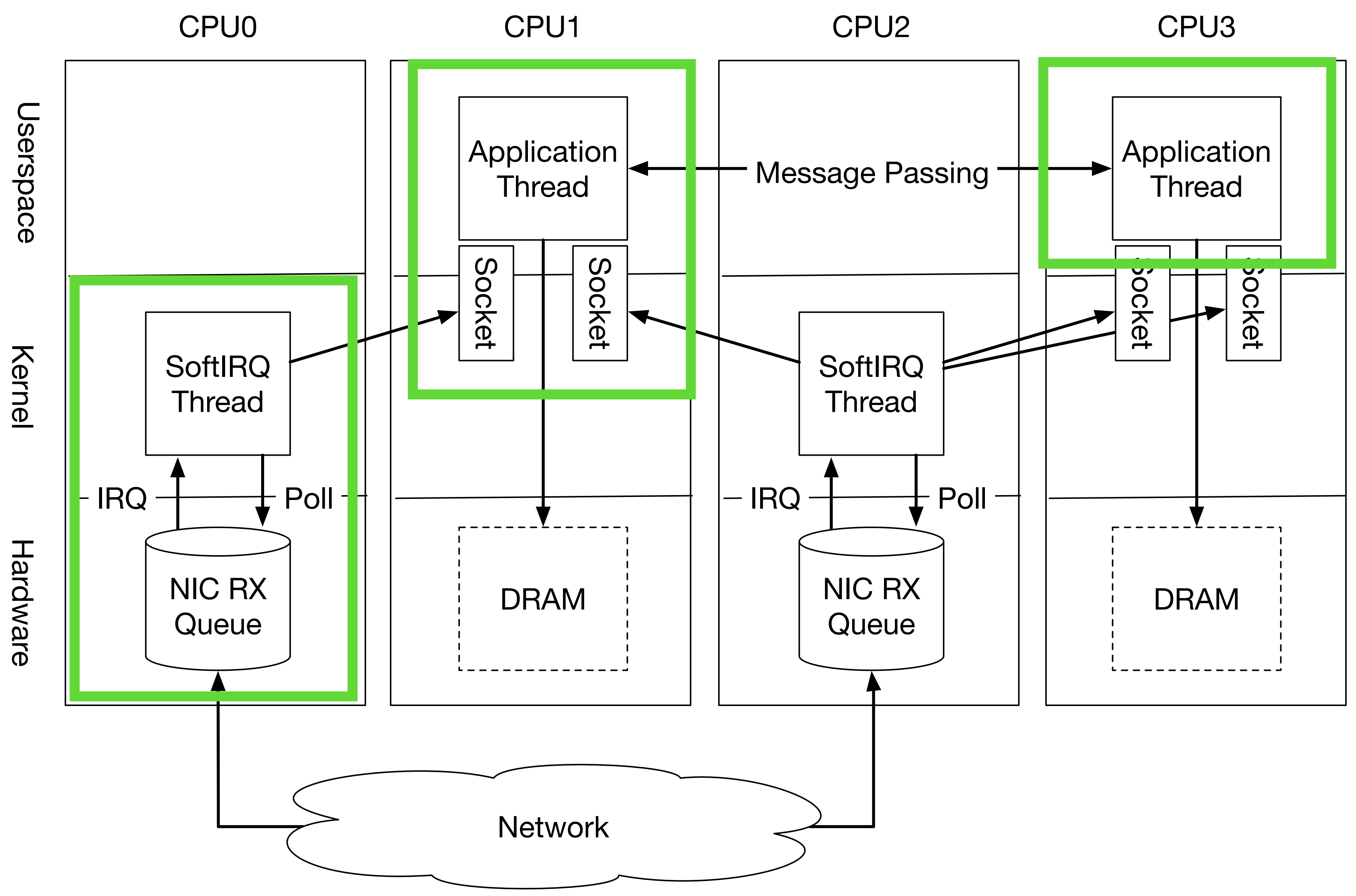
A packet arrives on NIC RX queue and is processed by in-kernel network stack on CPU0.

Packet movement between CPU cores



Application thread receives the request on CPU1.

Packet movement between CPU cores



Request is steered to an application thread on CPU3.

Request steering inefficiency

- Inter-thread communication efficiency matters for software steering:
  - Message passing by copying is a bottleneck. Avoiding copies makes the implementation more complex.
  - Thread wakeup are expensive, batching is needed, but it increases latency.
  - Busy-polling is a solution, but it wastes CPU resources in some scenarios.

Partitioning scheme and skewed workloads

- Partitioning scheme is critical, but the design decision is application specific. Not always easy to partition.
- Skewed workloads are difficult to address with shared-nothing model.

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Request steering with a programmable NIC?

- Program running on the NIC parses request headers, and steers request to correct application thread [Floem, 2018].
- Eliminates request software steering overheads and packet movement cost.
- On Linux, the Express Data Path (XDP) and eBPF interface could be used for this.

Mangpo, *et al.* Floem: A Programming System for NIC-Accelerated Network Applications. OSDI '18.

OS support for inter-core communication?

- On Linux, wakeup needed for inter-thread messaging are performed using eventfd interface or signals, but both have overheads.
- Adding better support for *inter-core communication* in the OS would help.

Non-blocking OS interfaces

- Thread-per-core requires non-blocking OS interfaces.
- New asynchronous I/O interfaces, such as io_uring on Linux, will help.
- Paging and memory-mapped I/O are effectively blocking operations (when you take a page fault), and must be avoided.

Network stack scheduling control

- In-kernel network stack runs in kernel threads, which interfere with application threads.
- Configuring IRQ isolation is possible, but hard and error-prone. Better interfaces are needed.
- Moving the network stack to user space helps.

Summary

- Thread-per-core architecture addresses kernel thread overheads.
- Partitioning of hardware resources has advantages and disadvantages, applications need to consider different trade-offs.
- Request steering is critical: CPU and NIC co-design and better OS interfaces are needed to unlock full potential of thread-per-core.

Thank you!

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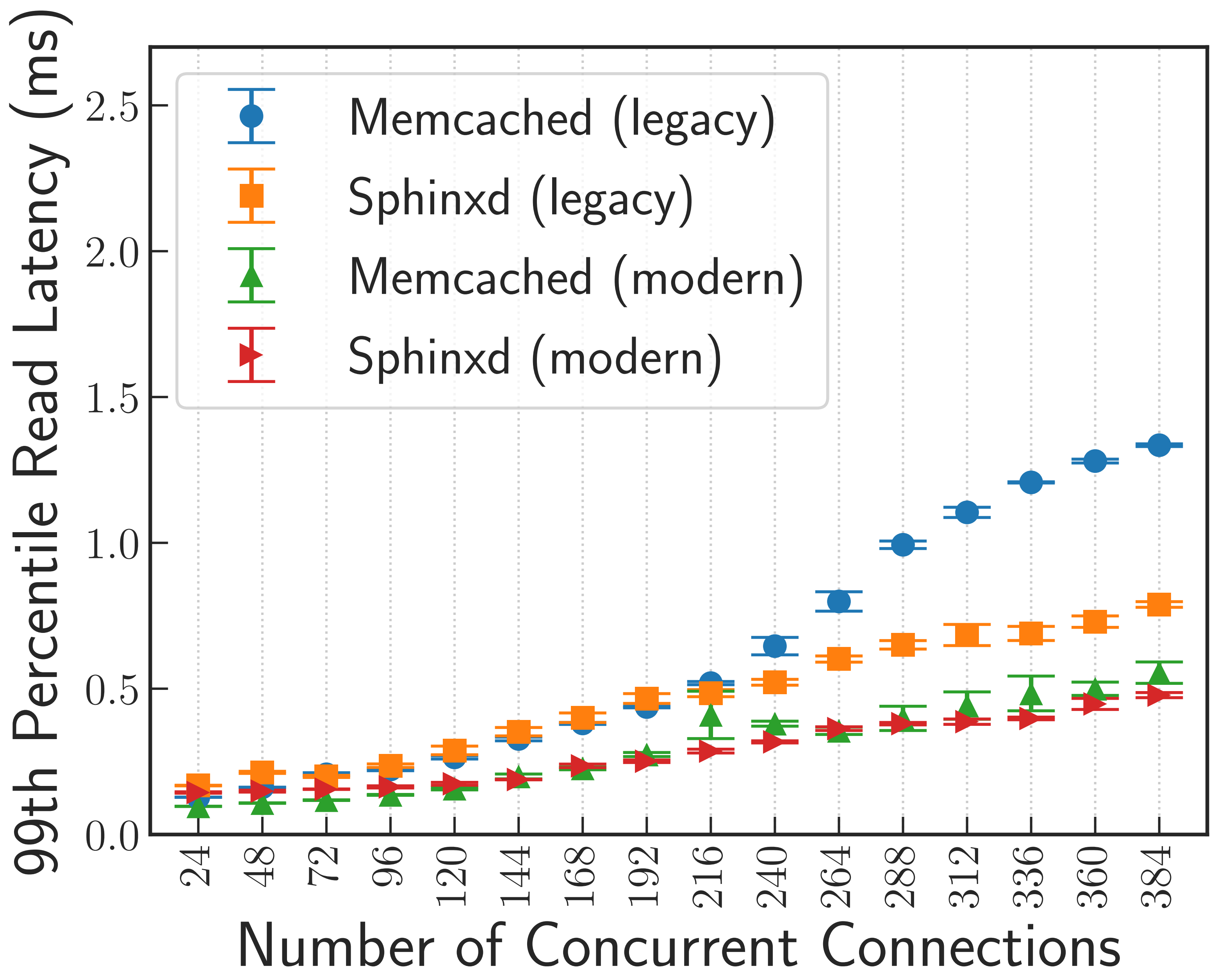
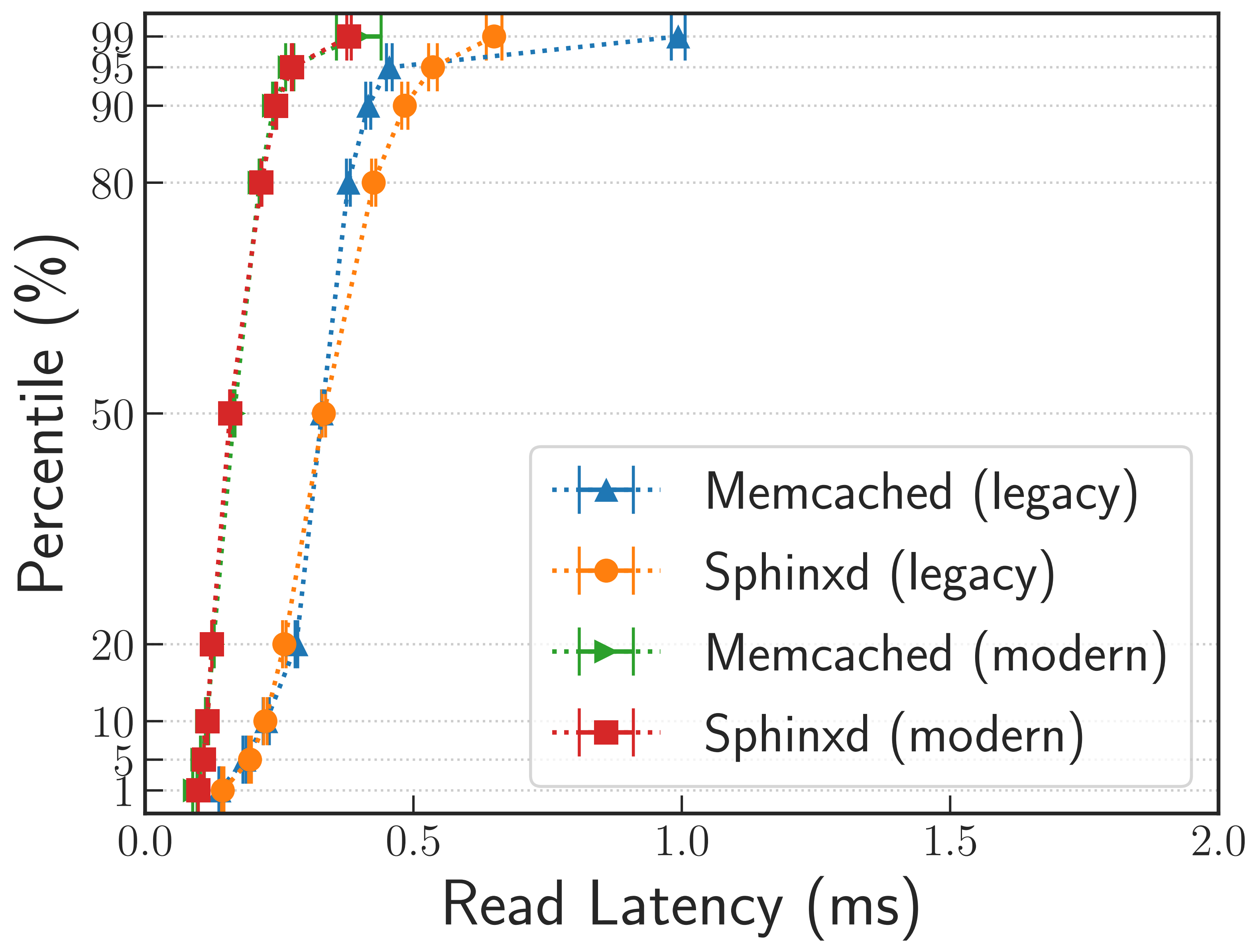
Backup slides

Read latency (99th)



Read latency


Percentile (%)
Read Latency (ms)
Memcached (legacy)
Sphinxd (legacy)
Memcached (modern)
Sphinxd (modern)