Iterator Interface Extended LSM-tree-based KVSSD for Range Queries

Youngjae Kim (PhD)

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Anand Sivasubramaniam, Youngjae Kim

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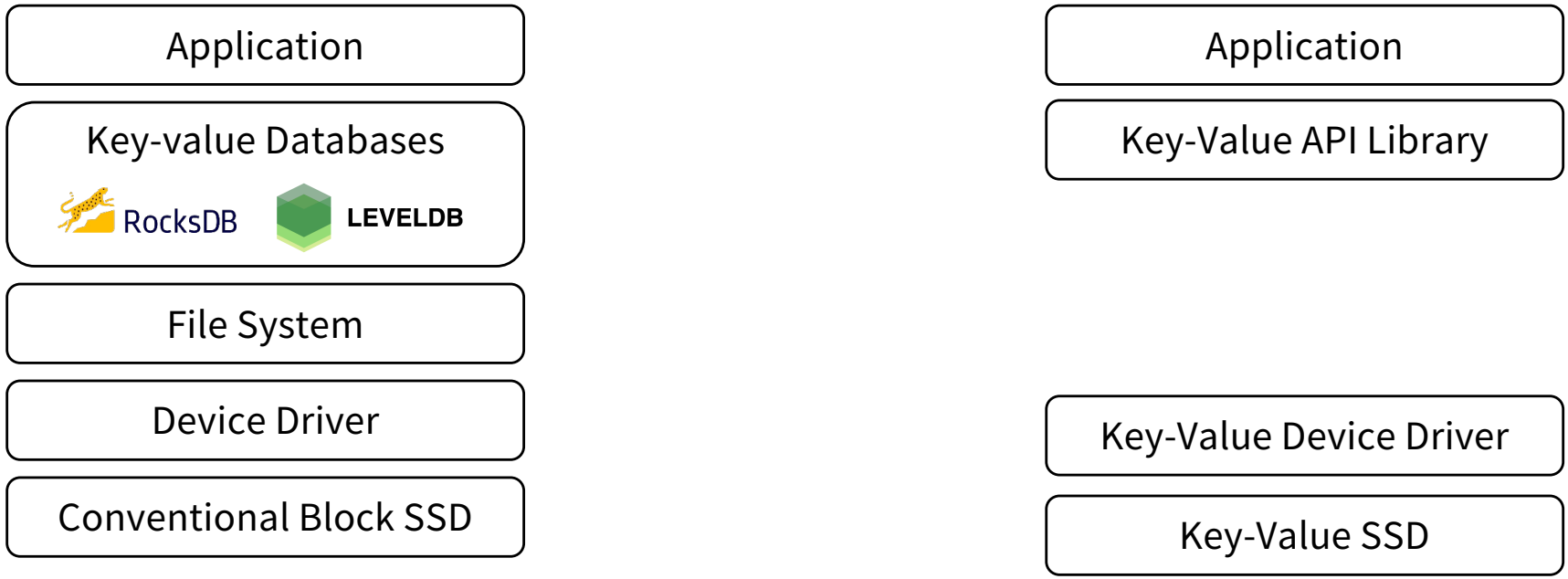
NVRAMOS'23

Key-Value SSD

- **Key-Value SSD: Removing the host software I/O stack**



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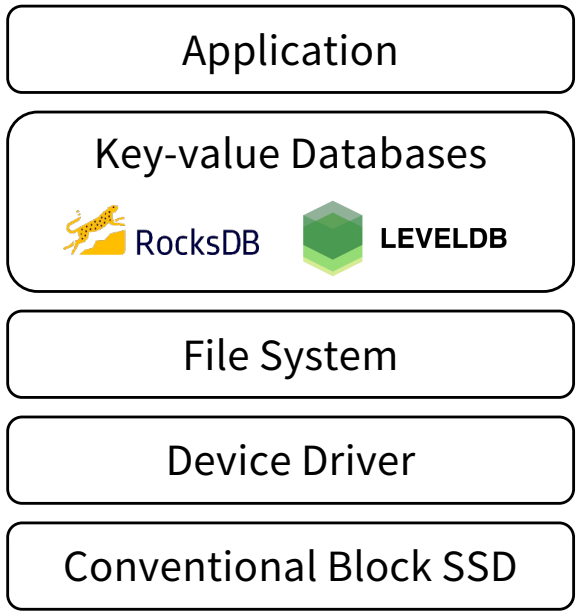

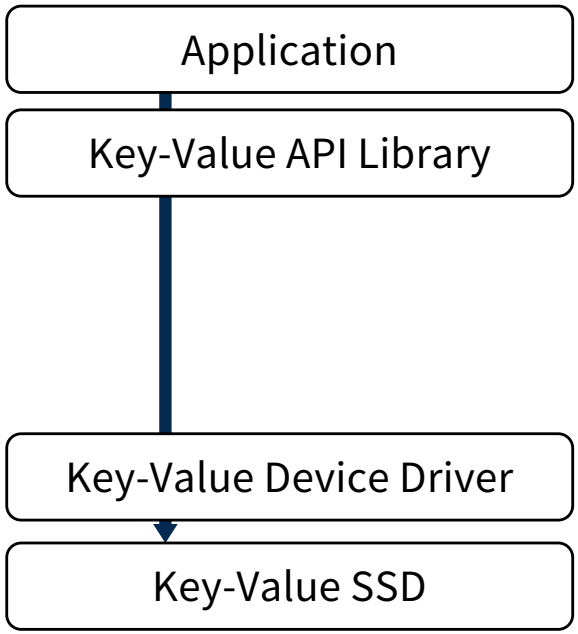

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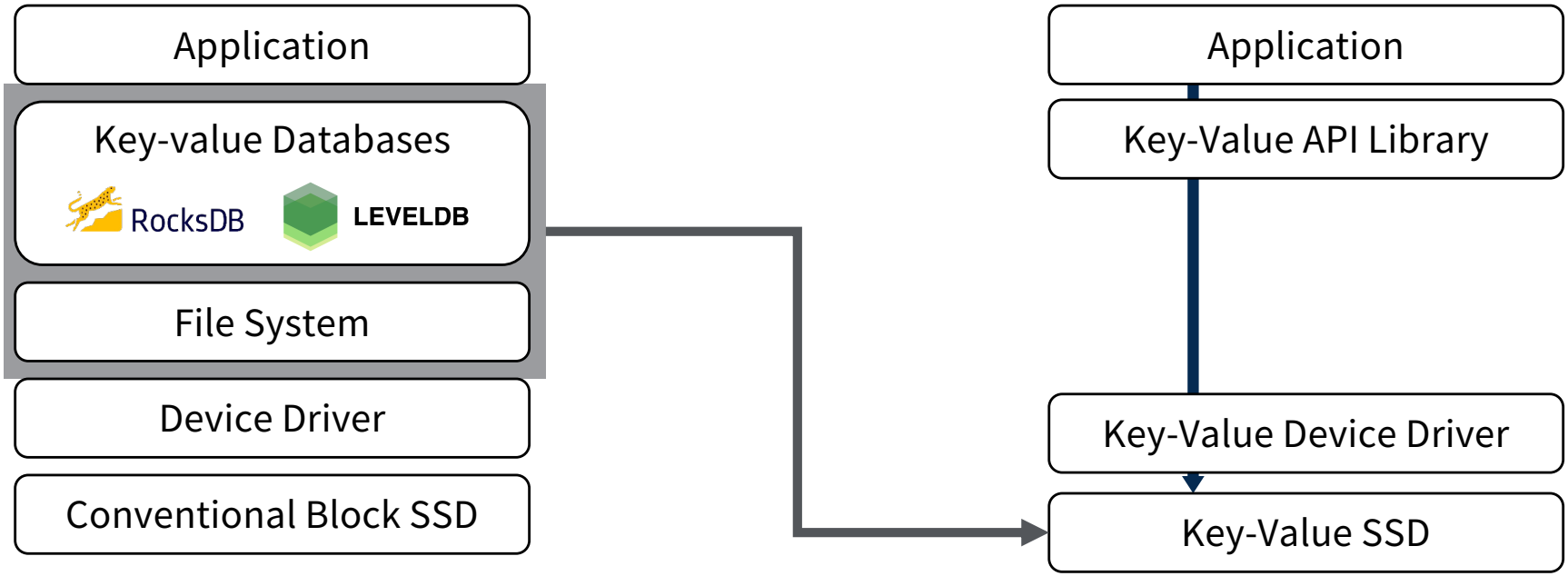

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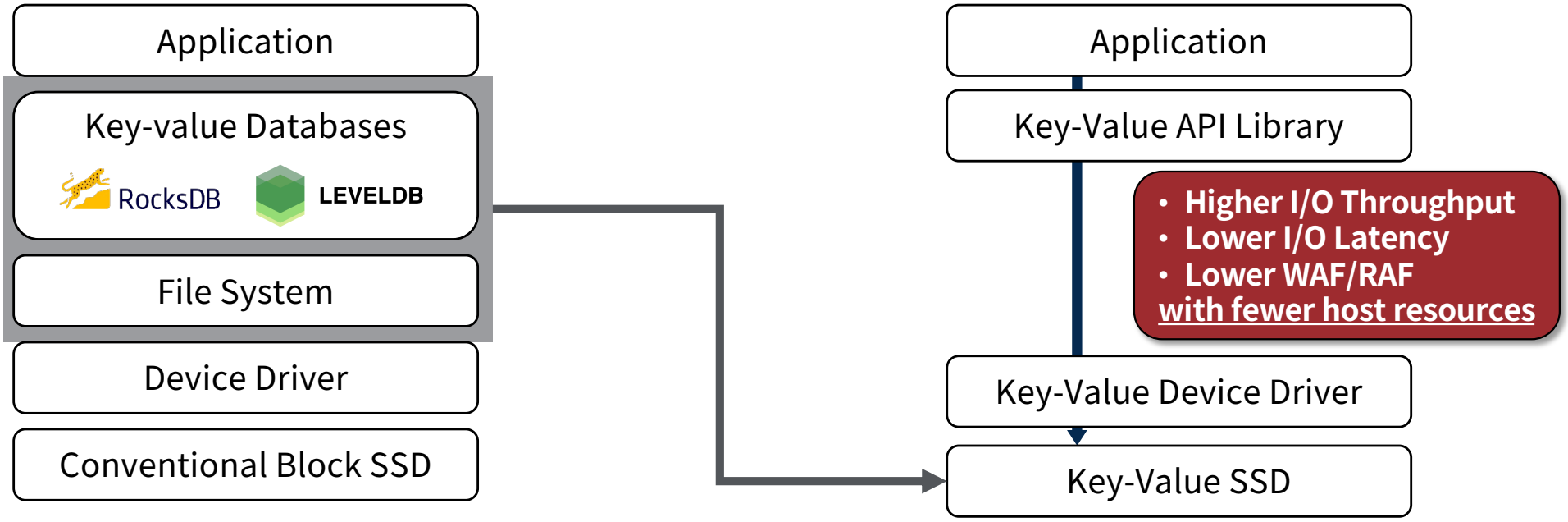

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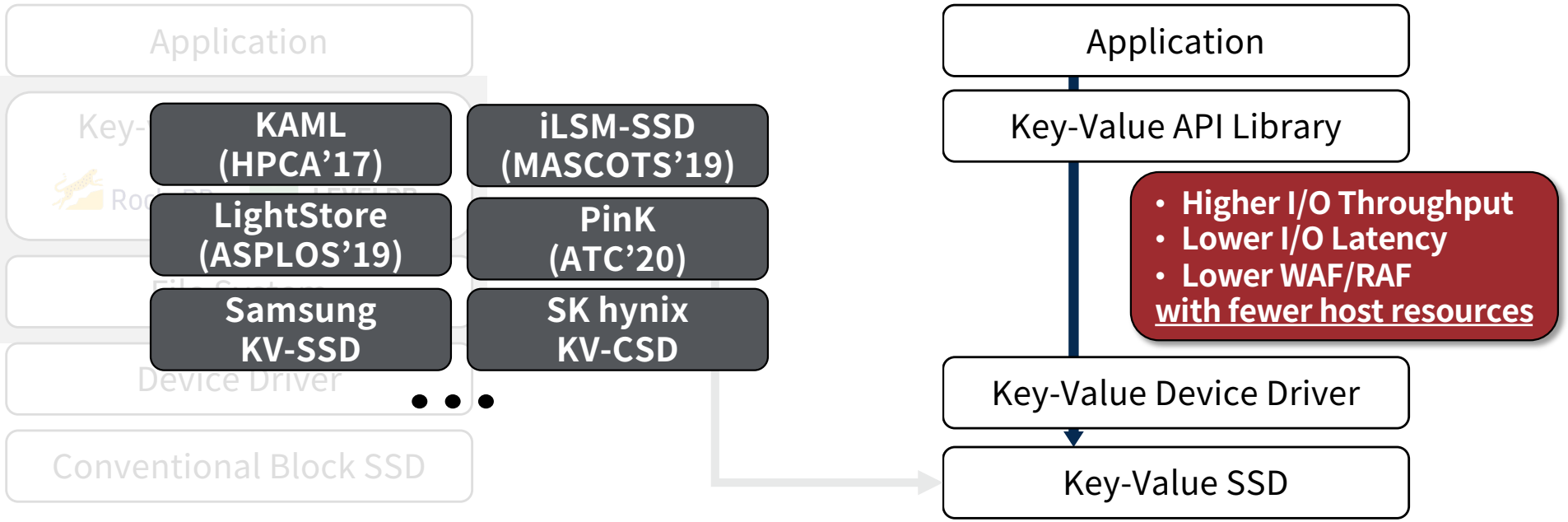

Range Query for KVSSD

[1] PinK: High-speed In-storage Key-value Store with Bounded Tails, USENIX ATC 2020
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- **Existing KVSSDs mostly focus on Point Query (Put/Get)**
  - Index Pinning[1], Index Compression[2]
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  - Using a sorted data structure makes range query implementation simple.
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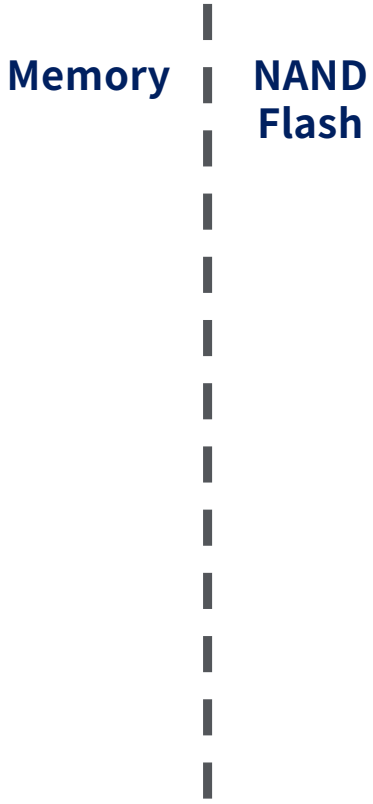

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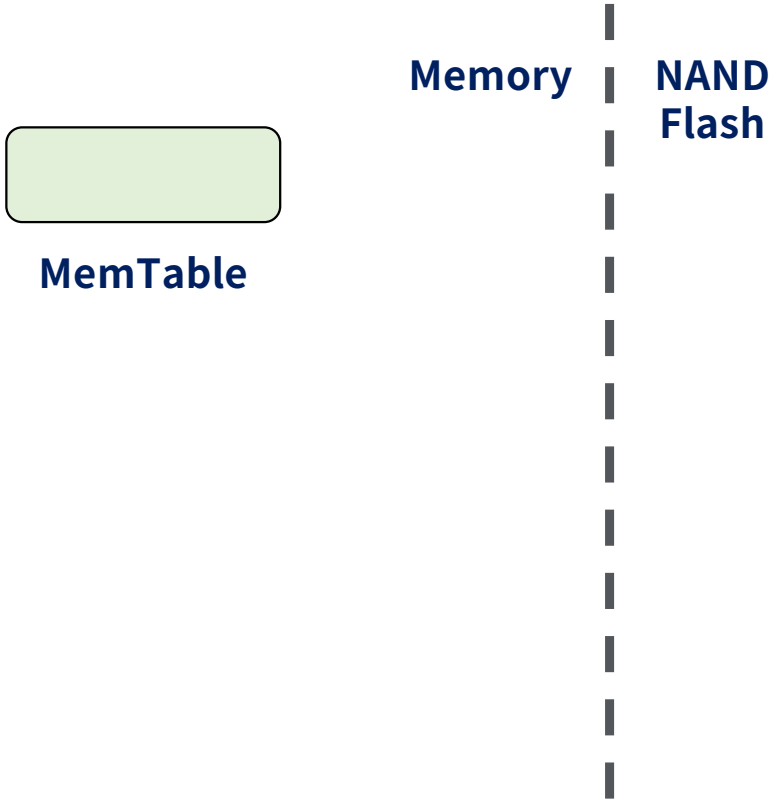

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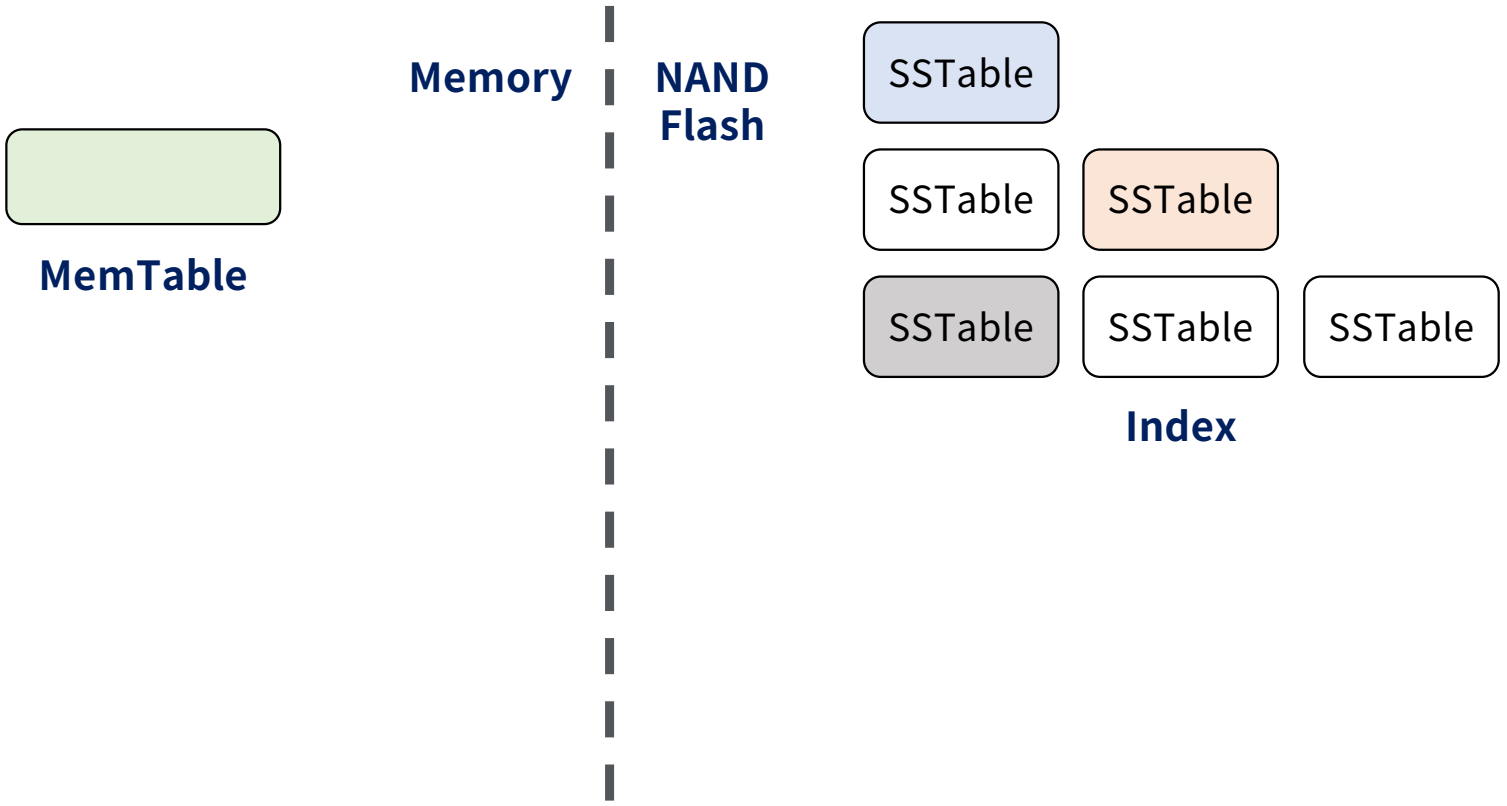

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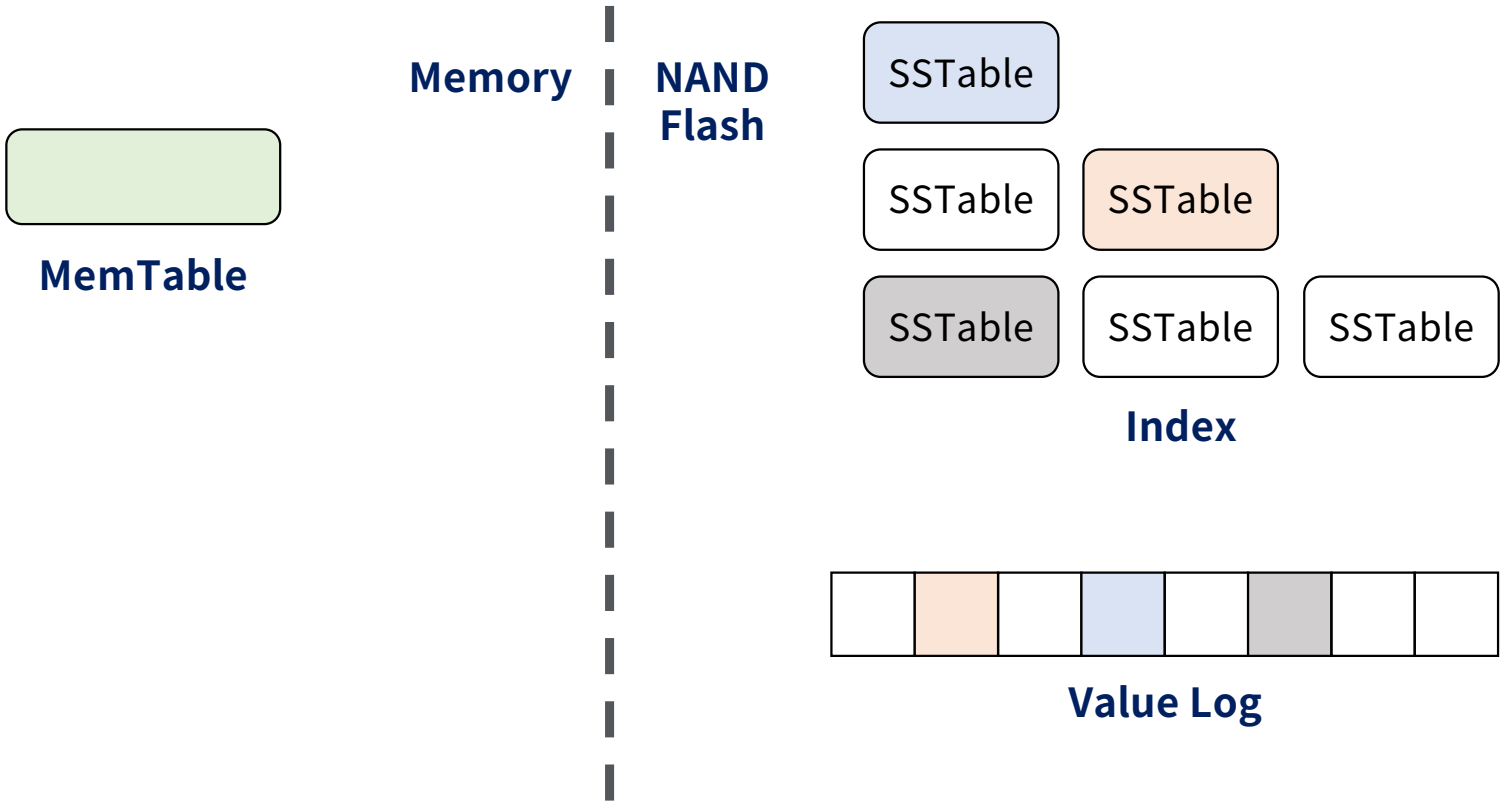

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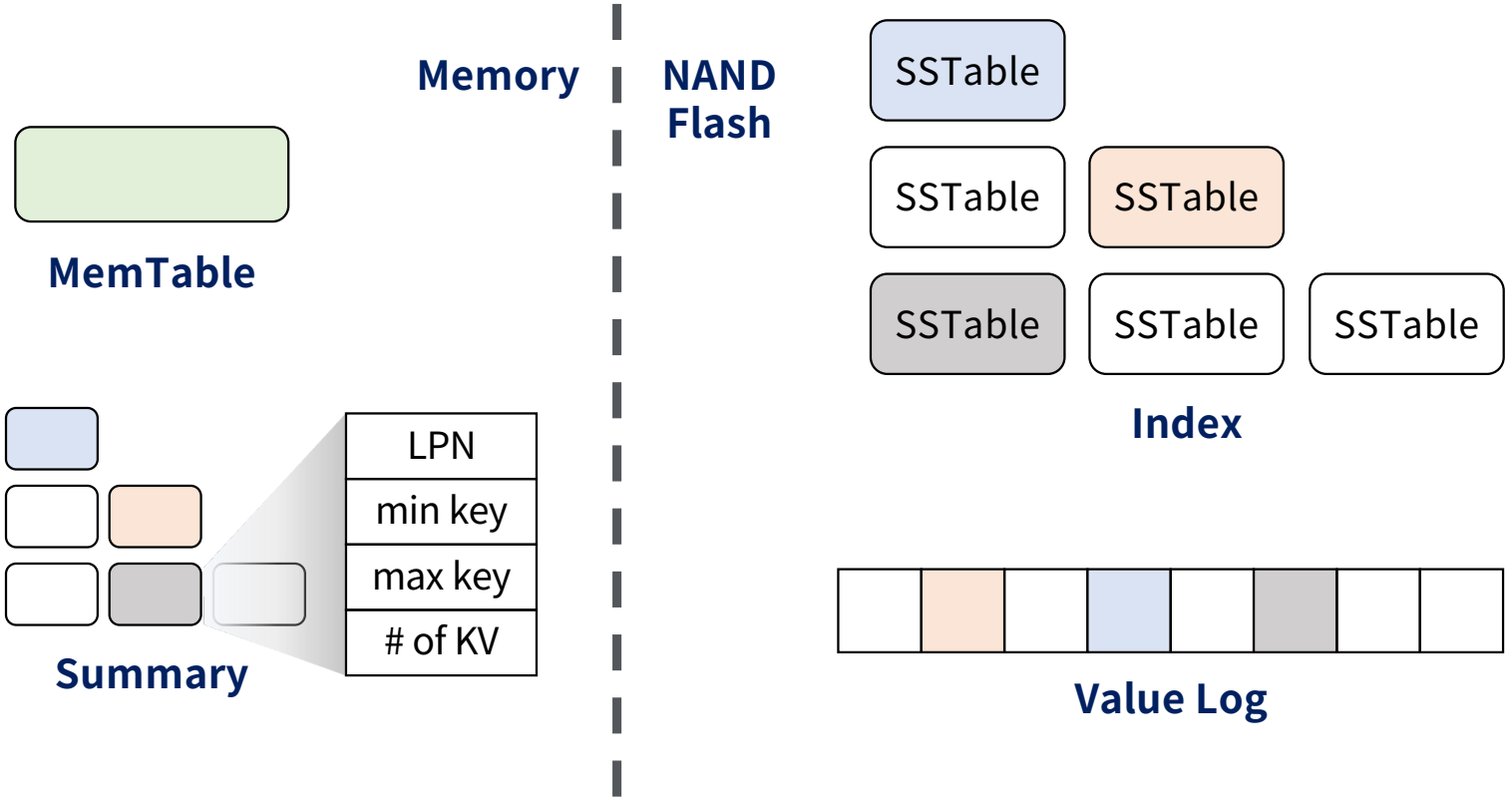

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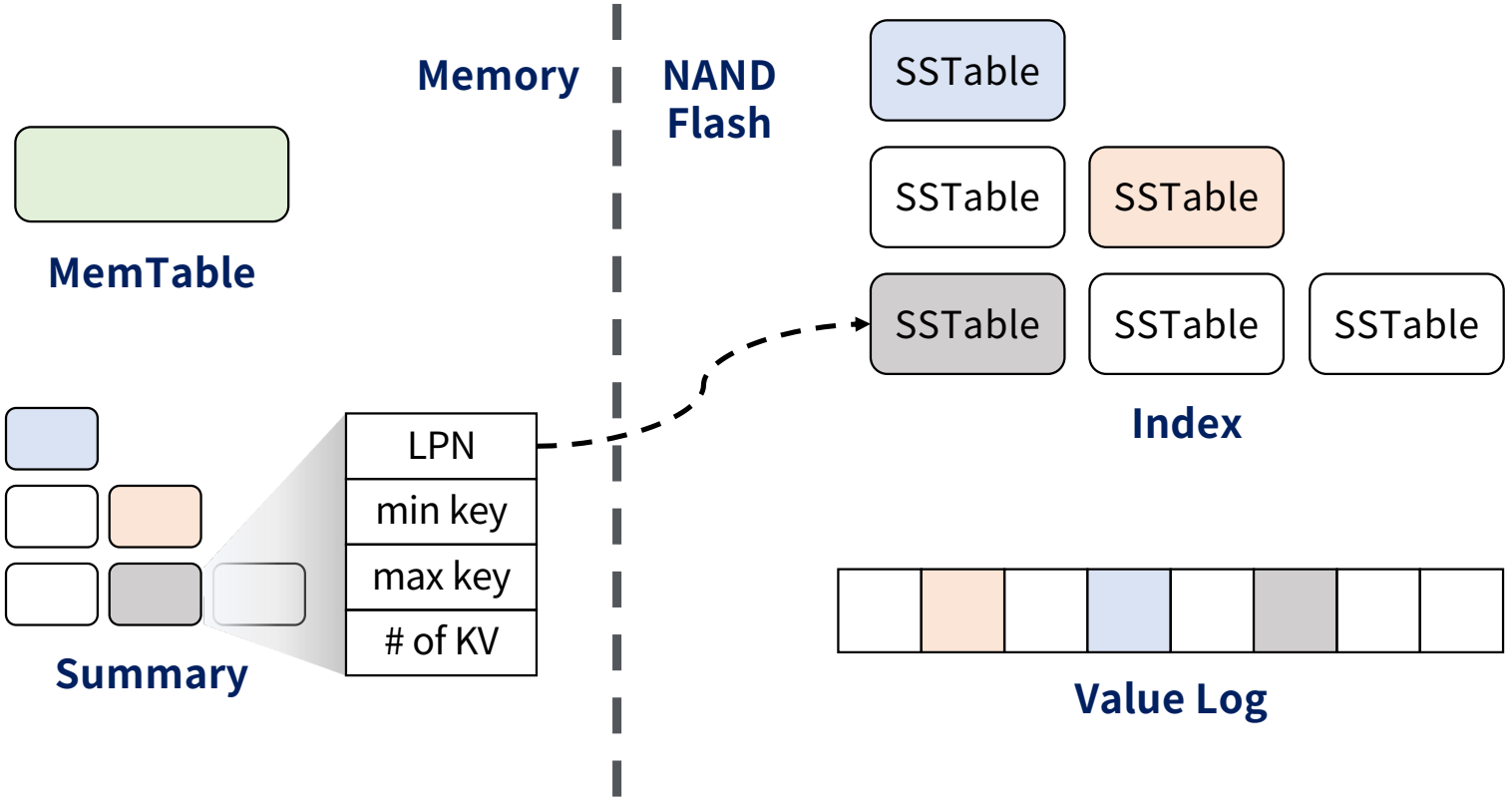

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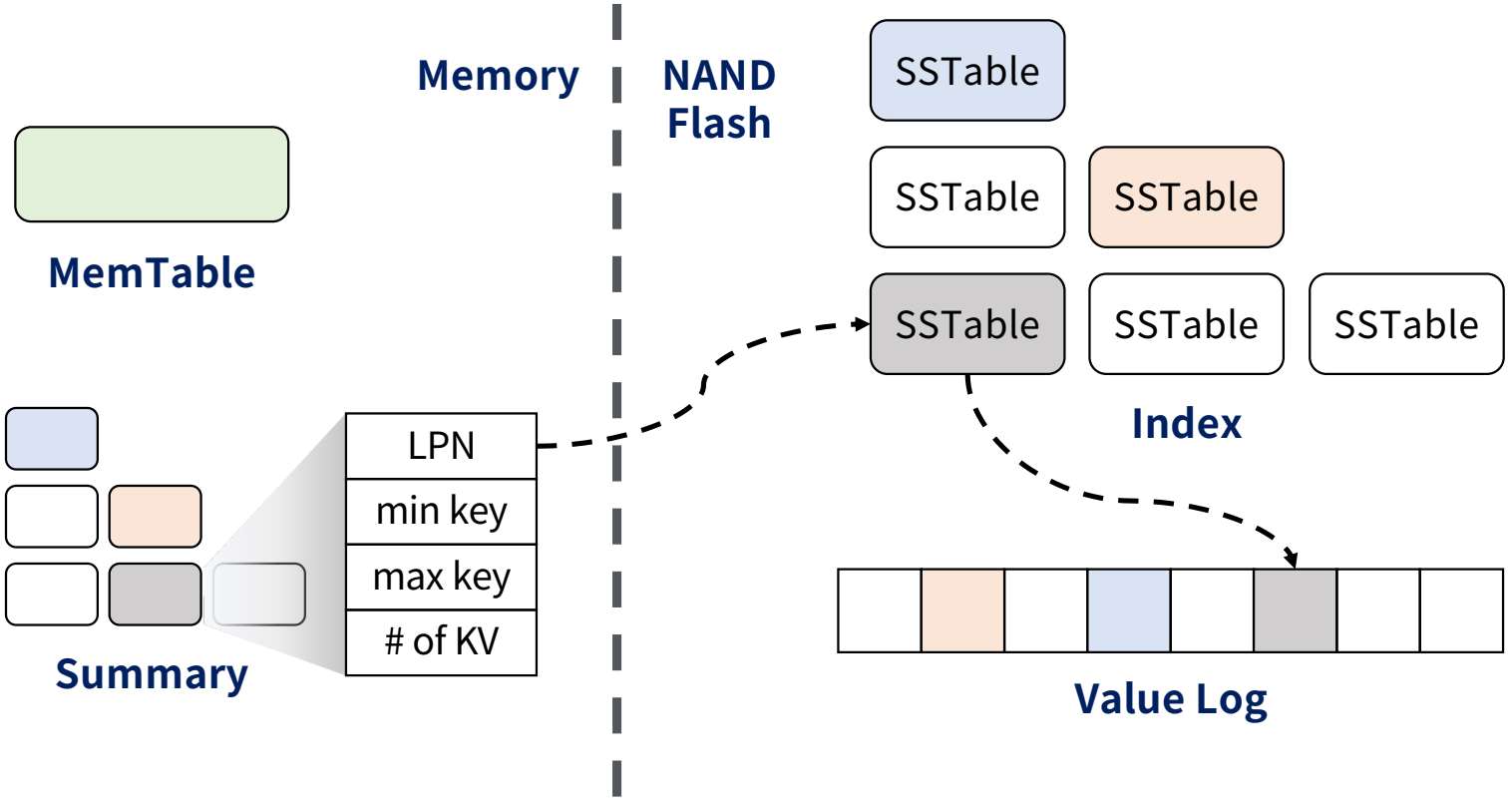

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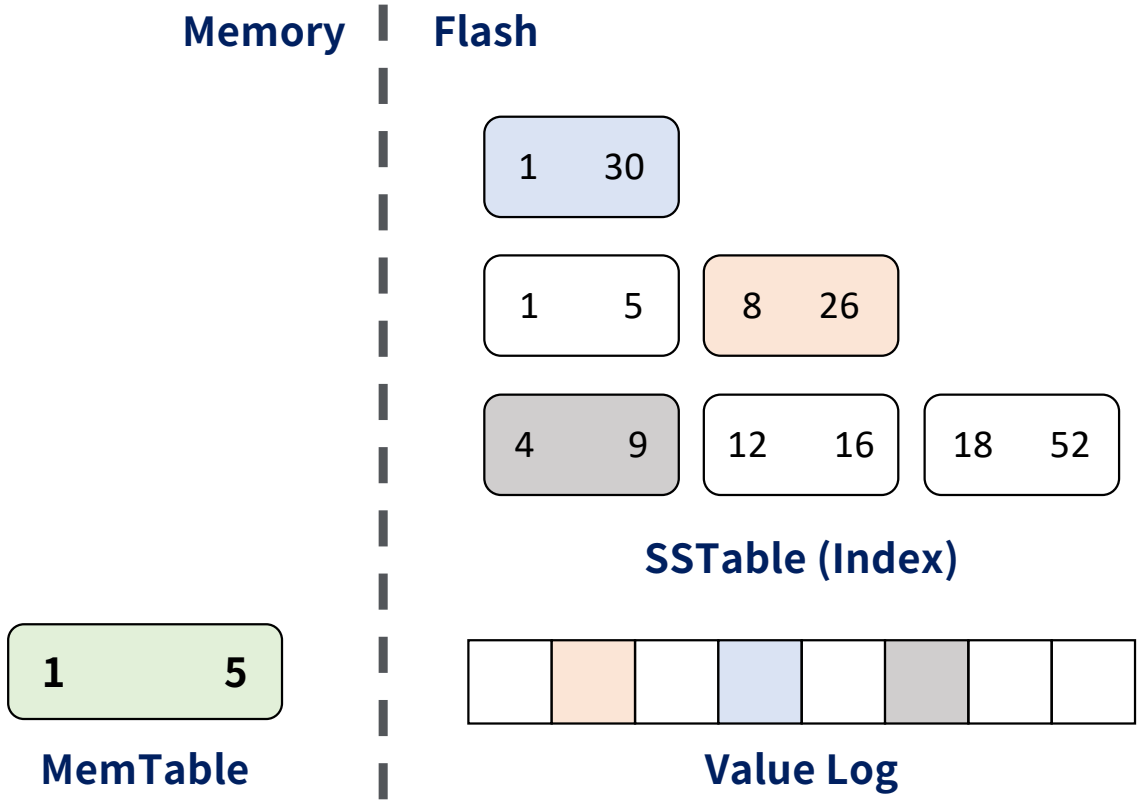

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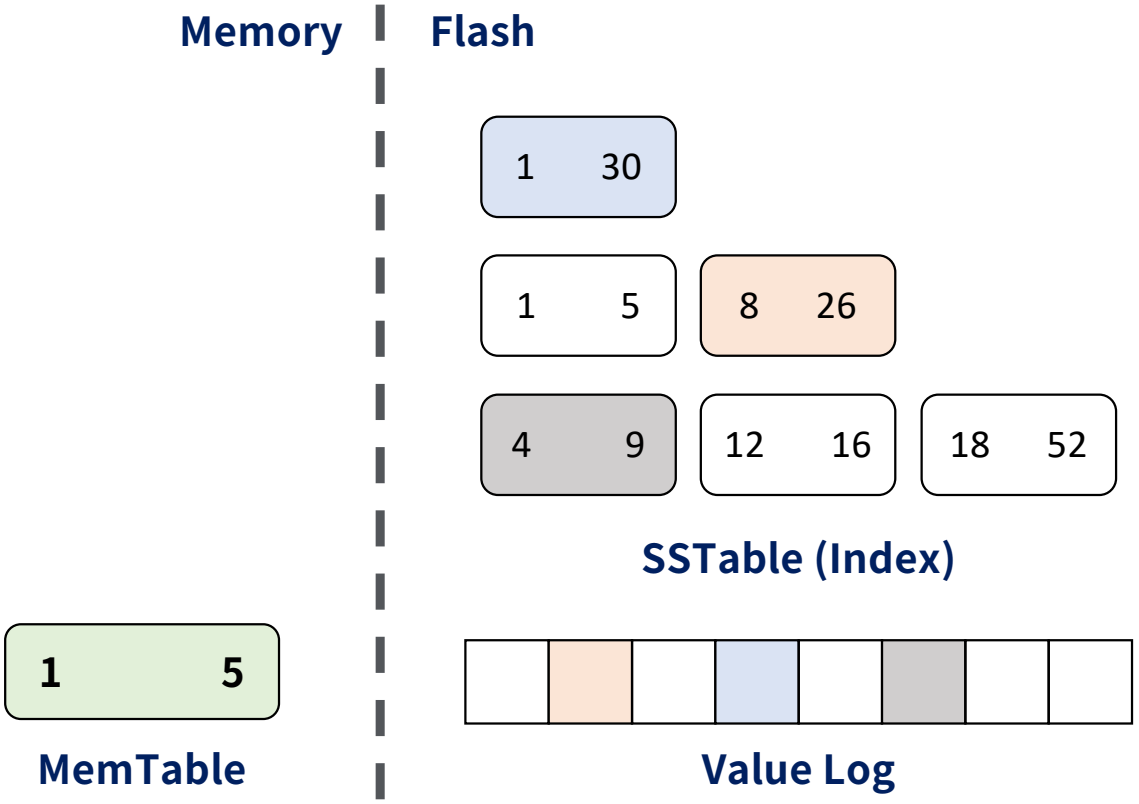

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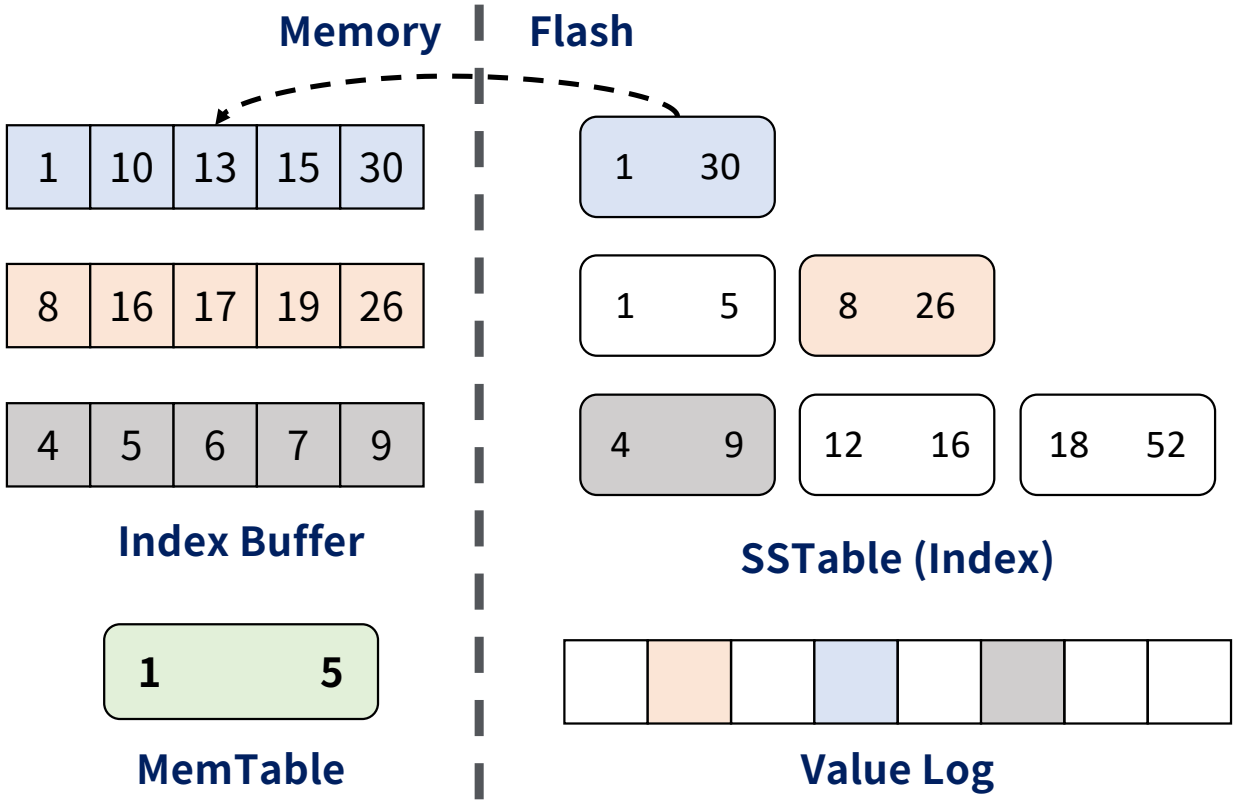

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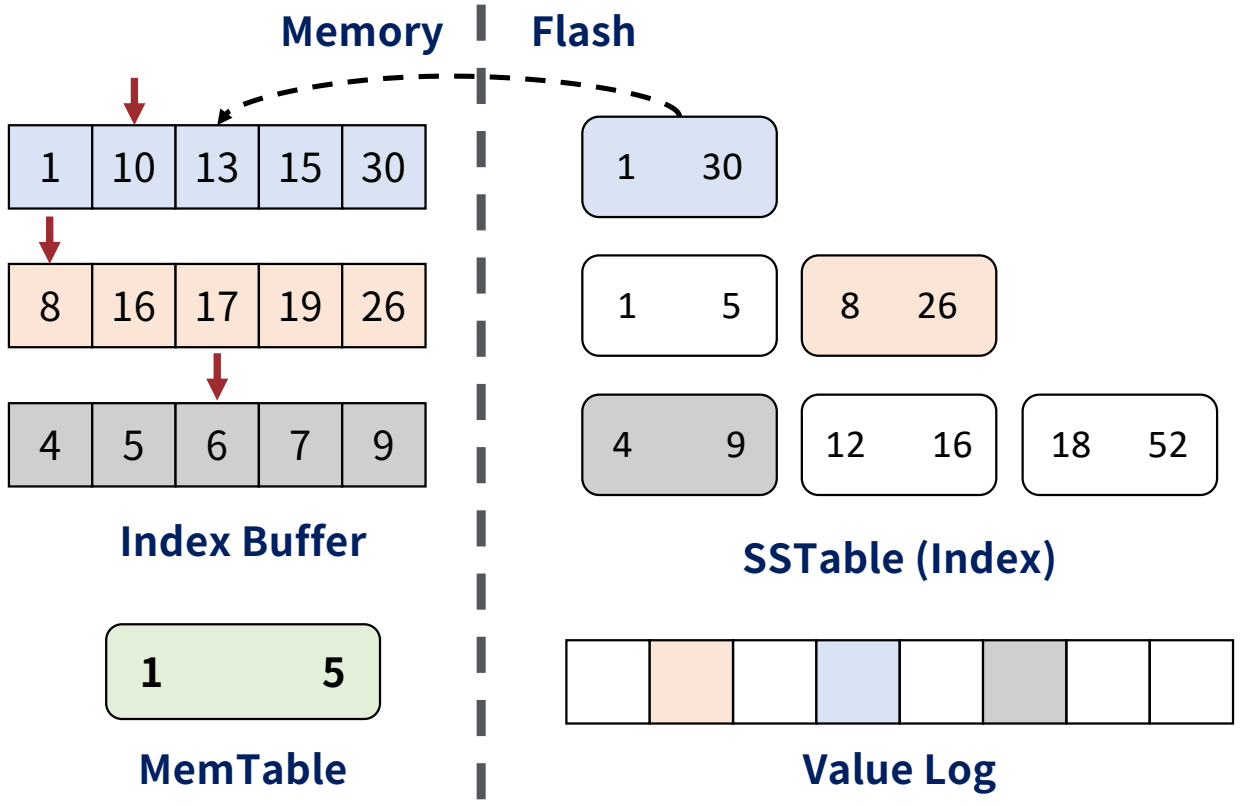

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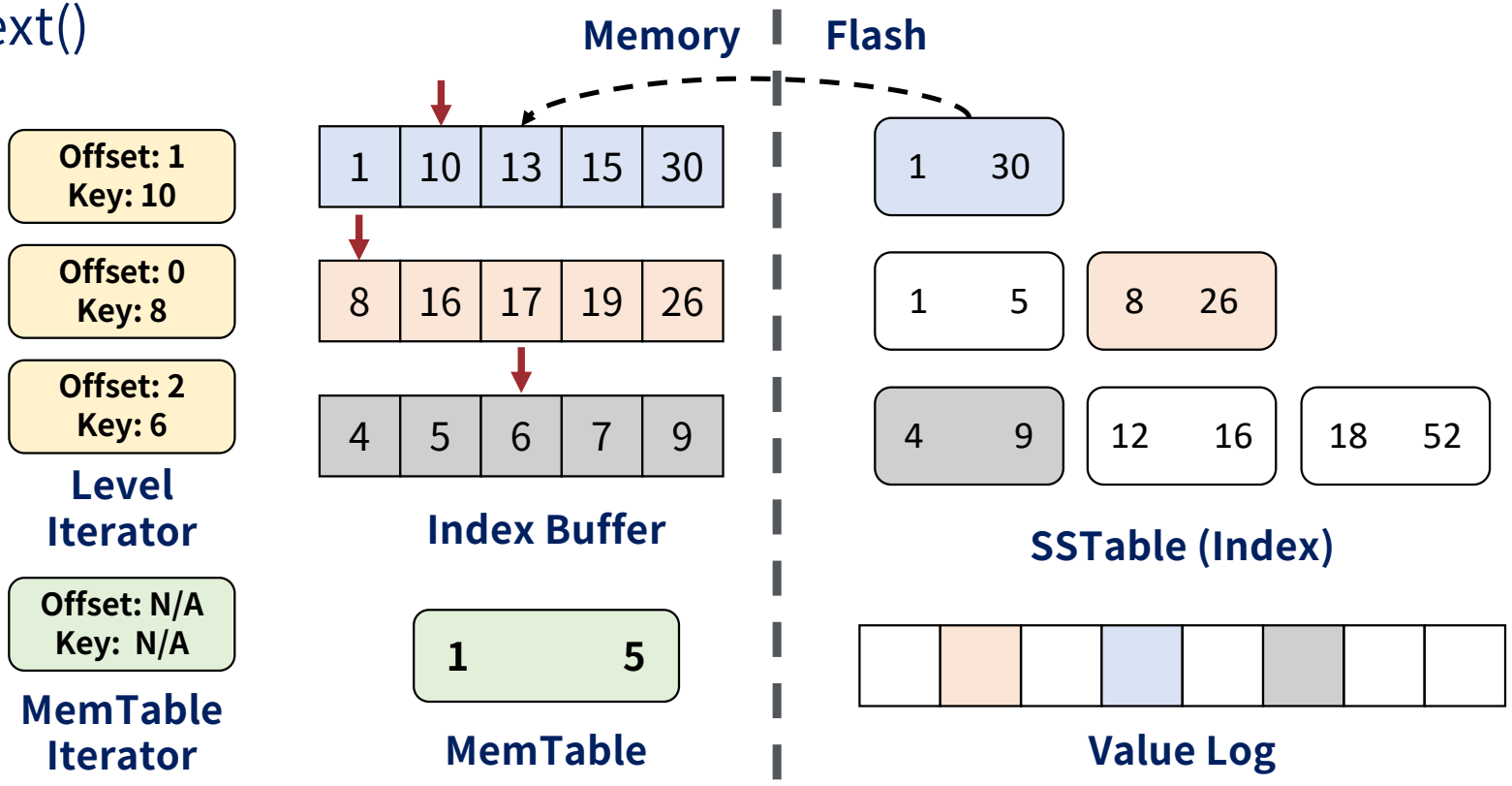

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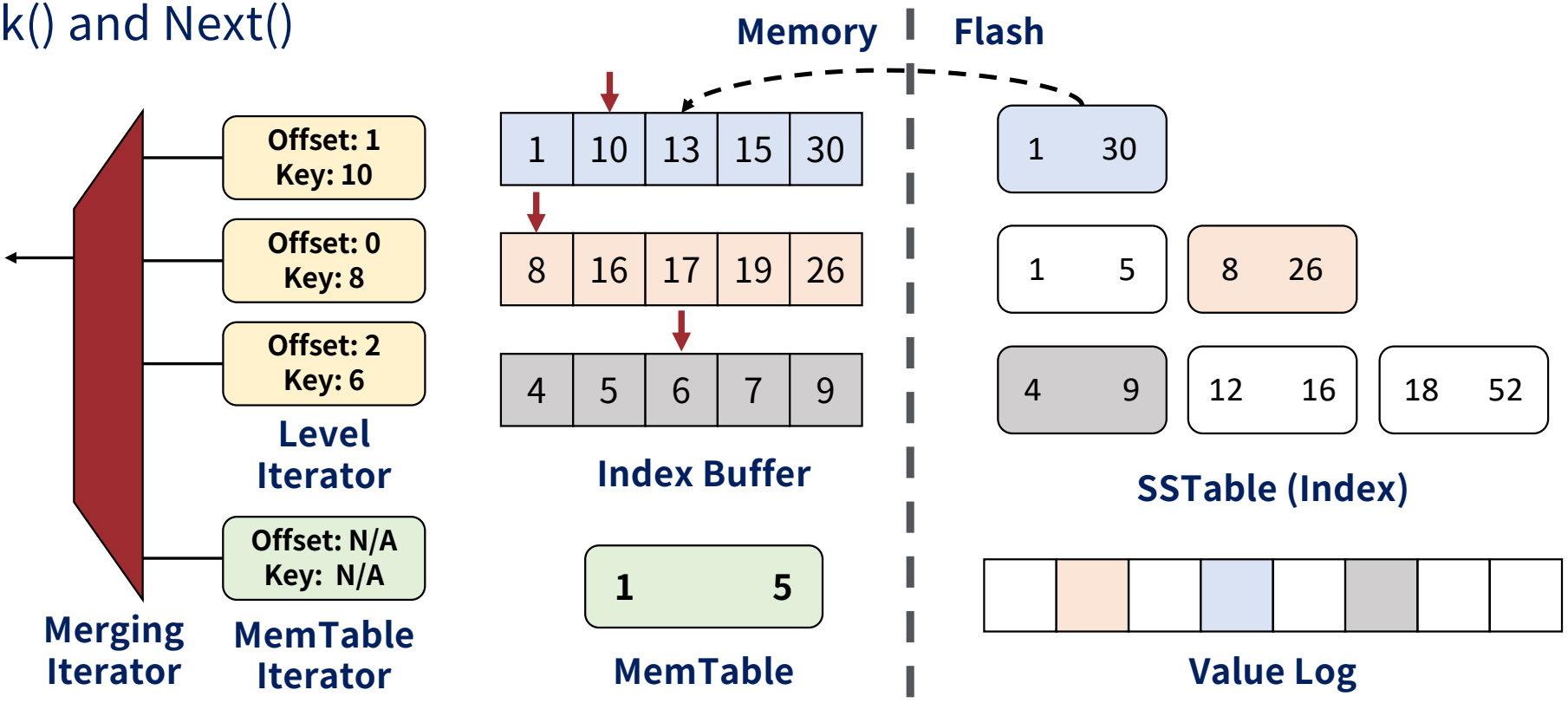

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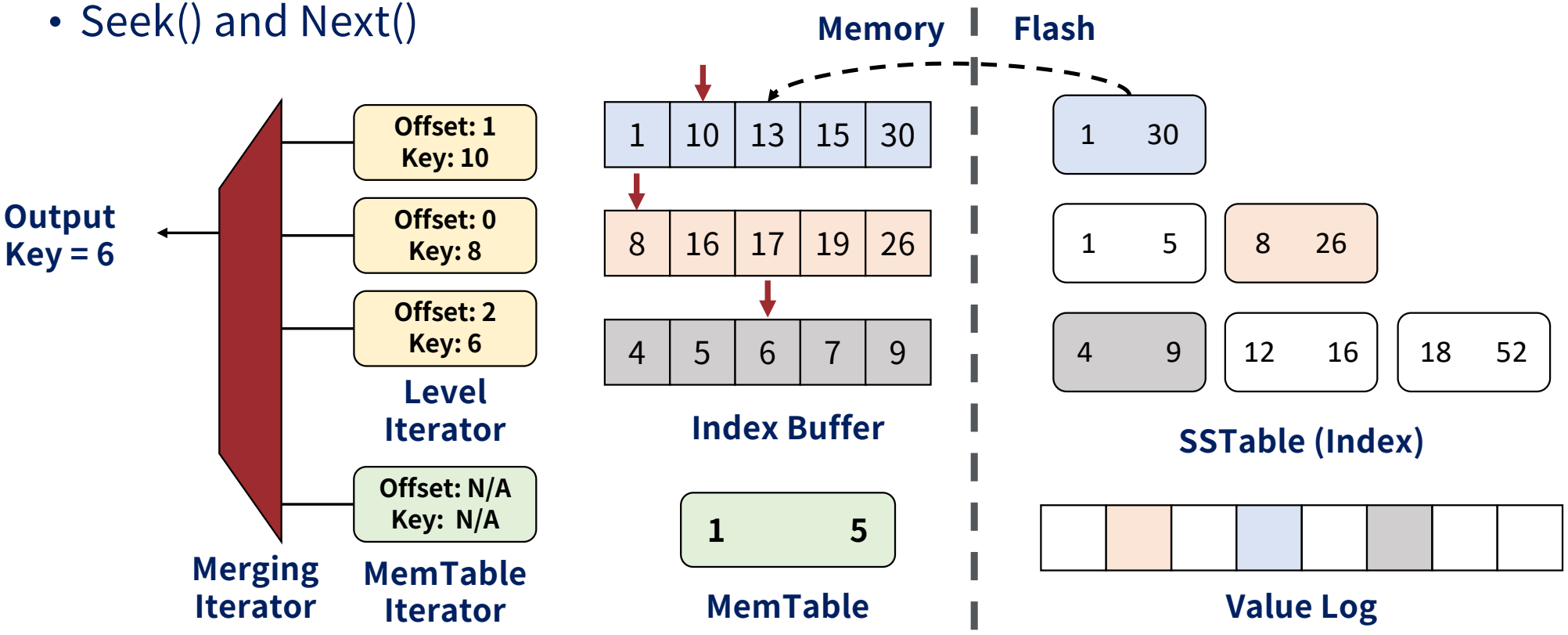

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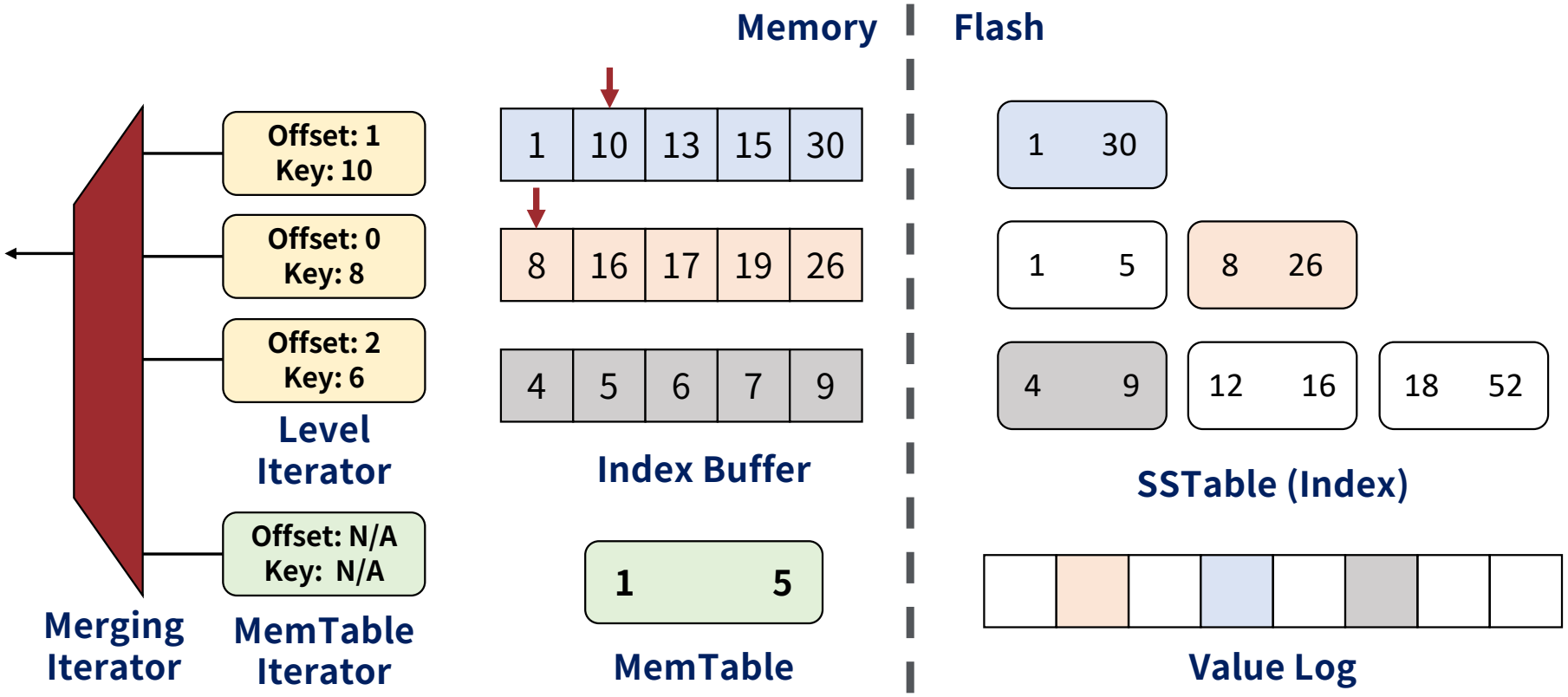

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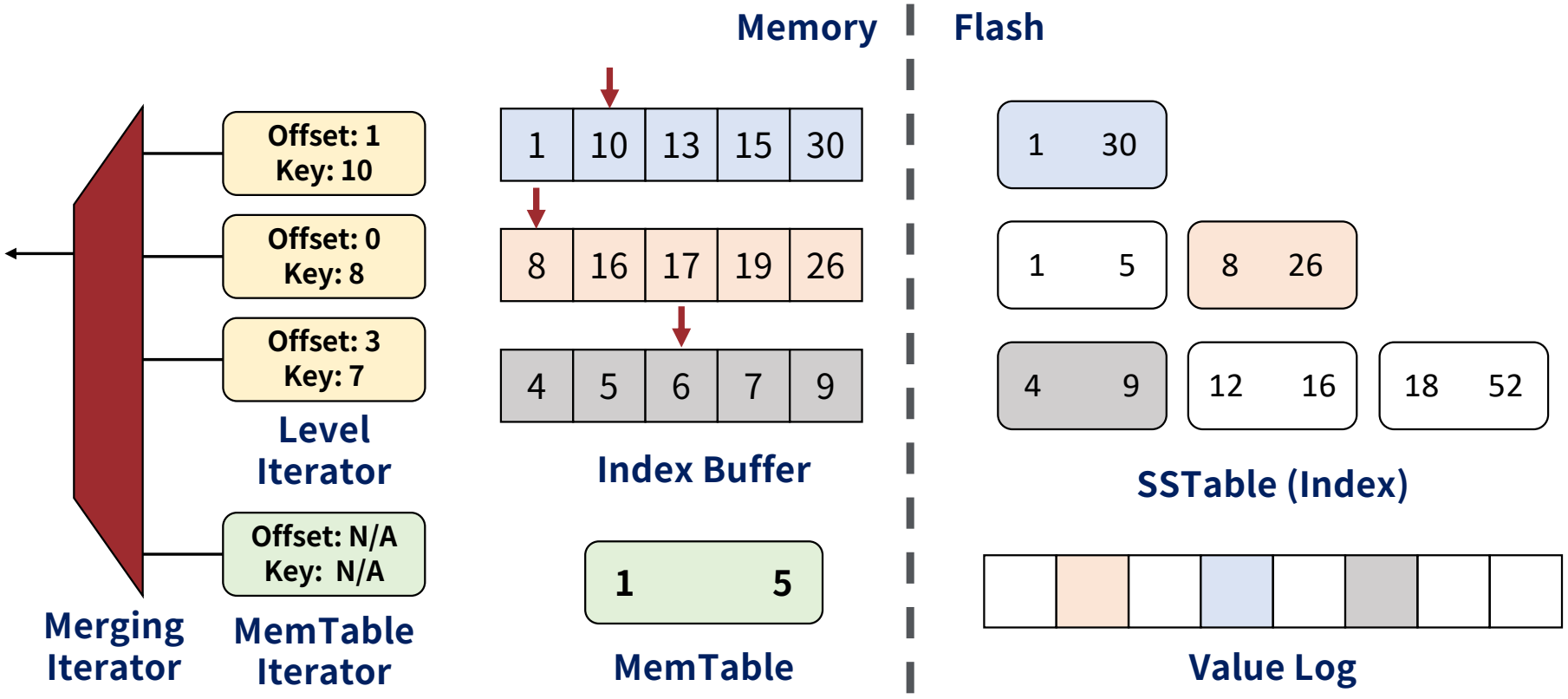

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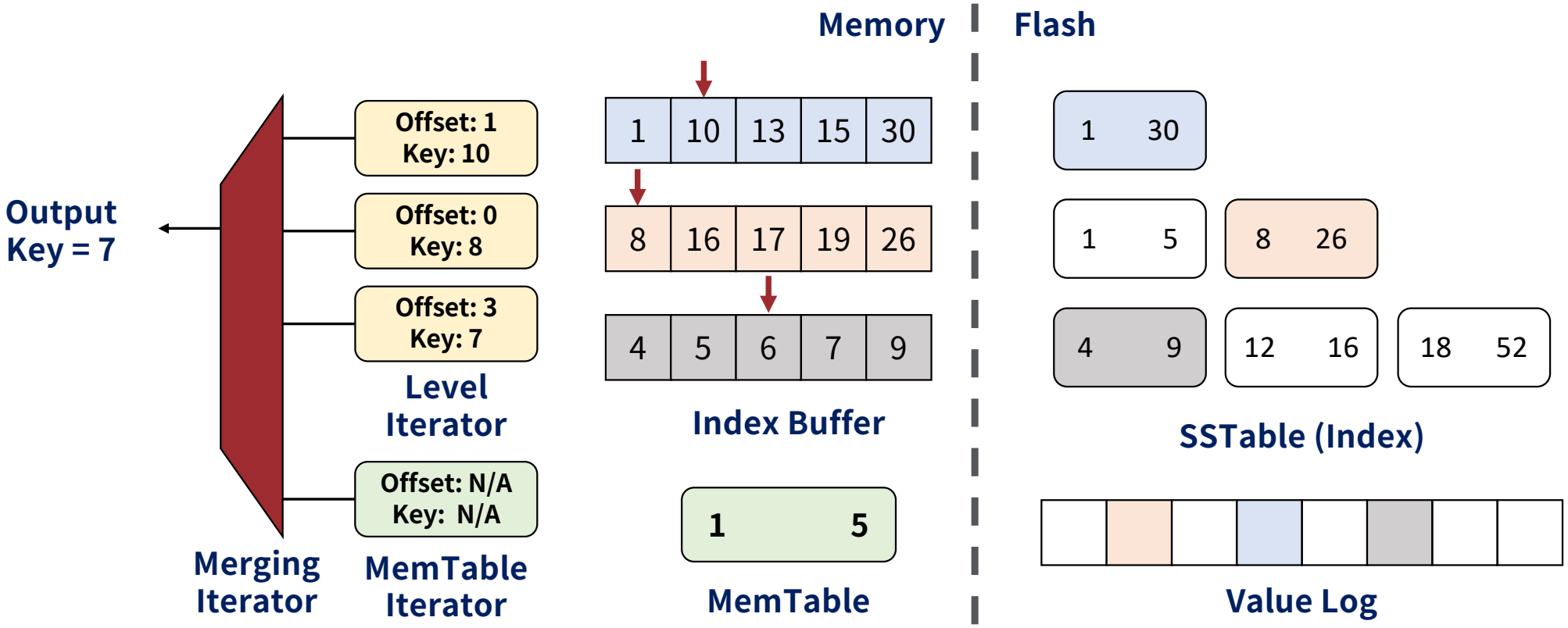

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  - Range queries are executed through **multiple iterator commands**
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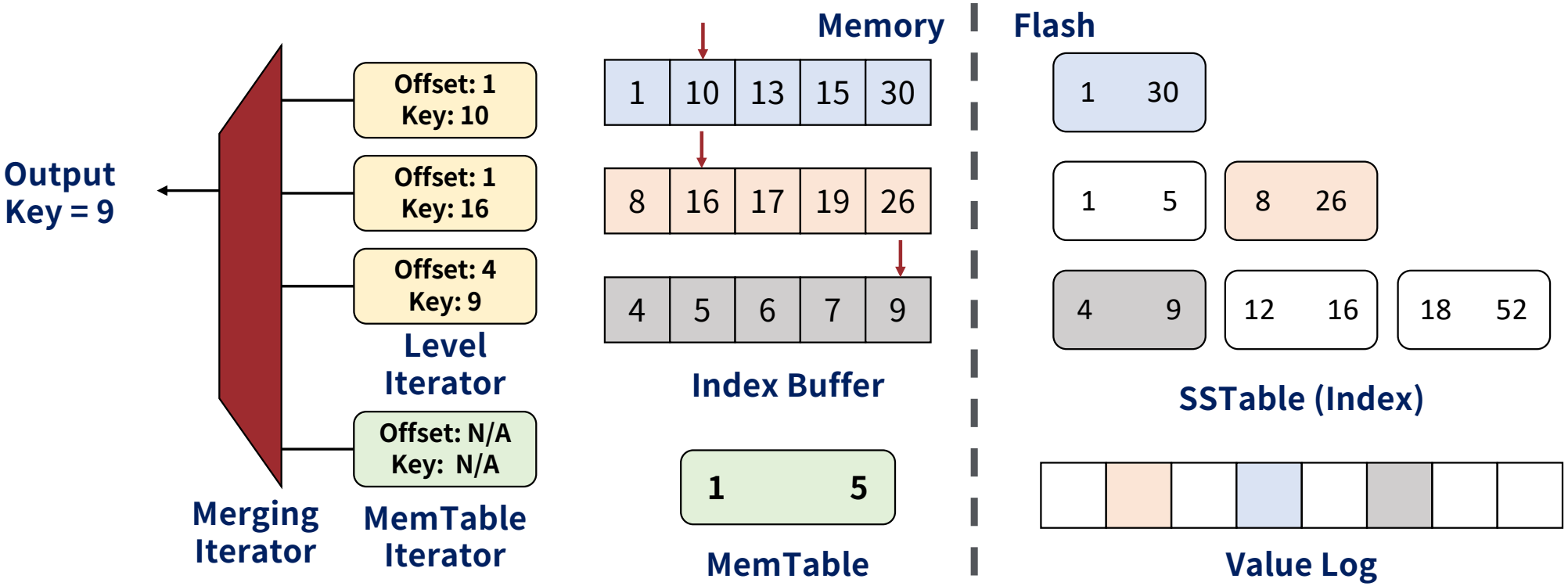

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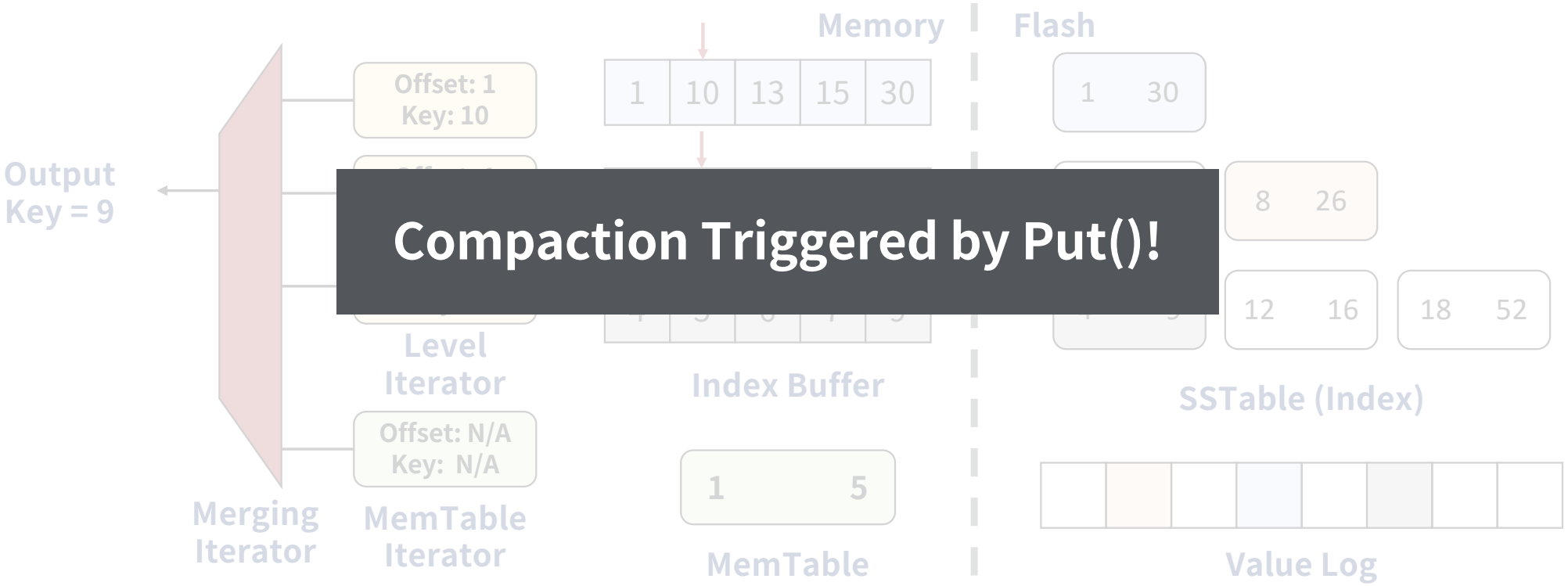

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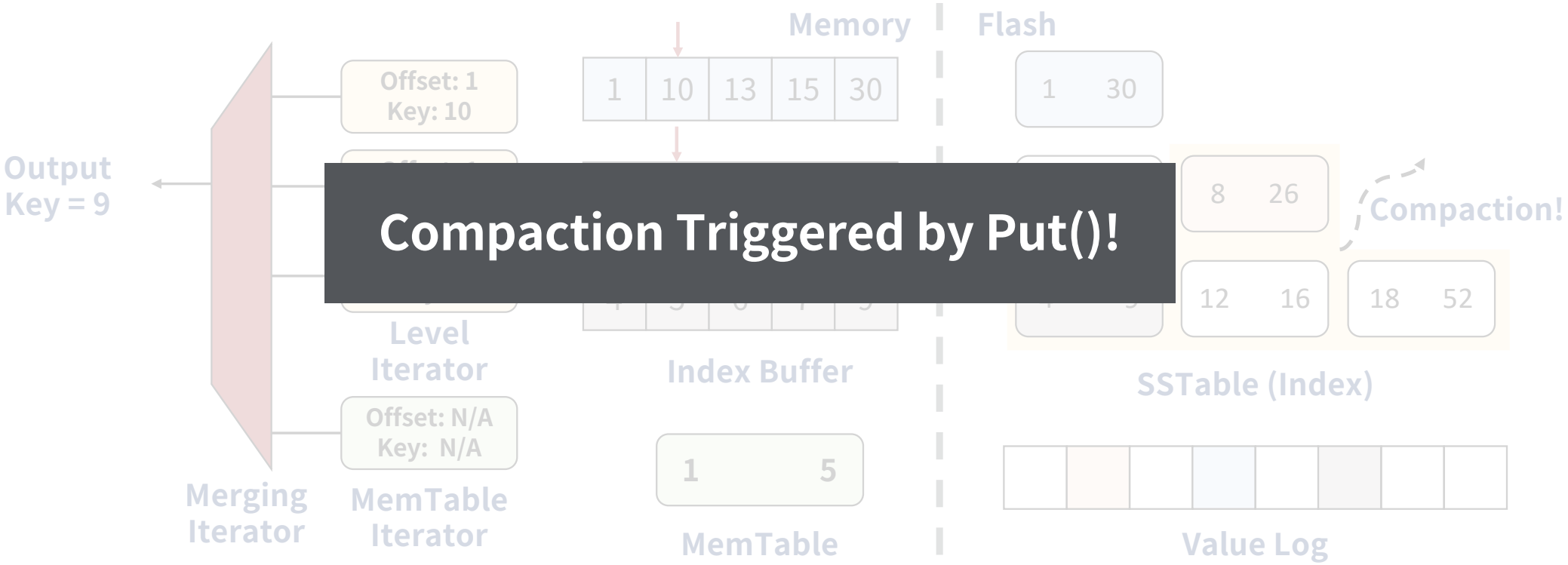

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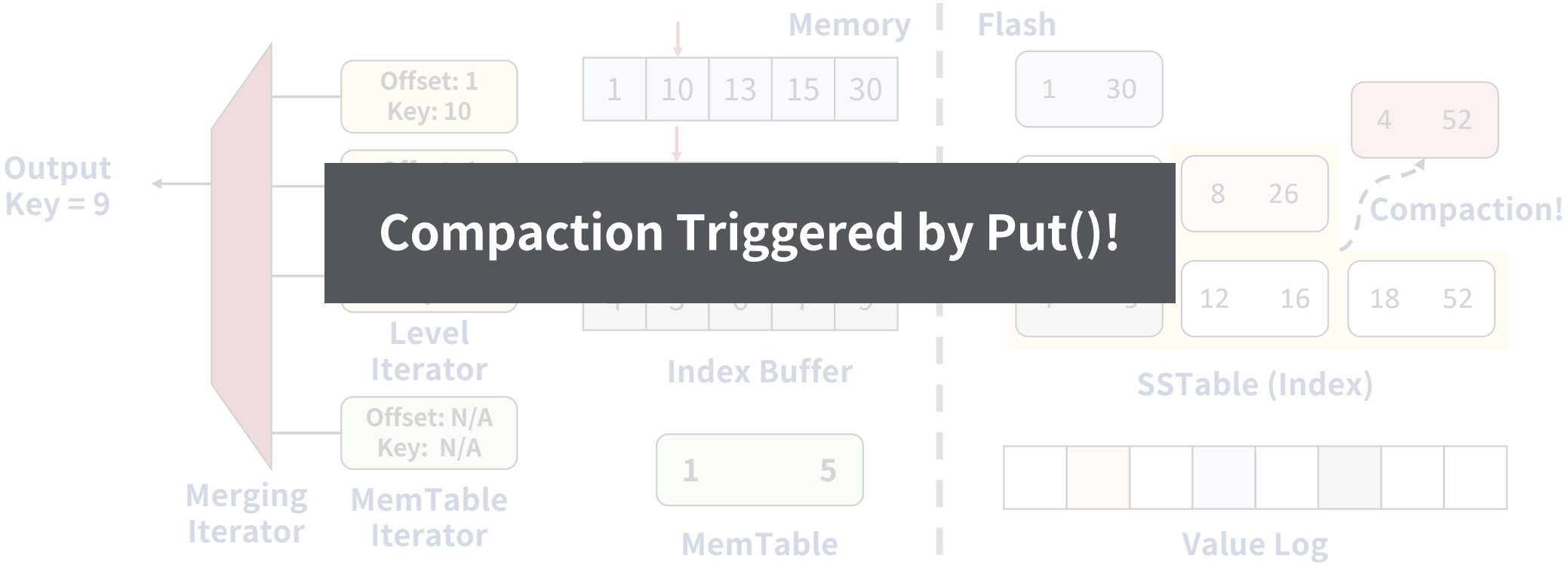

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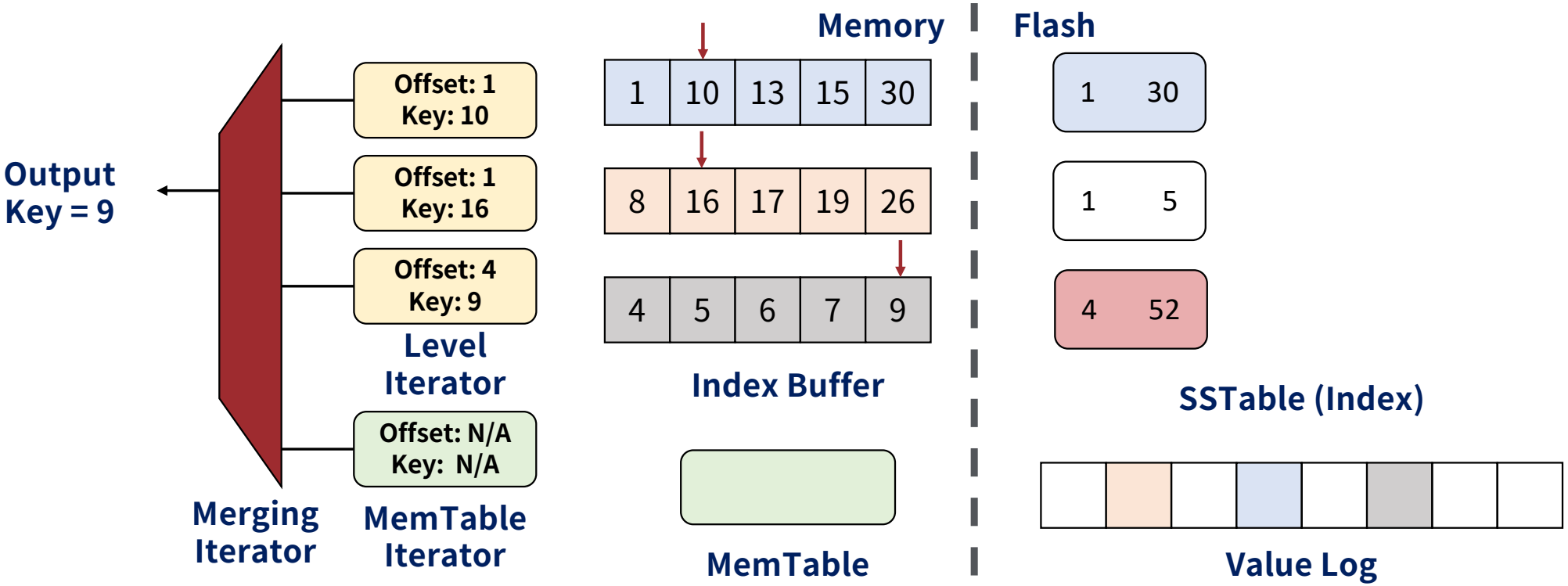

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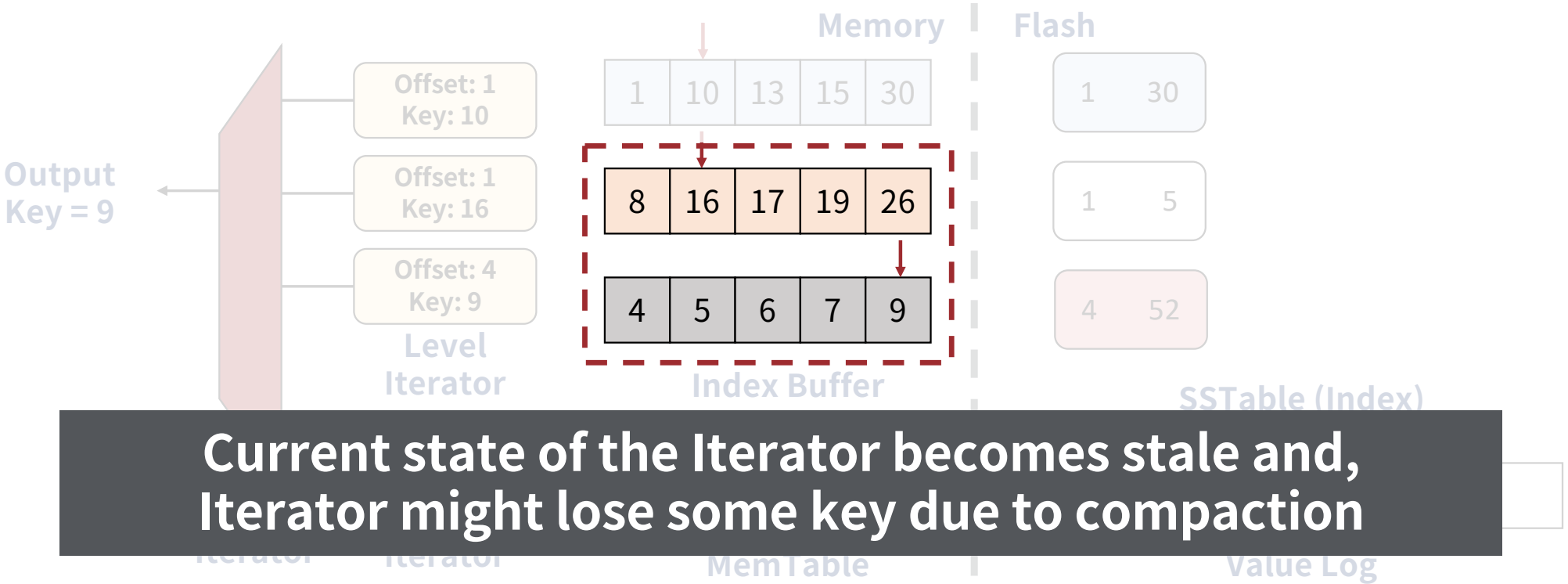

Current state of the Iterator becomes stale and, Iterator might lose some key due to compaction

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But,we need memory-efficient versioning inside the device!

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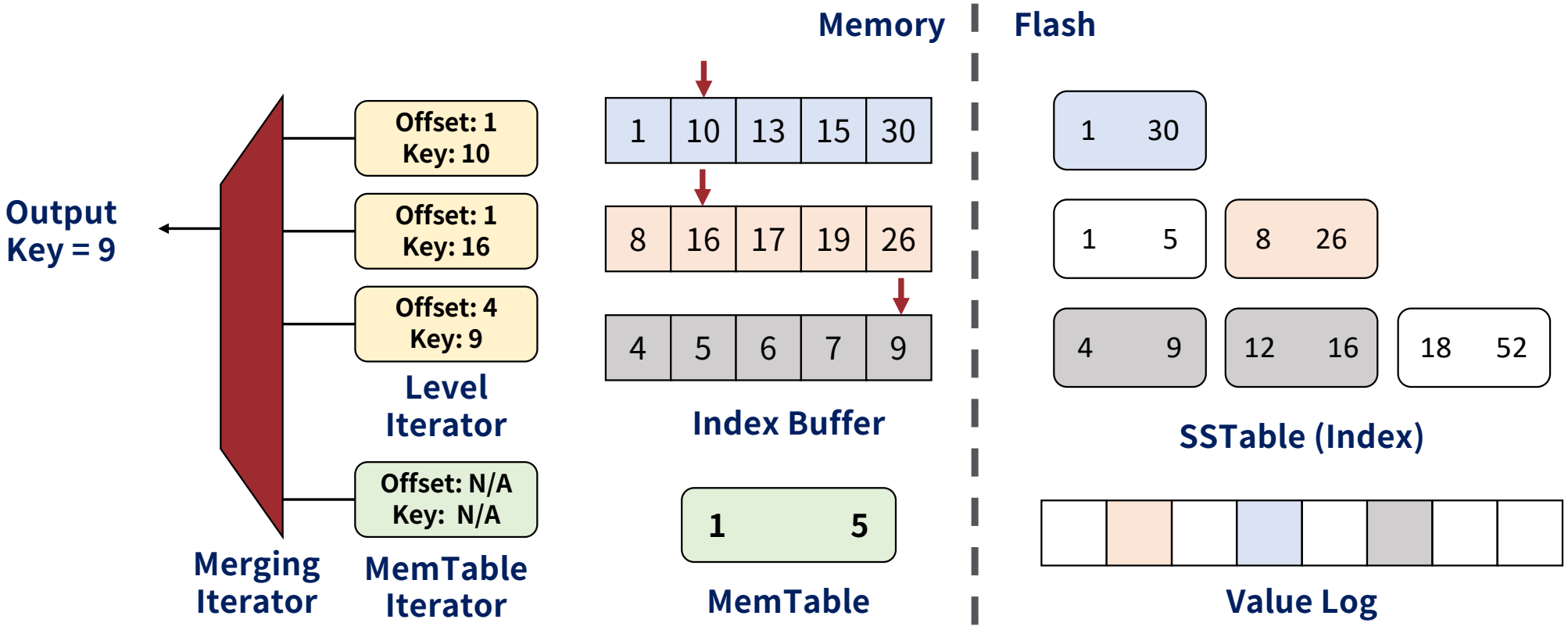

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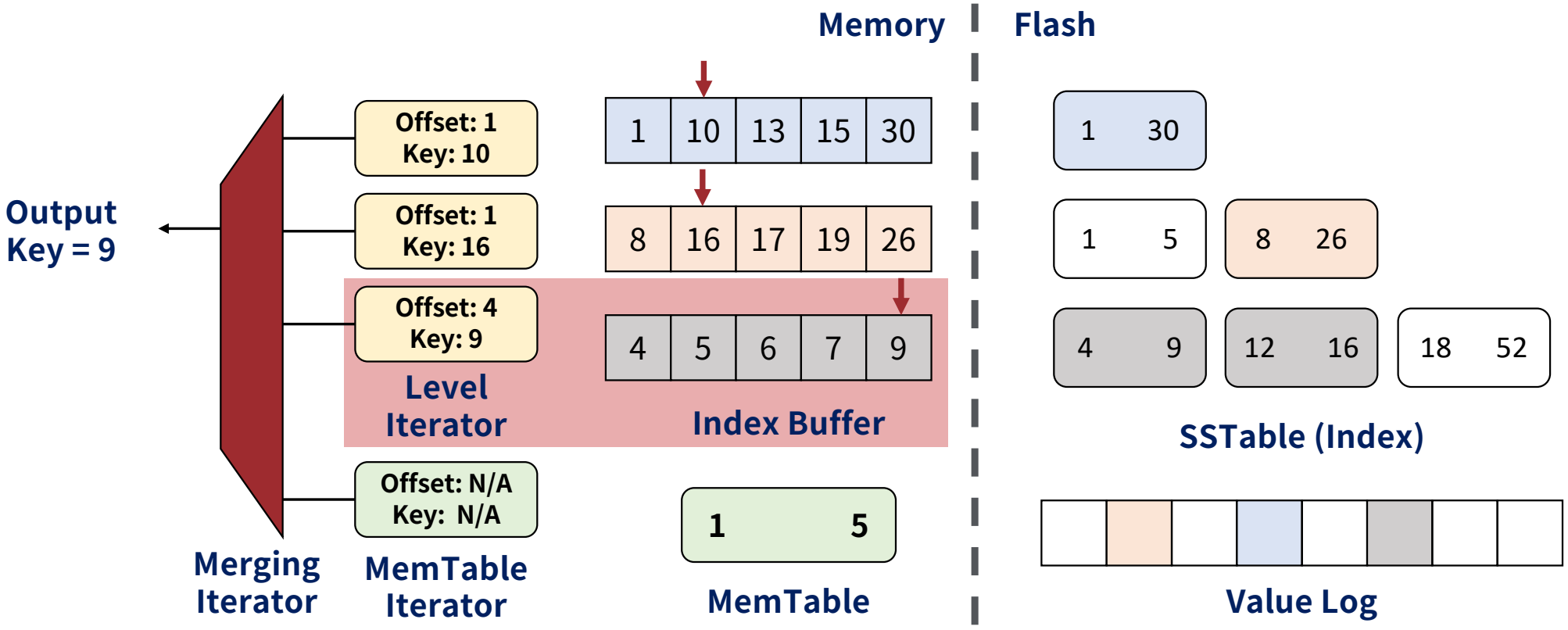

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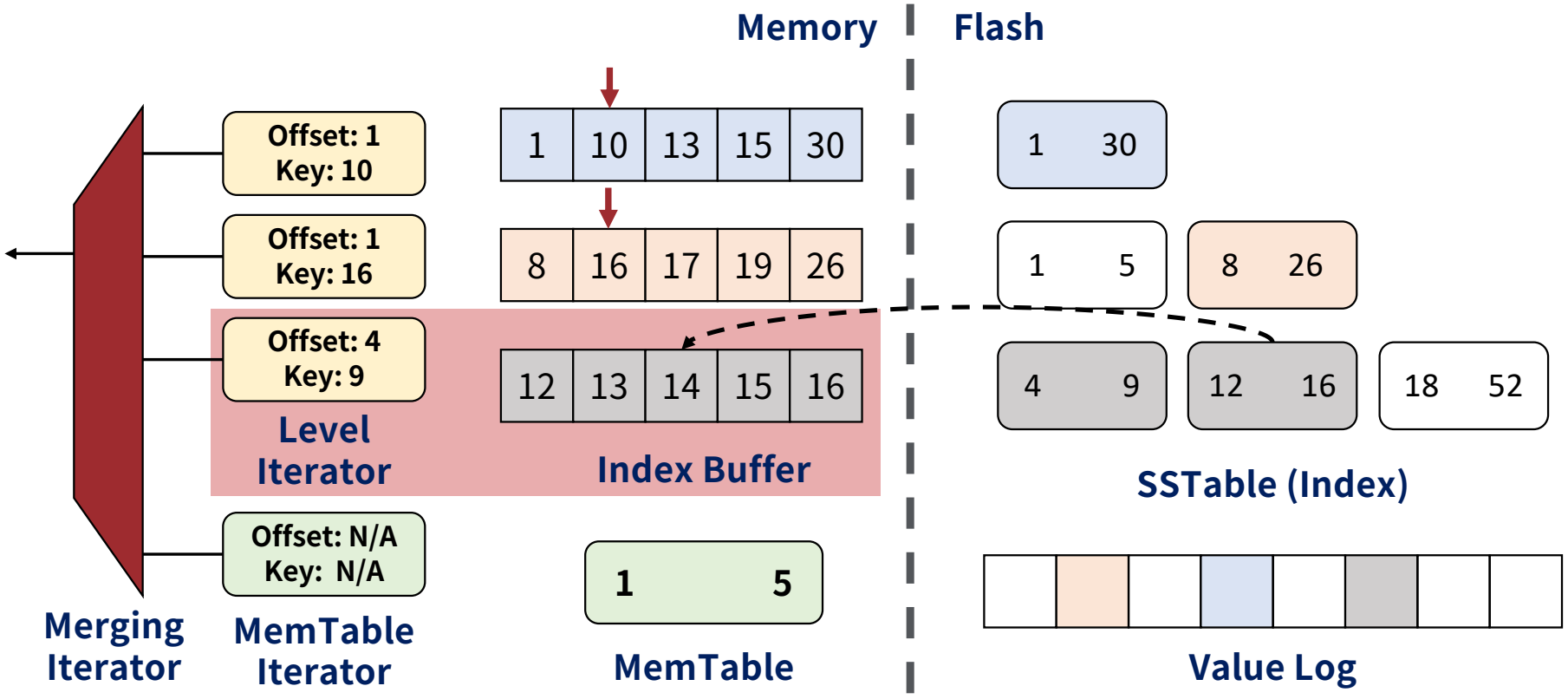

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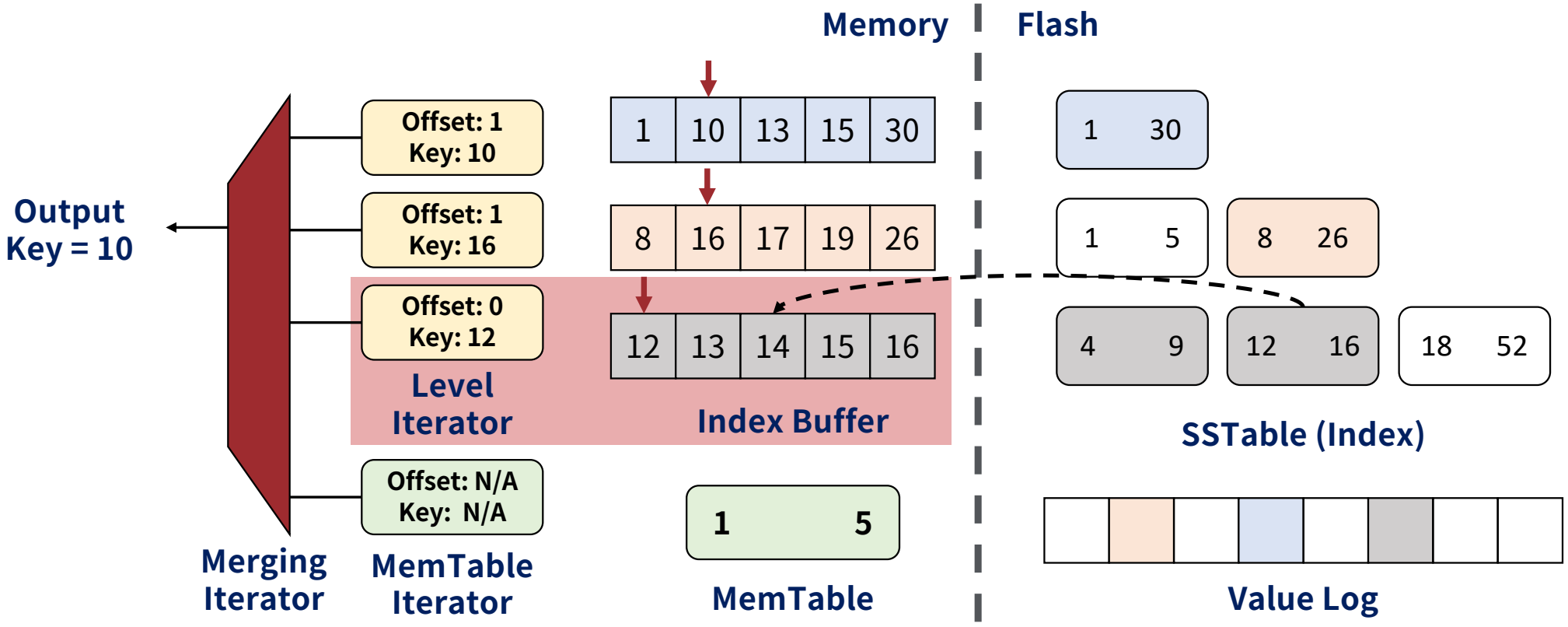


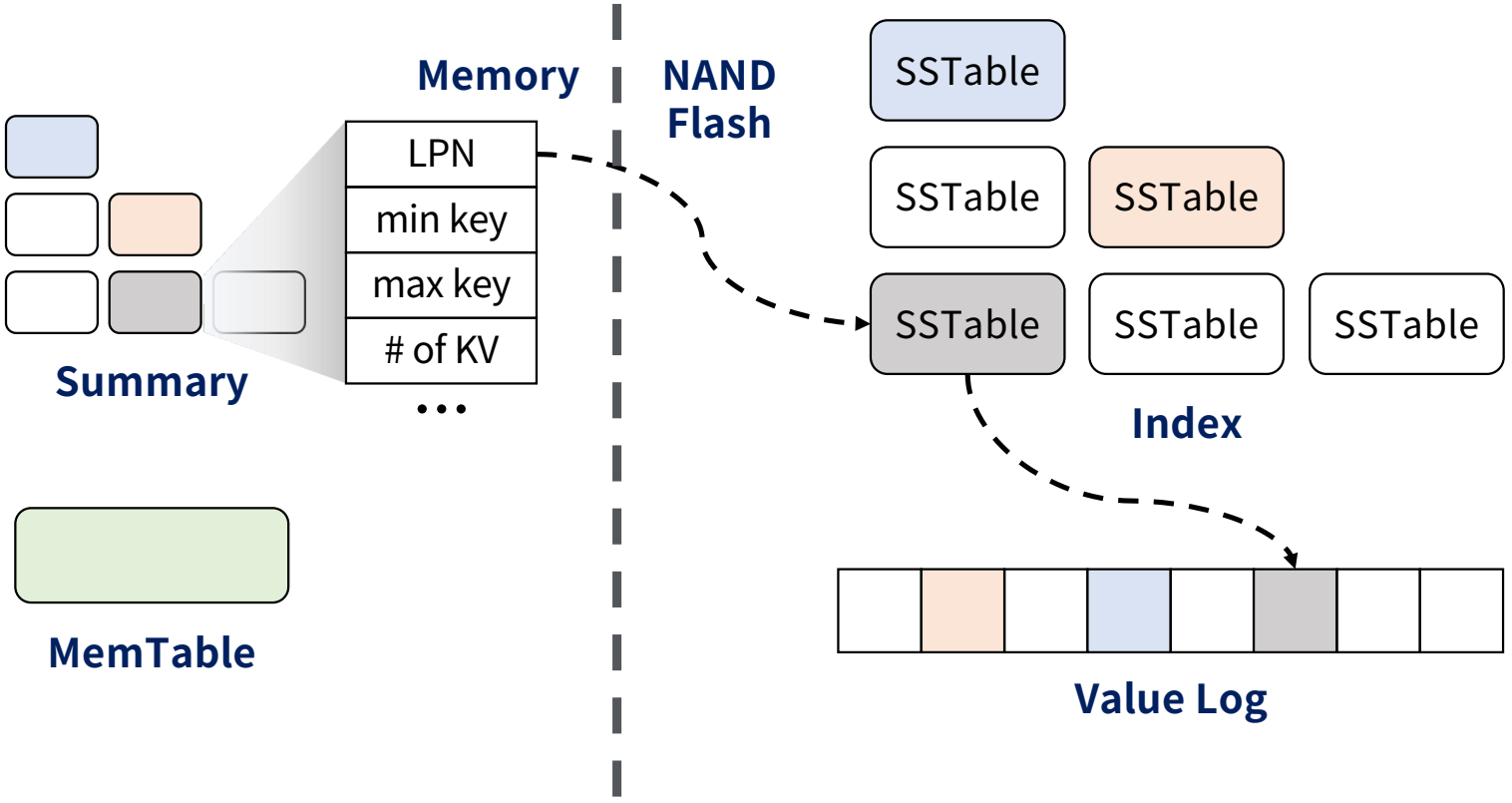
Problem #3 – Synchronous Value Read

- **Design Challenge #3 – NAND Flash Access for Value Read**
  - **Every Seek() and Next() command** requires NAND Flash Access for Value
  - Considering that NAND Flash access is much slower than the other steps, synchronous NAND Flash access for Value may woefully aggravate the overall performance

Design of IterKVSSD

Memory Efficient Versioning Data Structure

- How to support Versioning inside the device?



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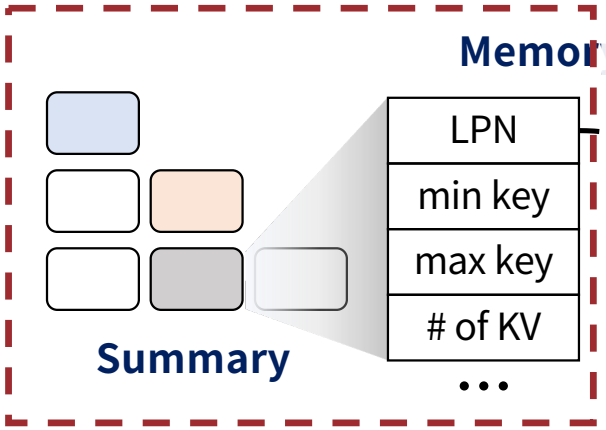

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- In our setup,
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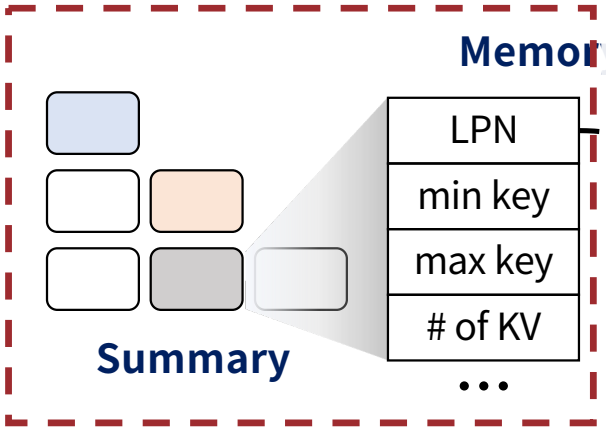

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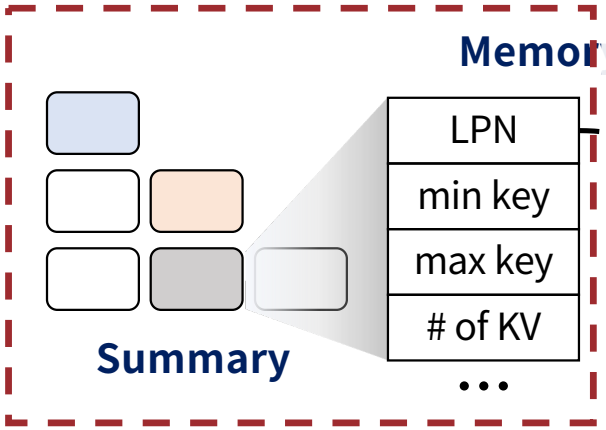

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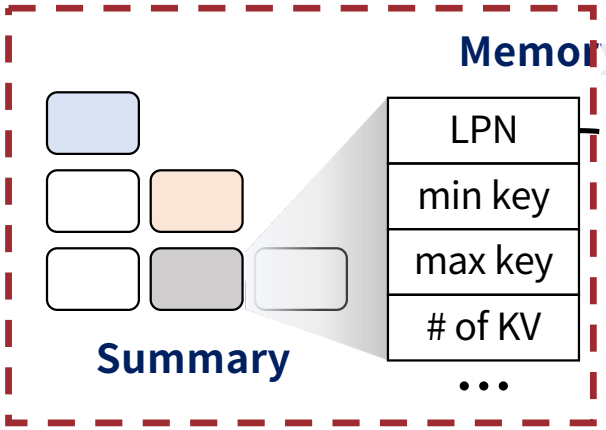

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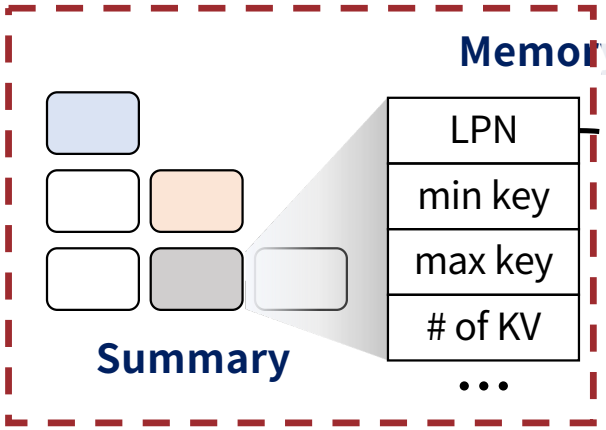

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Keeping Summary for every Iterator is too expensive!

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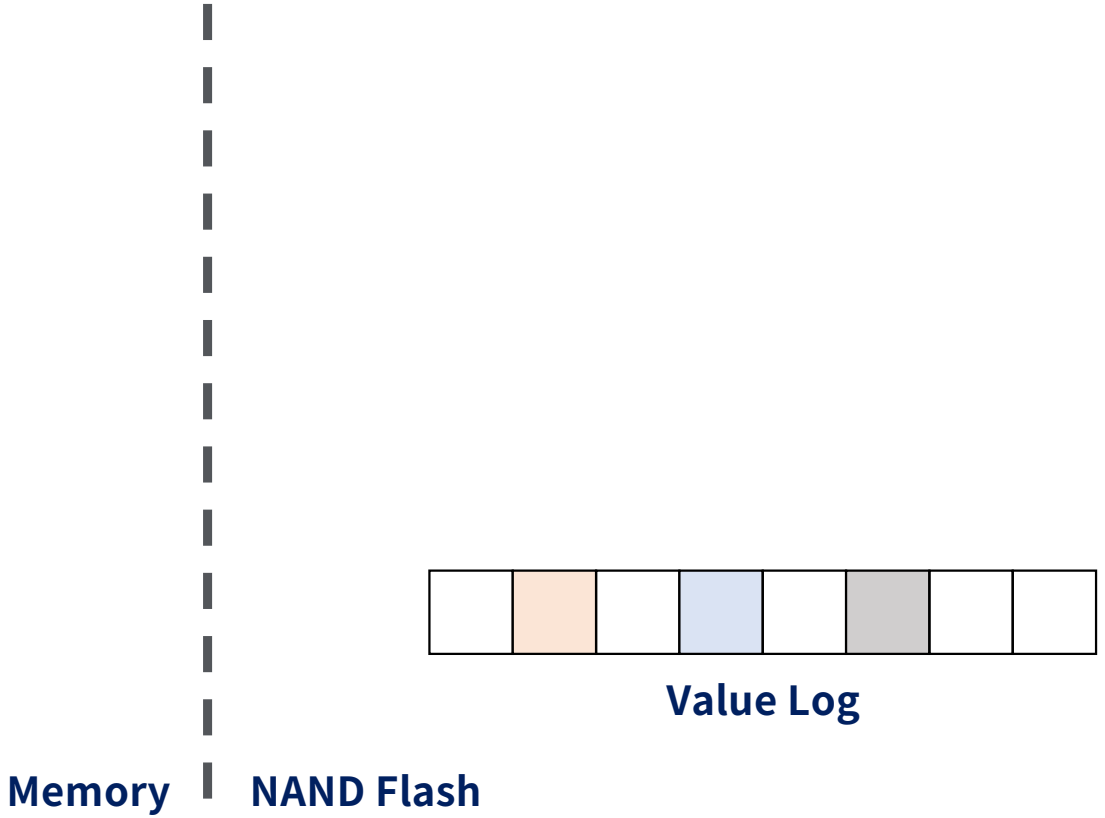

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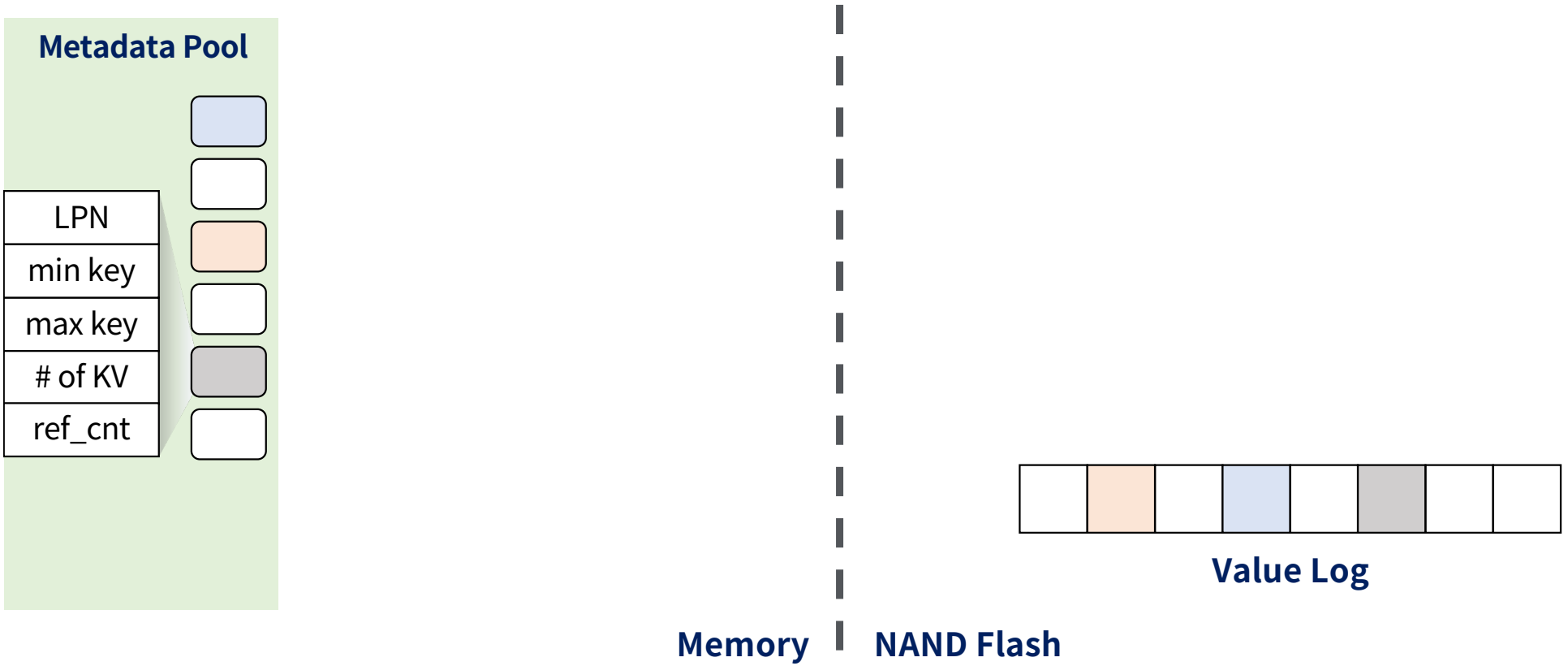

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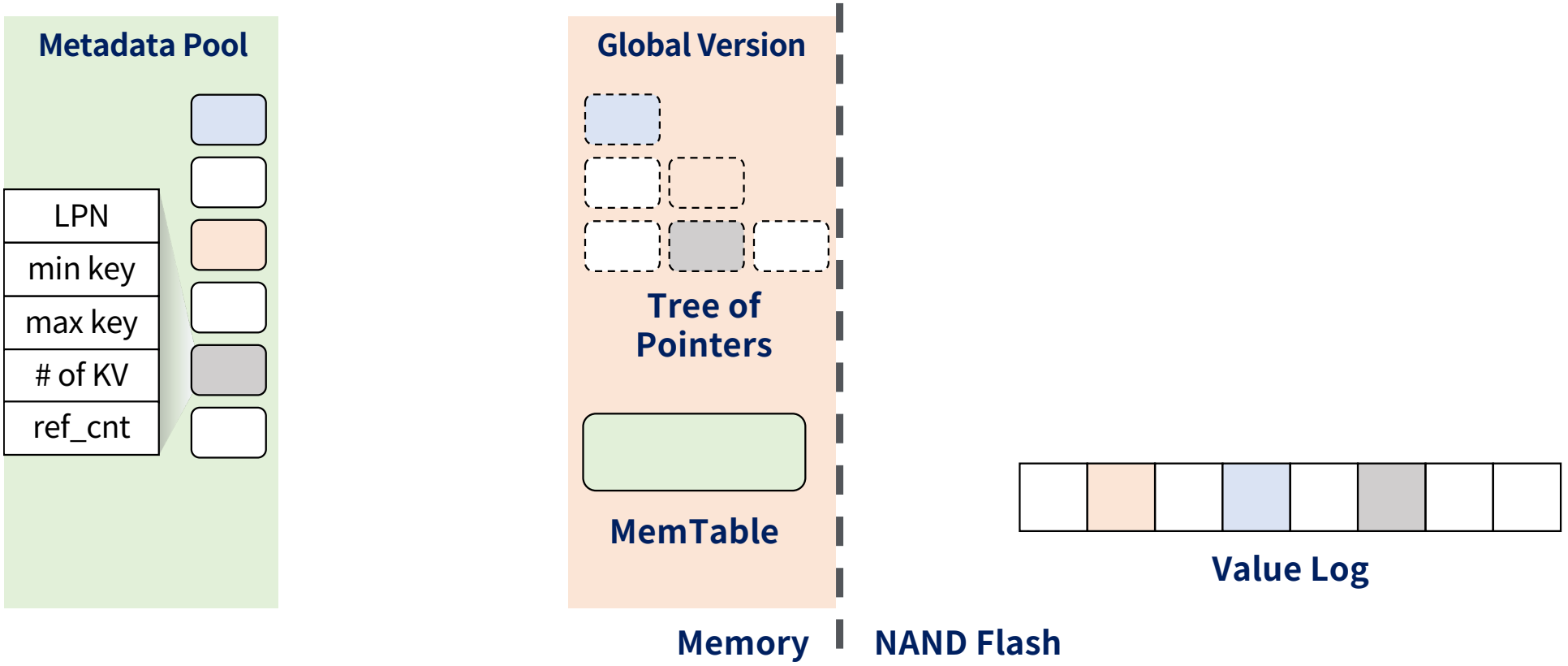

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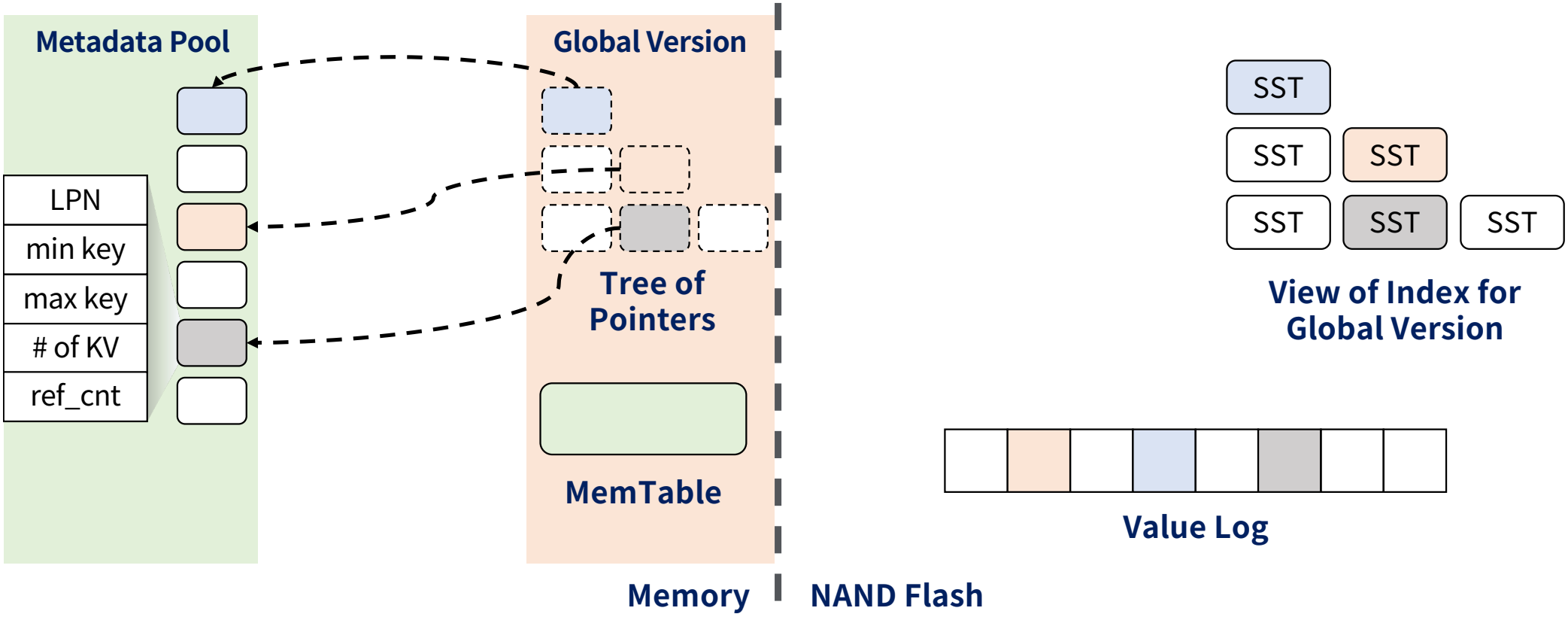

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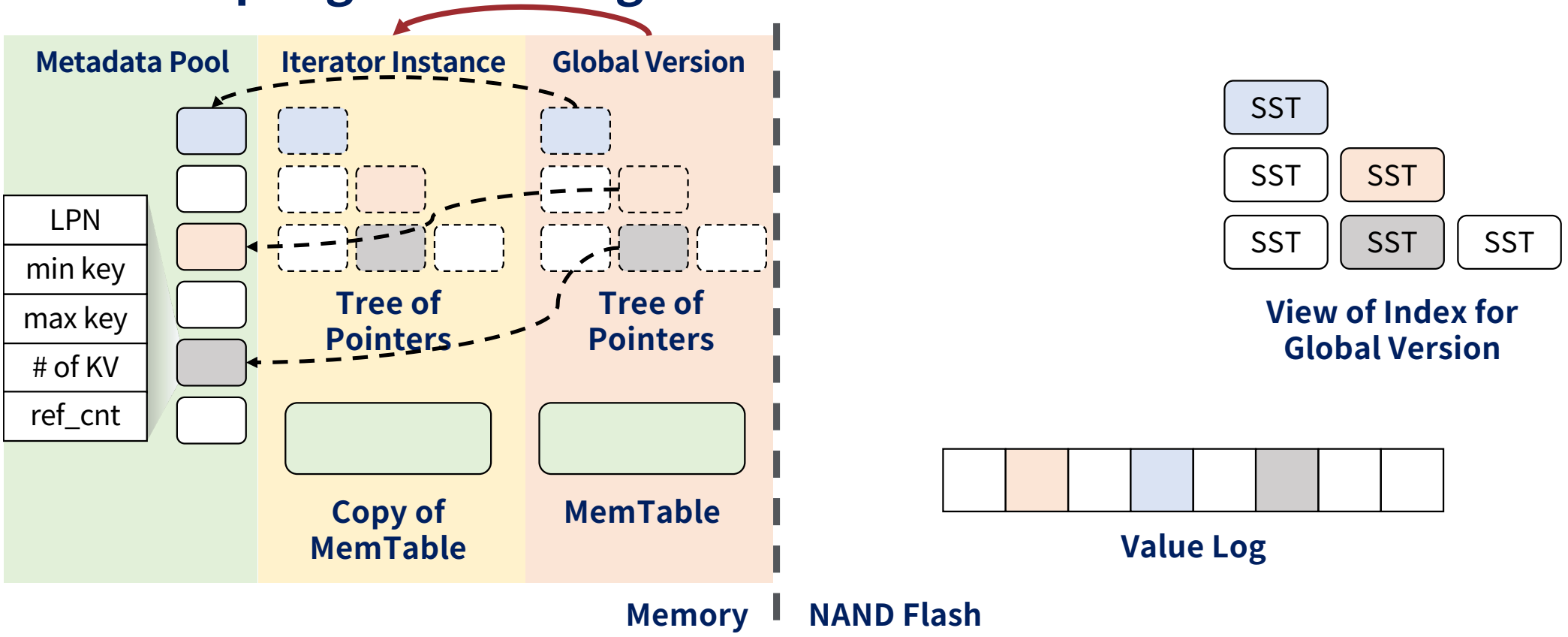

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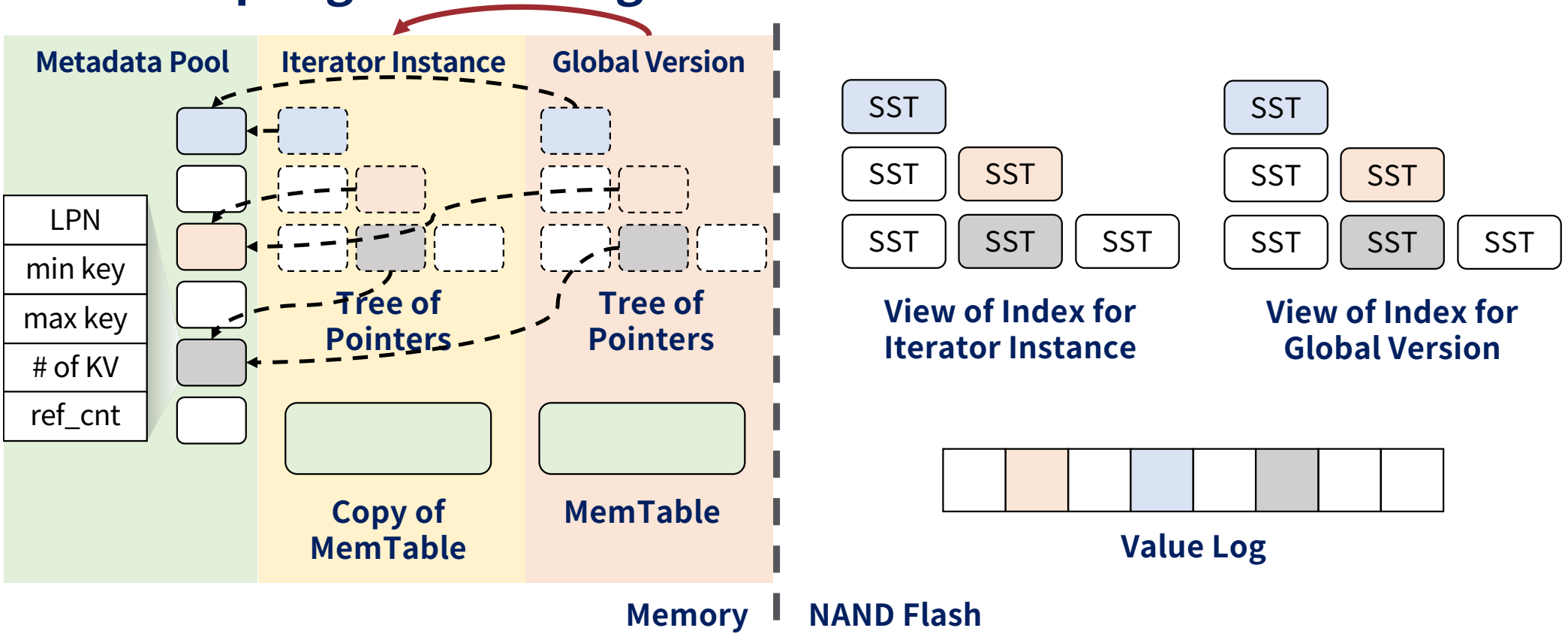

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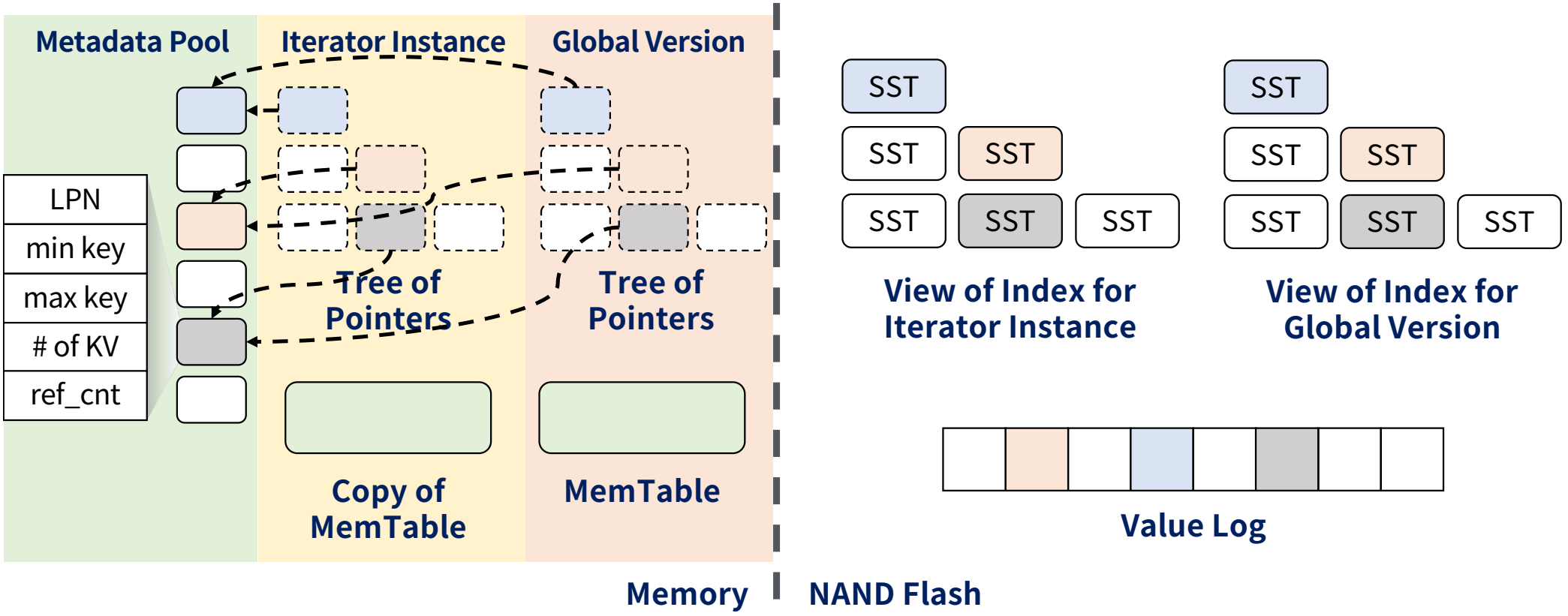

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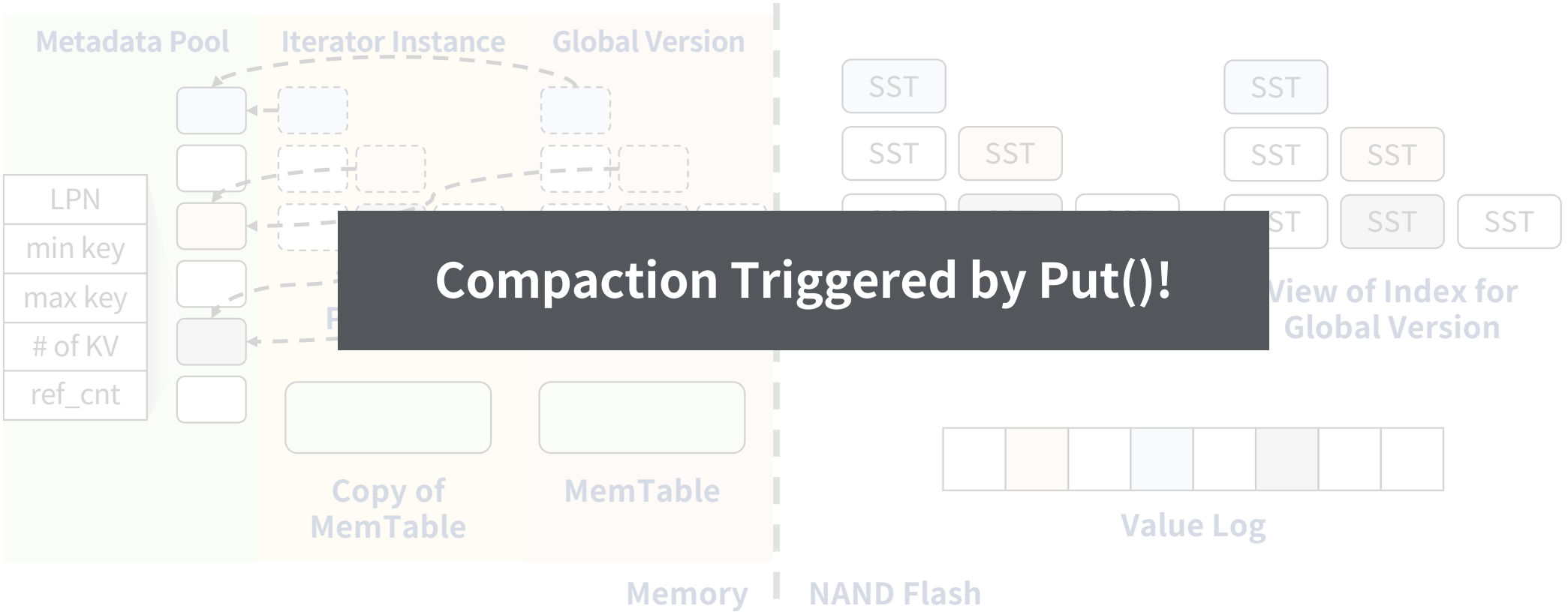

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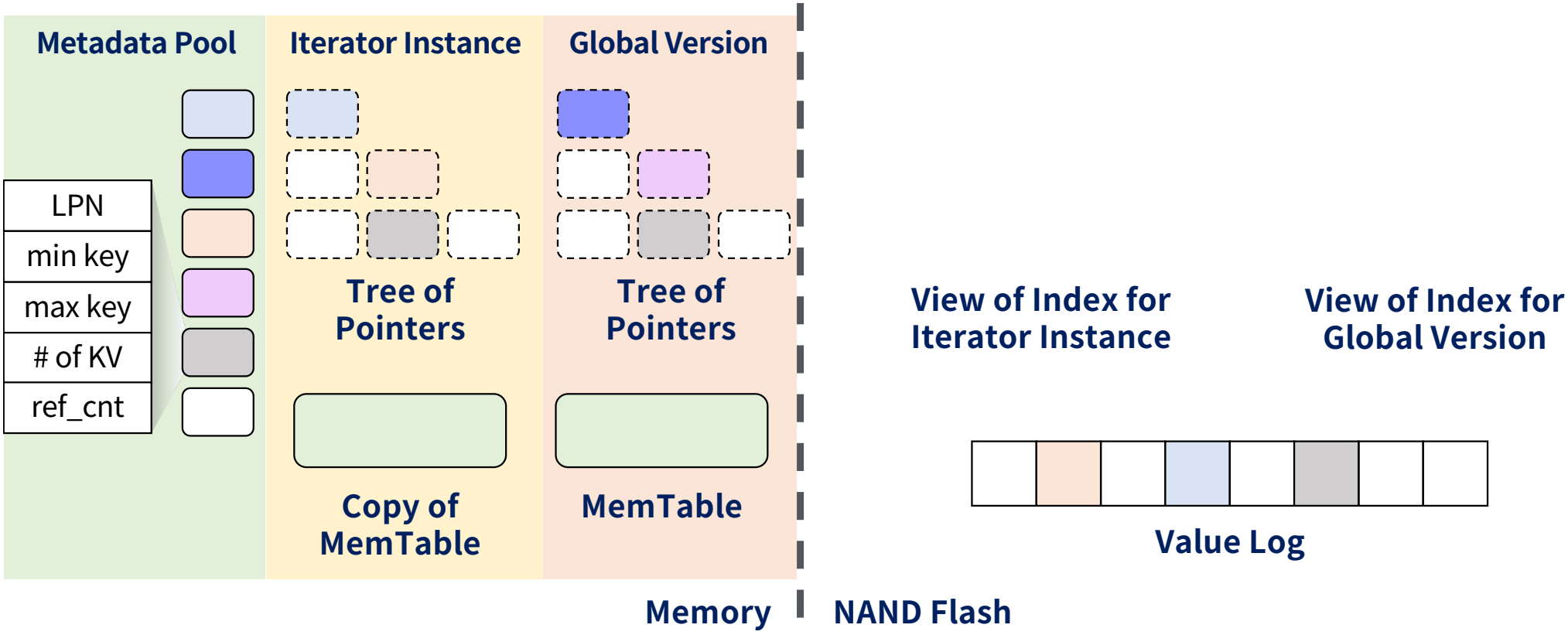

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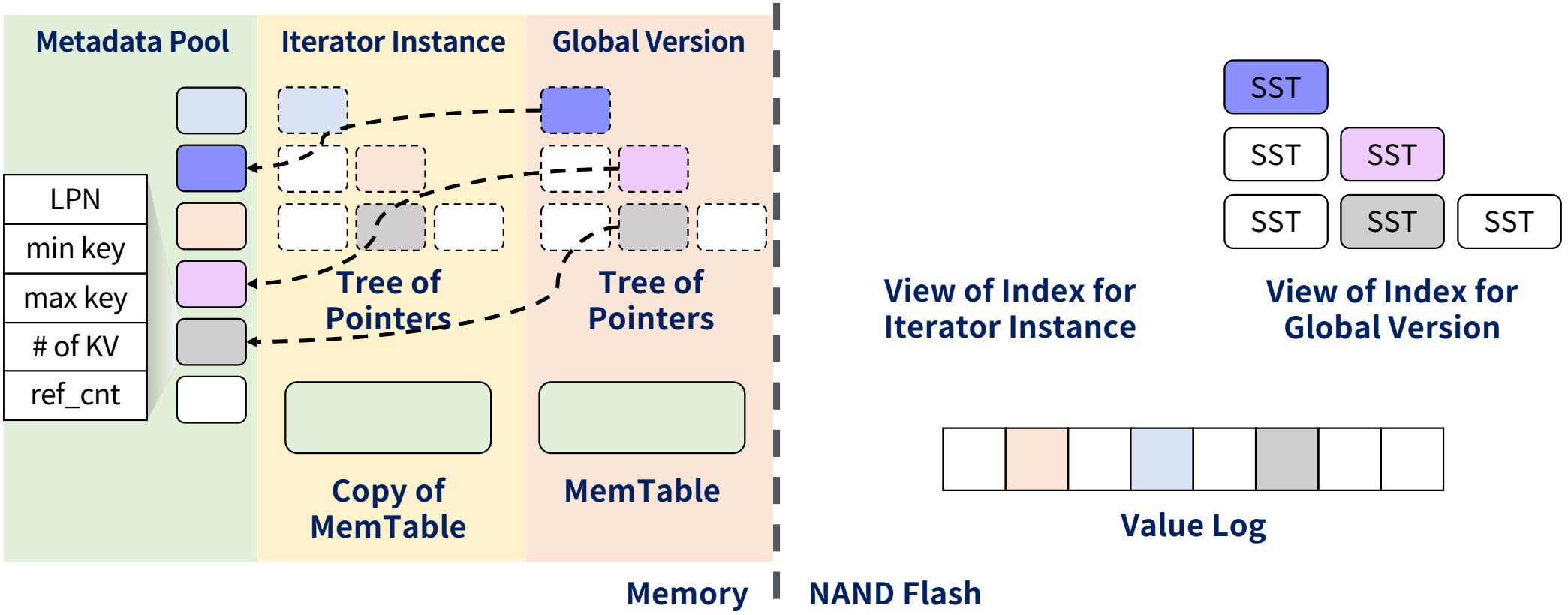

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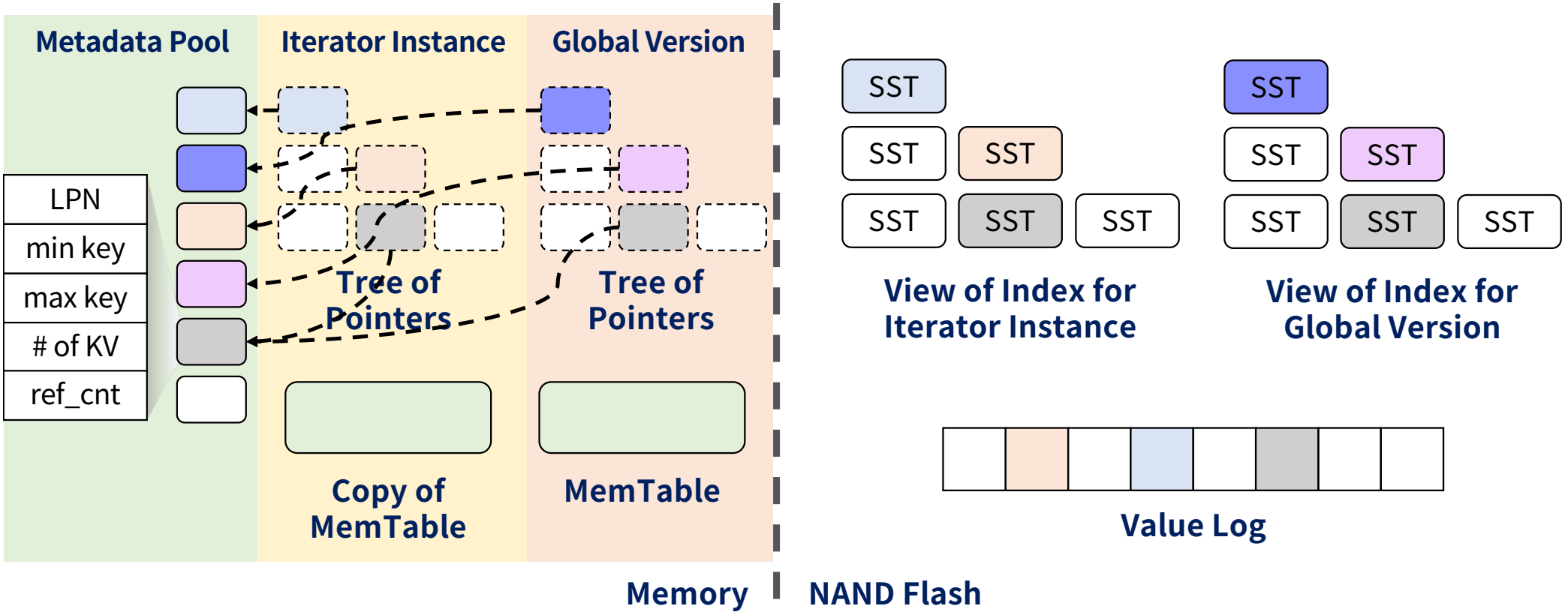

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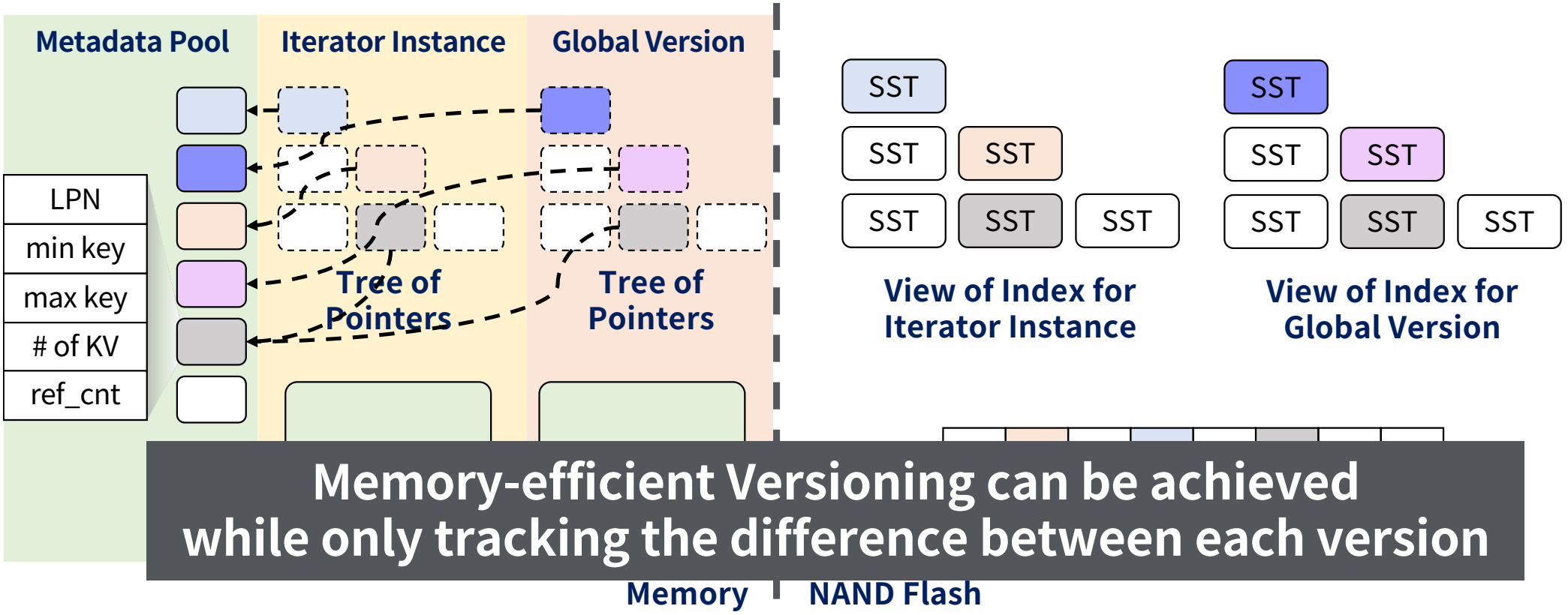

Memory-efficient Versioning can be achieved while only tracking the difference between each version

How to Reduce NAND Flash Access Cost?

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- **Key ideas to minimize synchronous NAND Flash access penalty**

1. **Range query sequentially retrieves Key-Value pairs in a row**
   - KVSSD knows what is the next key to read
2. **Key-Value semantic is enabled inside the device**
   - KVSSD knows where in physical memory the next Key-Value pairs are stored
3. **Exploit multiple independent channel controllers**
   - KVSSD can overlap NAND Flash access with processing storage protocol and the other steps in parallel

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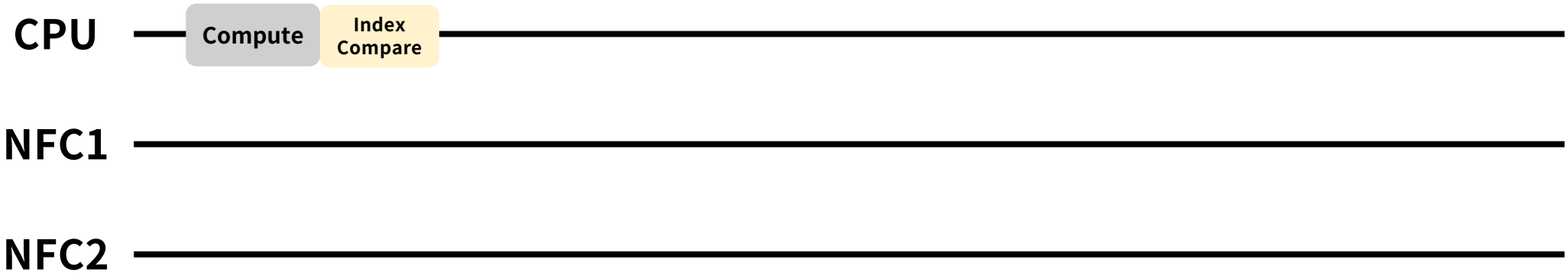

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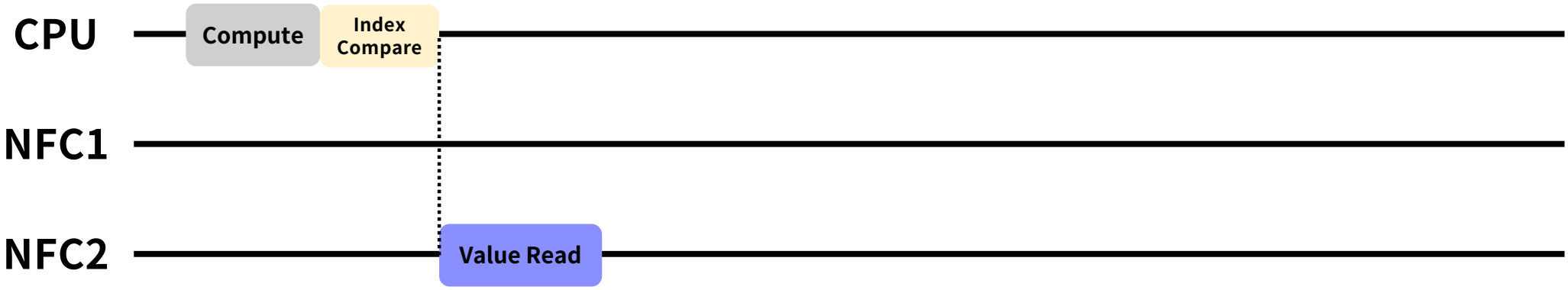

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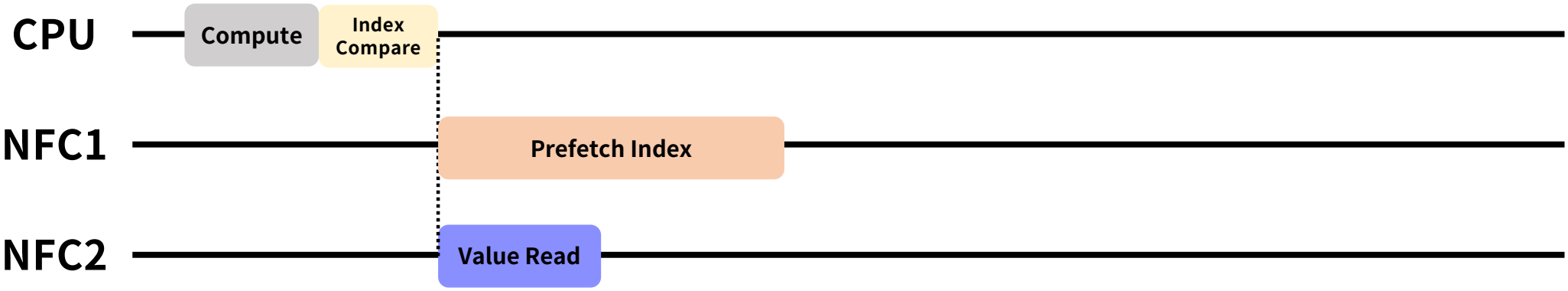

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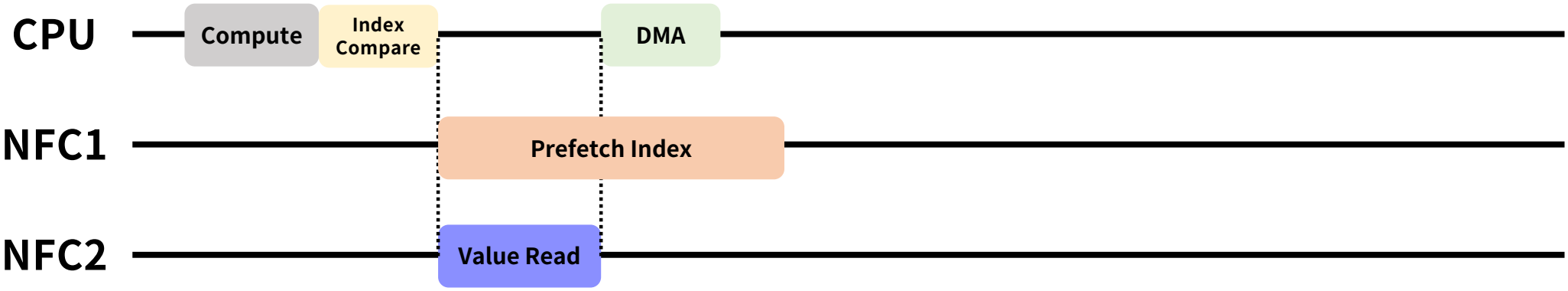

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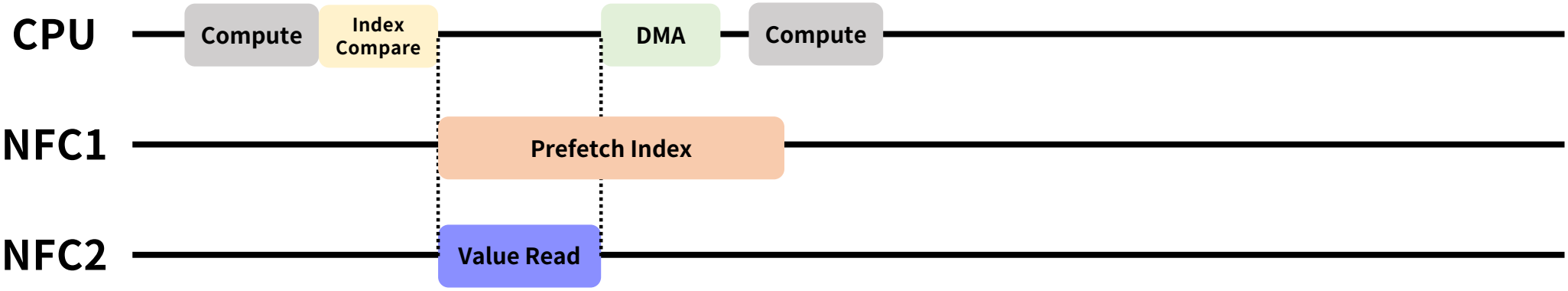

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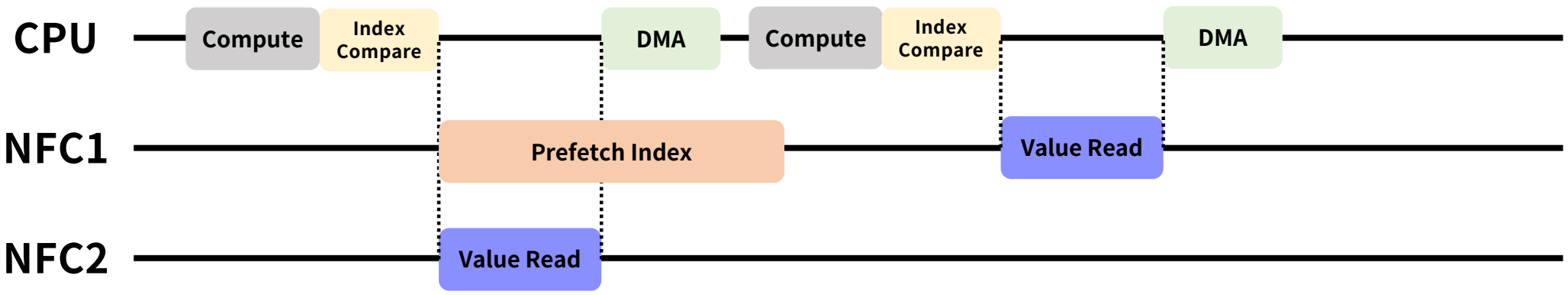

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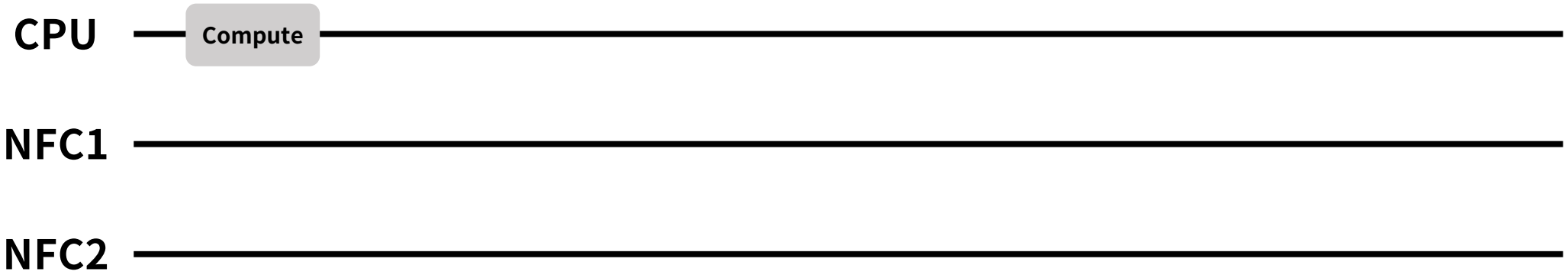

- When processing **Nth** Next command, the device issues prefetch request for the **(N+D)th** Next command in the future (**D**: Prefetching Degree).
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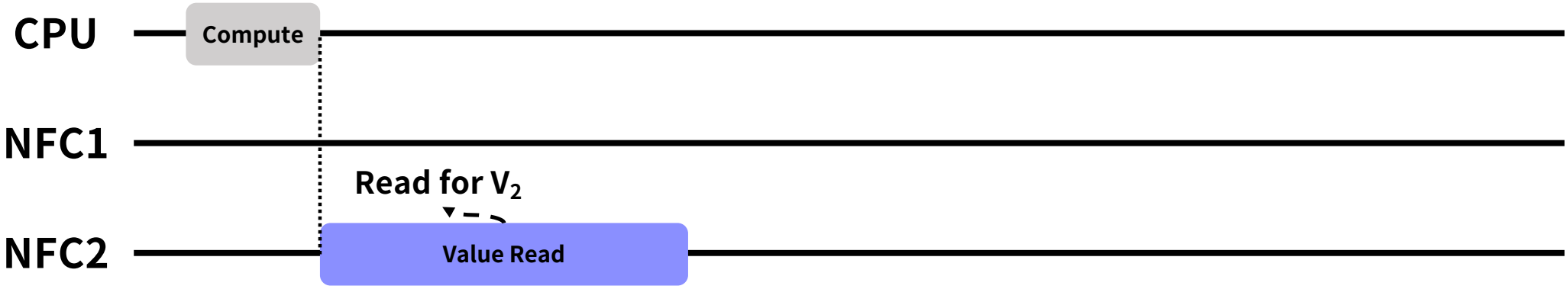

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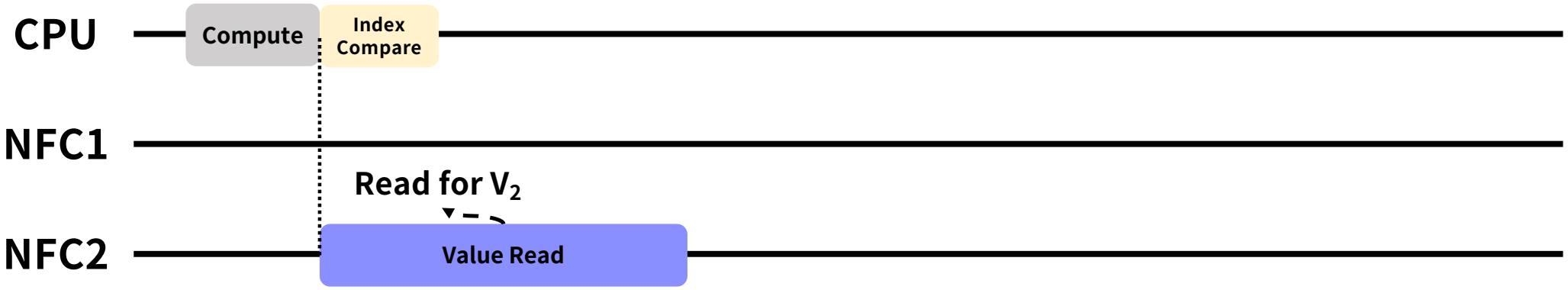

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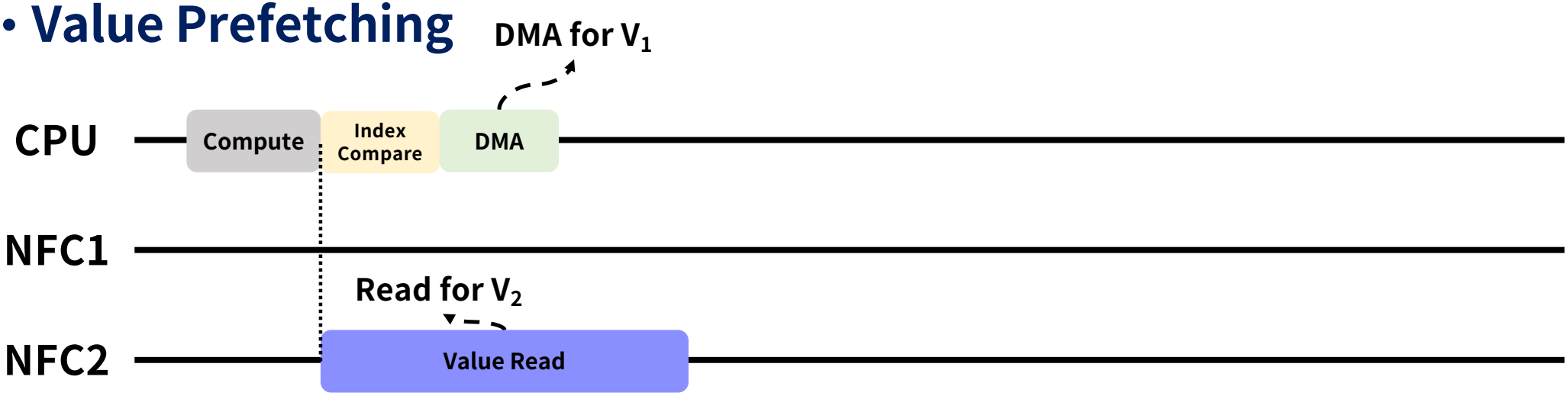

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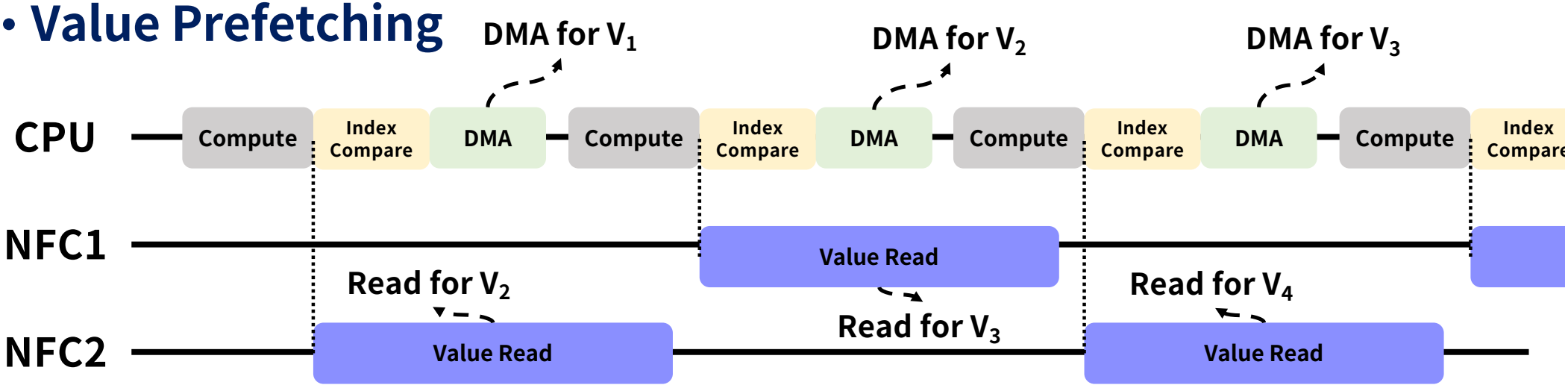

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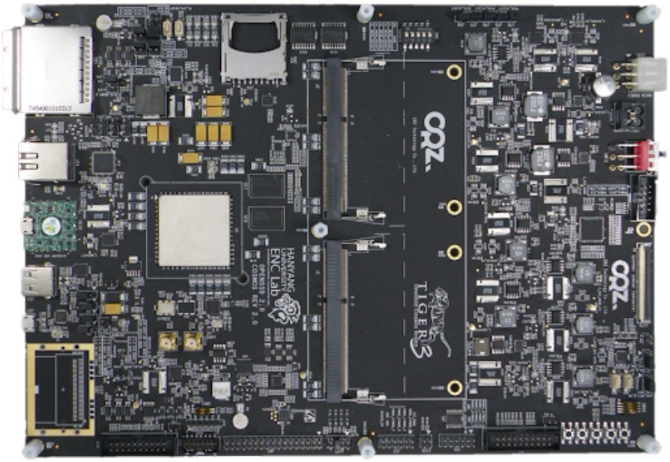
Experimental Setup

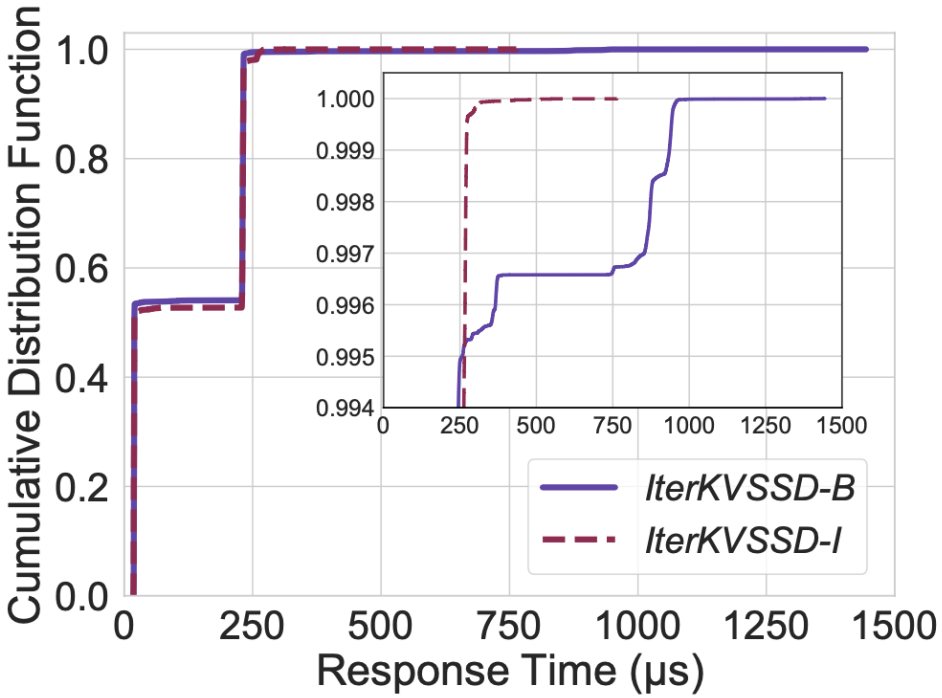
- **IterKVSSD prototyped on OpenSSD Cosmos+**
  - Extended NVMe Protocol for Iterator Command
- **Workloads**
  - RocksDB ***db_bench*** benchmark for ***SeekRandom*** workload
  - 3M Key-Value pairs with 4B Key
  - Varied scan length*, value size, and prefetch degree for value prefetch



scan length = the number of KV pairs retrieved during a range query

Evaluation – Index Prefetch

- **Effect of Index Prefetching**



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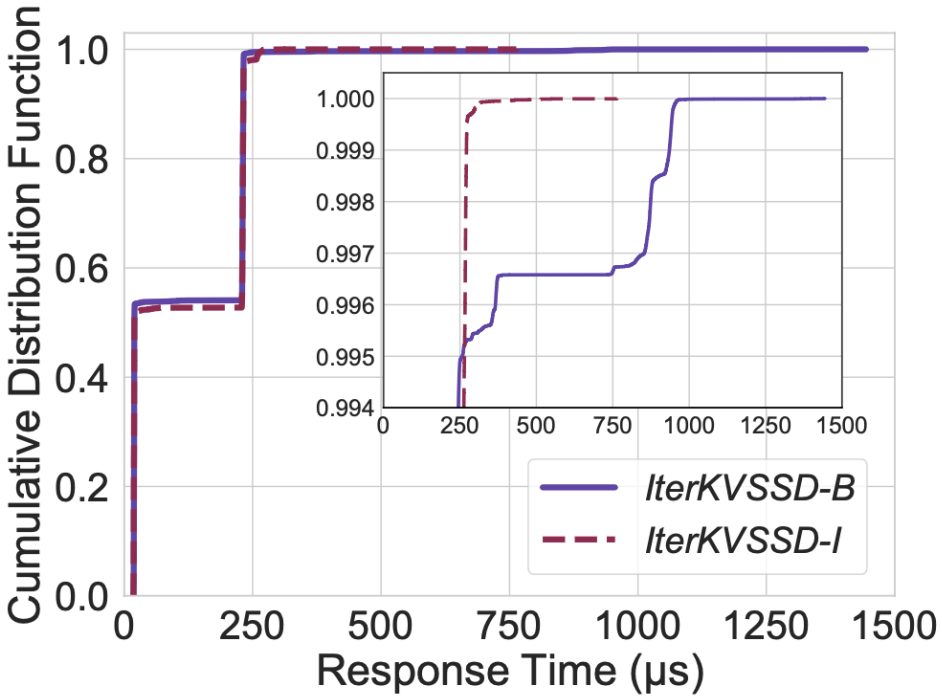

- **IterKVSSD-B**: Baseline w/o prefetch
- **IterKVSSD-I**: w/ Index Prefetch + w/o Value Prefetch
- Scan Length = 200,000 which is enough to trigger Synchronous Index Read
- Show about 3.6x better P99.9 tail latency
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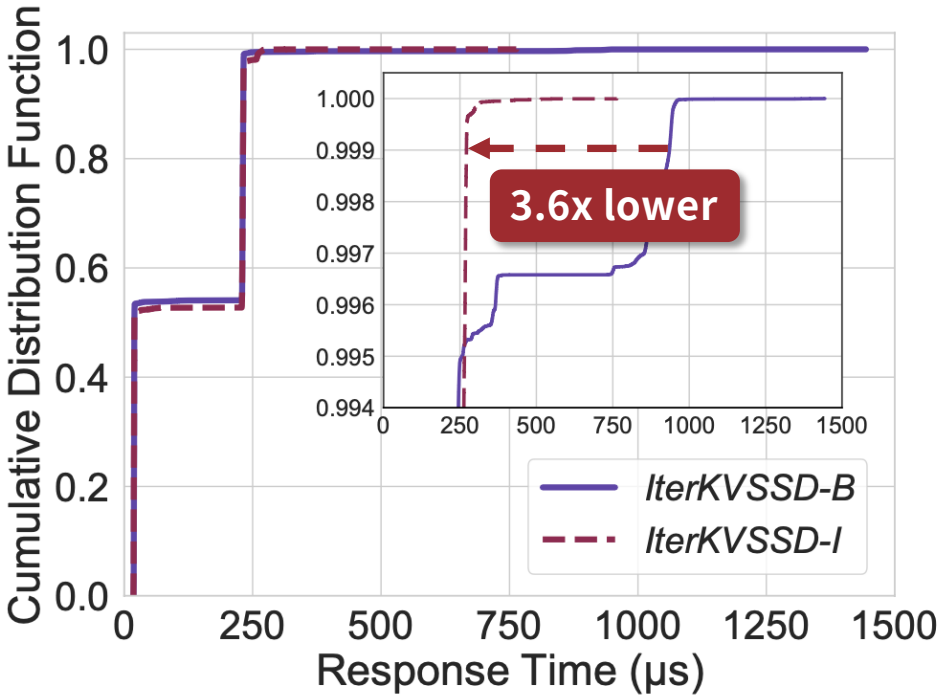

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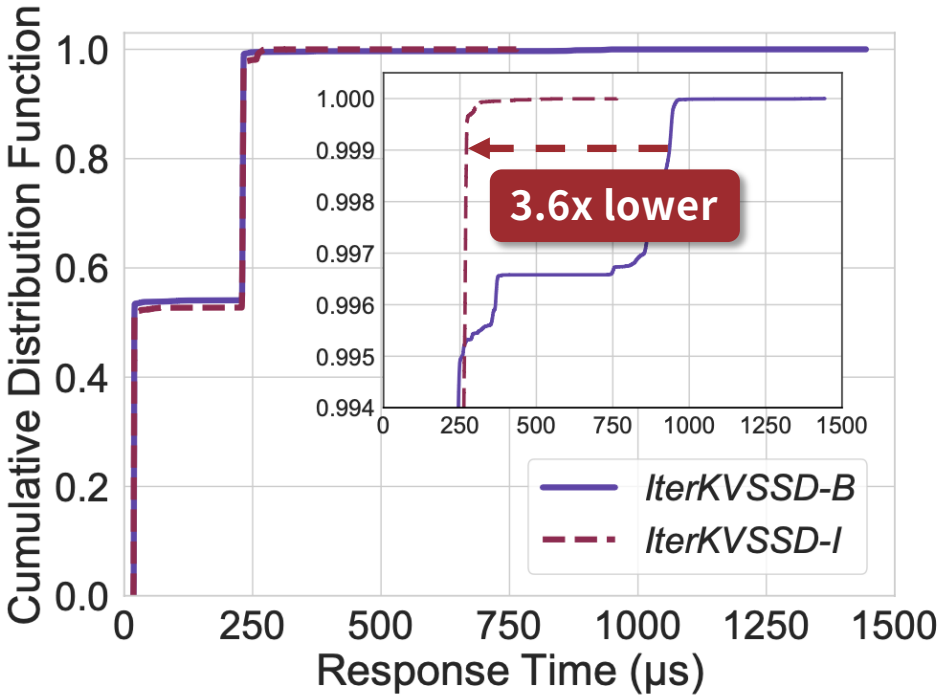

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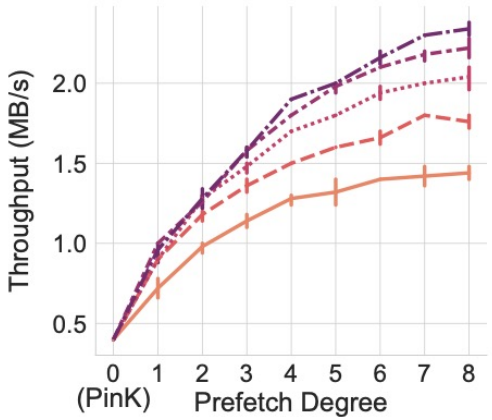
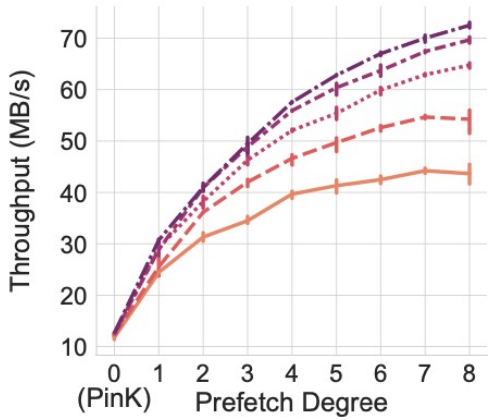
Evaluation – Value Prefetch

- **Effect of Value Prefetching**
  - Evaluated with ***SeekRandom*** workload
  - Prefetch Degree: 0 – 8
  - Value Size : 128B, 4KB, 16KB, 128KB
  - Scan Length: 128, 256, 512, 1024, 2048

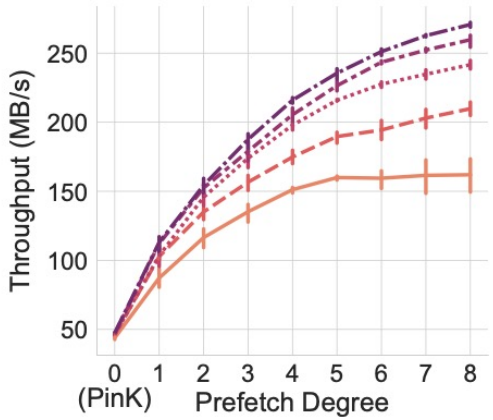
Evaluation – Value Prefetch



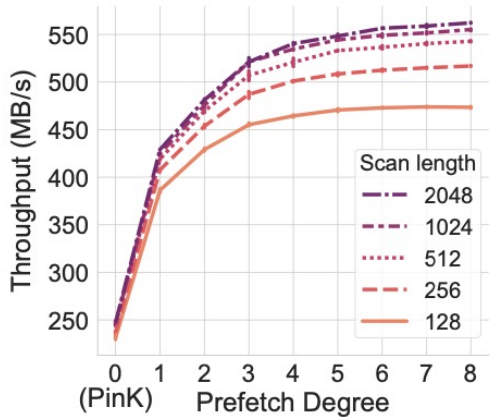
(a) 128 B



(b) 4 KB



(c) 16 KB



(d) 128 KB

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- **Effect of Prefetching Degree**
  - With higher prefetch degree, better I/O performance because small prefetch degree is not enough to hide NAND Flash access latency completely
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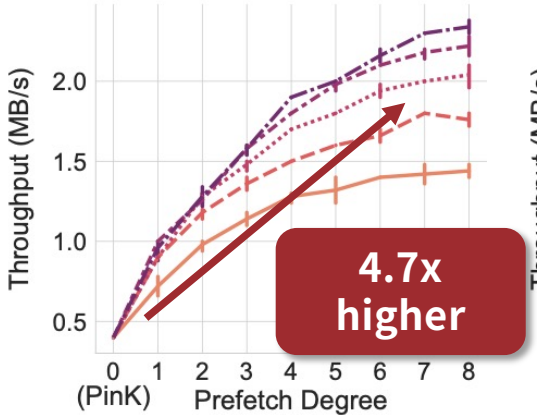

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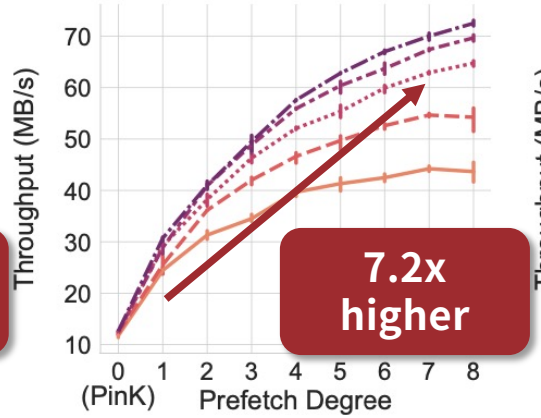

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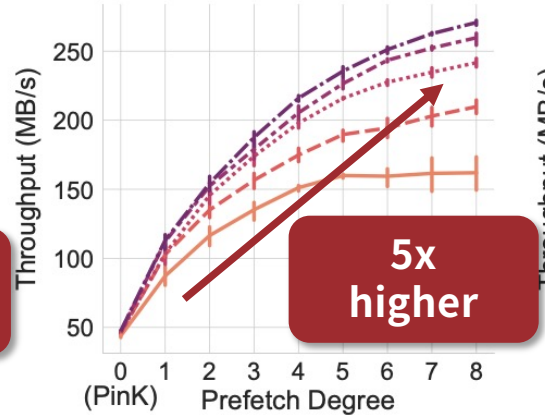

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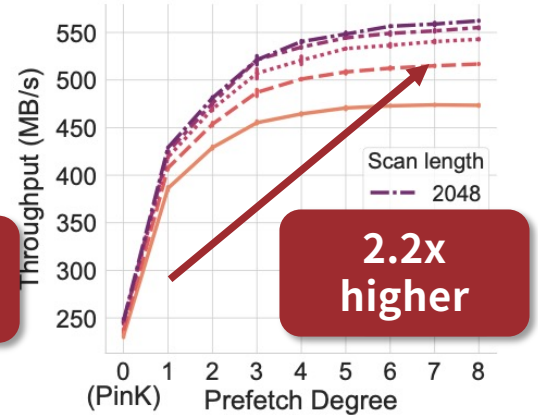

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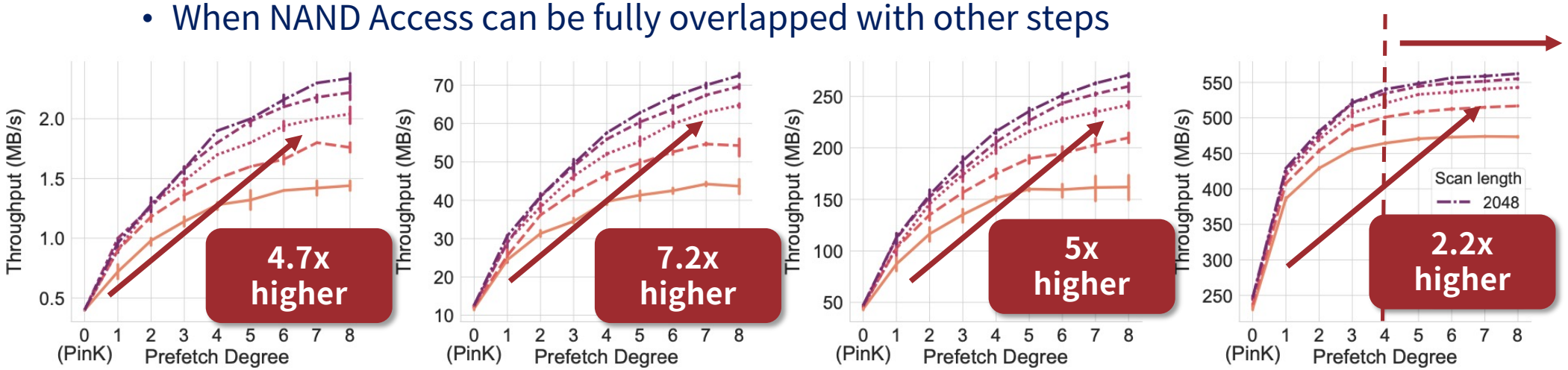

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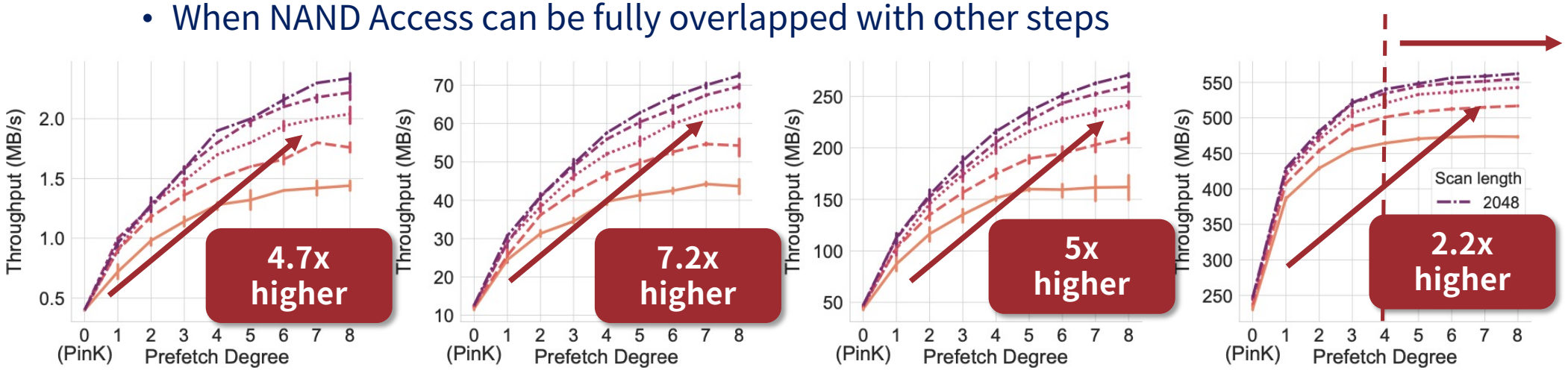
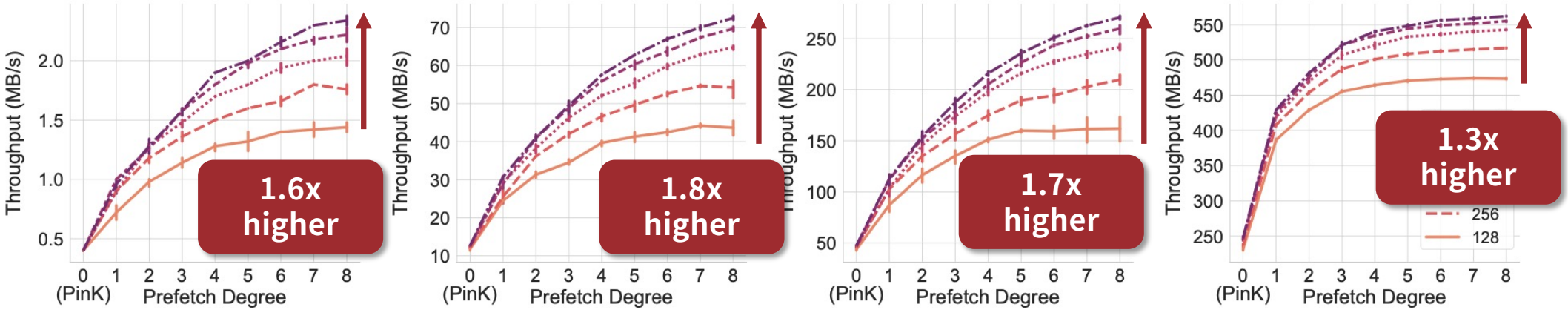


Evaluation – Value Prefetch

- **Effect of Scan Length in Range Query**
  - With higher scan length, better I/O throughput



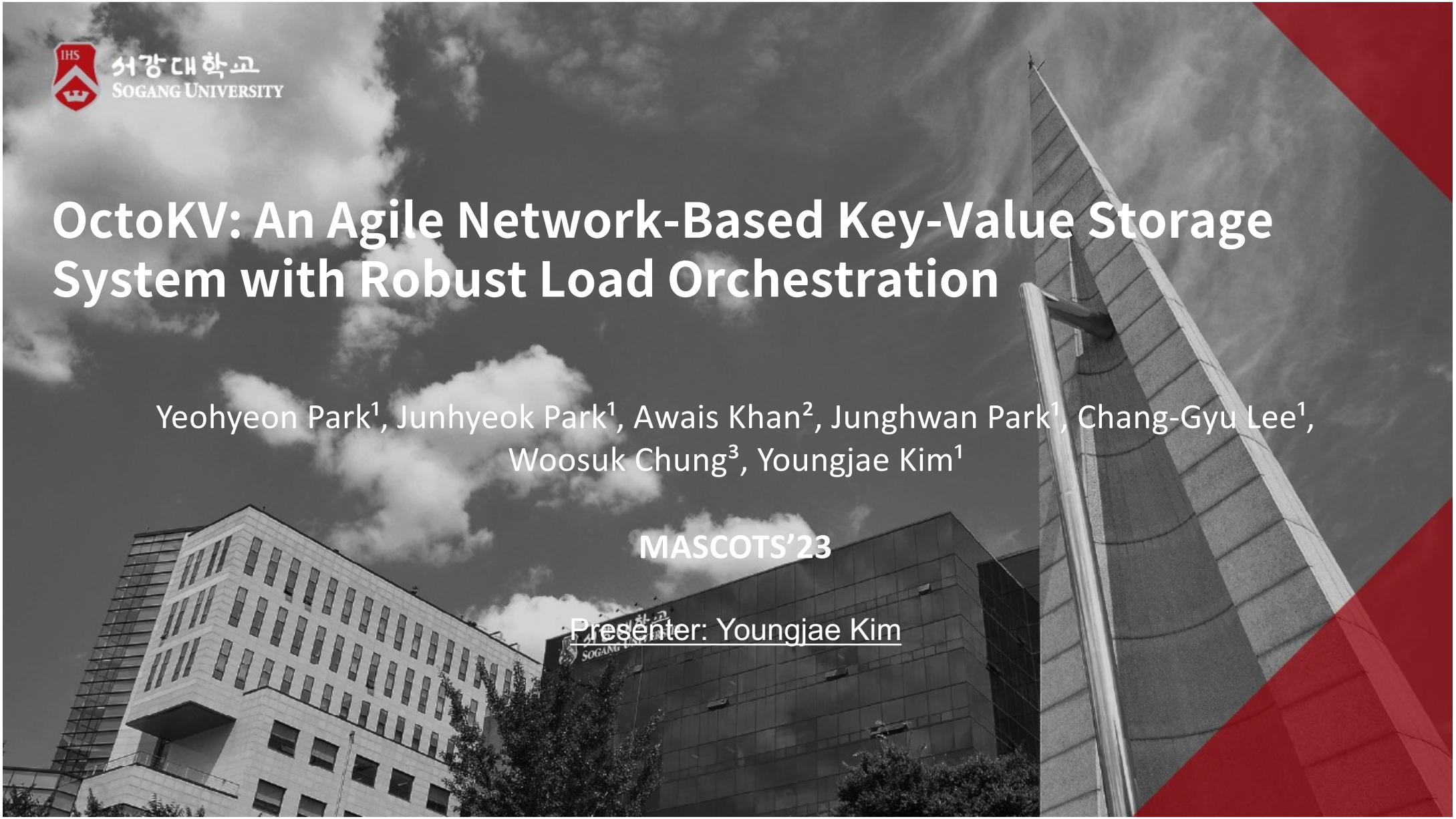
(a) 128 B (b) 4 KB (c) 16 KB (d) 128 KB

Conclusion

- **Explored three problems of current iterator interface**
  1. Versioning Problem
  2. Synchronous Index Read Problem
  3. Synchronous Value Read Problem

- **Proposed IterKVSSD**
  - Memory-efficient Versioning through decoupling and pooling metadata
  - Index/Value Prefetch to mitigate NAND Flash Access Penalty

- **Showed 2x lower P99.9 tail latency, up to 7.2x better I/O throughput**



OctoKV: An Agile Network-Based Key-Value Storage System with Robust Load Orchestration

Yeohyeon Park[1], Junhyeok Park[1], Awais Khan[2], Junghwan Park[1], Chang-Gyu Lee[1], Woosuk Chung[3], Youngjae Kim[1]

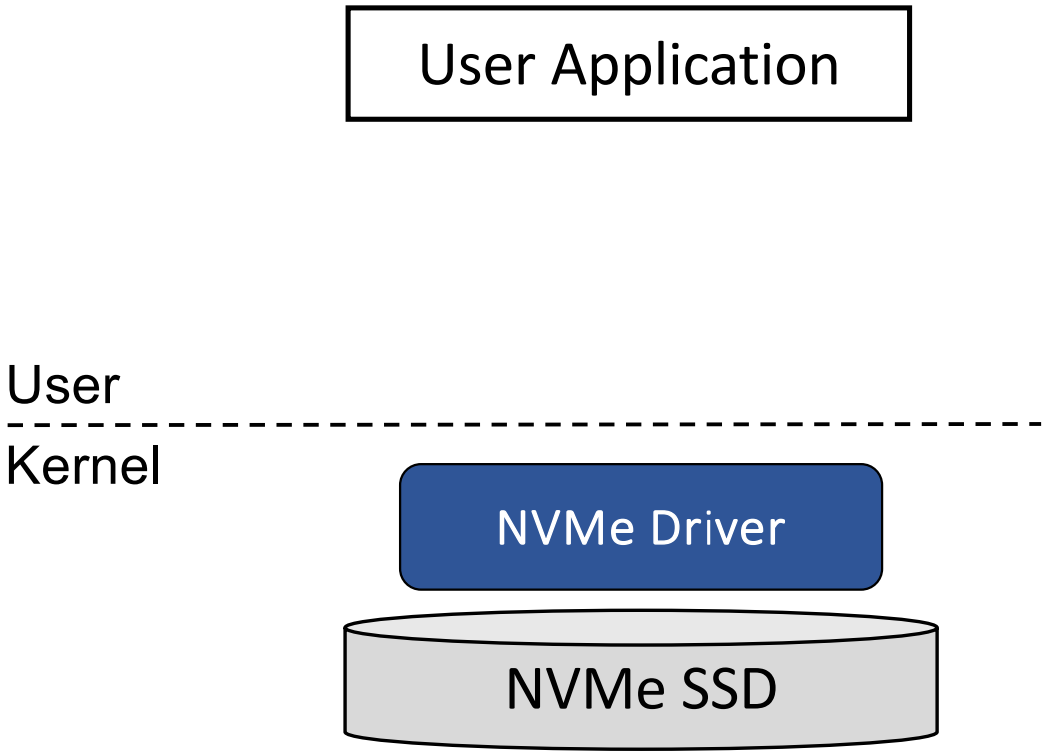
MASCOTS'23

Presenter: Youngjae Kim

Content

- Background
- Problem Definition
- Motivational Experiments
- OctoKV: Design and Implementation
- Evaluation
- Conclusion

(1) User Space NVMe Driver



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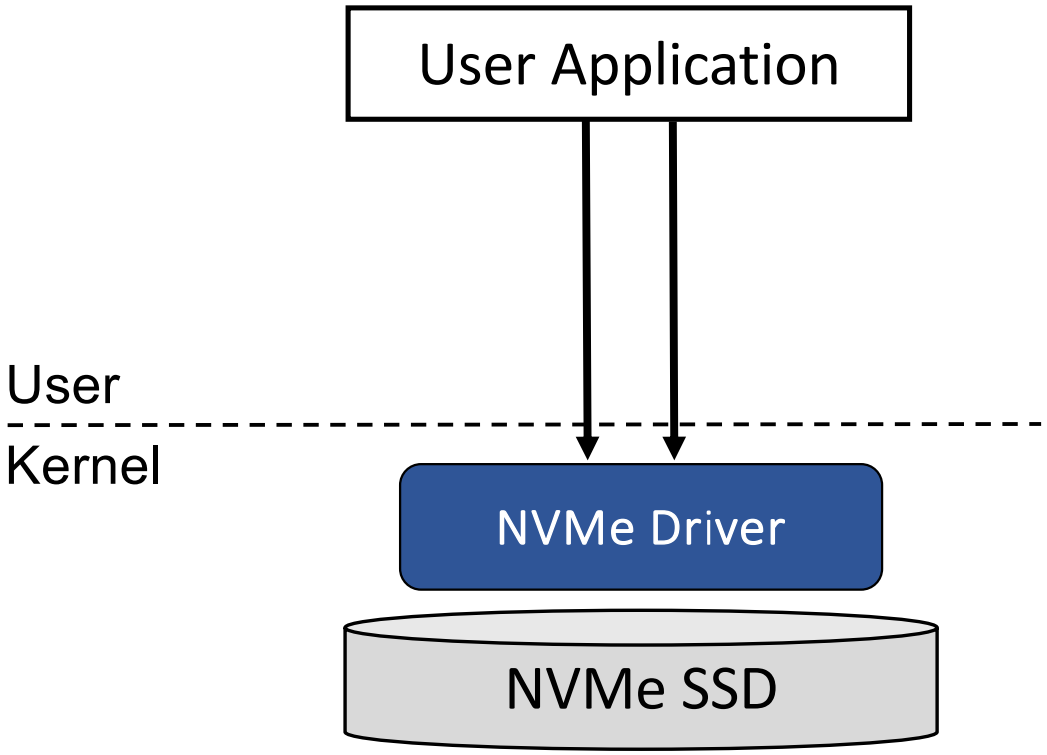

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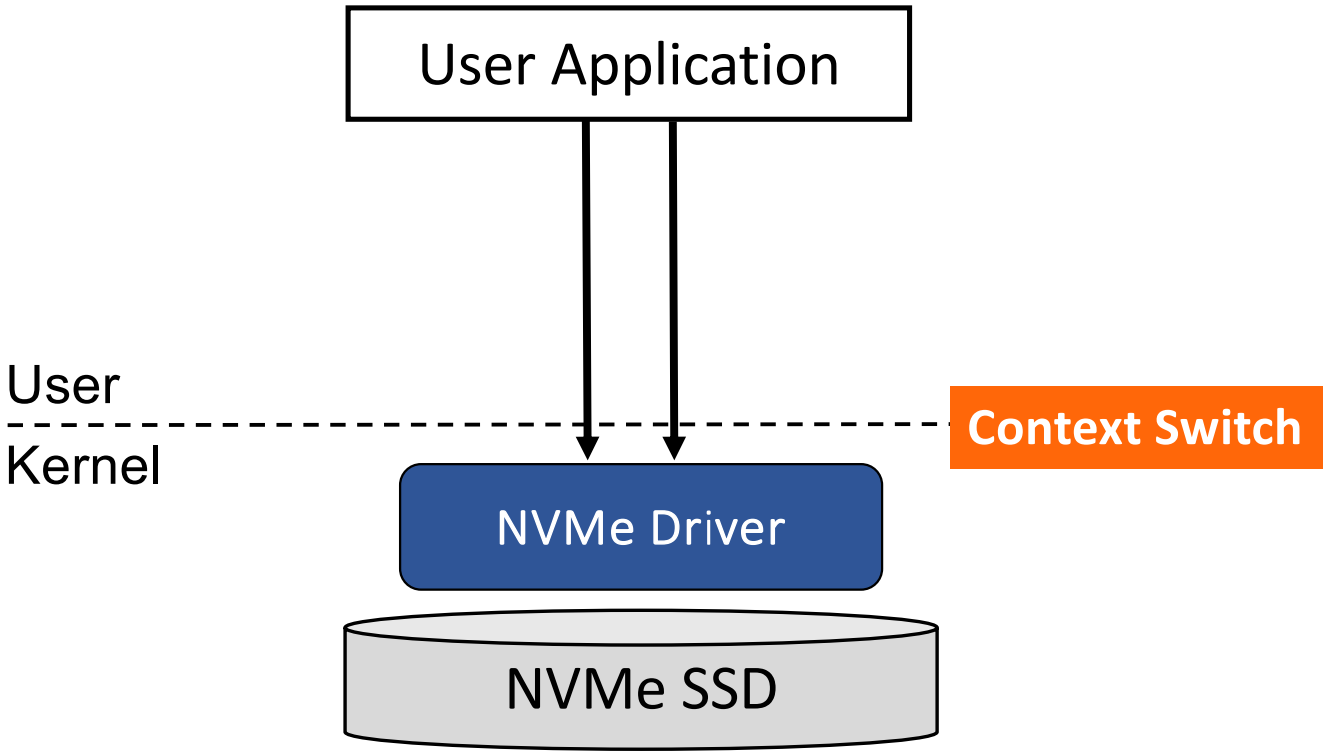

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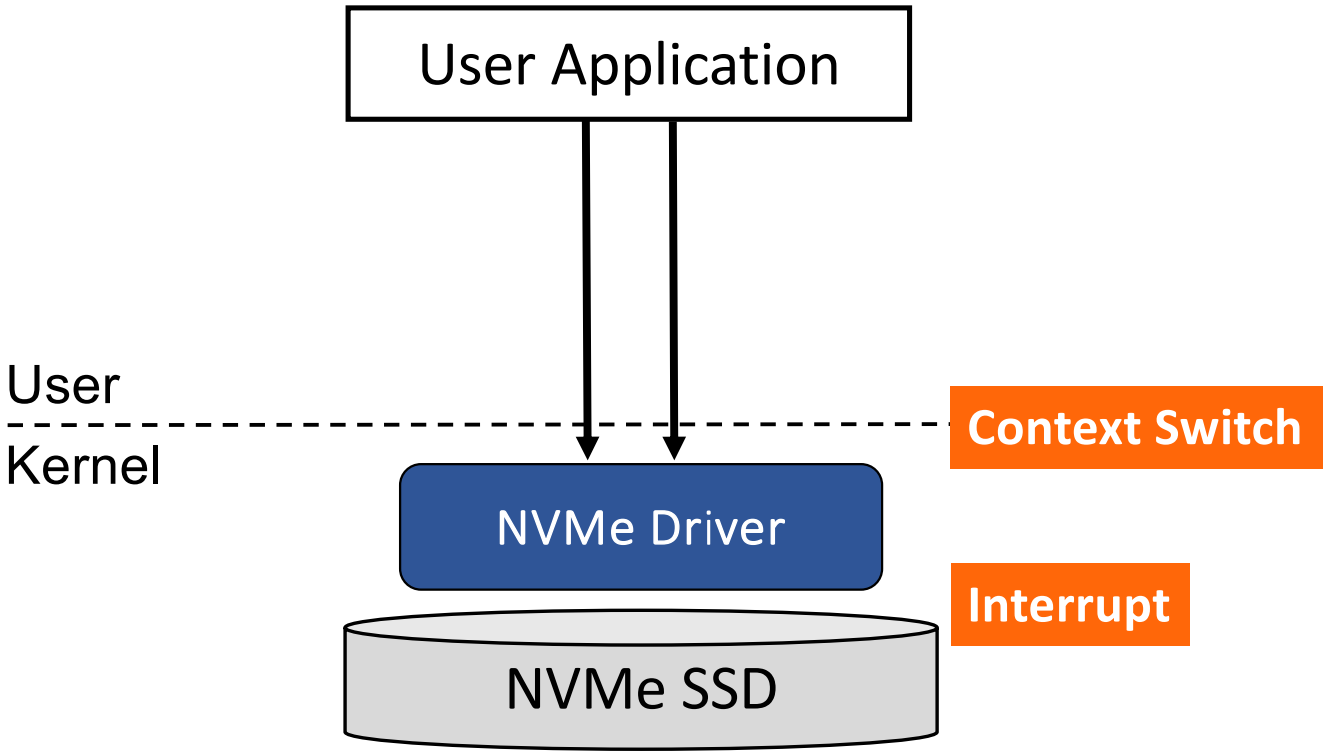

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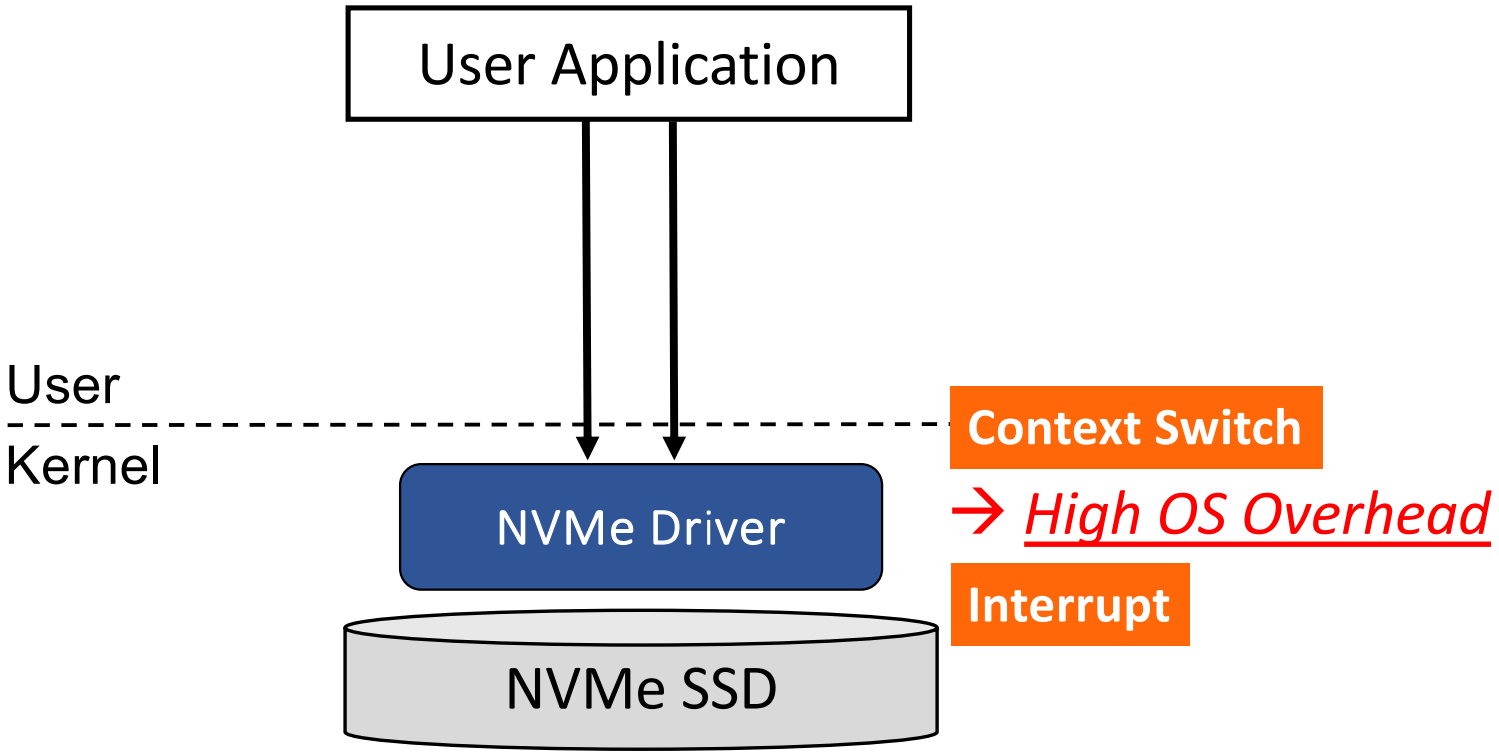
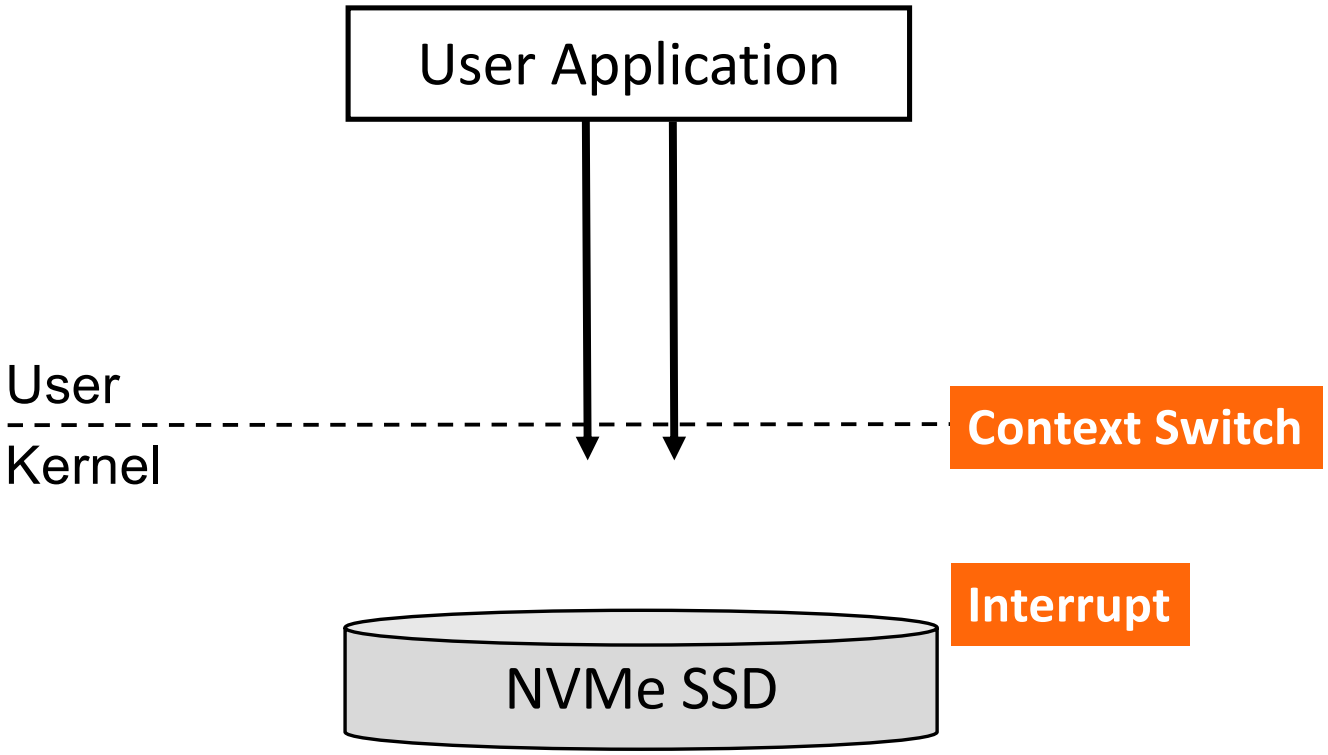


(1) User Space NVMe Driver



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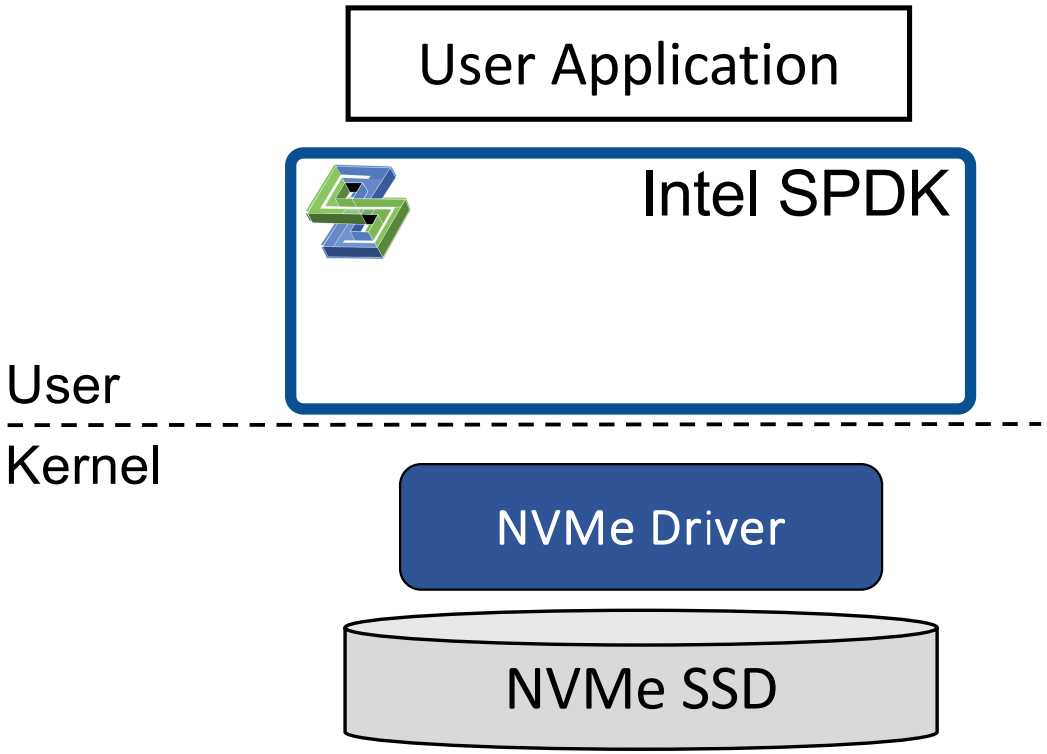

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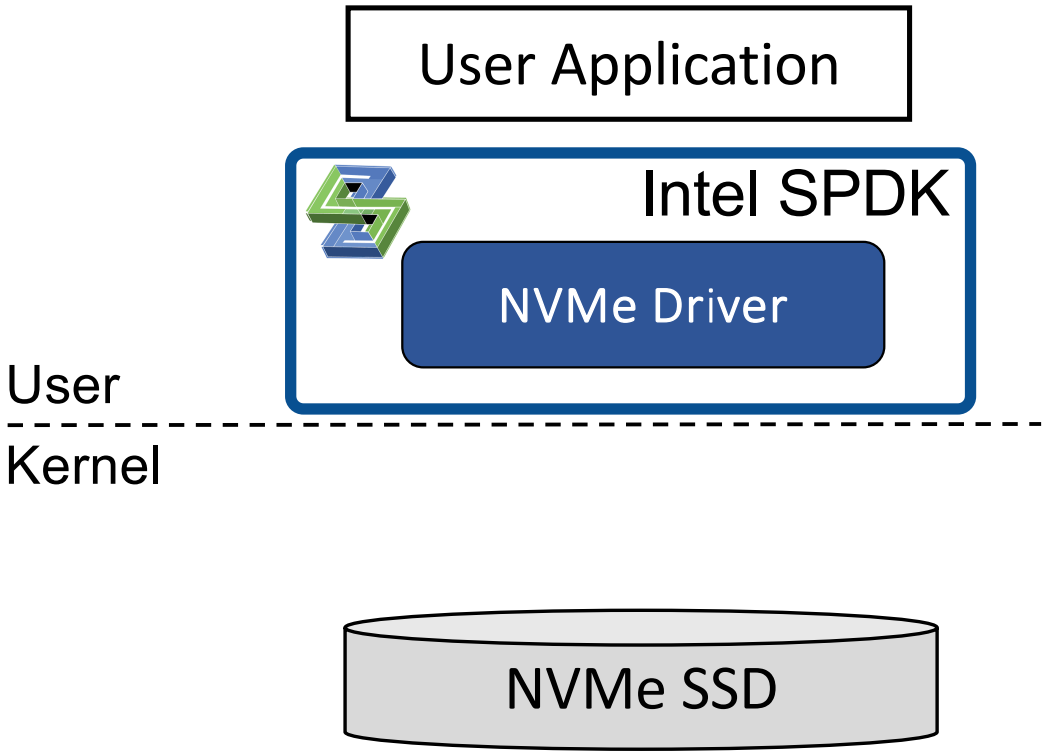

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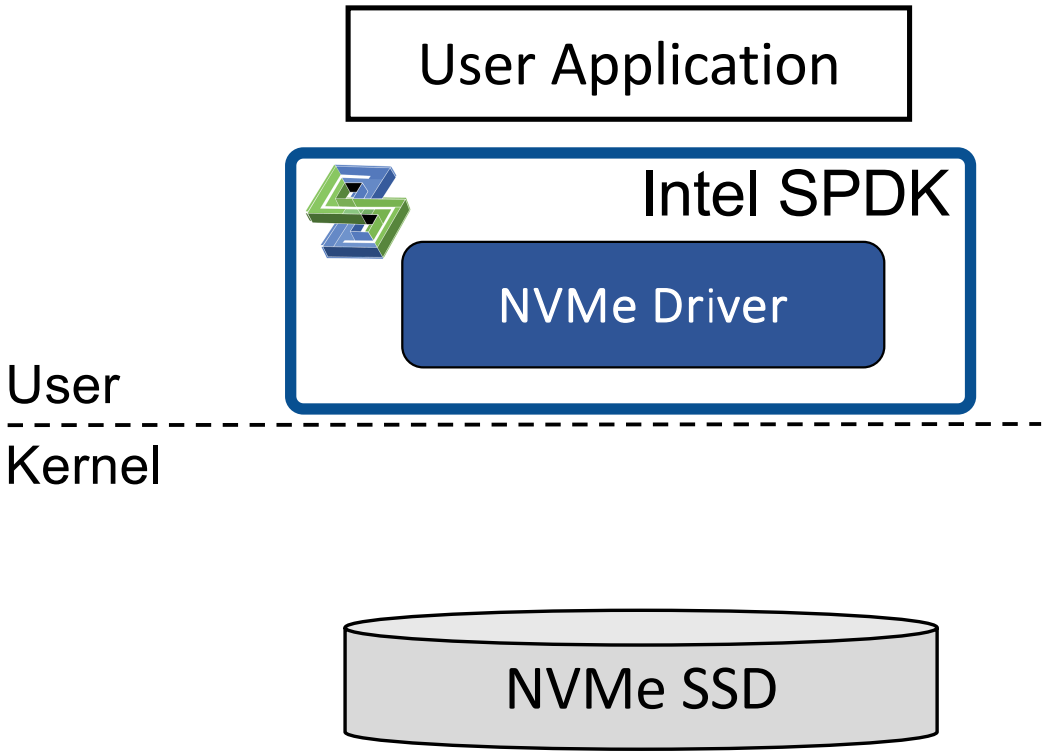
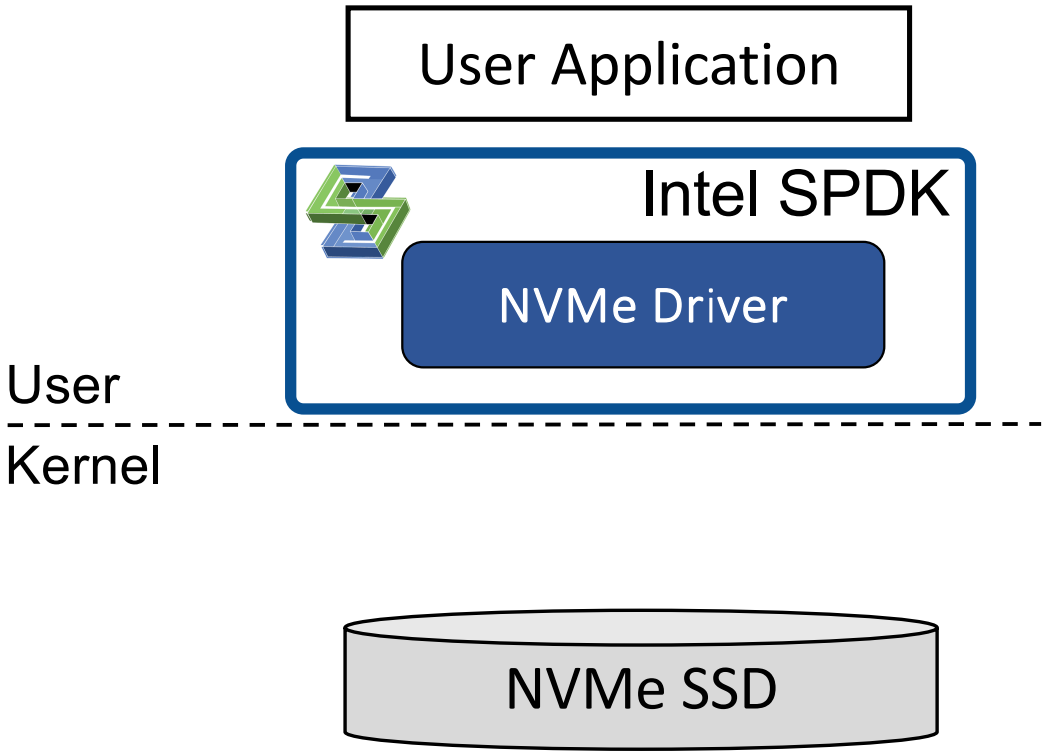


1. User level NVMe driver

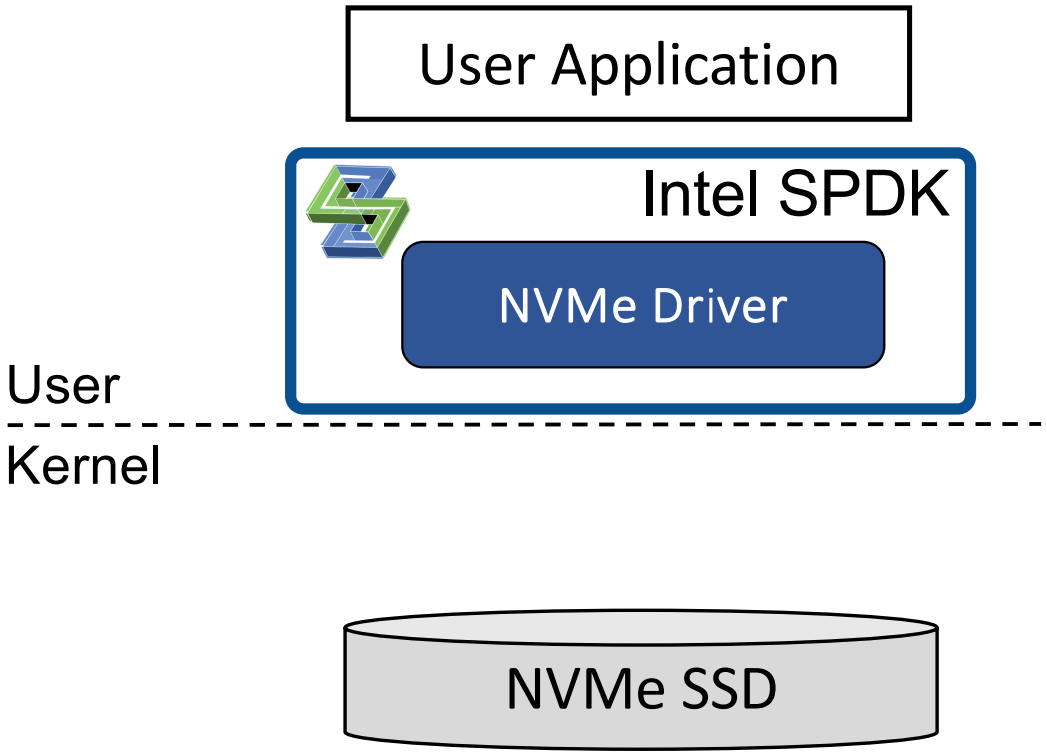
(1) User Space NVMe Driver



1. User level NVMe driver

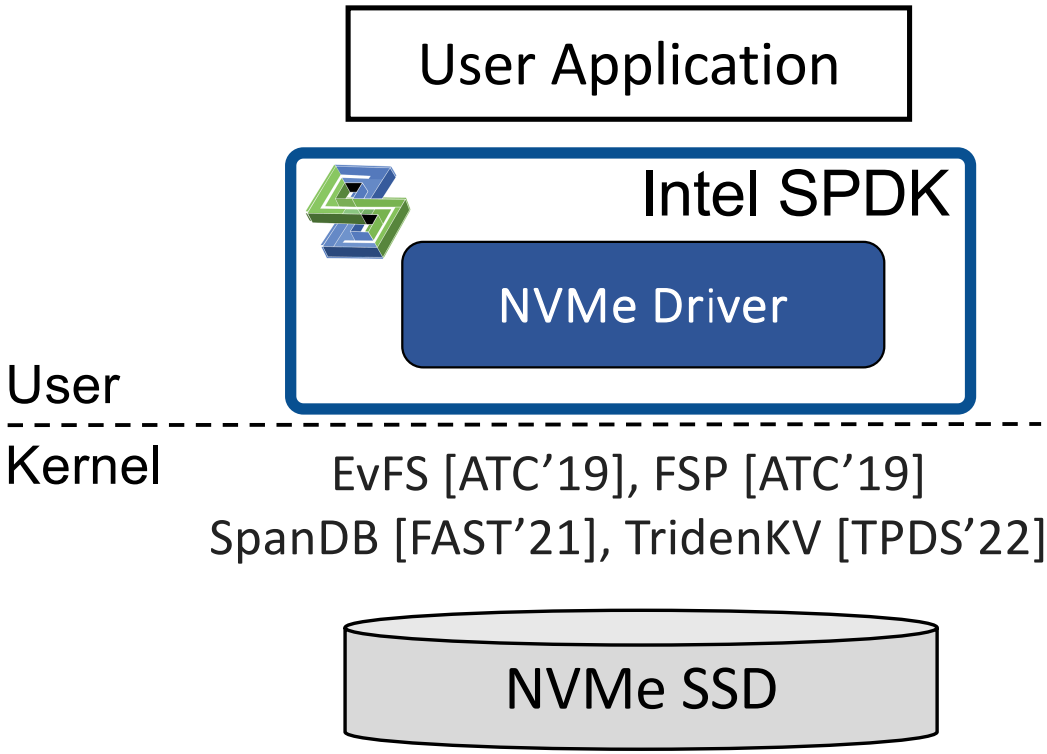
2. Bind I/O to a specific core

(1) User Space NVMe Driver



1. User level NVMe driver
2. Bind I/O to a specific core
3. Use polling for completion

(1) User Space NVMe Driver



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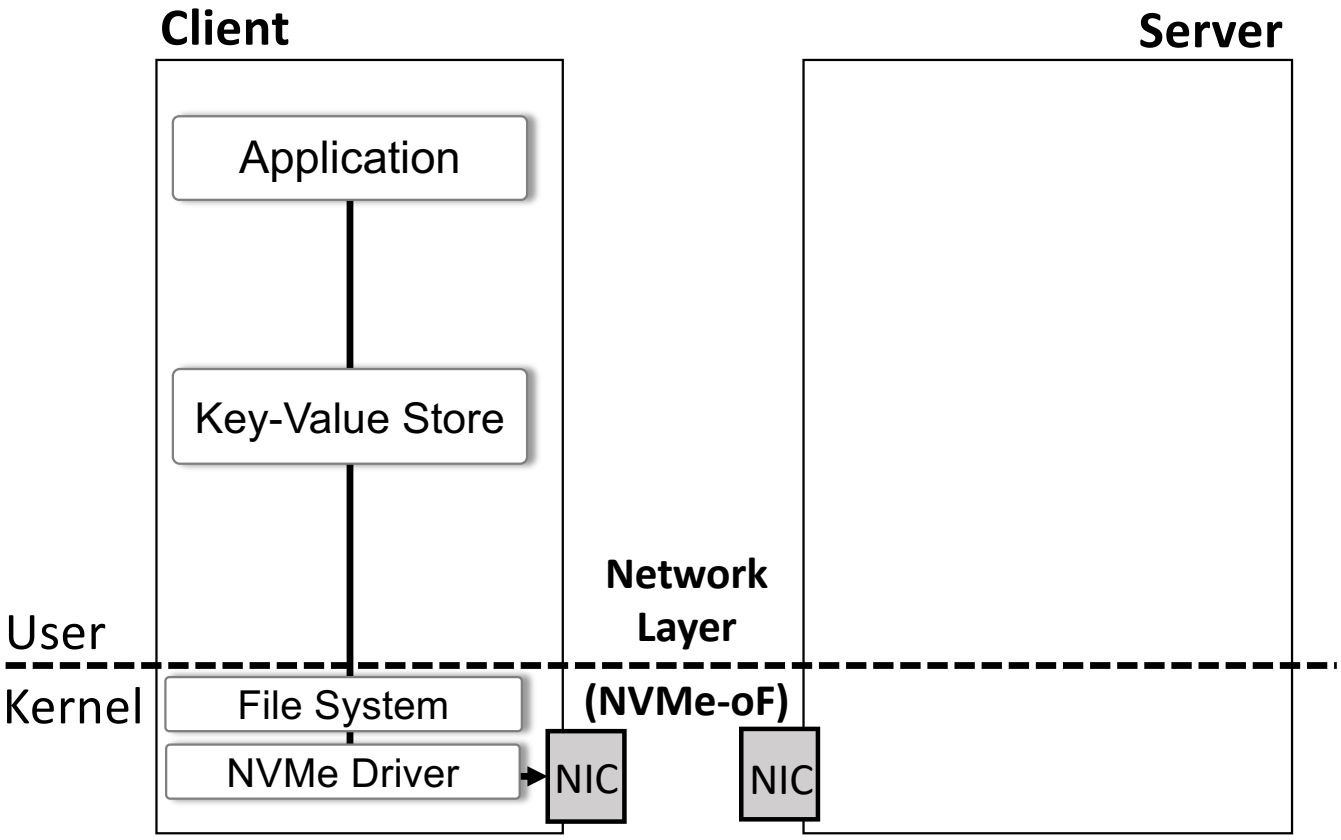
(2) SPDK-based Network-based Block Storage



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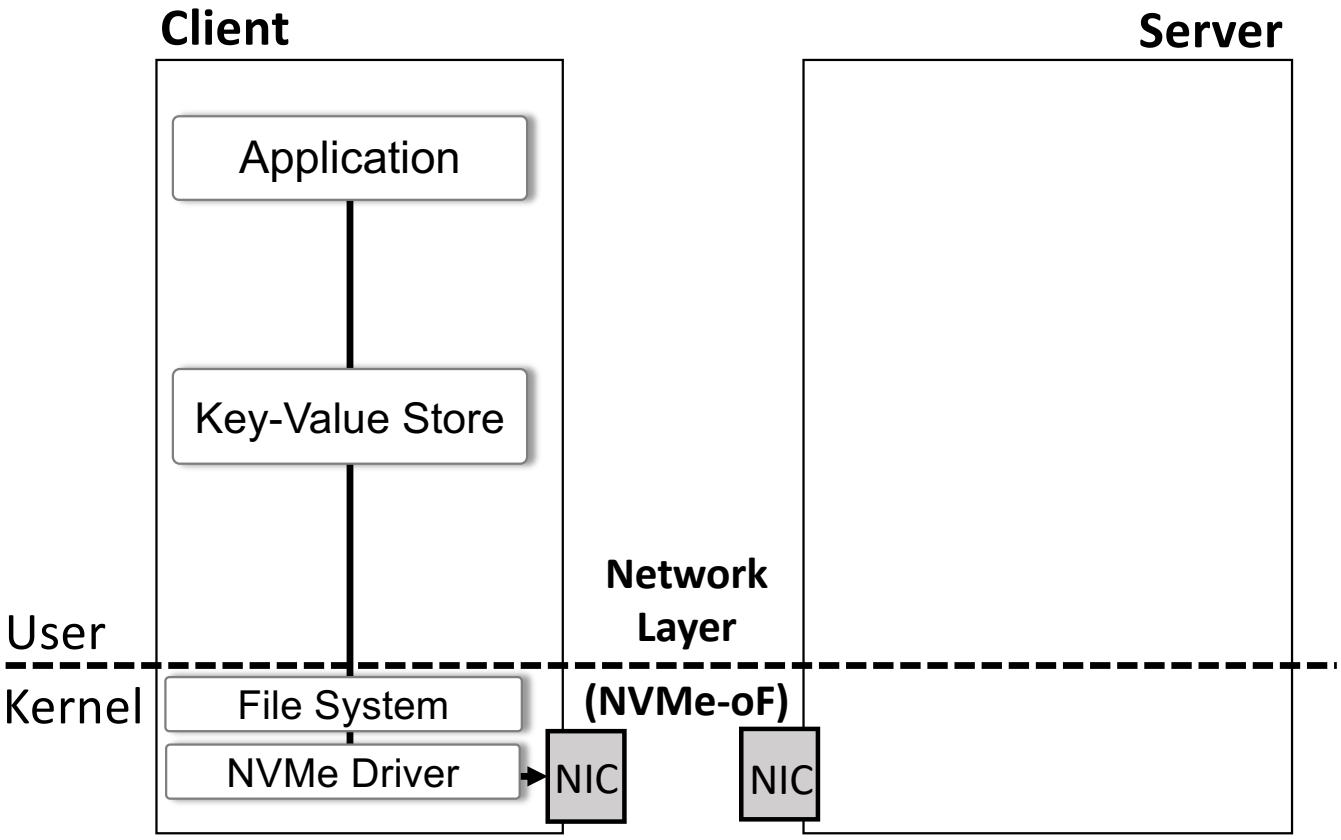

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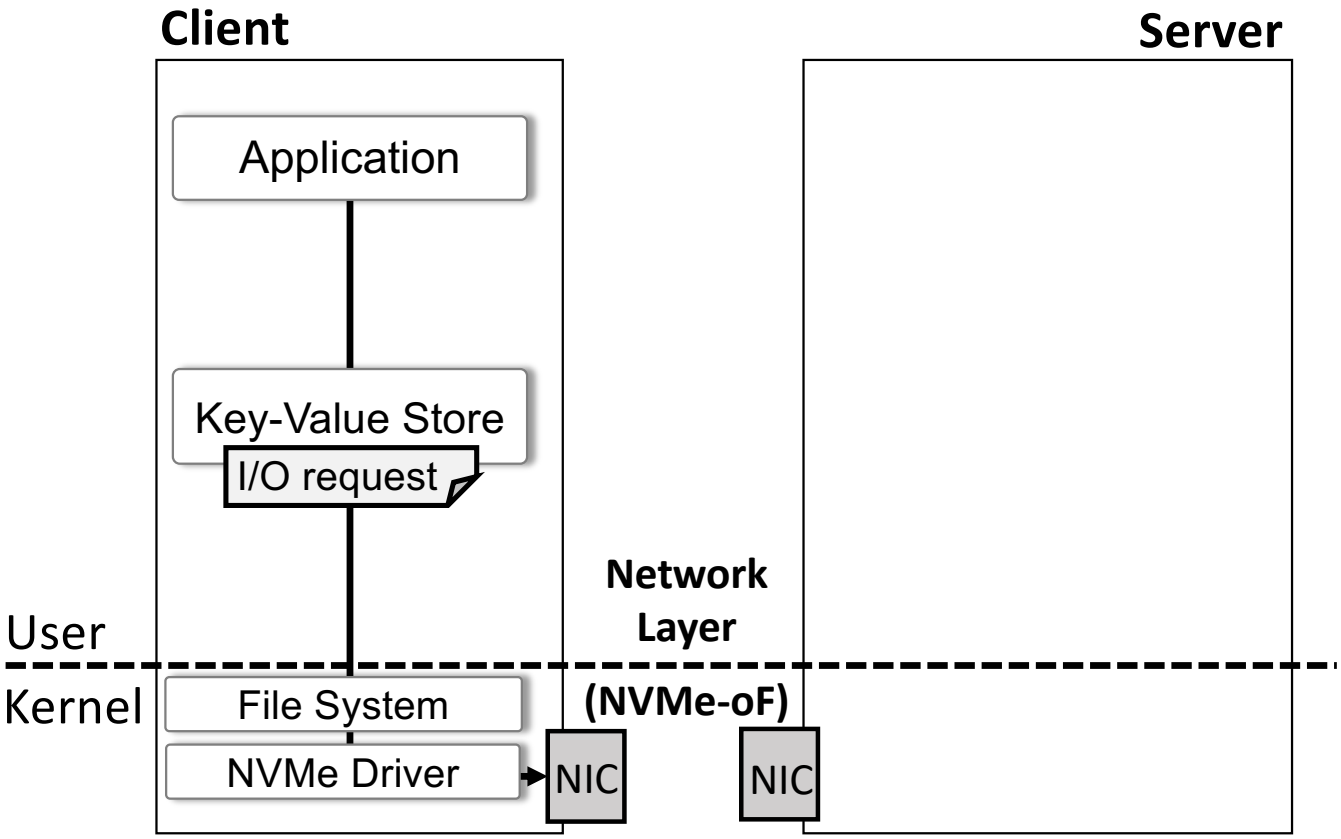

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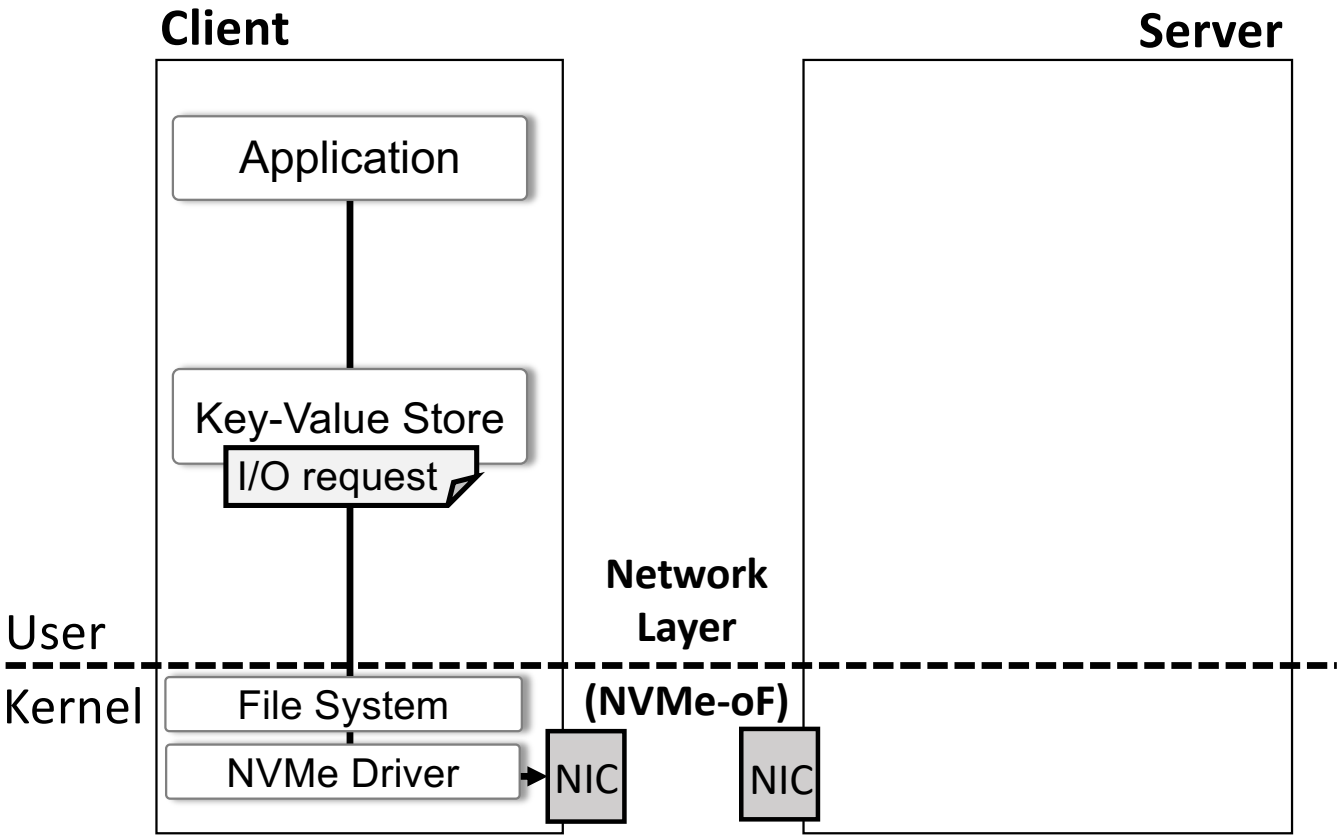

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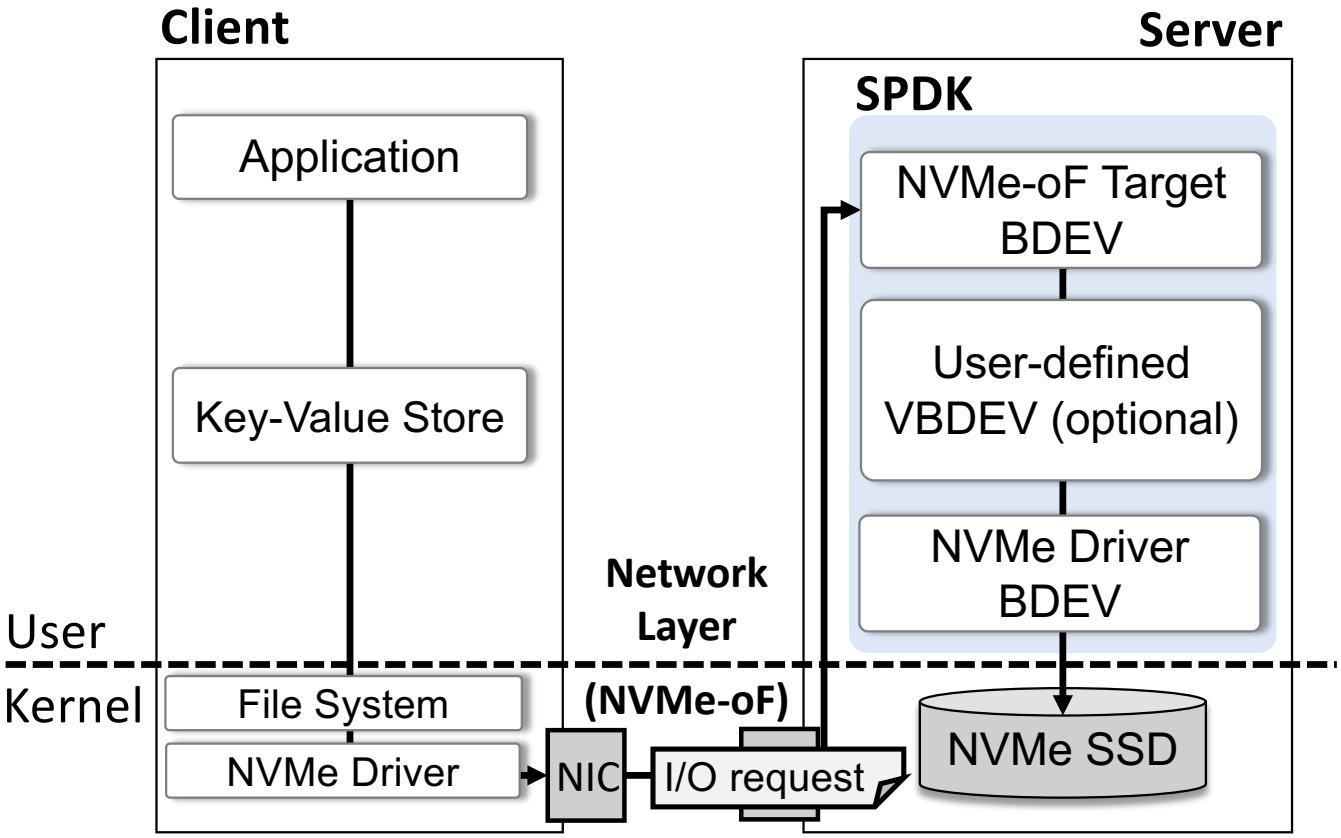

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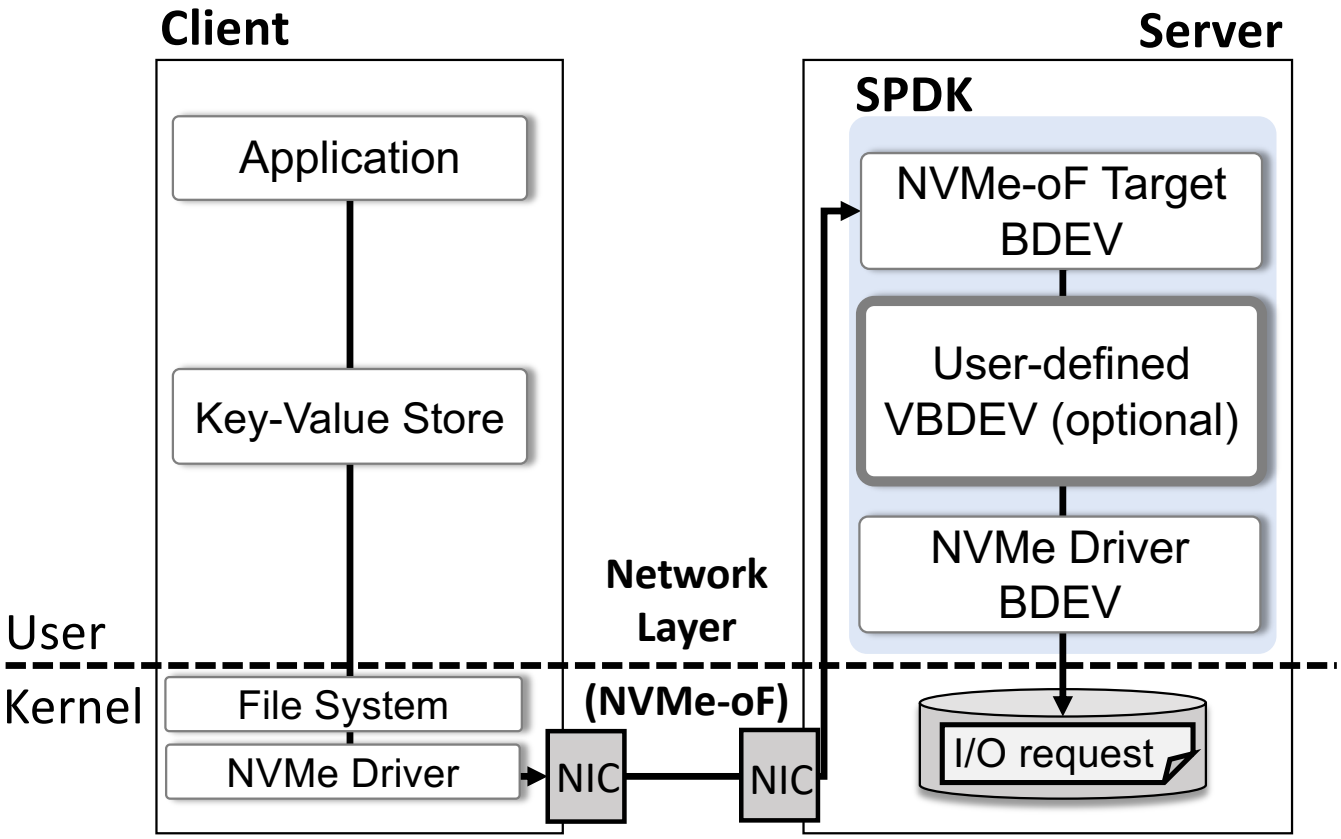

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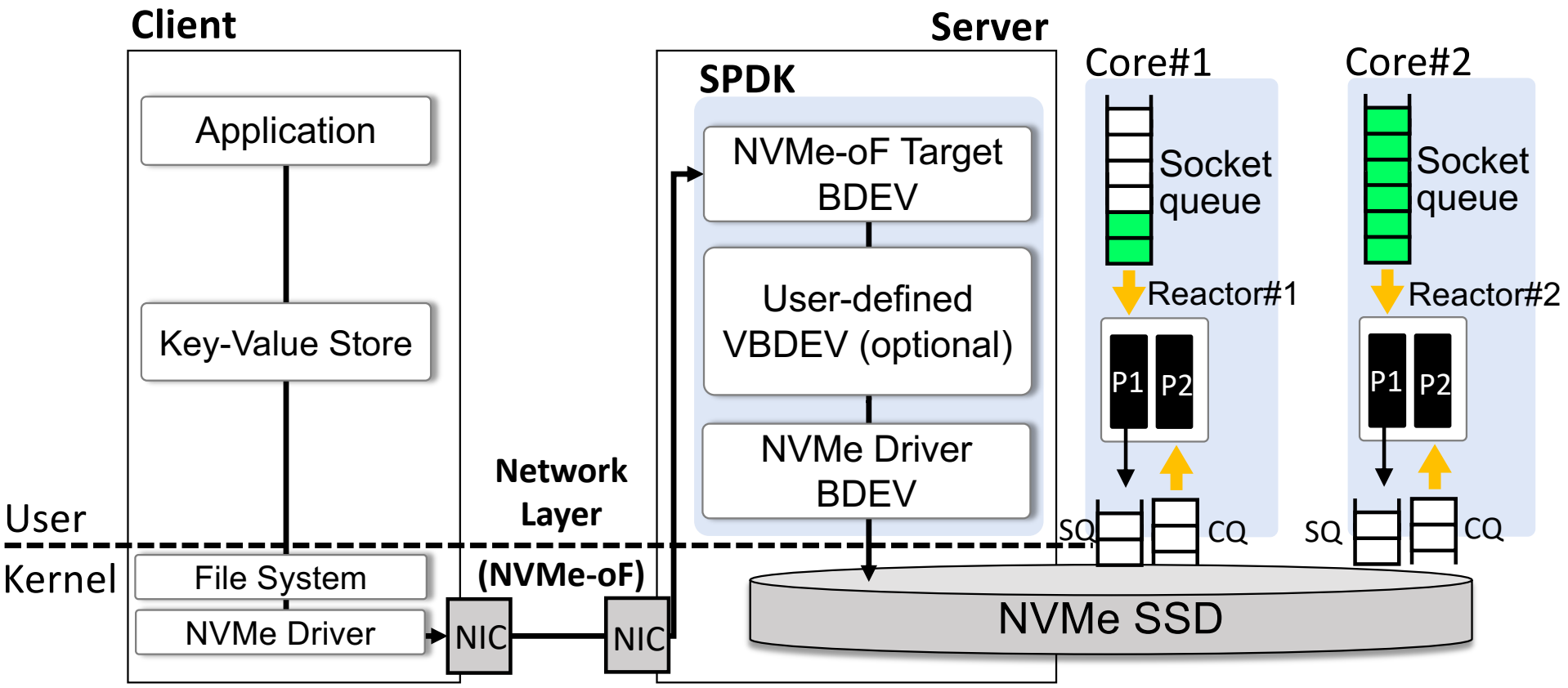

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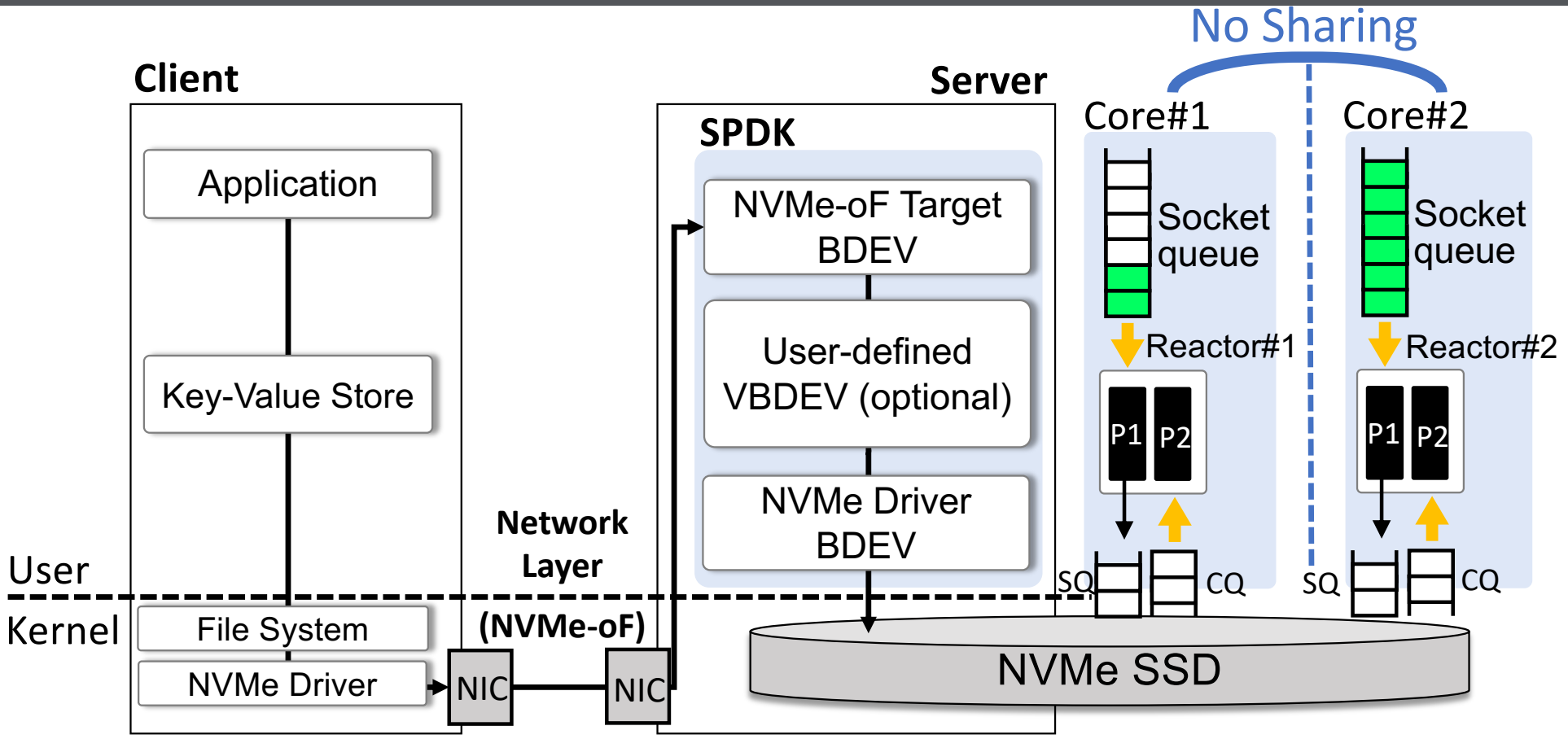

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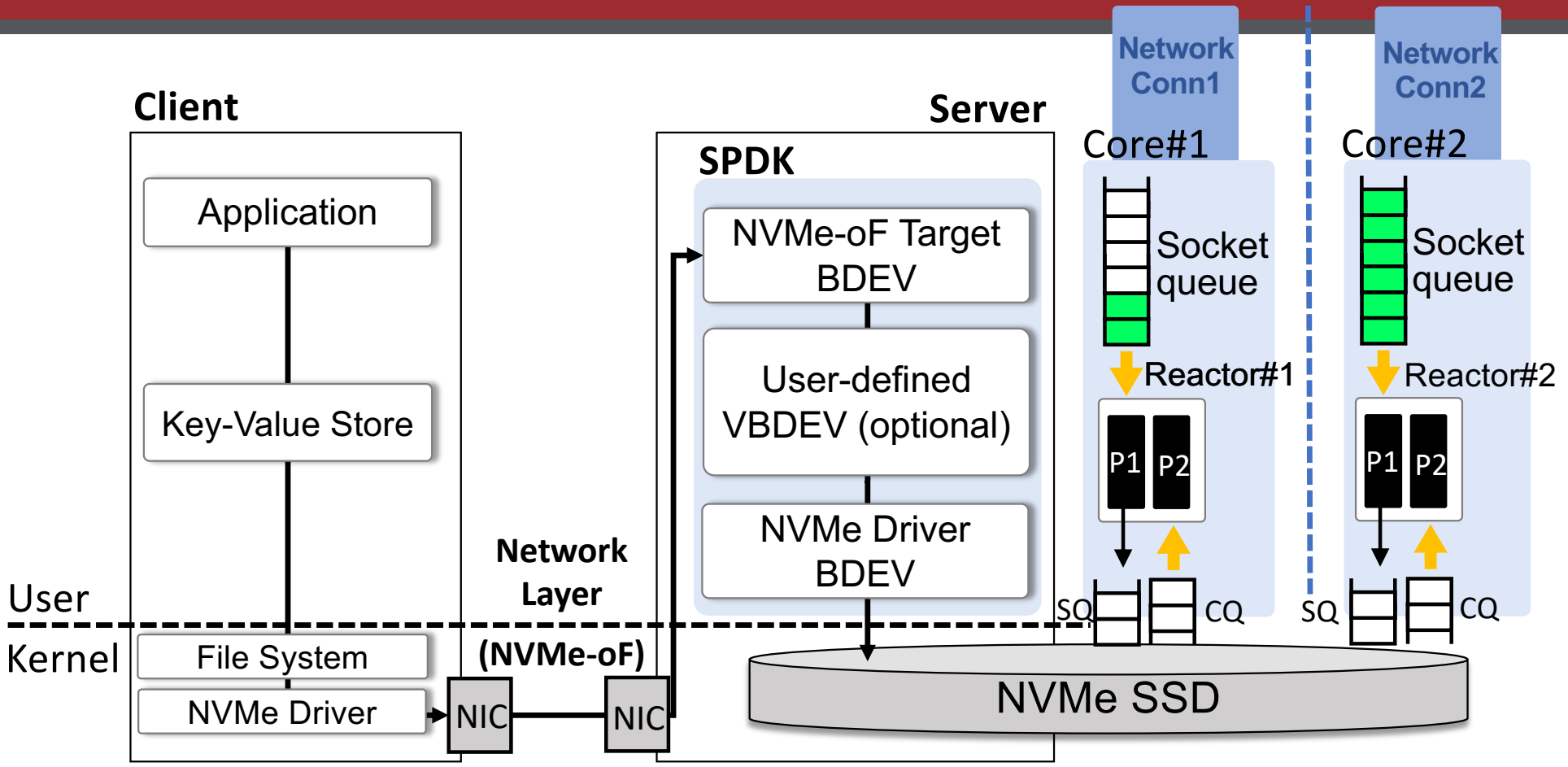

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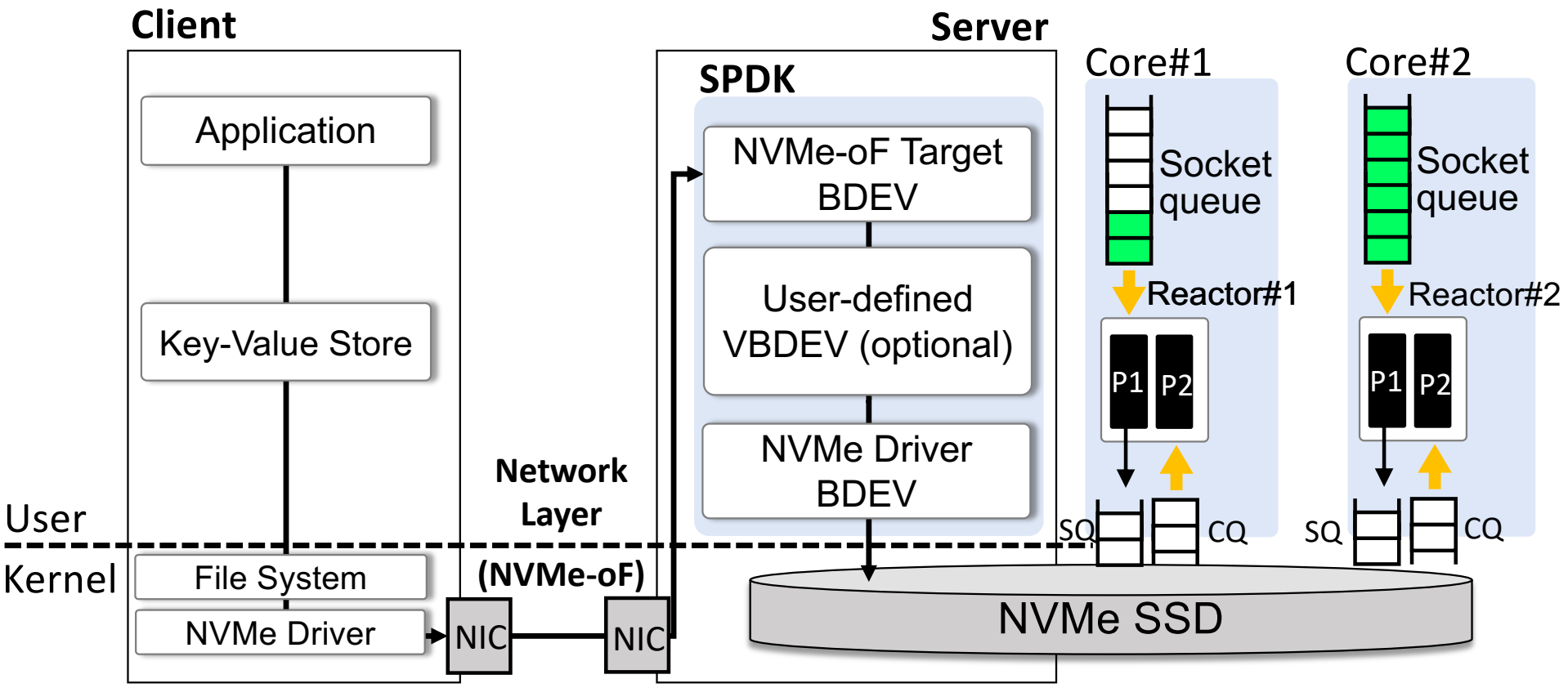

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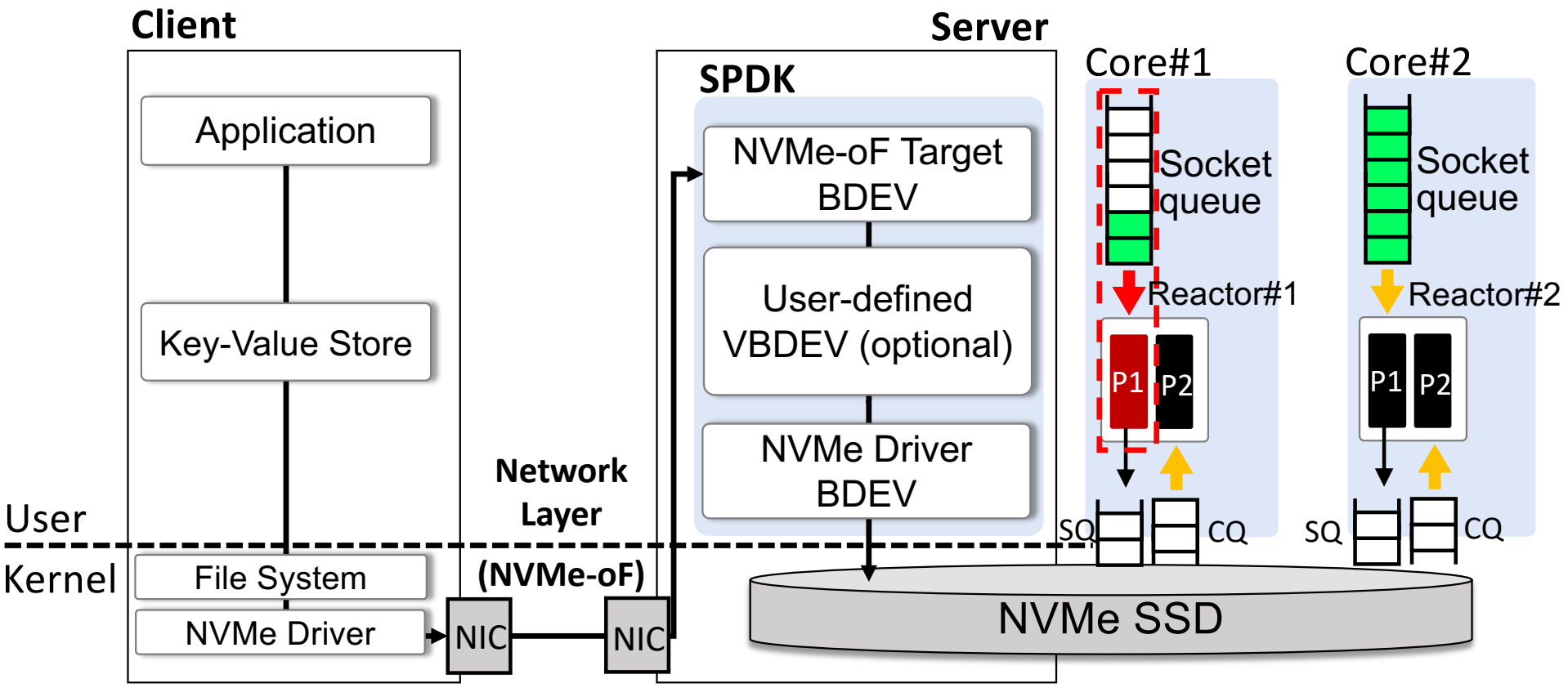

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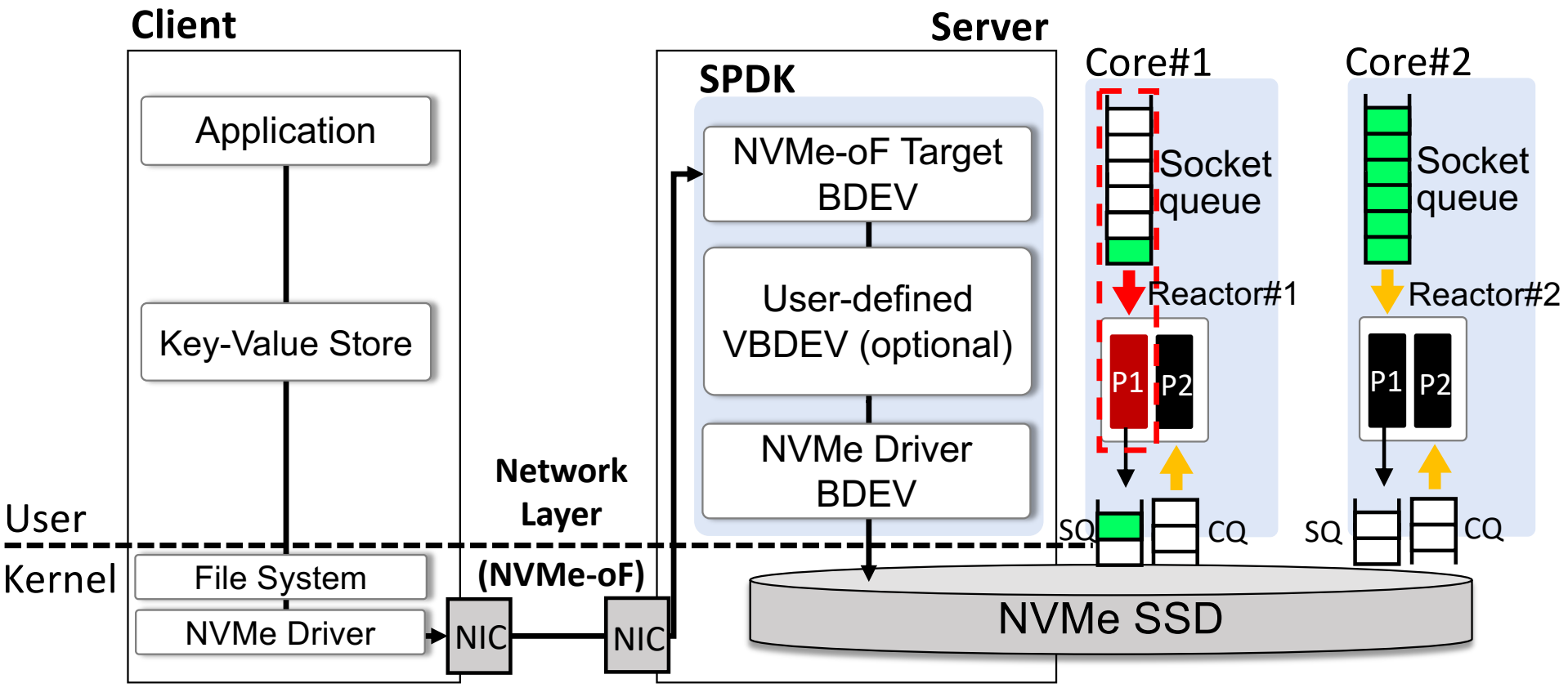

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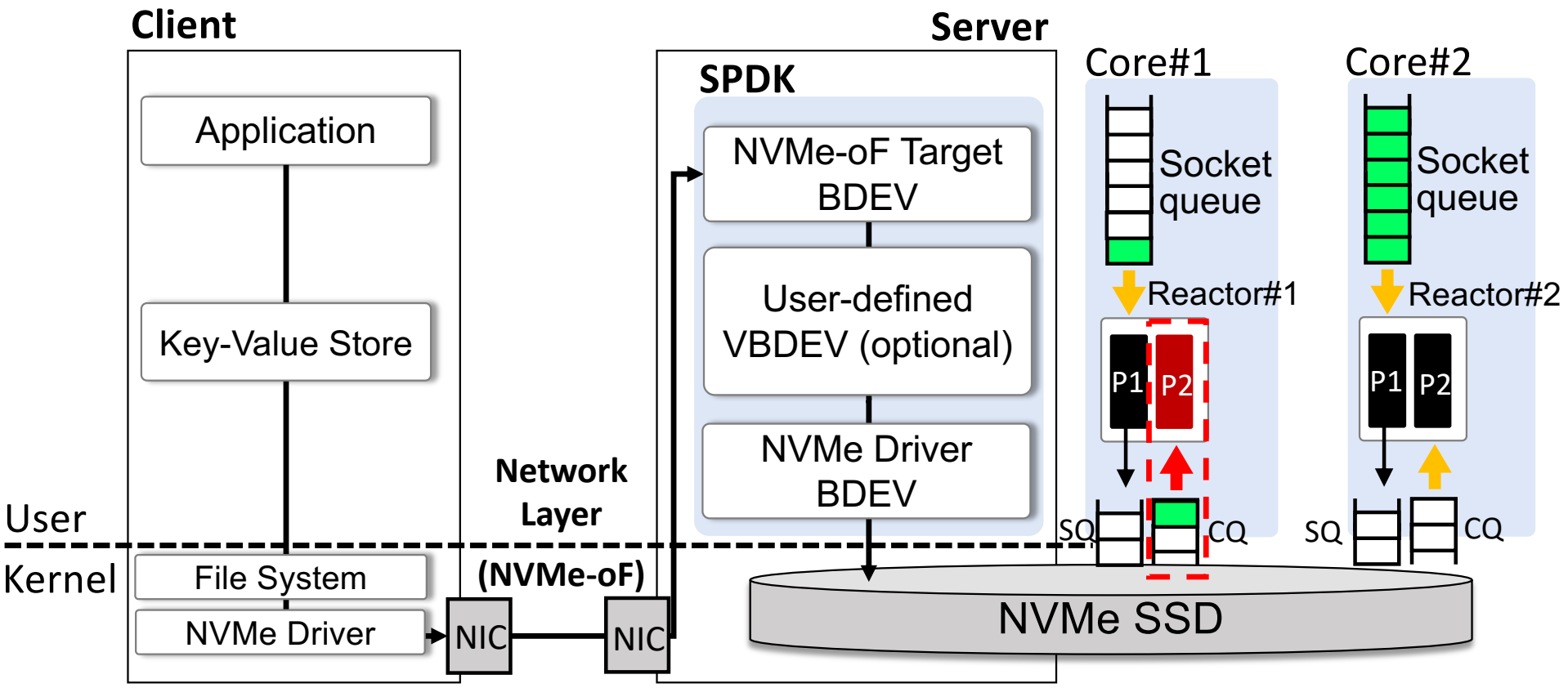

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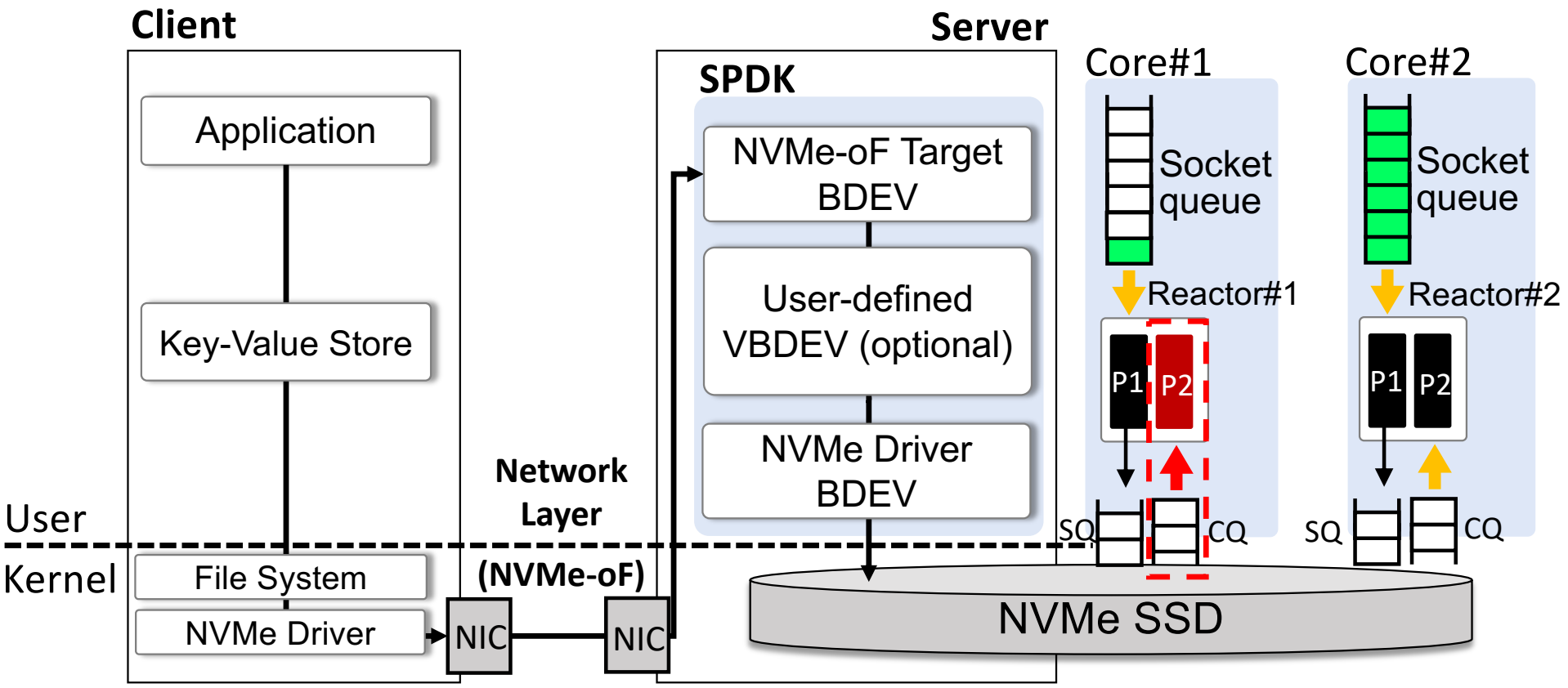

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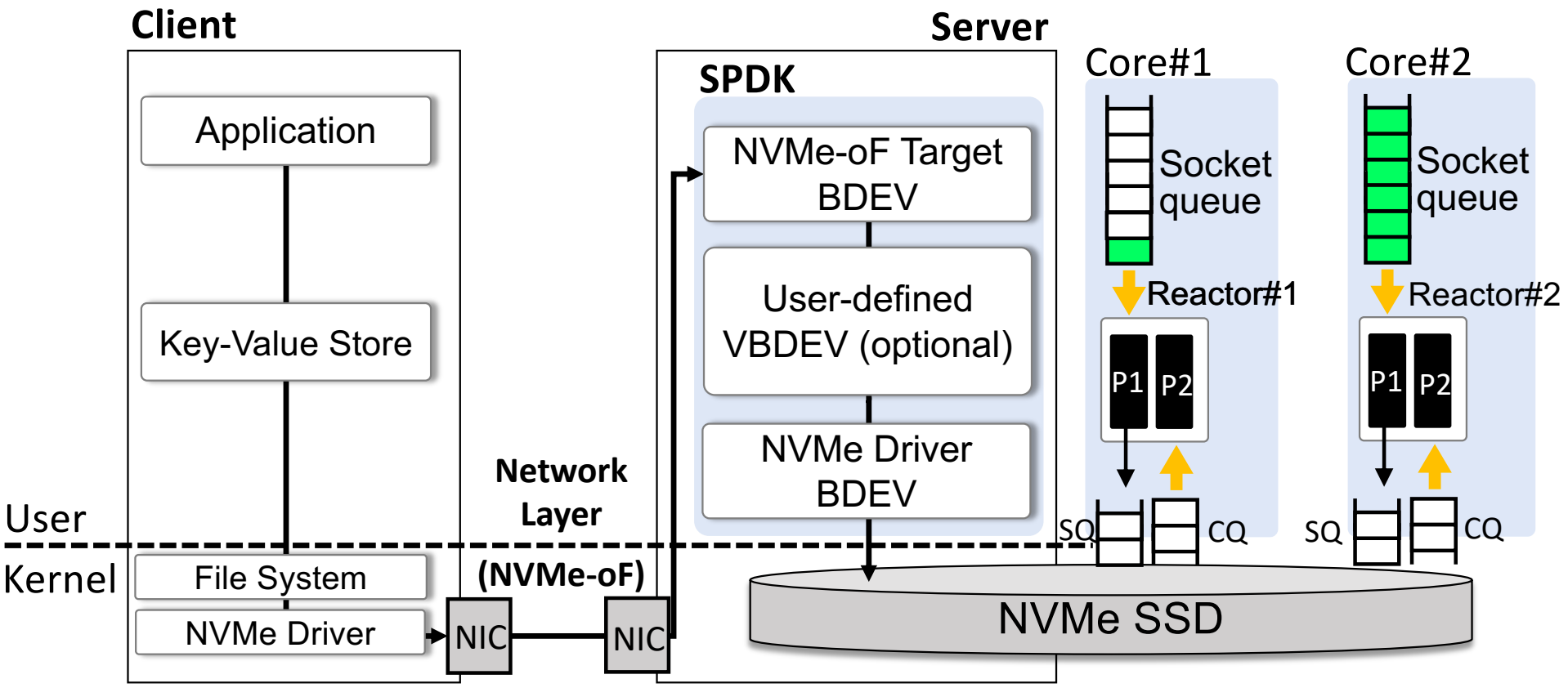
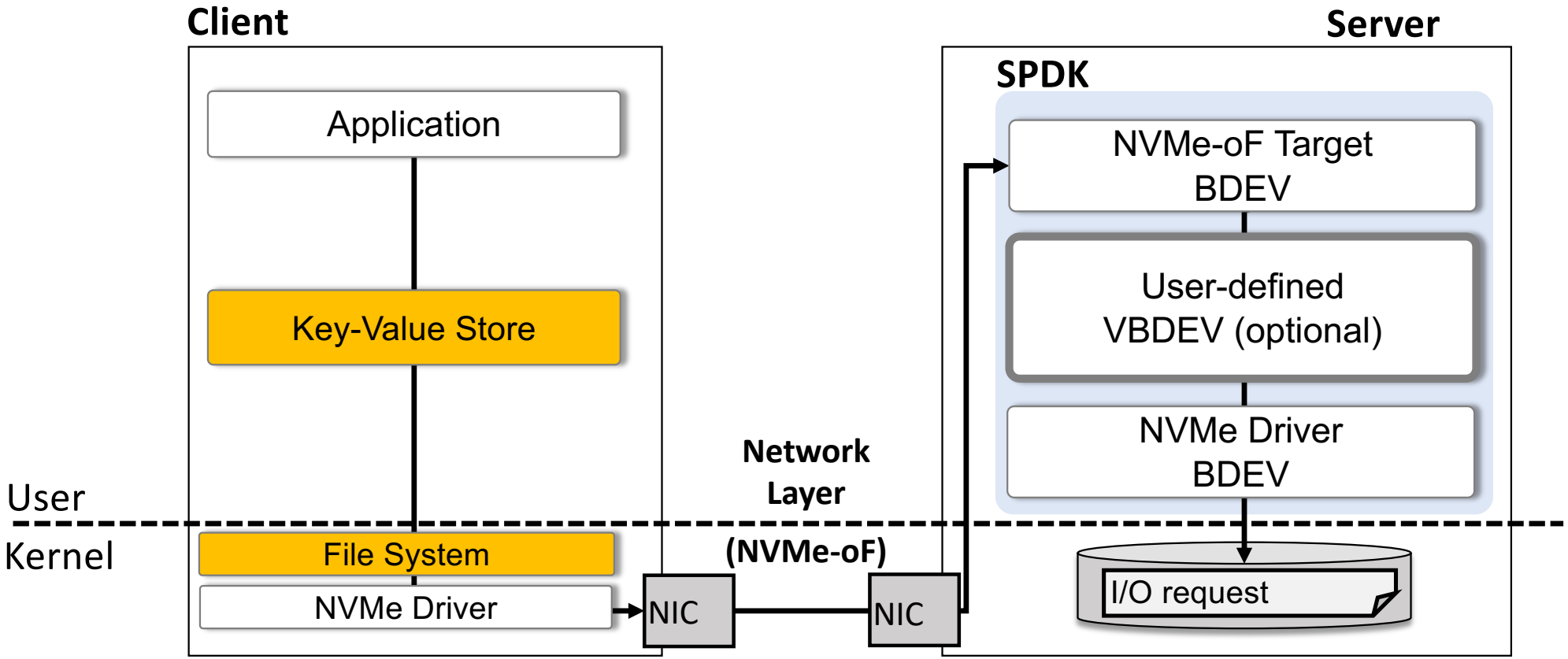


Target Archiecture

Disaggregated Network-based Key-Value Storage System



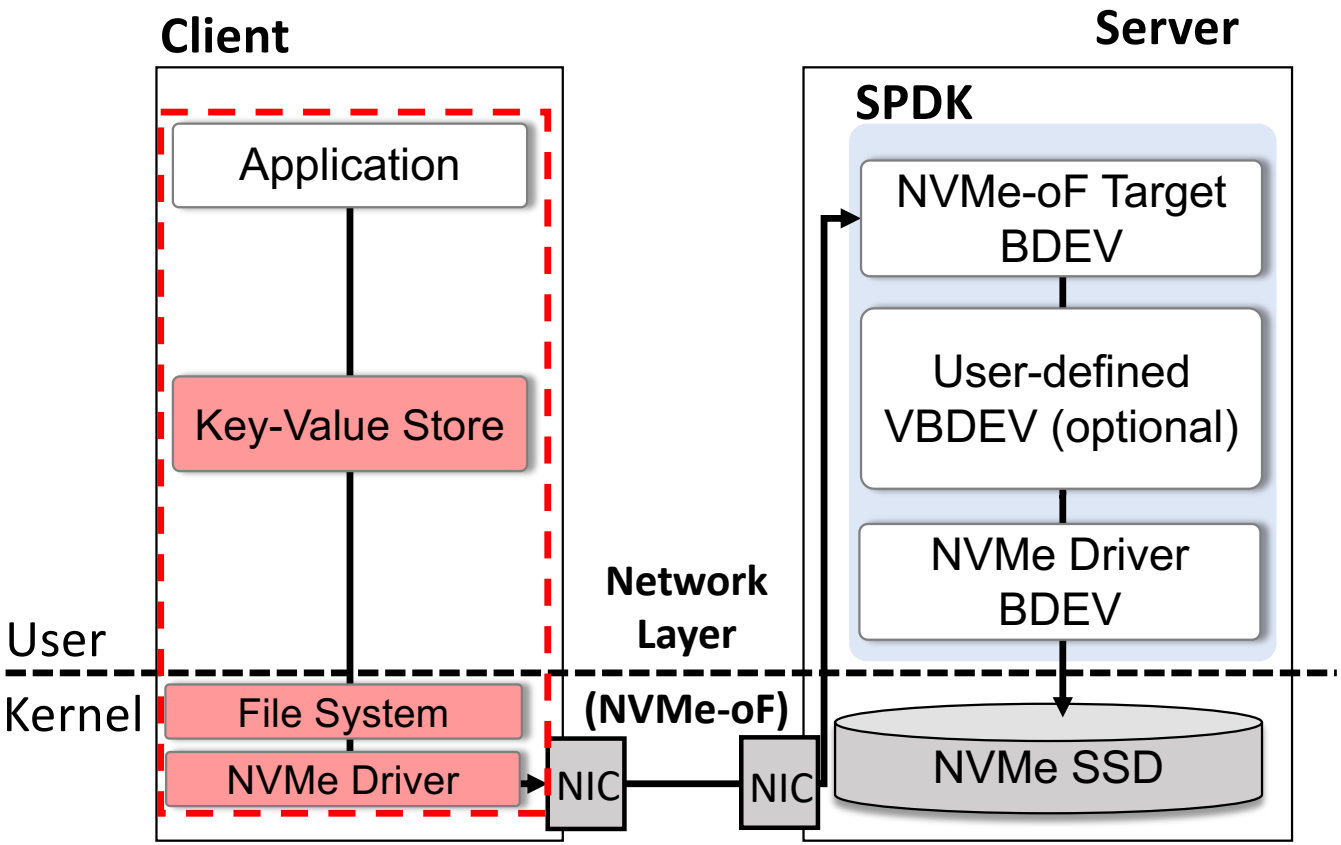
Problem Definition

Disaggregated Networked-based Key-Value Storage System has the following two problems

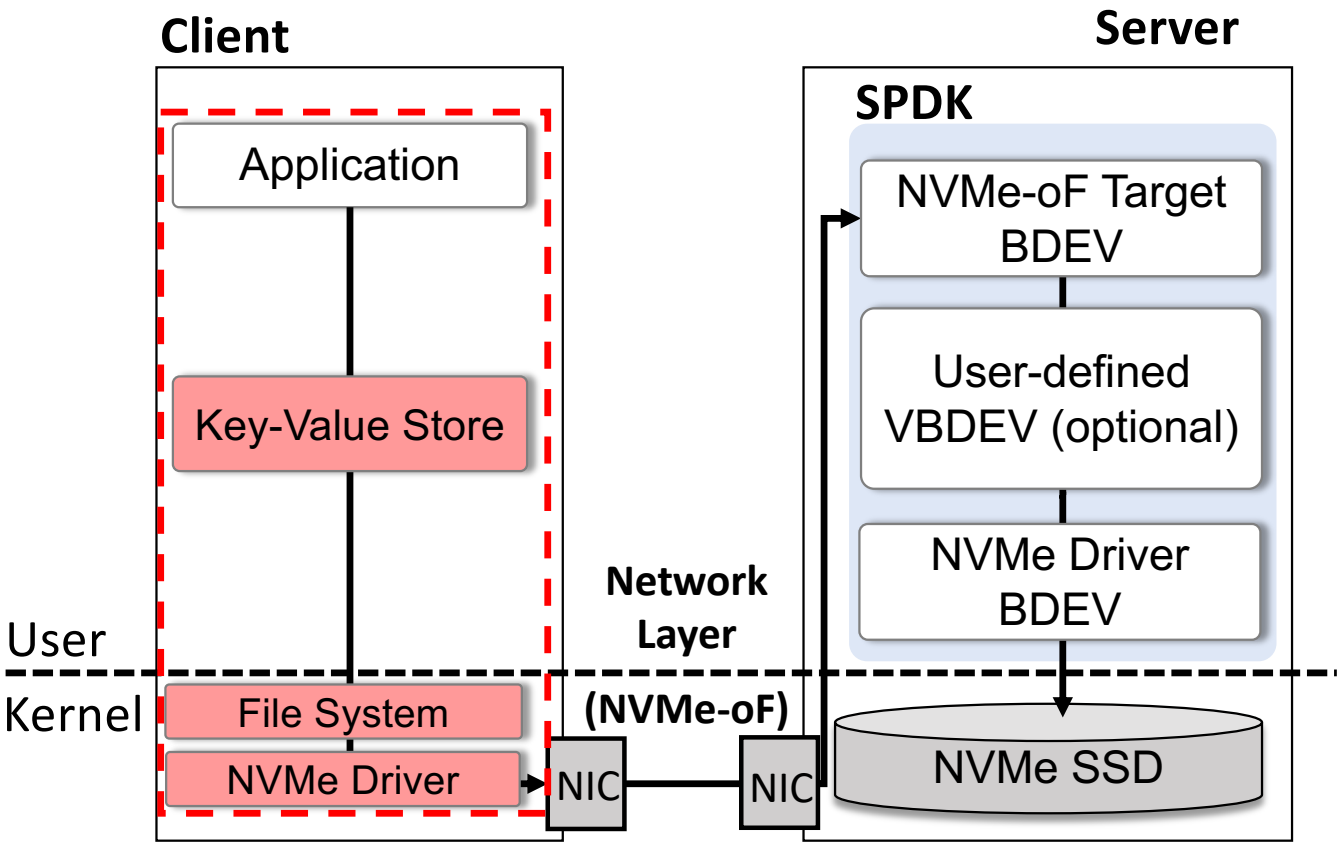
(1) High I/O Stack Overhead Problem

(2) Core Load Imbalance Problem

Problem#1: High I/O Stack Overhead

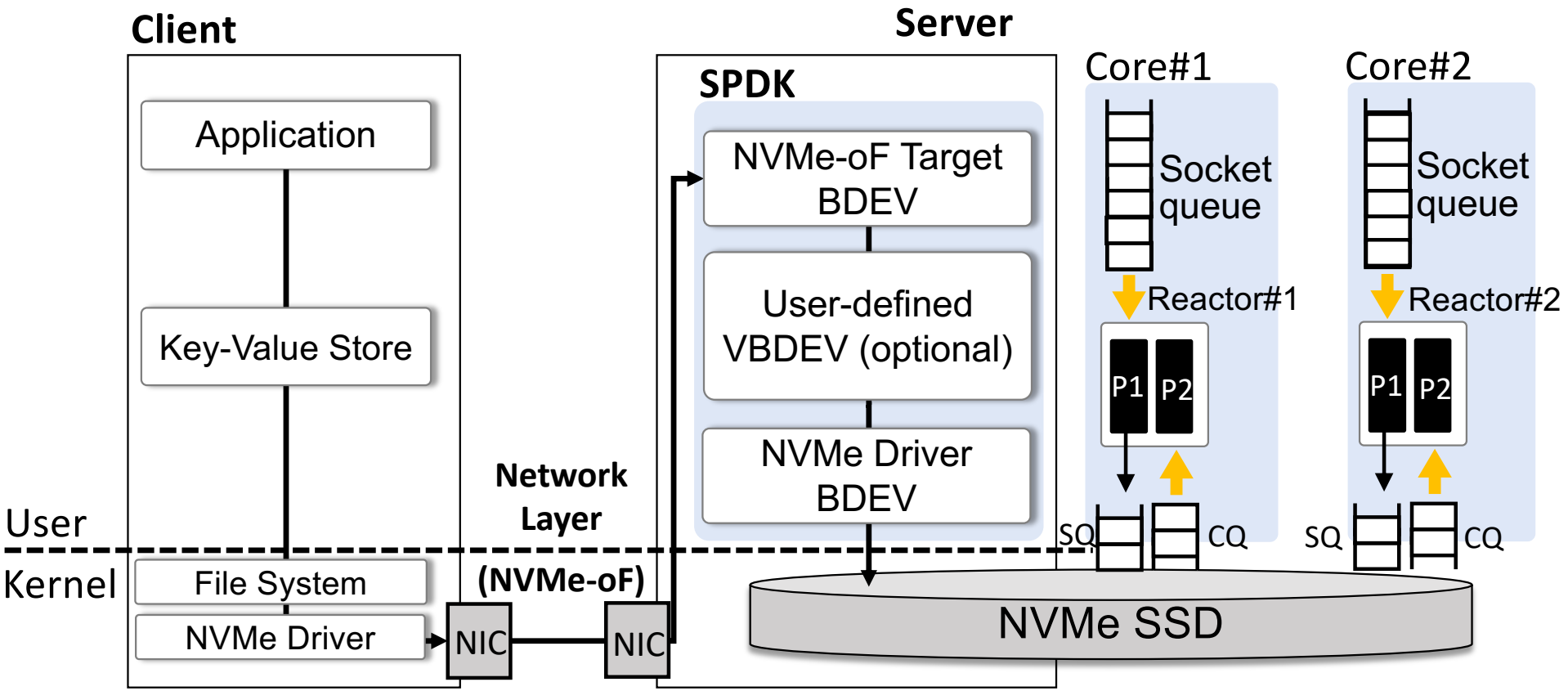


Problem#1: High I/O Stack Overhead

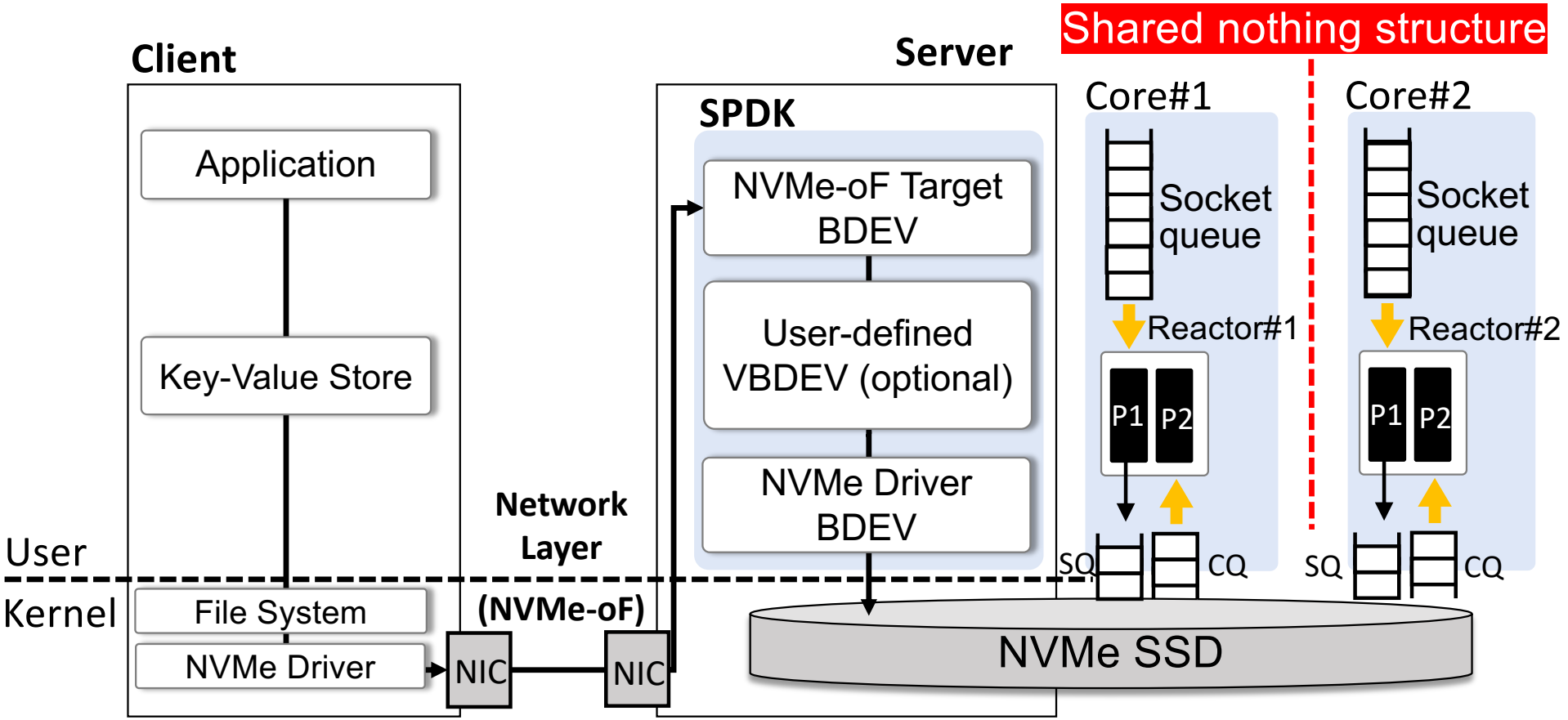


(1) KV to file, file to block address translation overhead
(2) User-to-kernel context switch overhead

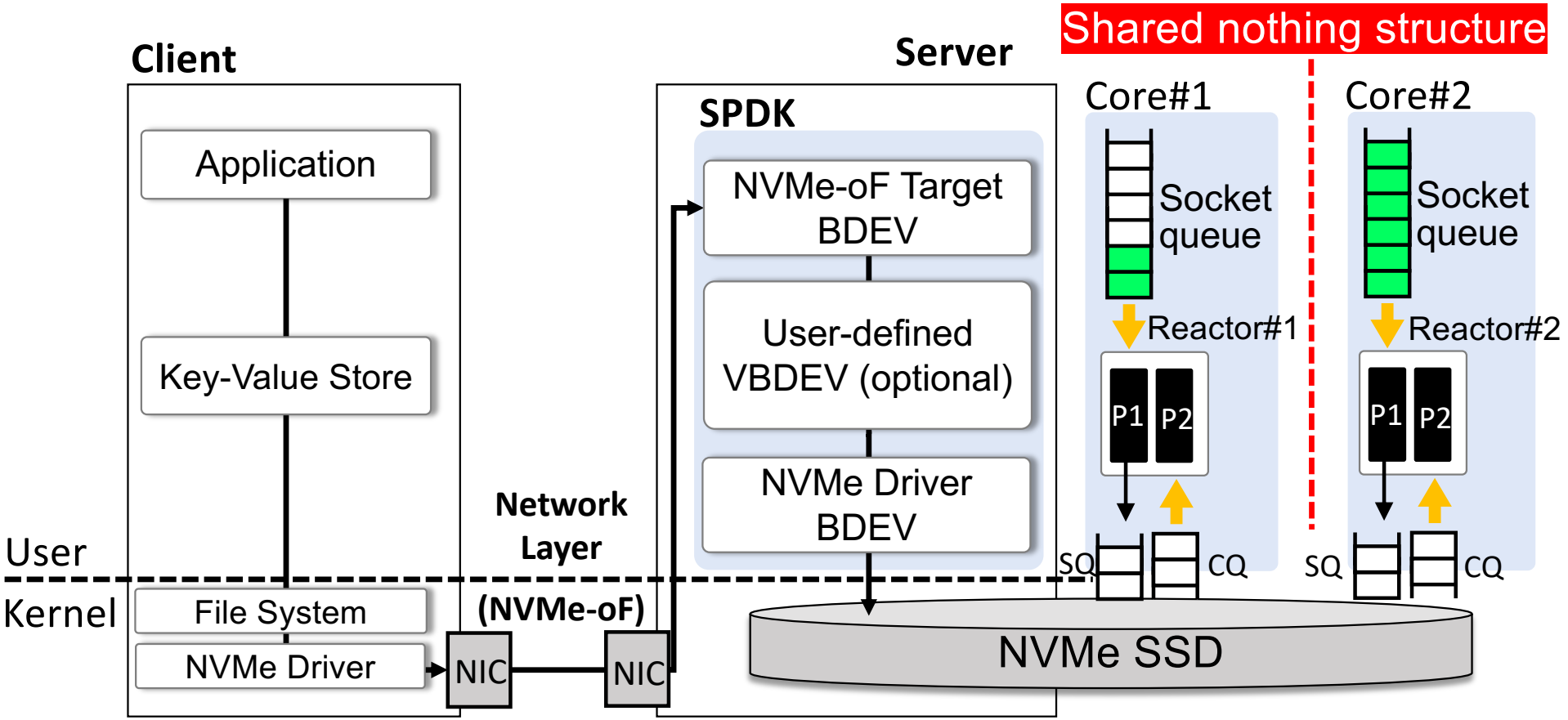
Problem#2: Core Load Imbalance



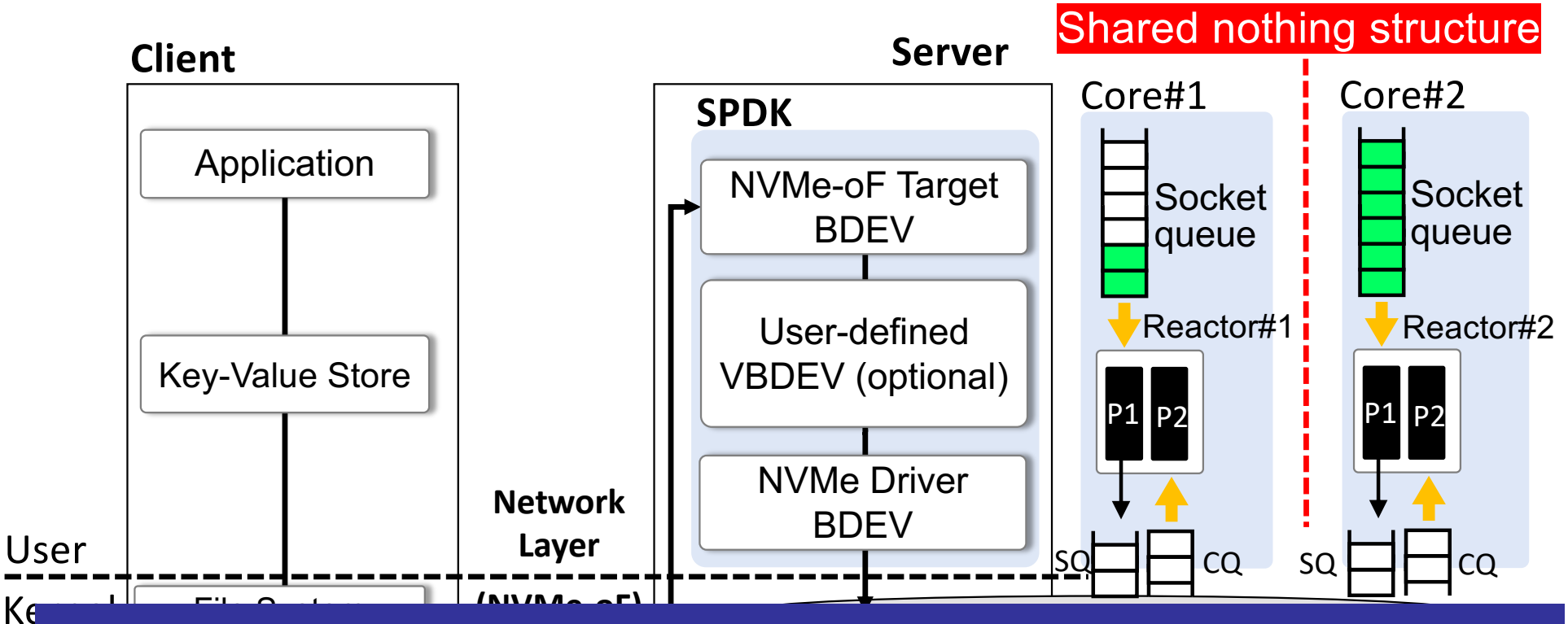
Problem#2: Core Load Imbalance



Problem#2: Core Load Imbalance



Problem#2: Core Load Imbalance



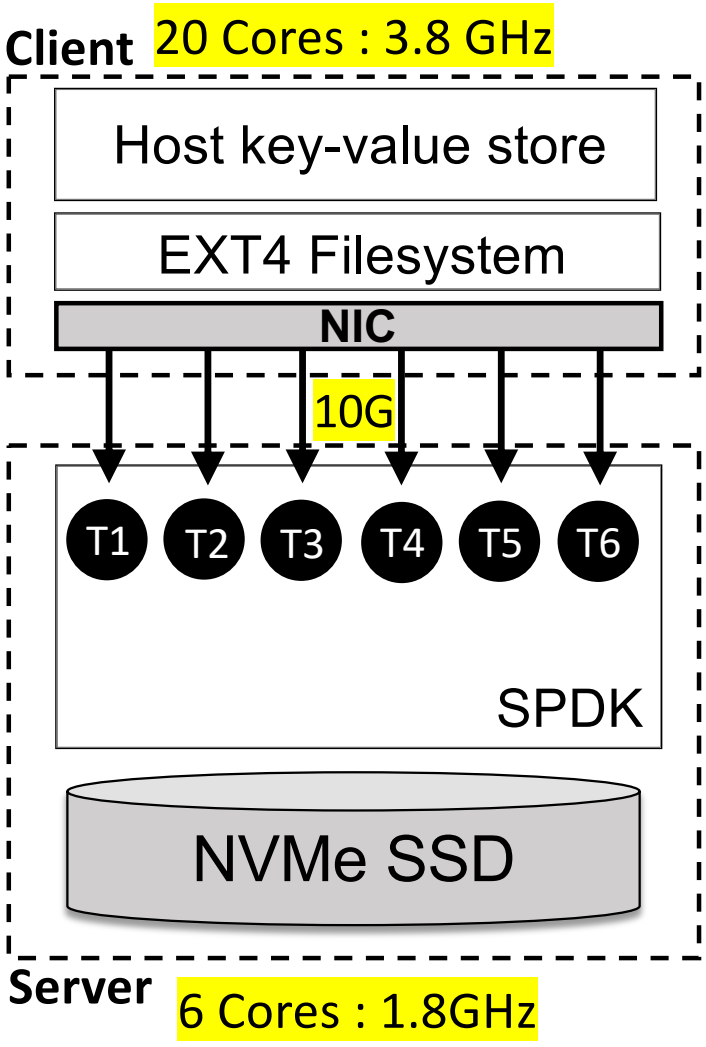
There is a lack of structures for sharing data between cores, resulting in load imbalance.

Content

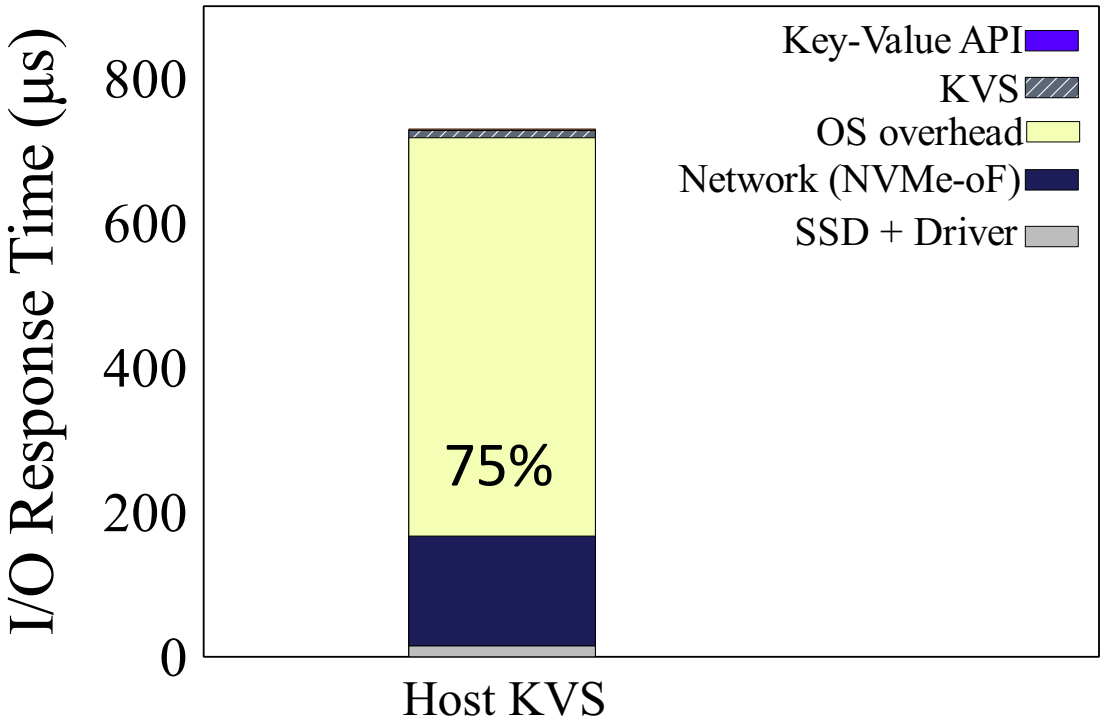
- Background
- Problem Definition
- Motivational Experiments
- OctoKV: Design and Implementation
- Evaluation
- Conclusion

Problem#1: High I/O Stack Overhead

- Client
  - § 20 CPU cores
  - § Running a host hash-based key-value store
- Server
  - § 6 CPU cores
  - § Running a Linux OS using Intel SPDK
- Workloads
  - § Running a db_bench
  - § I/O request size = 16KB



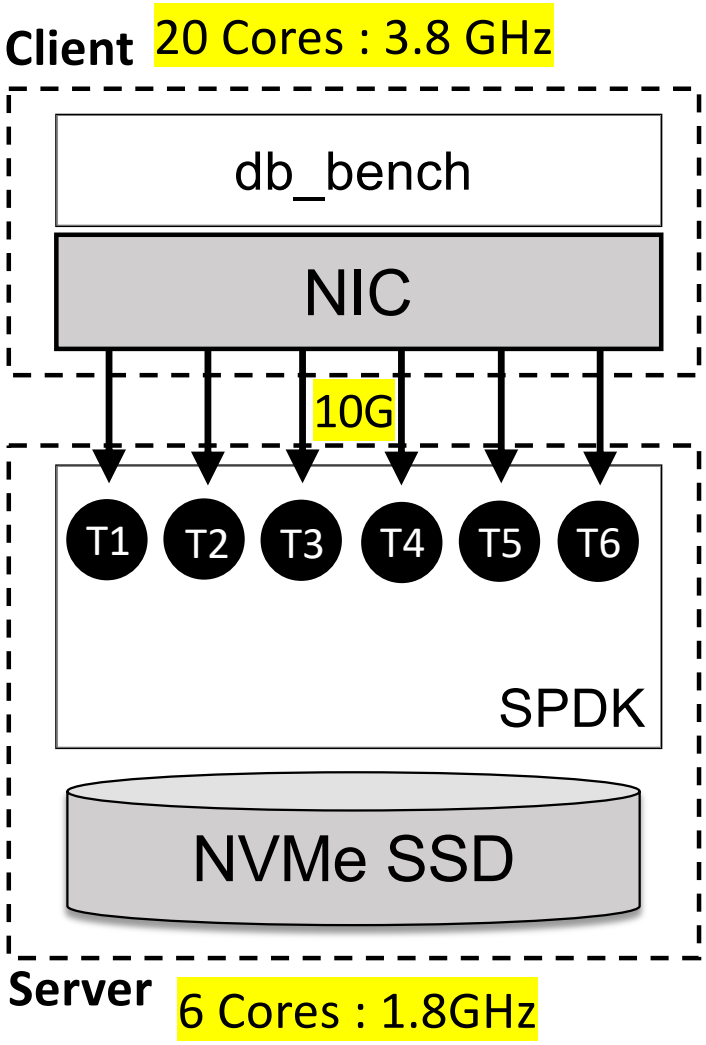
Problem#1: High I/O Stack Overhead



Running key-values store on top of the file system
in a disaggregated architecture has significant I/O overhead

Problem#2: Core Load Imbalance

- Workloads
  - § Running a db_bench
    - 1) Light workload
      - *7 I/O threads issue write I/Os*
    - 2) Heavy workload
      - *12 I/O threads issue write I/Os*
  - § I/O request size = 16KB



Problem#2: Core Load Imbalance

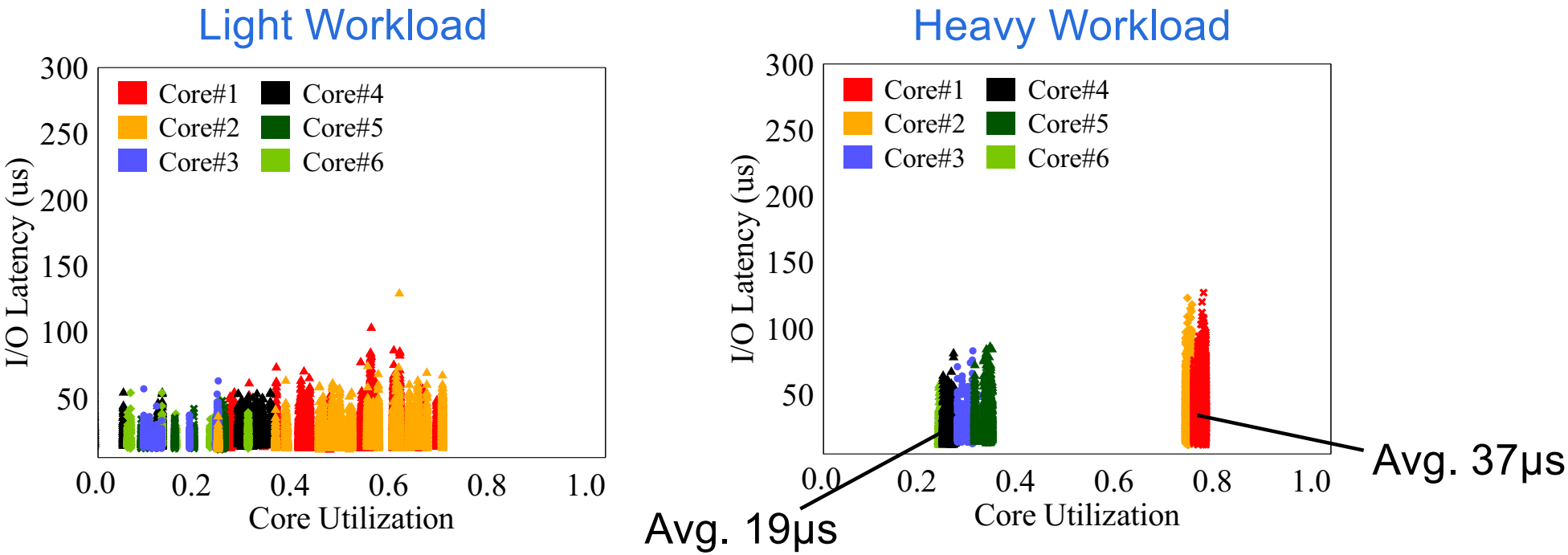
Thread Queue Depth for each core/SPDK thread

Queue Depth	Core#1	Core#2	Core#3	Core#4	Core#5	Core#6	Avg	Stdev
Light Workload (Put)	2.00	2.21	0.75	1.58	0.67	0.33	1.26	0.78
Heavy Workload (Put)	5.25	5.48	2.00	2.06	2.13	2.13	3.18	1.70
Light Workload (Get)	3.95	4.23	1.27	1.36	2.00	1.82	2.43	1.31
Heavy Workload (Get)	6.06	6.54	2.69	2.62	2.92	2.65	3.91	1.86

The amount of NVMe commands delivered to the core is imbalanced

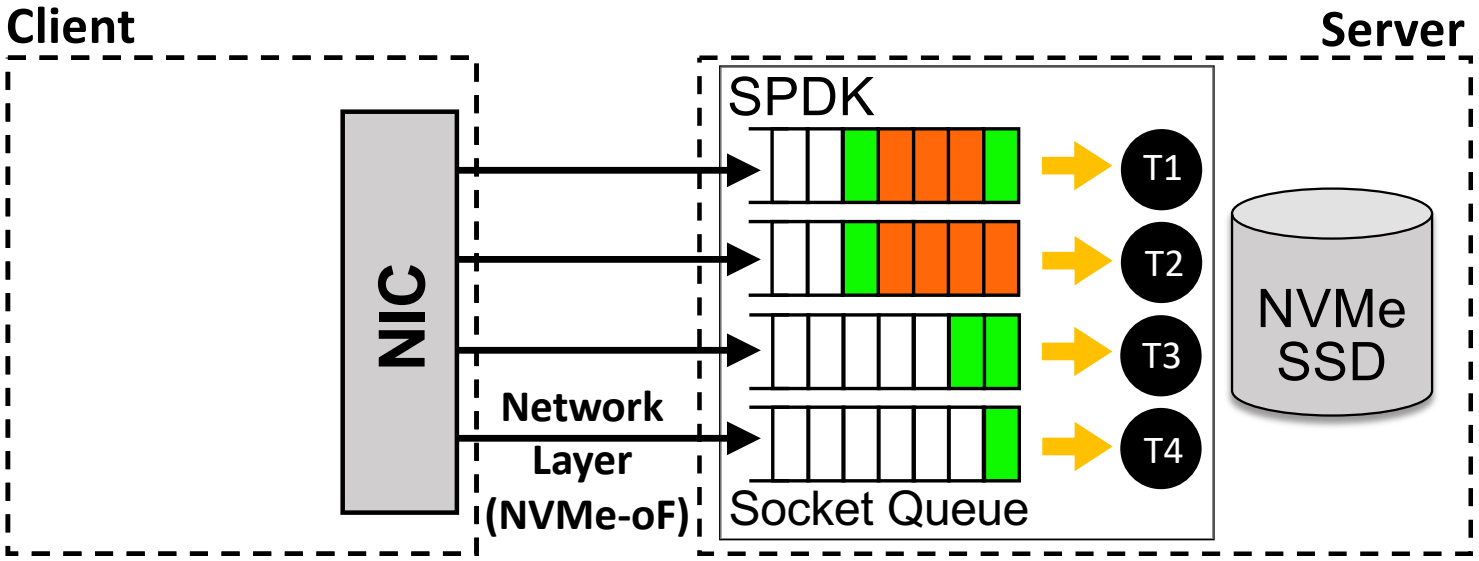
Problem#2: Core Load Imbalance

Core Utilization vs I/O Latency



Core utilization between cores forms a bimodal distribution,
I/Os processed on busy cores show high latency

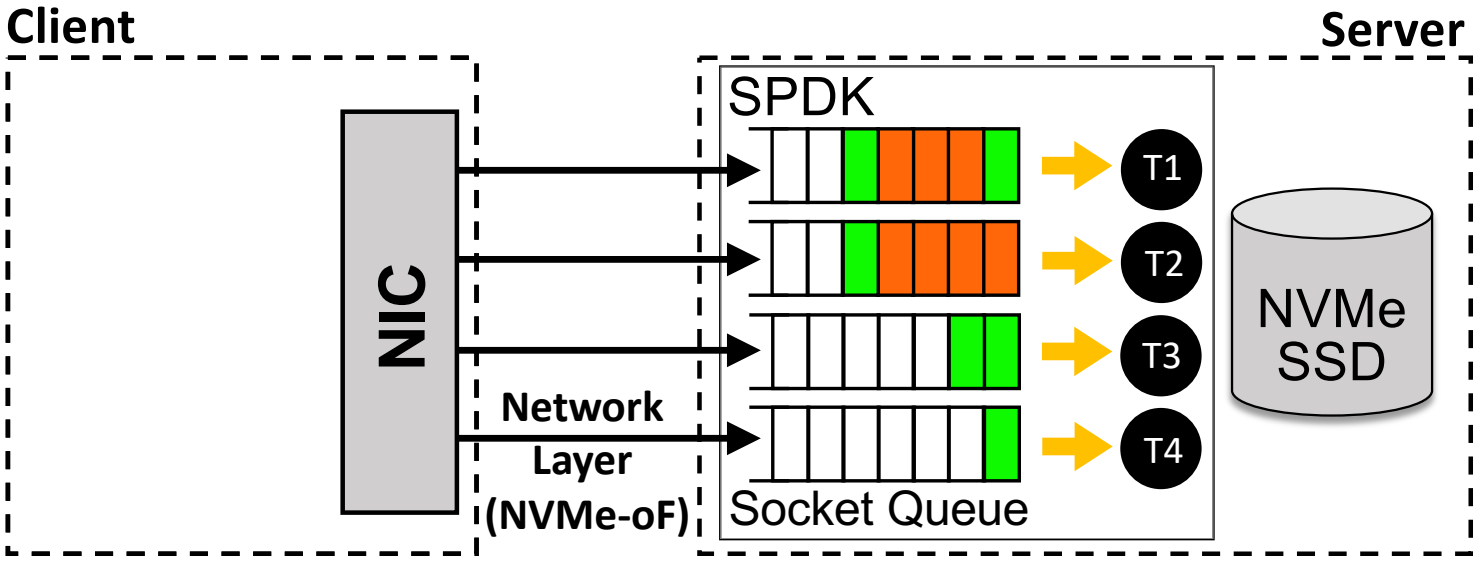
Problem#2: Core Load Imbalance



→ hash function, compaction, background task …

Ti SPDK thread → TCP connection NVMe request (Light) NVMe request (Heavy)

Problem#2: Core Load Imbalance



→ hash function, compaction, background task …

Performing compute-intensive tasks on the server increases the CPU load and increases the load imbalance problem

OctoKV: *An Agile Network-Based Key-Value Storage System with Robust Load Orchestration*

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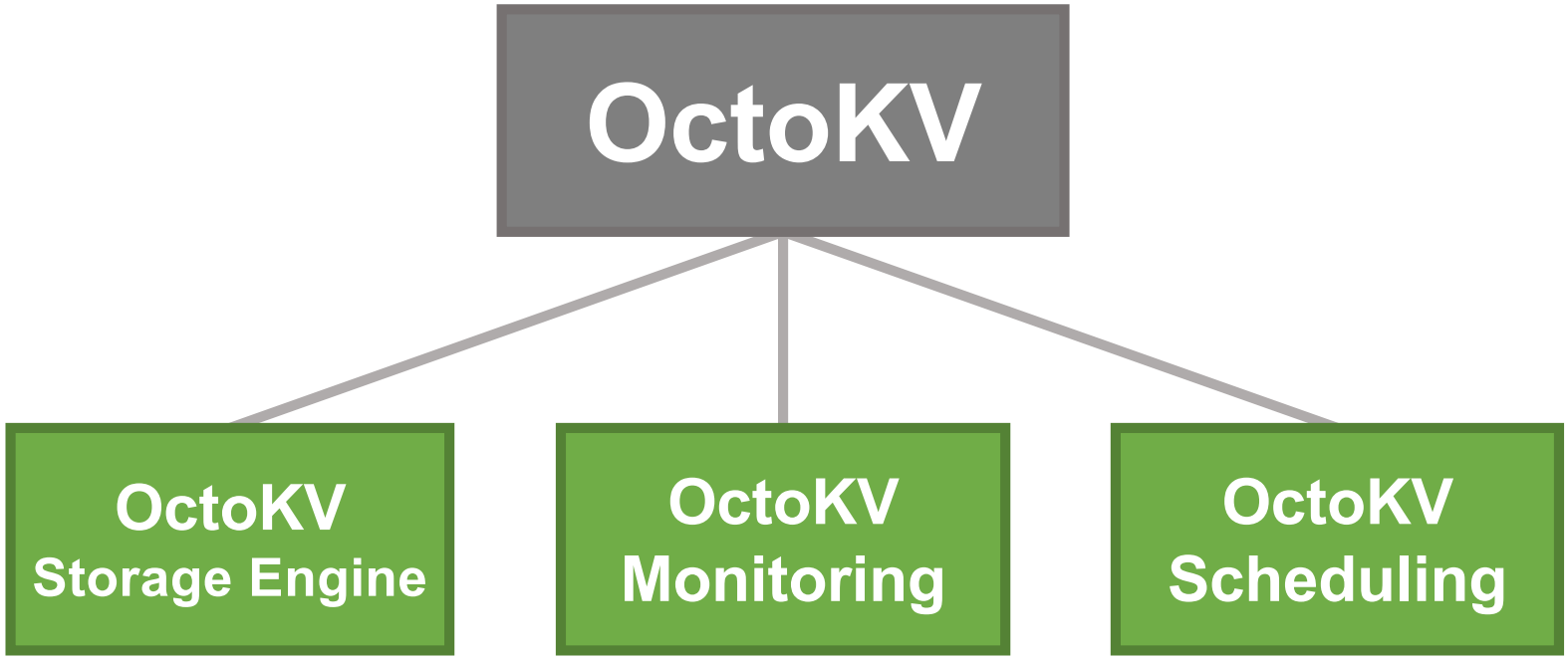
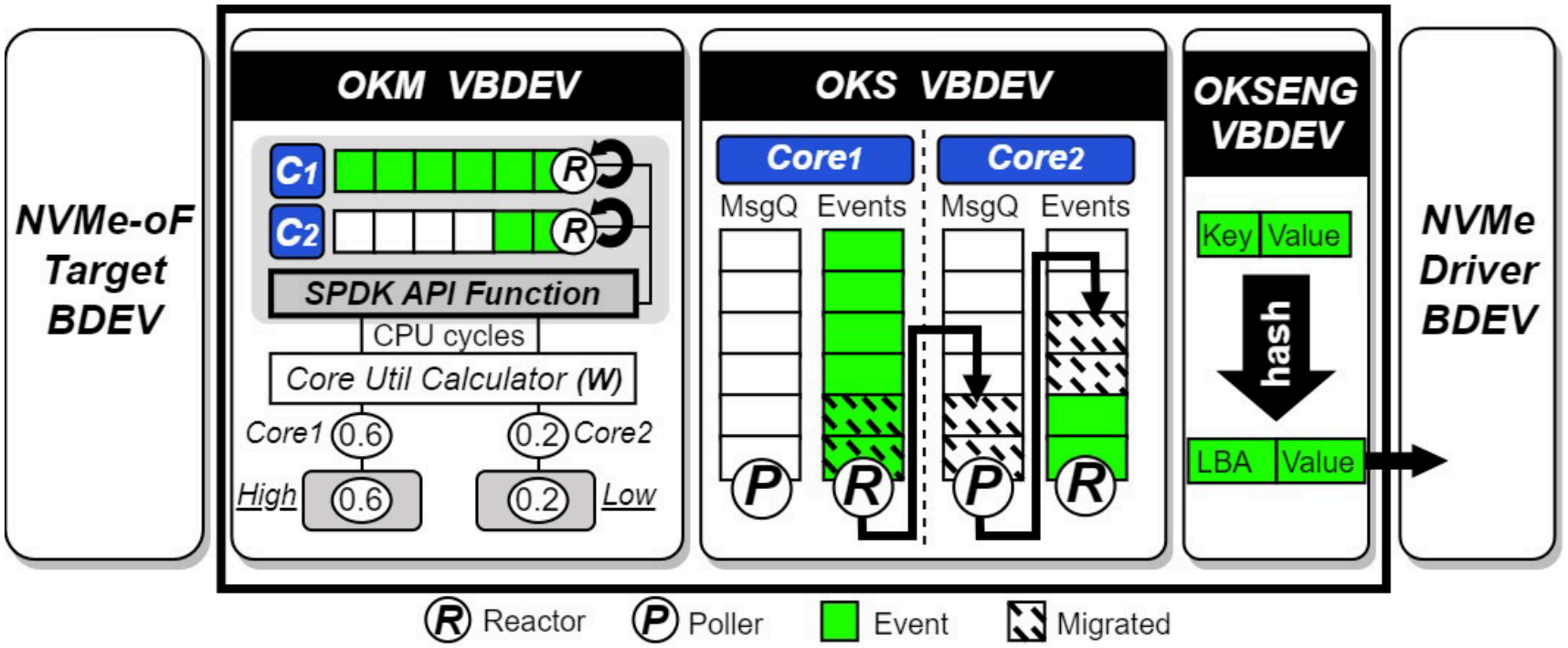
OctoKV Overview



OctoKV Overview



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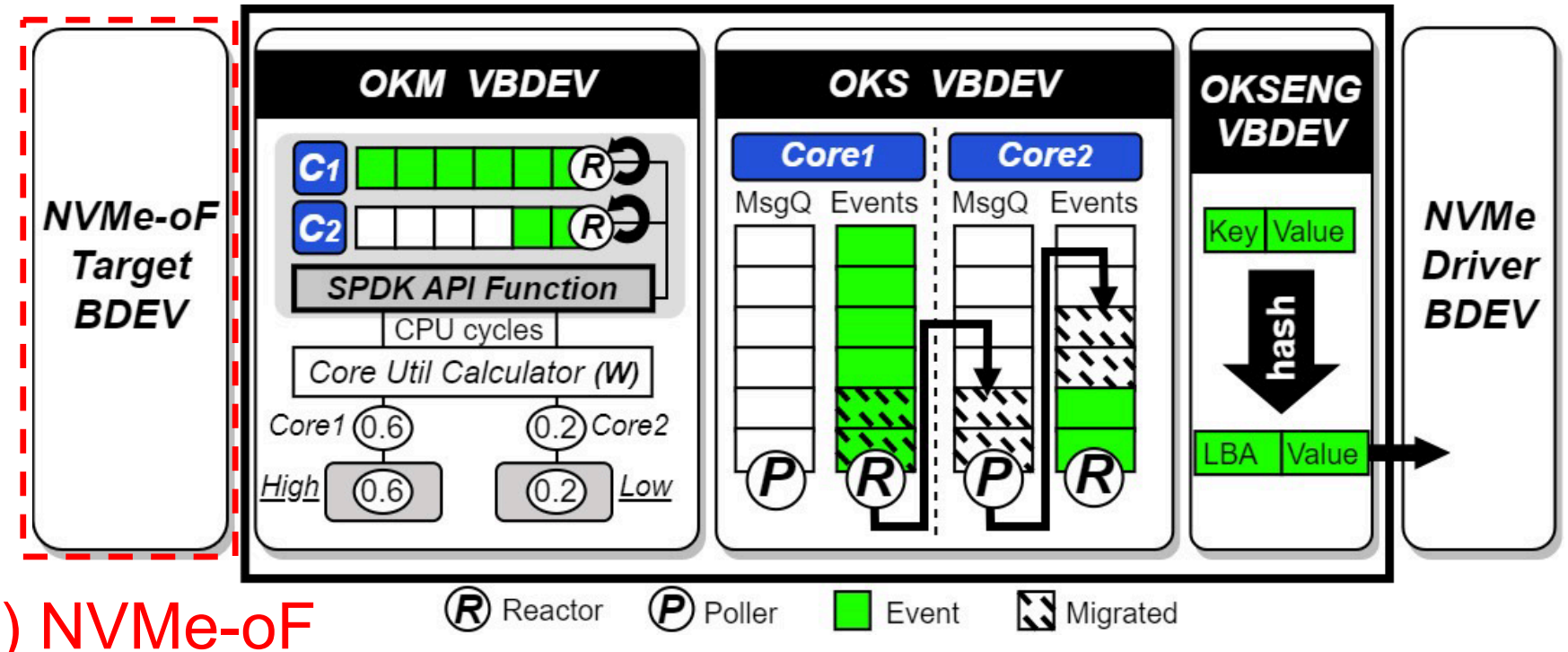
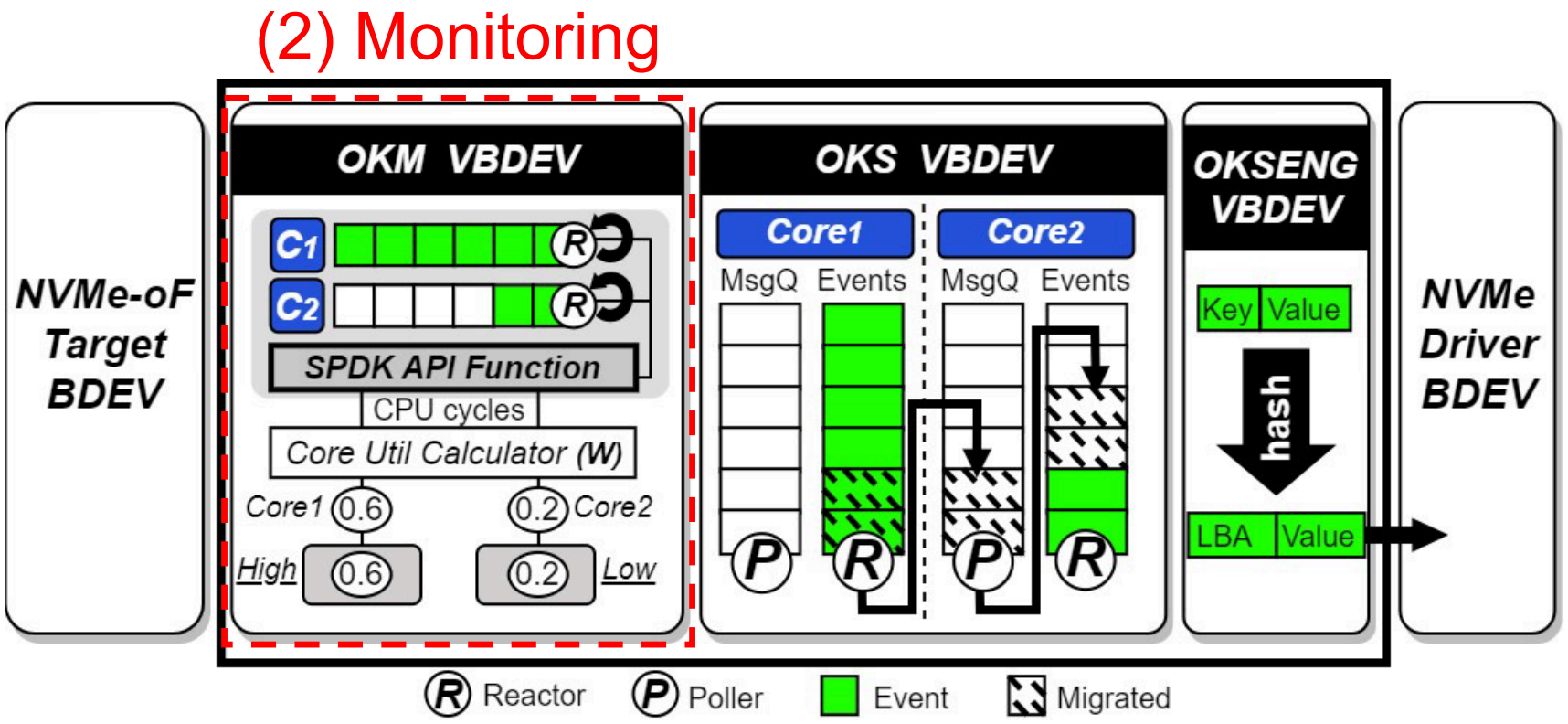
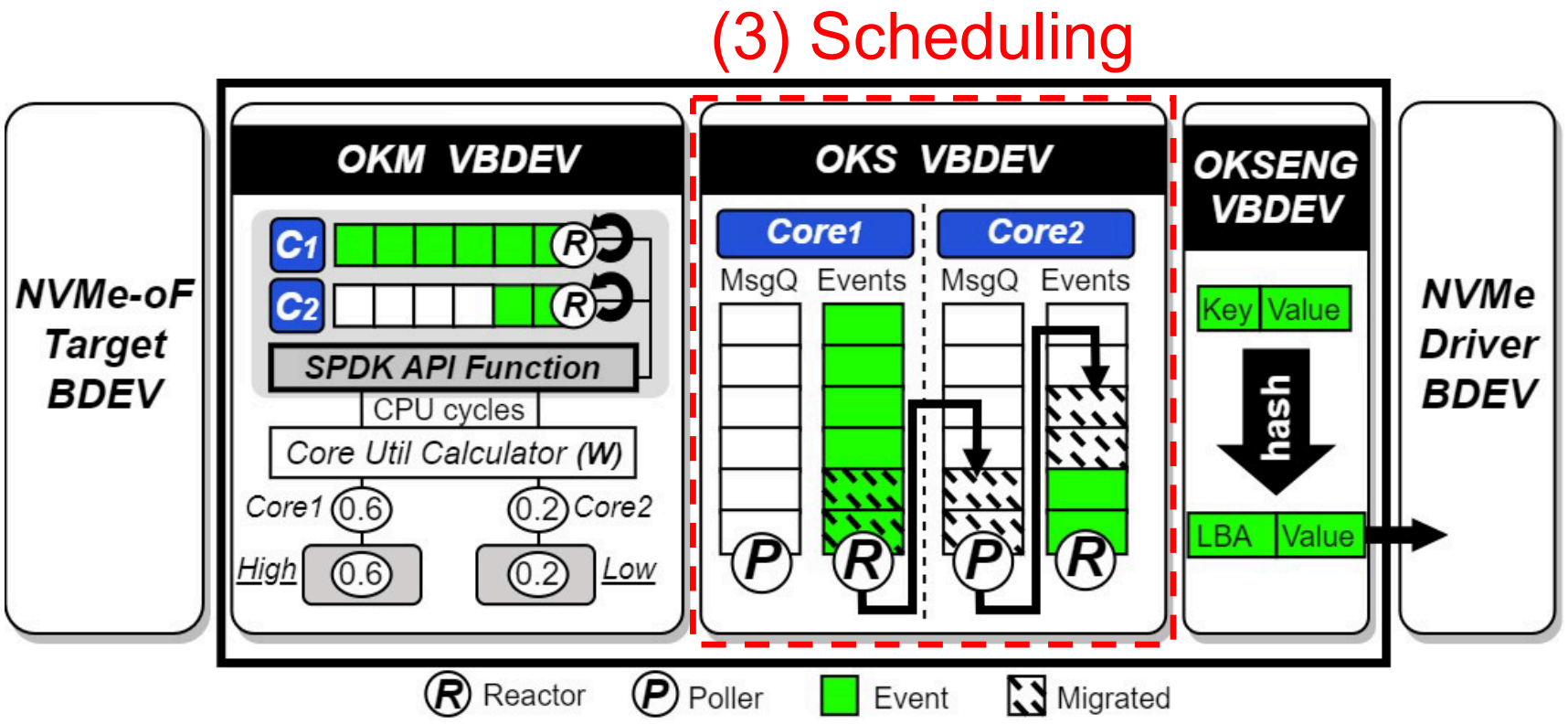


(1) NVMe-oF

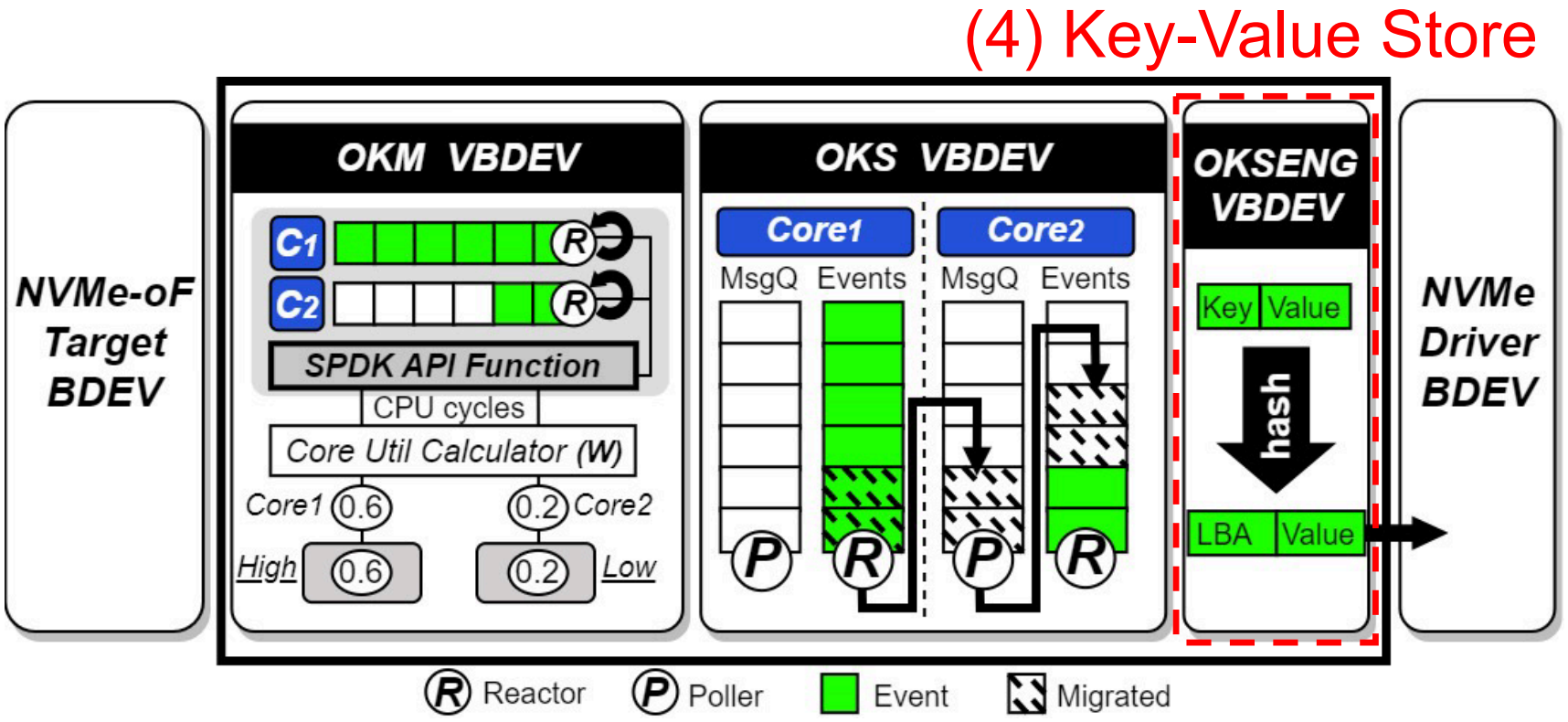
OctoKV Overview



OctoKV Overview



OctoKV Overview



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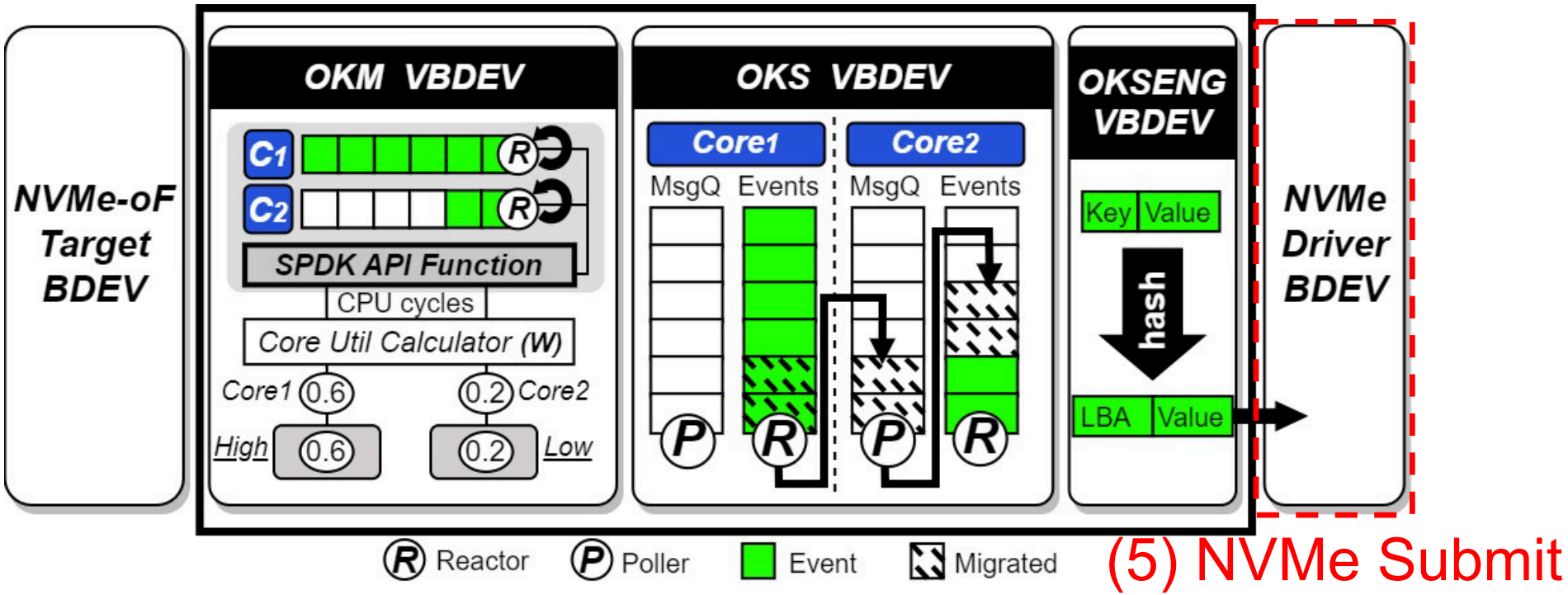
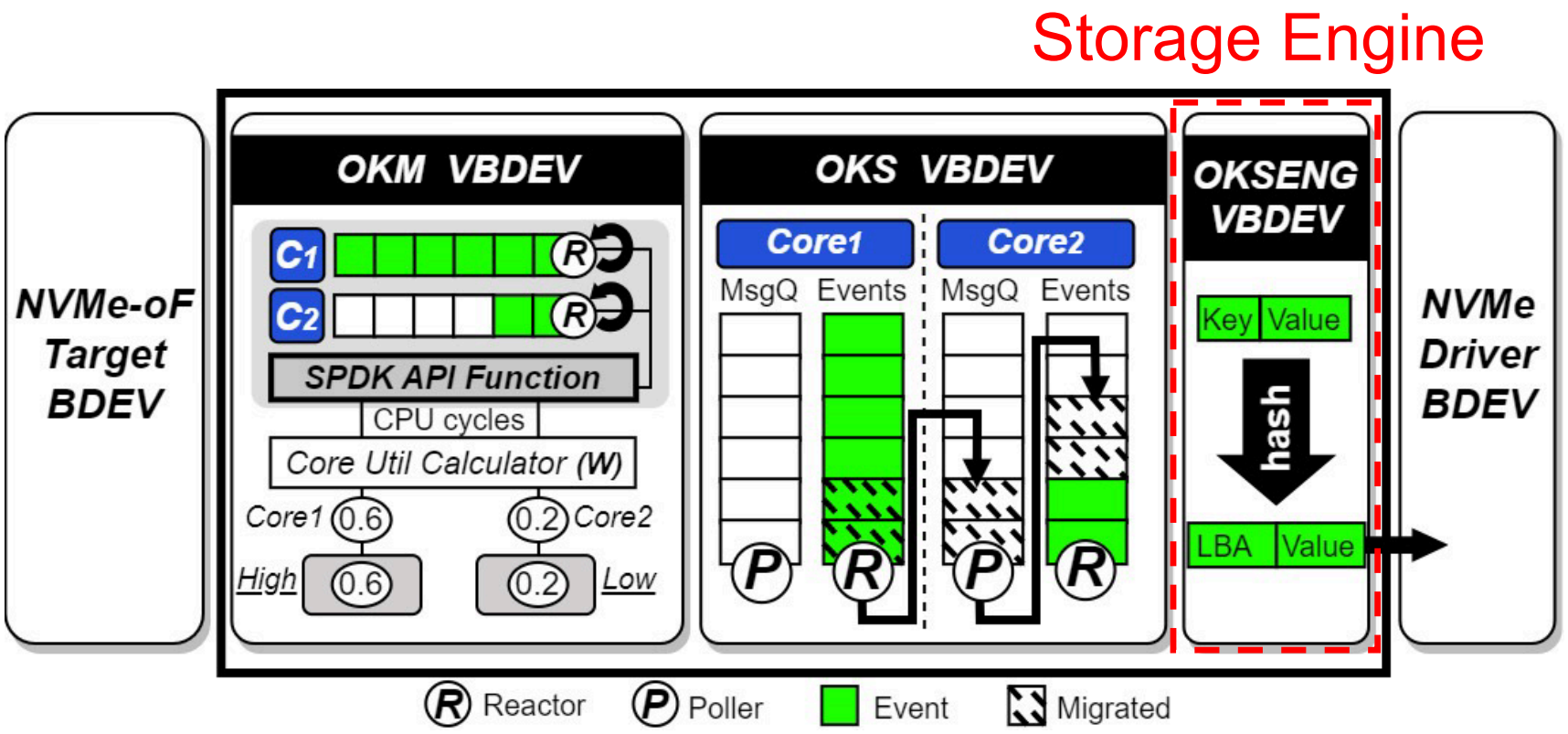
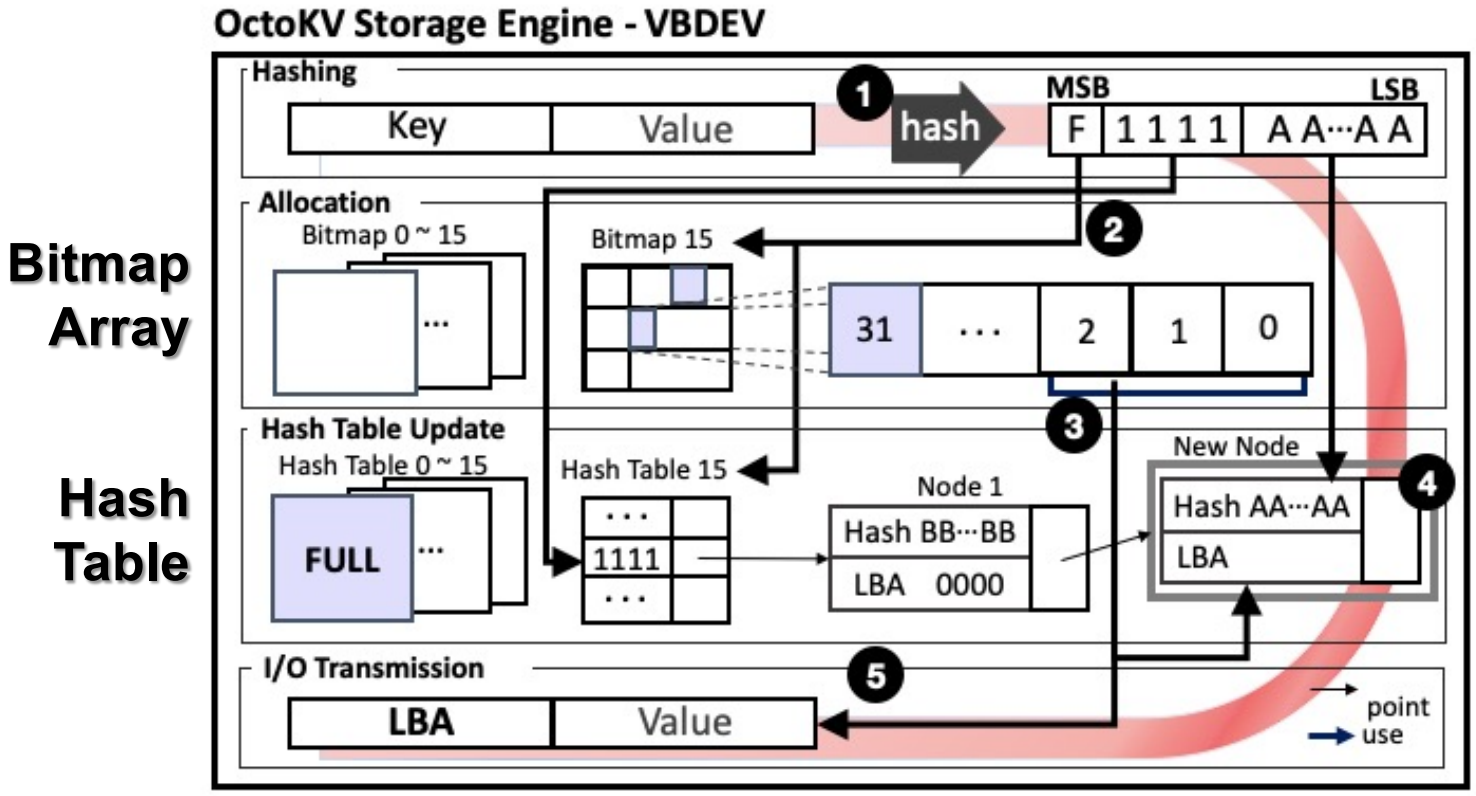


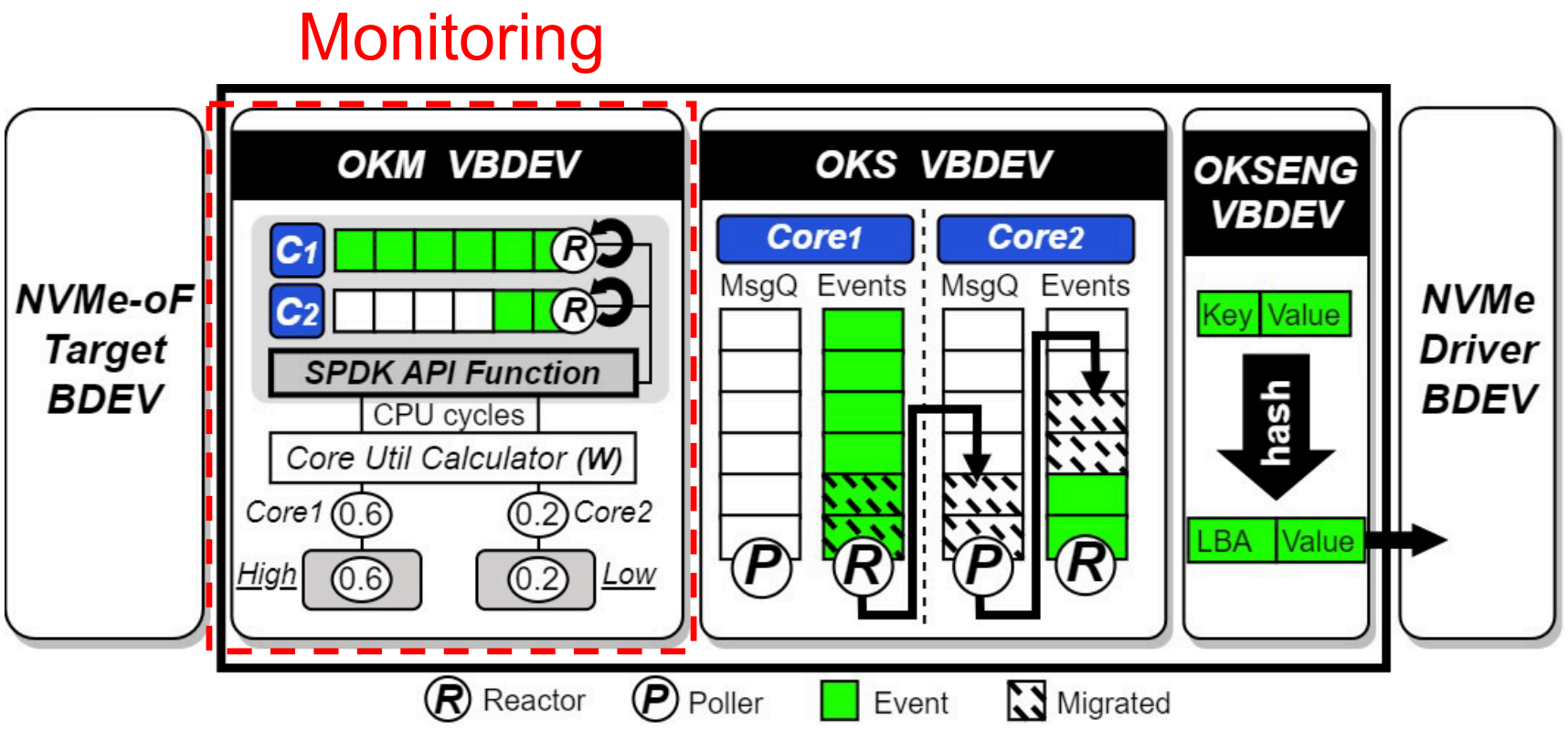
OctoKV: Design and Implementation



Module#1: Storage Engine

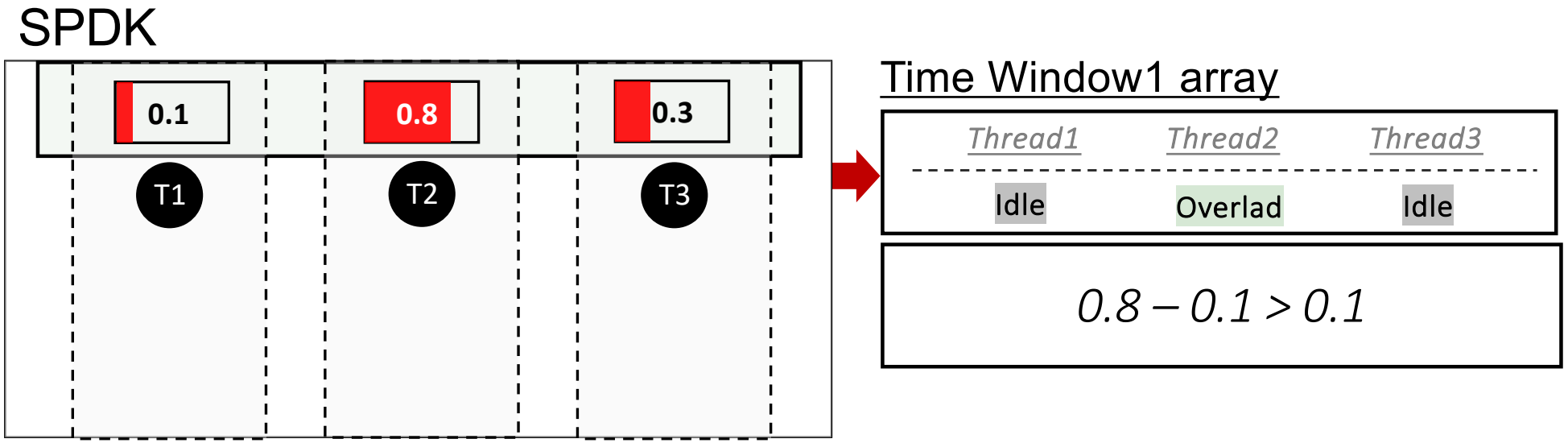


Module#2: Monitoring



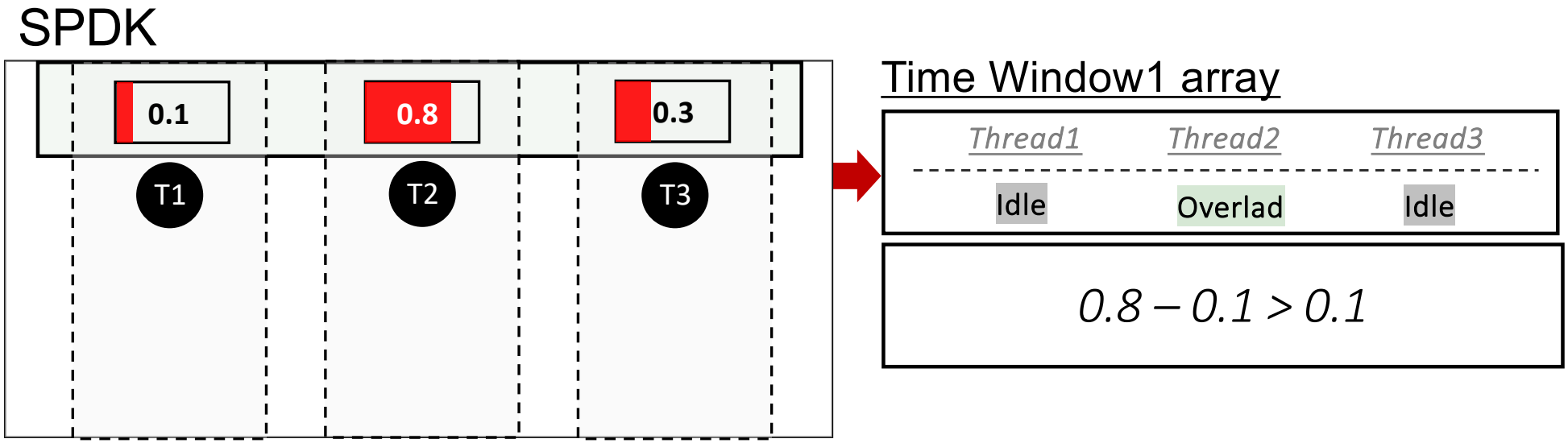
Module#2: Monitoring

- Monitors the utilization of each core



Module#2: Monitoring

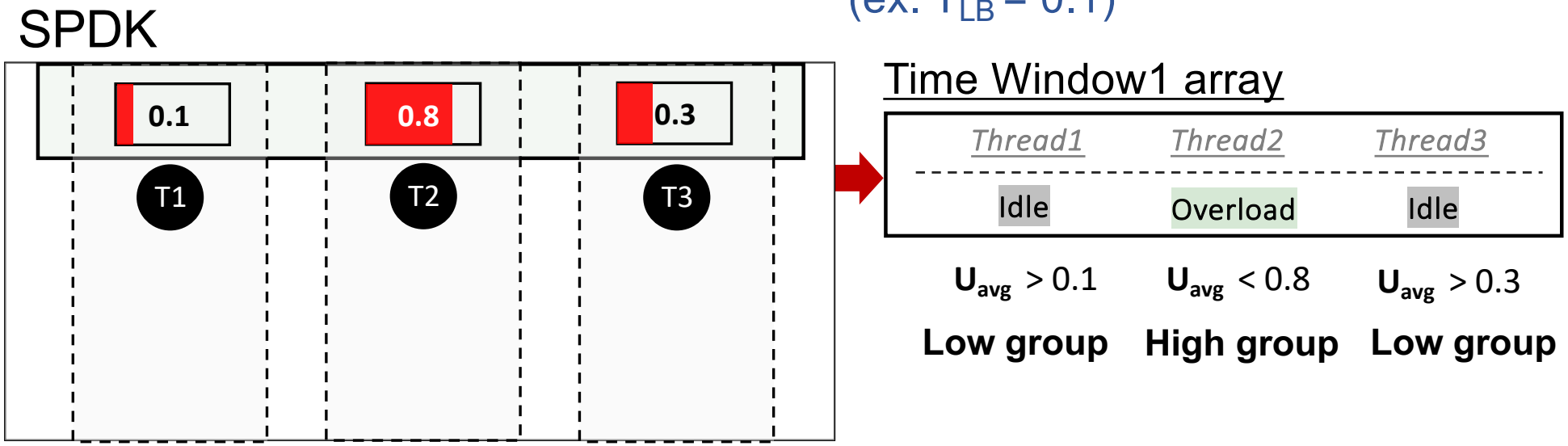
- Monitors the utilization of each core
  Condition#1: Core Overloading $F_{cutil}(C) > T_{OL}(T_{OL} = 0.4)$



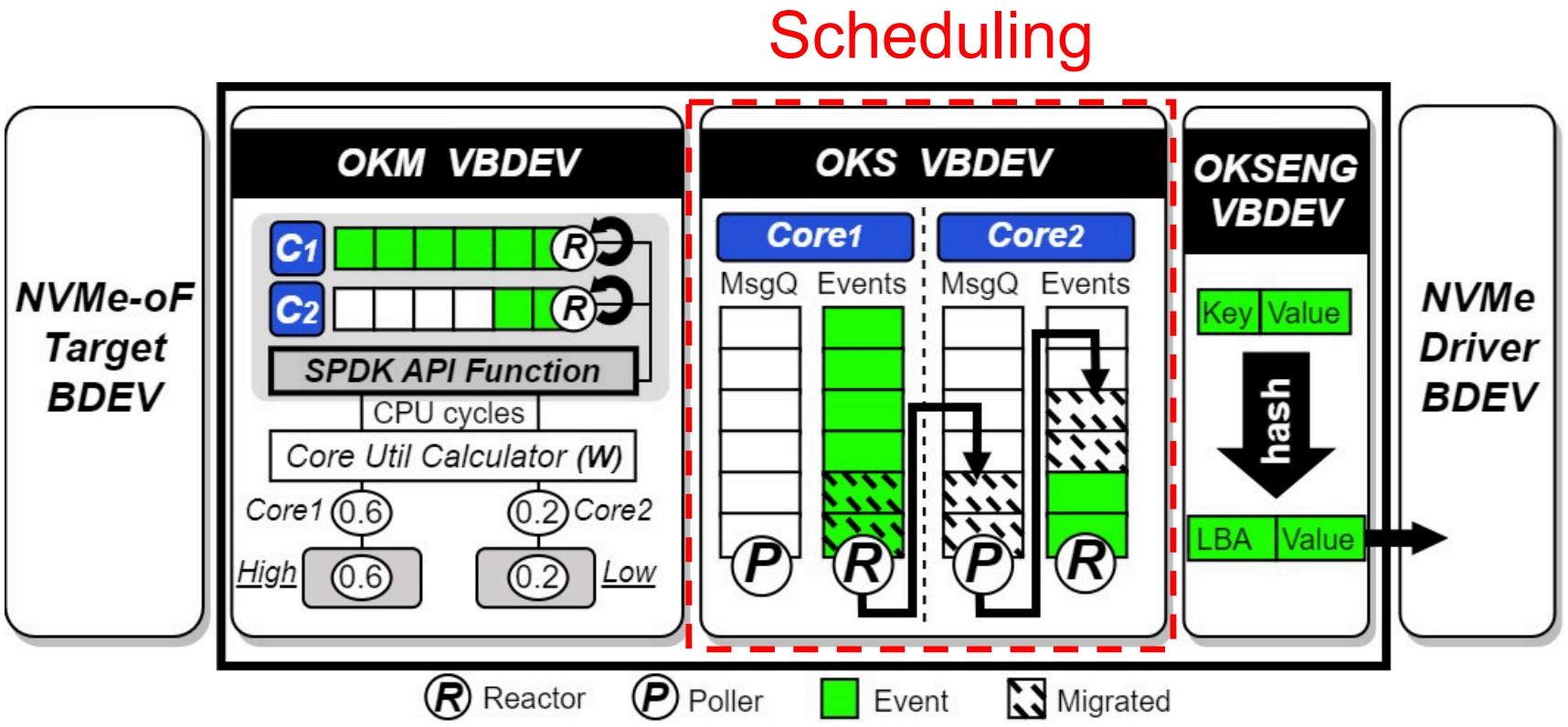
Module#2: Monitoring

- Monitors the utilization of each core
  Condition#1: Core Overloading
  Condition#2: Load Imbalance

$Max\{F_{cutil}(C)\} - Min\{F_{cutil}(C)\} > T_{LB}$
(ex. $T_{LB} = 0.1$)



Module#3: Scheduling



Module#3: Scheduling

- OctoKV Scheduling Module migrates I/O requests from overloaded cores to idle cores
- A single I/O request consists of three stages

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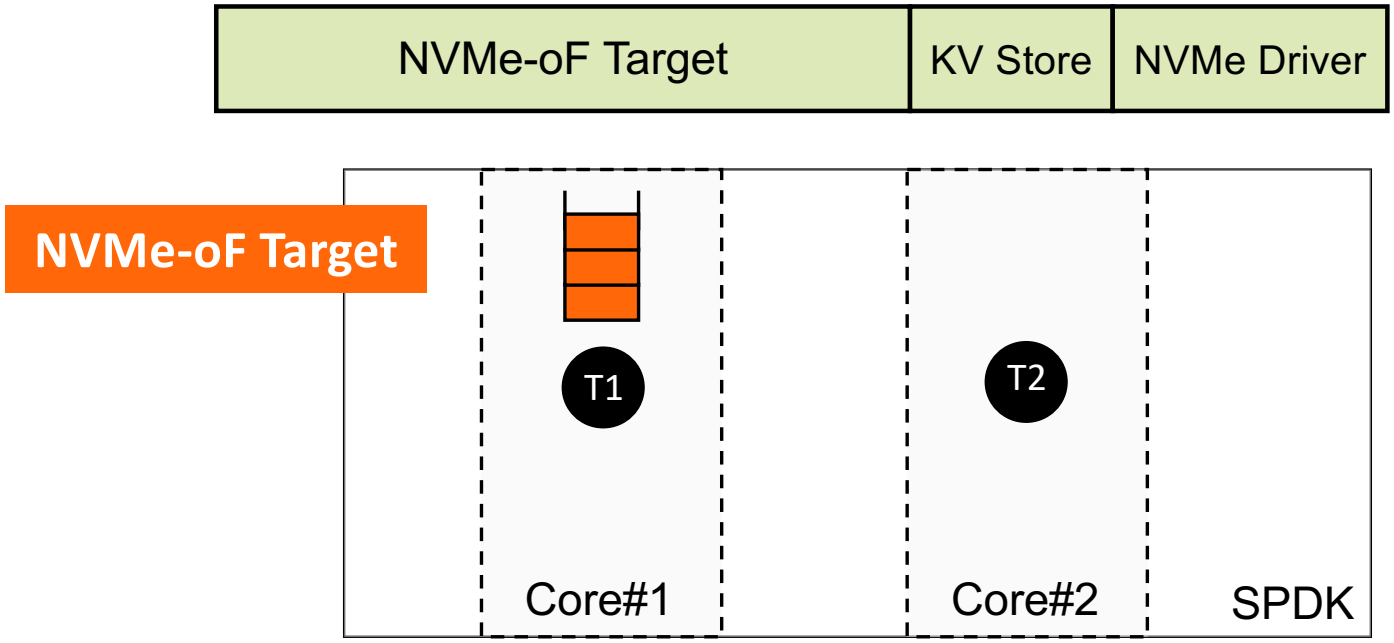
- A single I/O request consists of three stages



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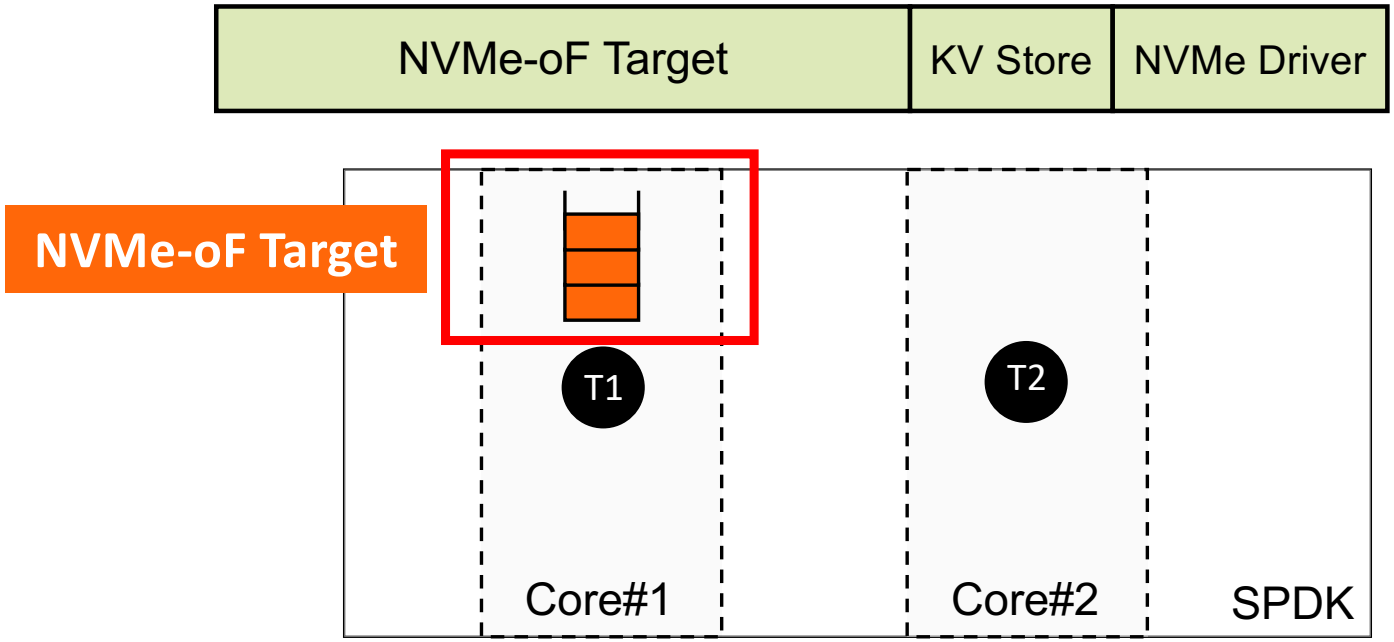

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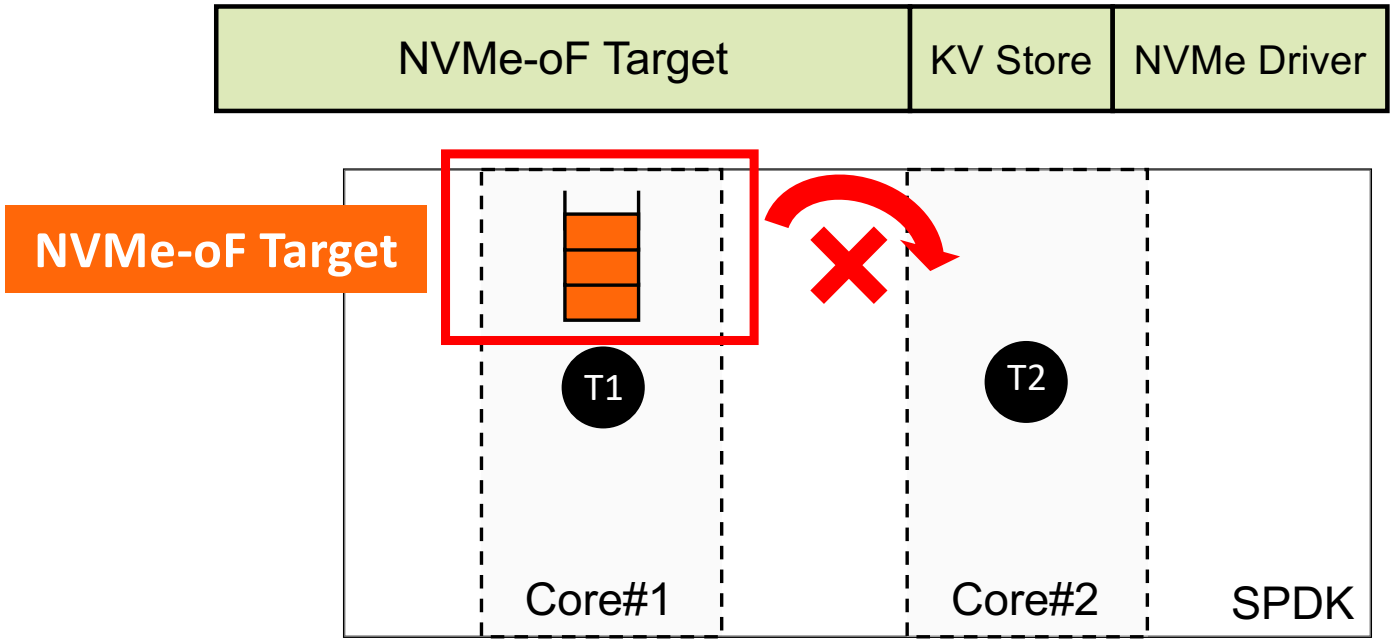

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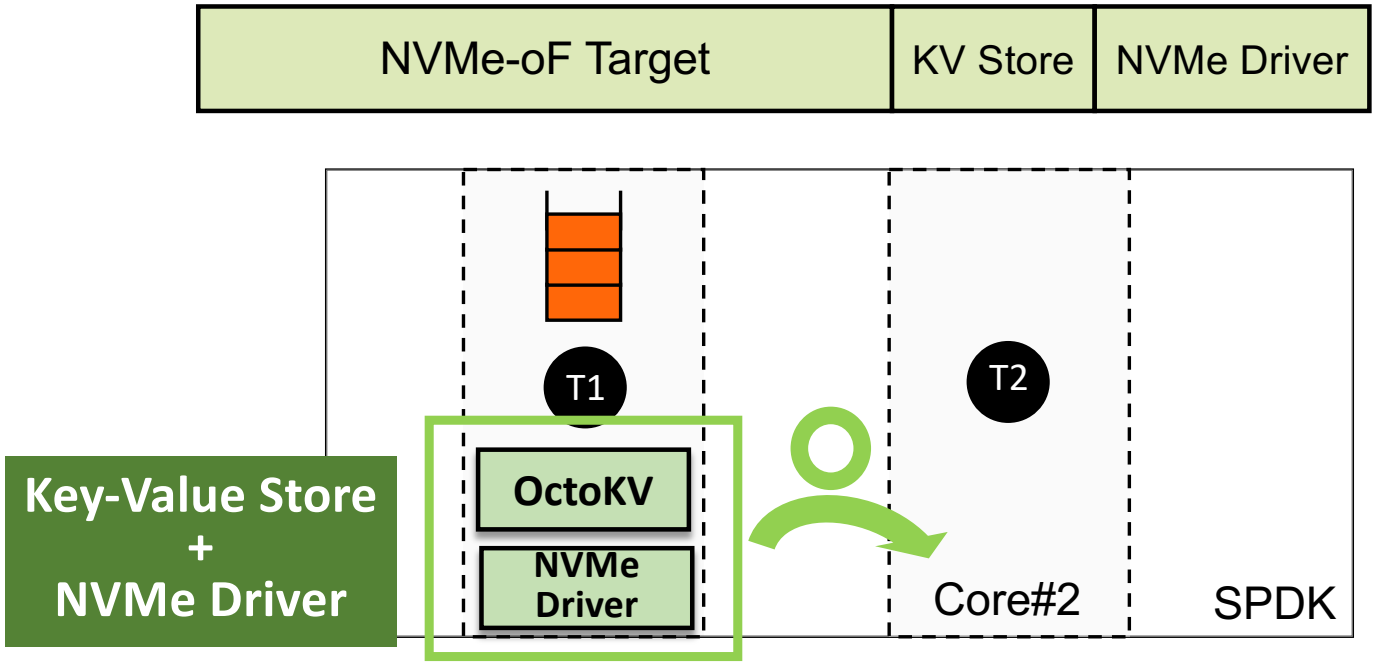

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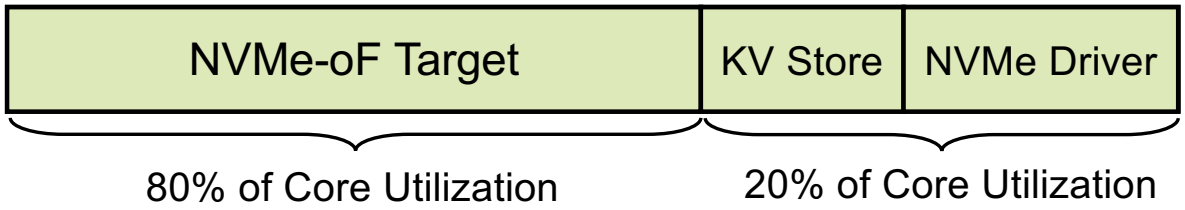


High Group

Thread2 : 0.8

➡ Movable core utilization
20% of 0.8 => 0.16

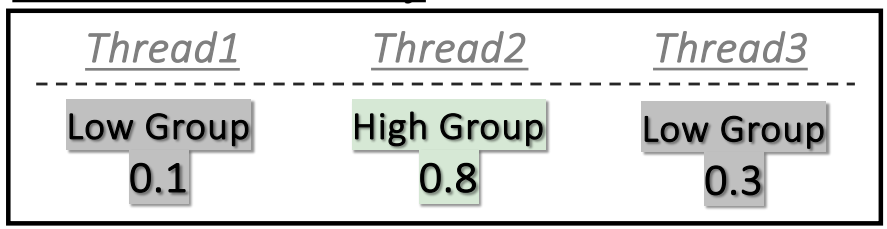
Low Group

Thread1 : 0.1

Thread3 : 0.3

➡ Acceptable core utilization
(U_{avg} – 0.1) + (U_{avg} – 0.3) => 0.4

Time Window1 array



All KV stores and NVMe Driver stages in the high group core can be moved to the low group core for processing.

Module#3: Scheduling

- Two heuristic algorithms determine
  how much I/O to migrate to each core of low group

(Ex) *Thread1: 0.1* *Thread3: 0.3* *U_{avg} : 0.4*

RoundRobin (RR)

Thread1 : Thread3 = 1 : 1

Proportional Share (PS)

Thread1 : U_{avg} - 0.1 = 0.3
Thread1 : U_{avg} - 0.3 = 0.1

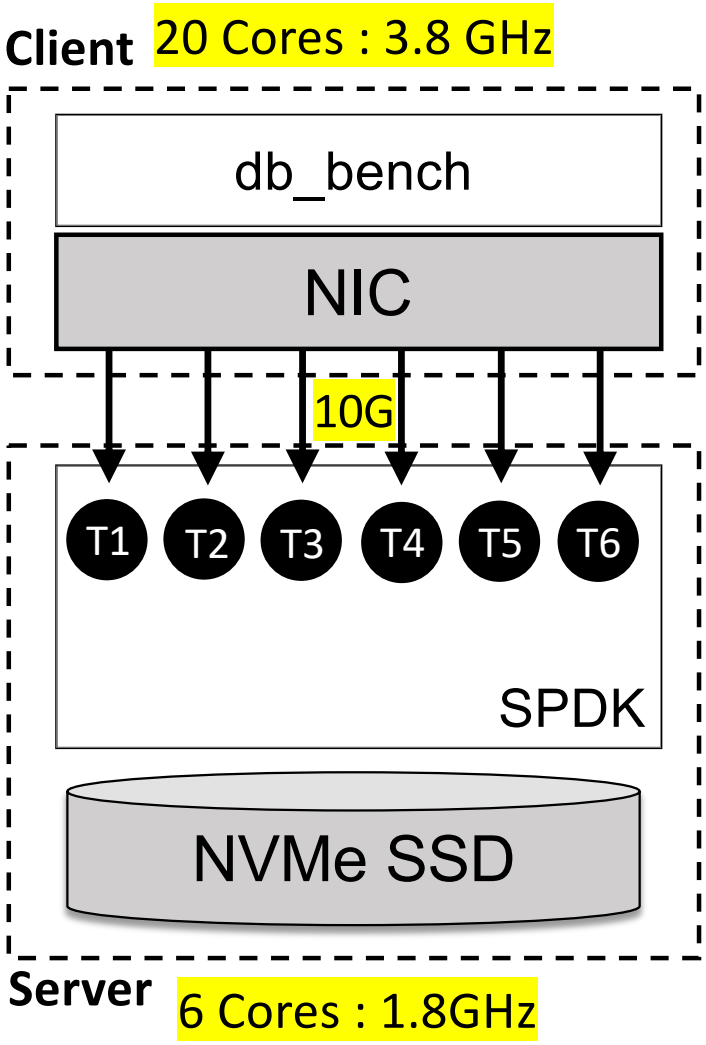
Thread1 : Thread3 = 3 : 1

Content

- Background
- Problem Definition
- Motivational Experiments
- OctoKV: Design and Implementation
- Evaluation
- Conclusion

Experimental Setup

- Client
  - § Running a db_bench benchmark
    - 1) Light workload
      - *7 I/O threads issue Put/Get I/Os*
    - 2) Medium workload
      - *10 I/O threads issue Put/Get I/Os*
    - 3) Heavy workload
      - *12 I/O threads issue Put/Get I/Os*
  - § I/O request size = 16KB
- Server
  - § 6-core device
  - § Running a Linux OS using Intel SPDK



Comparison

(1) **Host KVS**

→ A hash-based key-value storage engine running on the client, layered atop the kernel and file systems

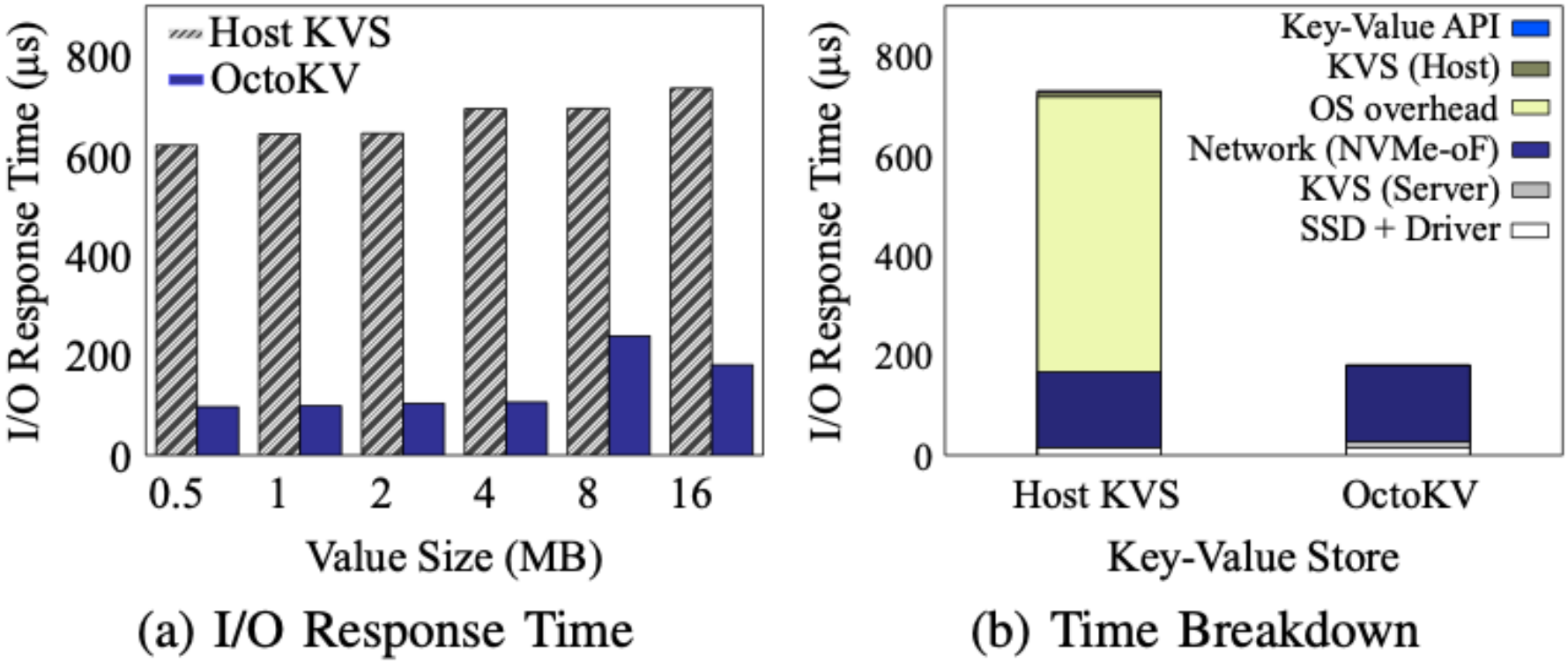
(2) **OctoKV**

→ The proposed system with only the key-value storage engine running on the server

(3) **OctoKV-LB**

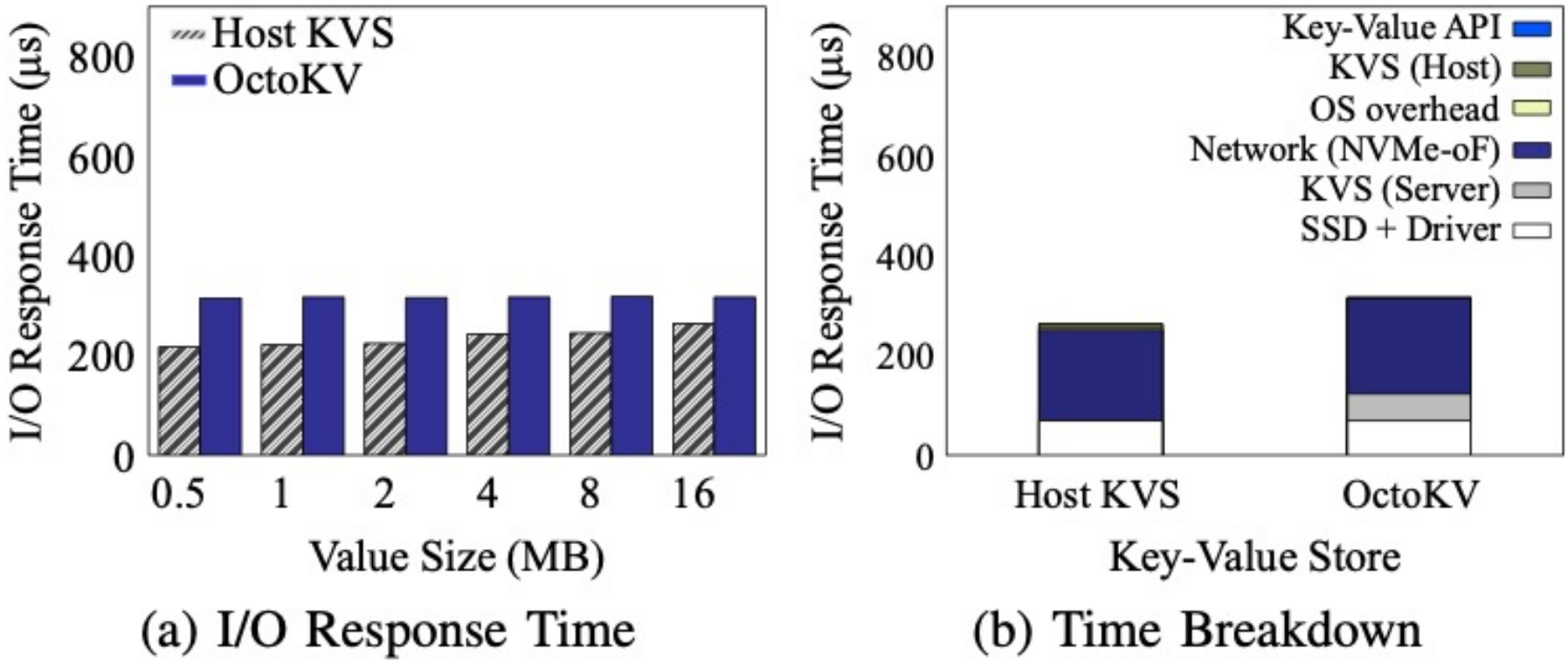
→ OctoKV with the load-aware balanced I/O scheduling

Evaluation – Put Workload



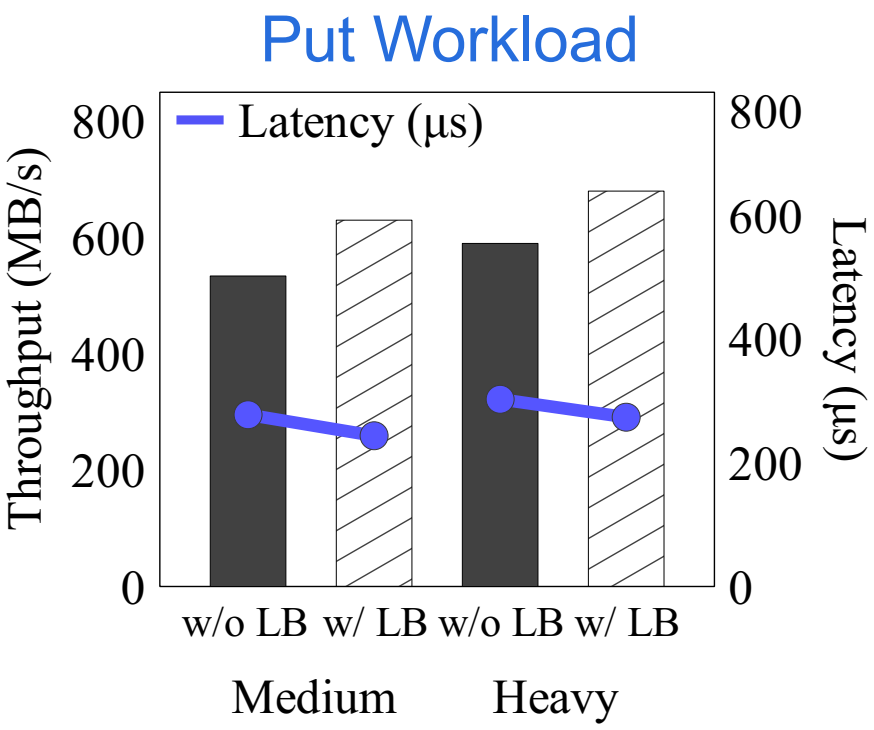
The fsync() overhead of the DB file is quite large.

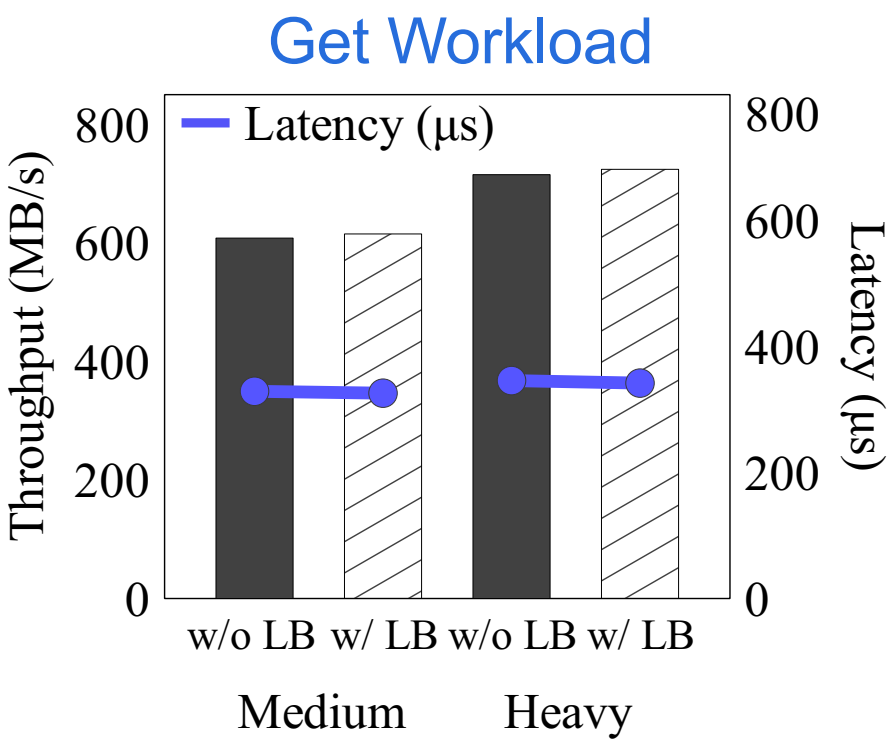
Evaluation – Get Workload



Storage servers have low CPU performance and are slow to run key-value stores.

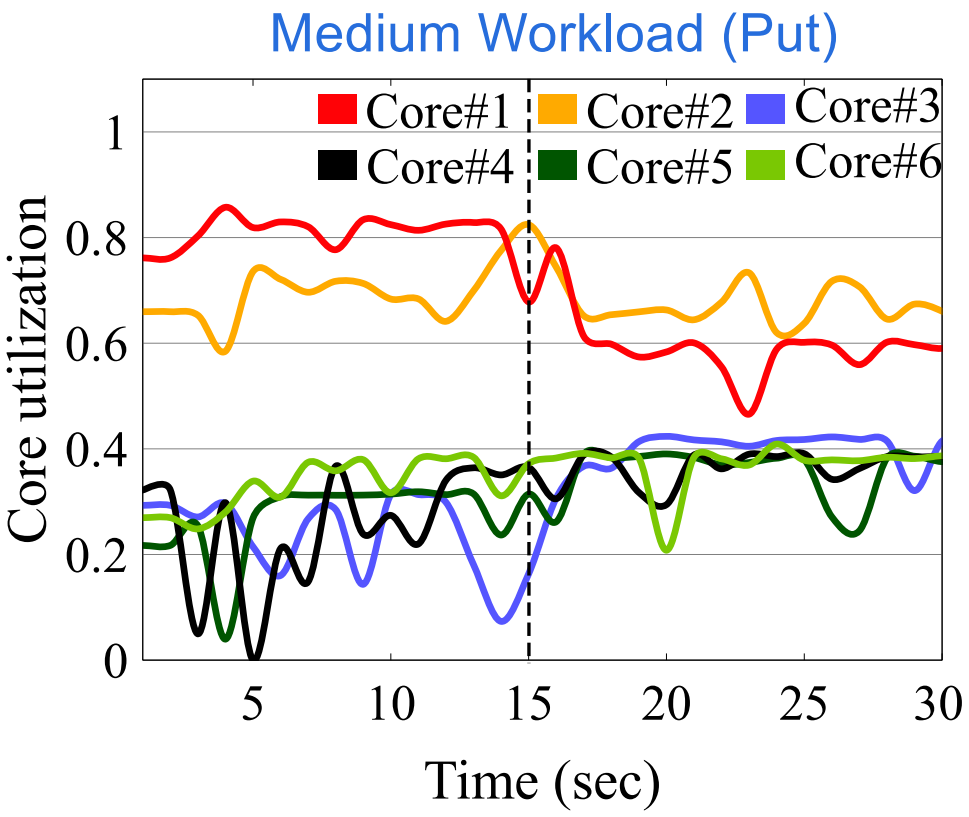
Evaluation – Load Balancing

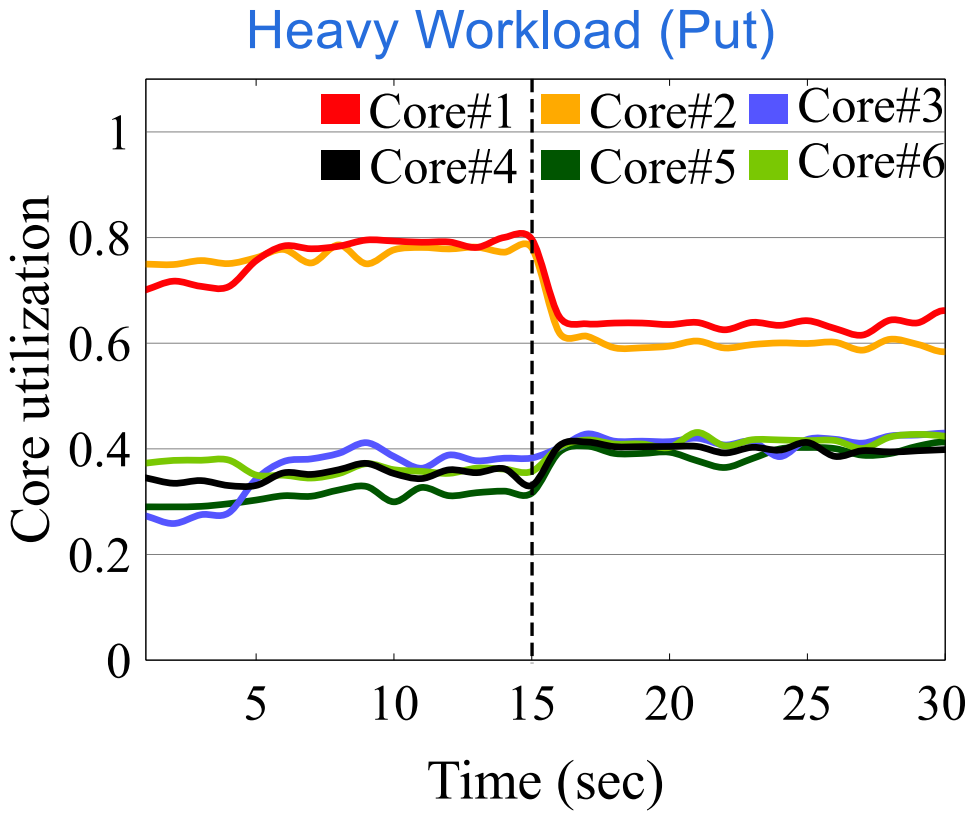




The performance gain was significant in the Put workload.

Evaluation – Load Balancing





Conclusion

- Proposed an **OctoKV, An Agile Network-Based Key-Value Storage System with Robust Load Orchestration**

  - OctoKV is a server-side key-value store that leverages the SPDK capabilities for high-performance in disaggregated storage

  - OctoKV has proposed a powerful load-aware balanced I/O scheduling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