USENIX ATC '22

Pacman: An Efficient Compaction Approach for Log-Structured Key-Value Store on Persistent Memory

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Tsinghua University

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Persistent Memory (PM)

PM brings opportunities and challenges to storage systems !

Benefits

- ❖ Persistent storage
- ❖ Byte-addressability

The figure of Optane DIMM is from https://www.intel.com/content/www/us/en/architecture-and-technology/optane-dc-persistent-memory.html

Persistent Memory (PM)

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Benefits

- ❖ Persistent storage
- ❖ Byte-addressability

Idiosyncrasies (compare with DRAM)

- ❖ High access latency (~300 ns)
- ❖ Limited write bandwidth (2.2 GB/s)
- ❖ Access granularity (256 bytes)

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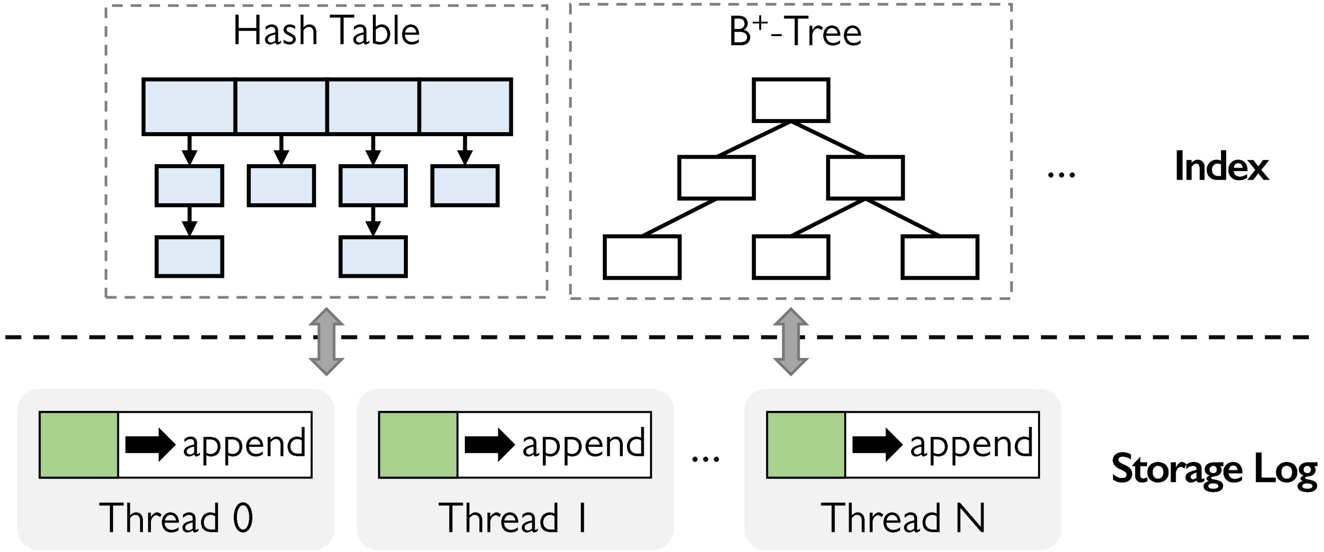
Log-structured KV Systems

Advantages

- ❖ Fast allocation
- ❖ High capacity utilization
- ❖ Small write amplification
- ❖ Easy failure recovery



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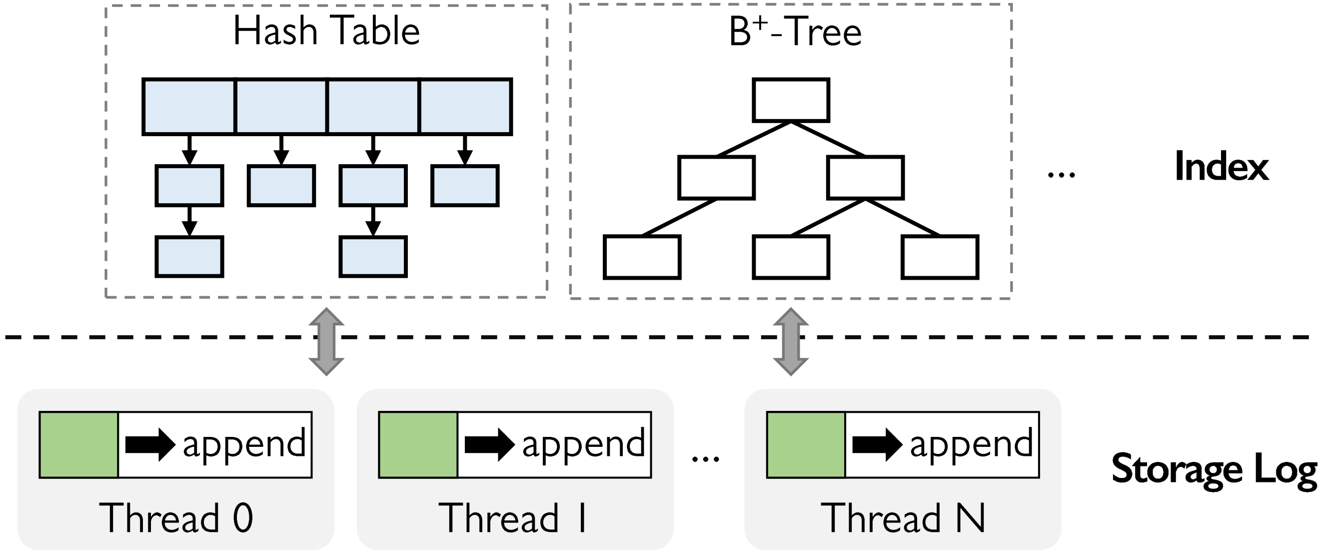

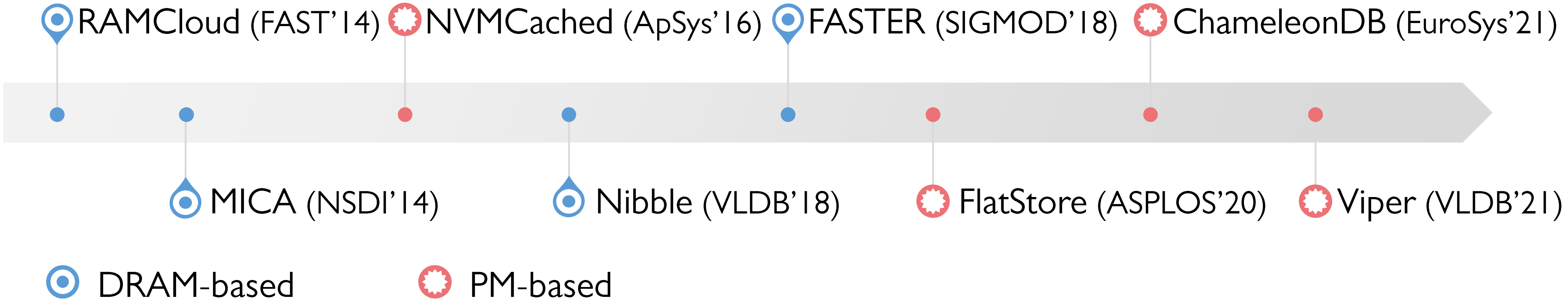

Garbage Collection Overheads (1)

- **Garbage collection has huge overhead at high capacity utilizations**
  - RAMCloud (FAST'14) drops by 20-50%
  - Nibble (VLDB'18) drops by up to 75%

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  - RAMCloud (FAST'14) drops by 20-50%
  - Nibble (VLDB'18) drops by up to 75%
- **Capacity utilization is important**
  - Google: keep disks full and busy to minimize storage TCO (PDSW-DISCS'17)
  - Facebook: space utilization was far more important than write amplification (FAST'21)

Garbage Collection Overheads (2)

PM’s idiosyncrasies exacerbate the bottleneck of compaction.

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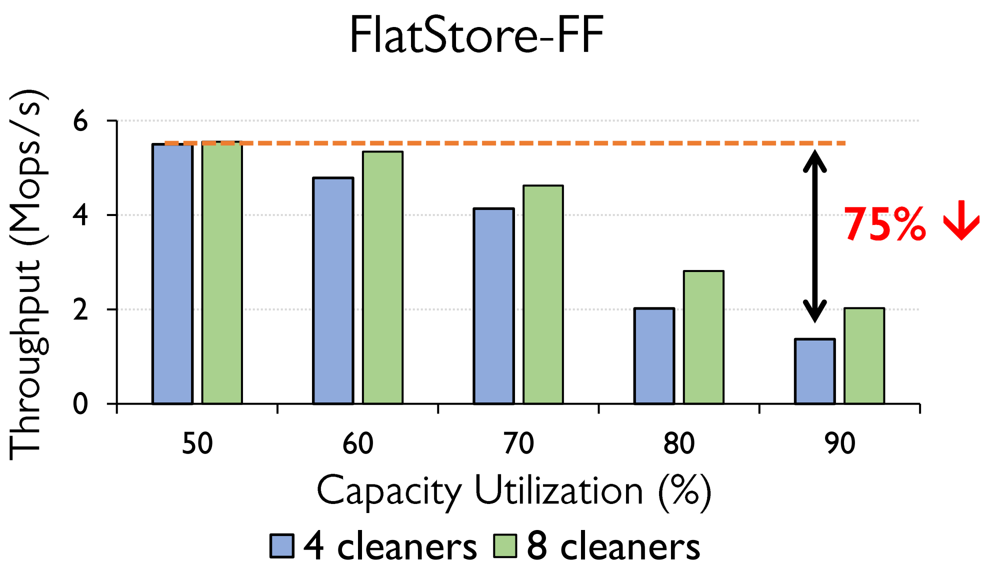
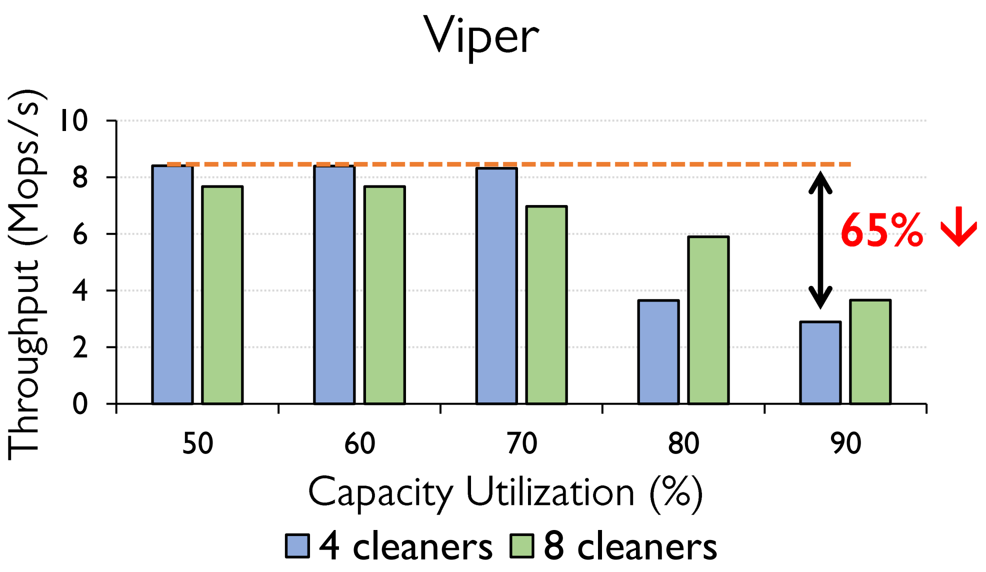
PM's idiosyncrasies exacerbate the bottleneck of compaction.

Experiments on FlatStore (ASPLOS'20) & Viper (VLDB'21)

YCSB-A (50% Get, 50% Put) , 12 service threads, 4/8 cleaners





Motivation

Existing compaction approaches are unaware of PM's characteristics.

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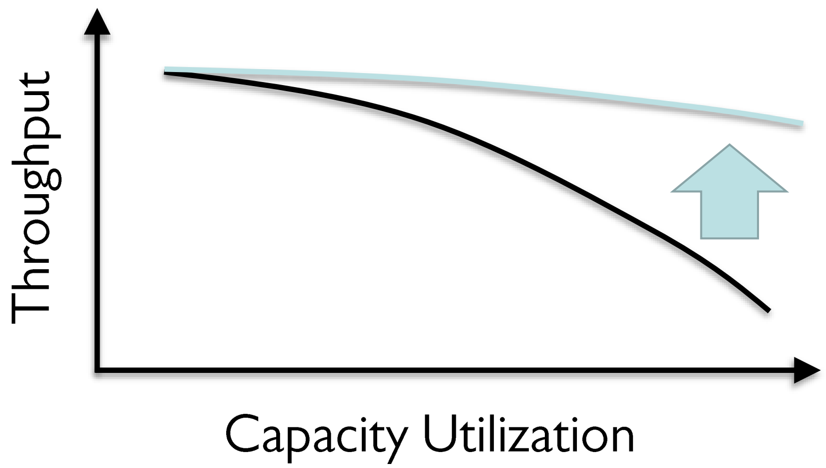


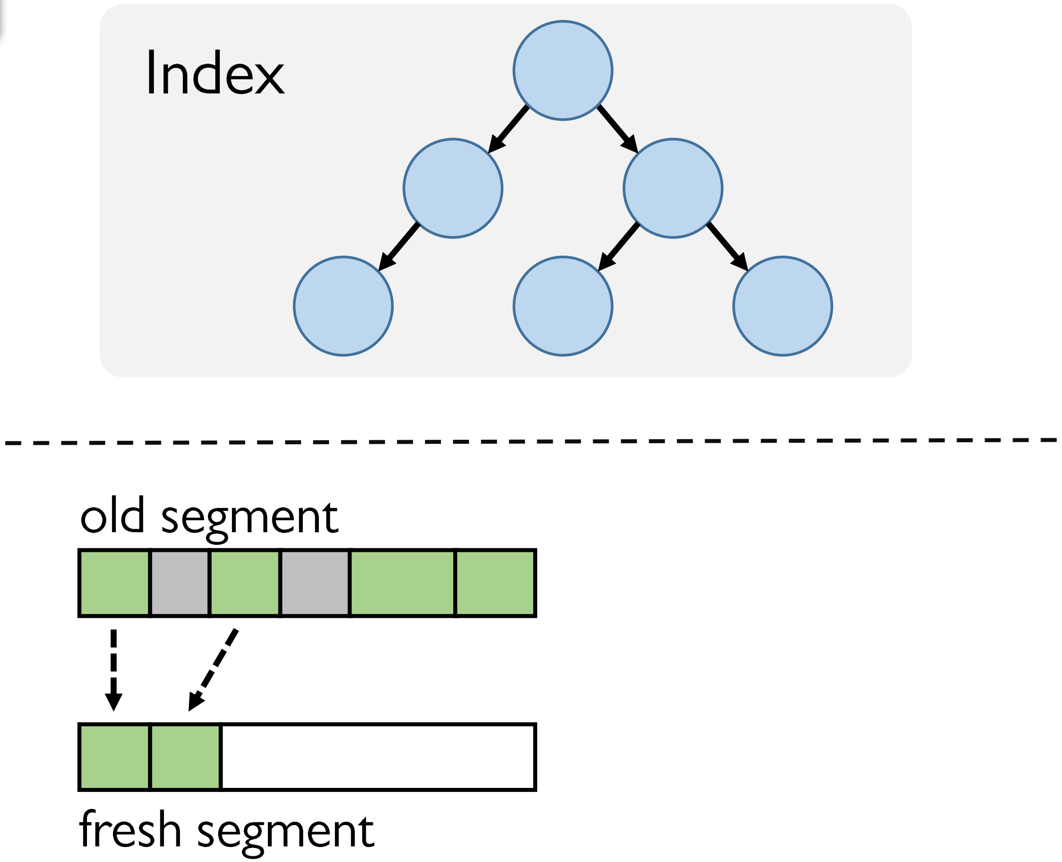
Our goal: Improving the compaction efficiency and log-structured KV store's performance at high capacity utilizations

Outline

- ❖ Background & Motivation
- ❖ Pacman – A PM-aware Compaction Approach for Log-structured KVS
- ❖ Results
- ❖ Conclusion

Problem (1) - High-latency Index Traversal

Background Compaction



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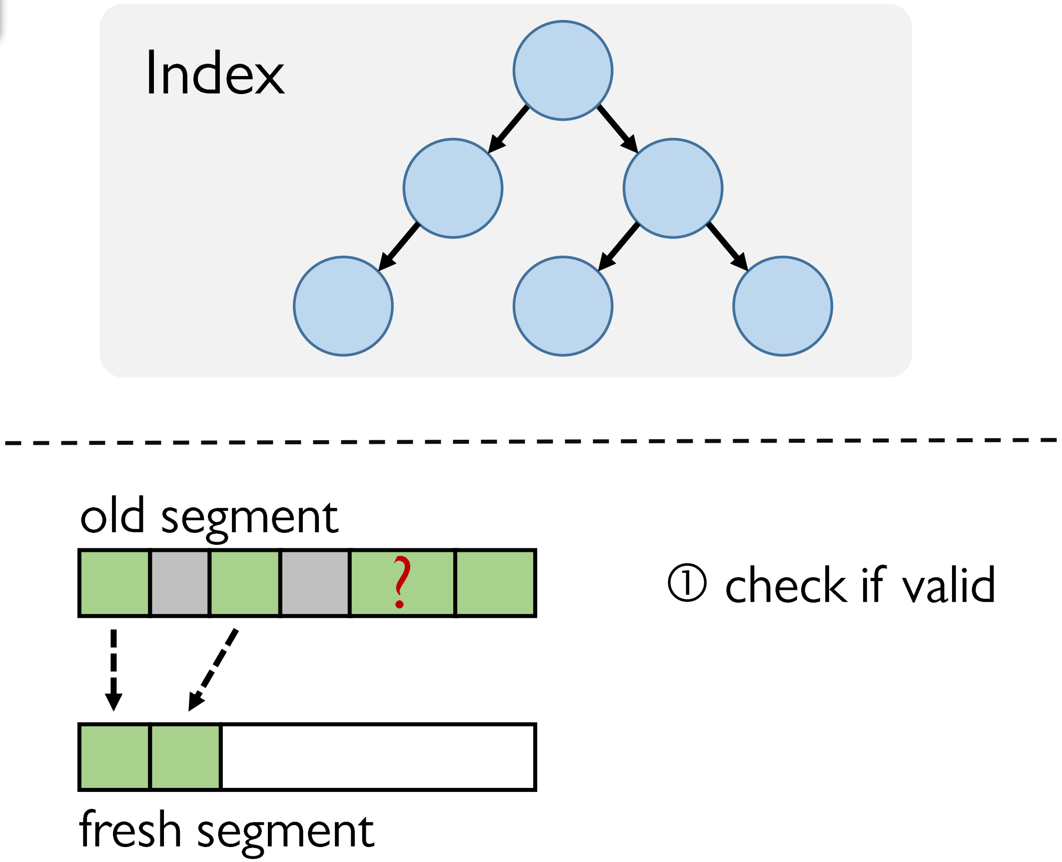

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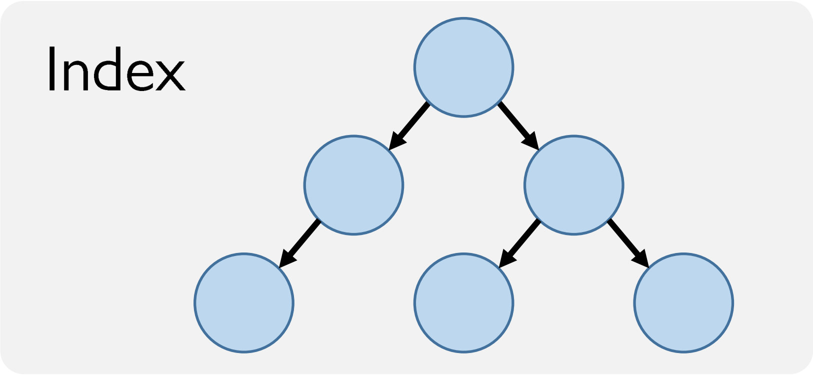

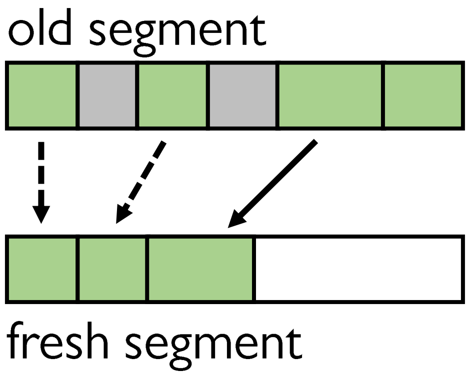

① check if valid

② copy valid object

Problem (1) - High-latency Index Traversal

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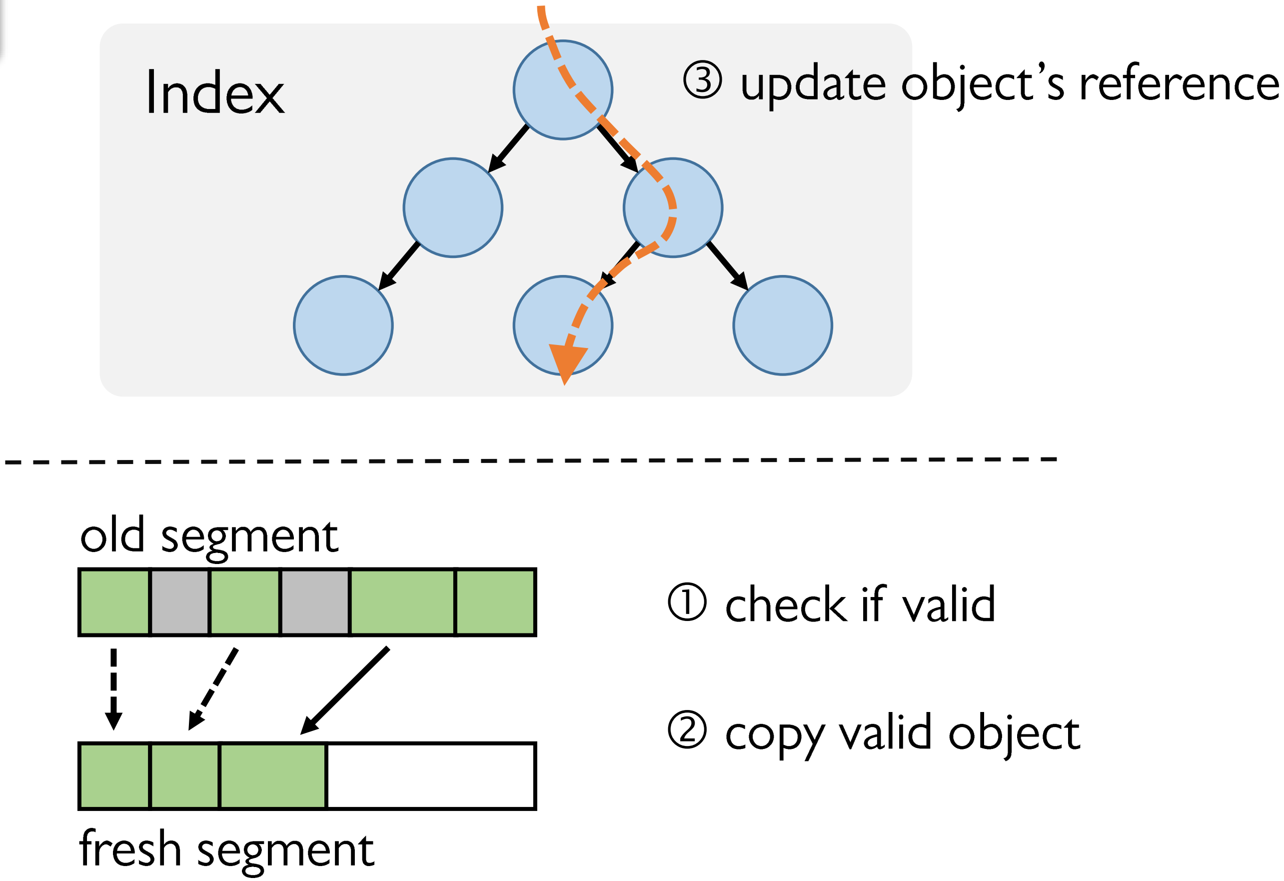

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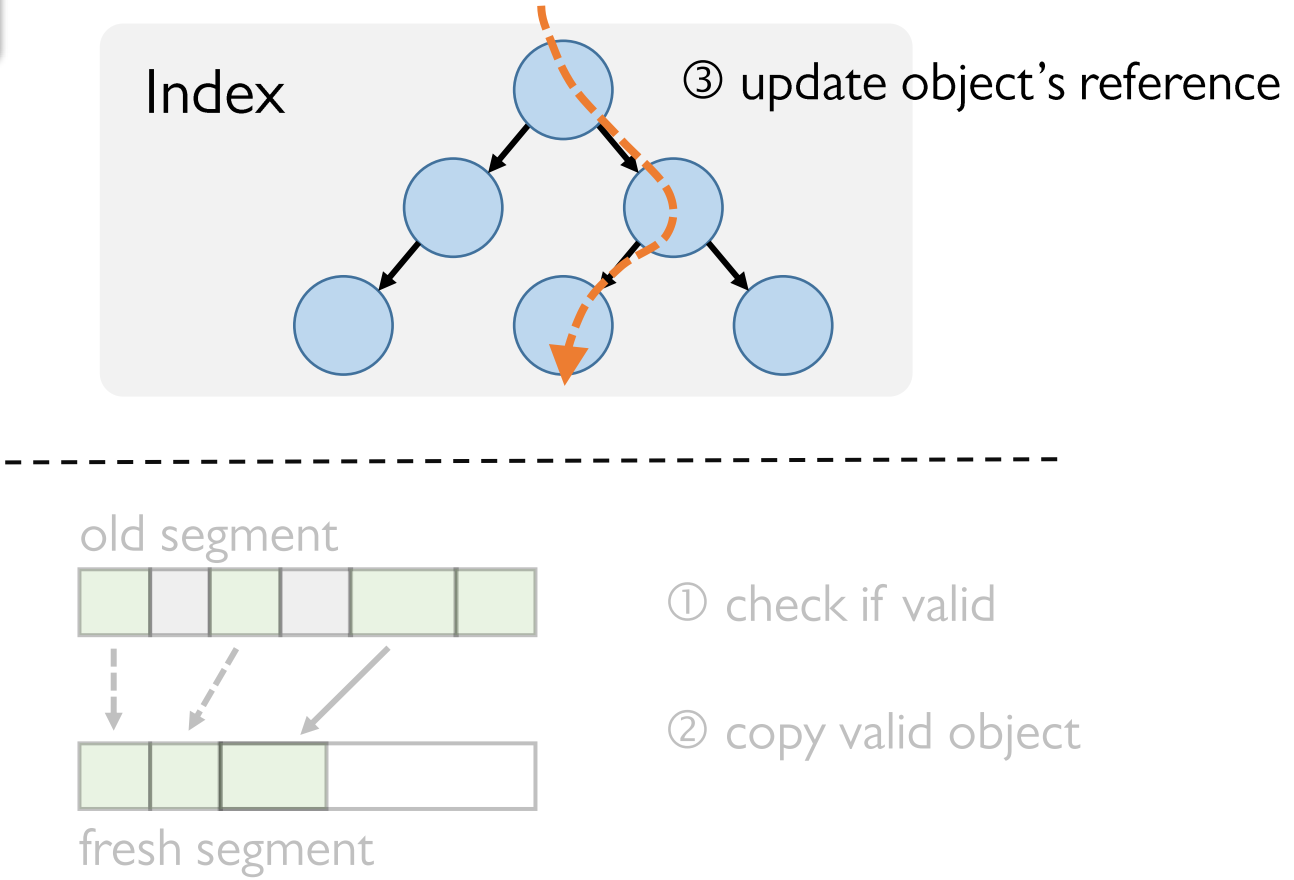
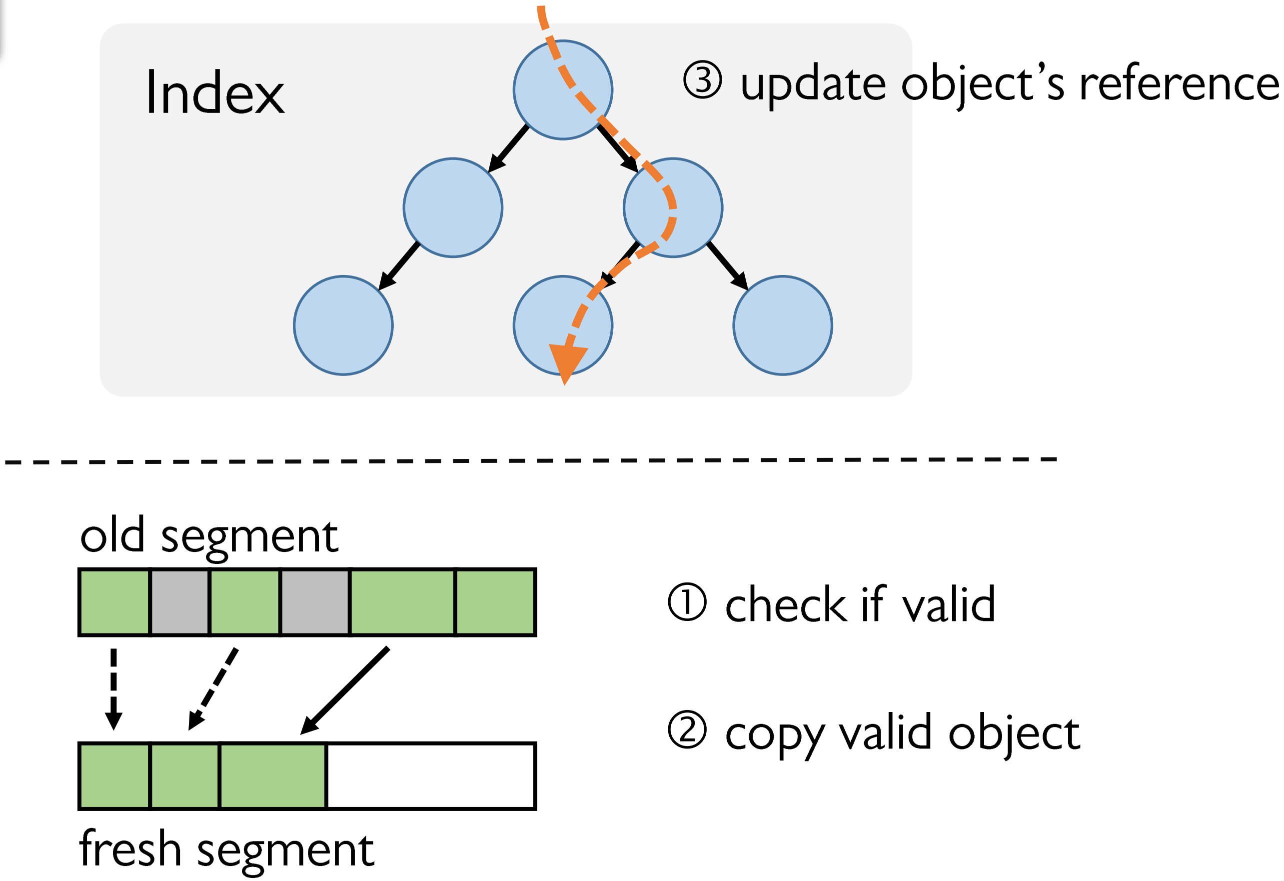


Problem 1: Traversing the index ↔ high access latency

Problem (2) – Extra persistence work

Background Compaction



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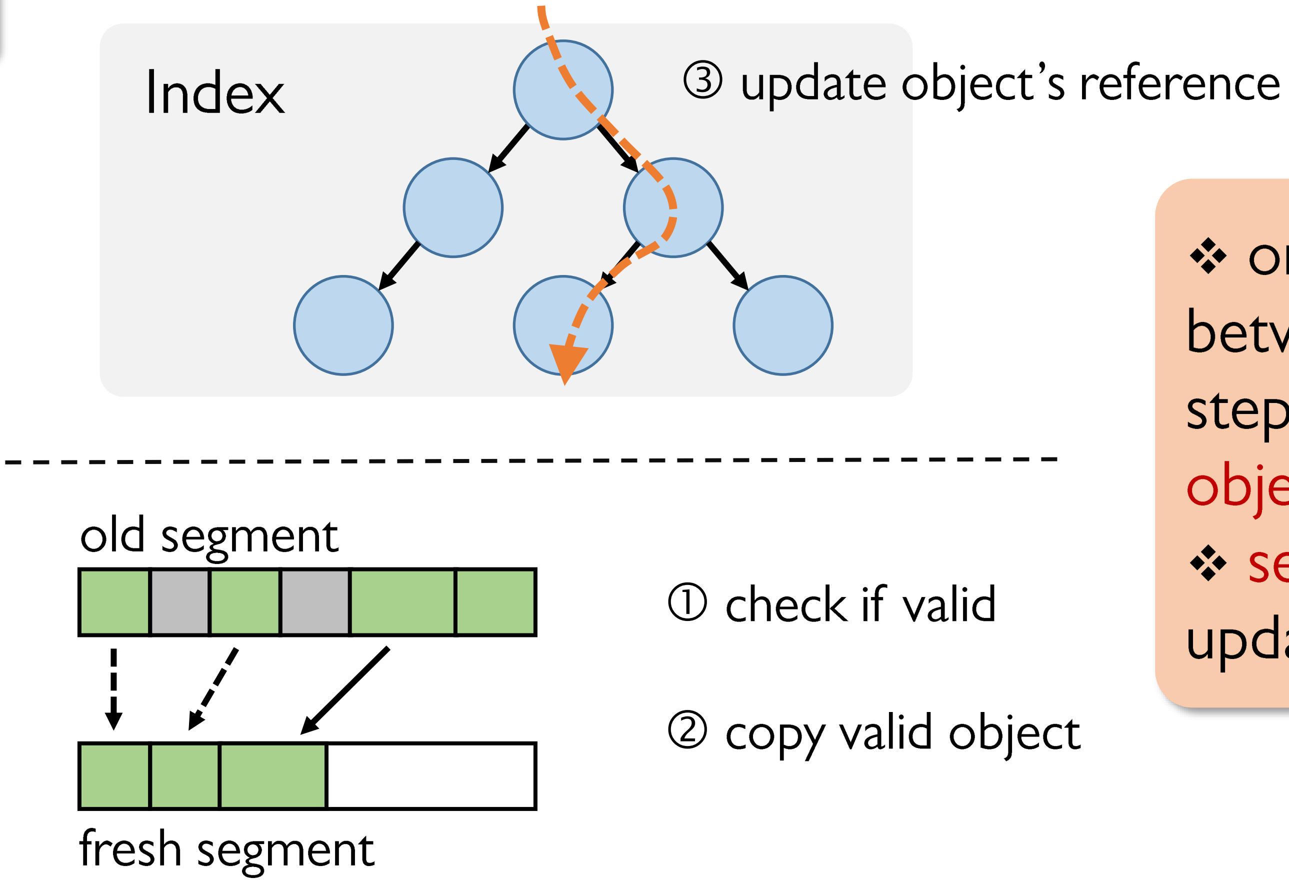

❖ one flush and fence between step ② and step ③ for each valid object

❖ serial flush on each updated reference

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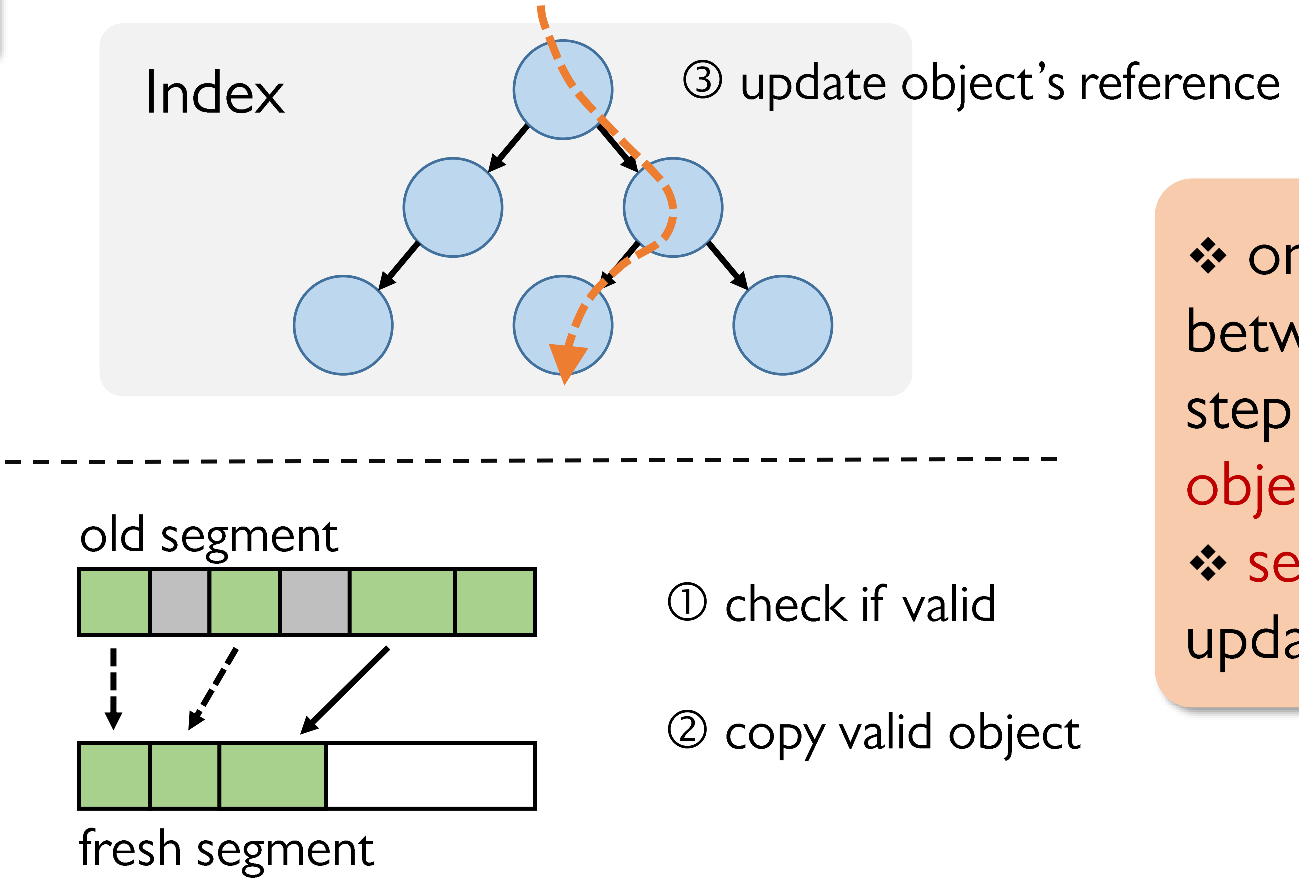
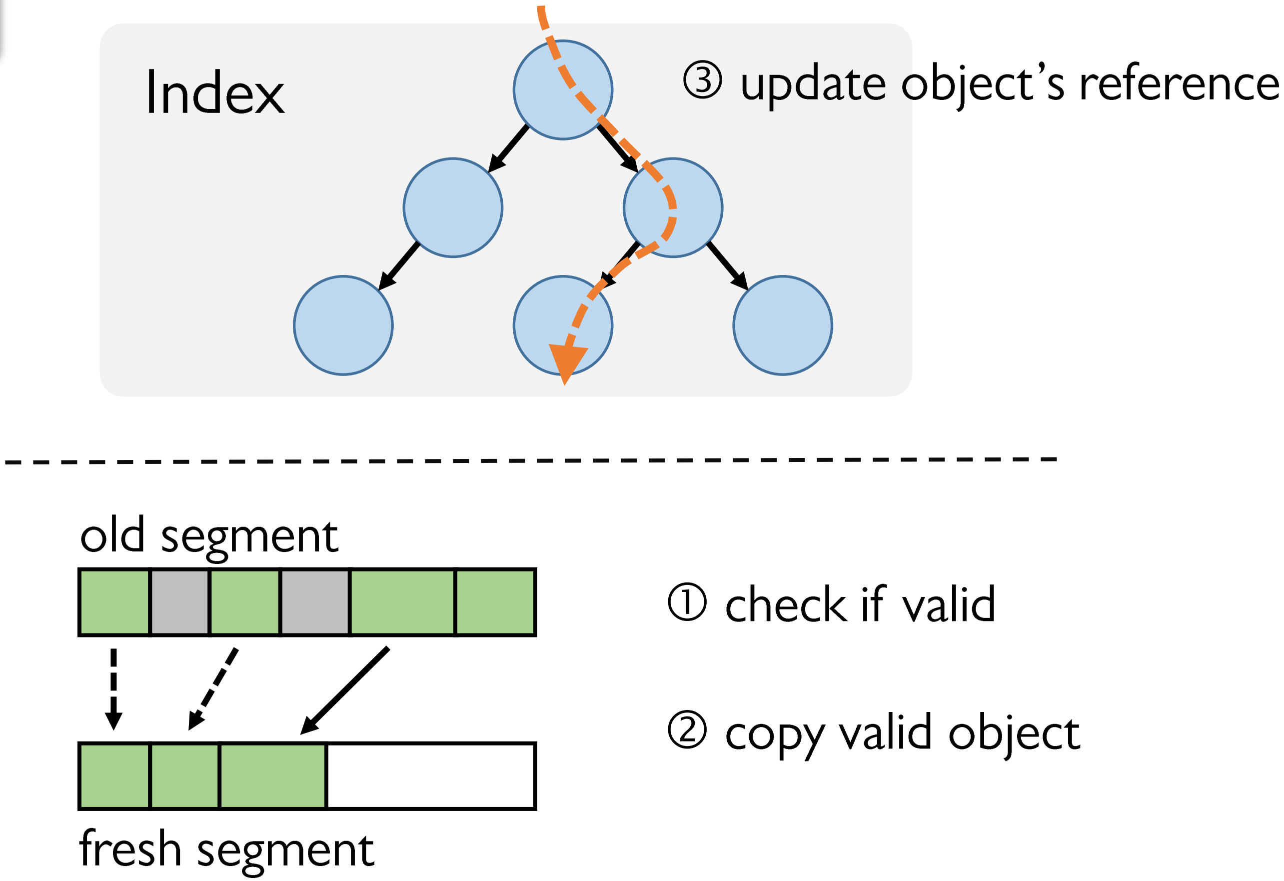


❖ one flush and fence between step ② and step ③ for each valid object
❖ serial flush on each updated reference

Problem 2: Extra persistence work ↔ expensive flush/fence instructions

Problem (3) – A large amount of data copying

Background Compaction



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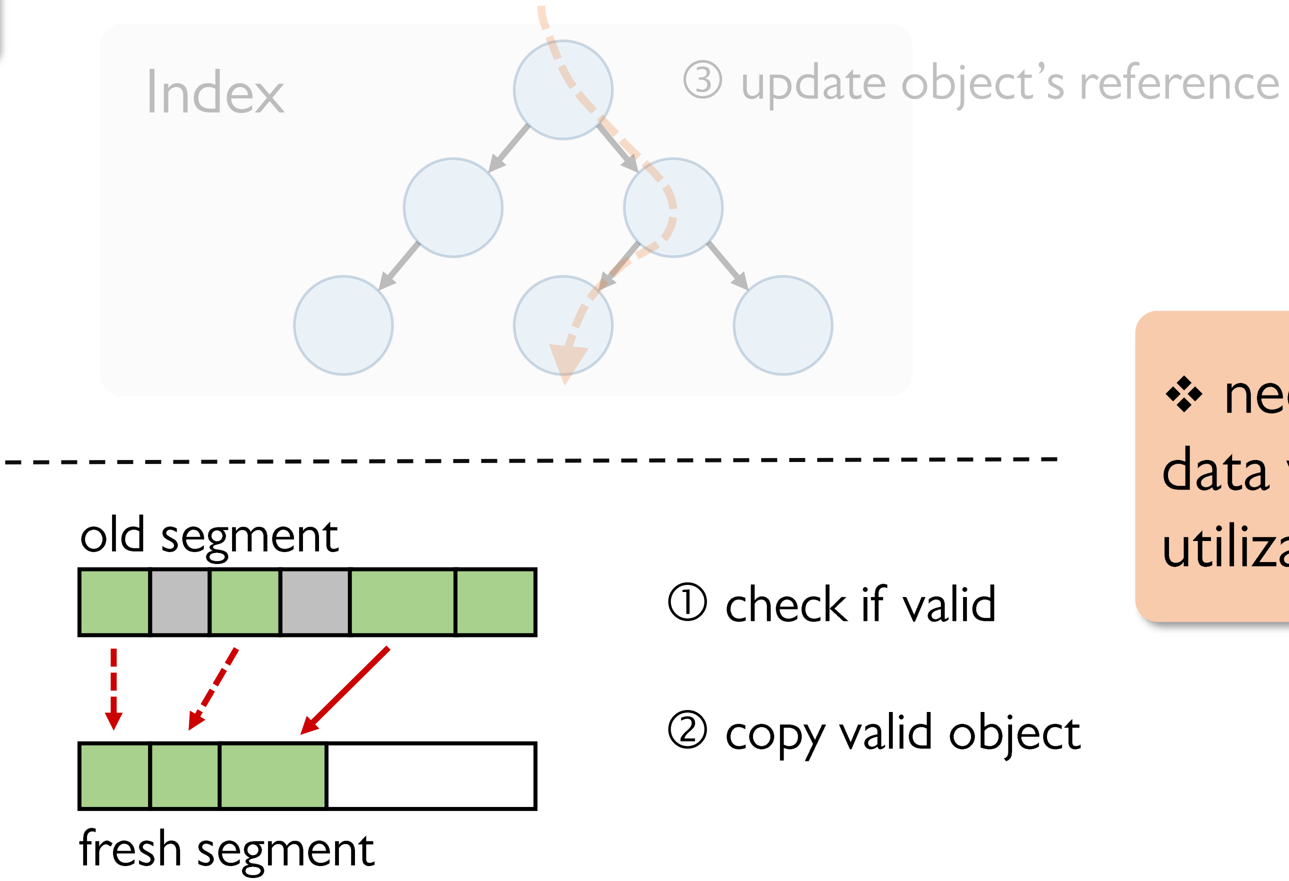

❖ need to copy more data when the capacity utilization is high

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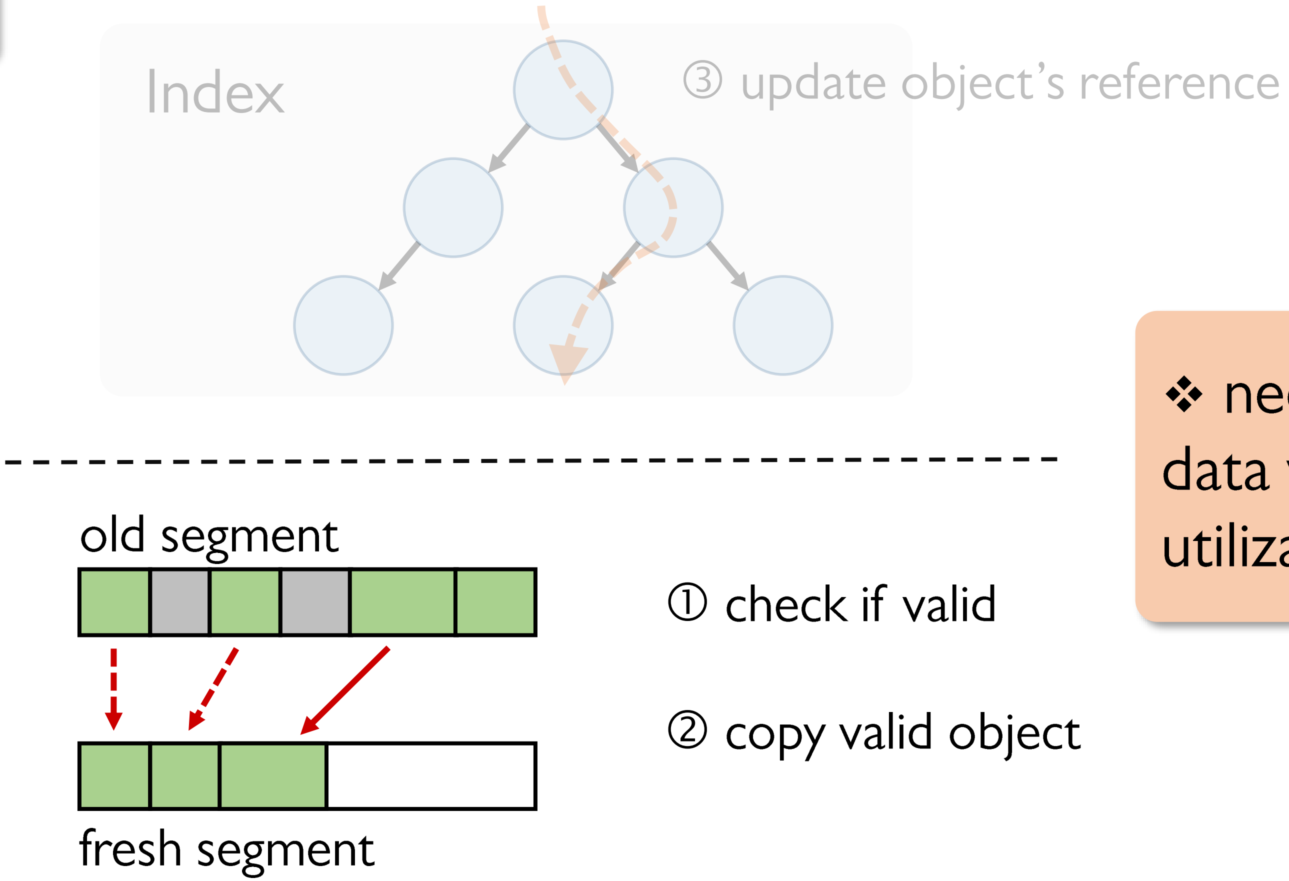
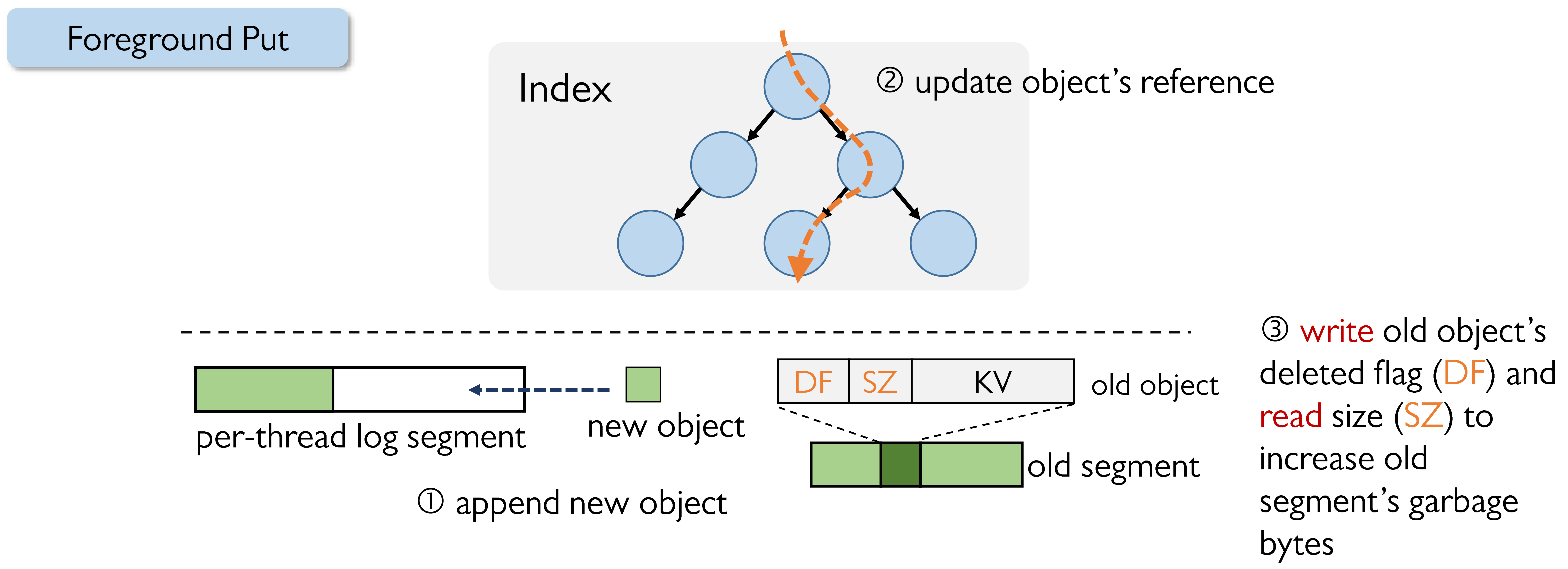


❖ need to copy more data when the capacity utilization is high

Problem 3: A large amount of data copying on PM ↔ limited write bandwidth

Problem (4) – Excessive small random accesses



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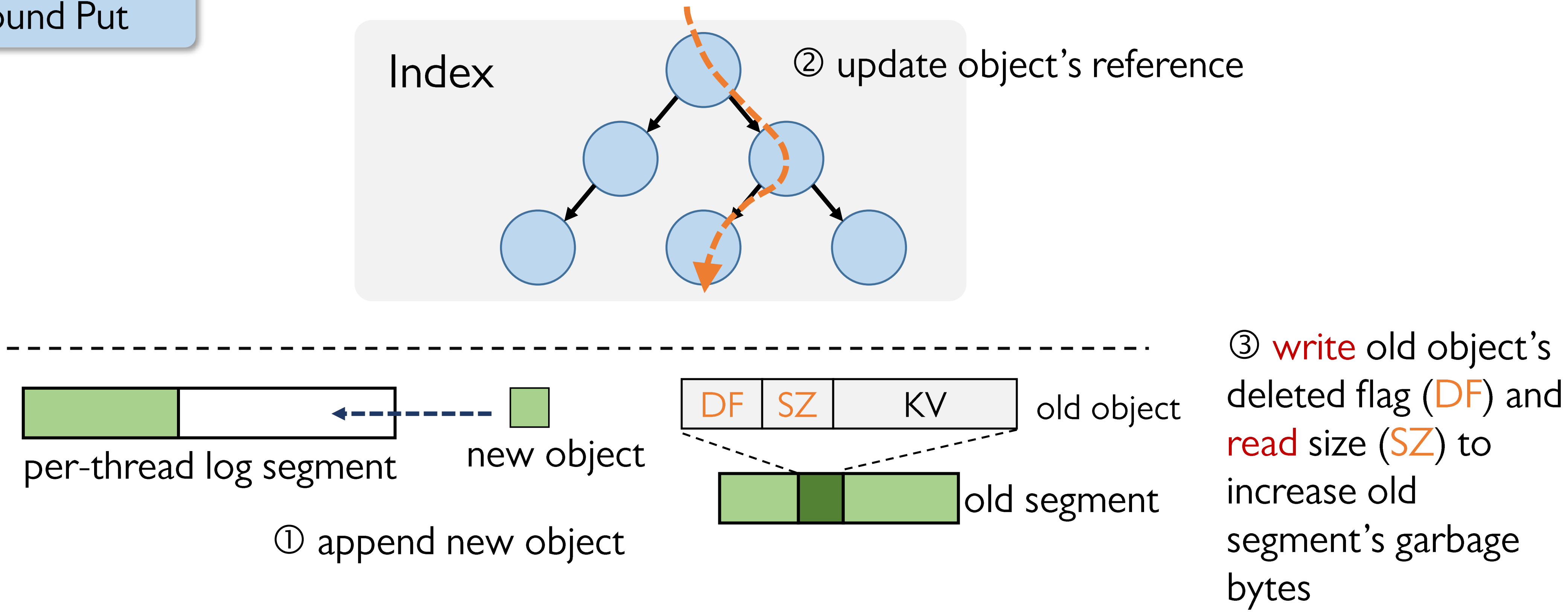
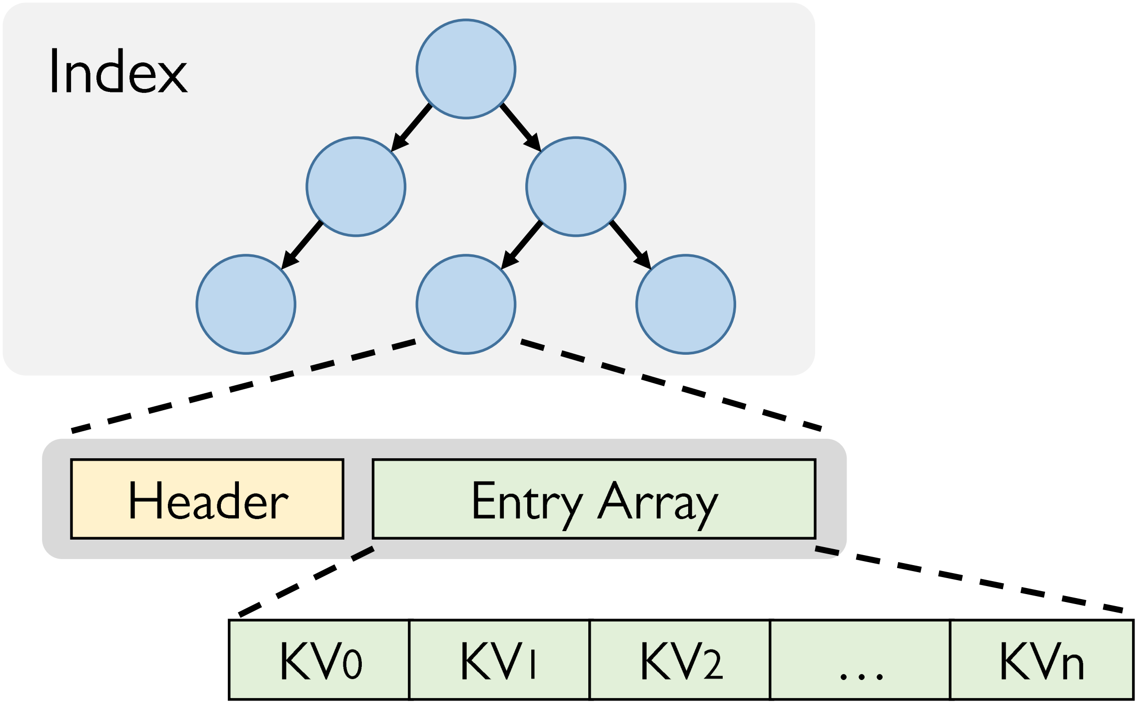


Problem 4: Excessive small random accesses on PM ↔ high access latency & write amplification

Design (1) - Traverse Index with Shortcut

Pacman uses shortcuts to traverse the index in compaction



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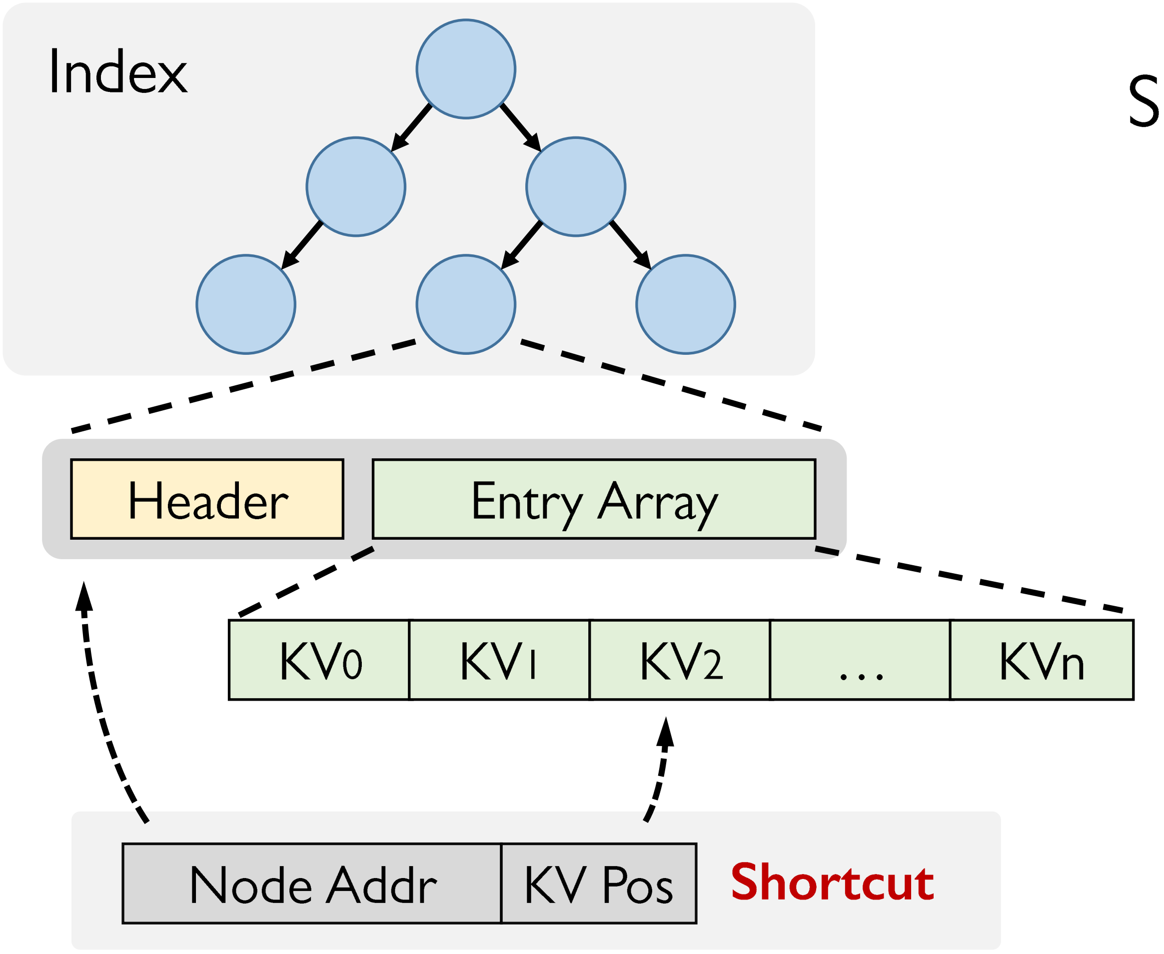

Shortcuts

- ❖ Point at the reference in the index

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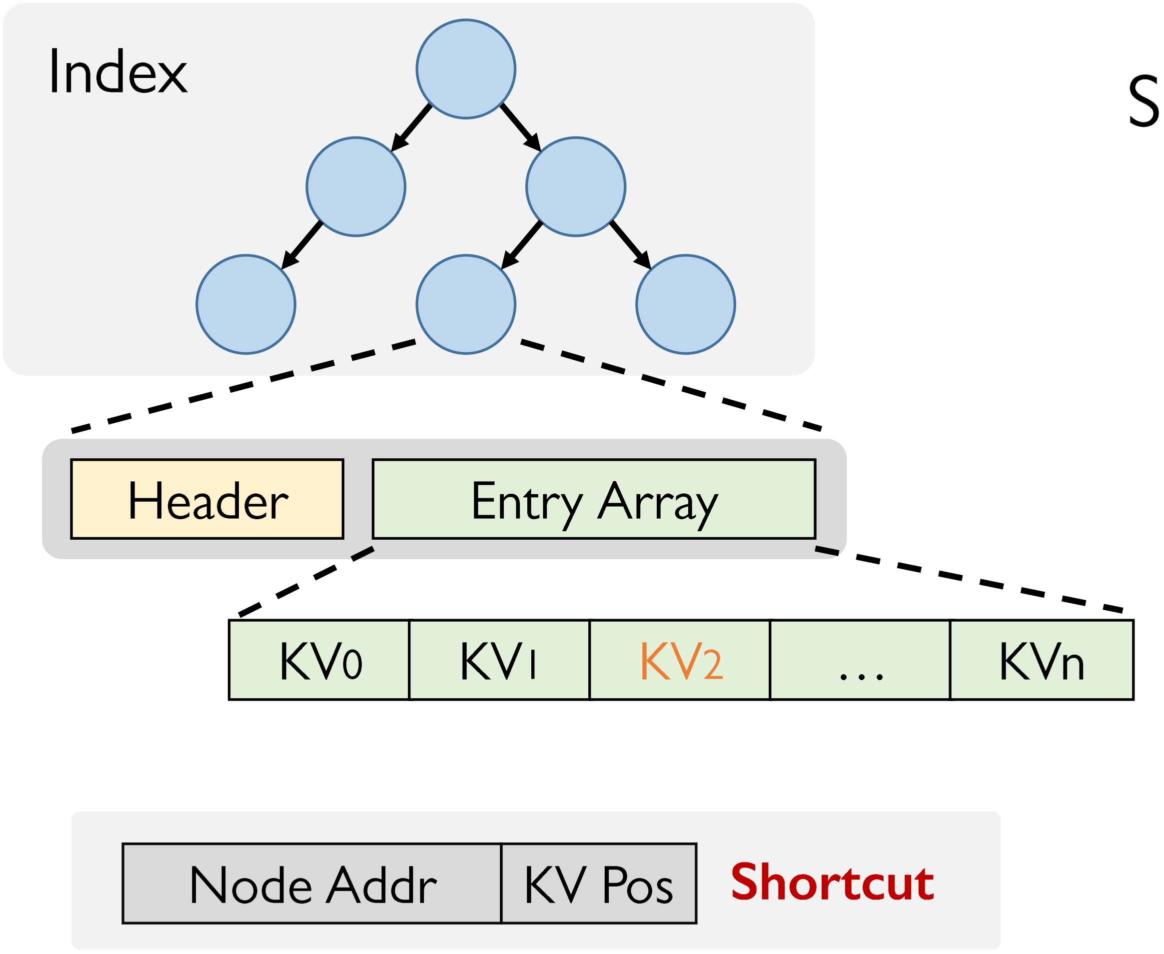

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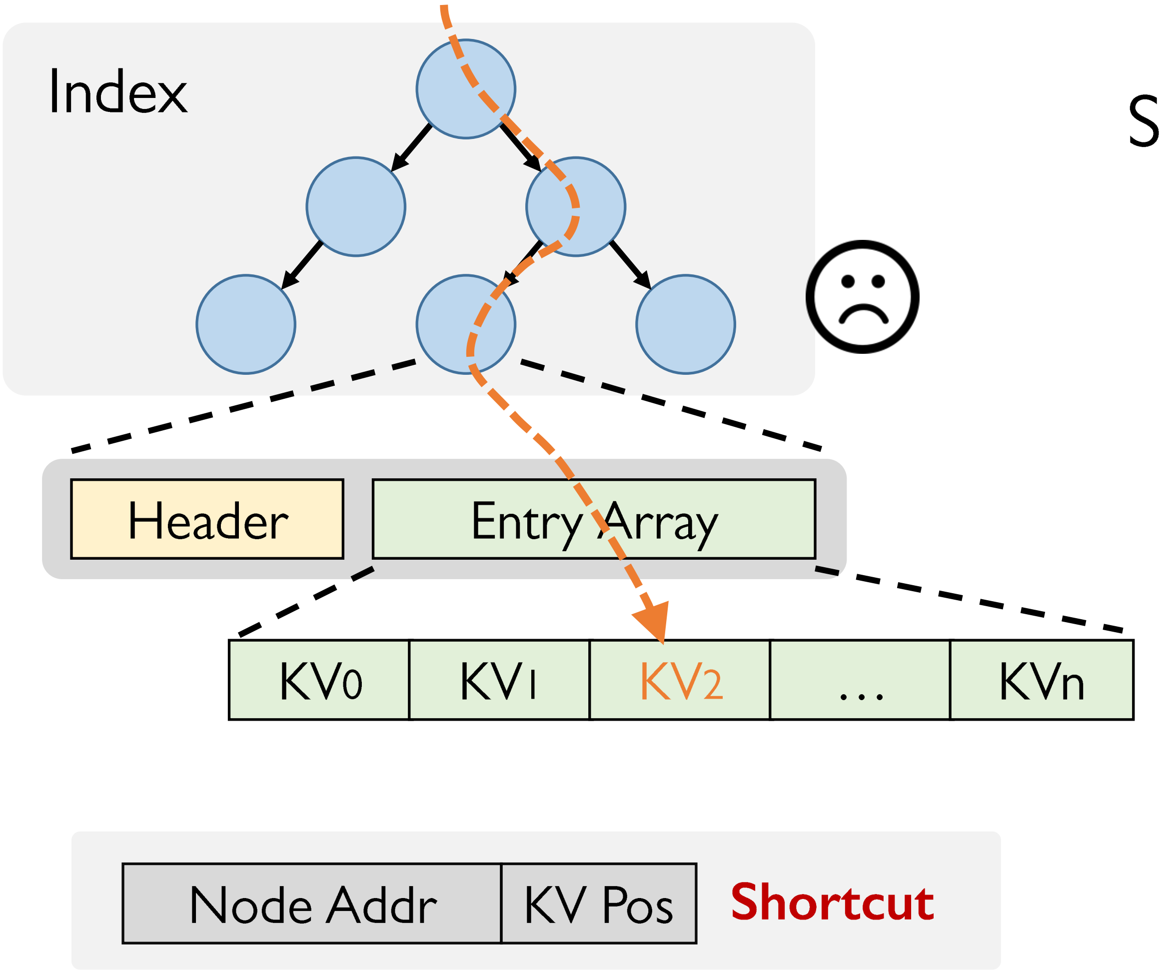

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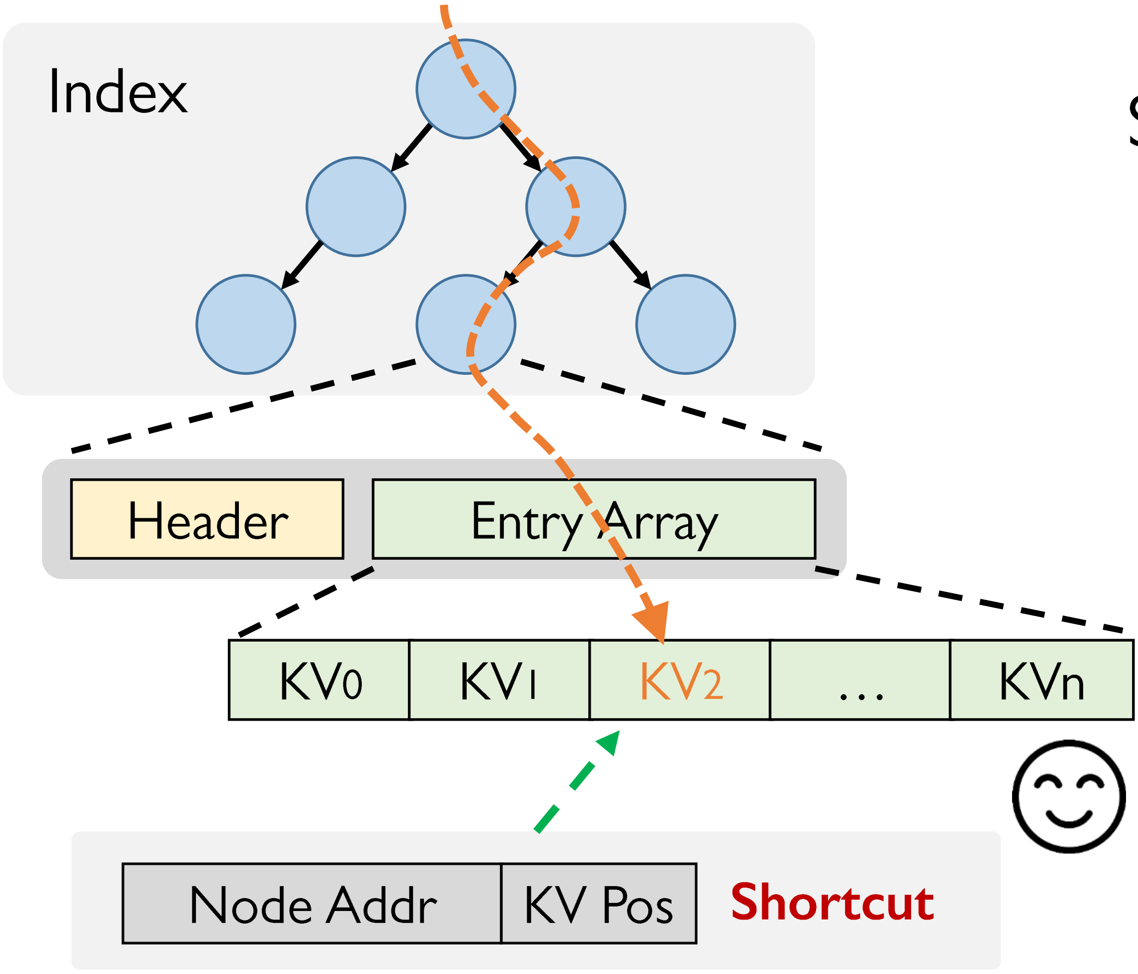

Shortcuts

- Point at the reference in the index
- Skip the high-latency root-to-leaf path

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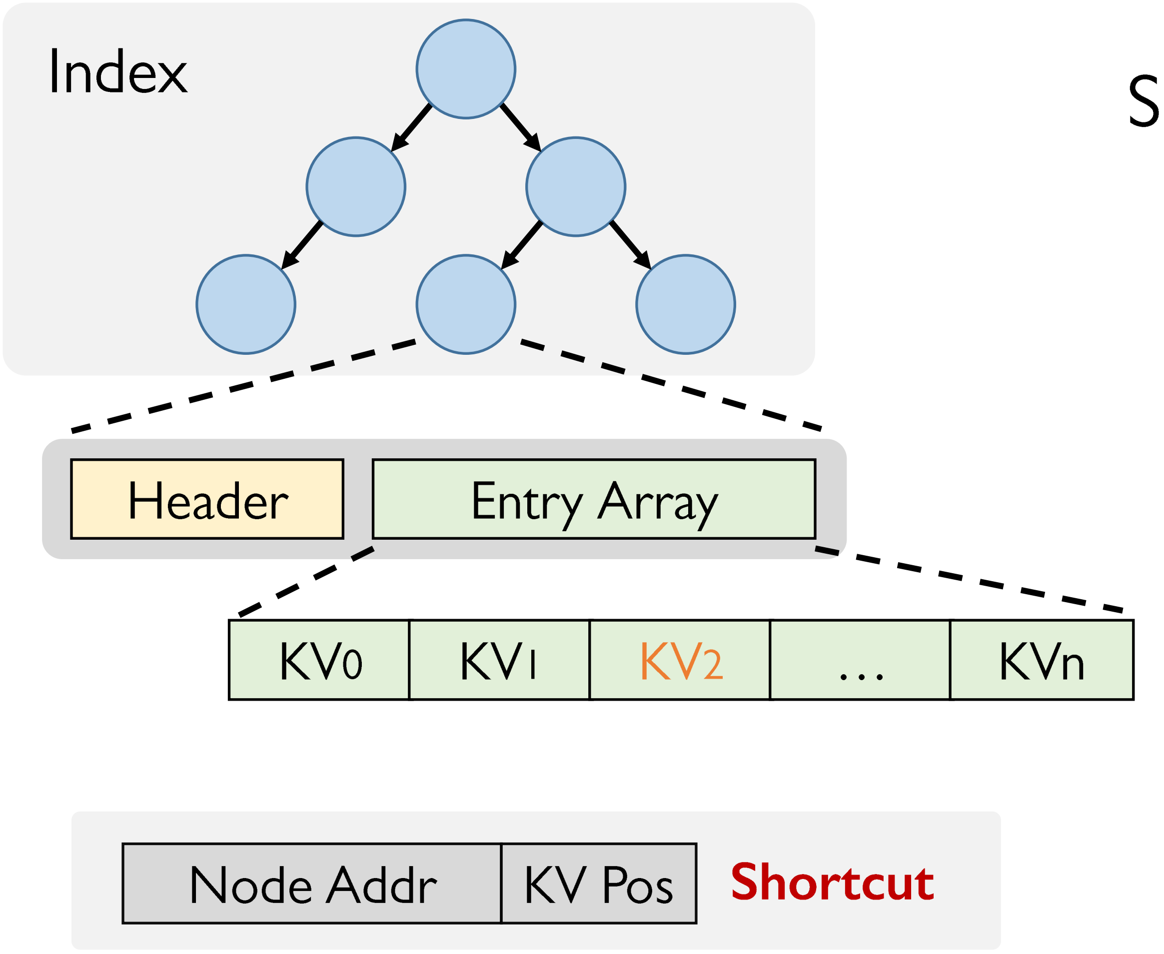
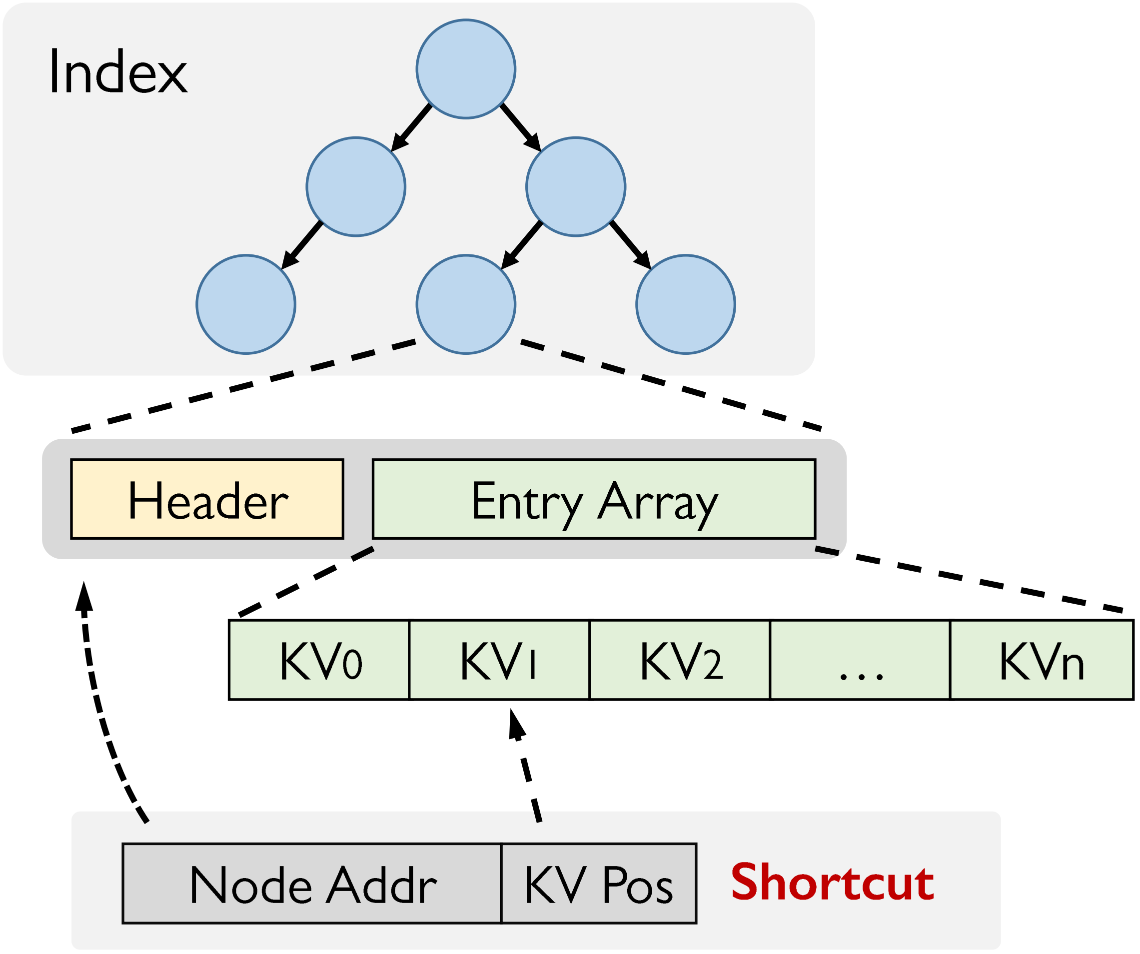


Shortcuts

- Point at the reference in the index
- Skip the high-latency root-to-leaf path
- Recorded by foreground threads in passing when writing new objects
- Stored with corresponding objects in PM log

Design (1) - Traverse Index with Shortcut

How to handle shortcut invalidation ?



1. *KV Pos* is invalid (e.g., caused by shift)

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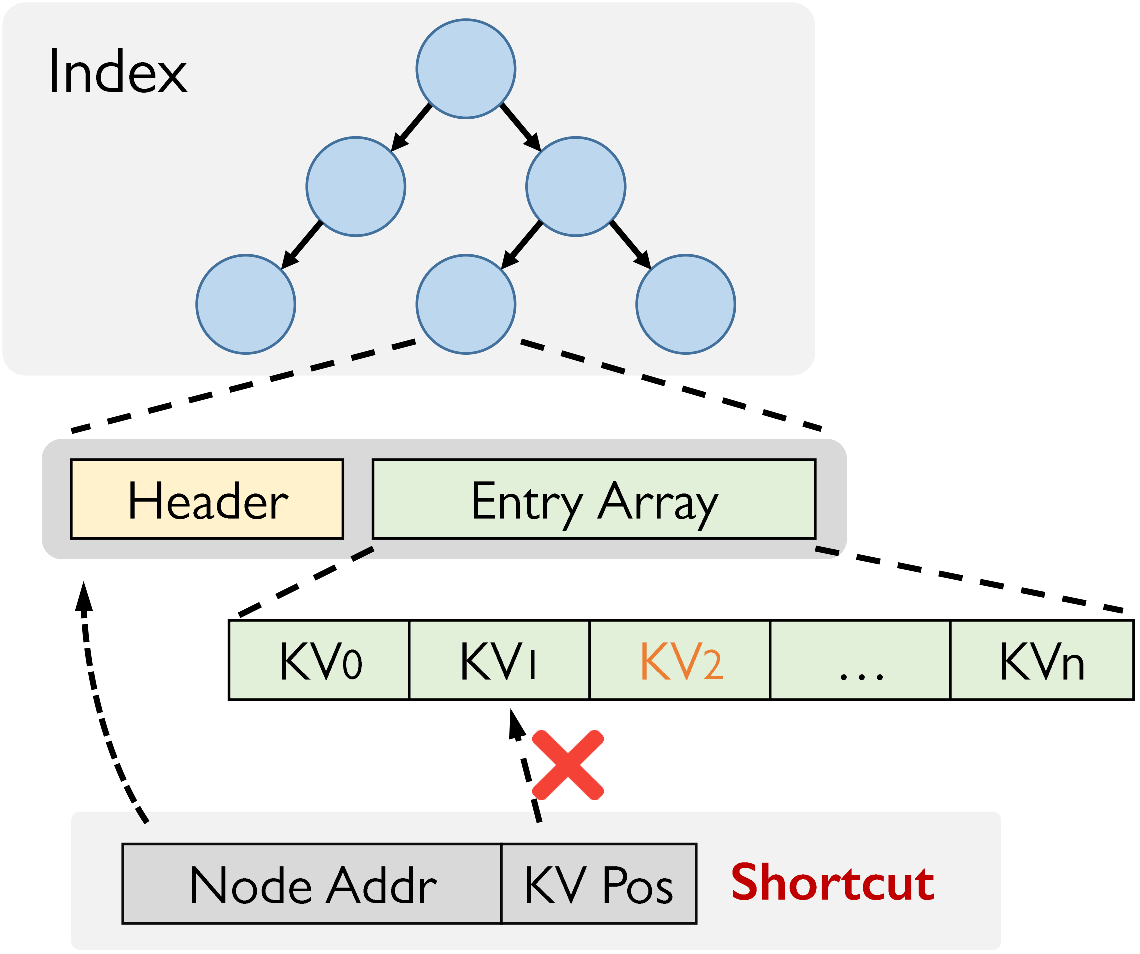

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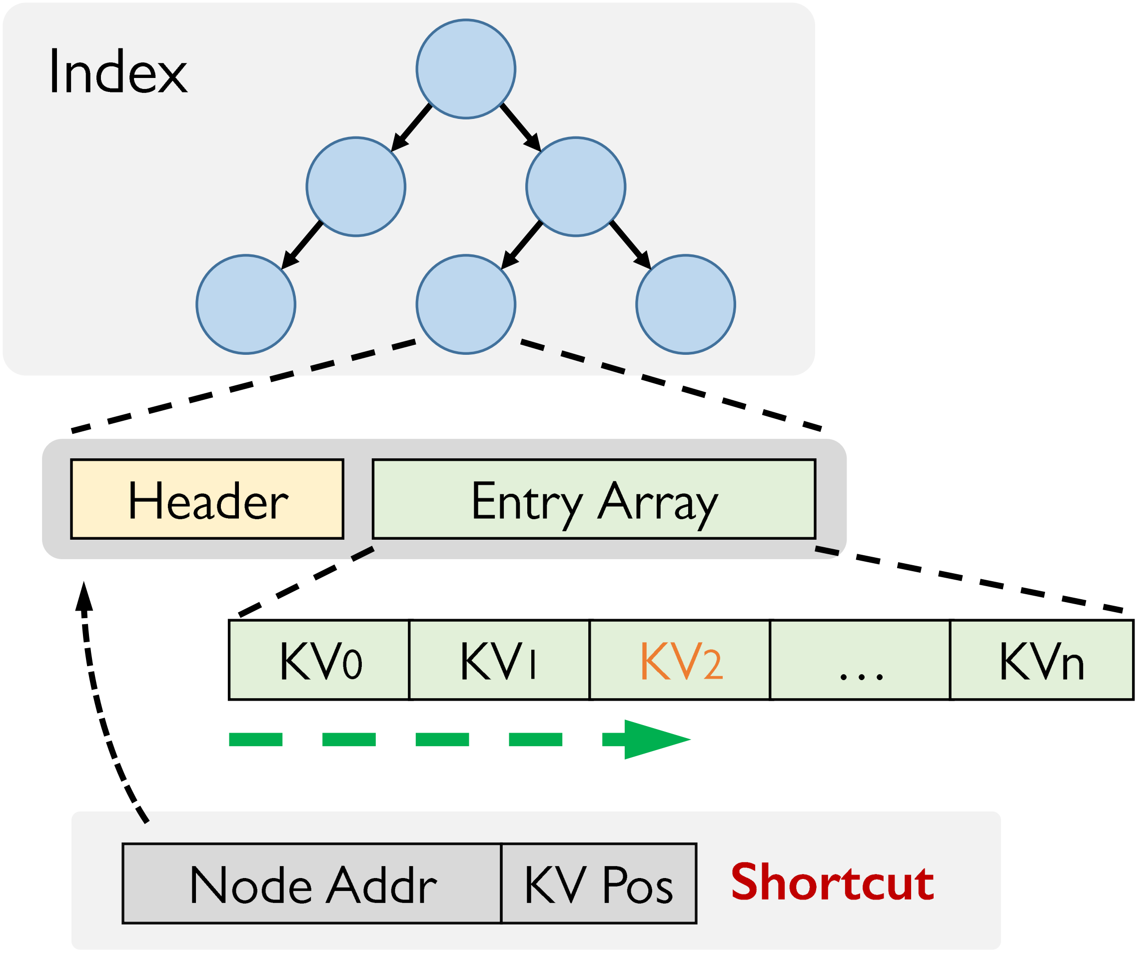

1. *KV Pos* is invalid (e.g., caused by shift)

re-search the leaf node

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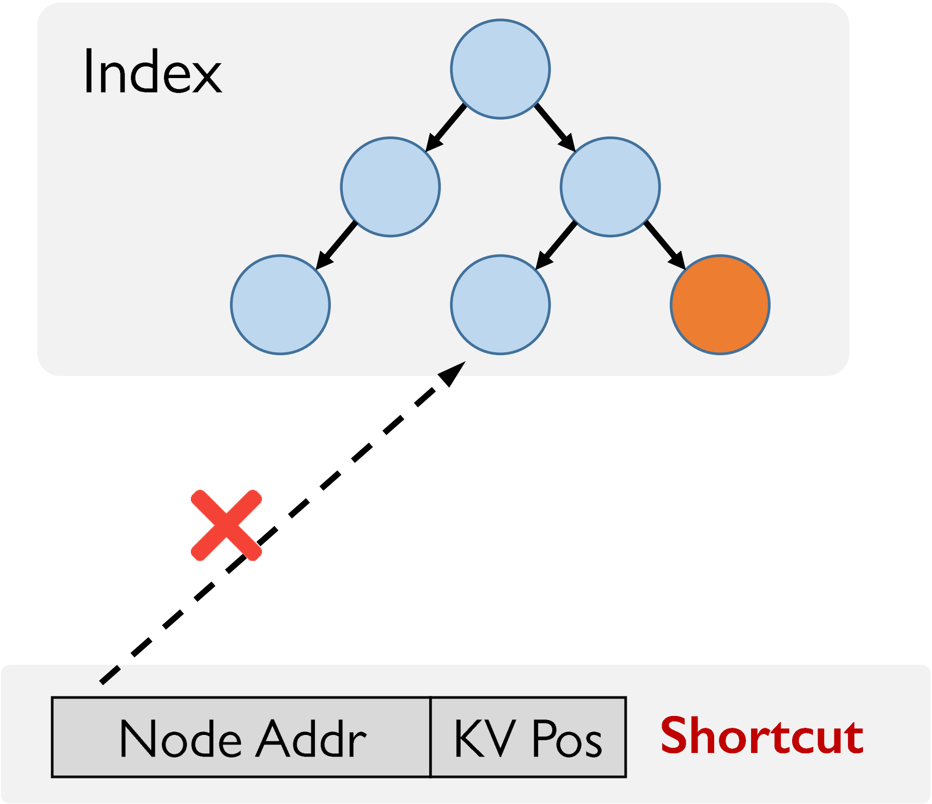

2. the reference has been moved to another node (e.g., caused by shift or rehashing)

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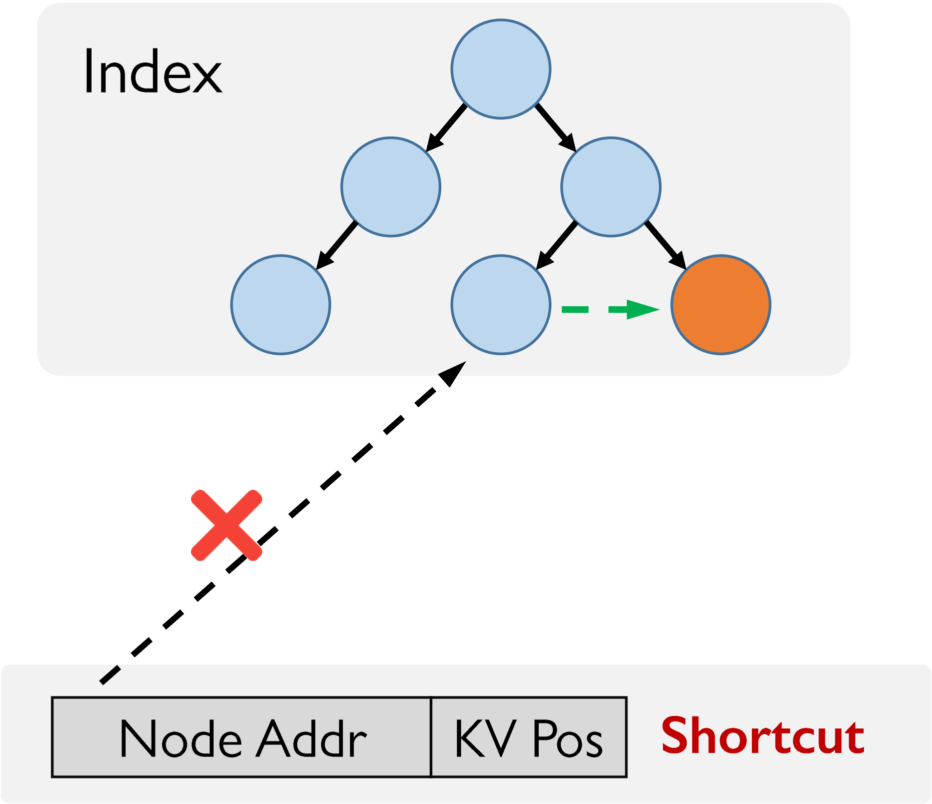

2. the reference has been moved to another node (e.g., caused by shift or rehashing)

try to search the sibling node or fall back to normal search

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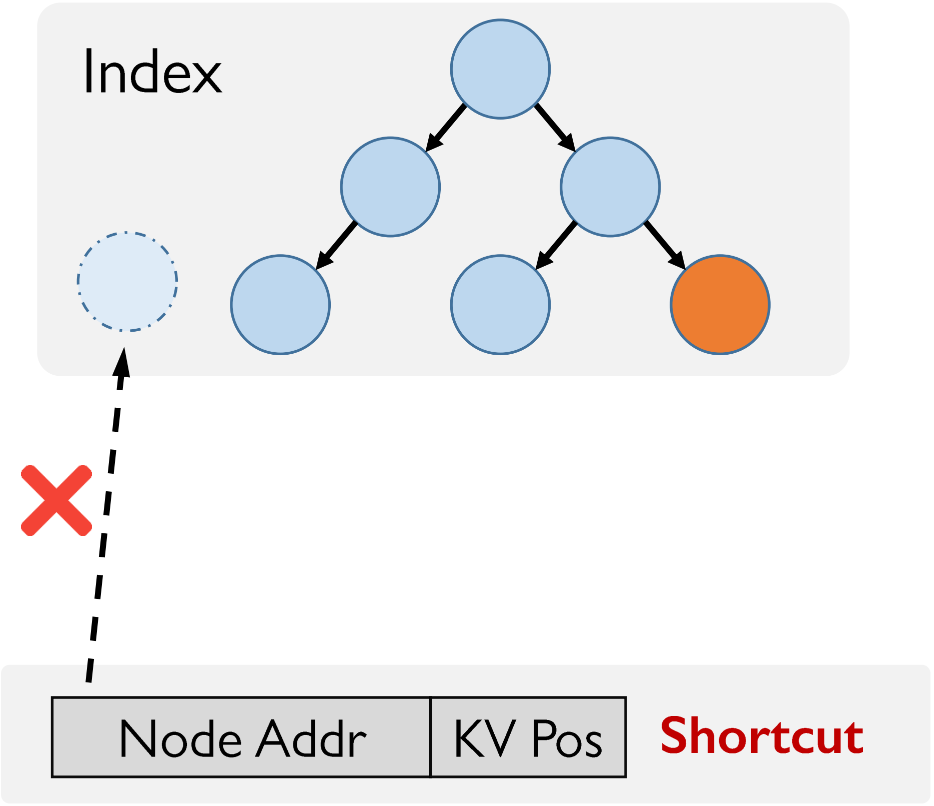

3. the original node pointed by *Node Addr* has been deleted

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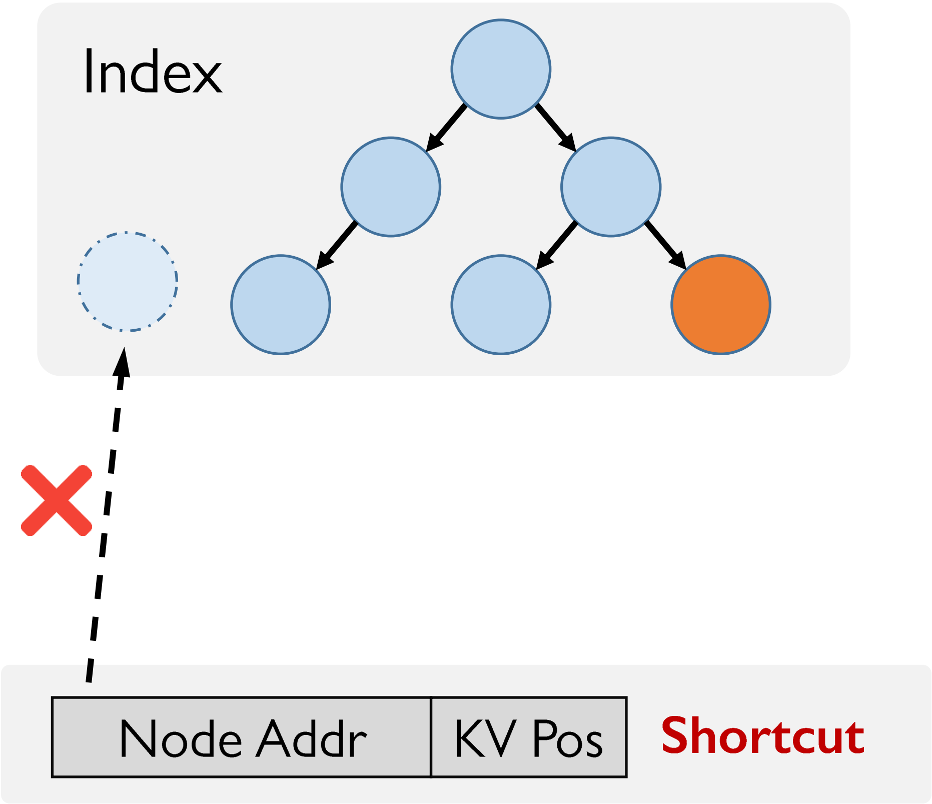


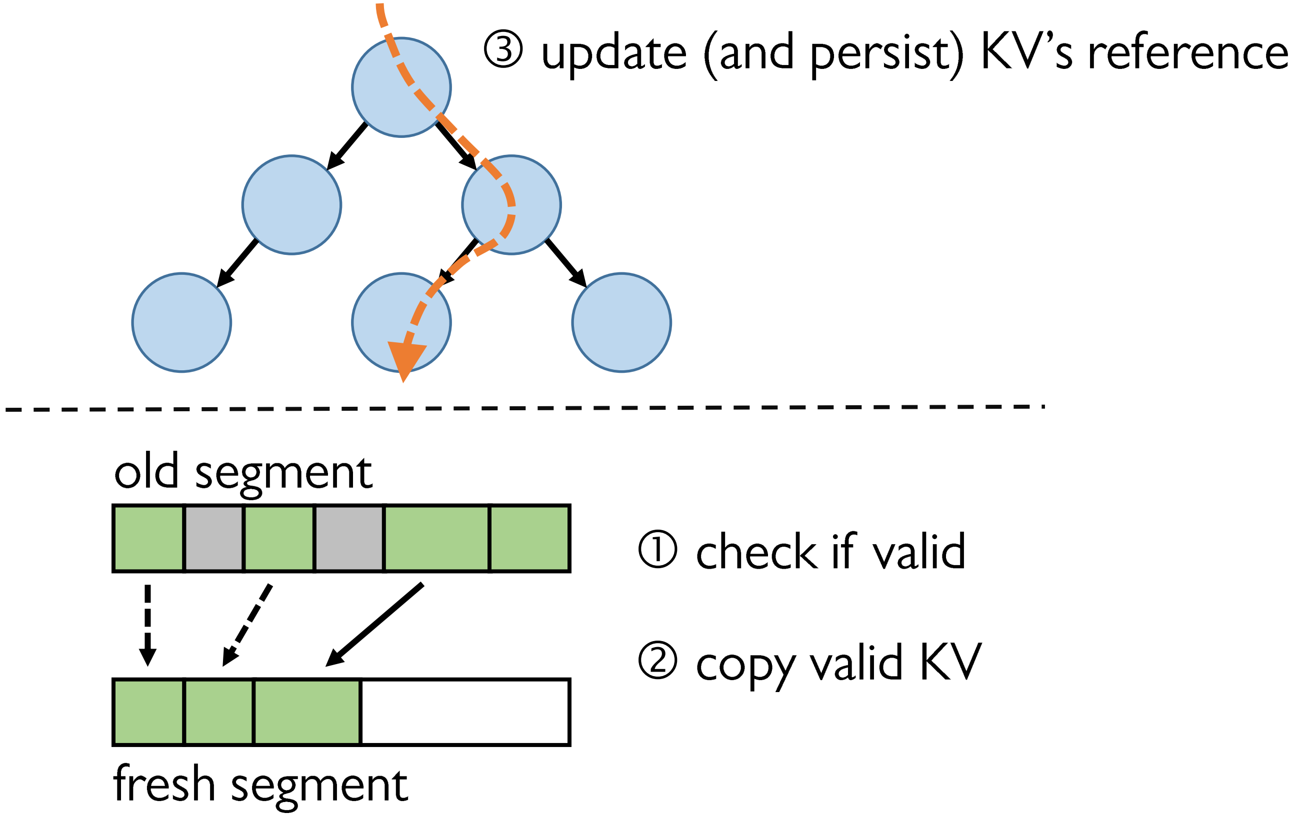
3. the original node pointed by *Node Addr* has been deleted

❖ delete the node logically and reserve its space for future re-allocation

❖ fall back to normal search

Design (2) - Redesign Compaction Pipeline

Background Compaction



Per-object manner:

❖ one flush and fence between step ② and step ③ for each valid object

❖ serial flush on each updated reference

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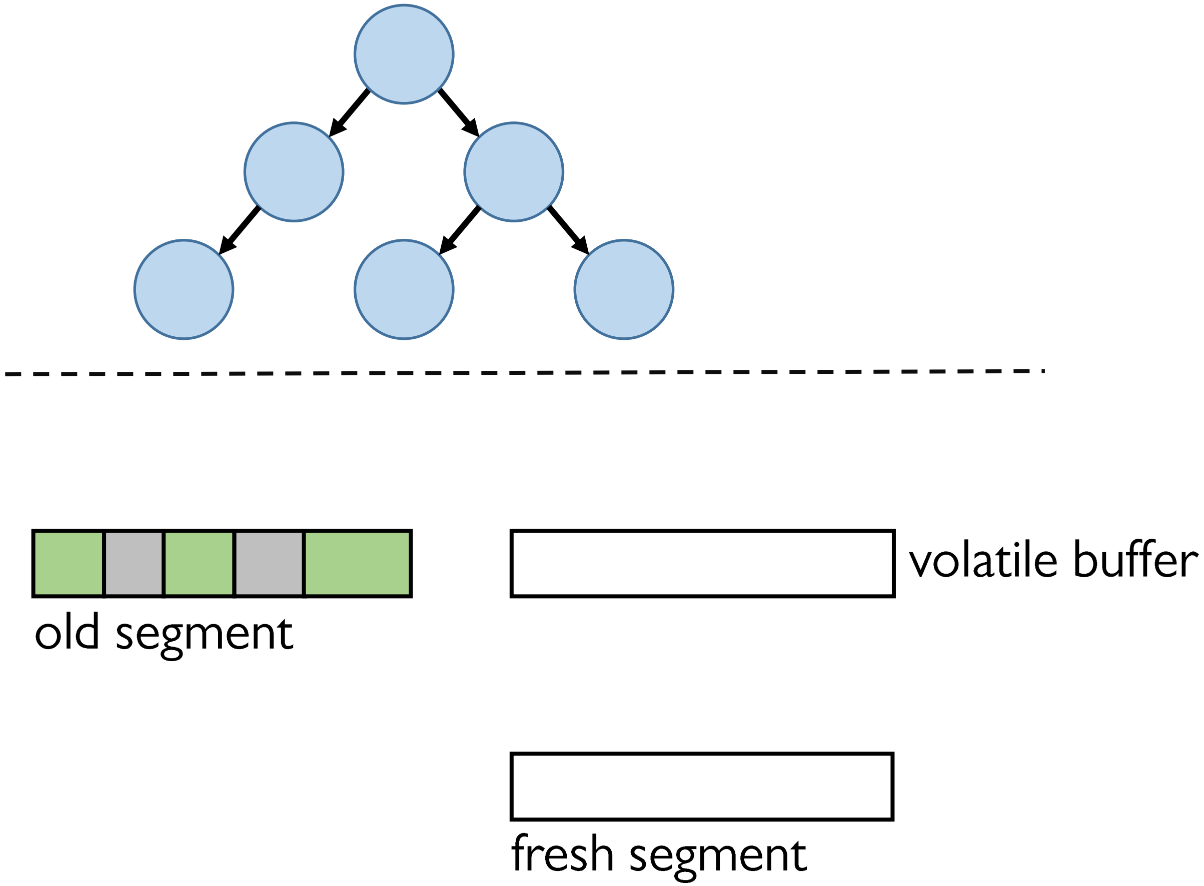

Batch manner:

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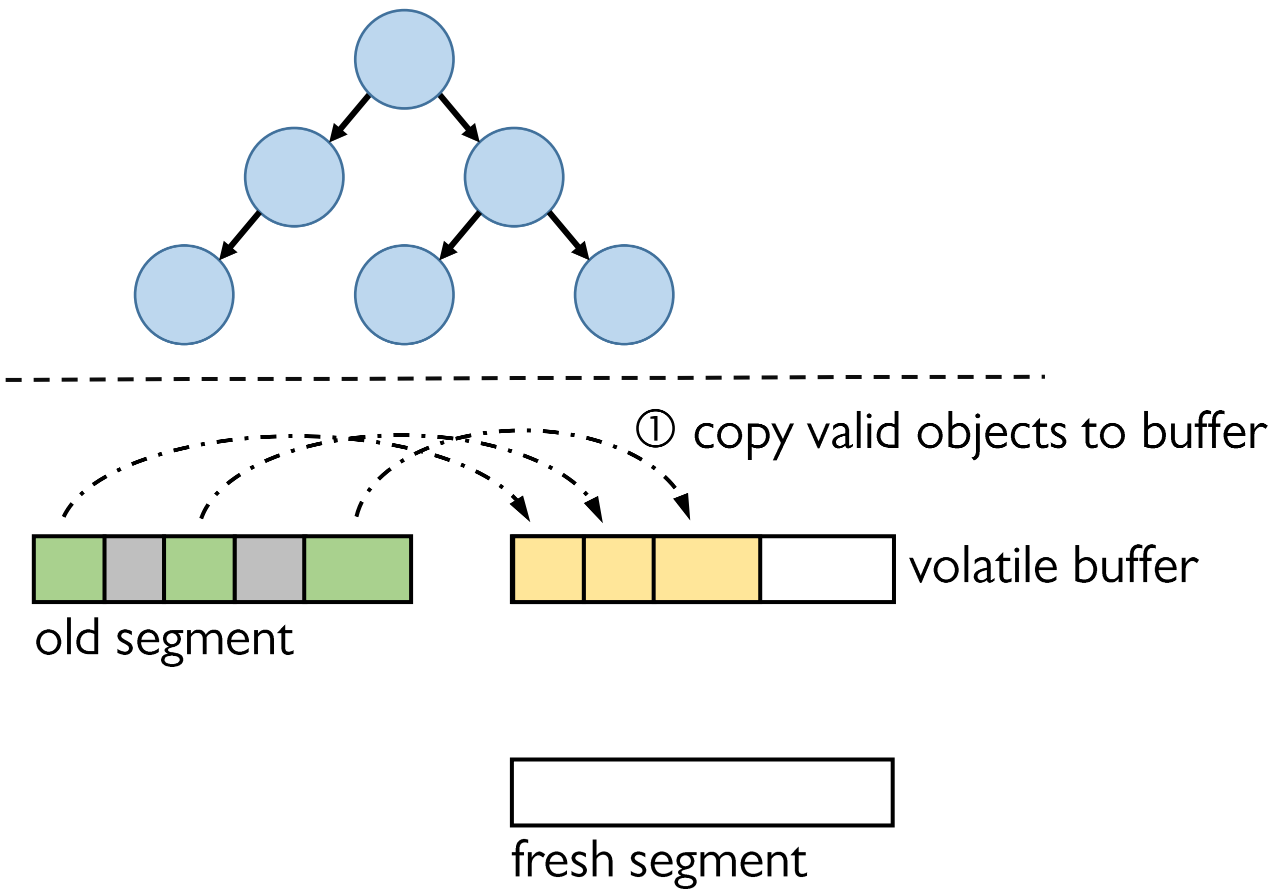

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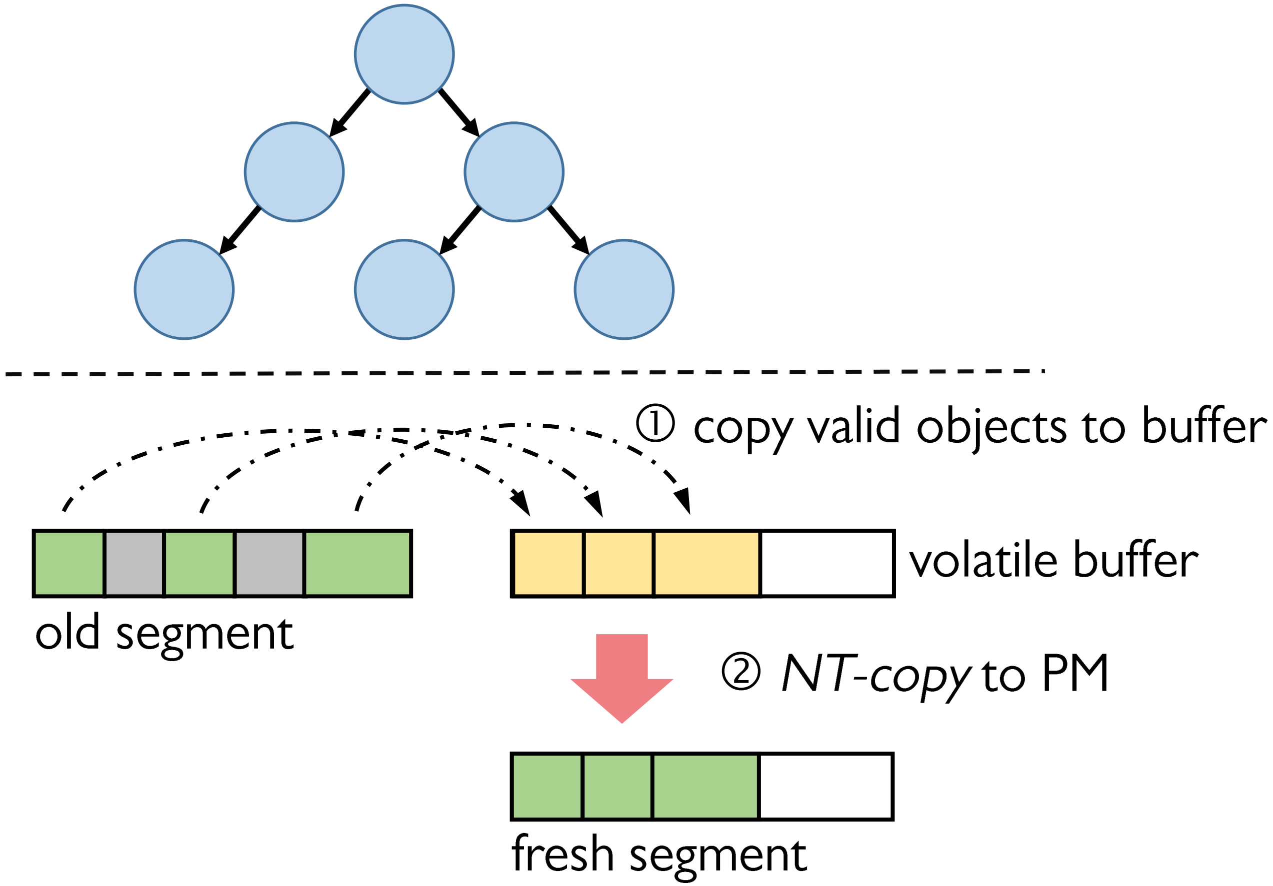

Batch manner:

❖ non-temporal stores (higher bandwidth) to copy bulk of data (step ②)

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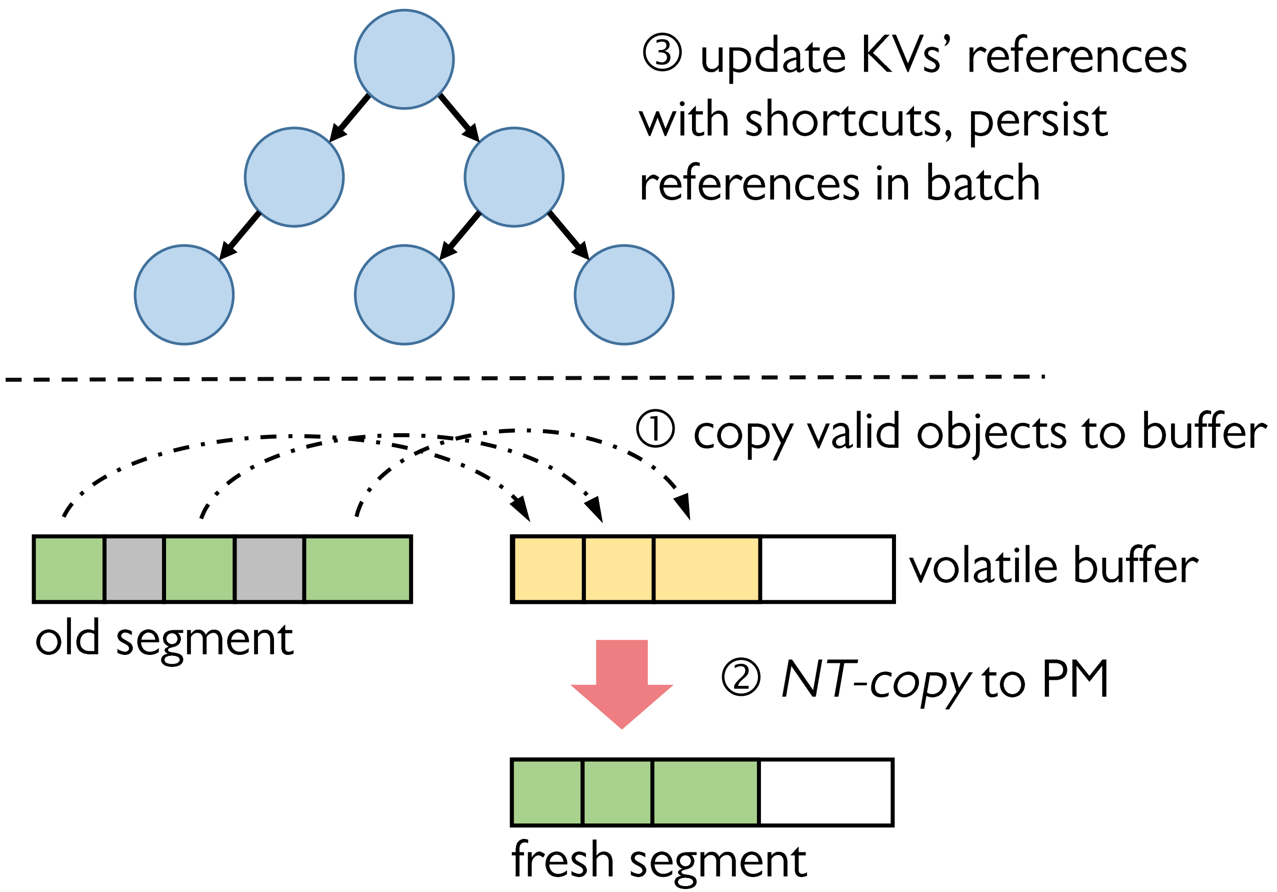

Batch manner:

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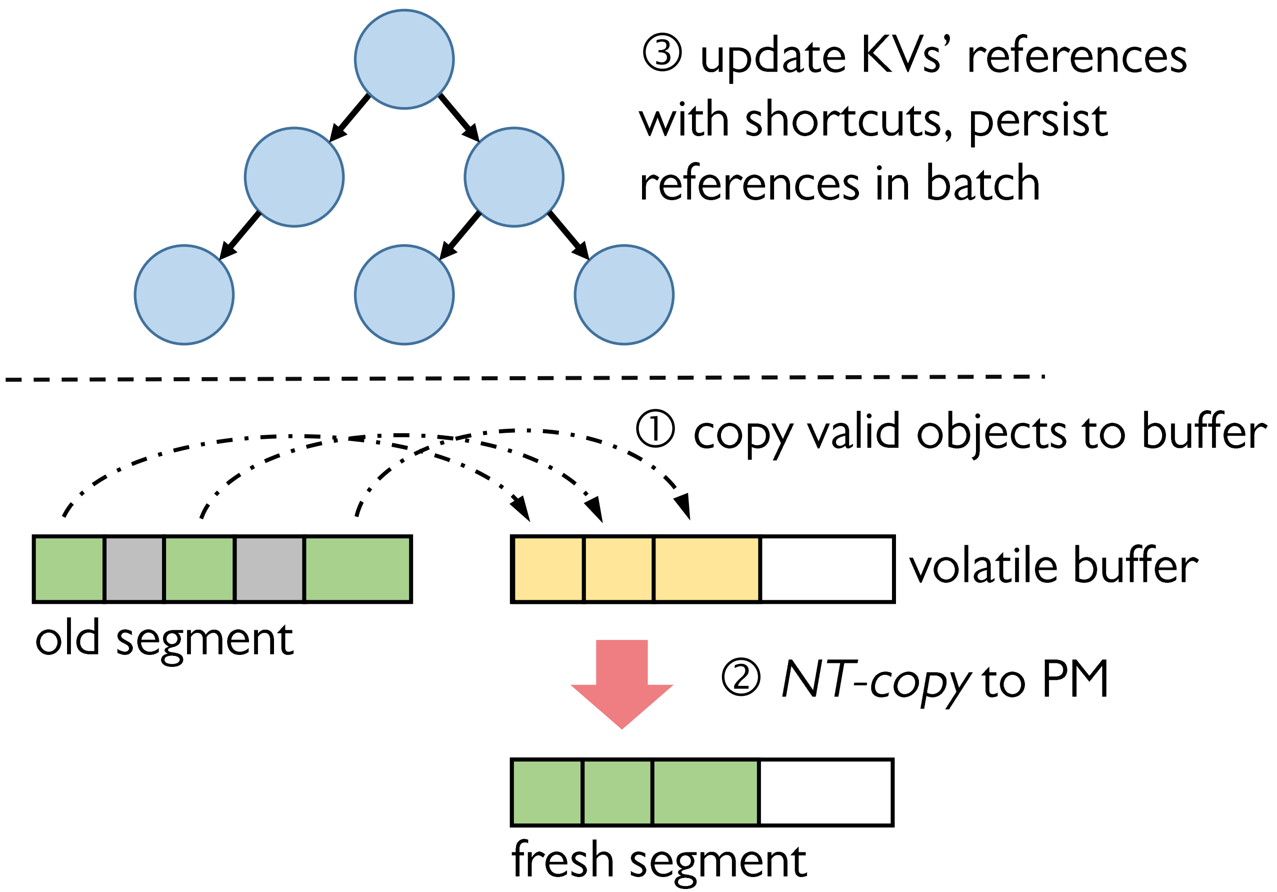

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❖ non-temporal stores (higher bandwidth) to copy bulk of data (step ②)

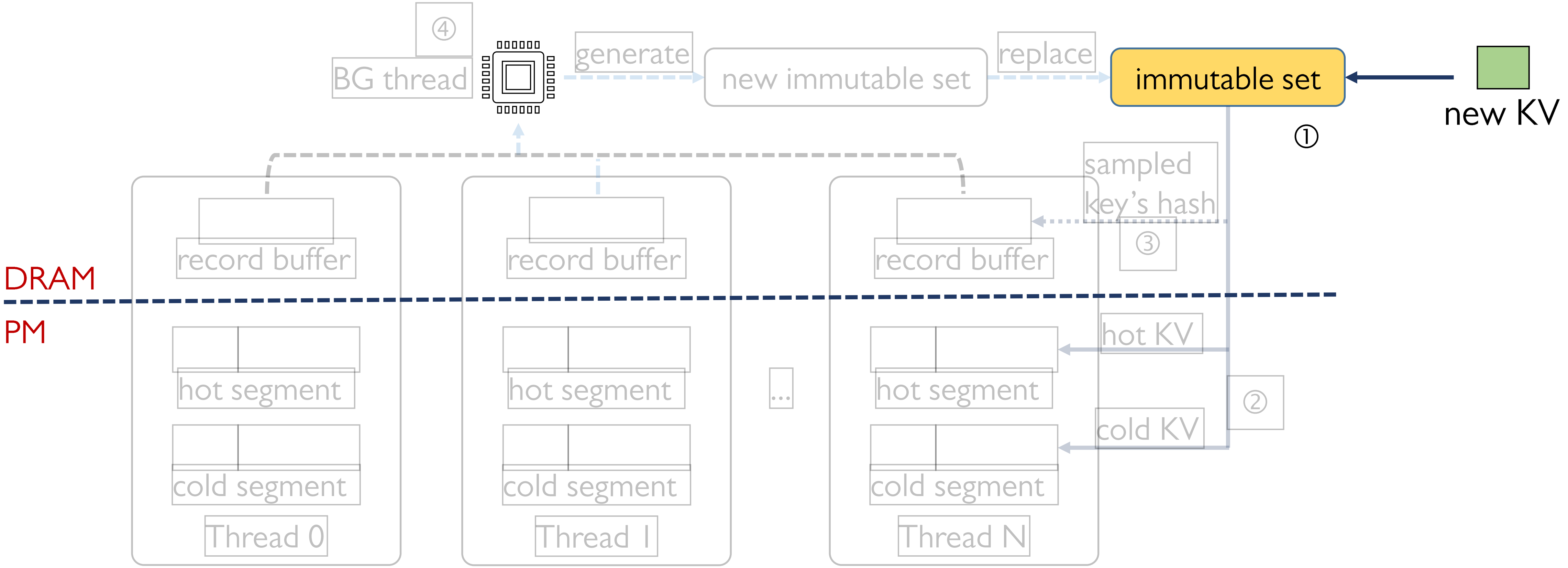
❖ one fence between step ② and step ③ for the whole segment

❖ launch concurrent flushes on batched updated references (step ③)

❖ prefetch references via shortcuts to cover access latency

Design (3) - Separate Hot-Cold Data

① a lightweight approach to identify hot and cold KV
② store hot and cold objects in different log segments
③ count hot proportion and record key's hash by sampling
④ a background thread generate new hot set if hotspots shift



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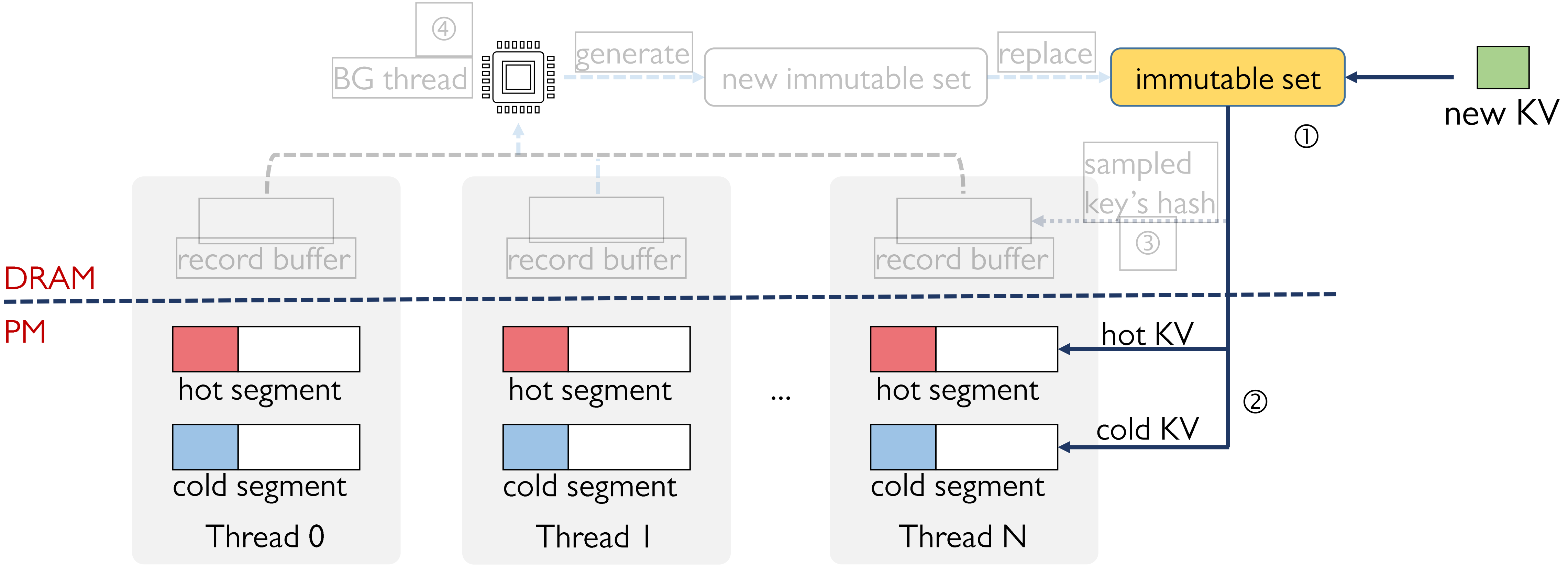

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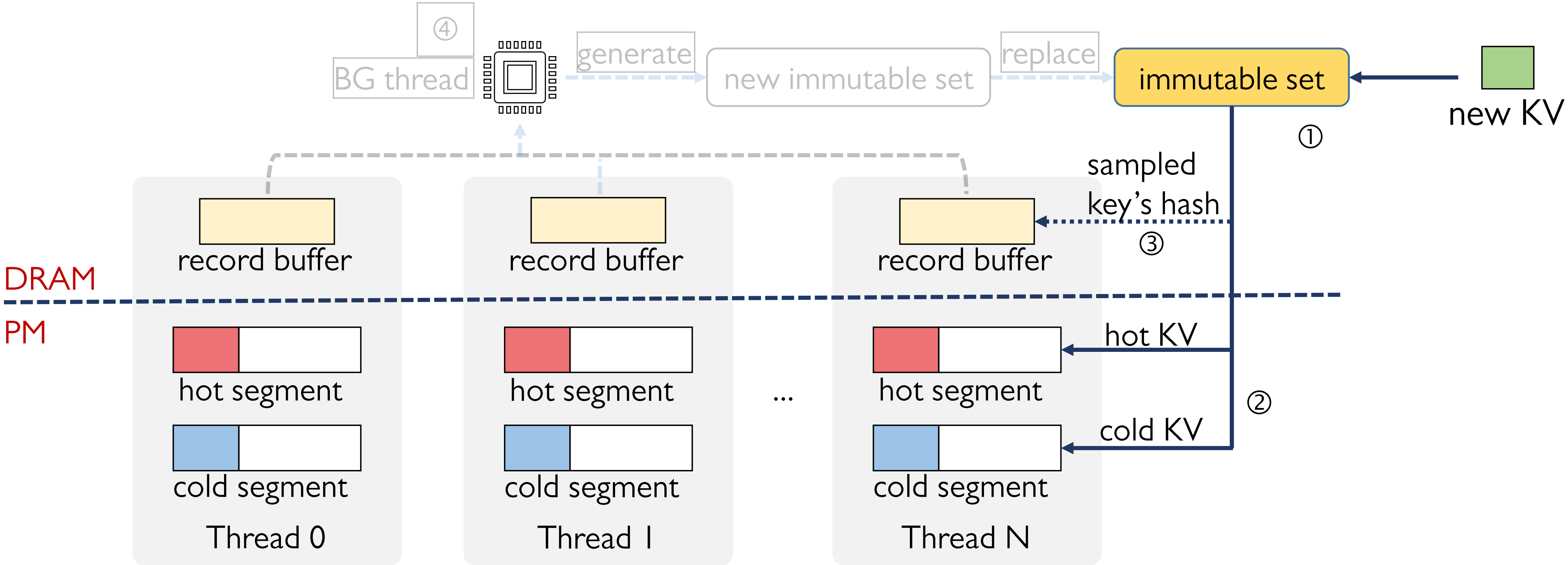

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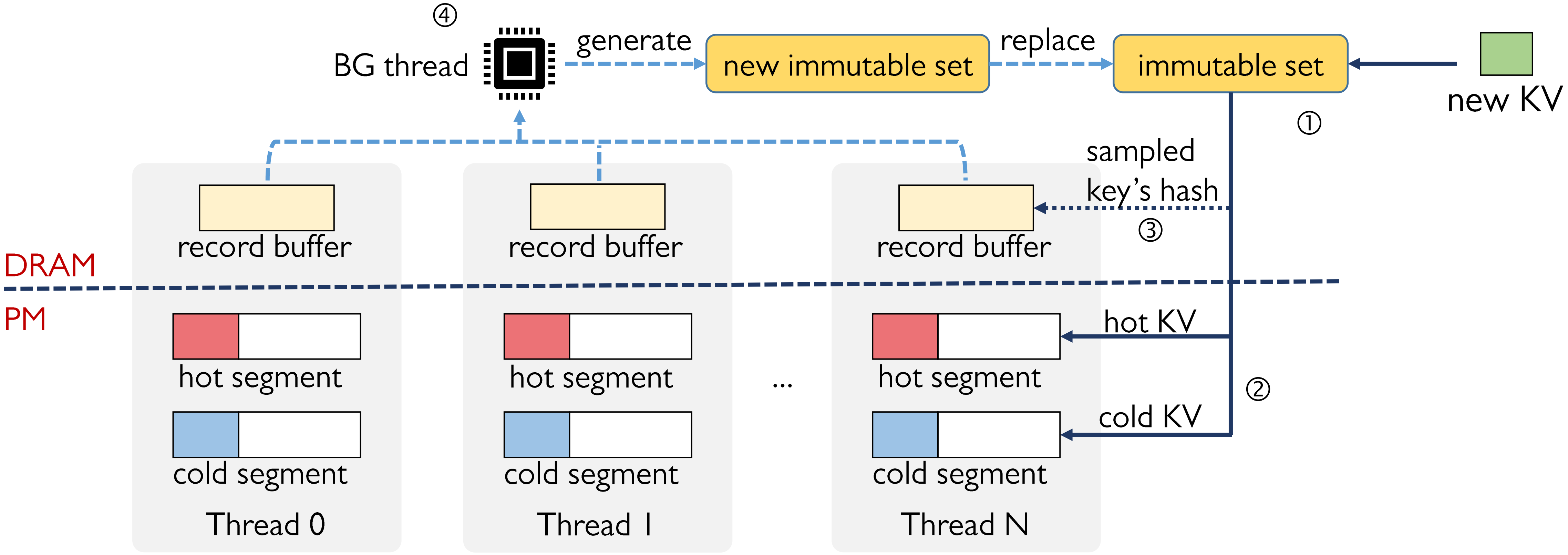
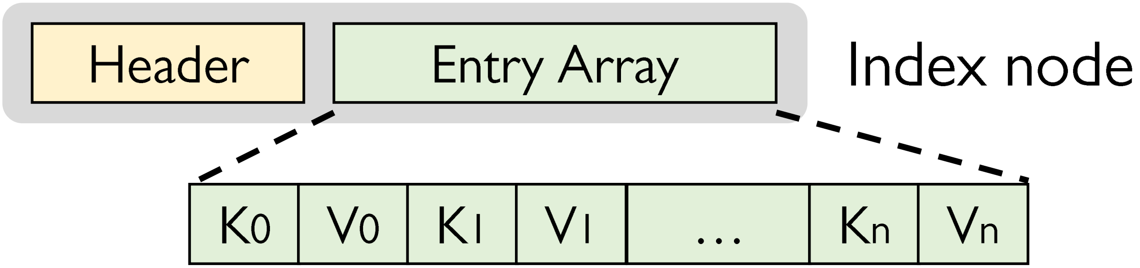
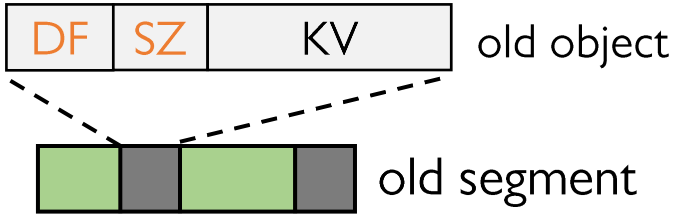


Design (4) – Reduce excessive PM accesses

Foreground Put





read size (SZ) to increase old segment's garbage bytes and write old object's deleted flag (DF)

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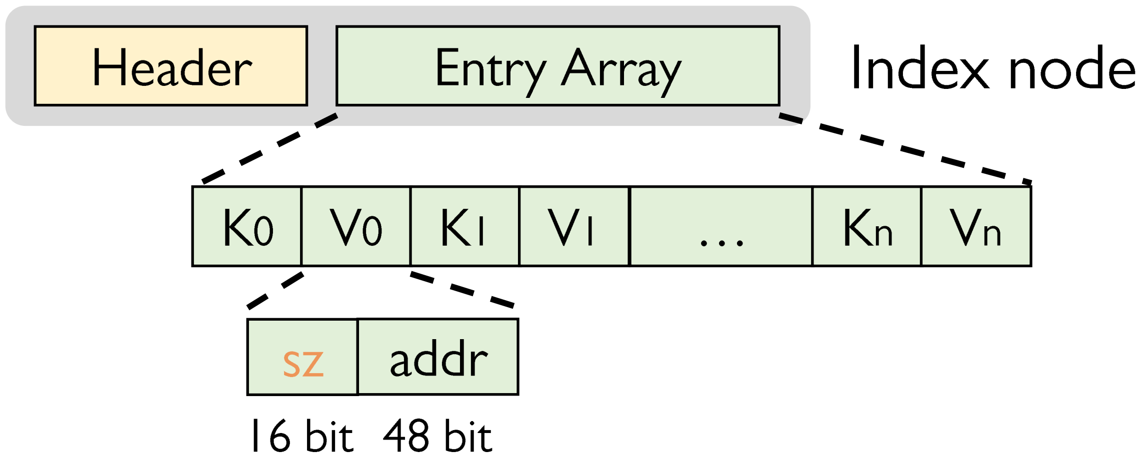

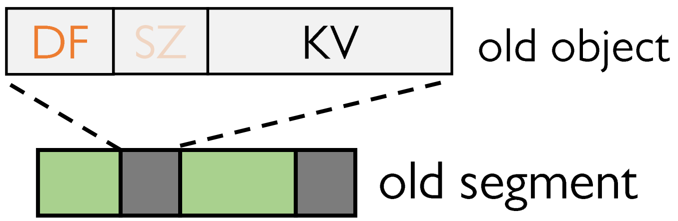

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❖ Embed size (SZ) in the reference

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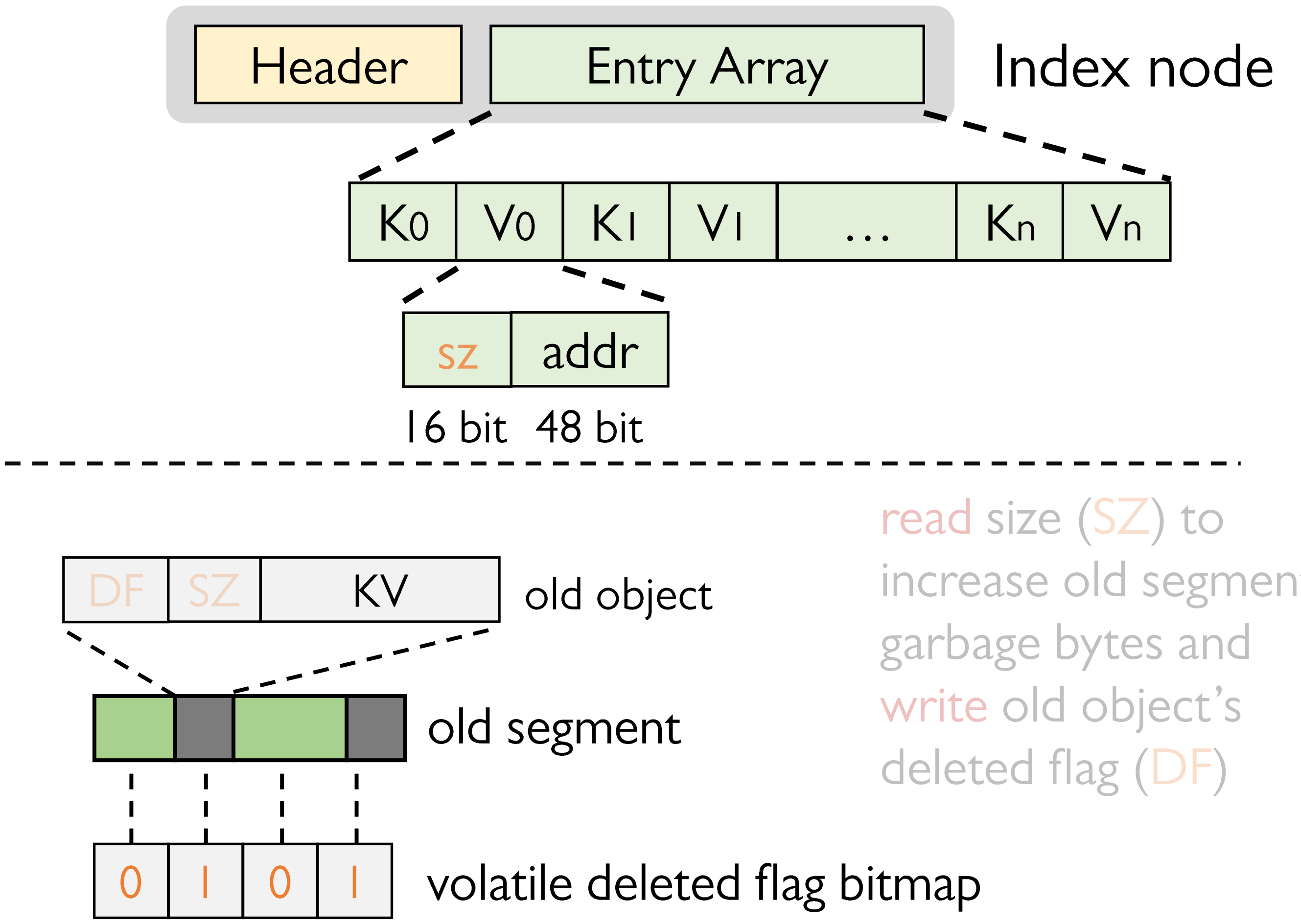

read size (SZ) to increase old segment's garbage bytes and write old object's deleted flag (DF)

- ❖ Embed size (SZ) in the reference
- ❖ In-DRAM deleted flag (DF) bitmap

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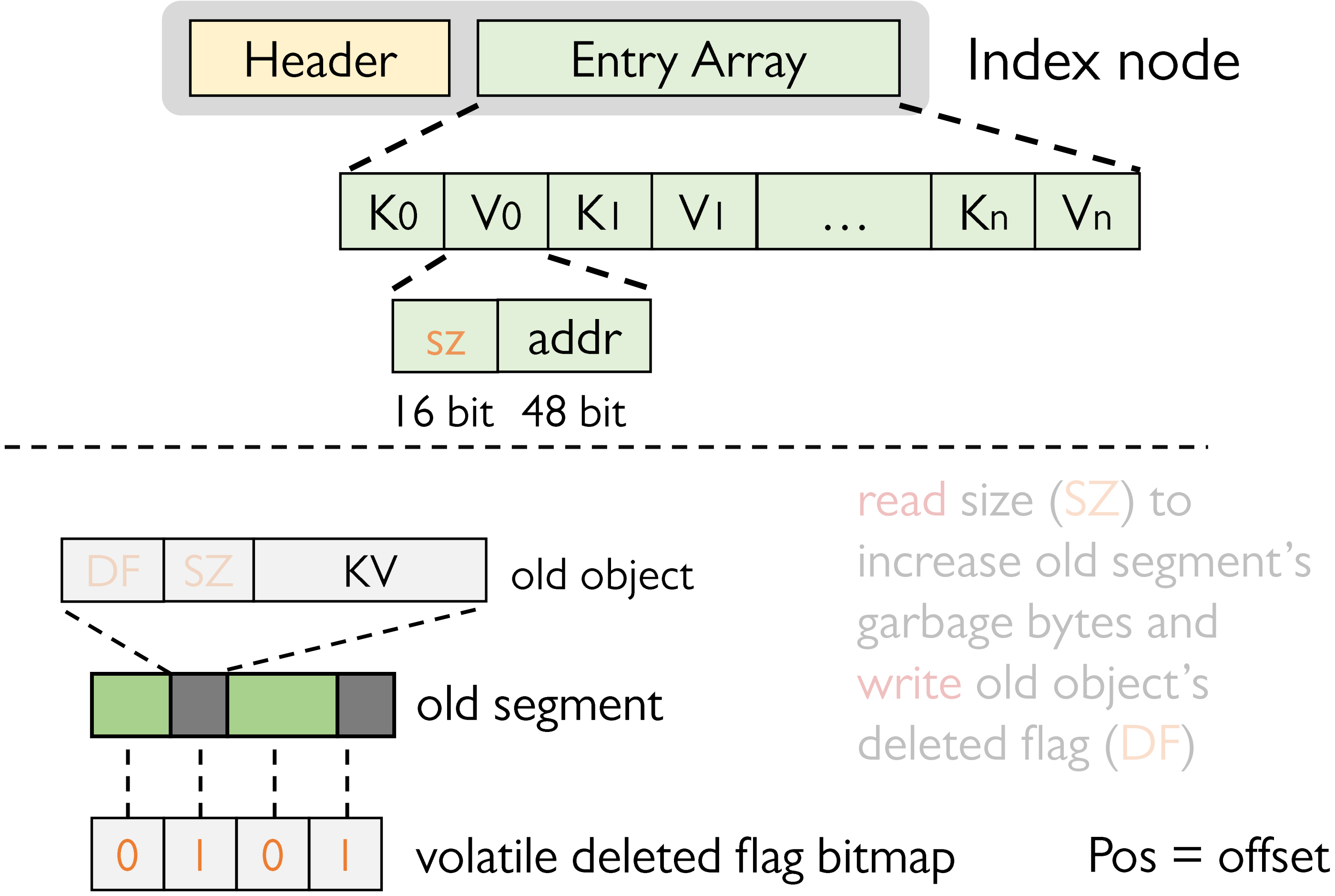

Pos = offset / MIN_SIZE

- Embed size (SZ) in the reference
- In-DRAM deleted flag (DF) bitmap

More design details: Check our paper

Optimize space overhead of shortcut

- compress size of shortcut
- do not store shortcut for hot objects

Recovery of Pacman

- shortcut and DRAM-resident data structures
- crash of batch compaction

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Experimental Setup

Hardware Platform (one socket)

CPU	18-core Intel Xeon Gold 6240 CPU
PM	3 * 128 GB Intel Optane DC PMMs
DRAM	96 GB DDR4 DIMMs

Applied KV stores

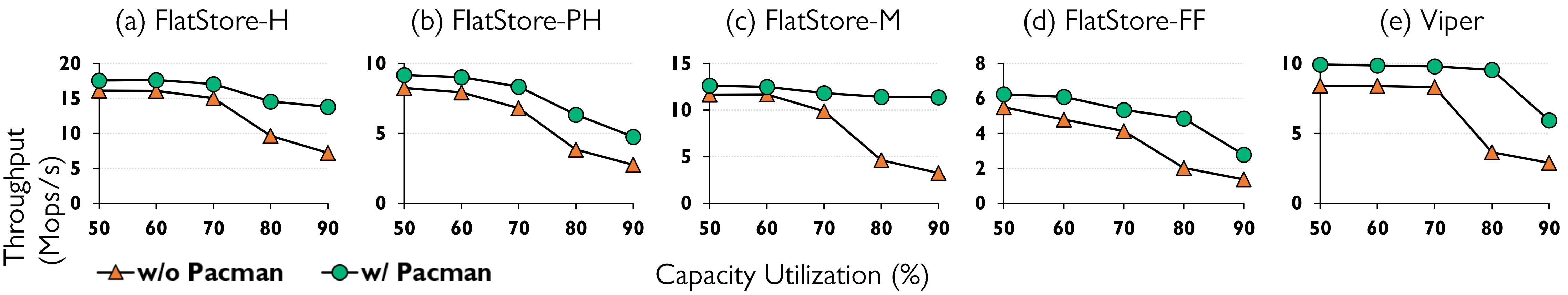
- FlatStore (ASPLOS'20): 4 version: [volatile CCEH, CCEH, Masstree, FastFair] + PM log
- Viper (VLDB'21): volatile CCEH + PM log

Workloads

- YCSB (varying thread count, value size, r/w ratio, etc)
- Facebook ETC Pool: Mixture of small & large KV pairs

Overall Performance

YCSB-A (50% Get, 50% Put) , 8B key, 48B value, 12 service threads, 4 cleaners



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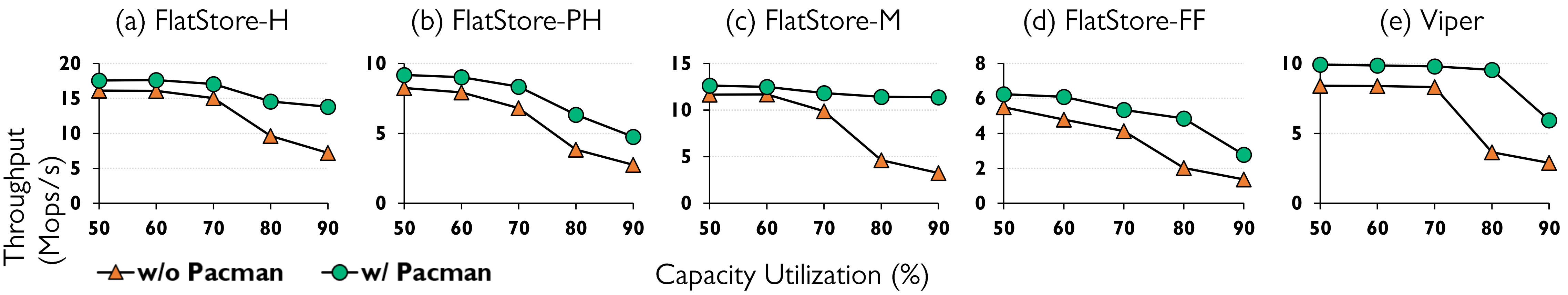


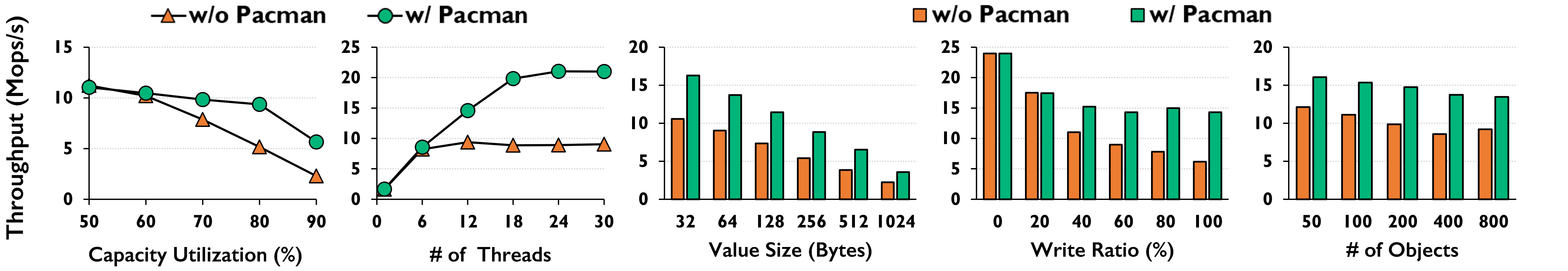
Pacman

- obviously curtails performance decline at high capacity utilizations, 1.5-3.5× speedup
  → efficient PM-aware compaciton
- also enhances performance at low capacity utilizaitons
  → reduces small random accesses and saves PM's limited bandwidth

Sensitivity Analysis

Default settings

distribution	capacity utilization	# of threads	# of cleaners	value size	write ratio	# of objects
Zipfian	80%	12	4	48 bytes	50%	200 M



(a) uniform workloads (b) thread scalability (c) varying value sizes (d) varying write ratios (e) varying numbers of objects

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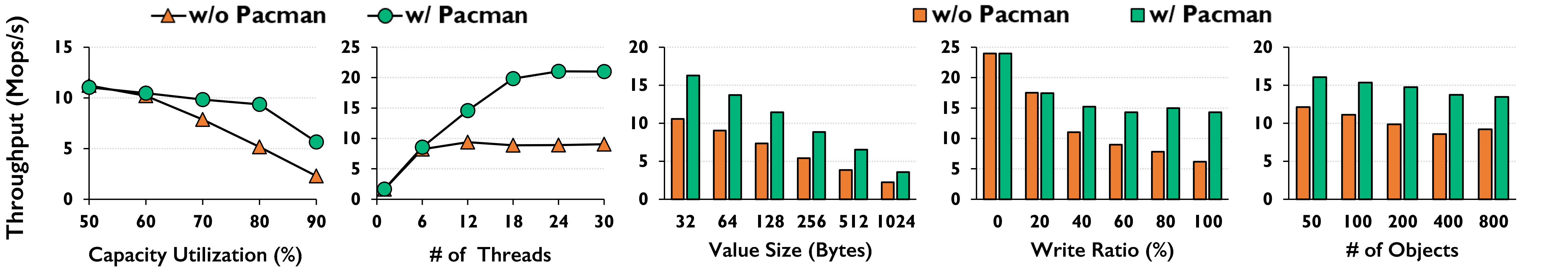

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Pacman is effective in write-intensive workloads with various settings

Facebook ETC workload

- Facebook ETC Pool: mixture of small & large KV pairs
  - Tiny (1-13 bytes, 40%), Zipfian distribution
  - Median (14-300 bytes, 55%), Zipfian distribution
  - Large (> 300 bytes, 5%), uniform distribution

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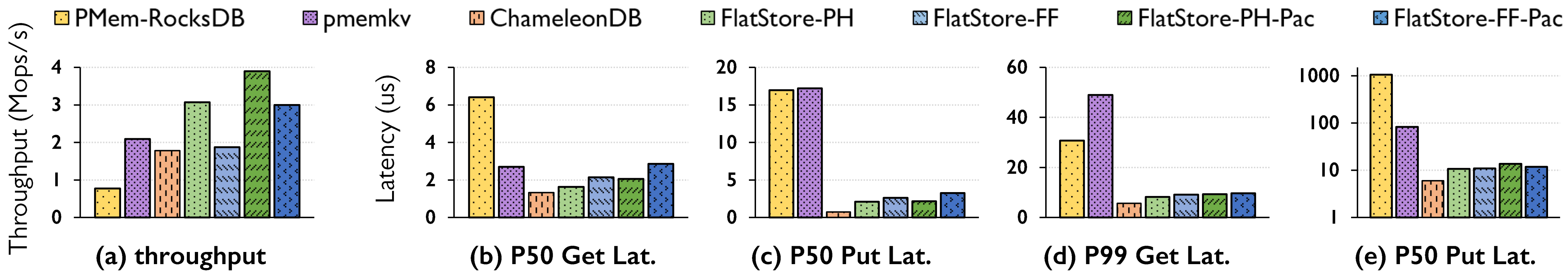

Outline

- ❖ Background & Motivation
- ❖ Pacman – A PM-aware Compaction Approach for Log-structured KVS
- ❖ Results
- ❖ Conclusion

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- We propose Pacman, an efficient PM-aware compaction approach for log-structured KV stores on PM.
- Enhance state-of-the-art PM-based log-structured KV stores (FlatStore & Viper)
- More evaluation results and analysis are in the paper

Thanks & QA

Pacman: An Efficient Compaction Approach for Log-Structured Key-Value Store on Persistent Memory

Open-source code: https://github.com/thustorage/pacman

Contact Information: wangjing19@mails.tsinghua.edu.cn