DENKV: Addressing Design Trade-offs of Key-value Stores for Scientific Applications

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Sogang University
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KISTI www.kisti.re.kr Korea Institute of Science and Technology Information
Oak Ridge National Laboratory

SC22 Dallas, TX | hpc accelerates.

DENKV: Deduplication-extended Node-local LSM-tree-based Key-value Store

- HPC applications generate huge amount of redundant data
- Distributed key-value stores gained attention for HPC systems
- A node-local LSM-tree-based key-value store for HPC systems
- Integrate data deduplication to overcome write and space amplification problems
- Introduced asynchronous partly inline deduplication (APID)
  - Leverages background thread pool
- Maintained performance while reducing **4x** write and **8x** space amplification

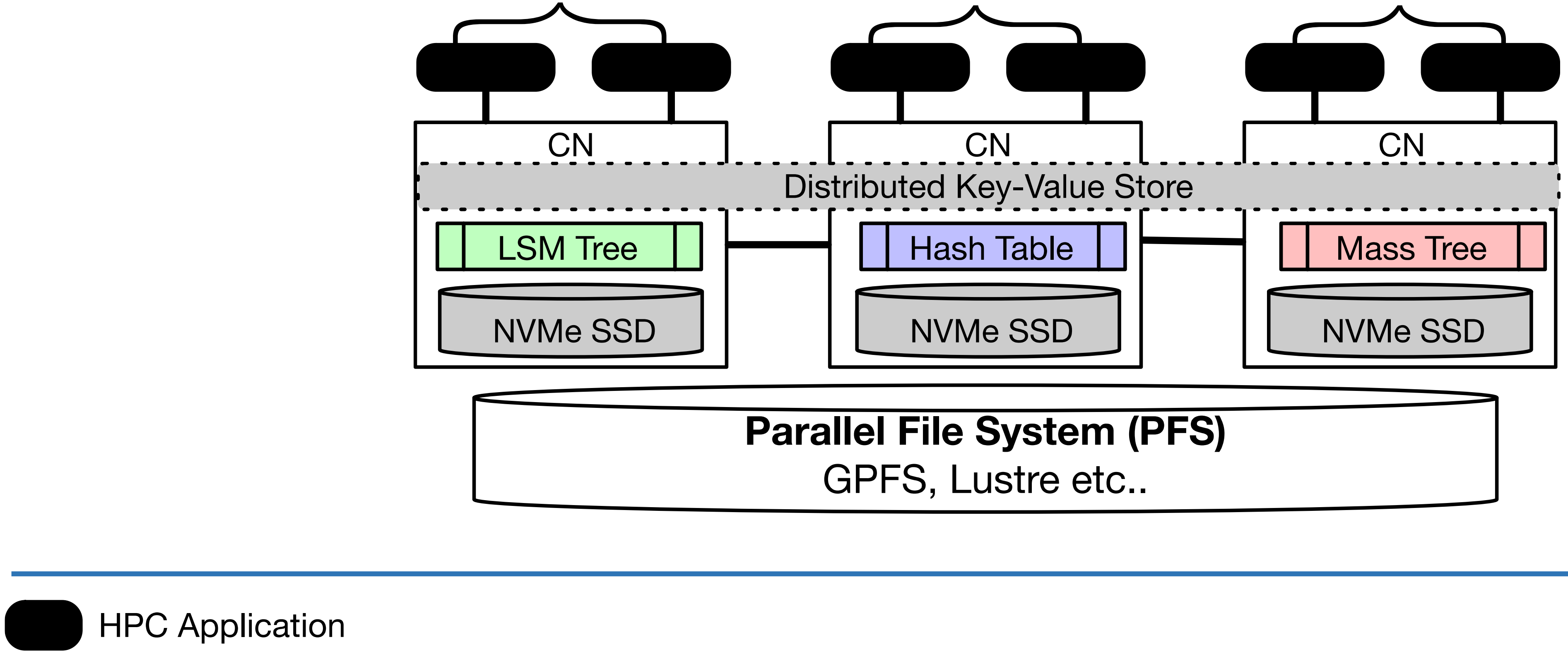
Outline

- ❑ Background
  - ❑ Distributed Key-Value stores in HPC
  - ❑ Log-Structured Merge (LSM) Tree-based KV stores
  - ❑ Deduplication 101
- ❑ Deduplication in HPC
- ❑ Proposed Architecture
  - ❑ DENKV: Design goals
  - ❑ Write and Read operation flow
- ❑ Evaluation
- ❑ Conclusion and Q&A

Background

Distributed Key-Value Stores in HPC

- Emerging storage technologies have opened new opportunities for the use of KV stores in HPC
  - The use-case includes storing intermediate results



Distributed Key-Value Stores in HPC

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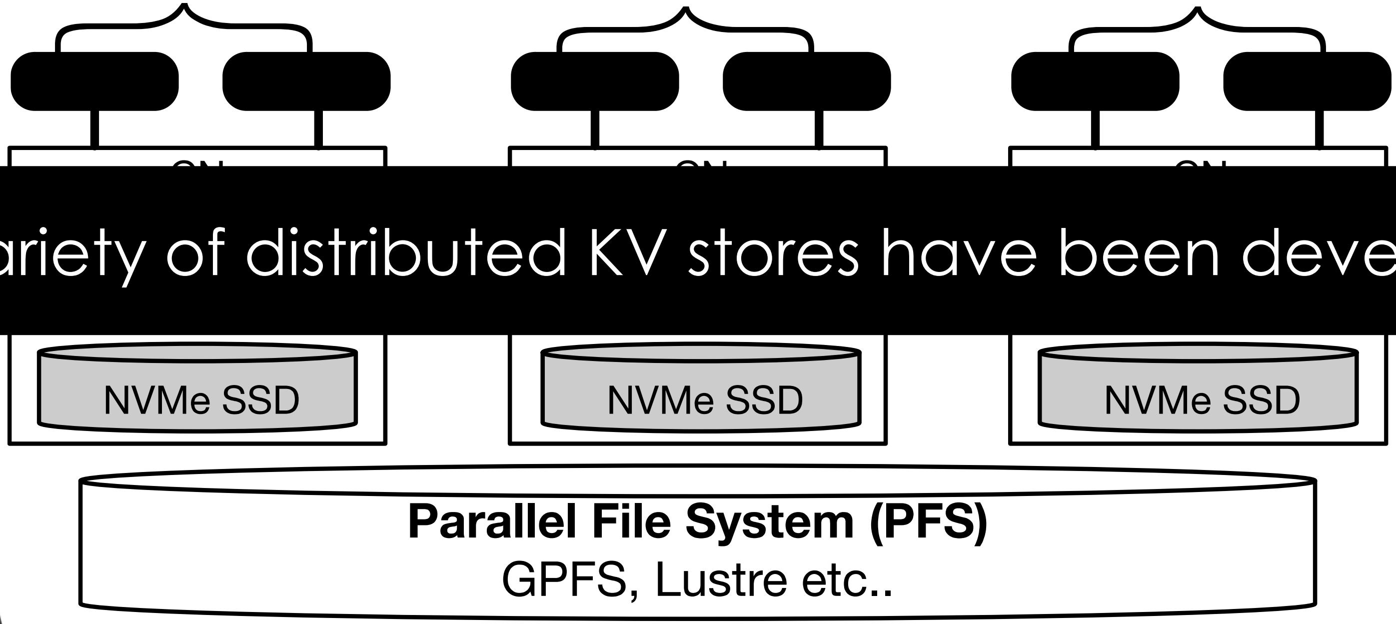
  - ❑ The use-case includes storing intermediate results

twitter/twemproxy

A fast, light-weight proxy for memcached and redis



❑ A variety of distributed KV stores have been developed.

HPC Application

HPC applications

- ❑ Compute and data intensive → Solve complex problems
- ❑ Execution time in weeks → Simulate world-class scenarios
- ❑ Generate huge amount of data
  - ❑ In terms of terabytes to petabytes
  - ❑ 4 petabytes of data generated for single image
- ❑ High IO bandwidth demand

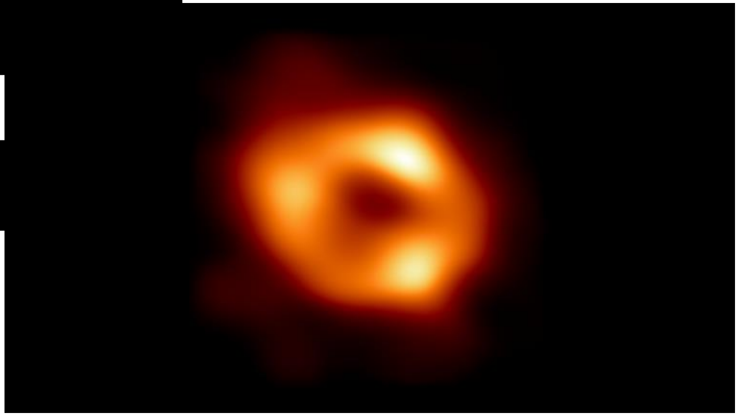
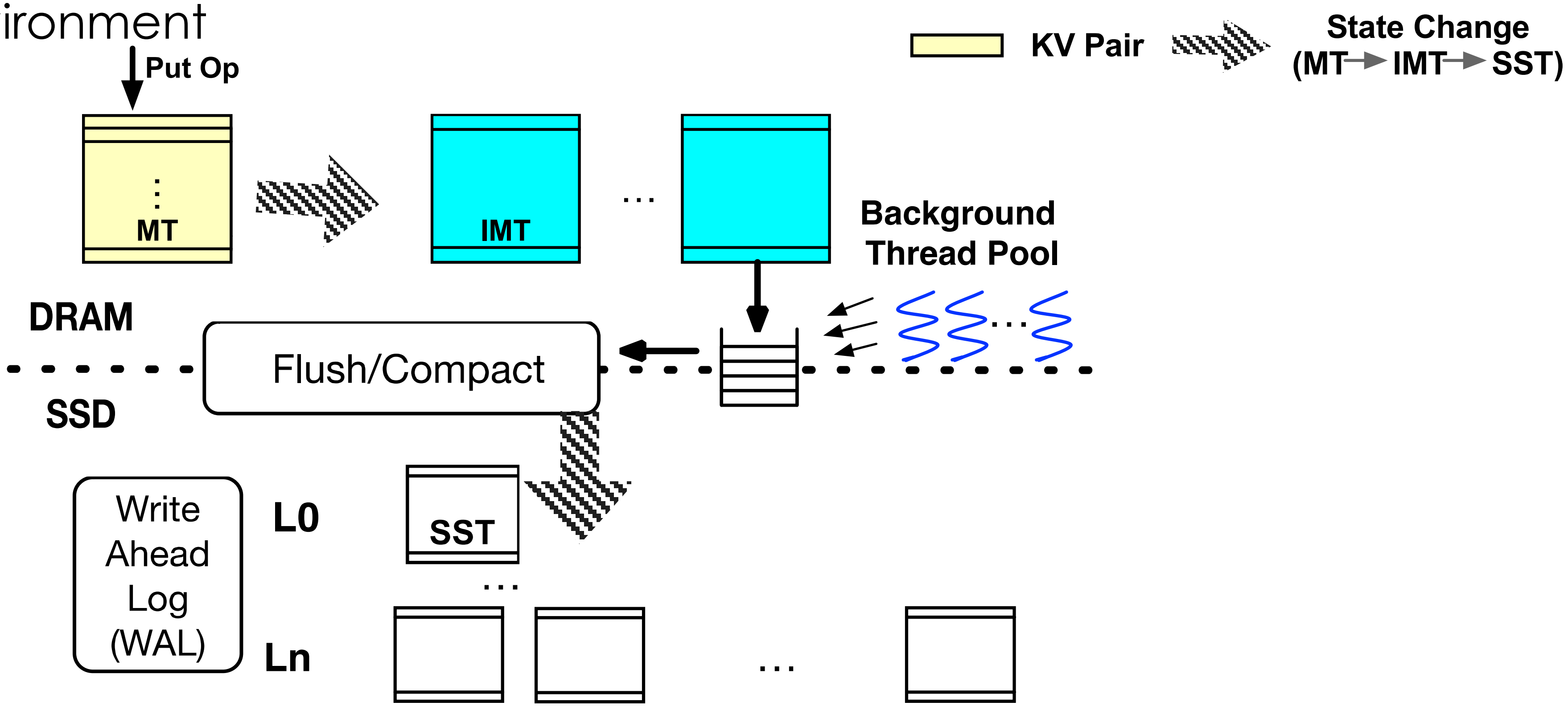


Photo credit: https://eventhorizontelescope.org/blog/astronomers-reveal-first-image-black-hole-heart-our-galaxy

Log-Structured Merge Tree-based Key-Value Stores

- Log-Structed merge (LSM) tree-based KV stores
  - Highly write-optimized
  - Suitable candidates for node-local NVMe SSDs or burst buffers in HPC environment



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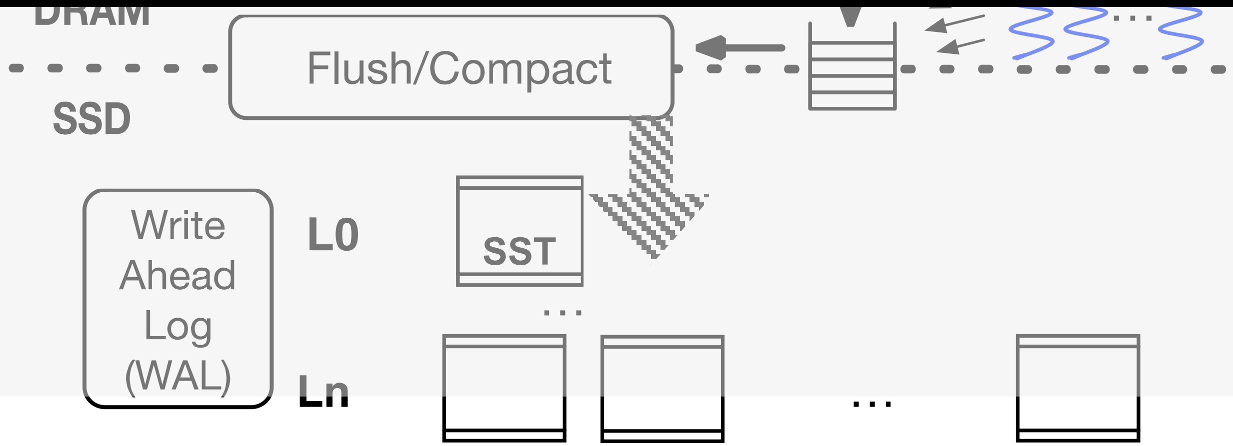
- Limitations of LSM-tree
  - High write amplification (WA) – more writes than application intended
  - High space amplification (SA) – more space utilization than application required



서강대학교 SOGANG UNIVERSITY

Log-Structured Merge Tree-based Key-Value Stores

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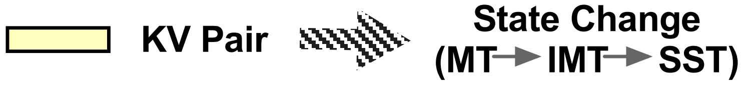

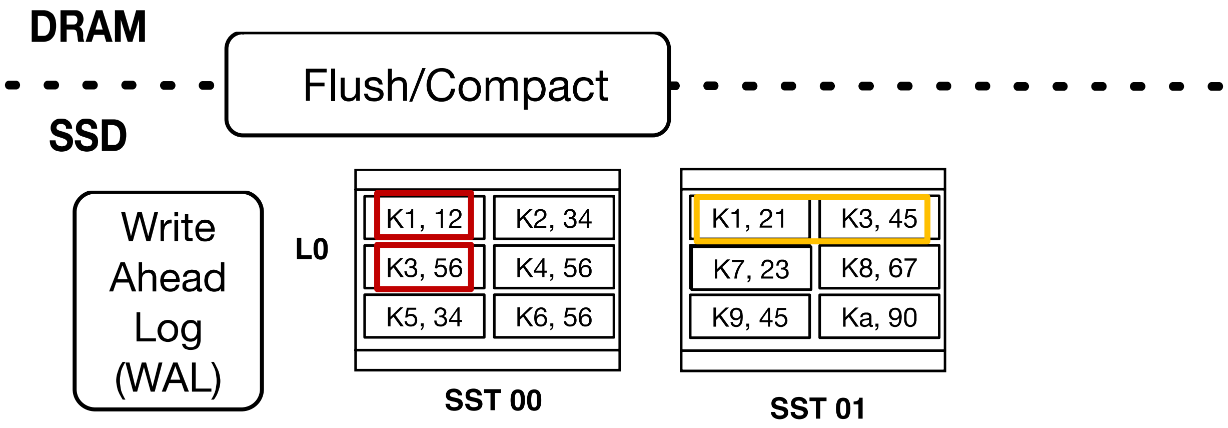

Updated key-value pair   Invalid key-value pair

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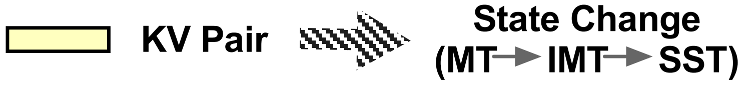
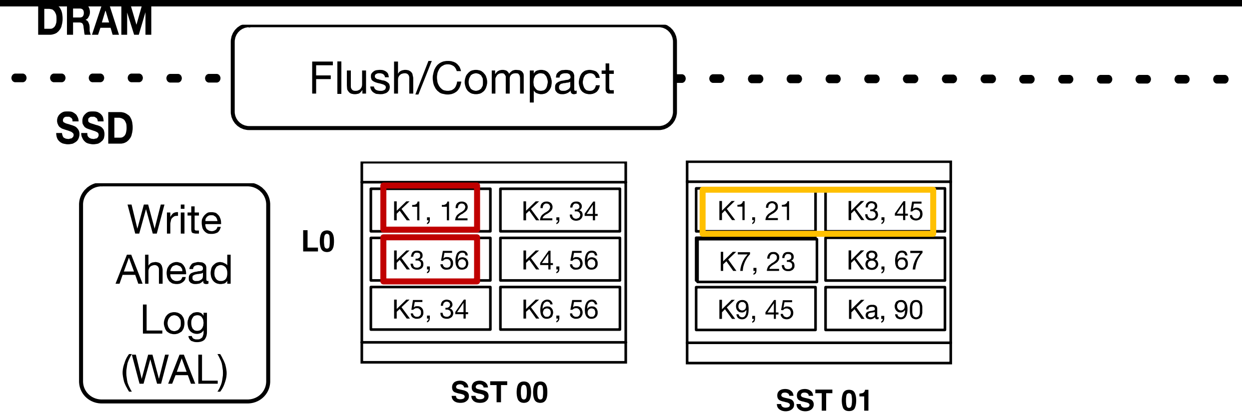


- Unclaimed invalid key-value pairs lead to space amplification



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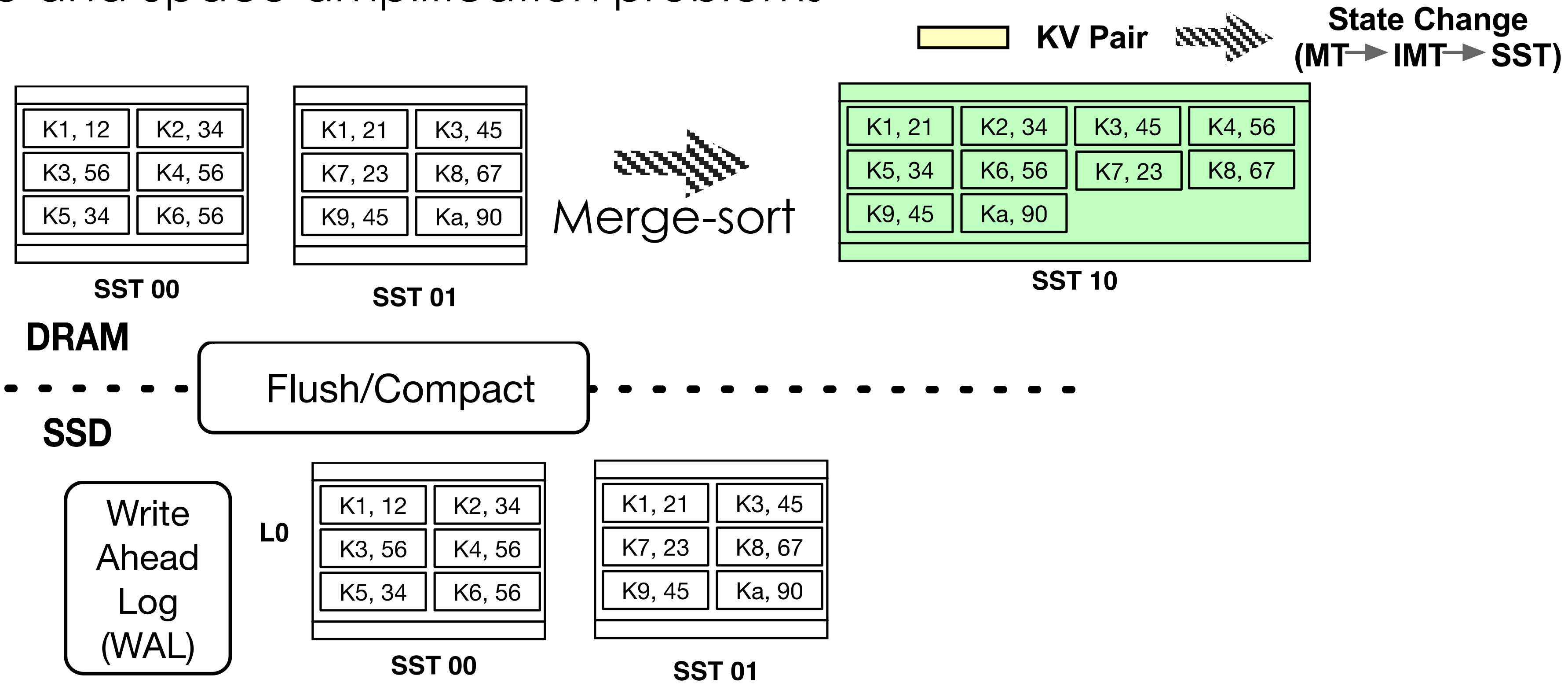

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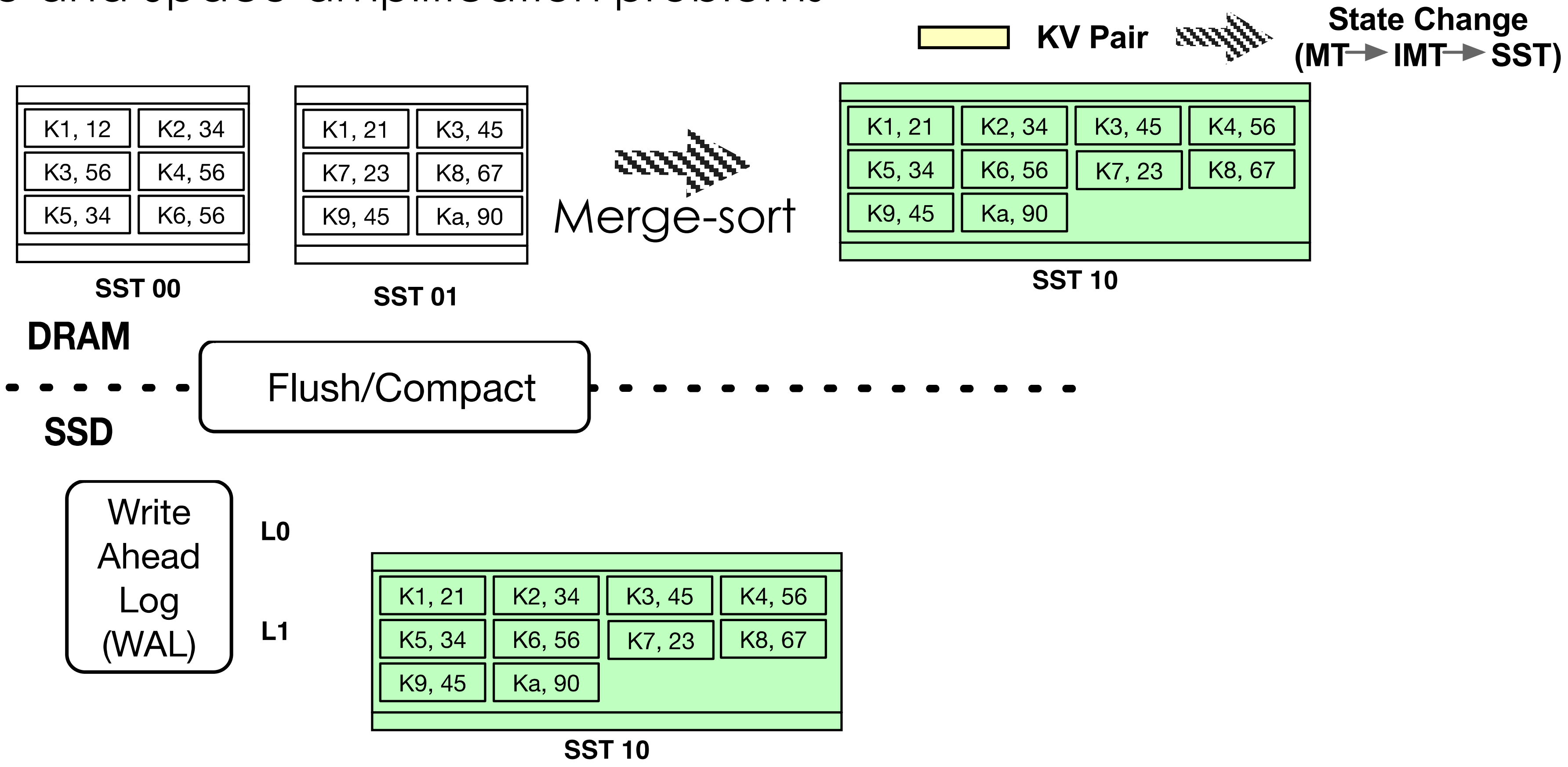

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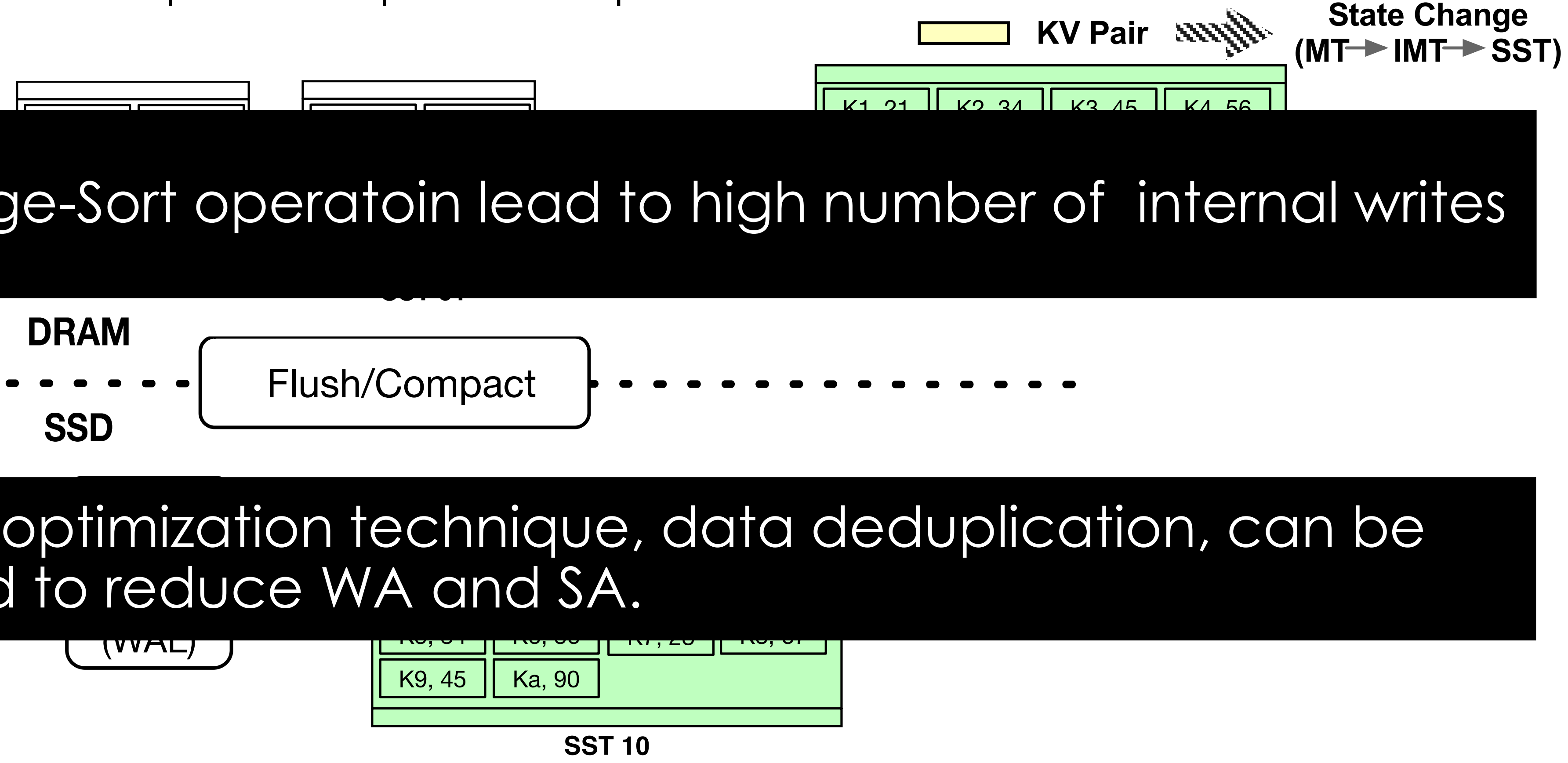
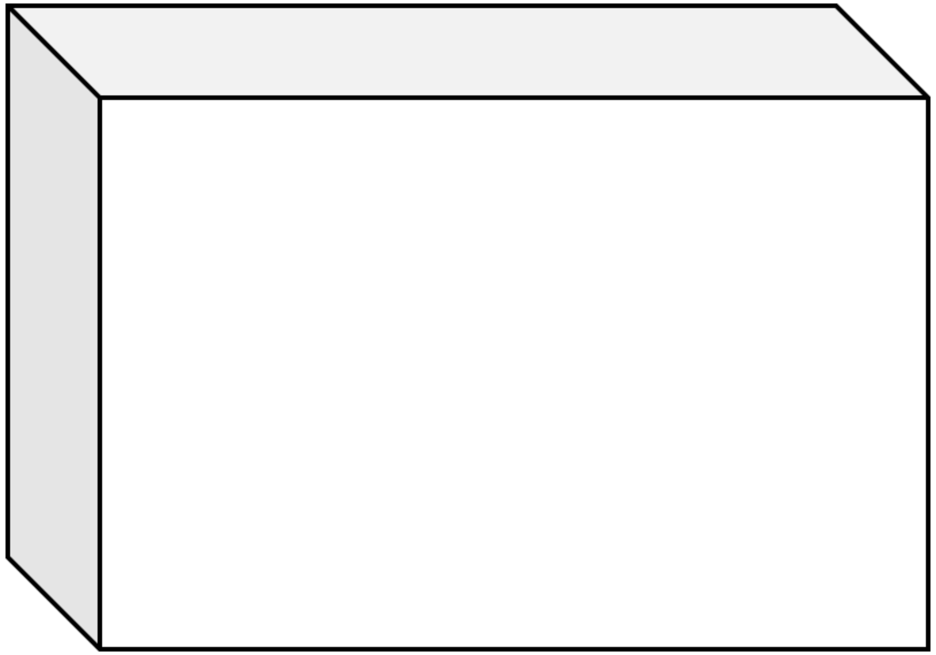


❑ This Merge-Sort operatoin lead to high number of internal writes

❑ Storage optimization technique, data deduplication, can be adopted to reduce WA and SA.

Deduplication 101

0. User Data



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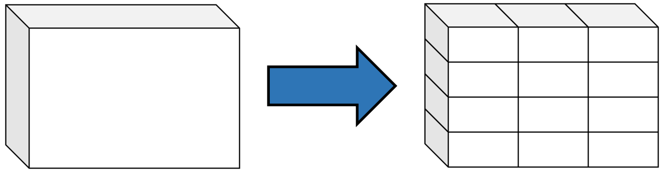
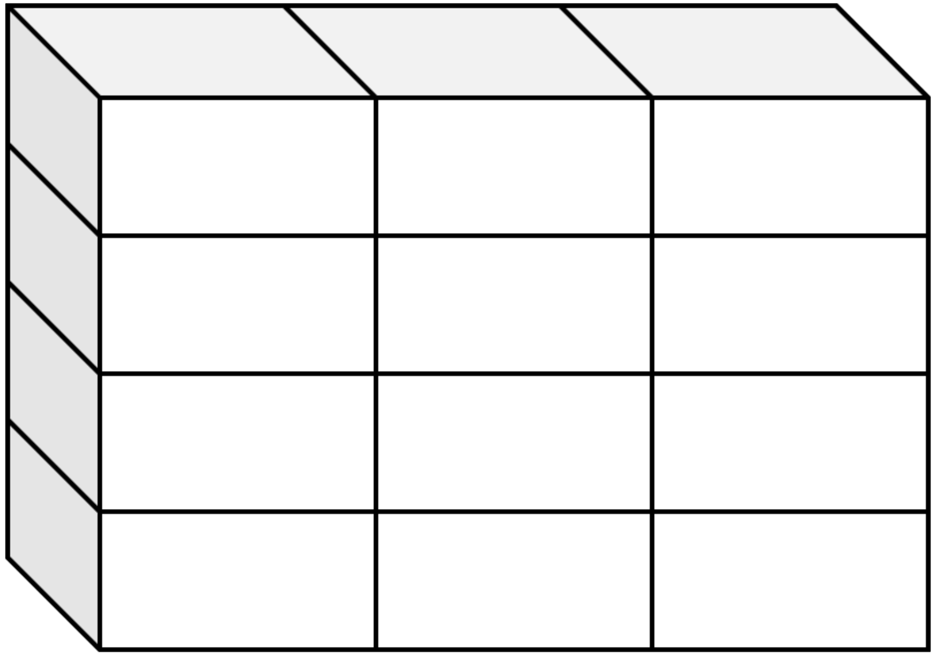
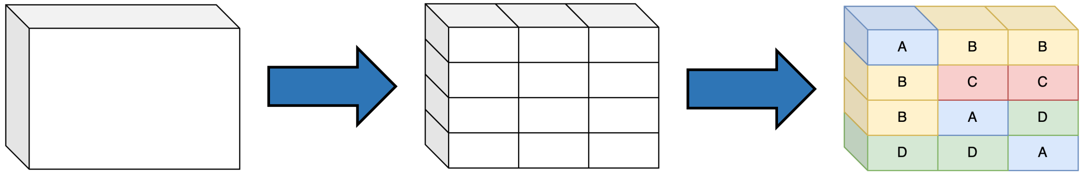


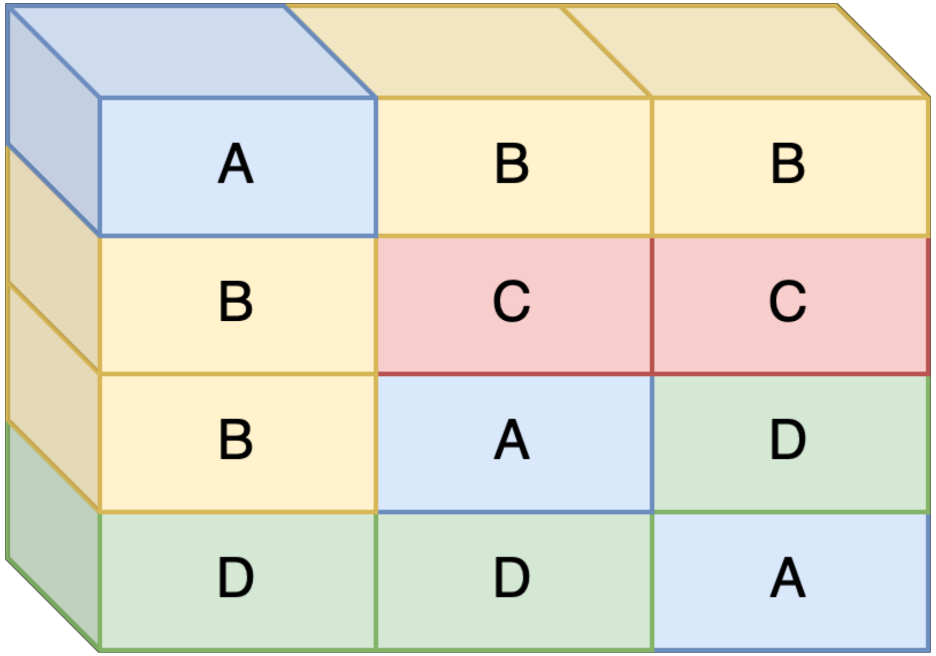


0. User Data

1. Chunking

Deduplication 101





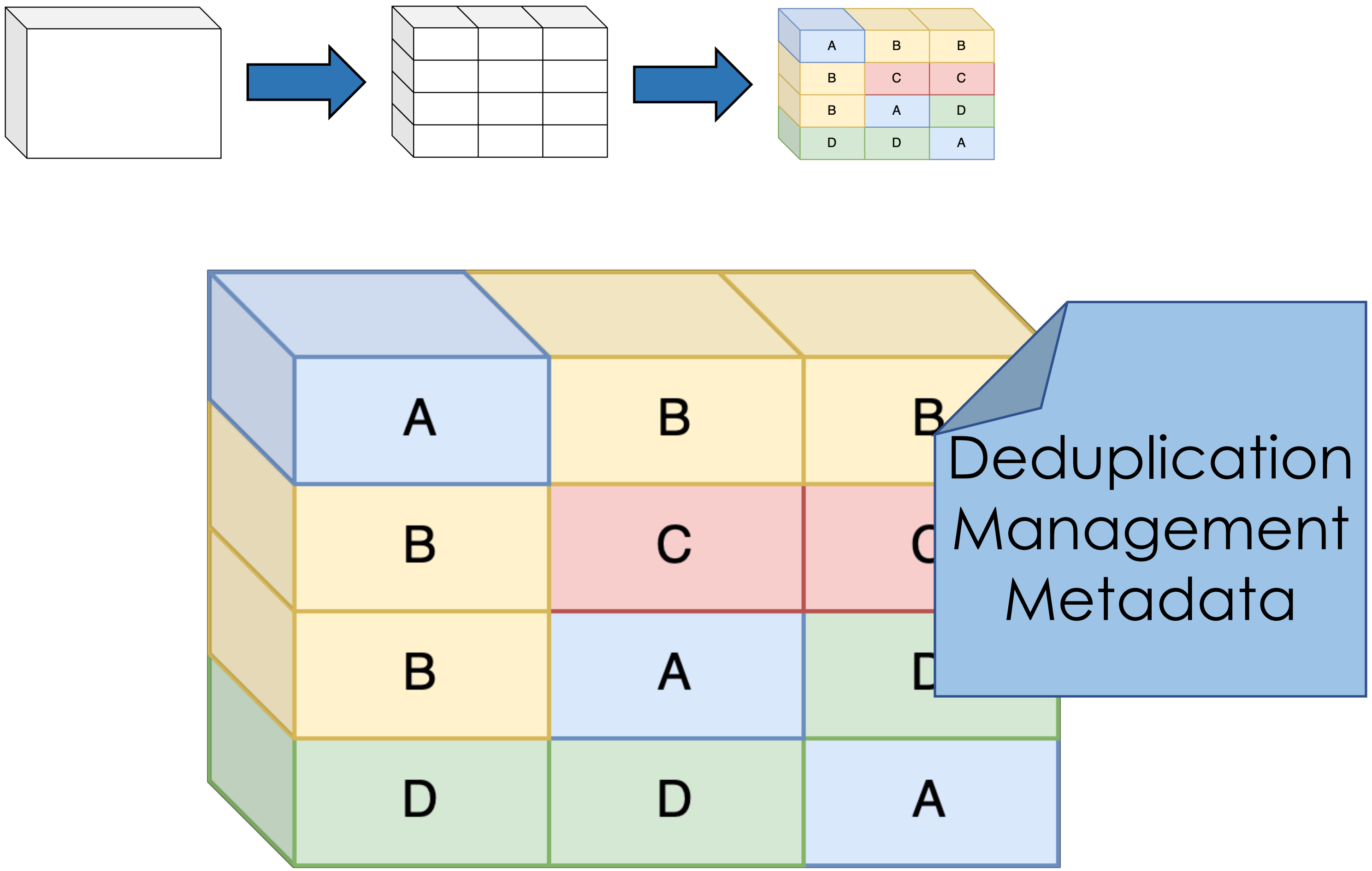
0. User Data

1. Chunking

2. Fingerprinting

Deduplication in HPC

Deduplication 101



0. User Data

1. Chunking

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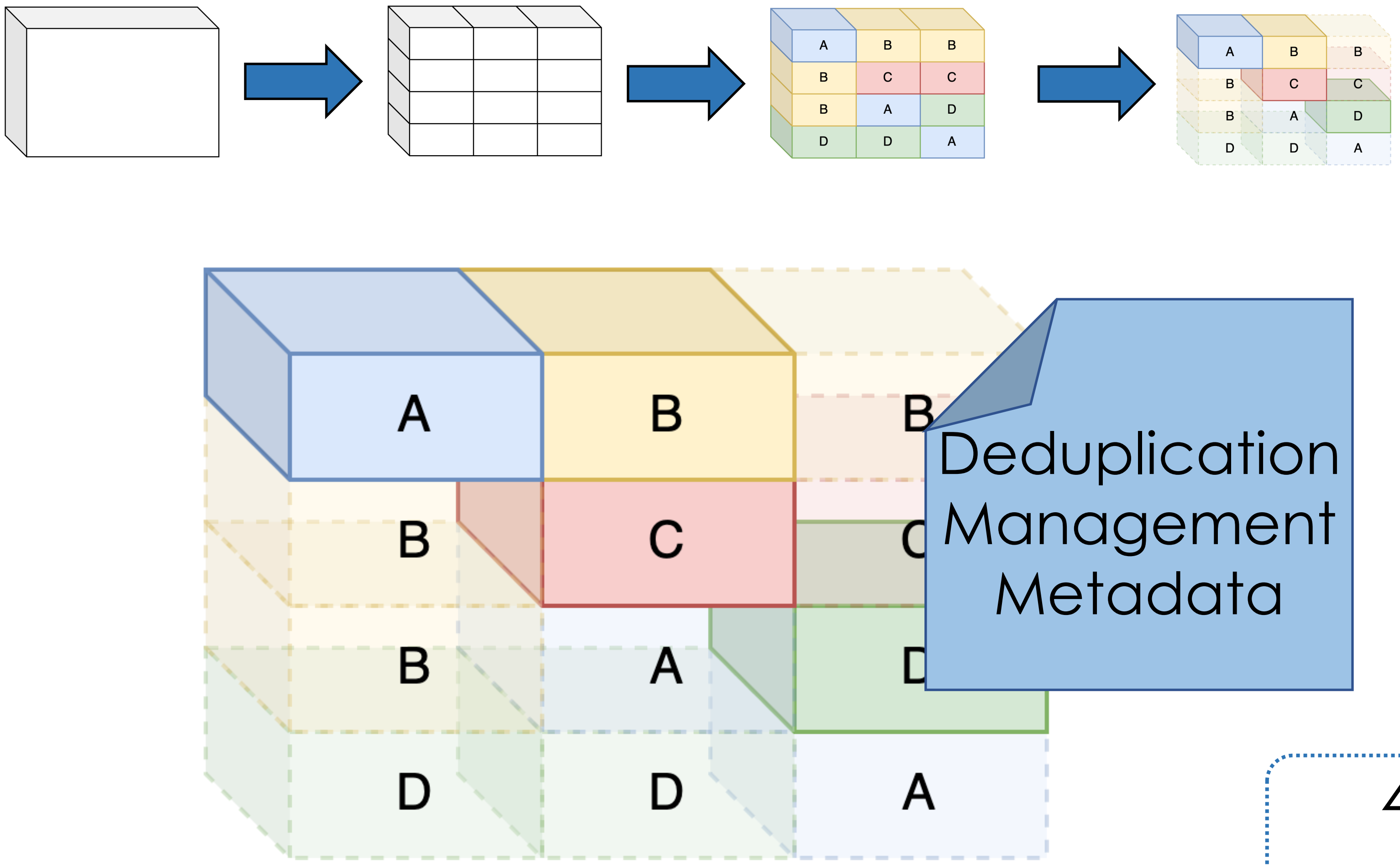
3. Duplicate Lookup

Deduplication in HPC

Deduplication 101



0. User Data
1. Chunking
2. Fingerprinting
3. Duplicate Lookup
4. Update Deduplication Metadata

Classification of Deduplication

- Inline Deduplication
  - Performs deduplication during the write process (within critical section)
  - Normally increased write latency
  - Helps improve write endurance problem
  - Immediate improvement of storage

- Offline Deduplication
  - Performs deduplication after the write process finishes (outside of critical section)
  - Lowers write latency compared to inline deduplication
  - Requires temporal storage space to acquire the duplicate data

Deduplication in HPC

Deduplication in HPC applications datasets

- Korean Institute of Science and Technology Information (KISTI) host 5th Supercomputer, Nurion
- A petaflop machine ranked 11th in 2018 by Top500
- Peak performance of 25.3 petaflops
- Cray CS500 with 8,305 compute nodes
- 21 Petabytes of Storage
- Lustre File system

Deduplication in HPC applications datasets

- Collected Top 10 applications dataset at Nurion supercomputer[*]
- Sample of data is collected for only 10 minutes copying
- Implemented in-house deduplication analysis tool
- Analyzed the deduplication ratio
  - Deduplication ratio – amount of data that can be removed

Application	Total Size	Dedup. Ratio	Application	Total Size	Dedup. Ratio
Abacus	386 GB	41.8 %	CESM	273 GB	25.7 %
Charmm	382 GB	23.1 %	Gaussian	293 GB	20.4 %
Lammps	24 GB	42.5 %	MOM	323 GB	53.9 %
MPAS	197 GB	81.7 %	Siesta	566 GB	52.1 %
VASP	1 TB	27.3 %	ANSYS	544 GB	23.8 %

[*]. https://www.ksc.re.kr/eng/resource/nurion

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- HPC applications generate highly redundant data [SC'12].

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Deduplication in LSM-tree

- Novel way to minimize WA and SA
- Incorporating value-based deduplication
  - Can help reduce the actual size of KV store
- Adopting deduplication at tradition LSM-tree

Performance overhead of inline dedup at MemTable

Breaks structural constraints at SSTables
(Single instance of valid KV Pairs)

Complex compaction operation

Deduplication in LSM-tree

- ❑ Adopting deduplication at tradition LSM-tree

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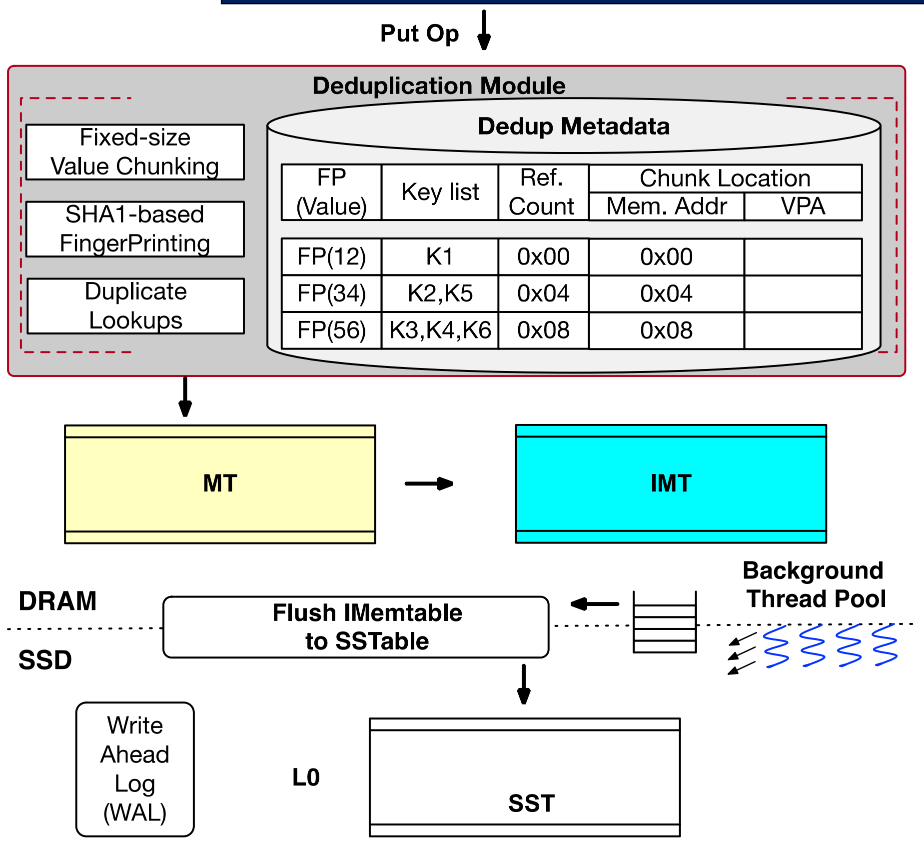
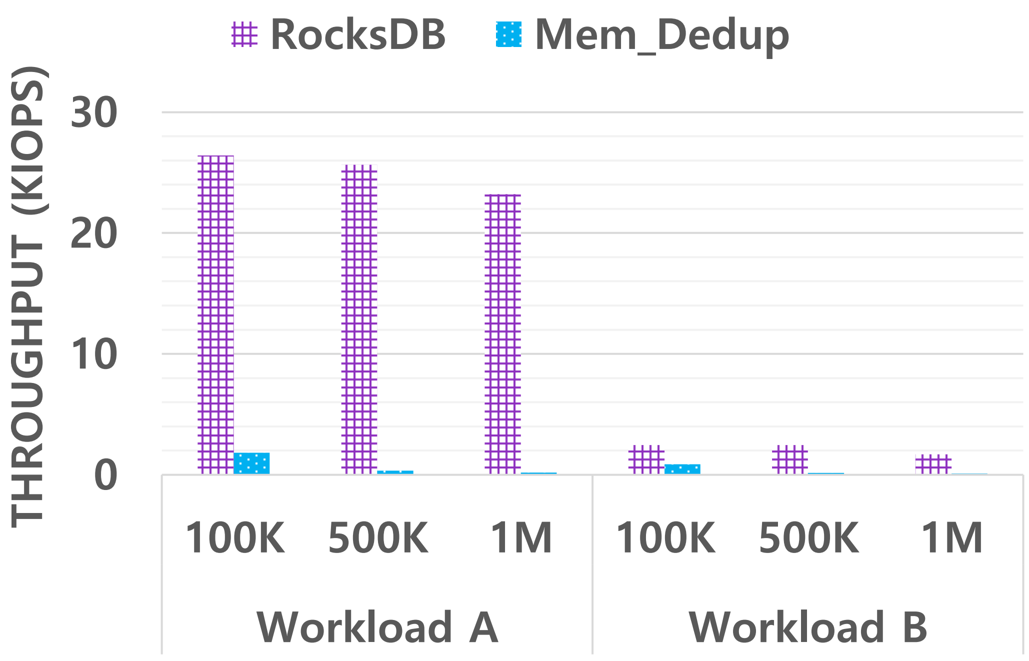
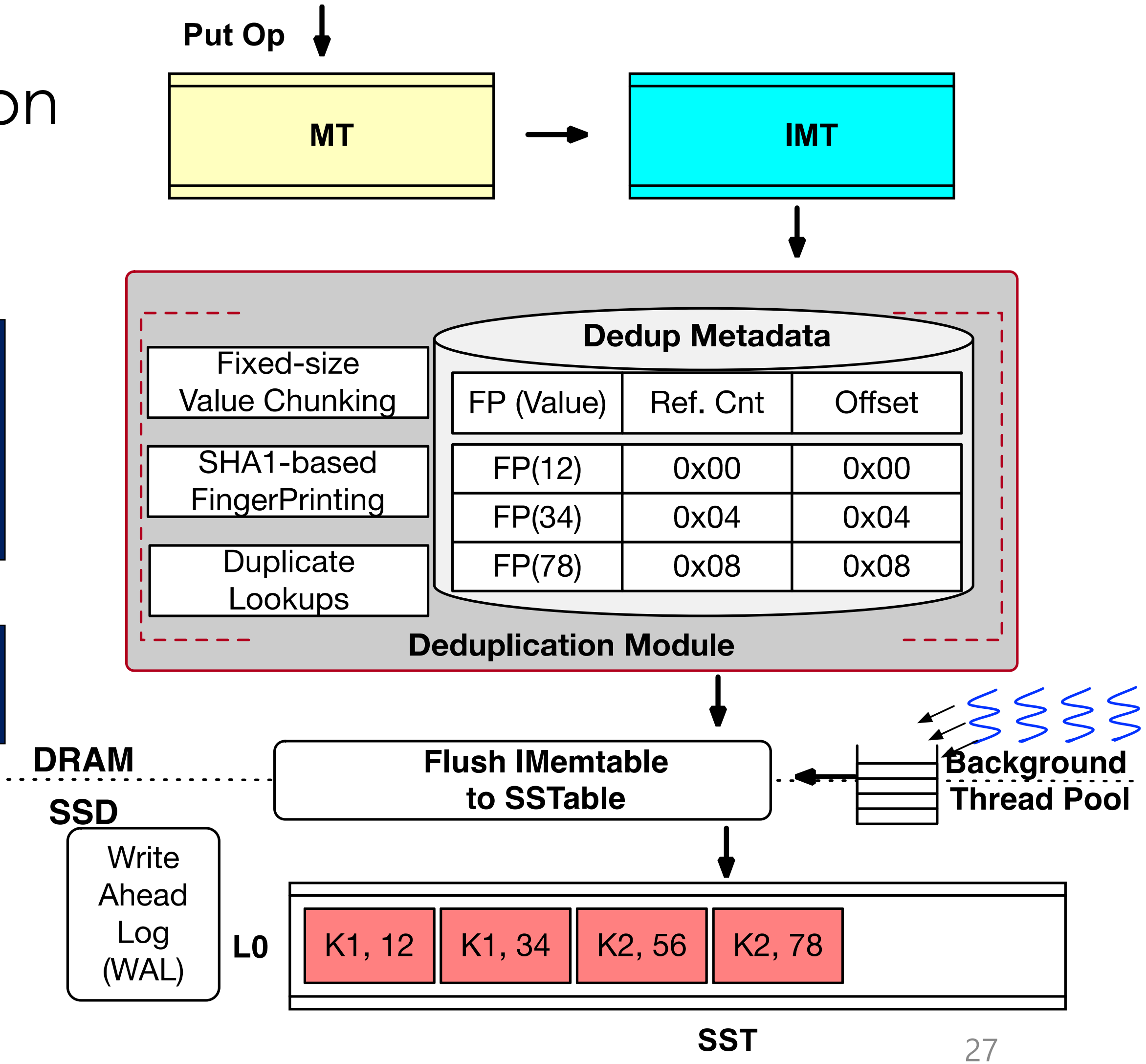




YCSB Benchmark | Workload A: 100% Write | Workload B: 50% write & 50% read

Deduplication in LSM-tree

- ❑ Adopting deduplication at tradition LSM-tree



Breaks structural constraints at SSTables (Single instance of valid KV Pairs)

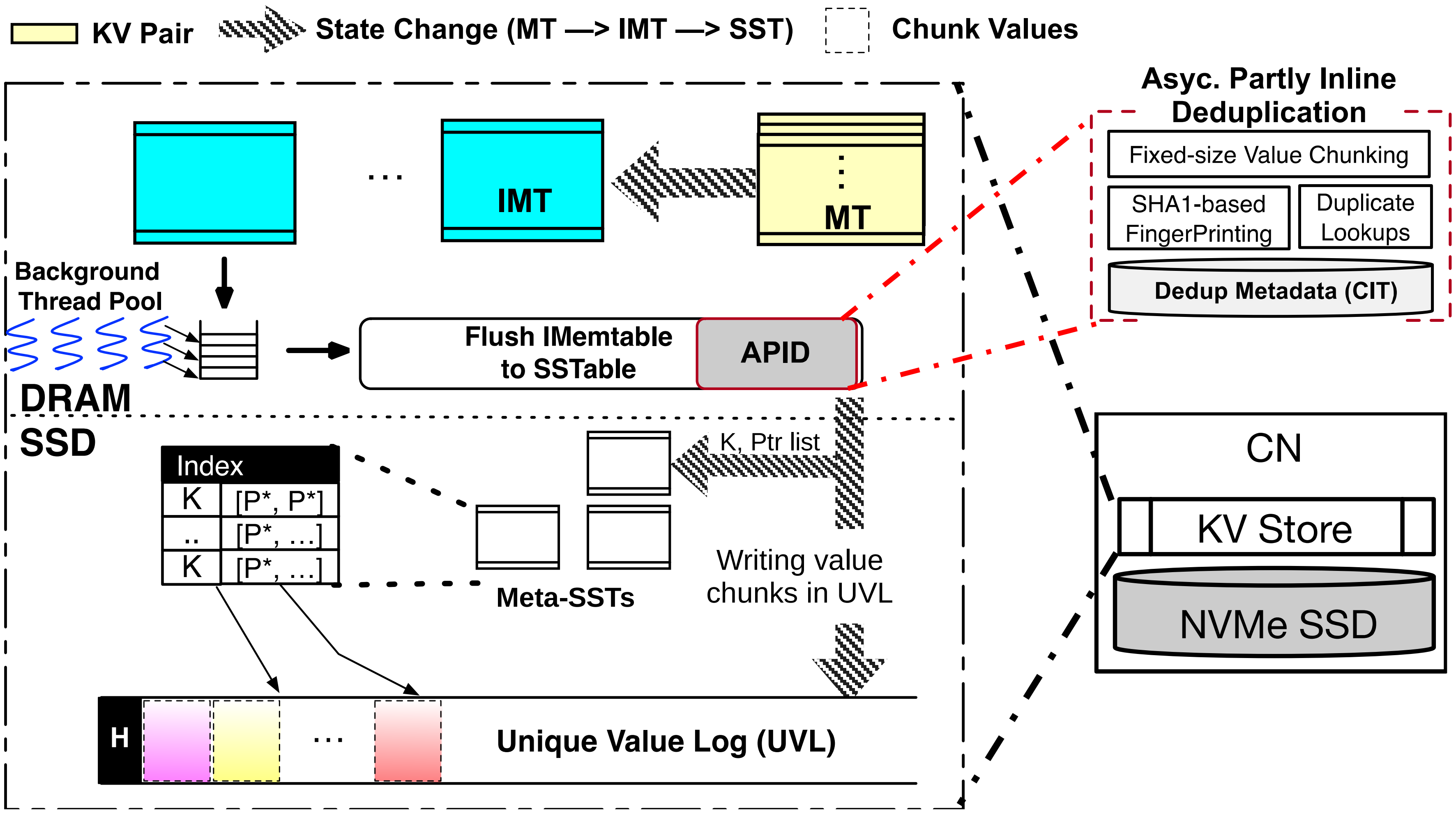
Complex compaction operation

Proposed Architecture

DENKV: Deduplication-extended Node-local LSM-tree-based Key-value Store

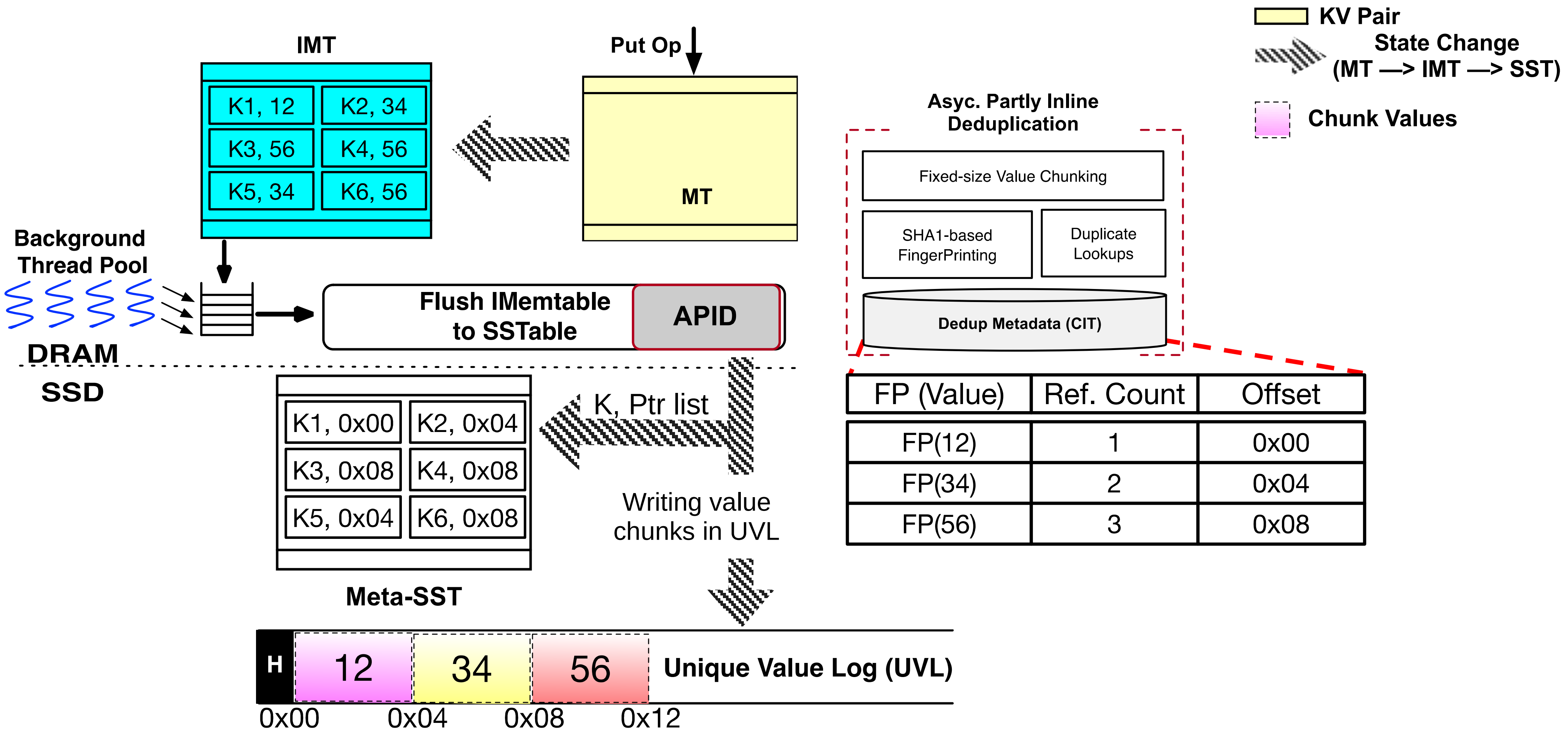
- Design Goals
  - Maintain performance characteristics of LSM-tree
  - Minimum deduplication overhead for client operations
  - Reduce write and space amplification
  - Maintain the structural constraint of LSM-tree

DENKV: Design Overview

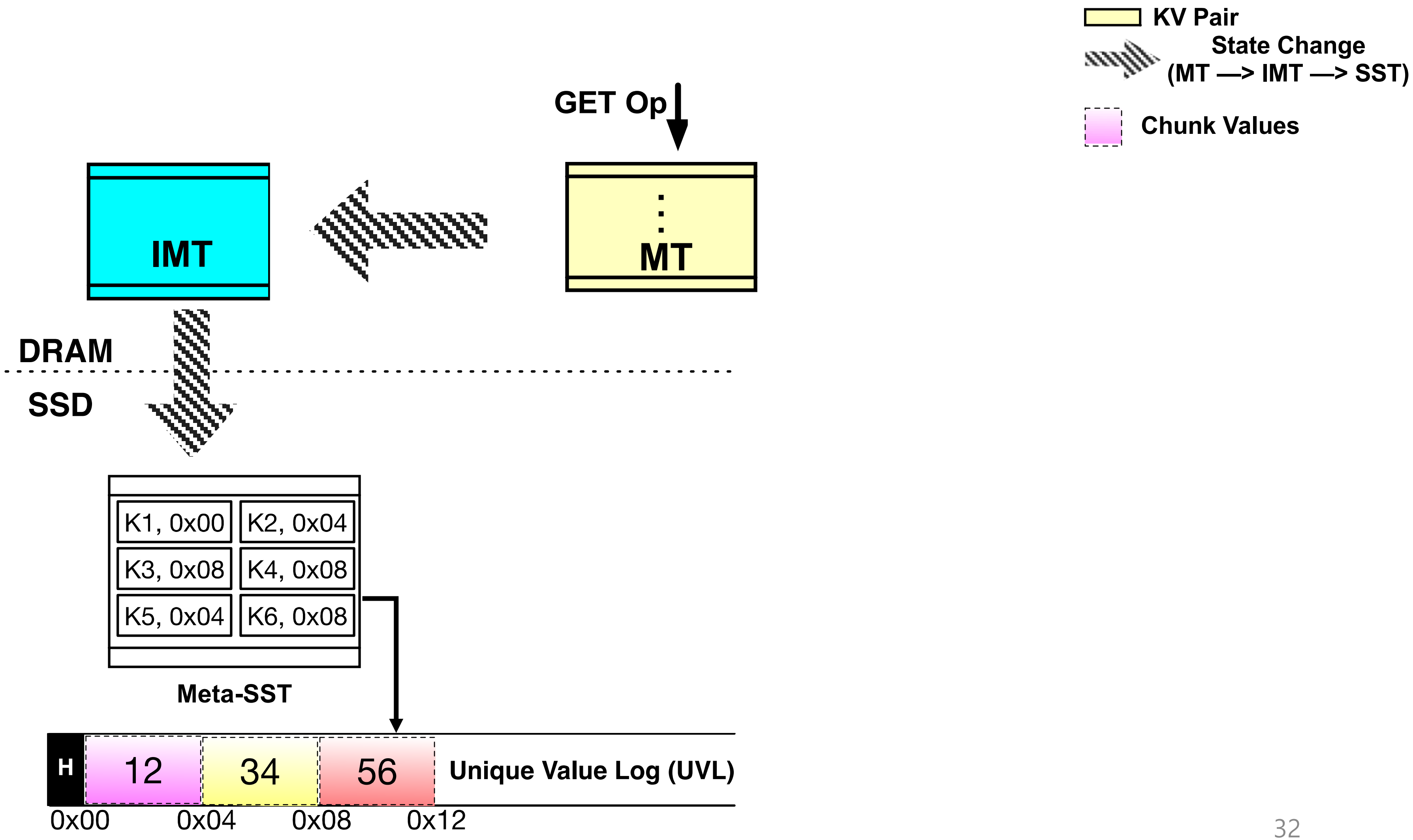


- ➢ Asynchronous
  - Background thread pool
- ➢ Partly inline
  - Out of critical section

DENKV: Write Operation Flow



DENKV: Read Operation Flow



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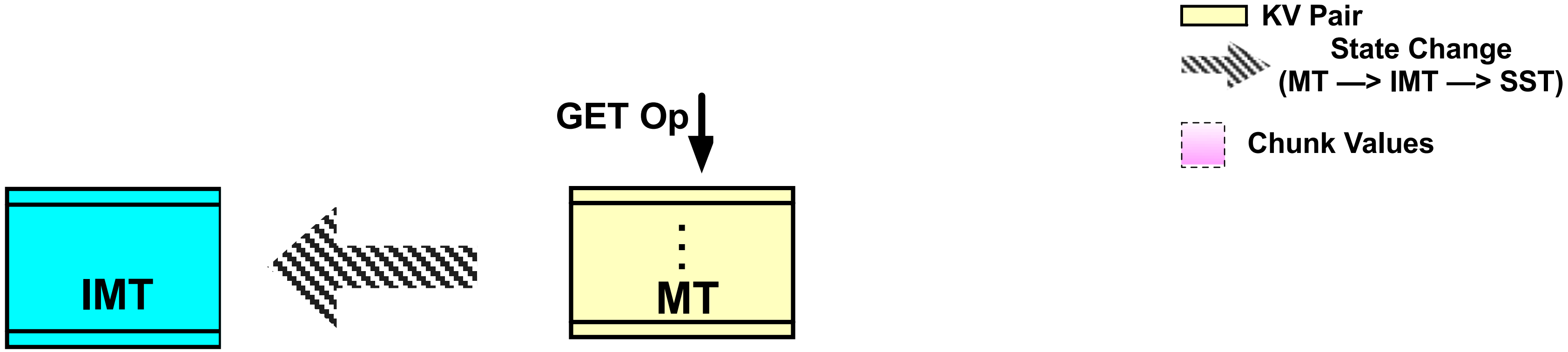
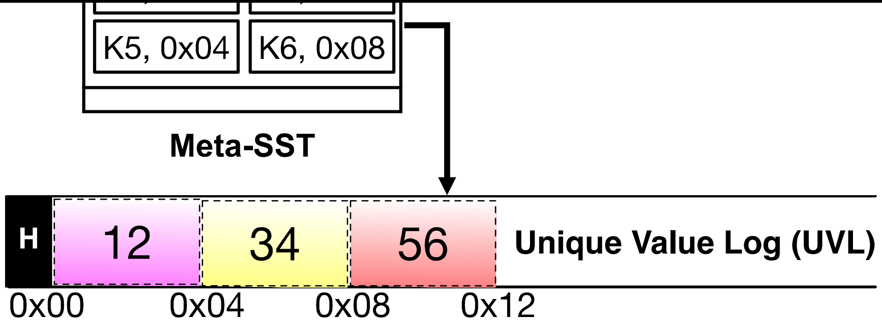


Refer Manuscript

- ❑ Garbage Collection
- ❑ Crash Consistency of Chunk Information Table



Evaluation

System configuration

System Setup

CPU	Intel(R) Xeon(R) CPU E5-4640 v2 @ 2.20GHz 4 CPU nodes (10 cores per node)
DRAM	256 GB DDR3 DRAM
Storage	Samsung SSD 970 EVO 1TB

Benchmark

- In-house simulation of dedup patterns of HPC application
- Varying value sizes: 4KB and 1MB
- Fixed size keys 16 bytes
- 1 Million KV pairs for 4KB
- 100 thousand KV pairs for 1MB

Compared systems

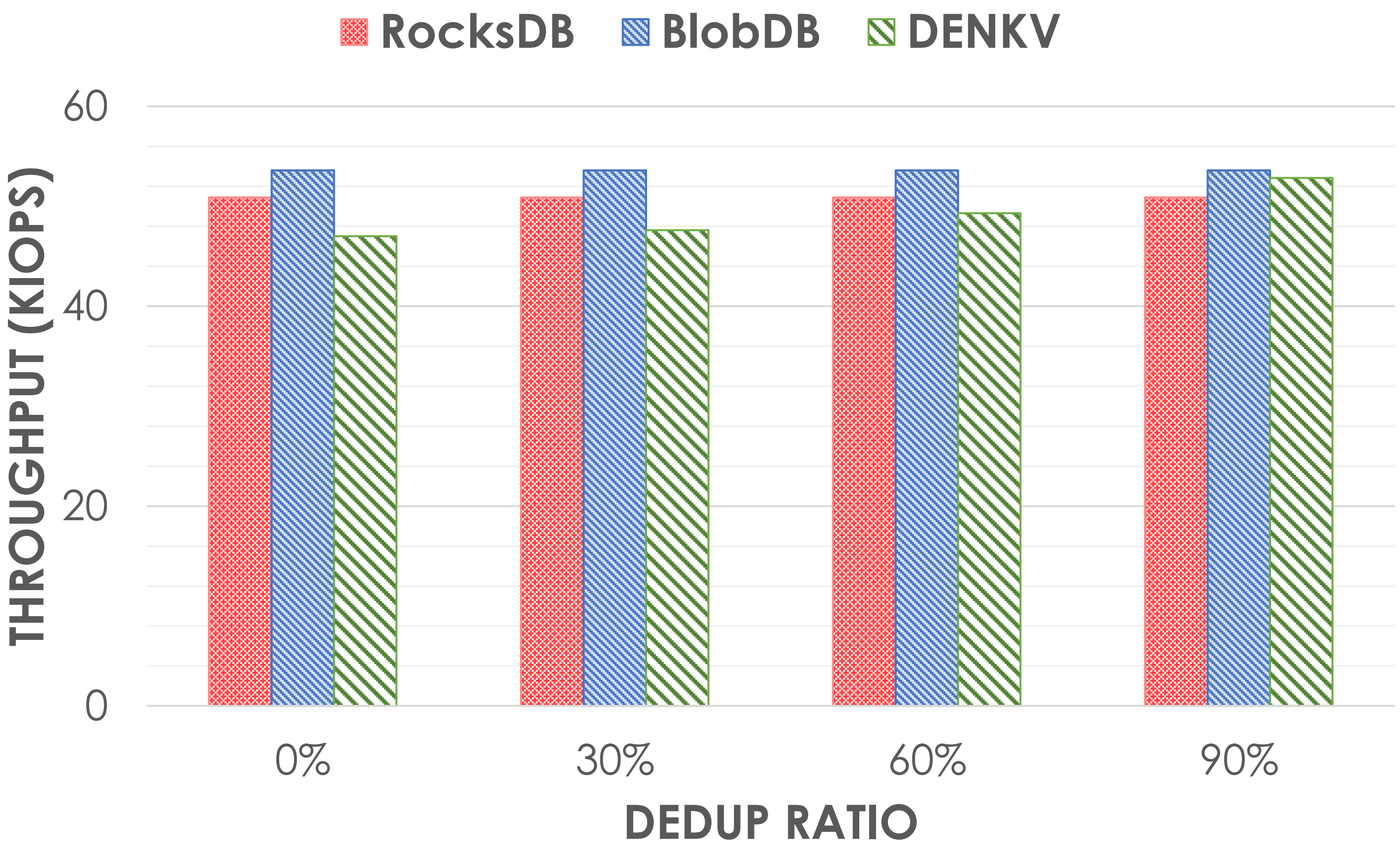
- RocksDB
  - Vanilla LSM-Tree based KV Store
  - Follows the traditional LSM-Tree structure
- BlobDB
  - KV separation design atop of RocksDB
  - Optimized for write and read operations
- DENKV
  - Our proposed deduplication incorporated KV Store

Questions to be answered

- How much deduplication influence the performance in general?
- How much write amplification is reduced?
- How much space amplification is reduced?
- What are the bottlenecks?

Performance analysis

- 4 KB KV Pairs



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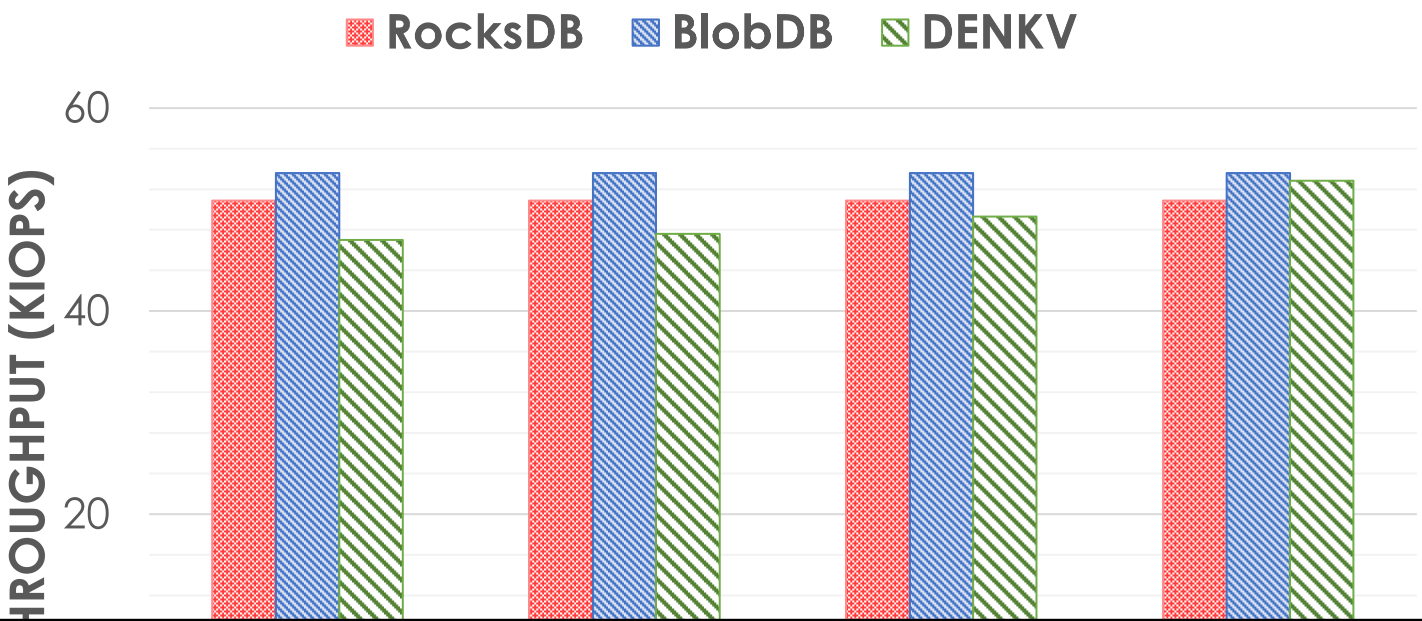
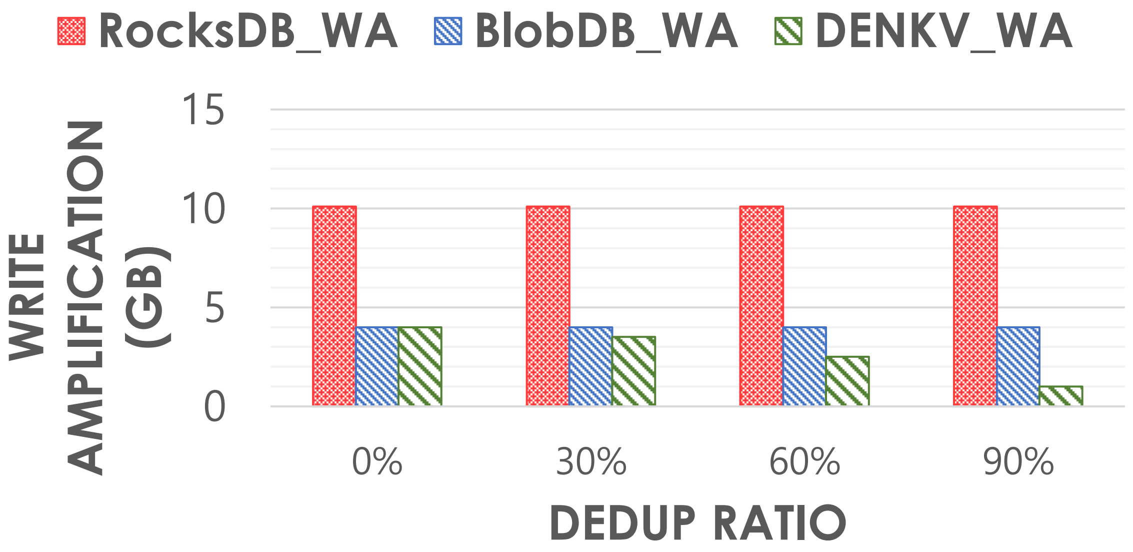


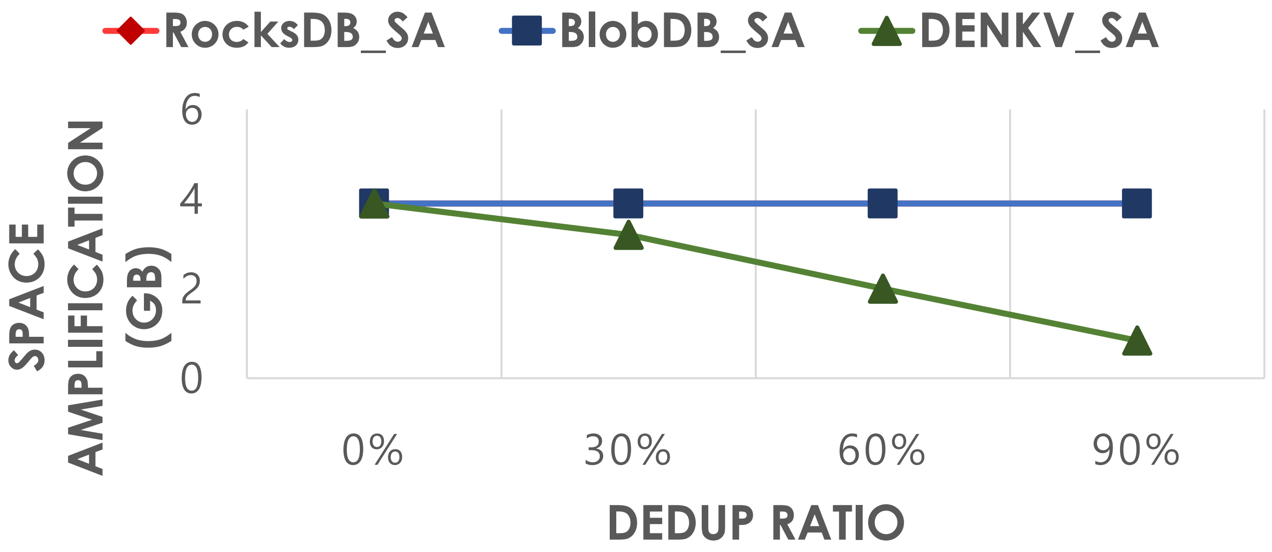
❑ Performance drops due to extra deduplication steps

❑ With increasing dedup ratio, performance improves

Write and space amplification analysis

- 4 KB KV Pairs





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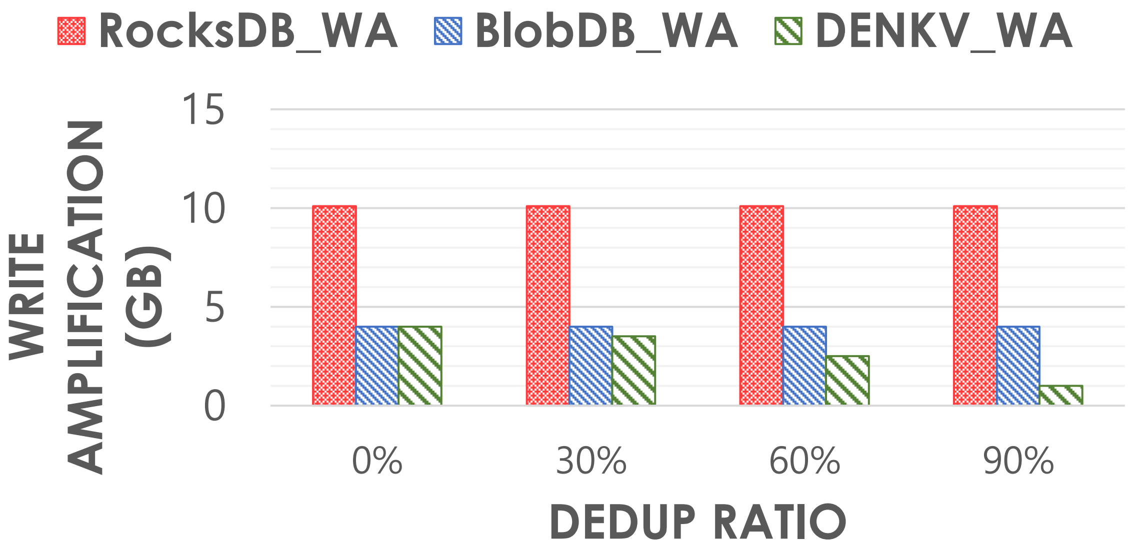
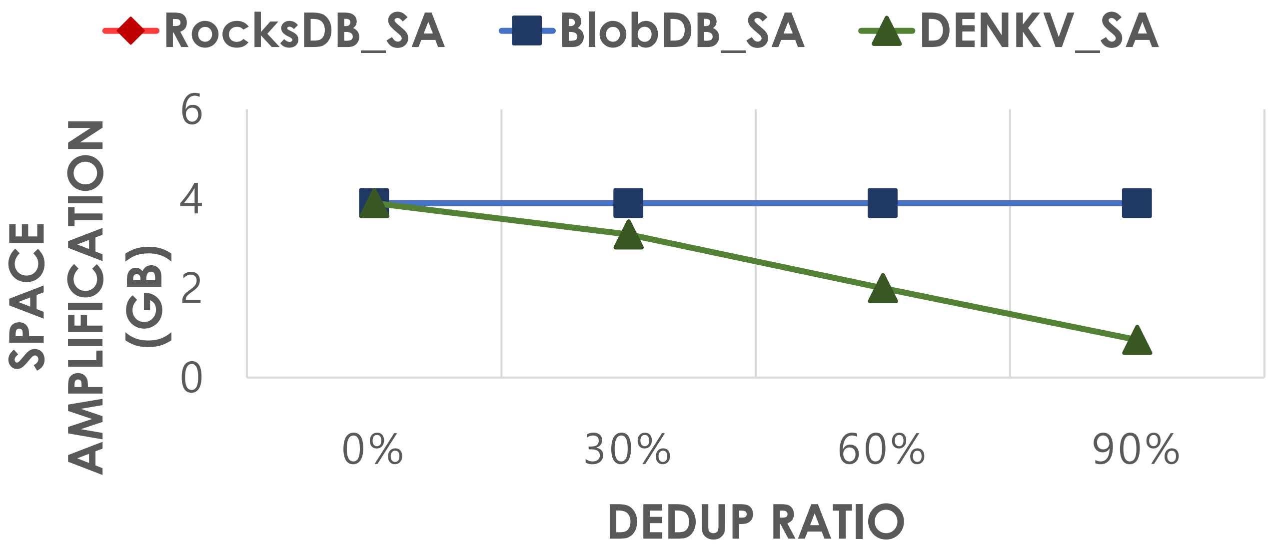
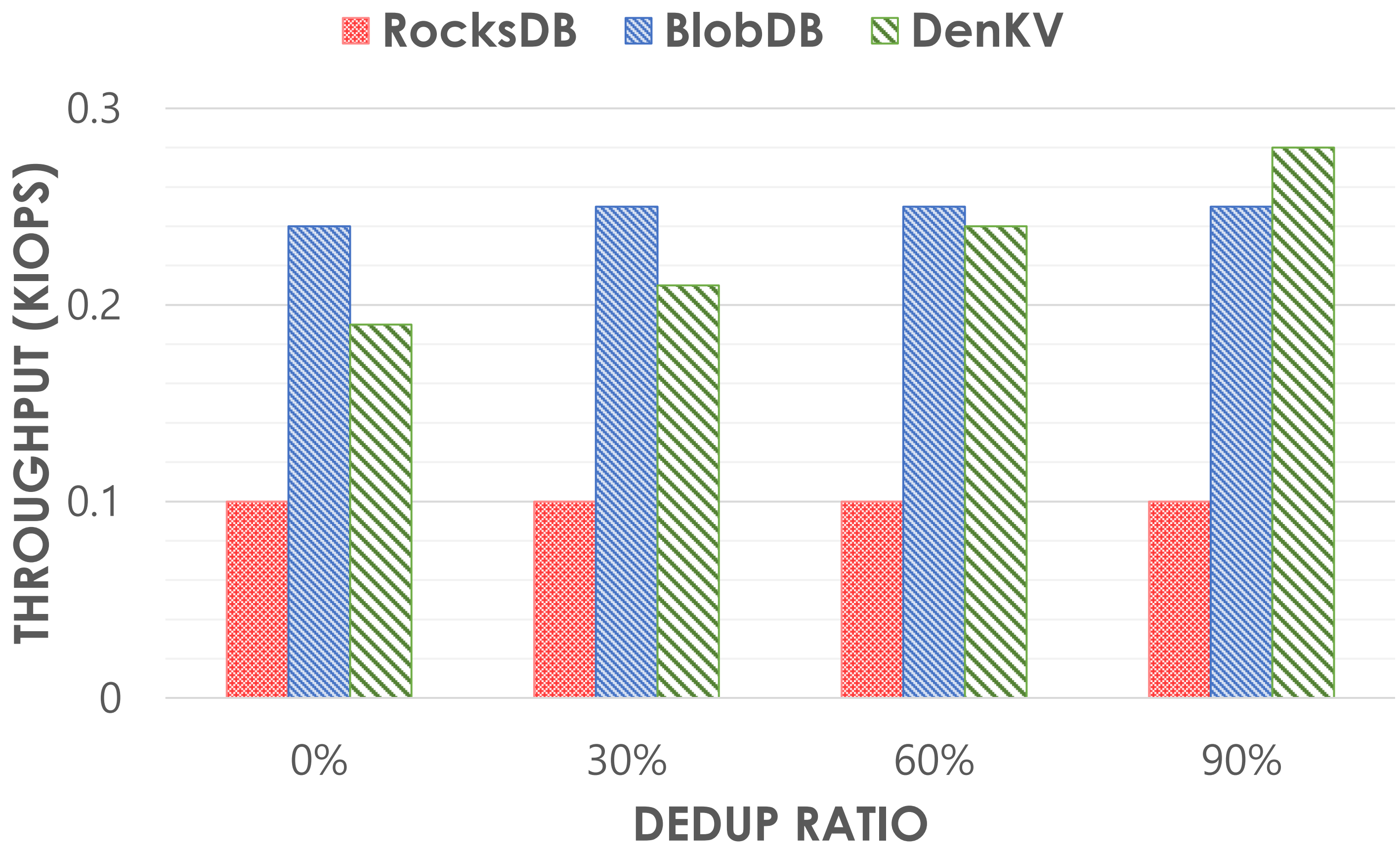




- ❑ 4x WA reduced with small KV pairs
- ❑ 4.6x SA reduced with small KV pairs

Performance analysis

- 1 MB KV Pairs



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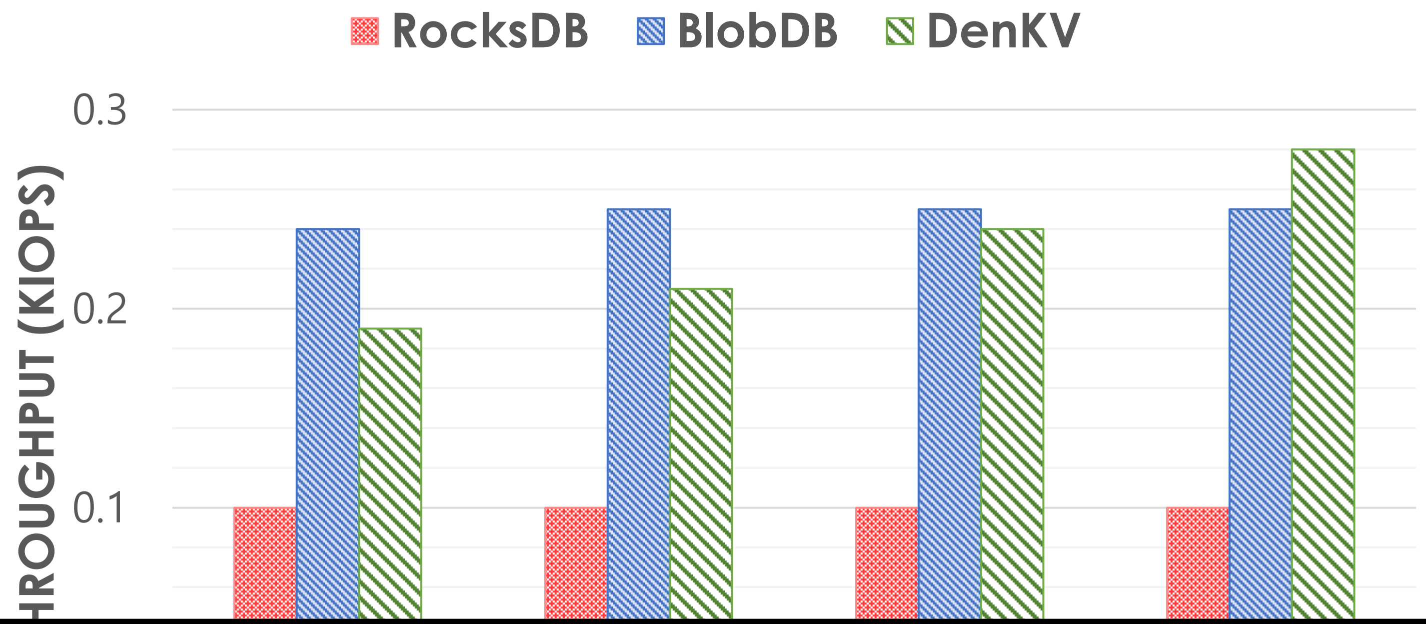

❑ Performance drops due to extra deduplication steps

❑ Outperforms all with highest dedup ratio

Write and space amplification analysis

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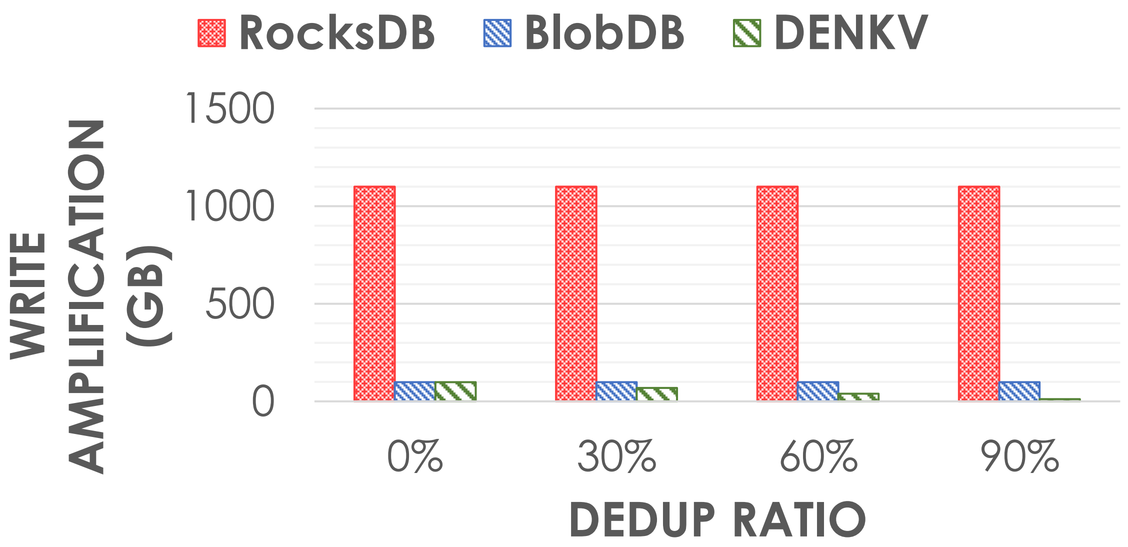

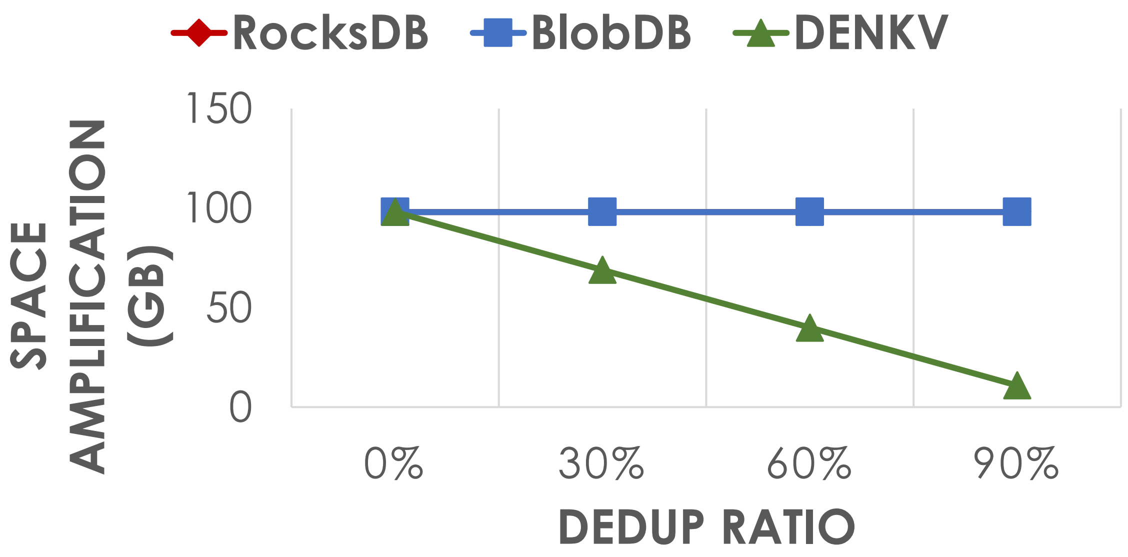

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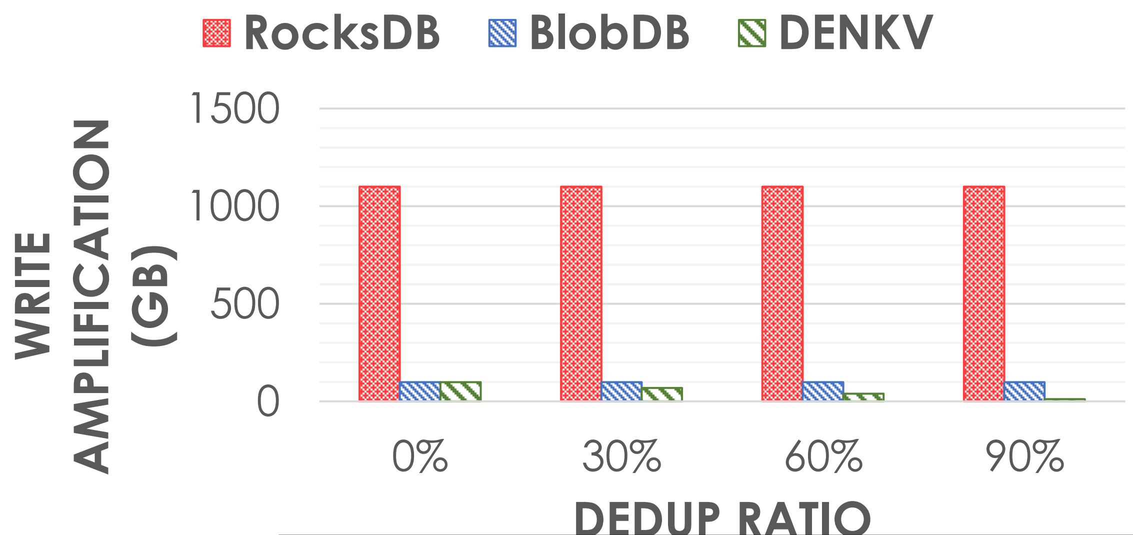

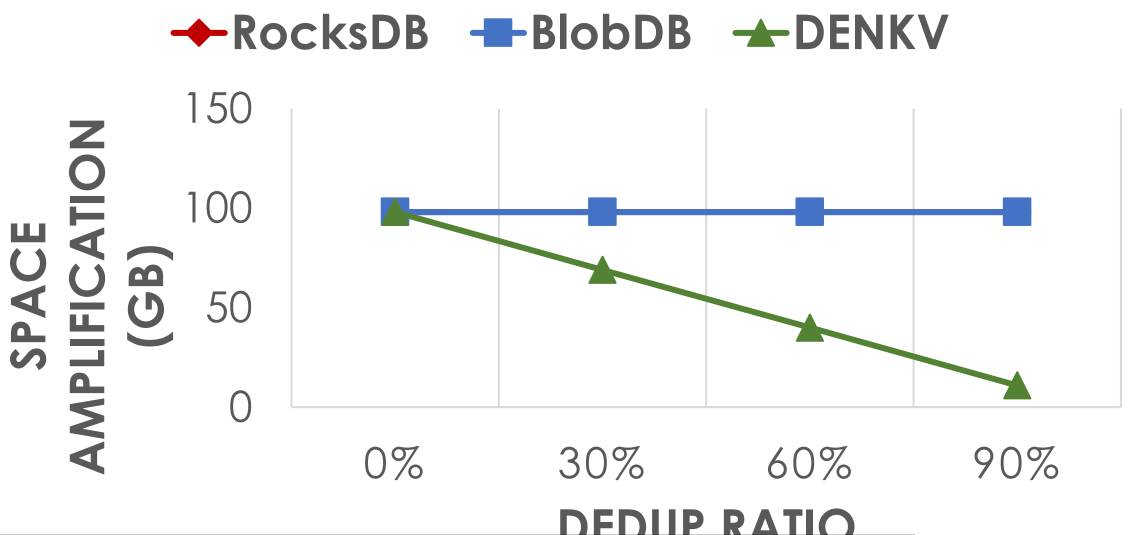

- ❑ 8x WA reduced with small KV pairs
- ❑ 8.9x SA reduced with large KV pairs

Questions to be answered

- How much deduplication influence the performance in general?
  - With small keys, performance is comparable.
  - There is a performance drop with large KV pairs.
- How much write amplification is reduced?
  - With 50% deduplication ratio, around 43% write amplification is reduced on average
- How much space amplification is reduced?
  - With 50% deduplication ratio, on average 45% less amount of space is utilized
- What are the bottlenecks?
  - Deduplication operation interfere the foreground IOs results in write stalls.

Conclusion

Conclusion

- HPC applications generate significant amount of redundant data
- Distributed KV stores are gaining significant attention in HPC
  - Distributed KV stores rely on monolithic KV stores
  - LSM-tree-based KV stores suffer from high WA and SA
- DENKV introduced APID (asynchronous partly inline deduplication) module
  - Reduces WA and SA while maintaining the performance

Thank you

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https://sites.google.com/view/safdarjamil95