Write-Optimized and High-Performance Hashing Index Scheme for Persistent Memory

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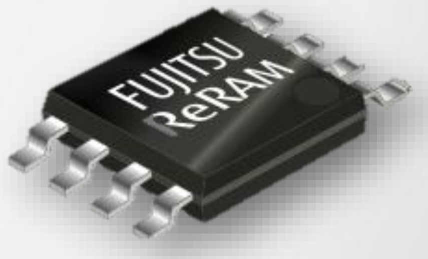
OSDI 2018

Persistent Memory (PM)

- Non-volatile memory as PM is expected to replace or complement DRAM as main memory
  - Non-volatility, low power, large capacity

	PCM	ReRAM	DRAM
Read (ns)	20-70	20-50	10
Write (ns)	150-220	70-140	10
Non-volatility	√	√	×
Standby Power	~0	~0	High
Density (Gb/cm^2)	13.5	24.5	9.1

PCM

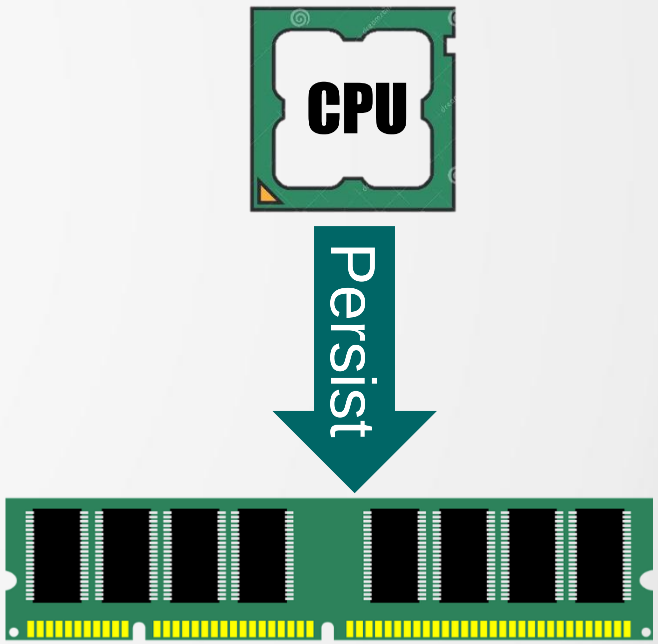


ReRAM

C. Xu et al. "Overcoming the Challenges of Crossbar Resistive Memory Architectures", HPCA, 2015.
K. Suzuki and S. Swanson. "A Survey of Trends in Non-Volatile Memory Technologies: 2000-2014", IMW 2015.

Index Structures in DRAM vs PM

- Index structures are critical for memory&storage systems
- Traditional indexing techniques originally designed for DRAM become inefficient in PM
  - Hardware limitations of NVM
    - Limited cell endurance
    - Asymmetric read/write latency and energy
    - Write optimization matters
  - The requirement of data consistency
    - Data are persistently stored in PM
    - Crash consistency on system failures



Tree-based vs Hashing Index Structures

- Tree-based index structures
  - **Pros:** good for range query
  - **Cons:** O(log(n)) time complexity for point query
  - Ones for PM have been widely studied
    - CDDS B-tree [FAST'11]
    - NV-Tree [FAST'15]
    - wB+-Tree [VLDB'15]
    - FP-Tree [SIGMOD'16]
    - WORT [FAST'17]
    - FAST&FAIR [FAST'18]

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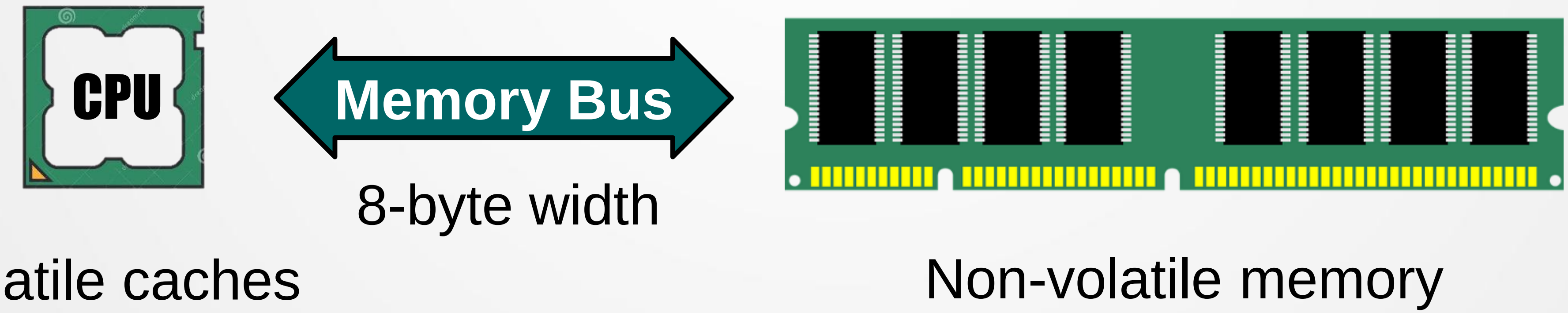
- Hashing index structures
  - **Pros:** constant time complexity for point query
  - **Cons:** do not support range query
  - Widely used in main memory
    - Main memory databases
    - In-memory key-value stores, e.g., Memcached and Redis
  - When maintained in PM, multiple non-trivial challenges exist
    - Rarely touched by existing work

Challenges of Hashing Indexes for PM

① High overhead for consistency guarantee

- Ordering memory writes
  - Cache line flush and memory fence instructions
- Avoiding partial updates for non-atomic writes
  - Logging or copy-on-write (CoW) mechanisms



Challenges of Hashing Indexes for PM

① **High overhead for consistency guarantee**

② **Performance degradation for reducing writes**

– Hashing schemes for DRAM usually cause many extra writes for dealing with hash collisions [INFLOW’15, MSST’17]

– Write-friendly hashing schemes reduce writes but at the cost of decreasing access performance

- PCM-friendly hash table (PFHT) [INFLOW’15]
- Path hashing [MSST’17]

Challenges of Hashing Indexes for PM

① **High overhead for consistency guarantee**

② **Performance degradation for reducing writes**

③ **Cost inefficiency for resizing hash table**

- Double the table size and iteratively rehash all items
- Take O(N) time to complete
- N insertions with cache line flushes & memory fences

Existing Hashing Index Schemes for PM

("✗": bad, "✓": good , "–": moderate)

	Bucketized Cuckoo (BCH)	PFHT[1]	Path Hashing[2]
Memory efficiency	✓	✓	✓
Search	✓	–	–
Deletion	✓	–	–
Insertion	✗	–	–
NVM writes	✗	✓	✓
Resizing	✗	✗	✗
Consistency	✗	✗	✗

[1] B. Debnath et al. "Revisiting hash table design for phase change memory", INFLOW, 2015.

[2] P. Zuo and Y. Hua. "A write-friendly hashing scheme for non-volatile memory systems", MSST, 2017.

Existing Hashing Index Schemes for PM

("✗": bad, "✓": good , "–": moderate)

	Bucketized Cuckoo (BCH)	PFHT[1]	Path Hashing[2]	Level Hashing
Memory efficiency	✓	✓	✓	✓
Search	✓	–	–	✓
Deletion	✓	–	–	✓
Insertion	✗	–	–	✓
NVM writes	✗	✓	✓	✓
Resizing	✗	✗	✗	✓
Consistency	✗	✗	✗	✓

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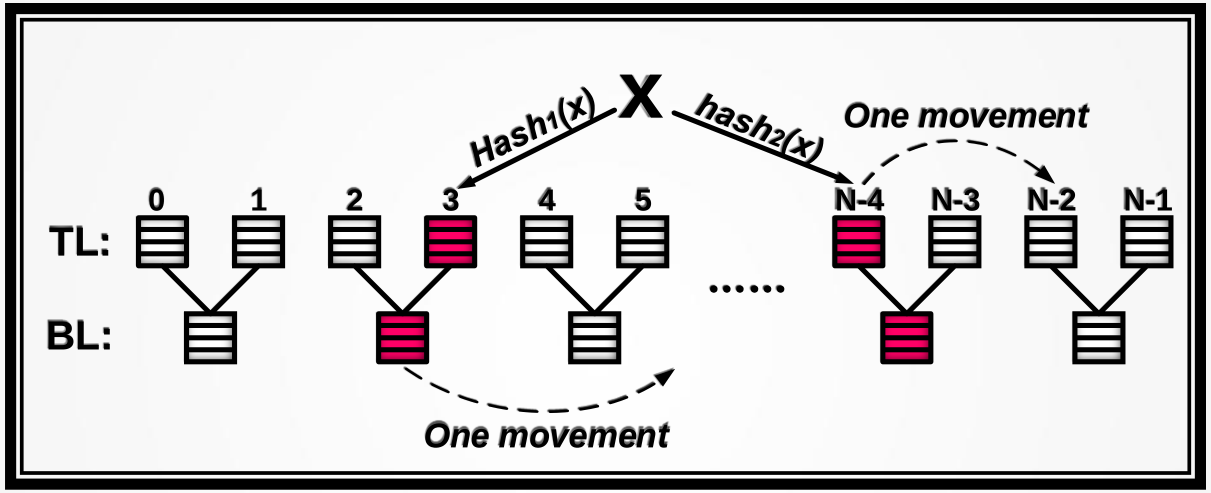
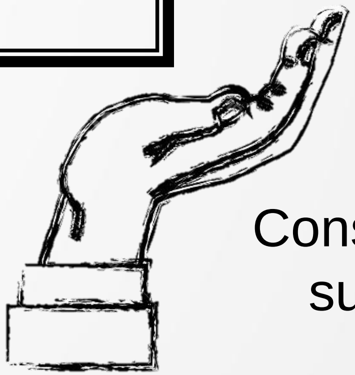
Level Hashing

Write-optimized & High-performance Hash Table Structure



Resizing support



Consistency support

Cost-efficient In-place Resizing Scheme

Low-overhead Consistency Guarantee Scheme

Write-optimized Hash Table Structure

① Multiple slots per bucket
② Two hash locations for each key
③ Sharing-based two-level structure
④ At most one movement for each successful insertion

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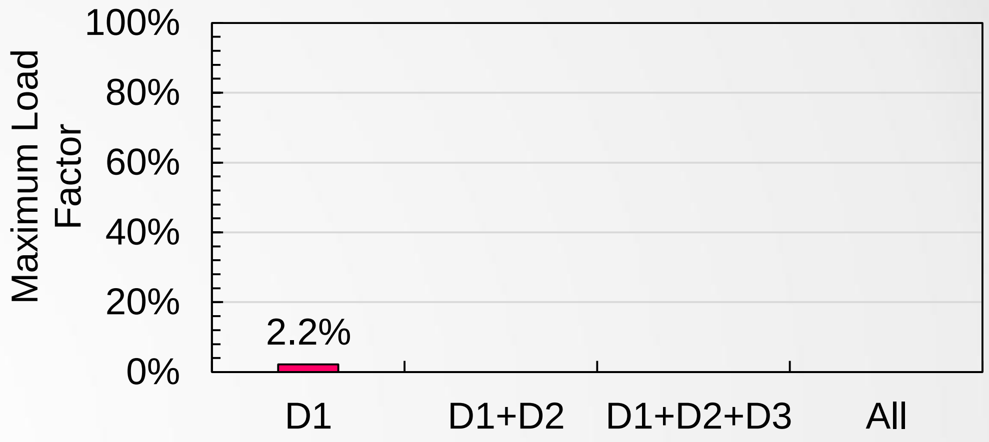

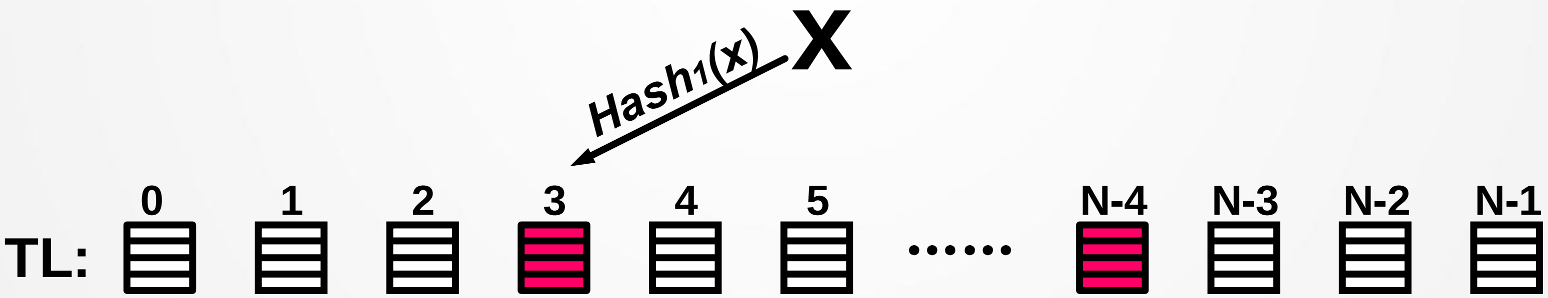

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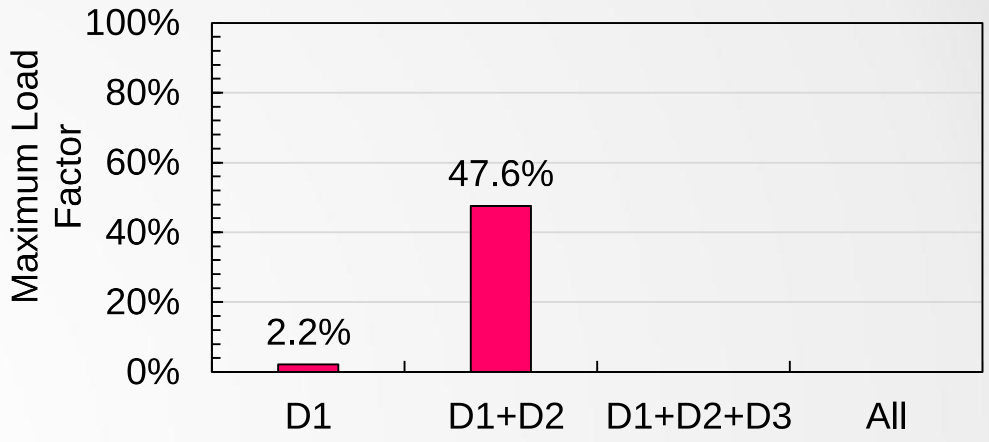

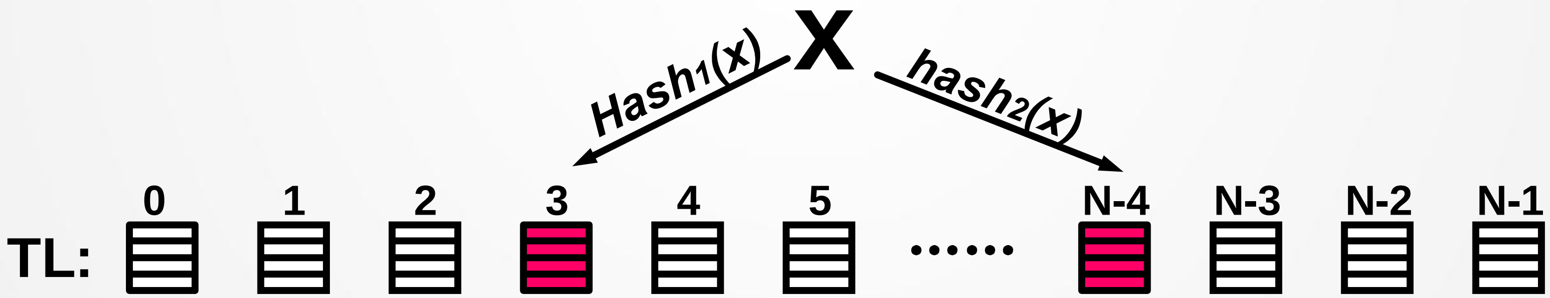

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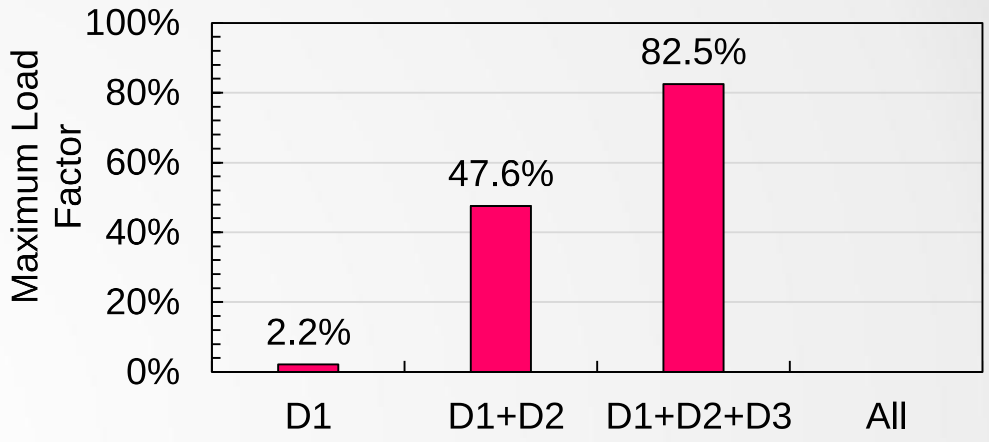

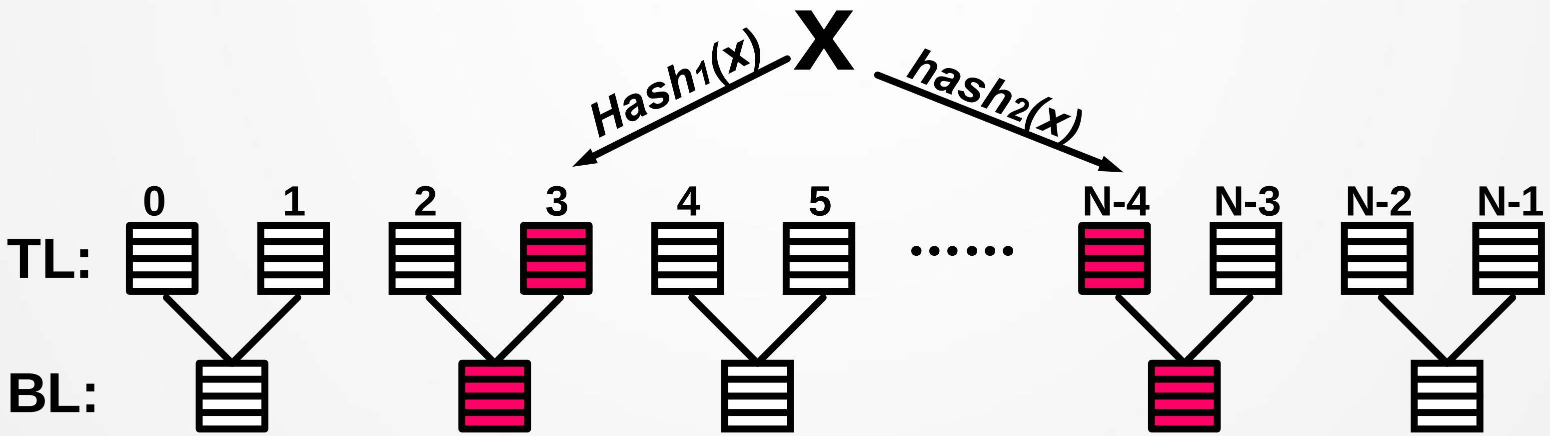

Write-optimized Hash Table Structure

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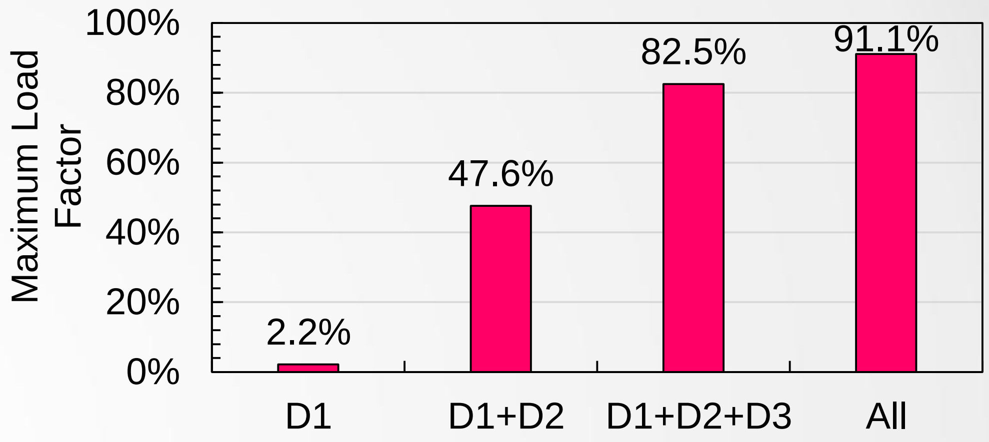
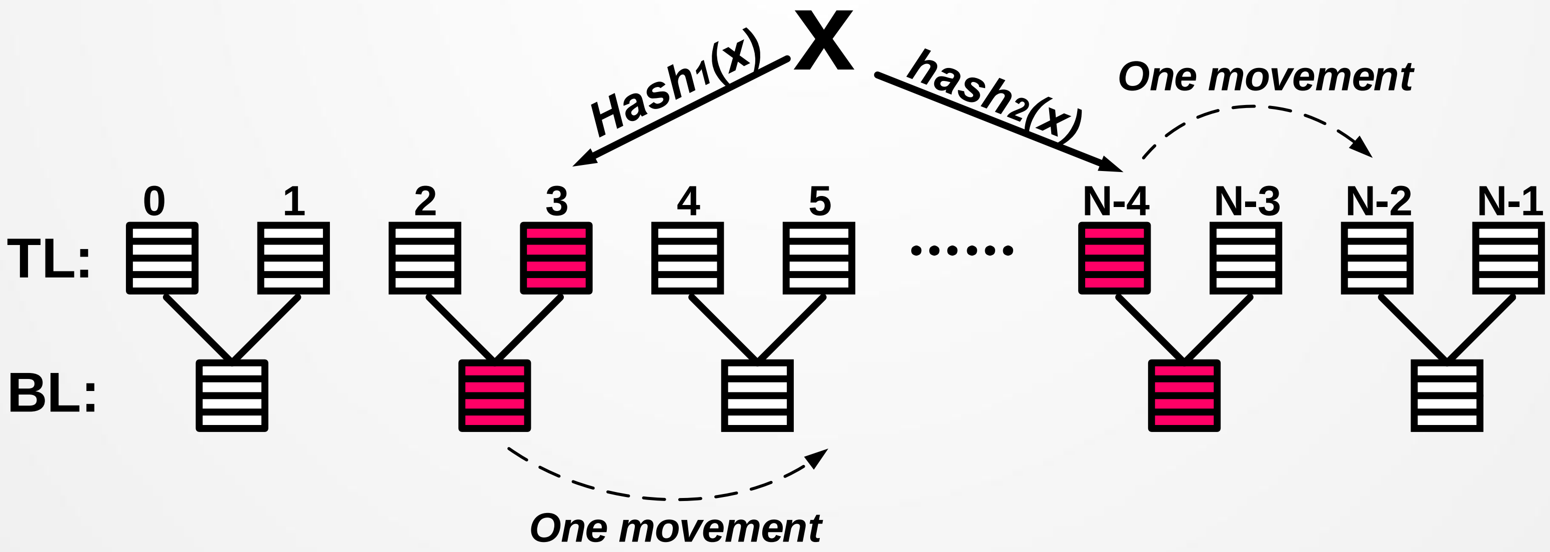
③ Sharing-based two-level structure

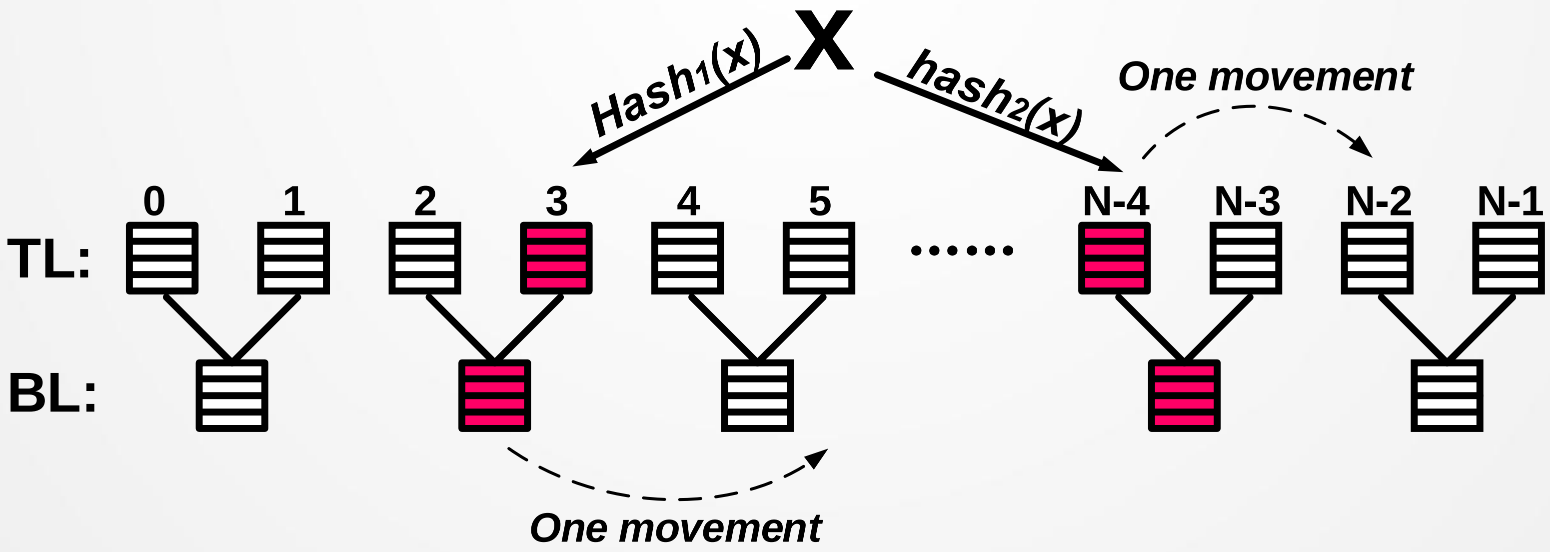
④ **At most one movement for each successful insertion**





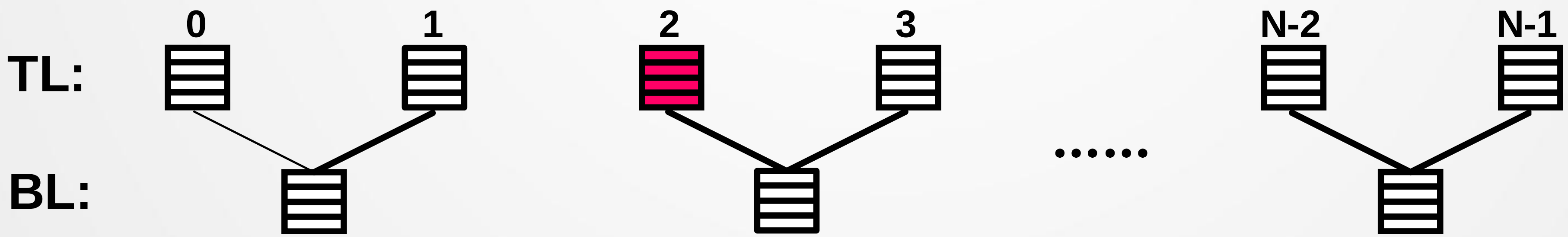
Write-optimized Hash Table Structure

- **Write-optimized:** only 1.2% of insertions incur one movement
- **High-performance:** constant-scale time complexity for all operations
- **Memory-efficient:** achieve high load factor by evenly distributing items



Cost-efficient In-place Resizing

- Put a new level on top of the old hash table and only rehash items in the old bottom level



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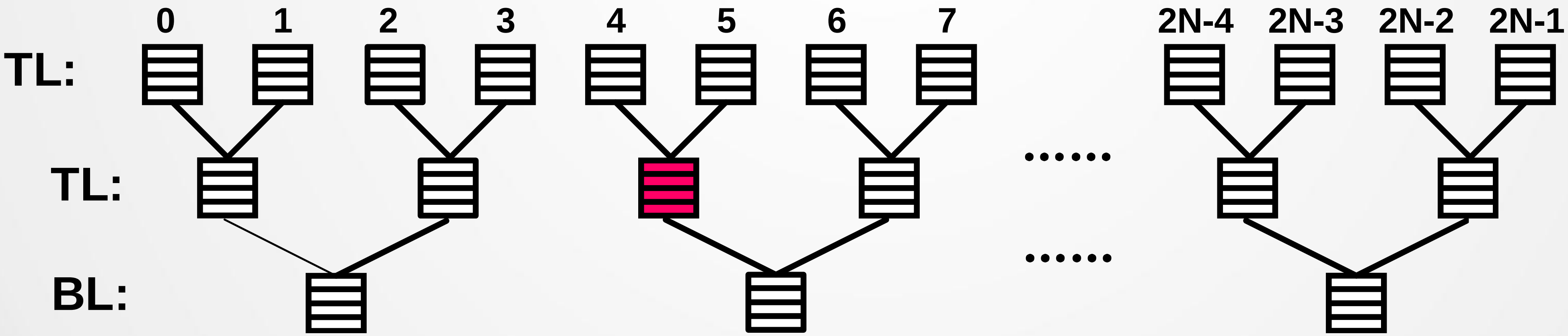

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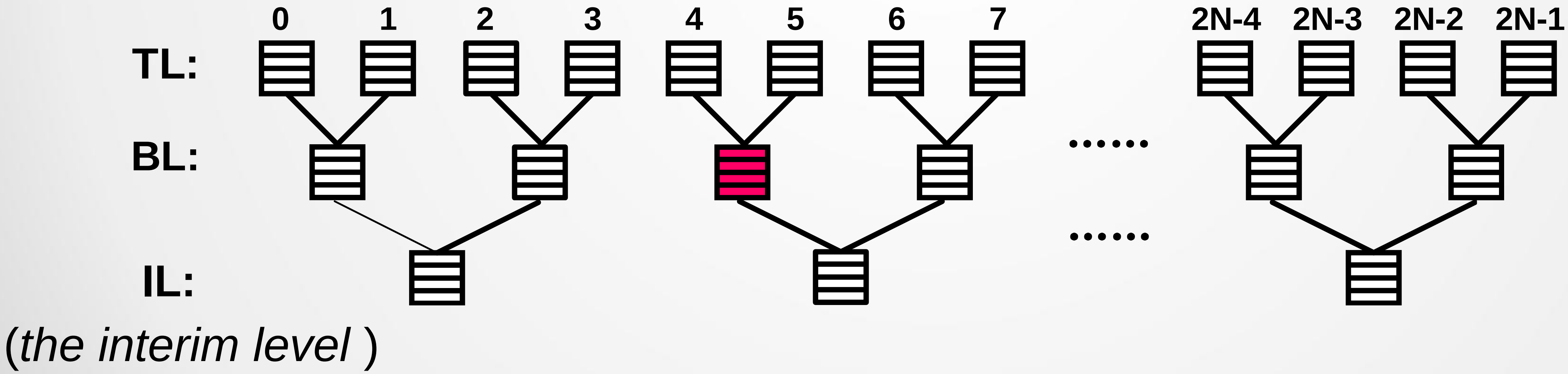

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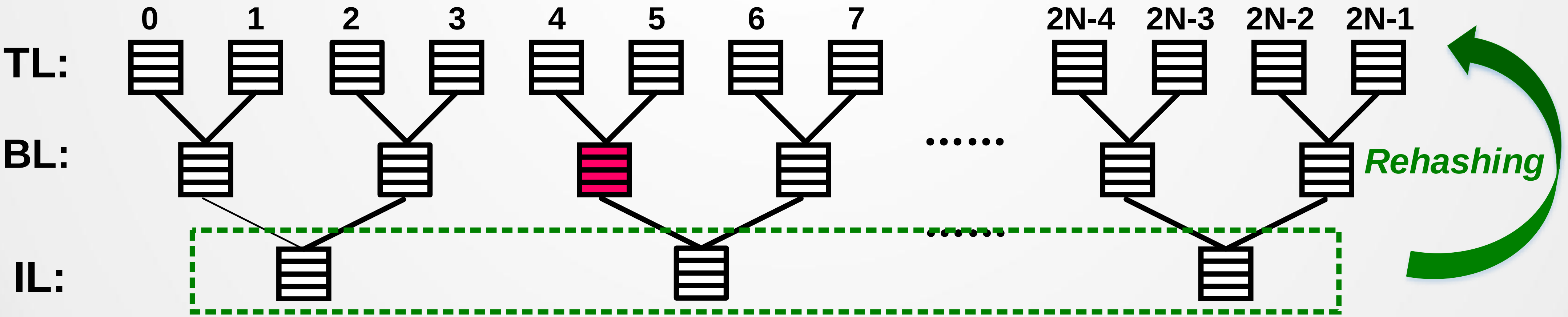

(the interim level)

Cost-efficient In-place Resizing

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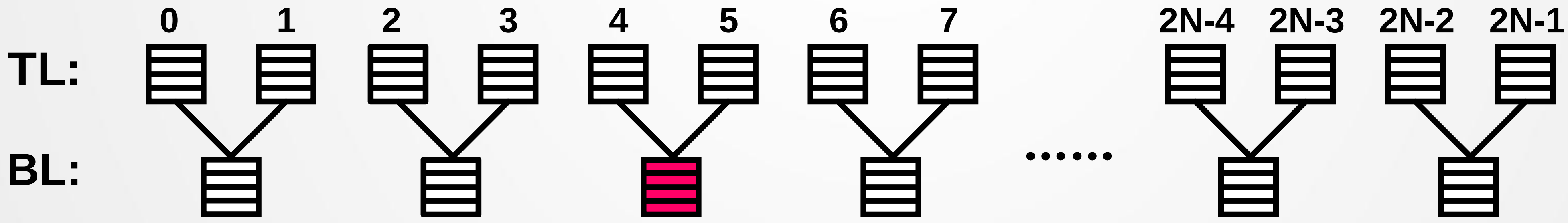
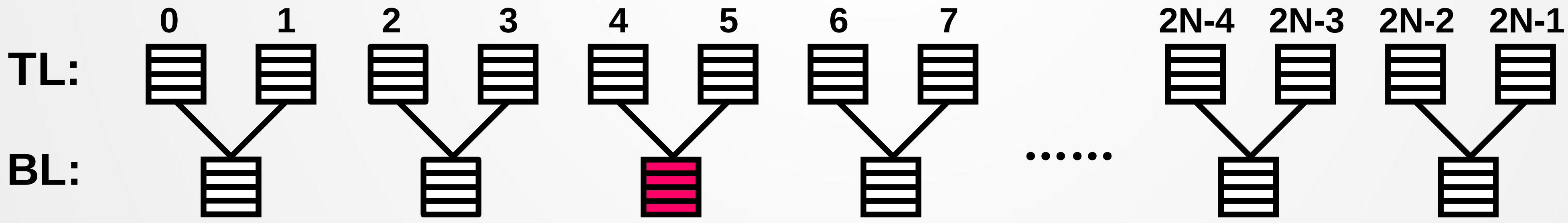


Cost-efficient In-place Resizing

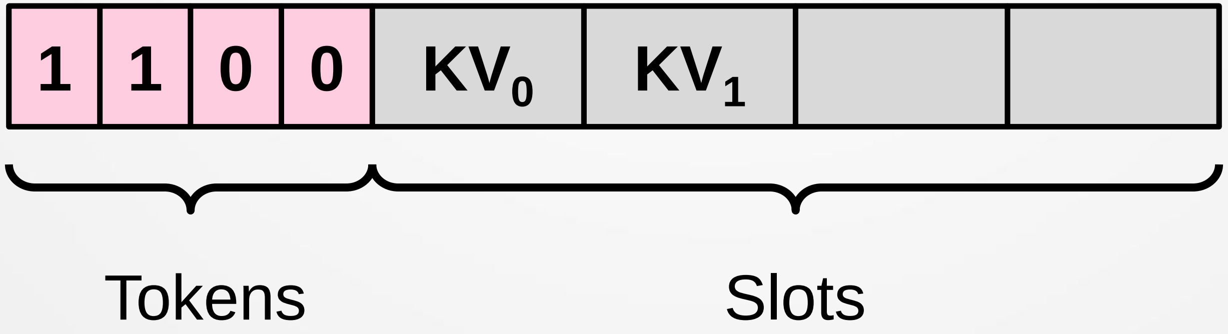
- Put a new level on top of the old hash table and only rehash items in the old bottom level
  - The new hash table is exactly double size of the old one
  - Only 1/3 buckets (i.e., the old bottom level) are rehashed



Low-overhead Consistency Guarantee

- A token associated with each slot in the open-addressing hash tables
  - Indicate whether the slot is empty
  - A token is 1 bit, e.g., “1” for non-empty, “0” for empty

A bucket:



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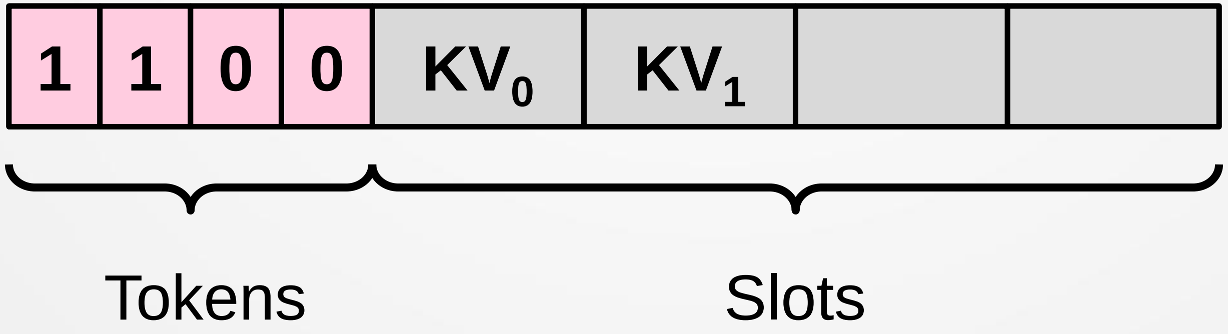
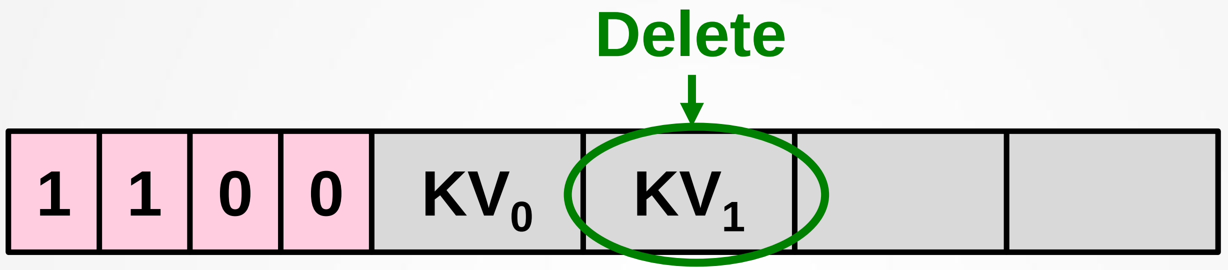
- A token associated with each slot in the open-addressing hash tables
  - Indicate whether the slot is empty
  - A token is 1 bit, e.g., “1” for non-empty, “0” for empty
- Modifying the token area only needs an atomic write
  - Leveraging the token to perform log-free operations

A bucket:



Log-free Deletion

- Delete an existing item



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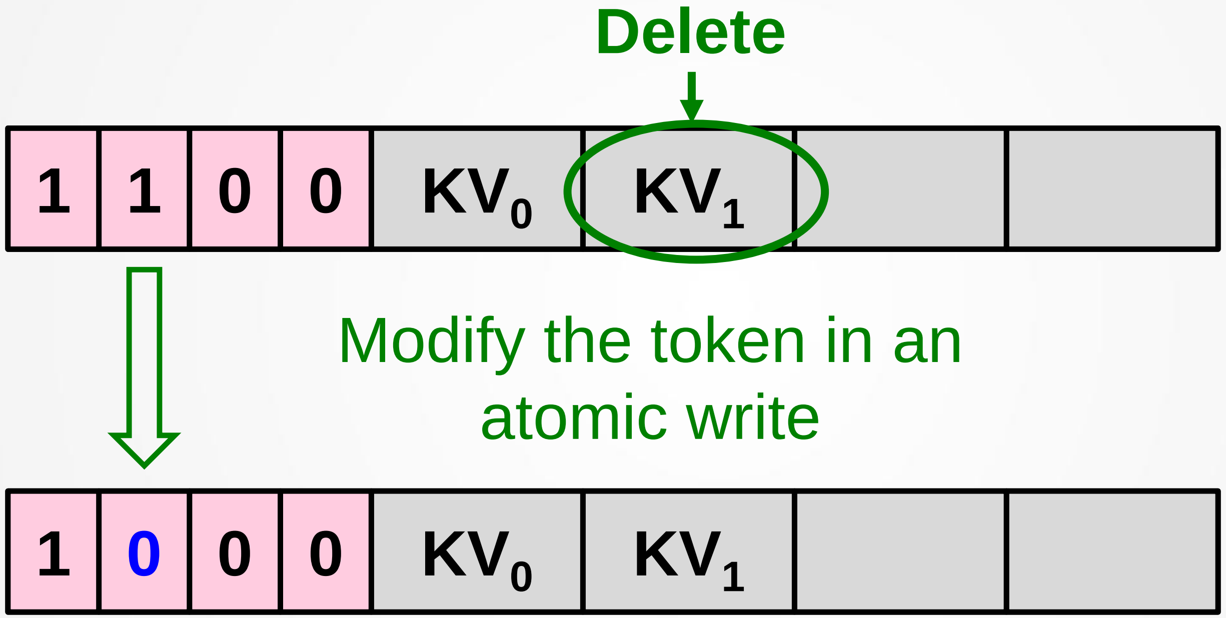

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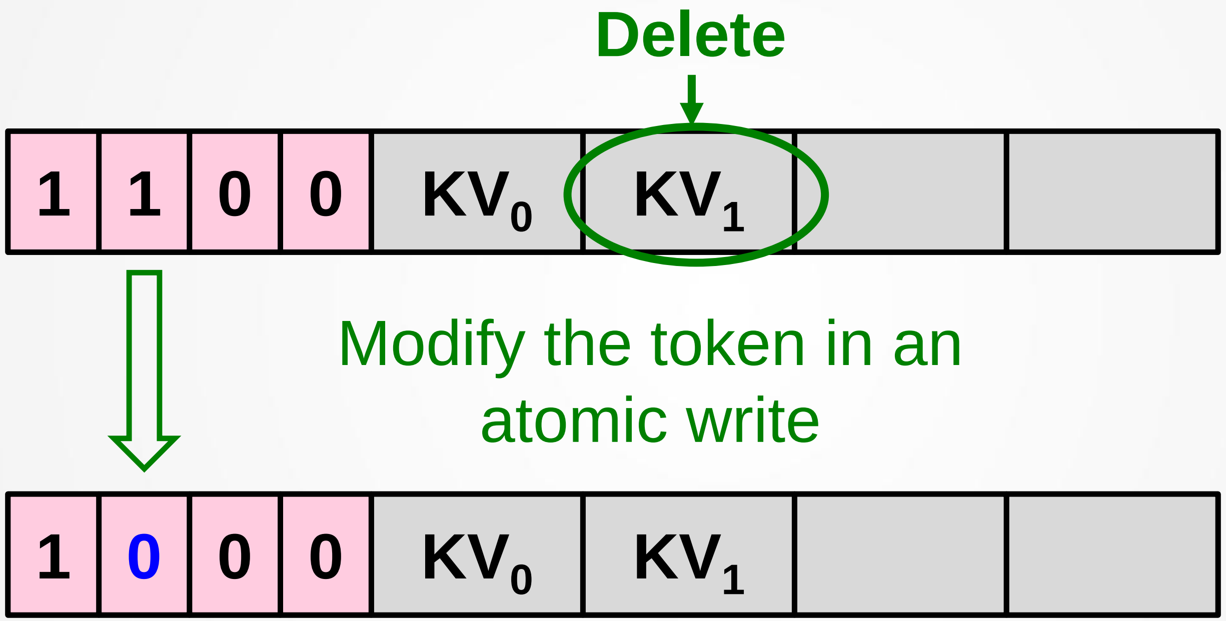
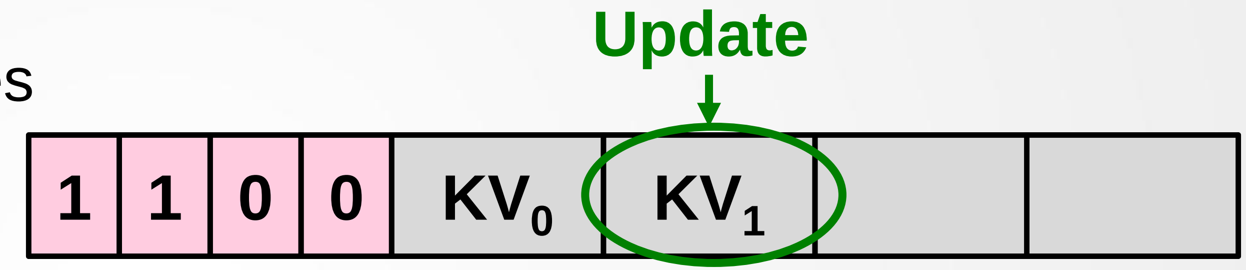


- **Log-free insertion and log-free resizing**
  - **Please find them in our paper**

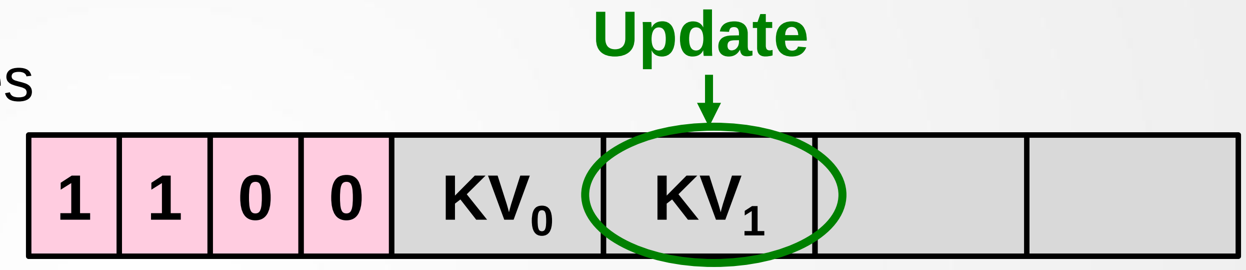
Consistency Guarantee for Update

- If directly update an existing key-value item in place
  - Inconsistency on system failures



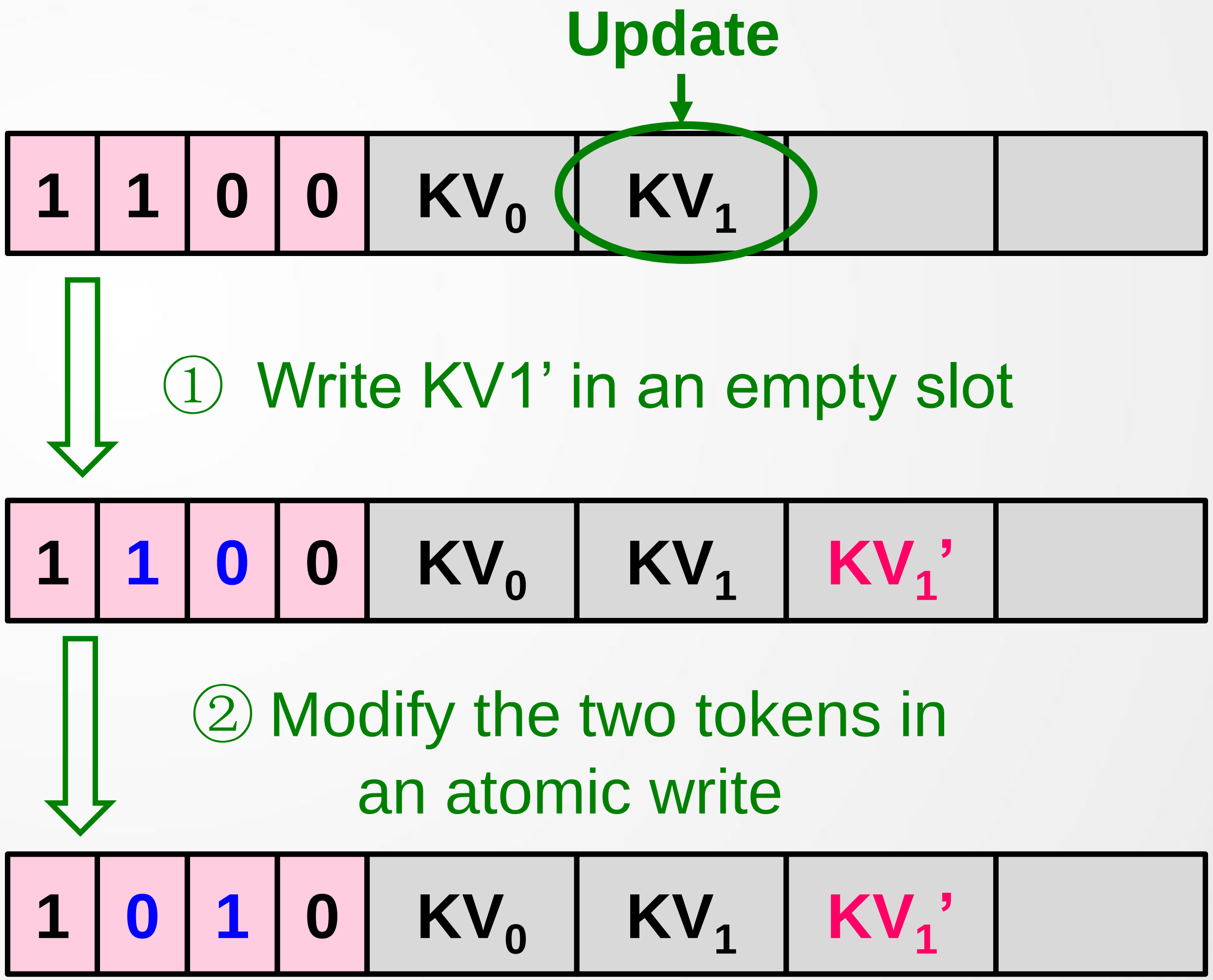
Consistency Guarantee for Update

- If directly update an existing key-value item in place
  - Inconsistency on system failures
- A straightforward solution is to use logging



Opportunistic Log-free Update

- Our scheme: check whether there is an empty slot in the bucket storing the old item
  - Yes: log-free update
  - No: using logging



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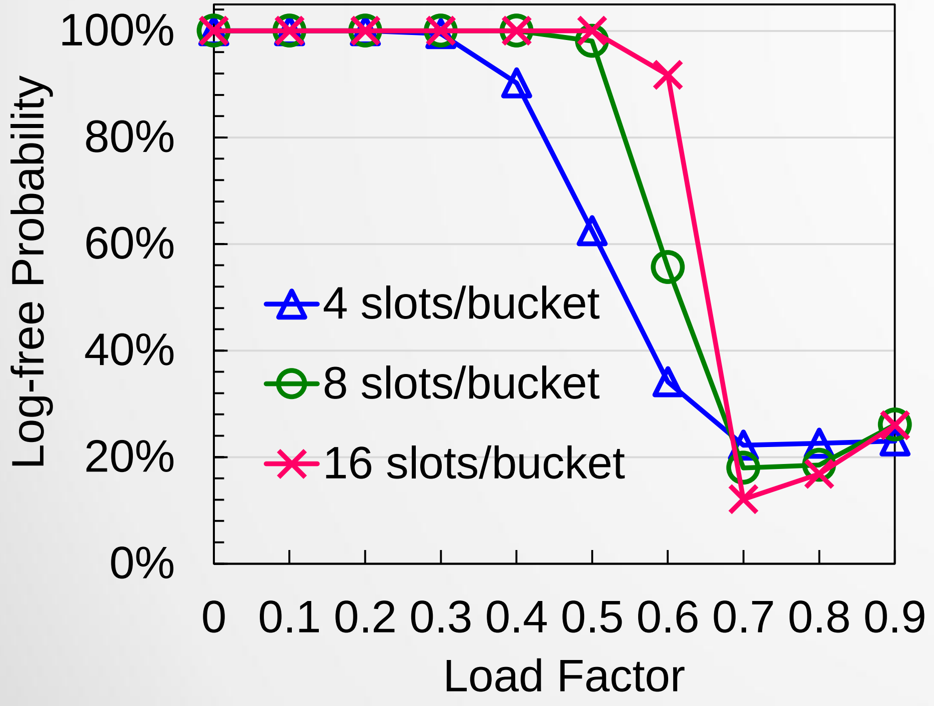
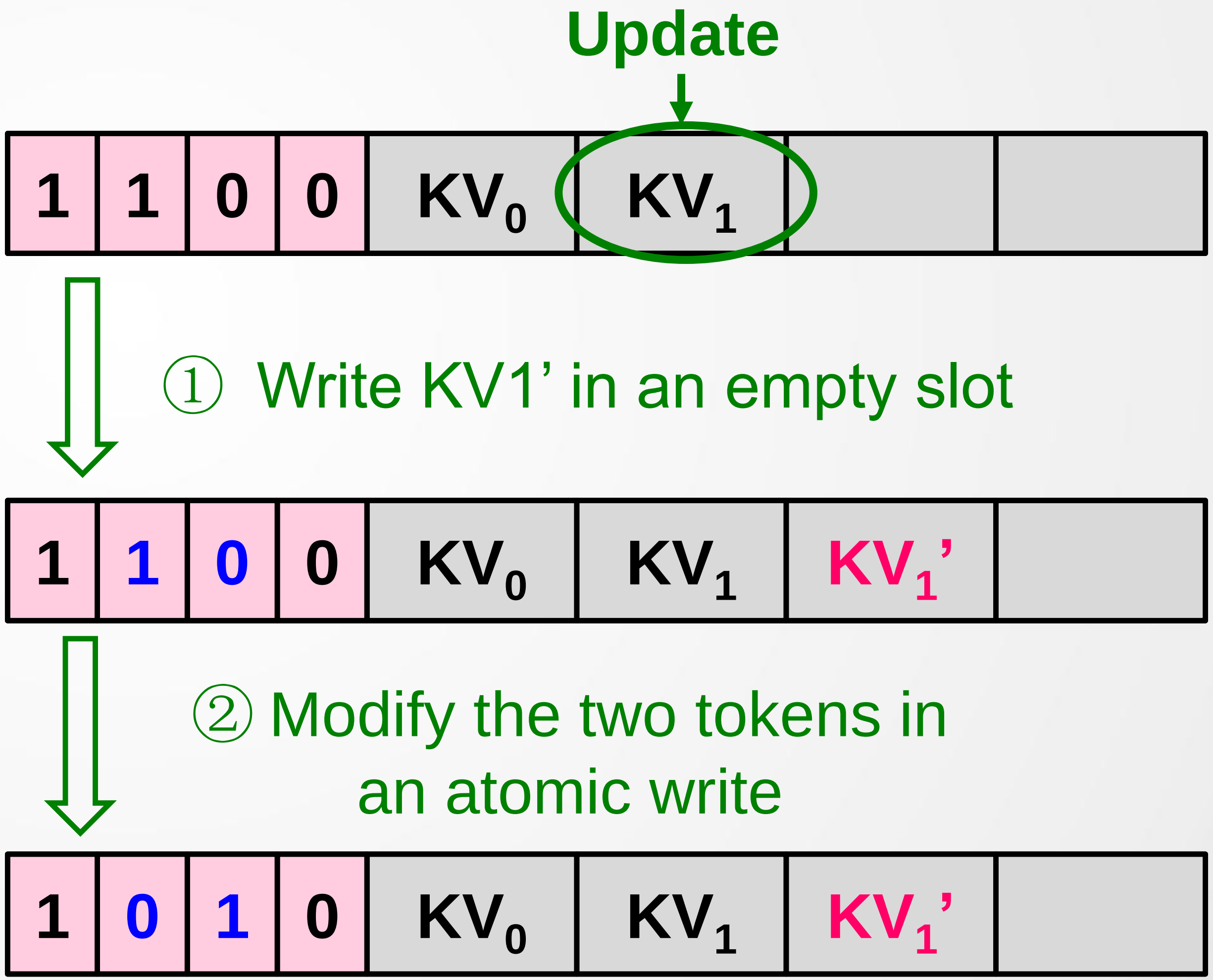
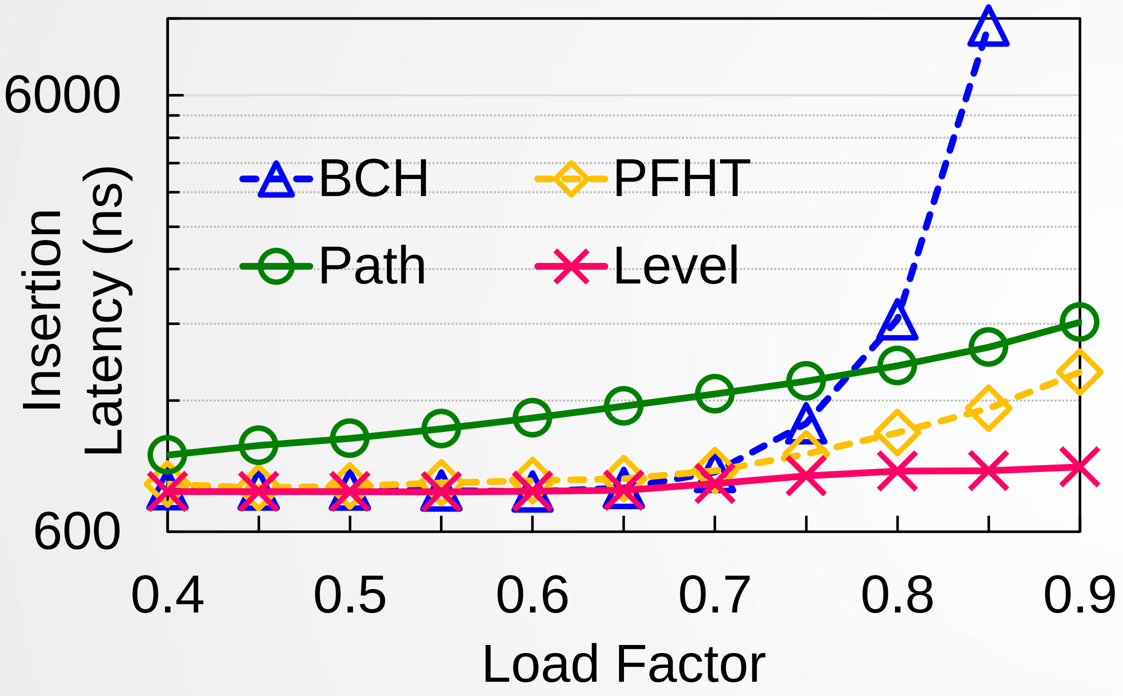




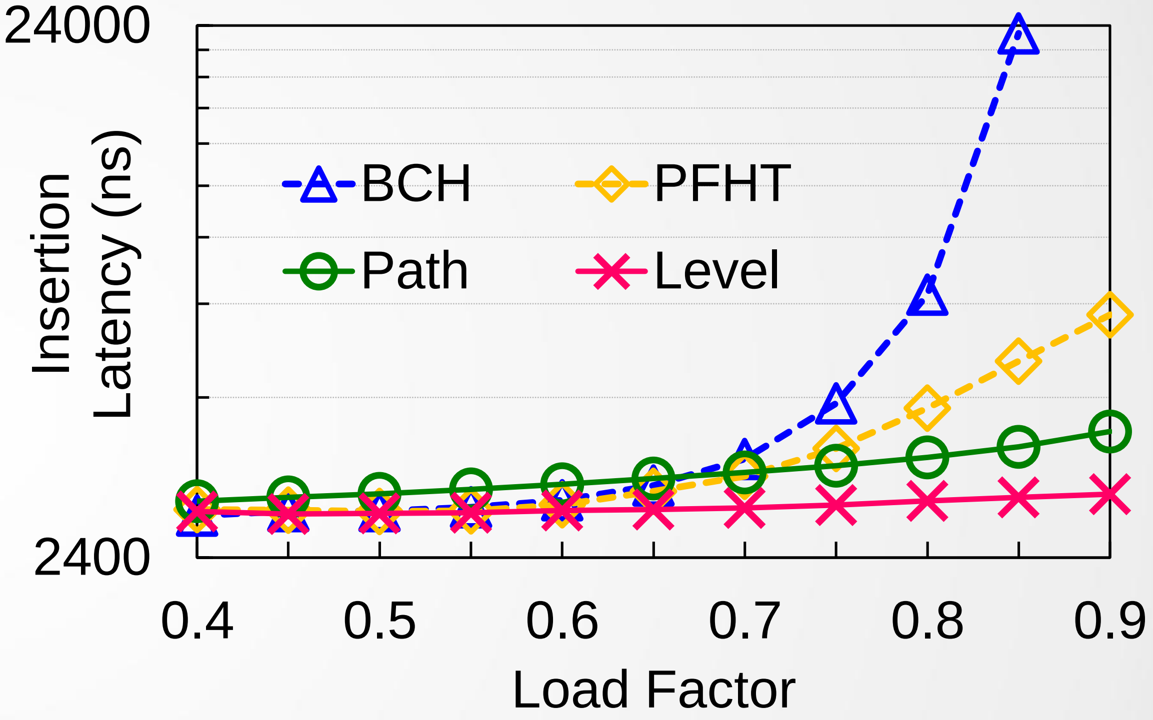
Performance Evaluation

- Both in DRAM and simulated PM platforms
  - Quartz (Hewlett Packard)
    - A DRAM-based performance emulator for PM
- Comparisons
  - Bucketized cuckoo hashing (BCH) [NSDI'13]
  - PCM-friendly hash table (PFHT) [INFLOW'15]
  - Path hashing [MSST'17]
  - In PM, implement their persistent versions using our proposed log-free consistency guarantee schemes

Insertion Latency



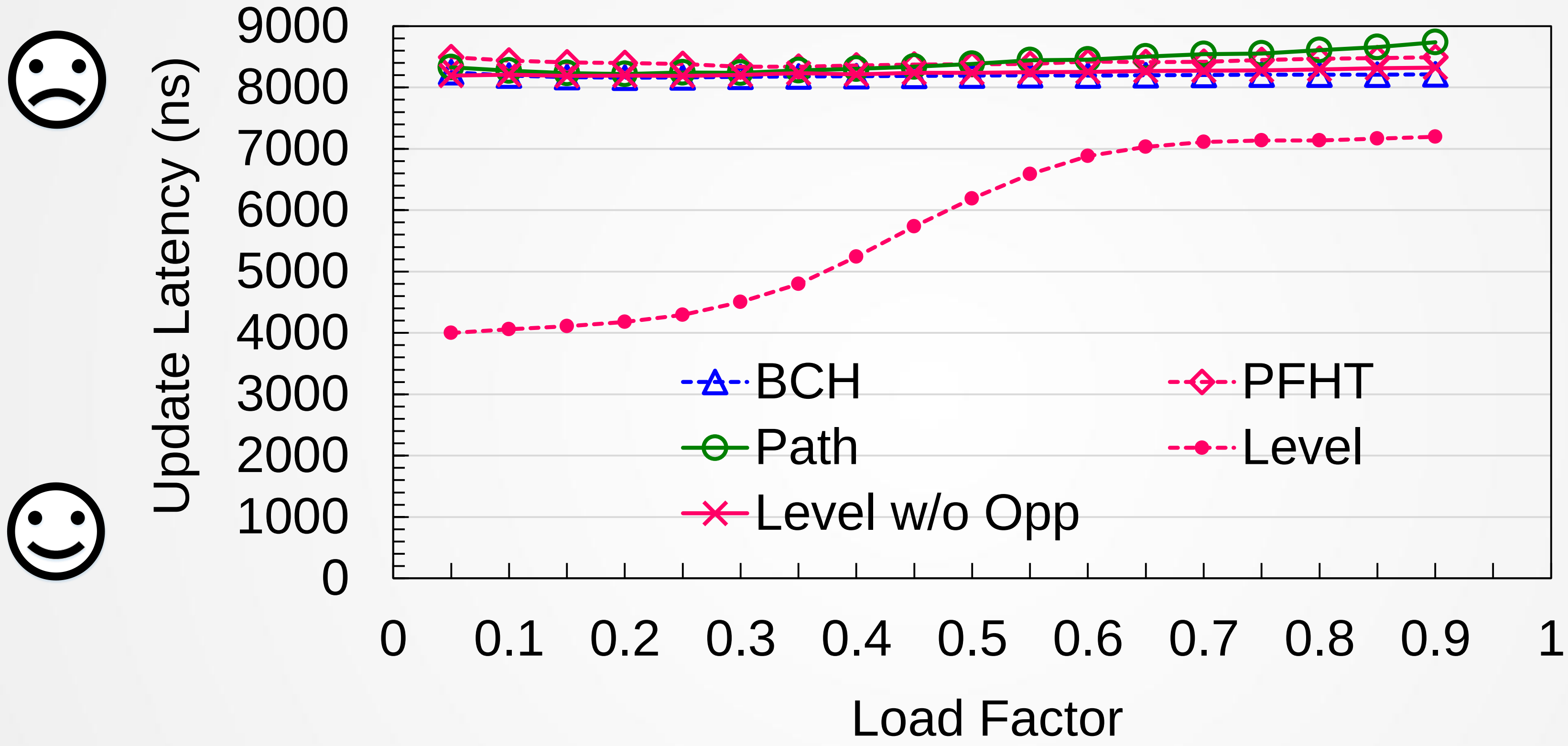
DRAM



NVM read/write latency: 200/600

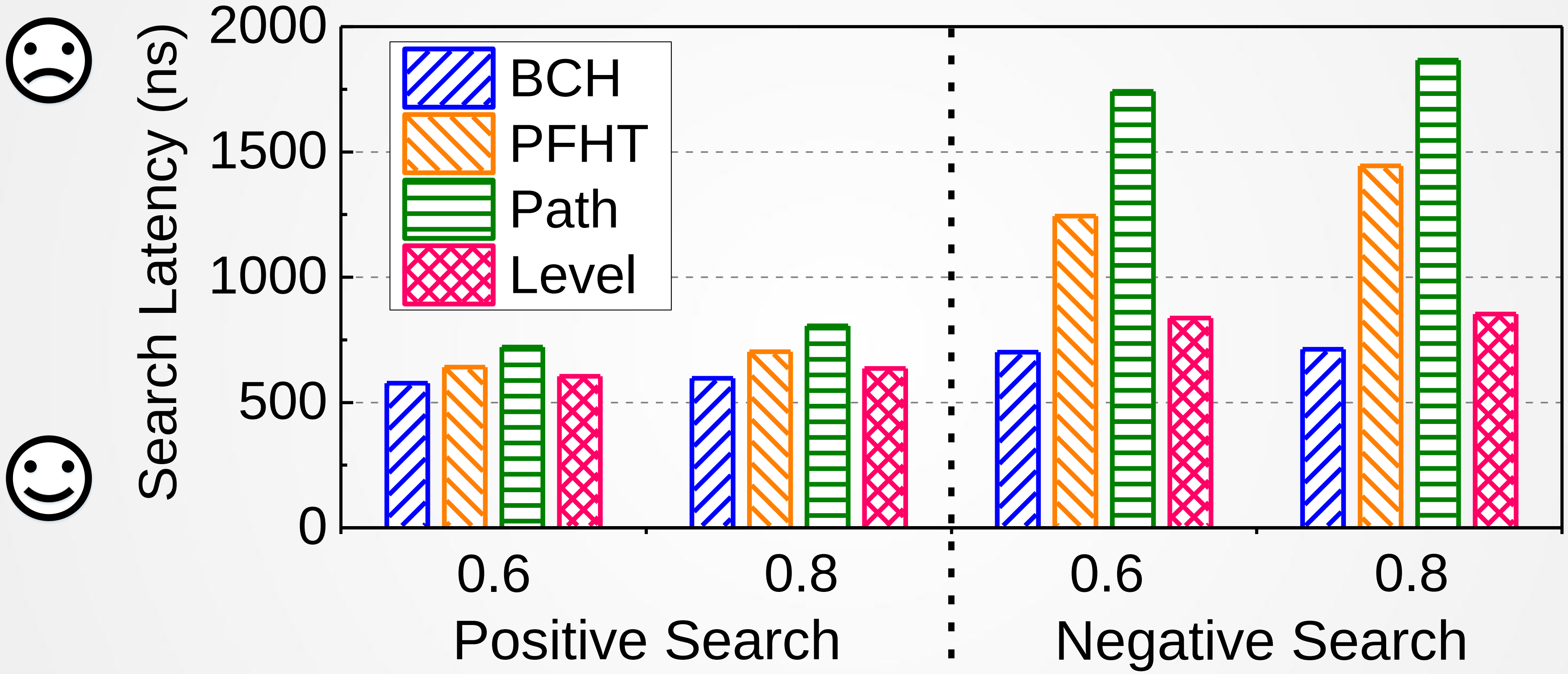
➢ Level hashing has the best insertion performance in both DRAM and NVM

Update Latency



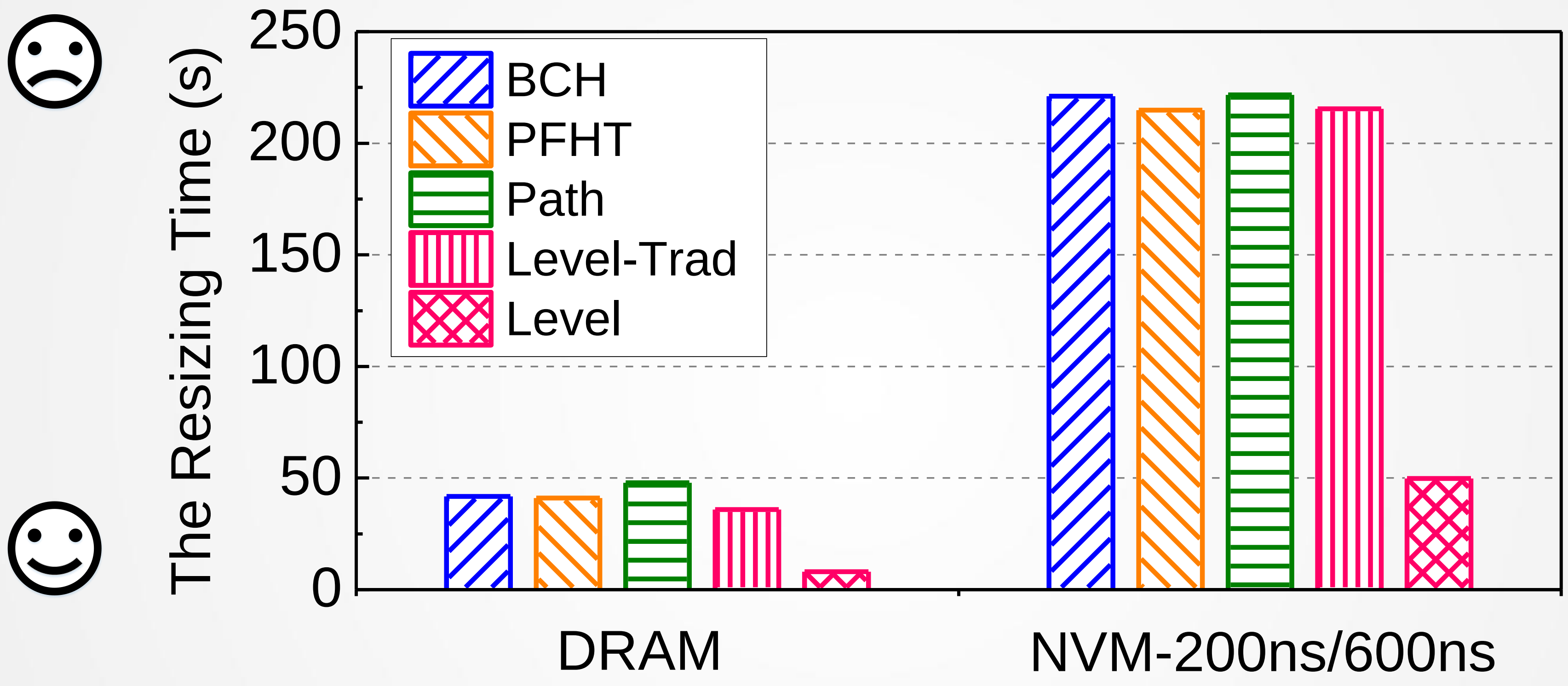
- Opportunistic log-free update scheme reduces the update latency by 15%～52%, i.e., speeding up the updates by 1.2×−2.1×

Search Latency



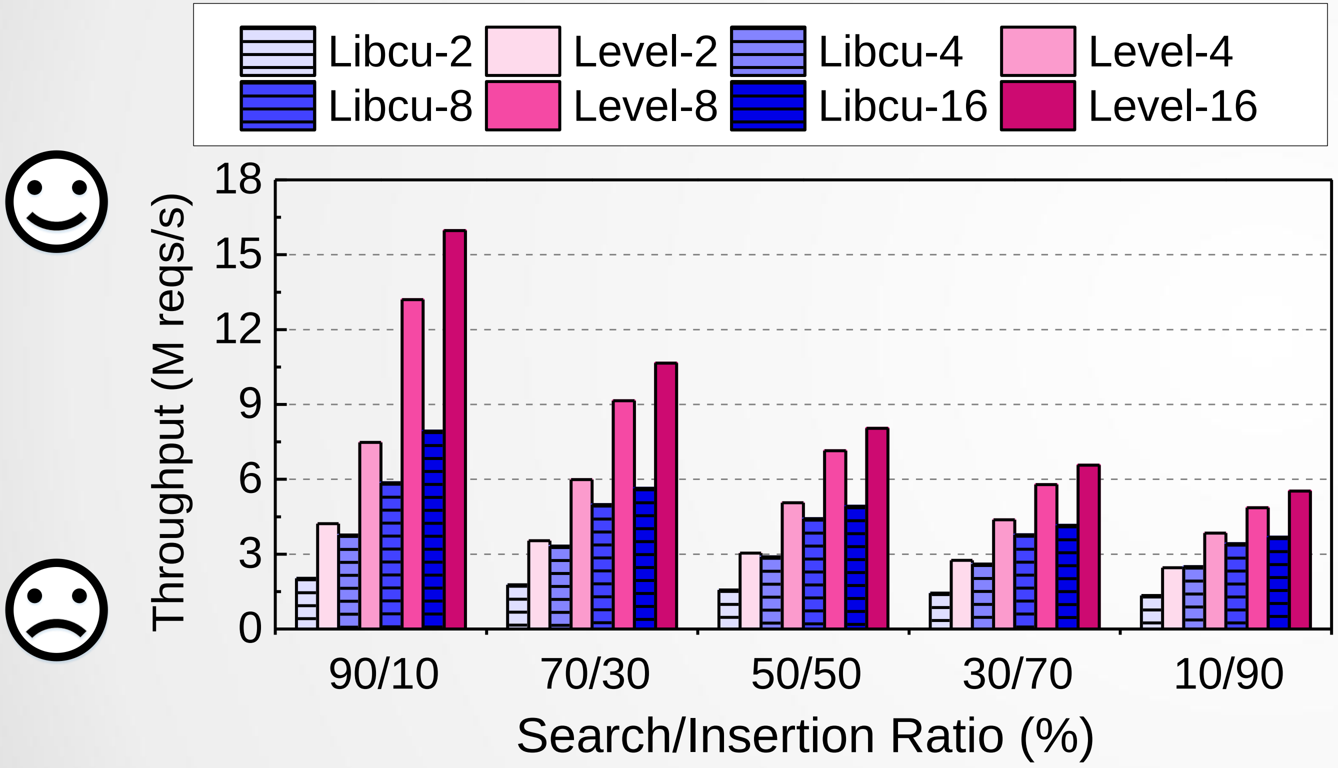
- ➢ The search latency of level hashing is close to that of BCH, which is much lower than PFHT and path hashing

Resizing Time



➢ Level hashing reduces the resizing time by about 76%, i.e., speeding up the resizing by 4.3×

Concurrent Throughput



- **Concurrent level hashing:** Support multiple-reader multiple-writer concurrency via simply using fine-grained locking
- Concurrent level hashing has 1.6× − 2.1× higher throughput than libcuckoo[1], due to locking fewer slots for insertions

[1] X. Li et al.. "Algorithmic improvements for fast concurrent cuckoo hashing", Eurosys, 2014.

Conclusion

- Traditional indexing techniques originally designed for DRAM become inefficient in PM
- We propose level hashing, a write-optimized and high-performance hashing index scheme for PM
  - Write-optimized hash table structure
  - Cost-efficient in-place resizing
  - Log-free consistency guarantee
- 1.4×−3.0× speedup for insertion, 1.2×−2.1× speedup for update, and over 4.3× speedup for resizing

Thanks! Q&A

(Poster #10)

Open-source code: https://github.com/Pfzuo/Level-Hashing