ListDB: Union of Write-Ahead Logs and Persistent SkipLists for Incremental Checkpointing on Persistent Memory

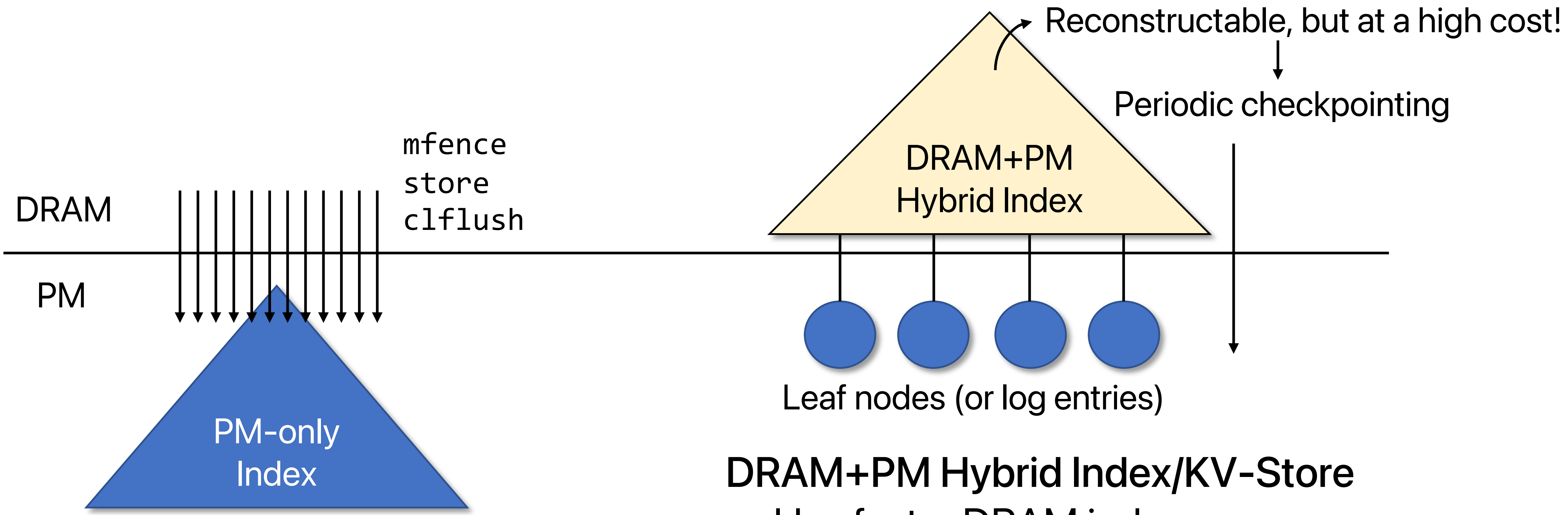
Wonbae Kim[1], Chanyeol Park[2,5], Dongui Kim[3,5], Hyeongjun Park[5], Young-ri Choi[1], Alan Sussman[4], Beomseok Nam[5]

[1]UNIST, [2]Naver, [3]Line, [4]University of Maryland, College Park, [5]Sungkyunkwan University

OSDI 22

7/11/2022

Indexing/Key-Value Store for Persistent Memory



PM-Only Index

- Slower than DRAM index
- `mfence` and `clflush` overhead

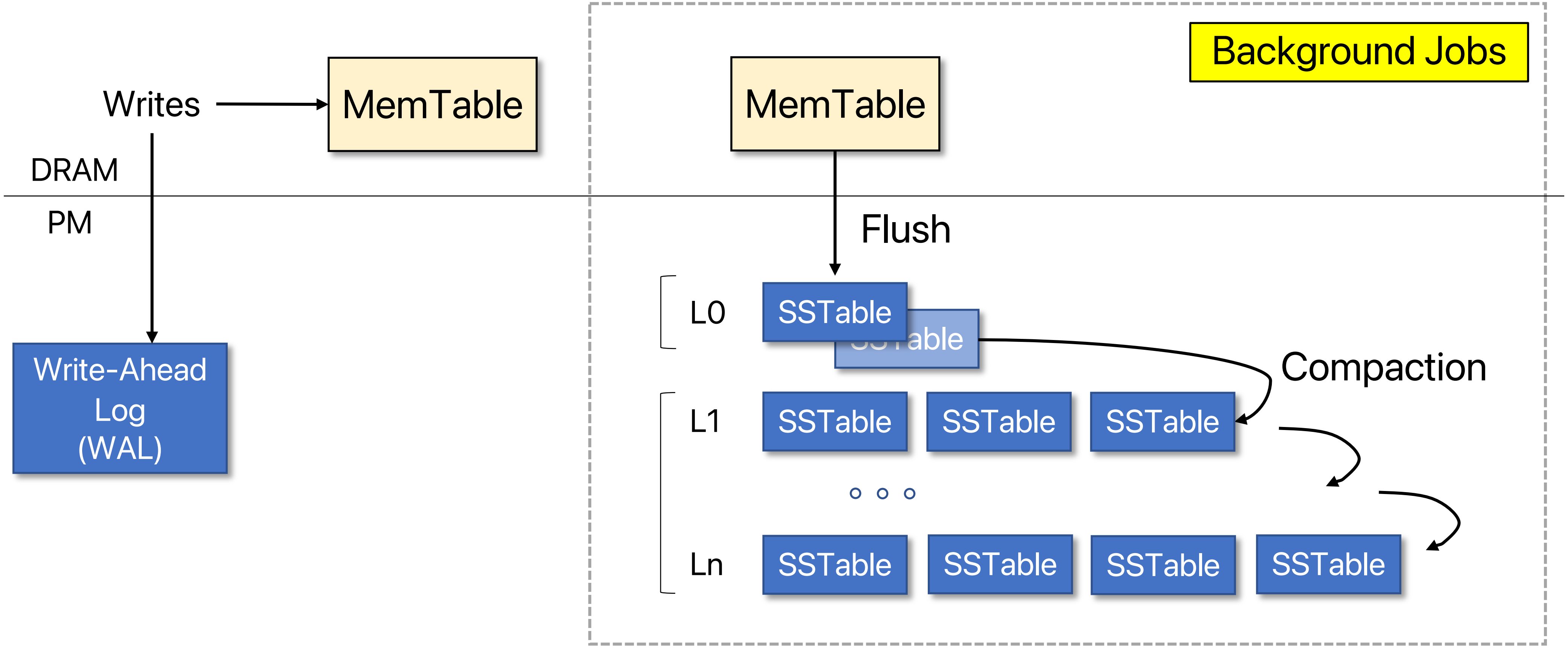
DRAM+PM Hybrid Index/KV-Store

- Use faster DRAM index
- Avoid use of `mfence` and `clflush`
- Periodic synchronous checkpointing

  → **High Tail Latency**

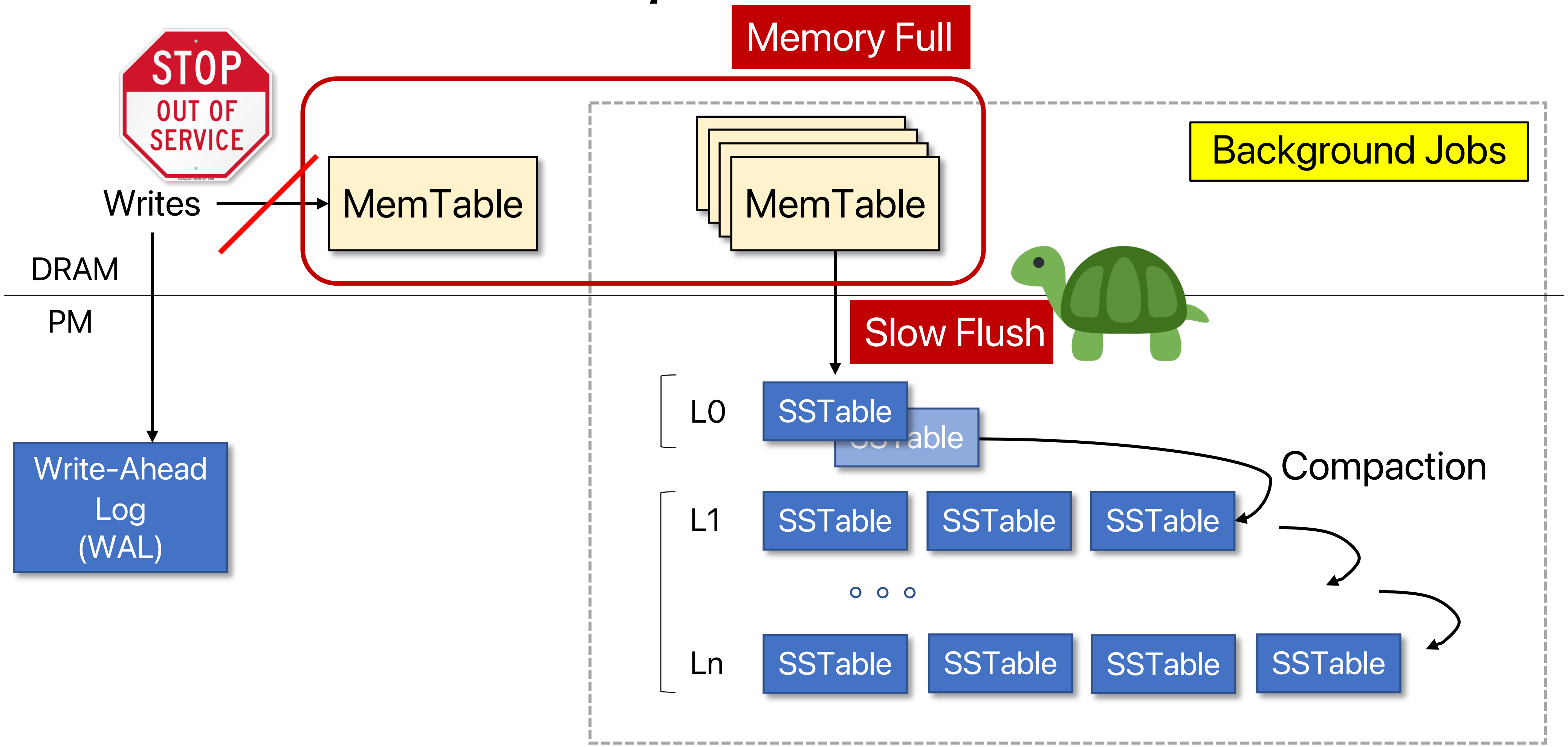
Asynchronous Incremental Checkpointing

- **Log-Structured Merge (LSM) tree**
  checkpoints small DRAM index incrementally and asynchronously.



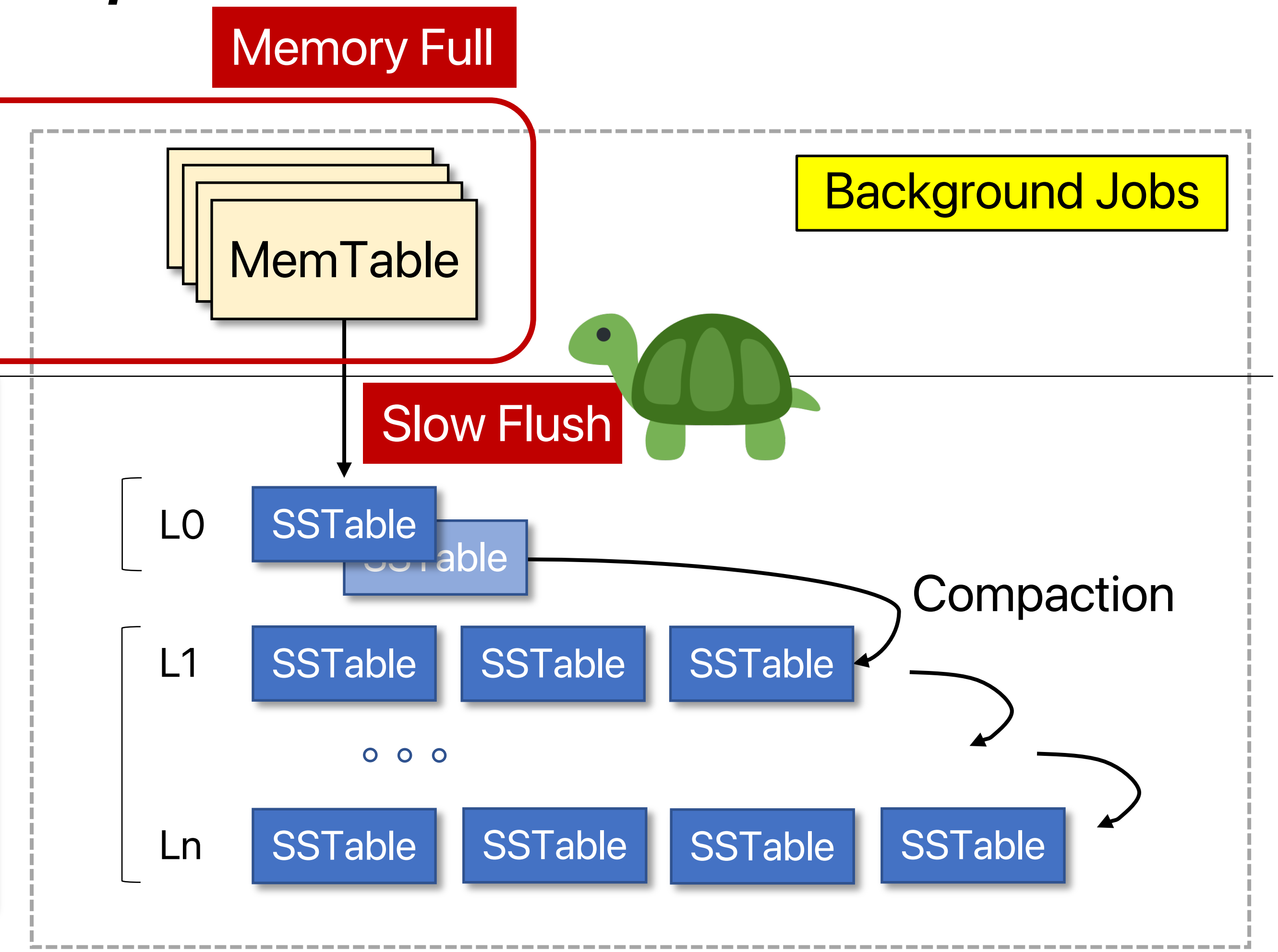
Write Stall Problem

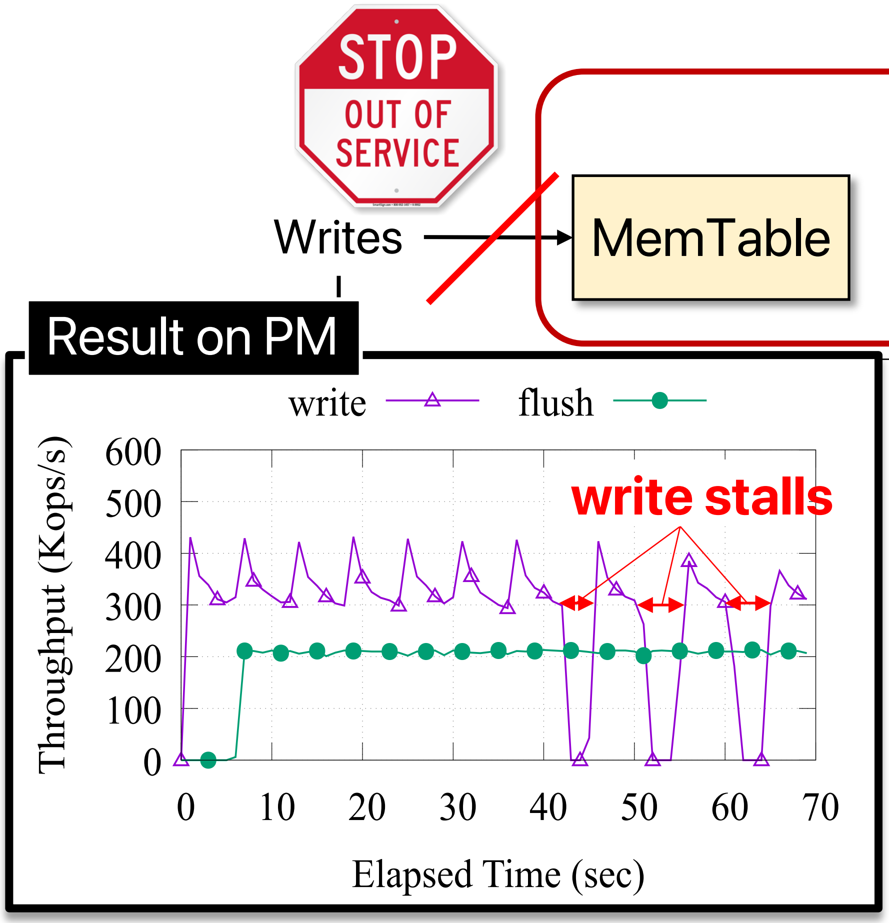
- LSM-trees suffer from ***write stall problem***.



Write Stall Problem

- LSM-trees suffer from ***write stall problem***.





Challenges to Avoid Write Stalls

1. Write latency gap between DRAM and PM
2. Write amplification
3. PM is more sensitive to NUMA effects than DRAM

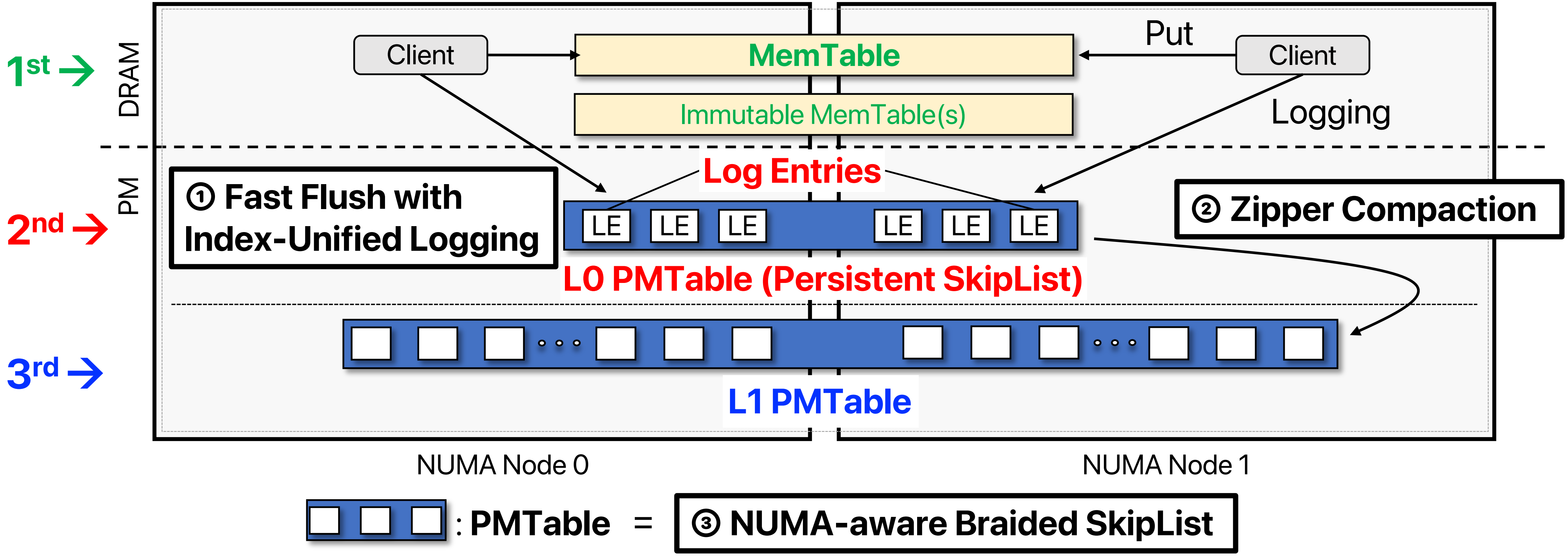
Three Novel Designs of ListDB

1. Write latency gap between DRAM and PM
    - → **Index-Unified Logging** (Convert Logs into SkipLists for Faster Flush)
2. Write amplification
    - → **Zipper Compaction** (In-place Merge Sort)
3. PM is more sensitive to NUMA effects than DRAM
    - → **NUMA-aware Braided SkipList**

- ListDB resolves the write stall problem and shows 25x higher write throughput than Intel Pmem-RocksDB

Design of ListDB: High-Level Architecture

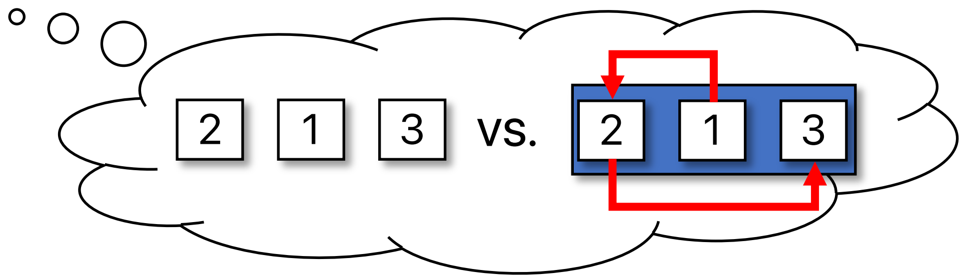
- Three-level architecture: **MemTable**, **Log+L0 PMTable**, **L1 PMTable**



Fast MemTable Flush with Index-Unified Logging

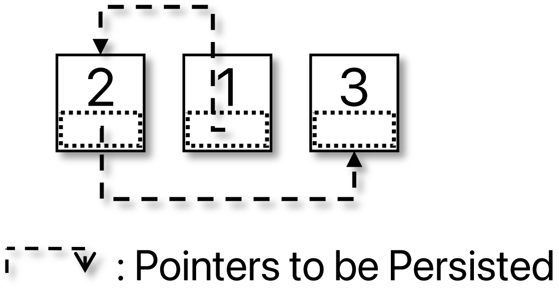
The only difference between WAL and L0 SkipList

- Order of Keys



Let's union WAL and persistent SkipList

- Pre-allocate pointer space in log entries
- Flush only pointers, not key-values
- No need to call persist instructions when flushing
- Pointers are persisted when merging L0 and L1

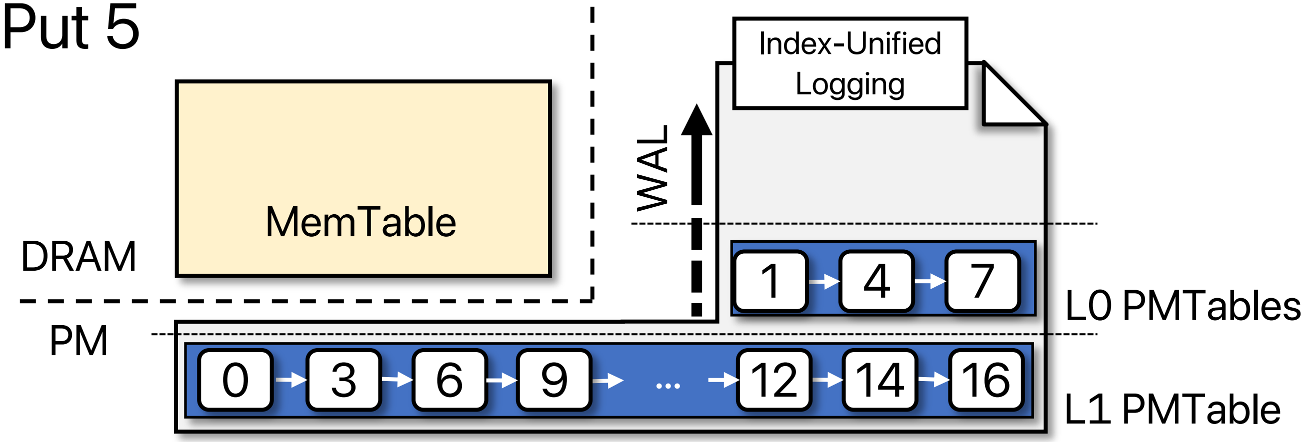


With Index-Unified Logging, a MemTable can be flushed before the next one becomes full.

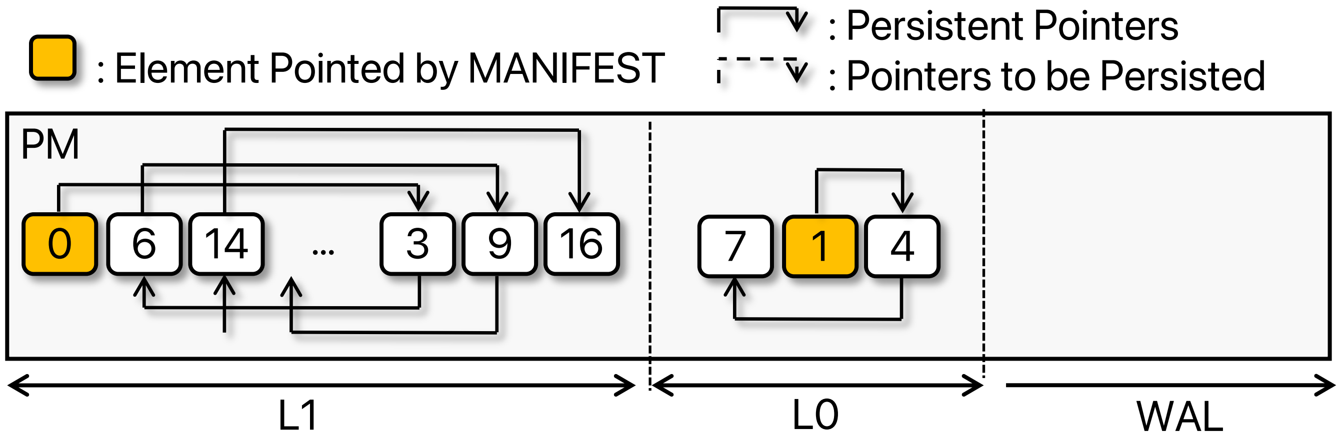
Physical PM Layout for MemTable Write

- ❑ Ex) Put 8 → Put 2 → Put 5

Logical View



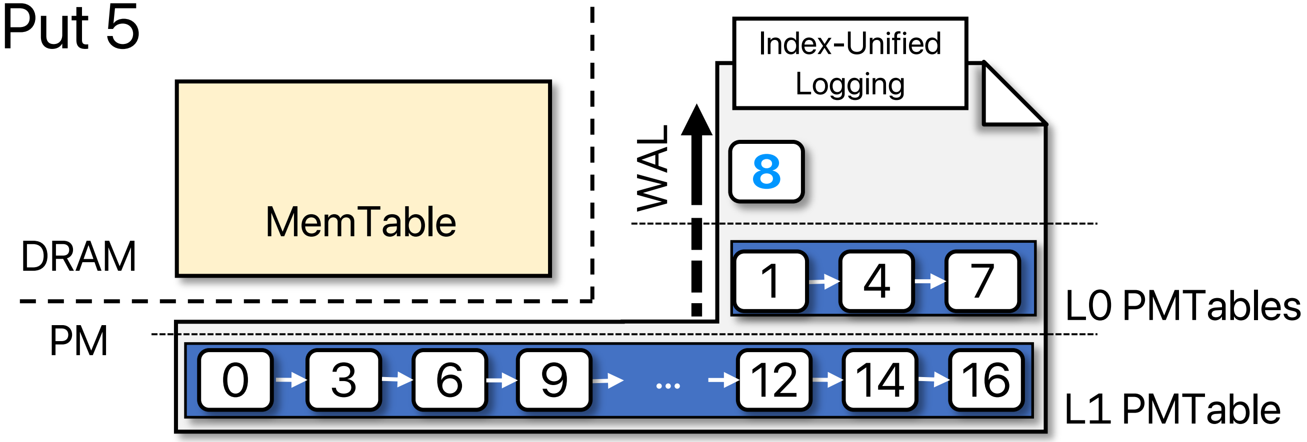
Physical
PM Layout



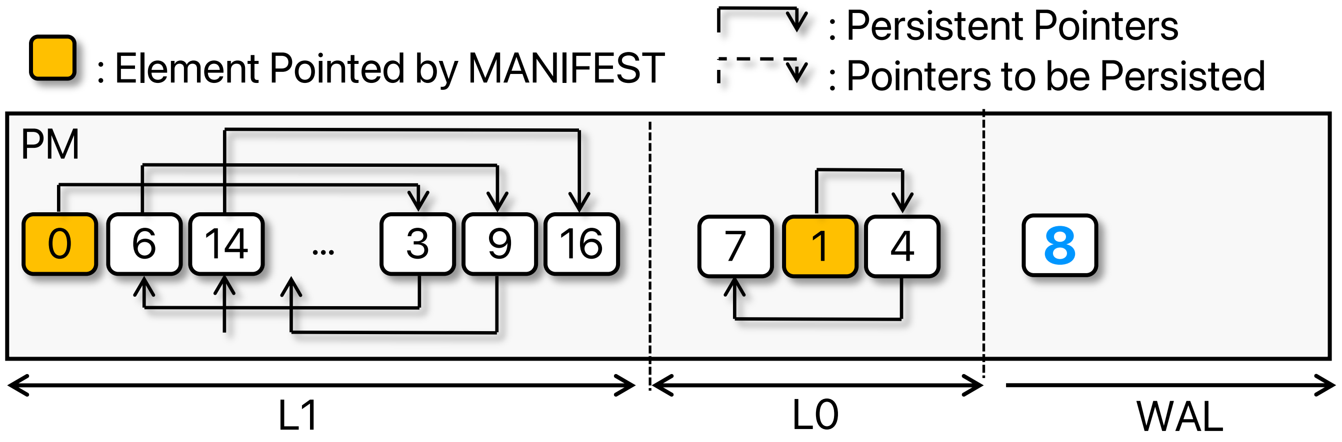
Physical PM Layout for MemTable Write

❑ Ex) Put 8 → Put 2 → Put 5

Logical View



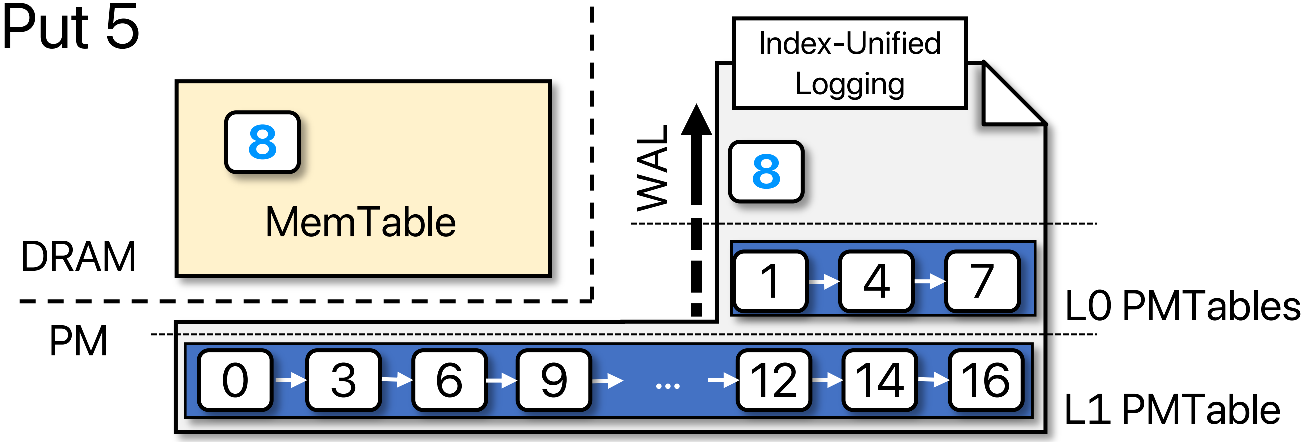
Physical PM Layout



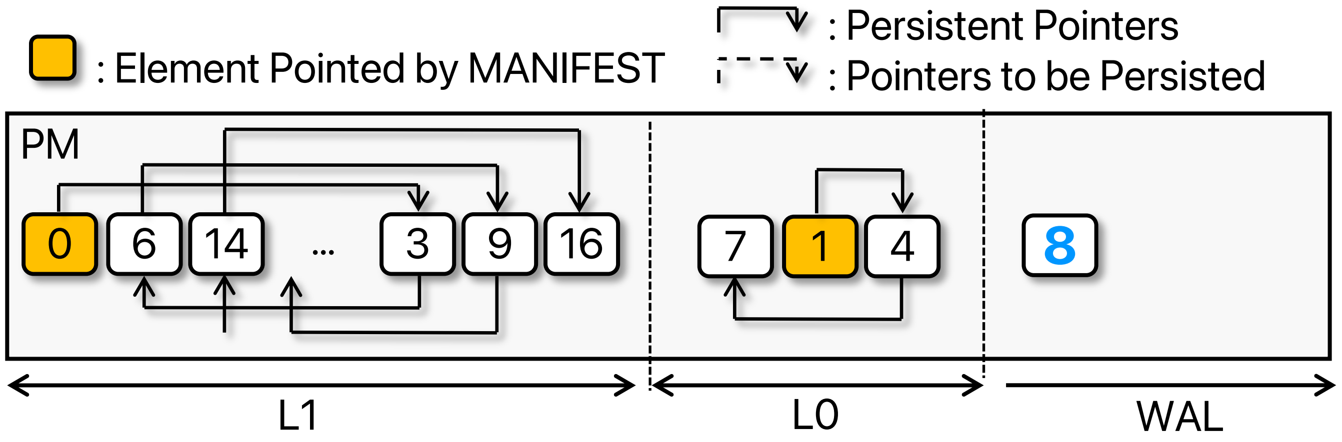
Physical PM Layout for MemTable Write

- ❑ Ex) Put 8 → Put 2 → Put 5

Logical View



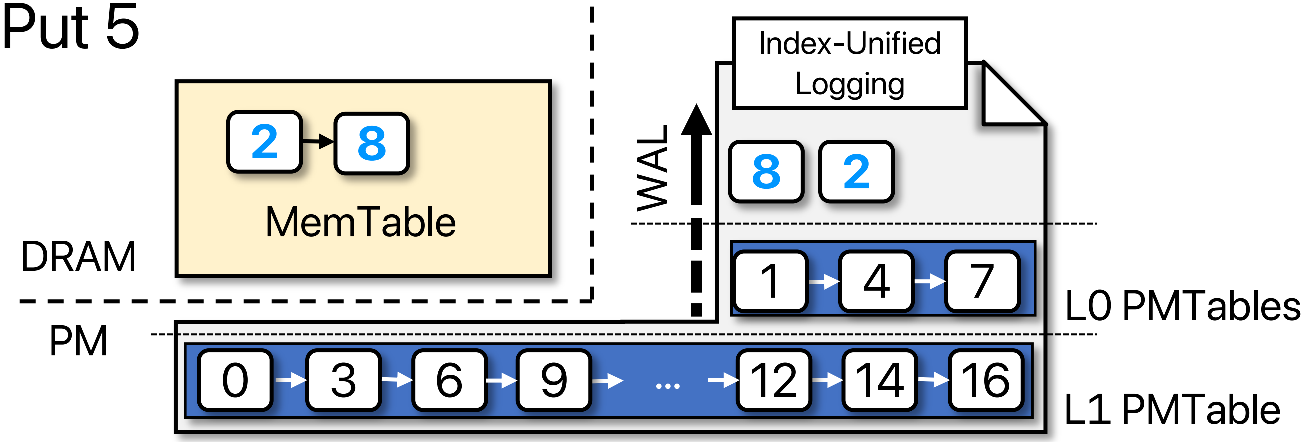
Physical PM Layout



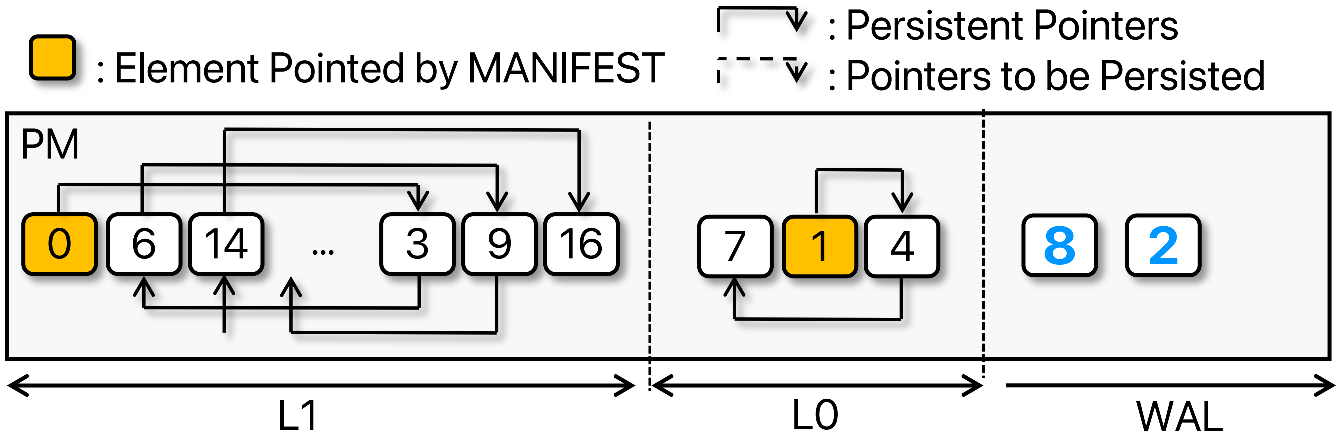
Physical PM Layout for MemTable Write

❑ Ex) Put 8 → Put 2 → Put 5

Logical View



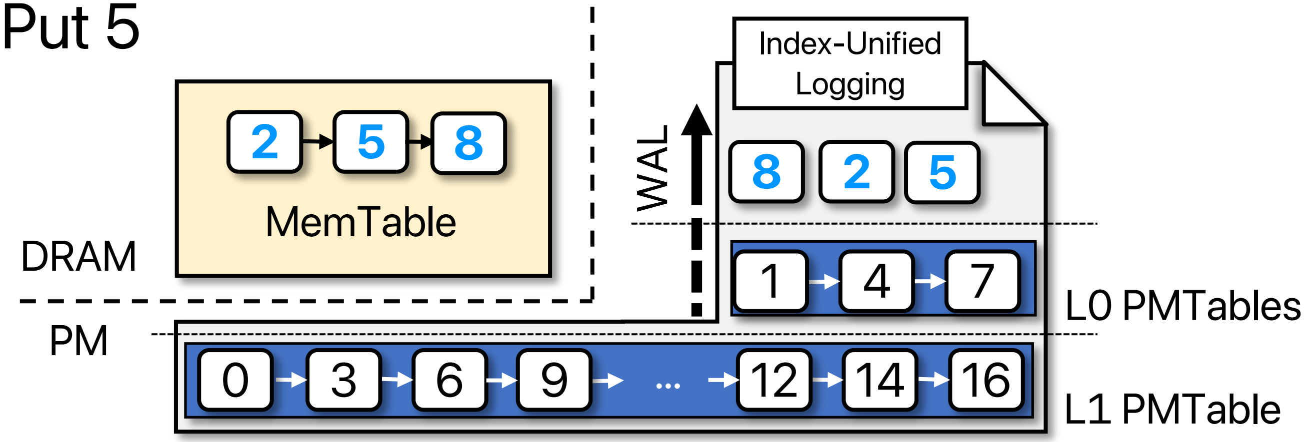
Physical PM Layout



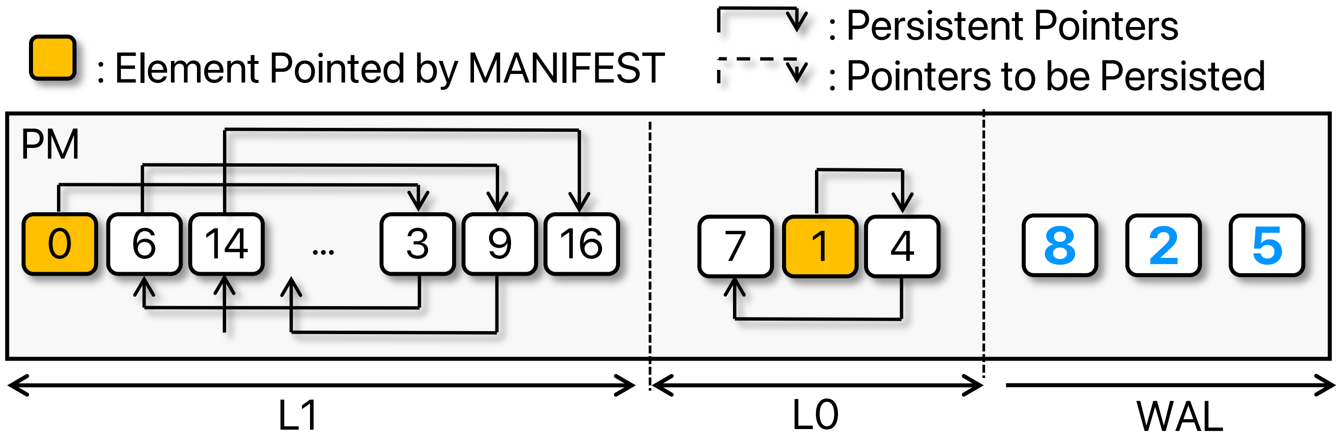
Physical PM Layout for MemTable Write

- ❑ Ex) Put 8 → Put 2 → Put 5

Logical View



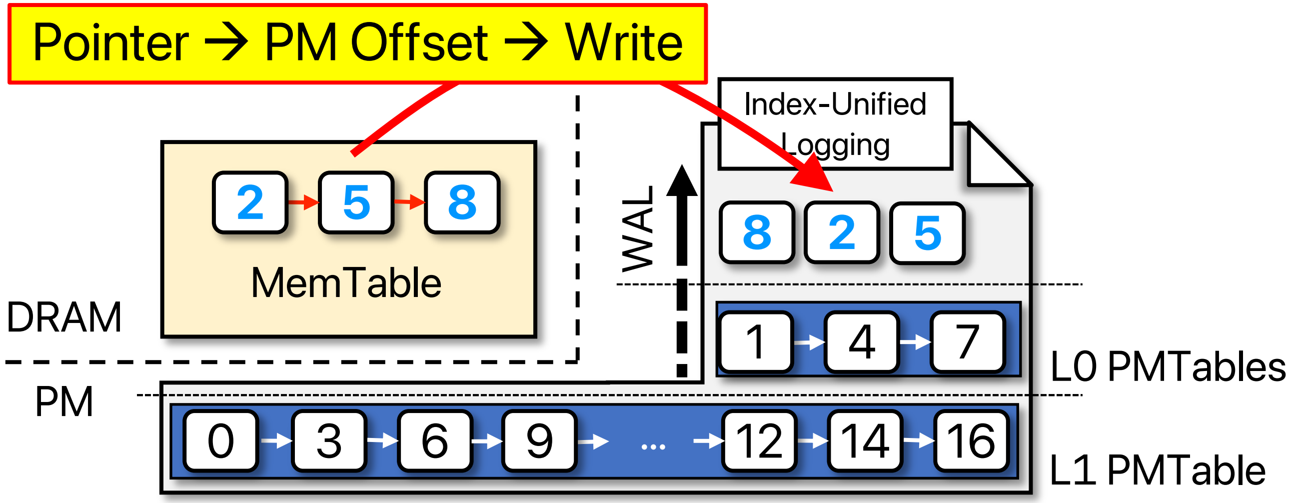
Physical PM Layout



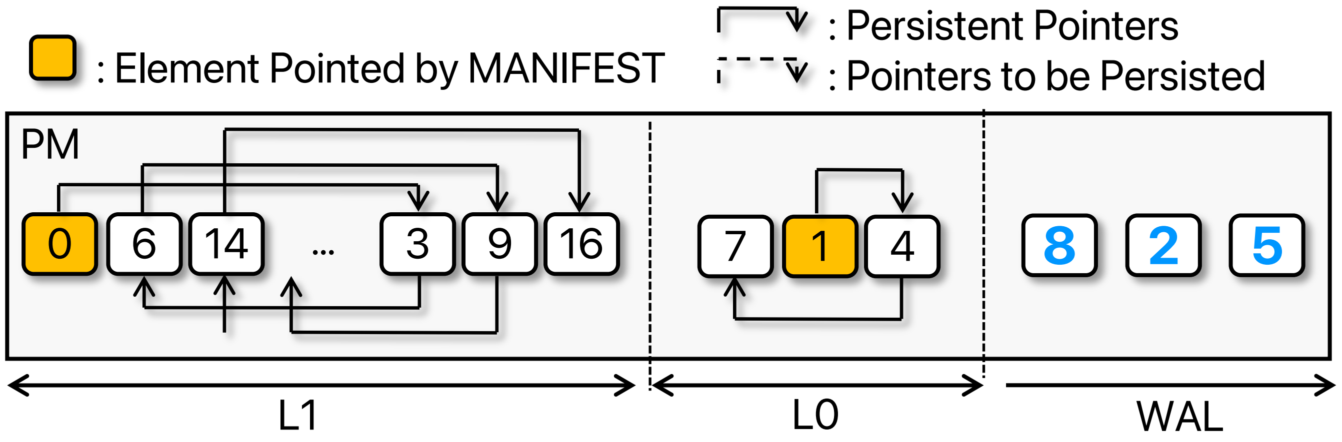
Physical PM Layout for Flush

❑ Ex) Flush MemTable

Logical View



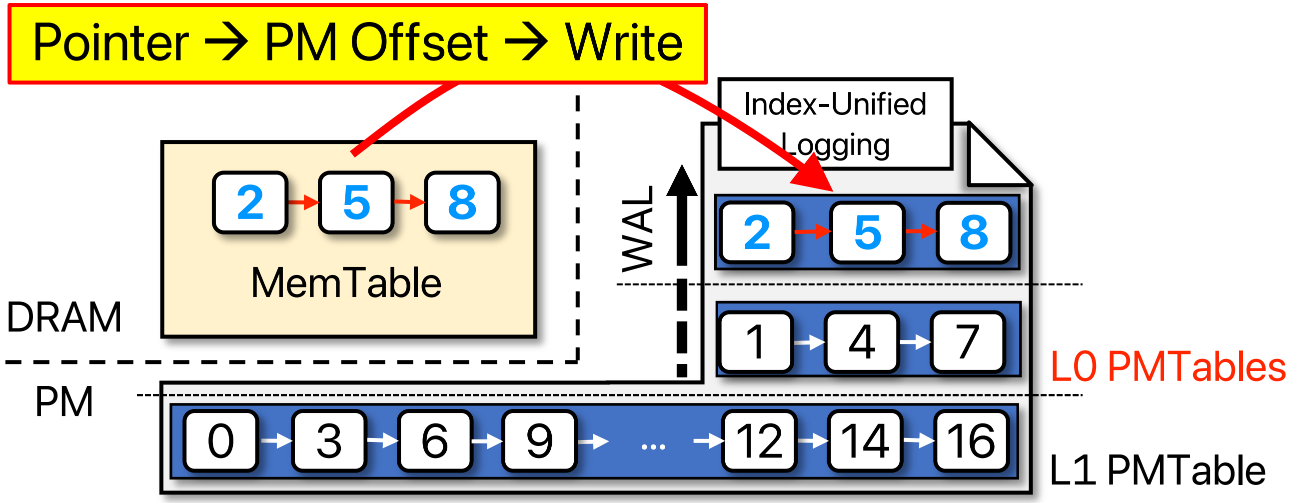
Physical PM Layout



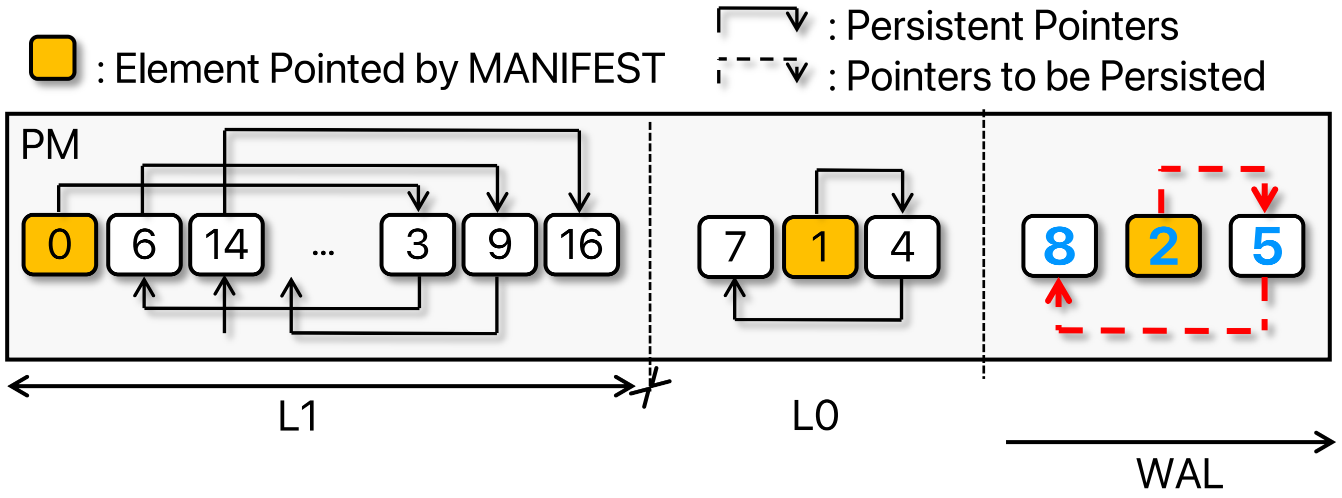
Physical PM Layout for Flush

❑ Ex) Flush MemTable

Logical View



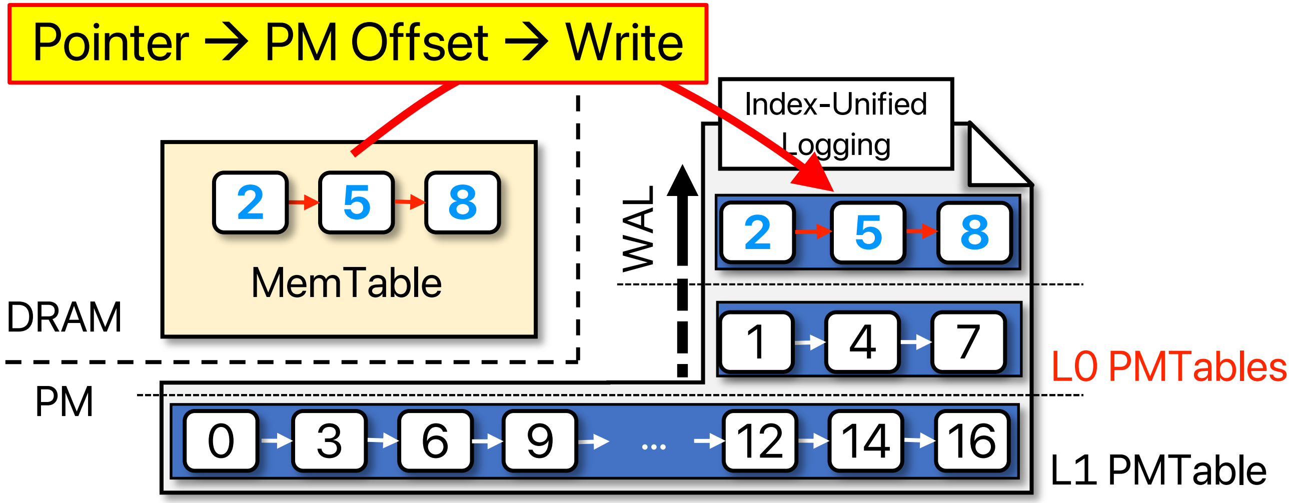
Physical PM Layout



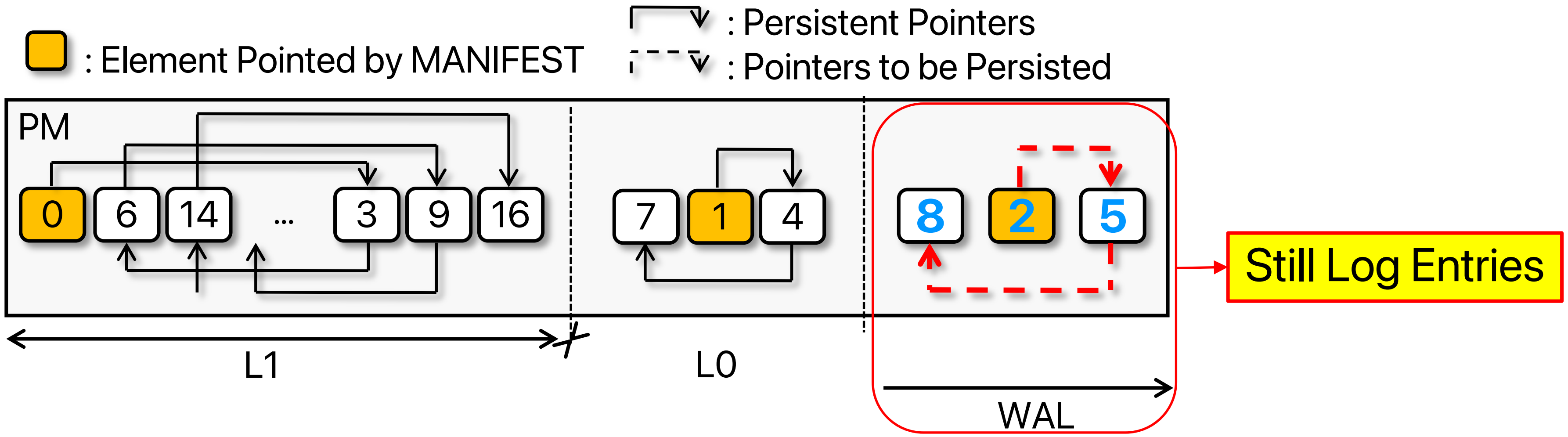
Physical PM Layout for Flush

❑ Ex) Flush MemTable

Logical View



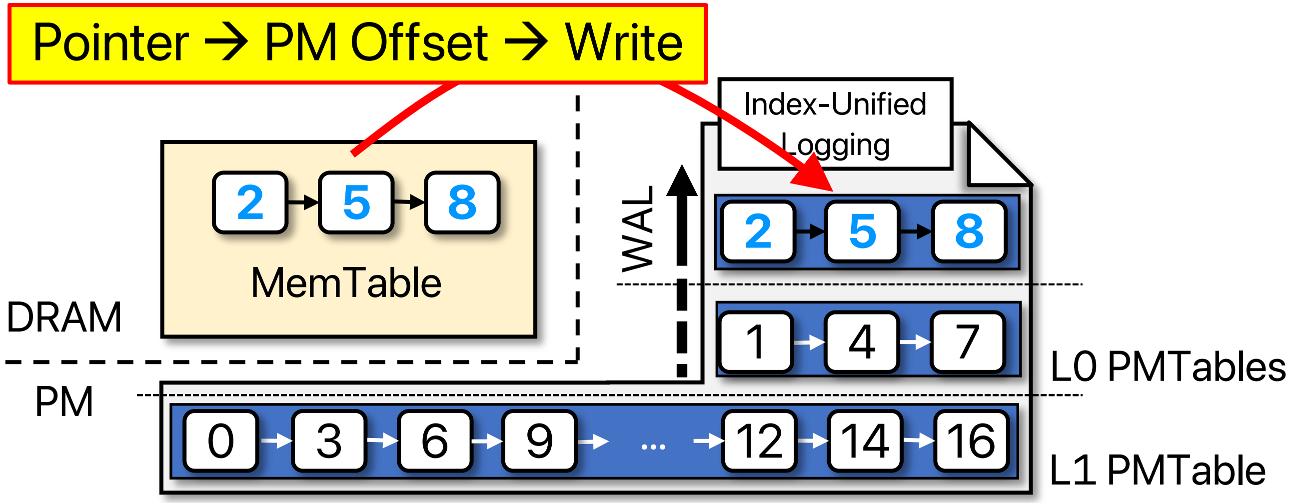
Physical PM Layout



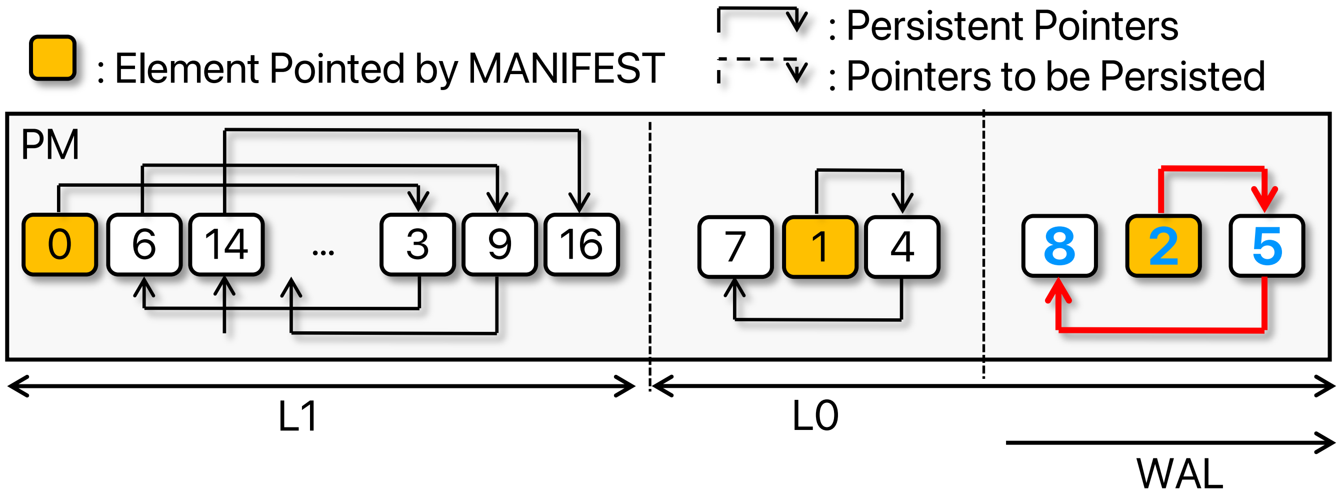
Physical PM Layout for Flush

- ❑ Ex) Flush MemTable

Logical View



Physical PM Layout

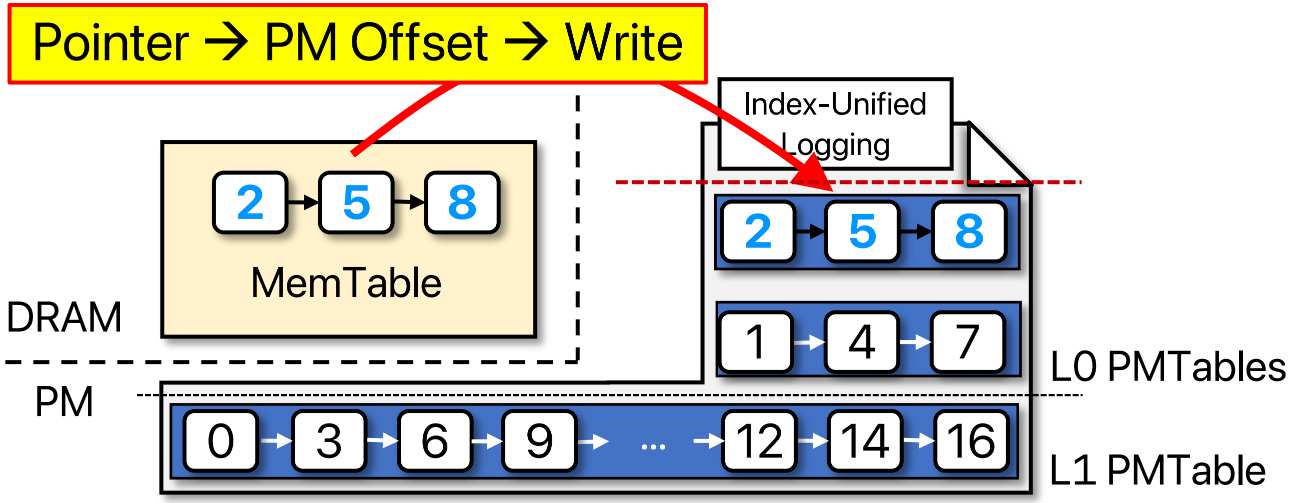


Checkpointing

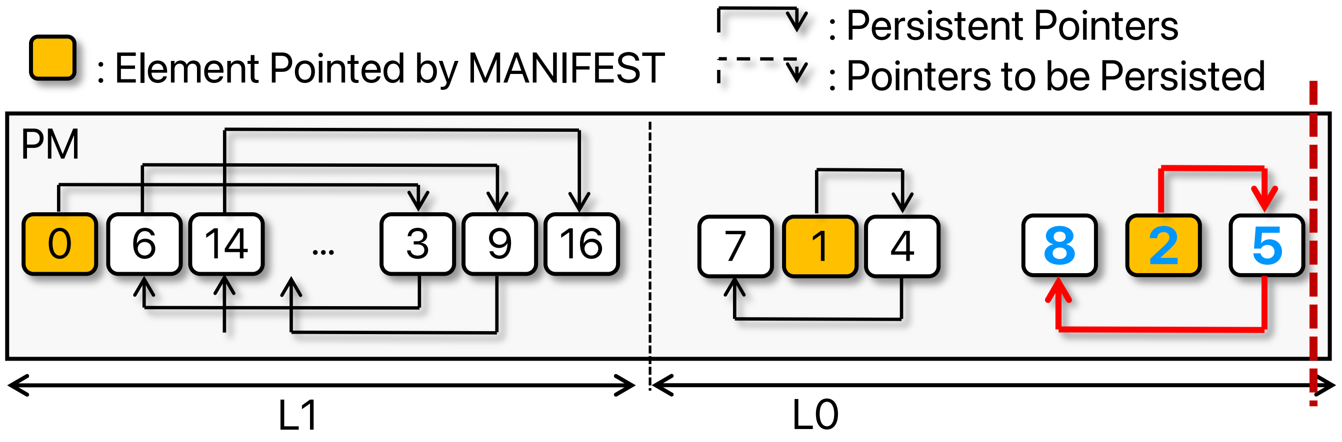
Physical PM Layout for Flush

❑ Ex) Flush MemTable

Logical View



Physical PM Layout



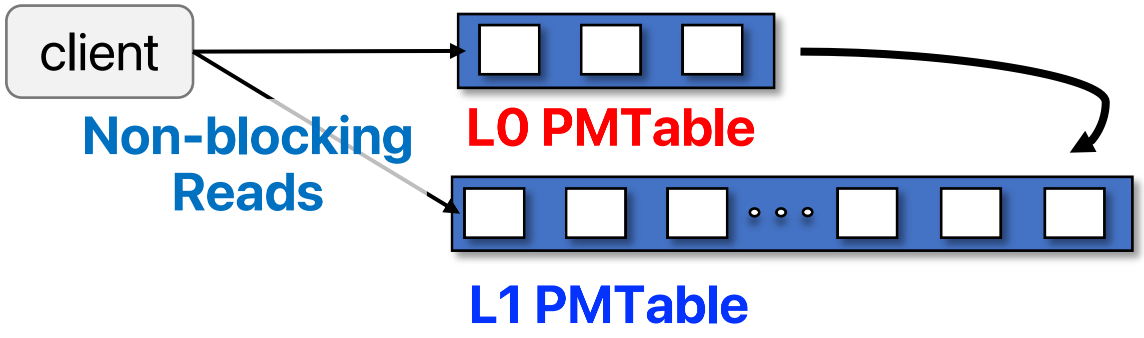
Checkpointing

Zipper Compaction

In-place merge-sort L0 → L1

- Only pointers are updated

  → Reduce write amplification



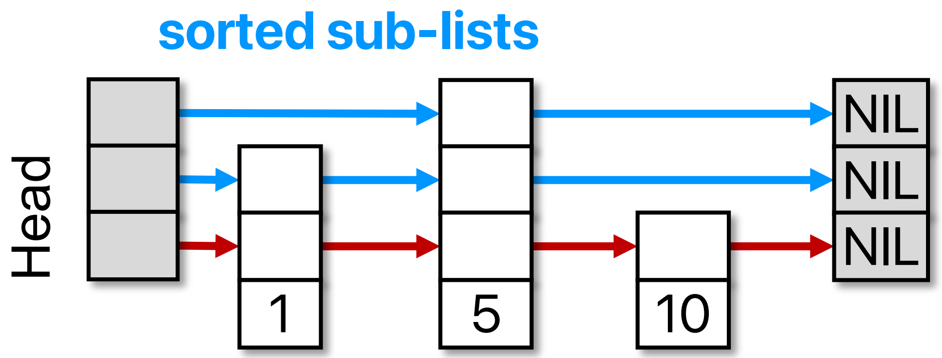
Zipper Compaction does not block concurrent reads

- Every step preserves the SkipList invariant for correct search
- SkipList Invariant: Upper layer list is a sorted sub-list of the bottom layer

Two phases to preserve the invariant

(i) Scan: HEAD → TAIL

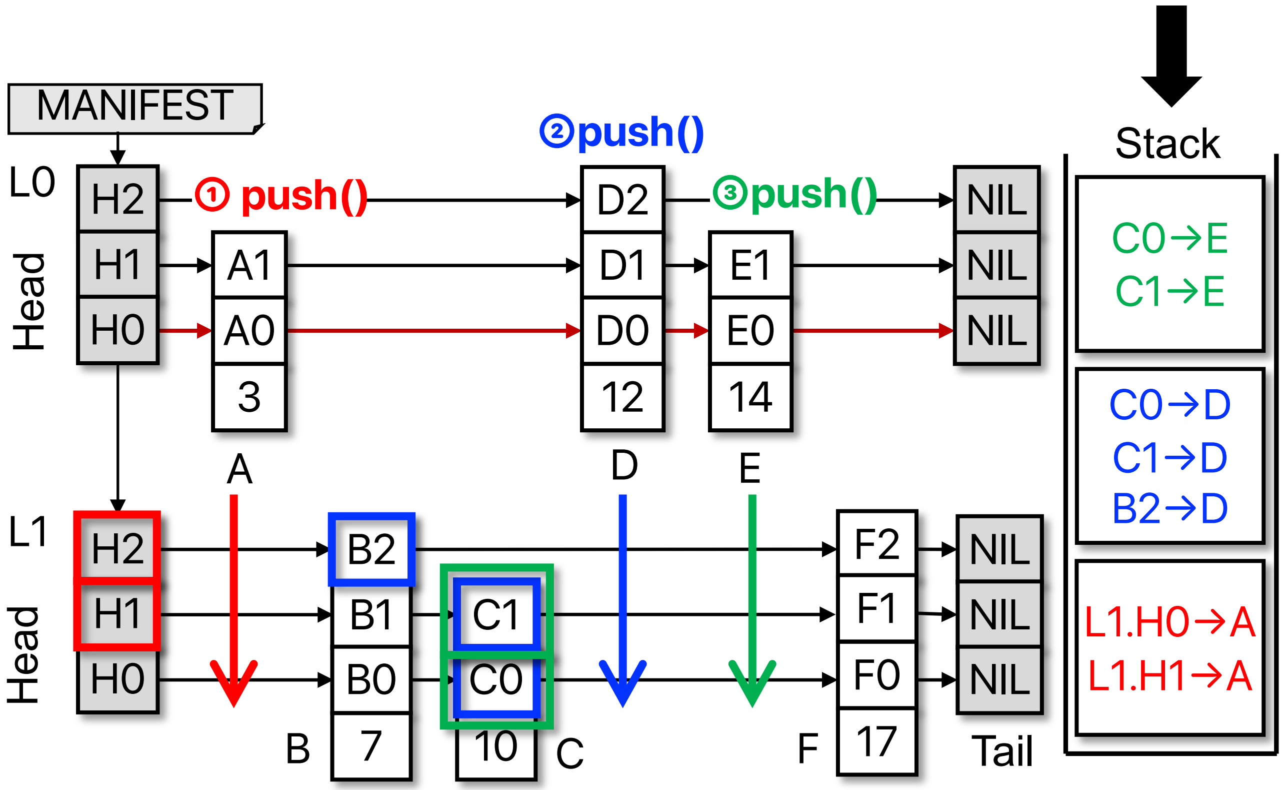
(ii) Merge: TAIL → HEAD



Zipper Compaction: Scan Phase

Scan Phase:

- Traverse L0 and L1
- Determine where to insert each L0 element in the L1
- Store the pointer updates on a stack



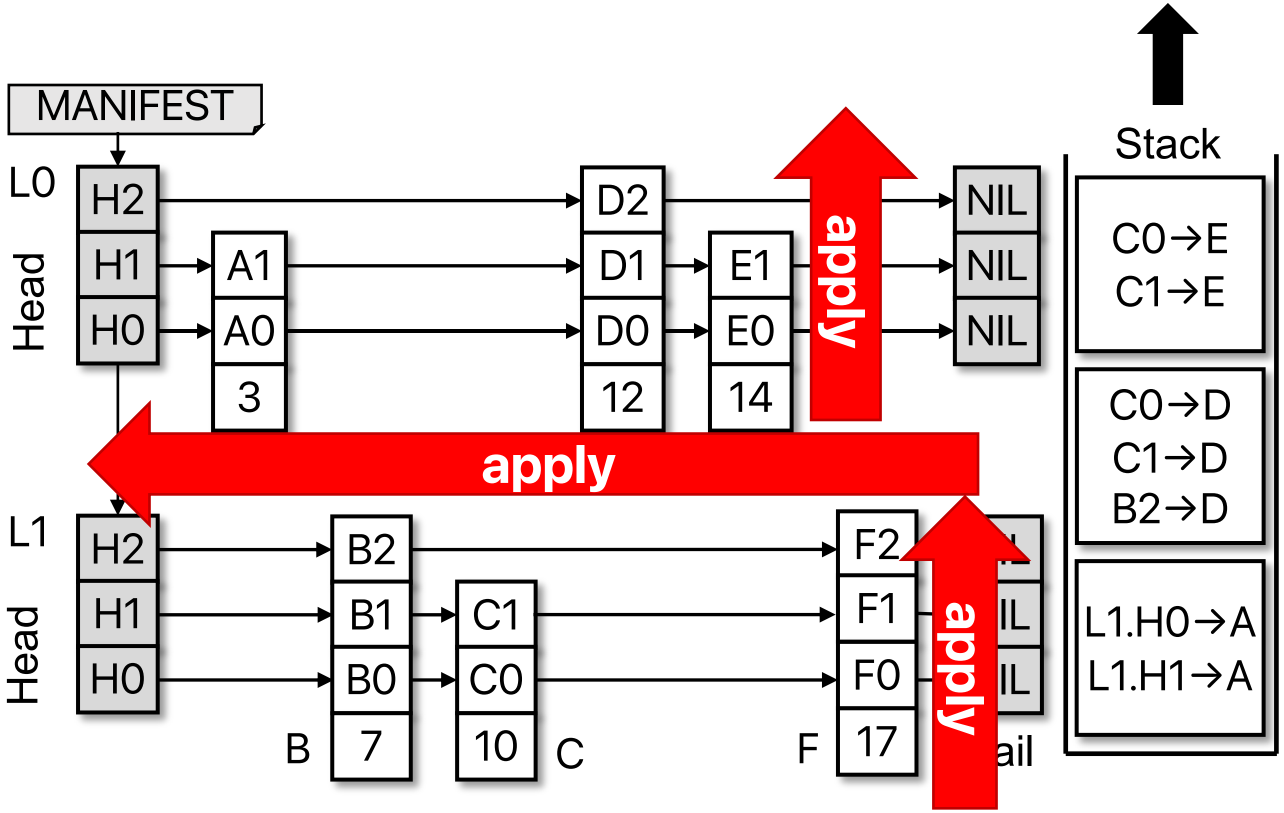
Zipper Compaction: Merge Phase

Merge Phase:

- Pop and apply
- From **TAIL to HEAD (bottom first)**

→ Preserves the SkipList invariant

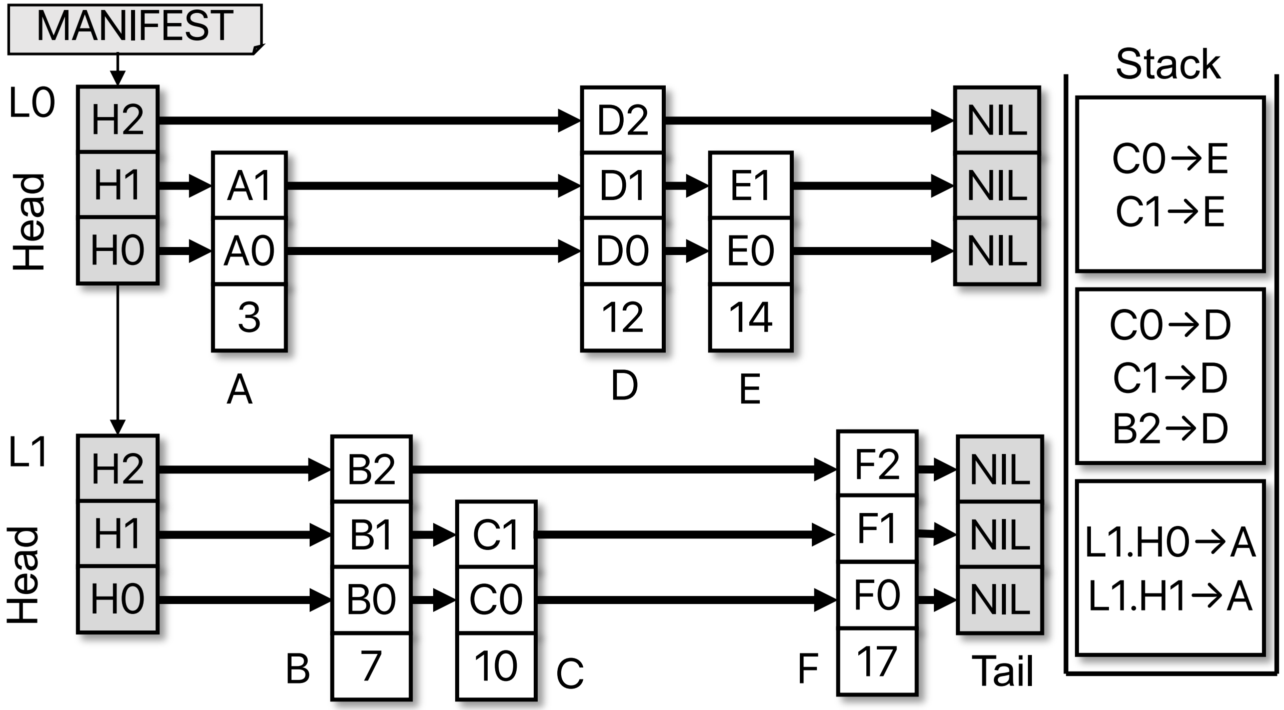
→ **Correct search** result at every step



Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

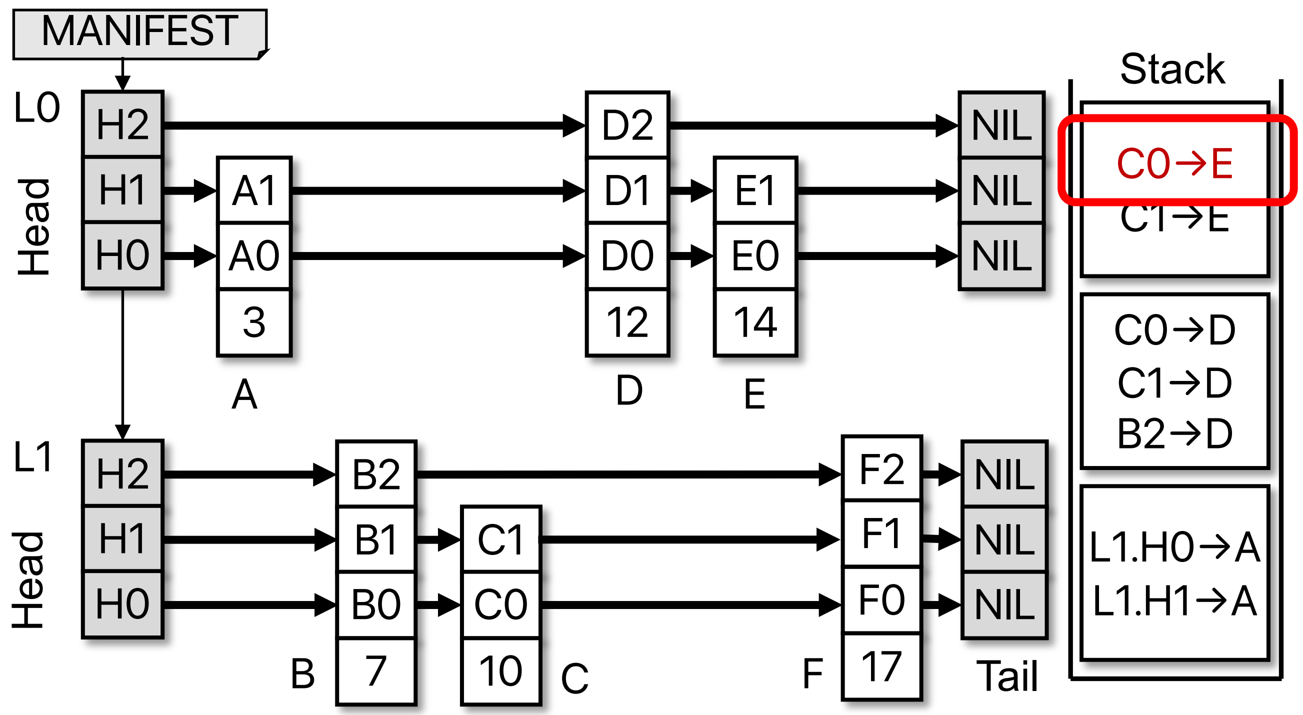
1. Update Y_n to the value of X_n
2. Update the X_n to point to Y



Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

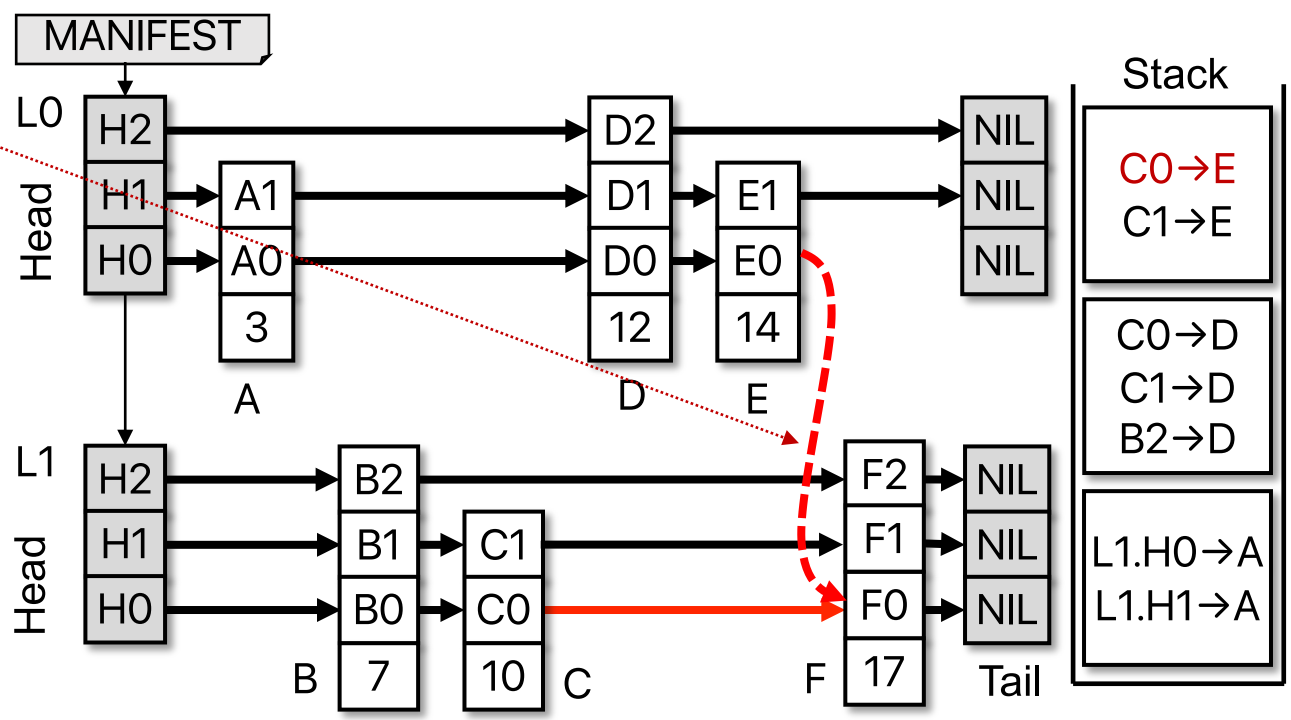
1. Update Y_n to the value of X_n
2. Update the X_n to point to Y



Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

1. Update Y_n to the value of X_n
2. Update the X_n to point to Y



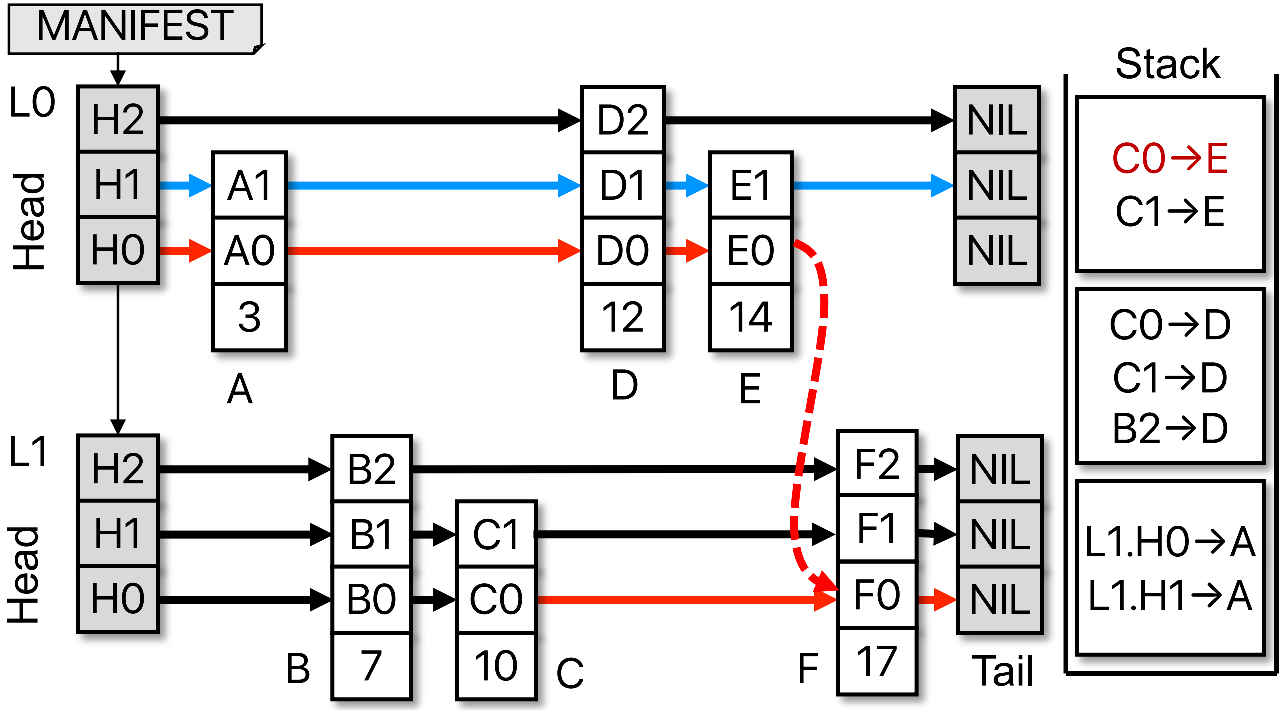
Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

1. Update Y_n to the value of X_n
2. Update the X_n to point to Y

- [A, D, E] is a sub-list of [A, D, E, F]

→ The invariant is preserved



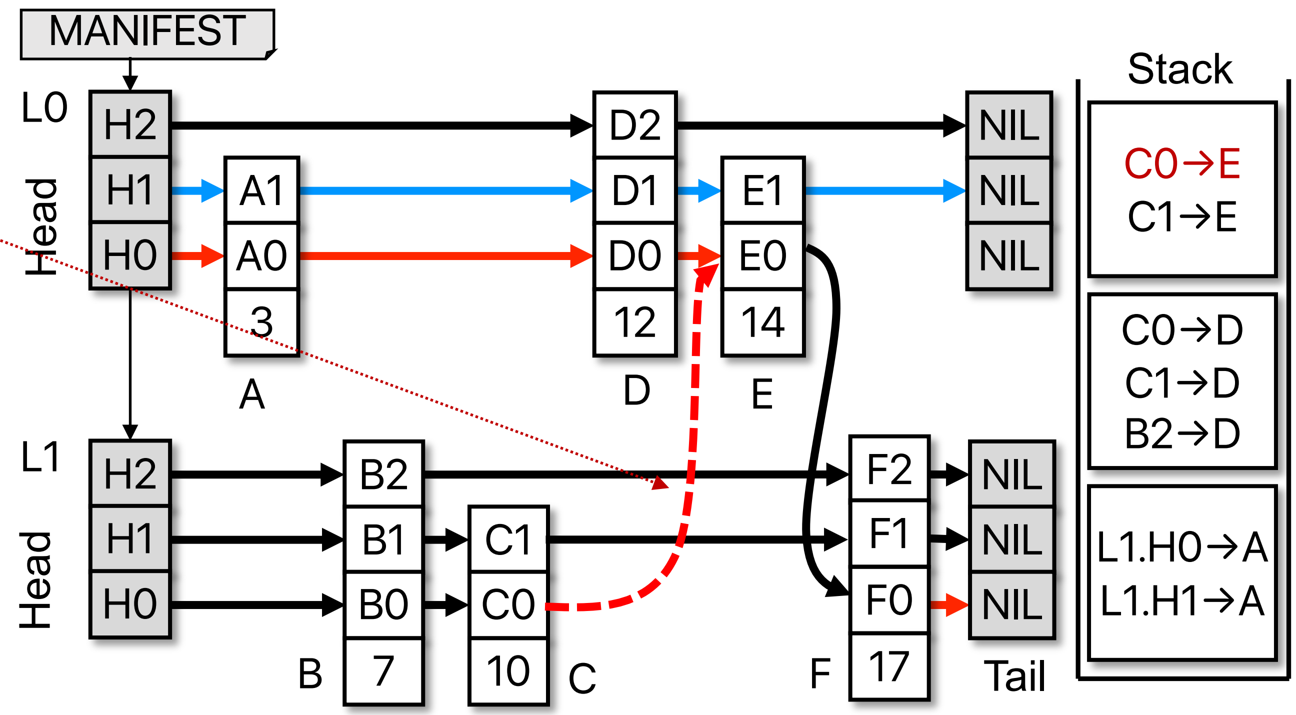
Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

1. Update Y_n to the value of X_n
2. Update the X_n to point to Y

- [A, D, E] is a sub-list of [A, D, E, F]

→ The invariant is preserved



Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

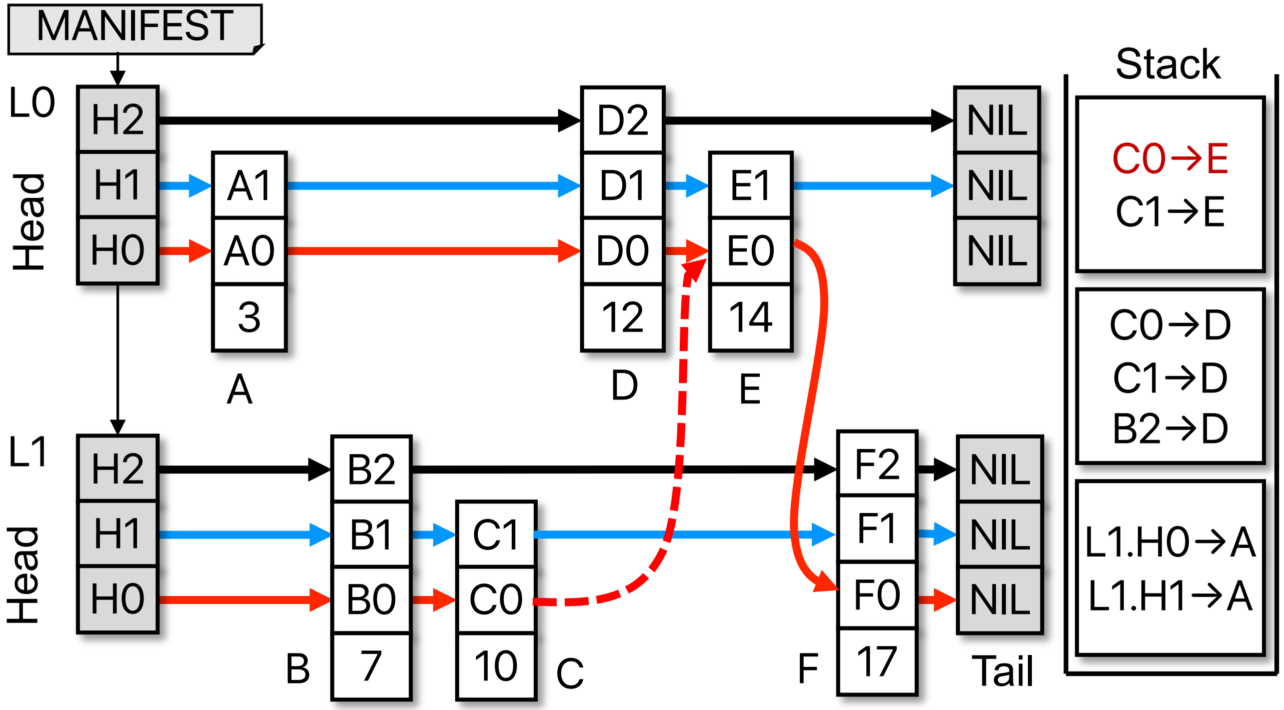
1. Update Y_n to the value of X_n
2. Update the X_n to point to Y

- [A, D, E] is a sub-list of [A, D, E, F]

→ The invariant is preserved

- [B, C, F] is a sub-list of [B, C, E, F]

→ The invariant is preserved



Zipper Compaction: Merge Phase

For each update item $X_n \rightarrow Y$,

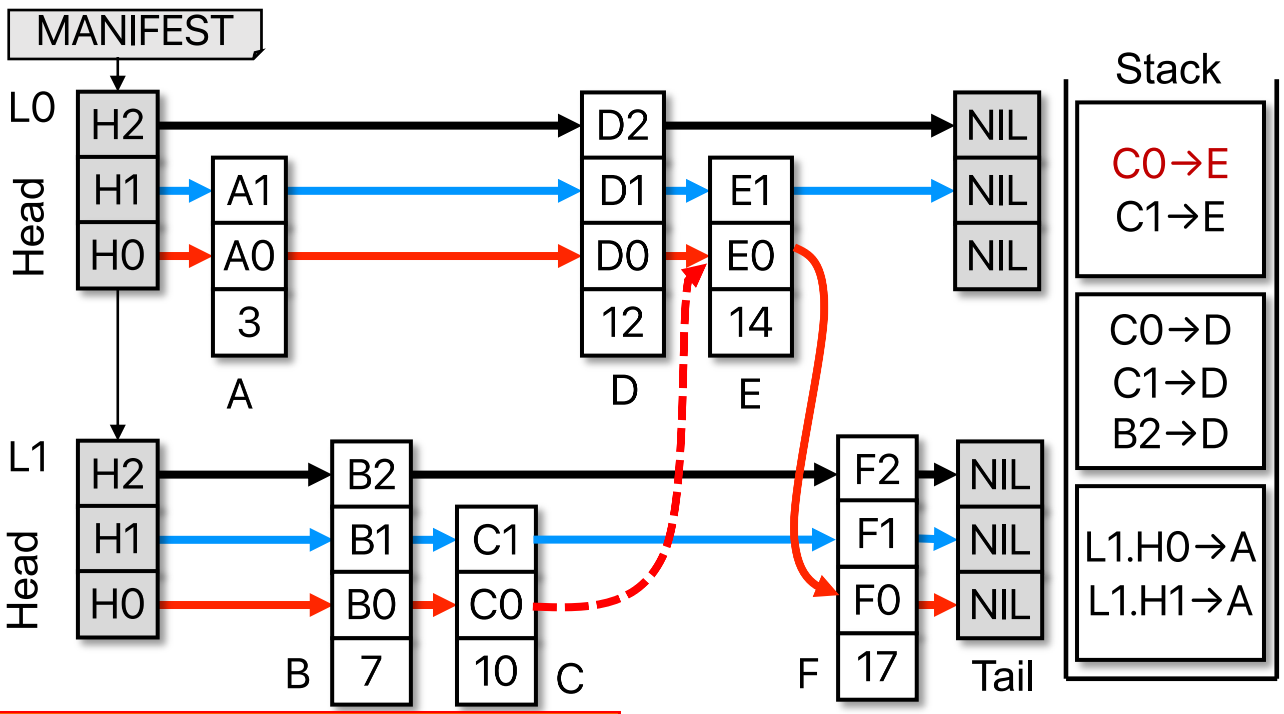
1. Update Y_n to the value of X_n
2. Update the X_n to point to Y

- [A, D, E] is a sub-list of [A, D, E, F]

→ The invariant is preserved

- [B, C, F] is a sub-list of [B, C, E, F]

→ The invariant is preserved

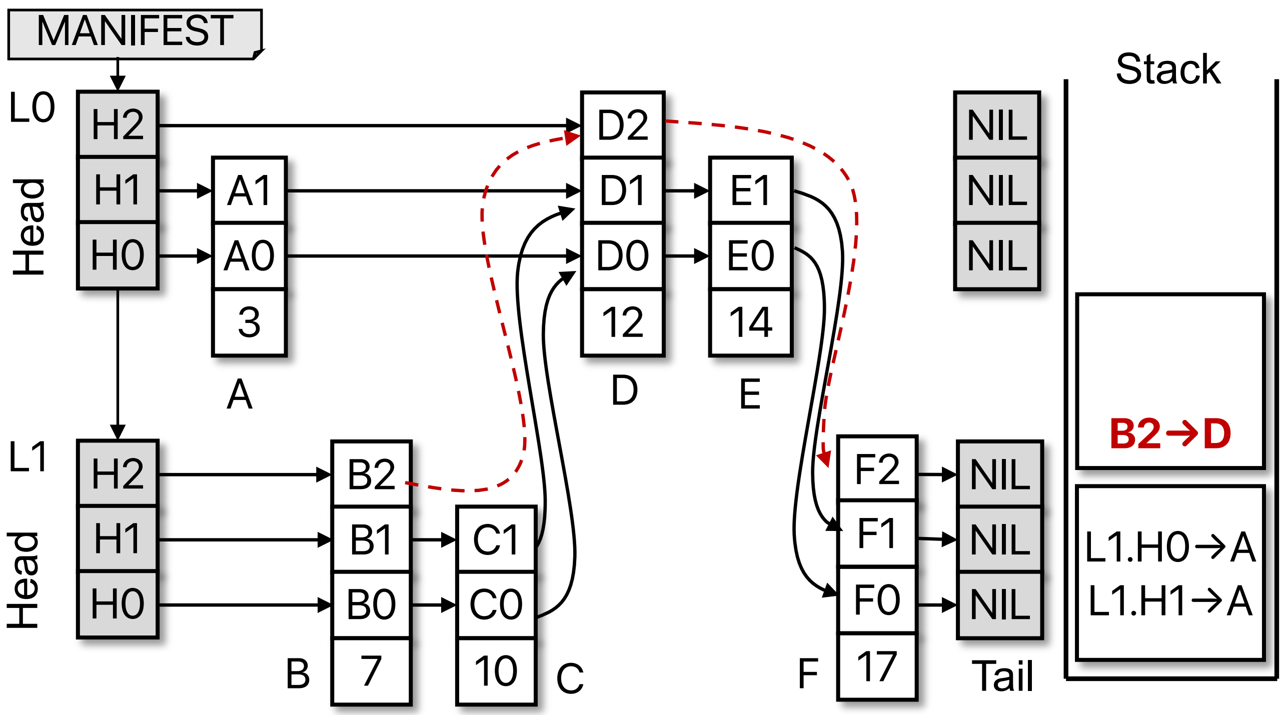


- E appears in both L0 and L1
- But correct search results guaranteed for concurrent reads

Zipper Compaction: Merge Phase

For each update $X_n \rightarrow Y$,

1. Update Y_n to the value of X_n
2. Set the X_n to point to Y



The Invariant is preserved at every step
→ Correct search result

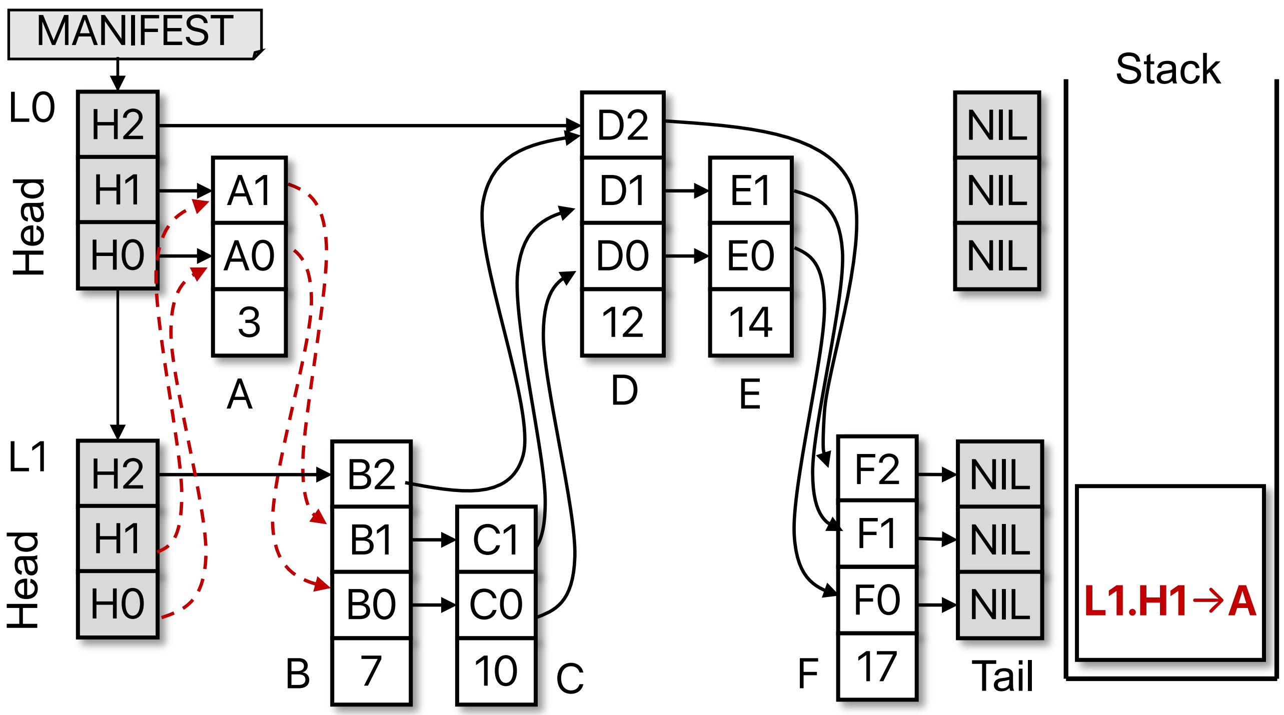
Zipper Compaction: Merge Phase

For each update $X_n \rightarrow Y$,

1. Update Y_n to the value of X_n
2. Set the X_n to point to Y

The Invariant is preserved at every step

→ Correct search result

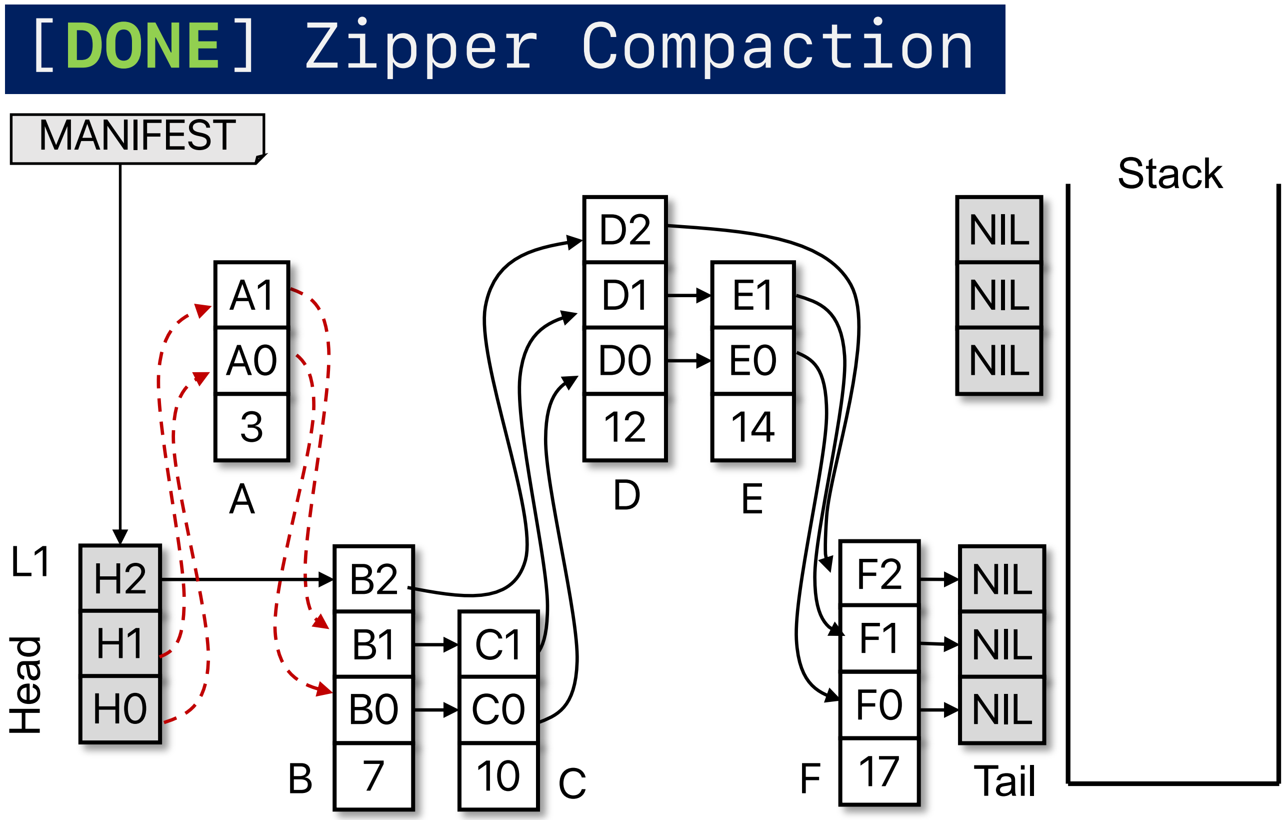


Zipper Compaction: Merge Phase

For each update $X_n \rightarrow Y$,

1. Update Y_n to the value of X_n
2. Set the X_n to point to Y

The Invariant is preserved at every step
→ Correct search result



NUMA-Aware Braided SkipList

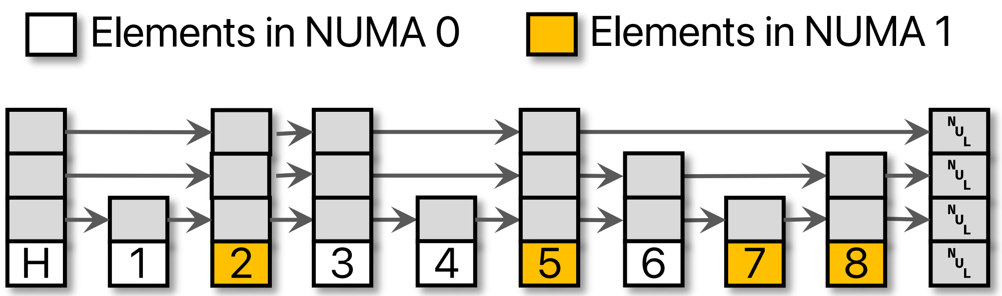
Correct Searches are guaranteed as long as the invariant is preserved

***NUMA-aware Braided SkipList*:**

- Elements in upper layers are NUMA locally linked
- All elements are connected at the bottom layer

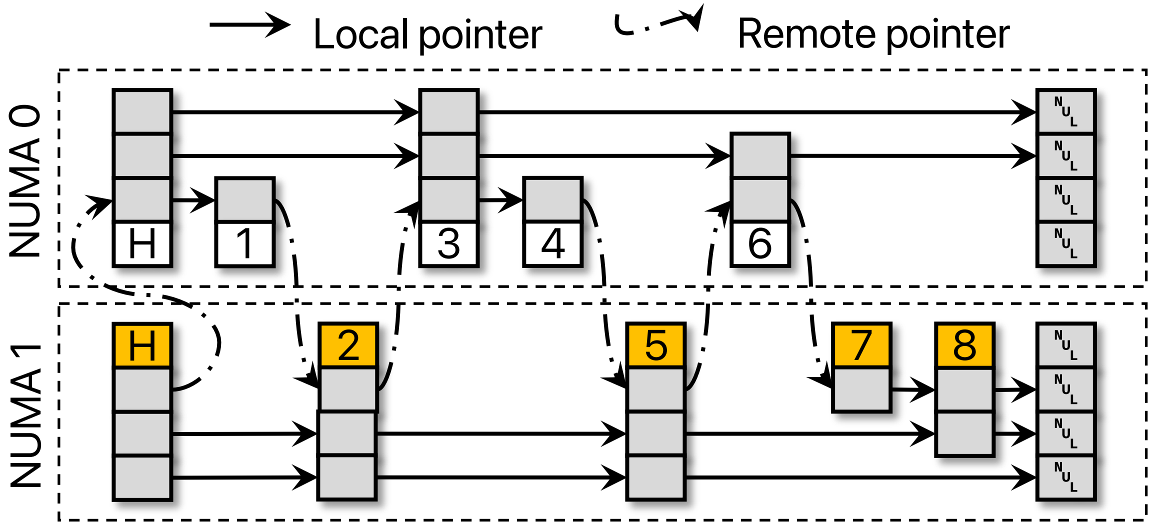
→ **The invariant is preserved**

→ Correct search results



NUMA-oblivious SkipList

* Elements are created by clients on random NUMA nodes

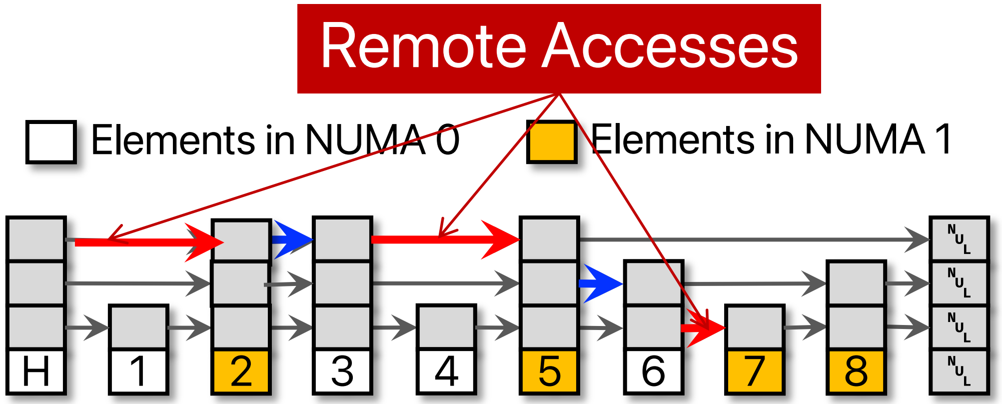


NUMA-aware Braided SkipList

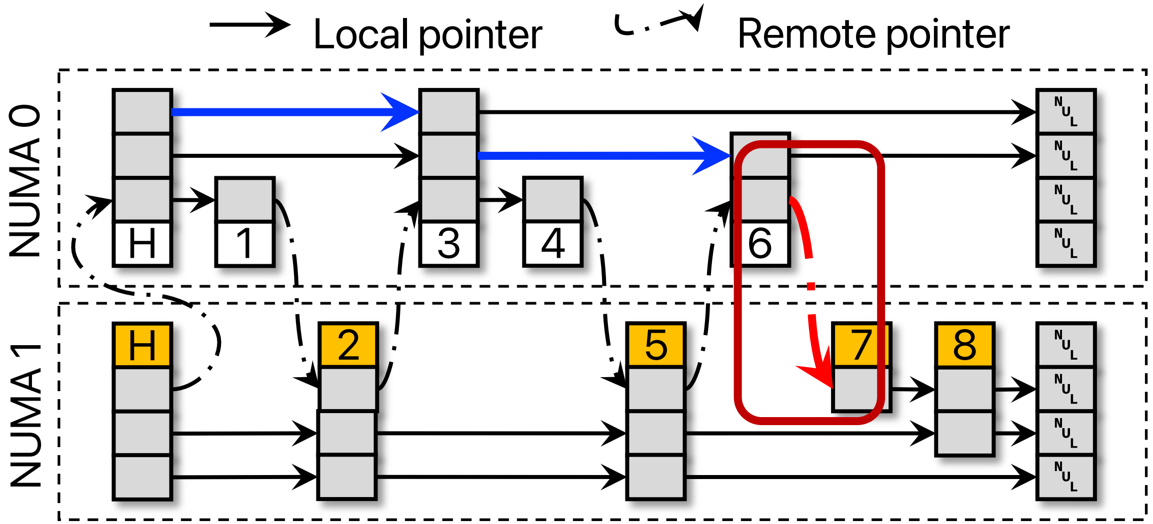
NUMA-Aware Braided SkipList

- Ex) a client on **NUMA 0** searches **key 7**

$1/N$ remote memory accesses compared to conventional SkipLists (N is the number of NUMA nodes).



NUMA-oblivious SkipList



NUMA-aware Braided SkipList

Experimental Setup

Testbed: 4-socket machine (4 NUMA nodes)

- CPU: 4 × Intel Xeon Gold 5215 (20 vCPUs per socket)
- DRAM: 256 GB
- PM: 2 TB

Benchmarks:

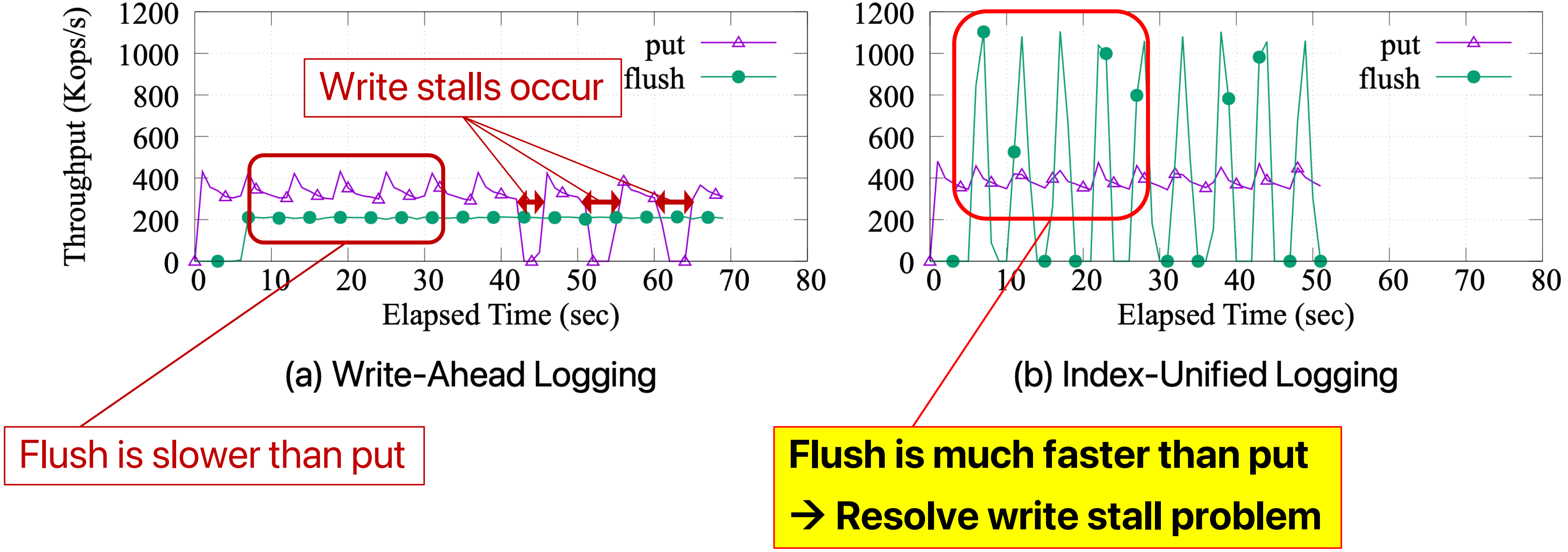
- YCSB
- Facebook Benchmark (modeling-based synthetic workload generator [FAST '20])

Evaluation Goal:

- The effectiveness of 3 designs
- Recovery performance of asynchronous checkpointing
- Comparison with Pmem-RocksDB

IUL vs. WAL: Flush Throughput

- ❑ Load A – 1 client thread, 1 worker thread

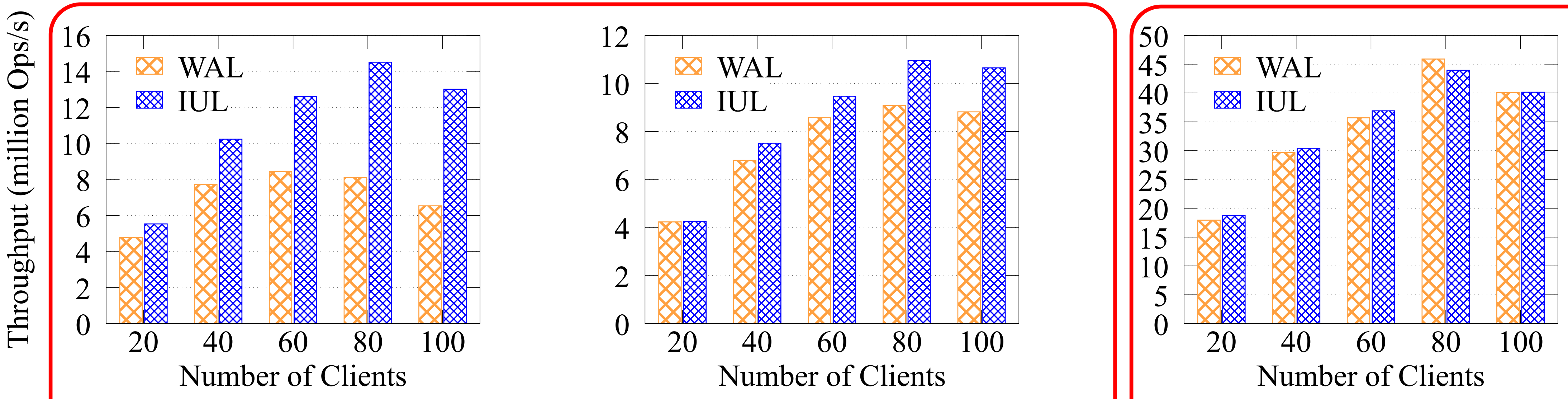


(a) Write-Ahead Logging

(b) Index-Unified Logging

IUL vs. WAL: YCSB

- 100 million queries after Load 100 million records
- # background workers = ½ of clients



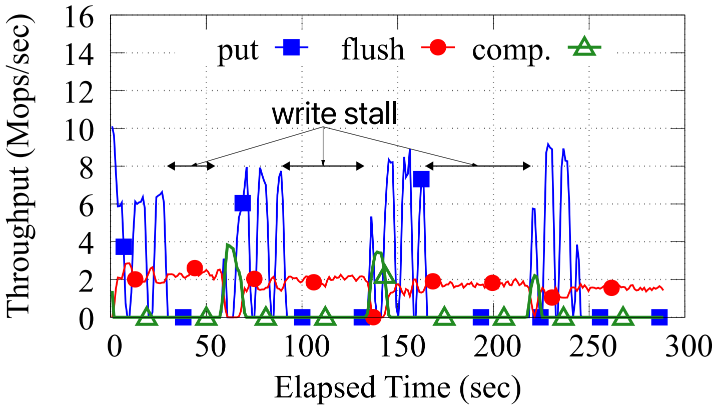
(a) Load A (Write 100%) (b) Workload A (Read 50% : Write 50%) (c) Workload C (Read 100%)

Without write stalls, IUL outperforms WAL for write-intensive workloads

IUL performs similarly to WAL for read-only workloads

Effectiveness of Each Design (Enabling one by one)

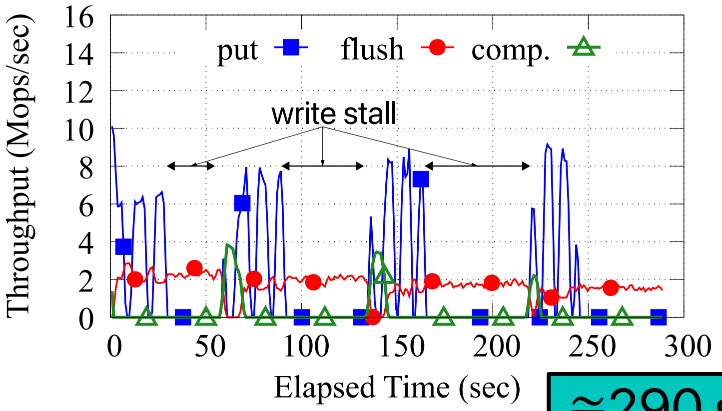
❑ Load A - 500 million records, 80 threads



(a) WAL

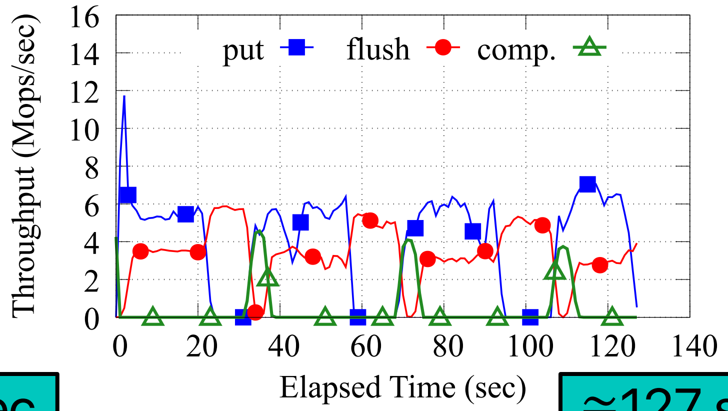
Effectiveness of Each Design (Enabling one by one)

- ❑ Load A - 500 million records, 80 threads



≅290 sec

(a) WAL



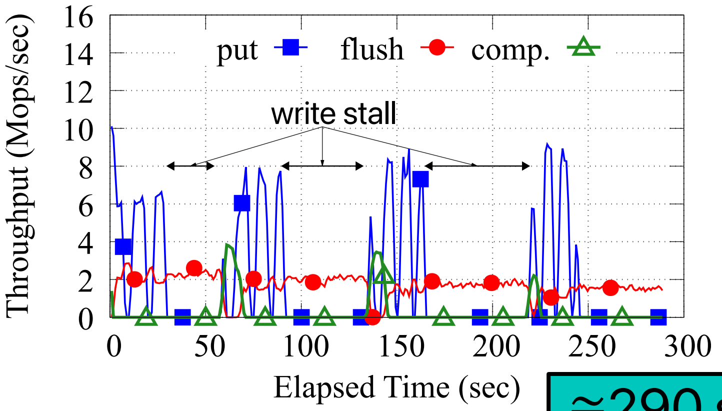
≅127 sec

(b) WAL+Braided

By ***reducing NUMA effects***, flush throughput increased
→ Put throughput increased

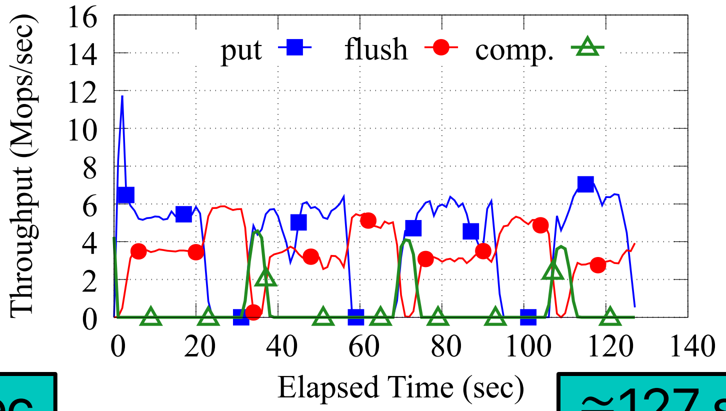
Effectiveness of Each Design (Enabling one by one)

- ❑ Load A - 500 million records, 80 threads



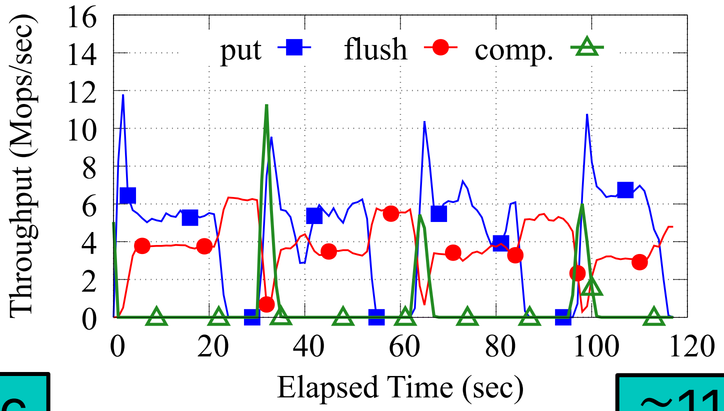
≅290 sec

(a) WAL



≅127 sec

(b) WAL+Braided



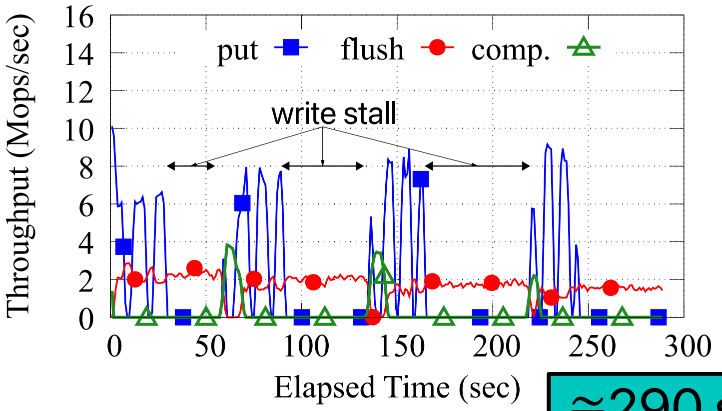
≅117 sec

(c) WAL+Braided+Zipper

Zipper Compaction makes compaction faster
→ Good for search performance

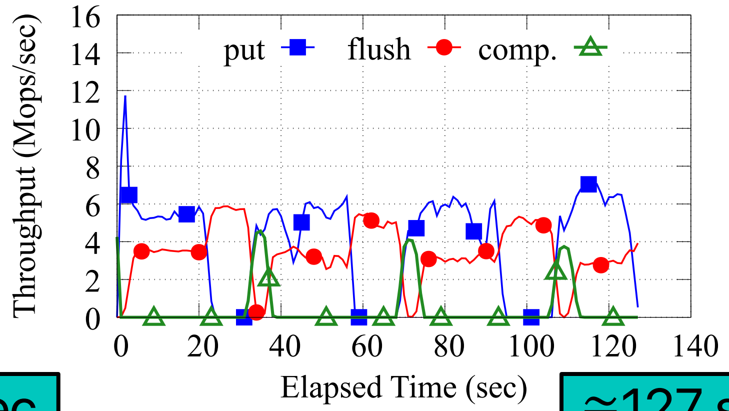
Effectiveness of Each Design (Enabling one by one)

- ❑ Load A - 500 million records, 80 threads



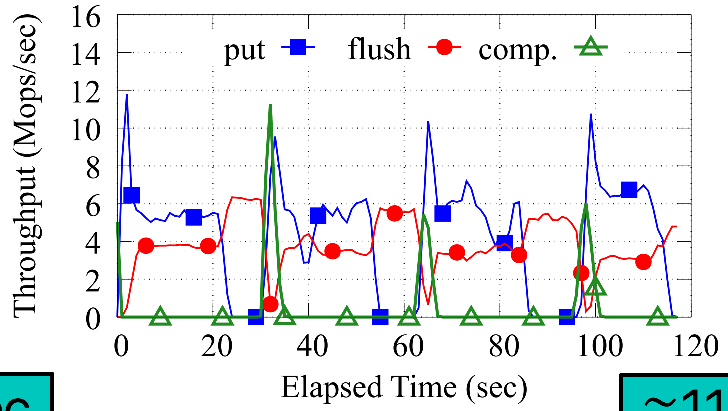
≅290 sec

(a) WAL



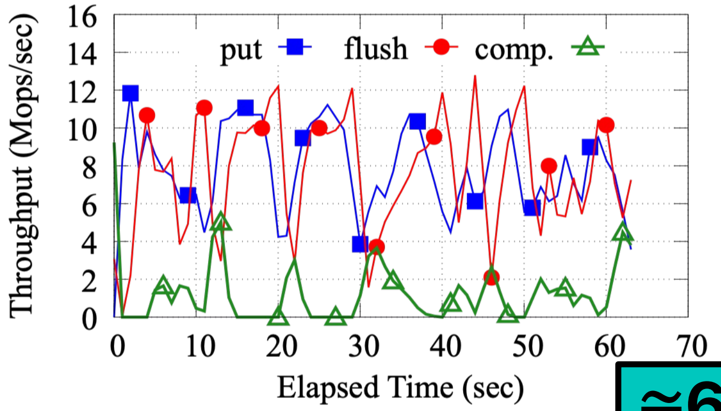
≅127 sec

(b) WAL+Braided



≅117 sec

(c) WAL+Braided+Zipper



≅63 sec

(d) IUL+Braided+Zipper

Index-Unified Logging enables faster flush
→ No write stalls
→ Put throughput significantly increased

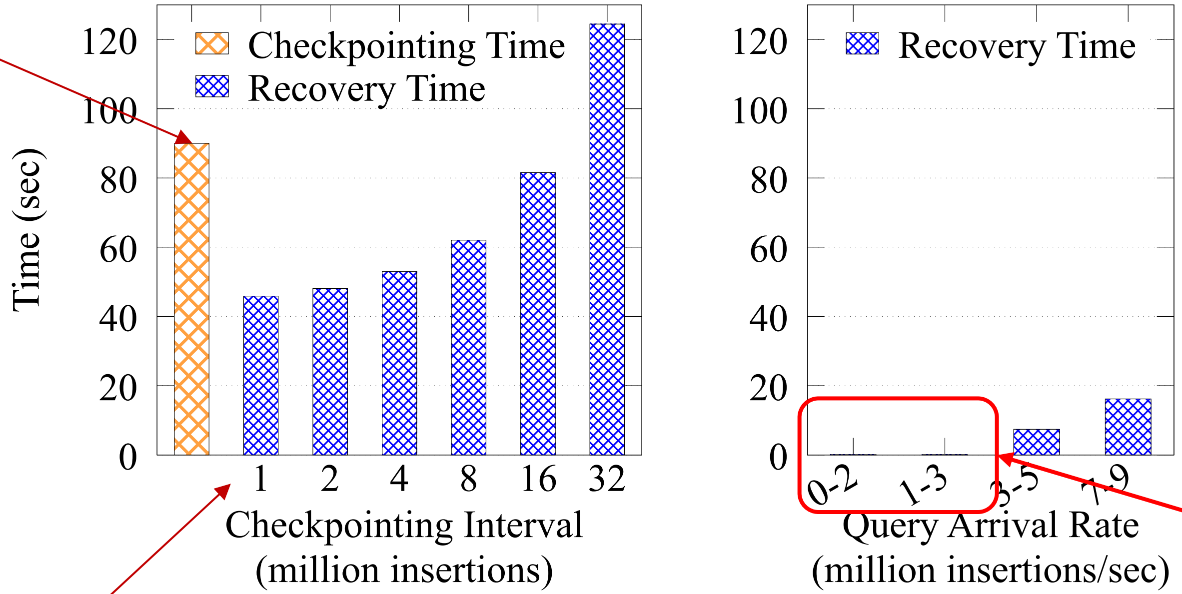
Recovery Performance

- Checkpointing and Recovery cost for around 100 million records

Checkpointing overhead for 100M records

→ Writes will be blocked for more than 90 sec at every interval

ListDB uses Asynchronous Checkpointing
→ Zero checkpointing overhead



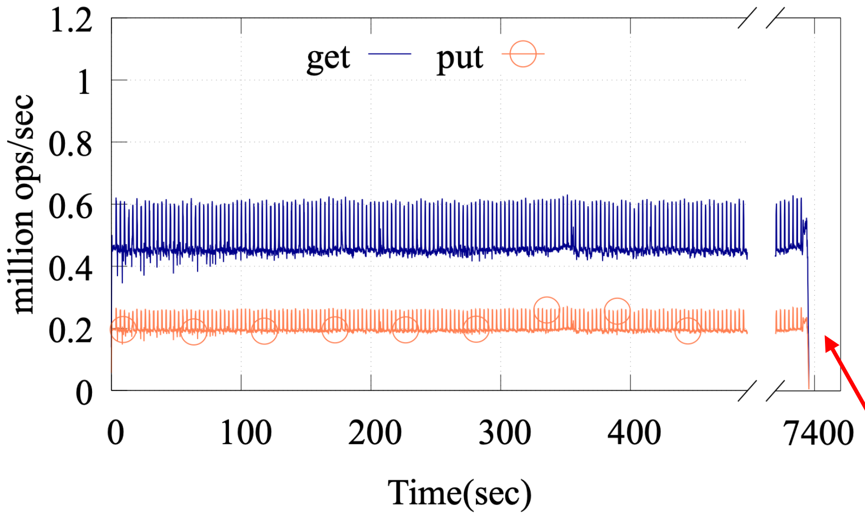
Instant recovery

(a) Synchronous Checkpointing (b) ListDB

↑ Checkpoint interval → ↑ Log replay time → ↑ Recovery cost

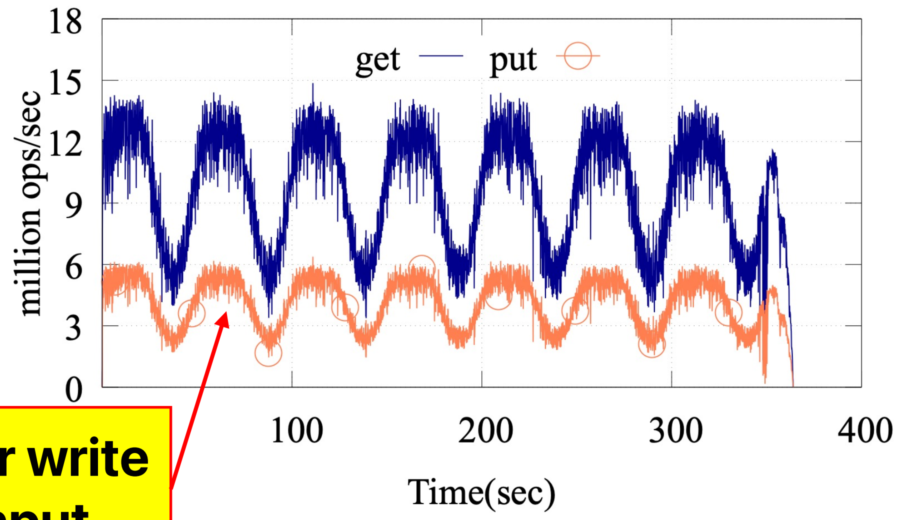
Comparison with Pmem-RocksDB

- Facebook Benchmark, 80 threads
  - Query Arrival Rate~Sine distribution (5 billion queries in total)
  - put : get = 3 : 7



(a) Pmem-RocksDB

25x higher write throughput



(b) ListDB

Throughput is saturated due to Write Amplification

Throughput = Query Arrival Rate

More Experiments in Our Paper

- NUMA effects
- Comparison with PM-only indexes
- Comparison with other LSM-based designs

Conclusion

ListDB avoids write stalls leveraging byte-addressability and high-performance of PM

- Avoiding data copies by restructuring data in-place
- Reducing write amplification
- NUMA-aware persistent index structure effectively reduces NUMA effects

With its three-level structure and **three novel designs**,
ListDB outperforms state-of-the-art PM-based key-value stores **in write throughput**.

❑ Our code is available at https://github.com/DICL/listdb

❑ **Looking for a Job!**

❑ **Email: wbkim@unist.ac.kr**