Persistent B+-Trees in Non-Volatile Main Memory

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Presentation By

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Persistent B^+ Trees in Non-Volatile Main Memory

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Persistent B^+ Trees in **Non-Volatile Main Memory**

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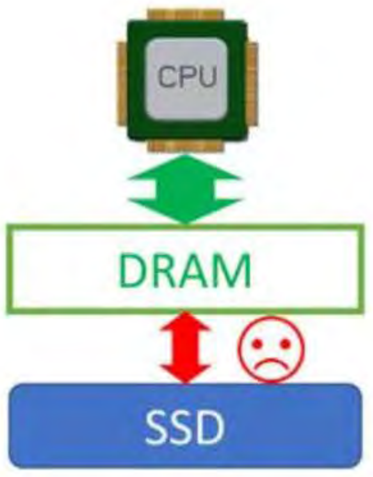
Persistent **B^+ Trees** in Non-Volatile Main Memory

Persistent B^+ Trees in **Non-Volatile Main Memory**

Main Memory	**Secondary Storage**
Fast	Slow
Volatile	Non-Volatile



Persistent B^+ Trees in **Non-Volatile Main Memory**

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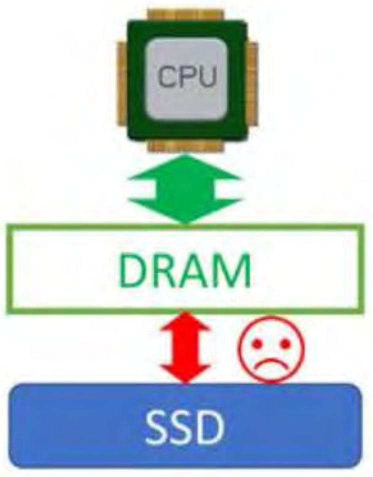

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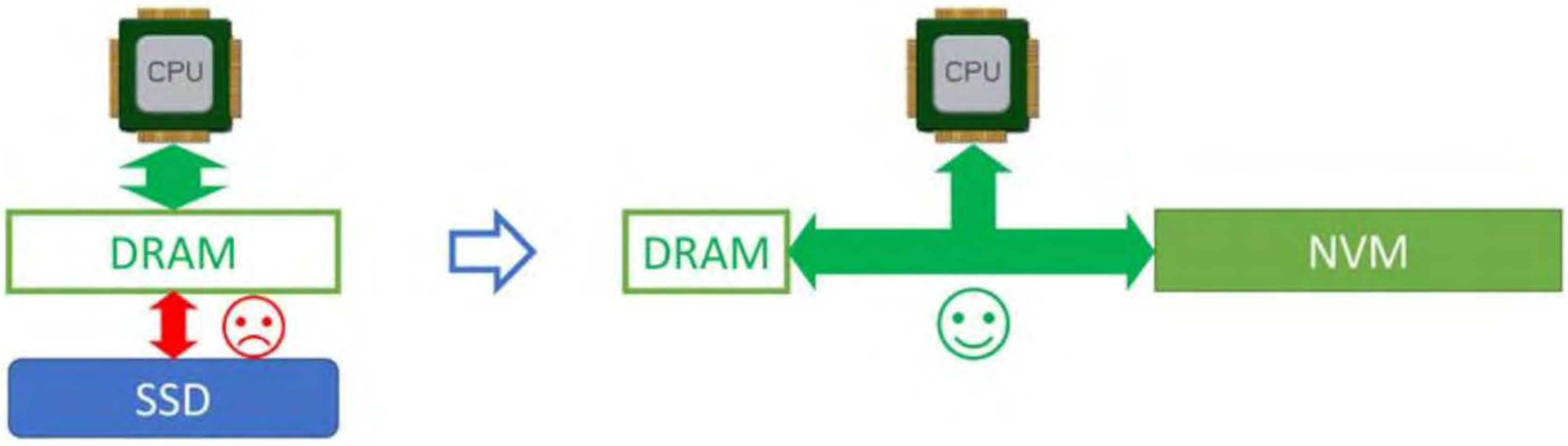


Image Source: https://slideplayer.com/slide/12767692/

Persistent B^+ Trees in Non-Volatile Main Memory

Basic Properties

- Byte-addressable reads and writes
- Performance very close to DRAM
- Requires lower power than DRAM
- Non-volatile
- Writes are generally slow
- Low endurance

Persistent B$^+$ Trees in **Non-Volatile Main Memory**

Different Types of NVMM

- Phase Change Memory (PCM)
- STT-MRAM
- Memristor

Persistent B$^+$ Trees in Non-Volatile Main Memory

Different Types of NVMM

- PCM has much slower writes (e.g., 200ns – 1μs) than reads (e.g., 50ns)
- STT-MRAM and Memristors show faster read and write performance, but are not mature enough yet

Persistent B^+ Trees in Non-Volatile Main Memory

Key Assumption

- NVM chip can guarantee atomic writes to aligned **8-byte** words

Persistent B^+ Trees in Non-Volatile Main Memory

Essential for instantaneous failure recovery (especially in NVMM)

In case of power failure or system crash data structure can be in

- Inconsistent state
- Non-recoverable state

Motivation of **Persistent** Data Structure

Two General Trends

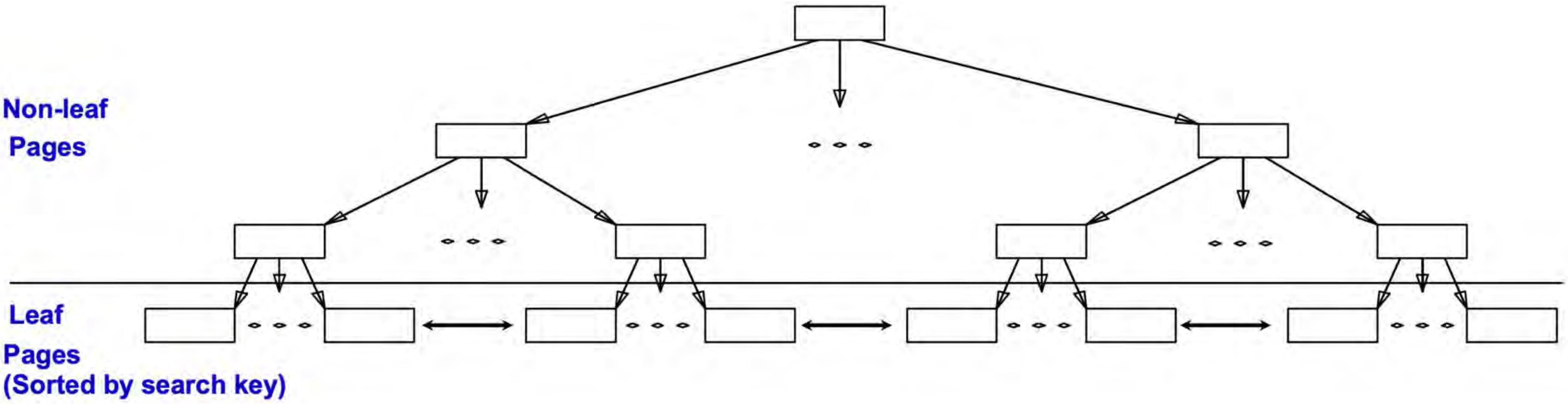
- NVMM
- Main memory database systems

Persistent **B$^+$ Trees** in Non-Volatile Main Memory

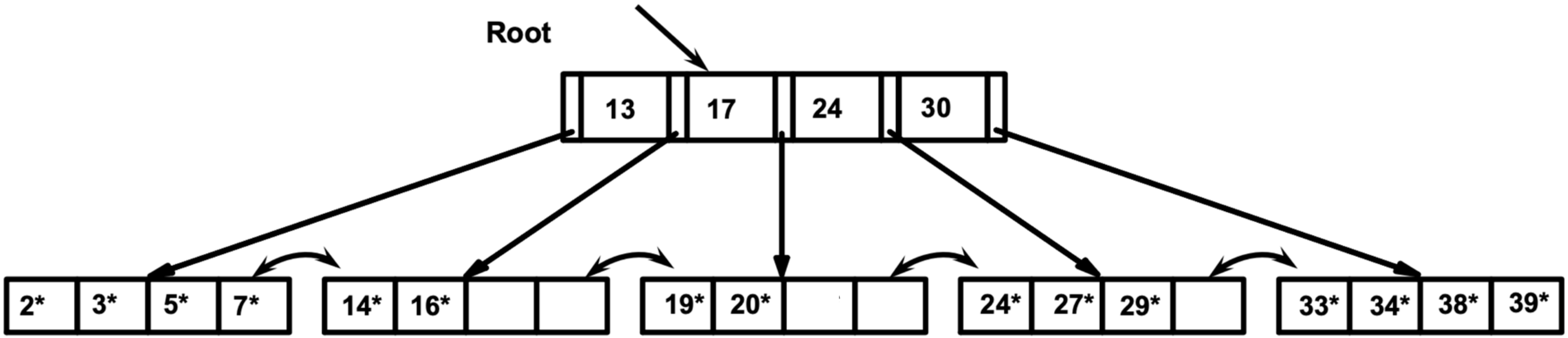
Widely used in Database Systems

- Supports equality and range-searches efficiently.
- Insert/Delete at $\log_F N$ cost (F = fanout, N = #leaf pages)
- Minimum 50% occupancy (except for root)
- Each node contains d <= m <= 2d entries

Persistent **B⁺ Trees** in Non-Volatile Main Memory

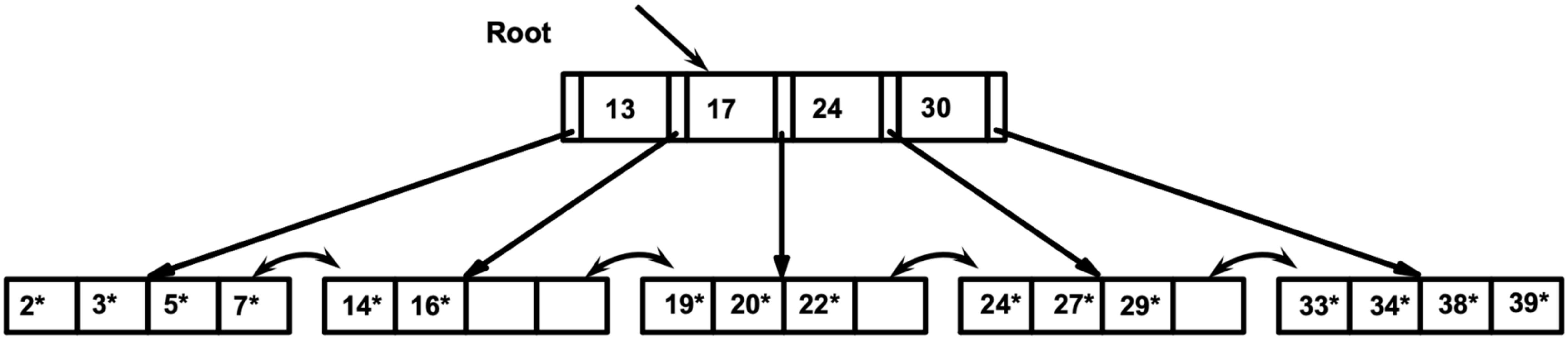


Persistent **B+ Trees** in Non-Volatile Main Memory



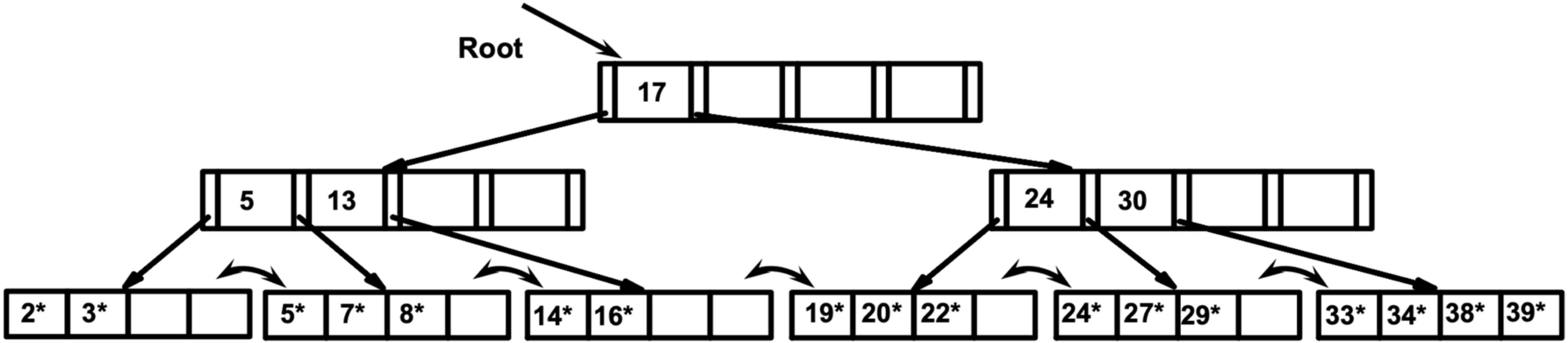
Insert 22

Persistent **B⁺ Trees** in Non-Volatile Main Memory



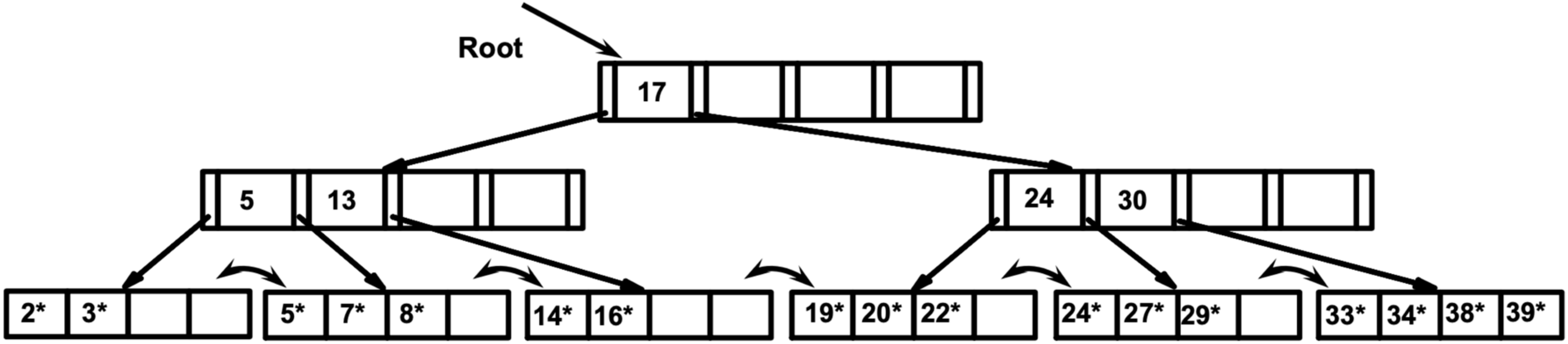
Insert 8

Persistent **B+ Trees** in Non-Volatile Main Memory



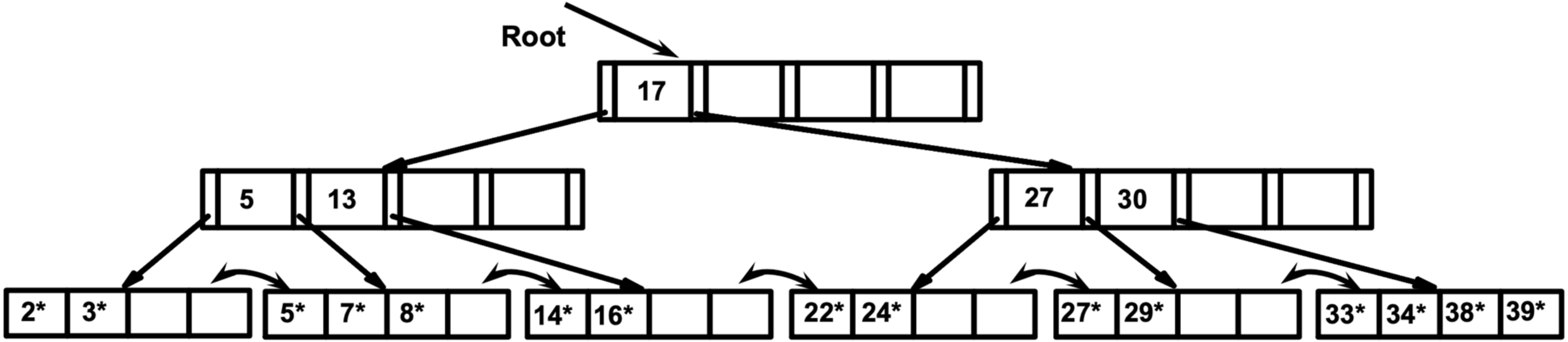
After inserting 8 (Root was *split*)

Persistent **B⁺ Trees** in Non-Volatile Main Memory



Delete 19, 20

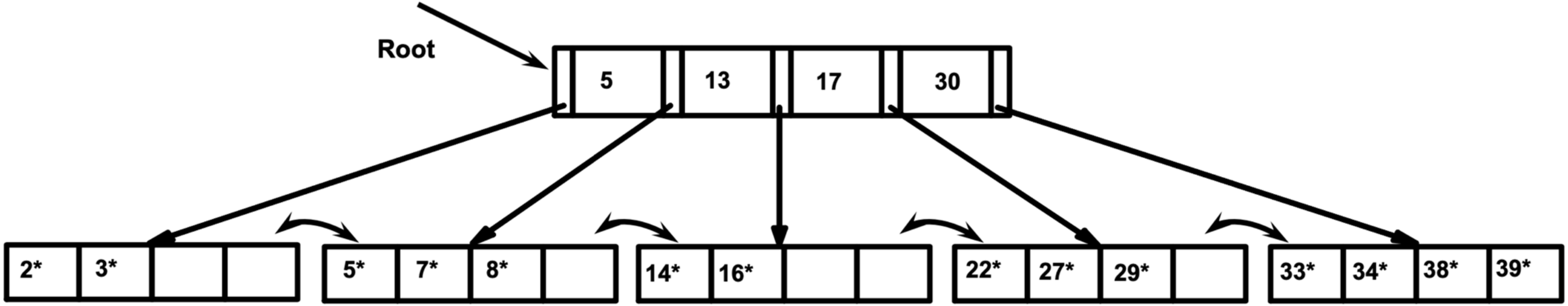
Persistent **B+ Trees** in Non-Volatile Main Memory



After deleting 19, 20 (*Redistribution* was performed)

Now Delete 24

Persistent **B$^+$ Trees** in Non-Volatile Main Memory



After deleting 24 (*Merging* was performed)

Persistent B^+ Trees in Non-Volatile Main Memory

- Leaf nodes are connected by sibling pointers
- For disk-based B^+ Trees, the node size is a few disk pages (e.g., 4KB–256KB)
- The node of main-memory B^+ Trees is typically a few cache lines large (e.g., 2–8 64-byte cache lines)

Persistent **B$^+$ Trees** in Non-Volatile Main Memory

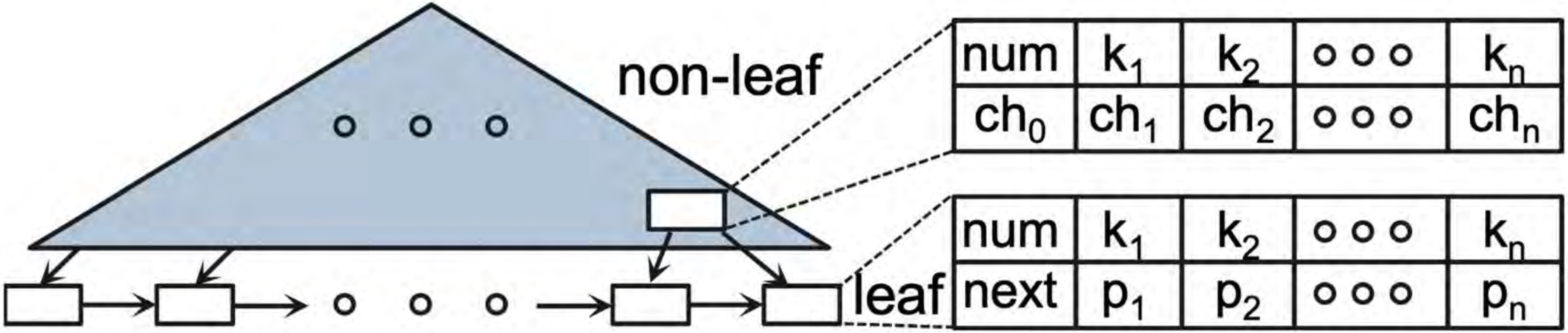


Figure 1: The main-memory B$^+$-Tree structure.

A non-leaf node contains n keys and n + 1 child pointers.

Persistent $\mathbf{B^+}$ Trees in Non-Volatile Main Memory

A non-leaf node contains *n* keys and *n + 1* child pointers.

Suppose each tree node is eight 64-byte cache lines large. If the keys are 8-byte integers in a 64-bit system, then what is the value of n?

$$(2n+1)8 = 64 \cdot 8$$

$$\Rightarrow n = 31$$

- A non-leaf node can hold 31 8-byte keys, 32 8-byte child pointers, and a number field.
- A leaf node has space for 31 8-byte keys, 31 8-byte record pointers, a number field, and an 8-byte sibling pointer.

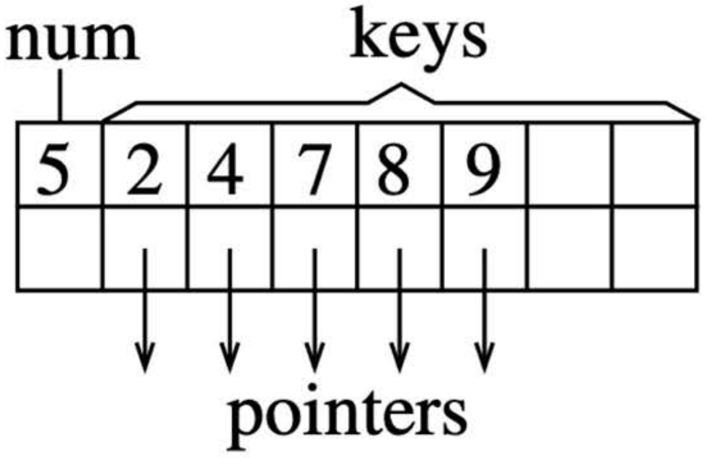
Persistent B^+ Trees in Non-Volatile Main Memory

Key Assumptions

- **NVM chip can guarantee atomic writes to aligned 8-byte words**
- Both key and value/record pointer are 8 byte
- If not otherwise mentioned, each node is eight 64-byte cache lines large

PCM-friendly B^+ tree

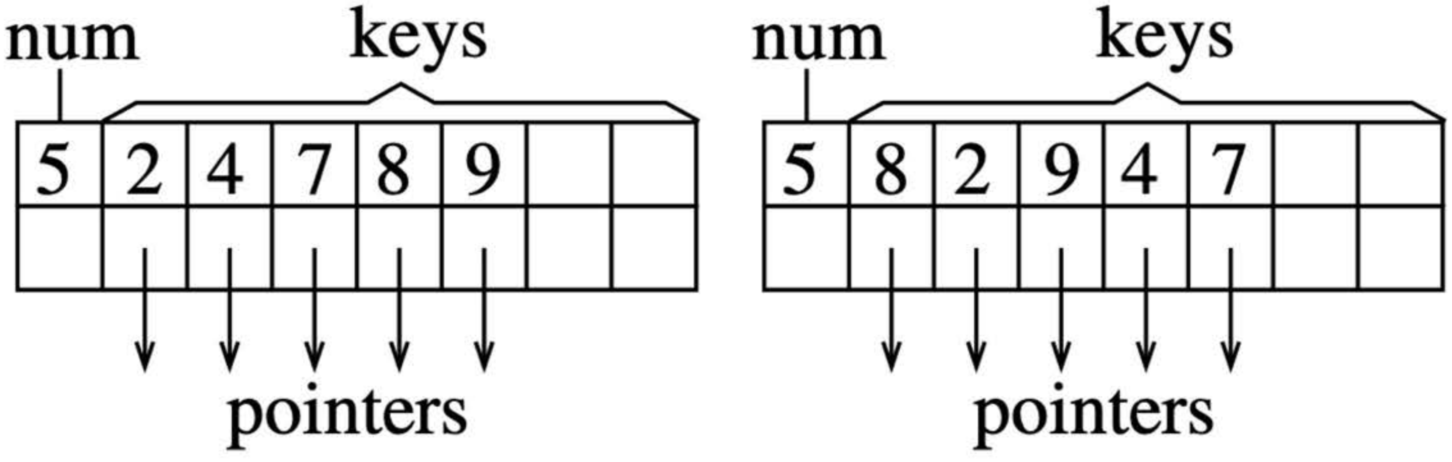
Chen et al. proposed PCM-friendly B^+-Tree



(a) Sorted

PCM-friendly B^+ tree

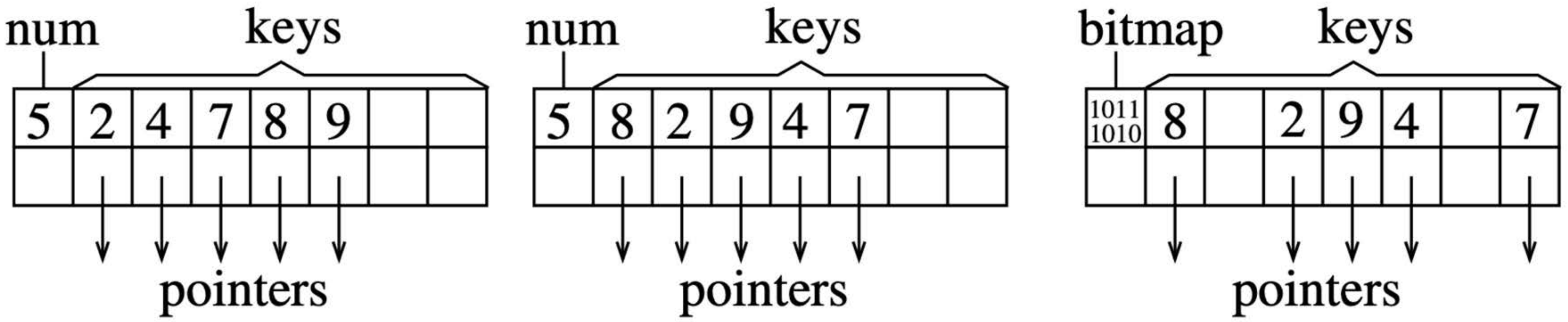
Chen et al. proposed PCM-friendly B^+-Tree



(a) Sorted (b) Unsorted

PCM-friendly B+ tree

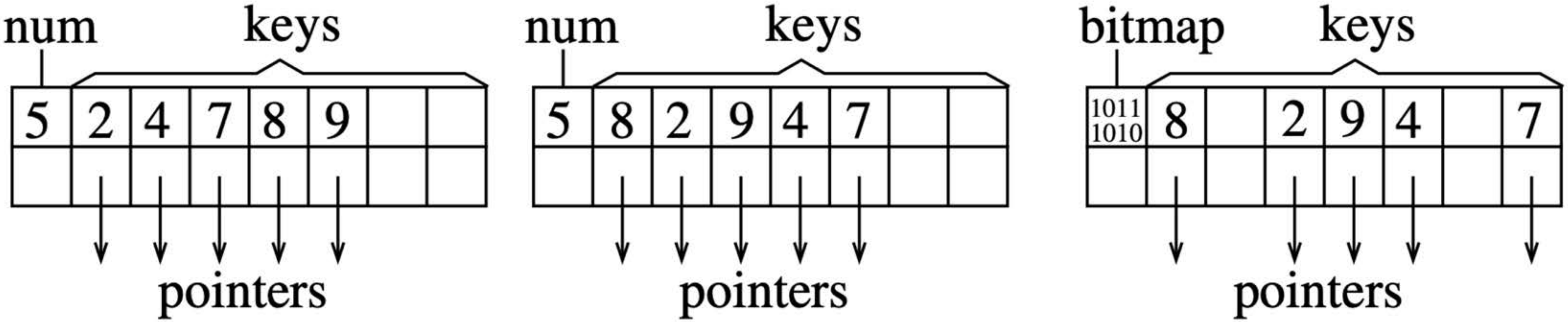
Chen et al. proposed PCM-friendly B+-Tree



(a) Sorted (b) Unsorted (c) Unsorted w/ bitmap

PCM-friendly B^+ tree

- **Sorted non-leaf nodes** and **unsorted leaf nodes with bitmap**
- Requires linear search, but reduces number of NVM writes.



(a) Sorted (b) Unsorted (c) Unsorted w/ bitmap

Data Structure Inconsistency Problem

Normal sequence of actions:

- Move 9, 7 and 4 one slot to the right
- Insert 3
- Increment the number field

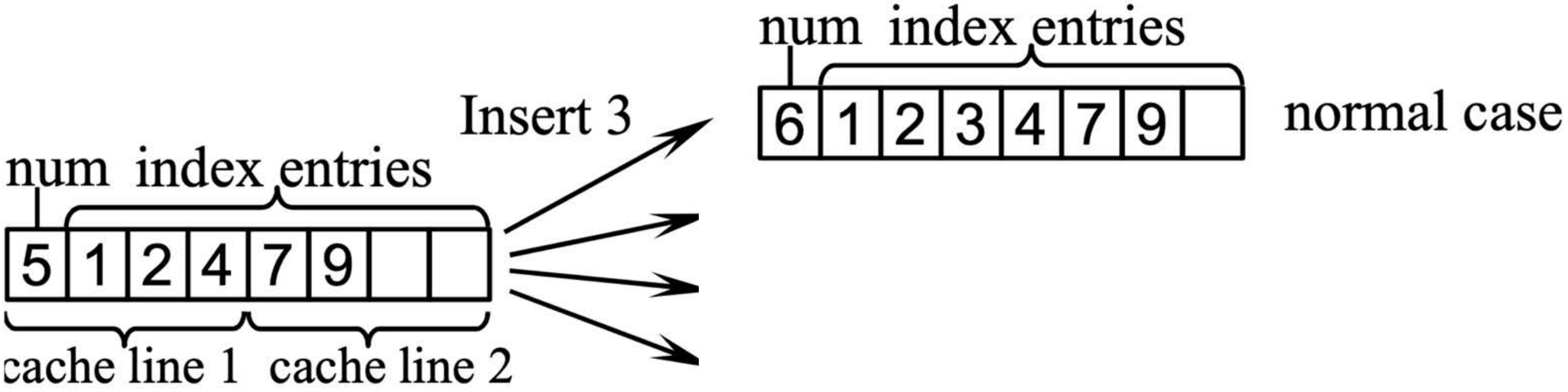


Figure 3: Potential inconsistencies upon failure.

Data Structure Inconsistency Problem

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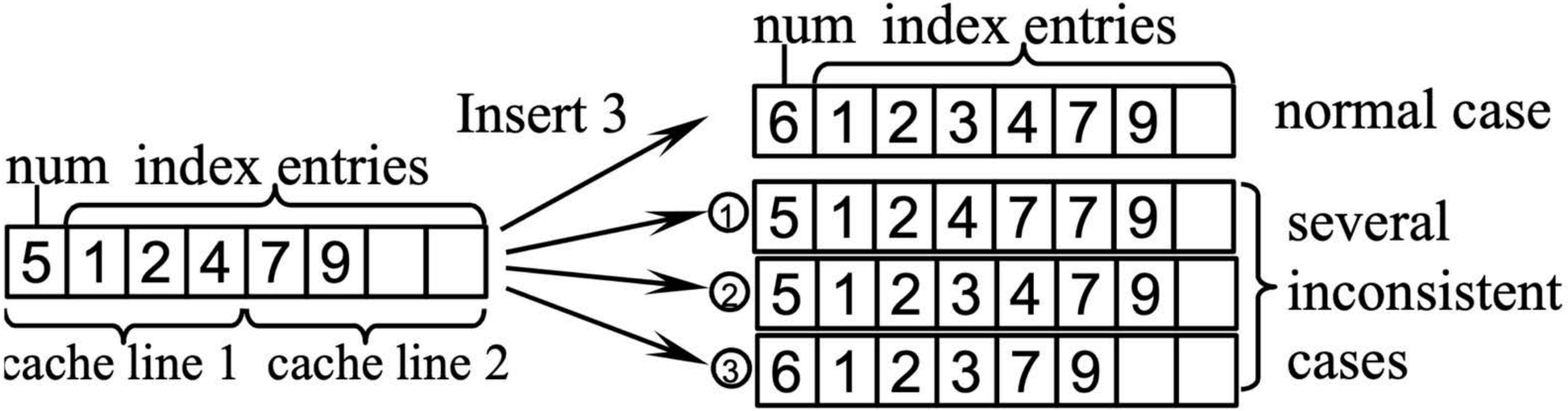


Figure 3: Potential inconsistencies upon failure.

Challenge: CPU Cache Hierarchy

- Limited control over CPU cache
- Can **NOT** guarantee when and in which order dirty cache line is written

`clflush` and `mfence` Instructions

`clflush`: invalidates the cache line on all levels of cache and broadcasts invalidation to all CPUs.

`clflush` and `mfence` Instructions

`mfence`: guarantees that all writes and reads that happened before `mfence` are globally visible before any of writes or reads that happen after `mfence`.

clflush and mfence Instructions

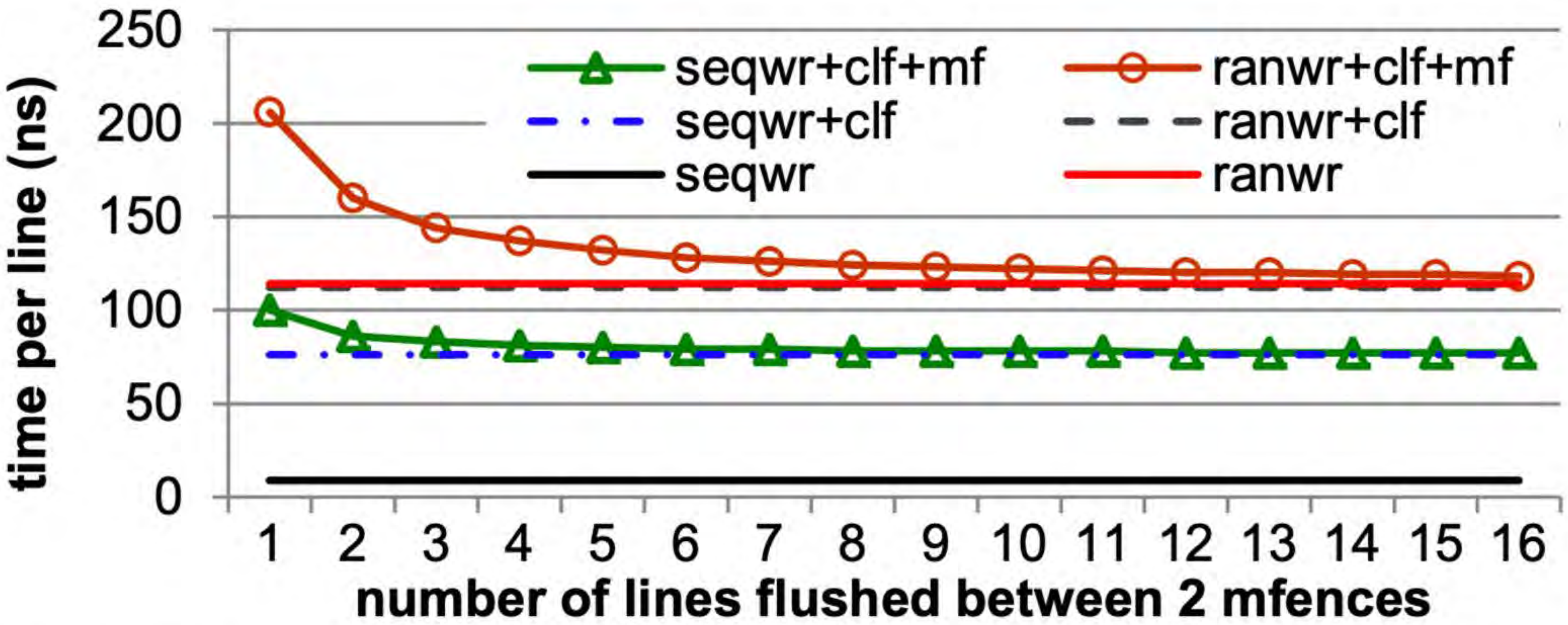
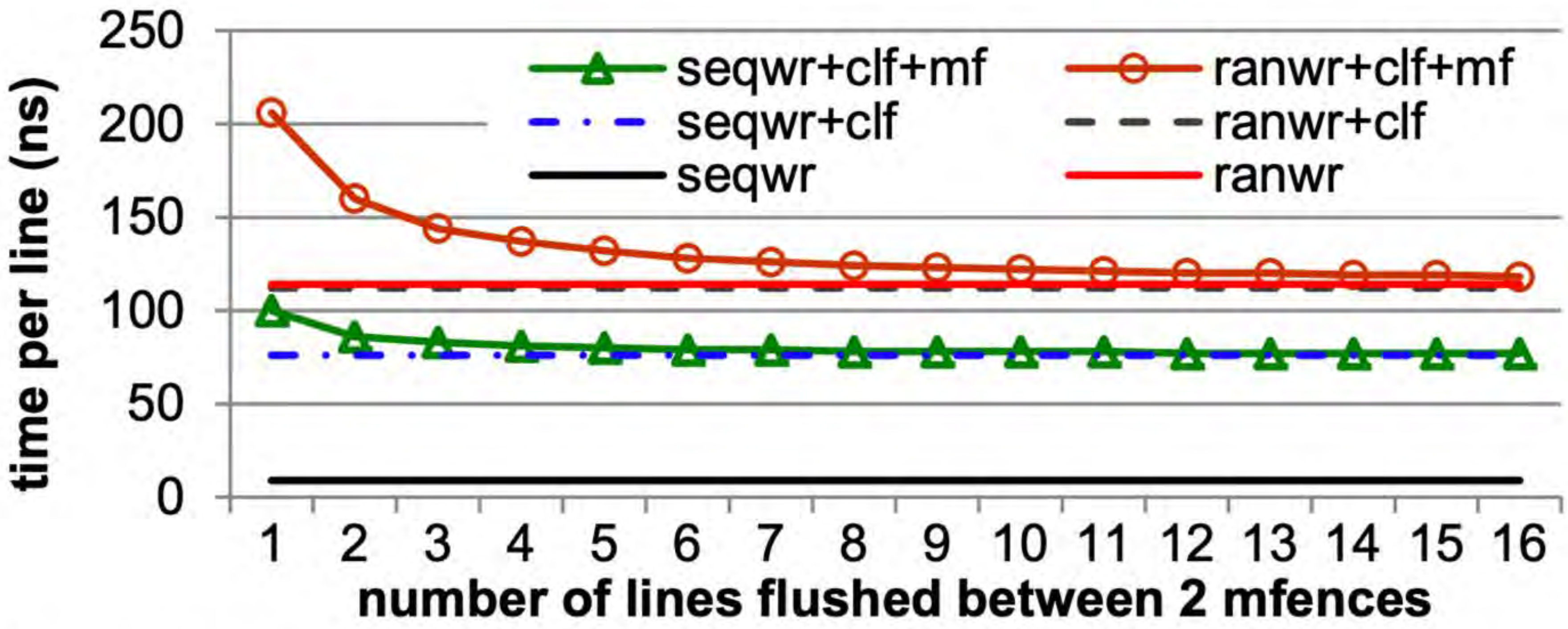


Figure 4: Performance impact of clflush and mfence instructions on sequential and random writes on a real machine.

clflush and mfence Instructions



- cflush significantly slows down sequential writes
- cflush has negligible impact on random writes
- Reducing the relative frequency of mfence is desirable

Metrics for Persistent Data Structures

N_w – number of writes

N_{clf} – number of `cflush`

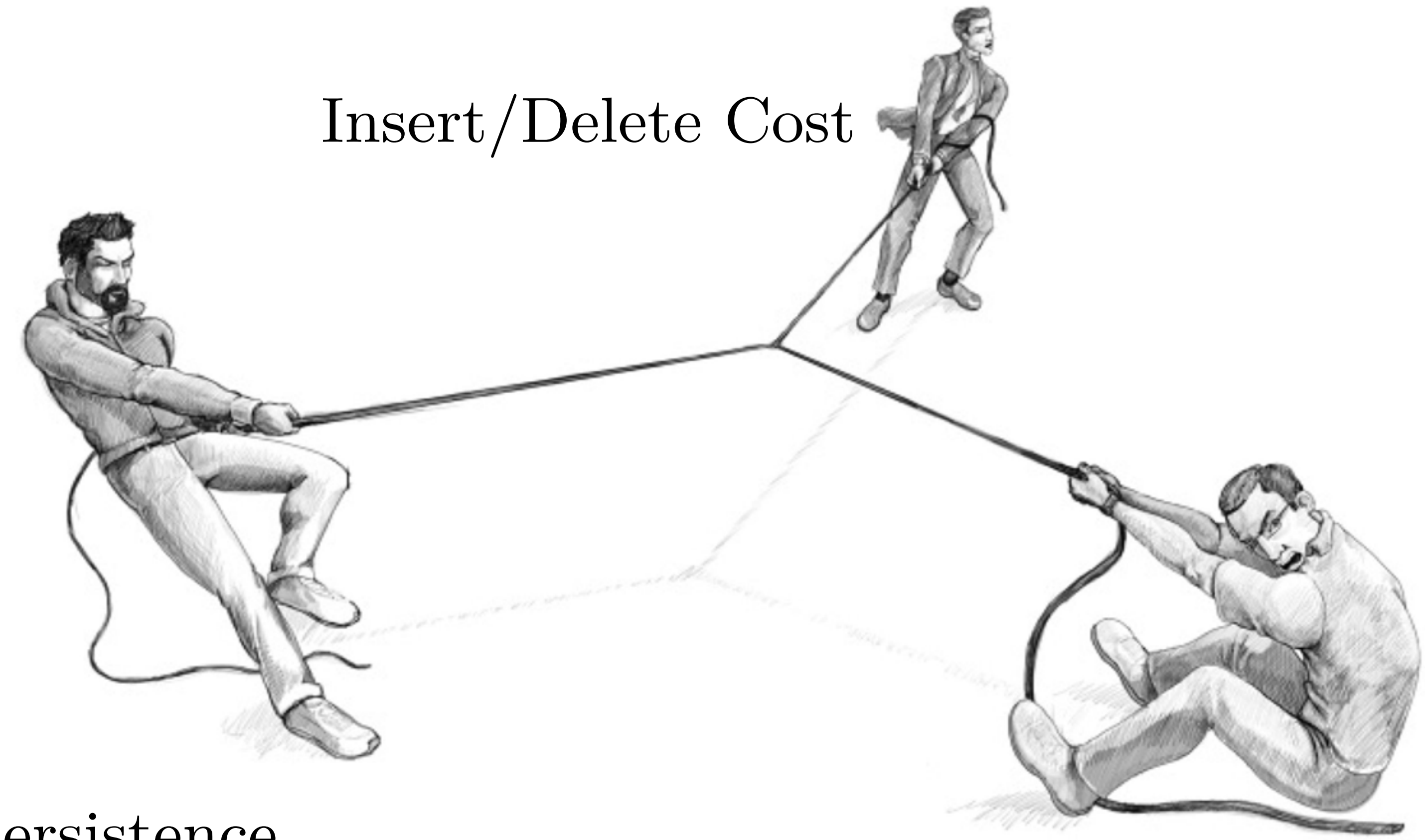
N_{mf} – number of `mfence`

Challenges

- Limited control of CPU cache
  - Can **NOT** guarantee when and in which order dirty cache line is written
  - Needs special CPU instructions (`clflush` and `mfence`) which have **non-trivial overhead**
- Different NVM technologies have different characteristics

Undo-Redo Logging and *Shadowing* can both incur drastic overhead because of extensive additional NVM writes and cache line flush instructions.

Challenges



Existing Solutions

Existing Solution

- Logging
- Shadowing

Undo-Redo Logging

```
procedure WriteUndoRedo(addr,newValue)
    log.write (addr, *addr, newValue);
    log.clflush_mfence ();
    *addr= newValue;
end procedure
```

- One `clflush` and a `mfence` per NVM write
- Multiple NVM writes to the log (three extra 8-byte writes for each 8-byte update)

NewRedo and CommitNewRedo

```
procedure WriteUndoRedo(addr,newValue)
    log.write (addr, *addr, newValue);
    log.clflush_mfence ();
    *addr= newValue;
end procedure
```

```
procedure NewRedo(addr,newValue)
    log.write (addr, newValue);
    *addr= newValue;
end procedure
procedure CommitNewRedo
    log.clflush_mfence ();
end procedure
```

- Writes in unused location, thus reducing some overhead
- Fewer `clflush` and `mfence` call
- Failure recovery easier because of using unused location.

Redo-Only Logging

It is applicable only if a newly written value is not to be accessed again before commit.

```
procedure WriteRedoOnly(addr,newValue)
    log.write (addr, newValue);
end procedure
procedure CommitRedoWrites
    log.clflush_mfence ();
    for all (addr,newValue) in log do
        *addr= newValue;
    end for
end procedure
```

Figure 6: Redo-only logging.

Terminology

Table 1: Terms used in analyzing persistent data structures.

Term	Description
N_w	Number of words written to NVMM
N_{clf}	Number of cache line flush operations
N_{mf}	Number of memory fence operations
n	Total number of entries in a B^+-Tree node
n'	Total number of entries in a wB^+-Tree node
m	Number of valid entries in a tree node
l	Number of levels of nodes that are split in an insertion

Insertion Cost Analysis of Logging (Basic B^+ Tree)

```
procedure WRITEUNDOREDO(addr,newValue)
    log.write (addr, *addr, newValue);
    log.clflush_mfence ();
    *addr= newValue;
end procedure
```

Sorted leaf B^+ tree (without node splits) using Undo-Redo Logging

- Moves on avg m/2 entries, inserts new entry, and increments the number.
- This requires writing m + 3 words (Each entry = 2 words)
- For each word write, Undo-Redo incurs 3 extra writes, a `clflush` and `mfence`.

$$N_w = 4m + 12$$

$$N_{clf} = N_{mf} = m + 3$$

Insertion Cost Analysis of Logging (PCM-Friendly B^+ Tree)

```
procedure WriteUndoRedo(addr,newValue)
    log.write (addr, *addr, newValue);
    log.clflush_mfence ();
    *addr= newValue;
end procedure
```

```
procedure NewRedo(addr,newValue)
    log.write (addr, newValue);
    *addr= newValue;
end procedure
procedure CommitNewRedo
    log.clflush_mfence ();
end procedure
```

For both packed unsorted and with bitmap,

- Writes the new index entry to an unused location using `NewRedo`
- Updates the number/bitmap using `WriteUndoRedo`

$$N_w = 2*3 + 1*4 = 10$$

$$N_{clf} = N_{mf} = 2$$

Deletion Cost Analysis of Logging (PCM-Friendly B^+ Tree)

```
procedure WriteUndoRedo(addr,newValue)
    log.write (addr, *addr, newValue);
    log.clflush_mfence ();
    *addr= newValue;
end procedure
```

```
procedure NewRedo(addr,newValue)
    log.write (addr, newValue);
    *addr= newValue;
end procedure
procedure CommitNewRedo
    log.clflush_mfence ();
end procedure
```

- For a packed unsorted leaf node, a deletion needs to move the last entry to fill the hole which must use WriteUndoRedo. Hence, $N_w = 3*4 = 12$
- For an unsorted leaf node with bitmap, only the bitmap needs to be overwritten. Hence, $N_w = 4$.

Shadowing

- Create copy of the node, update copy, flush copy, and commit. Update node's parent pointer as well.
- Propagate the same procedure to root.
- **Short-circuit Shadowing:** Use atomic in-place write instead of copying
- Problem: What about leaf sibling pointer?

Use `clflush` and `mfence` to solve this problem

Shadowing

```
procedure InsertToLeaf(leaf,newEntry,parent,ppos,sibling)
    copyLeaf= AllocNode();
    NodeCopy(copyLeaf, leaf);
    Insert(copyLeaf, newEntry);
    for i=0; i < copyLeaf.UsedSize(); i+=64 do
        clflush(&copyleaf + i);
    end for
    WriteRedoOnly(&parent.ch[ppos], copyLeaf);
    WriteRedoOnly(&sibling.next, copyLeaf);
    CommitRedoWrites();
    FreeNode(leaf);
end procedure
```

Figure 7: Shadowing for insertion when there is no node splits.

```
procedure WriteRedoOnly(addr,newValue)
    log.write (addr, newValue);
end procedure
procedure CommitRedoWrites
    log.clflush_mfence ();
    for all (addr,newValue) in log do
        *addr= newValue;
    end for
end procedure
```

Figure 6: Redo-only logging.

Insertion Cost Analysis of Shadowing (Basic B^+ Tree)

- 2m + 4 writes for copying the entries, the number field, and the sibling pointer field, and inserting the new entry.
- The two `WriteRedoOnlys` require 4 word writes, and the actual pointer updates require 2 writes.
- AllocNode will require an additional log write, clflush, and mfence to ensure persistence of the allocation operation.

$$N_w = 2m + 11$$

$$N_{clf} = (2m + 4)\frac{8}{64} + 1 + 1 = 0.25m + 2.5$$

$$N_{mf} = 2$$

Cost Analysis of Shadowing (PCM Friendly B^+ Tree)

- Since shadowing requires copying the whole node, unsorted leaves do not provide advantage.
- Deletion cost is similar

Write-Atomic B^+ Trees (wB^+ trees)

Design Goals

- Atomic write to commit all changes
- Minimize the movement of index entries
- Good search performance

wB$^+$ Trees

Previous Proposal

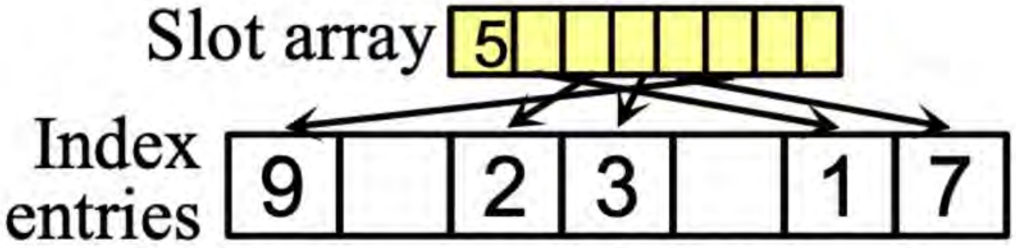
bmp	k_1	k_2	o o o	k_n
next	p_1	p_2	o o o	p_n

(b) Bitmap-only leaf

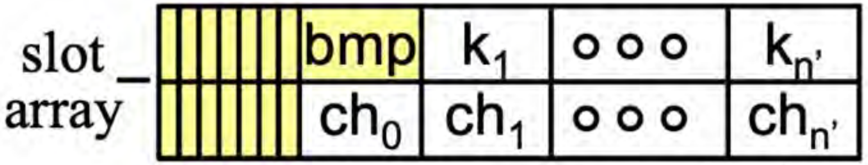
- Write atomicity possible if bitmap size is less than 8-byte word
- Binary search impossible because of unsortedness

Can we achieve both write atomicity and good search performance?

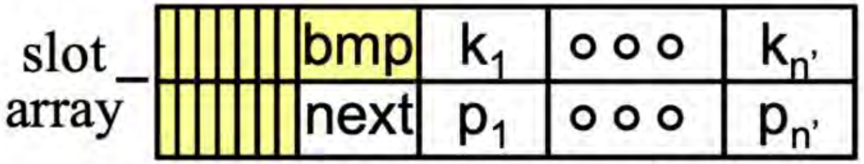
Slot Array



(a) Slot array with 1-byte slots



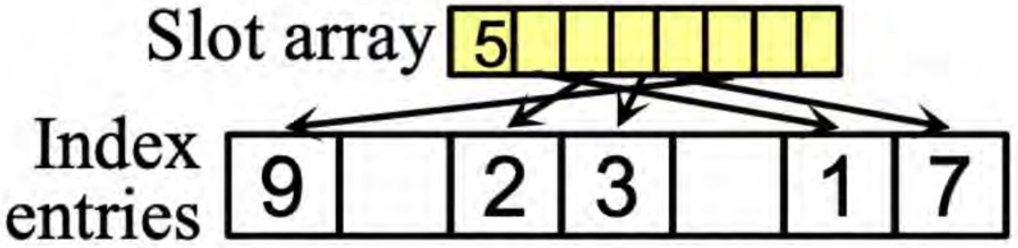
(e) Slot+bitmap nonleaf



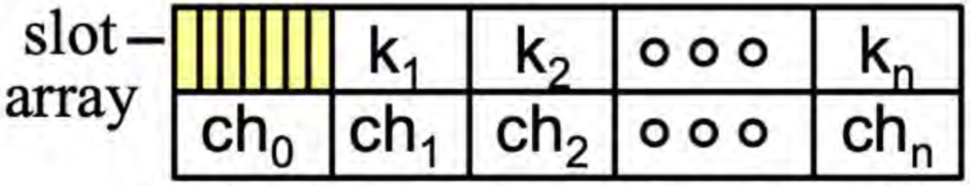
(f) Slot+bitmap leaf

- A small indirection array to a bitmap-only unsorted node
- The indirection slot array remembers the sorted order
- Slot 0 records the number of valid entries in the node.
- Lowest bit of the bitmap to indicate whether the slot array is valid.

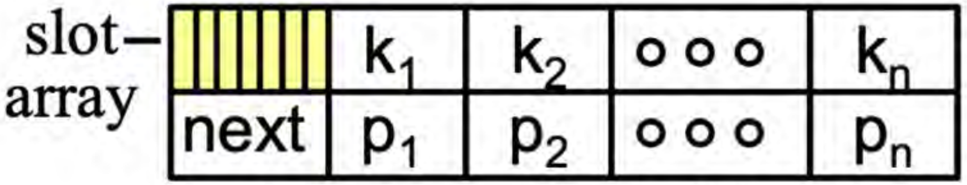
Slot Array: Optimization



(a) Slot array with 1-byte slots



(c) Slot-only nonleaf (n<8)



(d) Slot-only leaf (n<8)

- If the tree node size is small (number of index entry < 8), no need for bitmap. Entire slot array can fit into 8-byte word.
- Write atomicity can be achieved

wB+ Trees in This Paper

Table 2: wB$^+$-Tree structures considered in this paper.

Structure	Leaf Node	Non-leaf Node
wB$^+$-Tree	slot+bitmap leaf	slot+bitmap non-leaf
wB$^+$-Tree w/ bitmap-only leaf	bitmap-only leaf	slot+bitmap non-leaf
wB$^+$-Tree w/ slot-only nodes	slot-only leaf	slot-only non-leaf

When the node size is large (wB$^+$-Tree; wB$^+$-Tree w/ bitmap-only leaf)

When the node size is small (wB$^+$-Tree w/ slot-only nodes)

Space Overhead Analysis

- An 8-byte bitmap can support up to 63 index entries
- 1-byte sized slots can support up to 255 index entries

If an index entry is 16-byte large (with 8-byte keys and 8-byte pointers), then a slot + bitmap node can be as large as 1KB (16 cache lines)

Insertion

- Find insert position
- Find unused position
- Write
- `cflush` and `mfence`
- Generate up-to-date slot array
- Atomic write to update slot array

$$N_w = 3$$

$$N_{clf} = N_{mf} = 2$$

Similar algorithm for bitmap-only nodes

```
procedure INSERT2SLOTONLY_ATOMIC(leaf, newEntry)
    /* Slot array is valid */
    pos= leaf.GetInsertPosWithBinarySearch(newEntry);
    /* Write and flush newEntry */
    u= leaf.GetUnusedEntryWithSlotArray();
    leaf.entry[u]= newEntry;
    clflush(&leaf.entry[u]); mfence();
    /* Generate an up-to-date slot array on the stack */
    for (j=leaf.slot[0]; j≥pos; j - -) do
        tempslot[j+1]= leaf.slot[j];
    end for
    tempslot[pos]=u;
    for (j=pos-1; j≥1; j - -) do
        tempslot[j]= leaf.slot[j];
    end for
    tempslot[0]=leaf.slot[0]+1;
    /* Atomic write to update the slot array */
    *((UInt64 *)leaf.slot)= *((UInt64 *)tempslot);
    clflush(leaf.slot); mfence();
end procedure
```

Figure 9: Insertion to a slot-only node with atomic writes.

Insertion

- Recover slot array if it is invalid
- Mark slot array as invalid
- Write and flush new entry
- Modify and flush slot array
- `mfence` to make new entry and slot array stable
- Update bitmap atomically and `mfence`

```
procedure INSERT2SLOTBMP_ATOMIC(leaf, newEntry)
    if (leaf.bitmap & 1 == 0) /* Slot array is invalid? */ then
        Recover by using the bitmap to find the valid entries,
        building the slot array, and setting the slot valid bit;
    end if
    pos= leaf.GetInsertPosWithBinarySearch(newEntry);
    /* Disable the slot array */
    leaf.bitmap = leaf.bitmap - 1;
    clflush(&leaf.bitmap); mfence();
    /* Write and flush newEntry */
    u= leaf.GetUnusedEntryWithBitmap();
    leaf.entry[u]= newEntry;
    clflush(&leaf.entry[u]);
    /* Modify and flush the slot array */
    for (j=leaf.slot[0]; j≥pos; j - -) do
        leaf.slot[j+1]= leaf.slot[j];
    end for
    leaf.slot[pos]=u;
    for (j=pos-1; j≥1; j - -) do
        leaf.slot[j]= leaf.slot[j];
    end for
    leaf.slot[0]=leaf.slot[0]+1;
    for (j=0; j≤leaf.slot[0]; j += 8) do
        clflush(&leaf.slot[j]);
    end for
    mfence(); /* Ensure new entry and slot array are stable */
    /* Enable slot array, new entry and flush bitmap */
    leaf.bitmap = leaf.bitmap + 1 + (1<<u);
    clflush(&leaf.bitmap); mfence();
end procedure
```

Figure 10: Insertion to a slot+bitmap node with atomic writes.

Search

- Usage of slot array allows the logarithmic complexity of the search
- Slot array is especially useful for non-leaf nodes
- Slot array dereference overhead is nontrivial!!!
    - Optimize it by stopping binary search when range is narrow (<8 slot)
    - Retrieve everything in 8-byte integer
    - Use shift and logic operation

Deletion

- Similar to insertion
- No need to move any entries
- Simply update slot array and/or the bitmap
- Either atomic writes or redo-only logging can be employed

Comparison

Table 3: Comparison of persistent B$^+$-Tree solutions.

Solution	Insertion without node splits	Insertion with l node splits	Deletion without node merges
B$^+$-Trees undo-redo logging	$N_w = 4m + 12$, $N_{clf} = N_{mf} = m + 3$	$N_w = l(4n + 15) + 4m + 19$, $N_{clf} = l(0.375n + 3.25) + m + 4.125$, $N_{mf} = l(0.25n + 2) + m + 5$	$N_w = 4m$, $N_{clf} = N_{mf} = m$
Unsorted leaf undo-redo logging	$N_w = 10$, $N_{clf} = 2$, $N_{mf} = 2$	$N_w = l(4n+15)+n+4m+19$, $N_{clf} = l(0.375n+3.25)+0.25n + m + 4.125$, $N_{mf} = l(0.25n + 2) + 0.25n + m + 5$	$N_w = 12$, $N_{clf} = 3$, $N_{mf} = 3$
Unsorted leaf w/ bitmap undo-redo logging	$N_w = 10$, $N_{clf} = 2$, $N_{mf} = 2$	$N_w = l(4n+15)-n+4m+19$, $N_{clf} = l(0.375n+3.25)-0.25n + m + 4.125$, $N_{mf} = l(0.25n + 2) - 0.25n + m + 5$	$N_w = 4$, $N_{clf} = 1$, $N_{mf} = 1$
B$^+$-Trees shadowing	$N_w = 2m + 11$, $N_{mf} = 2$, $N_{clf} = 0.25m + 2.5$	$N_w = l(2n + 5) + 2m + 12$, $N_{clf} = l(0.25n + 1.5) + 0.25m + 2.625$, $N_{mf} = 2$	$N_w = 2m + 7$, $N_{mf} = 2$, $N_{clf} = 0.25m + 2$
Unsorted leaf shadowing	$N_w = 2m + 11$, $N_{mf} = 2$, $N_{clf} = 0.25m + 2.5$	$N_w = l(2n + 5) + 2m + 12$, $N_{clf} = l(0.25n + 1.5) + 0.25m + 2.625$, $N_{mf} = 2$	$N_w = 2m + 7$, $N_{mf} = 2$, $N_{clf} = 0.25m + 2$
Unsorted leaf w/ bitmap shadowing	$N_w = 2m + 11$, $N_{mf} = 2$, $N_{clf} = 0.25m + 2.5$	$N_w = l(2n + 5) + 2m + 12$, $N_{clf} = l(0.25n + 1.5) + 0.25m + 2.625$, $N_{mf} = 2$	$N_w = 2m + 7$, $N_{mf} = 2$, $N_{clf} = 0.25m + 2$
wB$^+$-Tree	$N_w = 0.125m+4.25$, $N_{clf} = \frac{1}{64}m + 3\frac{1}{32}$, $N_{mf} = 3$	$N_w = l(1.25n' + 9.75) + 0.125m + 8.25$, $N_{clf} = l(\frac{19}{128}n' + 1\frac{105}{128}) + \frac{1}{64}m + 3\frac{13}{32}$, $N_{mf} = 3$	$N_w = 0.125m + 2$, $N_{clf} = \frac{1}{64}m + 2$, $N_{mf} = 3$
wB$^+$-Tree w/ bitmap-only leaf	$N_w = 3$, $N_{clf} = 2$, $N_{mf} = 2$	$N_w = l(1.25n' + 9.75) - 0.25n' + 0.125m + 7.5$, $N_{clf} = l(\frac{19}{128}n' + 1\frac{105}{128}) - \frac{3}{128}n' + \frac{1}{64}m + 3\frac{43}{128}$, $N_{mf} = 3$	$N_w = 1$, $N_{clf} = 1$, $N_{mf} = 1$
wB$^+$-Tree w/ slot-only nodes	$N_w = 3$, $N_{clf} = 2$, $N_{mf} = 2$	$N_w = l(n + 9) + 7$, $N_{clf} = l(0.125n + 1.75) + 2.375$, $N_{mf} = 2$	$N_w = 1$, $N_{clf} = 1$, $N_{mf} = 1$

Comparison

	N_w	N_{clf}	N_{mf}	N_w	N_{clf}	N_{mf}
B^+ Tree (log)	4m + 12	m + 3	m + 3	4m	m	m
PCM B^+ w/o bitmap (logging)	10	2	2	12	3	3
PCM B^+ with bitmap (logging)	10	2	2	4	1	1
B^+ Tree (Shadow)	2m + 11	0.25m + 2.5	2	2m + 7	0.25m+2	2
wB^+ Tree	$\frac{m}{8} + 4.25$	$\frac{m}{64} + 3\frac{1}{32}$	3	$\frac{m}{8} + 2$	$\frac{m}{64} + 2$	3
wB^+ Tree (bitmap-only)	3	2	2	1	1	1
wB^+ Tree (slot-only)	3	2	2	1	1	1

wB+ Trees for Variable Sized Keys

- Contains 8-byte keys (*key pointers*), which are pointers to the actual variable sized keys.
- A slot+bitmap node has two indirection layers
  - First indirection layer is the key pointers
  - Second indirection layer is the slot array.

Experimental Evaluations

Experiment Setup

- Real machine modeling DRAM-like fast NVMM
  - Achieve up to 8.8x speedup
- Simulation modeling PCM-based NVMM
  - Achieve up to 27.1x speedup
- Full system experiment: replaced Memcached's internal hash on real machine
  - Achieve up to 3.8x improvements

B^+ Tree Implementations

Implemented 9 B+ tree solutions for fixed-size keys

- btree (volatile)
- btree log: employ undo-redo logging for btree
- unsorted leaf log: employ undo-redo logging for B^+-Tree with unsorted leaf nodes
- uleaf bmp log: employ undo-redo logging for B^+-Tree with bitmap-only unsorted leaf nodes
- btree shadow: employ shadowing for btree
- unsorted leaf shadow: employ shadowing for B^+-Tree with unsorted leaf nodes
- uleafbmp shadow: employ shadowing for B^+-Tree with bitmap-only unsorted leaf nodes
- wbtree: wb^+ tree
- wbtree w/bmp-leaf : wB -Tree with bitmap-only leaf nodes.

** If the node size $\leq$ 2 cache lines, they used wB^+-Tree with slot-only nodes to replace both (8) and (9), and report results as wbtree.

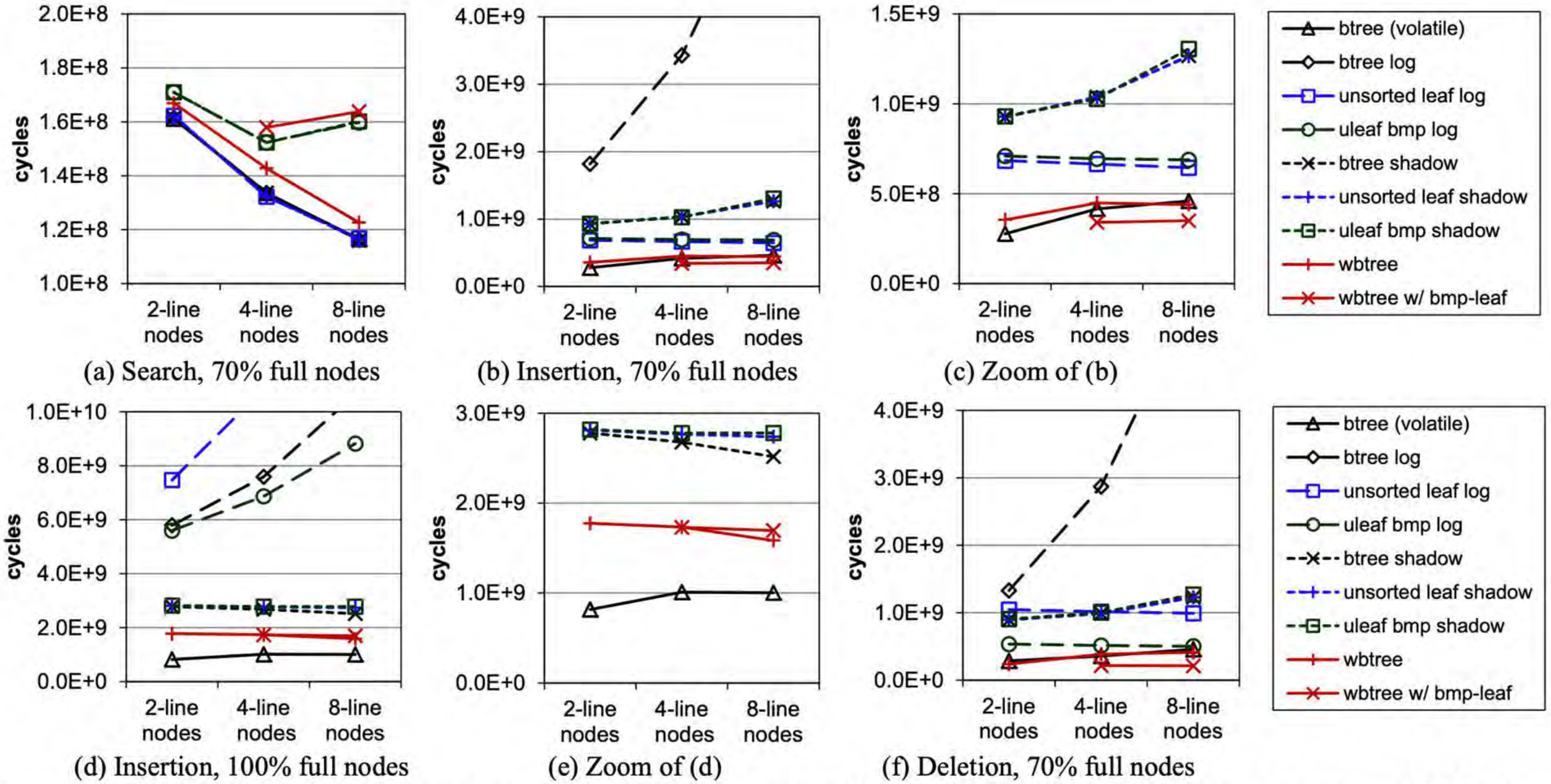
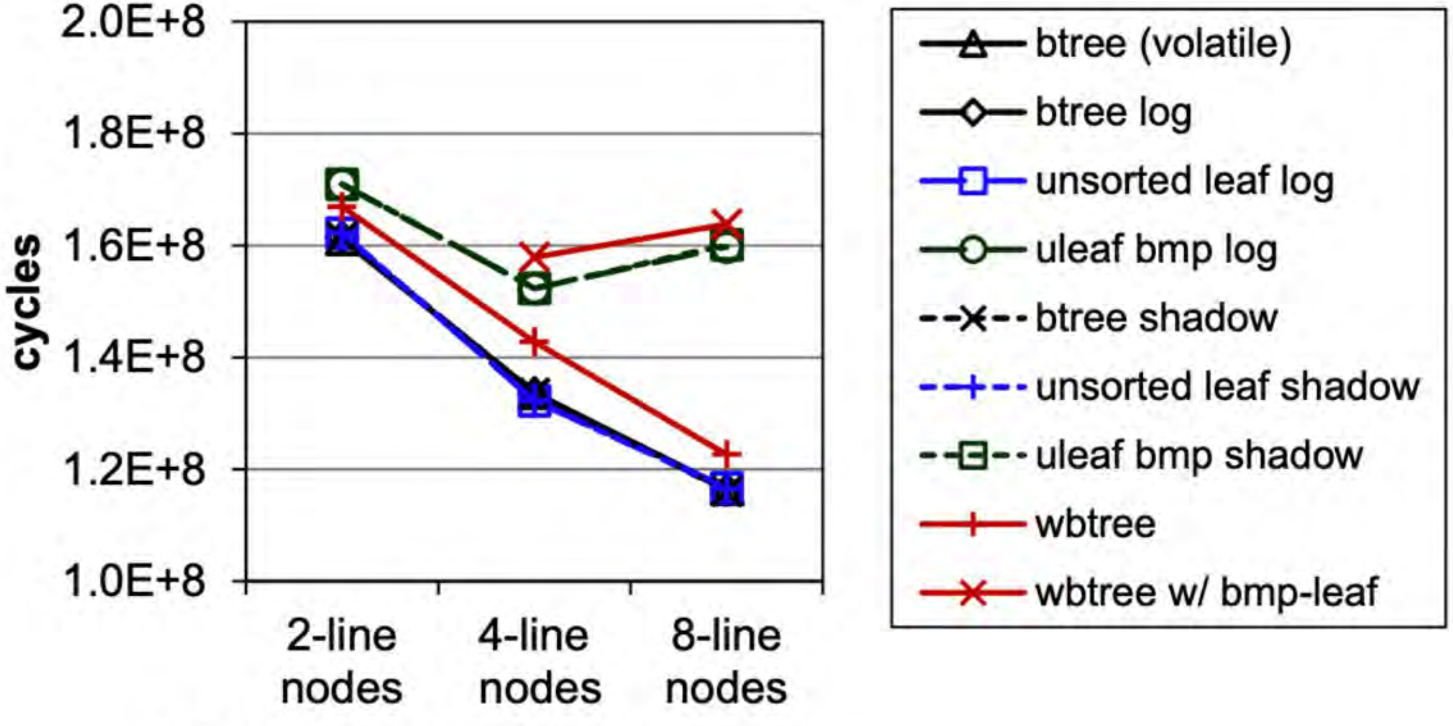


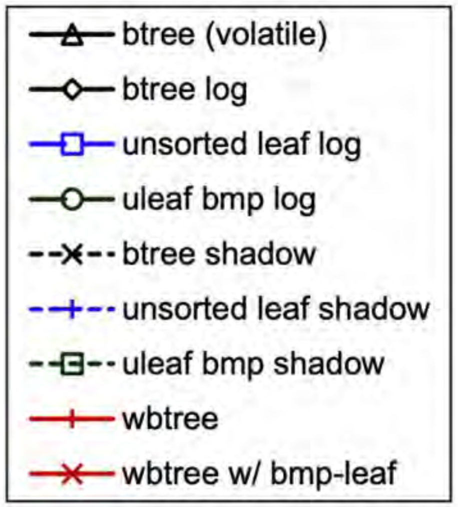
Figure 11: Index performance on a cycle-accurate simulator modeling PCM-based NVMM. (We bulkload a tree with 20M entries, then perform 100K random back-to-back lookups, insertions, or deletions. Keys are 8-byte integers.)

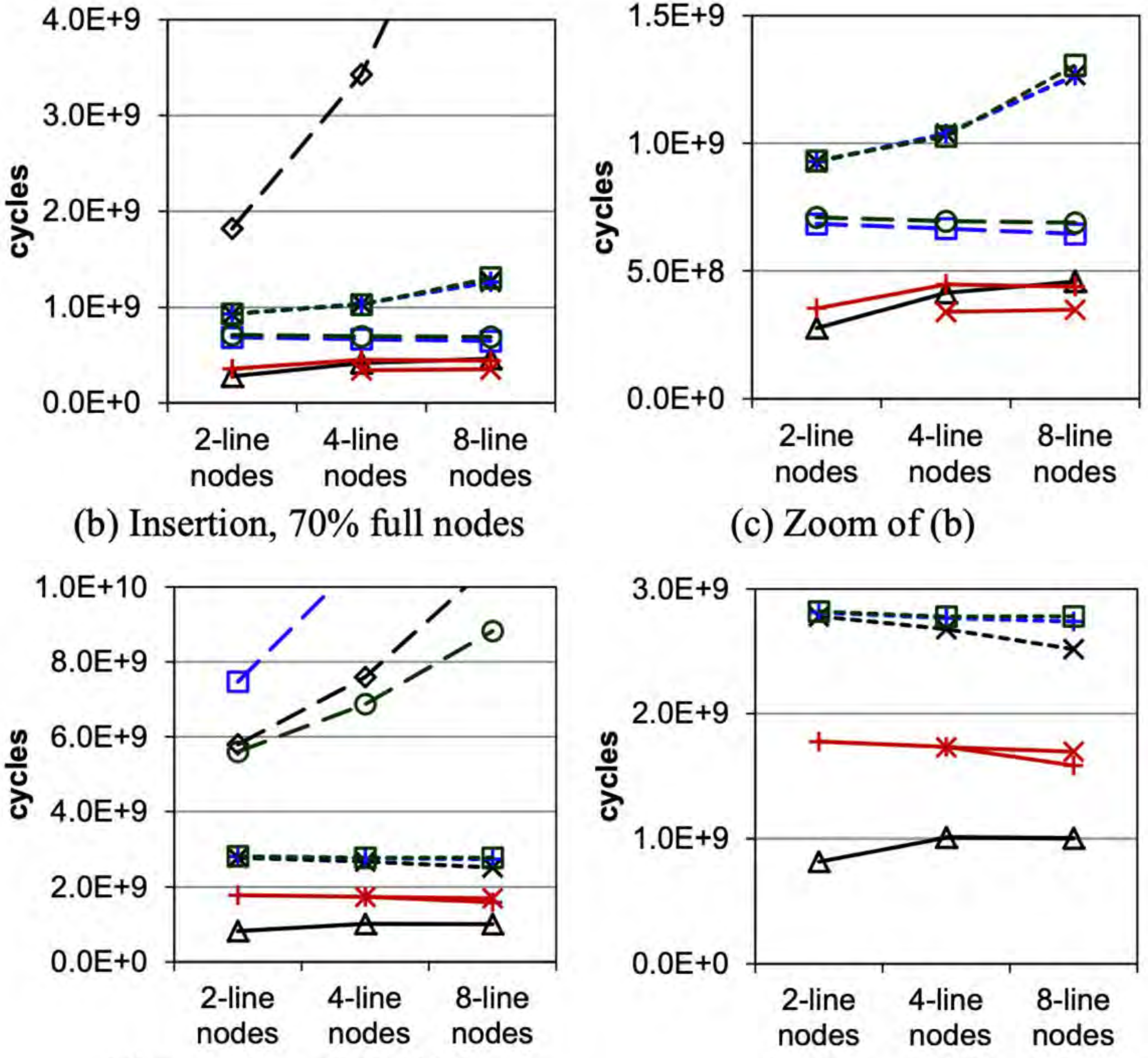
Experimental Results



(a) Search, 70% full nodes

- wB+-Tree achieves similar search performance as baseline
- Bitmap-only leaf nodes see up to 16% slowdowns because of the sequential search overhead in leaf nodes





(b) Insertion, 70% full nodes

(c) Zoom of (b)

(d) Insertion, 100% full nodes

(e) Zoom of (d)

- Undo-redo logging is extremely slow
- Shadowing is also slow
- wbtree w/bmp-leaf achieves slightly better insertion and deletion performance than wbtree, but sees worse search performance.

Experimental Results

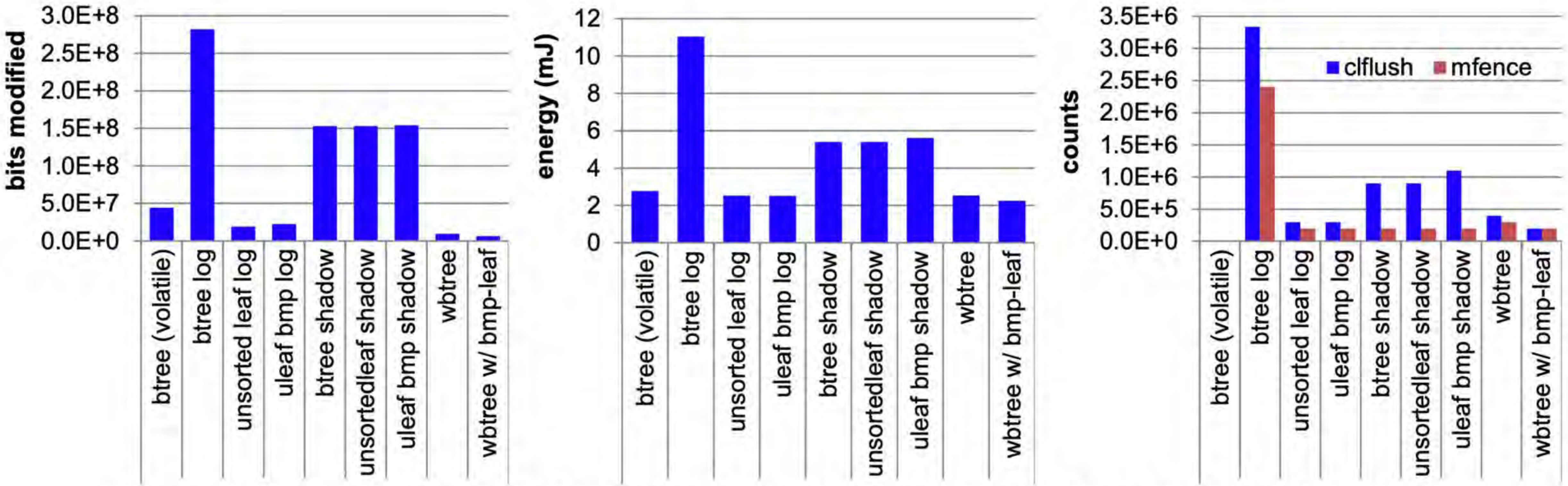
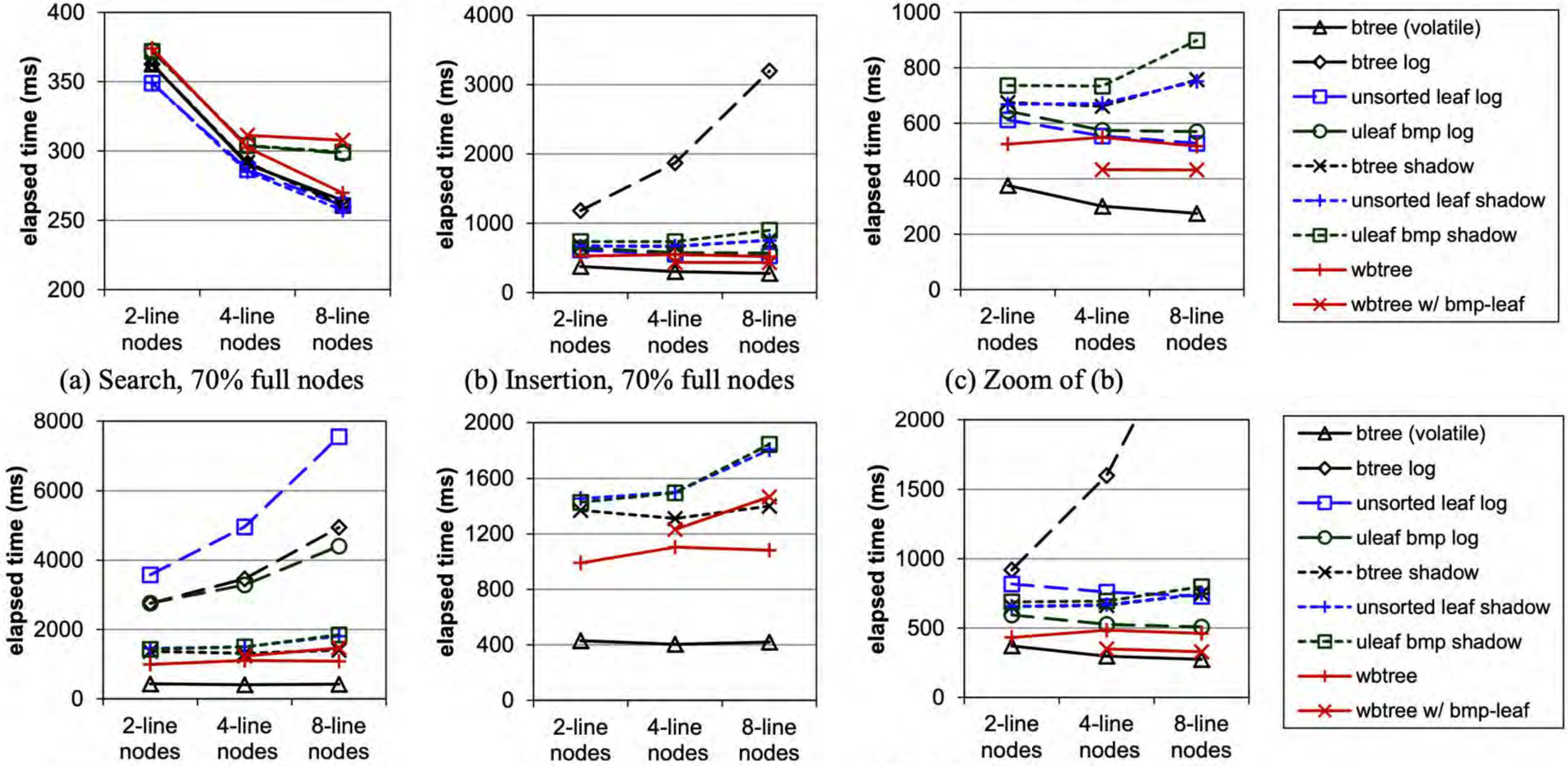


Figure 12: Wear, energy, and clflush/mfence counts of index operations for Figure 11(b) with 8-line nodes.

- Bits written for wbtrees are much less
- Slightly higher clflush than PCM-friendly B+ trees.



(a) Search, 70% full nodes
(b) Insertion, 70% full nodes
(c) Zoom of (b)
(d) Insertion, 100% full nodes
(e) Zoom of (d)
(f) Deletion, 70% full nodes

Figure 13: Index performance on a real machine modeling DRAM-like fast NVMM. (We bulkload a tree with 50M entries, then perform 500K random back-to-back lookups, insertions, or deletions. Keys are 8-byte integers.)

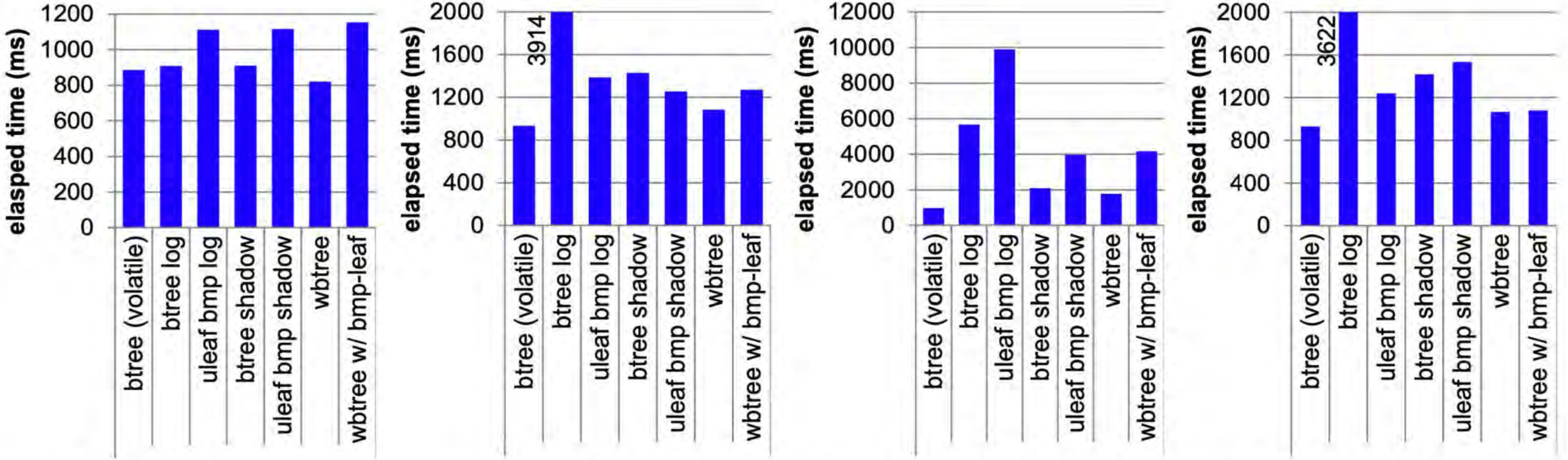
Difference between Real Machine and Simulation

- Bar charts of the simulation have similar shape to the **bits modified** charts
- Bar charts of the real machine results have similar shape to the **clflush** charts

PCM writes play a major role in determining the elapsed times on PCM based NVMM

Cache line flushes are the major factor in elapsed time on fast DRAM-like NVMM

Experimental Results



(a) Search, 70% full nodes, 20-byte string keys
(b) Insertion, 70% full nodes, 20-byte string keys
(c) Insertion, 100% full nodes, 20-byte string keys
(d) Deletion, 70% full nodes, 20-byte string keys

Figure 14: Index performance with string keys on a real machine. (We bulkload a tree with 50M entries, then perform 500K random back-to-back lookups, insertions, or deletions).

- Searches are costly than fixed-size

Experimental Results

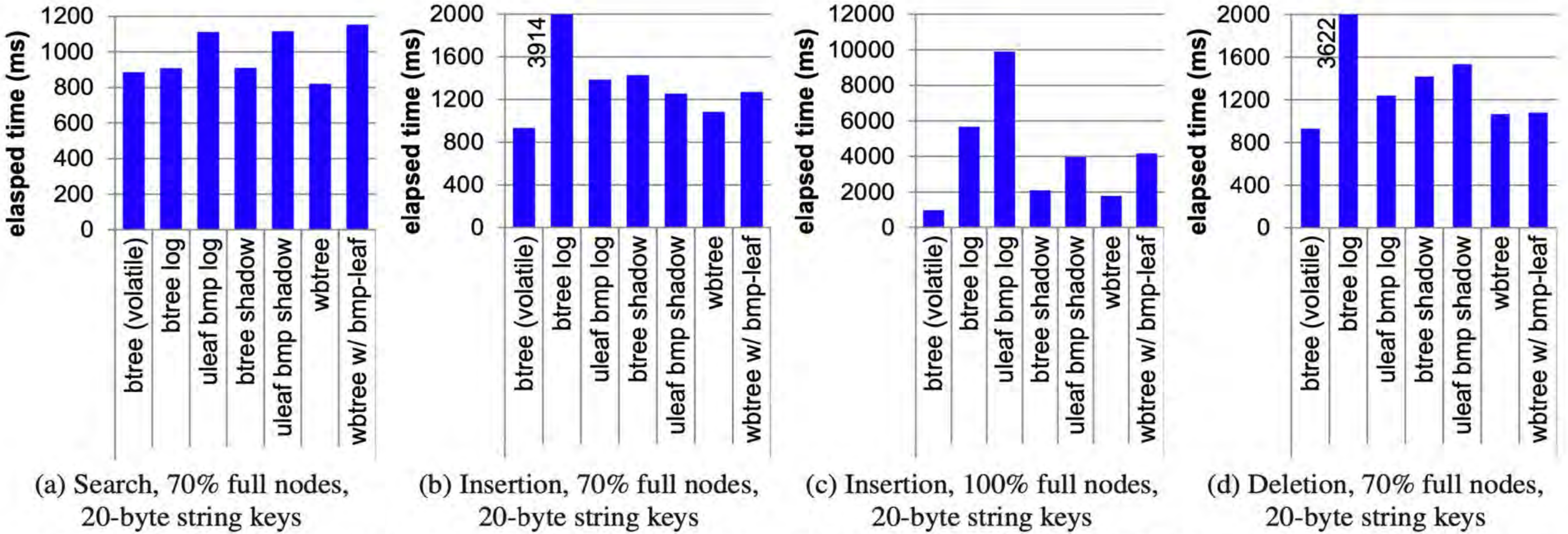
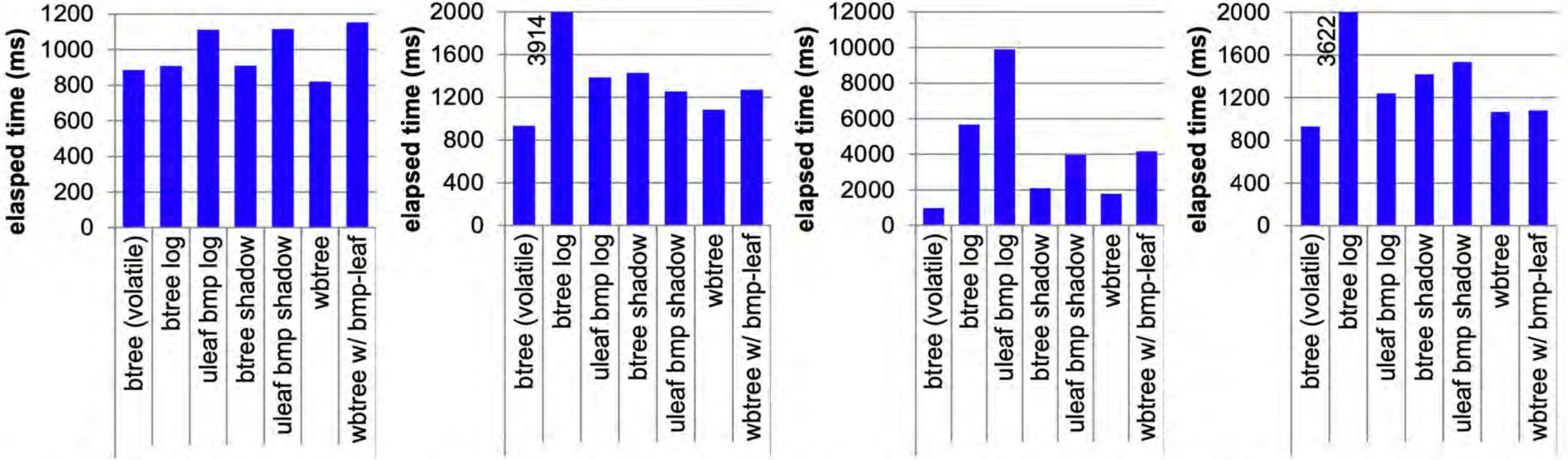


Figure 14: Index performance with string keys on a real machine. (We bulkload a tree with 50M entries, then perform 500K random back-to-back lookups, insertions, or deletions).

- wbtree is the best persistent tree solution.

Experimental Results



(a) Search, 70% full nodes, 20-byte string keys

(b) Insertion, 70% full nodes, 20-byte string keys

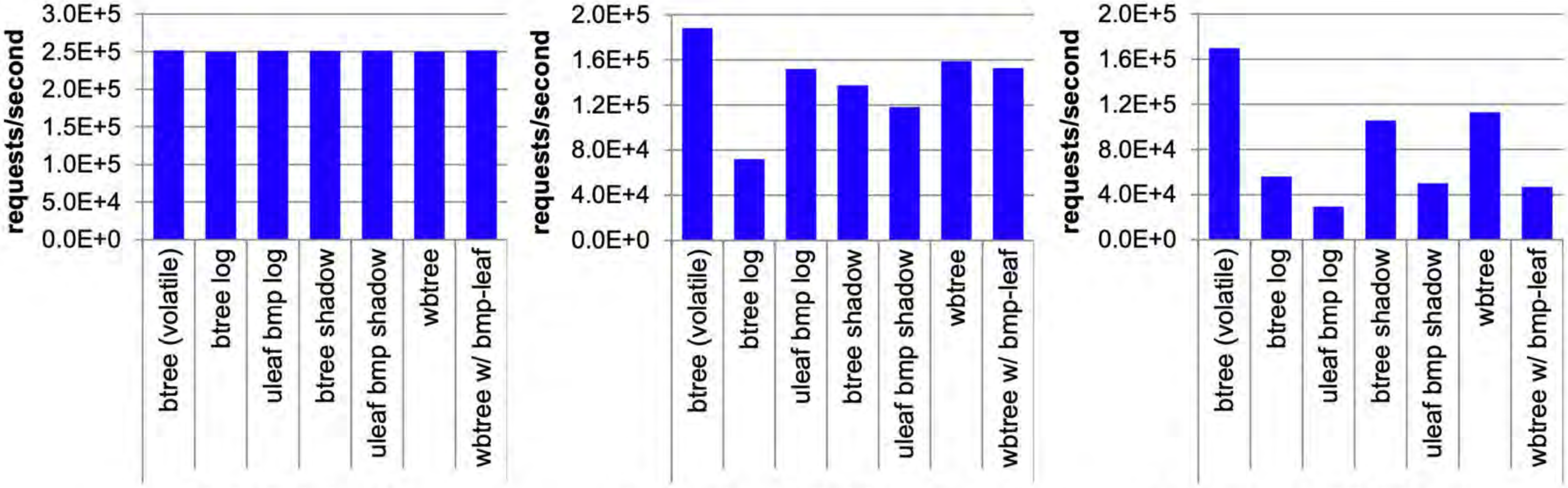
(c) Insertion, 100% full nodes, 20-byte string keys

(d) Deletion, 70% full nodes, 20-byte string keys

Figure 14: Index performance with string keys on a real machine. (We bulkload a tree with 50M entries, then perform 500K random back-to-back lookups, insertions, or deletions).

- wbtree w/bmp-leaf has significantly poorer performance

Experimental Results



(a) Search, 70% full nodes (b) Insertion, 70% full nodes (c) Insertion, 100% full nodes

Figure 15: Memcached throughput on a real machine. (We replace the hash index in Memcached with various types of trees. We bulkload a tree with 50M entries, and use mc-benchmark to insert and search 500K random keys. Keys are 20-byte random strings.)

- Performance difference across solutions is smaller because of the communication overhead

Experimental Results

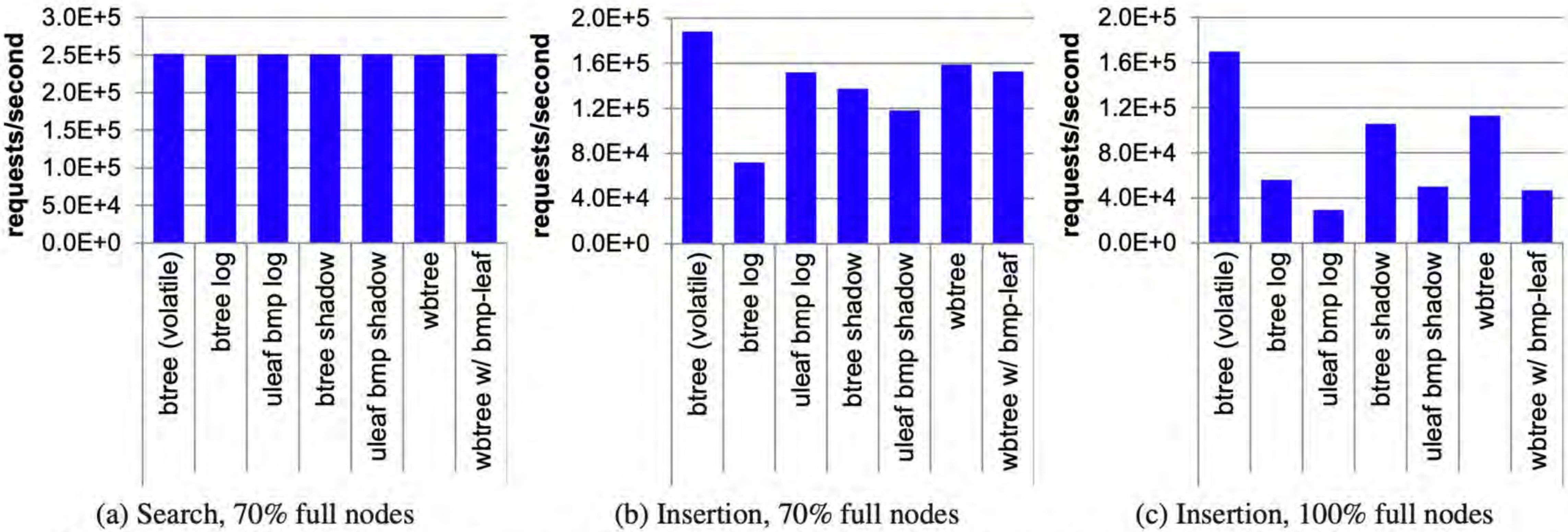


Figure 15: Memcached throughput on a real machine. (We replace the hash index in Memcached with various types of trees. We bulkload a tree with 50M entries, and use mc-benchmark to insert and search 500K random keys. Keys are 20-byte random strings.)

- The shorter search time is outweighed more by the communication overhead

Experimental Results

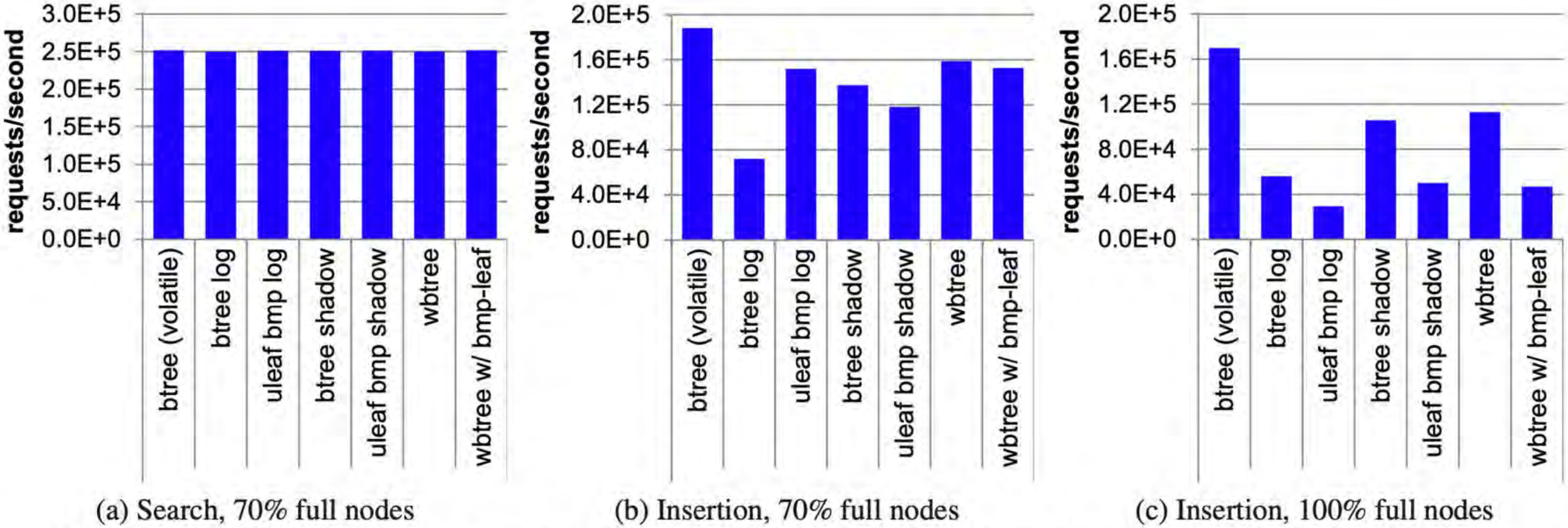


Figure 15: Memcached throughput on a real machine. (We replace the hash index in Memcached with various types of trees. We bulkload a tree with 50M entries, and use mc-benchmark to insert and search 500K random keys. Keys are 20-byte random strings.)

- wbtree achieves the highest throughput for insertions among persistent tree structures

Conclusion

Conclusion

- Persistence is crucial for NVMM data structures
- Undo-redo logging and shadowing perform extensive NVM writes and cacheline flushes
- Leaving leaves unsorted reduces writes, but makes search less effective
- The factors affecting performance have different weights for different NVM technologies
- Proposed wB^+-Trees improve the insertion and deletion performance, while achieving good search performance

Questions?

Insertion with Node Splitting

- Allocate new node and balance entries between old and new node
- No need to move entries in old node (because unsorted)
- Write bitmap/slot fields and sibling pointer of the new node
- Update bitmap/slot field and sibling pointer of old node. (redo-logging)
- Insert new lead node to parent node using insertion algorithm and commit redo writes.

Workload

- 8-byte integer keys for fixed-sized keys and 20-byte strings for variable sized keys
- B is large enough so that the tree size is much larger than LLC
- For simulation, B = 20 million, for real machine experiments, B = 50 million
- Total size of valid leaf entries is 320MB in simulation and 800MB on the real machine
- For variable sized keys, they perform only real-machine experiments, B = 50 million
- There will be an additional 1GB memory space for storing the actual strings on the real machine