Compress Objects, Not Cache Lines:
An Object-Based Compressed Memory Hierarchy

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CSAIL

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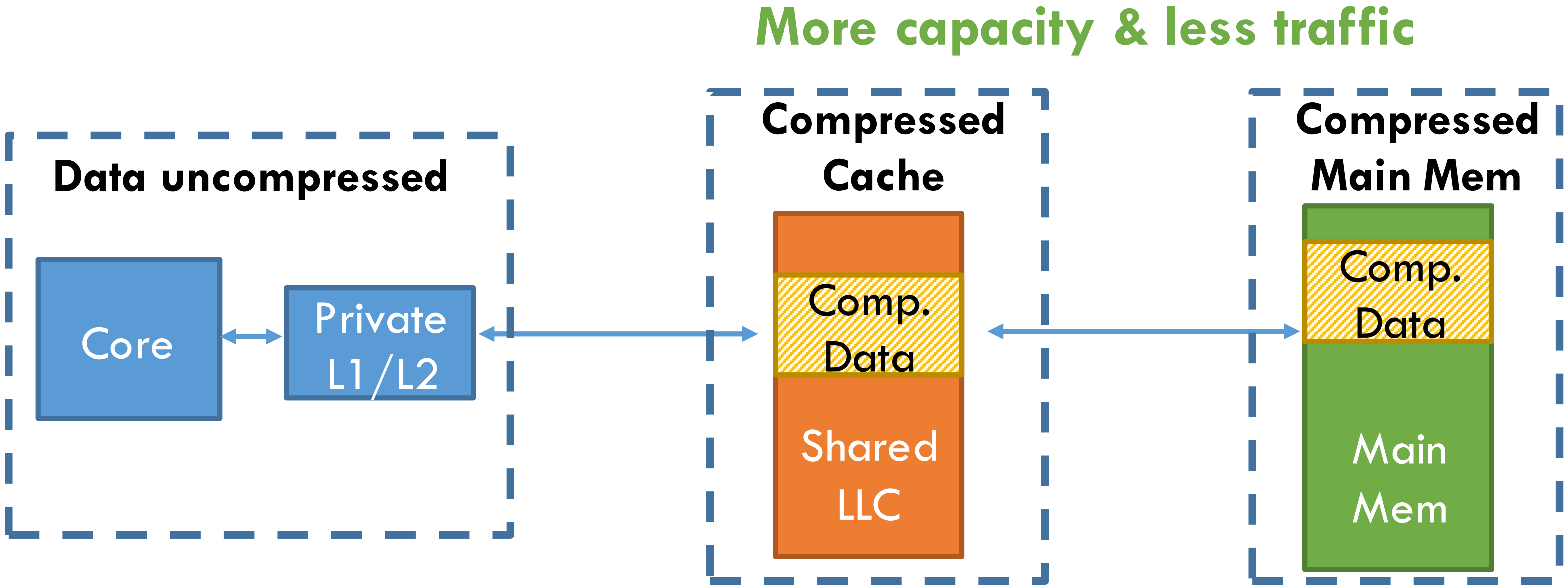

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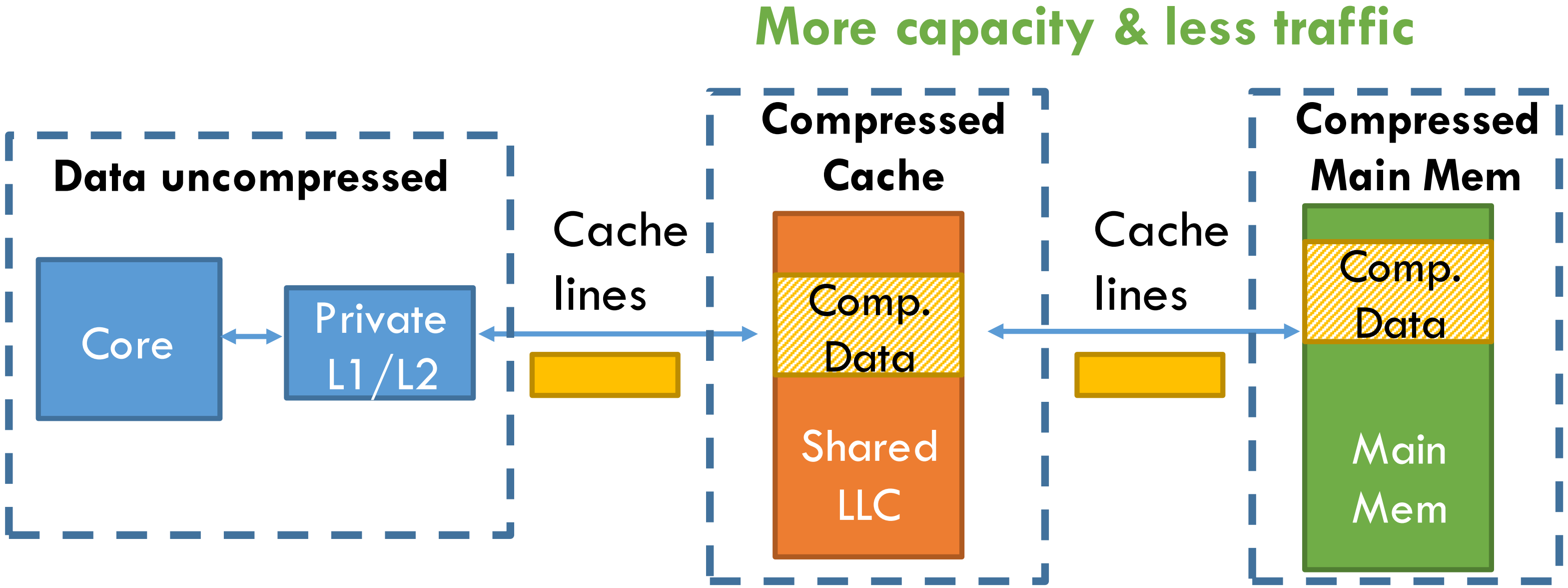
To support random accesses, the memory hierarchy transfers **cache lines** between levels

→ Prior techniques are thus limited to **compressing cache lines**



Challenges due to compressing at cache-line granularity

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1. Locating the compressed cache line (**architecture**)

Fixed-size cache lines become variable-size compressed blocks

→ HW needs to translate uncompressed addresses to compressed blocks

2. Compressing cache lines (**algorithm**)

Cache lines are small, and decompression latency is on the critical path

→ HW cannot compress more than 64B at a time

→ Only low-latency algorithms are practical

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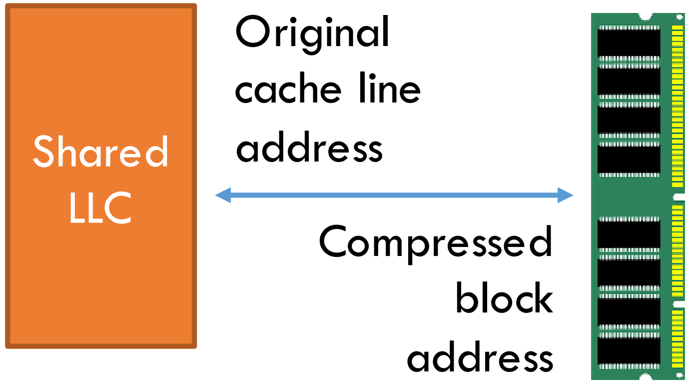
  - Example: Linearly compressed pages



Shared LLC

Original cache line address

Compressed block address

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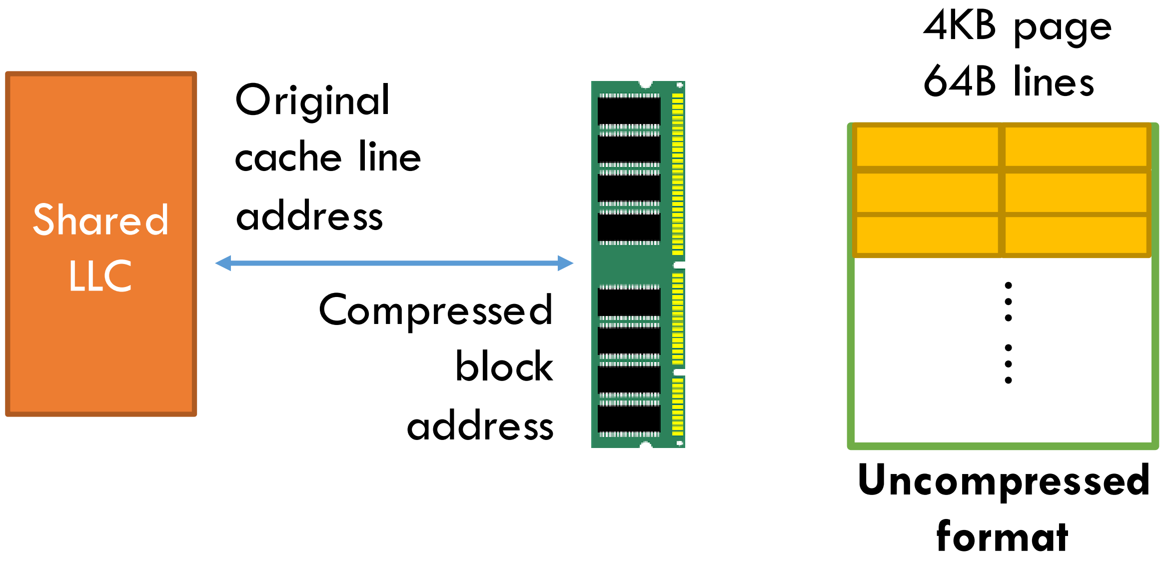

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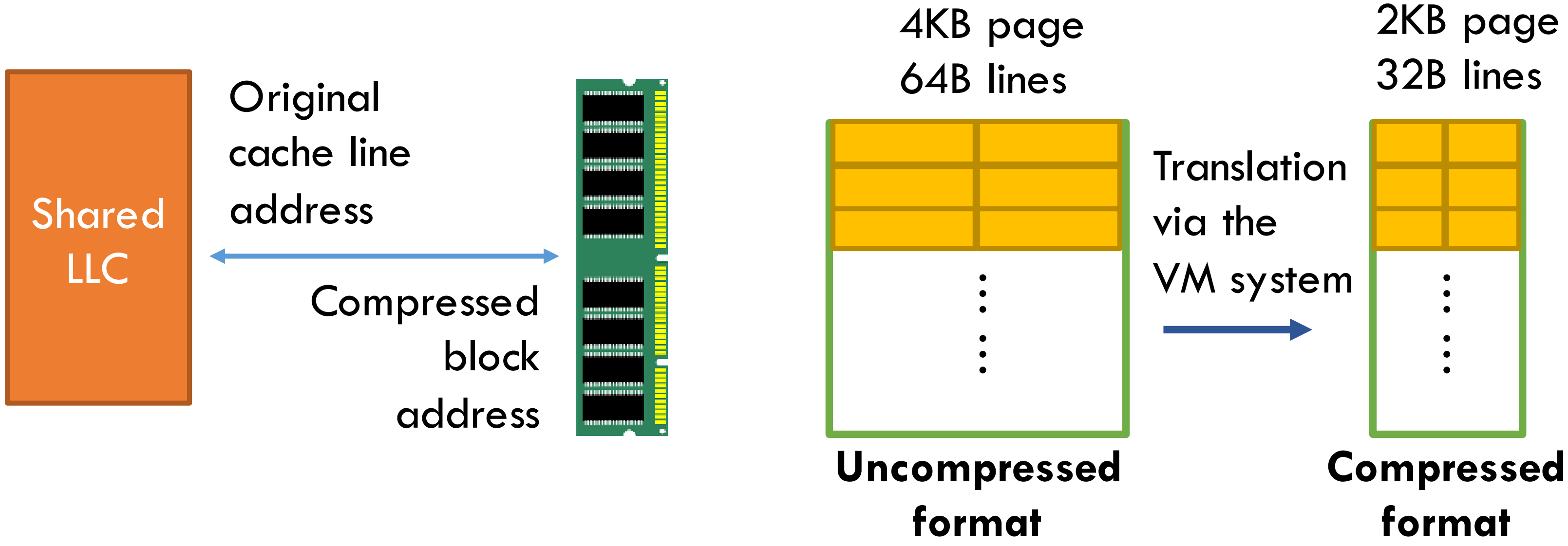

LCP compresses page by page to leverage VM for translation
→ Fast and low overhead

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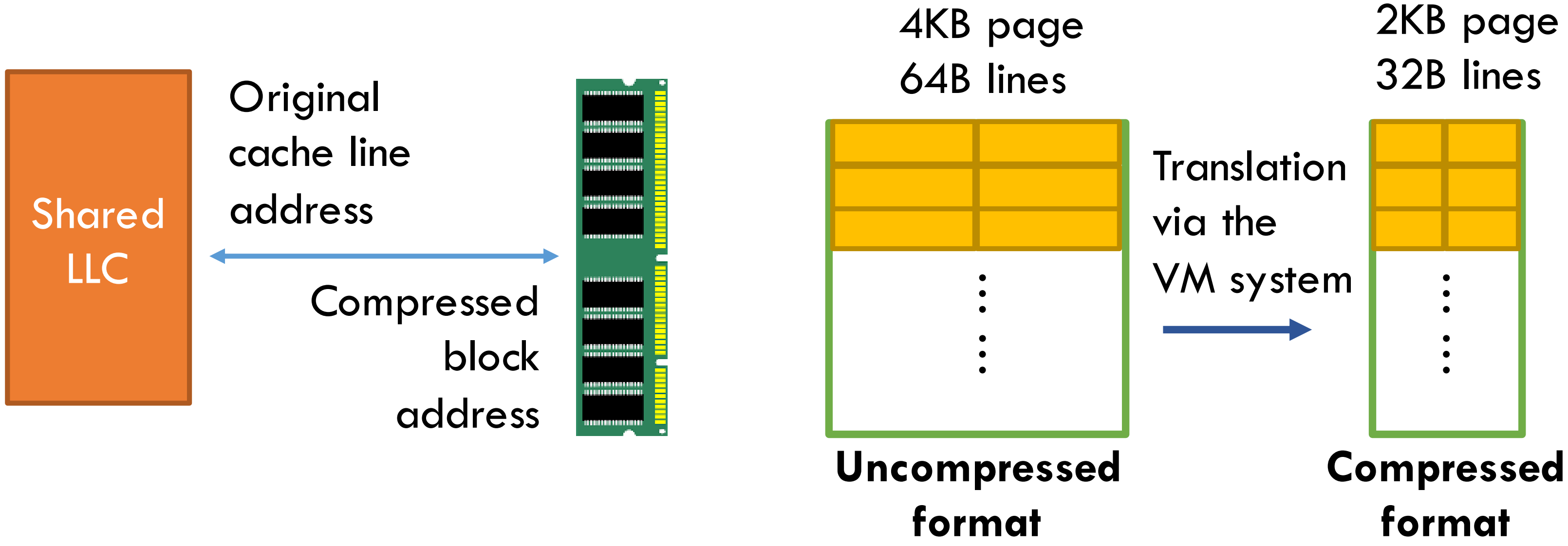

Shared LLC

Original cache line address

Compressed block address

4KB page
64B lines

Uncompressed format

Translation via the VM system

2KB page
32B lines

Compressed format

LCP compresses page by page to leverage VM for translation
→ Fast and low overhead

LCP forces cache lines in the same page to compress into the same size
→ Sacrifice compression ratio

- Other techniques make similar tradeoffs
  - E.g., 4 different sizes for cache lines in a page

[RMC, Ekman and Stenstorm, HPCA'06]
[DMC, Kim et al., PACT'17]
[Compresso, Choukse et al, MICRO'18]

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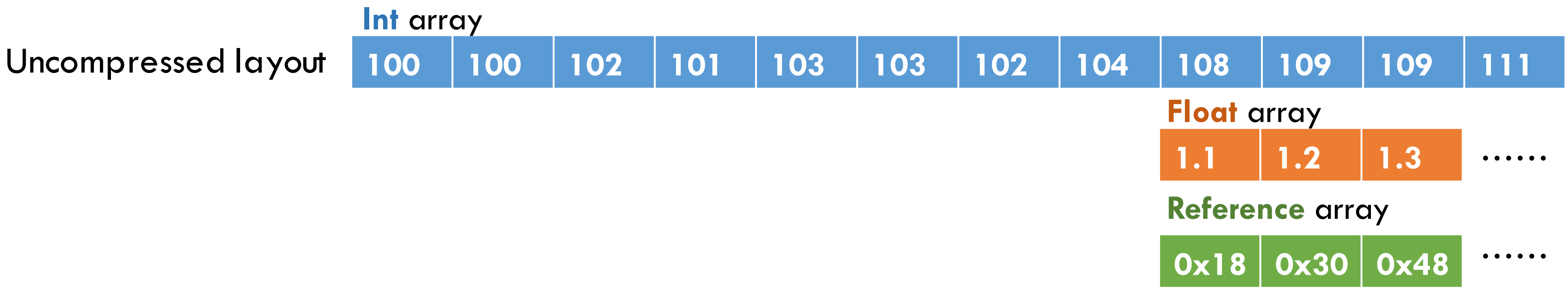

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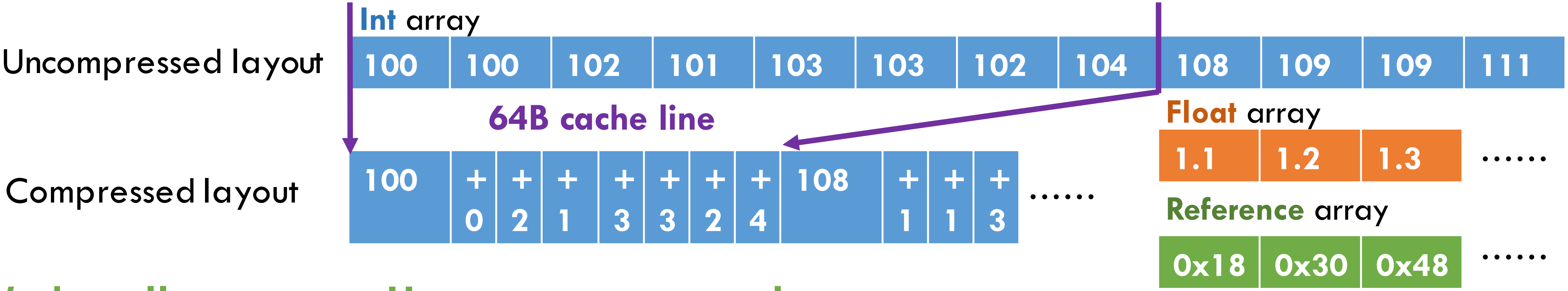

Int array

Uncompressed layout

100 | 100 | 102 | 101 | 103 | 103 | 102 | 104 | 108 | 109 | 109 | 111

64B cache line

Compressed layout

100 | +0 | +2 | +1 | +3 | +3 | +2 | +4 | 108 | +1 | +1 | +3 ……

Float array

1.1 | 1.2 | 1.3 ……

Reference array

0x18 | 0x30 | 0x48 ……

Work well on arrays: Homogeneous, regular

[FP-H, Arelakis et al., MICRO’15] [BPC, Kim et al., ISCA’16]

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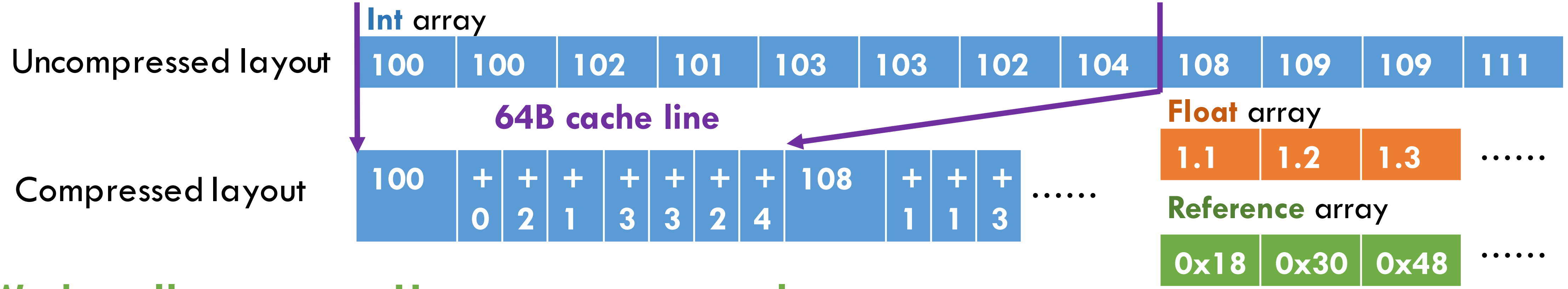

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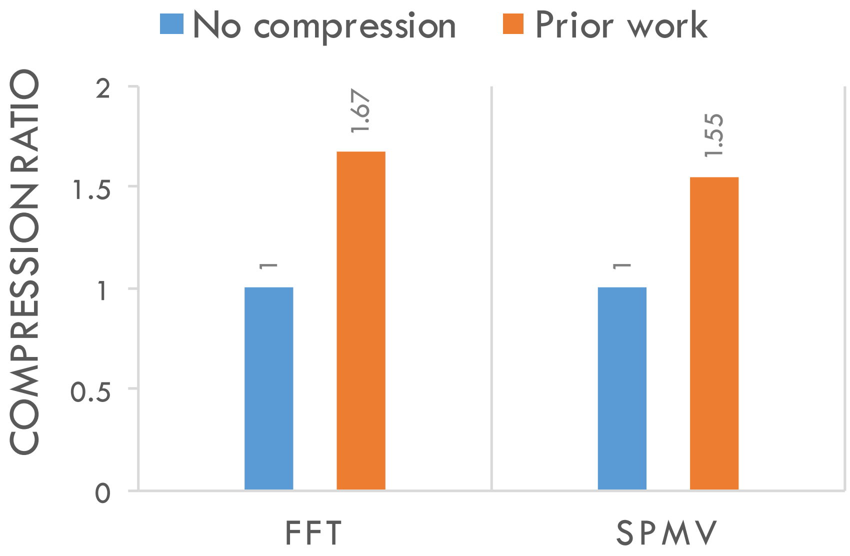

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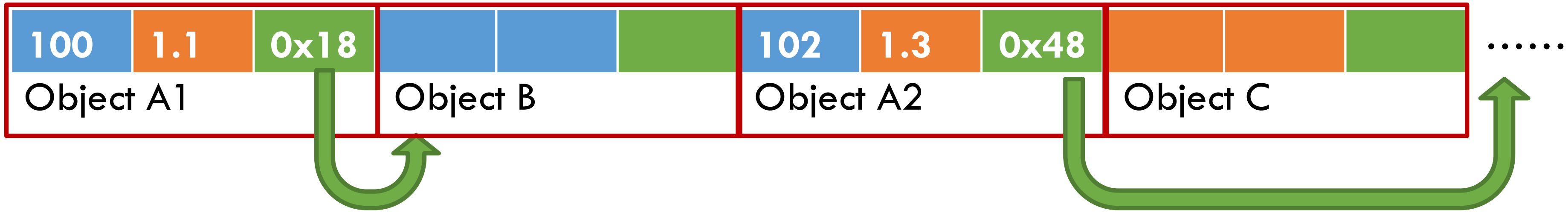
Work poorly on objects: Heterogeneous, irregular



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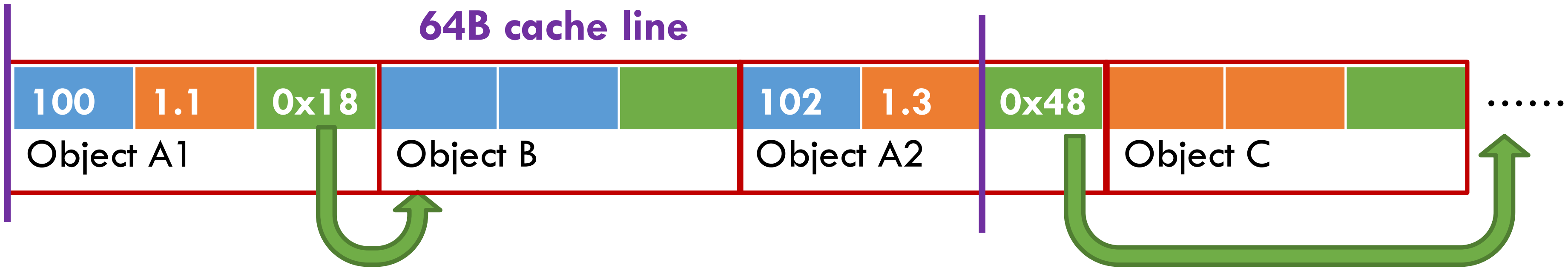

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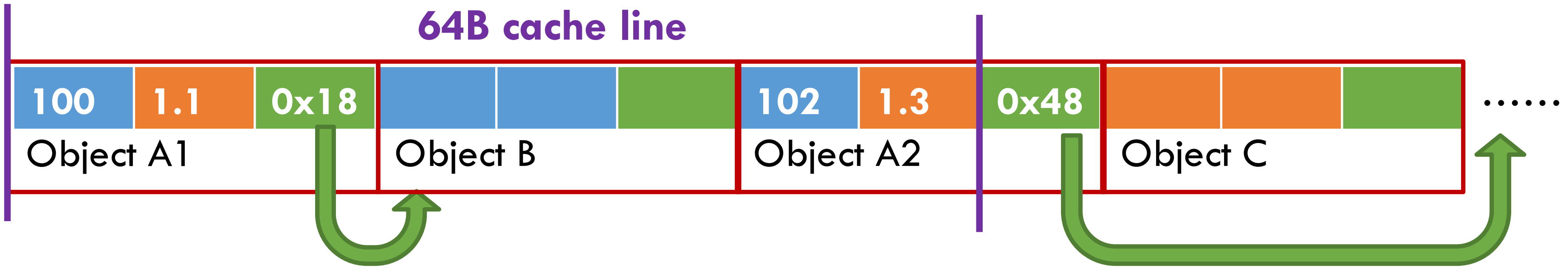

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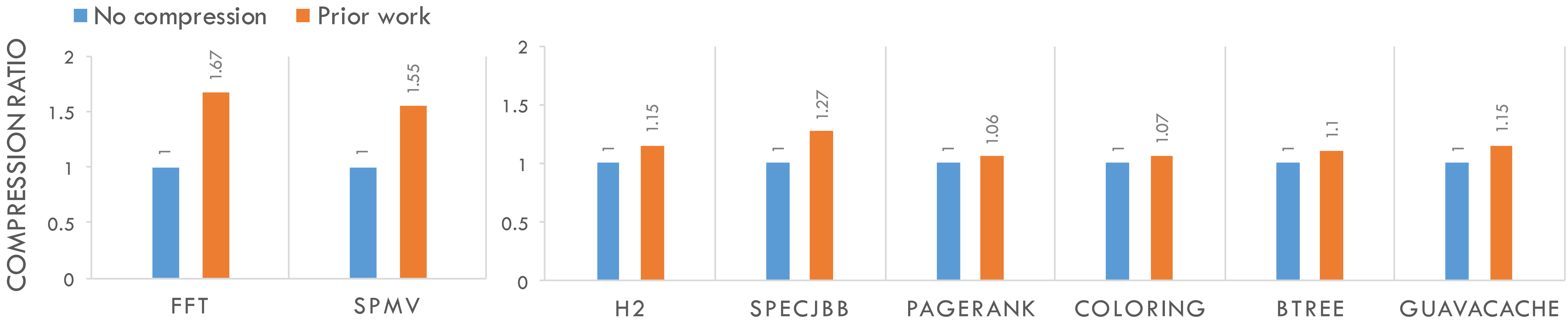

Array-heavy apps:
61% compression ratio

Object-heavy apps:
14% compression ratio

Objects, not cache lines, are the natural unit of compression

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Insight 1:
Object-based applications always follow pointers to access objects

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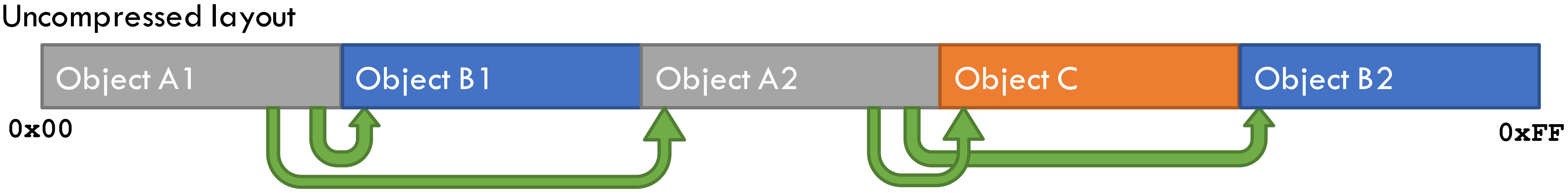

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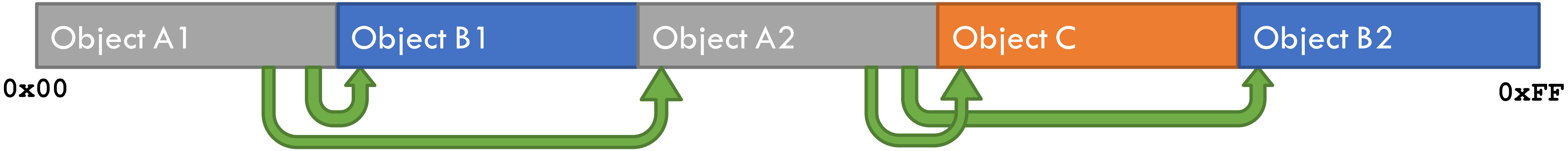
Object-based applications always follow pointers to access objects

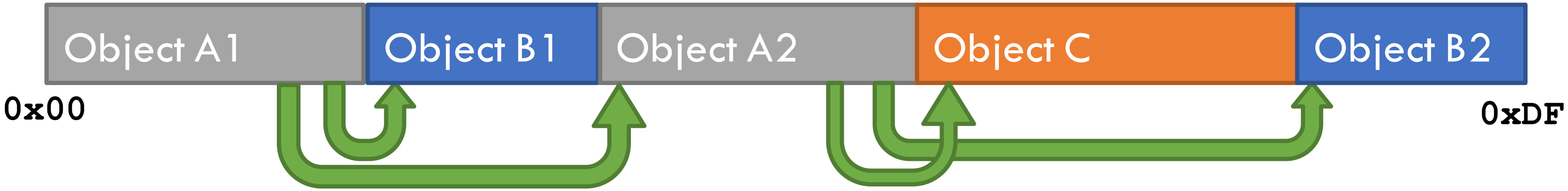
Uncompressed layout



Idea 1:

Point directly to the location of compressed objects to avoid uncompressed-to-compressed address translation!

Compressed layout



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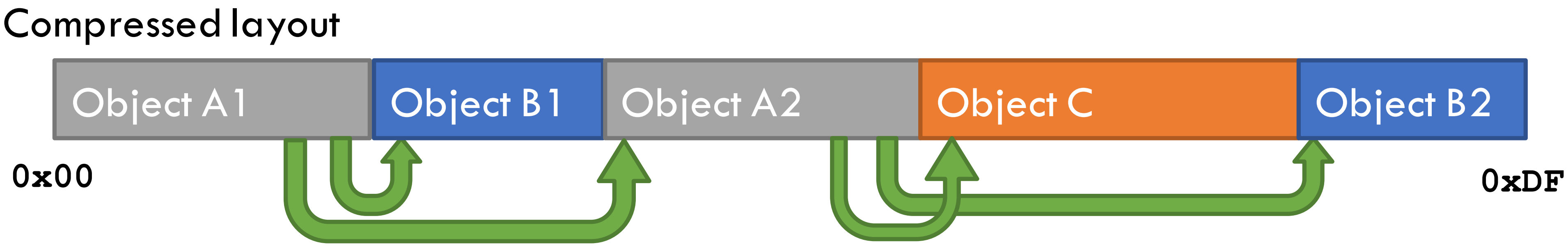

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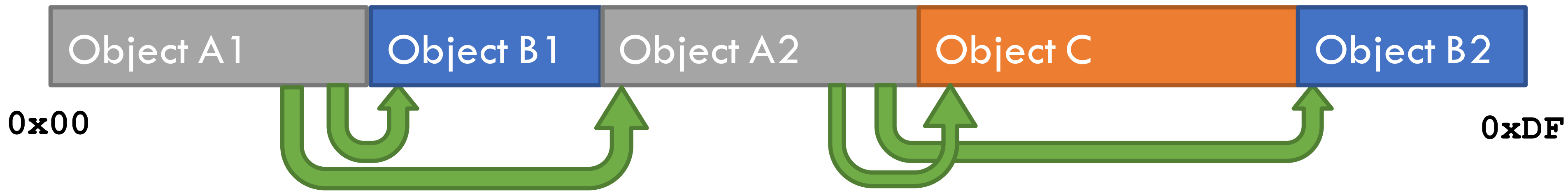
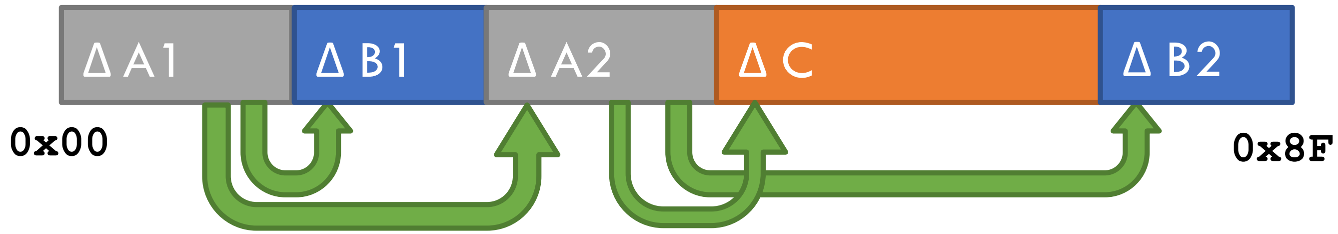


Idea 2:

Compress across objects, not within cache lines, to leverage more redundancy!

Further compressed layout



Δ A1 = Bytes that differ from a shared base object

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- Therefore, we realize our ideas on *Hotpads*
  - A recent *object-based* memory hierarchy

Baseline system: Hotpads overview

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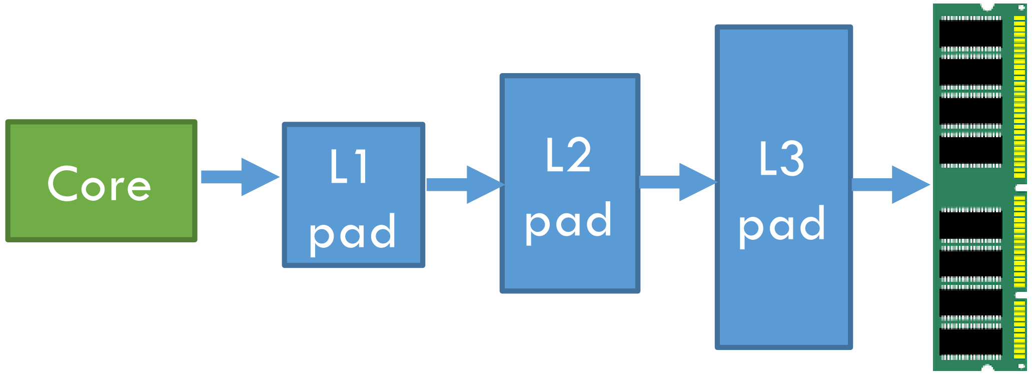

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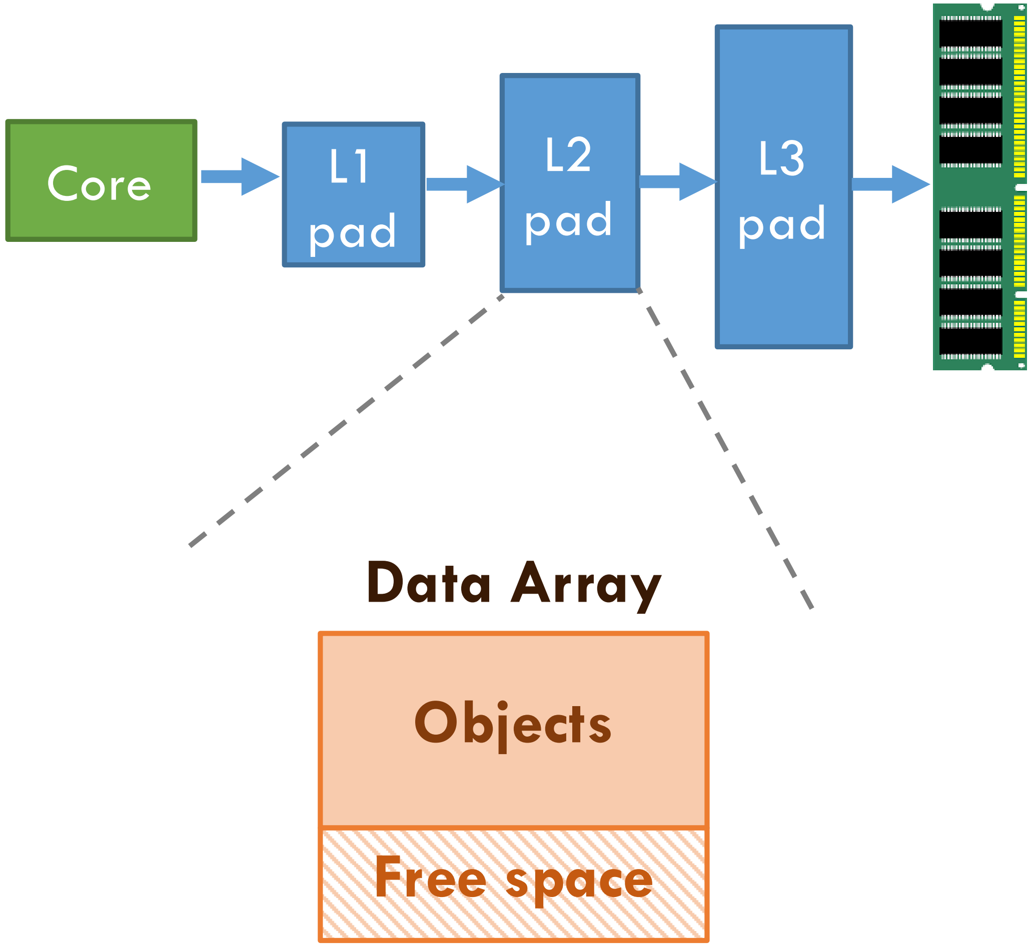

- Data array
  - Managed as a circular buffer using simple sequential allocation
  - Stores variable-sized objects compactly

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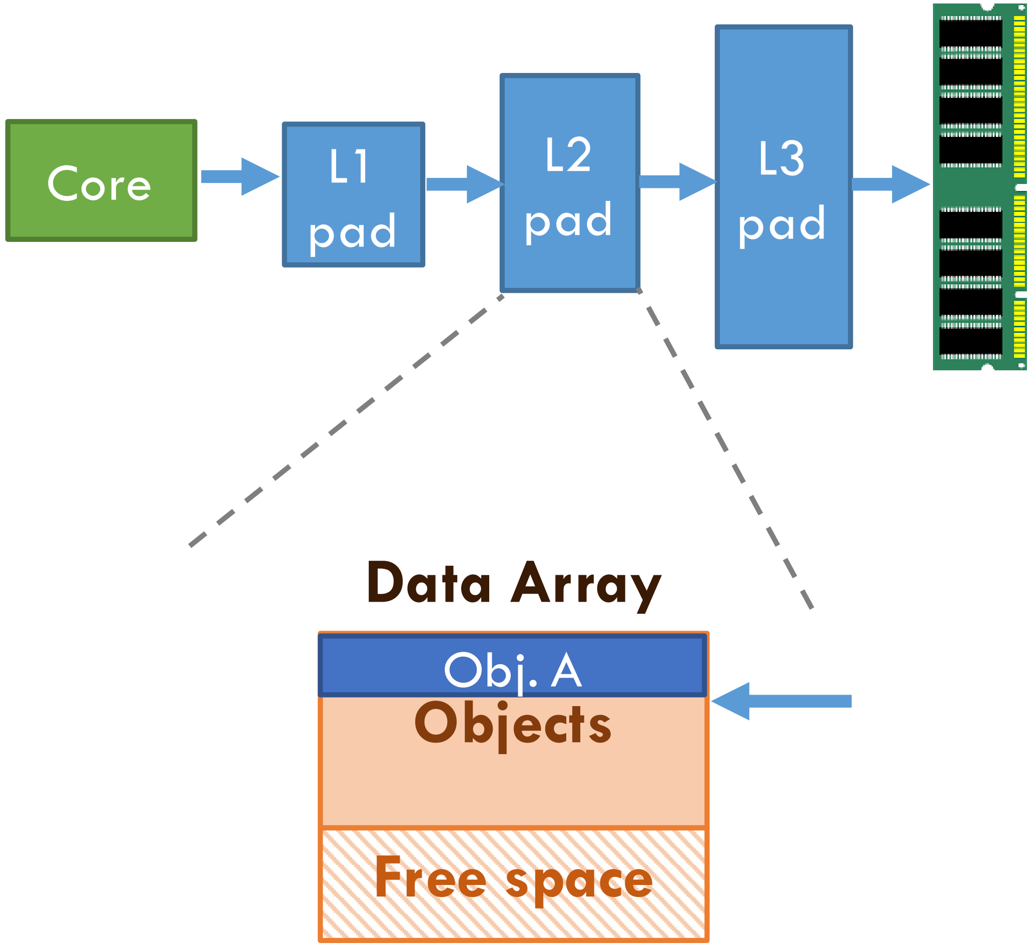

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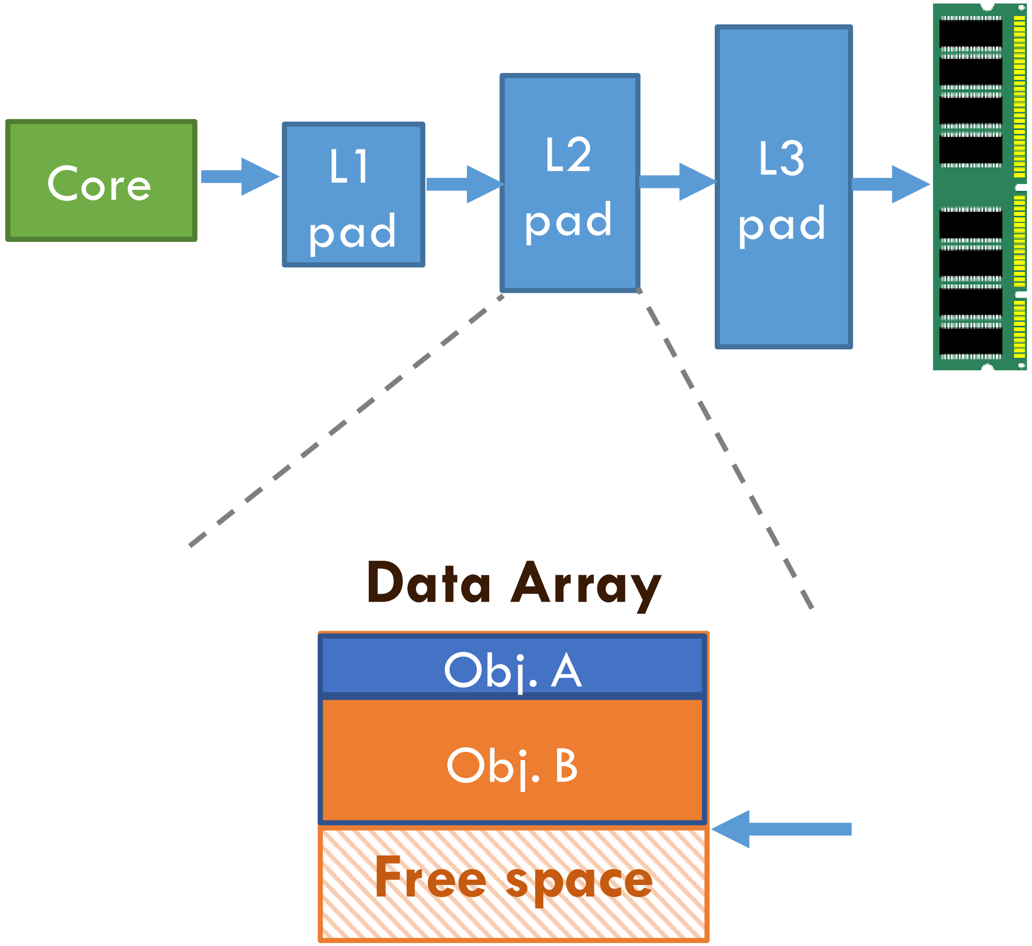

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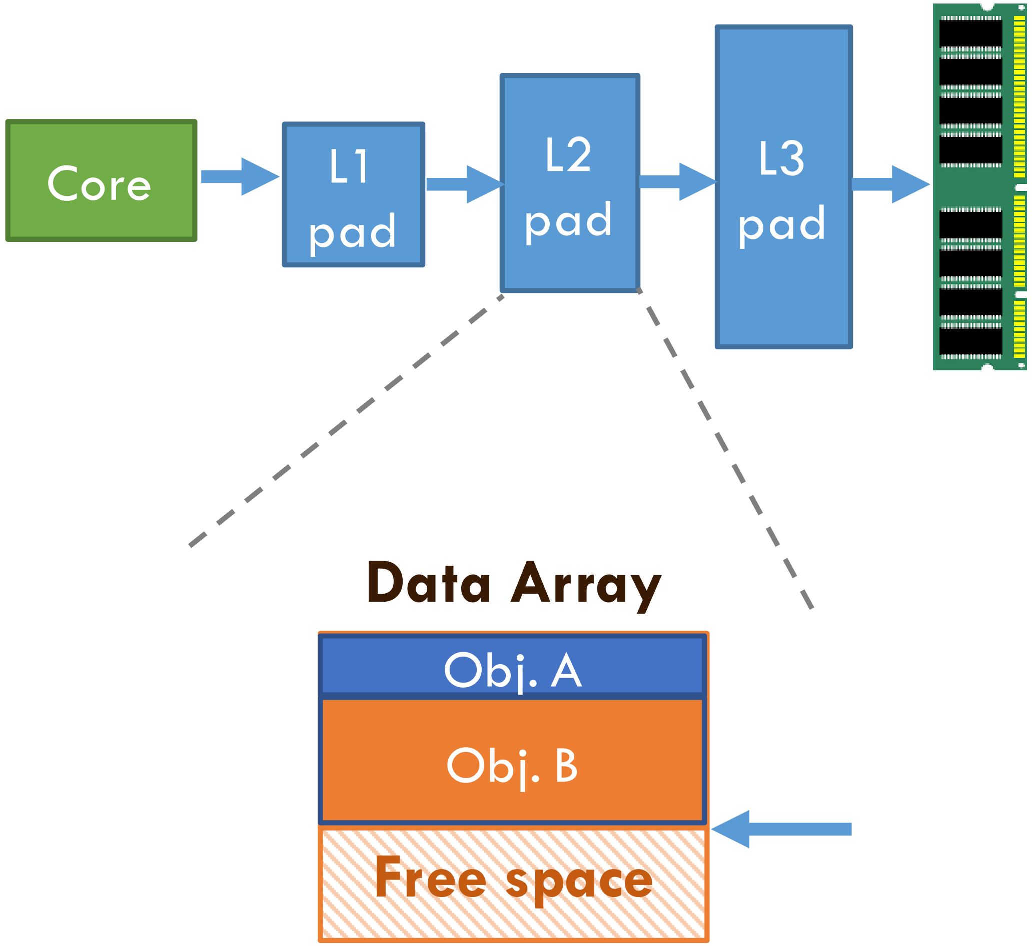

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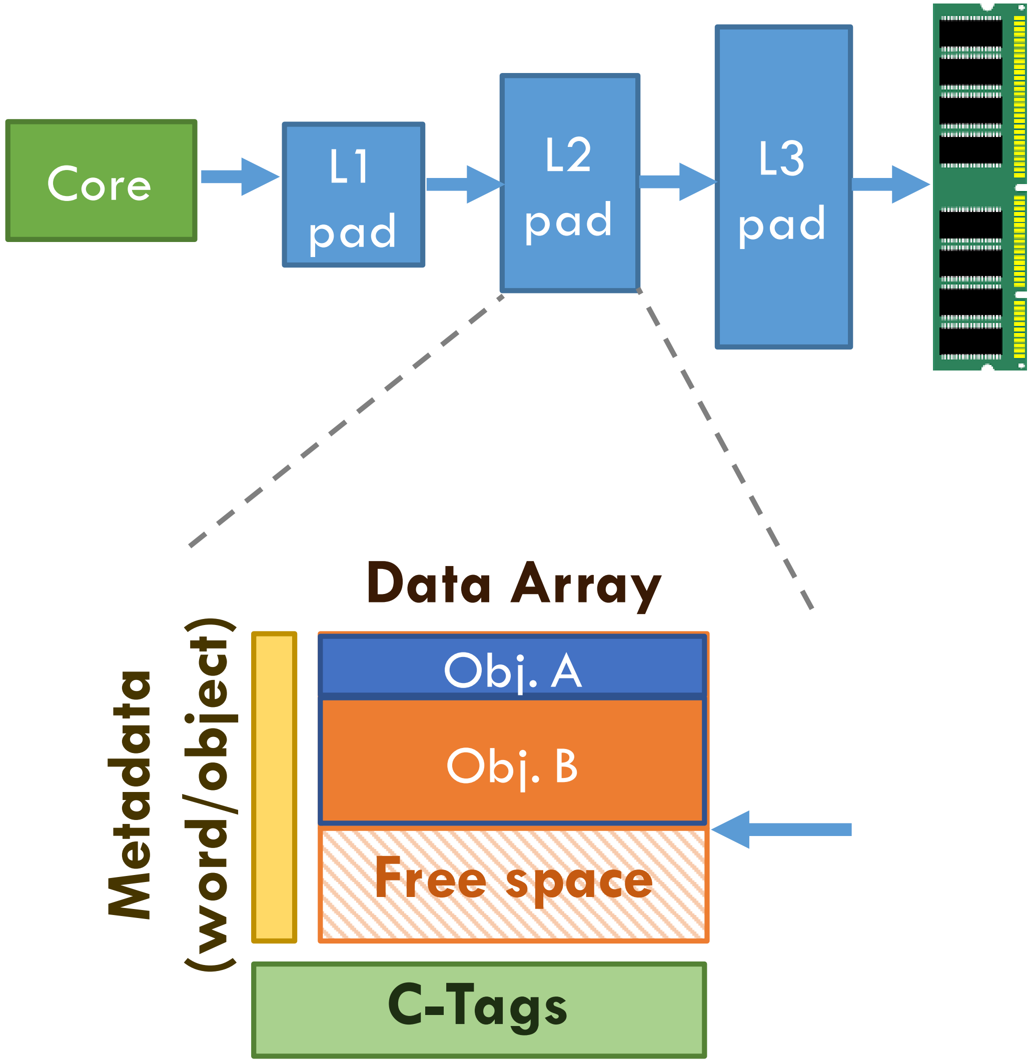

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- C-Tags
  - Decoupled tag store
- Metadata
  - Pointer? valid? dirty? recently-used?

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0

```
Example object:
class ListNode {
     int value;
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}
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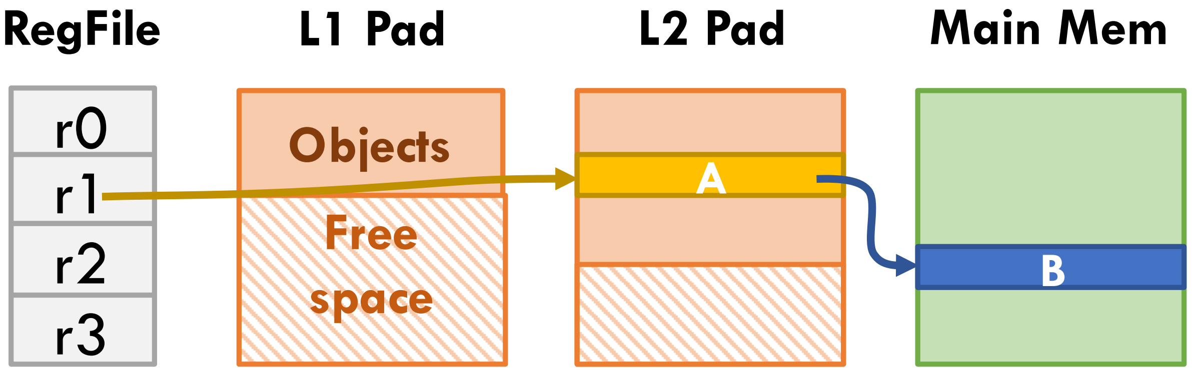

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⓪

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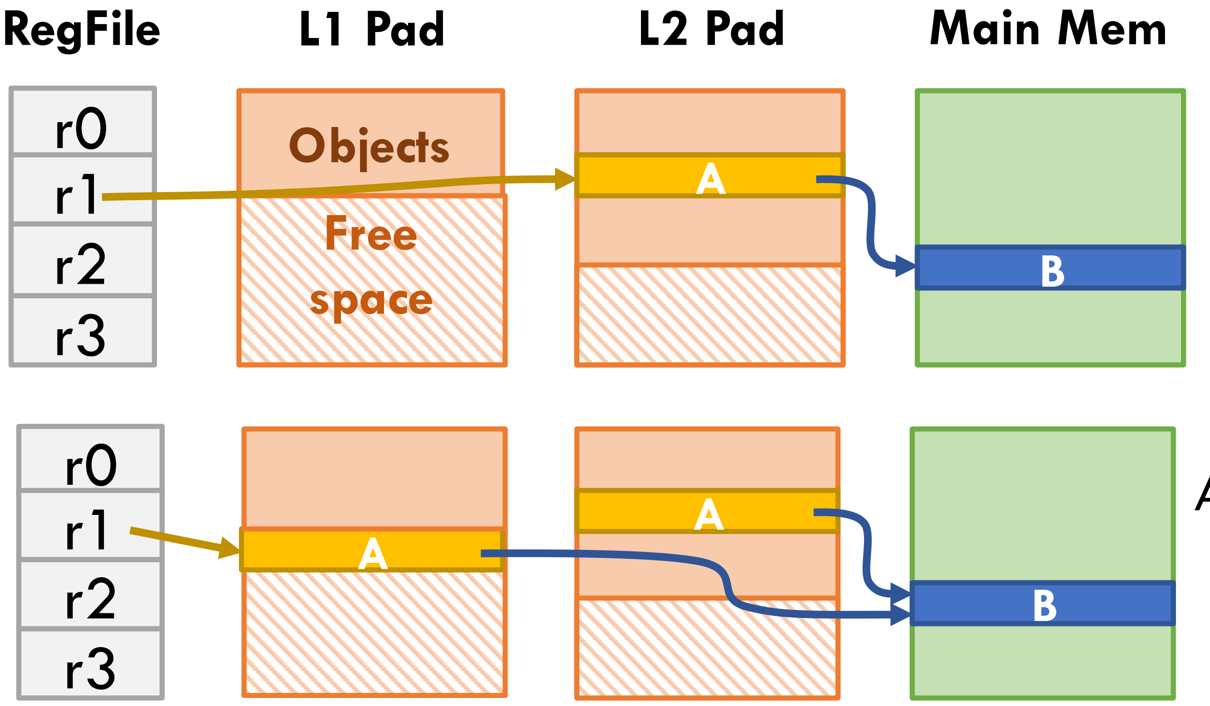

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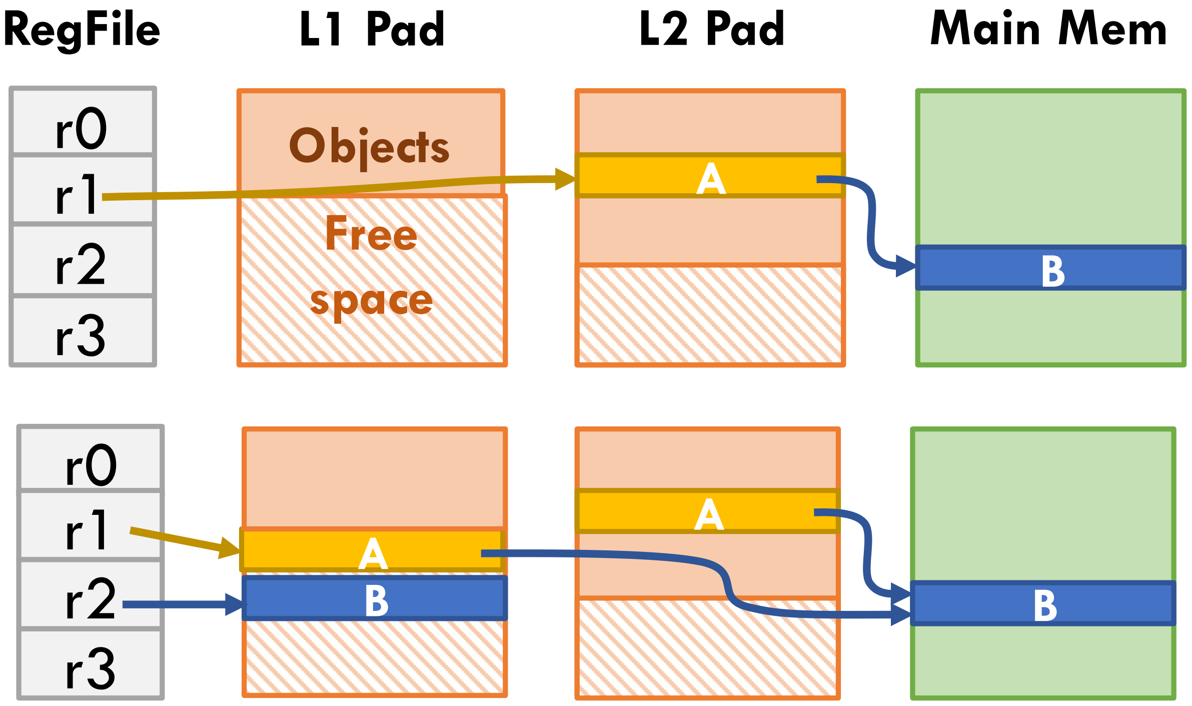

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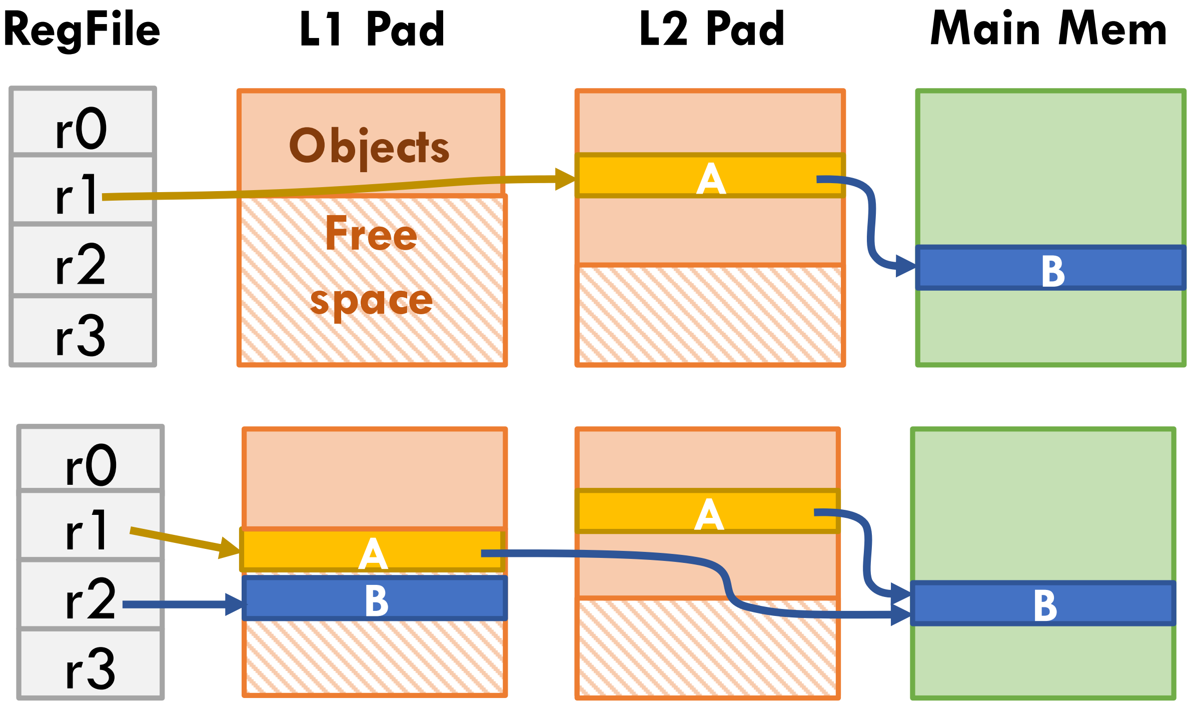

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Hotpads takes control of the memory layout, hides pointers from software, and encodes object information in pointers

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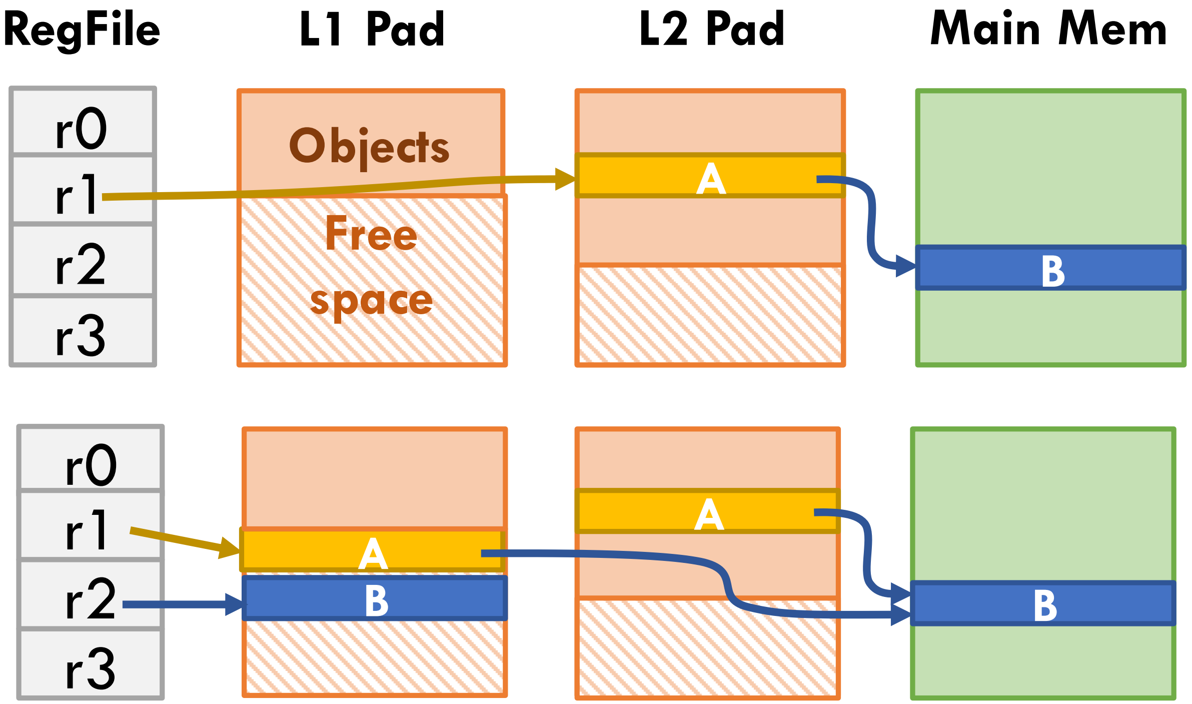

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Hotpads takes control of the memory layout, hides pointers from software, and encodes object information in pointers

Fetching **compressed** `size` words from the starting **compressed** address yields the entire **compressed** object

Hotpads updates pointers among objects on evictions

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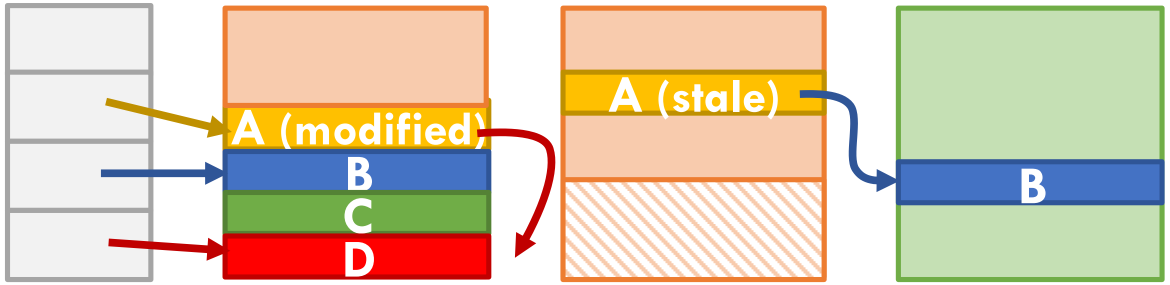
3

L1 pad is full because of fetched objects or newly-allocate objects



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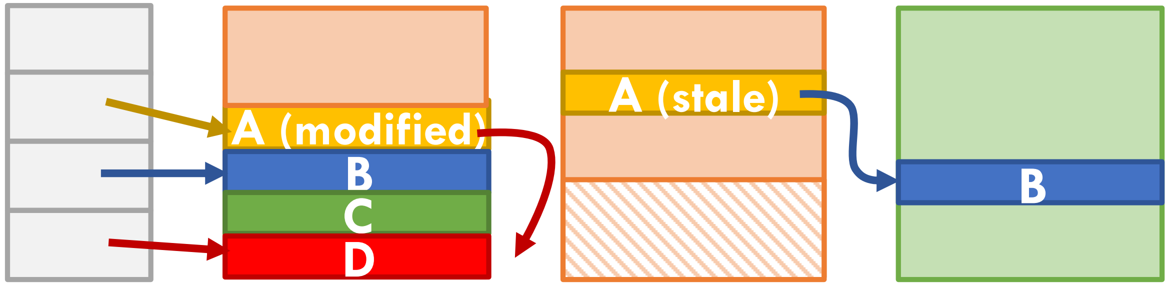

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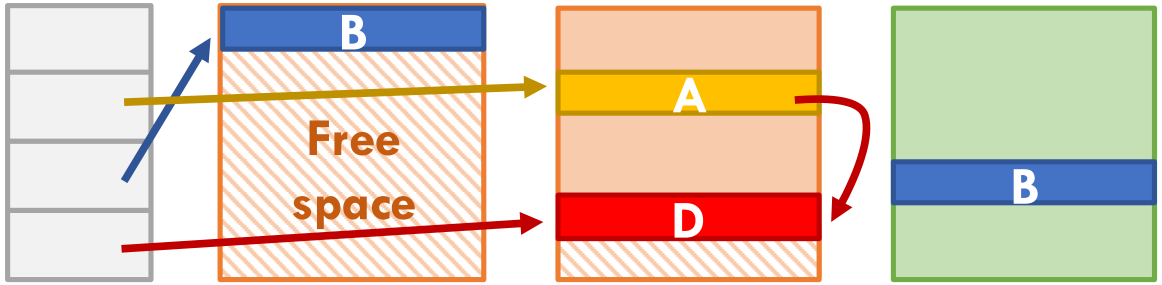

Copied objects (A) are back to old location

New objects (**D**) are sequentially allocated

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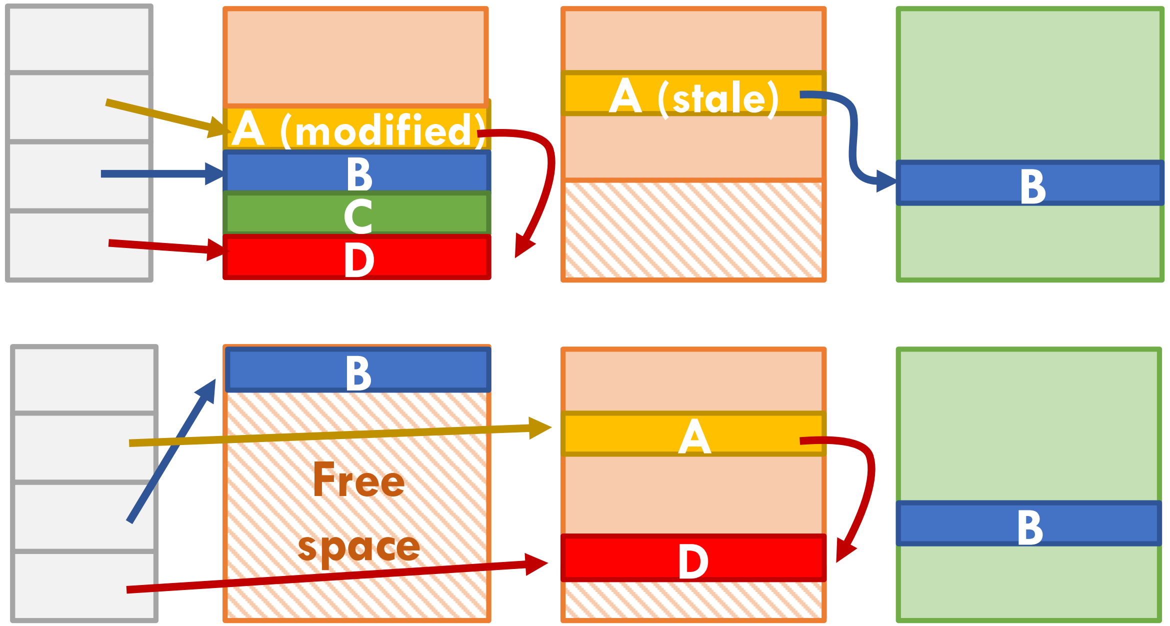

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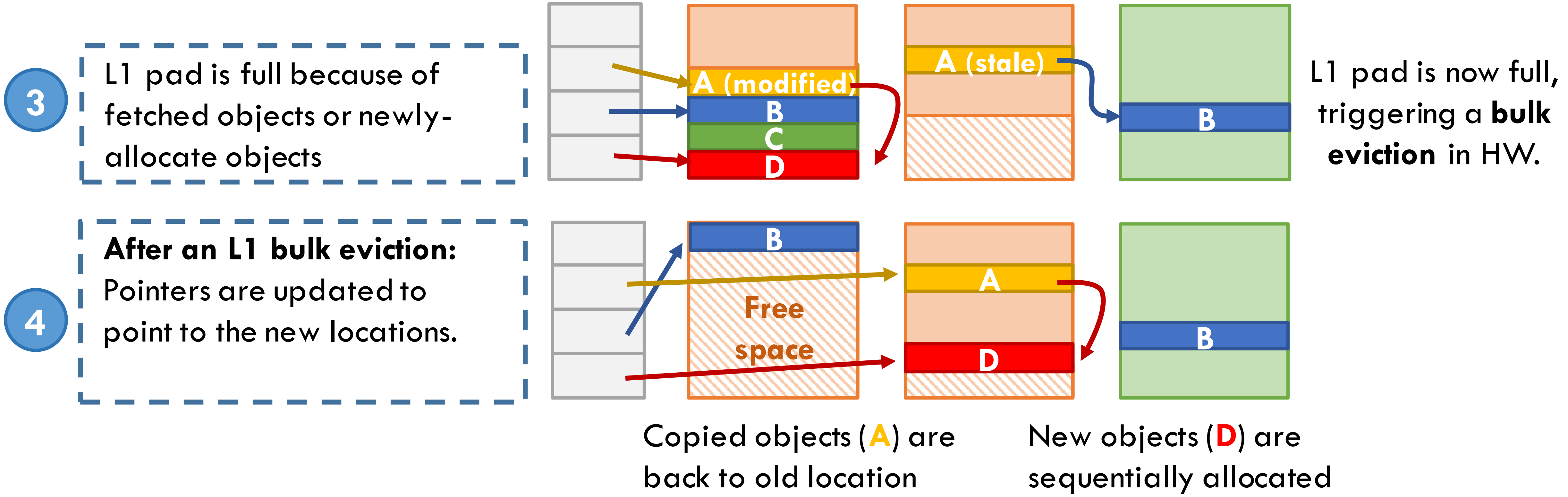

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New objects (D) are sequentially allocated

- Bulk eviction amortizes the cost of finding and updating pointers across objects
- Since updating pointers already happens in Hotpads, there is **no extra cost to update them to compressed locations!**

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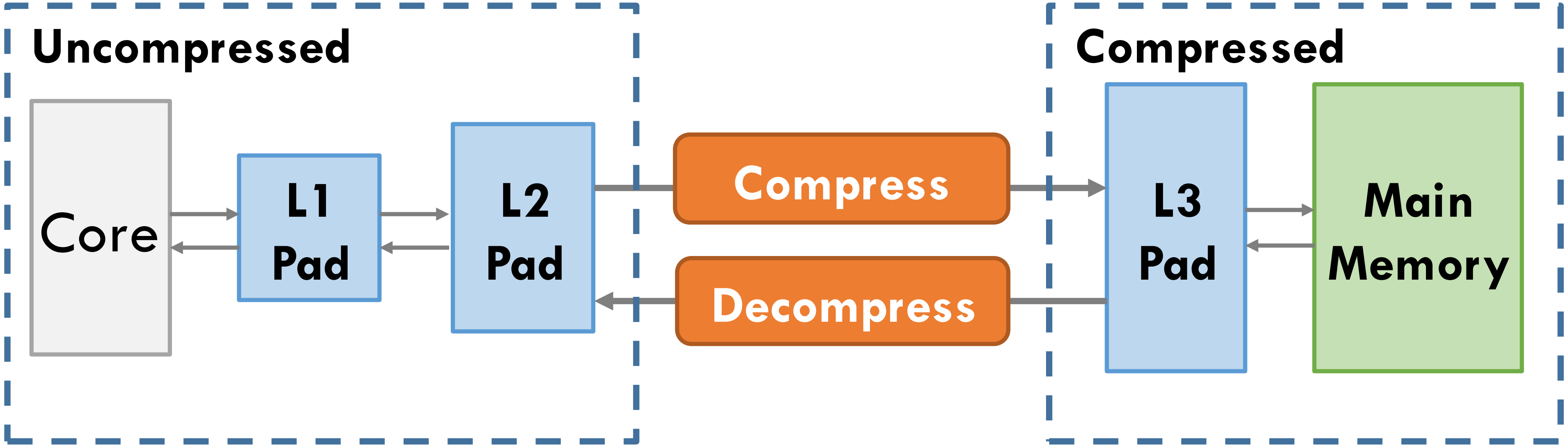

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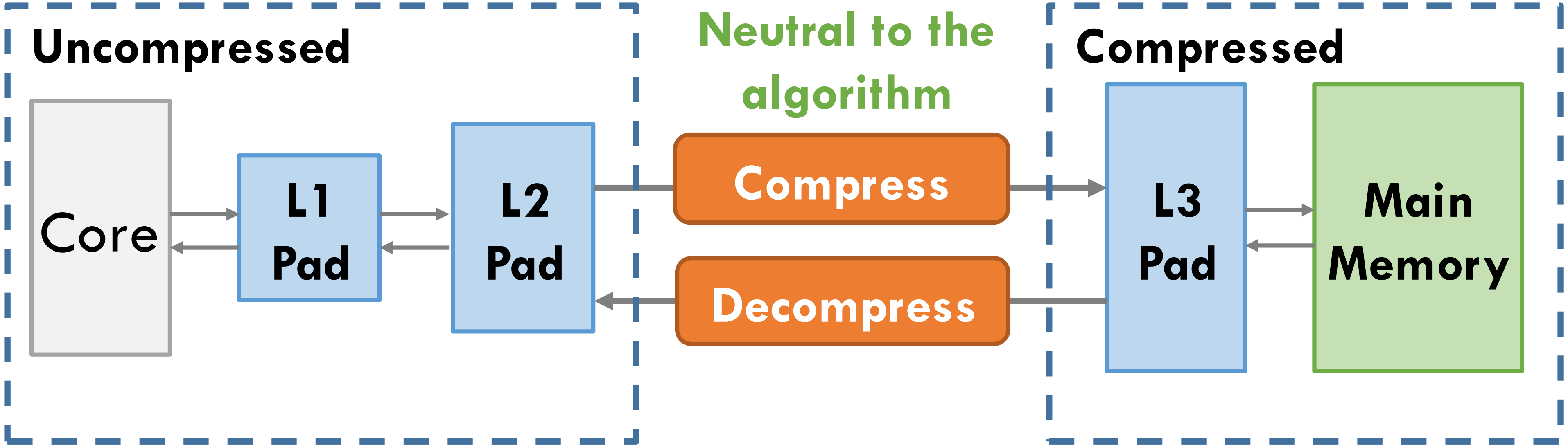

Compress both on-chip and off-chip memories

Zippads compresses objects when they move

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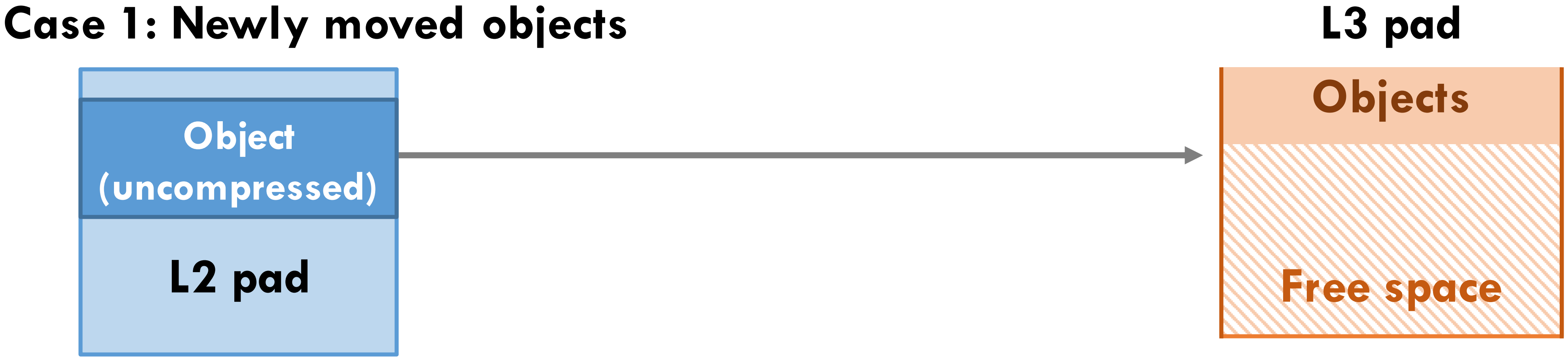

Objects start their lifetime uncompressed in private levels

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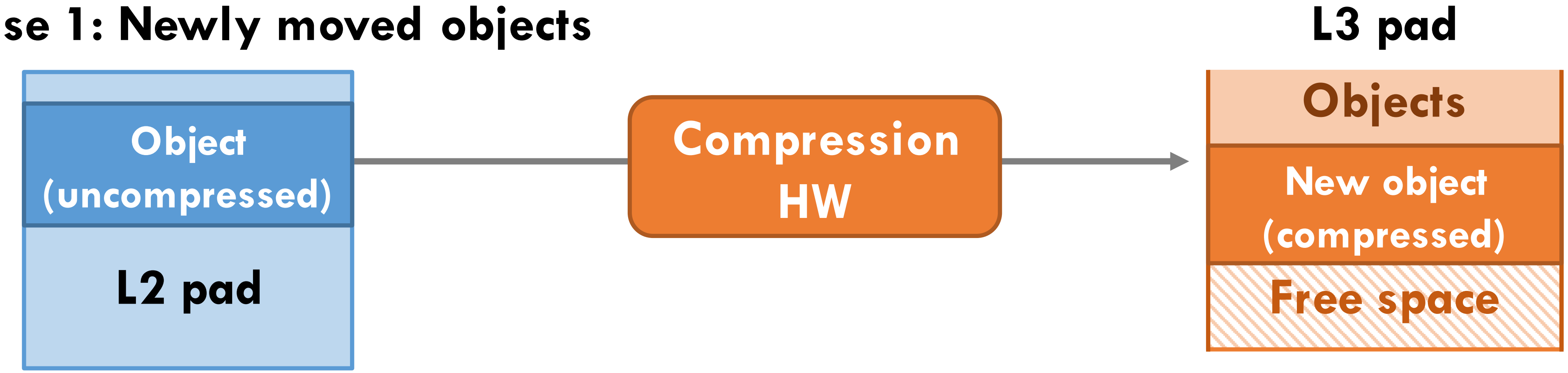
- ☐ Objects are compressed during bulk object evictions

Case 1: Newly moved objects



Objects start their lifetime uncompressed in private levels

When objects are evicted into a compressed level, they are compressed in that level and store compactly

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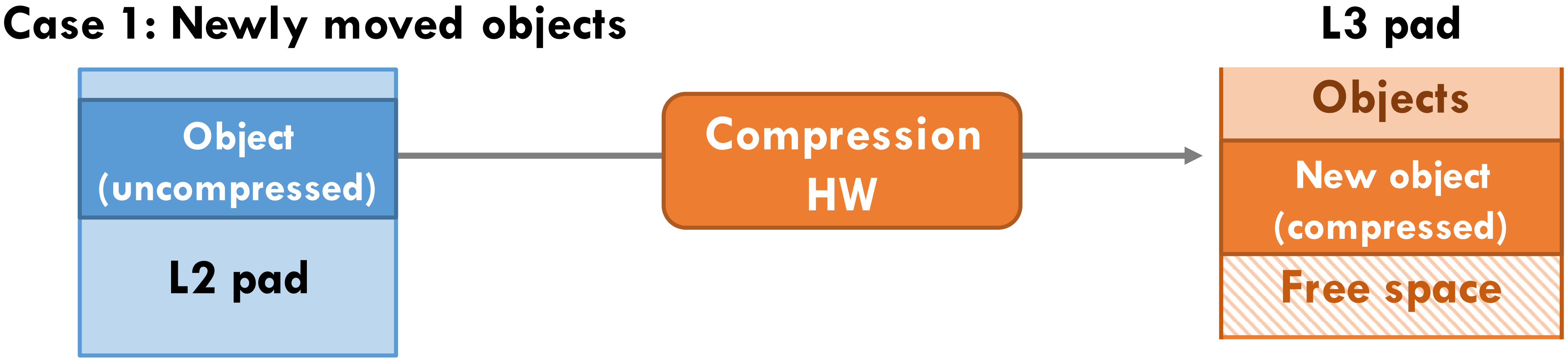

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When objects are evicted into a compressed level, they are compressed in that level and store compactly

Piggyback the bulk eviction process to find and update all pointers at once, amortizing update costs

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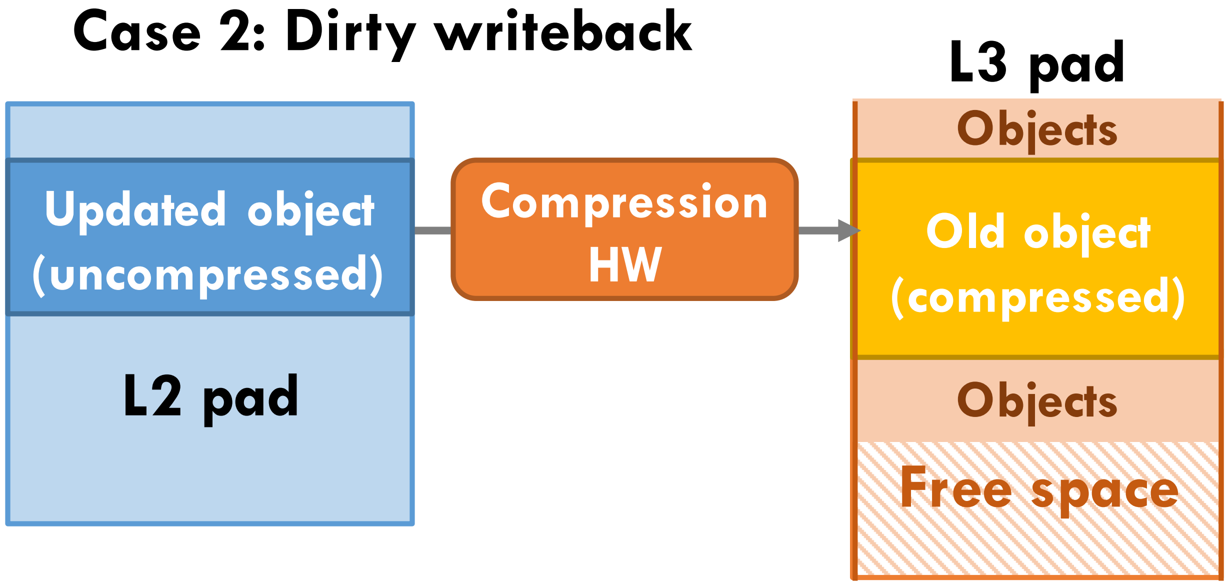

Case 2: Dirty writeback

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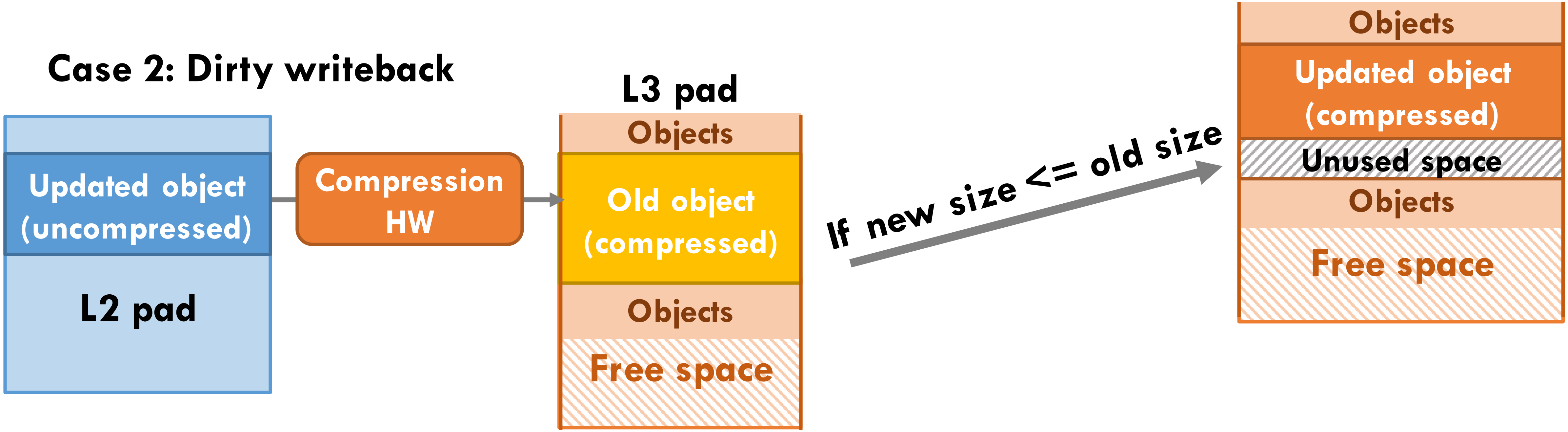

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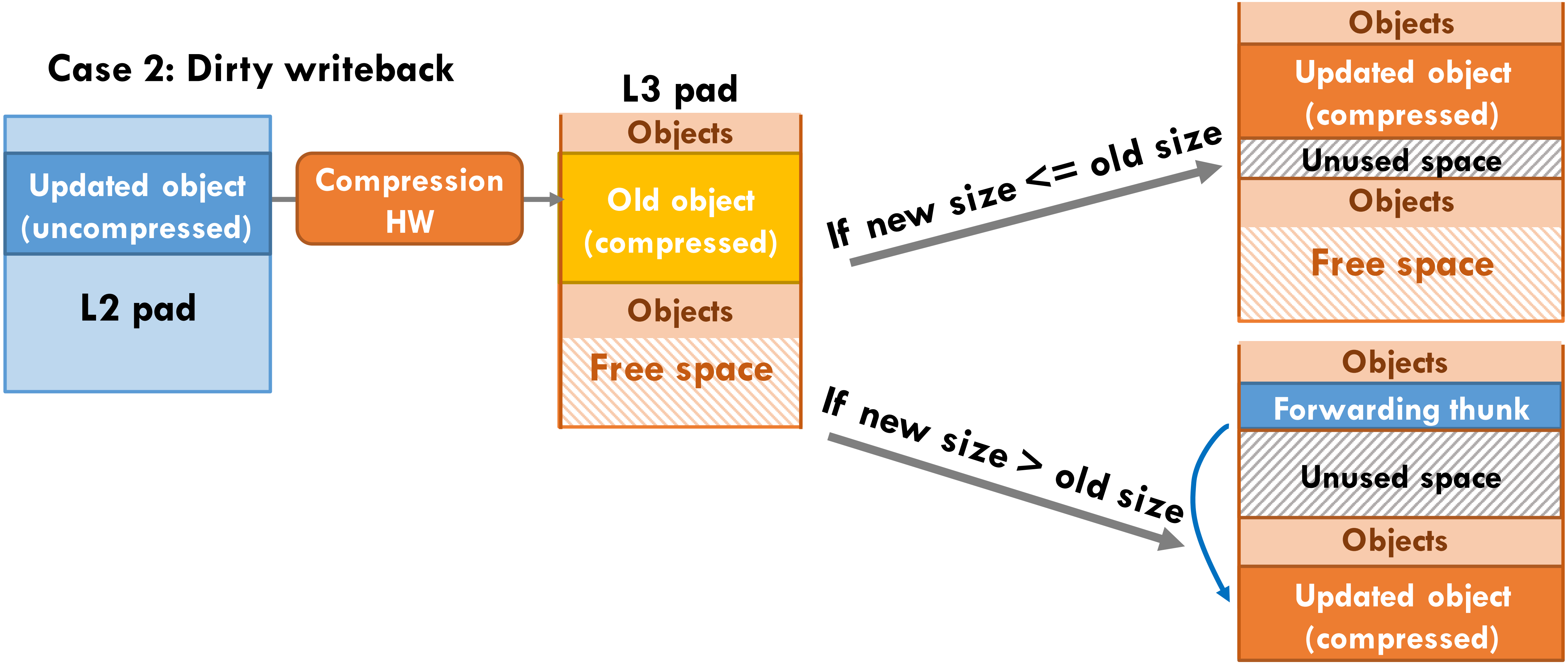
- ☐ Objects are compressed during bulk object evictions



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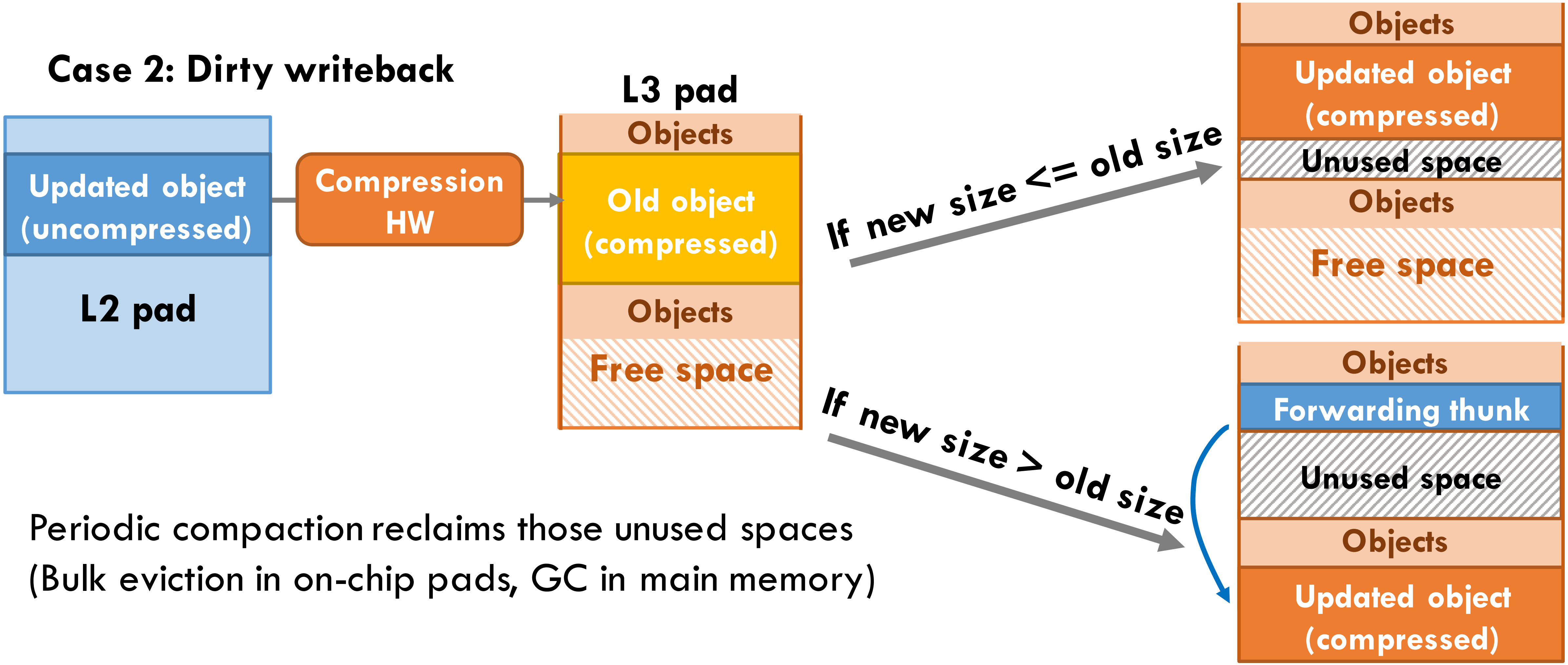

Periodic compaction reclaims those unused spaces
(Bulk eviction in on-chip pads, GC in main memory)

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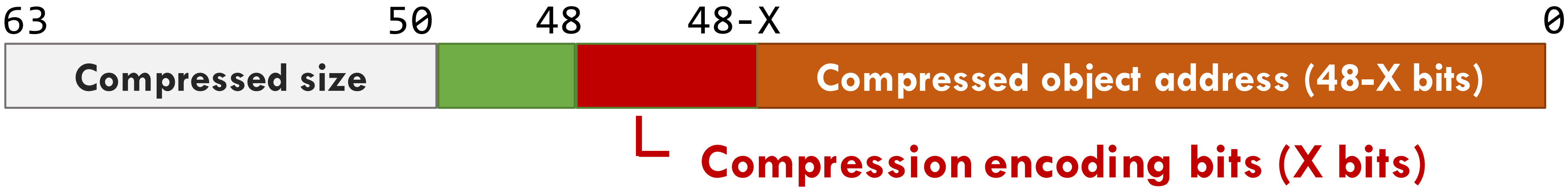

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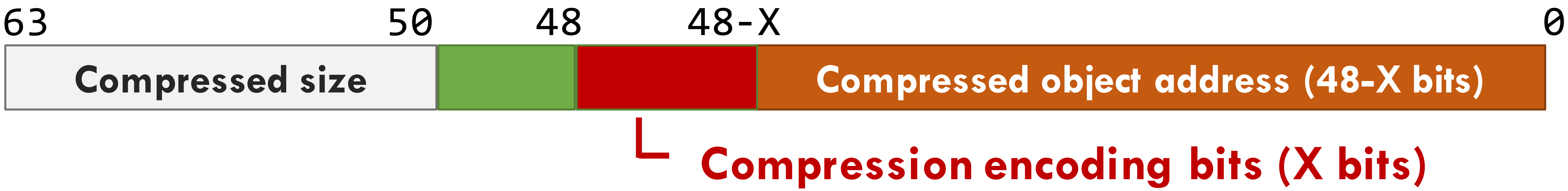

- Zippads thus knows how to locate and what decompression algorithm to use when accessing compressed objects with pointers

COCO: Cross-object-compression algorithm

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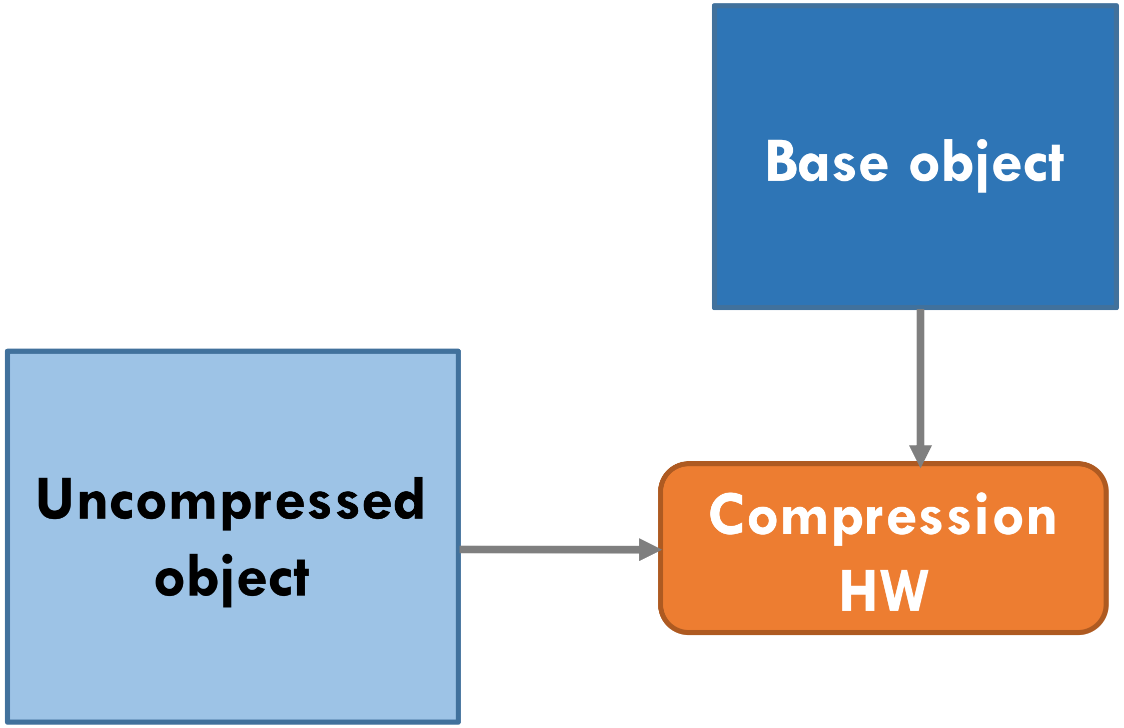

Base object

Uncompressed object

Compression HW

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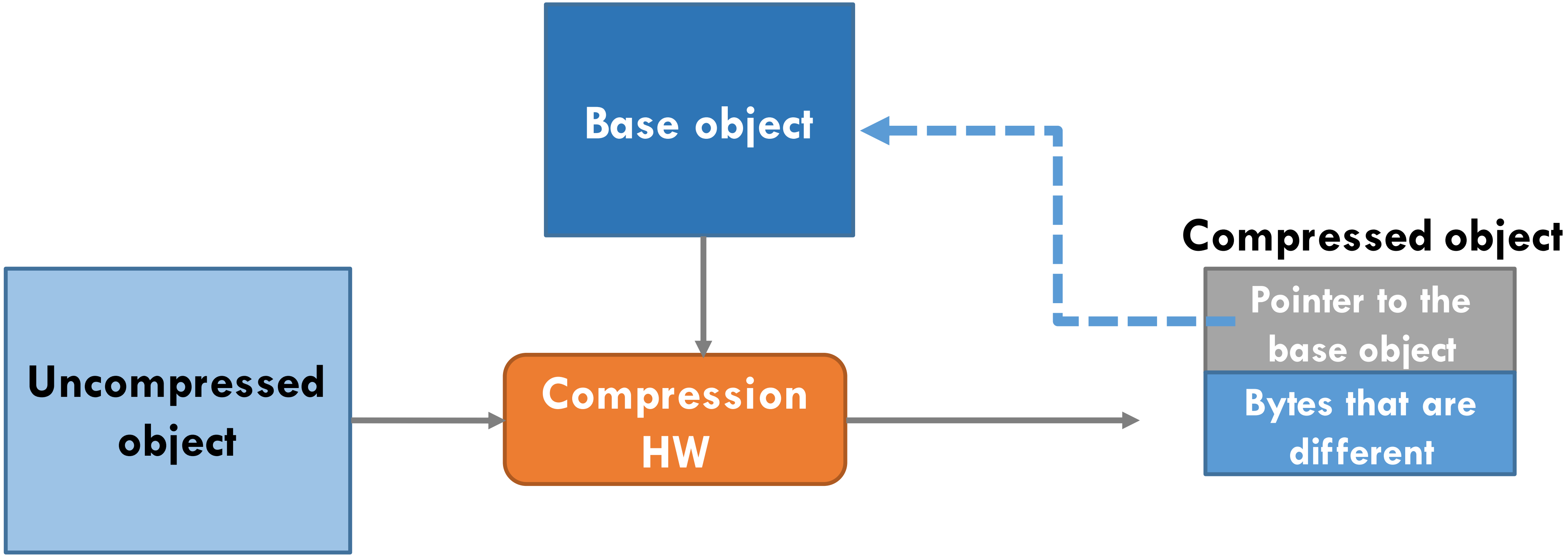

Base object

Uncompressed object

Compression HW

Compressed object

Pointer to the base object

Bytes that are different

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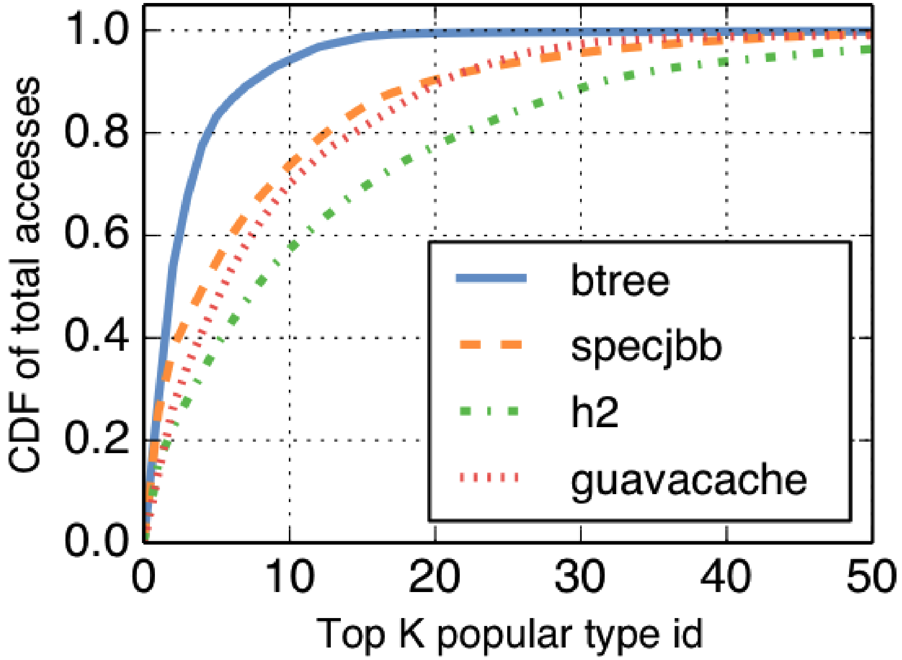
- Caching base objects avoids extra latency and bandwidth to fetch them

- A small (8KB) base object cache works well
  - Few types account for most accesses



See paper for additional features and details

- Compressing large objects with subobjects and allocate-on-access
- COCO compression/decompression circuit RTL implementation details
- Details on integrating Zippads and COCO
- Discussion on using COCO with conventional memory hierarchies

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- Workloads: 8 Java apps with large memory footprint from different domains

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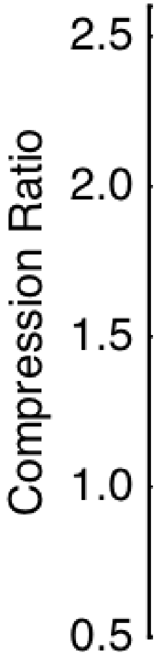

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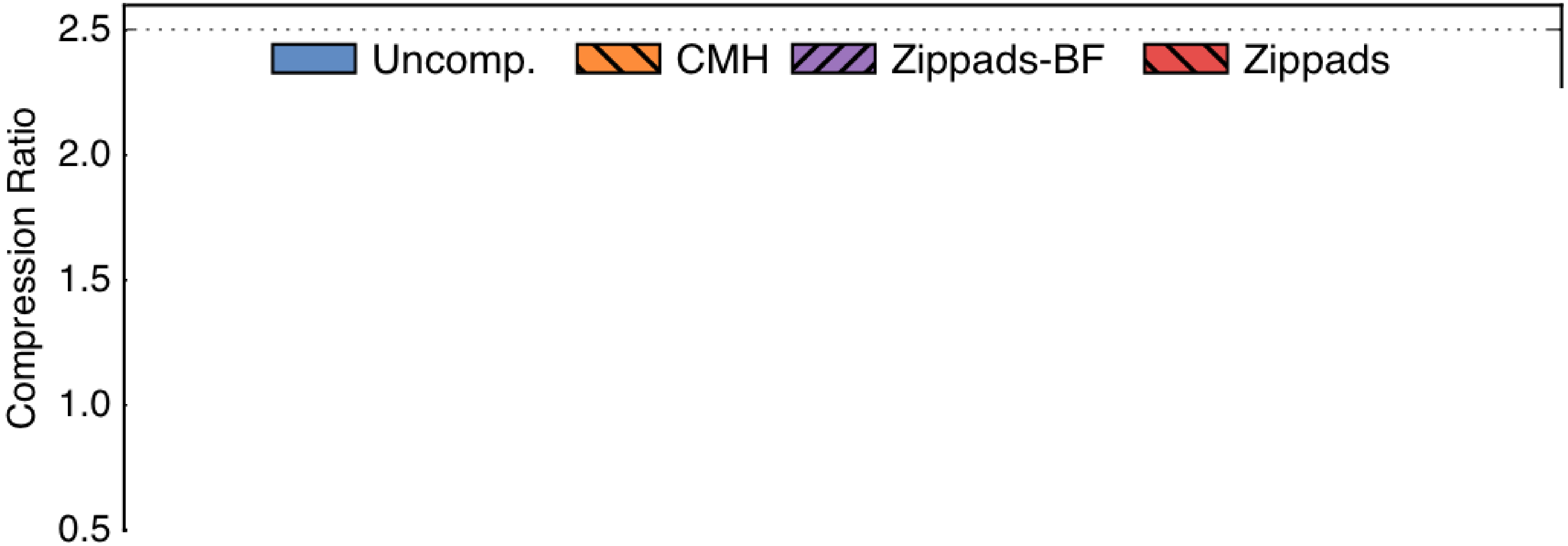

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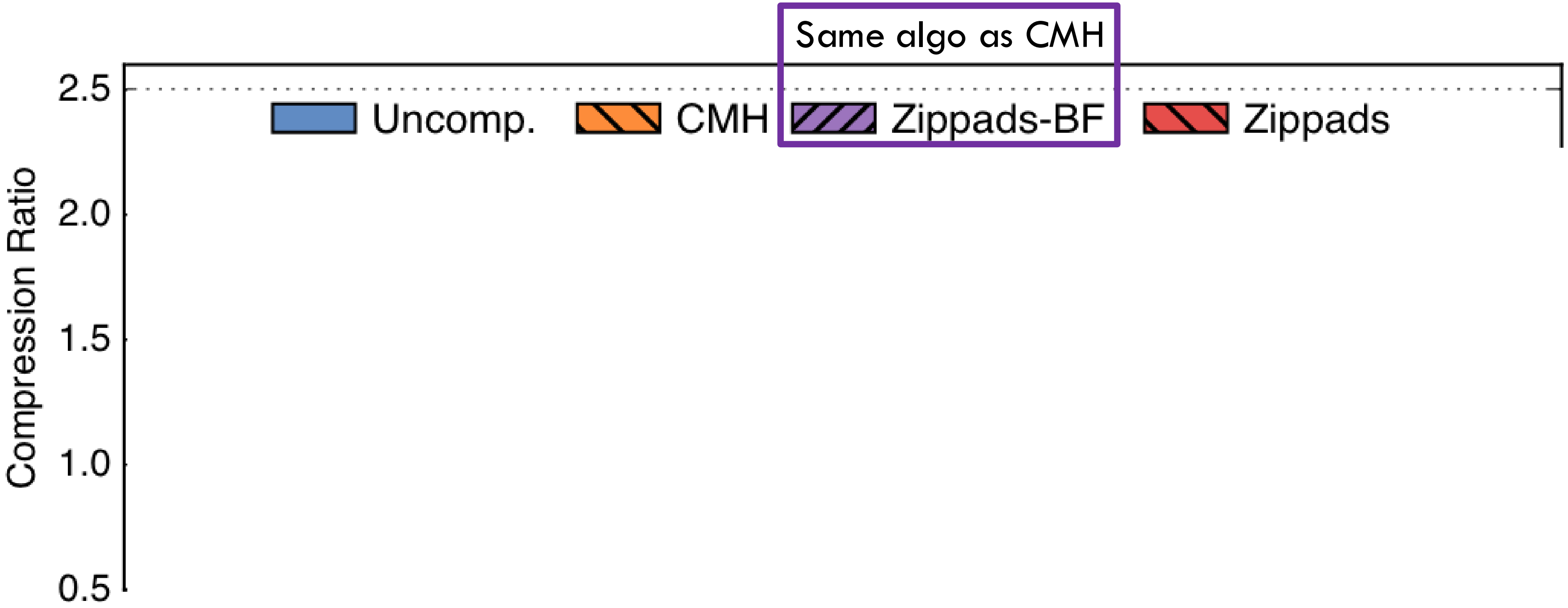

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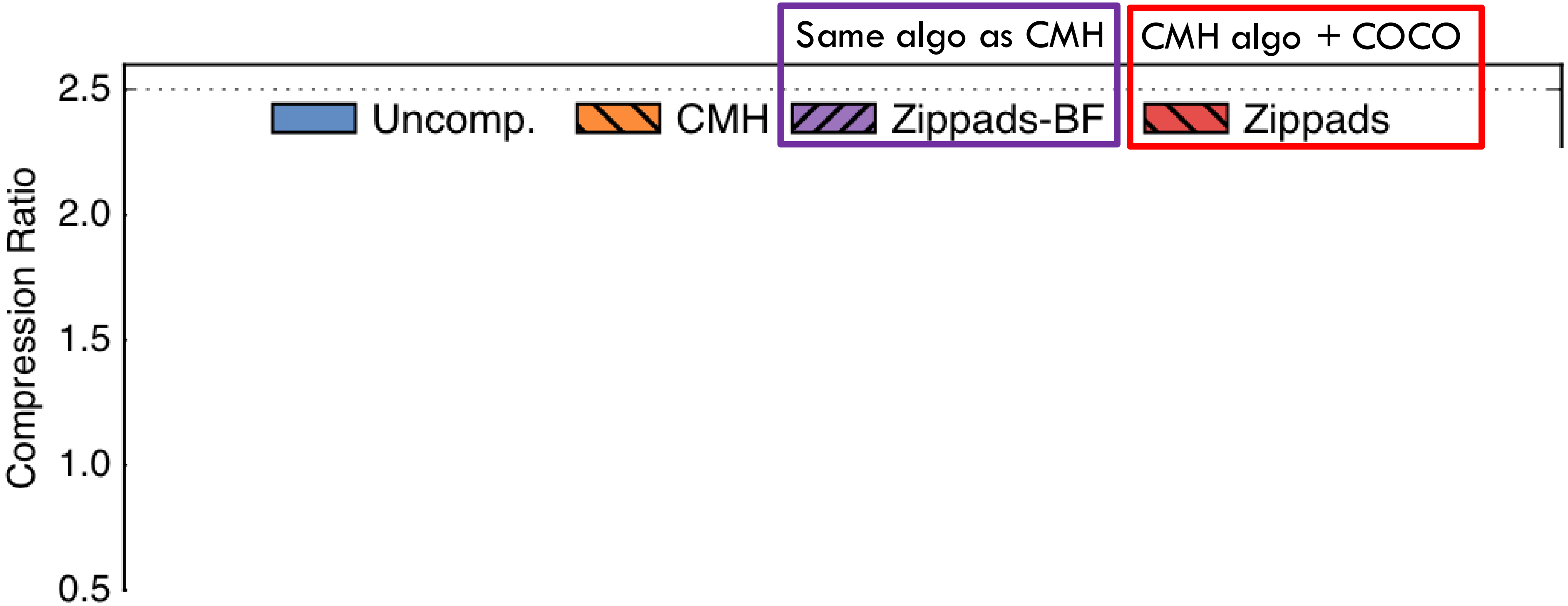

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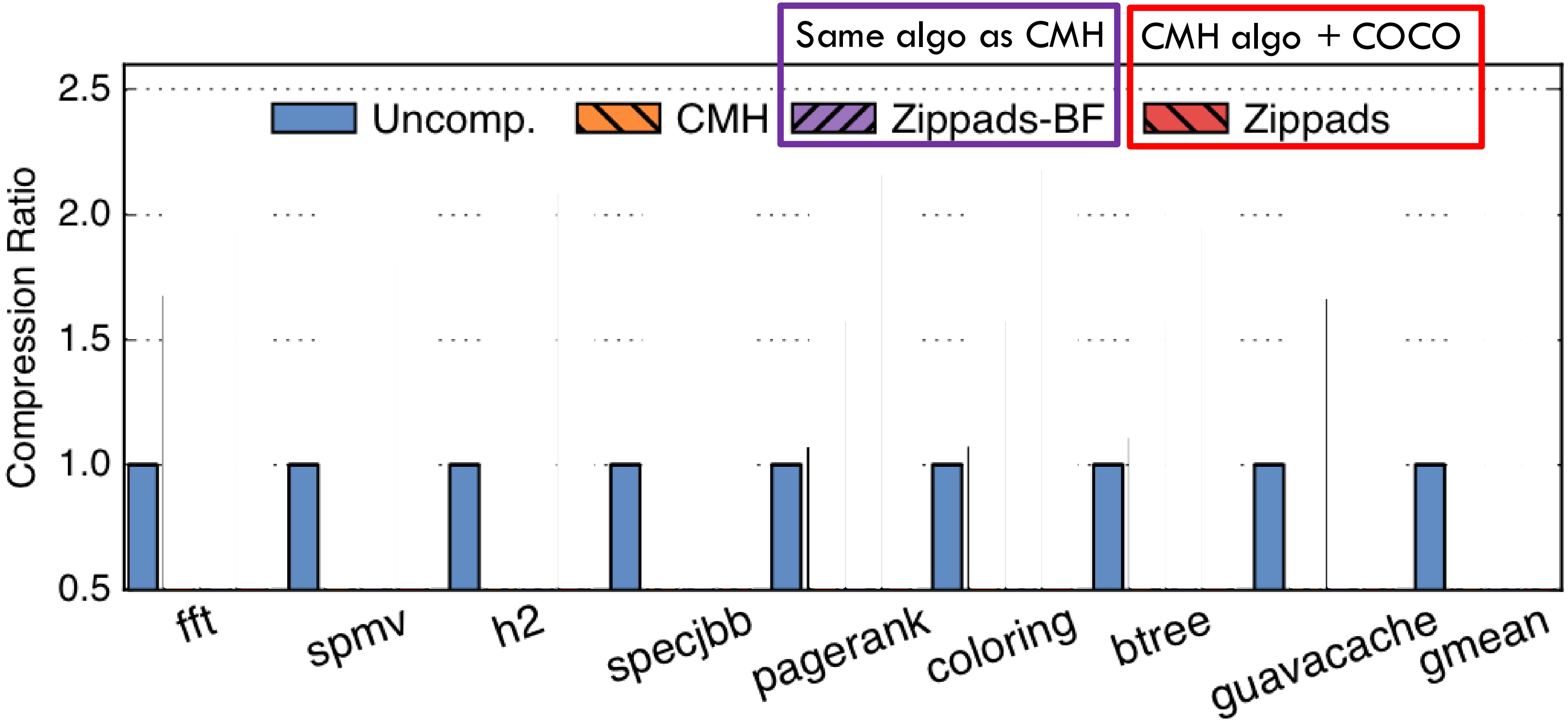

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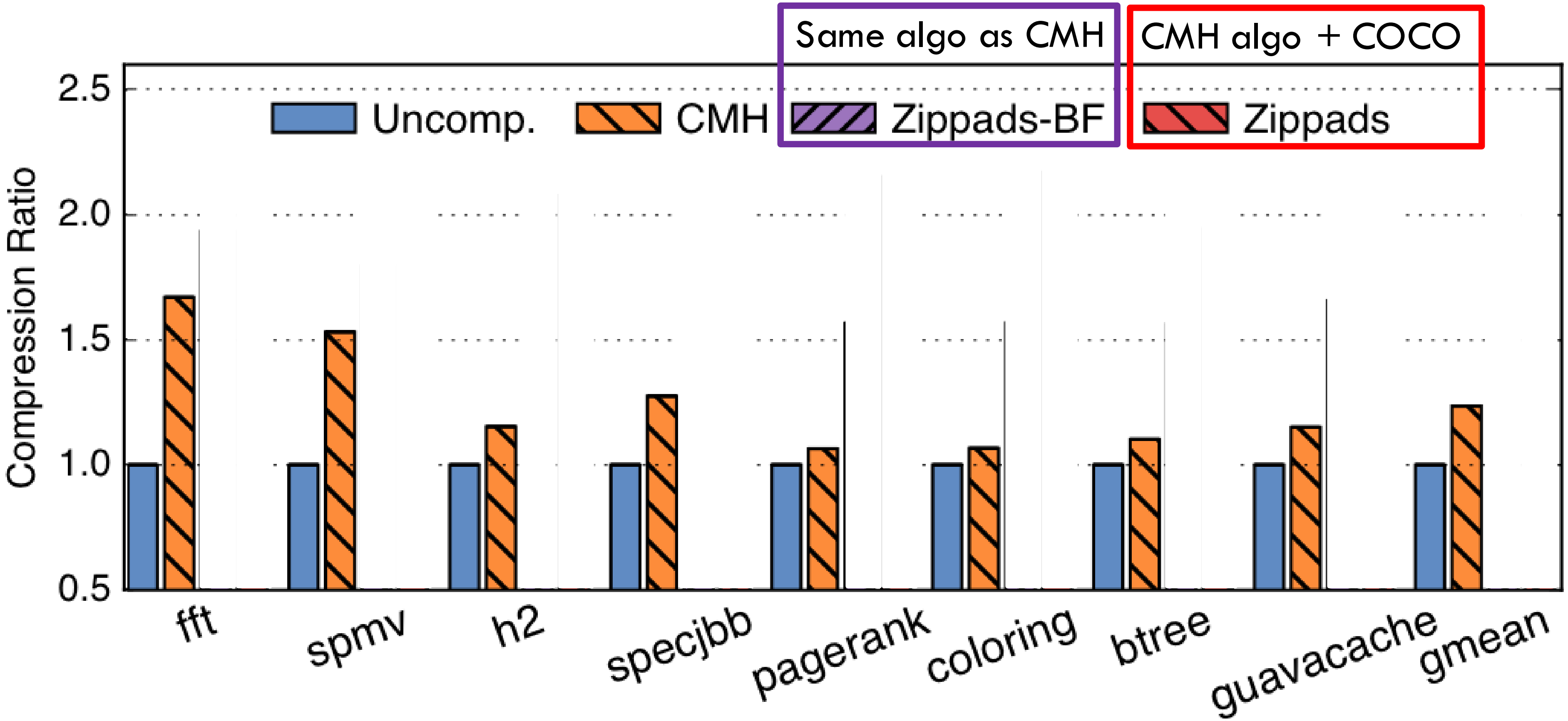

Only 24% better than Uncomp.

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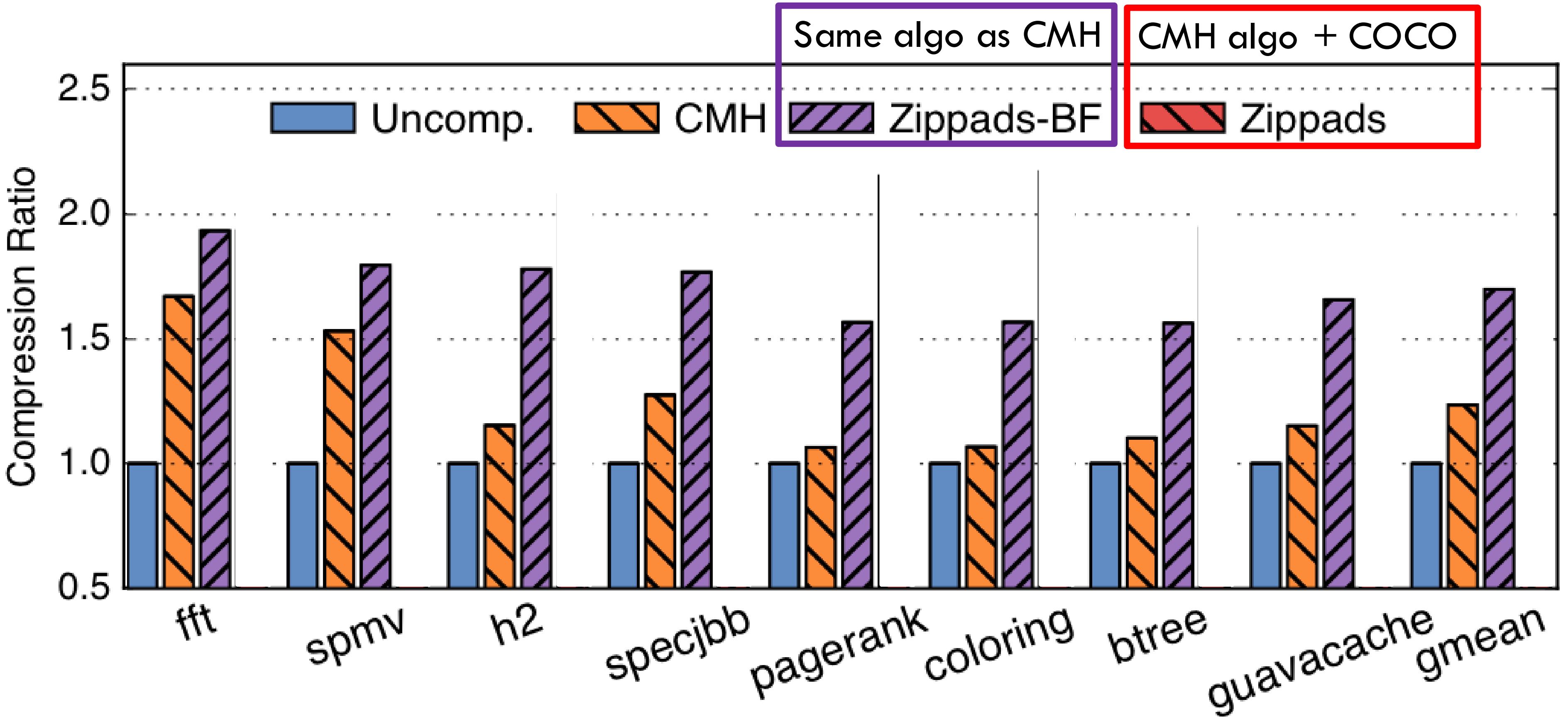

70% better

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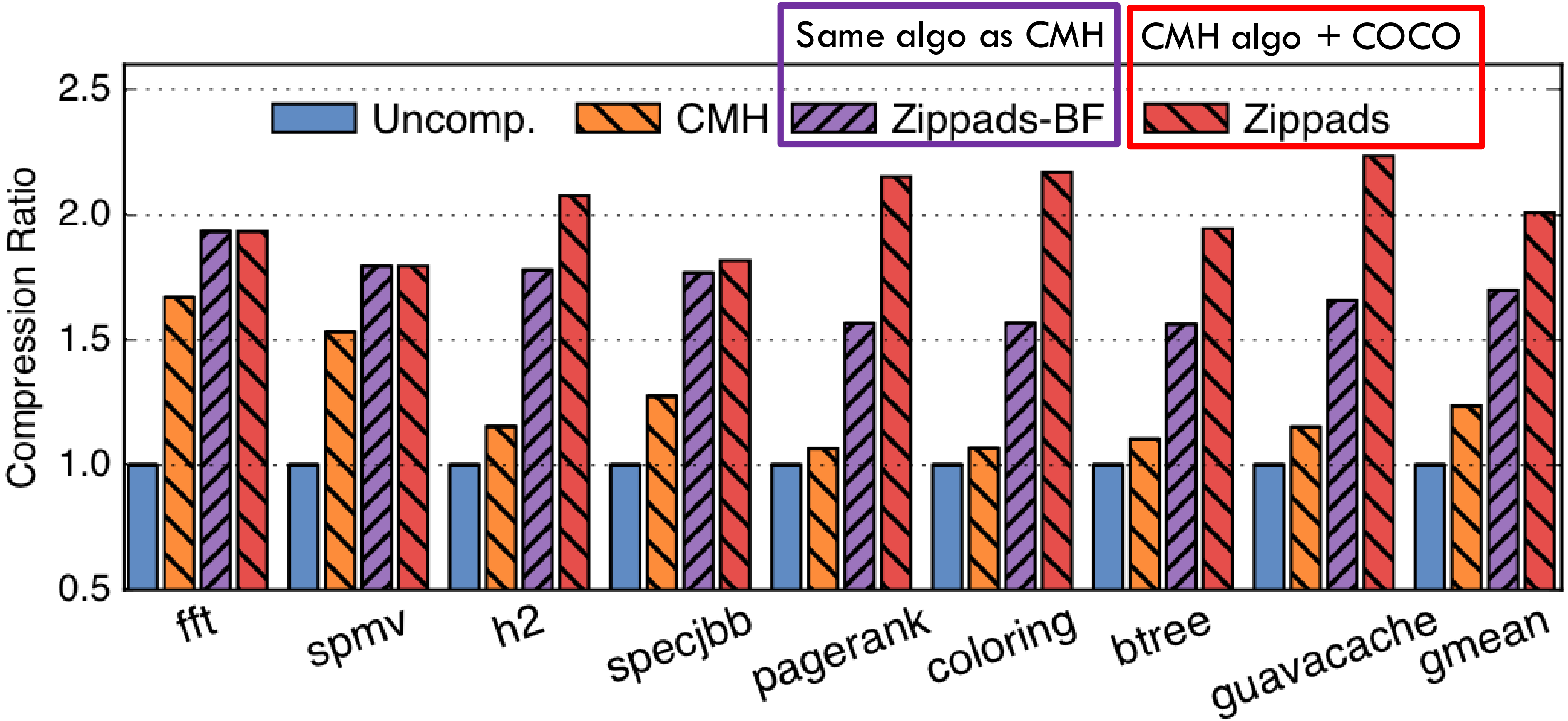

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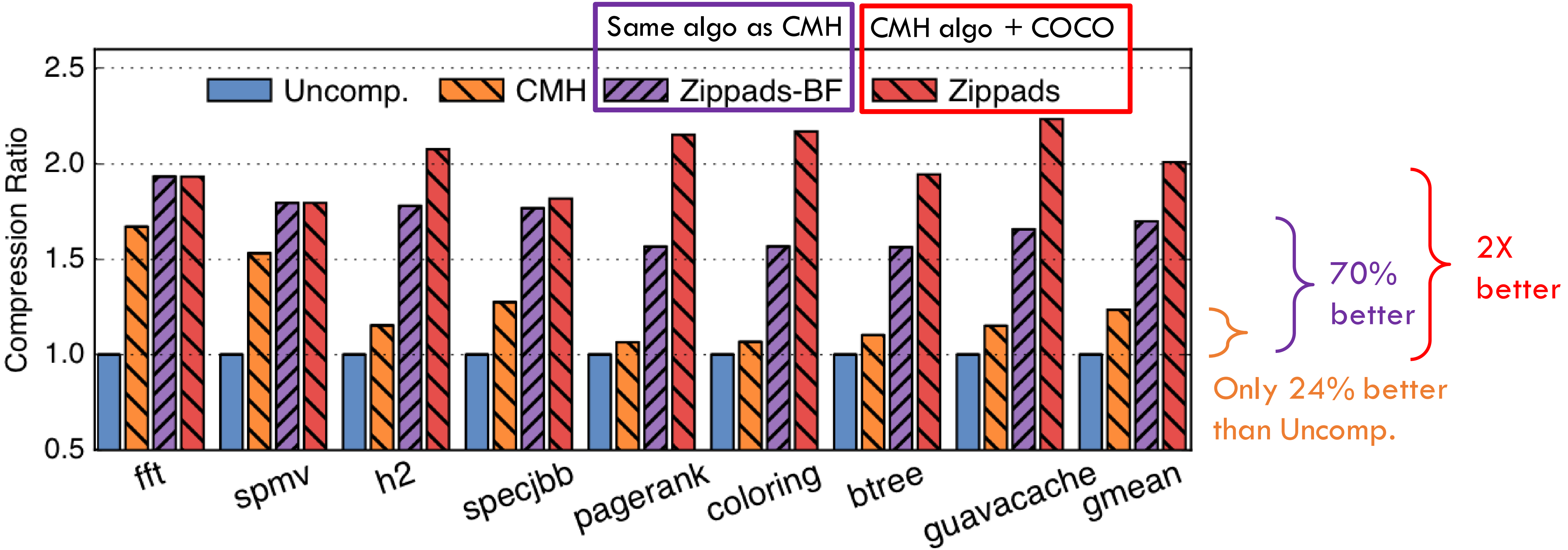

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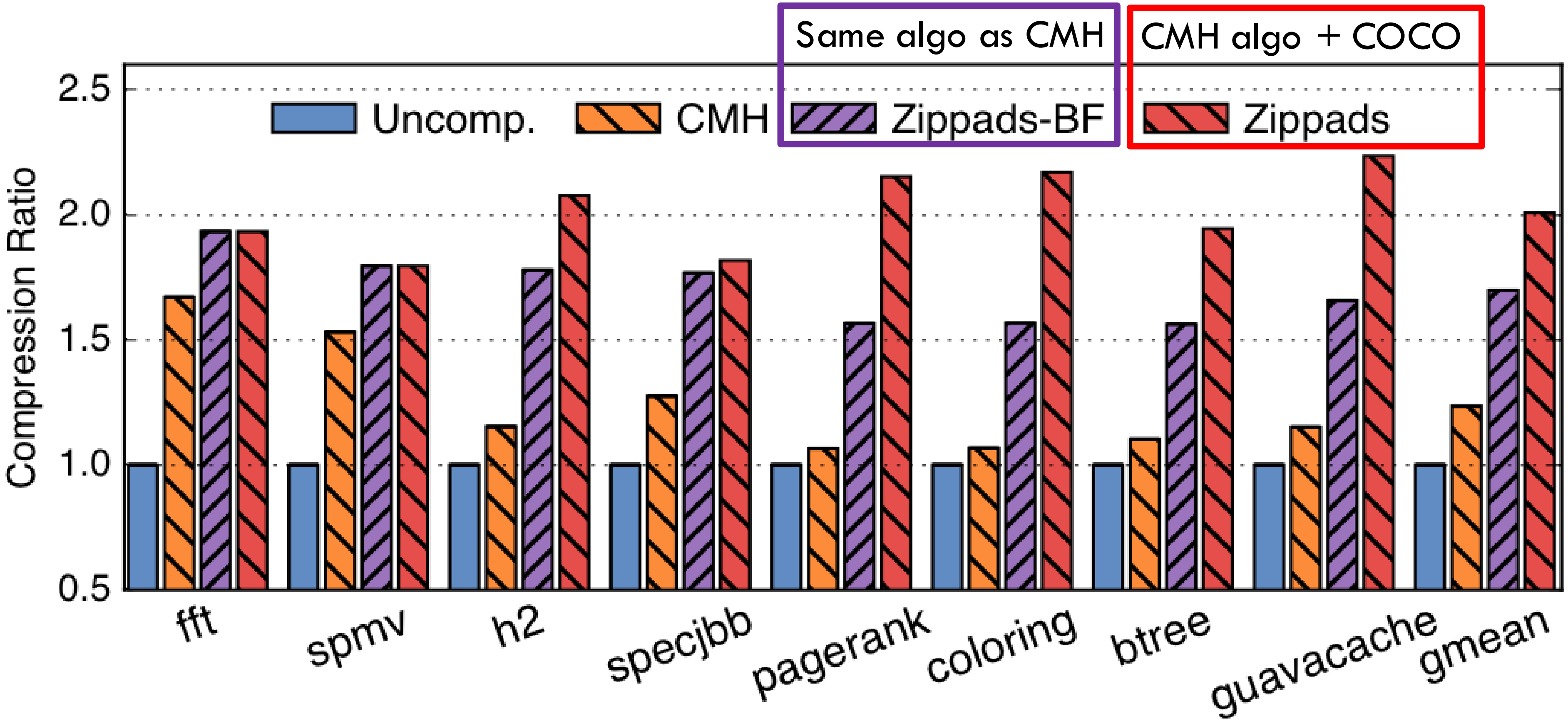

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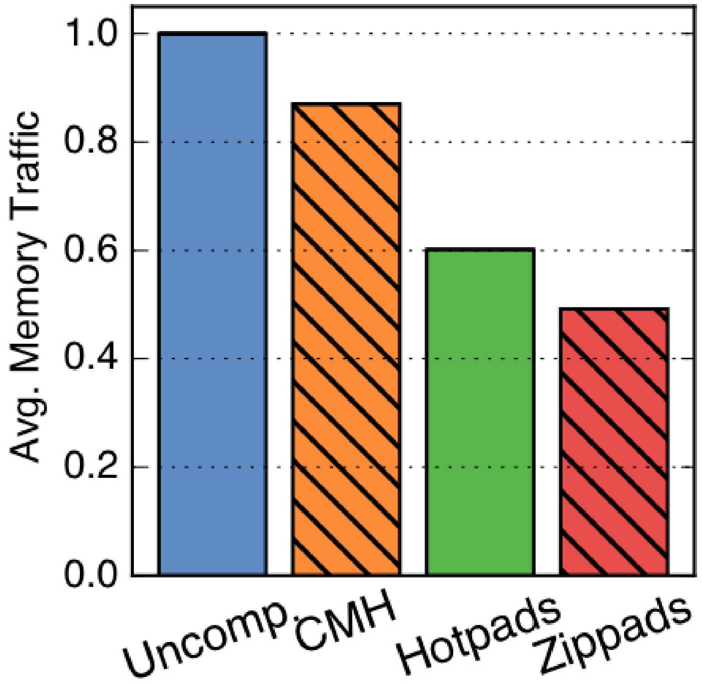

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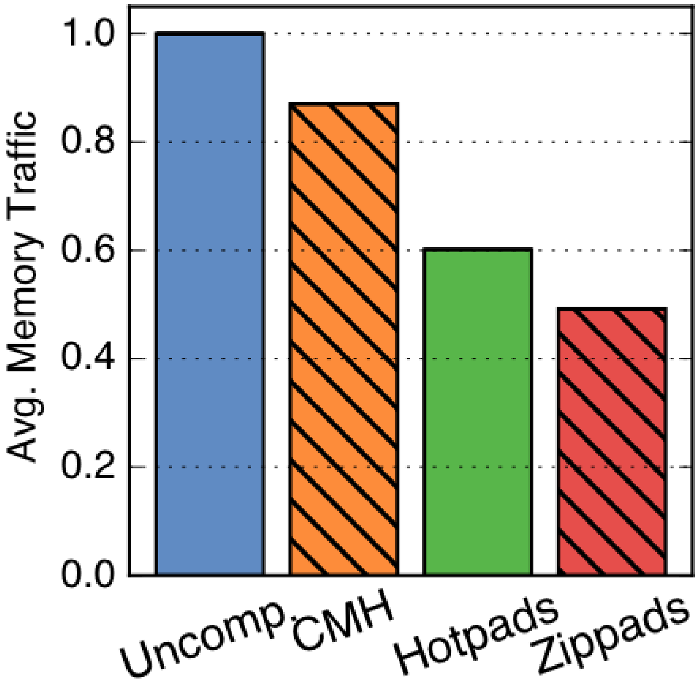

Lower is better

1. CMH reduces traffic **by 15%** with data compression

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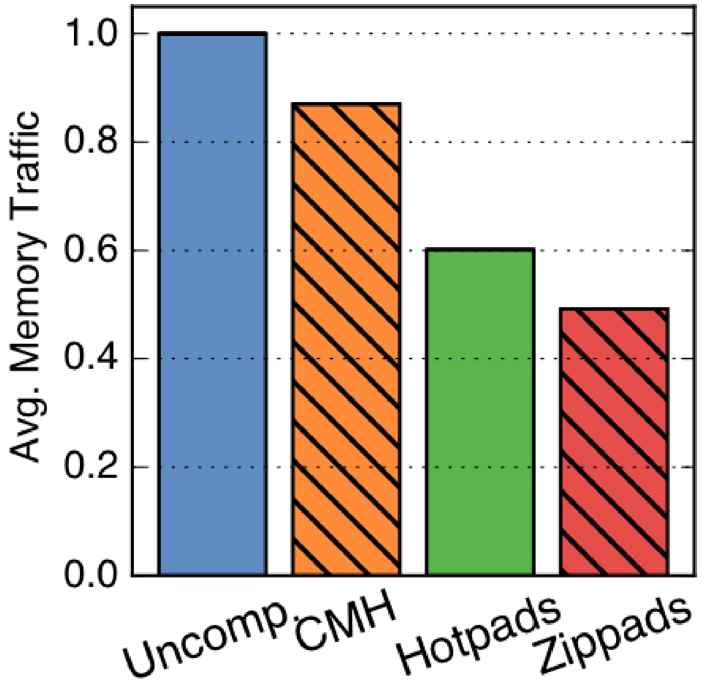

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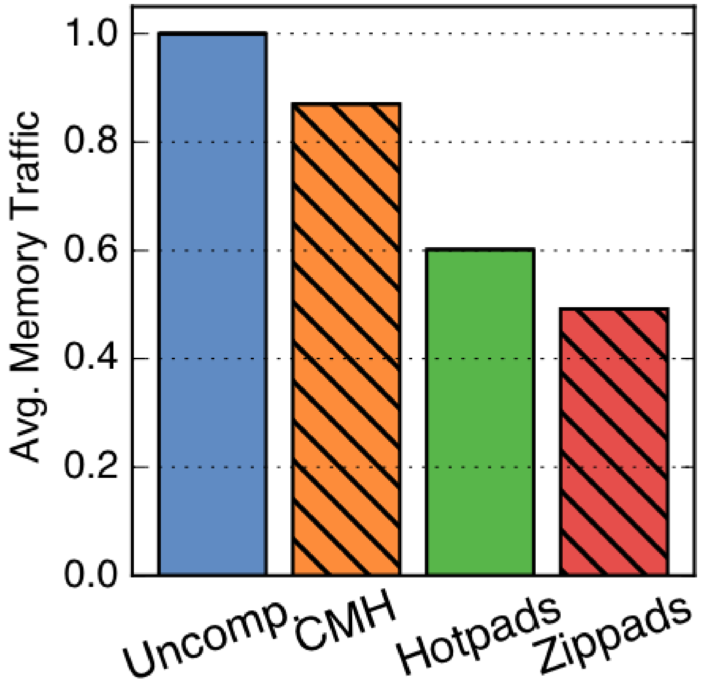

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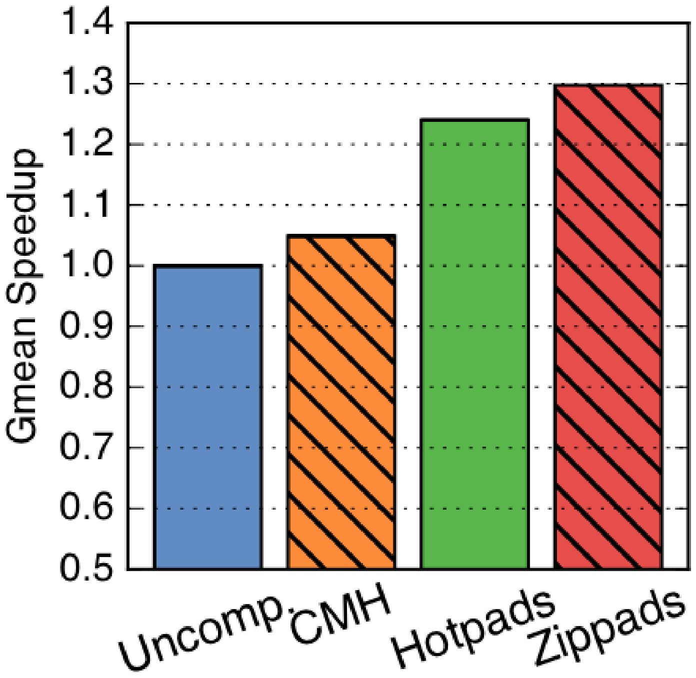
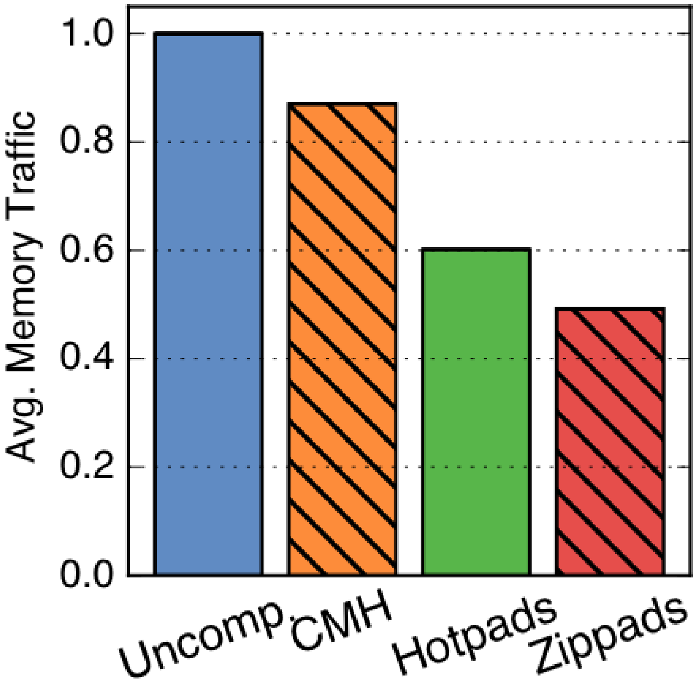


Higher is better



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Similar trend in performance: Zippads is **24%** faster than CMH; **30%** faster than Uncomp.

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🟦 Uncomp. ▧ CMH 🟩 Hotpads ▨ Zippads-BF ▧ Zippads

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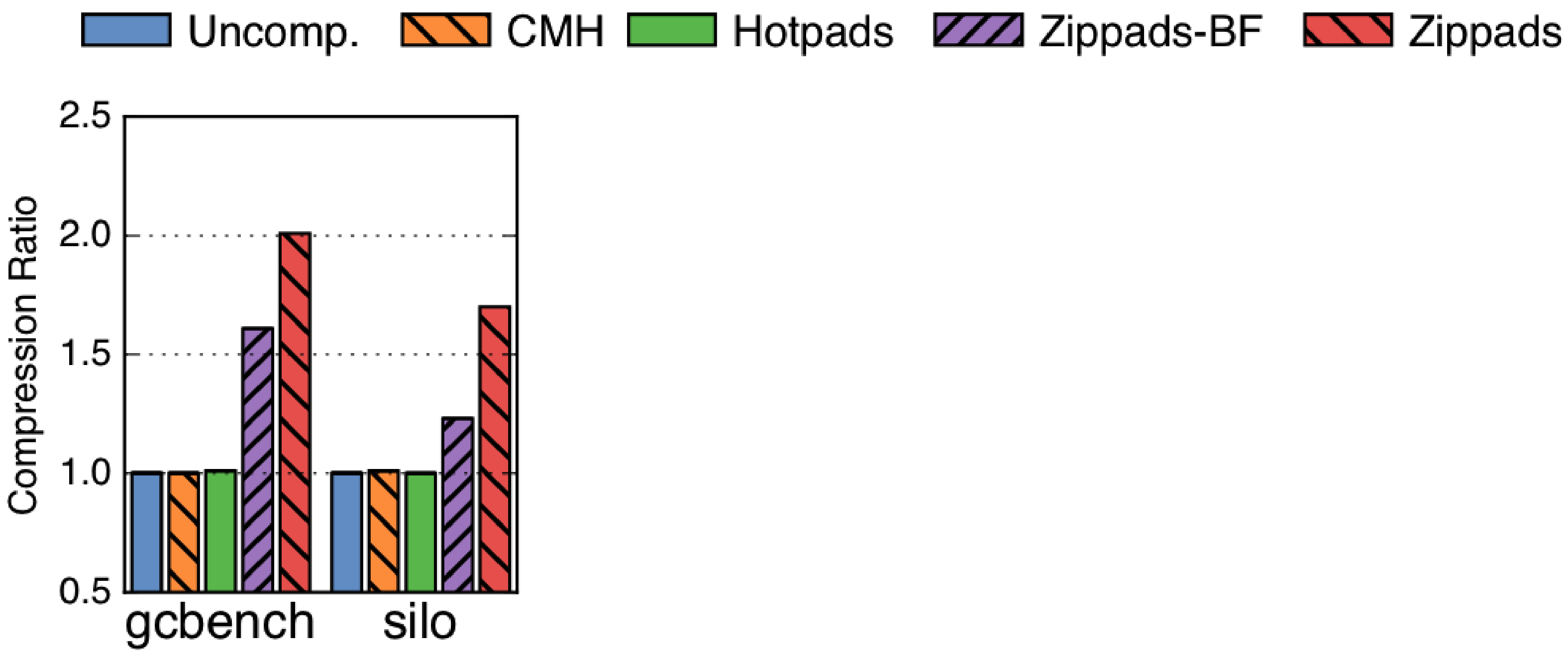

Zippads again works much better than CMH in compressing memory footprint

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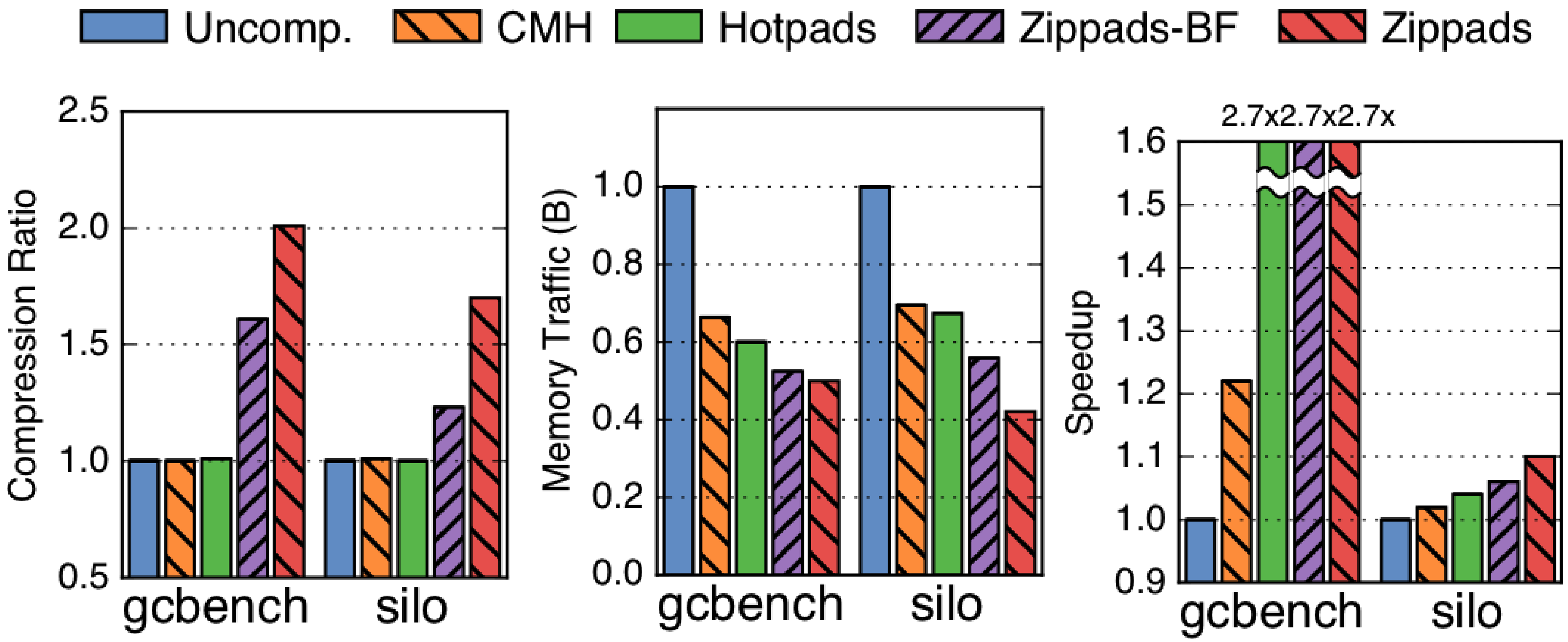

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Zippads improves both memory traffic and performance the most

See paper for more evaluation results

- Zippads hardware storage overhead analysis
- COCO RTL implementation result
- Comparison against CMH with hardware support for memory management
- Zippads analysis
  - Base object cache size sensitivity study
  - Overflow frequency

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Thanks! Questions?

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