FFCCD: Fence-Free Crash-Consistent Concurrent Defragmentation for Persistent Memory

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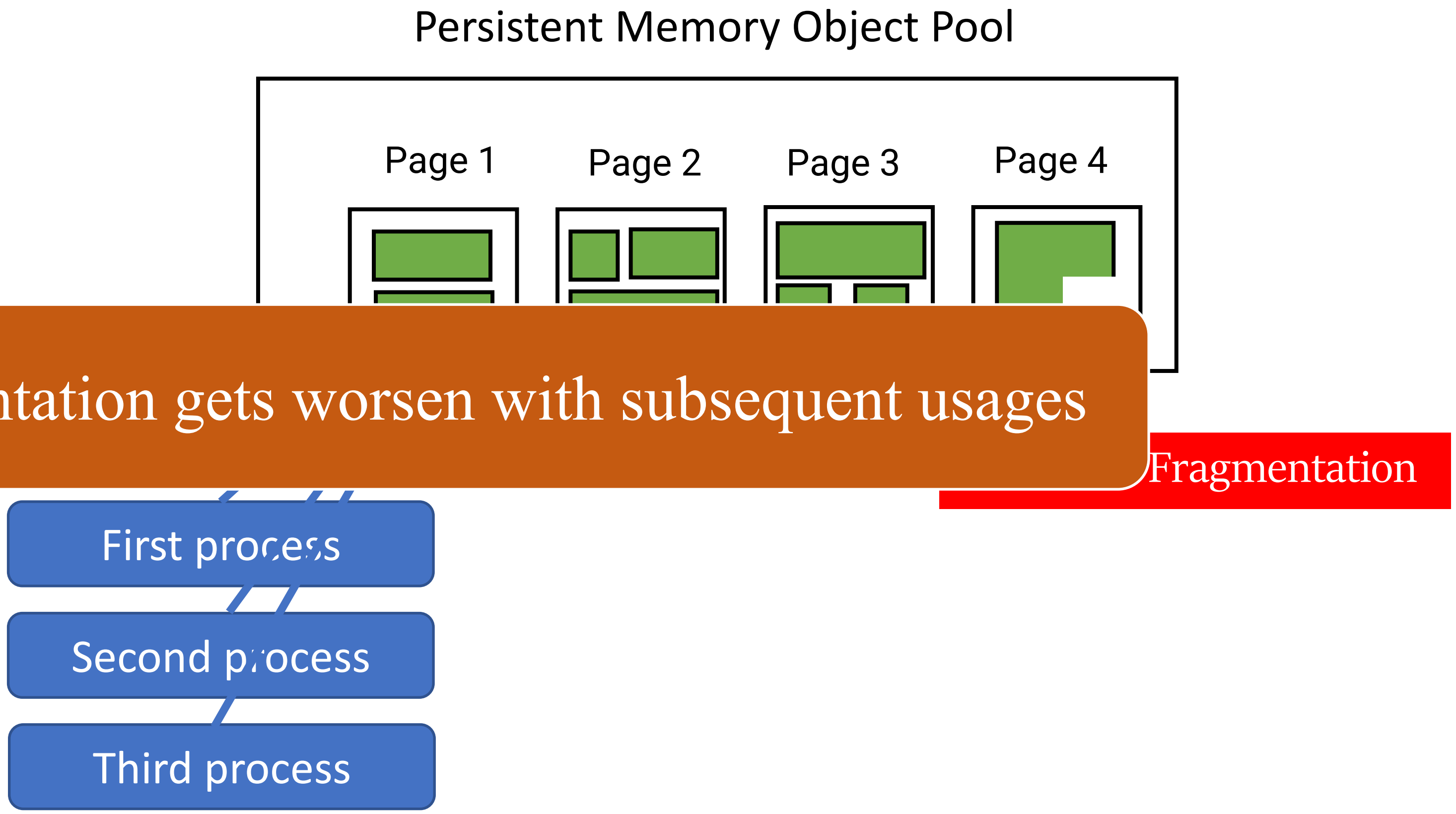
Persistent Fragmentation

Intel Persistent M

- Higher Density
- Byte-addressable Persistence
- DRAM-like Performance

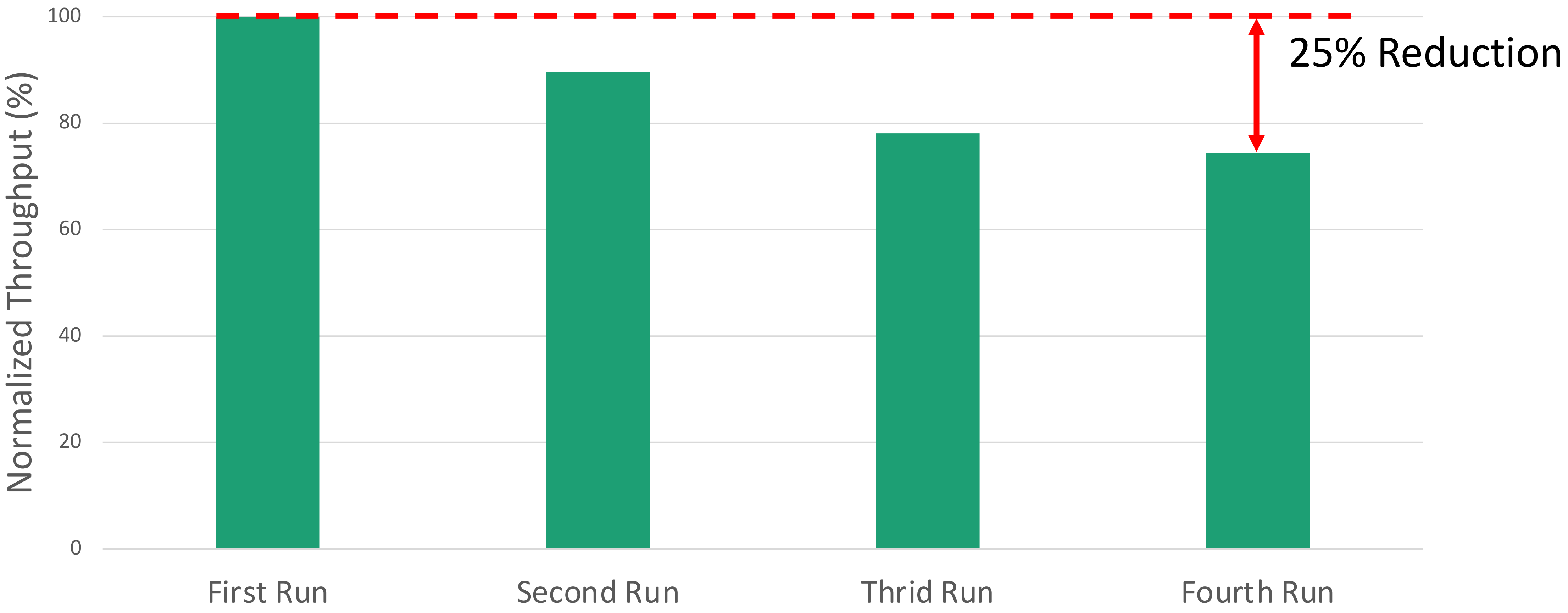


Persistent fragmentation gets worsen with subsequent usages

🟩 Live object

Performance Degradation from Persistent Fragmentation

Redis throughput for 2M insertions and 1M deletions

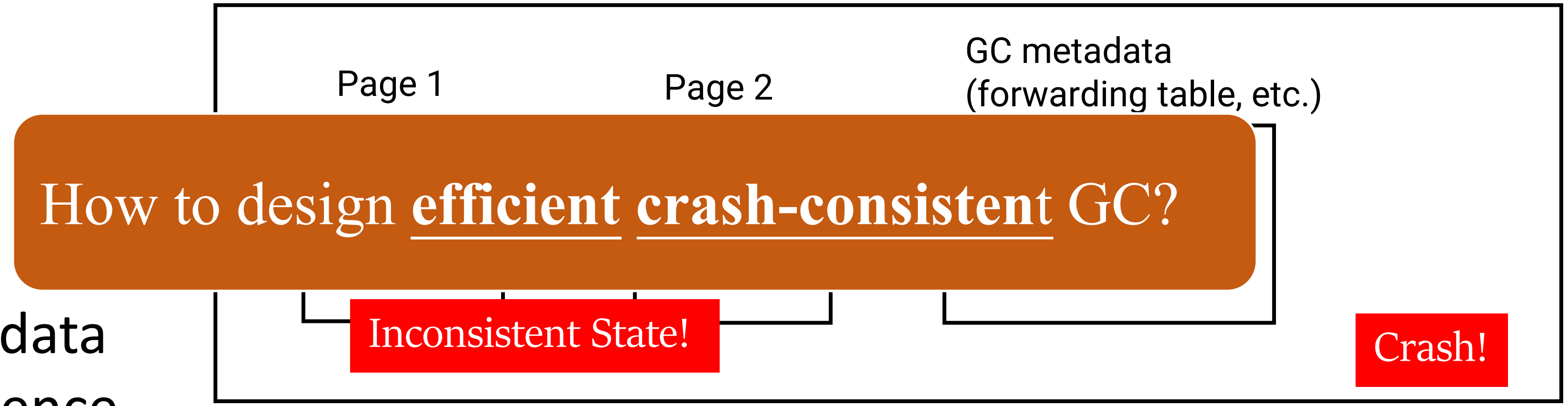


Garbage Collection (GC)

Garbage Collection Steps

1) Marking
2) Summary
3) Compaction
    - Relocation
    - Update metadata
    - Update Reference

Persistent Memory Object Pool



How to design **efficient** **crash-consistent** GC?

🟩 Live object → Pointer

Contributions

- First to analyze PM fragmentation systematically
  - Identify sfences as the key performance bottleneck
  - Analyze post-crash states to explore efficiency opportunities

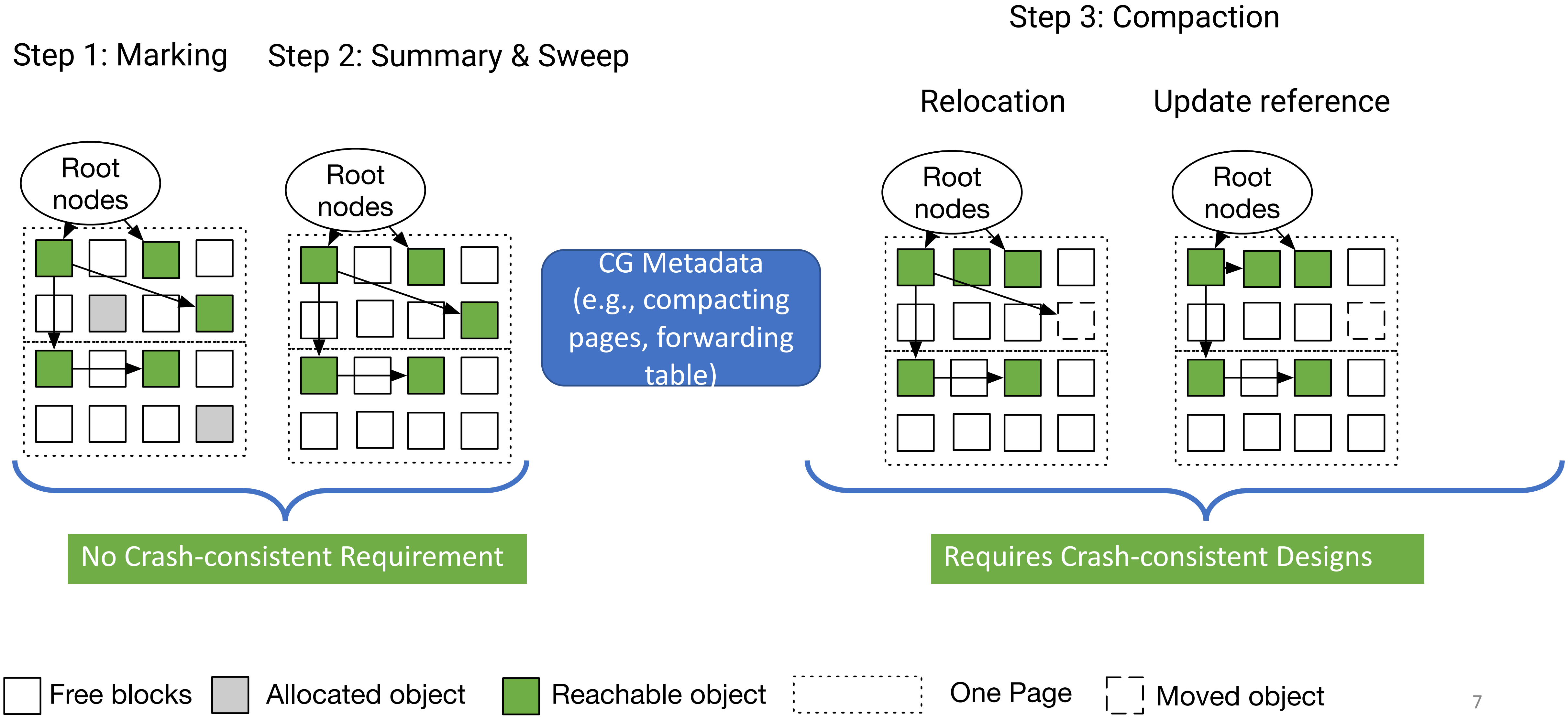
- Design multiple concurrent GC solutions
  - Pure software single-fence crash-consistent design (SFCCD)
  - Architectural support for fence-free crash-consistent design (FFCCD)

- We evaluate designs and show its effectiveness

Agenda

- Motivation
- Background
- Post-crash state exploration
- Architecture design
- Evaluation

Concurrent Garbage Collection



Step 1: Marking

Step 2: Summary & Sweep

Step 3: Compaction

Relocation

Update reference

CG Metadata (e.g., compacting pages, forwarding table)

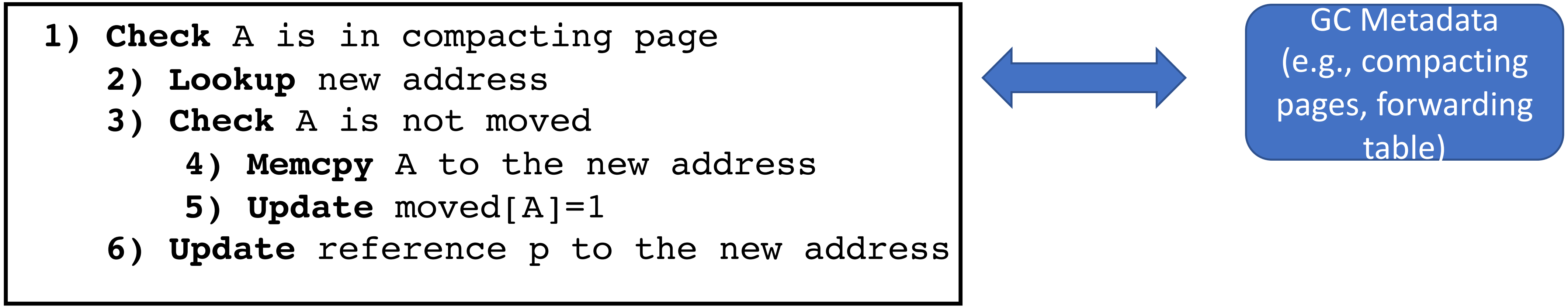
No Crash-consistent Requirement

Requires Crash-consistent Designs

☐ Free blocks ▨ Allocated object 🟩 Reachable object ⬚ One Page ⬚ Moved object

Concurrent Compaction: Read Barrier

```
p->first = input  //p points to object A
<read barrier>
```



```
1) Check A is in compacting page
    2) Lookup new address
    3) Check A is not moved
        4) Memcpy A to the new address
        5) Update moved[A]=1
    6) Update reference p to the new address
```

GC Metadata (e.g., compacting pages, forwarding table)

Crash-consistent Concurrent Compaction Baseline[1]

```
p->first = input  //p points to object A
<read barrier>
 1) Check A is in compacting page
    2) Lookup new address
    3) Check A is not moved
       4) Memcpy A to the new address
       sfence()
       5) Update moved[A]=1
       clwb(moved[A]);sfence()
    6) Update reference p to the new address
```

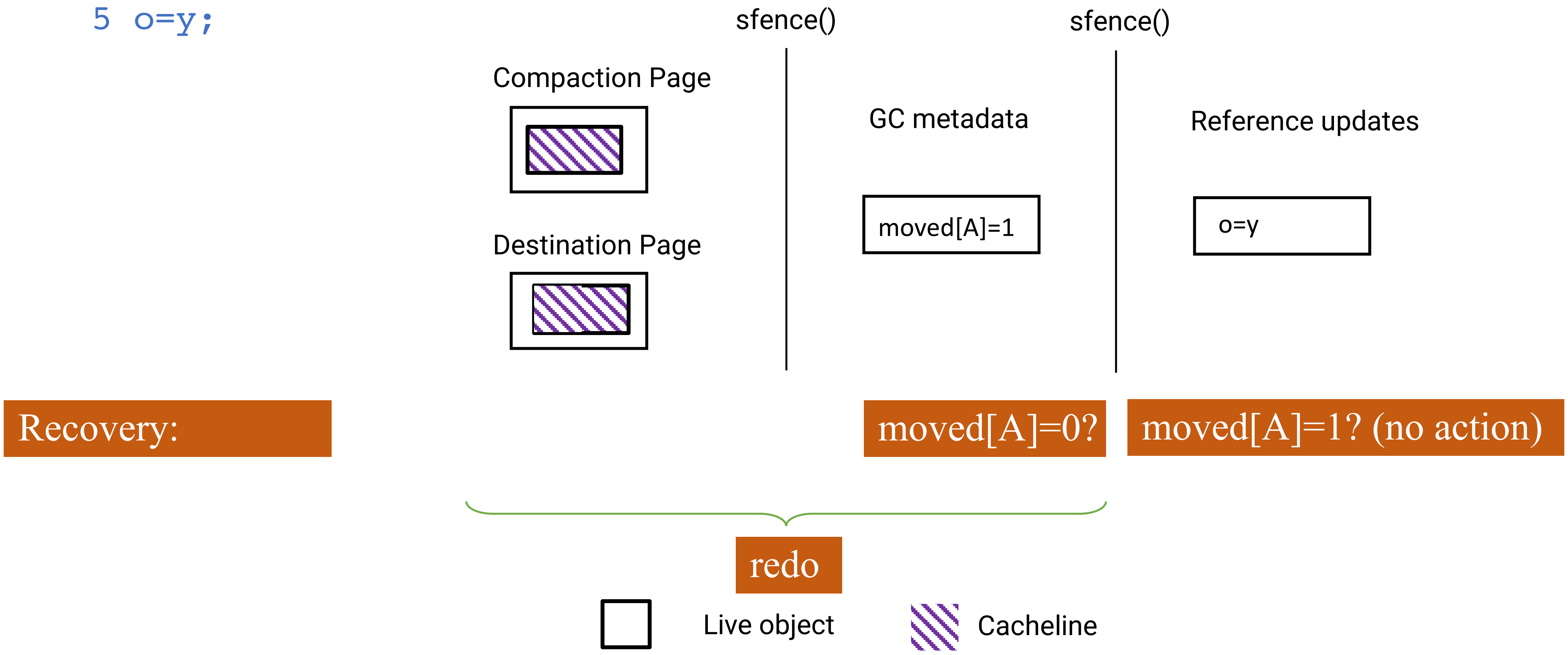
Persist GC metadata before compaction
(e.g., compacting pages, forwarding table)

Crash-consistency relocation incurs about 50% overhead!

[1] Mingyu Wu, et al. Espresso: brewing java for more non-volatility with non- volatile memory. ASPLOS 2018

Baseline Design

```
memcpy_nodrain(y,x,sizeof(A))
sfence();
moved[A]=1;
clwb(moved[A]);sfence();
o=y;
```



sfence()

sfence()

Compaction Page

Destination Page

GC metadata

moved[A]=1

Reference updates

o=y

Recovery:

moved[A]=0?

moved[A]=1? (no action)

redo

☐ Live object

▨ Cacheline

Can we remove the first sfence?

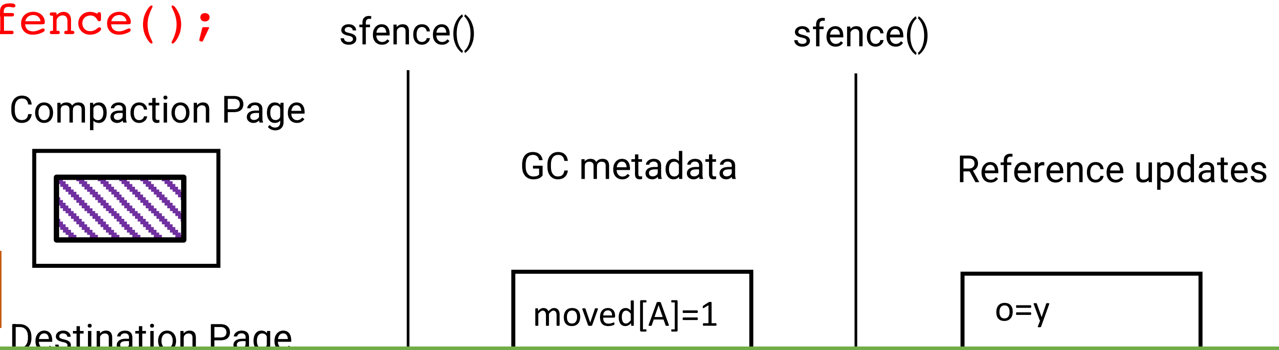
`memcpy_nodrain(y,x,sizeof(A))`

~~`sfence();`~~

`moved[A]=1;`

`clwb(moved[A]);sfence();`

`o=y;`



Post-crash states

Same?

Single-fence solution

Recovery: compare values with memcpy source for objects without reference update

Recovery:

Comparision Results	Recovery steps
Same	set moved[A]=1
Paritally Same	memcpy others & set moved[A]=1
Differ	unset moved[A]=1

oved[A]=1? (no action)

eference is updated? (no action)

☐ Live object ▨ Cacheline

Can we remove the second sfence?

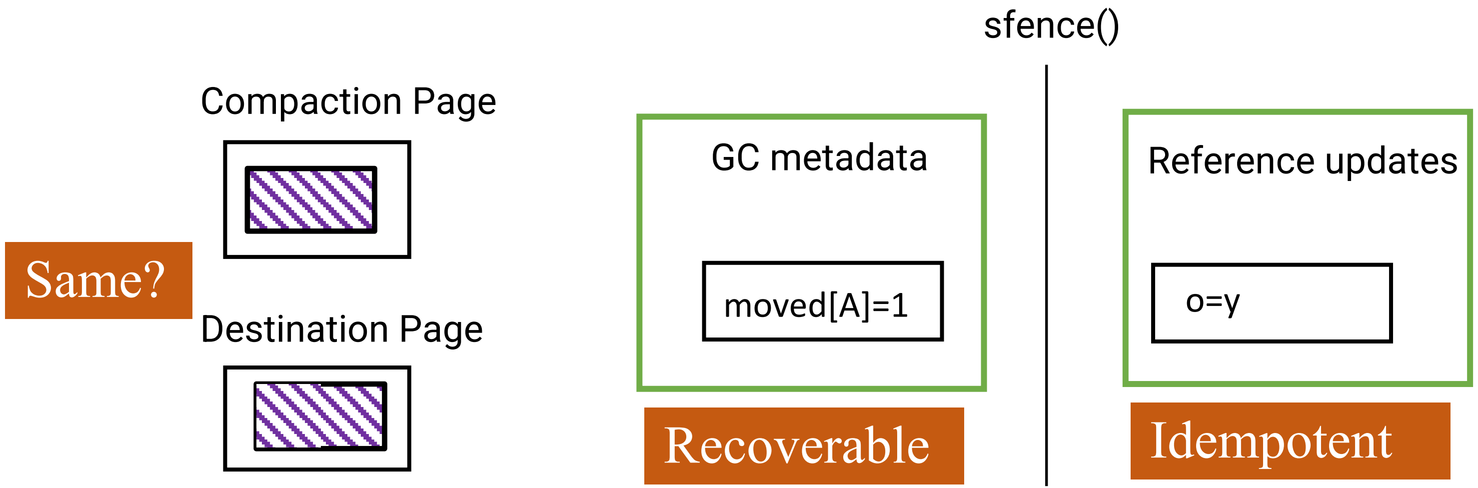
`memcpy_nodrain(y,x,sizeof(A))`

`moved[A]=1;`

~~`clwb(moved[A]);sfence();`~~

`o=y;`

Post-crash states



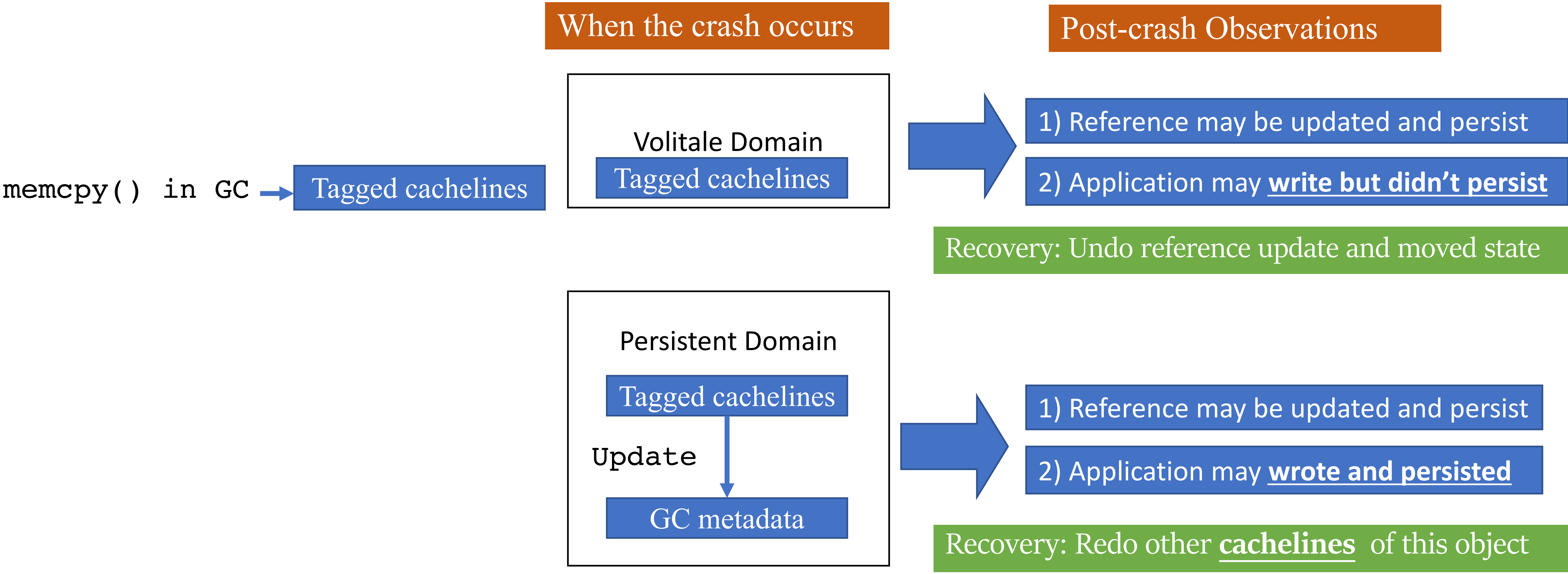
Recovery:

1) **Random**
2) Source
3) **New**

Destination Value for each cacheline	**Recovery steps**
Source	Set moved[A]=1
New	Set moved[A]=1
Random	Redo/undo

☐ Live object ▨ Cacheline

Idea: Track Relocated Cachelines



When the crash occurs

Post-crash Observations

`memcpy() in GC` → Tagged cachelines

Volitale Domain

Tagged cachelines

1) Reference may be updated and persist

2) Application may **write but didn’t persist**

Recovery: Undo reference update and moved state

Persistent Domain

Tagged cachelines

`Update`

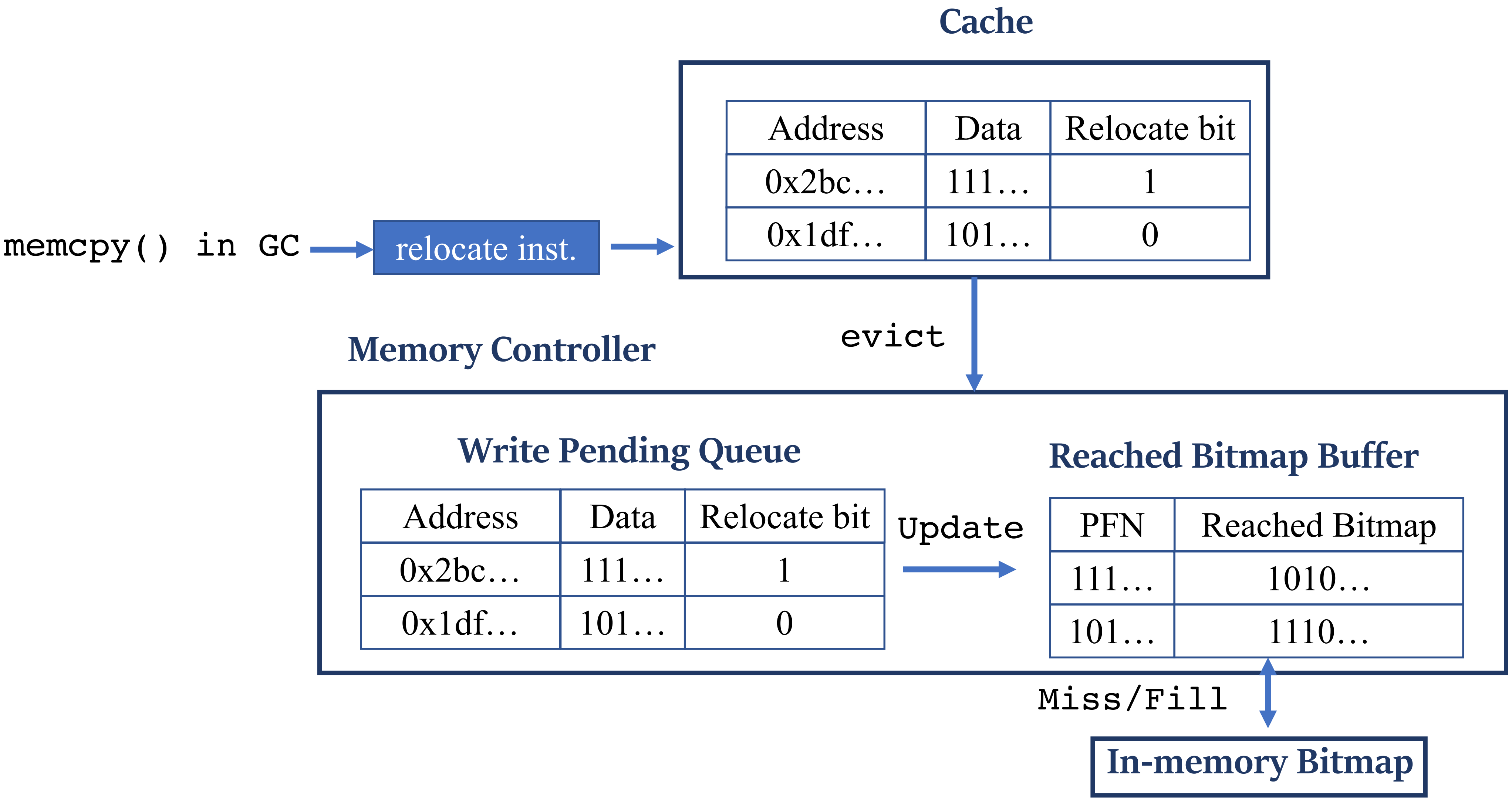
GC metadata

1) Reference may be updated and persist

2) Application may **wrote and persisted**

Recovery: Redo other **cachelines** of this object

Architecture support



Cache

Address	Data	Relocate bit
0x2bc…	111…	1
0x1df…	101…	0

`memcpy() in GC` → relocate inst. →

`evict`

Memory Controller

Write Pending Queue

Address	Data	Relocate bit
0x2bc…	111…	1
0x1df…	101…	0

`Update`

Reached Bitmap Buffer

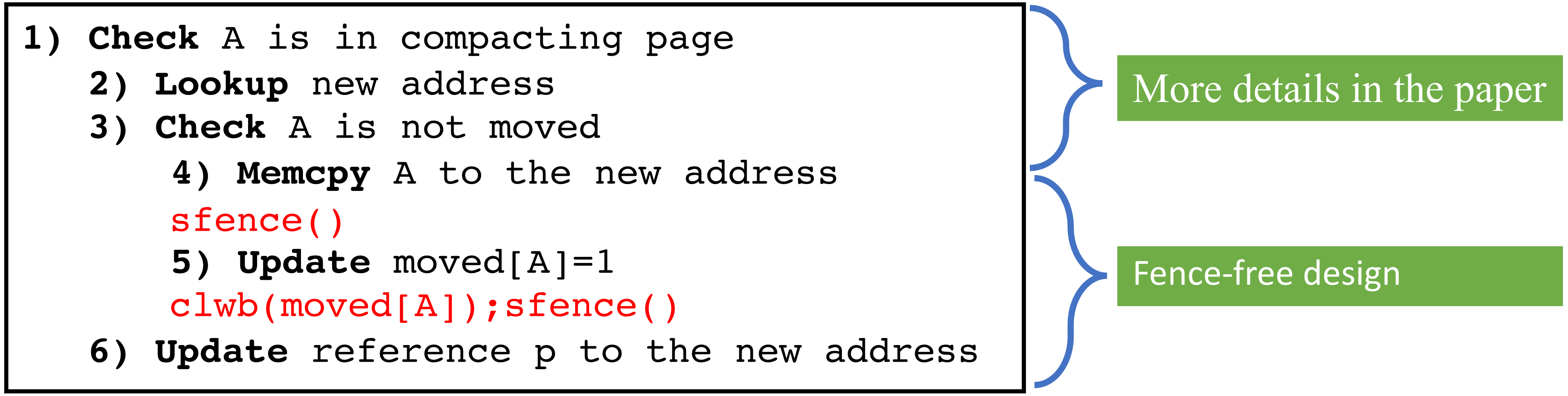
PFN	Reached Bitmap
111…	1010…
101…	1110…

`Miss/Fill`

In-memory Bitmap

Crash-consistent Concurrent Compaction Baseline

```
p->first = input  //p points to object A
<read barrier>
```



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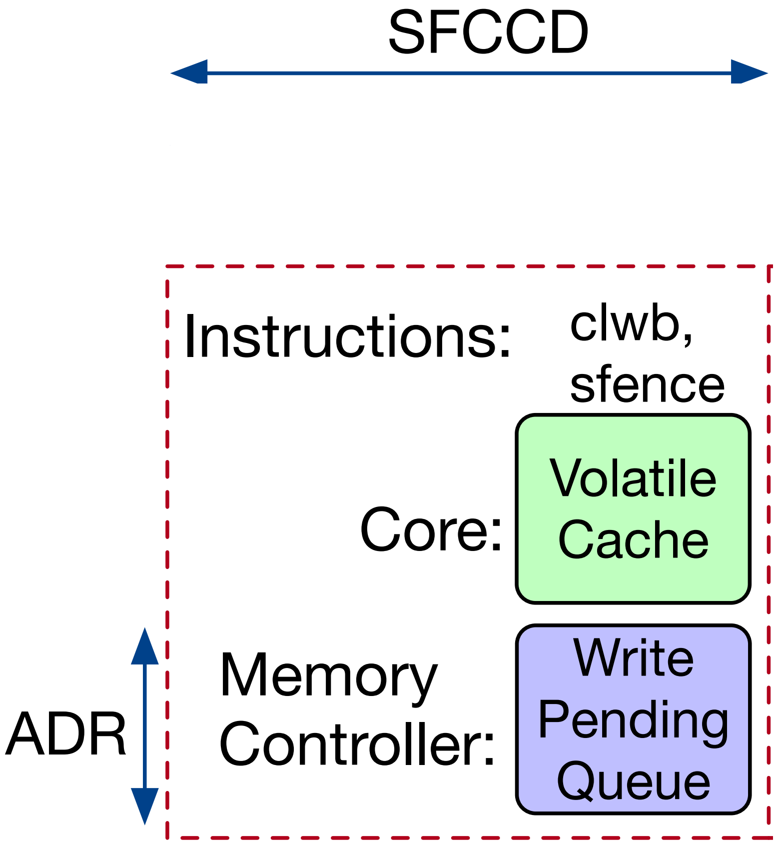
```

More details in the paper

Fence-free design

Design Summary



SFCCD

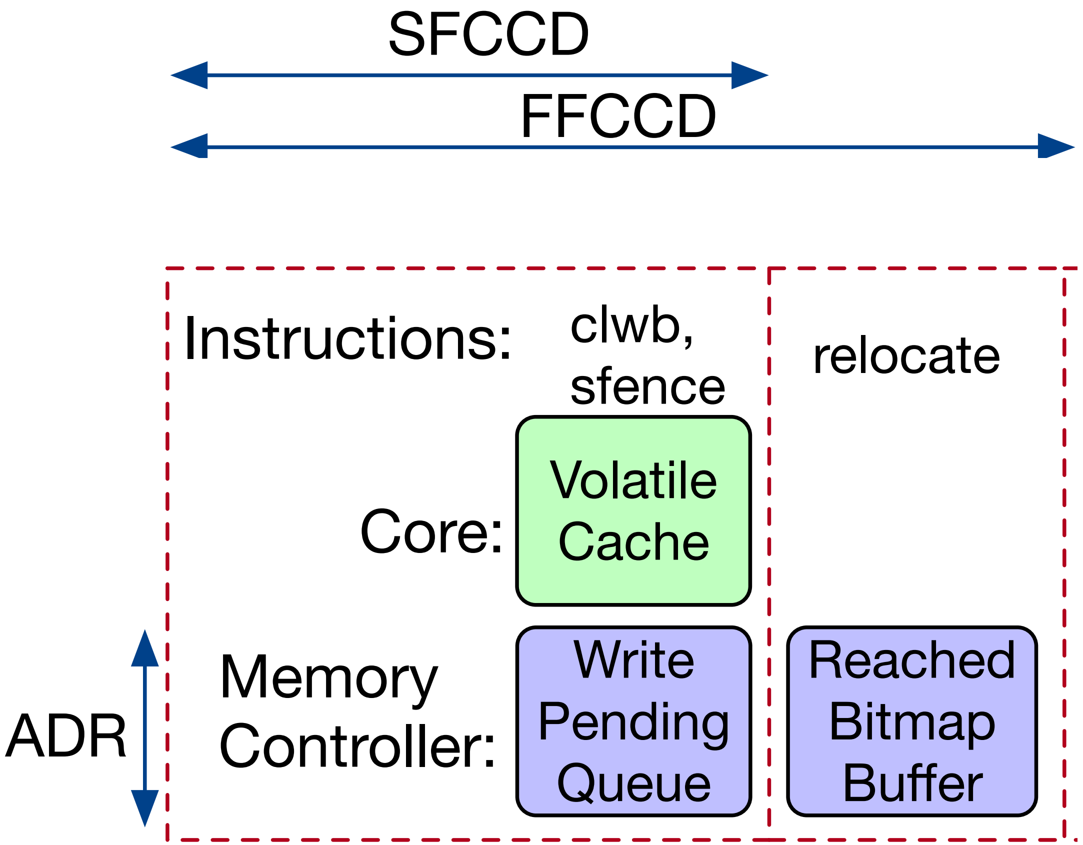
Instructions: clwb, sfence

Core: Volatile Cache

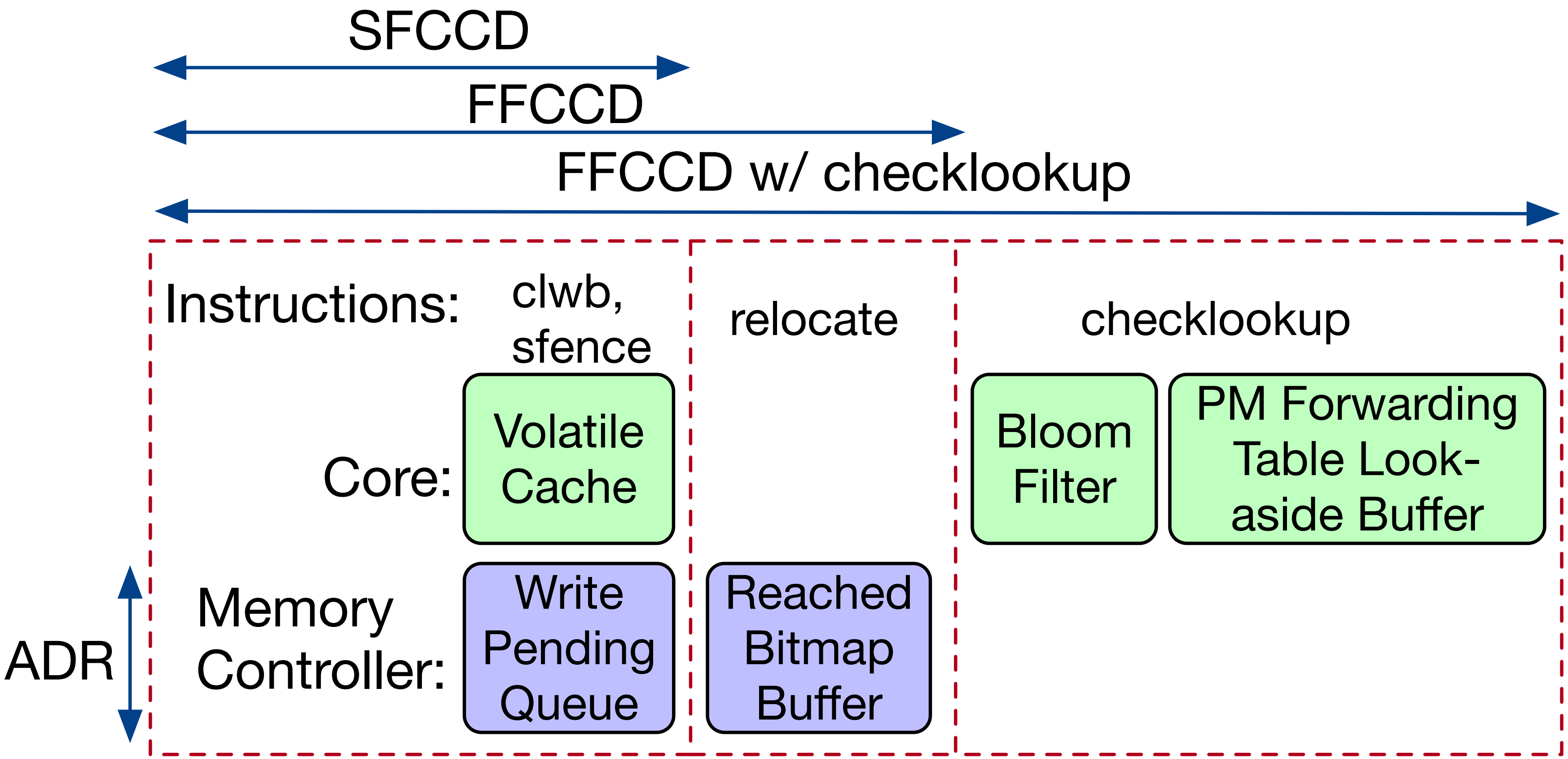
ADR

Memory Controller: Write Pending Queue

Design Summary



Design Summary



Evaluation

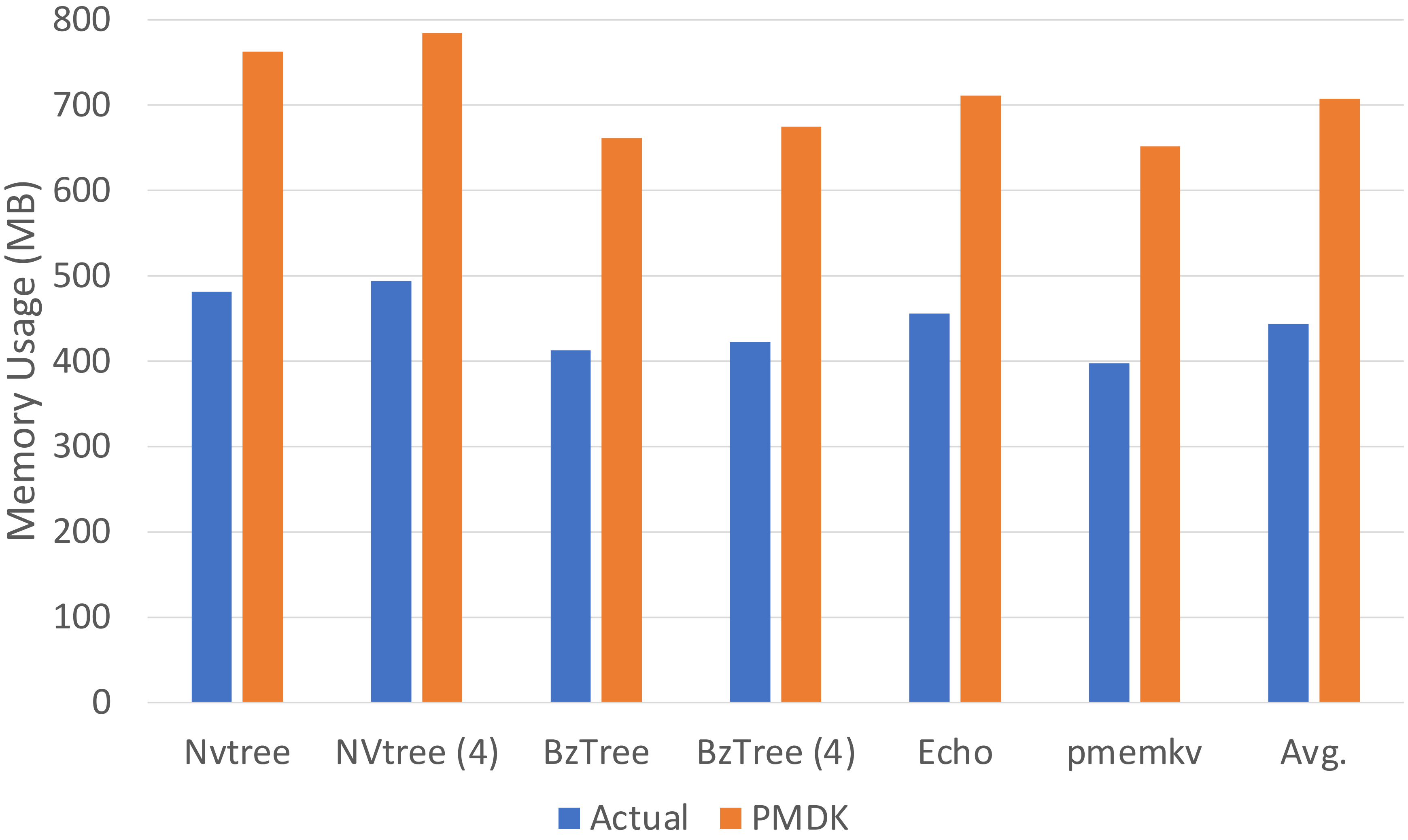
Benchmarks:

- PM data structures
- PM key-value stores

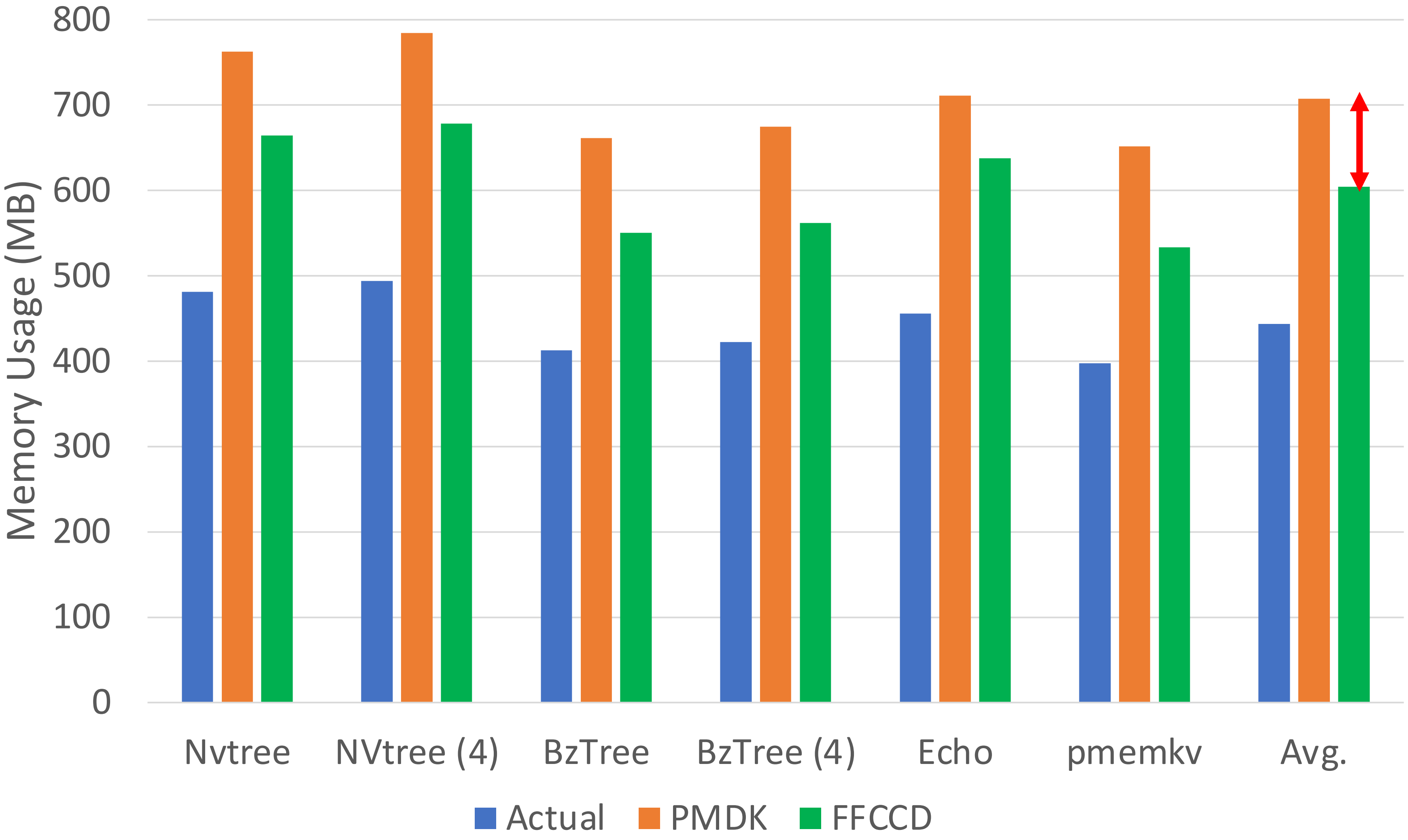
Workload:

1) Initialize data with 5M insertions
2) Delete 4M nodes
3) Insert 4M nodes
4) Delete 4M nodes

Defragmentation

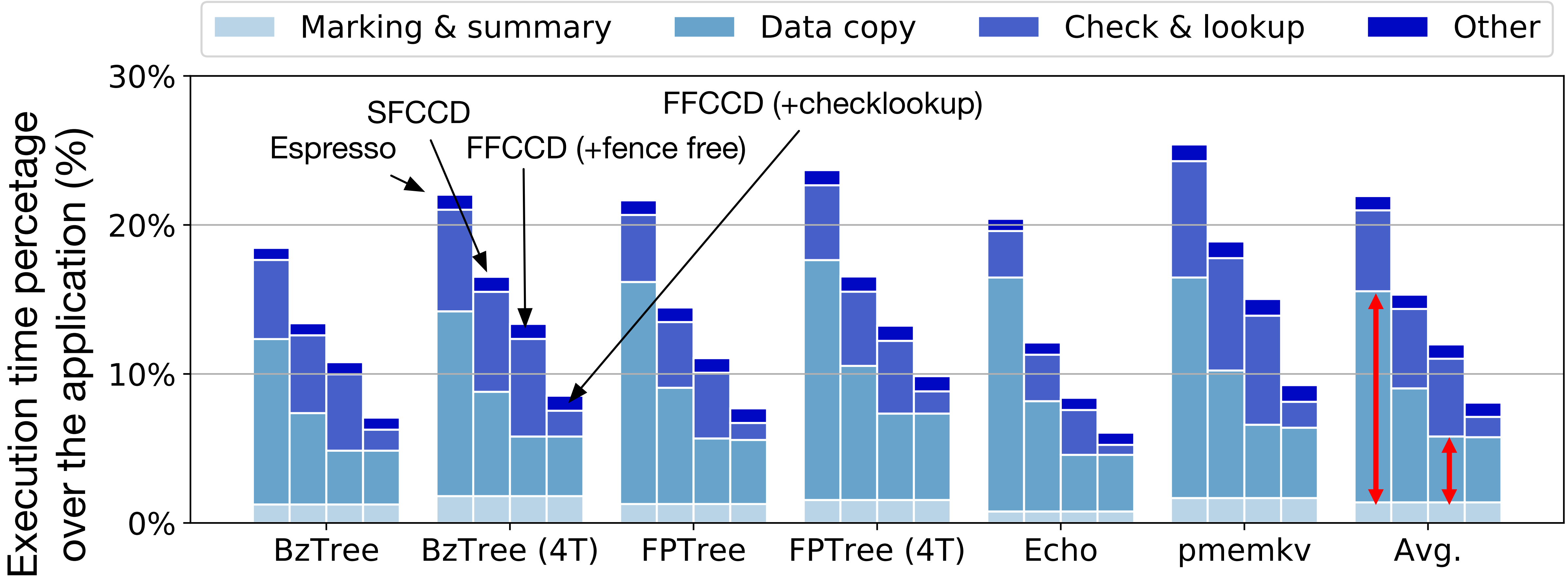


Defragmentation



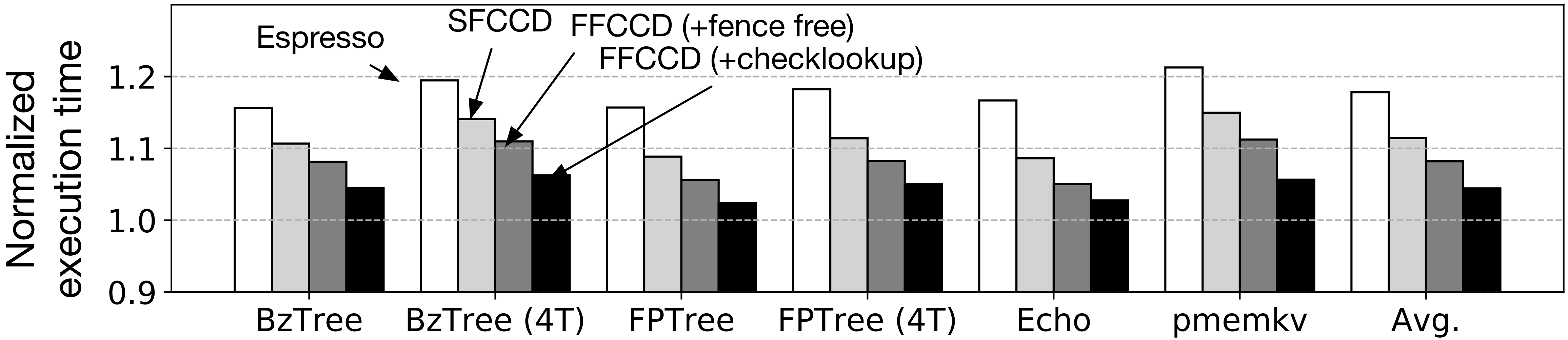
40% Reduction

GC Overhead Breakdown



FFCCD reduces 62% overhead in crash-consistent data copy

Total Execution Time with GC



FFCCD incurs 4.1% overhead than non-defragmentation performance

Conclusions

- We identify sfences as the key challenge to design efficient crash-consistent GC

- We design multiple solutions
  - SFCCD, software-only solution to remove 1 sfence
  - FFCCD, architectural-supp [illegible] ove 2 sfences

Thank you!
Q&A

- FFCCD provides 28–73% fragmentation reduction

- FFCCD incurs 4.1% overhead
  - Improve application performance due to better locality
  - Low overhead from GC