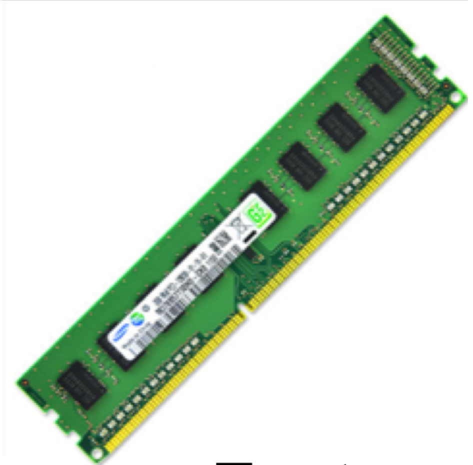
WineFS: A hugepage-aware file system for persistent memory that ages gracefully

Rohan Kadekodi, Saurabh Kadekodi, Soujanya Ponnapalli,
Harshad Shirwadkar, Gregory R. Ganger, Aasheesh Kolli,
Vijay Chidambaram

Persistent Memory

Non-volatile

+



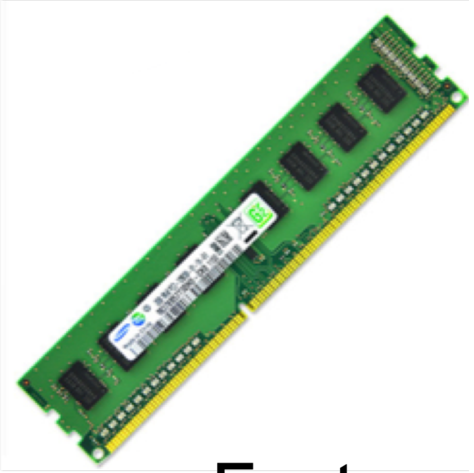
Fast

Persistent Memory

Non-volatile

Retain data across power cycles

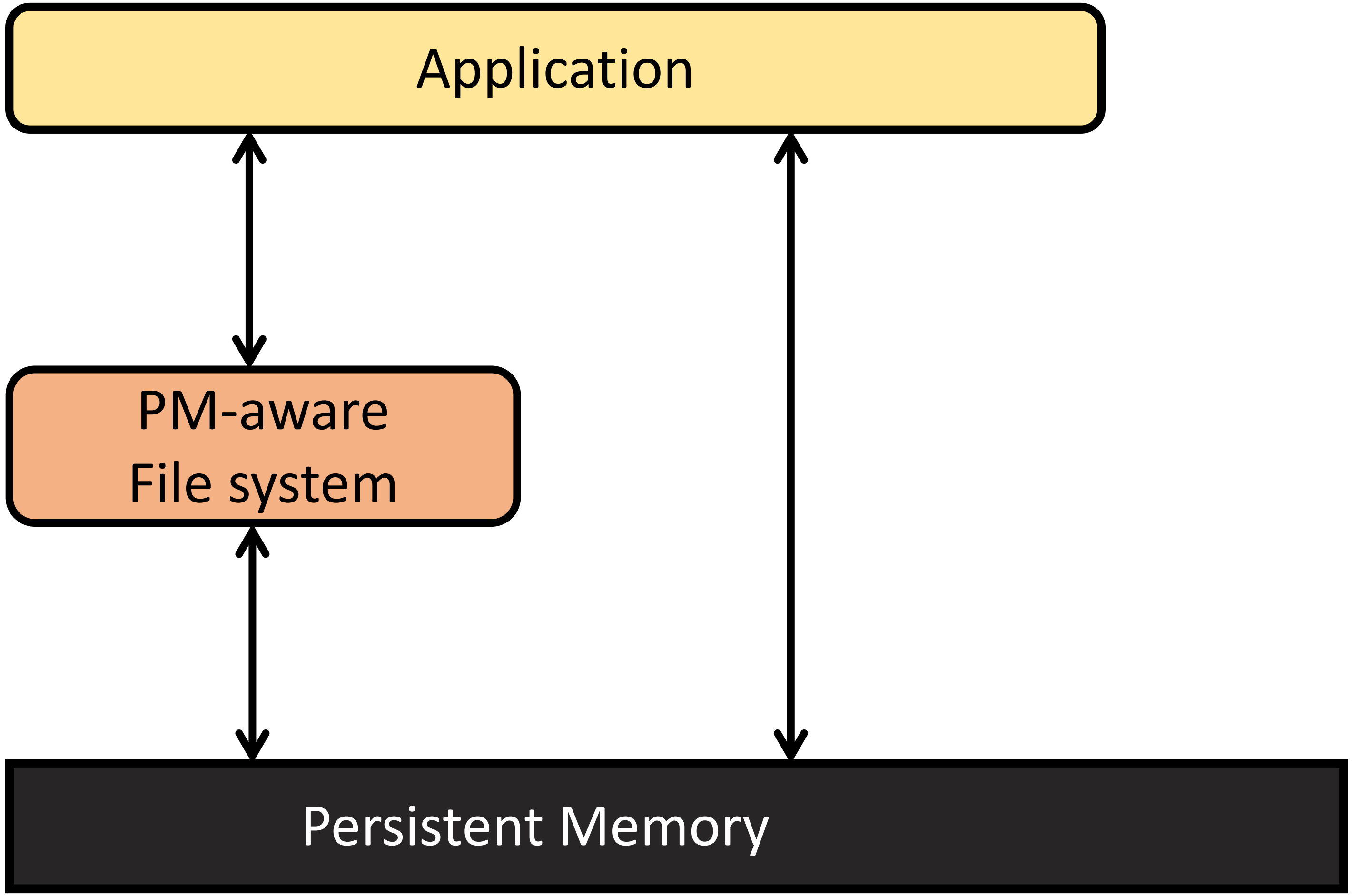
+



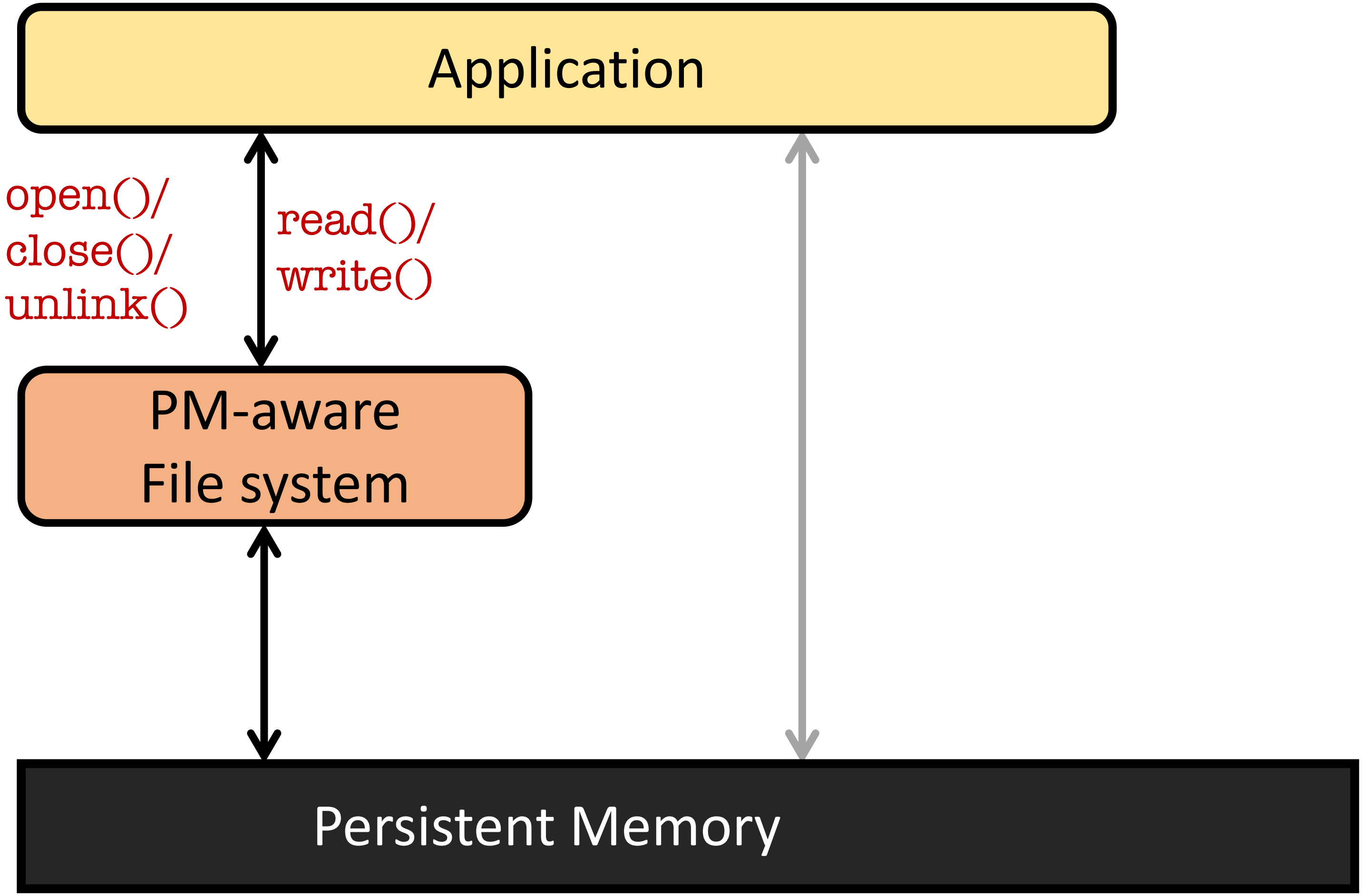
Fast

Access latencies similar to DRAM

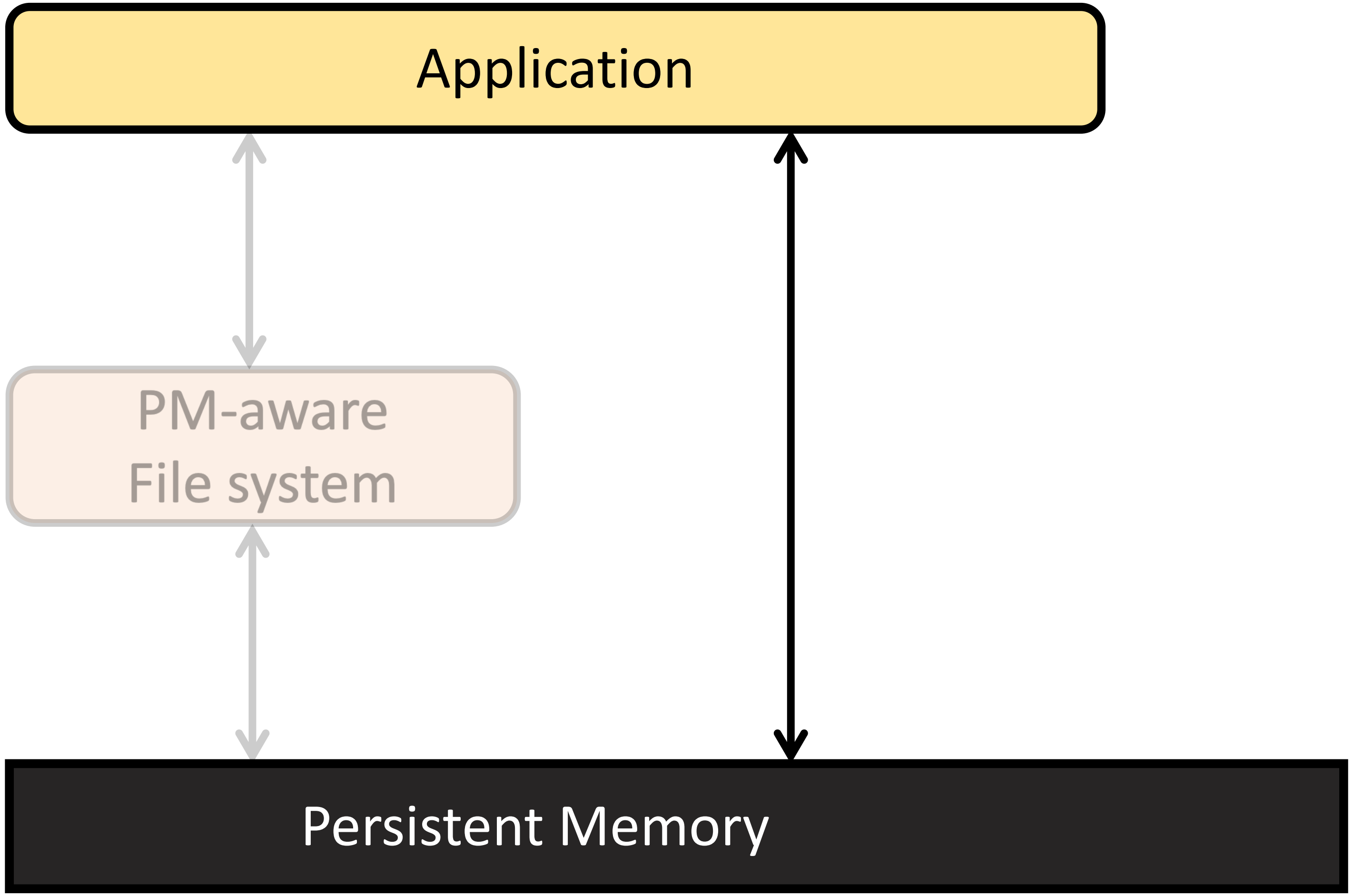
PM Applications



POSIX system-call applications



Memory-mapped Applications



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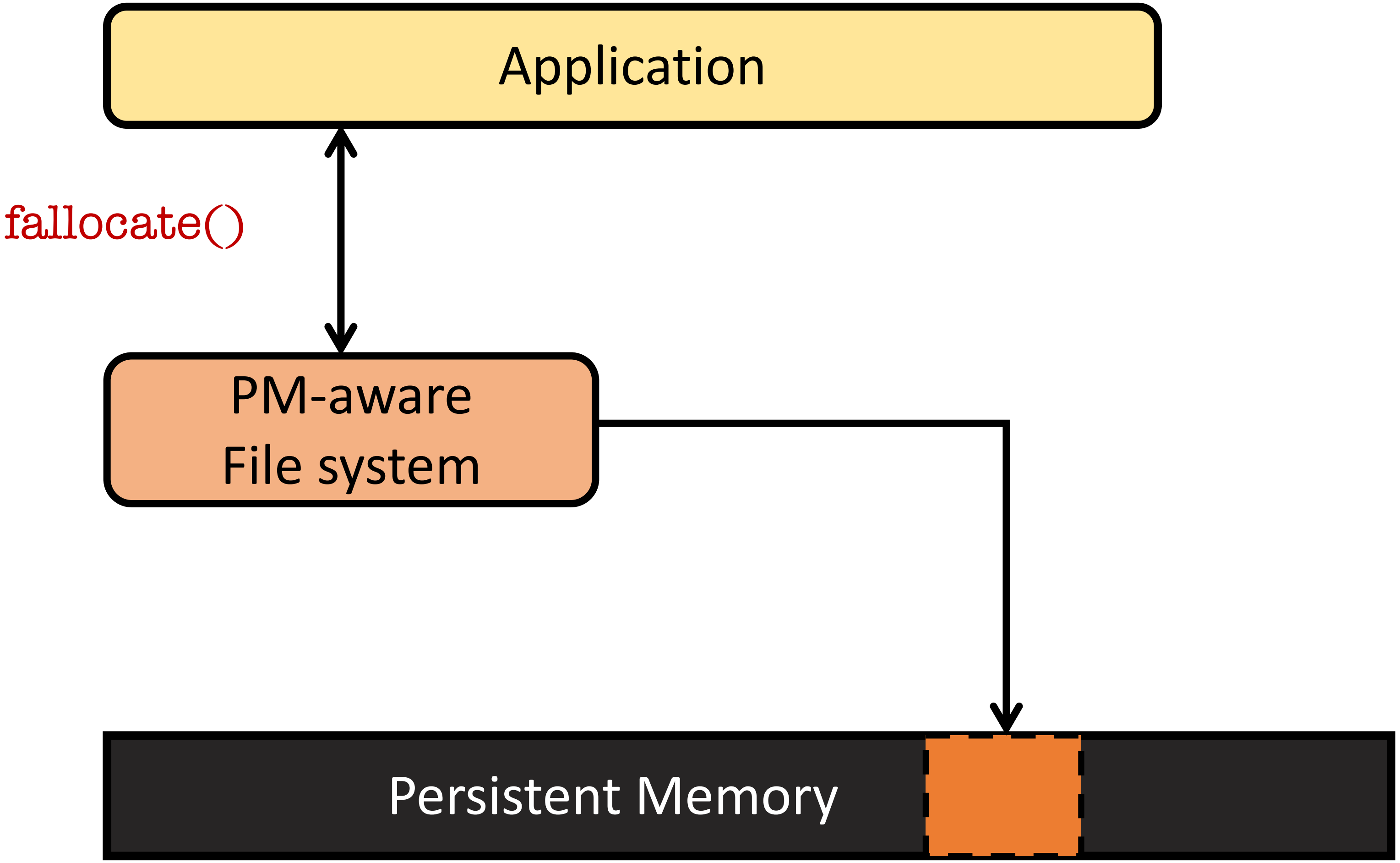

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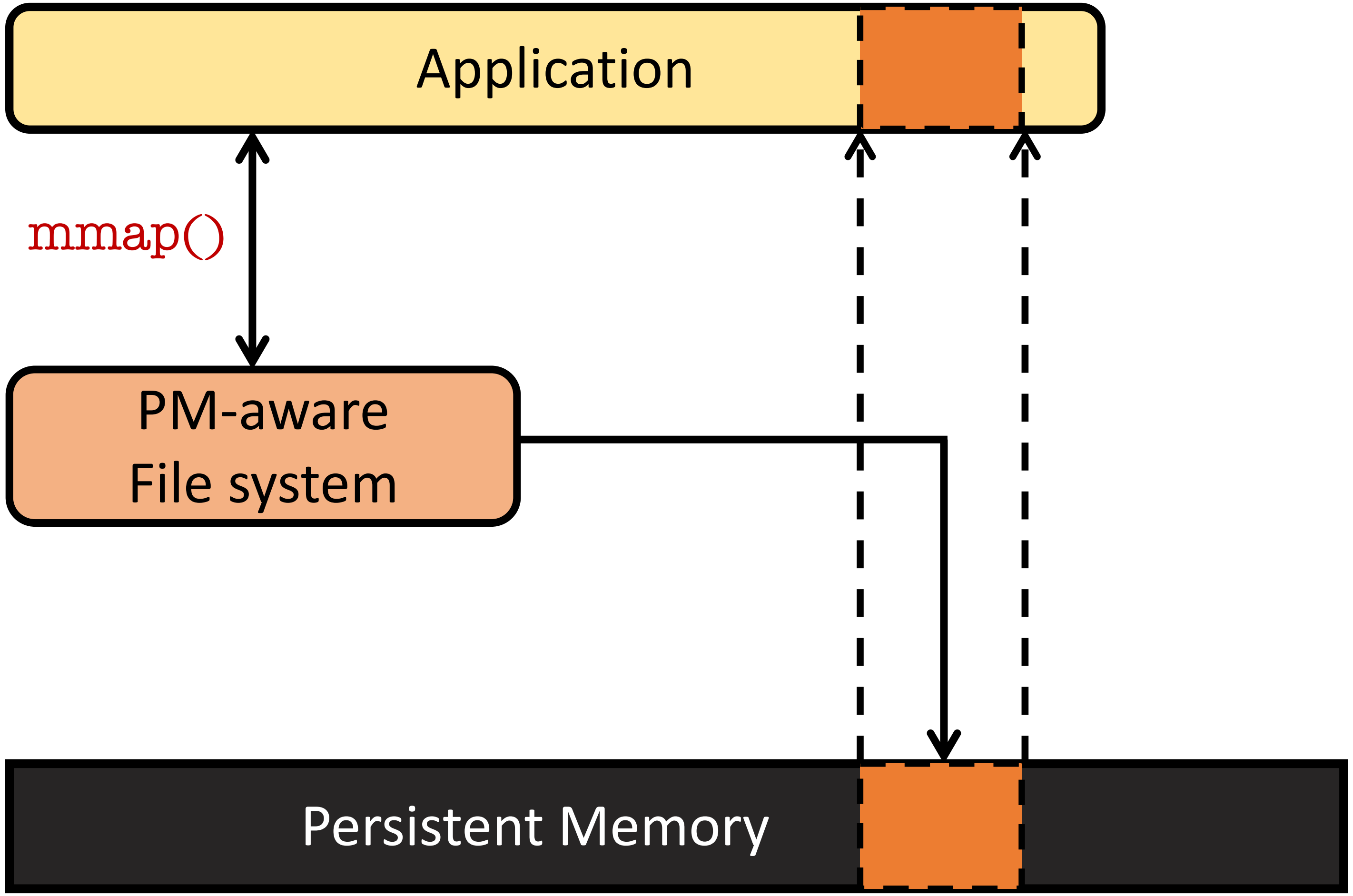

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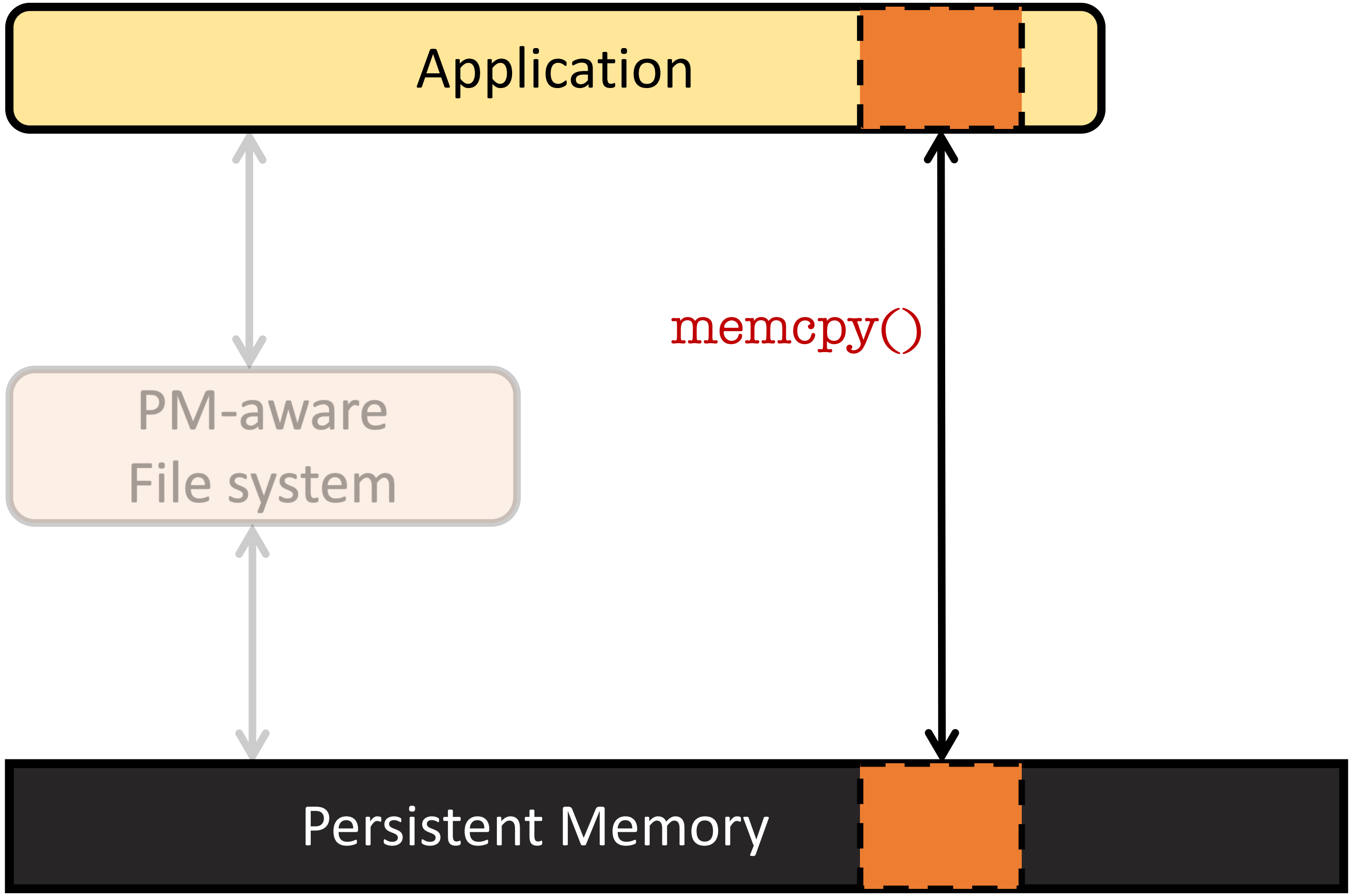

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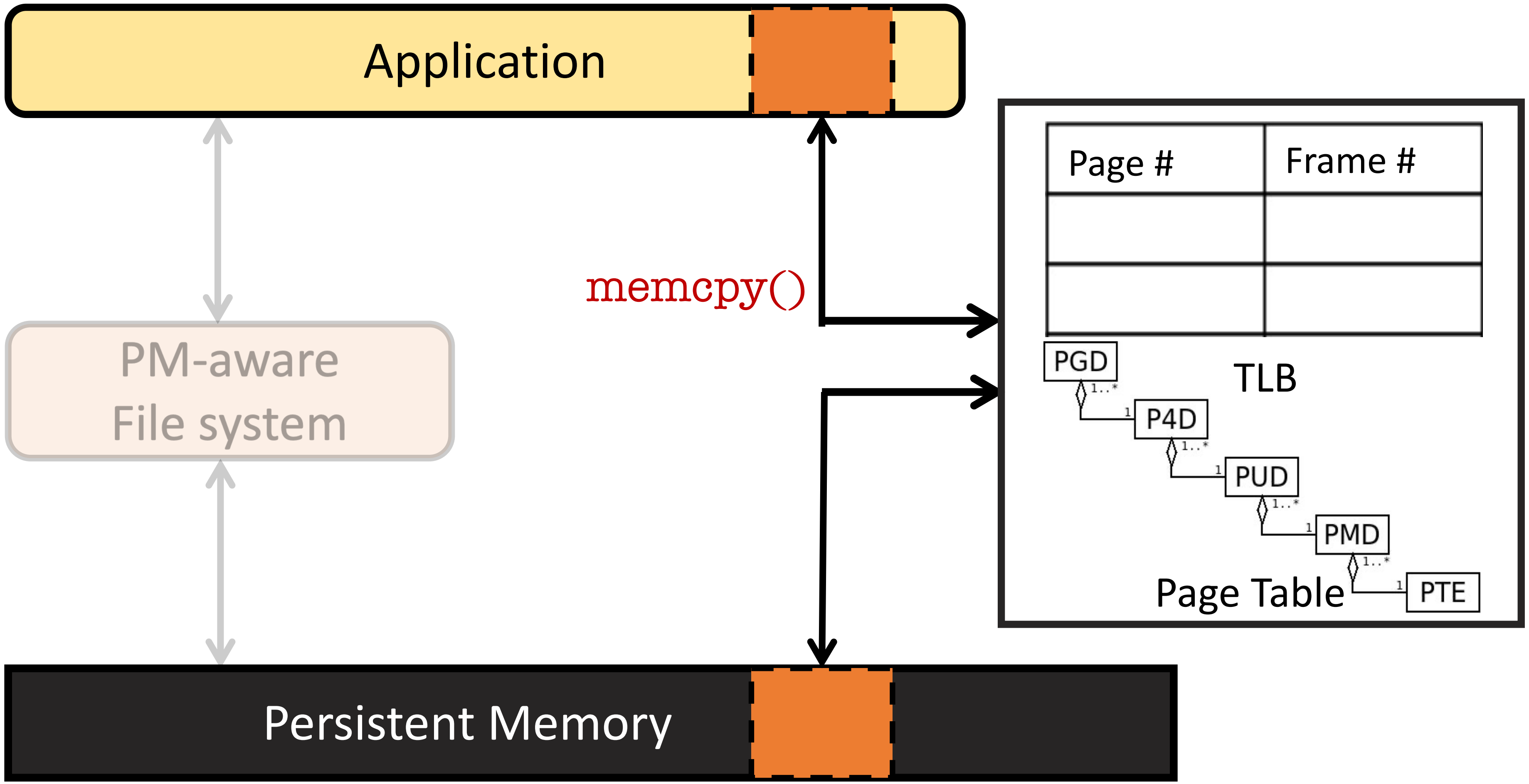

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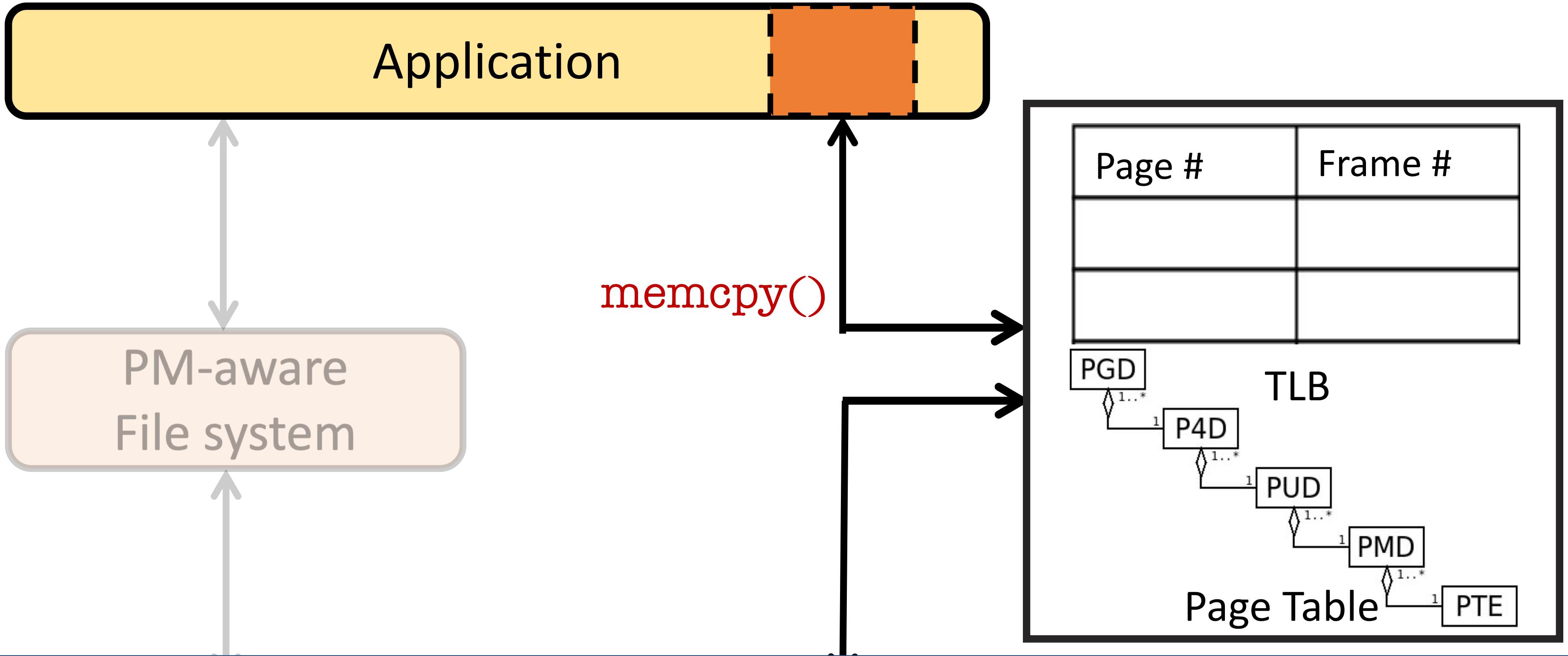

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Performance of memory-mapped applications depends on page faults and TLB misses

Hugepages

Large pages (2MiB/1GiB)

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Reduce the number of page faults and TLB misses by up-to 500x

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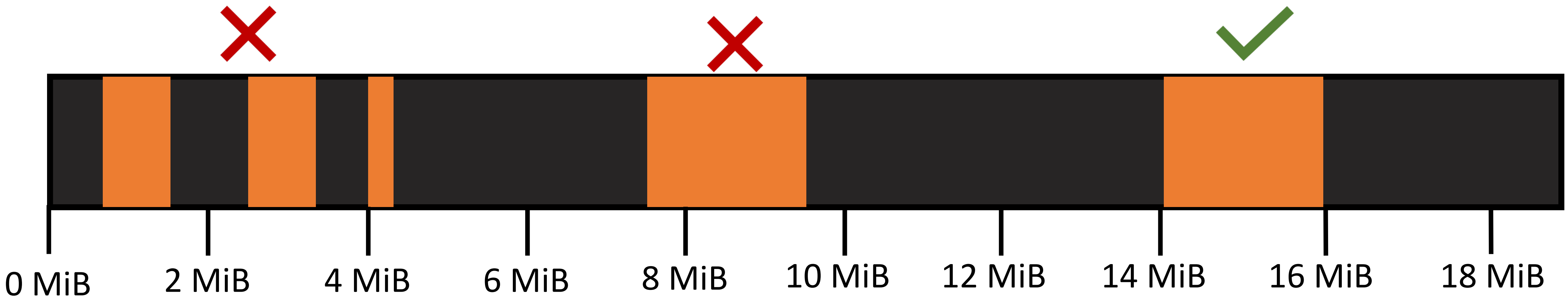
File systems need to allocate files using aligned & contiguous 2MiB extents



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File systems are responsible in issuing hugepages for memory-mapped applications

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File systems must preserve hugepages with age

What is aging and why should we care?

State of file systems as a result of continuous allocations/deallocations, over time

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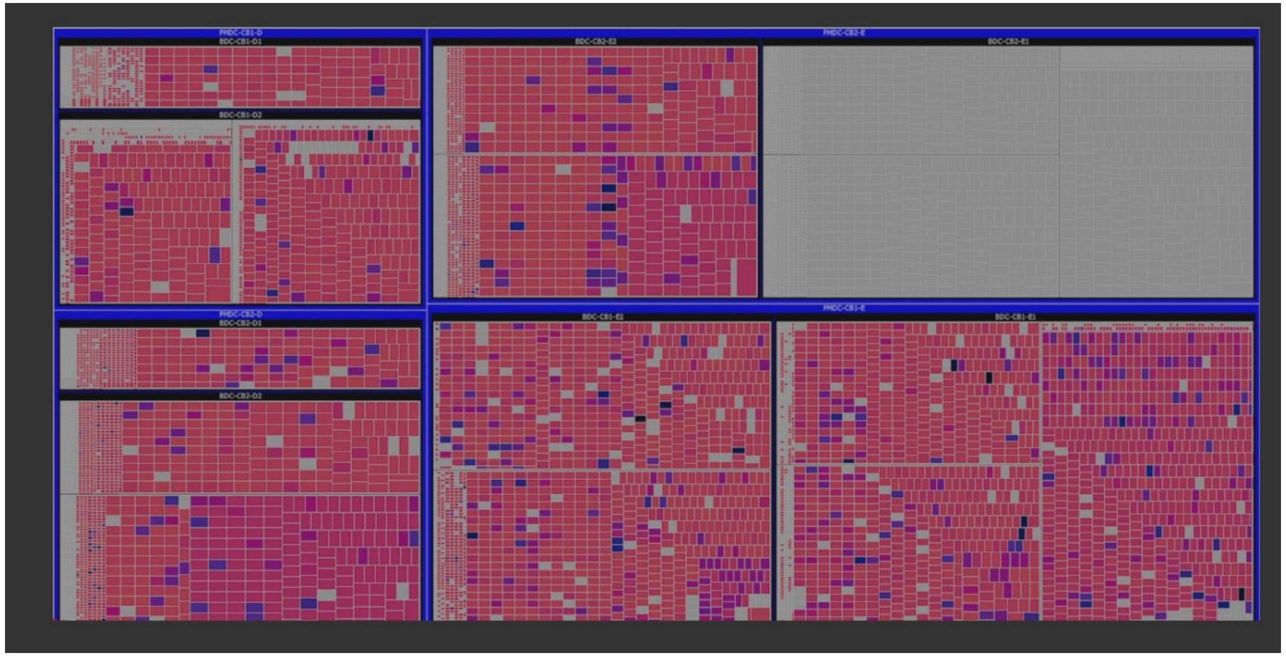

Google: “We want to keep disks full and busy to avoid excess inventory and wasted disk IOPs.”

Google. 2021. Colossus under the hood: a peek into Google’s scalable storage system. https://cloud.google.com/blog/products/storage- data-transfer/a-peek-behind-colossus-googles-file-system.

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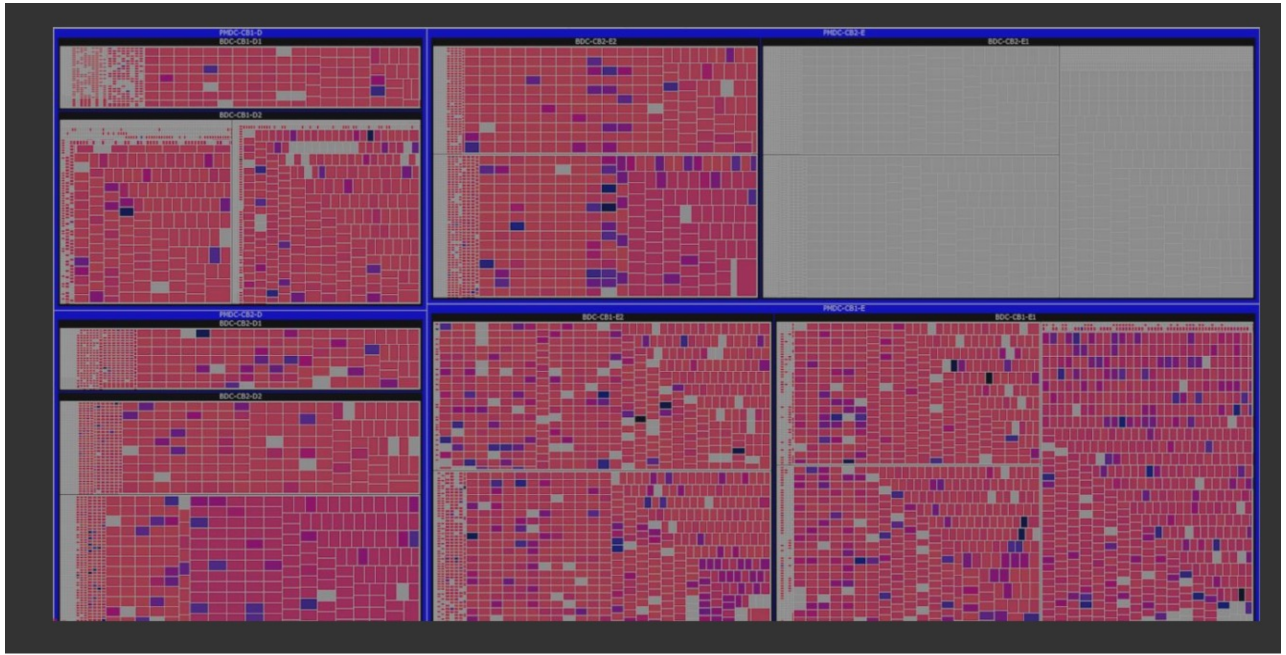

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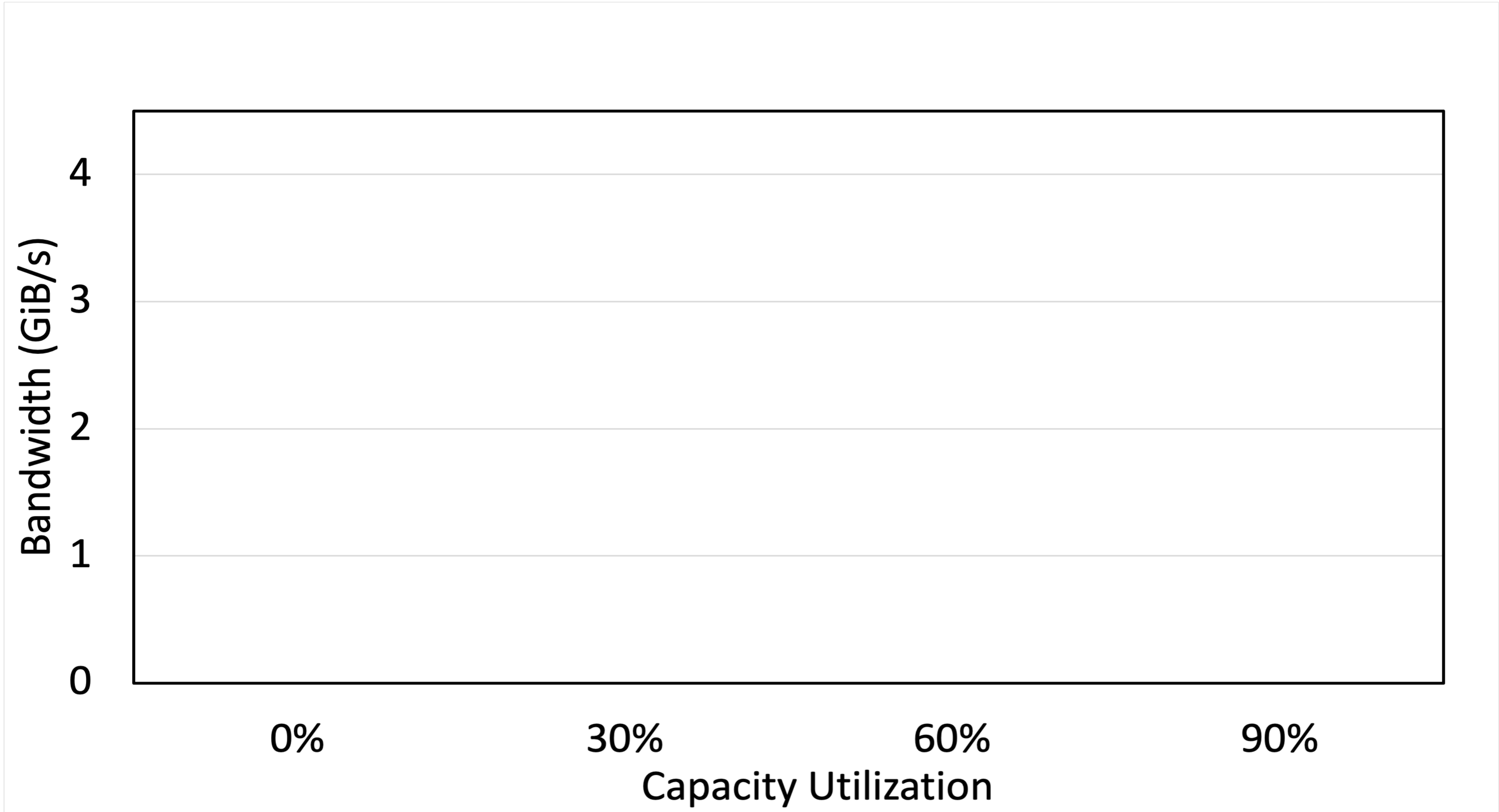
File systems become fragmented over time due to frequent allocations and deallocations[1]

[1] Smith, Keith A., and Margo I. Seltzer. "File system aging—increasing the relevance of file system benchmarks." *Proceedings of the 1997 ACM SIGMETRICS international conference on Measurement and modeling of computer systems*. 1997.

Performance impact of aging

Sequential write bandwidth using memcpy() on memory-mapped file



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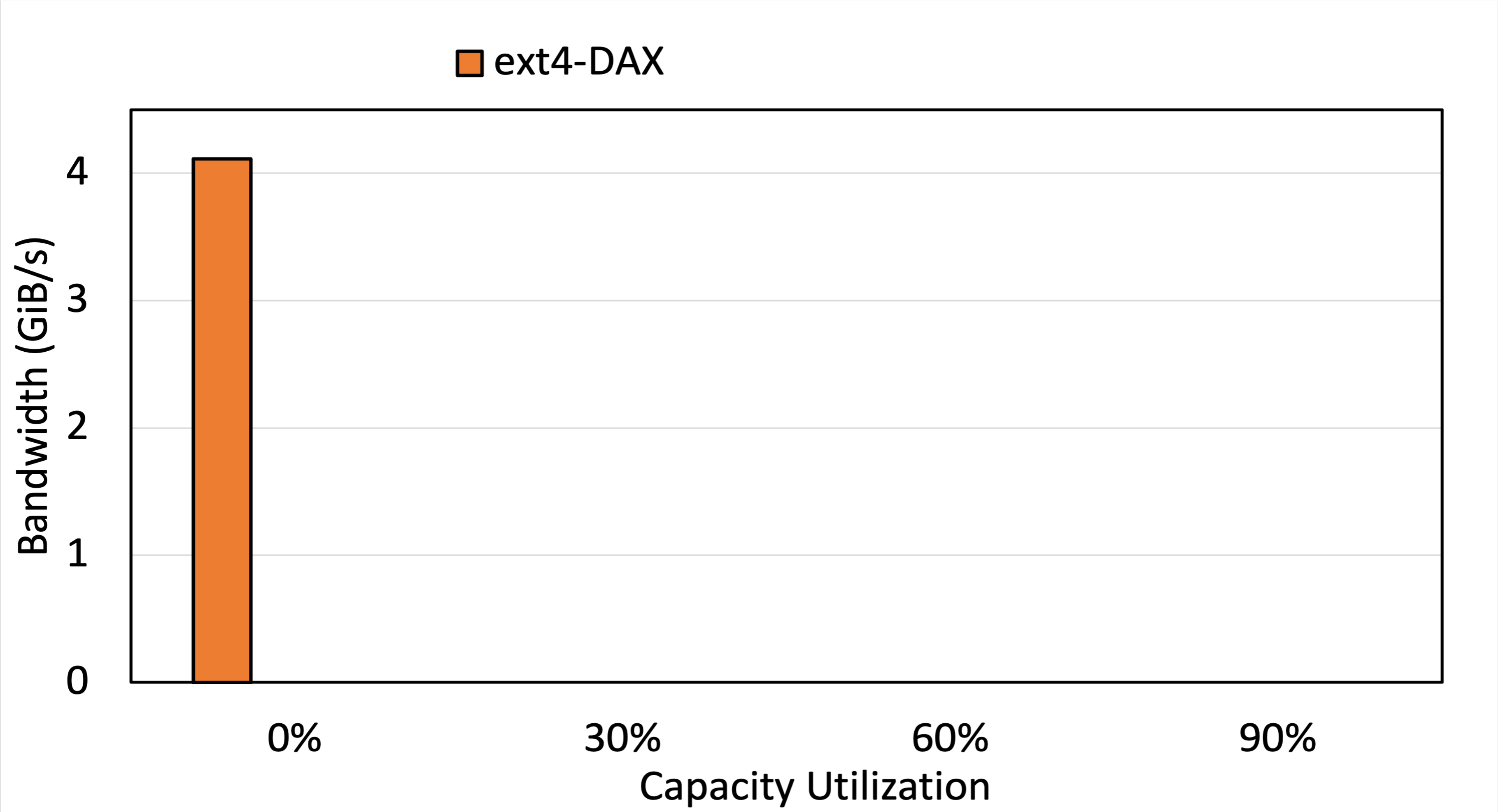

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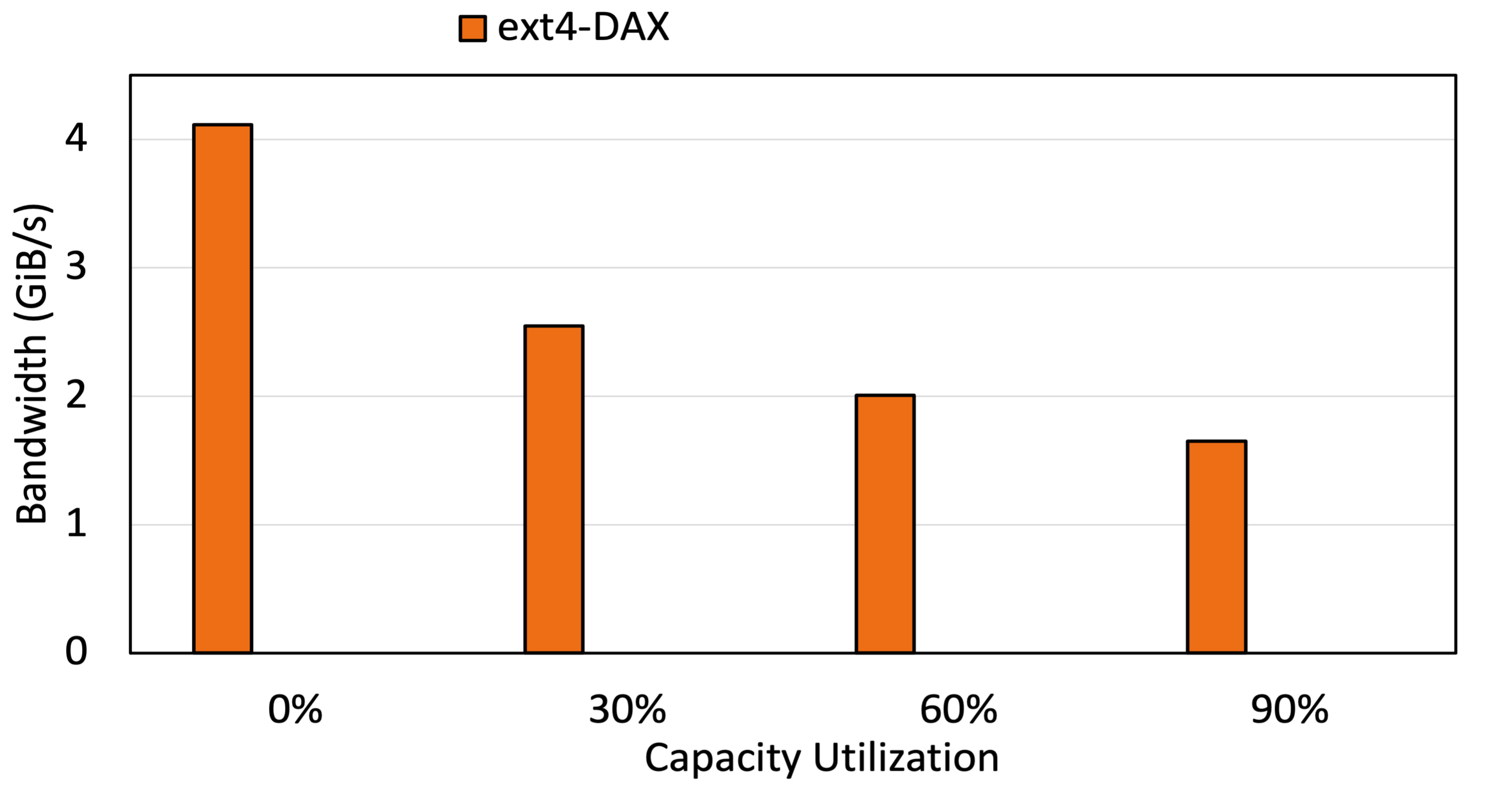

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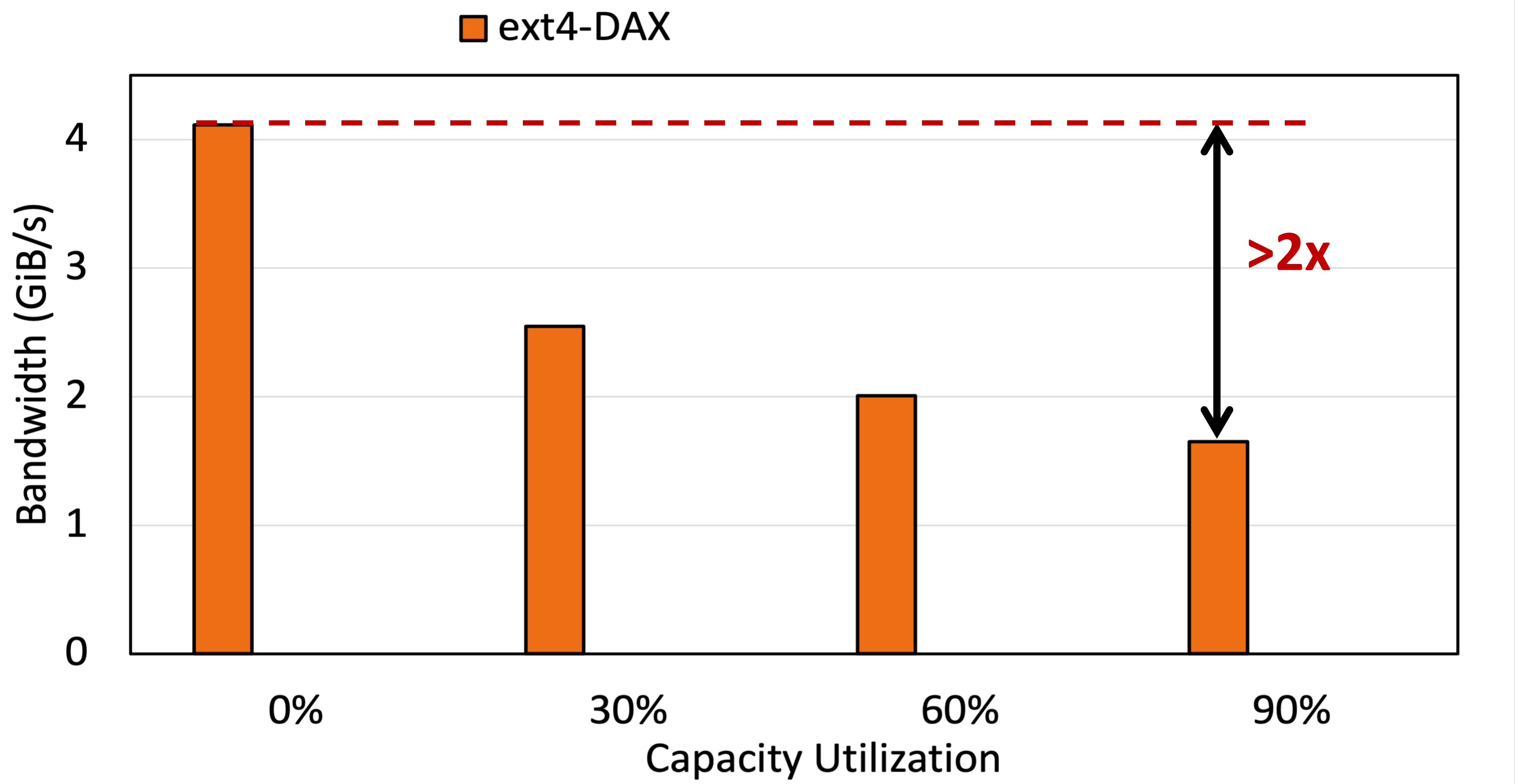

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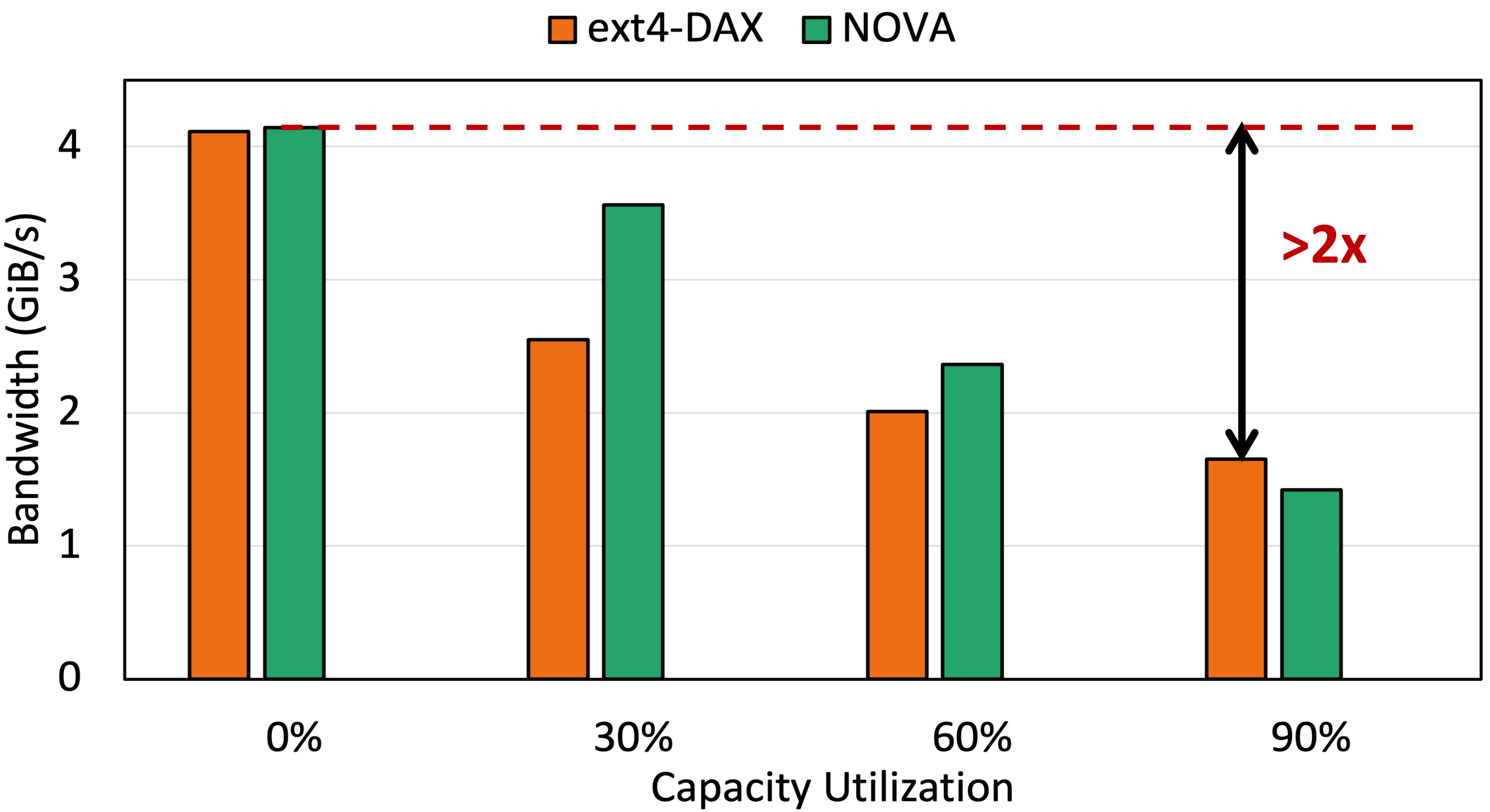

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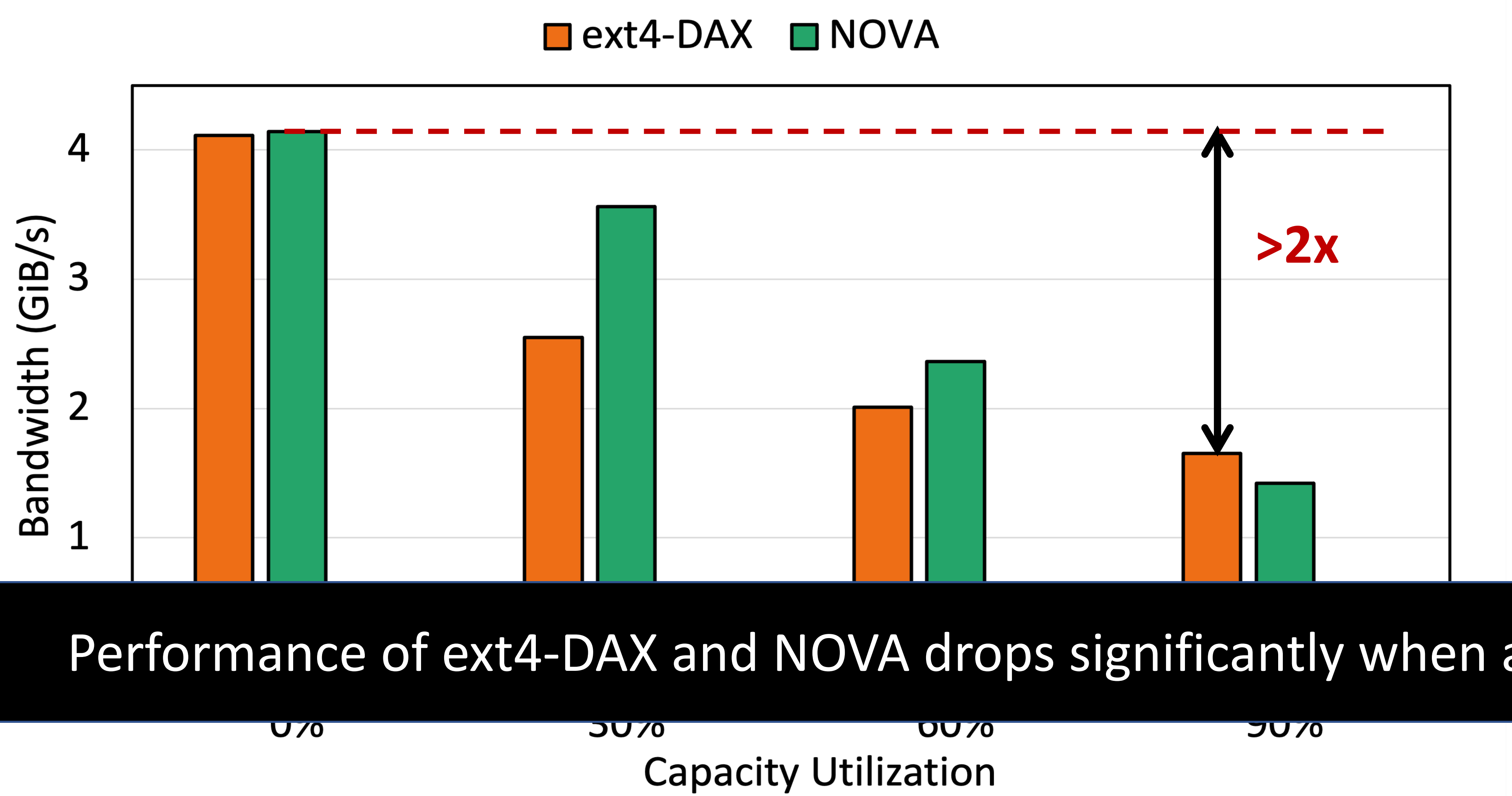

Performance of ext4-DAX and NOVA drops significantly when aged

WineFS

Hugepage-aware file system for PM that ages gracefully

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WineFS design achieves high scalability and works well on multiple NUMA nodes

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Hugepage-aware file system for PM that ages gracefully

WineFS uses a novel alignment-aware allocation policy to preserve hugepages

WineFS achieves high performance for memory-mapped applications and POSIX system-call applications

WineFS design achieves high scalability and works well on multiple NUMA nodes

WineFS performance almost stays the same when aged.
Aged WineFS performs better than freshly formatted NOVA

https://github.com/utsaslab/winefs

Insights behind WineFS

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- Allocate memory-mapped files on aligned & contiguous extents

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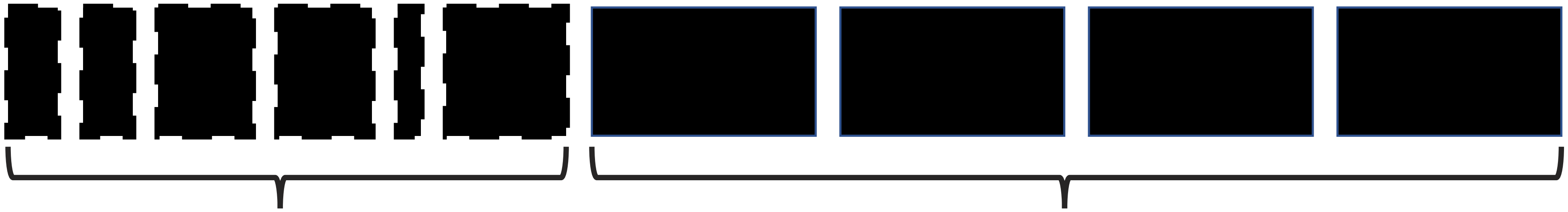
  Limitations of other file systems:

  - ext4-DAX and xfs-DAX preserve contiguity of free-space but not alignment

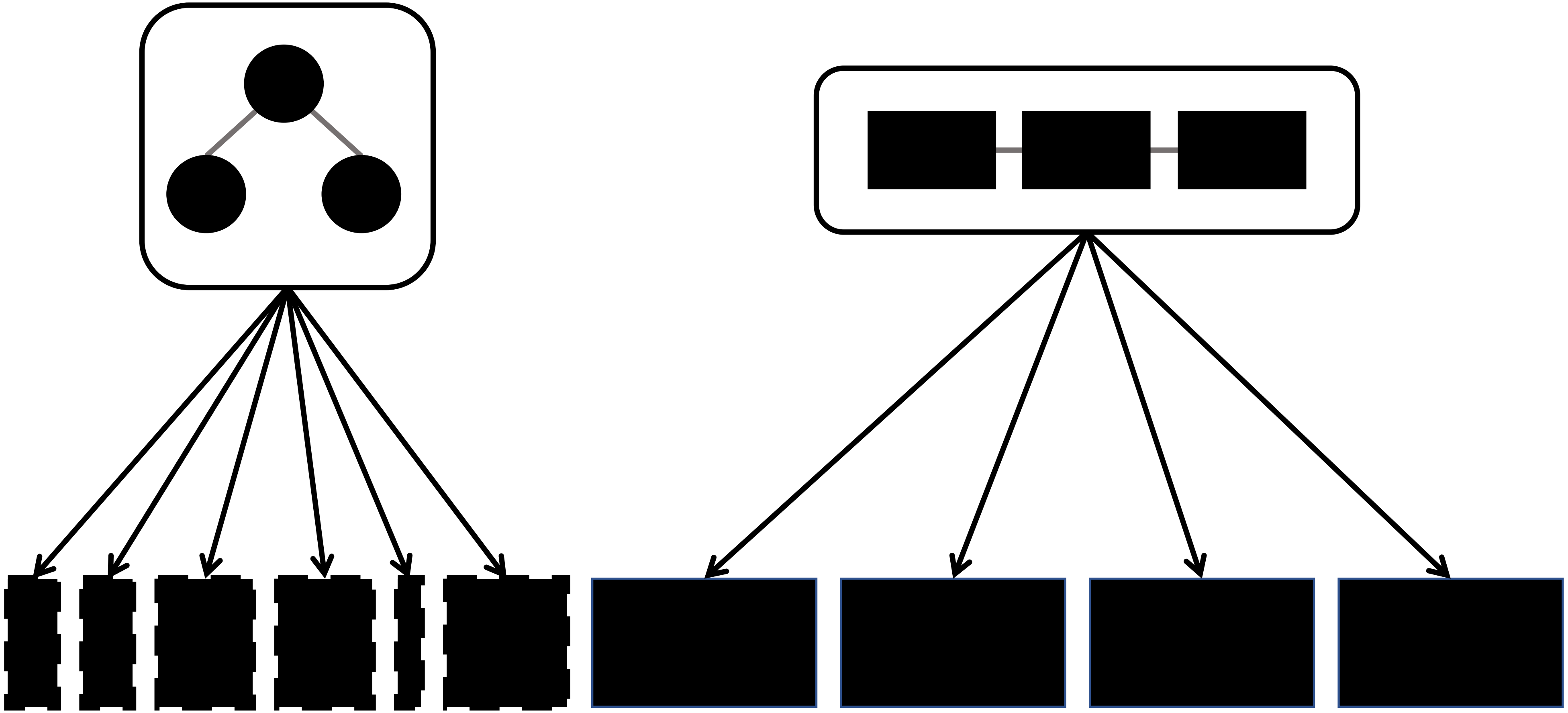
Alignment-aware allocation policy



small/unaligned holes

2MiB aligned extents

Alignment-aware allocation policy



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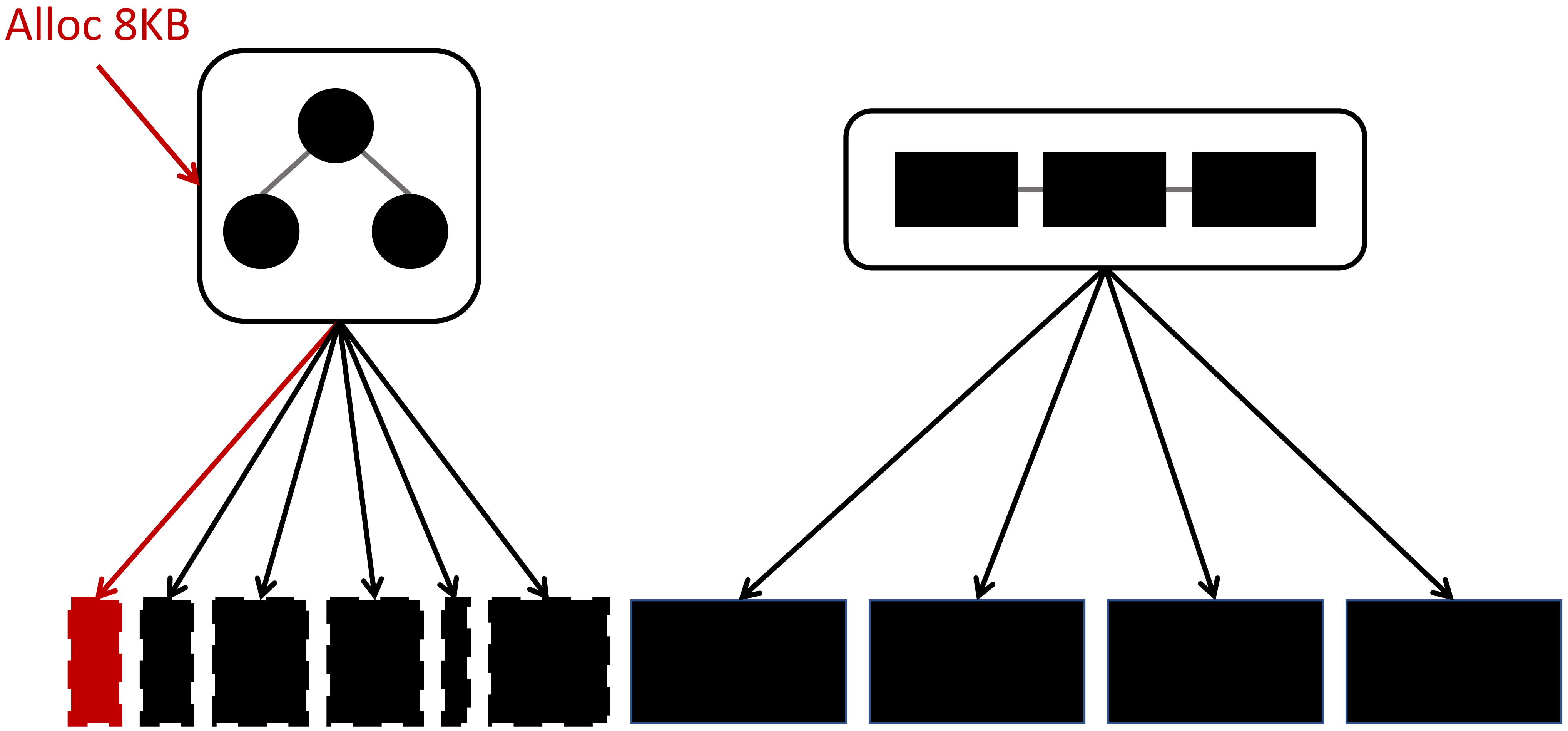

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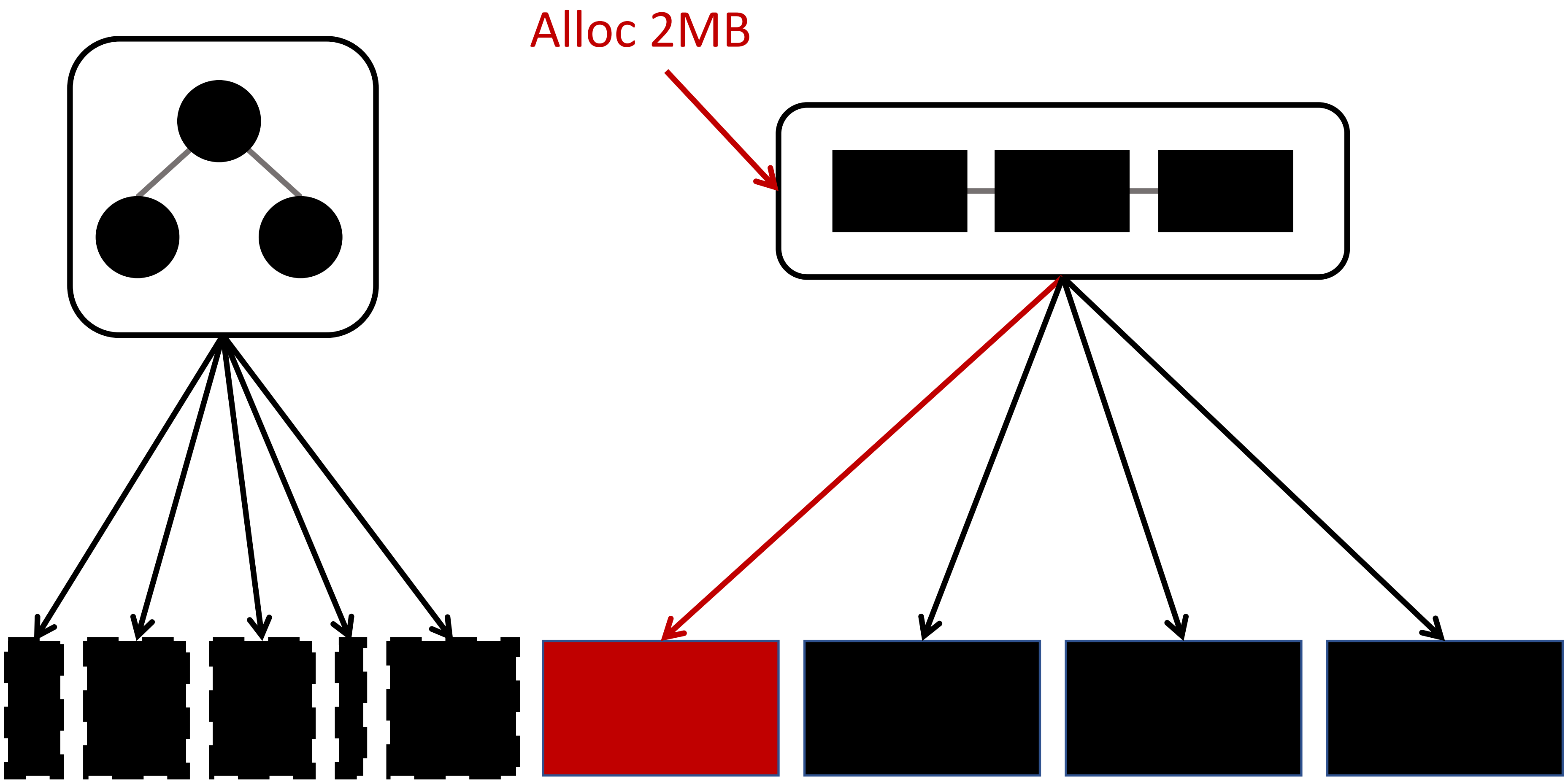

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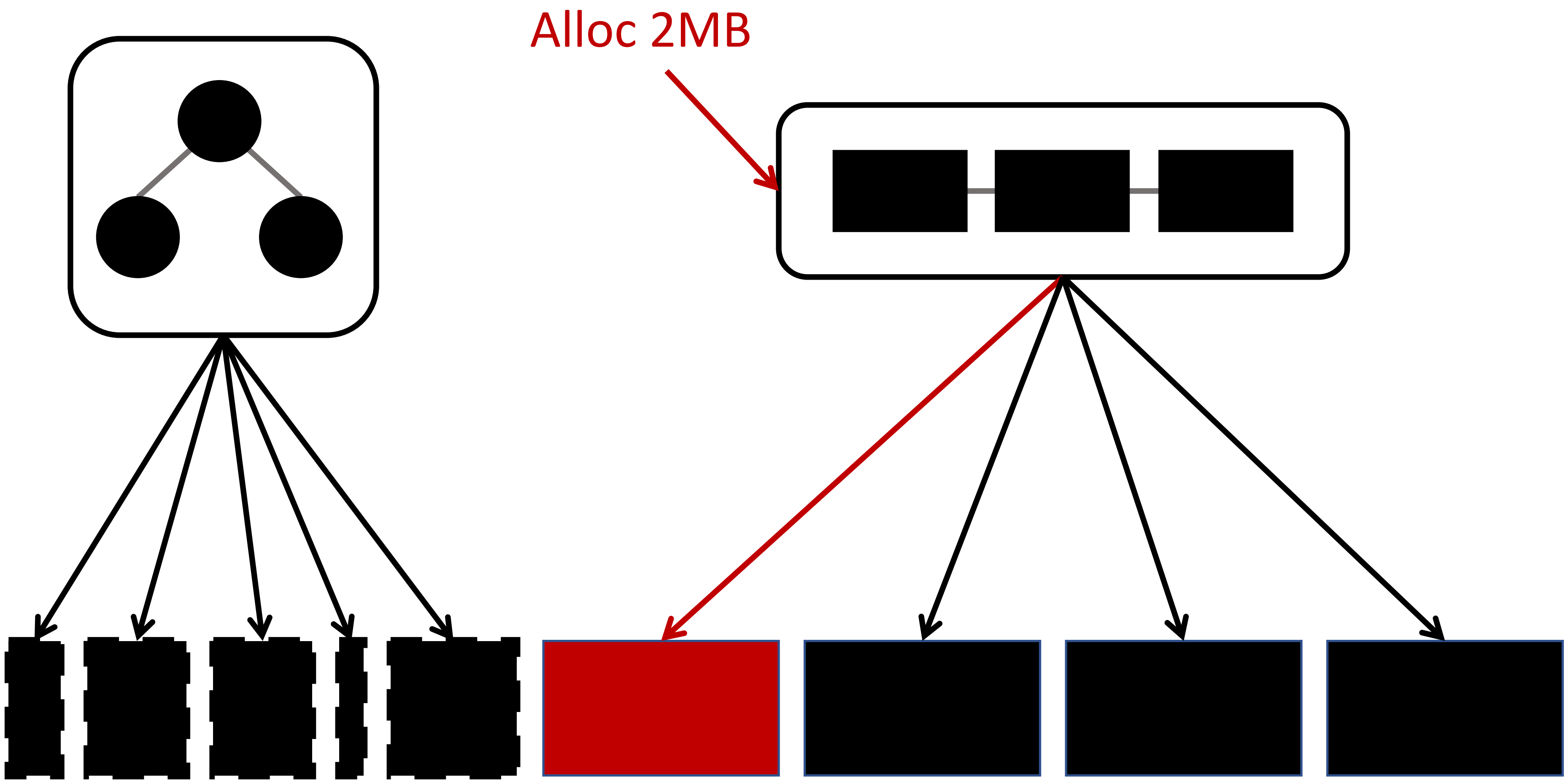
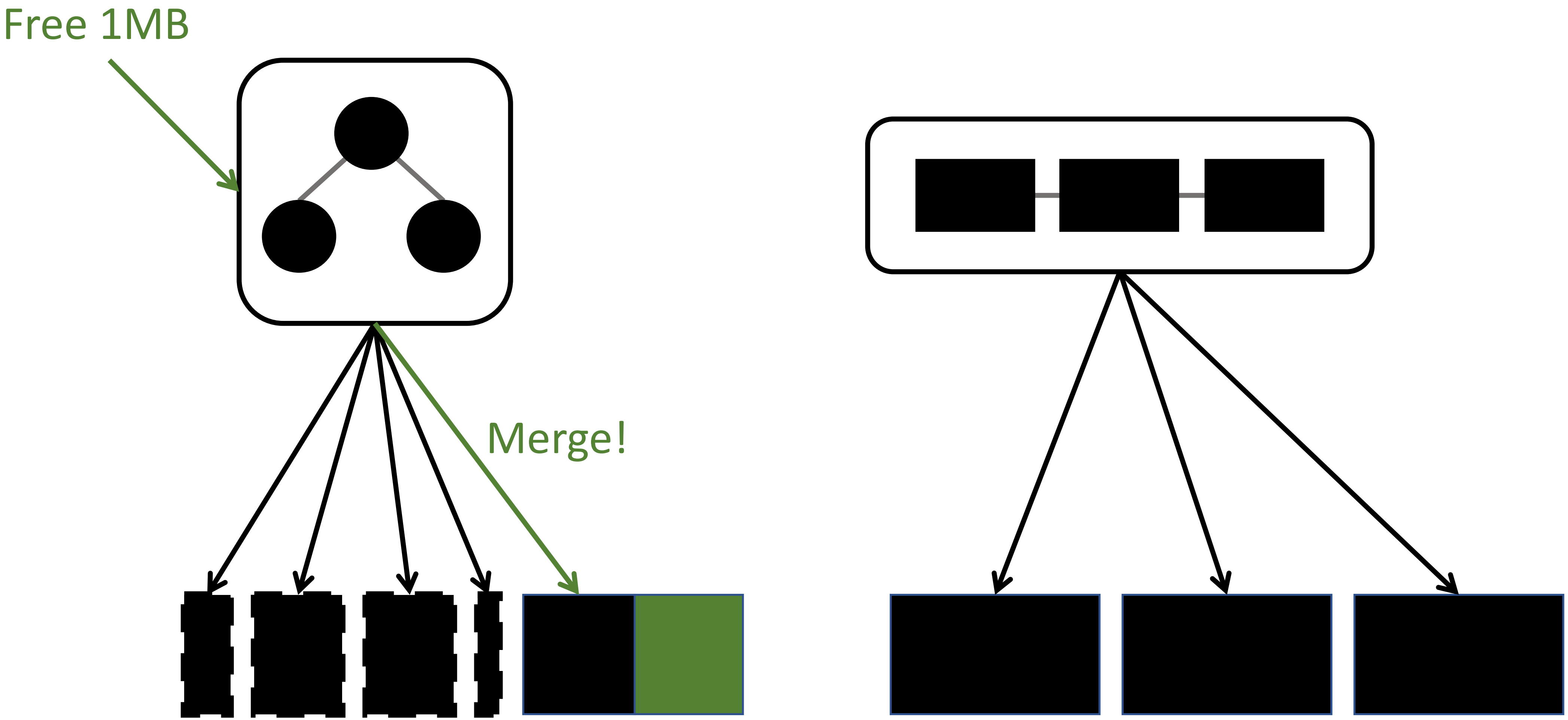


Larger allocations are broken down into multiple 2MiB allocations and allocated from the hugepage list

Alignment-aware allocation policy



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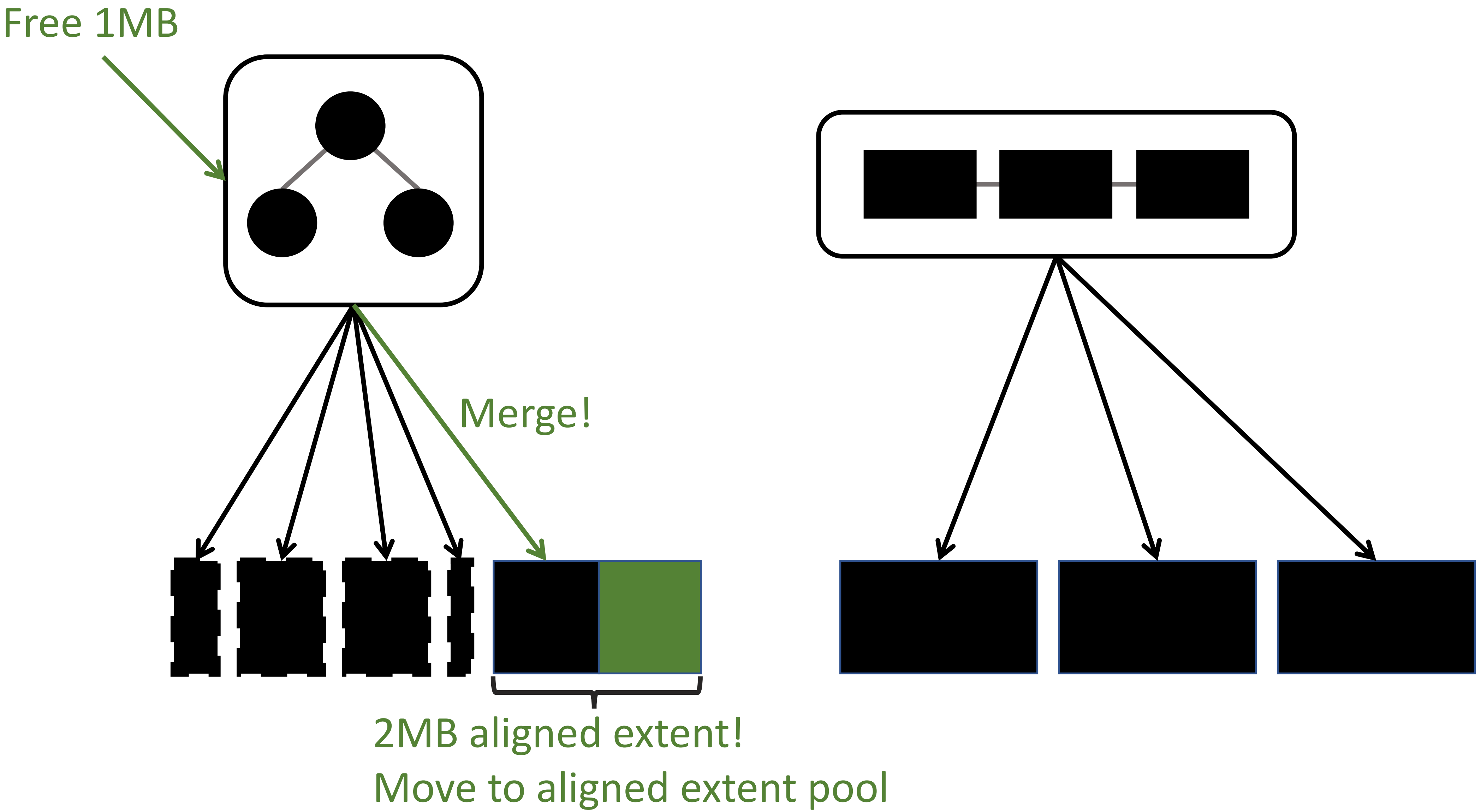

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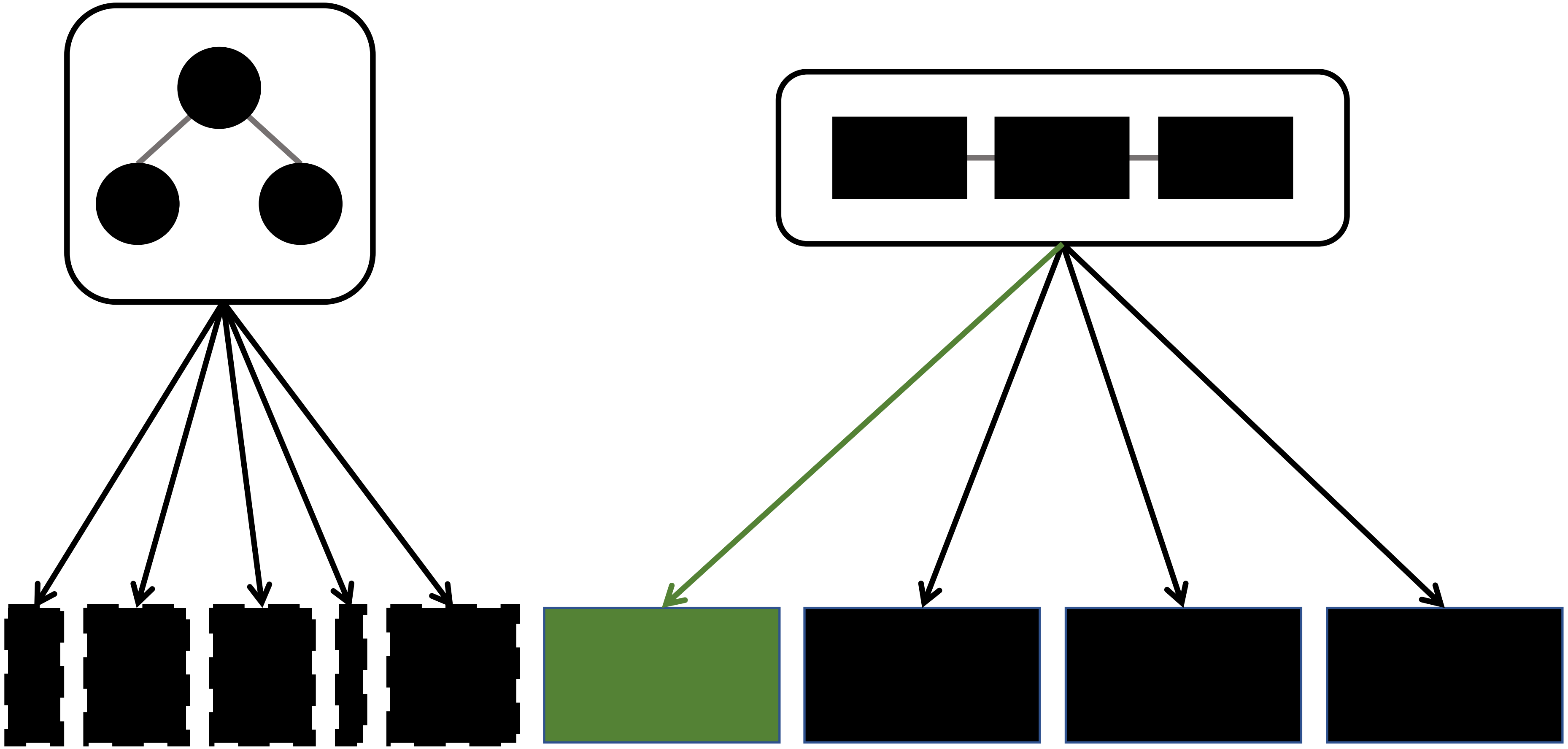

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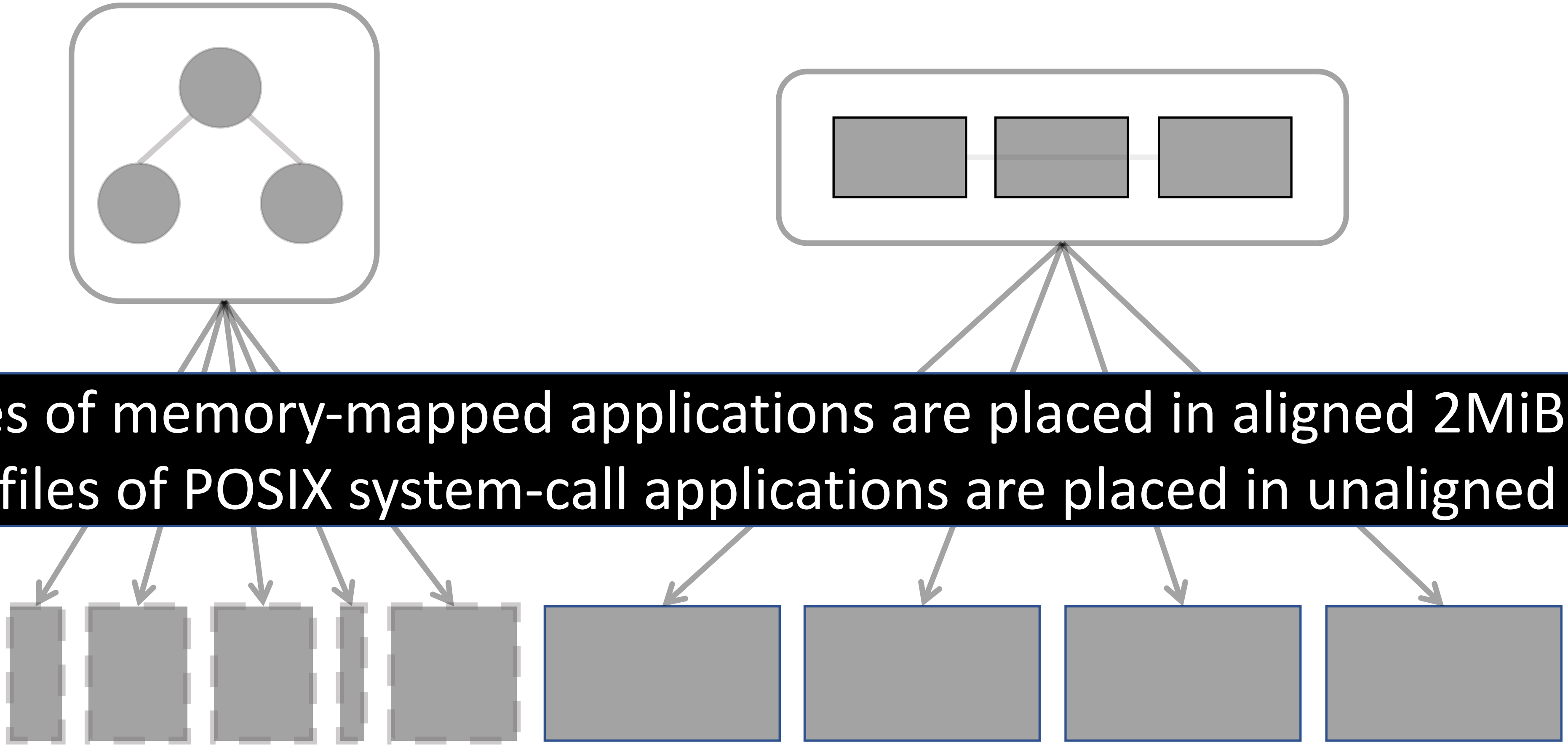

Large files of memory-mapped applications are placed in aligned 2MiB extents, small files of POSIX system-call applications are placed in unaligned holes

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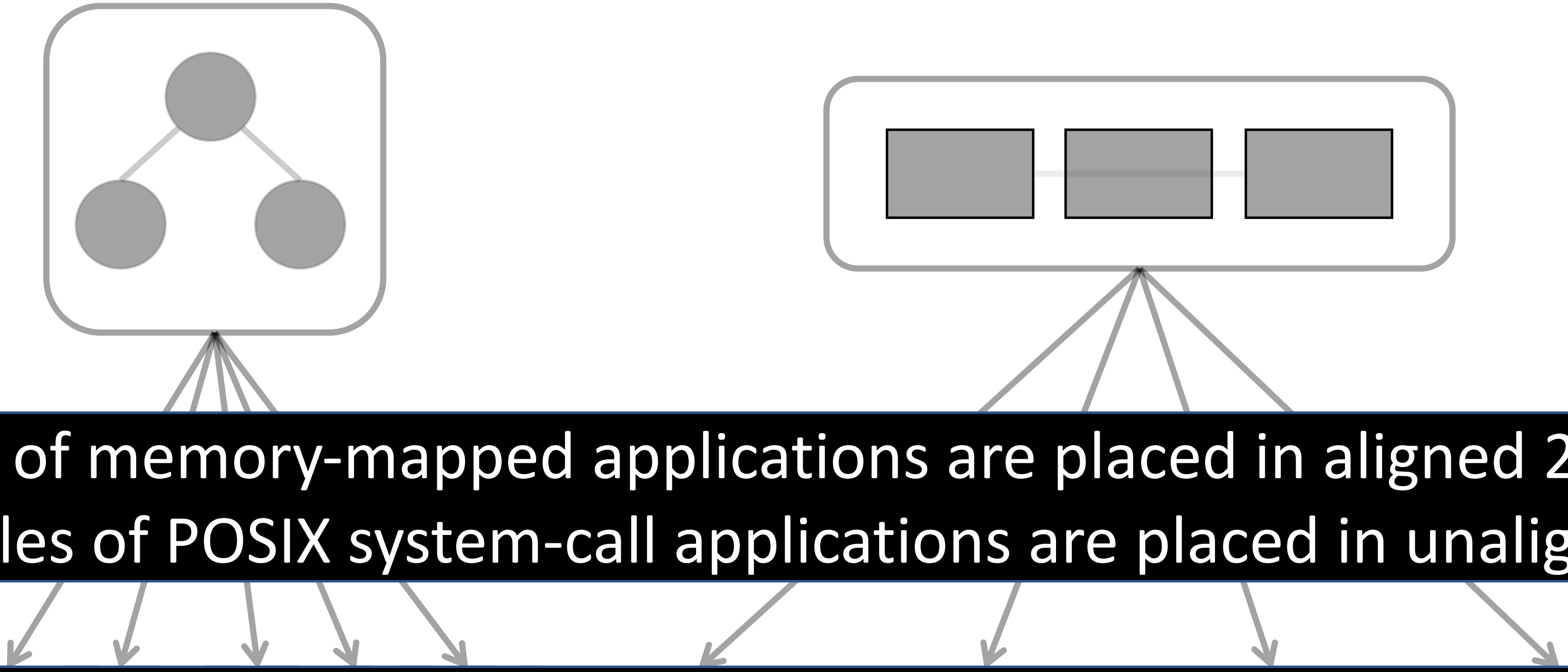

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Hugepages are aggressively reclaimed on file deallocations

Insights behind WineFS

- Allocate memory-mapped files on aligned & contiguous extents

  Limitations of other file systems:

  - ext4-DAX and xfs-DAX preserve contiguity of free-space but not alignment

- Achieve high scalability while preserving hugepage-aligned extents

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- Achieve high scalability while preserving hugepage-aligned extents

  Limitations of other file systems:

  - Per-inode log of NOVA fragments free space
  - Per-process log of Strata wastes aligned extents

Achieving high scalability while avoiding fragmentation

WineFS uses per-CPU journals & allocation groups for achieving high scalability

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WineFS uses per-CPU journals & allocation groups for achieving high scalability

WineFS uses a hybrid data consistency mechanism for avoiding fragmentation of free space

WineFS constructs on-PM layout that avoids fragmentation of free space by containing metadata structures to specific regions on PM

Evaluation

Setup:

- 500 GB partition of Intel Optane DC Persistent Memory
- 28 cores, 112 threads, 32MB LLC

File systems compared:

- ext4-DAX, xfs-DAX, NOVA, Strata, SplitFS

Evaluation

What is the memory-mapped performance of WineFS after aging?

What is the POSIX system-call performance of WineFS?

Is WineFS scalable?

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What is the memory-mapped performance of WineFS after aging?

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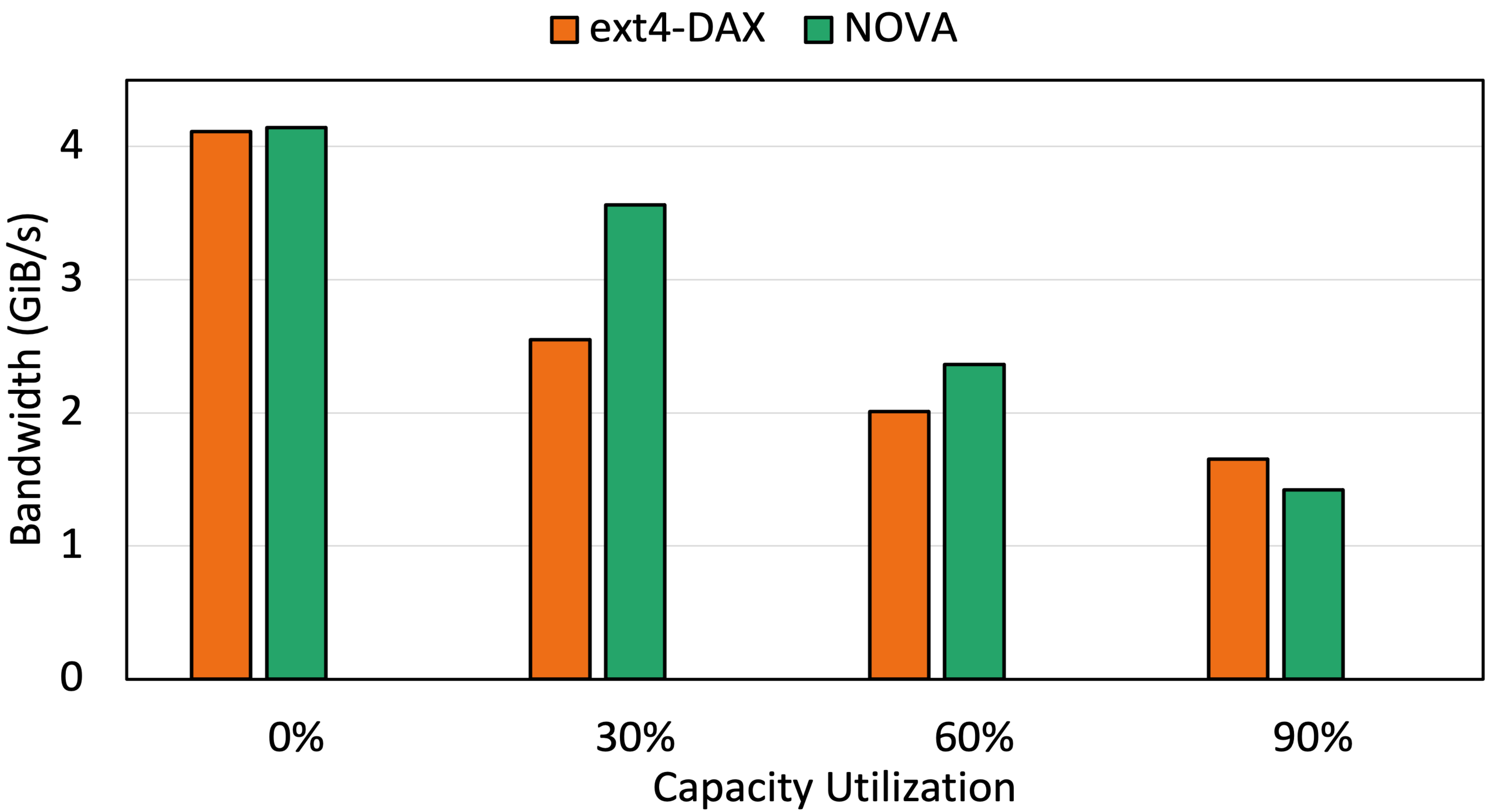

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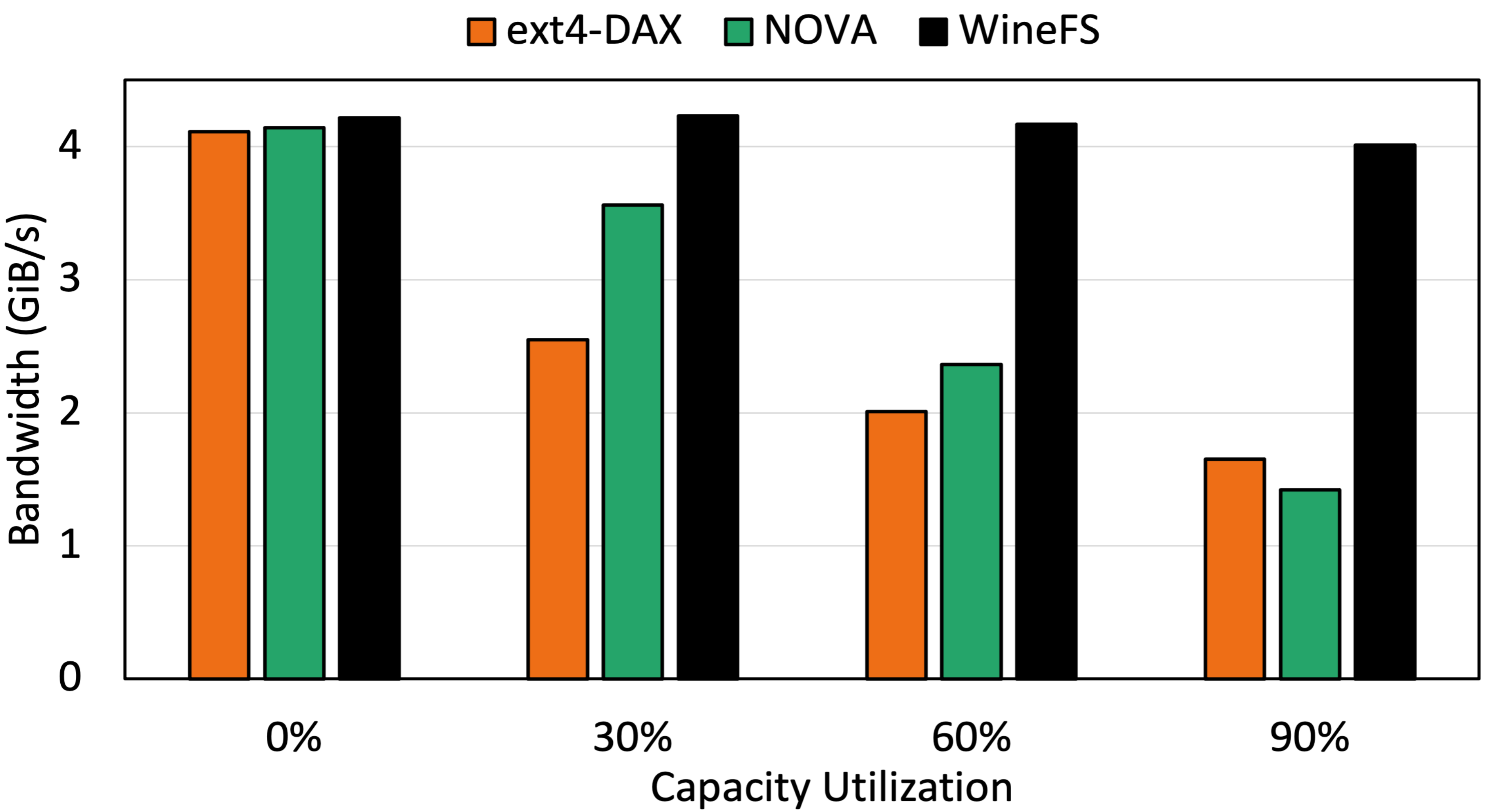
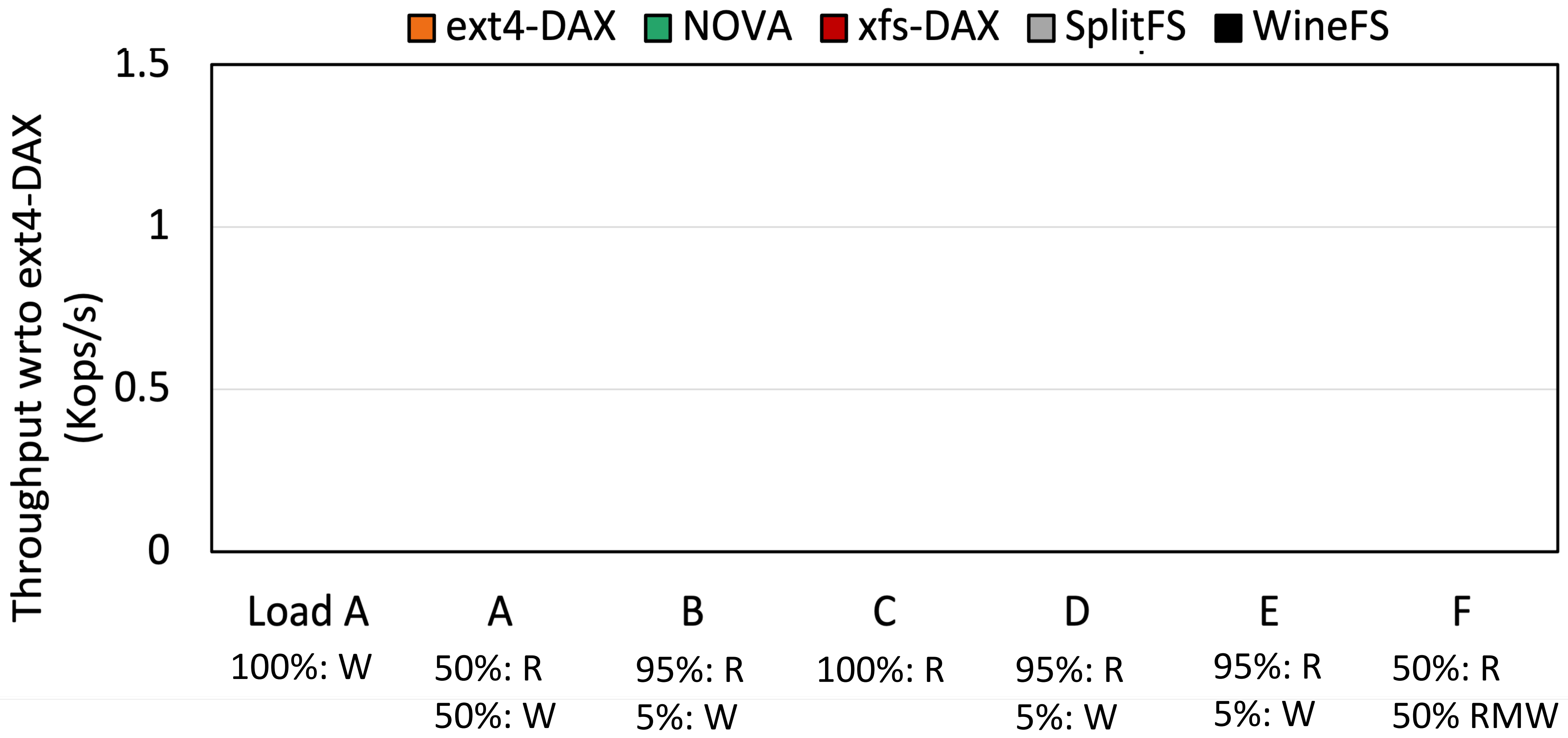


YCSB on RocksDB

Yahoo! Cloud Serving Benchmark - Industry standard macro-benchmark

Insert 5M keys. Run 5M operations. Key size = 16 bytes. Value size = 1K



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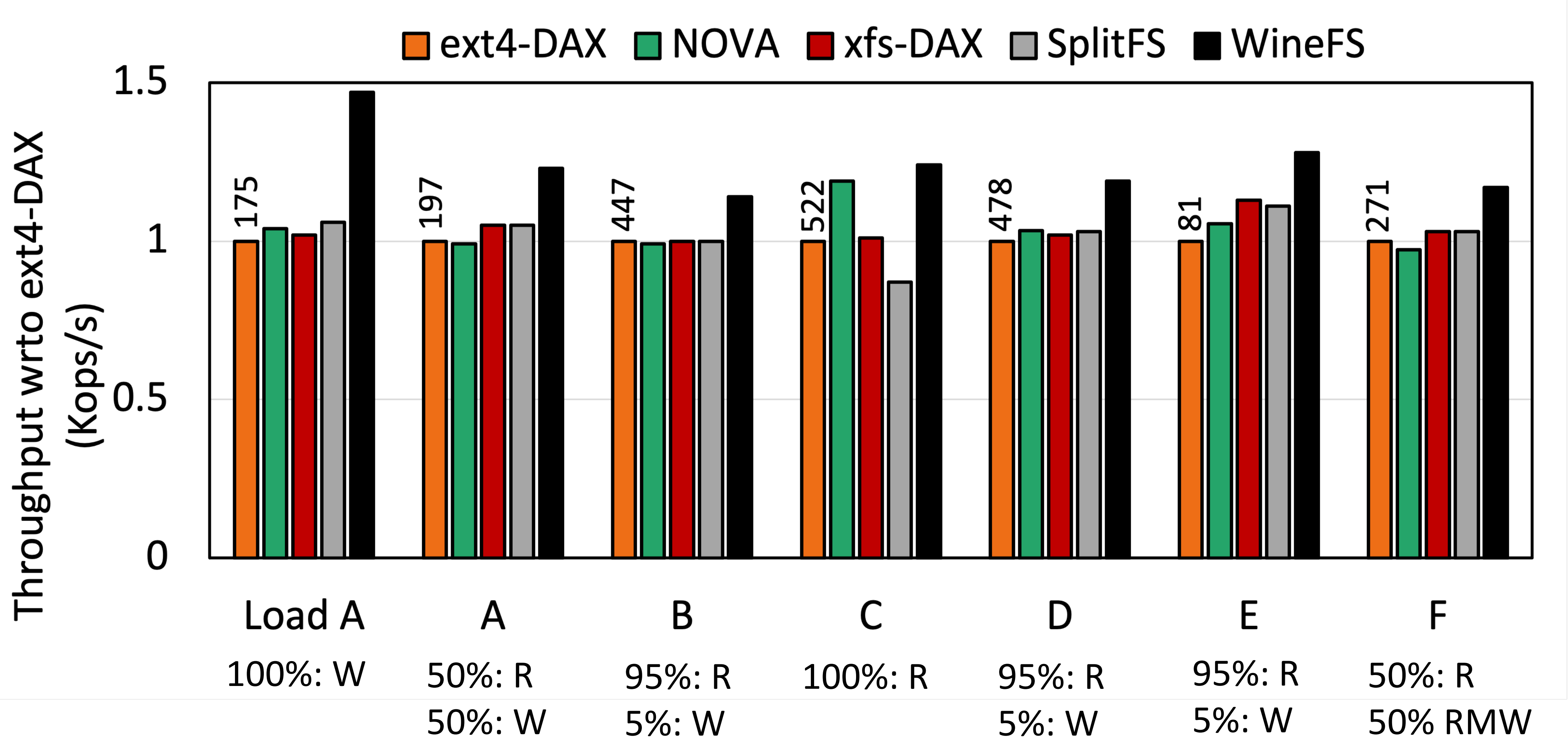

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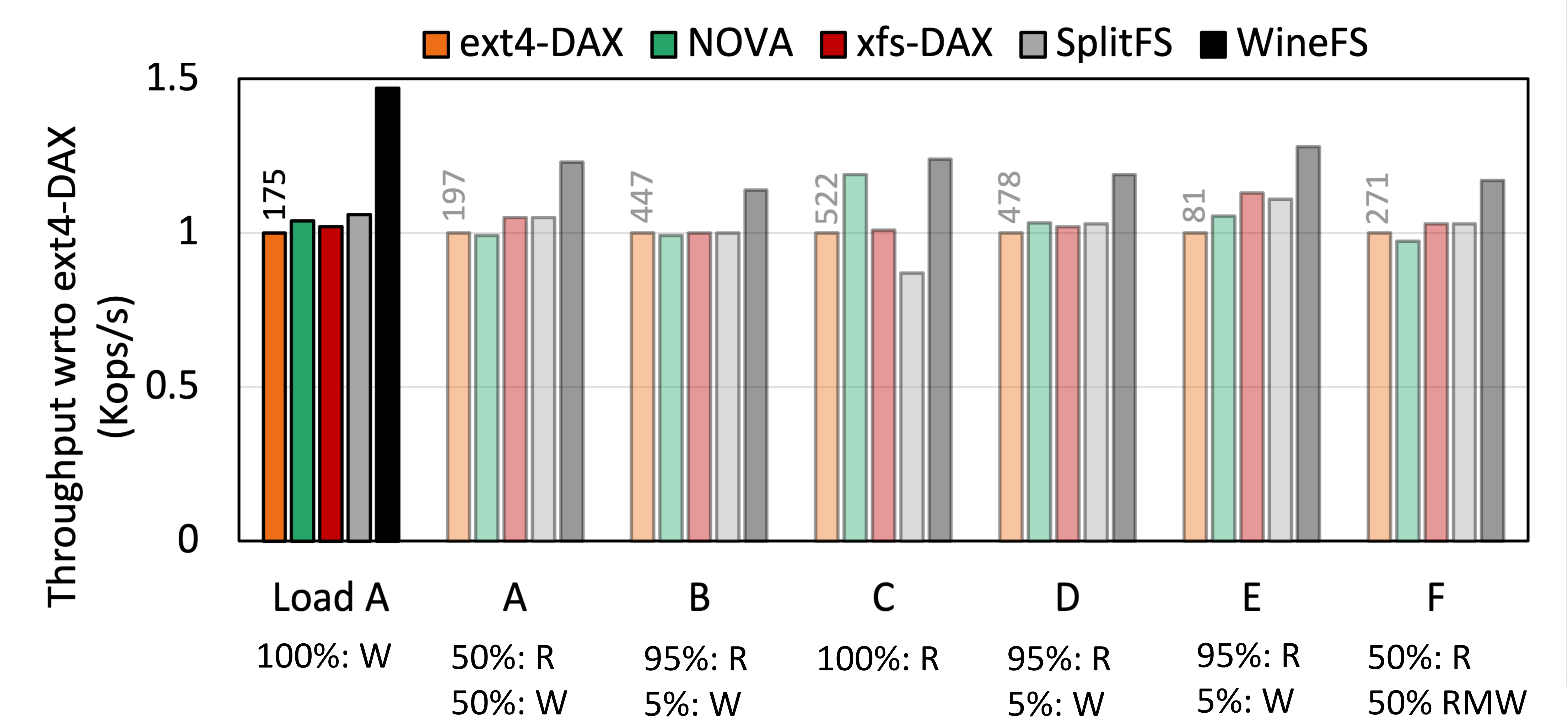

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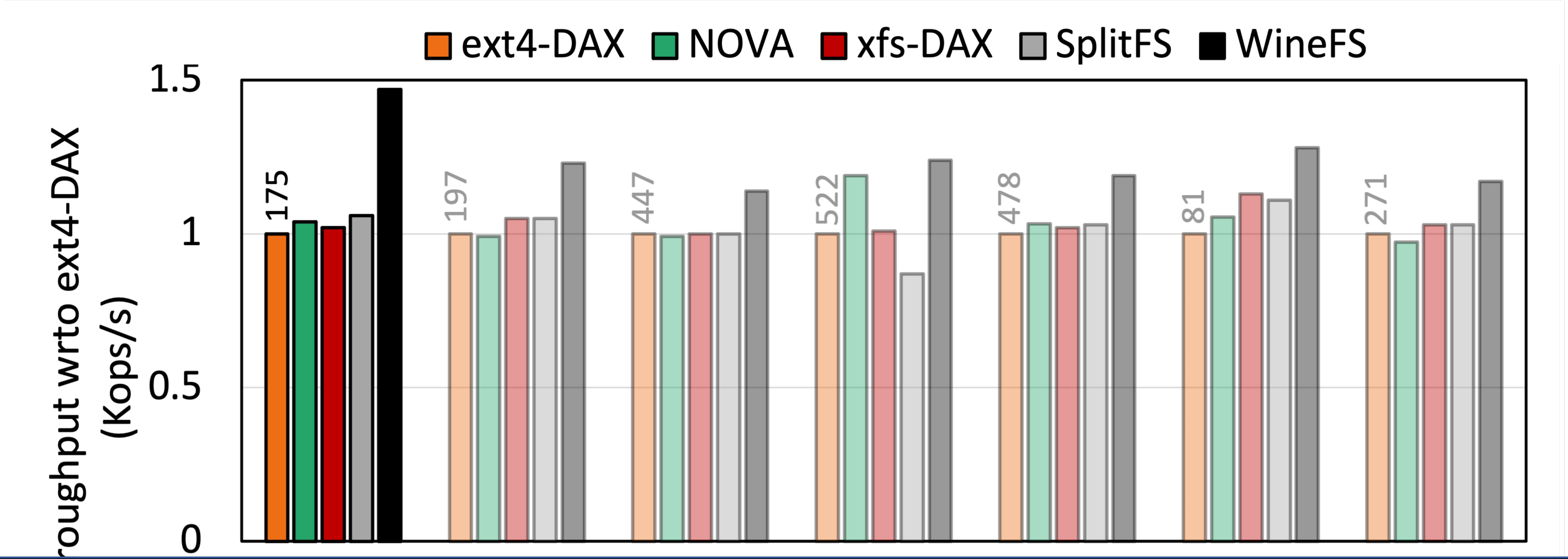


WineFS suffers from 30x fewer page faults compared to NOVA

Conclusion

WineFS demonstrates that it is possible to design a file system that…

Achieves high performance for new memory-mapped applications

Achieves high performance and scalability for legacy POSIX applications

Maintains high performance in the presence of aging and under high utilization

Artifacts Available acm V1.1

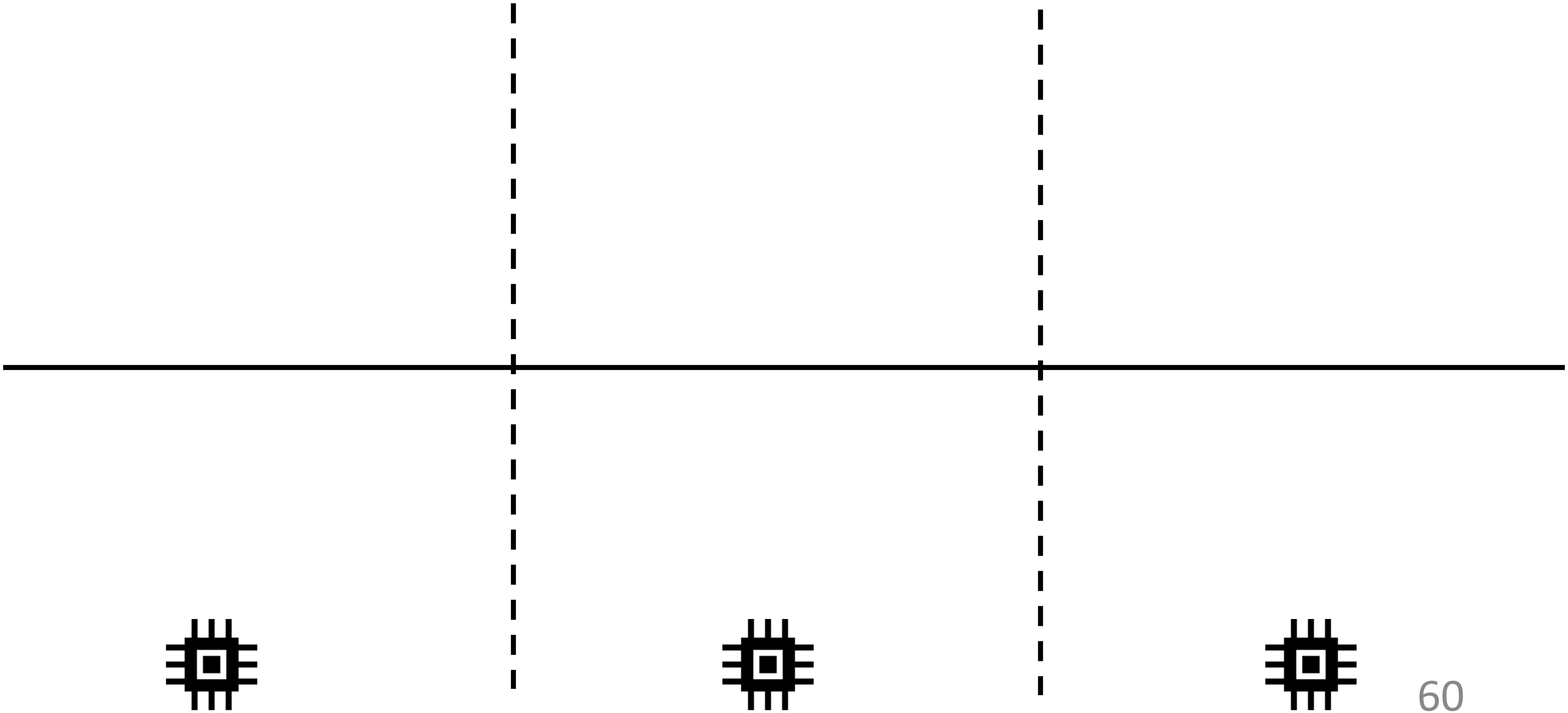
Artifacts Evaluated acm Functional V1.1

Results Reproduced acm V1.1

https://github.com/utsaslab/winefs

Backup Slides

High-level Design & On-PM Layout



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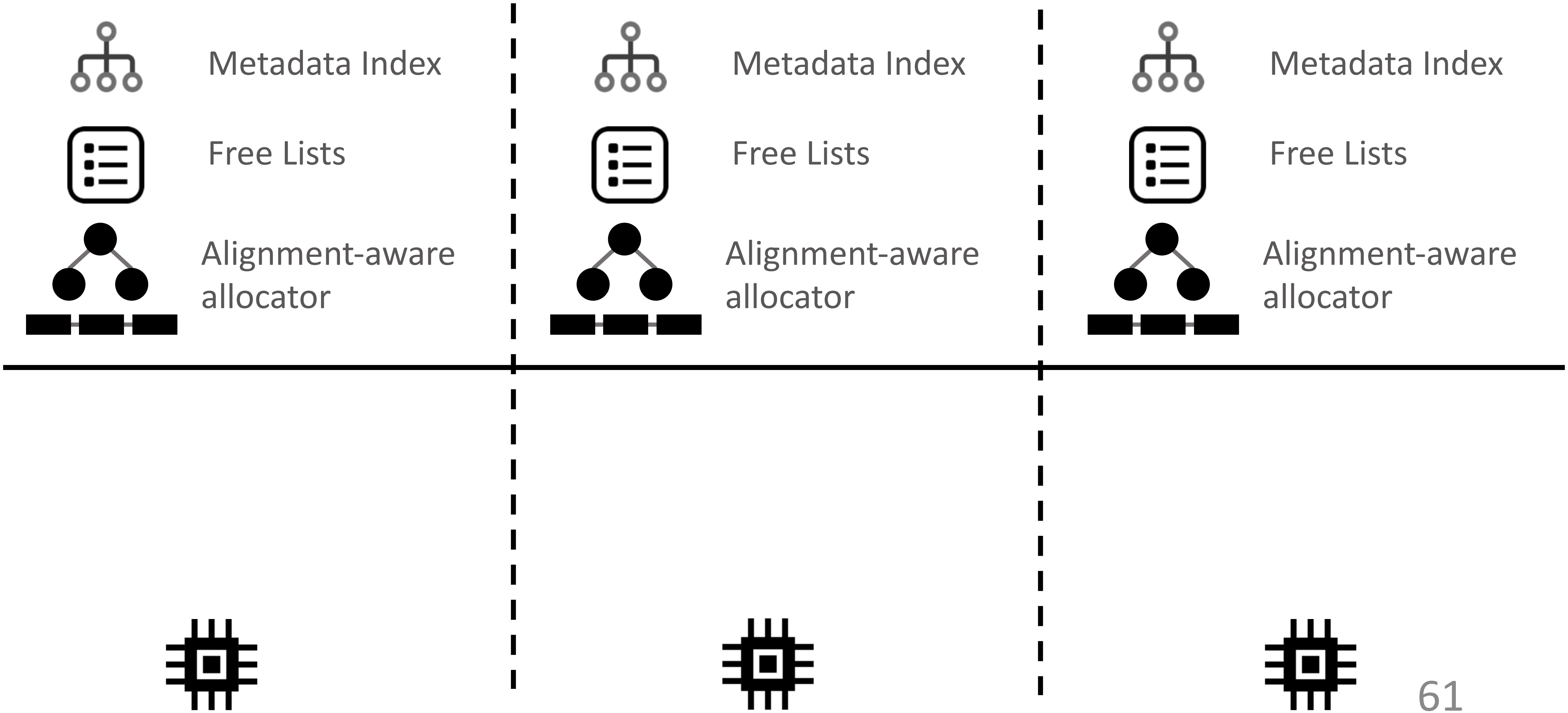

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Free Lists
Alignment-aware allocator
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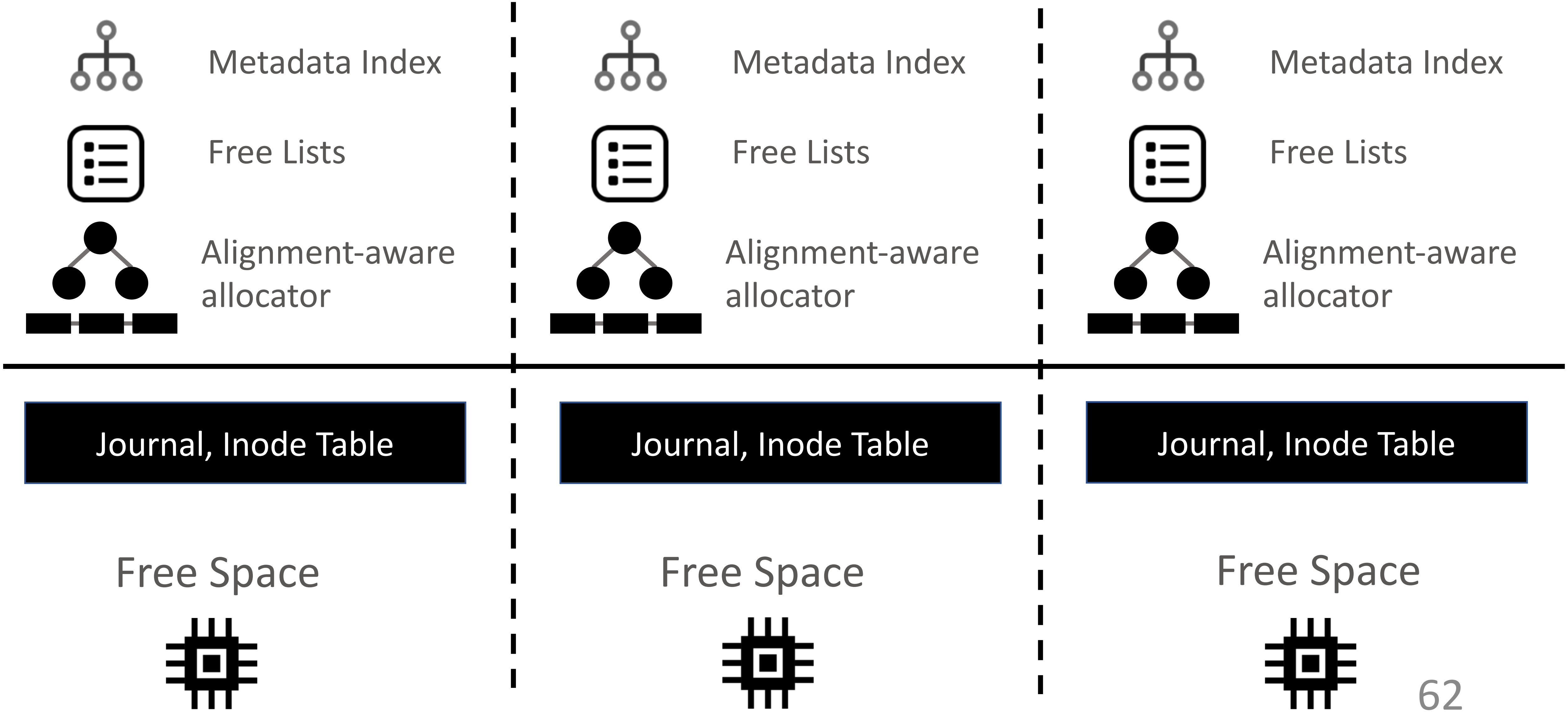

Metadata Index

Free Lists

Alignment-aware allocator

Journal, Inode Table

Free Space

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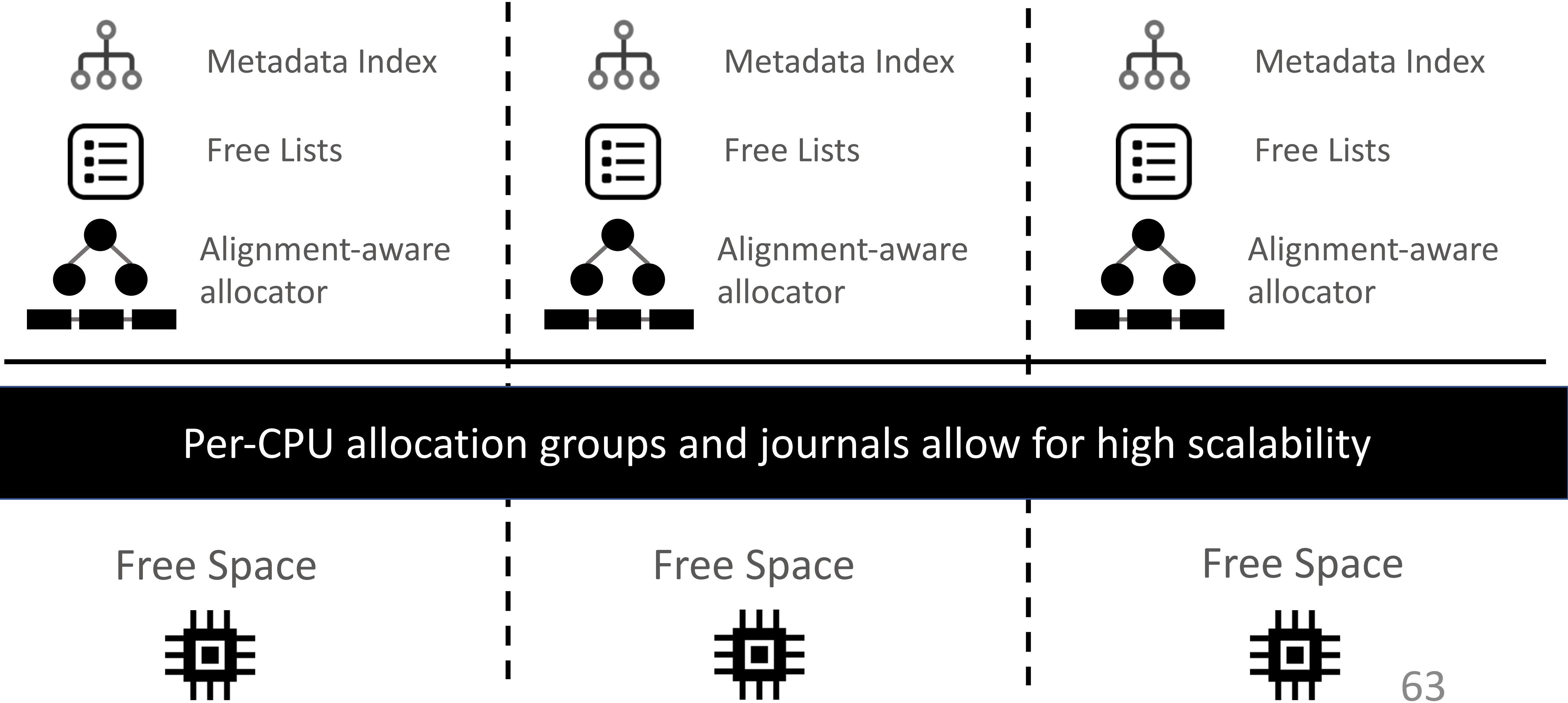

Per-CPU allocation groups and journals allow for high scalability

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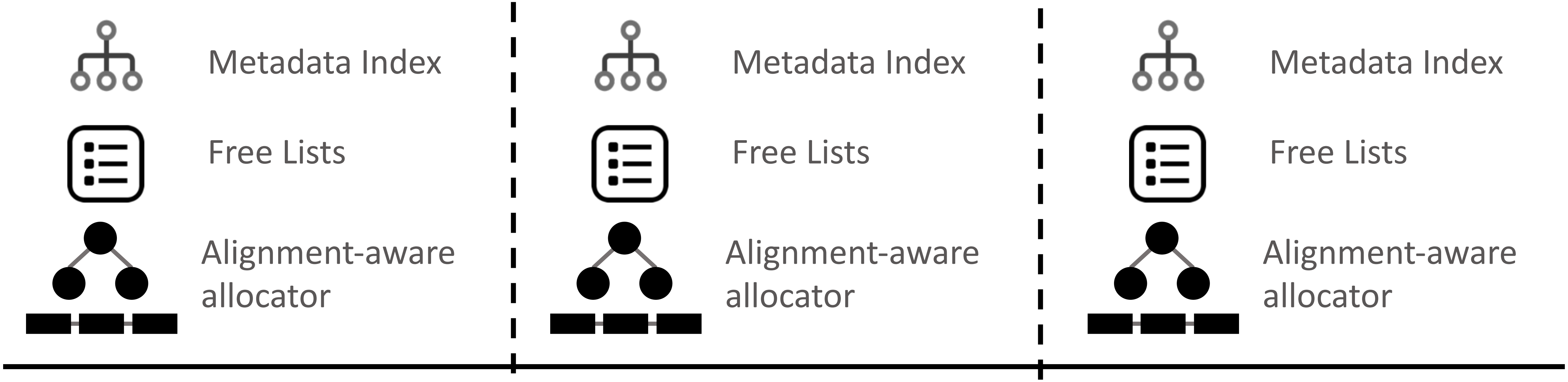

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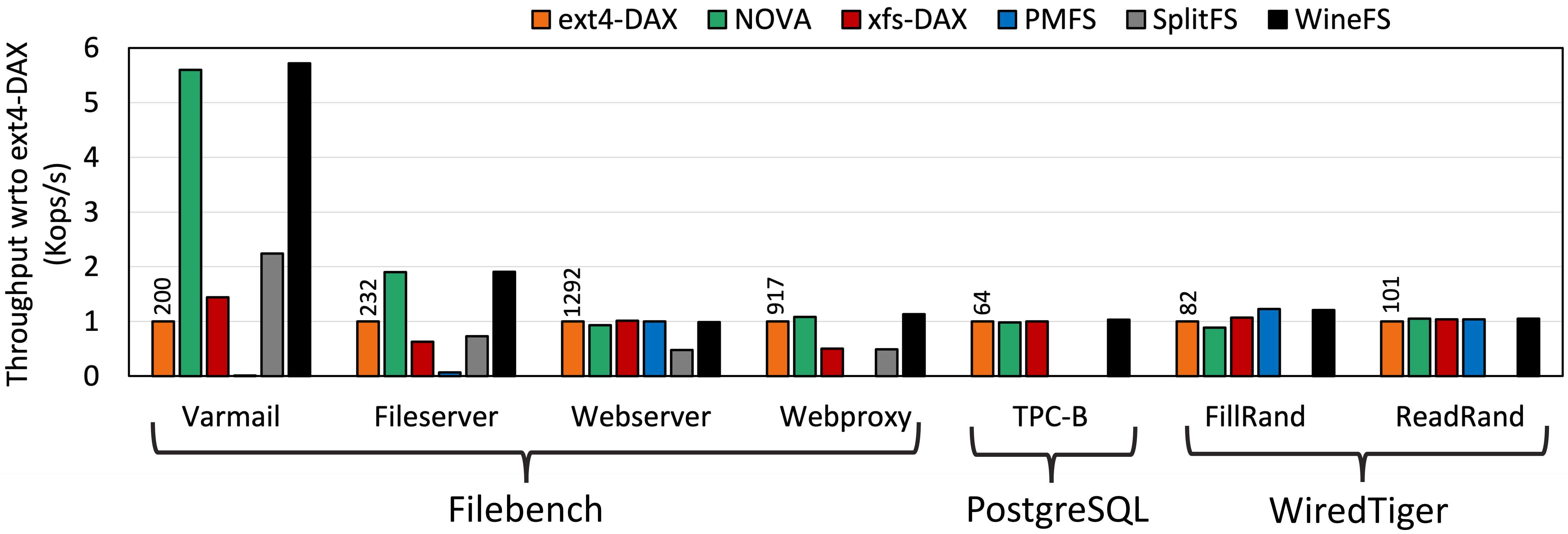
Contained metadata on PM avoids fragmentation of free-space

POSIX system-call Applications

Clean file system performance on POSIX system-call applications



WineFS equals or outperforms other file systems on all applications