OSDI 25

Fast and Synchronous Crash Consistency with Metadata Write Once File System

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Crash Consistency

Crash consistency is the **fundamental** demand for file systems to ensure **correct crash recovery** for applications.

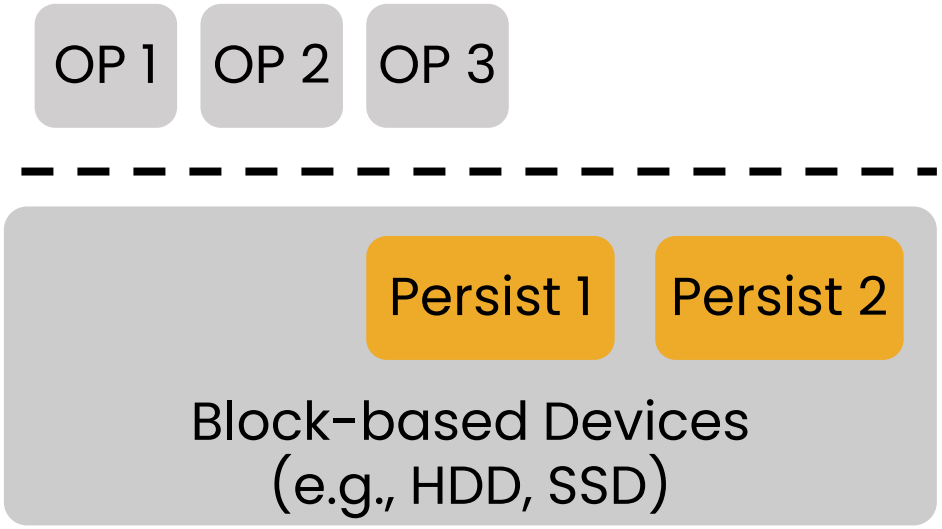
Database applications

Network storage

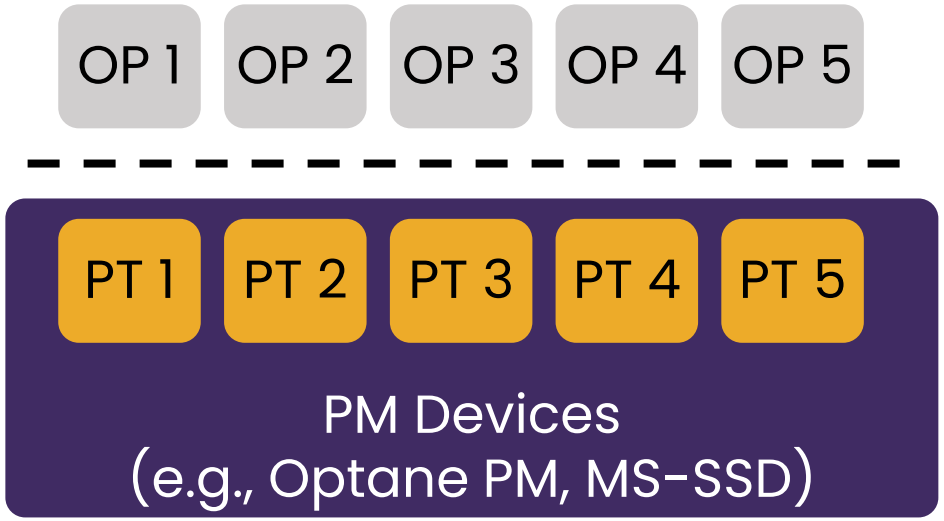
Storage for LLM

Synchronous Crash Consistency on PM

Low-latency persistent memory (PM) encourages file systems to pursue **synchronous crash consistency**.



Traditional Async Crash Consistency (for Block-based File Systems)



Synchronous Crash Consistency (for PM File Systems)

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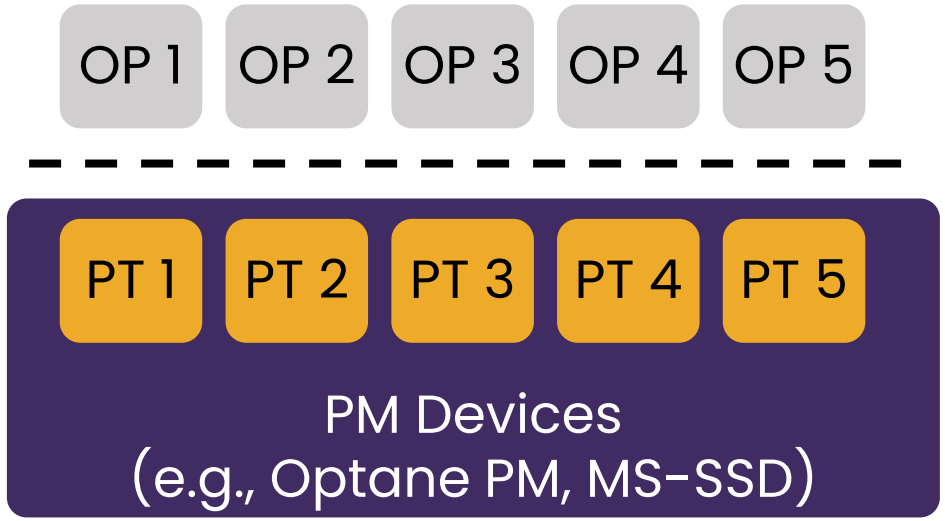


Synchronous Crash Consistency (for PM File Systems)

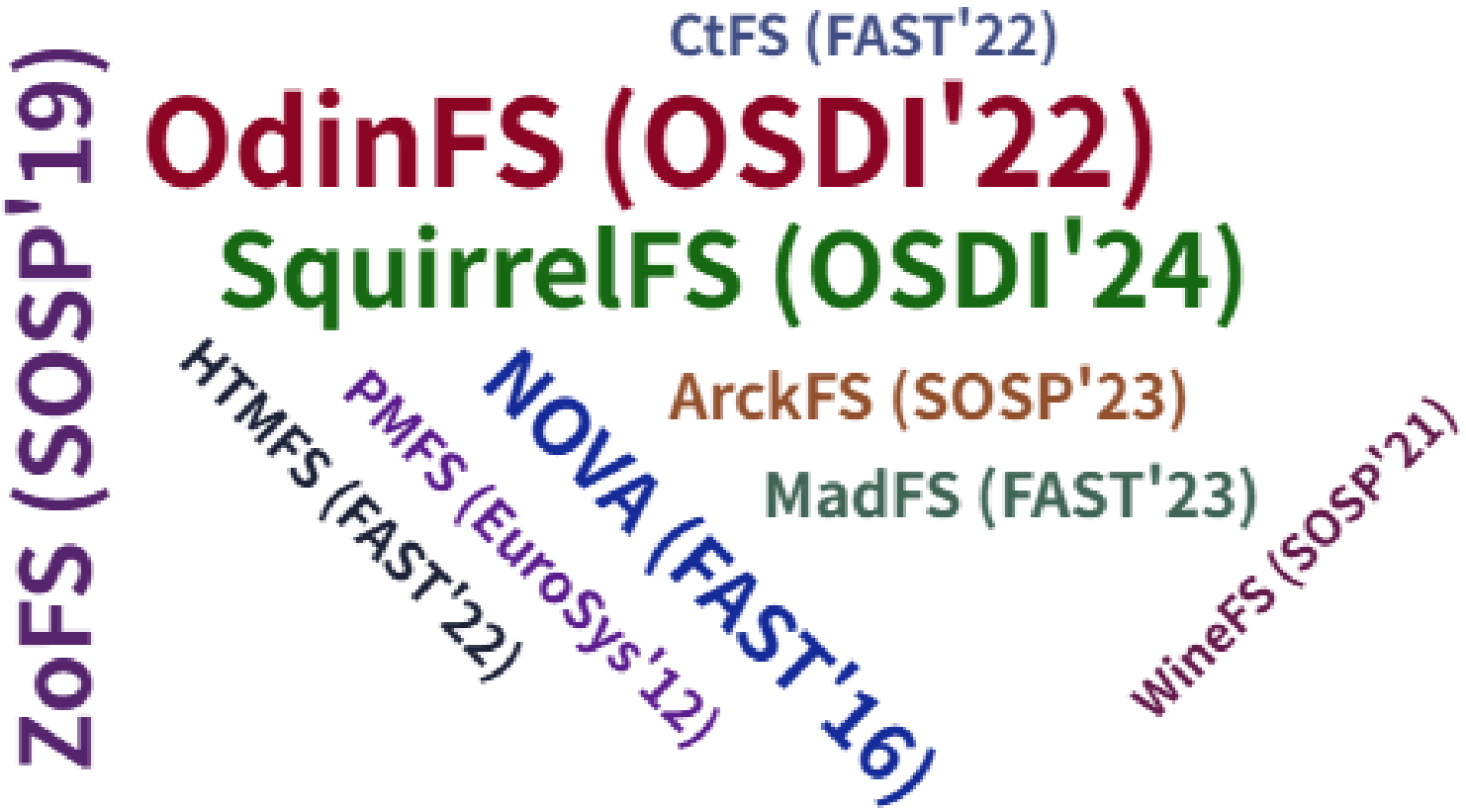
Advantages

✓**Avoid synchronization BUG**
(e.g., Avoid misused fsync)

✓**Reduce sync overhead**
(e.g., NFS strict sync protocol)

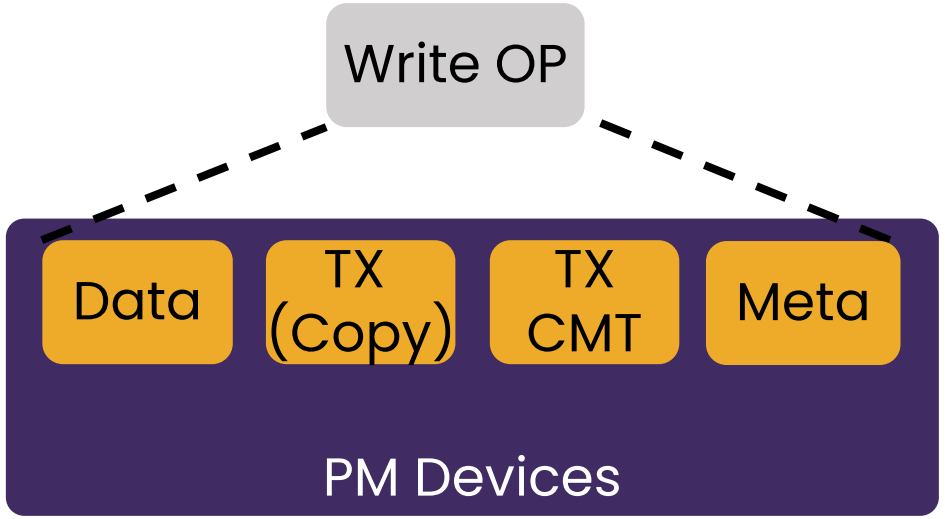
PM File Systems

Numerous PM file systems adopt synchronous crash consistency

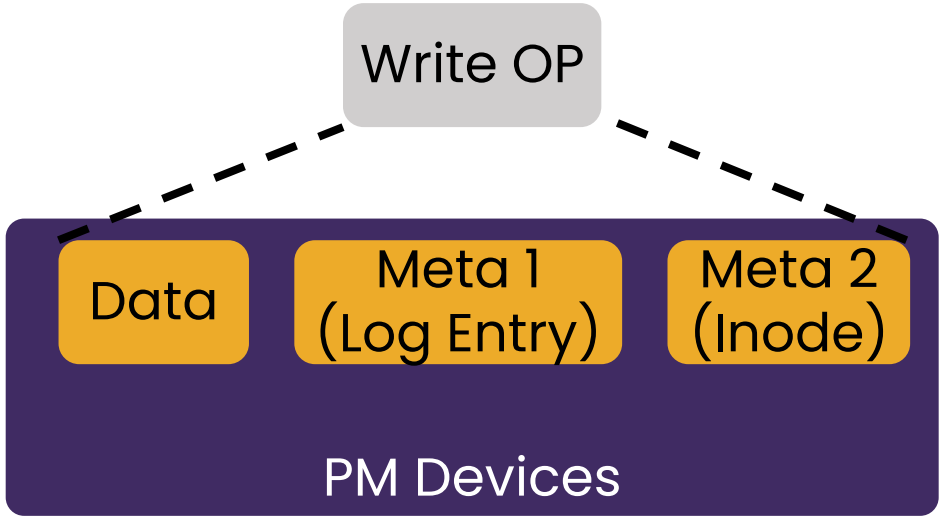


Synchronous Crash Consistency: How?

Two traditional methodologies are used for PM file systems



With Additional Writes
(e.g., Journaling File Systems: PMFS)



Without Additional Writes
(e.g., Log-structured File Systems: NOVA)

Synchronous Crash Consistency: How?

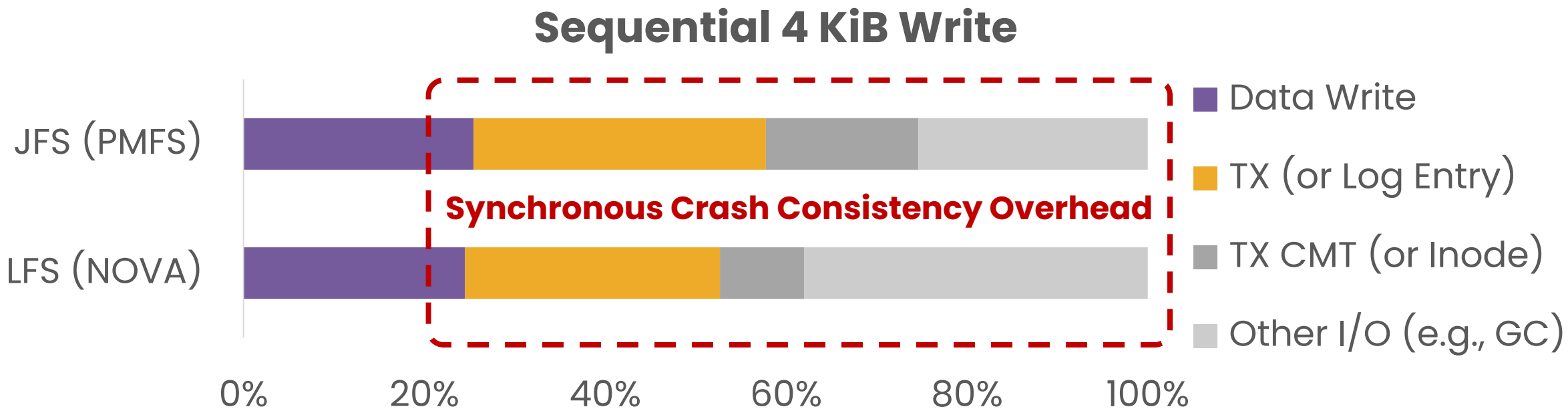
Two traditional methodologies are used for PM file systems

Do they perform well atop PM?

With Additional Writes
(e.g., Journaling File Systems: PMFS)

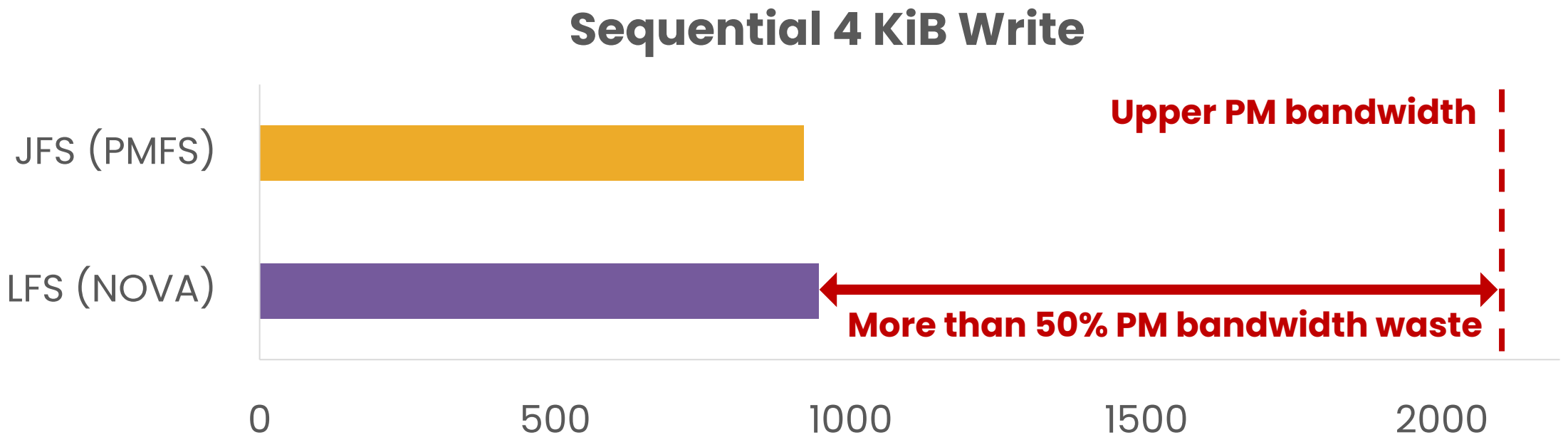
Without Additional Writes
(e.g., Log-structured File Systems: NOVA)

Crash Consistency Overhead on PM (1/2)



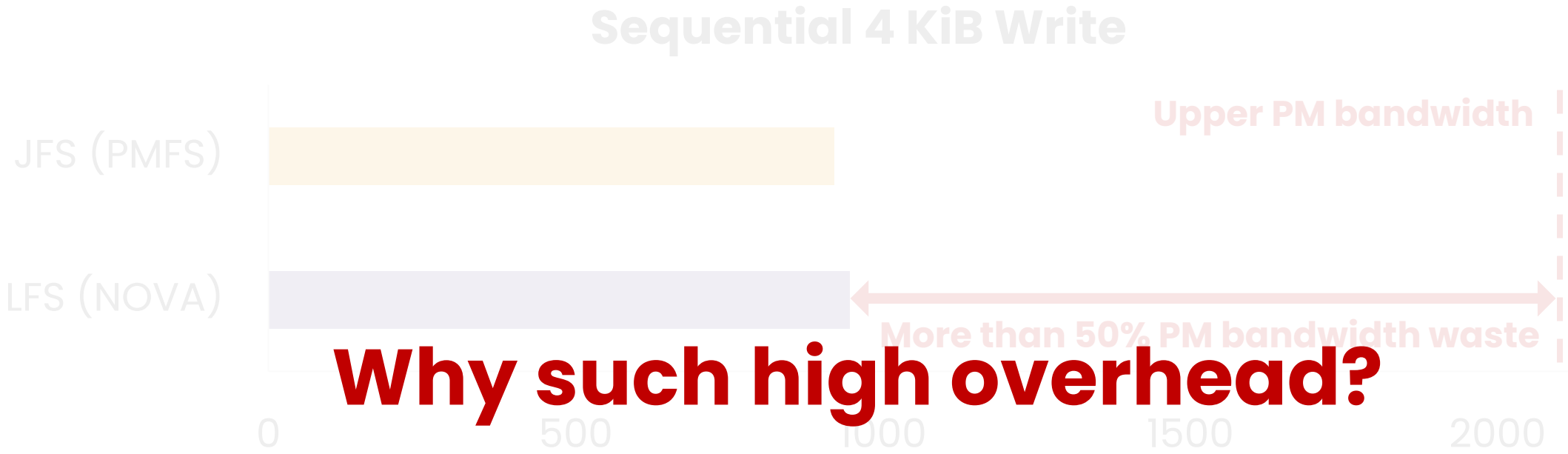
- **Additional Writes:** PMFS Journaling file system (JFS)
- **No Additional Writes:** NOVA Log-structured file system (LFS)
- **Takeaways:** Synchronous crash consistency overhead atop PM dominates **more than 75% overhead** of I/O path

Crash Consistency Overhead on PM (2/2)



- **Upper bound:** PM write BW is around 2.2 GiB/s in our machine
- **Results:** Existing synchronous crash consistency results in a more than 50% PM bandwidth waste.
- **Takeaways:** **Existing approaches do NOT suit well for PM.**

Crash Consistency Overhead on PM (2/2)



Why such high overhead?

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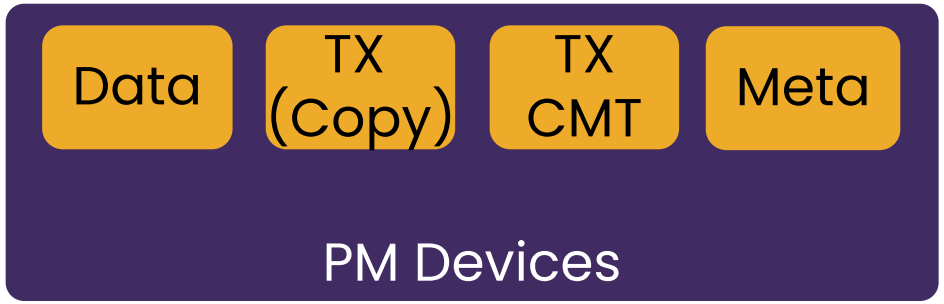
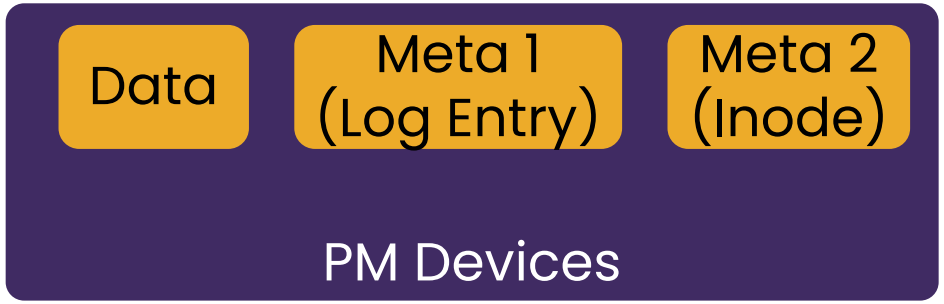
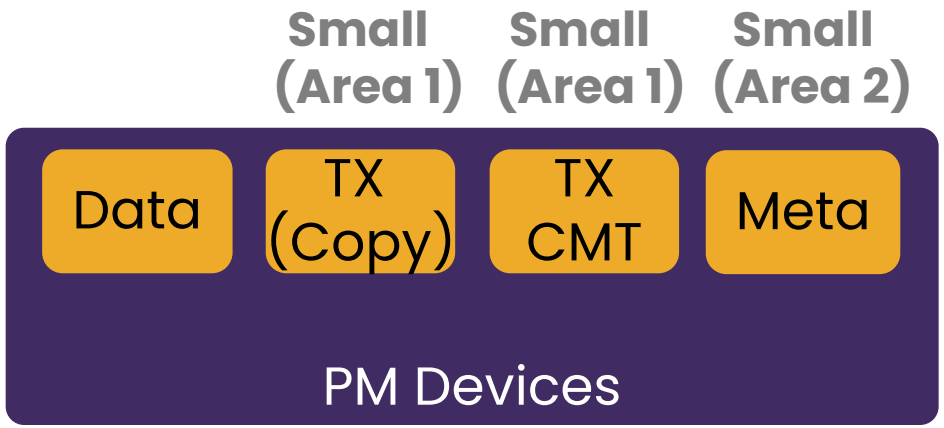
Deficiency Analysis

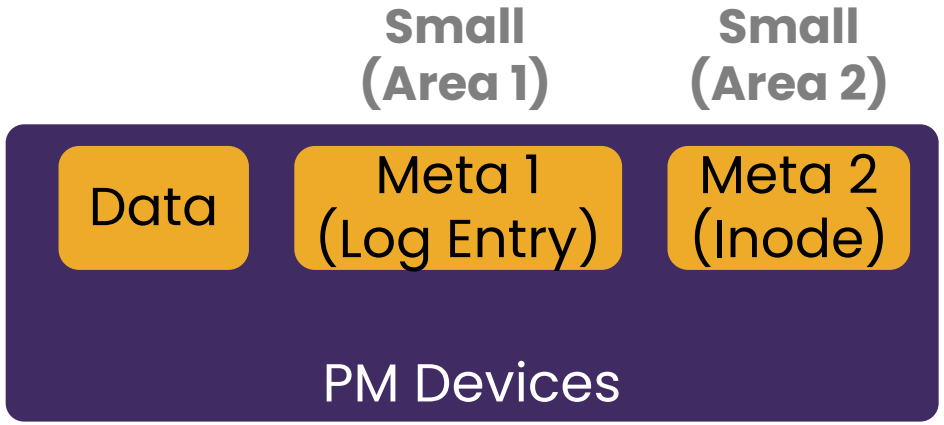
- **Root cause: Many small, random,** and **ordered** metadata I/O





Deficiency Analysis





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- **Small & Random:** I/O amplification due to PM's coarse I/O granularity

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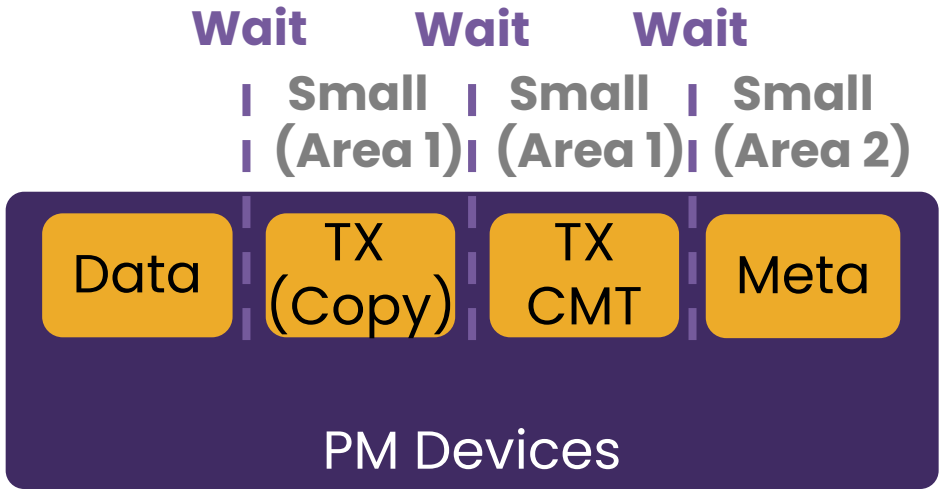

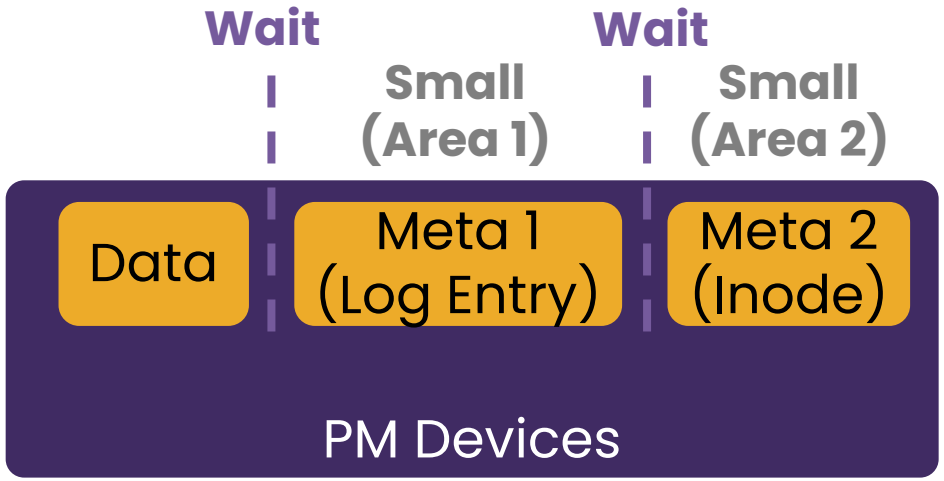

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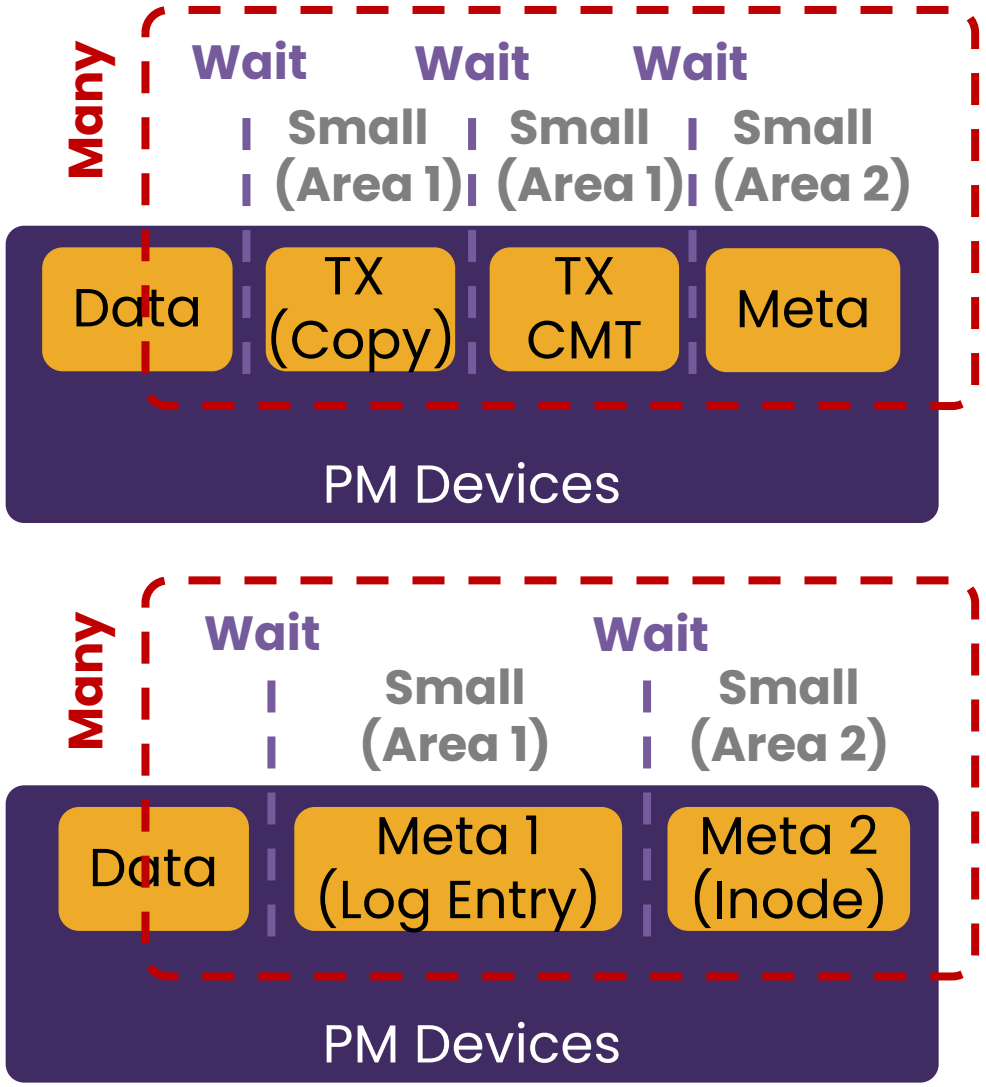

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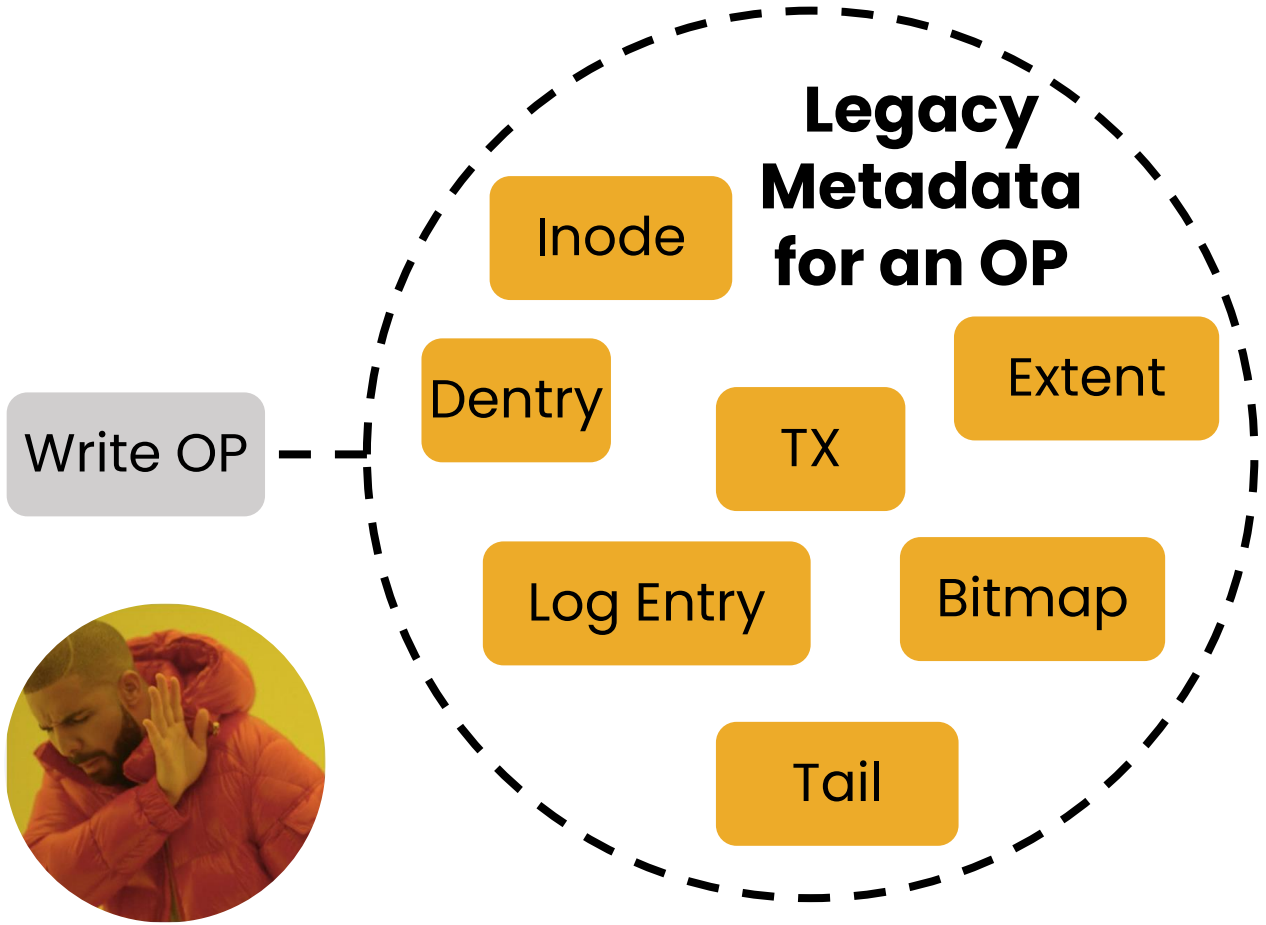
- **Small & Random:** I/O amplification due to PM's coarse I/O granularity
- **Ordered:** Waiting for previous data transfer, limiting I/O concurrency
- **Many:** Further exacerbate the previous I/O overheads.

Our Goal

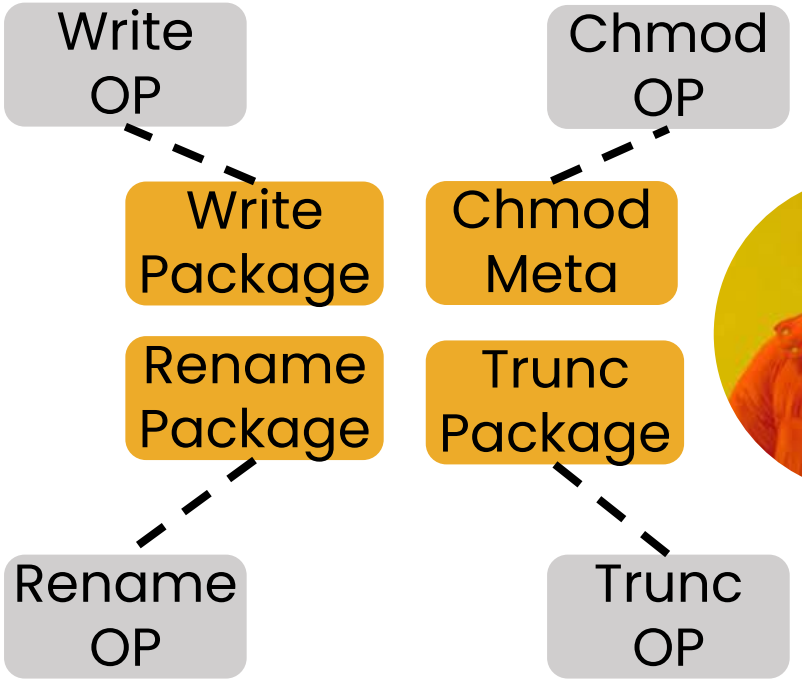
A new crash consistency mechanism to minimize metadata I/O and ordering points

Key Insight



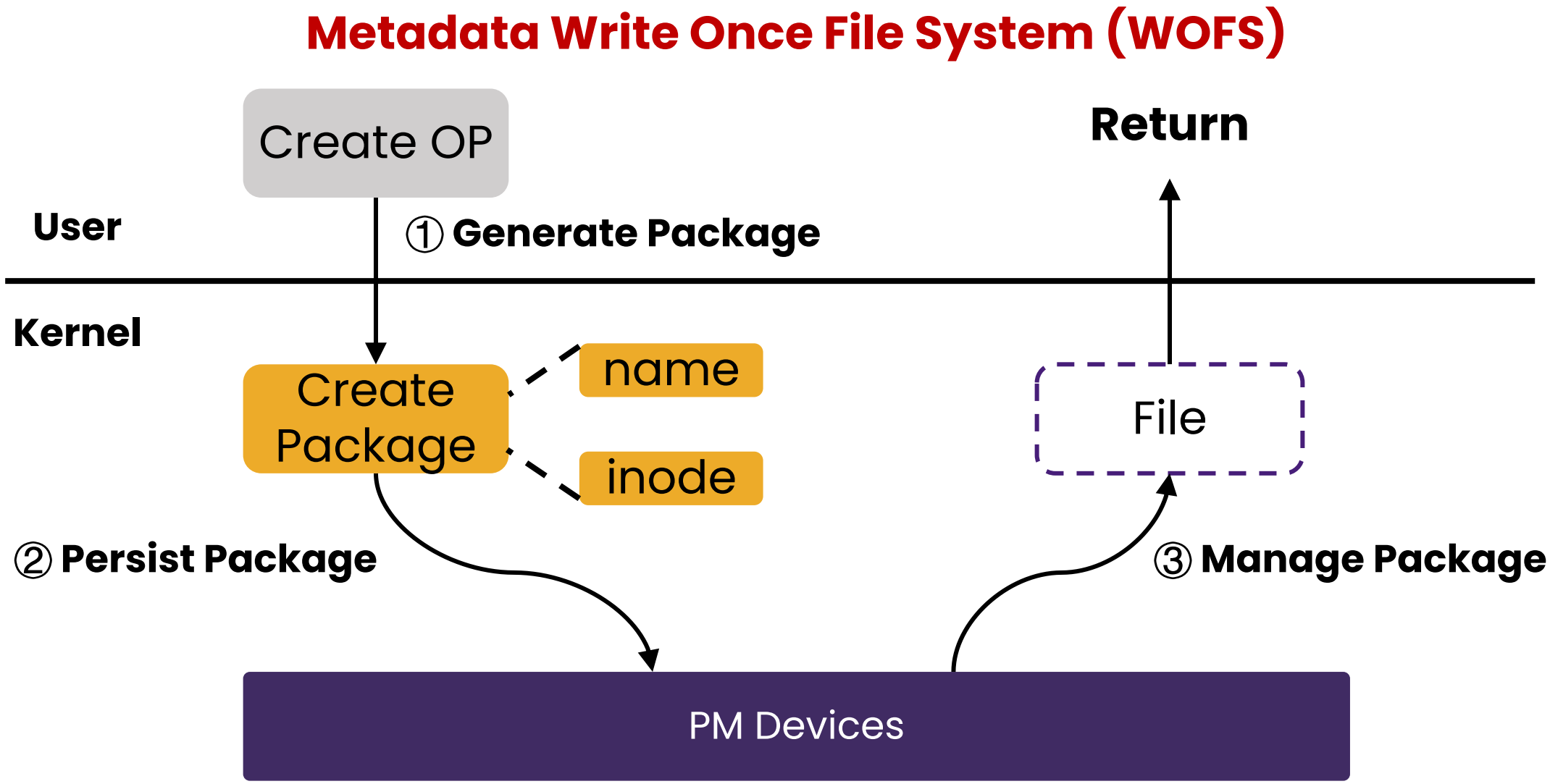
Struggle to orchestrate I/O for crash consistency

One package for one OP



Rethink metadata for the optimal crash consistency

Intuitive Example: Create



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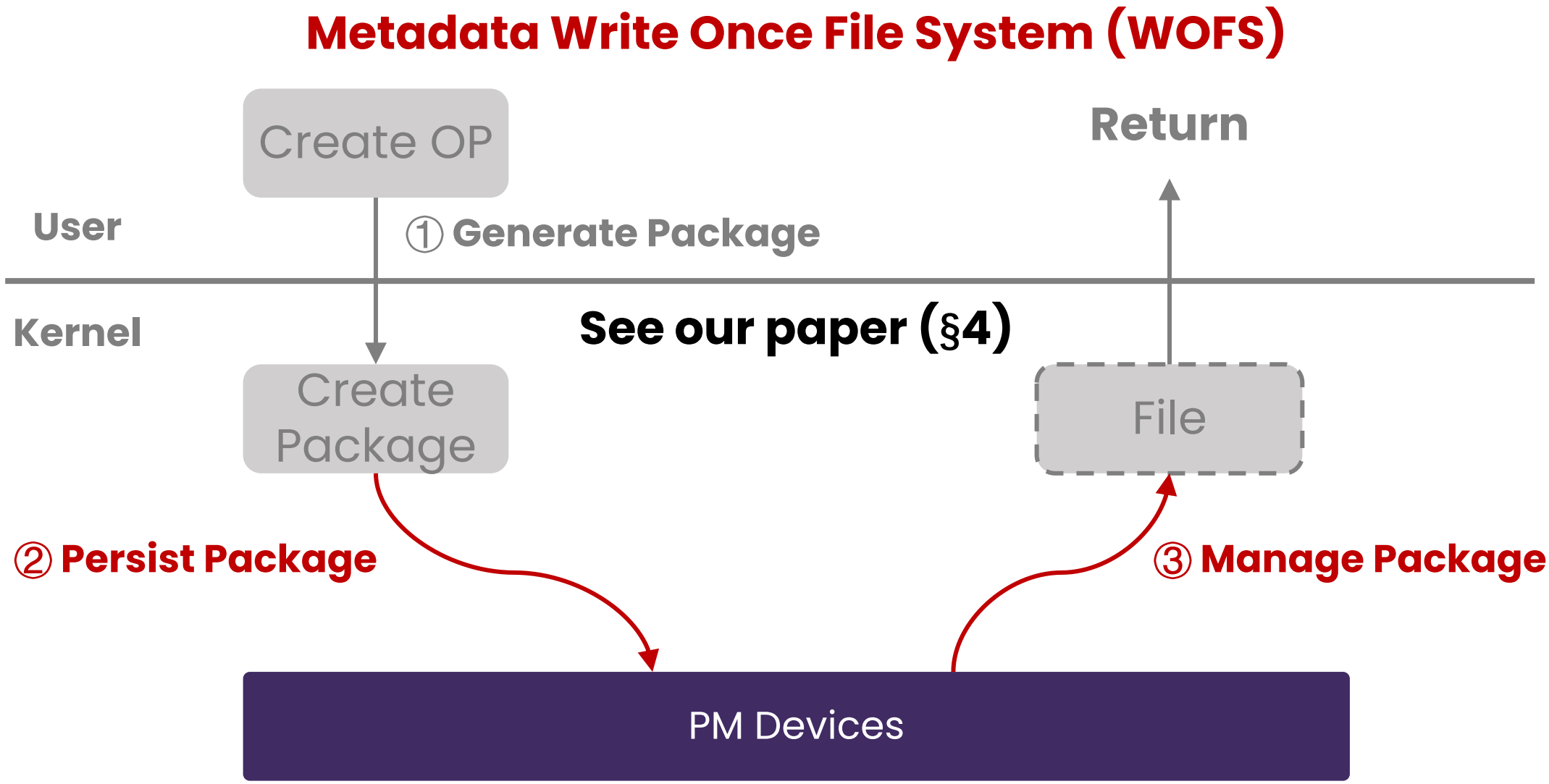

Package Persistence (1/2)

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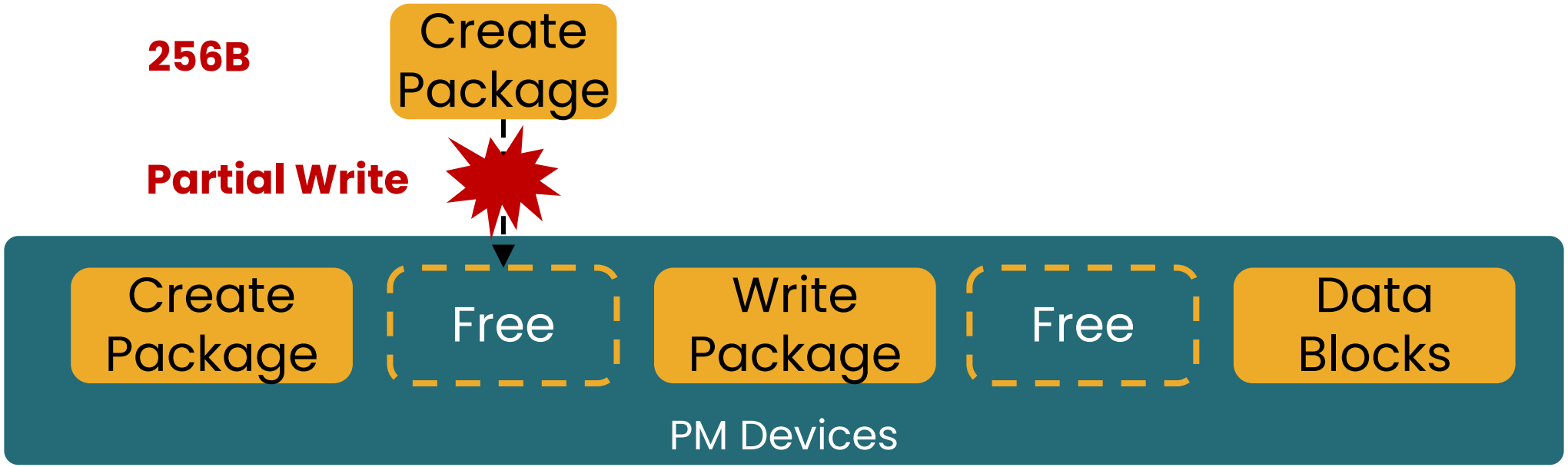
  - **Our approach:** **Non-log layout, using free lists for allocation**

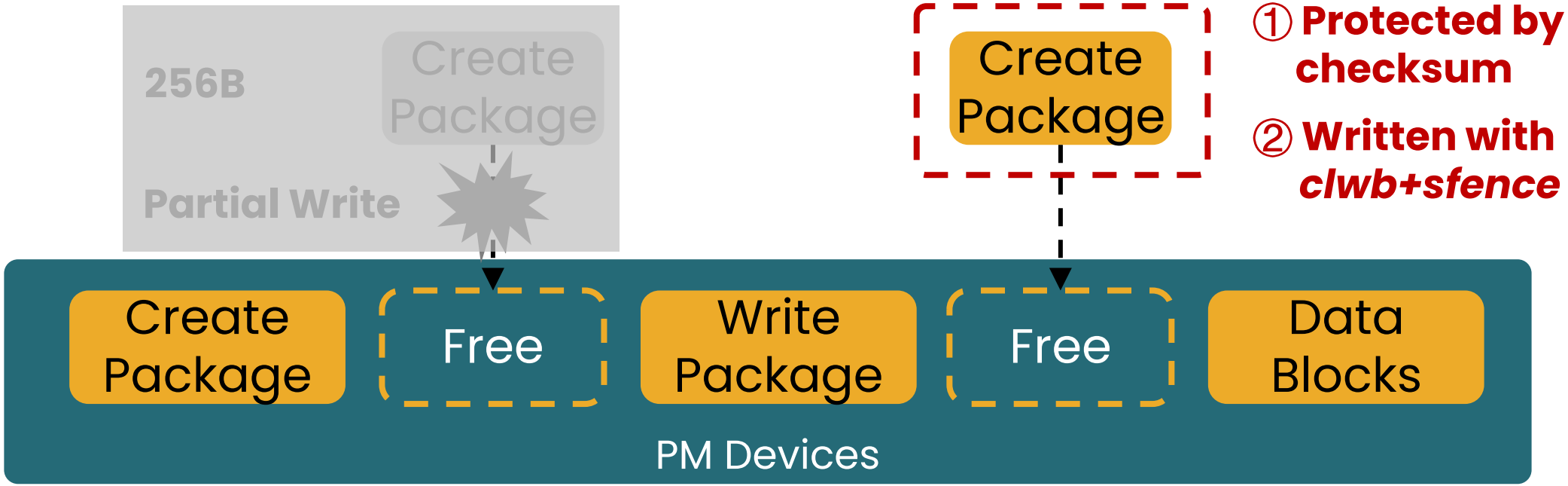
Package Persistence (2/2)

- **How to persist a package?**
  - **Problem:** The package can be large



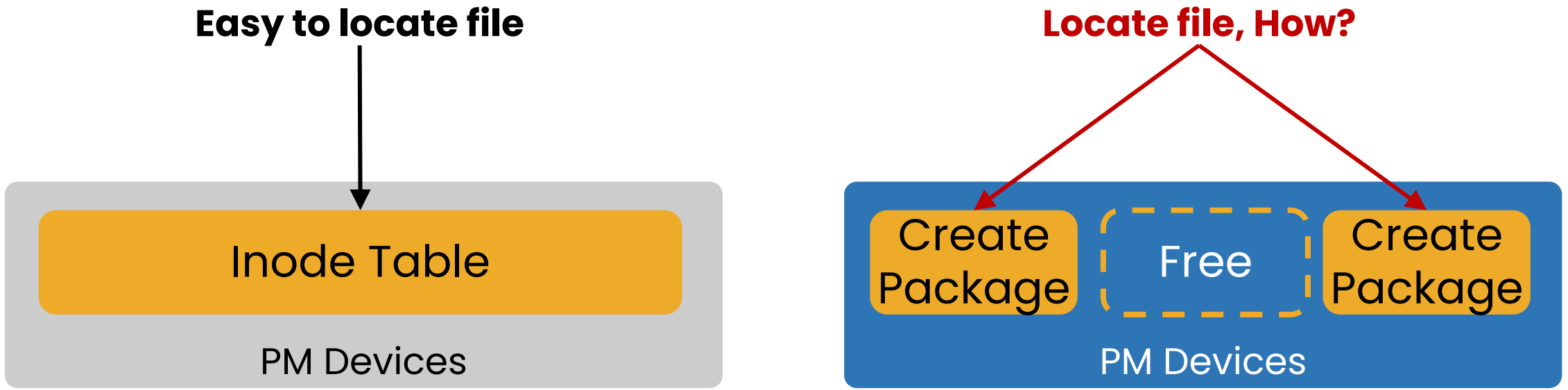
Package Persistence (2/2)

- **How to persist a package?**
  - **Problem:** The package can be large
  - **Our approach: Protect package with checksum**



Package Management (1/2)

- **How to provide compatible services?**
  - **Problem:** Packages violate metadata objects



Package Management (1/2)

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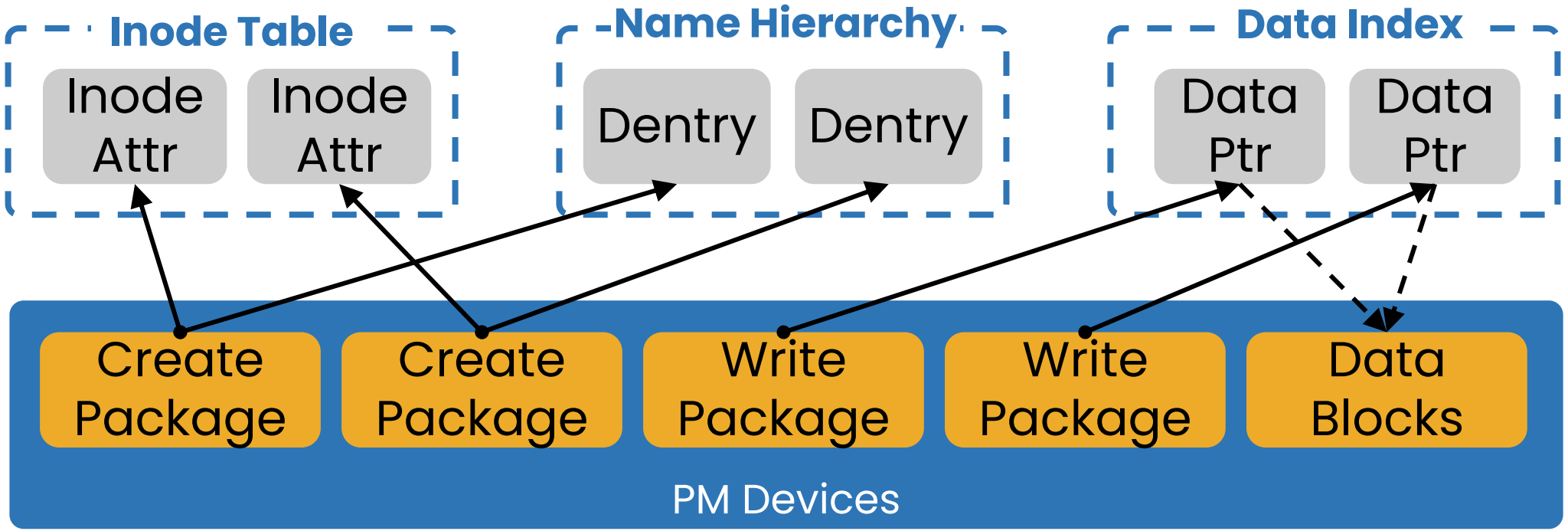
  - **Our approach:** **Package translation layer (PTL)**



Package Management (2/2)

- **How to reclaim packages?**
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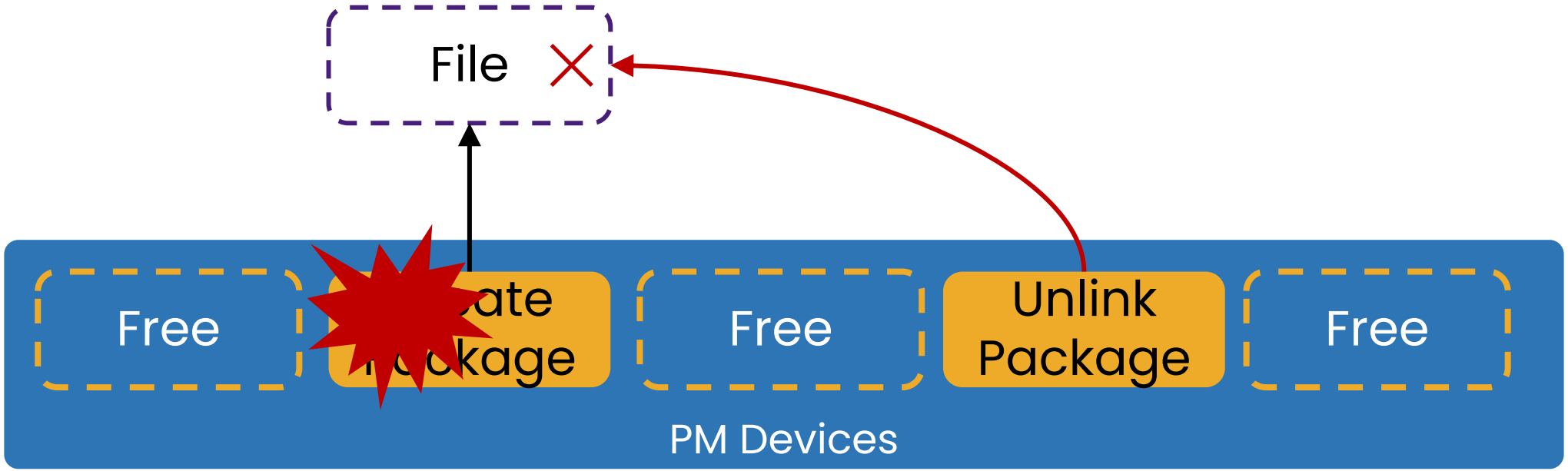

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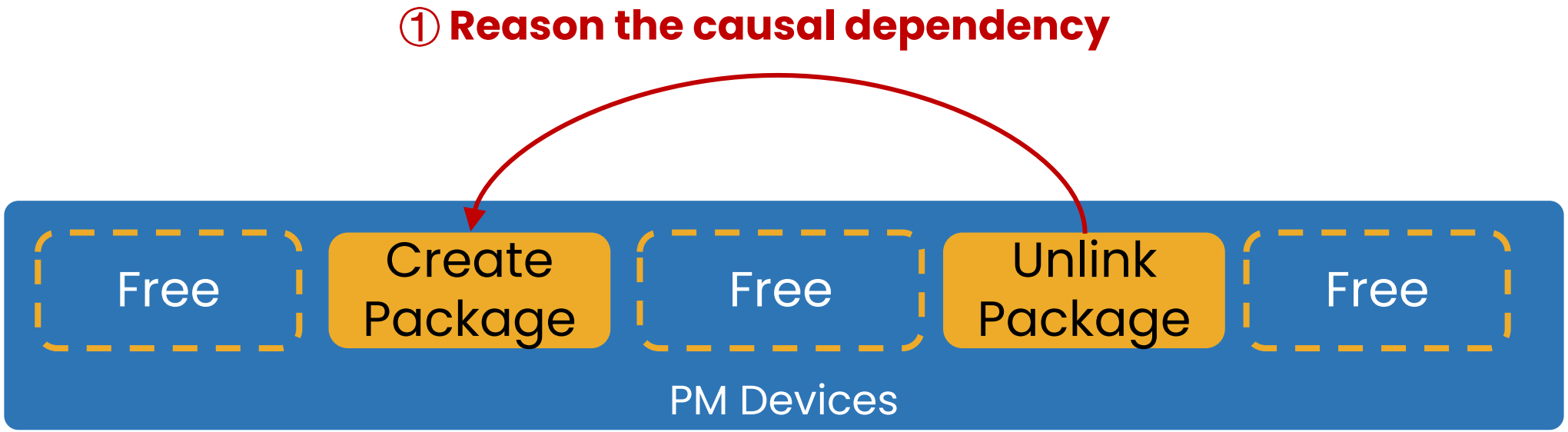

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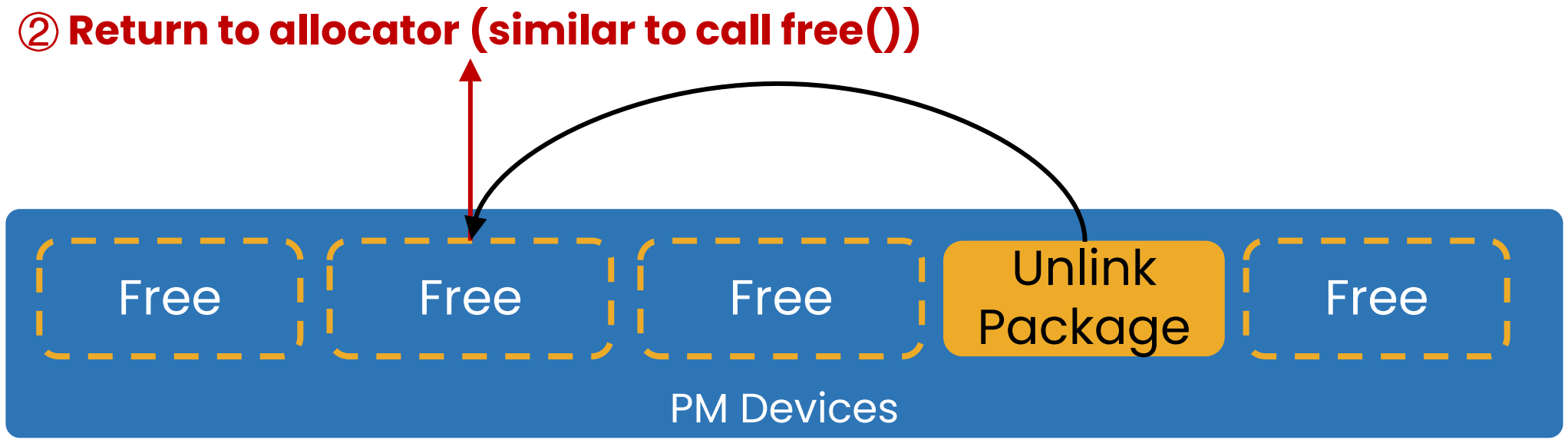
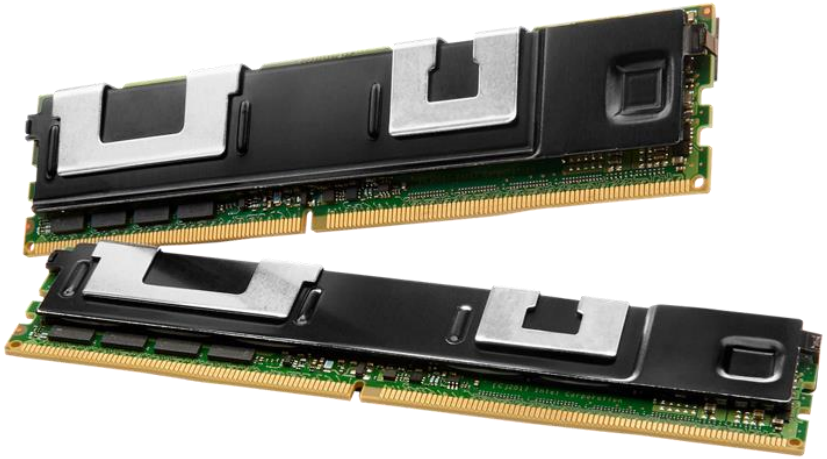


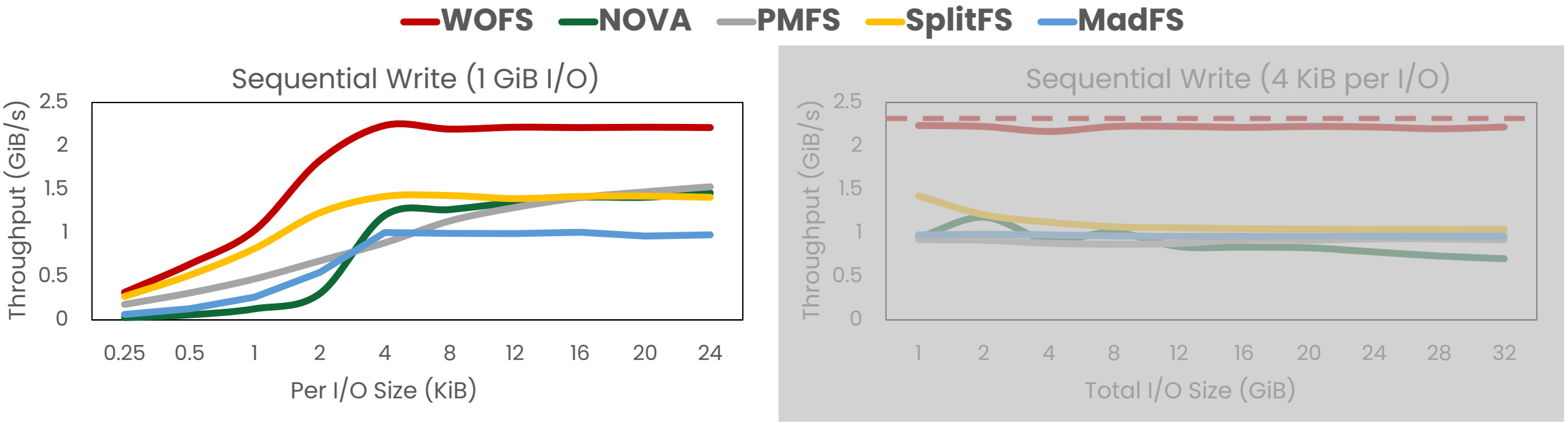
WOFS Evaluation

- **Experimental setup**
  - Implement WOFS in Linux kernel 5.1.0
  - Intel Xeon Gold 5218 CPU @ 2.3GHz
  - 256 GiB Optane DCPMM
  - 128 GiB DRAM



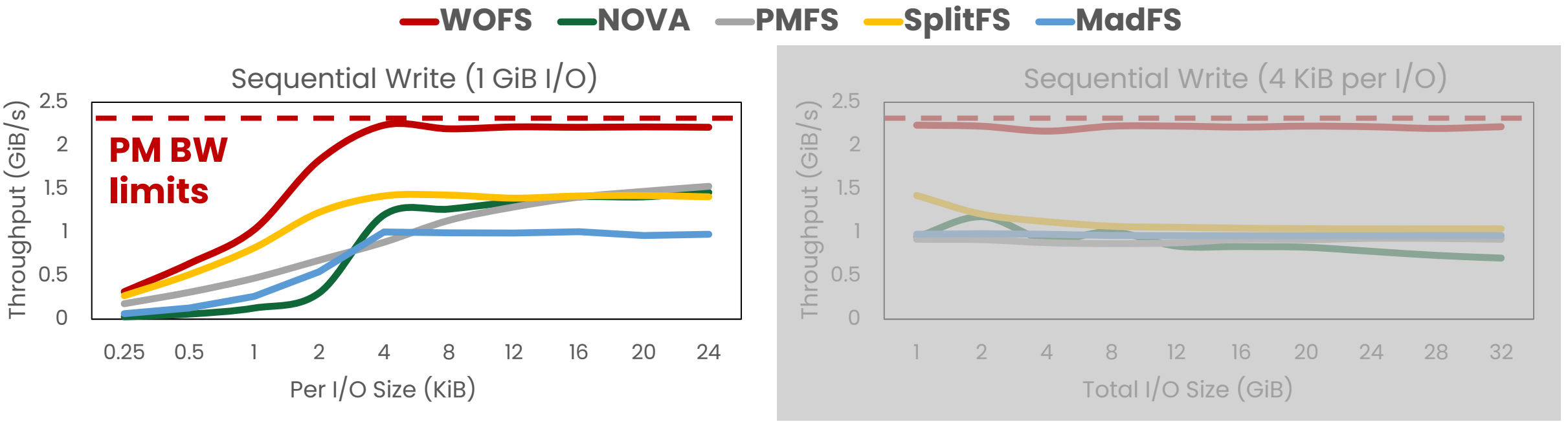
- **Competitors**
  - A number of existing PM file systems (e.g., NOVA, PMFS, SplitFS, etc.)

I/O Performance



- **Setup:** FIO with 1 GiB total I/O size, varying per I/O size
- **Results:** WOFS consistently outperforms competitors thanks to the metadata write once scheme

I/O Performance



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- **Important NOTE:** WOFS can reach PM bandwidth limits

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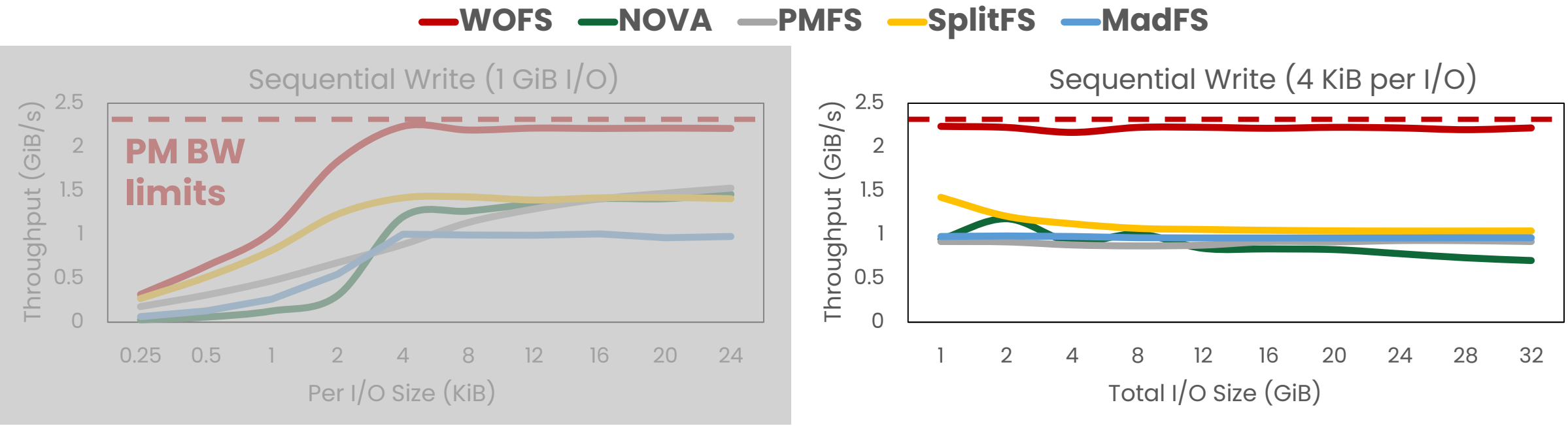

- **Setup:** FIO with 4 KiB per I/O, varying total I/O size
- **Results:** Similarly, WOFS outperforms competitors by more than 50%, very close to upper bandwidth limits

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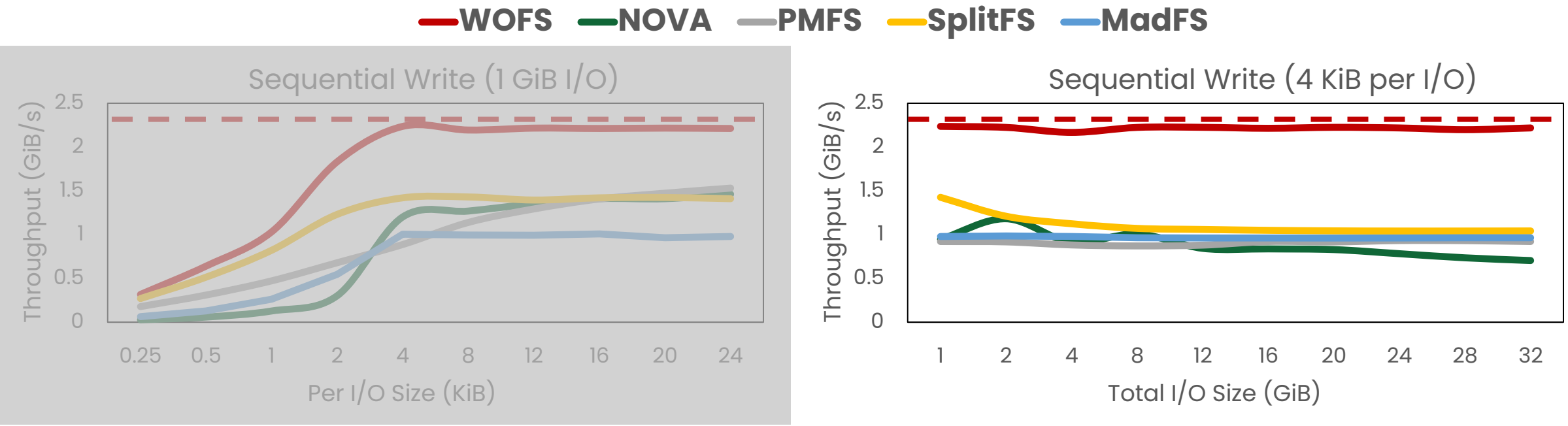
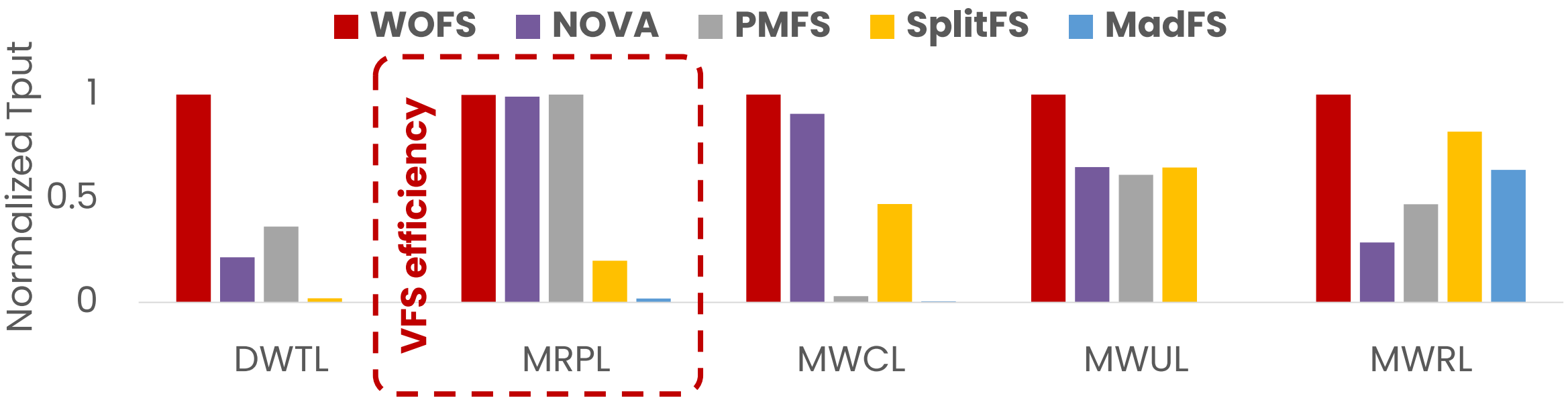


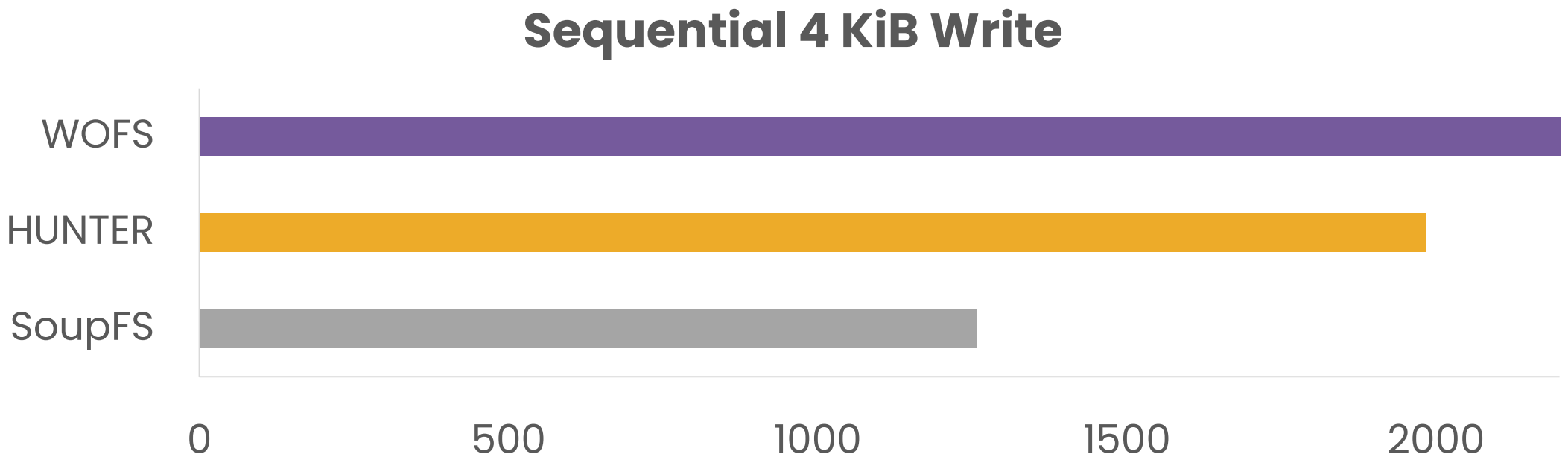
- **Setup:** FIO with 4 KiB per I/O, varying total I/O size
- **Results:** Similarly, WOFS outperforms competitors by more than 50%, very close to upper bandwidth limits
- **Important NOTE:** WOFS shows a stable performance trend

Metadata Performance



- **Setup:** FxMark with five single-threaded workloads, including data operation, dir traverse, file create/deletion, and rename
- **Results:** WOFS always shows the highest throughput as it minimizes metadata I/O and ordering points.

Vs. Asynchronous Crash Consistency



- **Setup:** FIO with 4 KiB per I/O, no fsync issued
- **Competitors with asynchronous crash consistency:** HUNTER and SoupFS both delay metadata writes to the background
- **Results:** WOFS still outperforms others, as latter's background flush interference with their foreground I/O performance

Other Results

- **Other Results**
  - Concurrency and tail latency
  - Real-world workload evaluation
  - Recovery overhead
  - Aging and fragmentation
  - Performance beyond Optane DCPMM
  - etc.

Please refer to our paper (§6)

Conclusion

- **Analysis of synchronous crash consistency overhead atop PM**
  - Many small, random and ordered metadata I/O can be the bottleneck
- **WOFS model to minimize crash consistency overhead**
  - Rethink file system metadata for optimal crash consistency
  - Design a specific package as one metadata for a single operation
  - Metadata write-once can minimize I/O and ordering points for crash consistency
- **Make WOFS architecture practical and efficient**
  - Propose a range of techniques to manage packages efficiently
  - Results. Outperform SOTA PM file systems, reaching upper PM bandwidth limits

github.com/WOFS-for-PM/

Thanks & QA