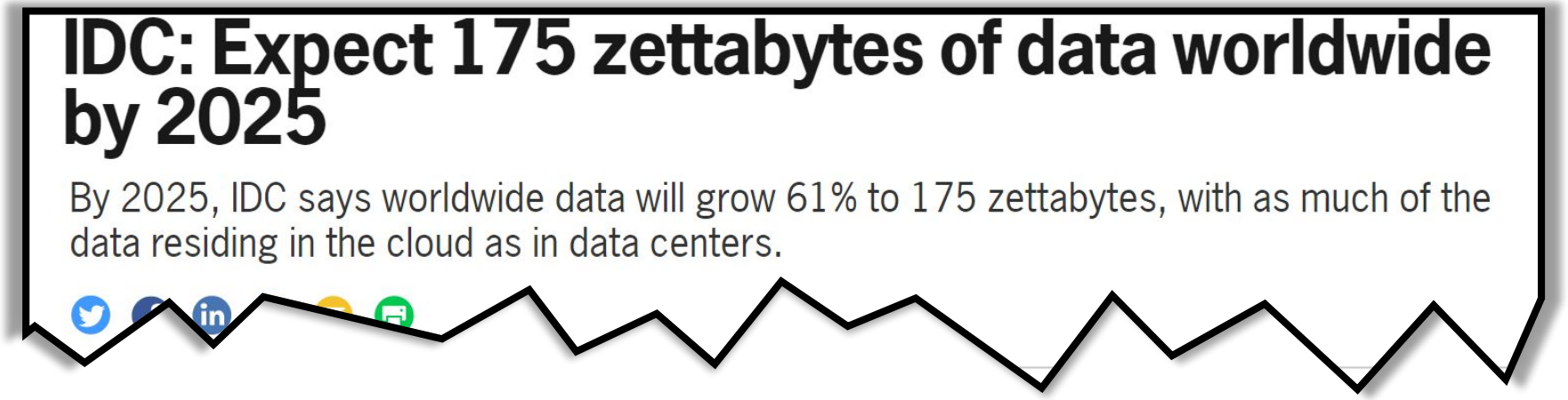
Scalable Storage Stack for Persistent Memory

Sanidhya Kashyap

EPFL

Data is growing by 61% every year



Source: NetworkWorld (2018) / Data Age 2025 by IDC (2017)

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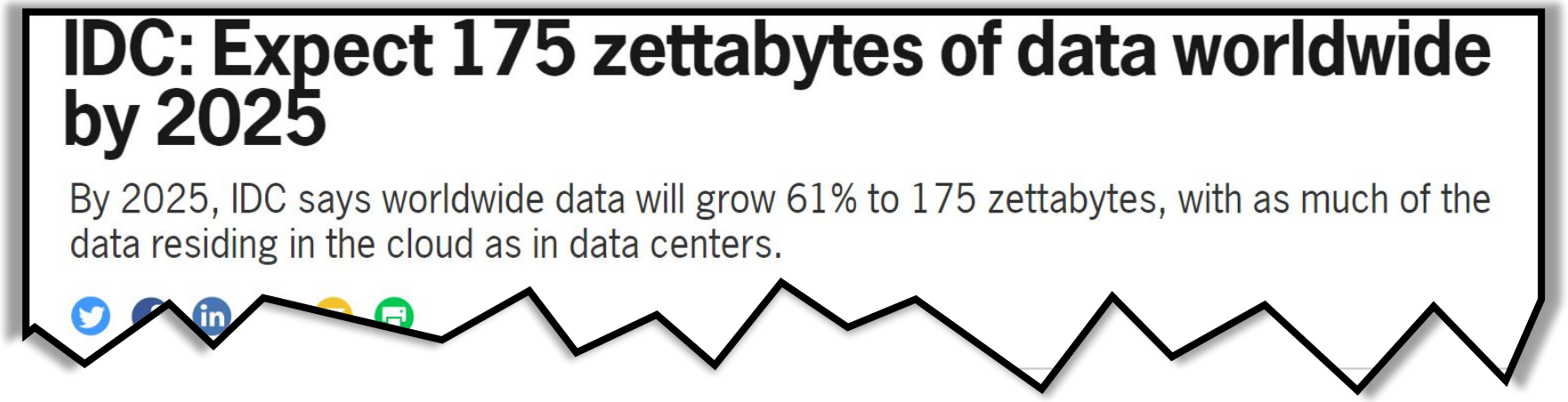

Data requires more *computation* and more **storage**

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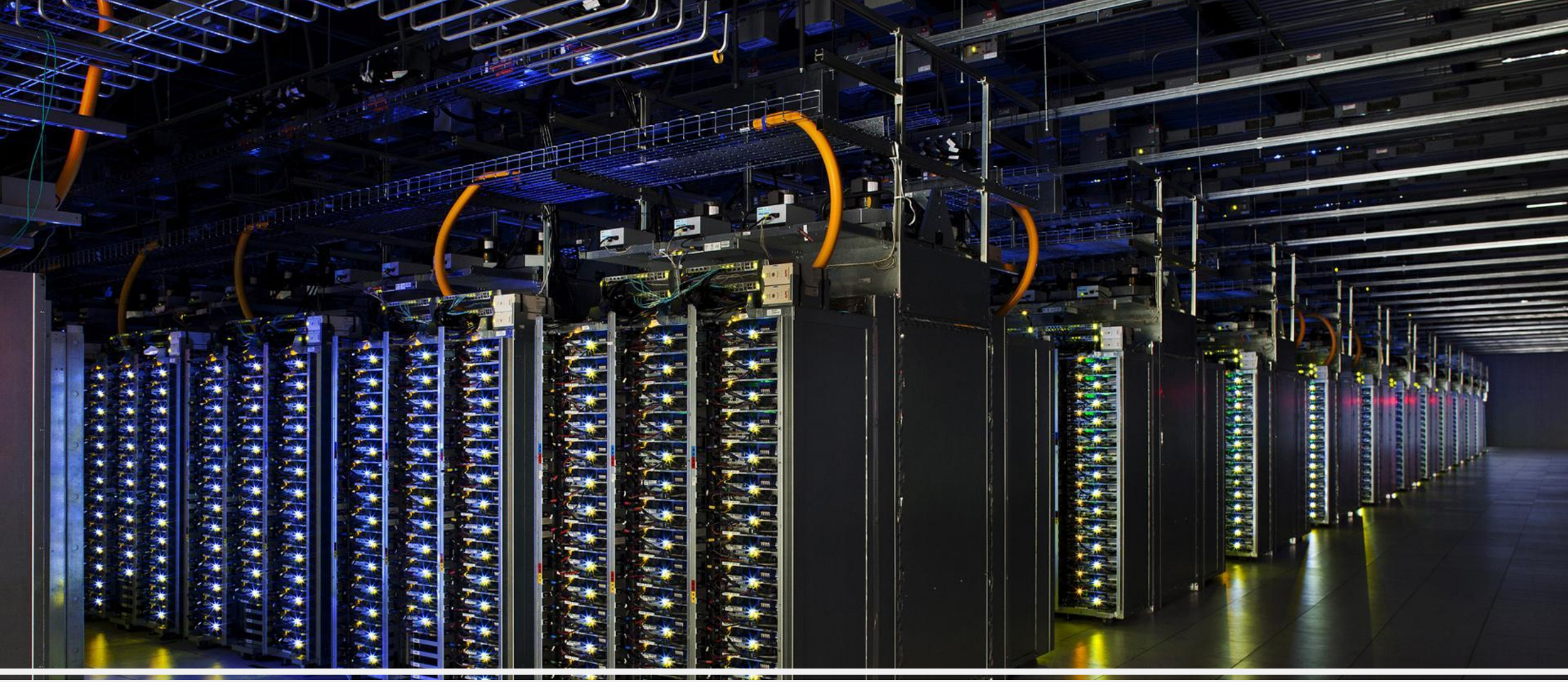
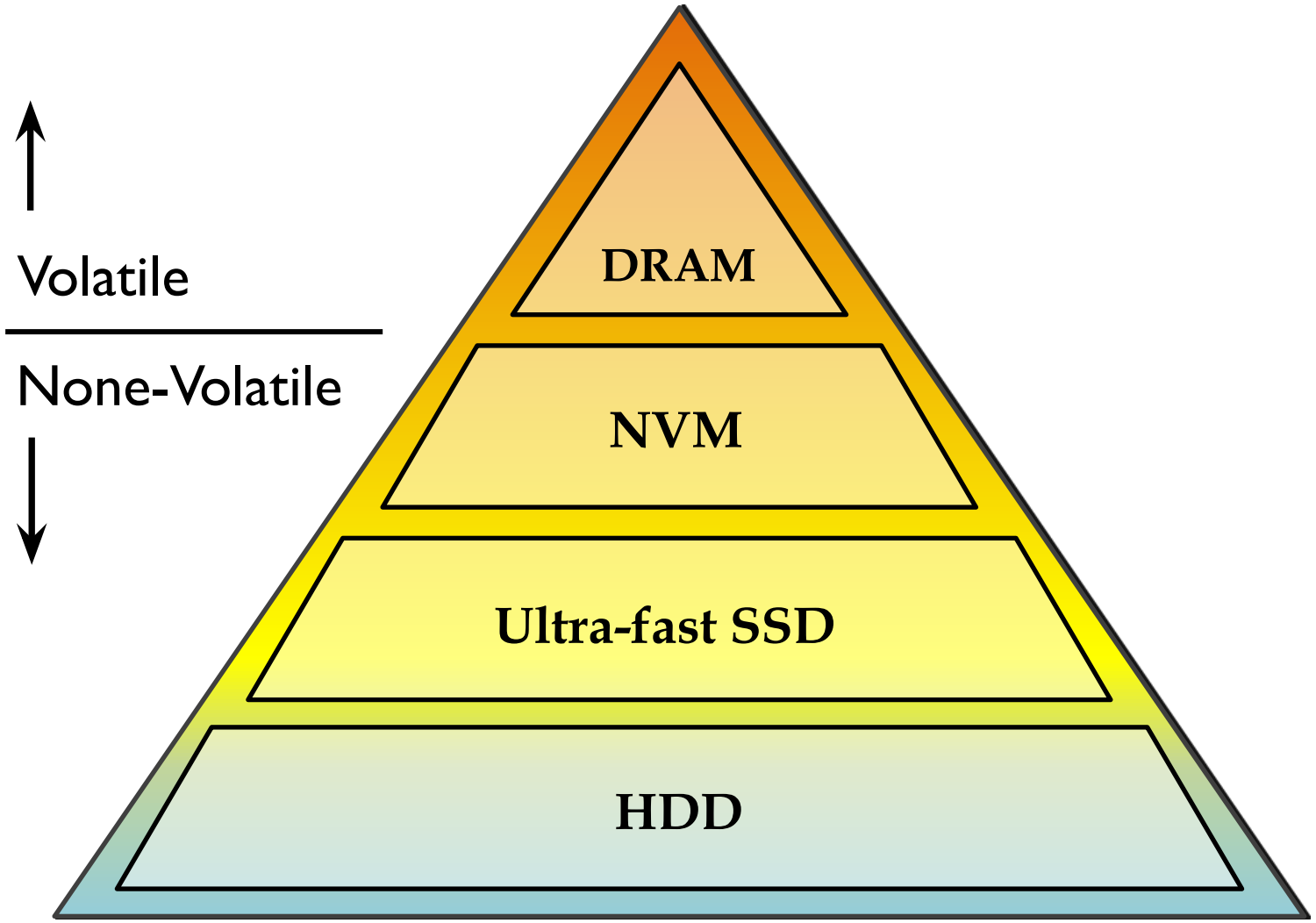


Data centers are responsible for handling data

Persistent memory (PM) in the storage jungle



	Latency	B/W	$/GB
DRAM	**300 ns**	**10 GB/s**	**4.0**
NVM	40 us	2.0 MB/s	0.25
Ultra-fast SSD			
HDD	5 ms	2.6 MB/s	0.02

Persistent memory brings …

1. **Byte addressability**
   - Loads & stores at the granularity of bytes
   - Faster random data access
2. **Non-volatility**
   - Persists data across power cycle
3. **Large capacity**
   - 3TB-per socket

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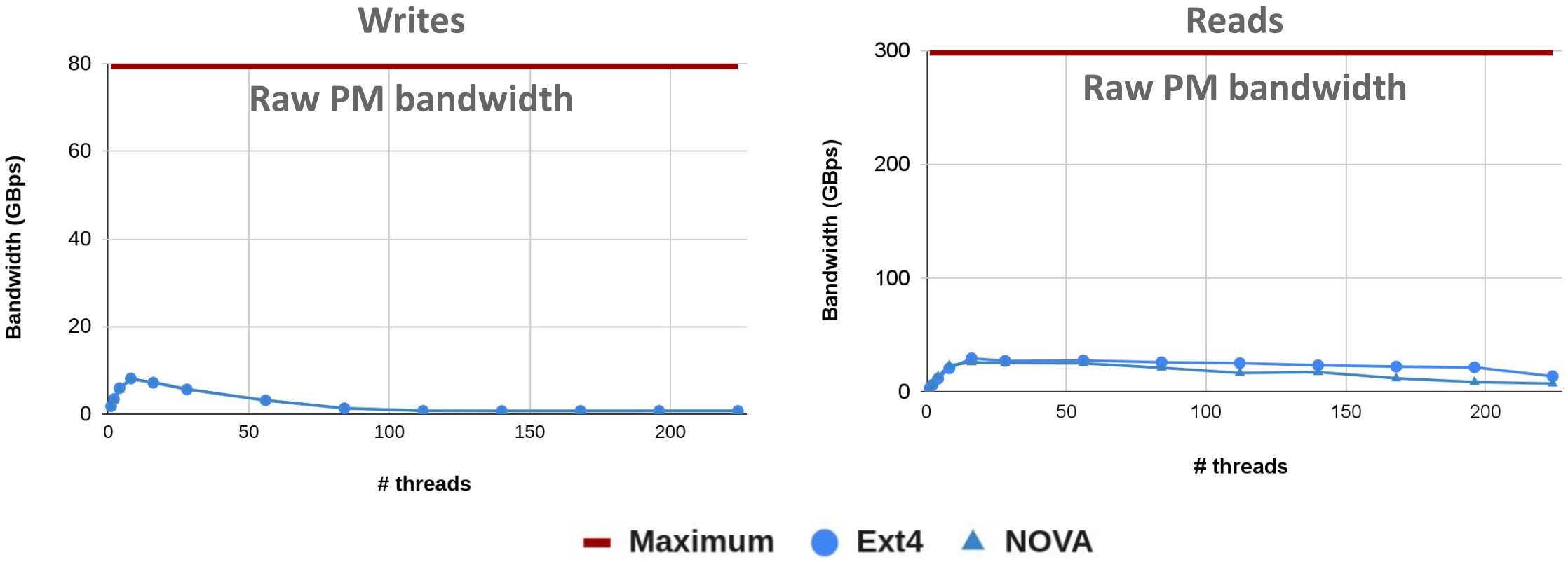
Exciting opportunity for **faster storage stack!**

Current IO performance with PM

Benchmark: Each thread reads/writes 2MB data privately in a 1GB file



Setup: 224-core/8-socket machine

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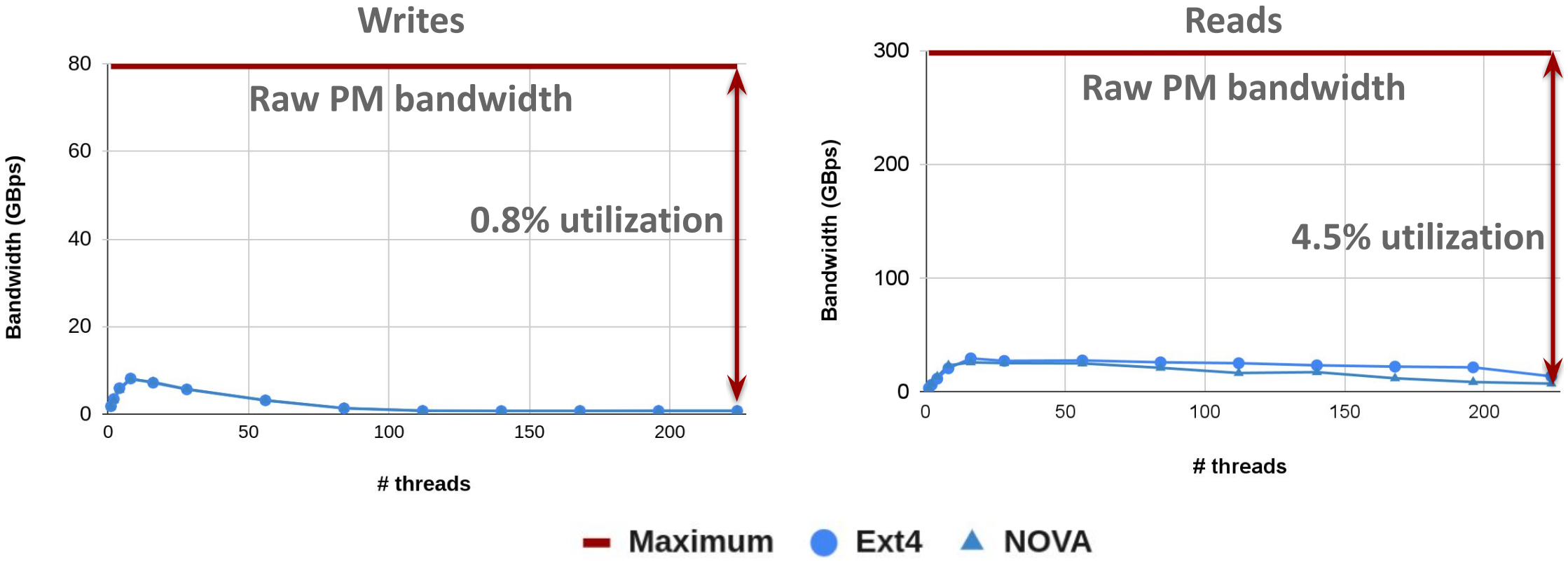

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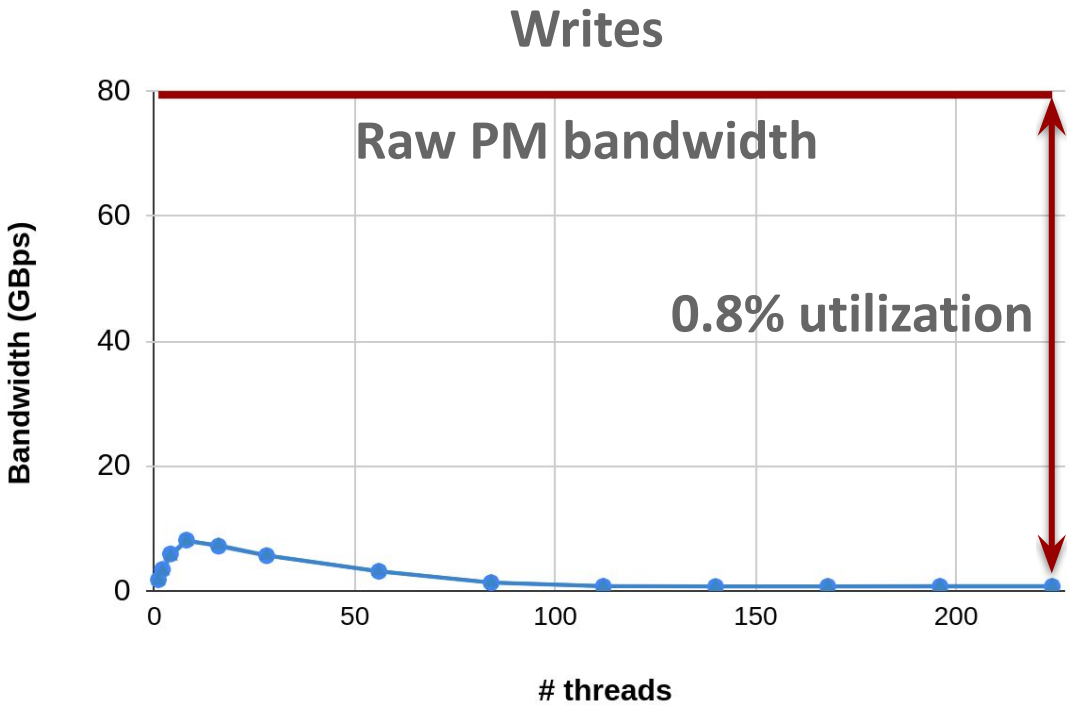
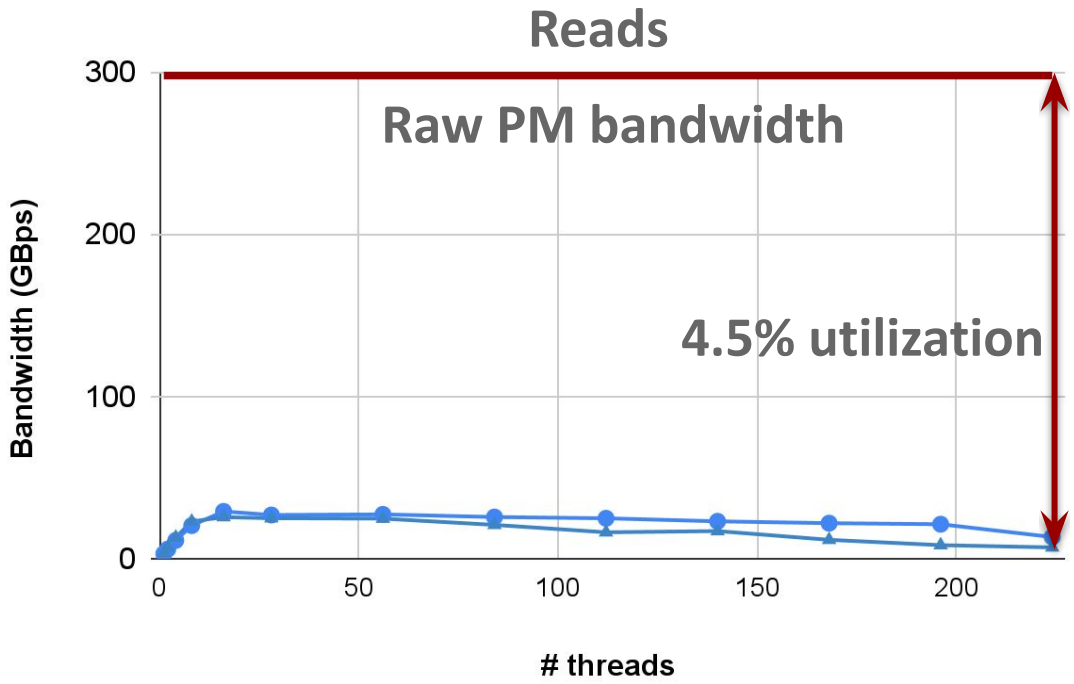




Unable to utilize existing PM's capability

Goal of our new file system design

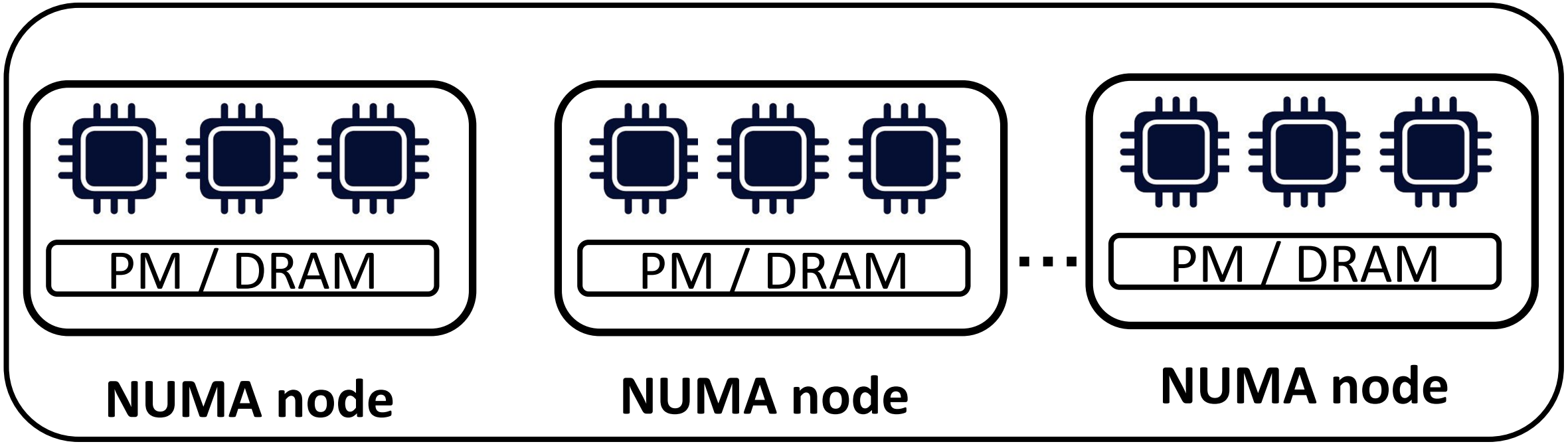
1) **Maximize PM's bandwidth utilization**

2) **Scale with increasing thread/core count**

Current hardware setup

PM DIMMs are attached to multiple different NUMA nodes

NUMA: Accessing the local socket memory is faster than the remote socket



Hardware setup: Consider one NUMA node

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Concurrent access degrades IO performance

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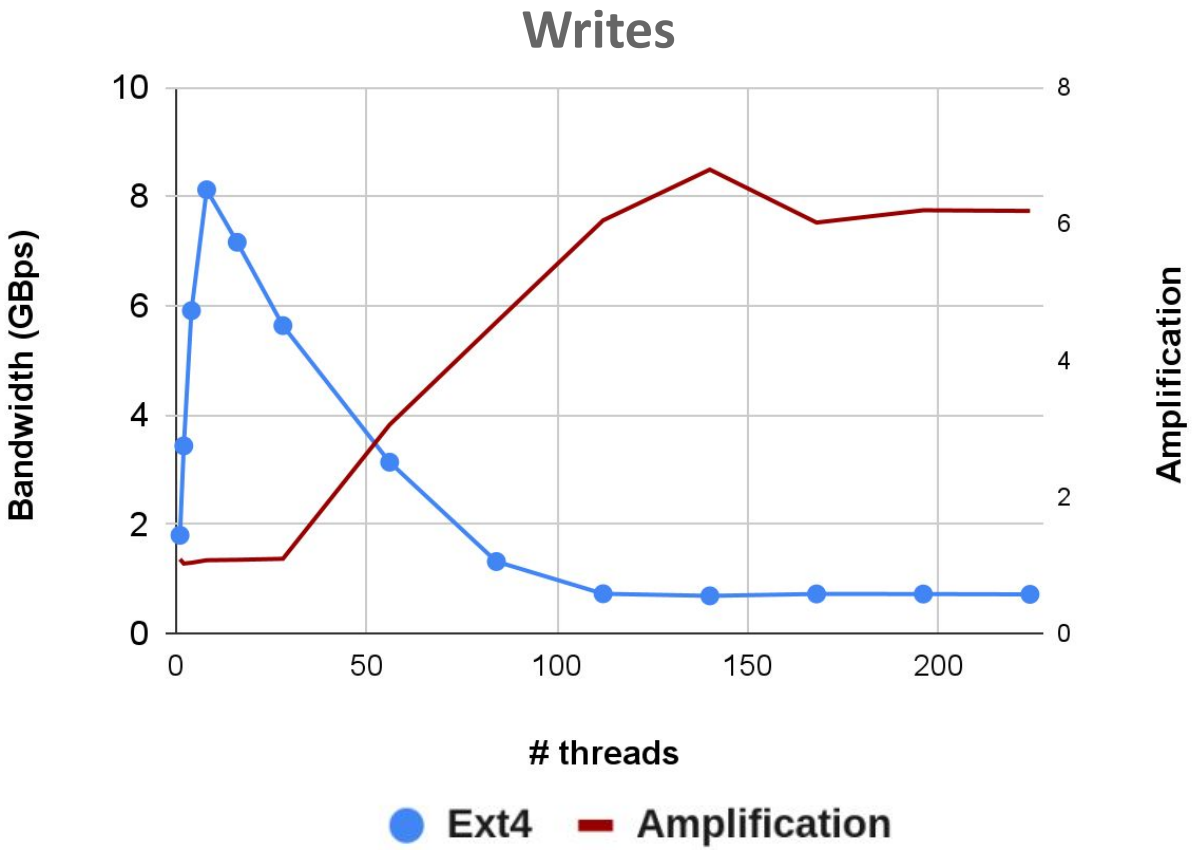
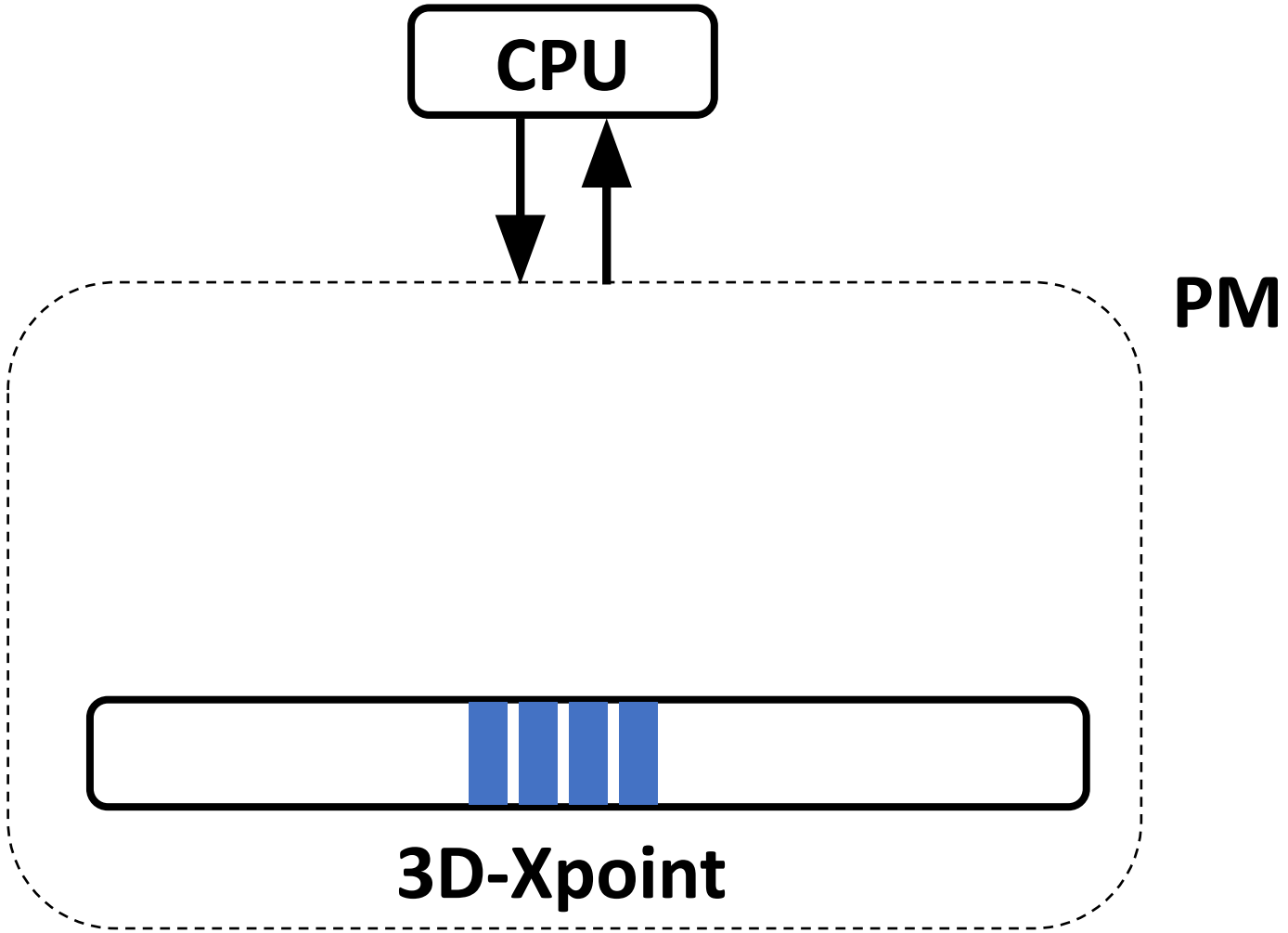


- High IO amplification measured
  - PM is slower than DRAM
    - **PM cache thrashing**

Primer on caching/prefetching in PM



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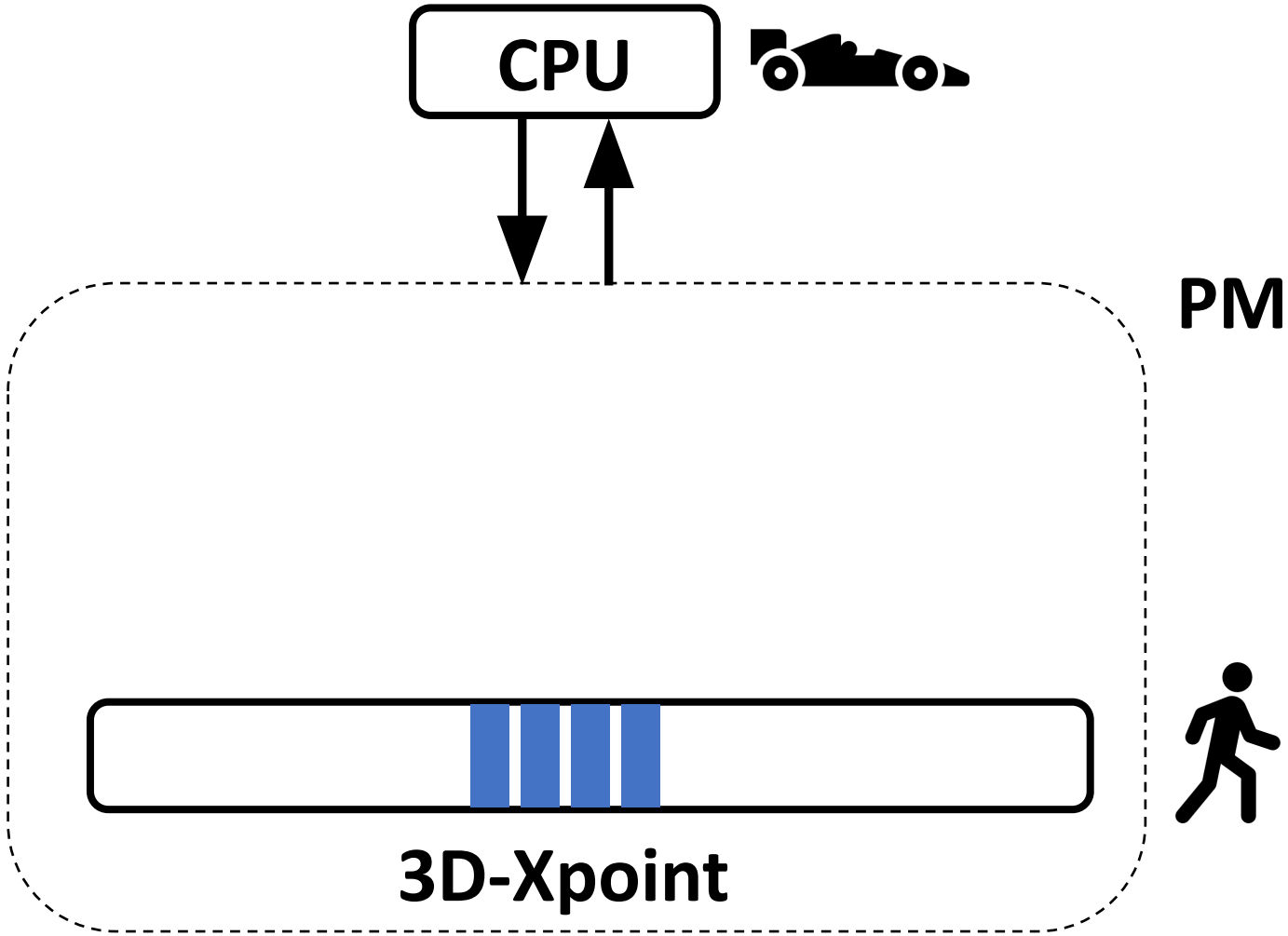

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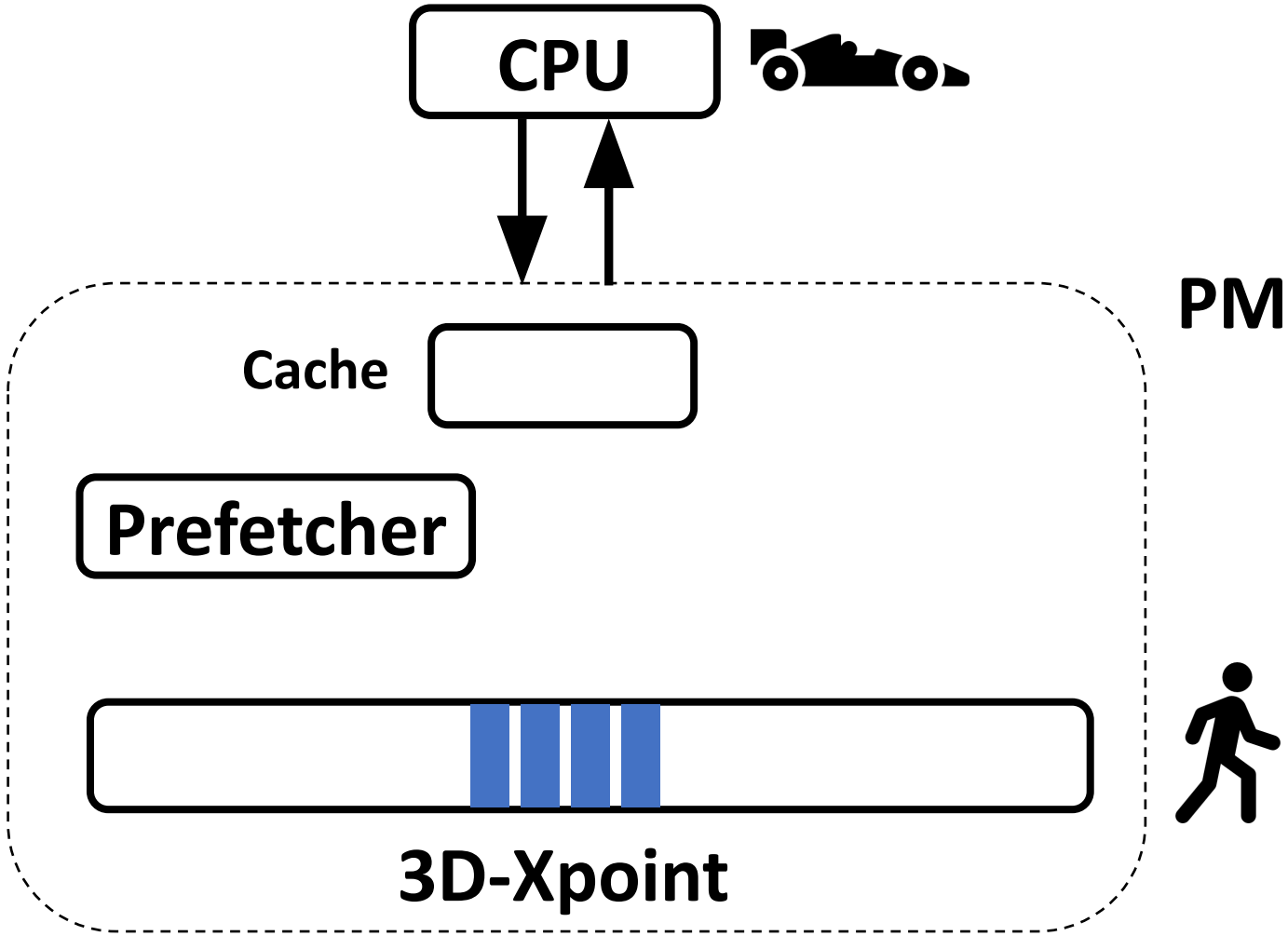

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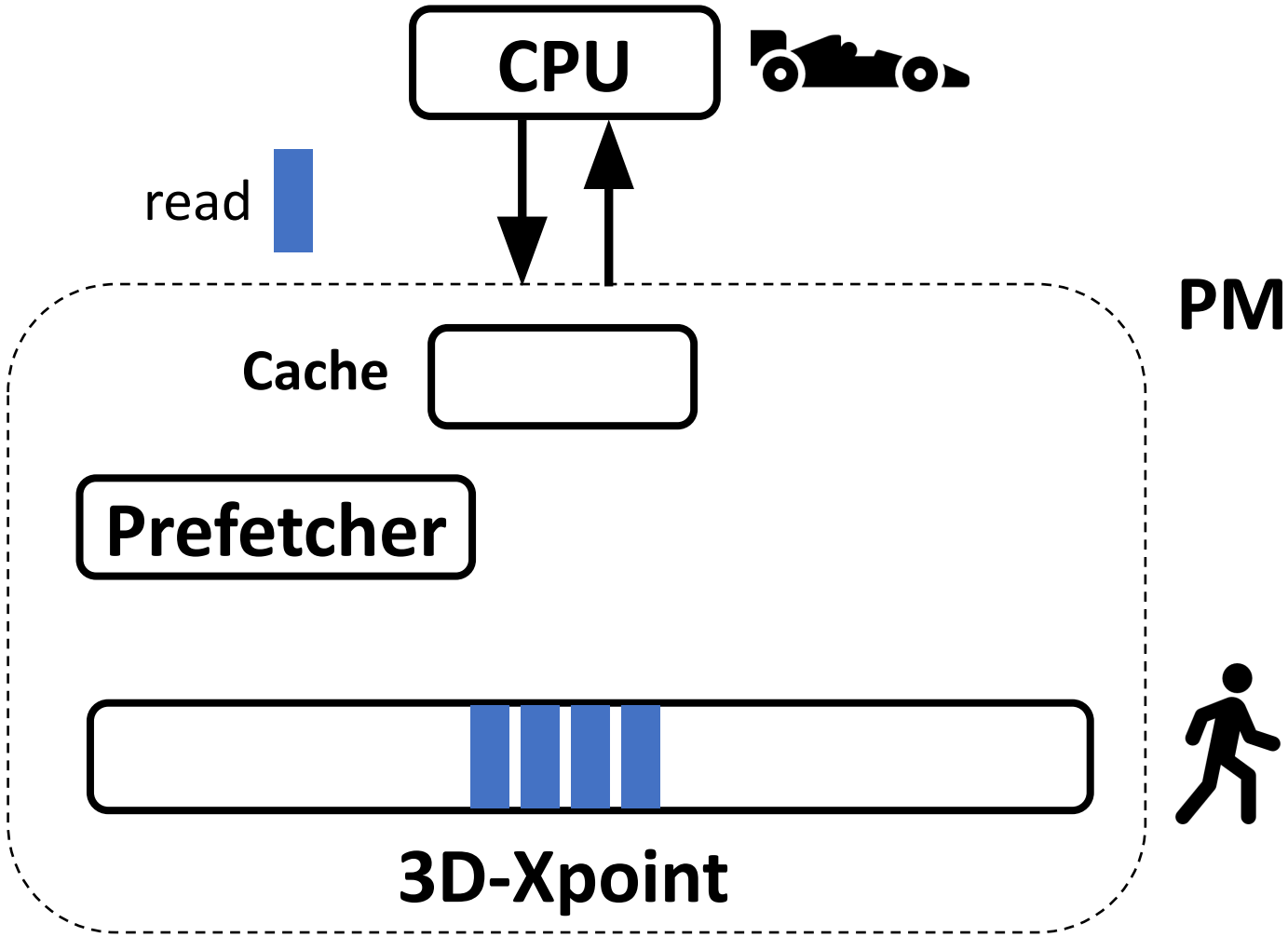

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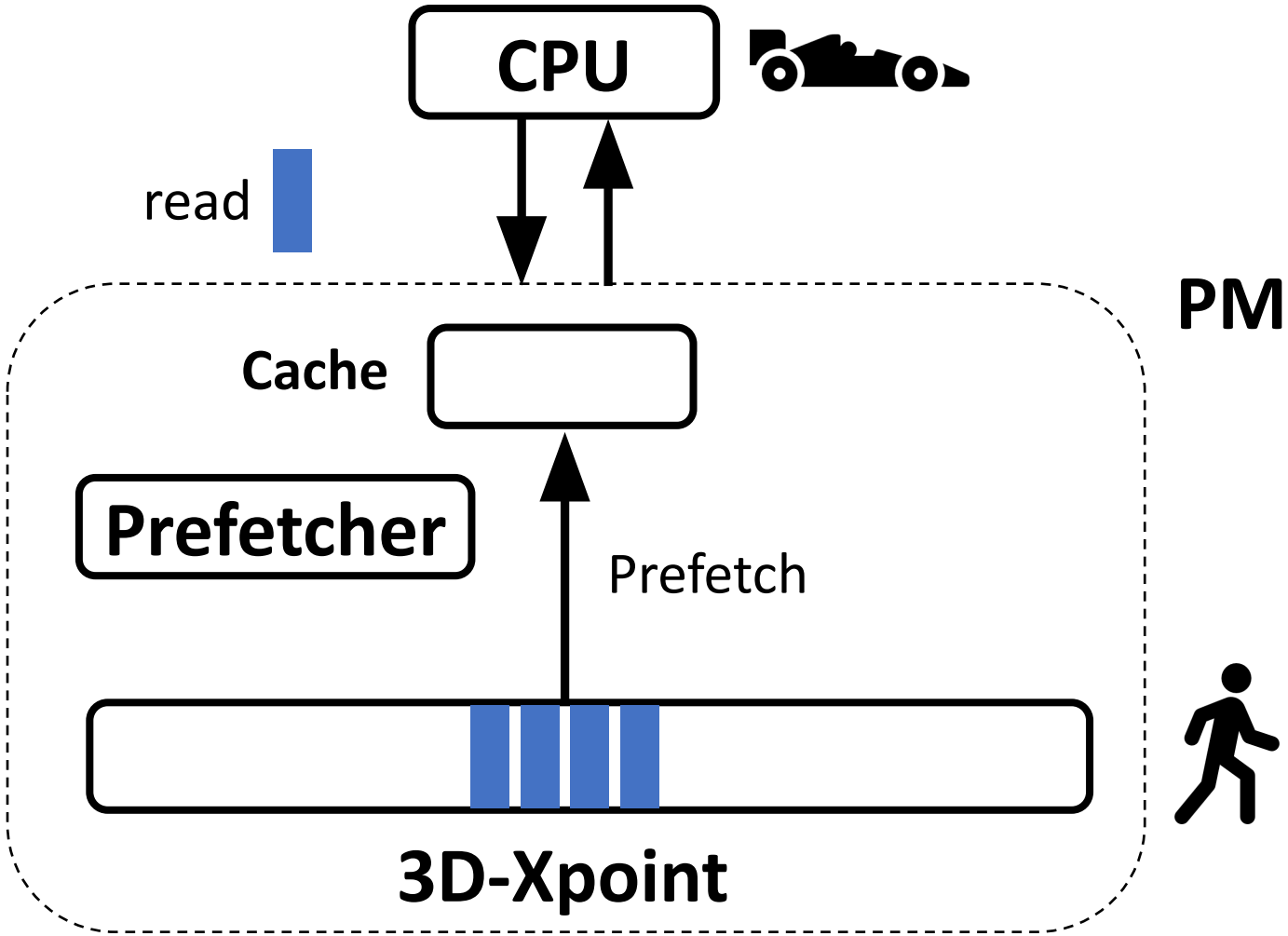

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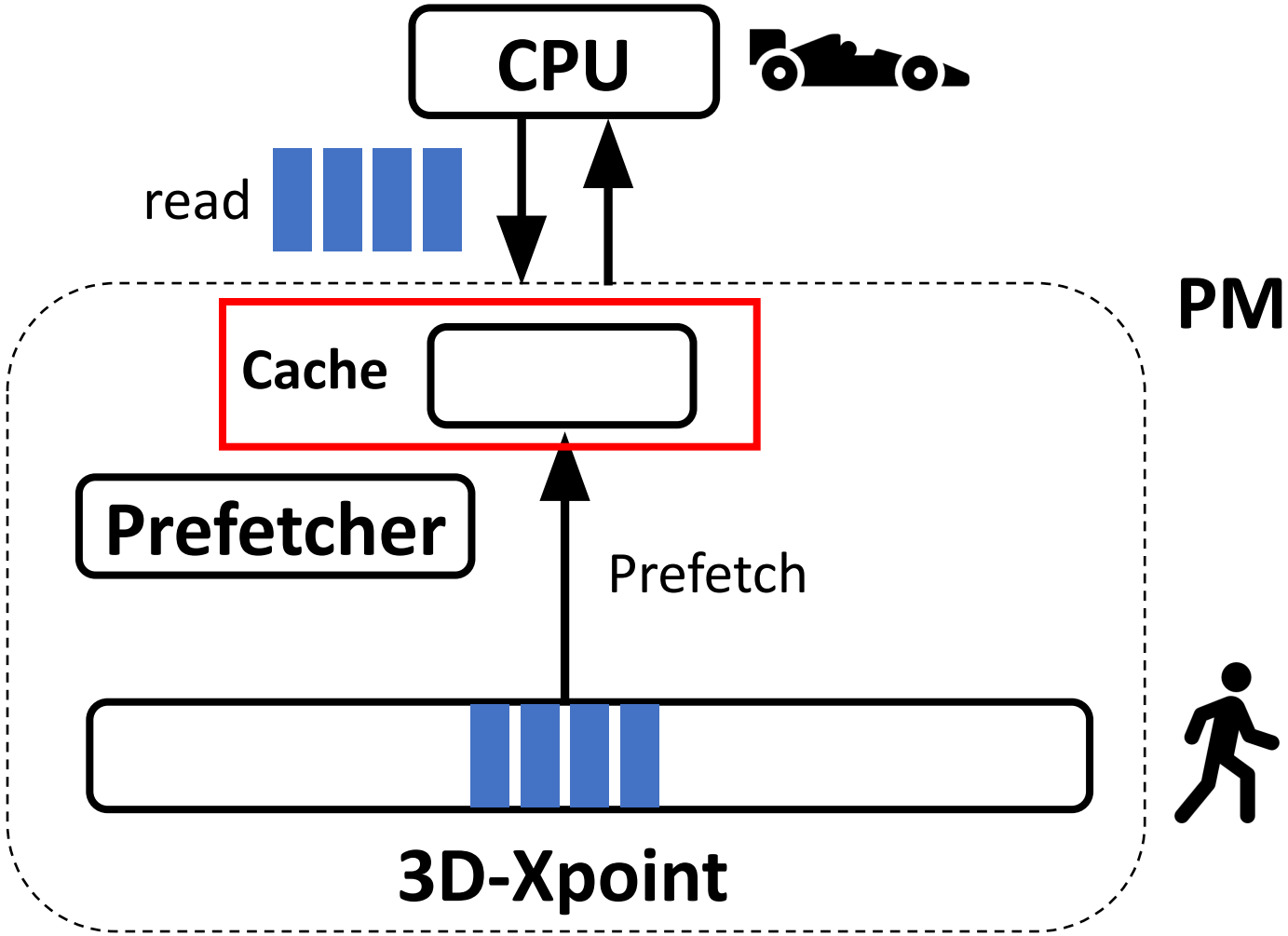

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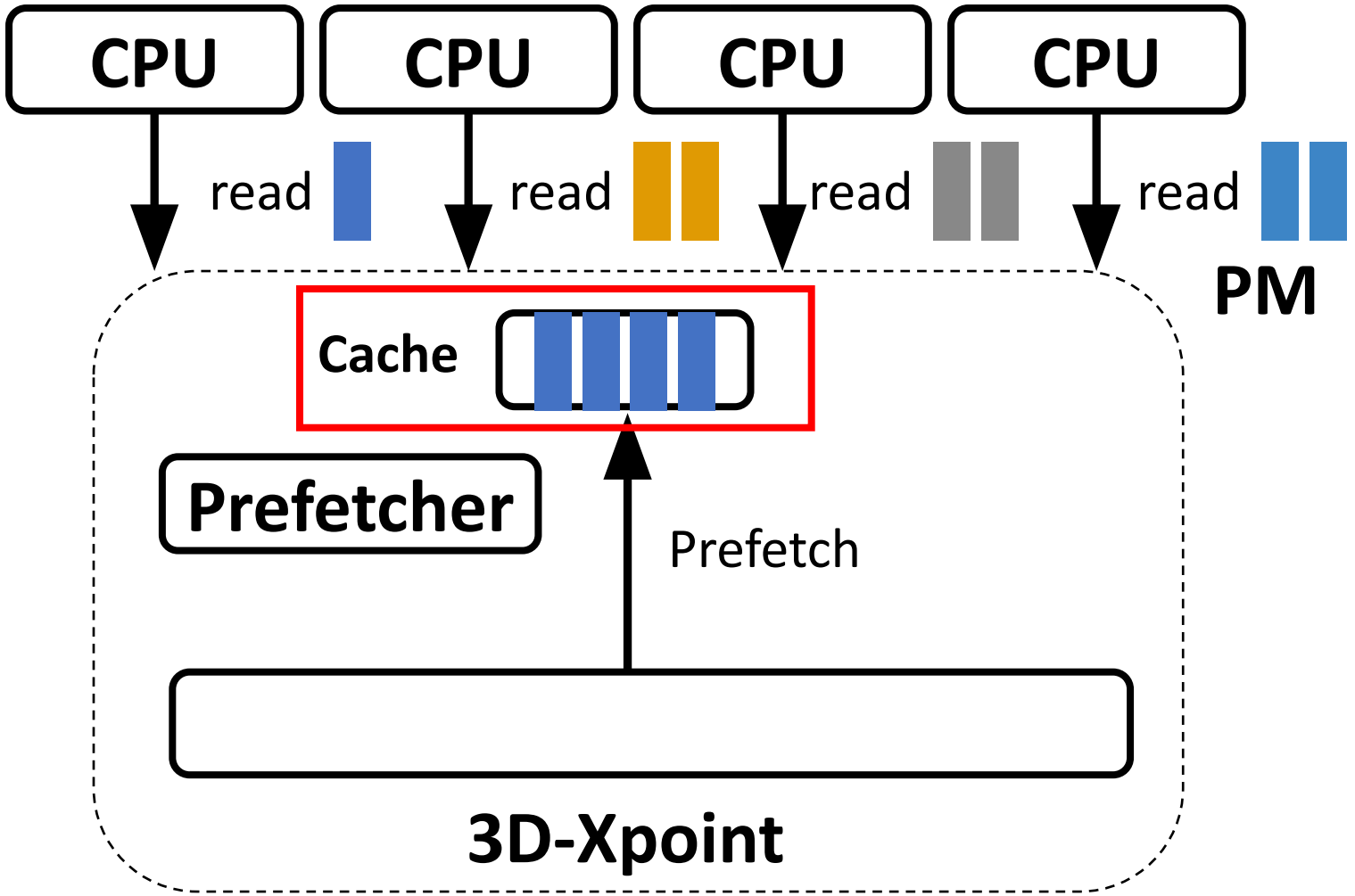

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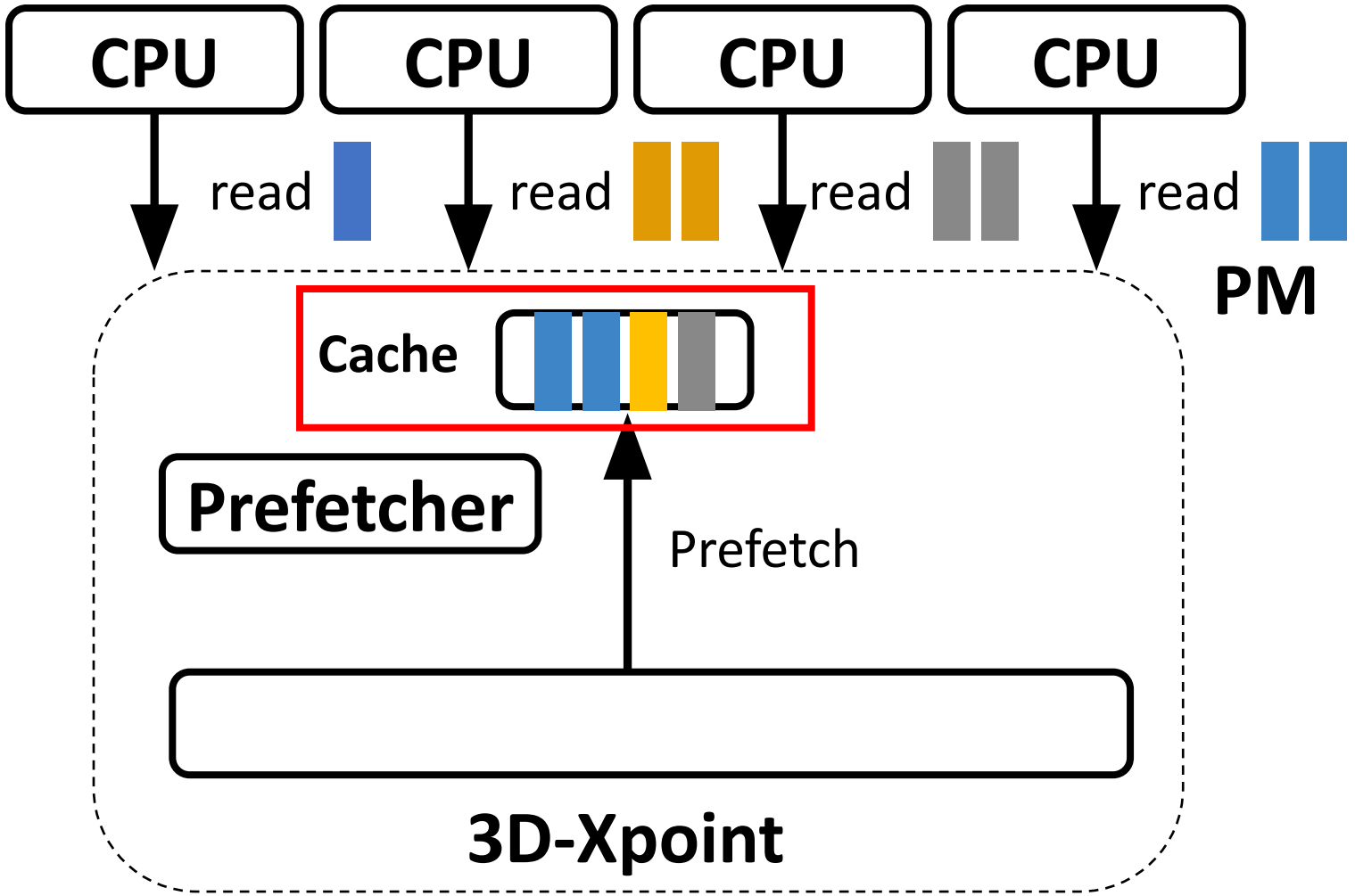

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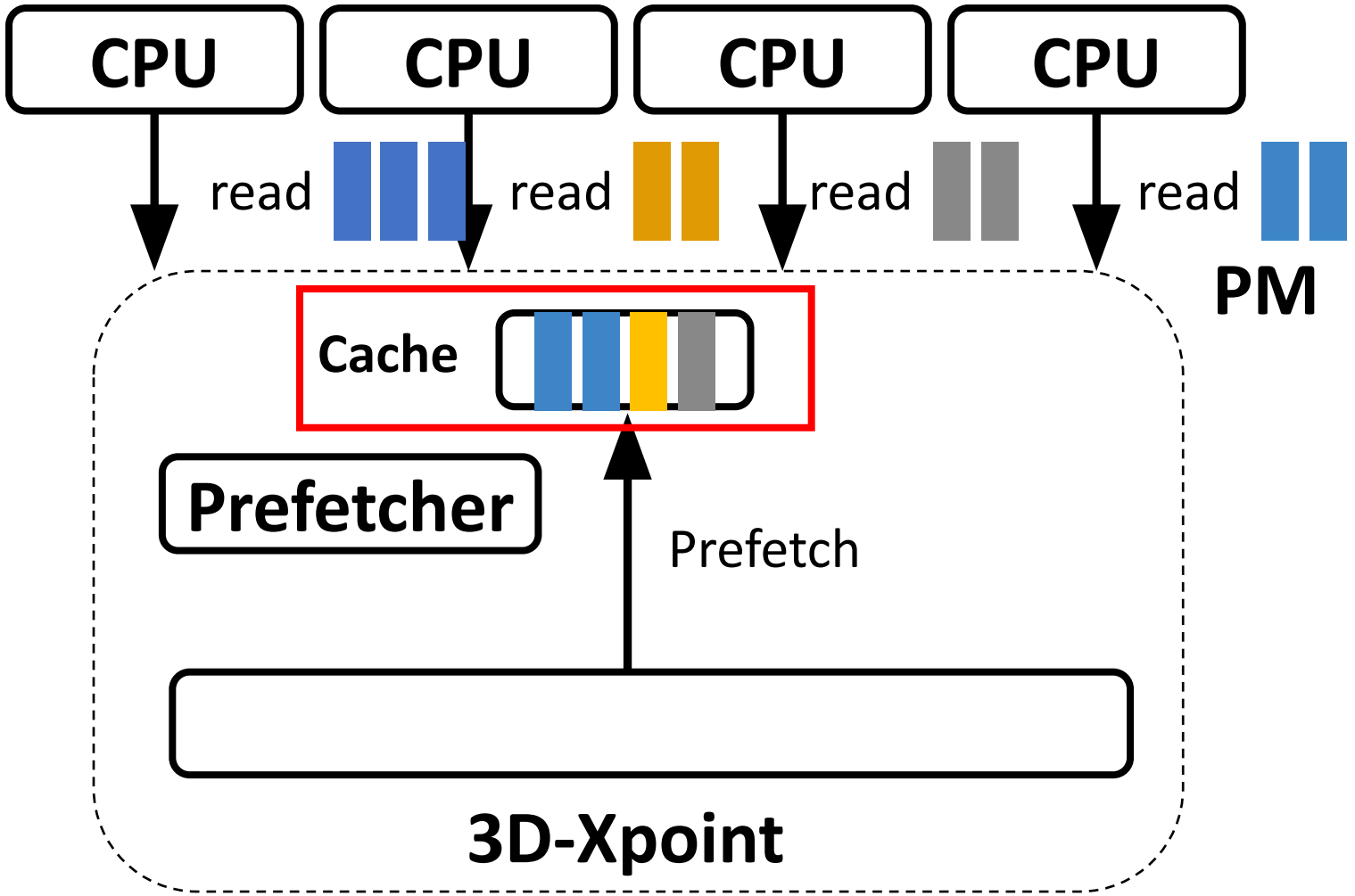

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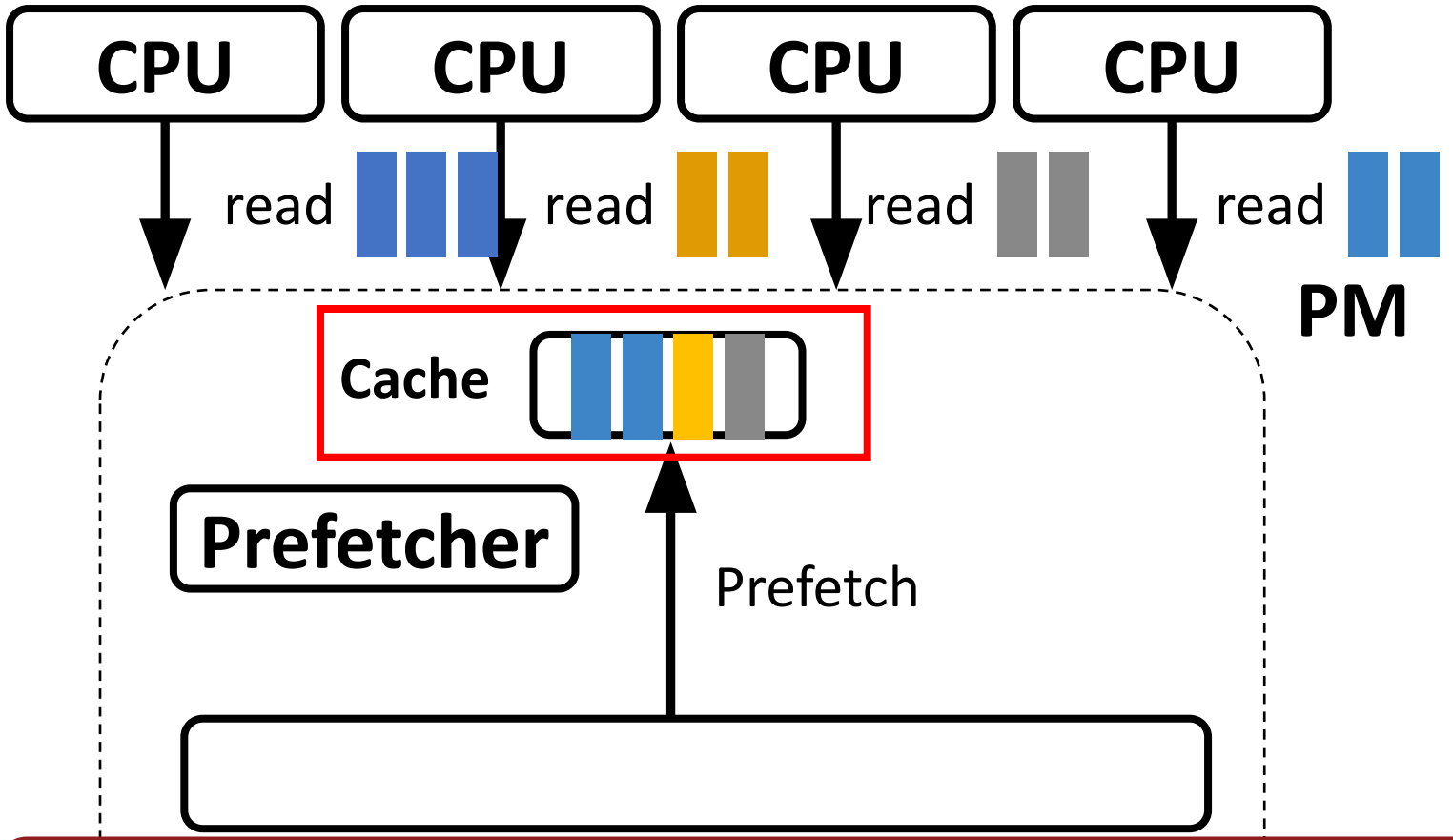

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PM cannot handle arbitrary concurrent accesses

Approach …

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Hardware setup: consider multiple PM nodes

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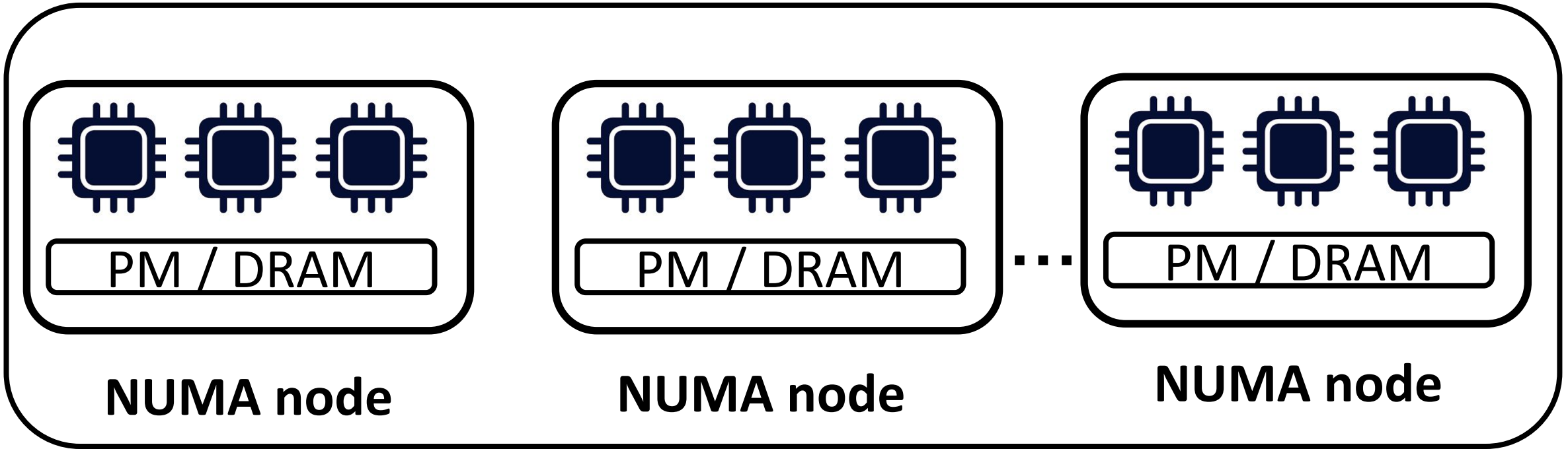
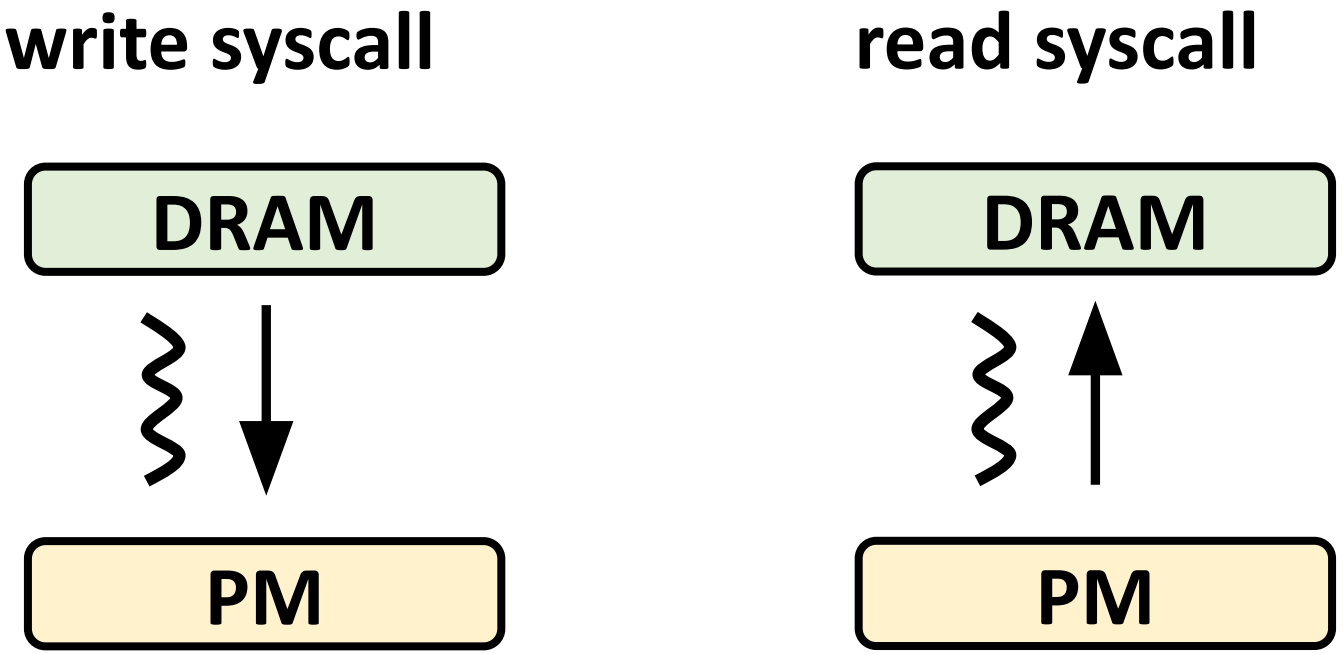


IO operations in a PM file system

Data transfer from/to the buffer (in DRAM) to/from the storage media (PM)

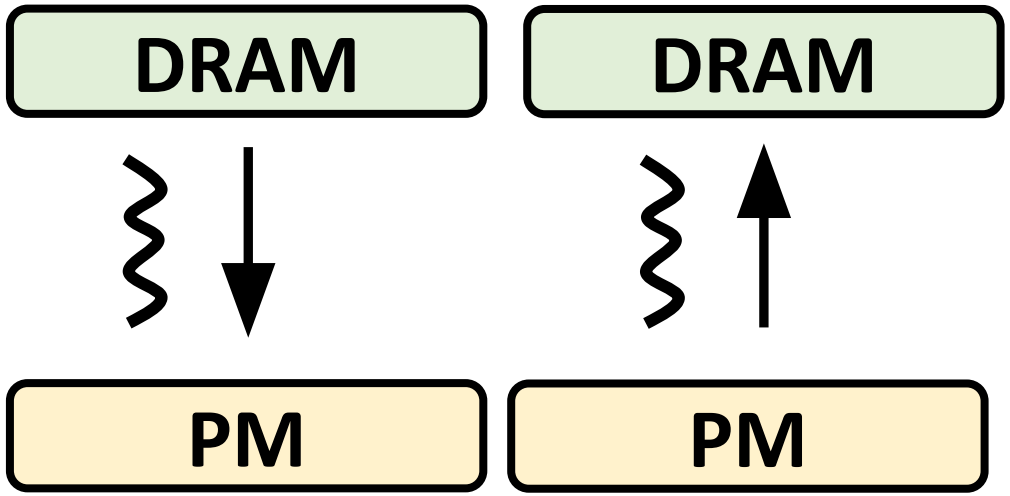


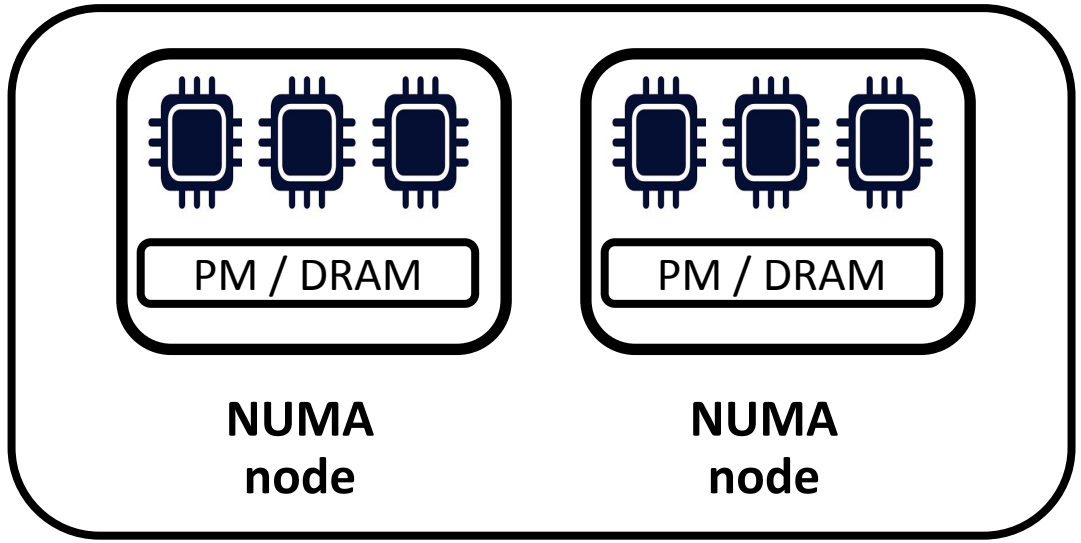
thread

IO ops in a PM file system in NUMA setup

Data transfer from/to the buffer (in DRAM) to/from the storage media (PM)

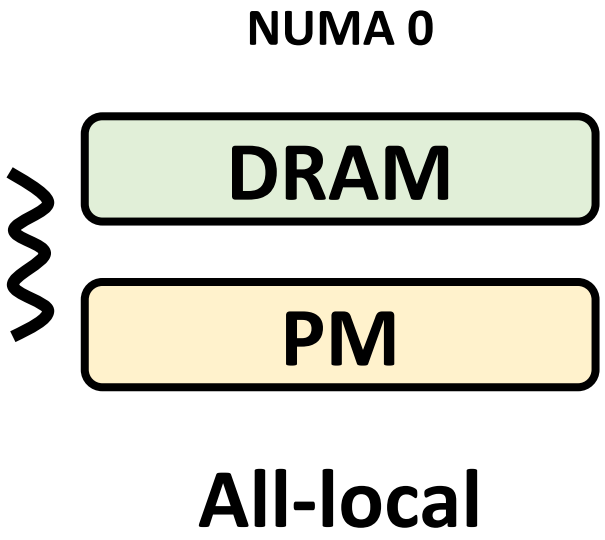
write syscall **read syscall**





Q. Impact of NUMA placement of DRAM, PM, and access thread on application performance?

PM IO operation in a NUMA setup



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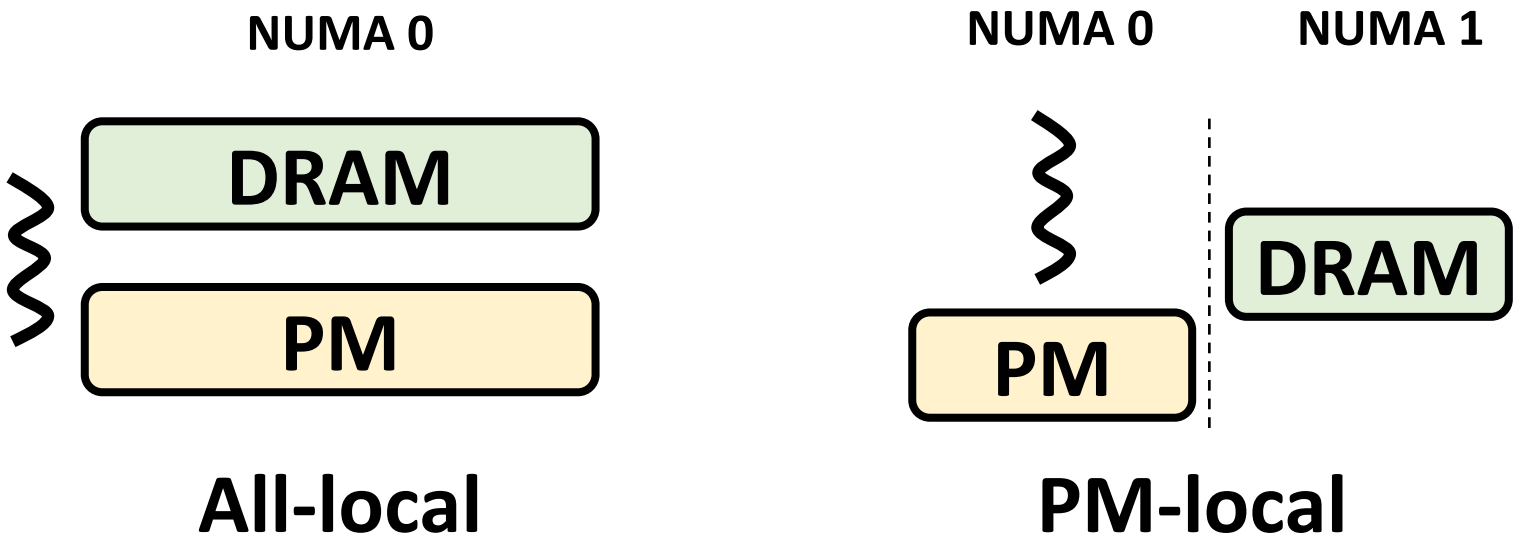

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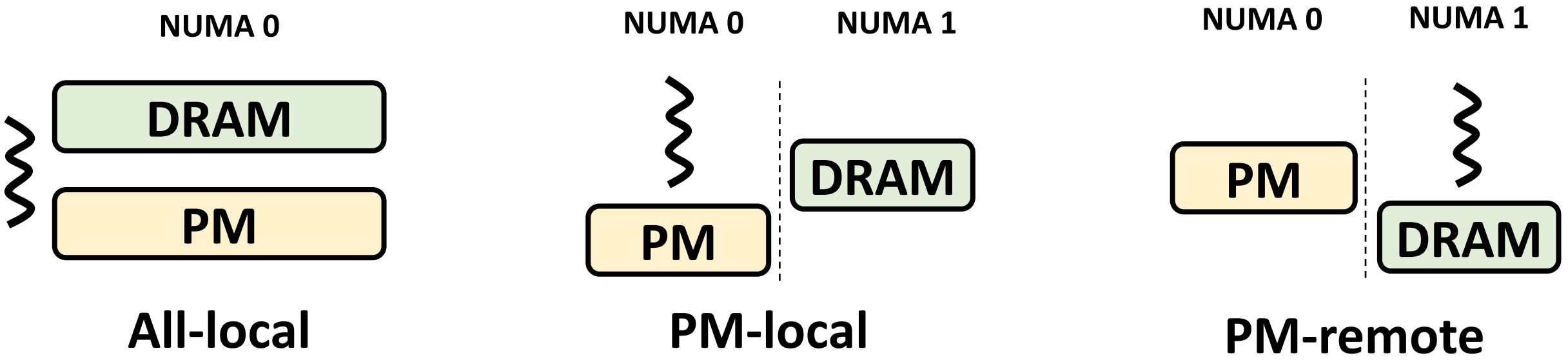

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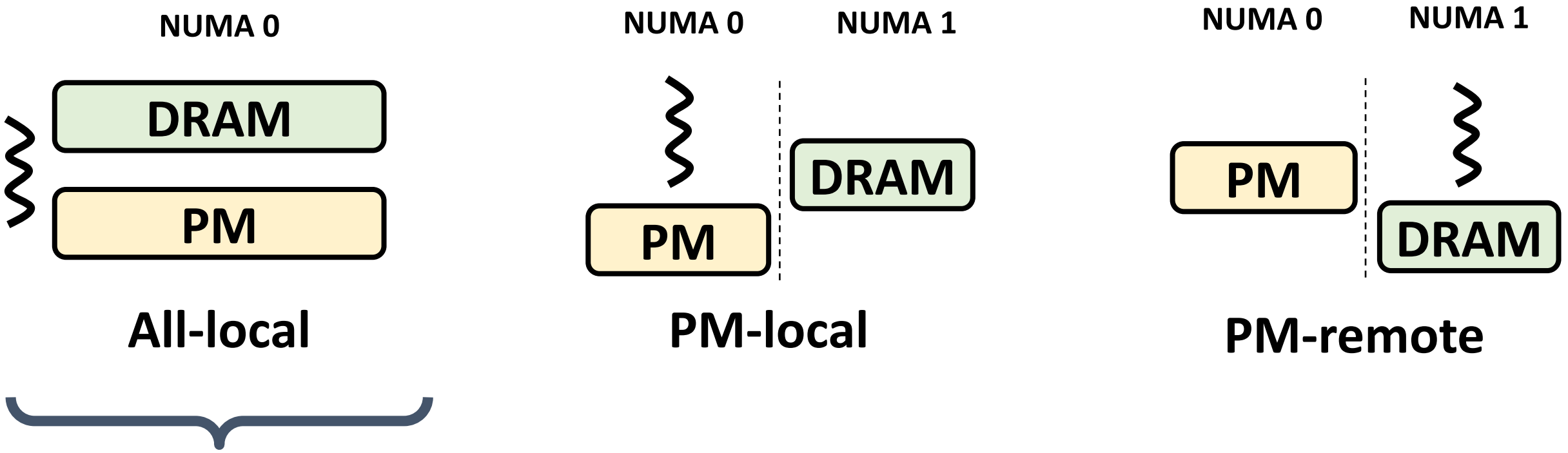
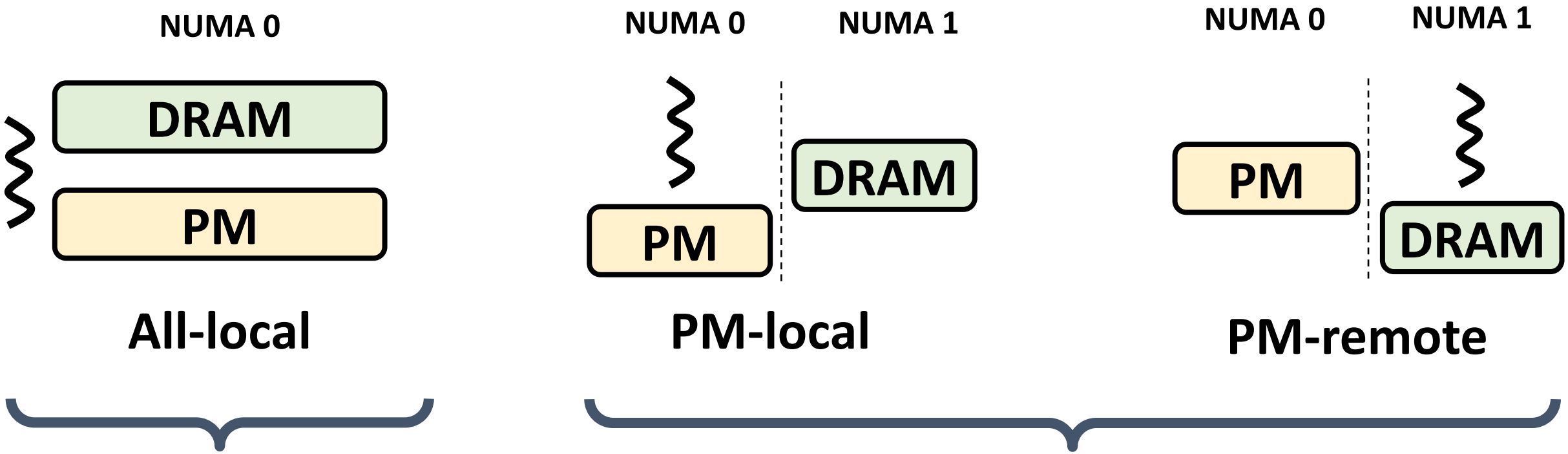


Best case scenario

thread

PM IO operation in a NUMA setup



Best case scenario

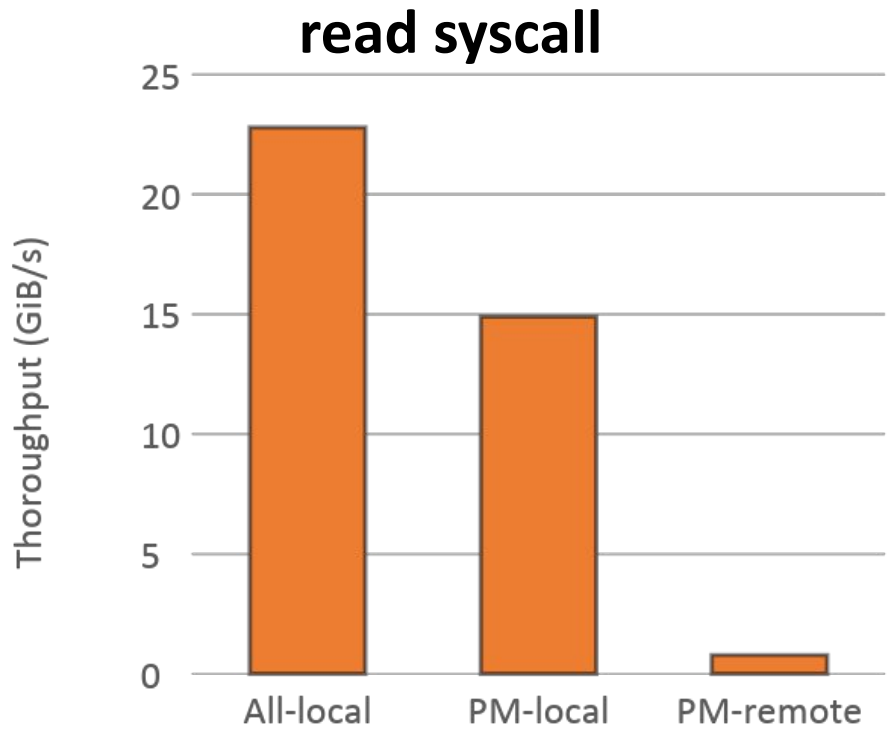
Copy data b/w PM (NUMA 0) & DRAM (NUMA 1)

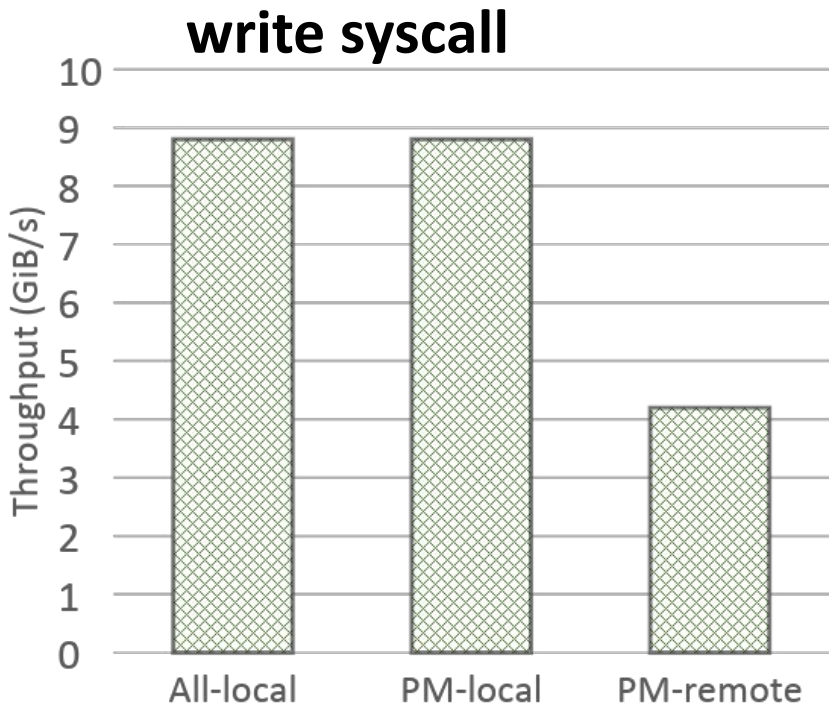
Mostly common but not the best case scenario

thread

NUMA impact: PM >> DRAM remote access

Benchmark: Single thread reads/writes 2MB data privately in a 1GB file





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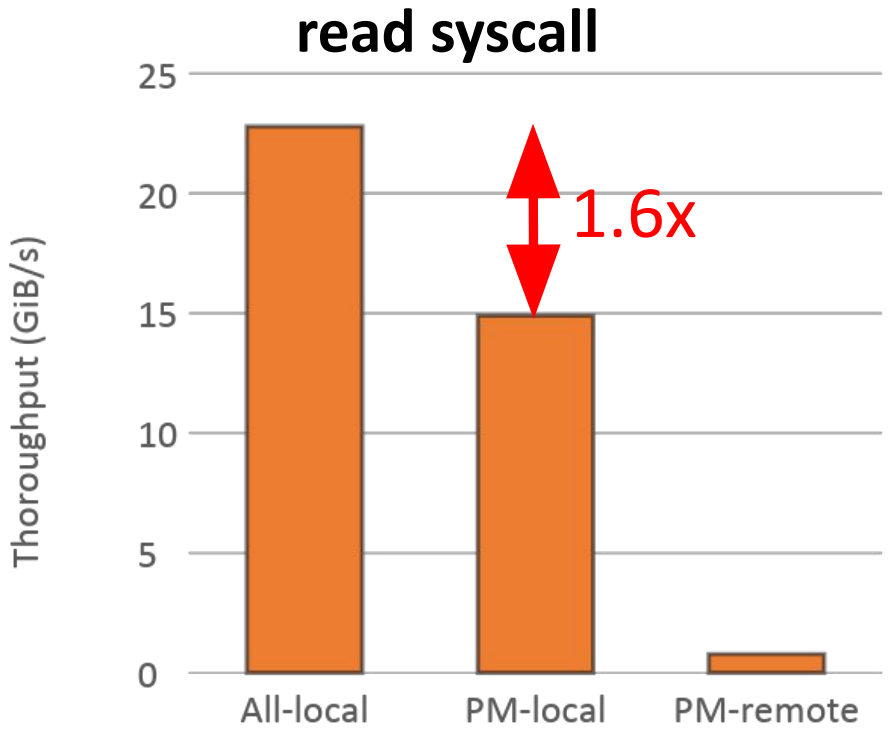

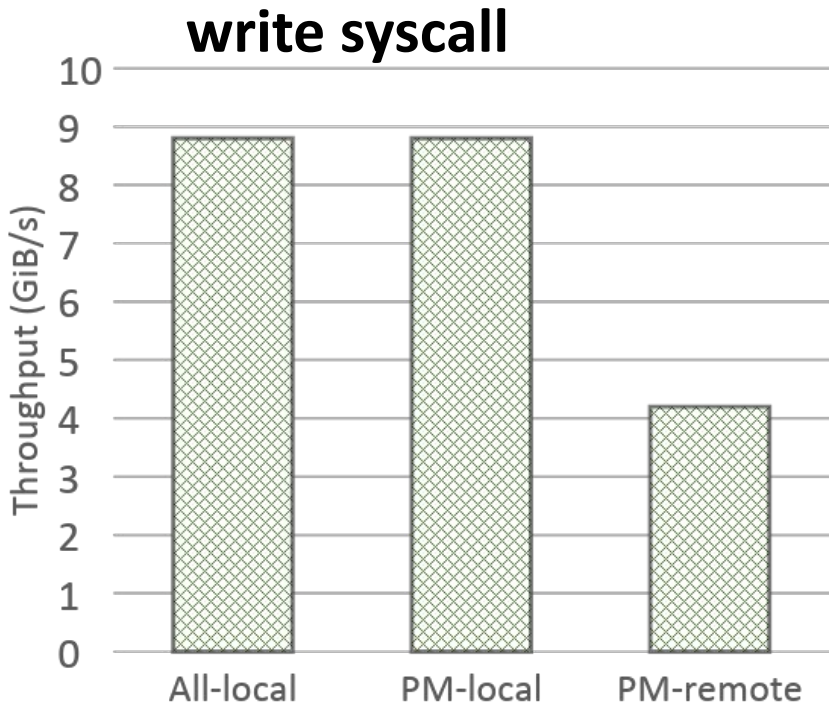

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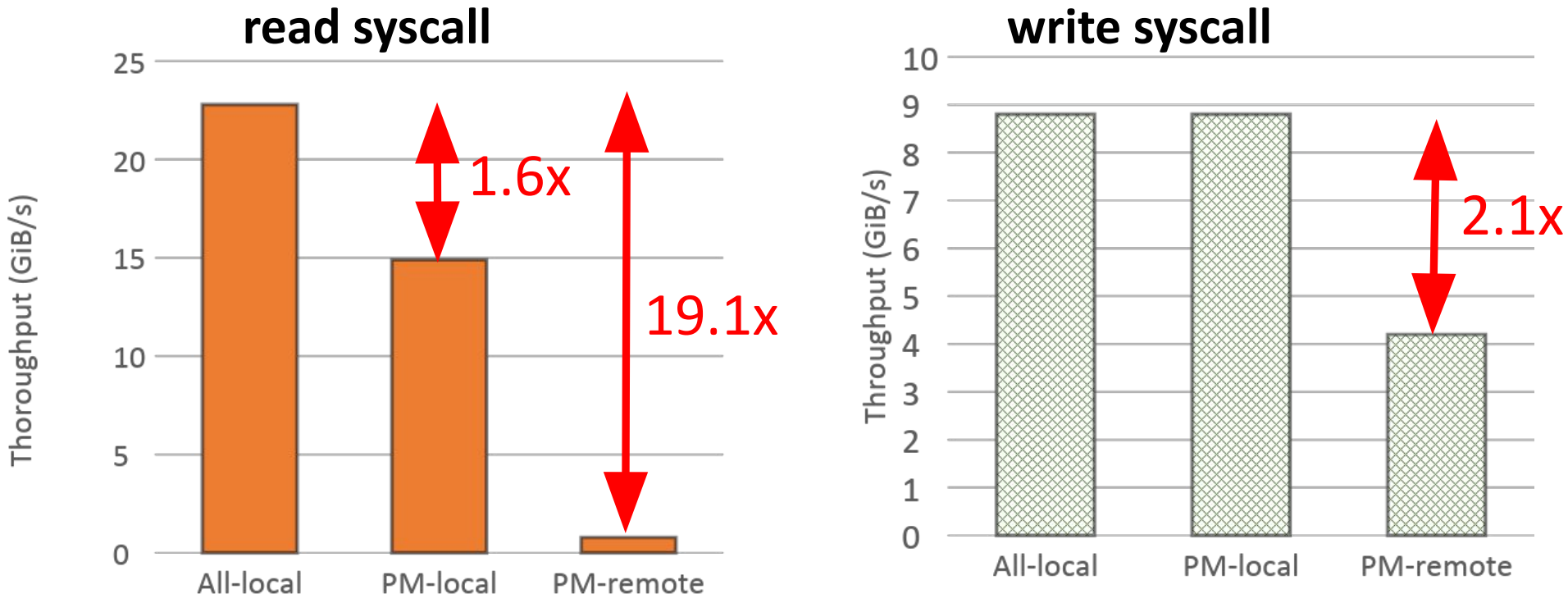

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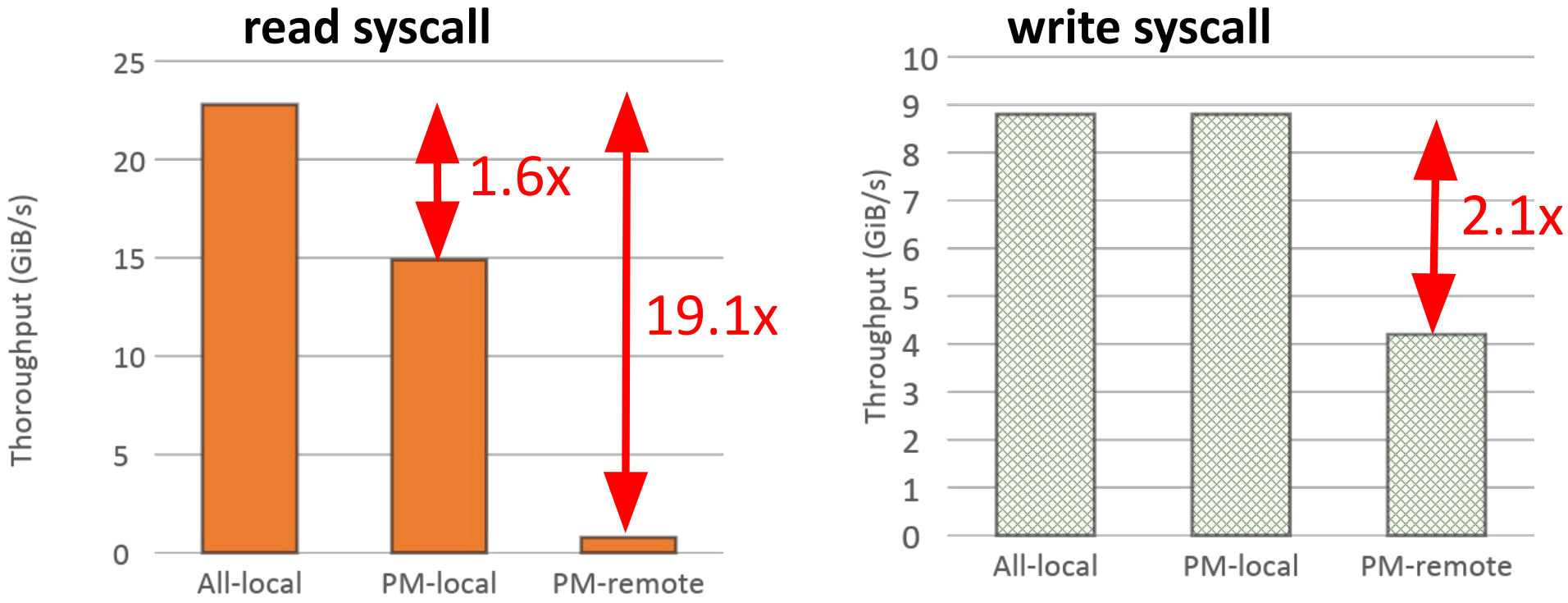

Impact of remote PM is more severe than remote DRAM access

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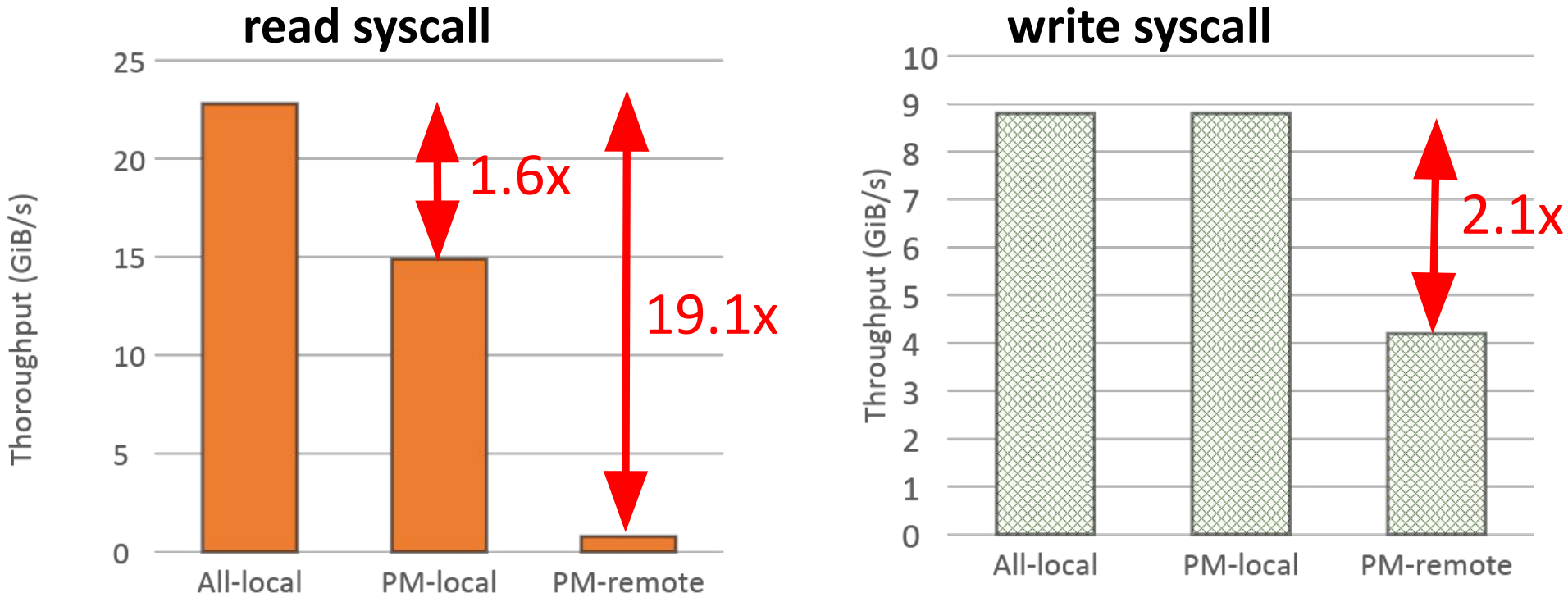
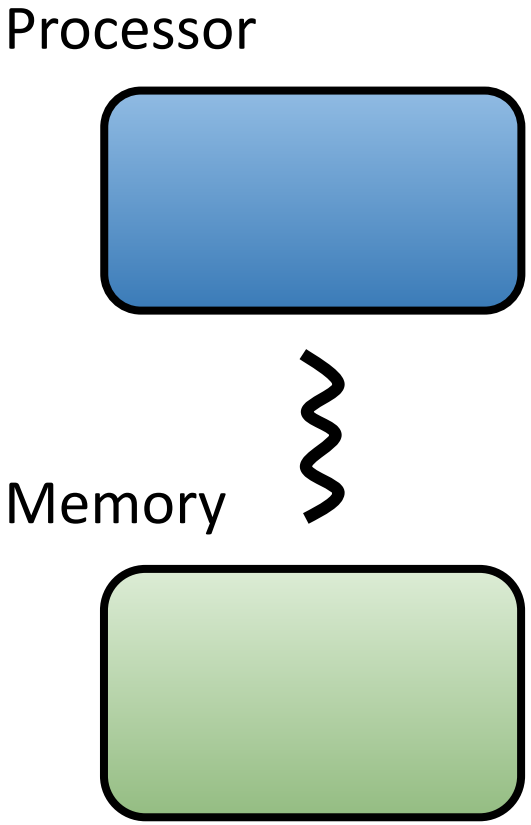


Cache coherence impedes NUMA scalability

NUMA PM impedes performance



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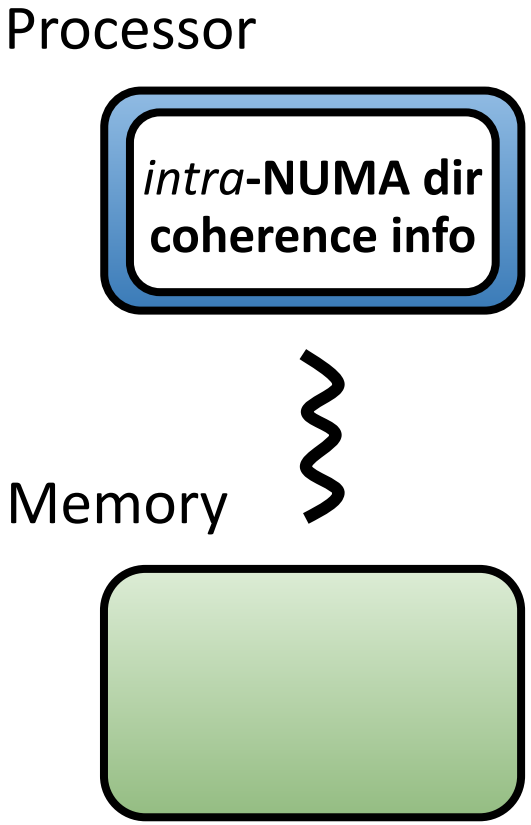

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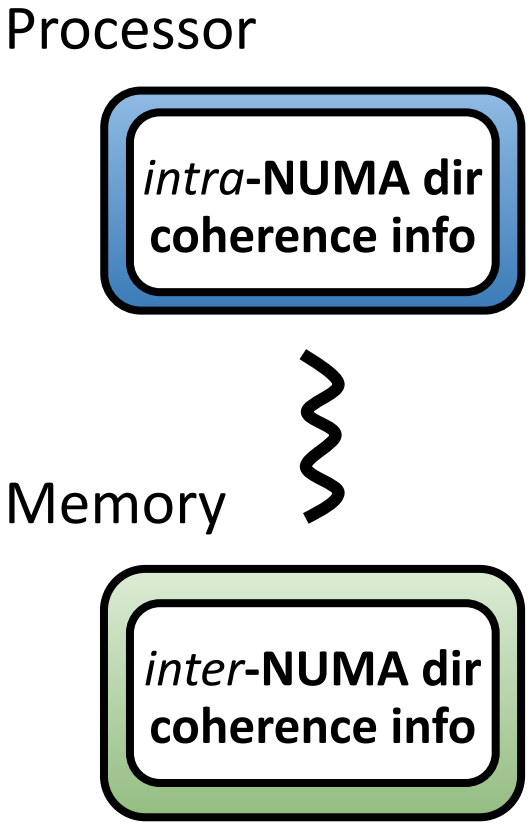

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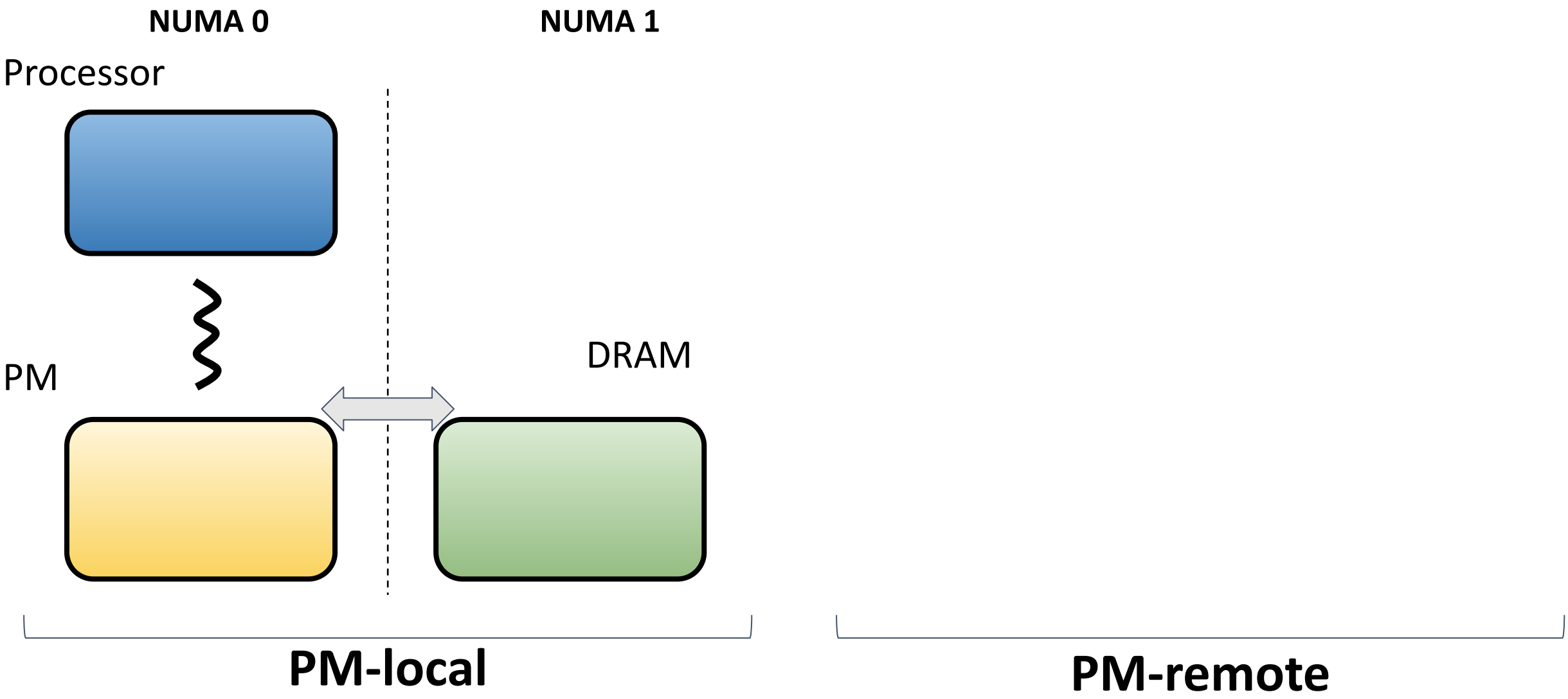

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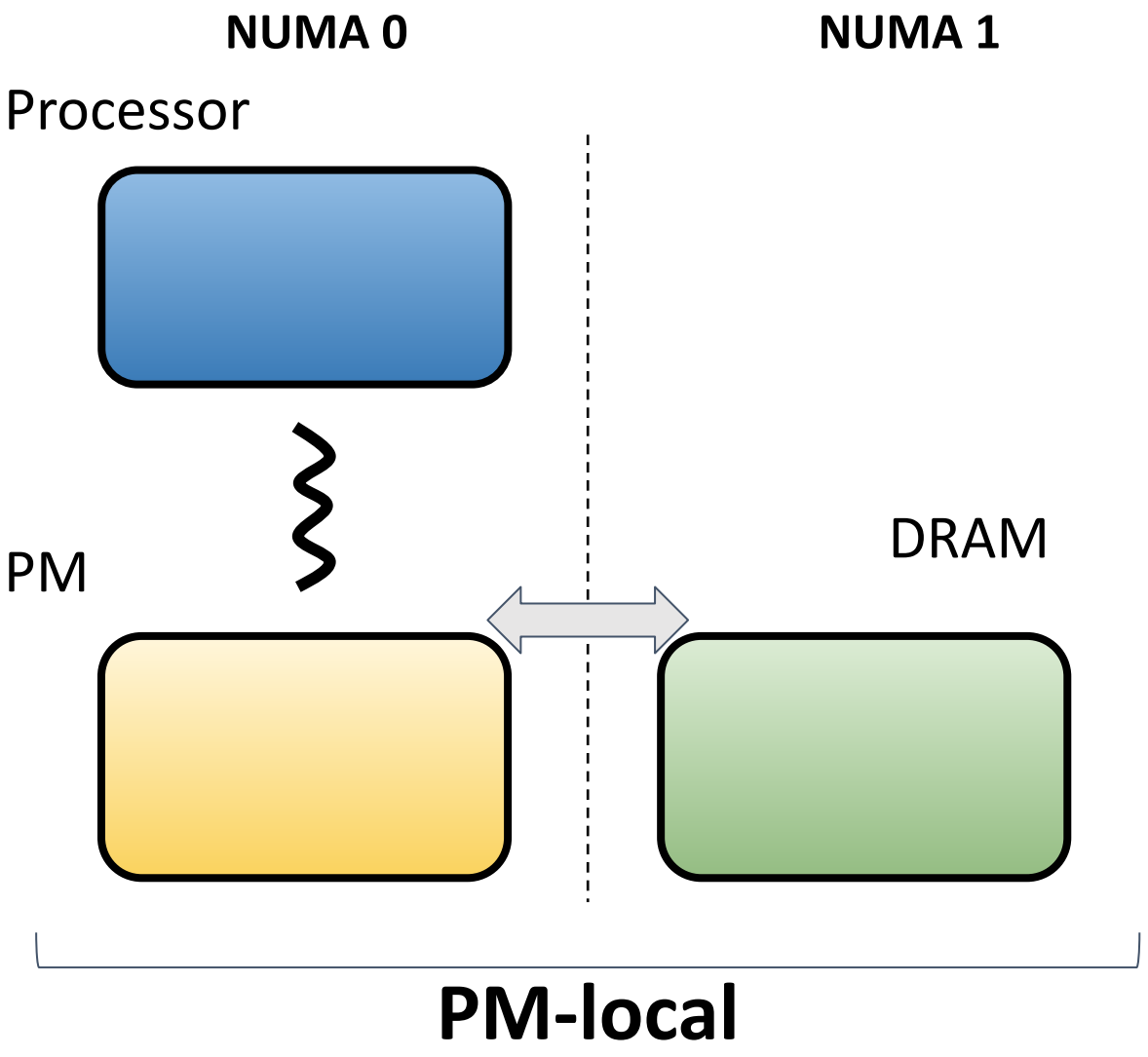

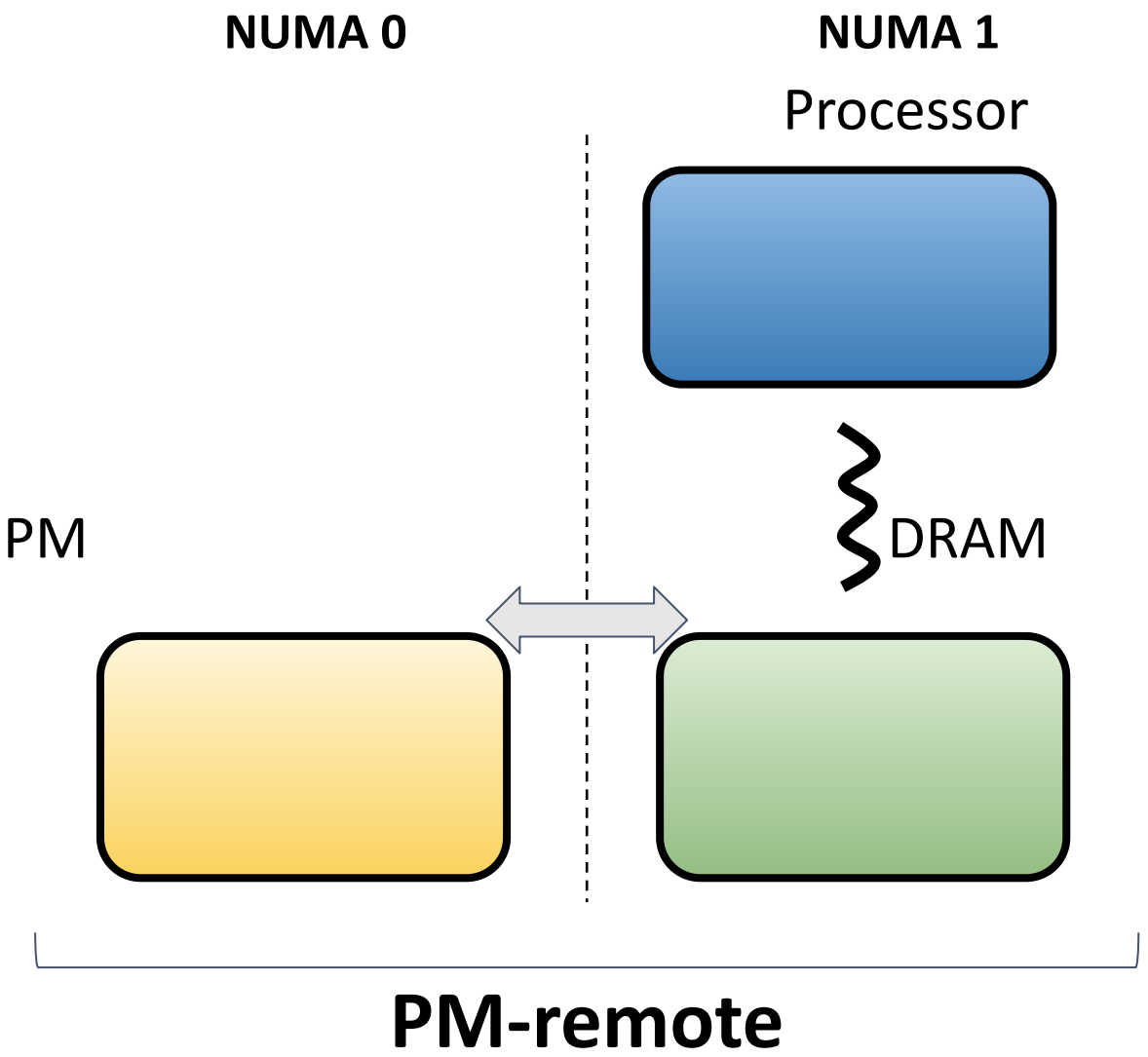

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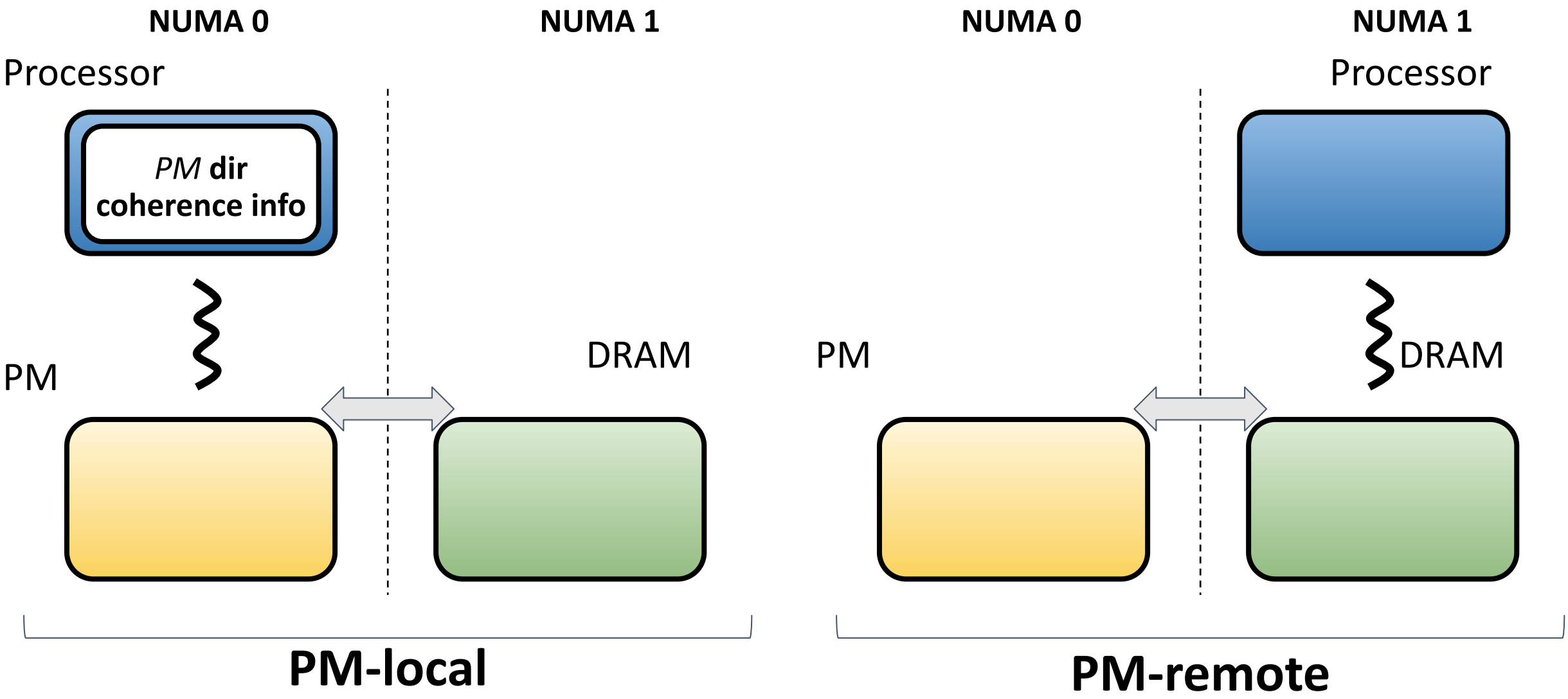

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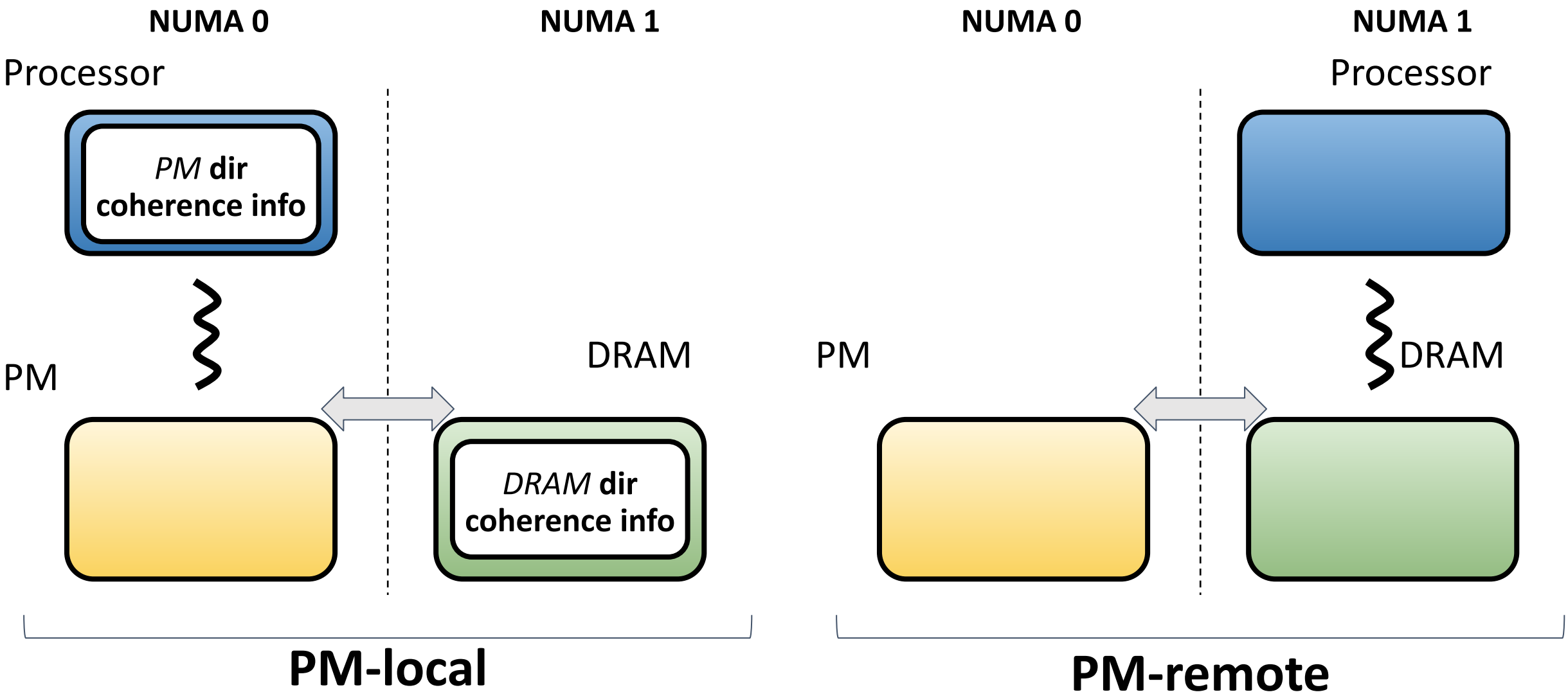

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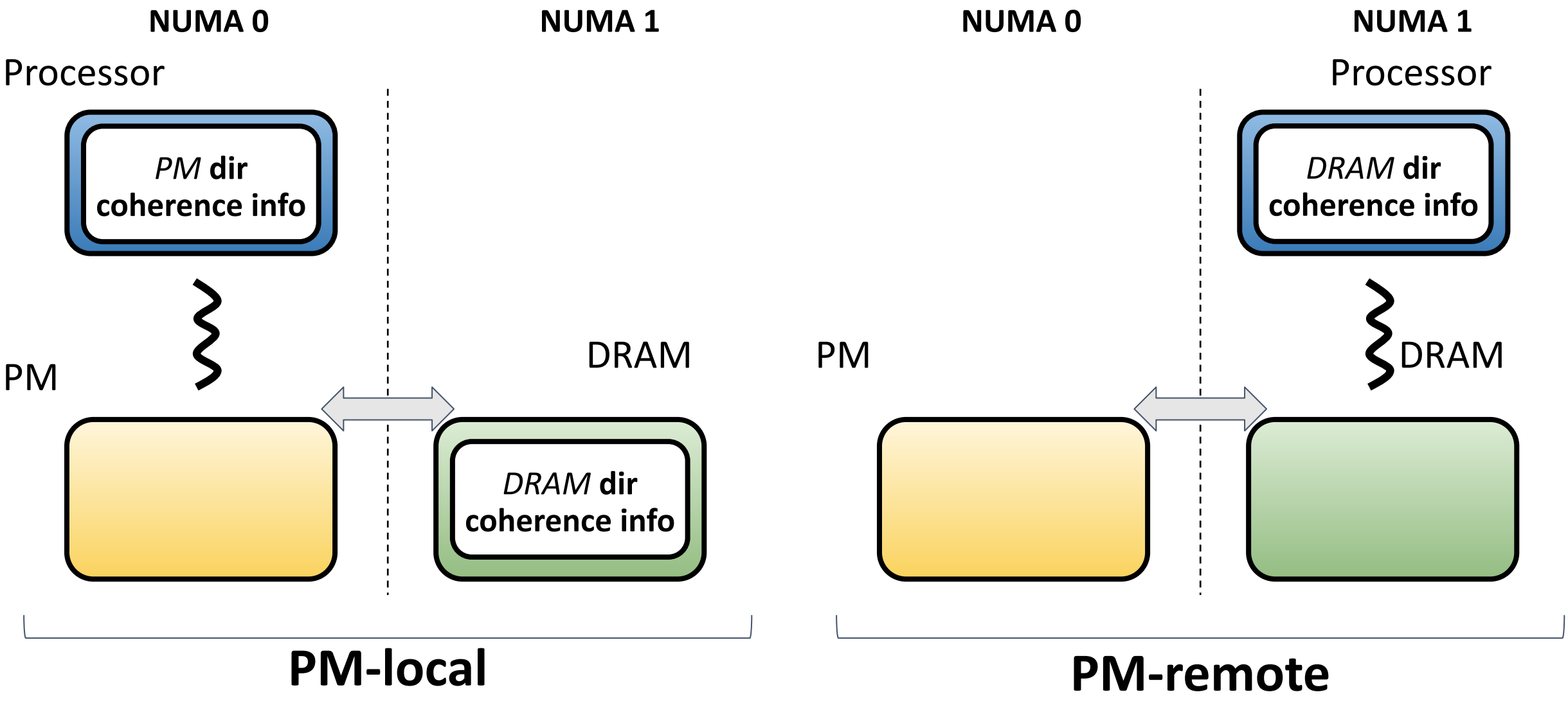

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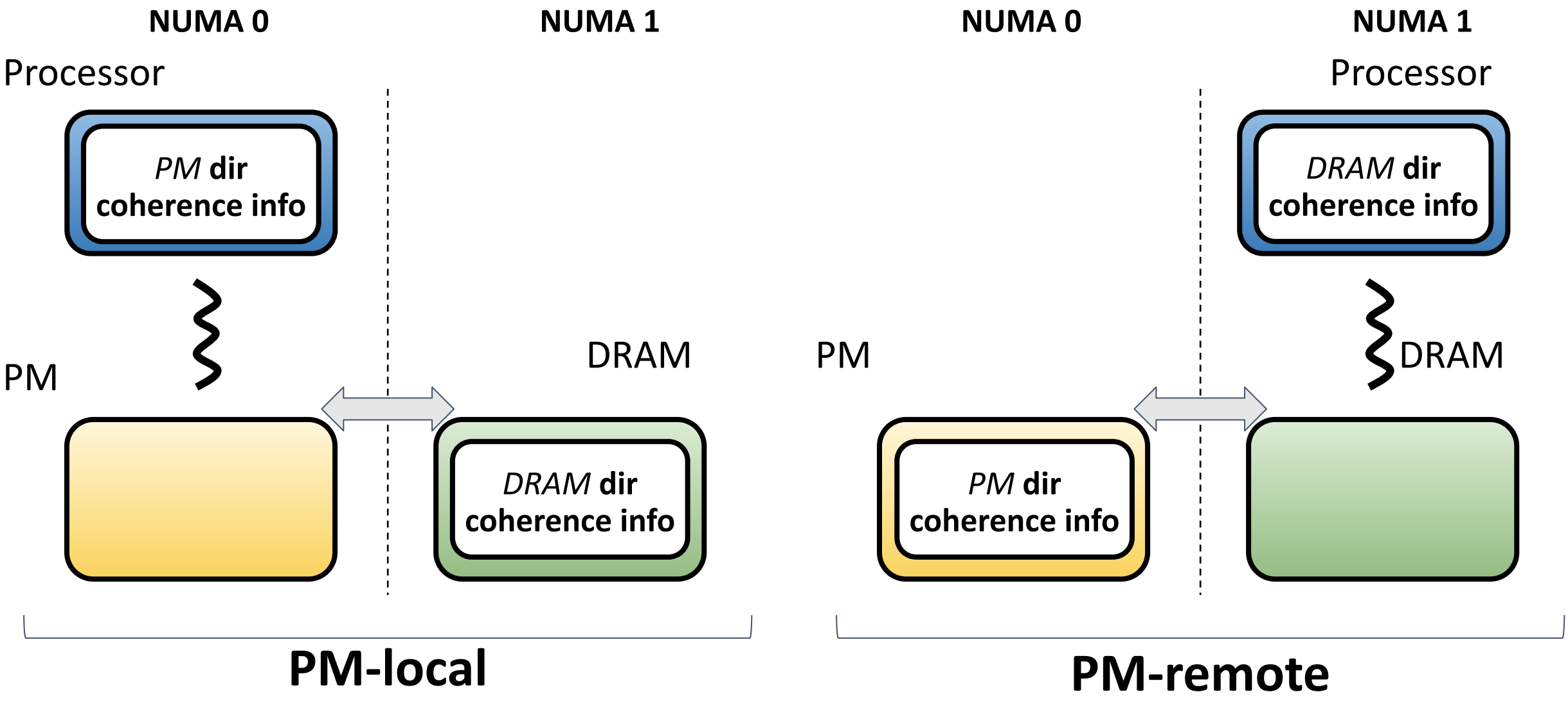

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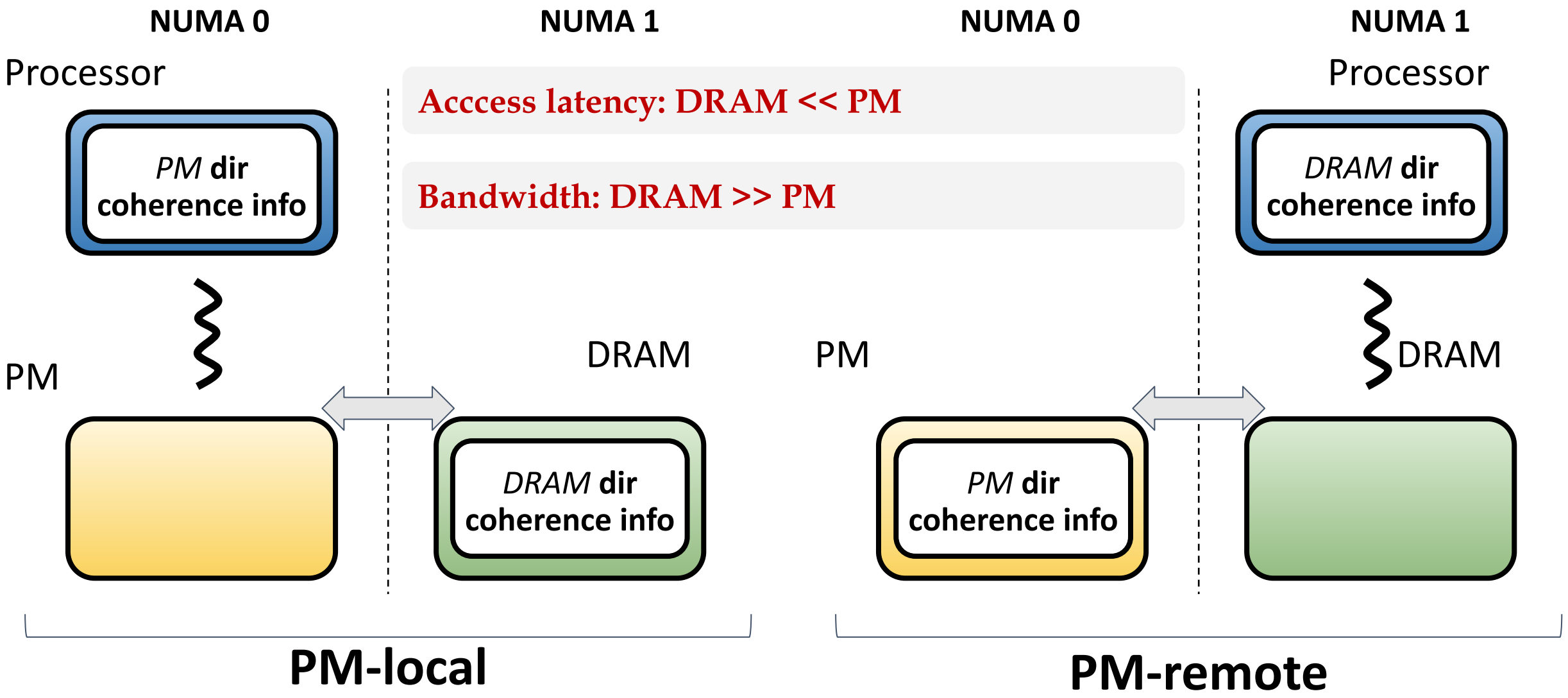

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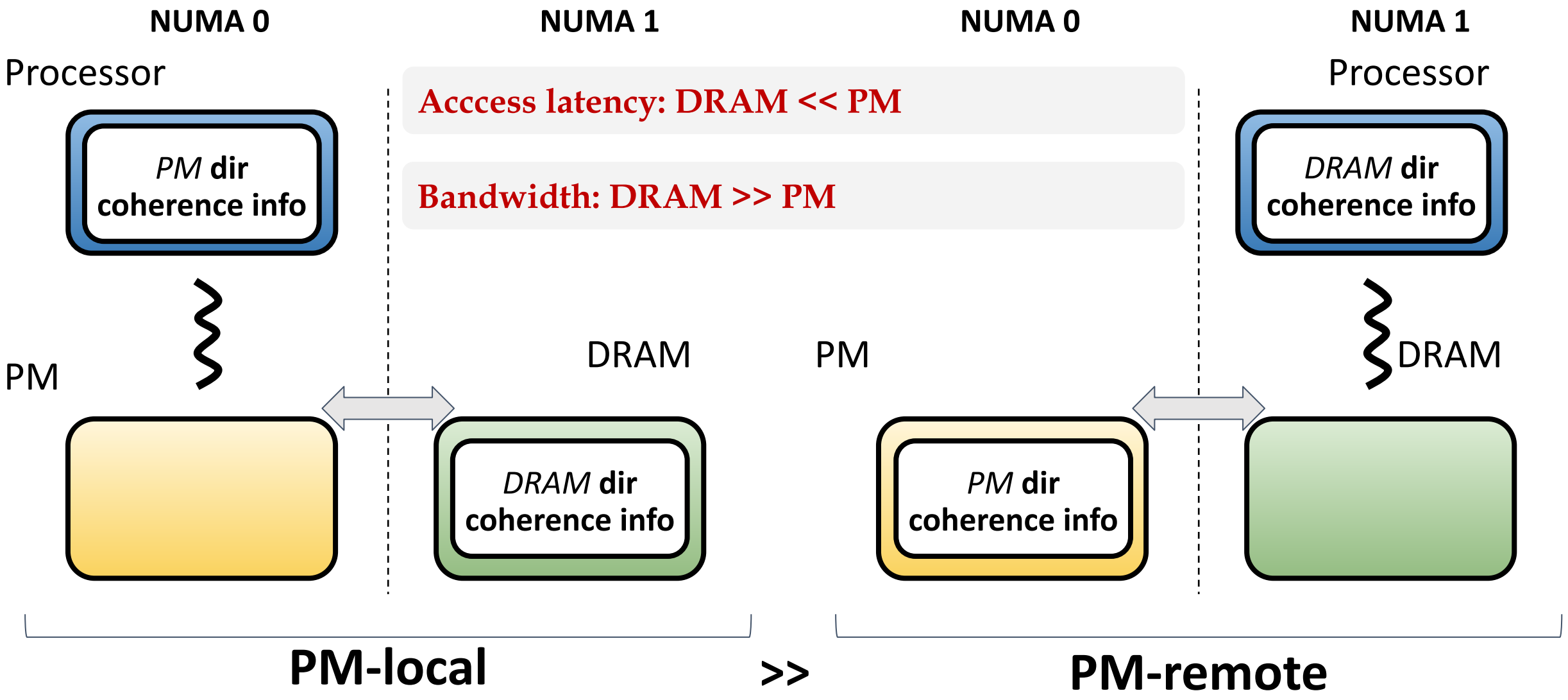

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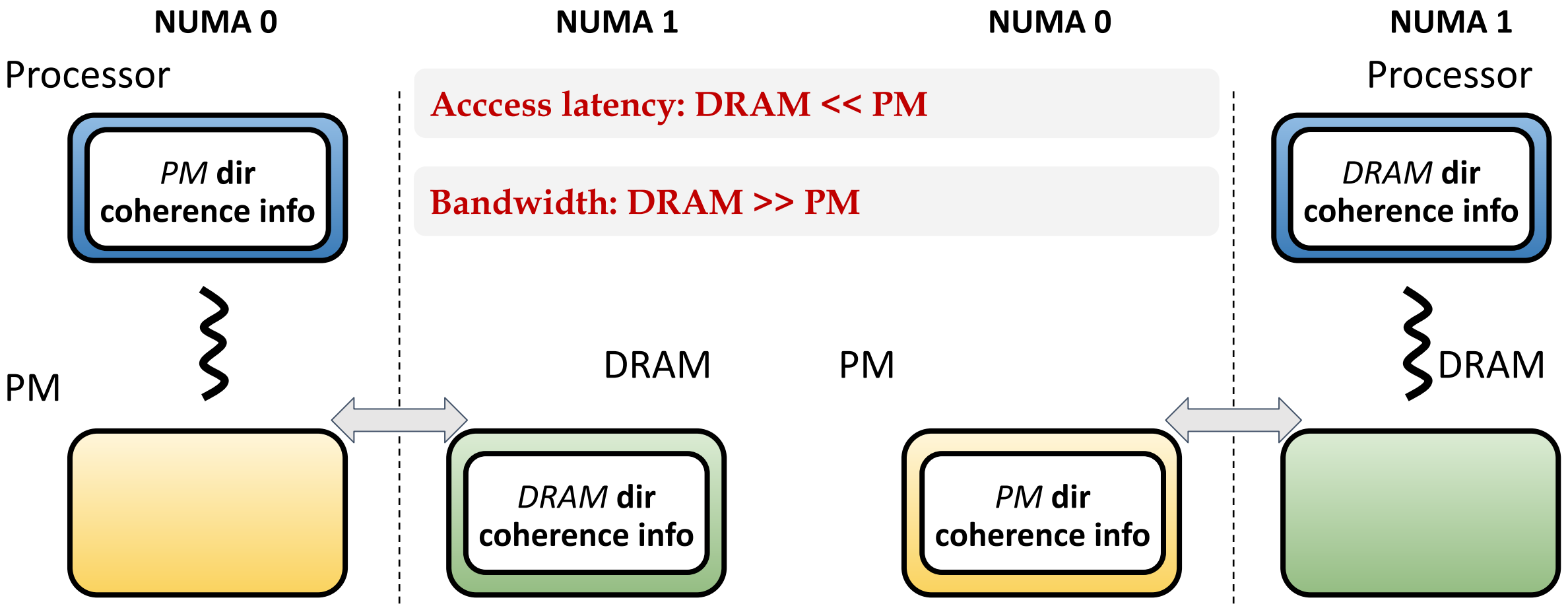


Remote PM access degrades severely

Approach …

Finding: PM cannot handle arbitrary concurrent accesses

Arbitrate the number of threads accessing PM

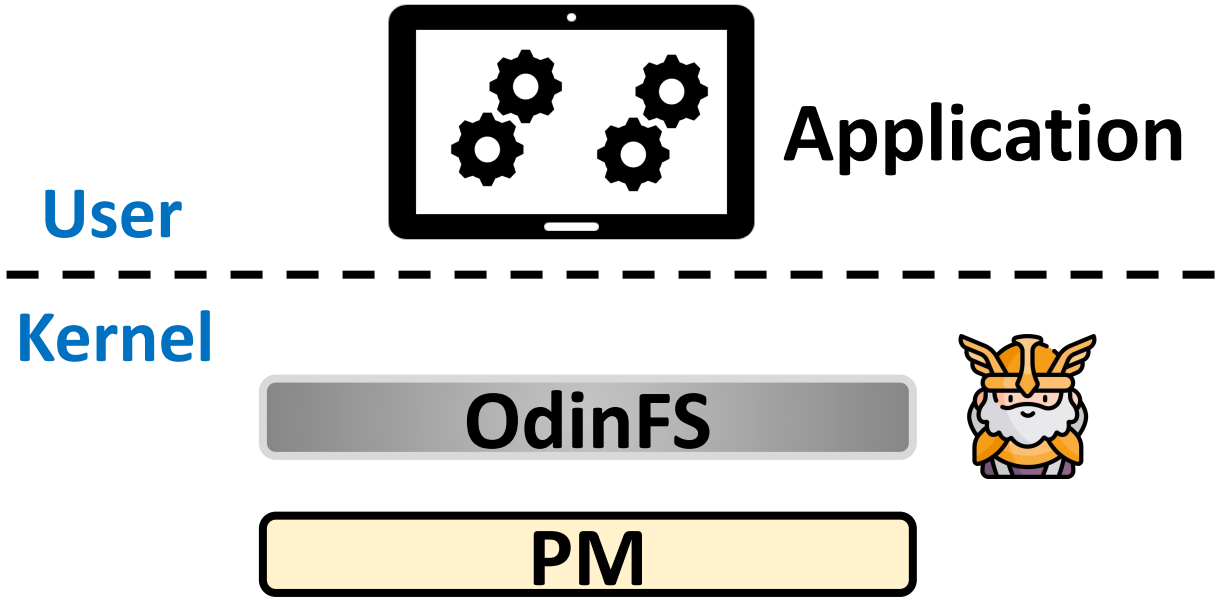
Finding: Remote PM access degrades severely

Access PM as local as possible

OdinFS

File system maximizes PM performance via opportunistic delegation

OdinFS



- In-kernel PM file systems
- POSIX-compliant

OdinFS design: Delegate IO requests

Idea: **Decouple PM access from application threads**

Limits concurrent access

→ Preserves maximal PM performance within a NUMA node

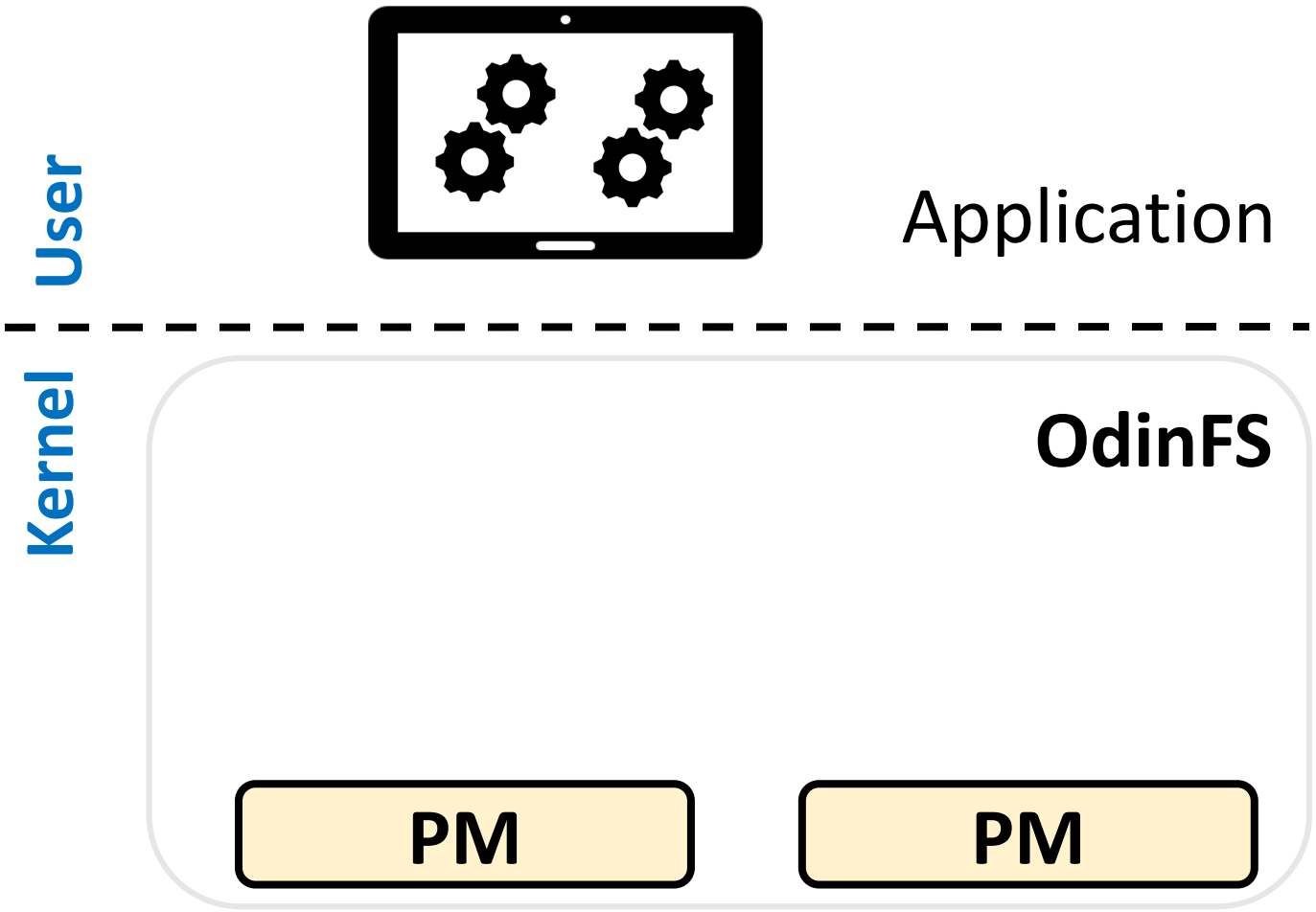
Localized PM access

→ Minimizes PM NUMA impact and enables efficient remote access

Efficiently utilizes the aggregated PM bandwidth

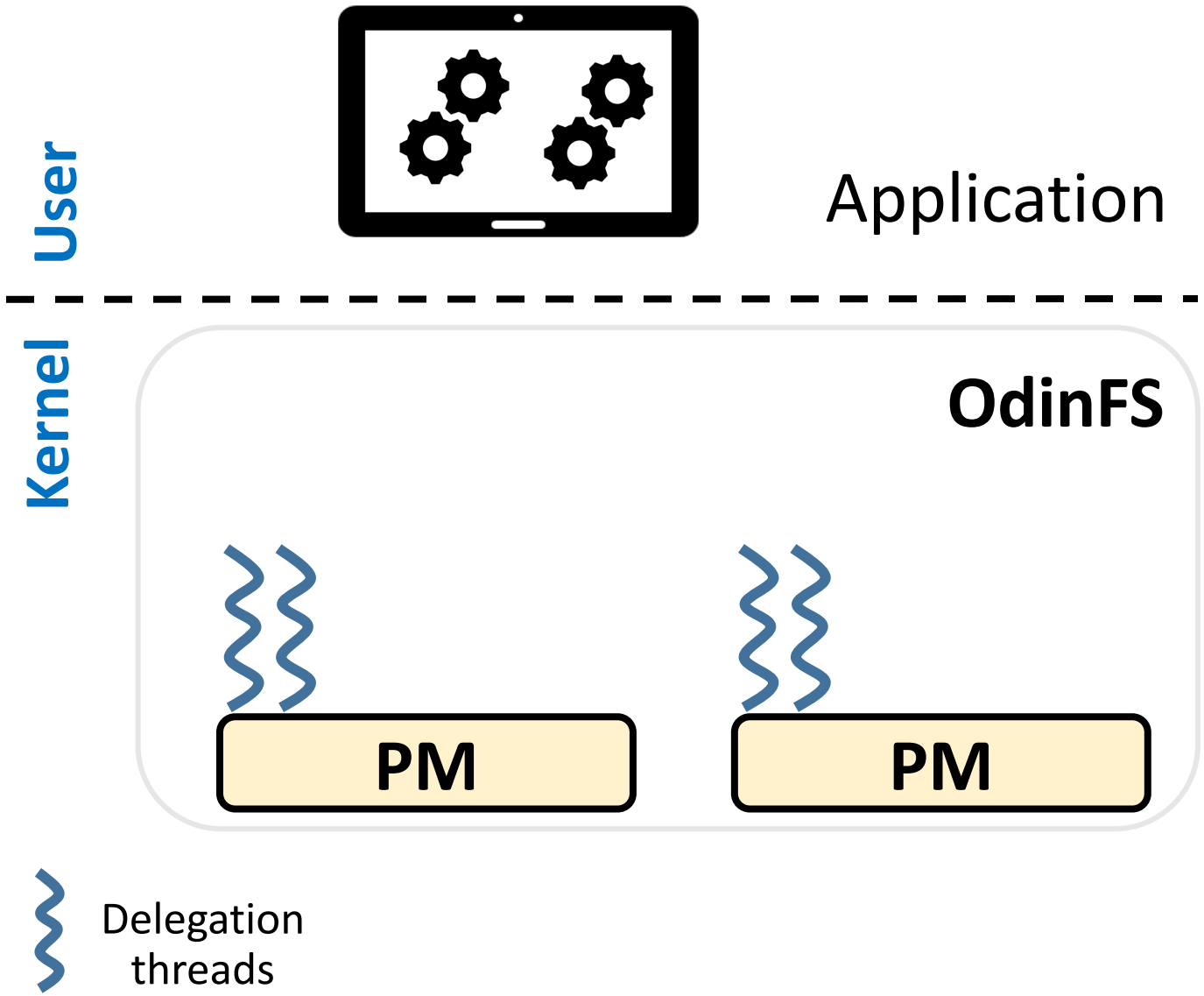
→ Arbitrary applications can utilize the entire machine bandwidth

Decouple PM access from application threads



- **Delegation threads access PM on application's behalf**

Decouple PM access from application threads



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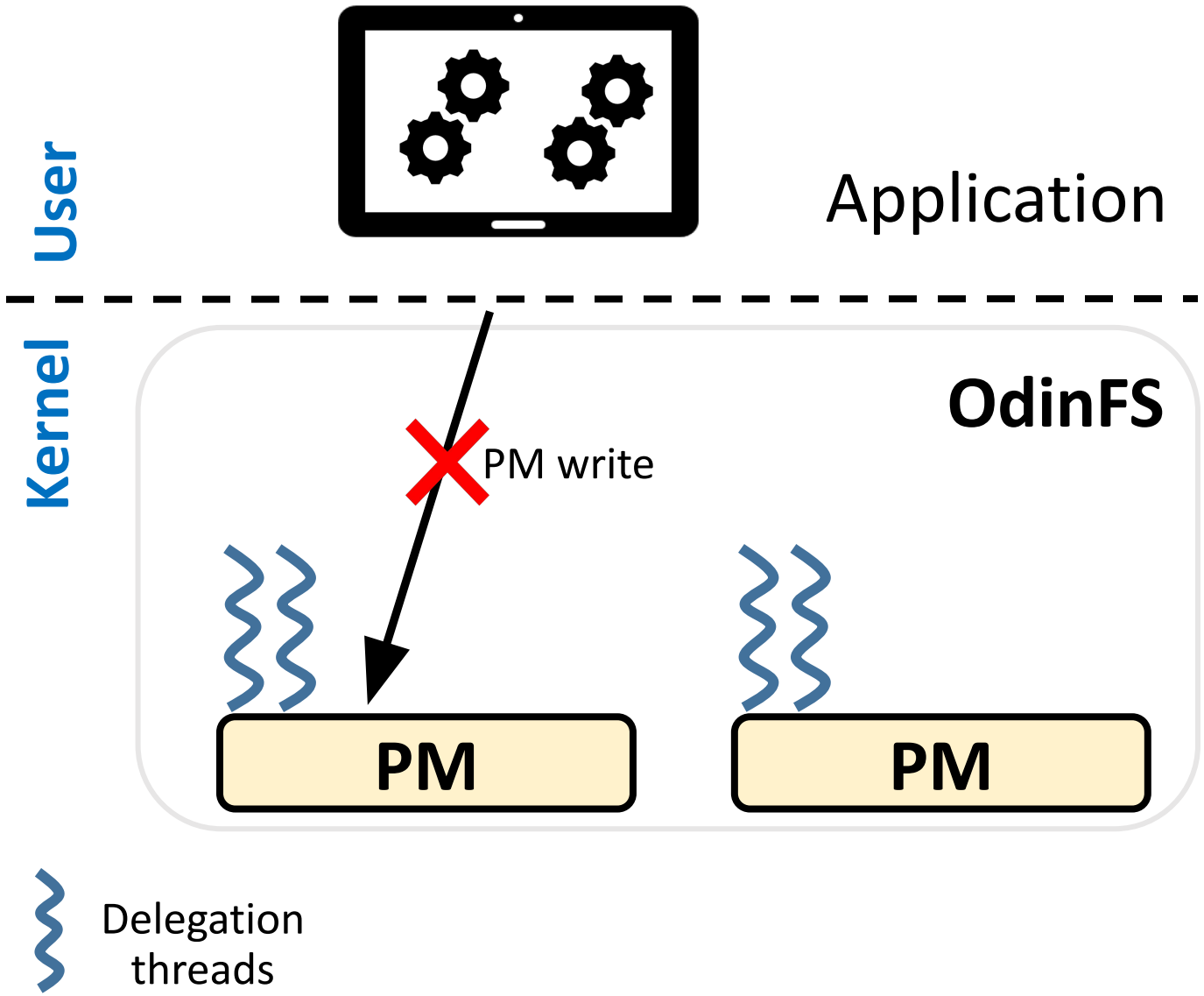

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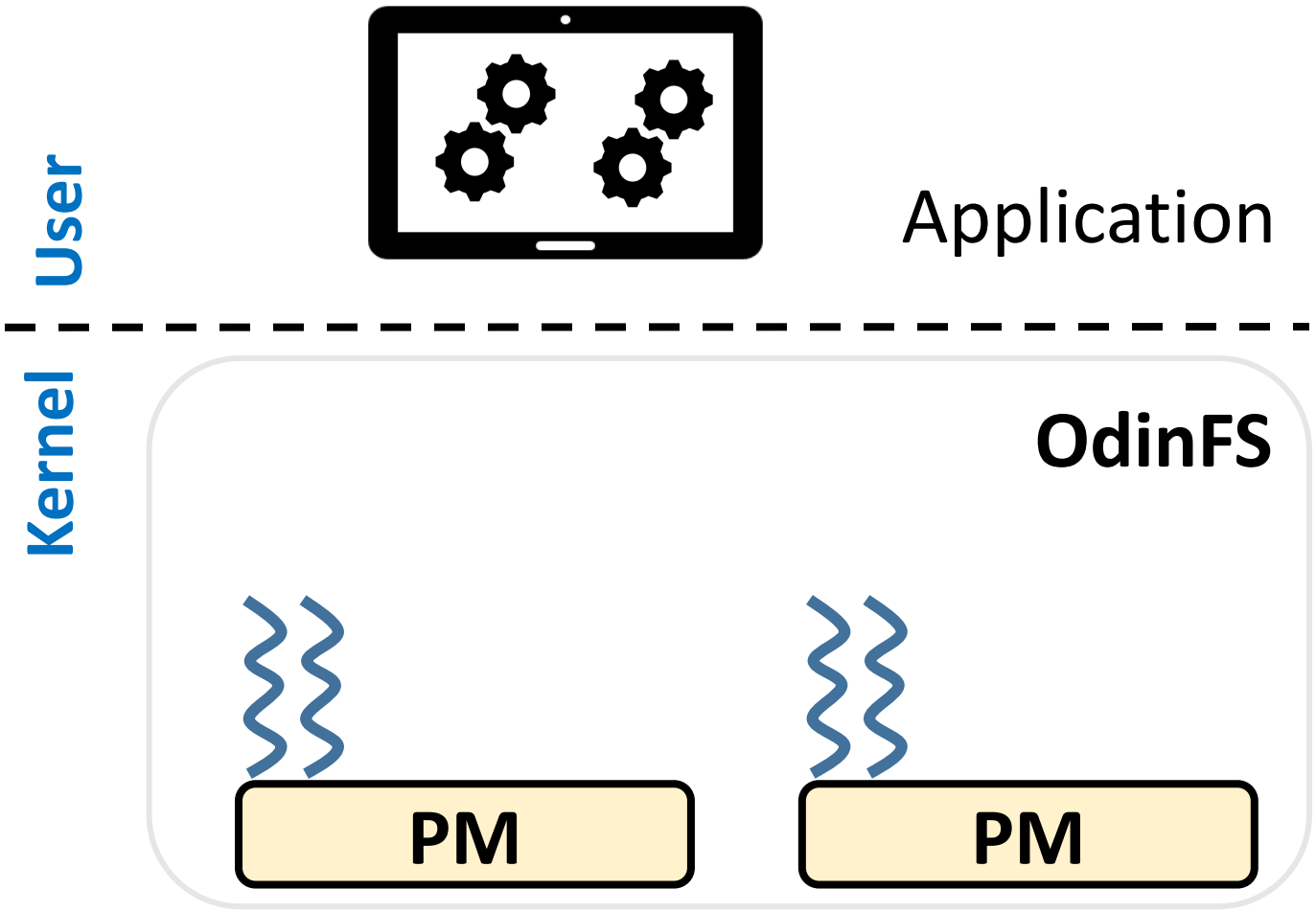

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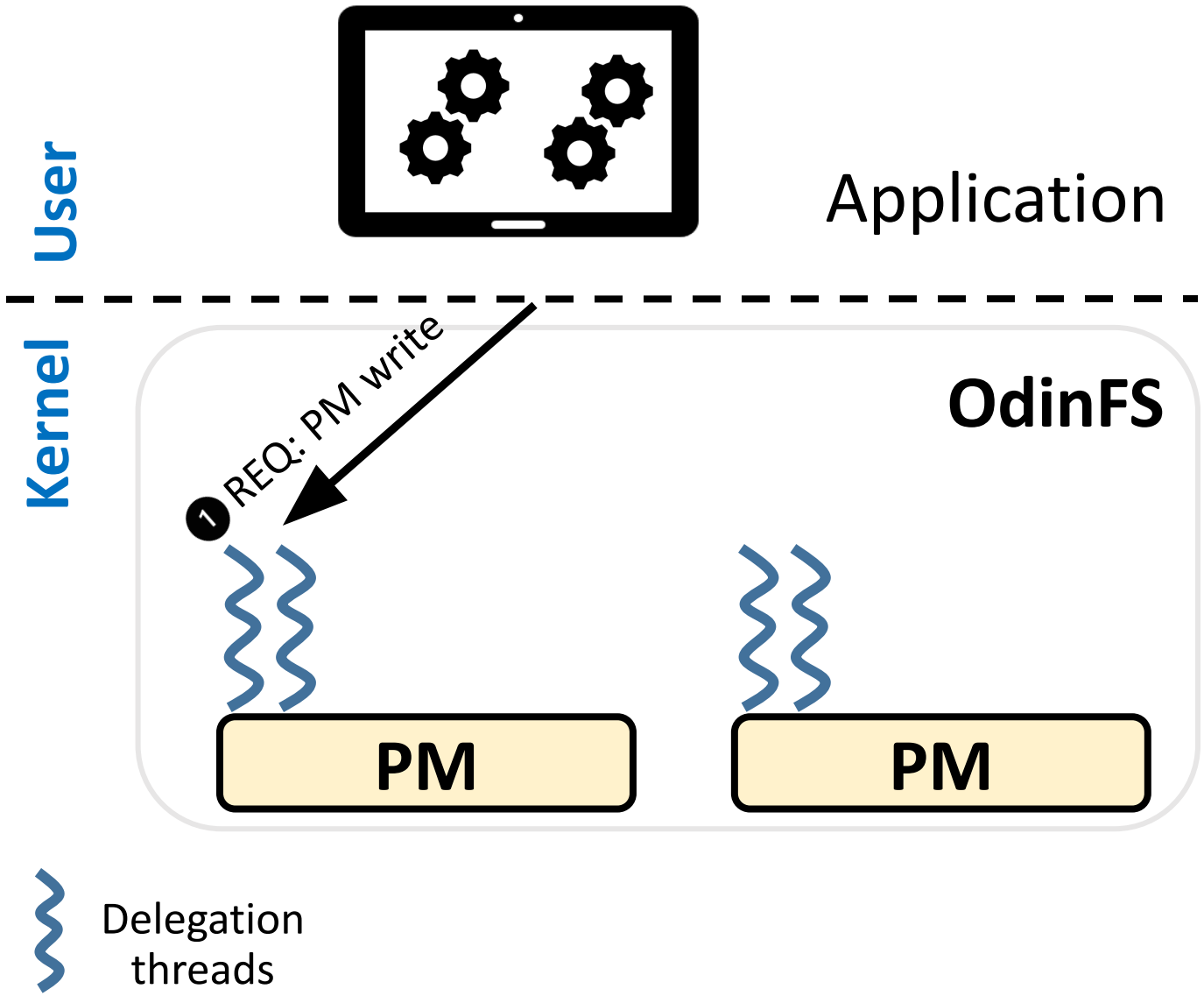

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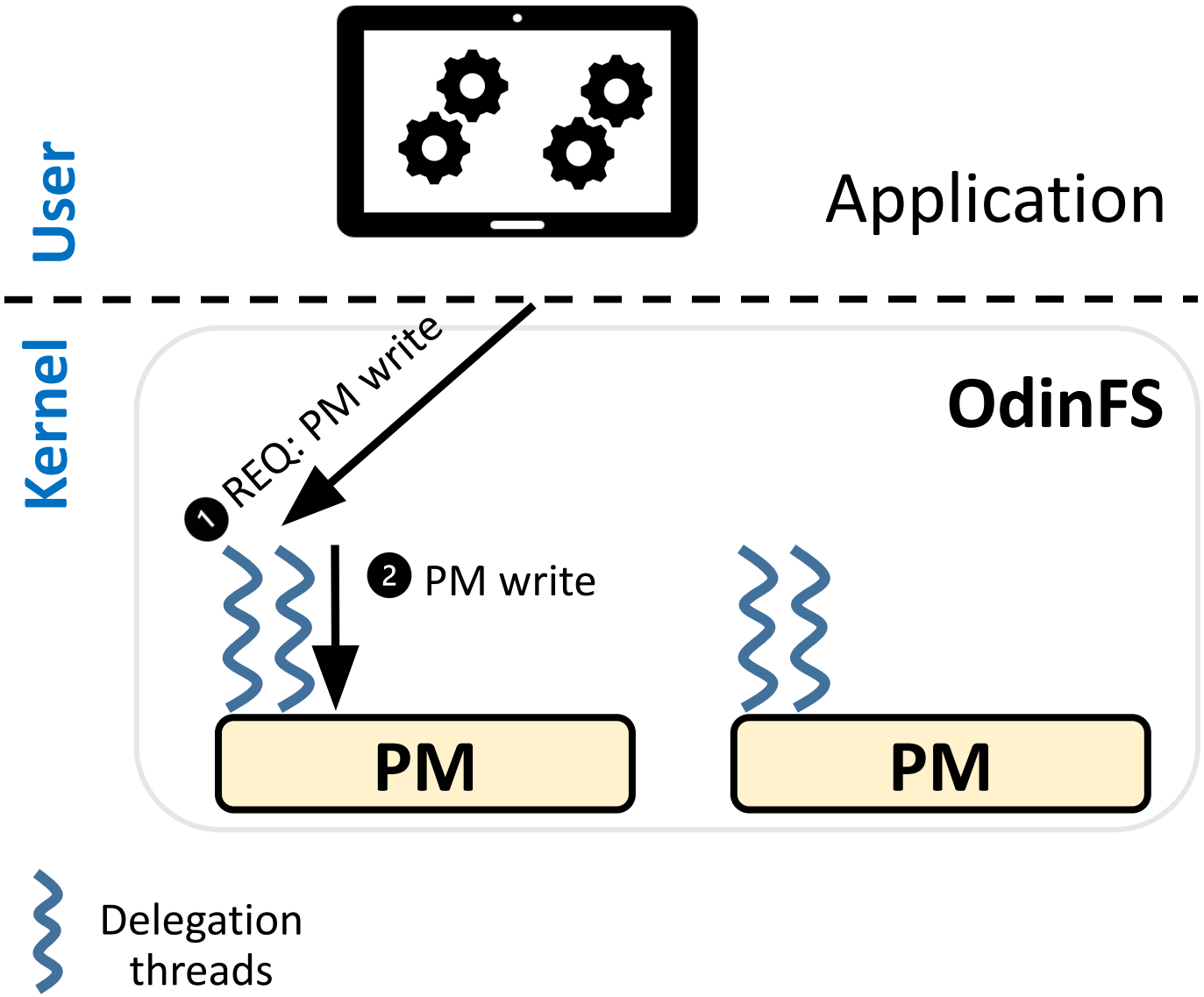

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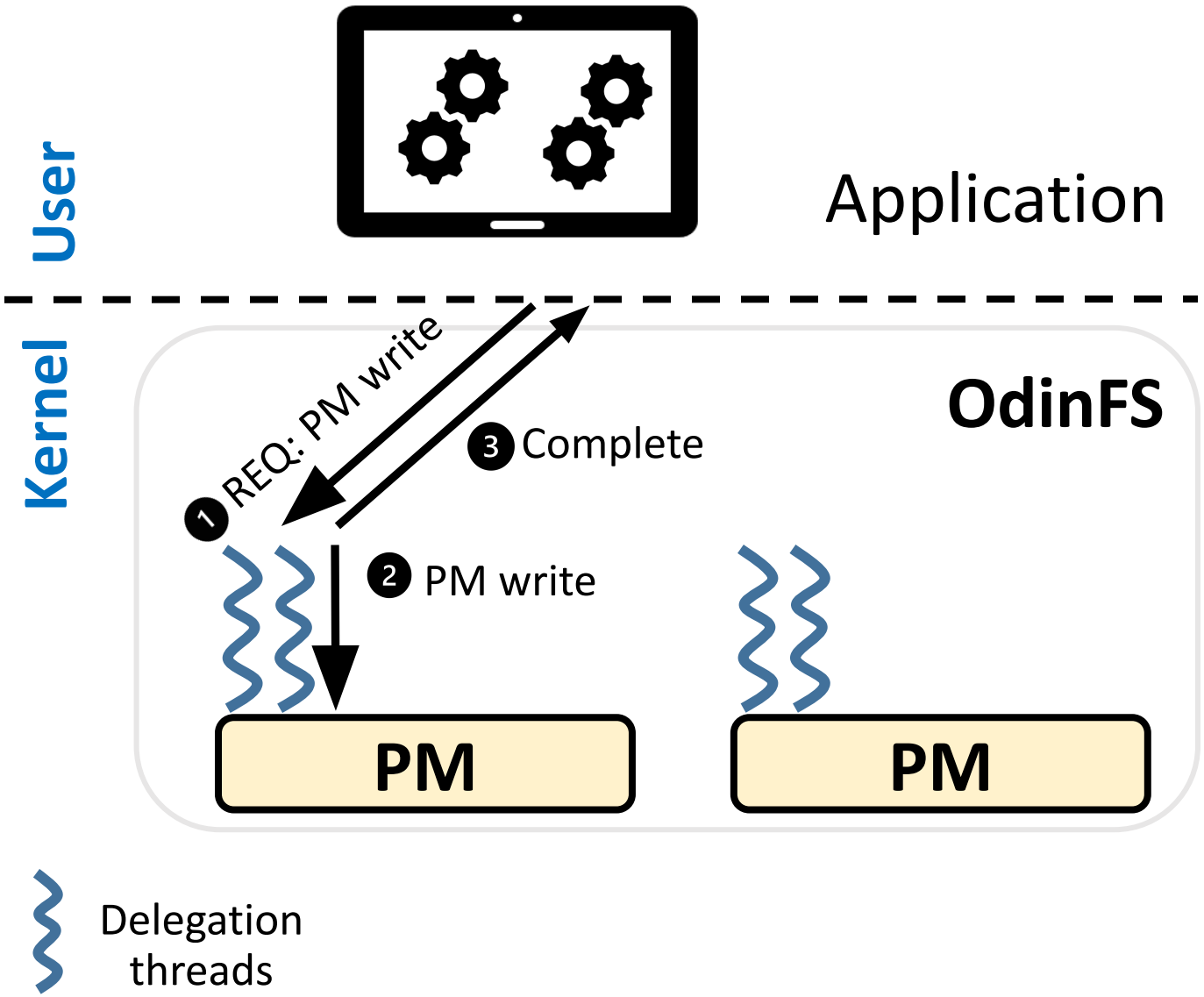

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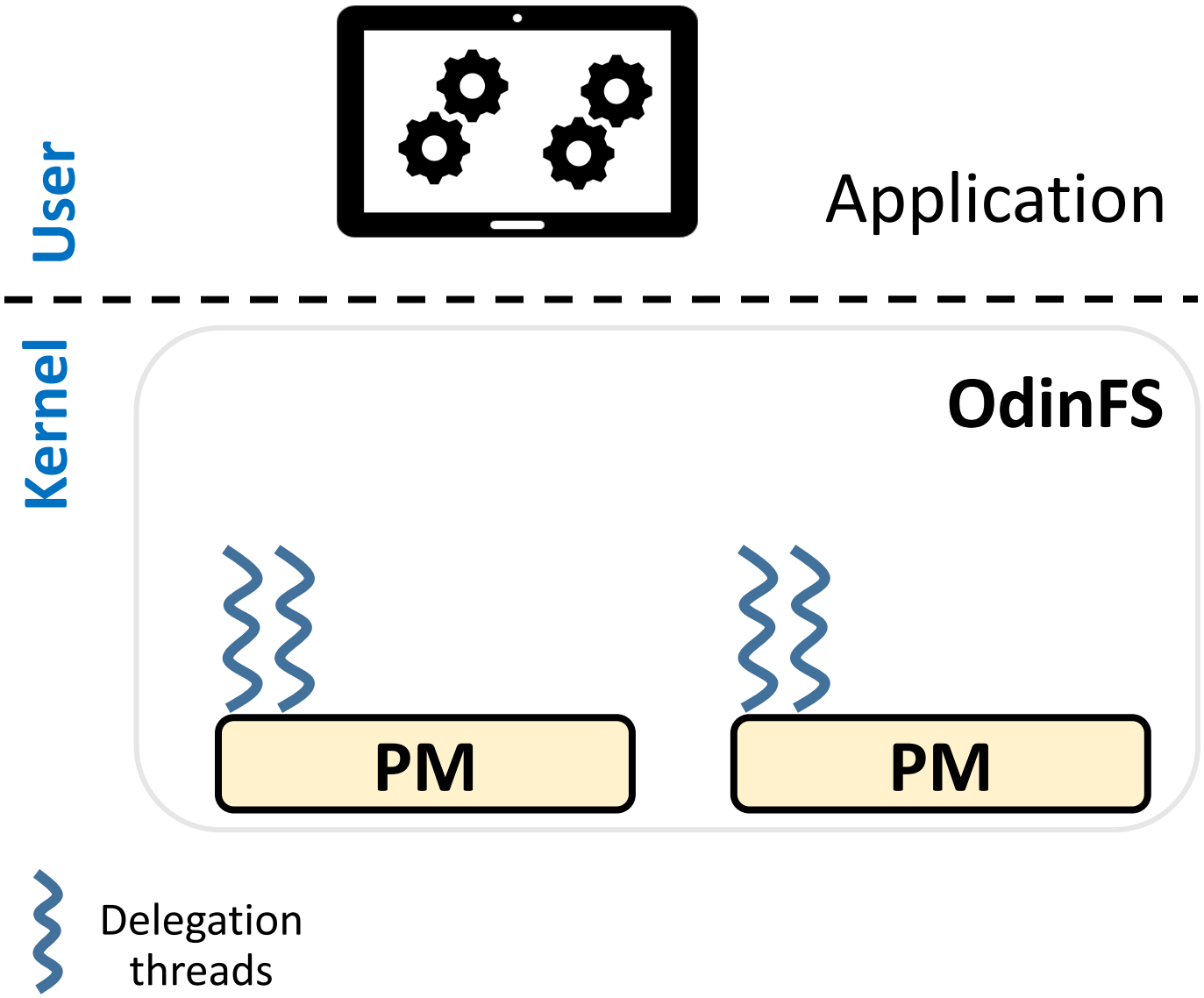
Delegation limits and localizes PM access



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- **Delegation threads control the access to PM**

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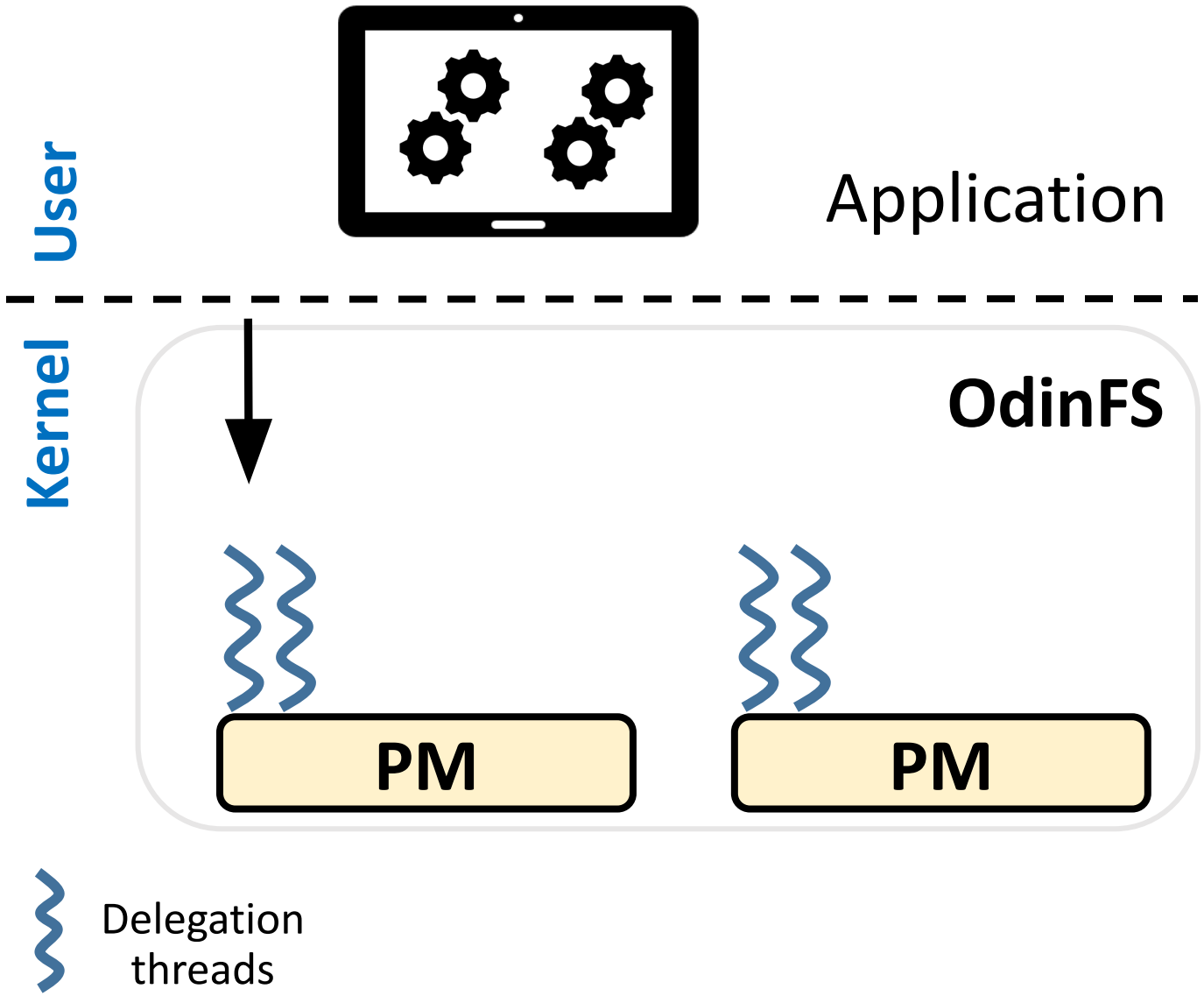

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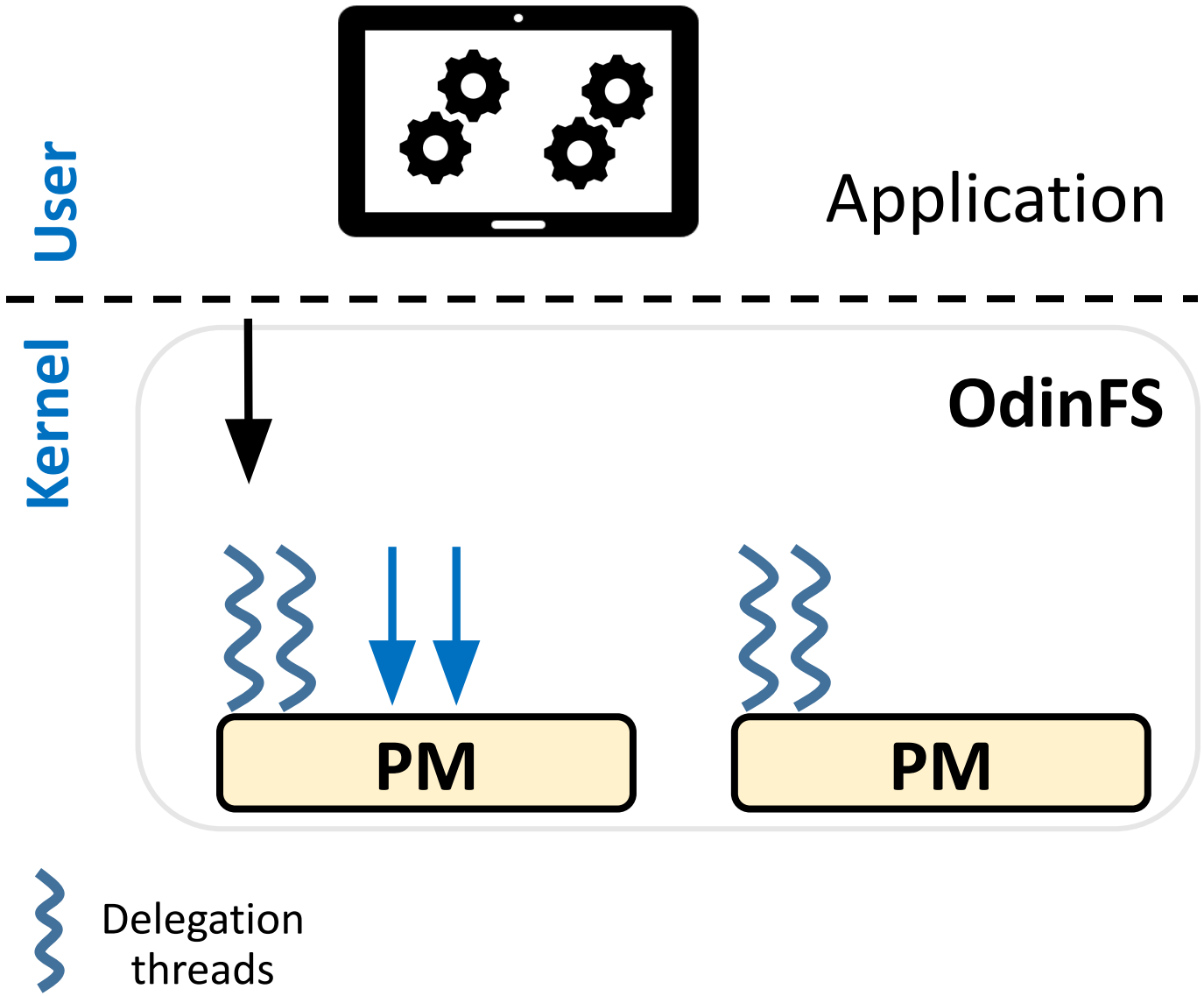

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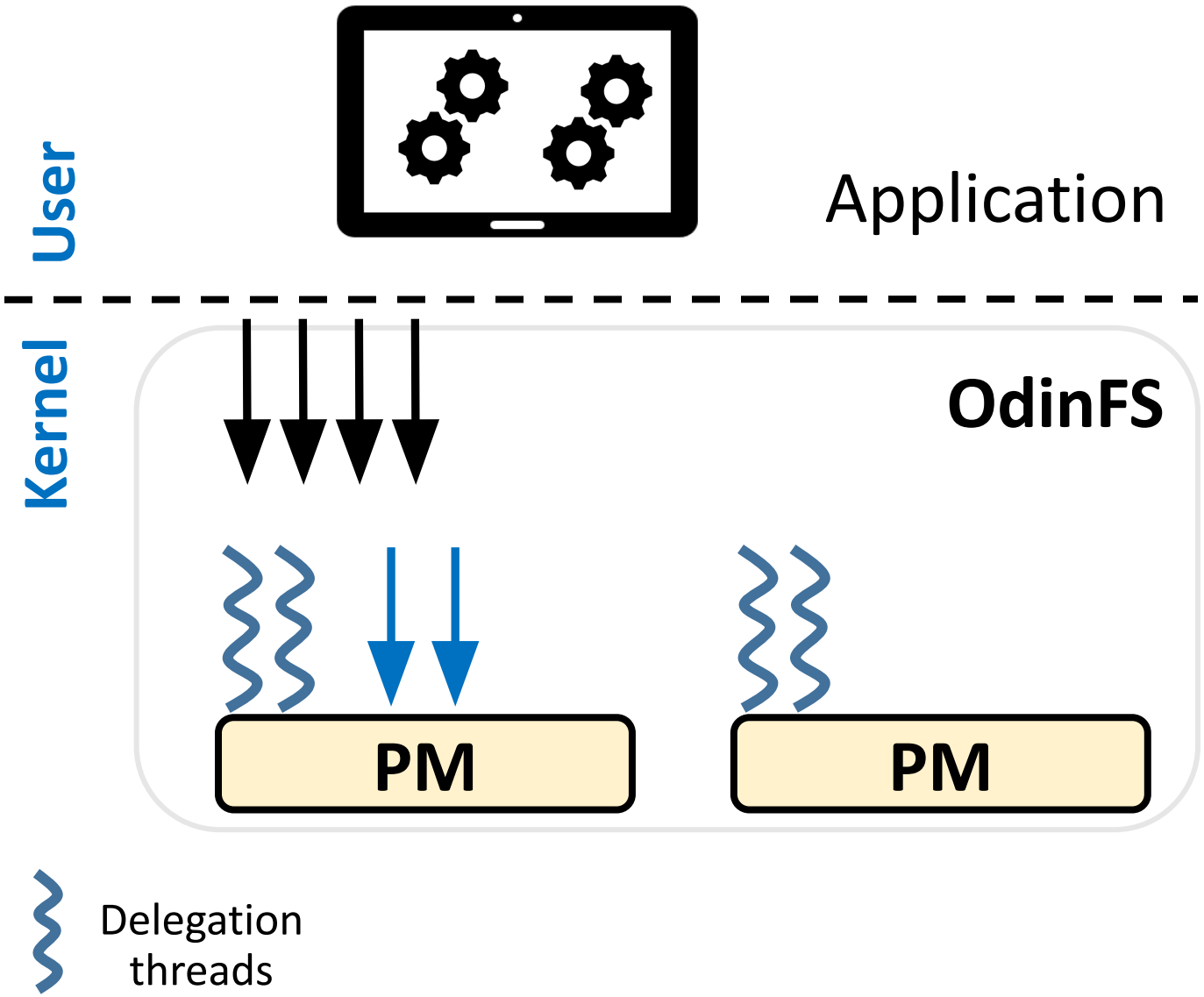

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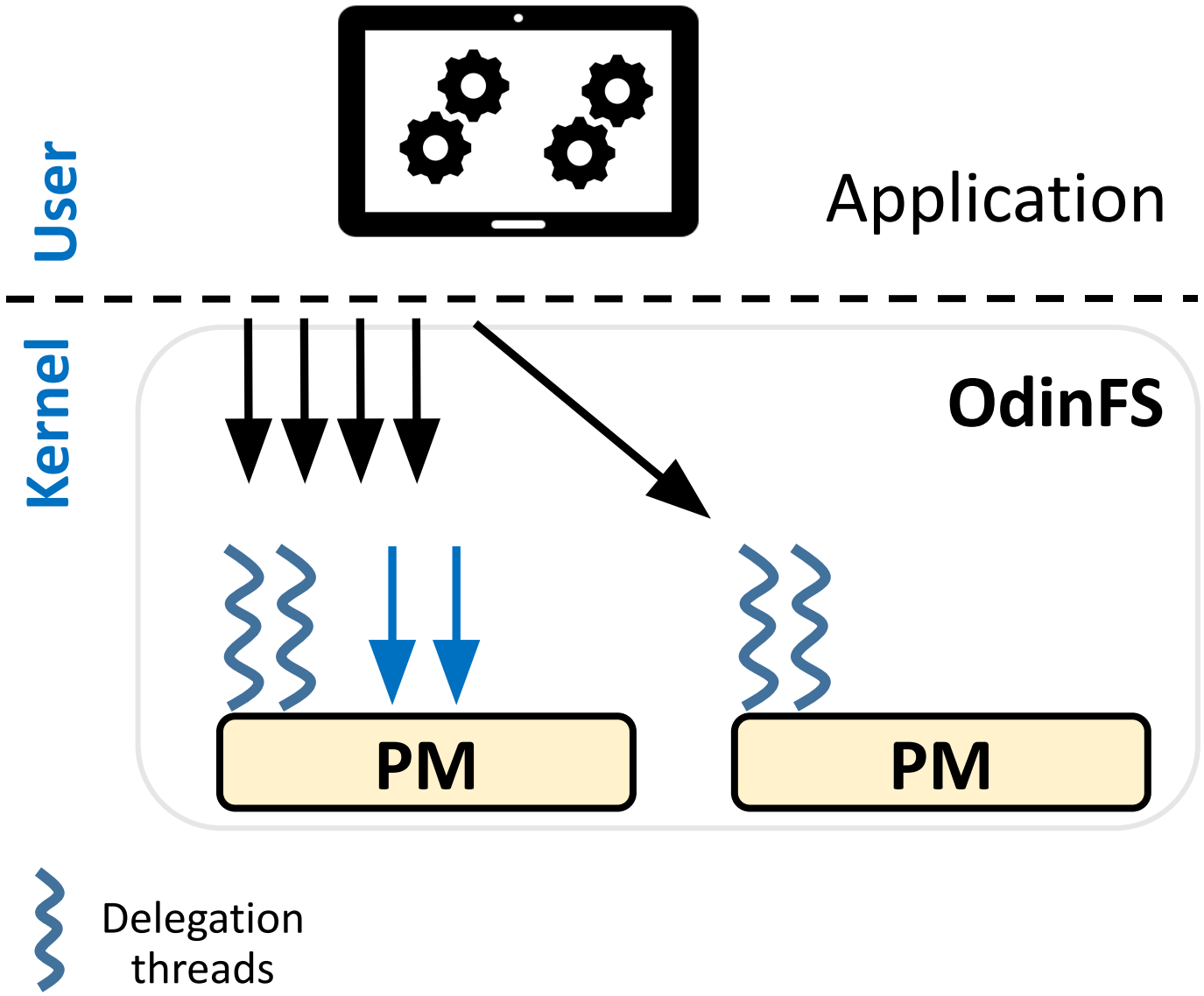

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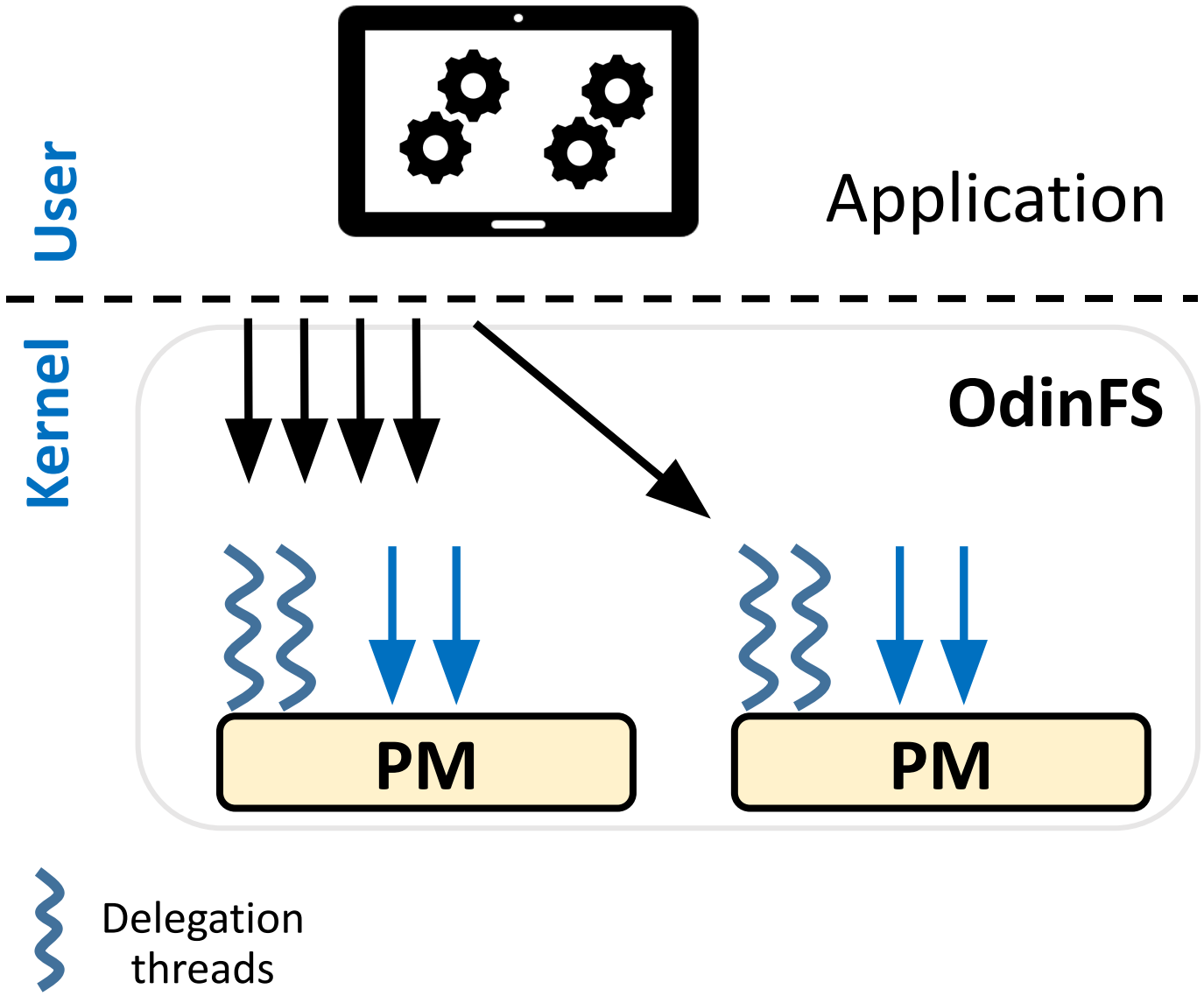

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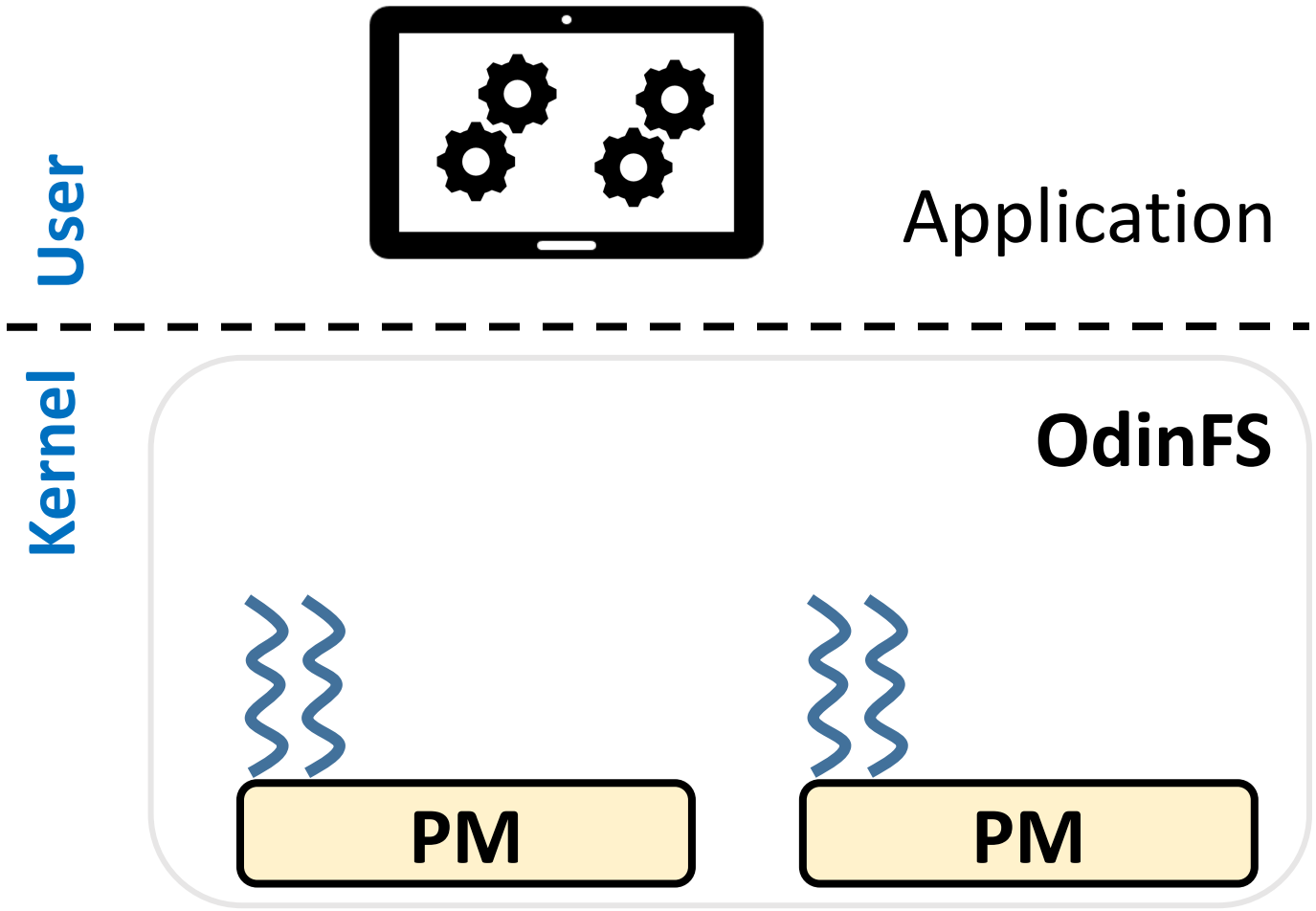
Delegation + data striping parallelize IO ops



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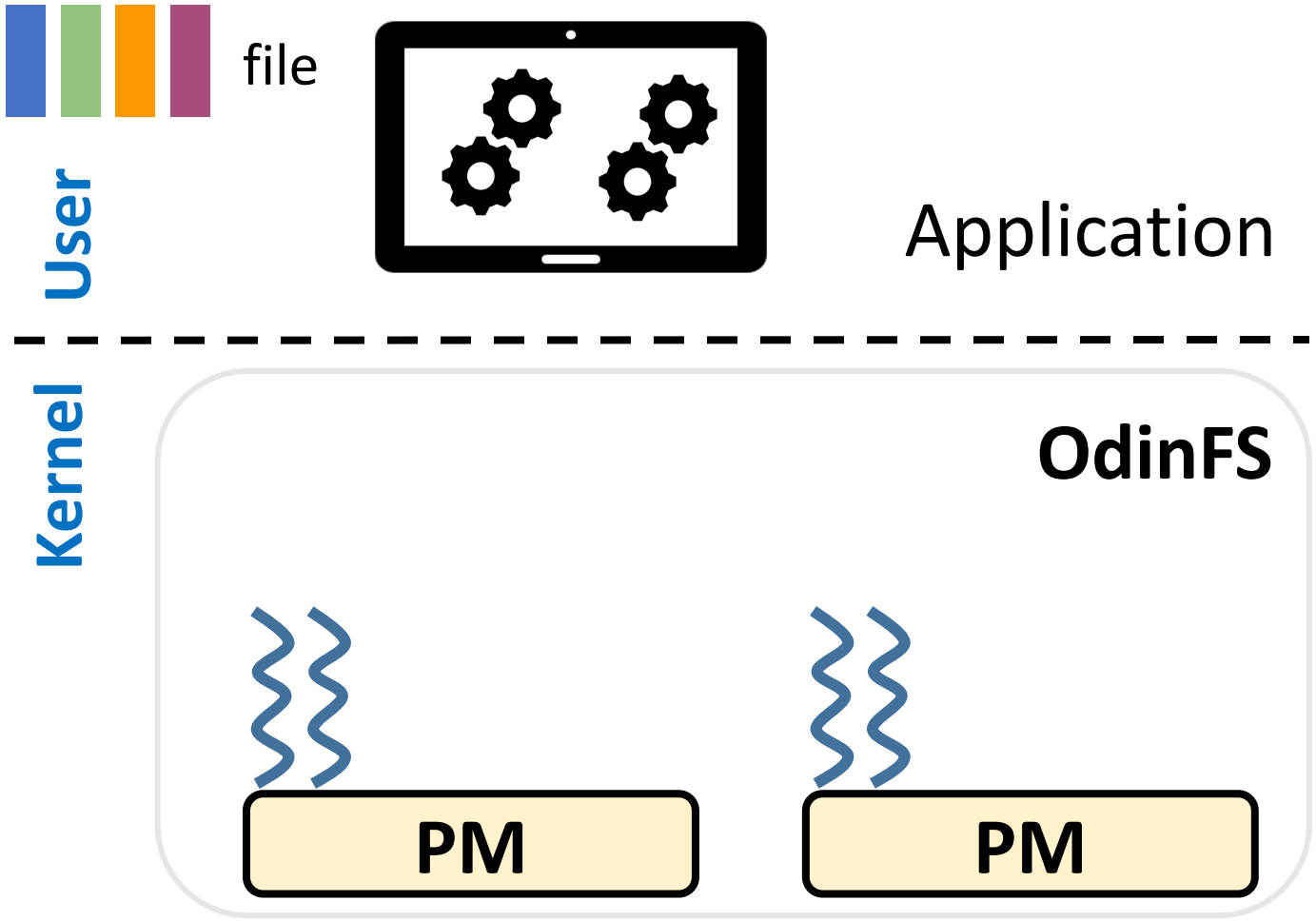

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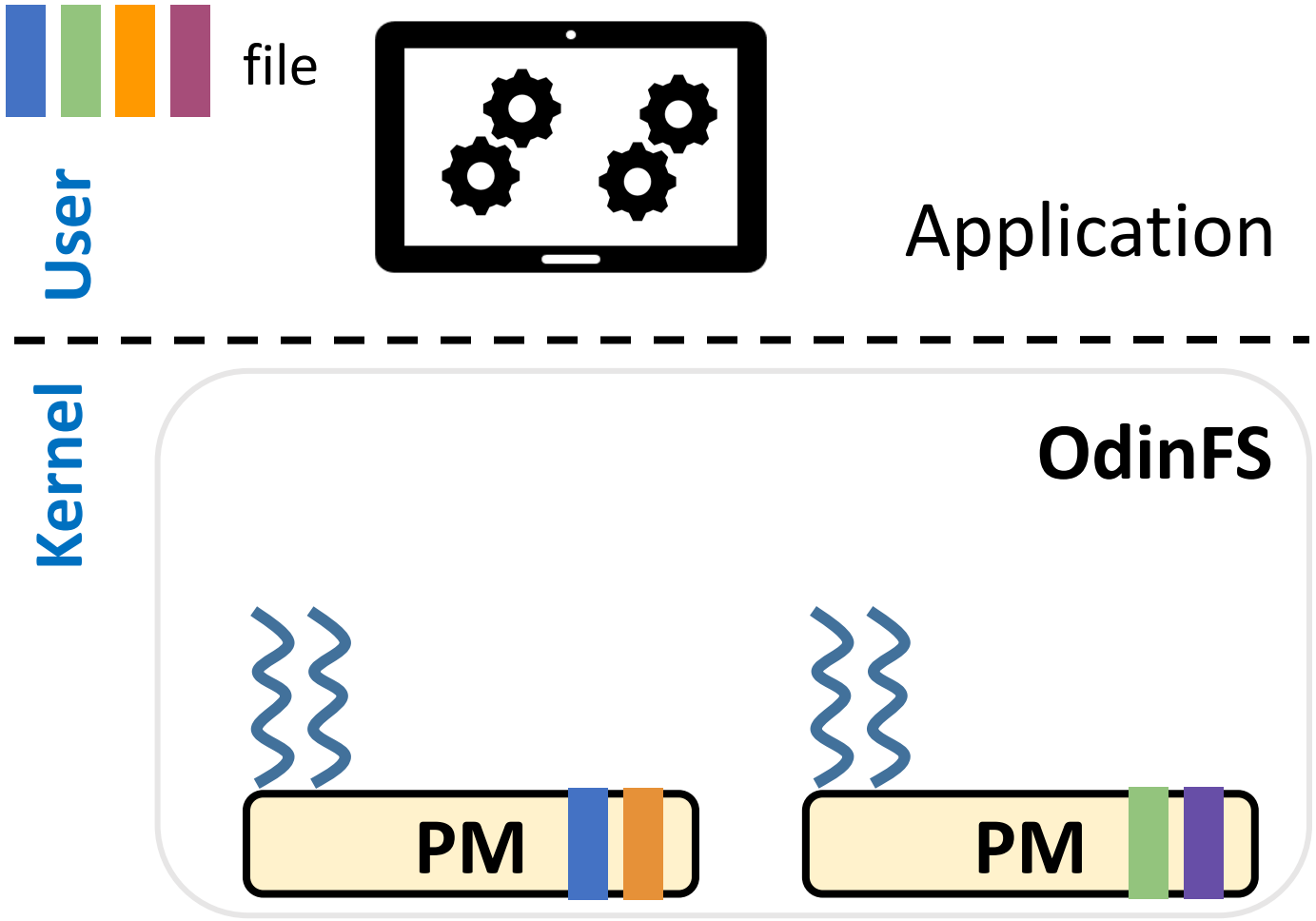

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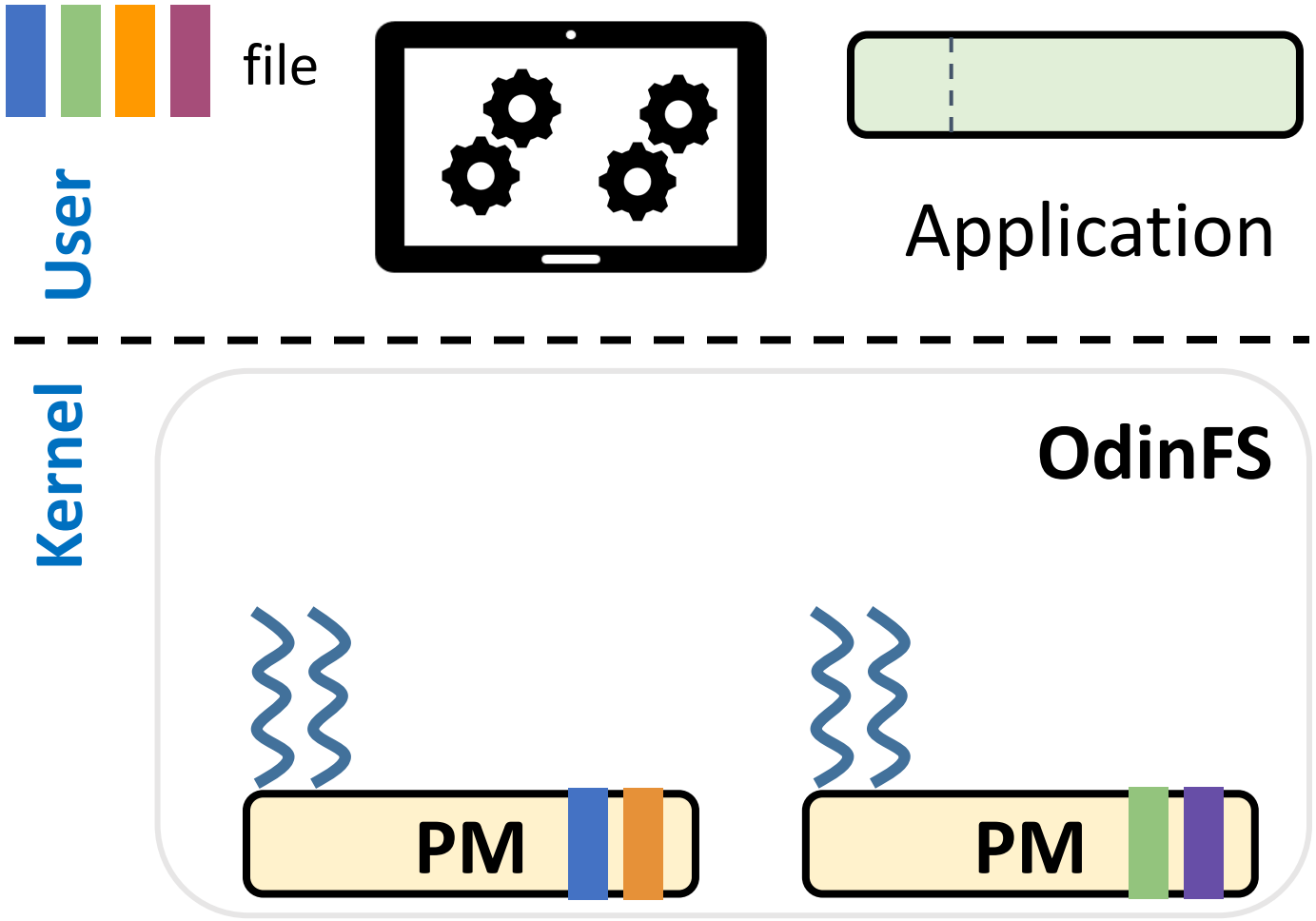

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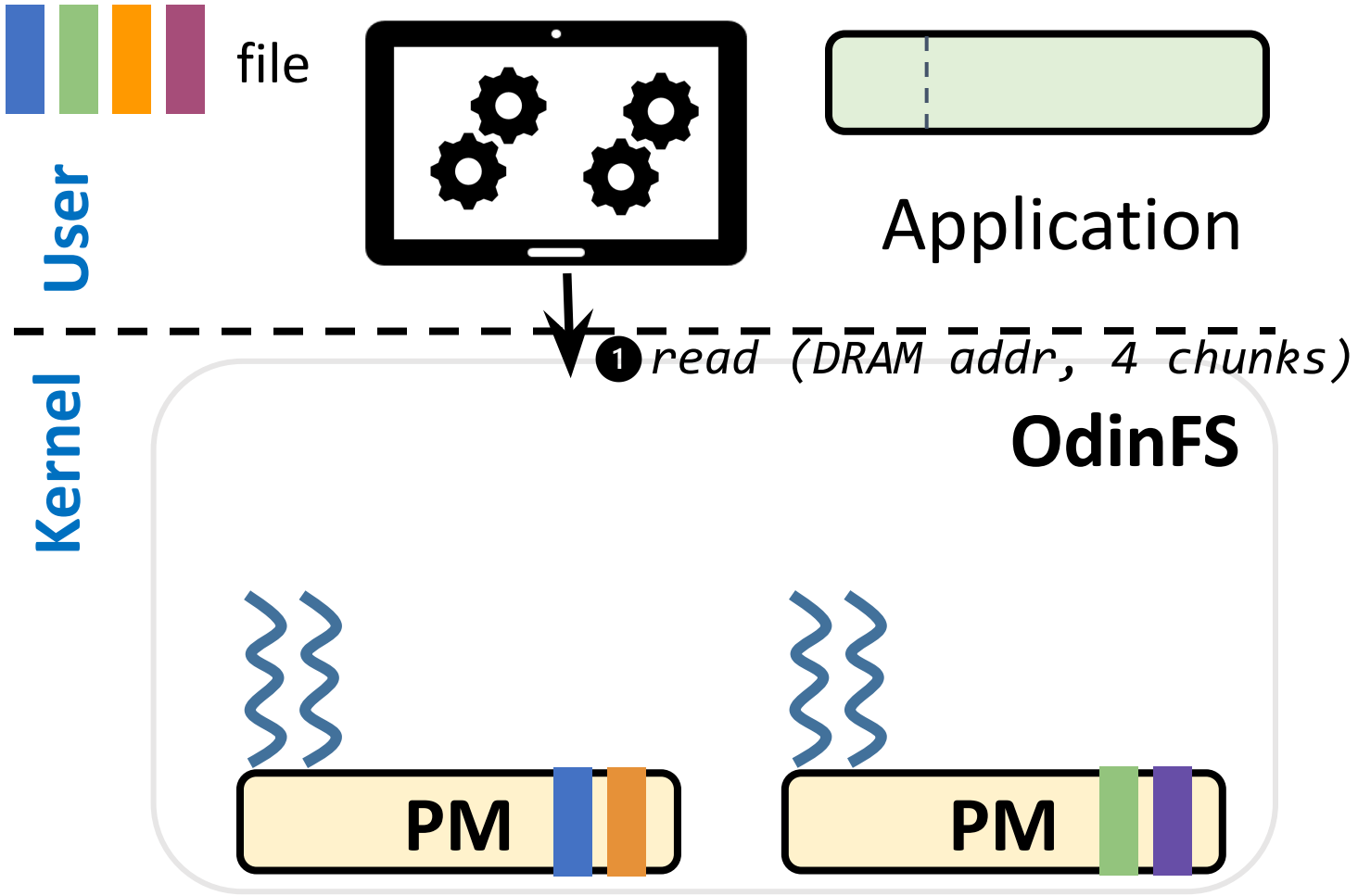

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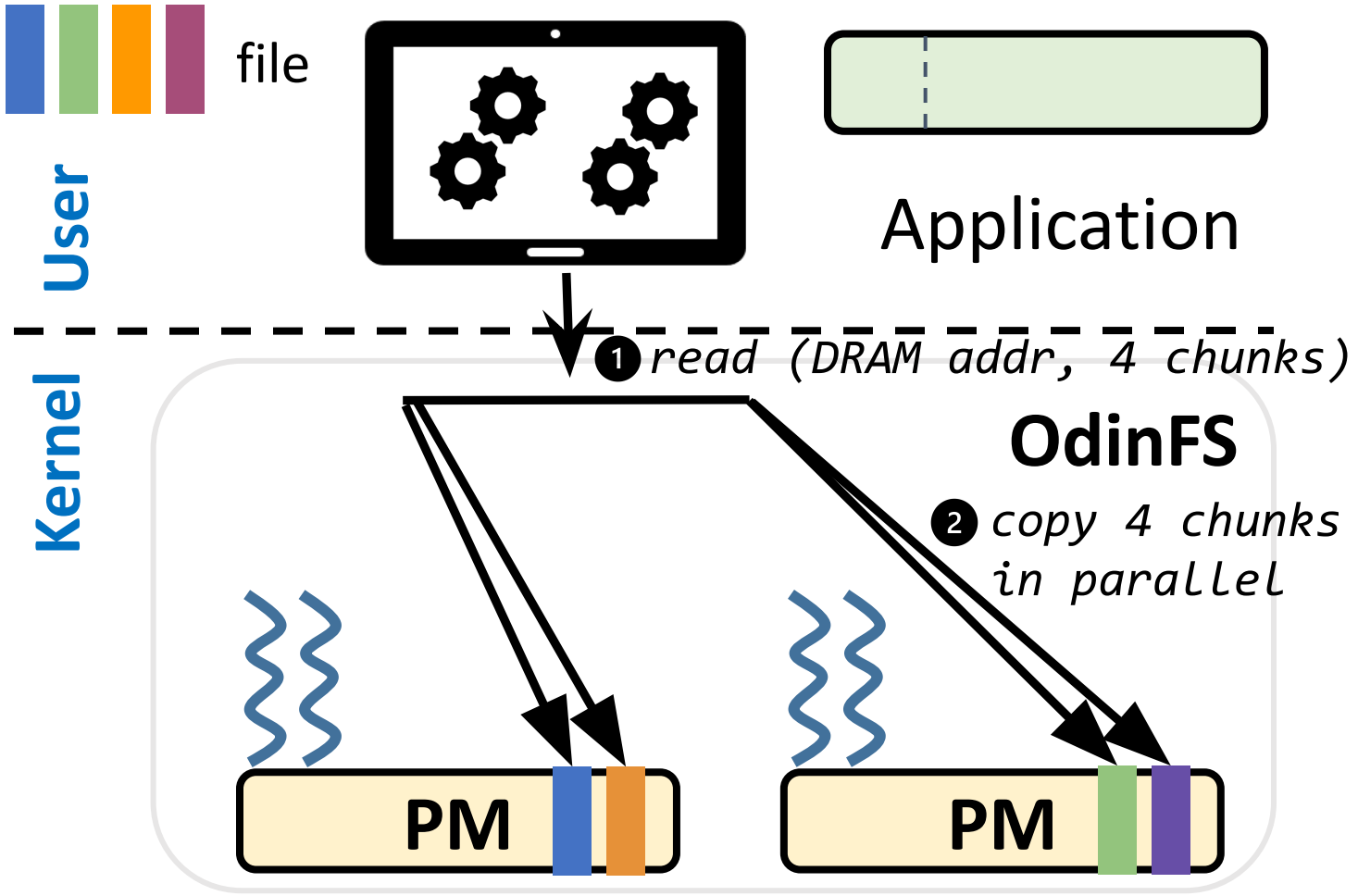

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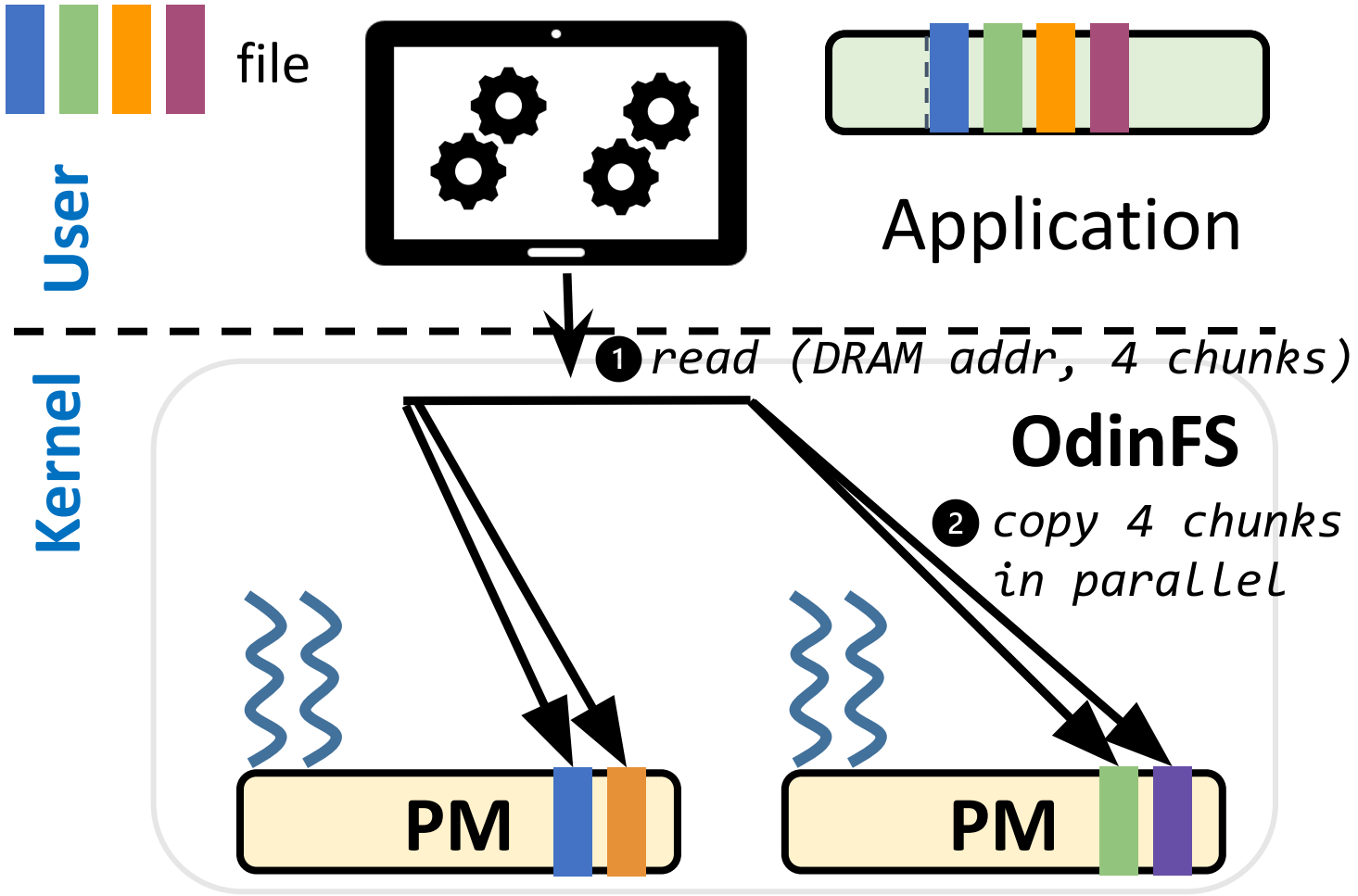

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OdinFS: Other design considerations

- Maximizes concurrent access by reducing synchronization overhead
  - Within a file: range locks
  - Across file system: per-CPU data structures

- Employs a new mechanism to ensure crash consistency

- Ensures minimal overhead of delegation threads

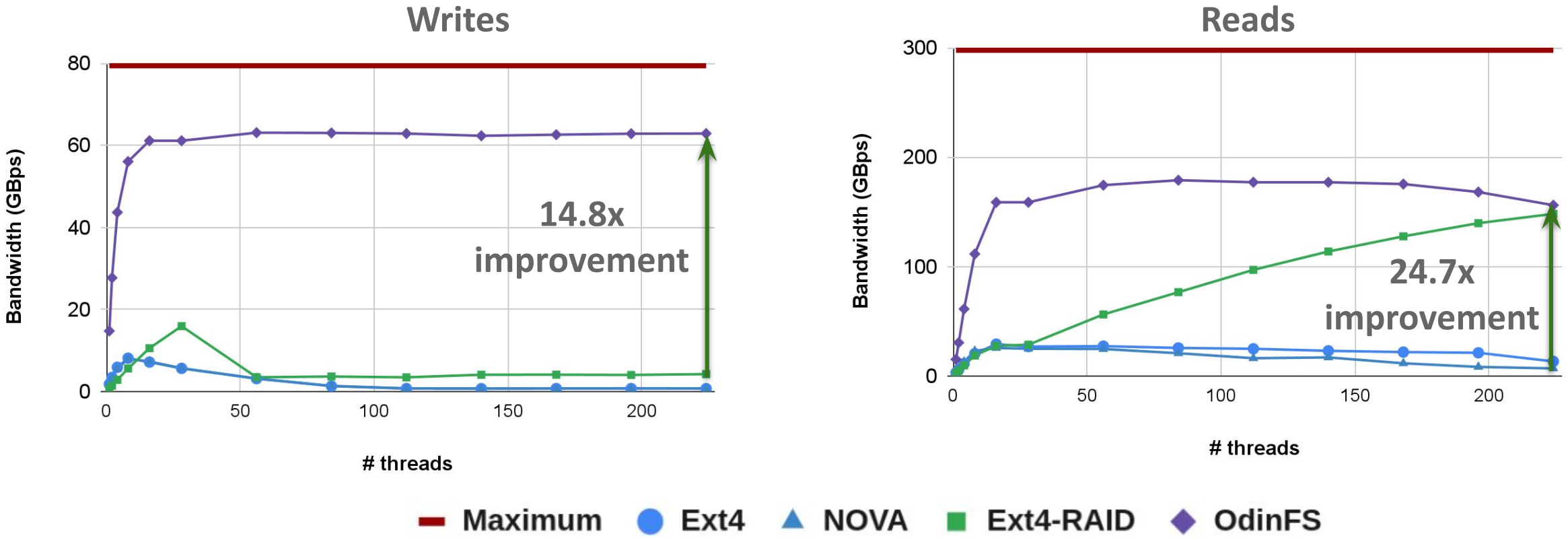
Analysis of OdinFS

- OdinFS performance:
  - Does OdinFS improves the IO performance?
    - Throughput, small access, high concurrency

Setup: 224-core/8-socket machine

OdinFS performance

Benchmark: Each thread reads/writes 2MB data privately in a 1GB file



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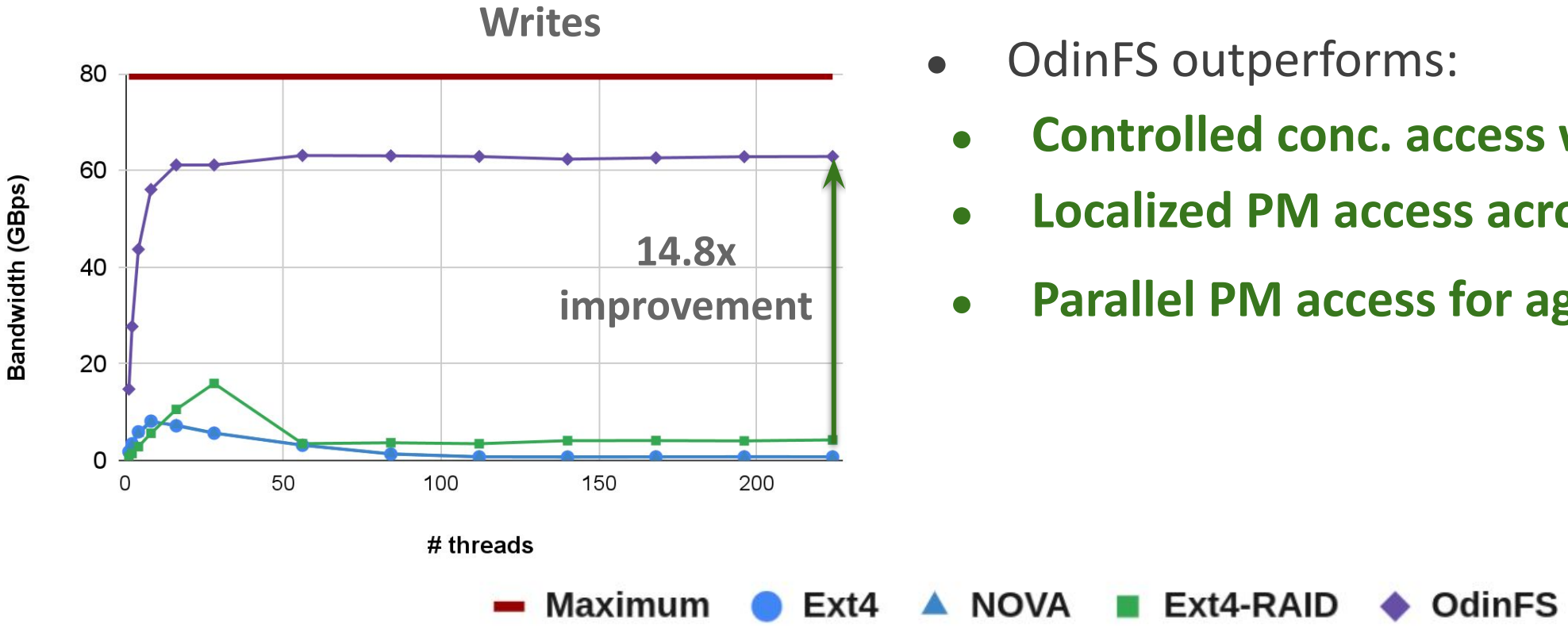

- OdinFS outperforms:
  - **Controlled conc. access within one PM**
  - **Localized PM access across PMs**
  - **Parallel PM access for aggregate PM bw**

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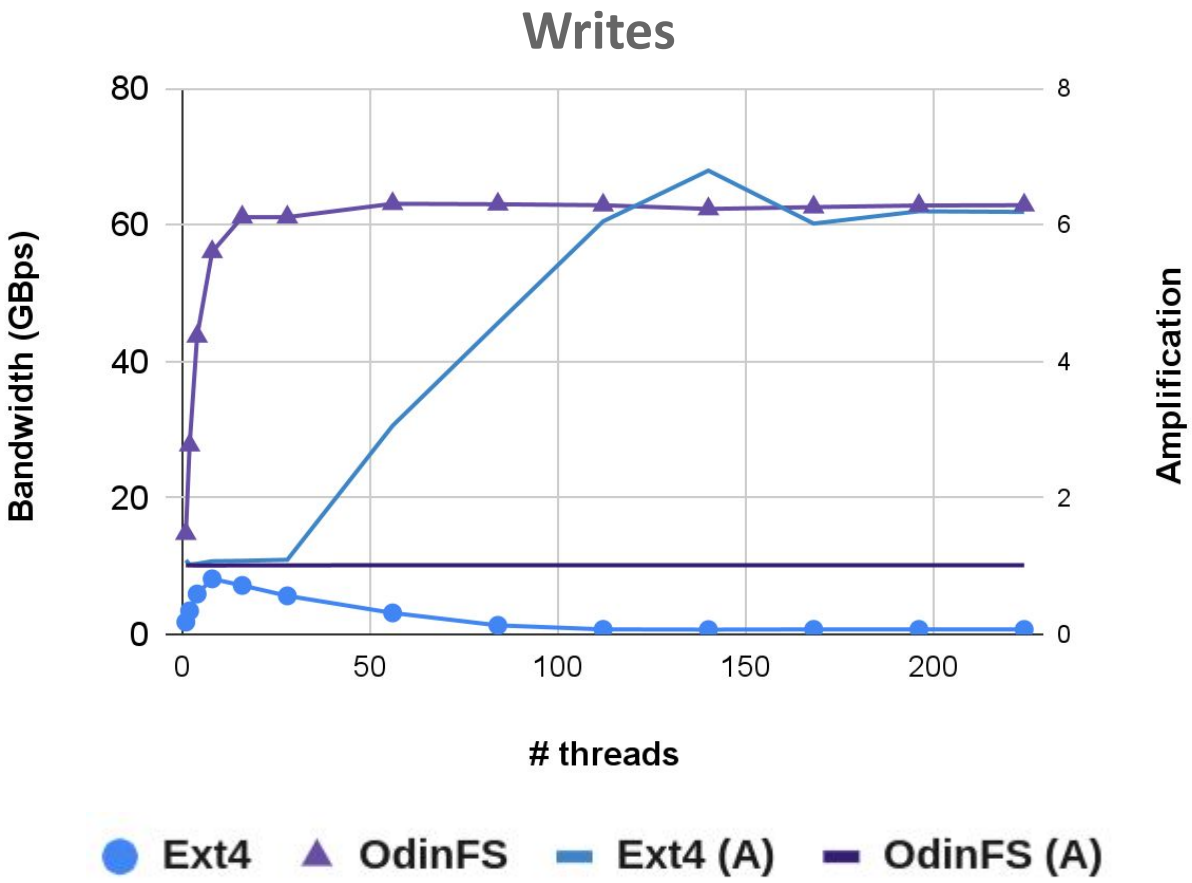
OdinFS performance: IO amplification



- OdinFS's amplification is ~1:
  - **Localized PM access across PMs**

OdinFS performance

- OdinFS outperforms other file systems:
  - By 9.4x and 8.1x for 4KB reads and writes respectively
  - Upto 24.7x on IO intensive real-world workloads
  - Upto 269x faster on highly contended data path scenarios

Conclusion

- Existing PM file systems do not utilize PM efficiently:
  - Uncontrolled concurrent access
  - Arbitrary remote access
  - Do not utilize the aggregate bandwidth

- **OdinFS**: Decouples PM access from application threads via delegation
  - Enables **controlled**, **localized**, and **parallel** PM access

- **Future**: Exploring the delegation model for other faster storage media

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Thank you!