

# OdinFS: Scaling PM Performance with Opportunistic Delegation

**Diyu Zhou\***, Yuchen Qian, Vishal Gupta, Zhifei Yang,  
Changwoo Min, Sanidhya Kashyap

**EPFL**

\*Looking for a faculty job



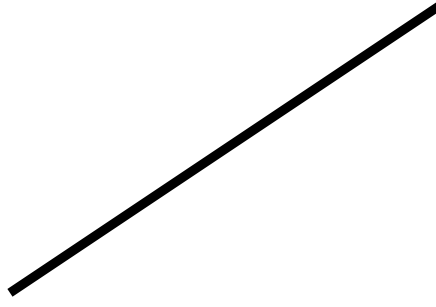
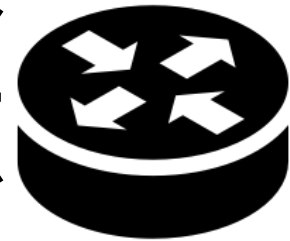
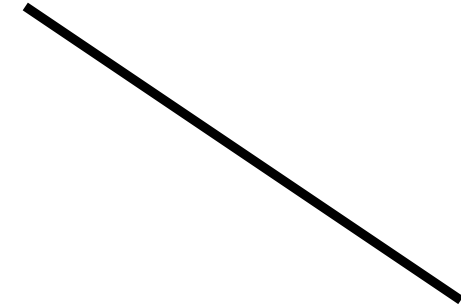
A short time ago, in Silicon Valley...



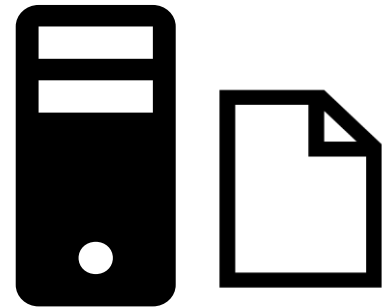
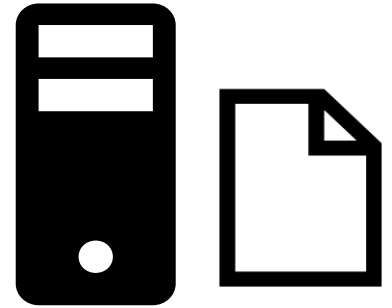
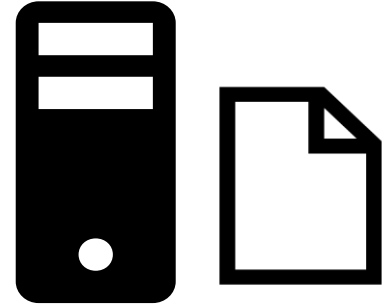
This is Mei

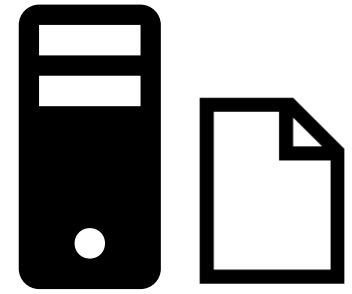
Mei builds a fileserver  
service for a startup  
company

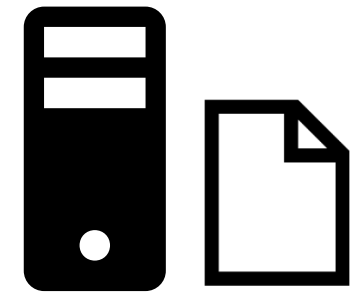
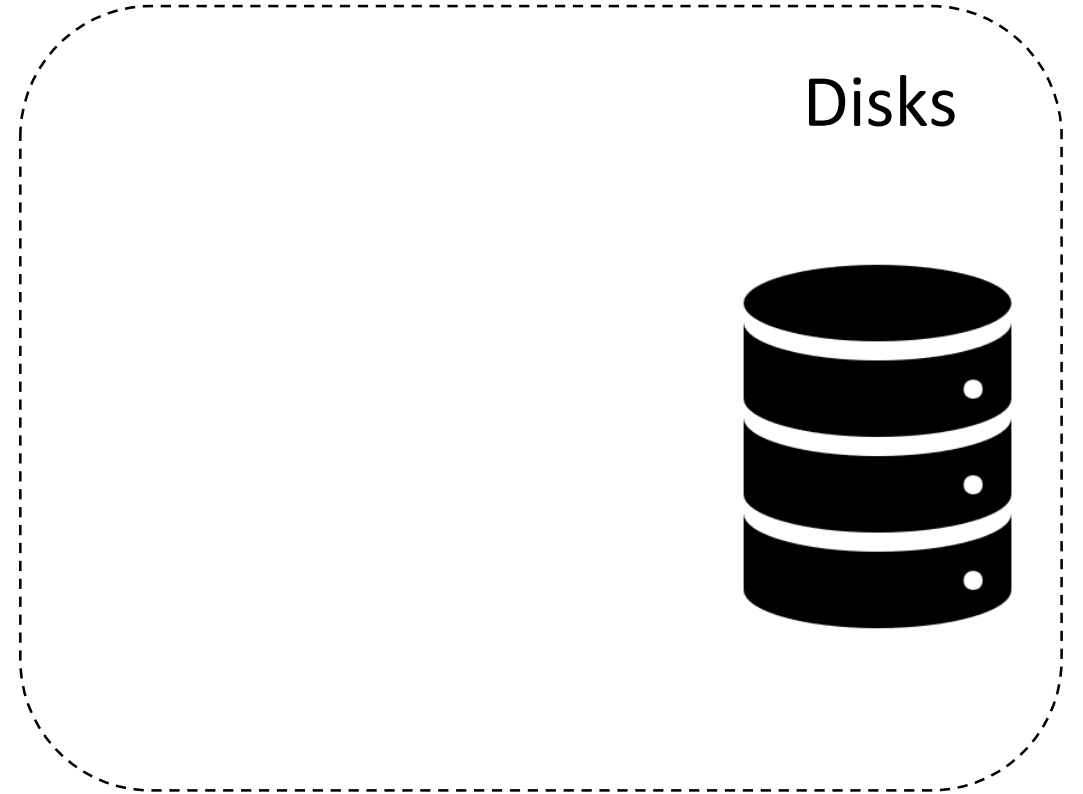
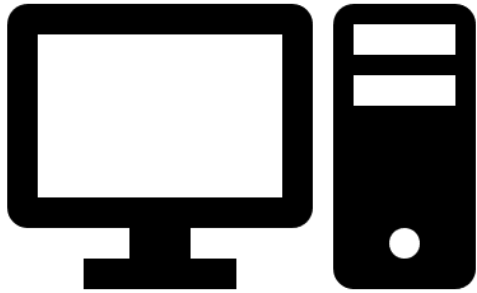
# Clients

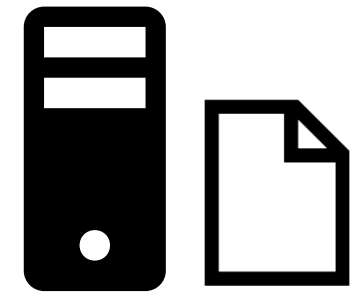
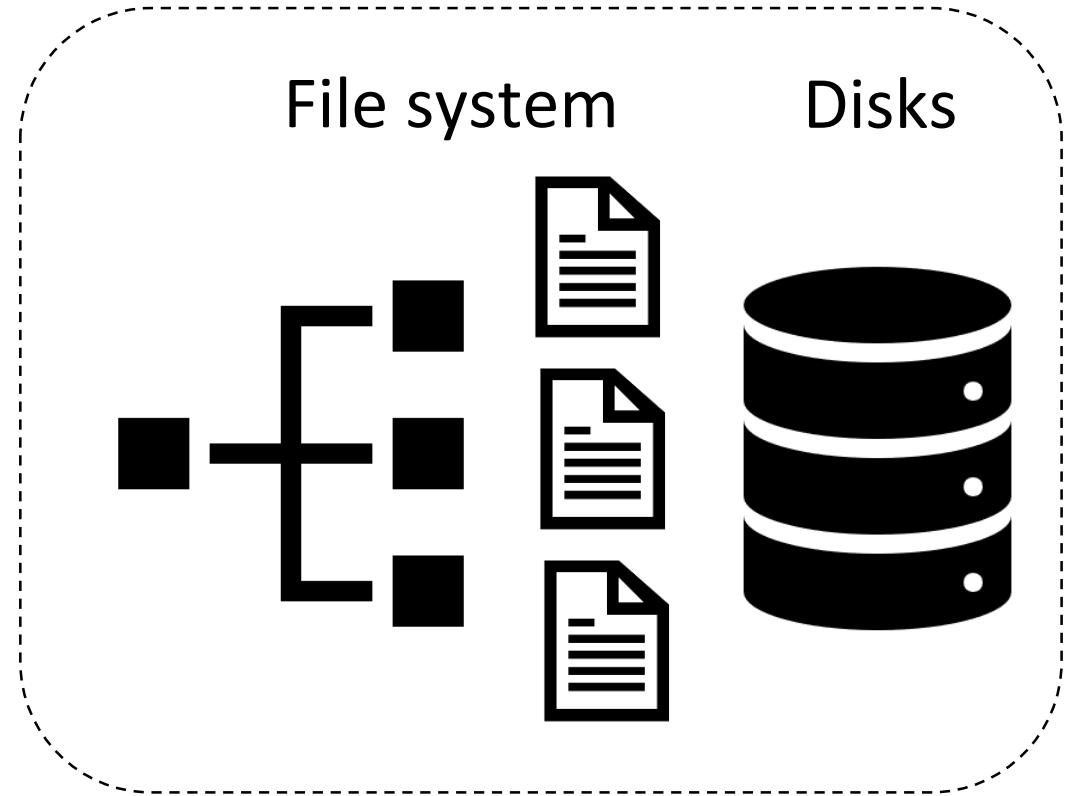


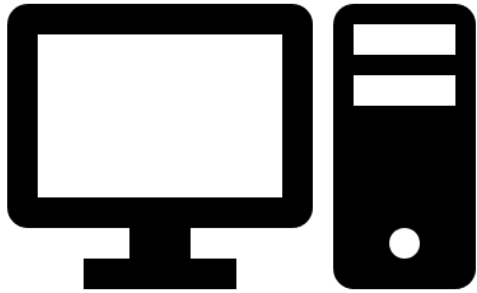
# File servers



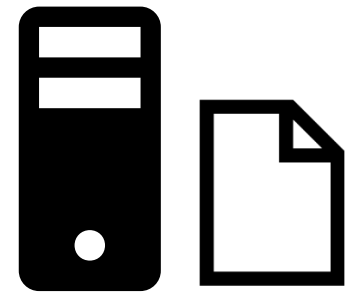
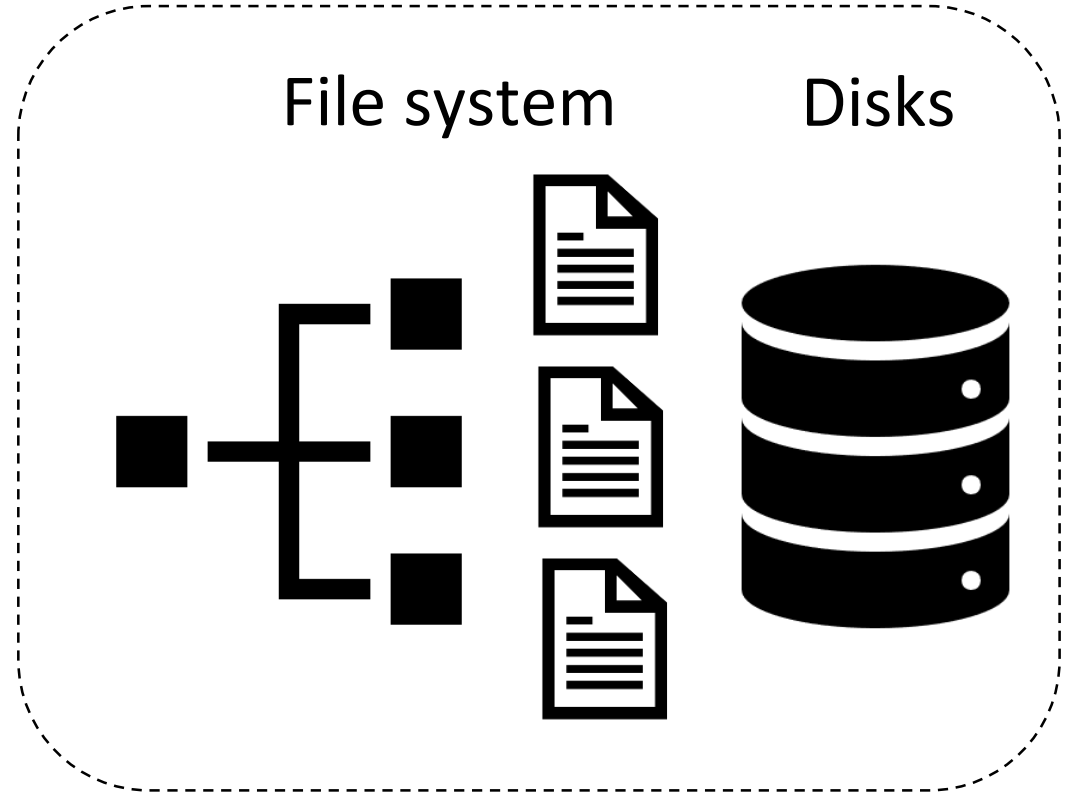




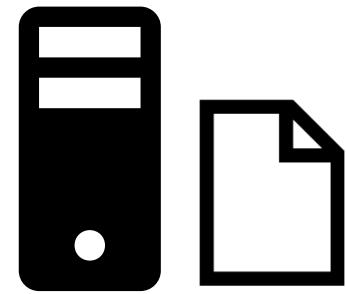
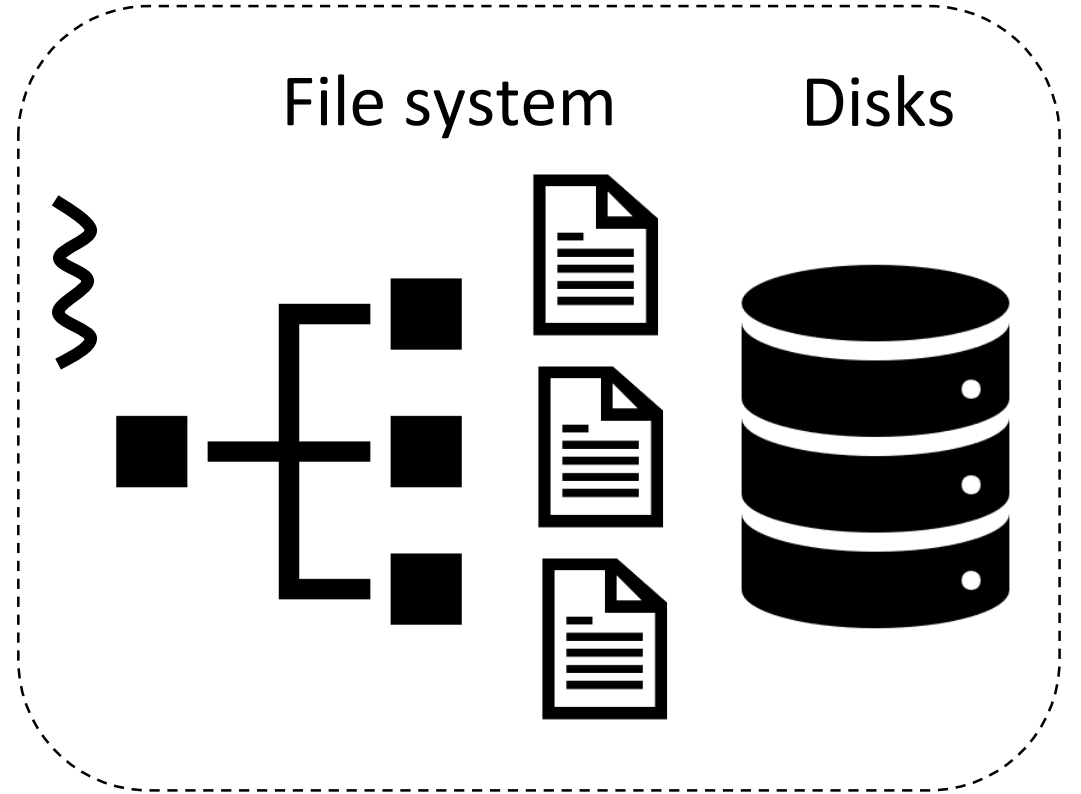
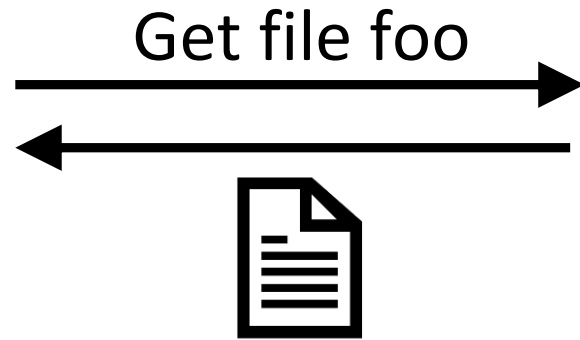
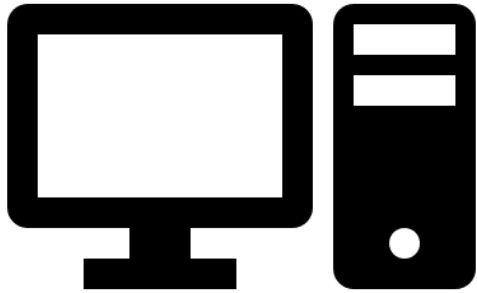


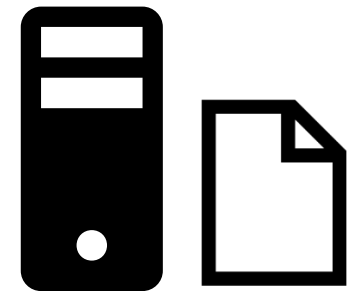
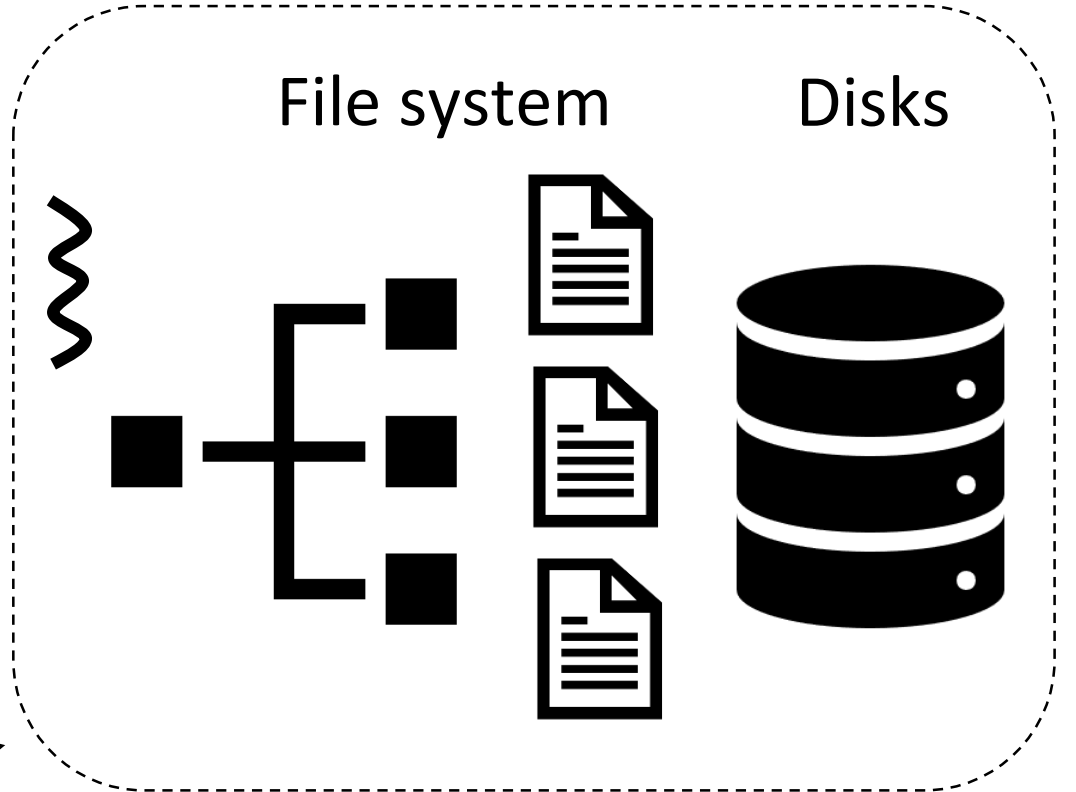
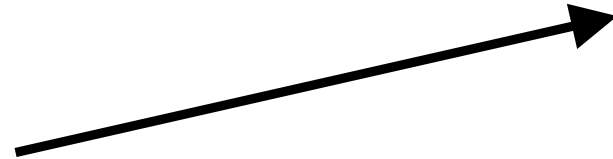
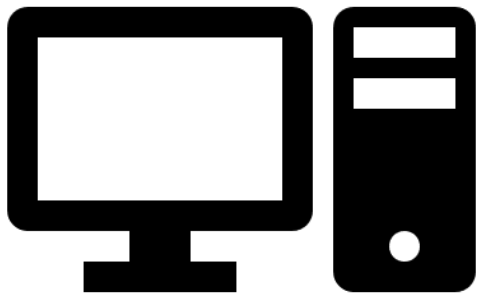
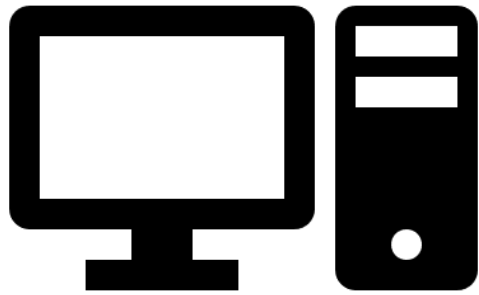


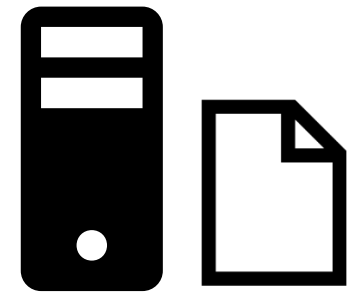
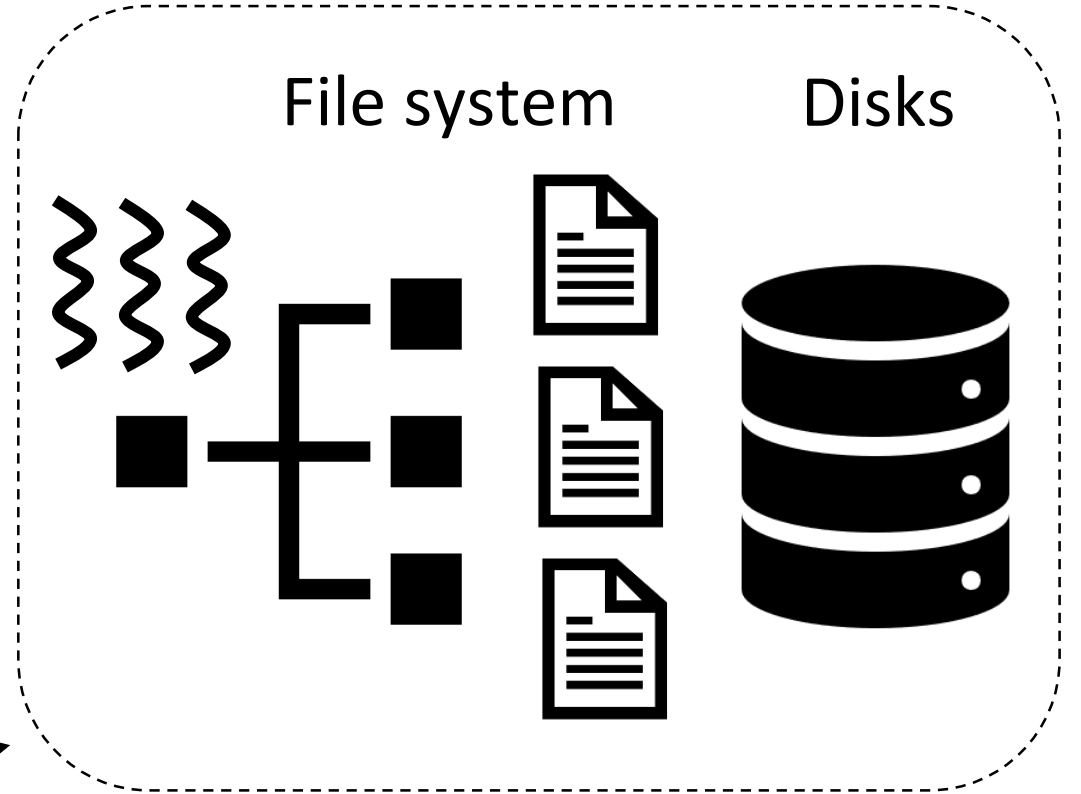
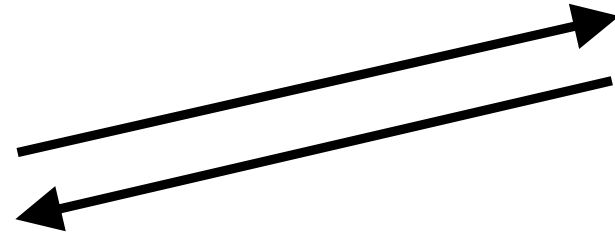
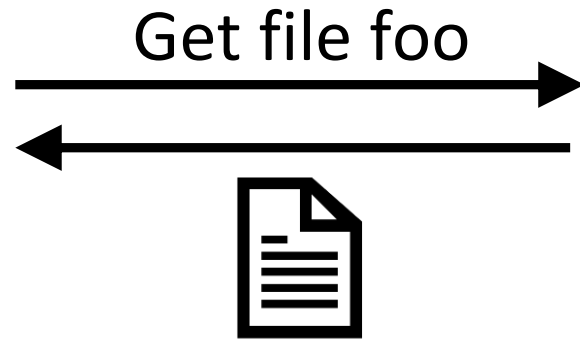
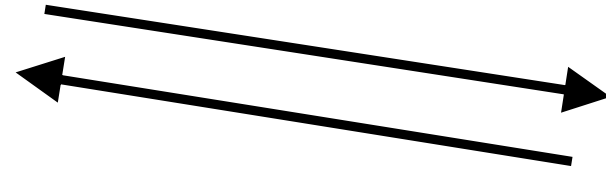
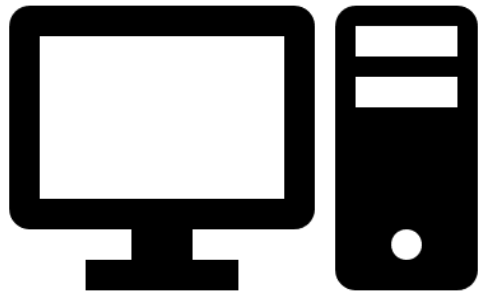
Get file foo →













The file server is too slow



The file server is too  
slow

Disks are the performance bottleneck!

- Low speed; e.g., 10s-100s of  $\mu$ s access latency



The file server is too  
slow

Disks are the performance bottleneck!

- Low speed; e.g., 10s-100s of  $\mu$ s access latency
- Performance collapses with concurrent access<sup>†</sup>

<sup>†</sup> Intel Optane: Faster Access to More Data



Persistent memory (PM) can solve the problem!

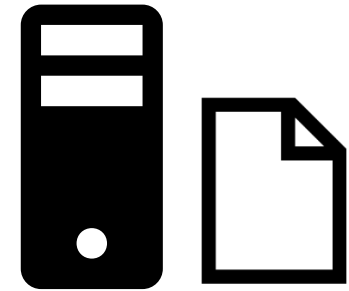
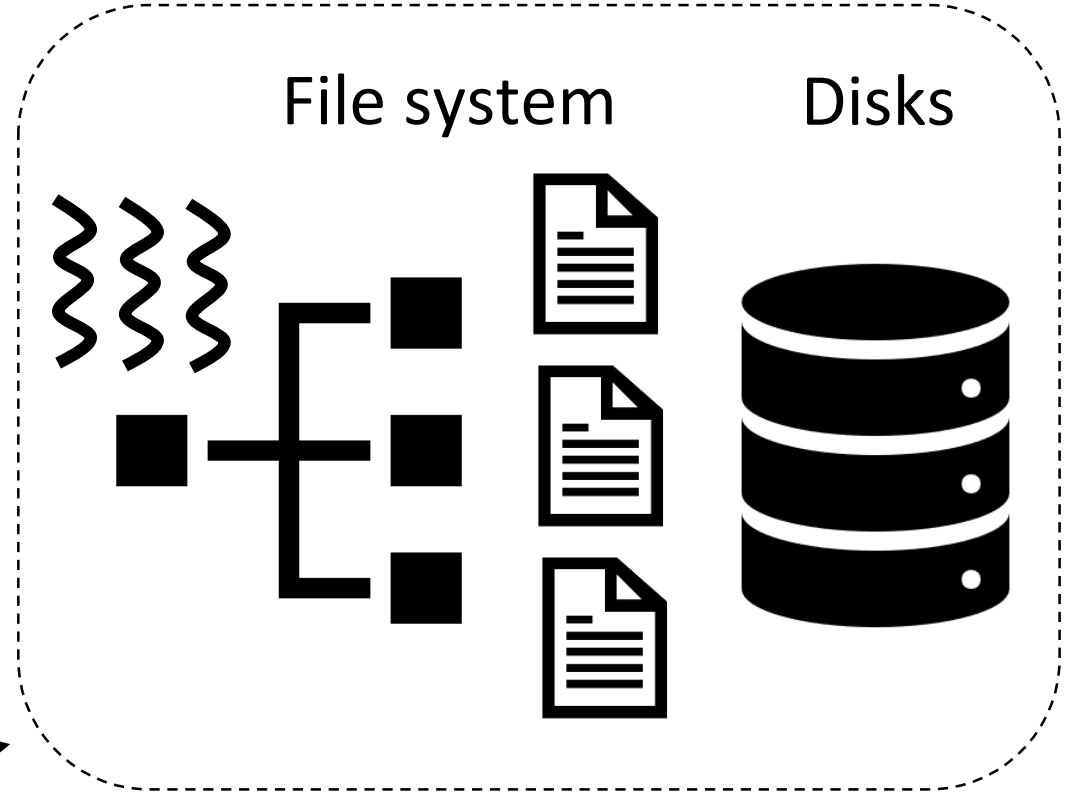
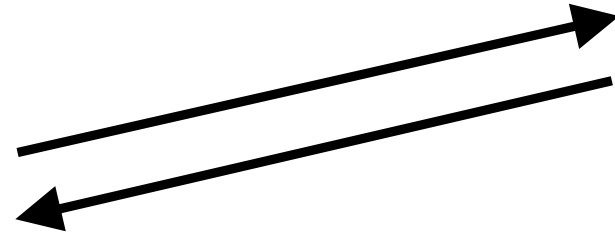
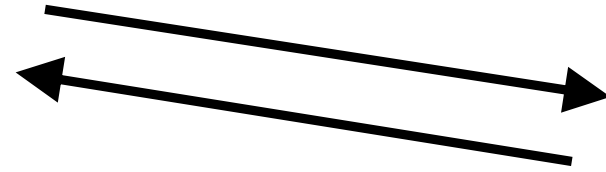
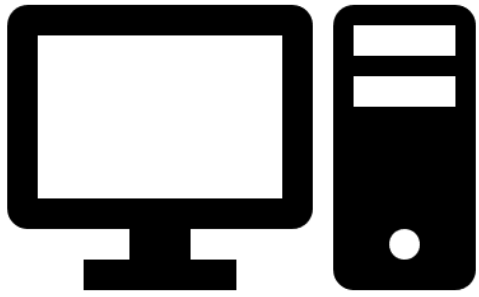


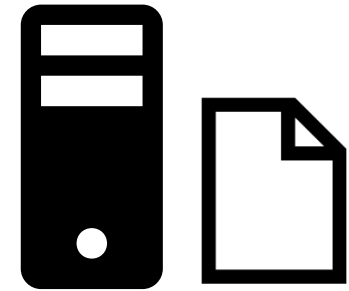
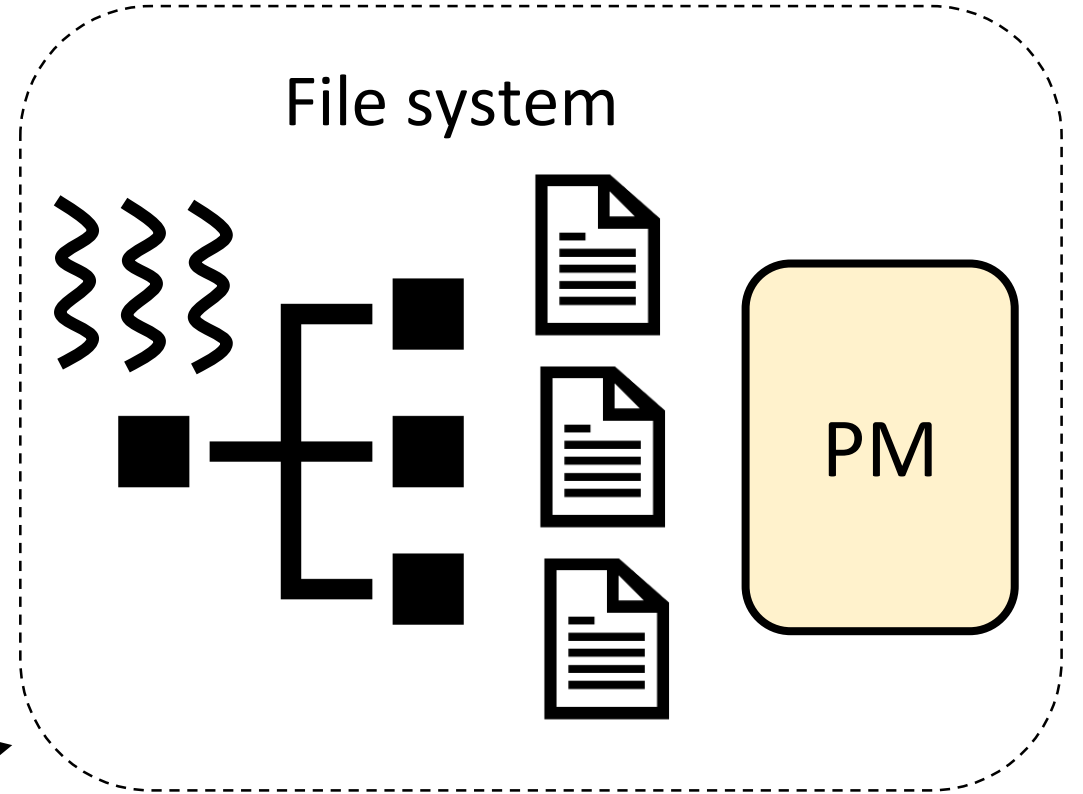
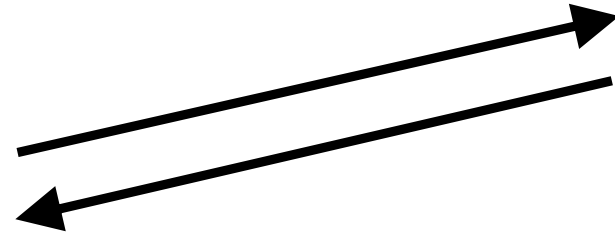
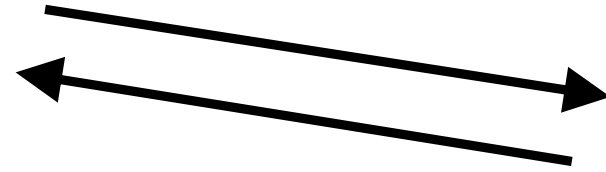
Persistent memory (PM) can solve the problem!

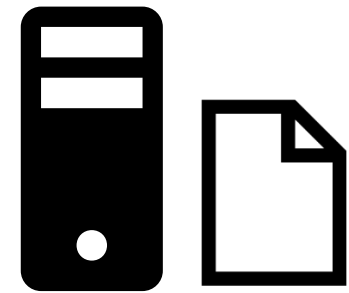
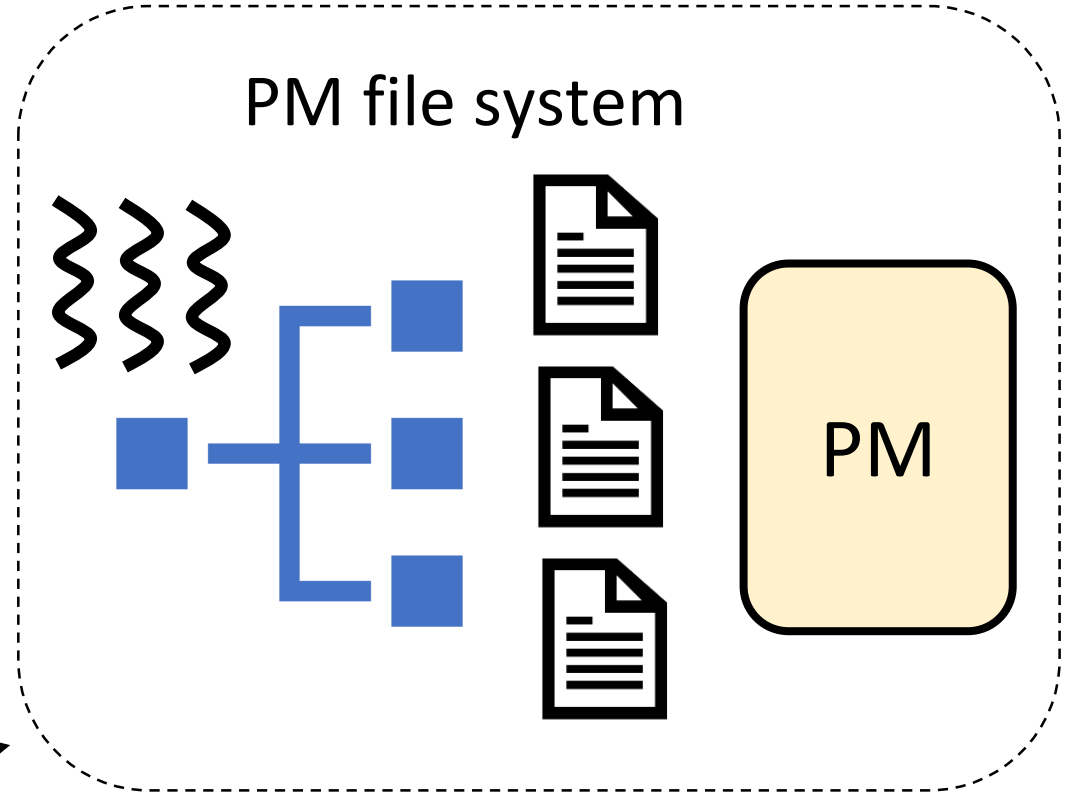
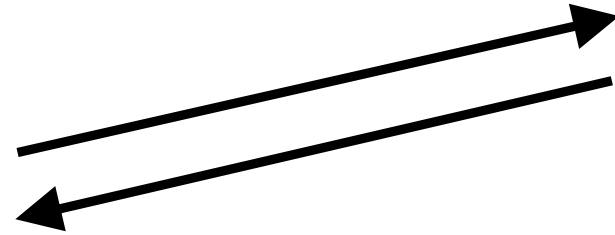
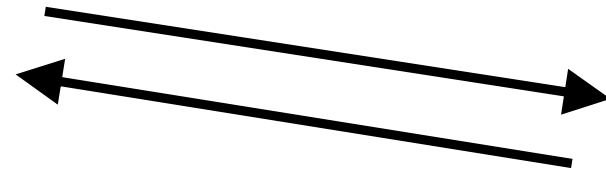
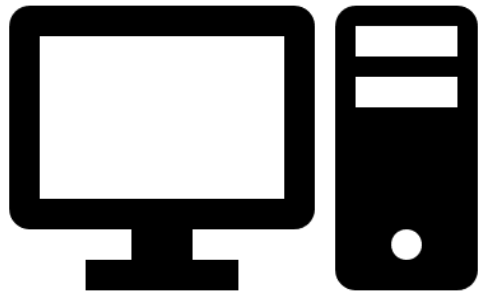
- High speed: e.g., 100s of ns access latency
- Preserves performance with concurrent access<sup>†</sup>

<sup>†</sup> Intel Optane: Faster Access to More Data

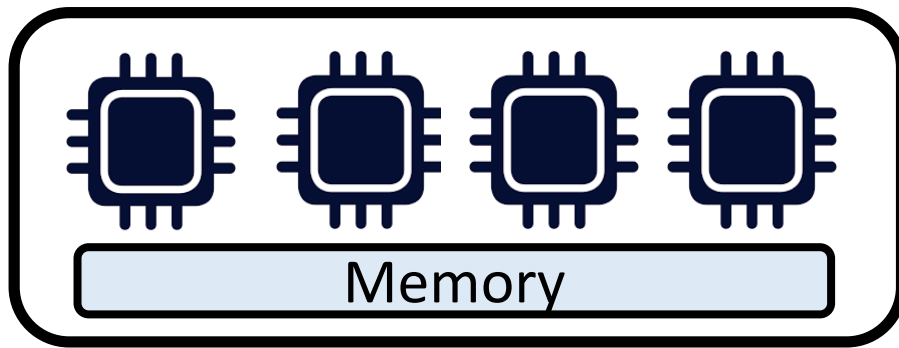




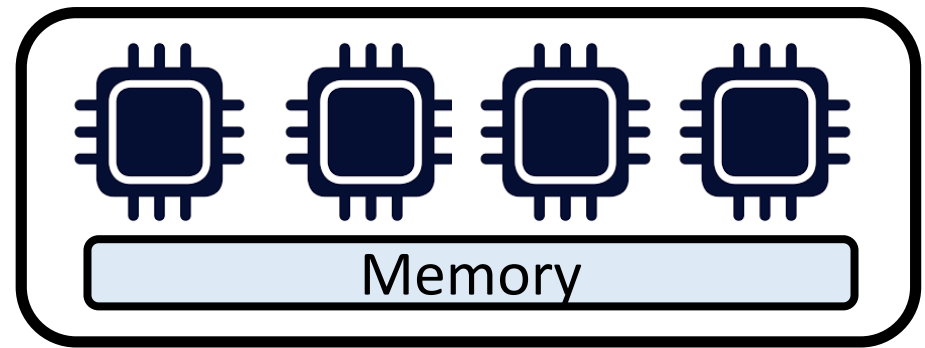




Core

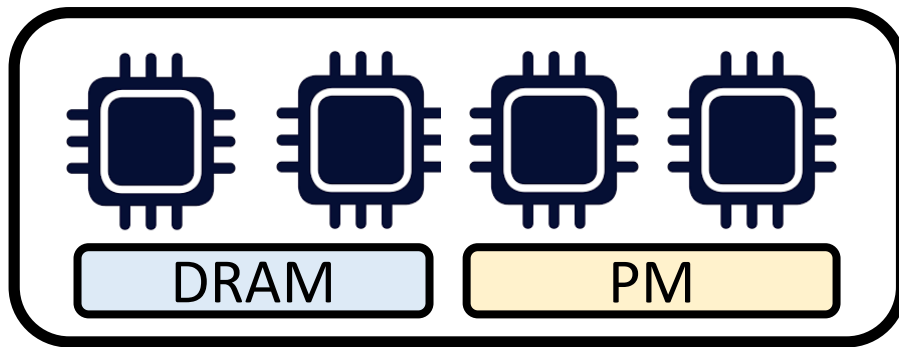


NUMA node

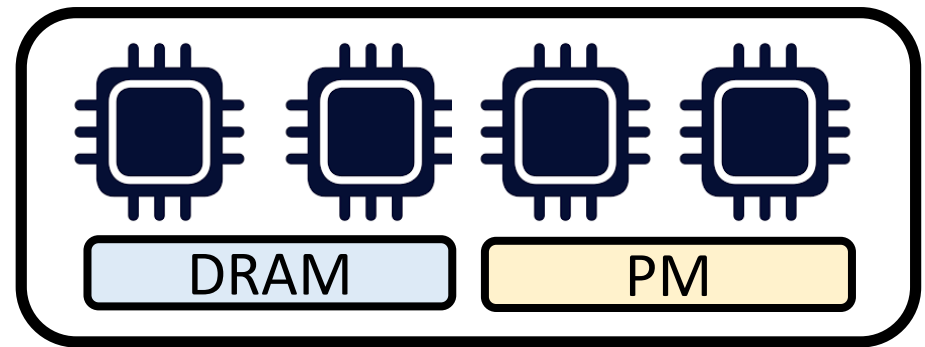


NUMA node

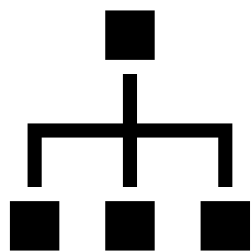
Core



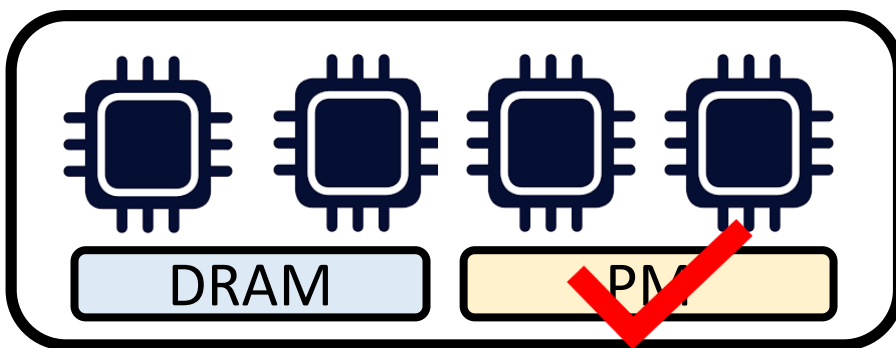
NUMA node



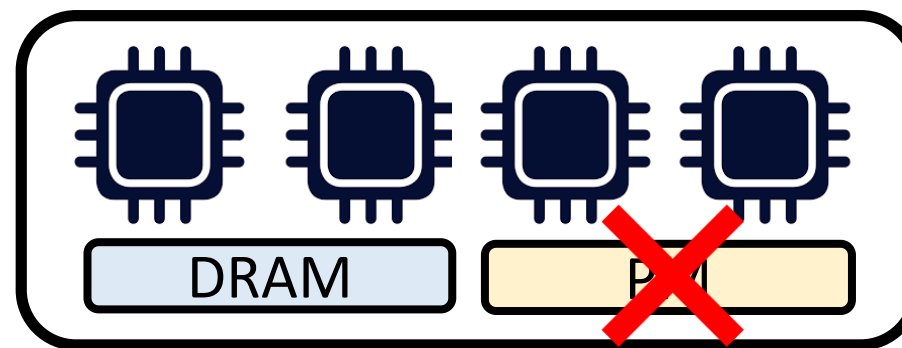
NUMA node



Core



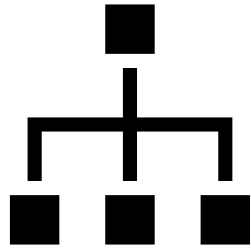
NUMA node



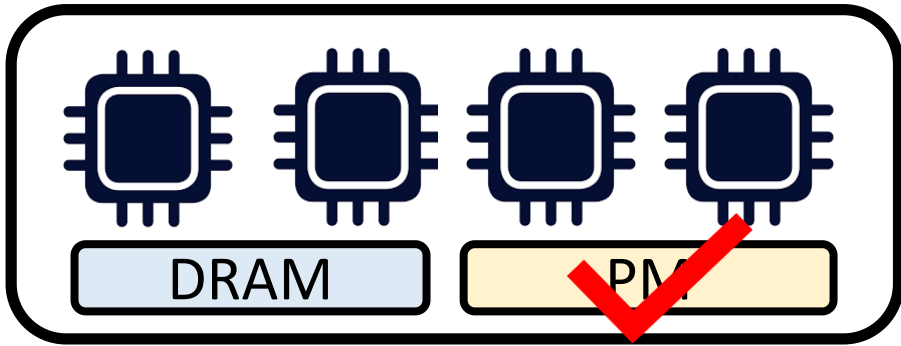
NUMA node



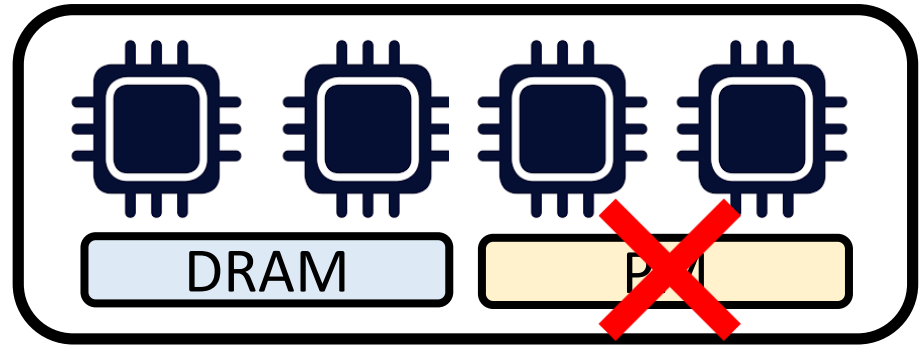
Let's see how PM performs



Core

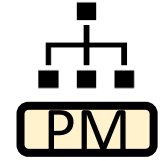


NUMA node



NUMA node

# PM performance on a single NUMA node

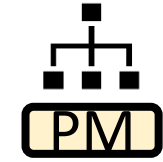


Workload: FIO: each thread writes/reads 2MB data in a private file

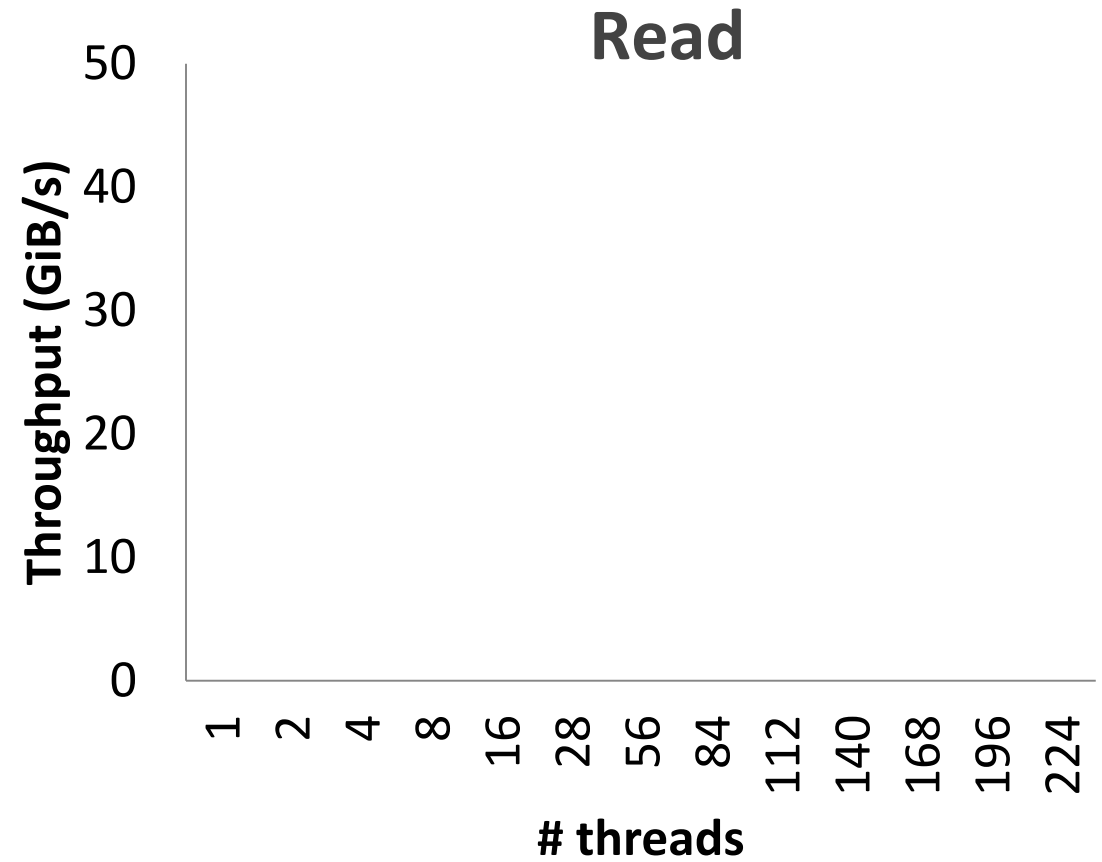
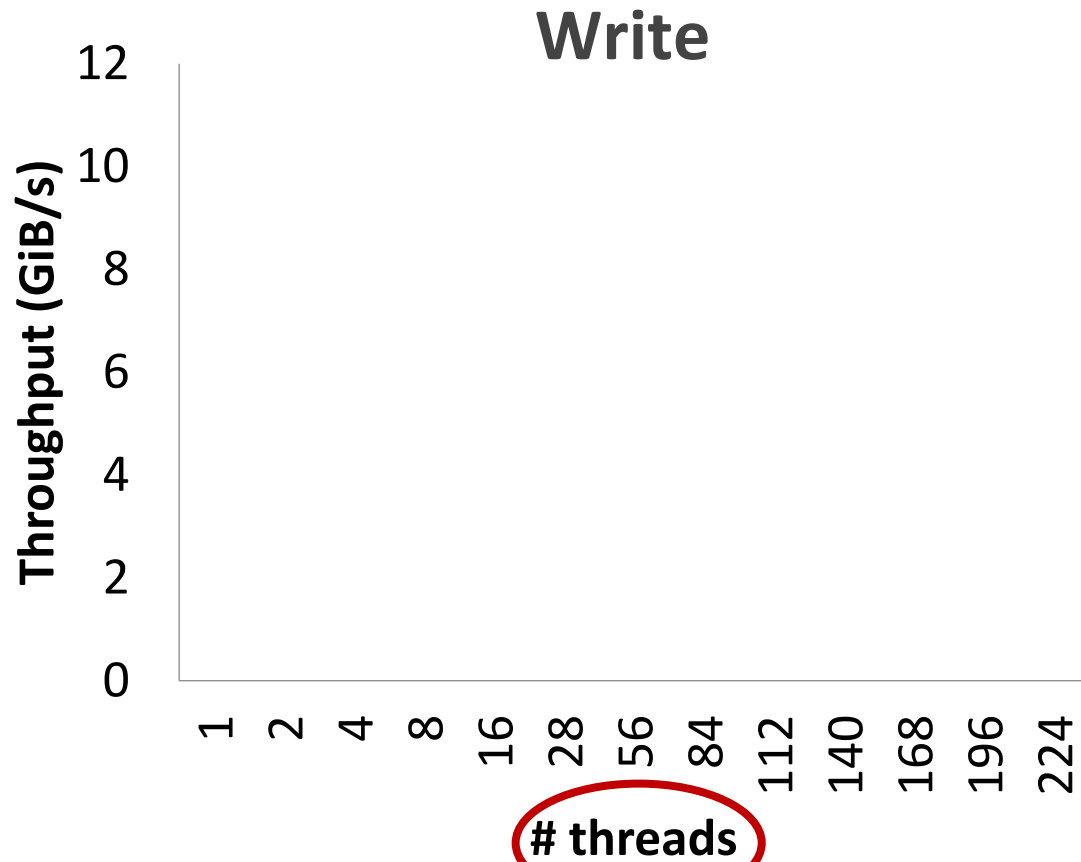
Setup: 224-core/8-socket machine



# PM performance on a single NUMA node

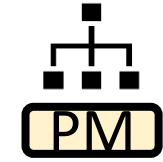


Workload: FIO: each thread writes/reads 2MB data in a private file



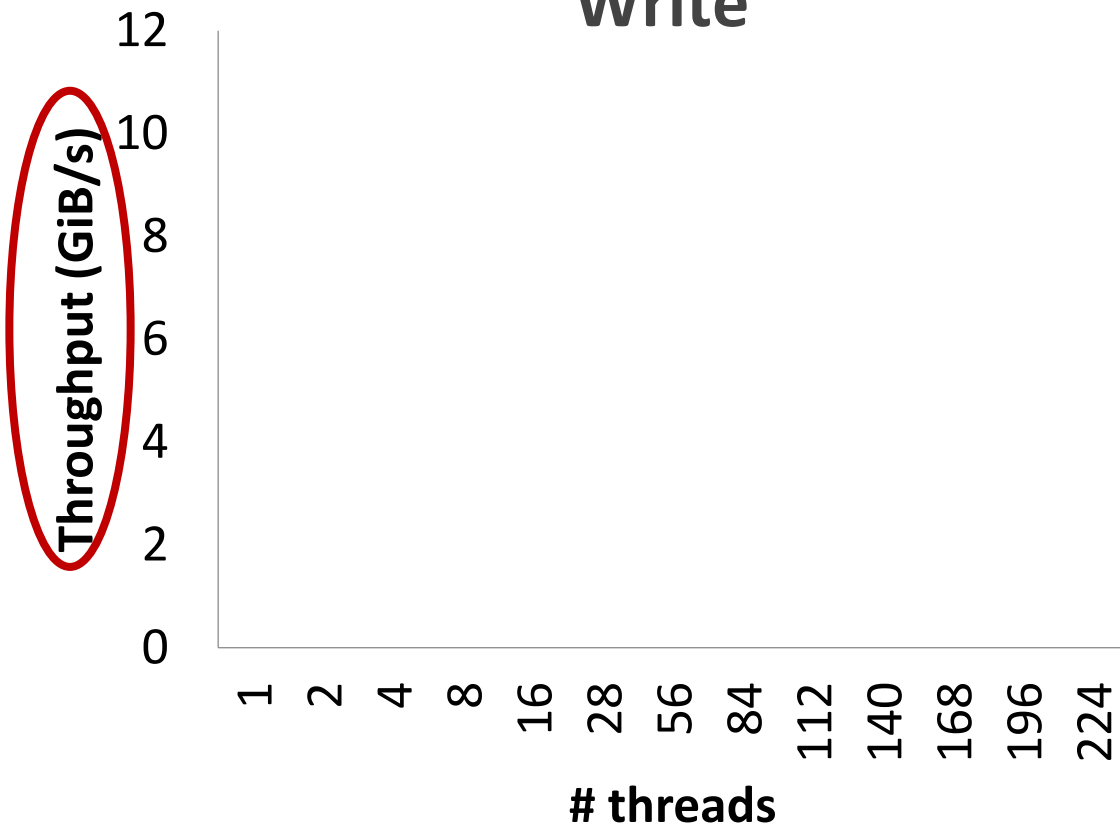
Setup: 224-core/8-socket machine

# PM performance on a single NUMA node

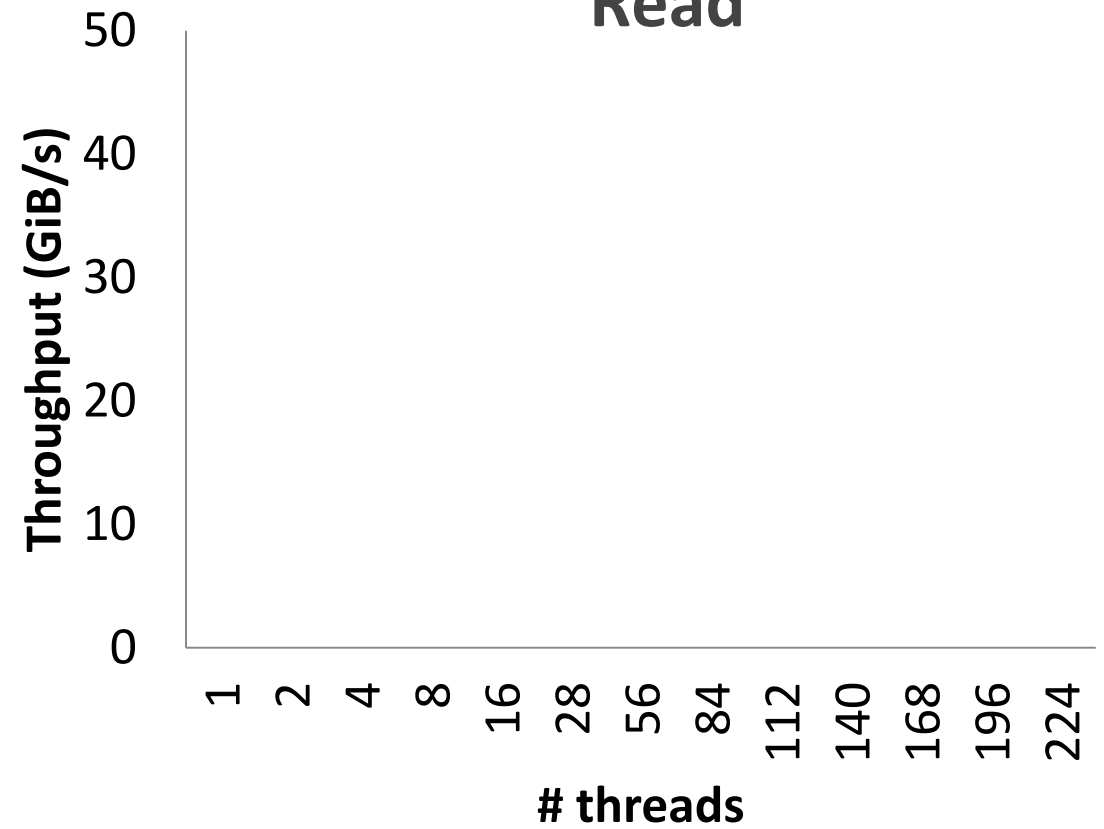


Workload: FIO: each thread writes/reads 2MB data in a private file

### Write

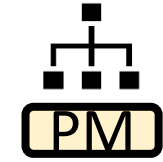


### Read

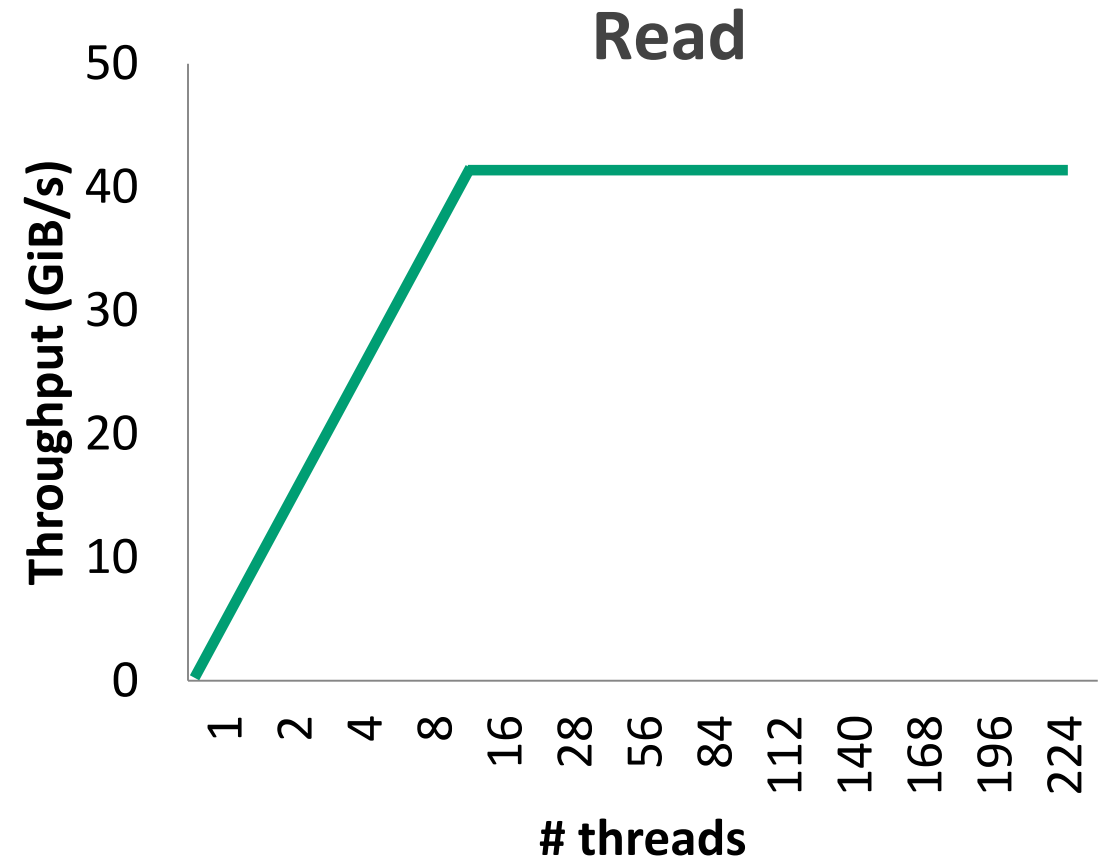
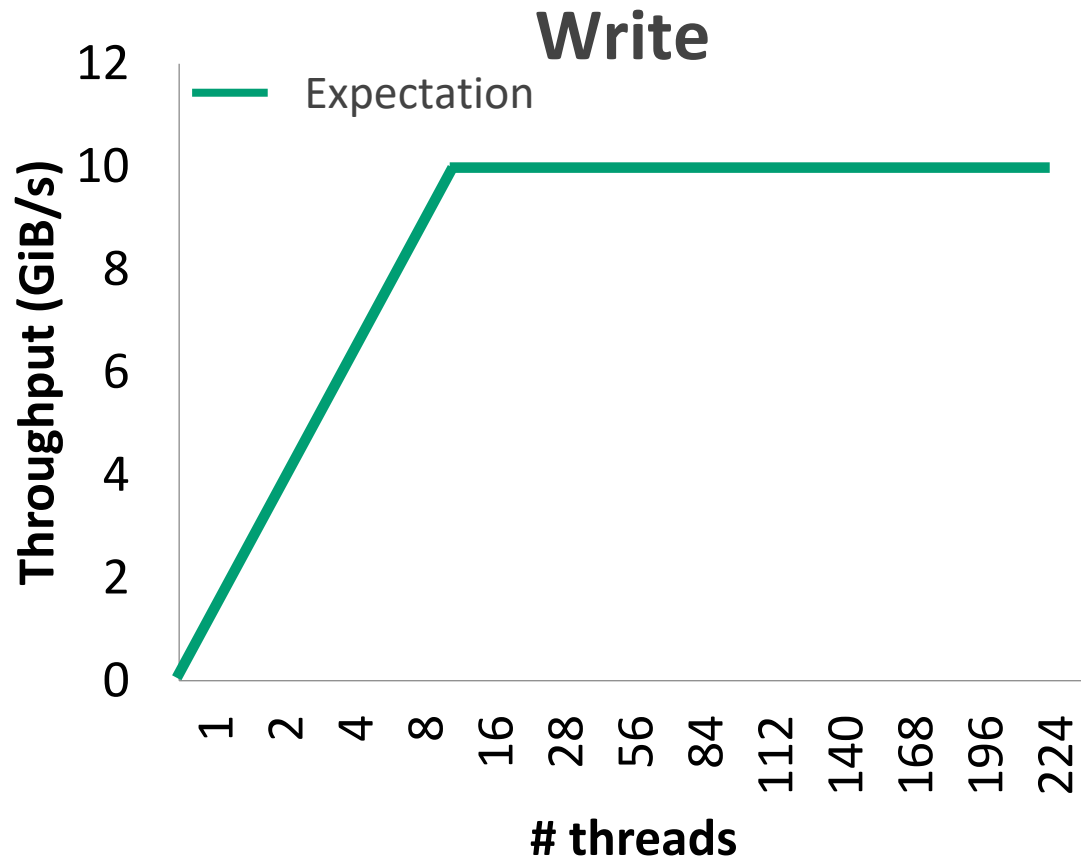


Setup: 224-core/8-socket machine

# PM performance on a single NUMA node

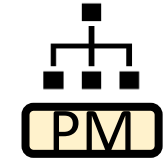


Workload: FIO: each thread writes/reads 2MB data in a private file

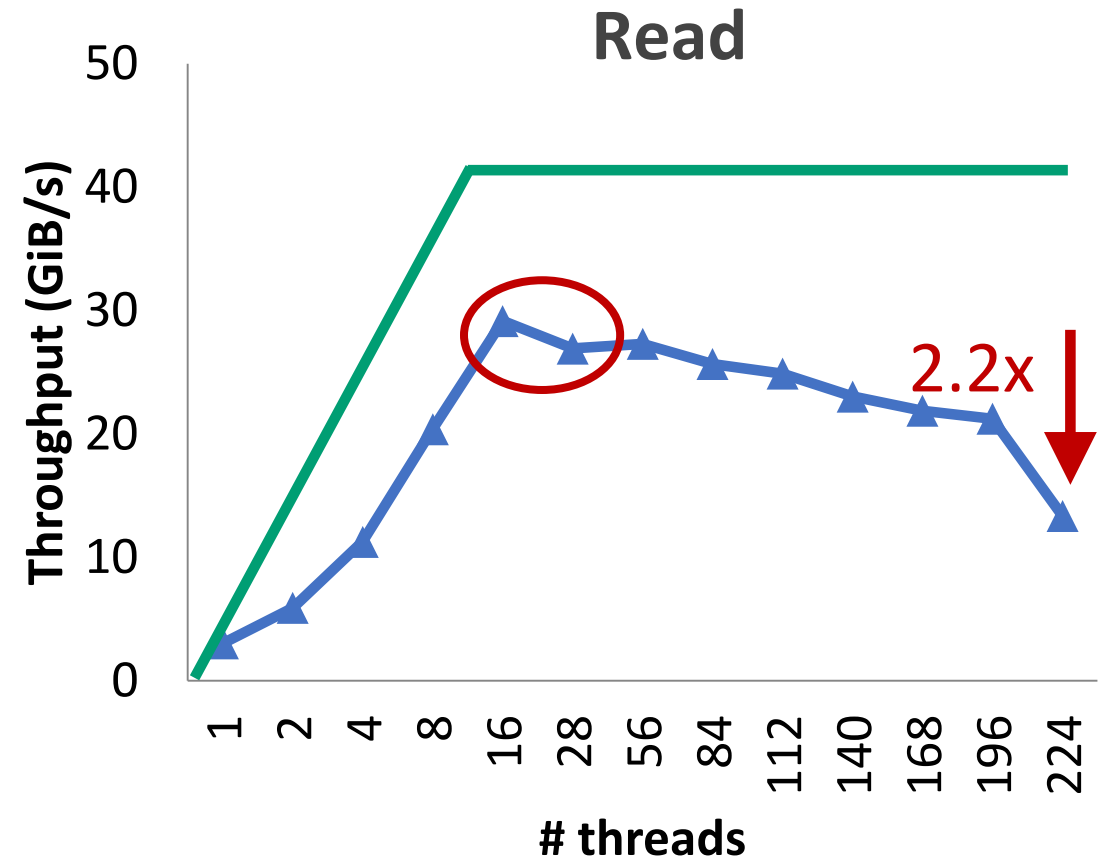
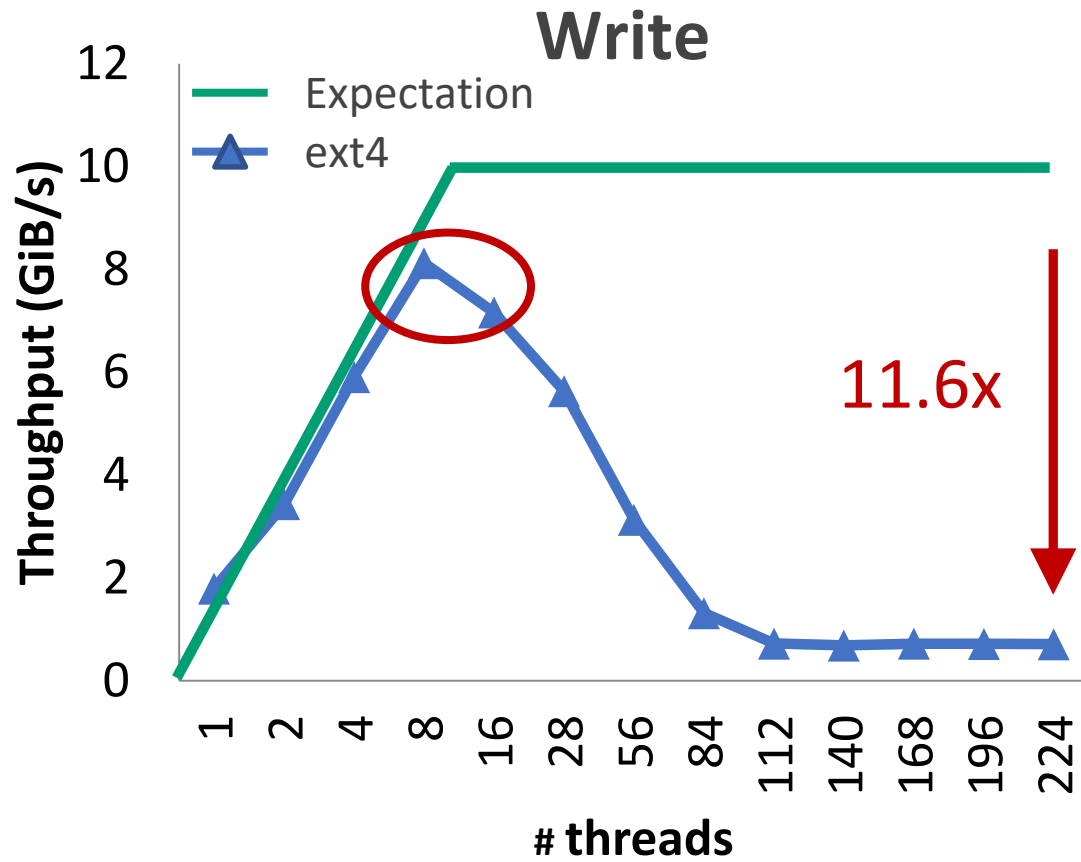


Setup: 224-core/8-socket machine

# PM performance on a single NUMA node

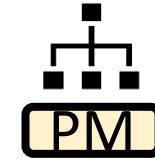


Workload: FIO: each thread writes/reads 2MB data in a private file

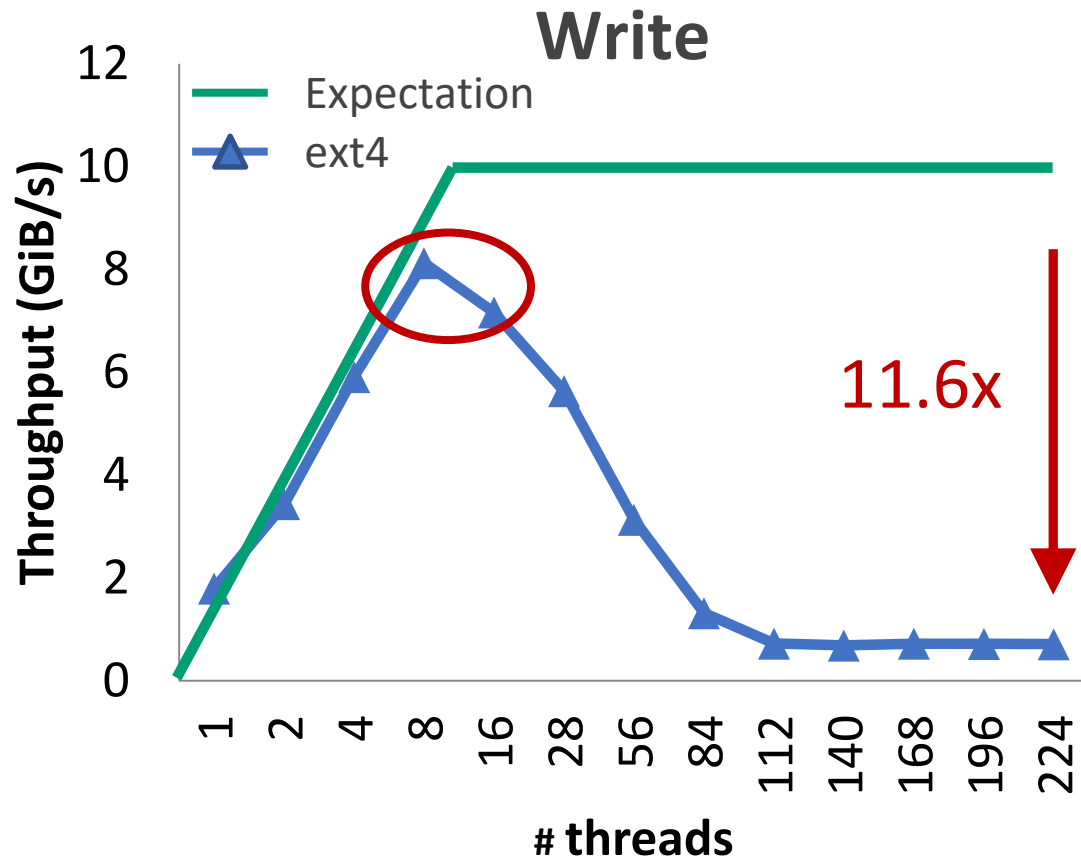


Setup: 224-core/8-socket machine

# PM performance on a single NUMA node



Workload: FIO: each thread writes/reads 2MB data in a private file

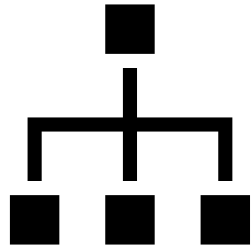


Excessive concurrent access  
→ PM performance collapse

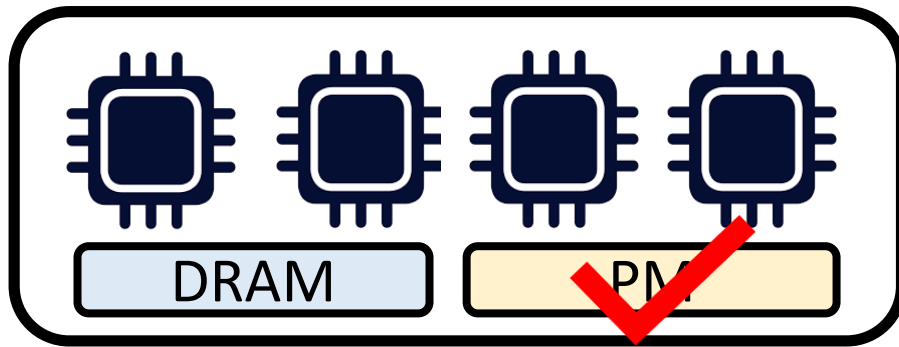
Setup: 224-core/8-socket machine



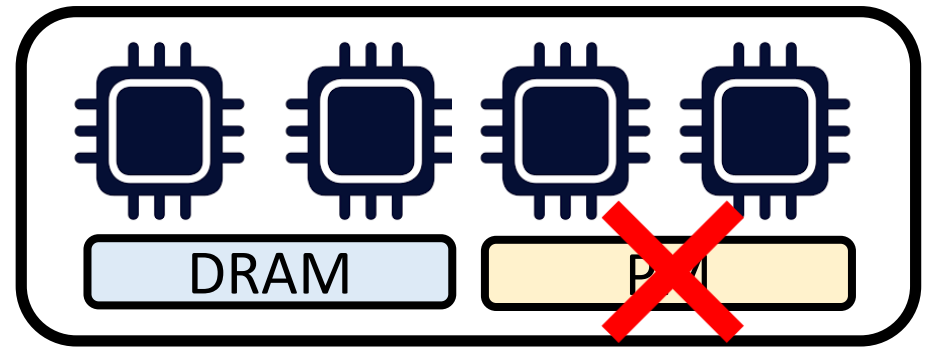
PM performance is bad  
on a single NUMA node



Core



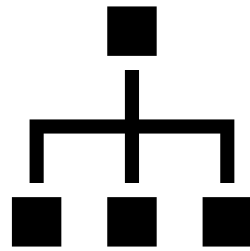
NUMA node



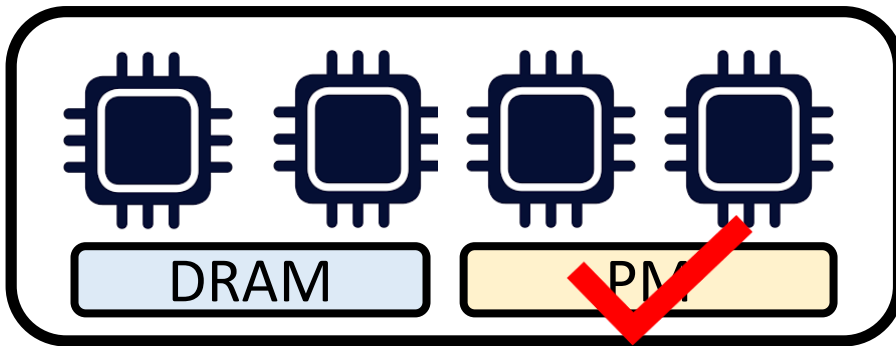
NUMA node



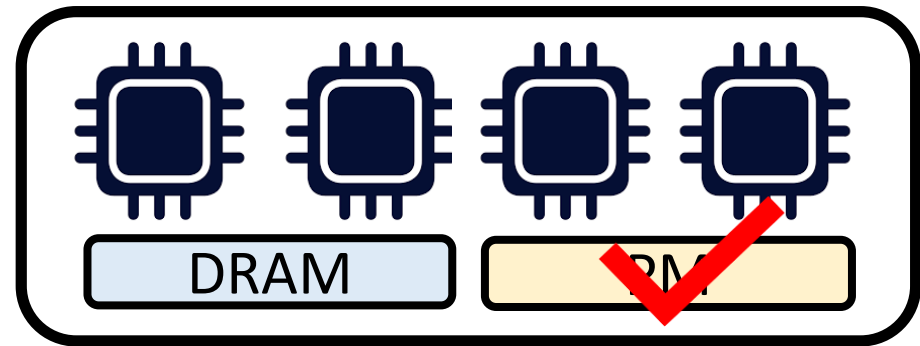
I will have a super fast  
file server



Core

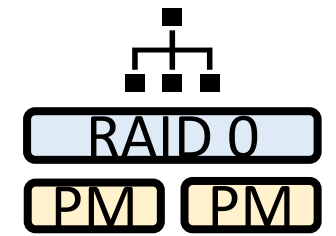


NUMA node

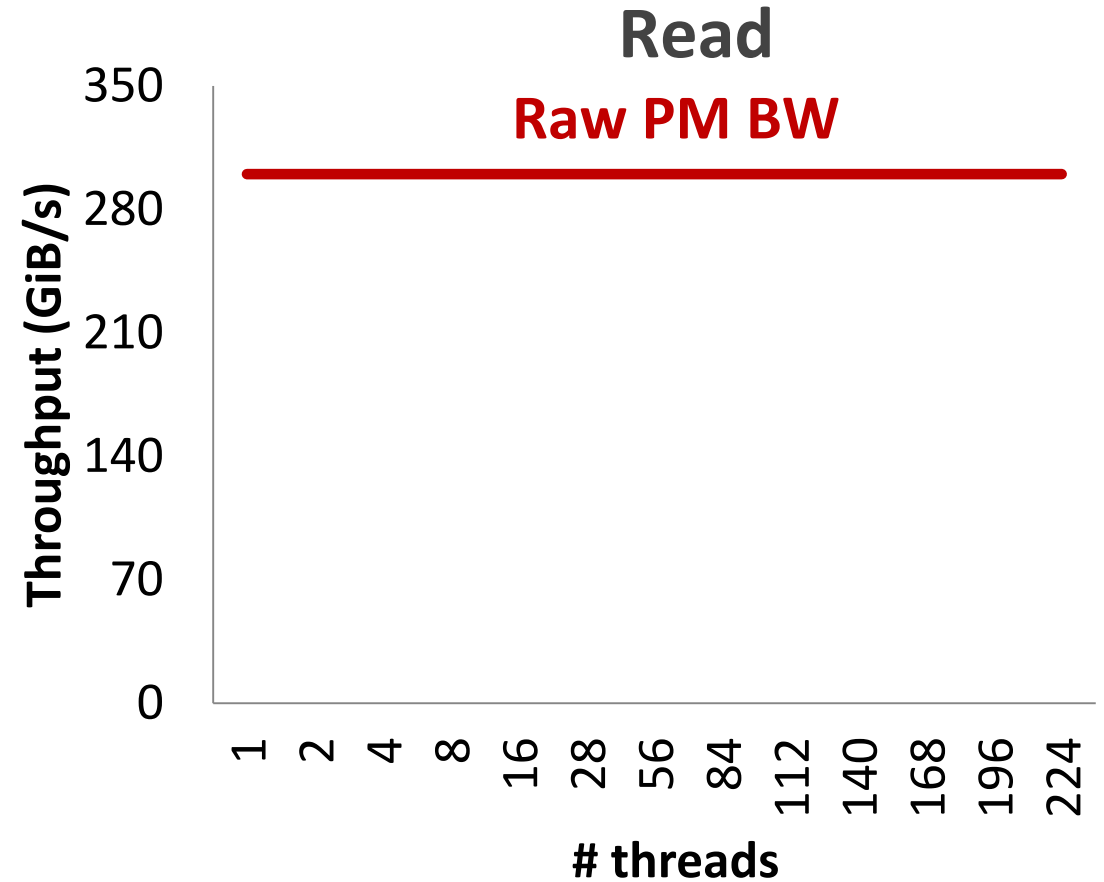
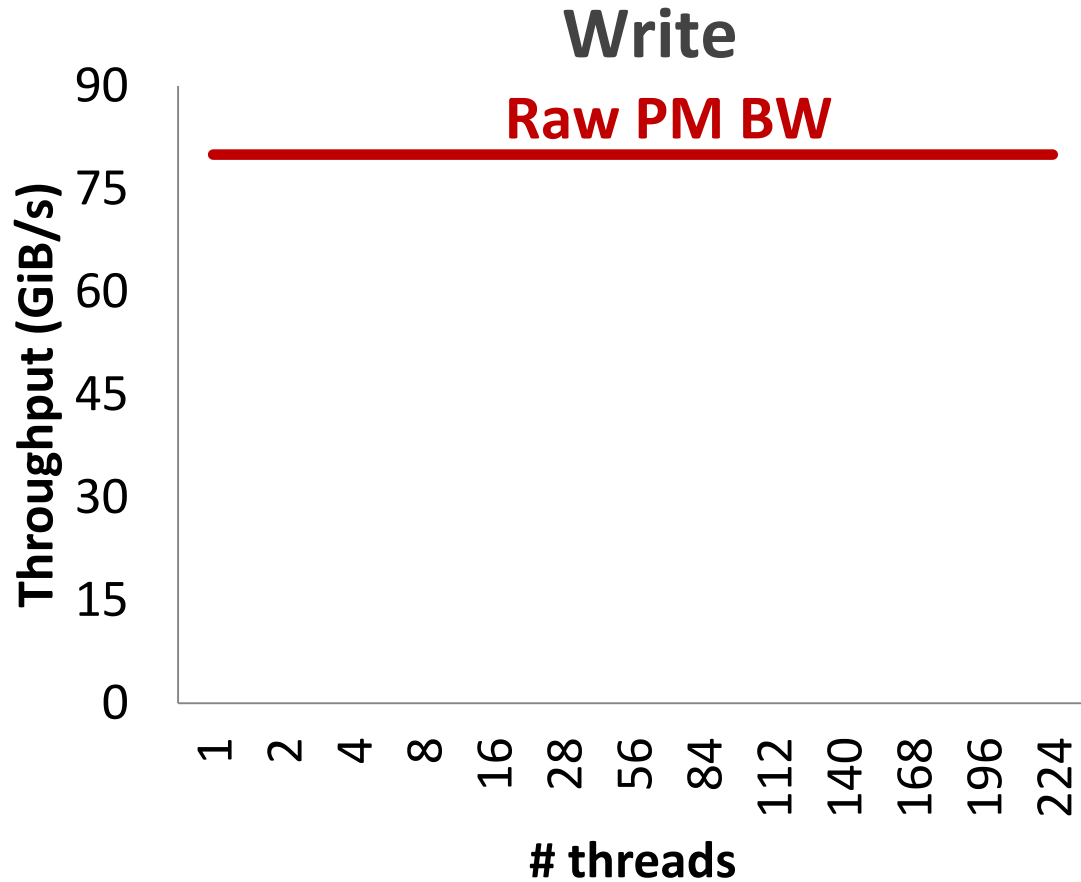


NUMA node

# PM performance on multiple NUMA nodes



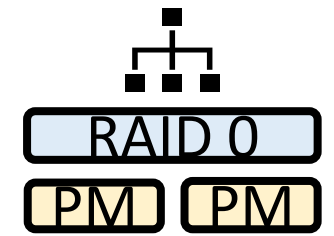
Workload: FIO: each thread writes/reads 2MB data in a private file



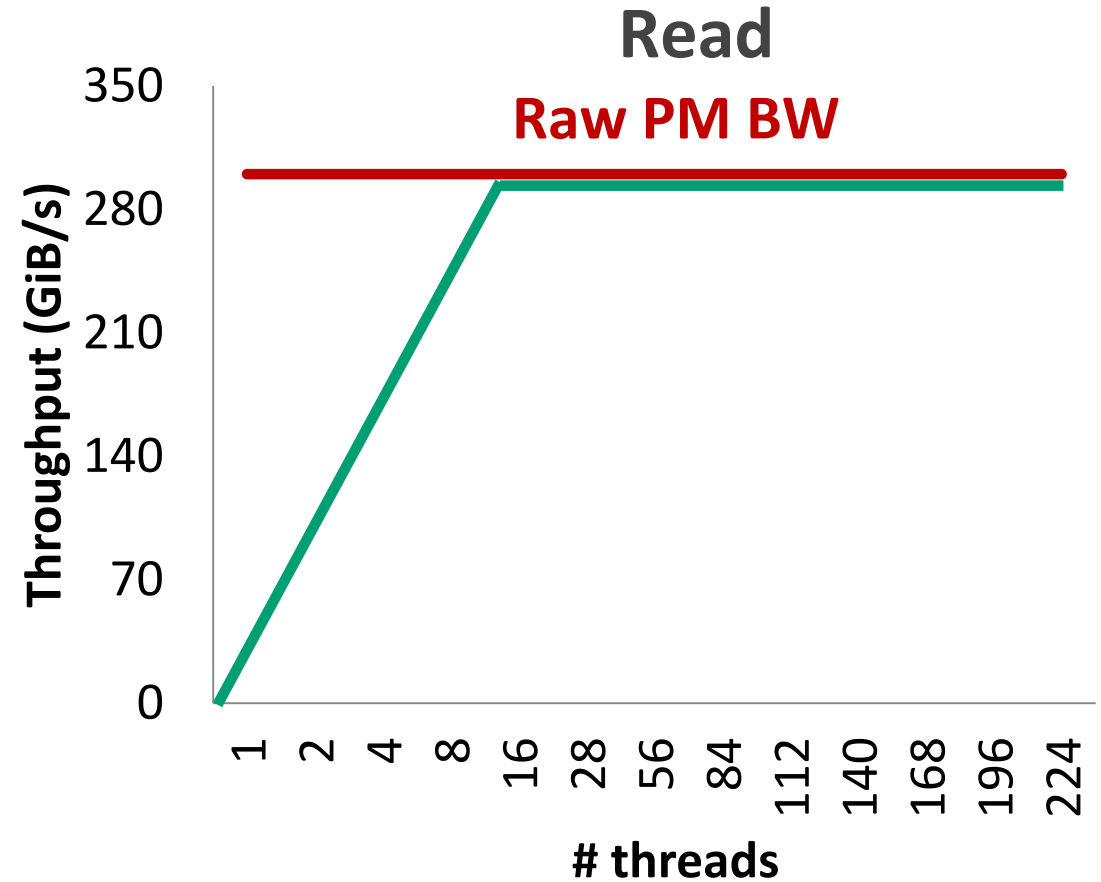
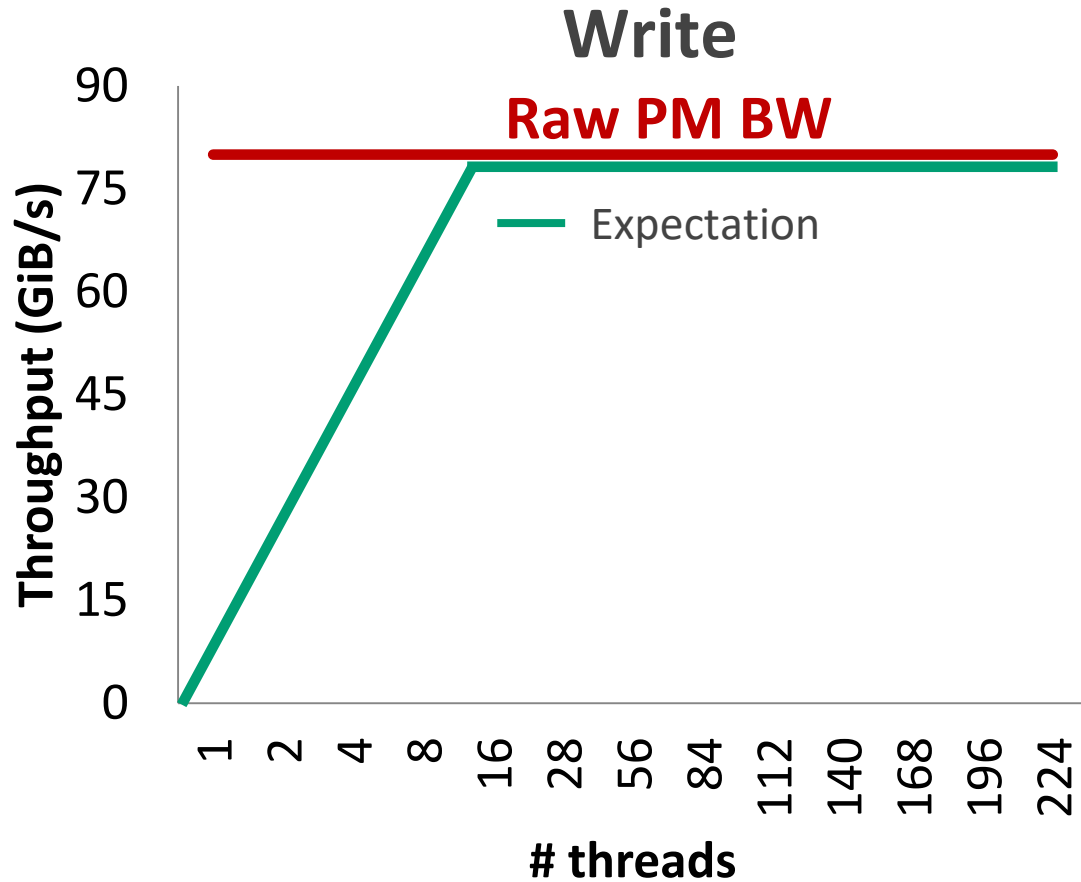
Setup: 224-core/8-socket machine



# PM performance on multiple NUMA nodes

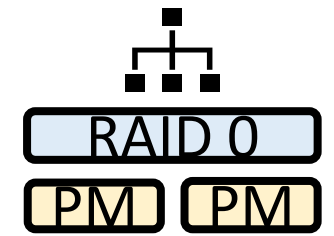


Workload: FIO: each thread writes/reads 2MB data in a private file

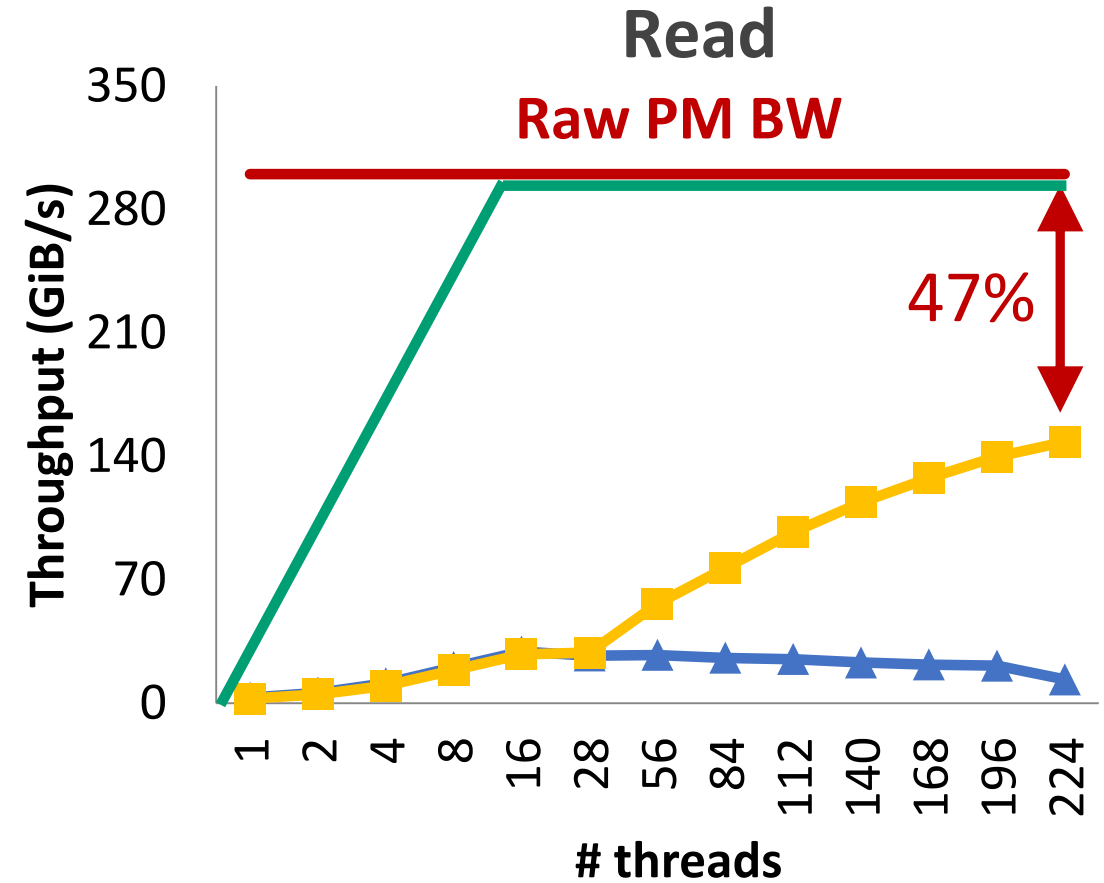
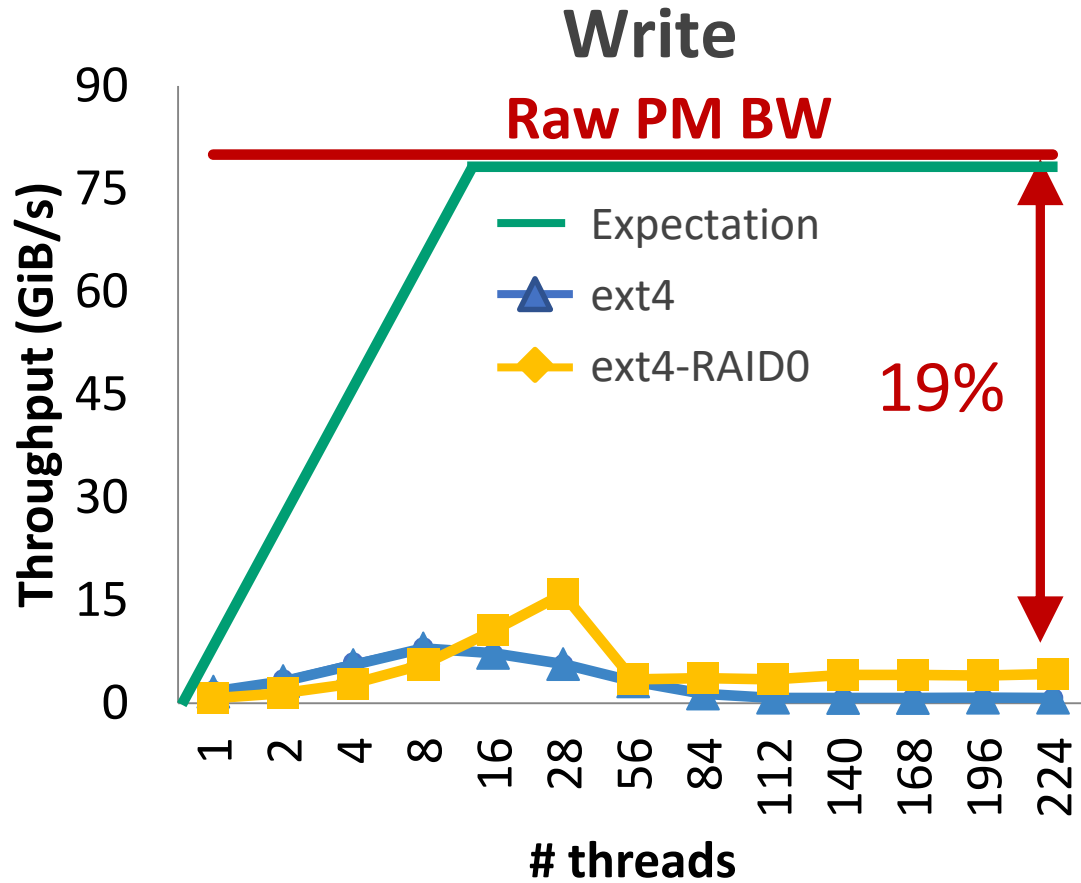


Setup: 224-core/8-socket machine

# PM performance on multiple NUMA nodes

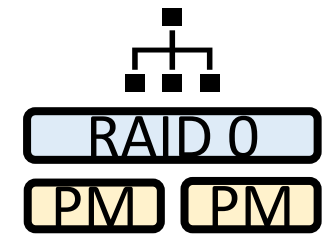


Workload: FIO: each thread writes/reads 2MB data in a private file



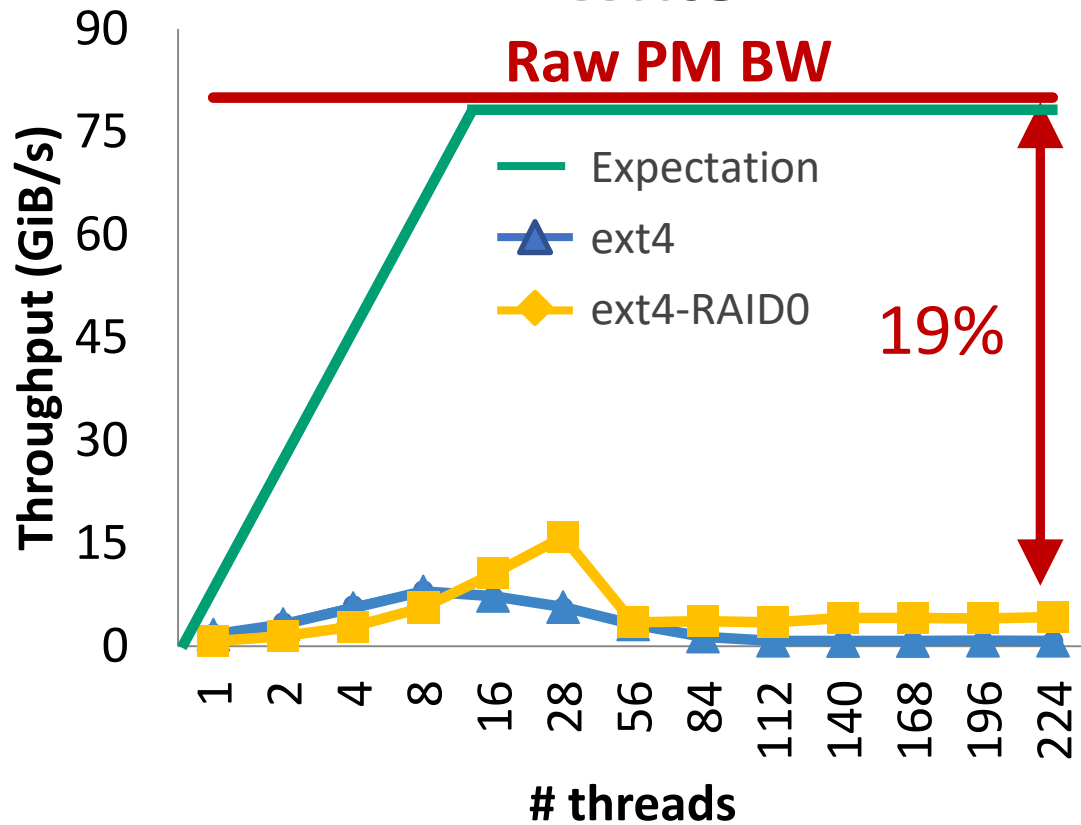
Setup: 224-core/8-socket machine

# PM performance on multiple NUMA nodes



Workload: FIO: each thread writes/reads 2MB data in a private file

Write



Inefficient remote PM access

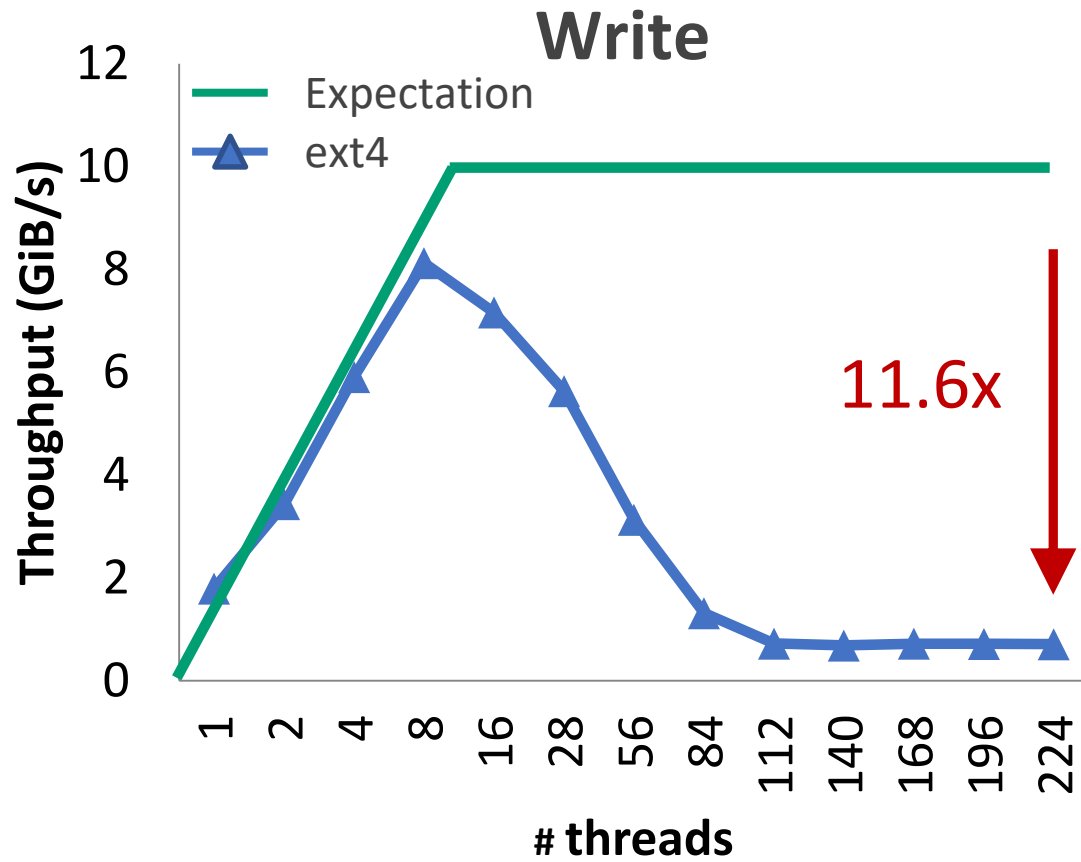
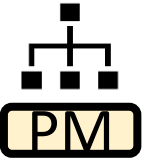
Setup: 224-core/8-socket machine

# Design goal of OdinFS:

Maximize PM performance

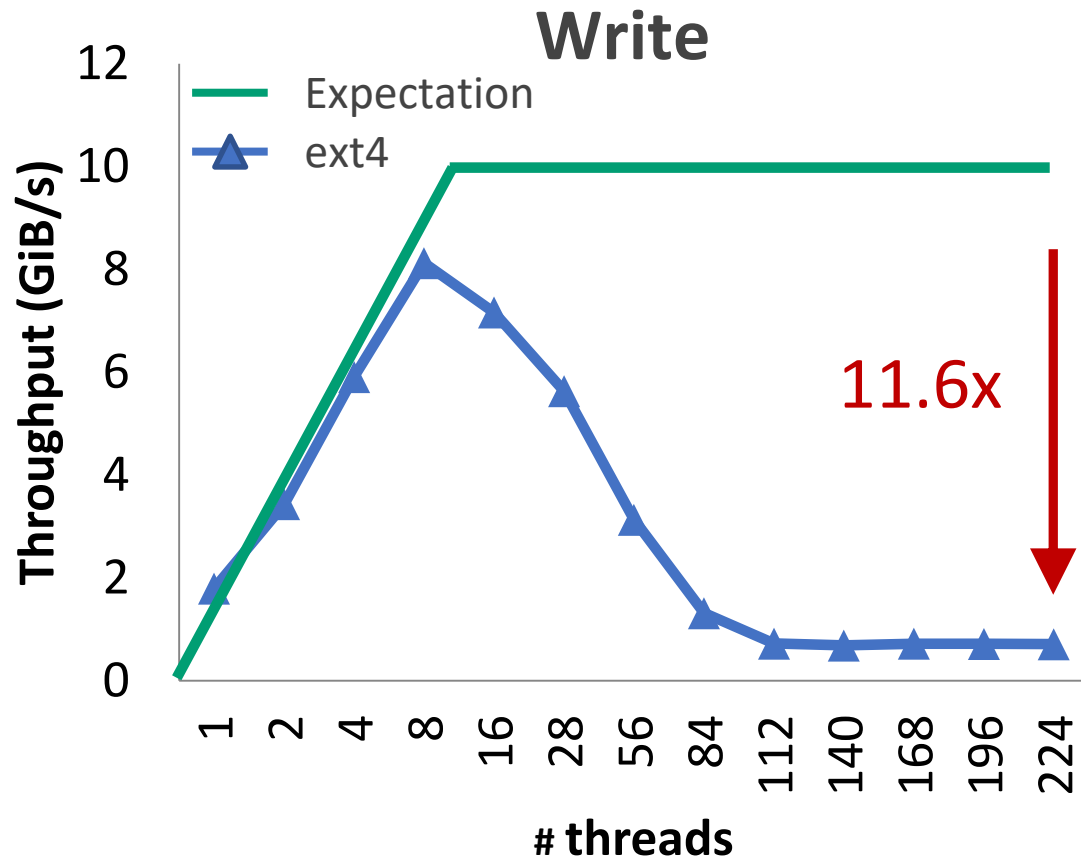
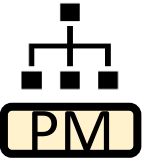
Maintain PM performance with concurrent access

# Single NUMA node: Why PM performance collapse



Excessive concurrent access →  
PM performance collapse

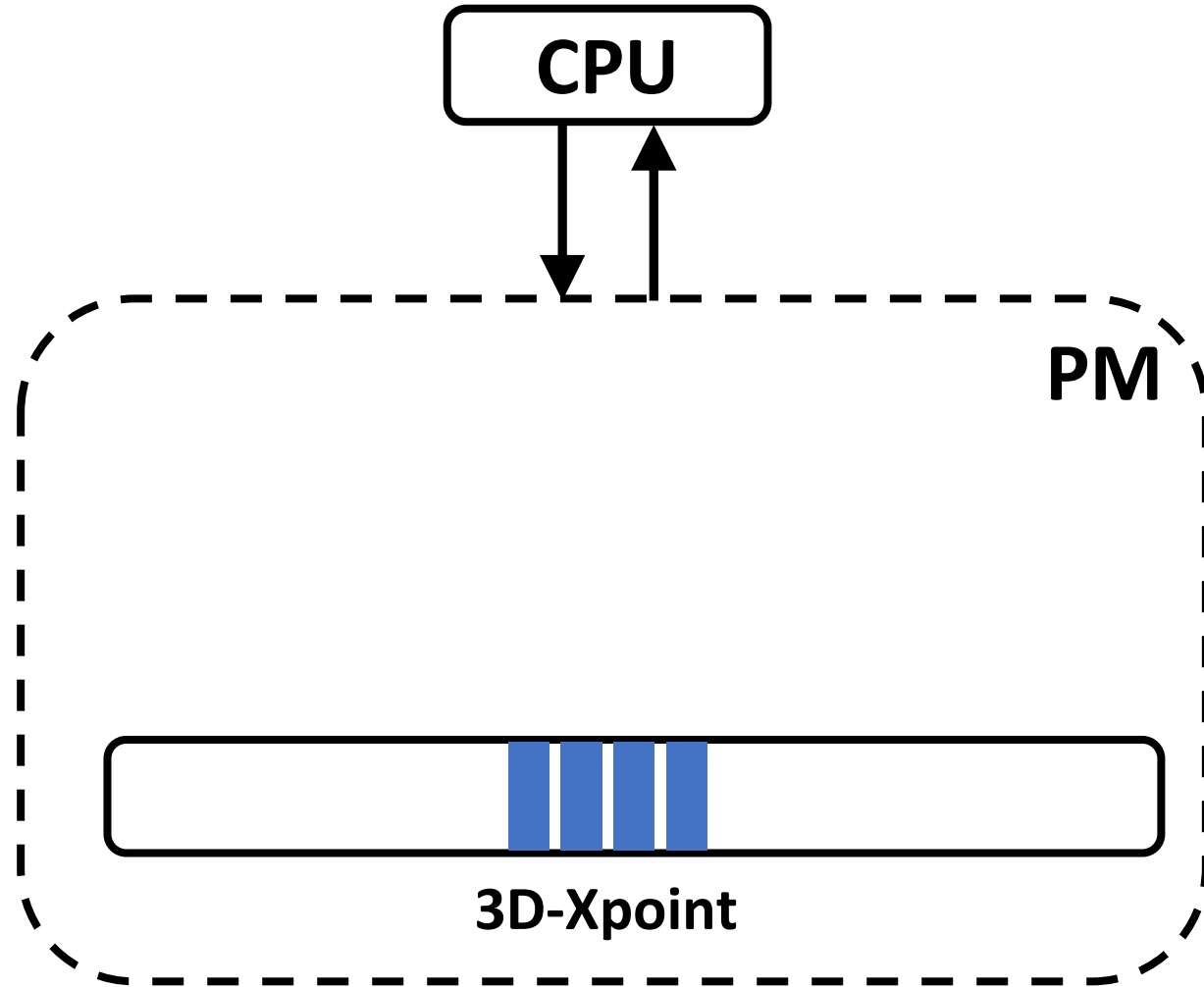
# Single NUMA node: Why PM performance collapse



Excessive concurrent access →  
PM performance collapse

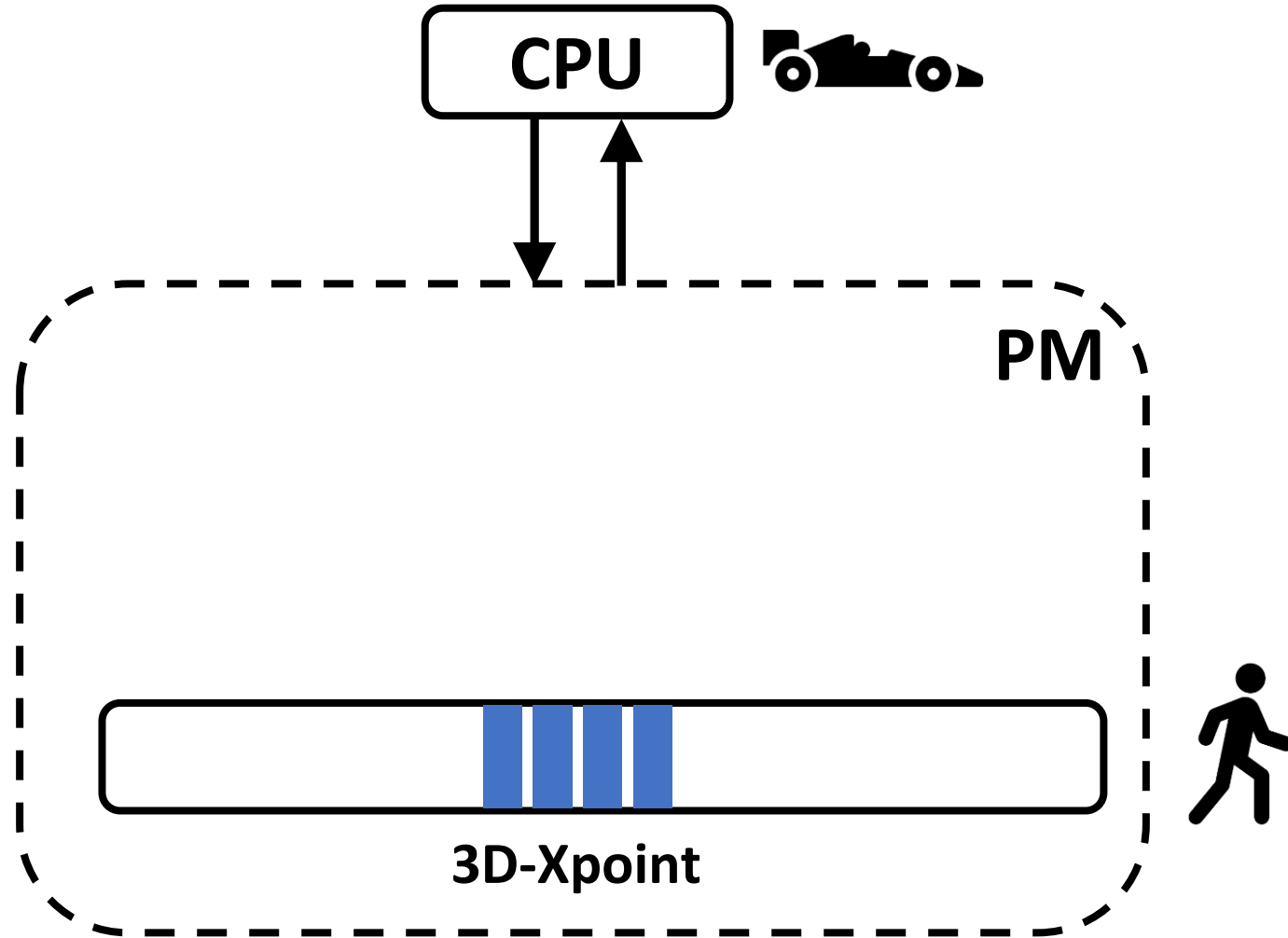
On-DIMM cache thrashing

# Caching and prefetching in PM



Hide performance gap  
with caching & prefetching

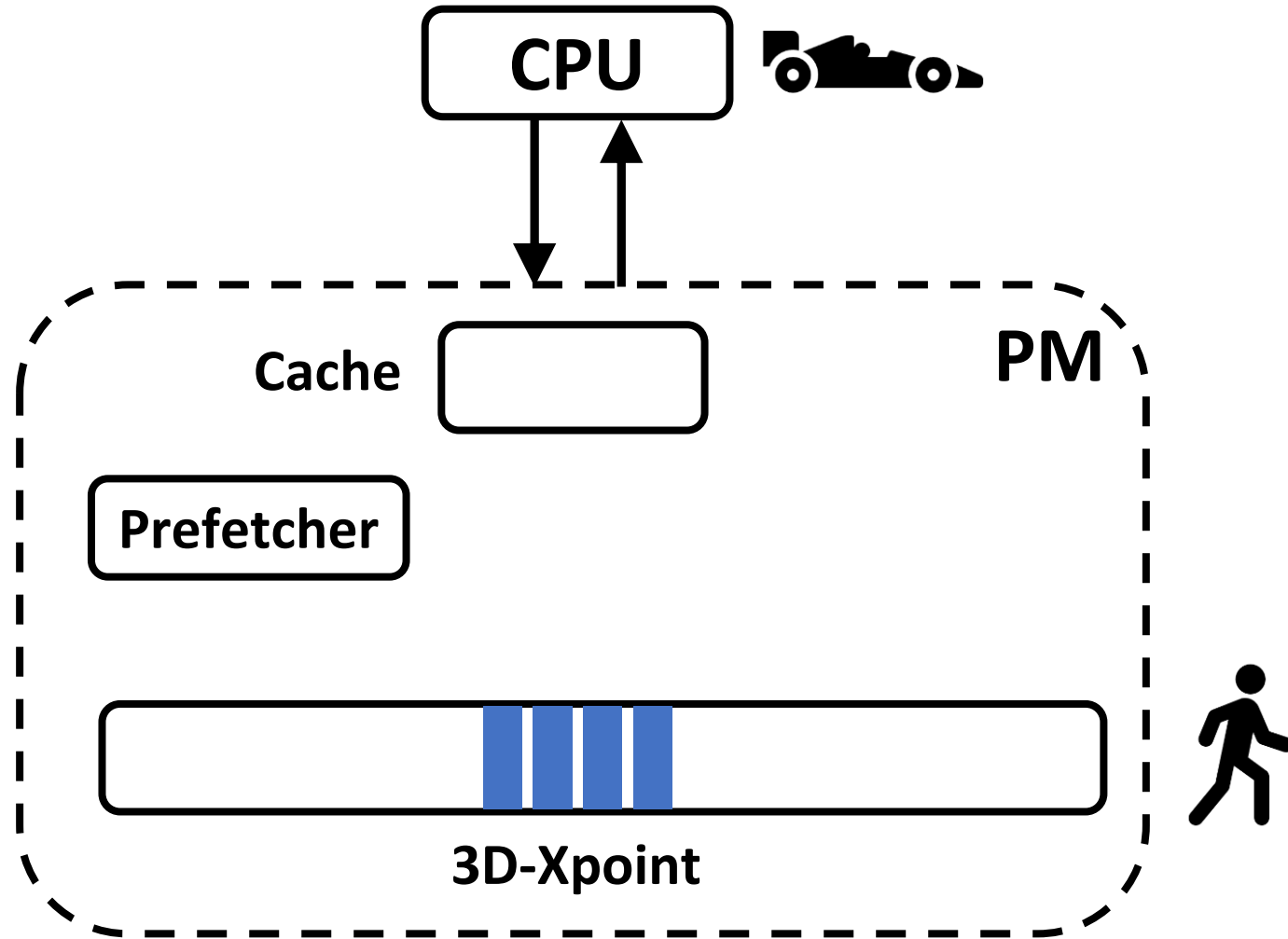
# Caching and prefetching in PM



Hide performance gap  
with caching & prefetching

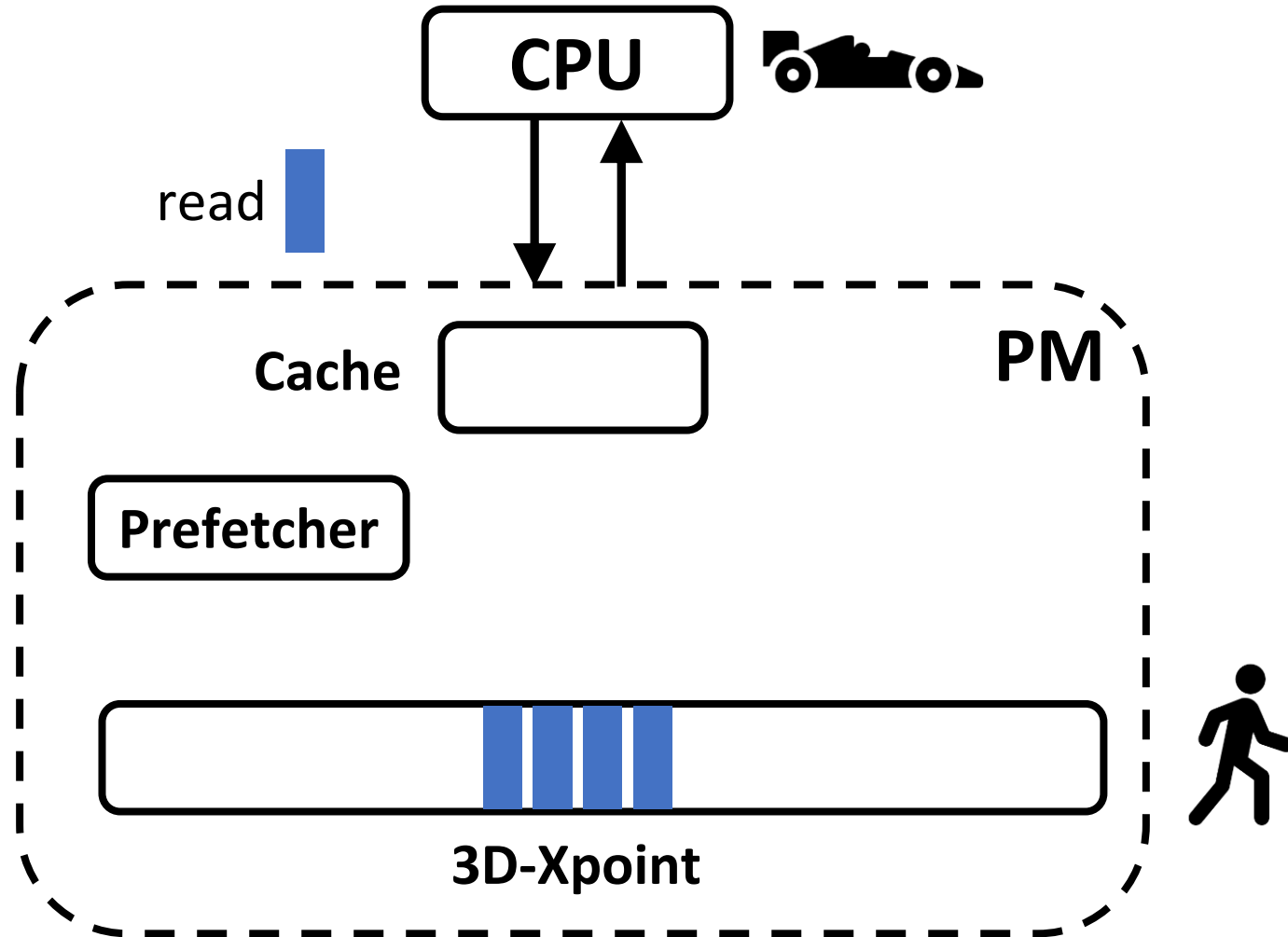


# Caching and prefetching in PM



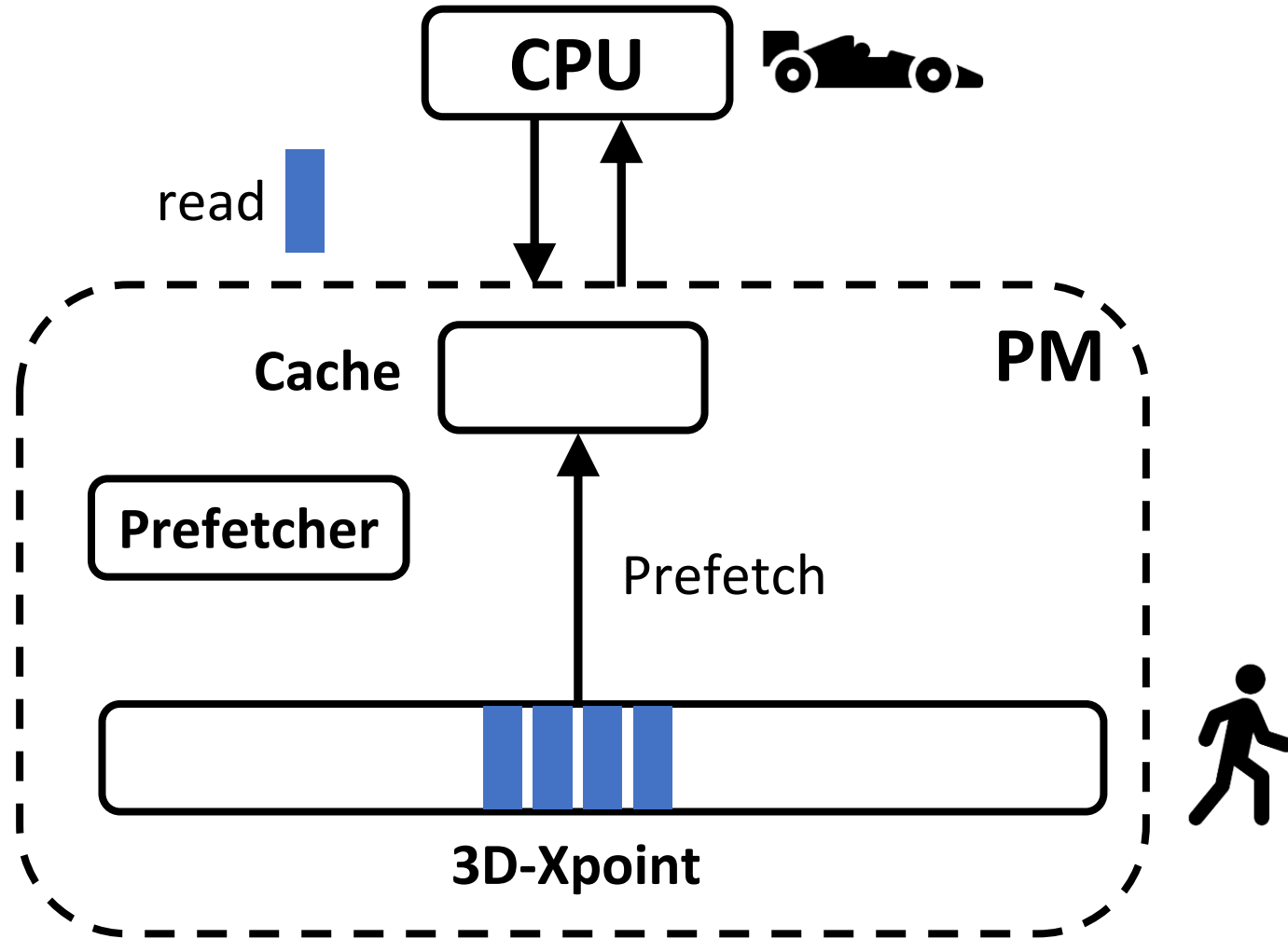
Hide performance gap  
with caching & prefetching

# Caching and prefetching in PM



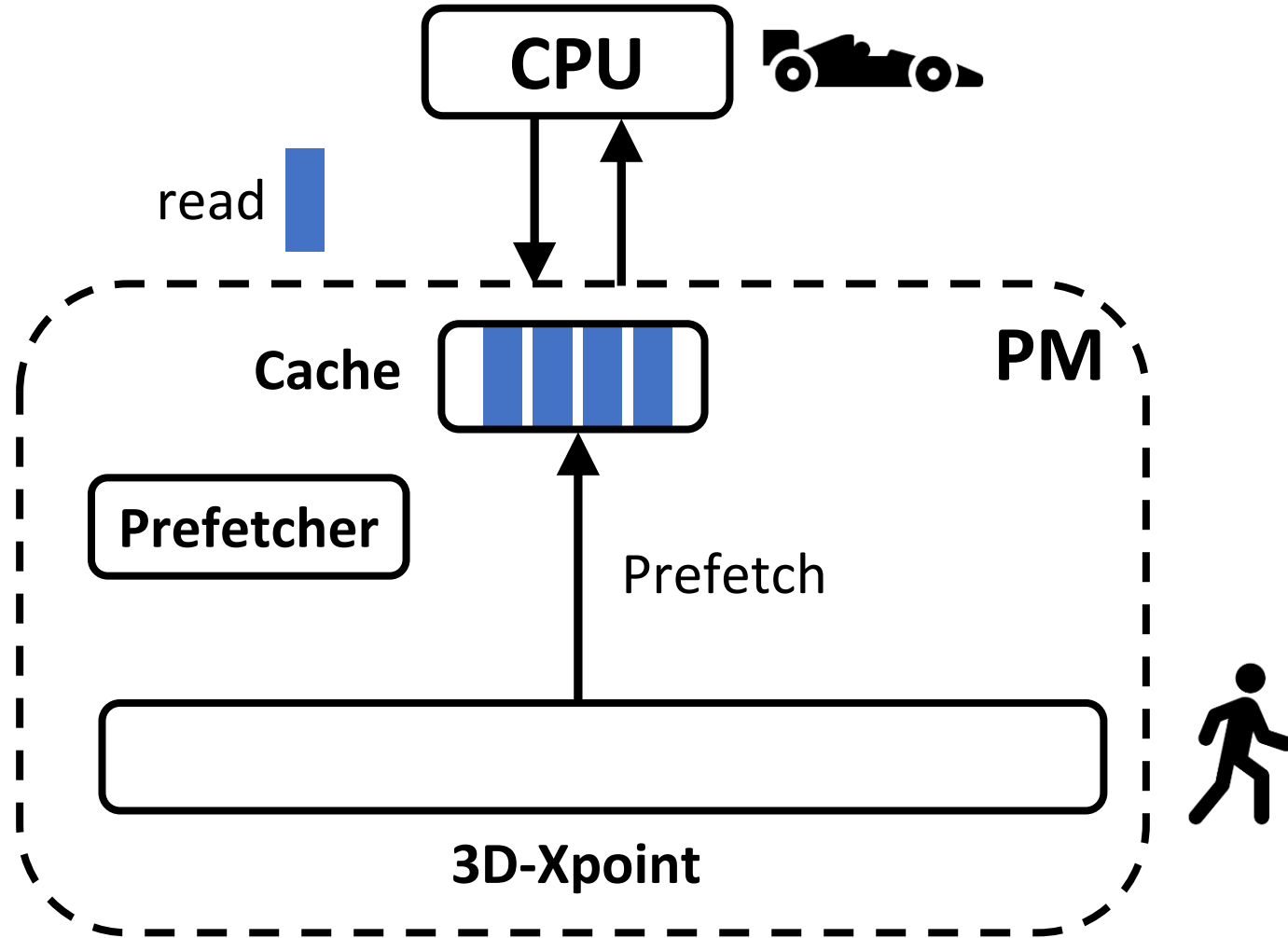
Hide performance gap  
with caching & prefetching

# Caching and prefetching in PM



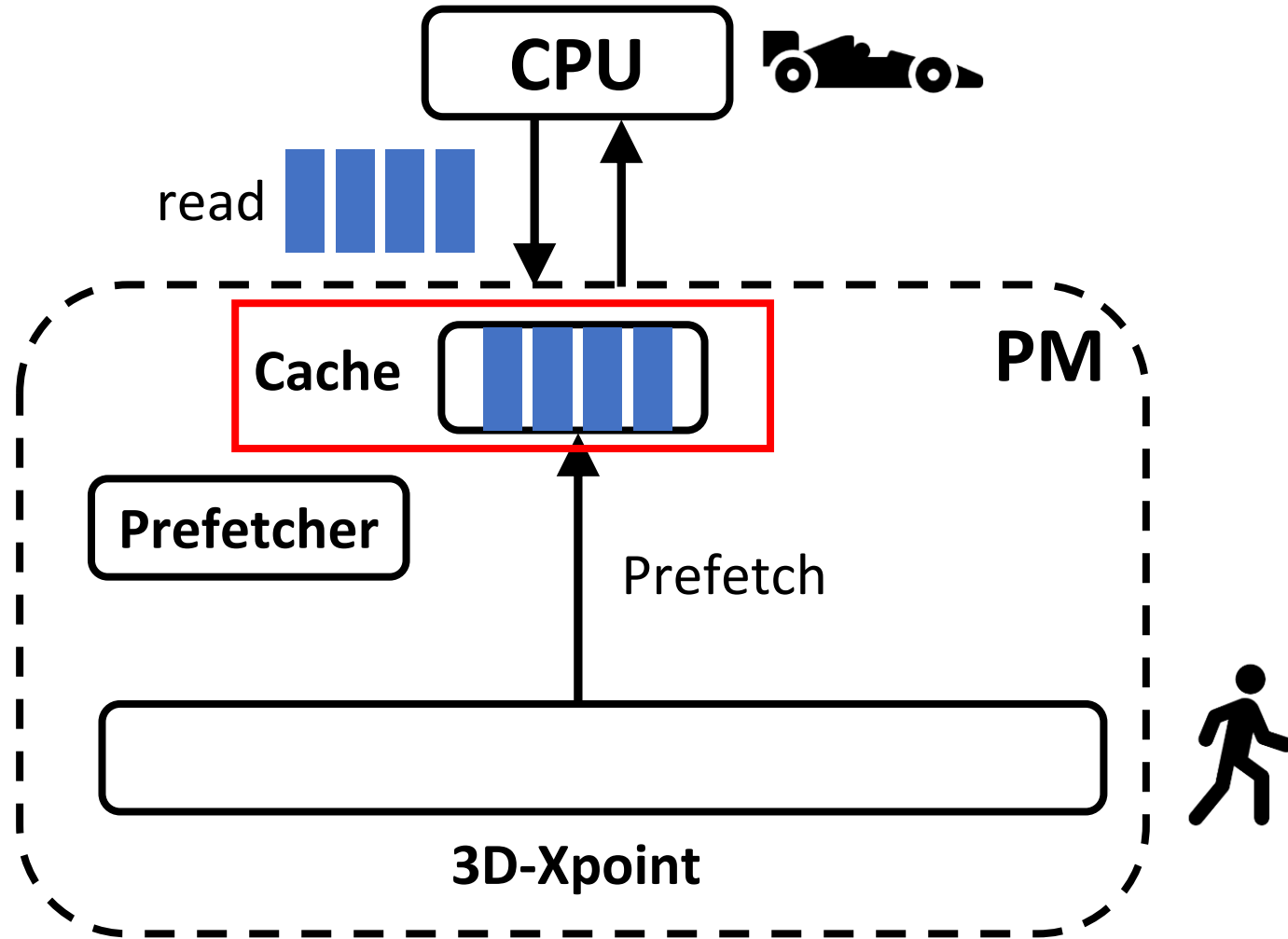
Hide performance gap  
with caching & prefetching

# Caching and prefetching in PM



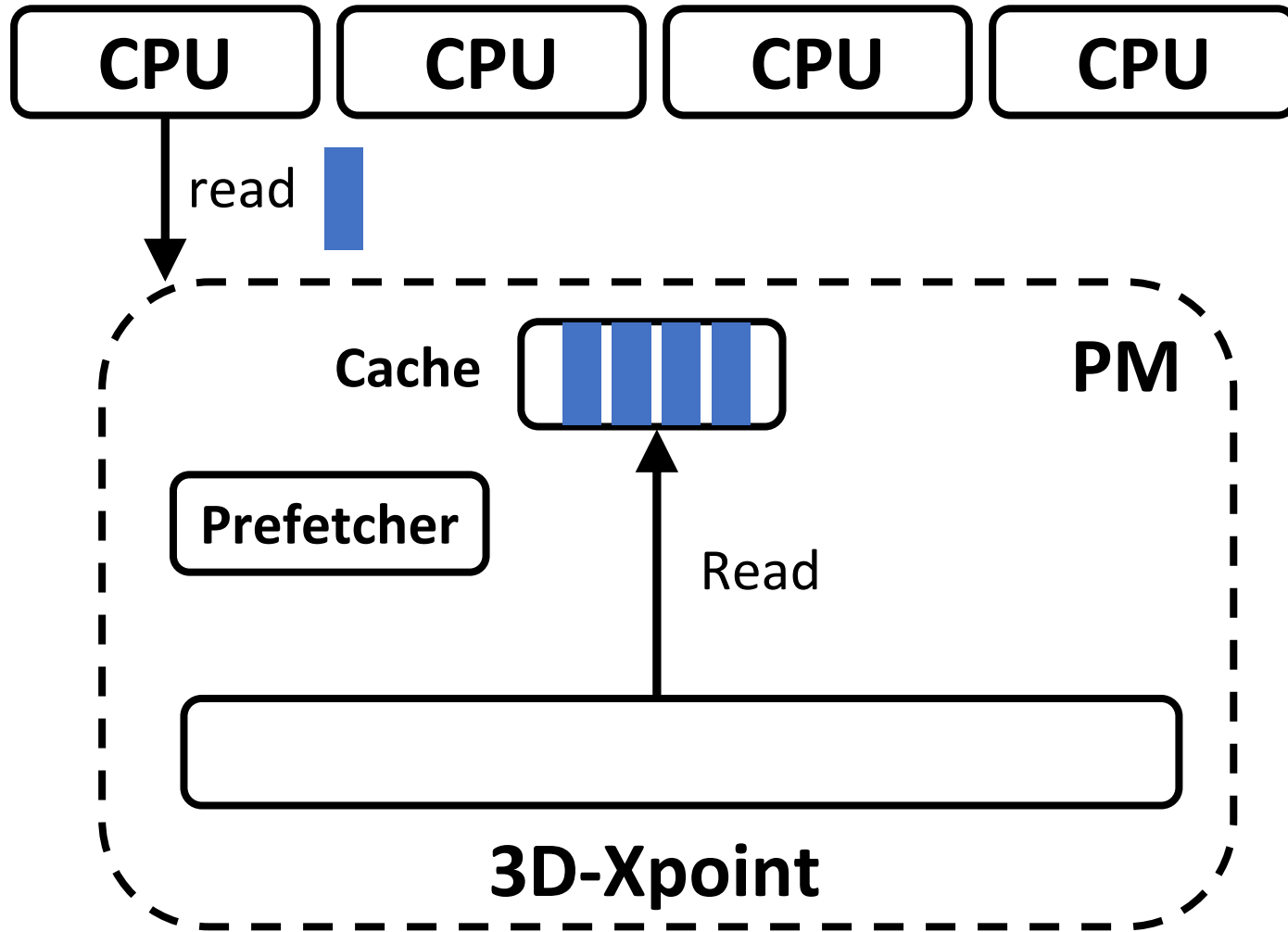
Hide performance gap  
with caching & prefetching

# Caching and prefetching in PM



Hide performance gap  
with caching & prefetching

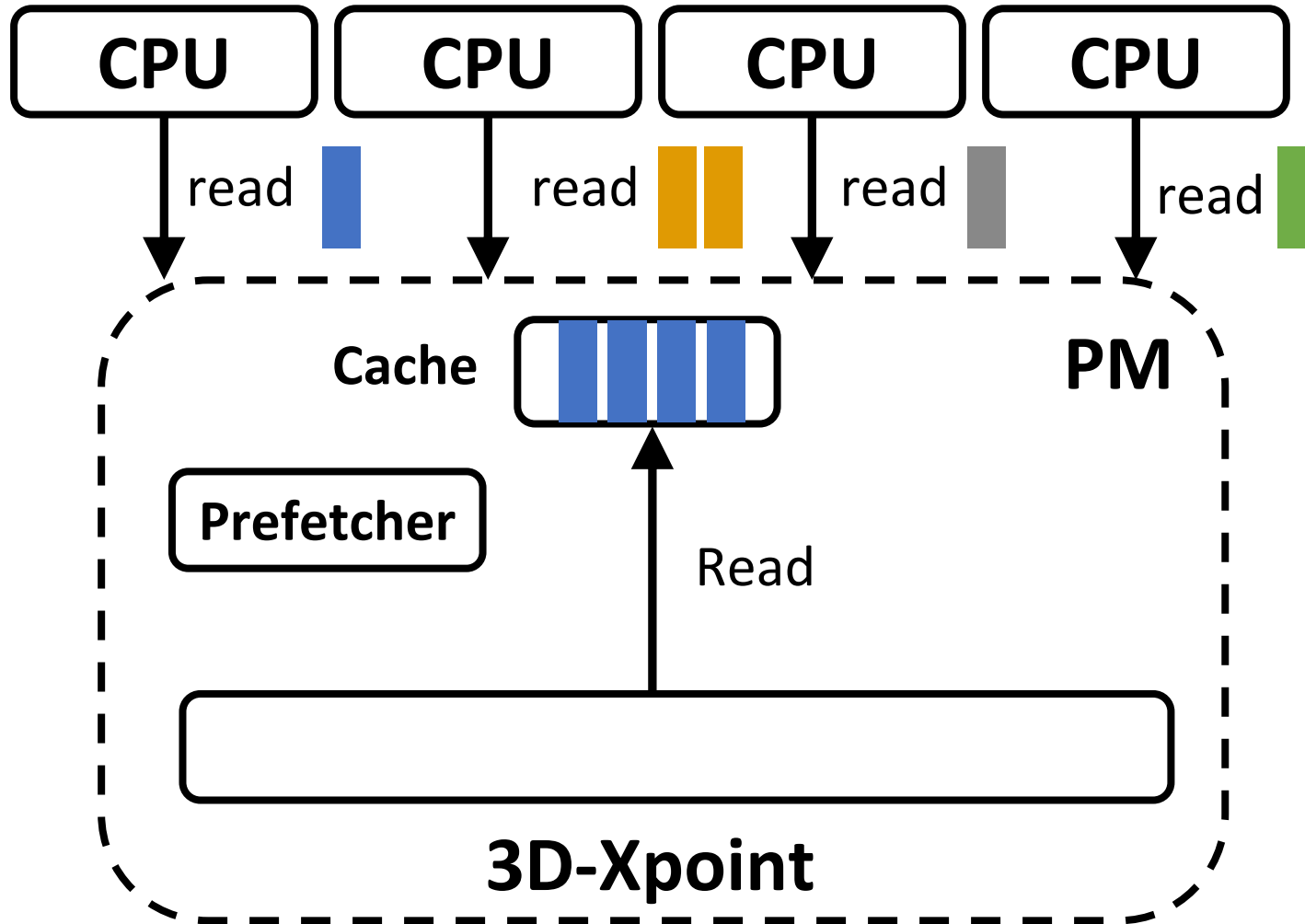
# PM cache thrashing due to concurrent access



Hide performance gap  
with caching & prefetching

Excessive concurrent access  
→ PM cache thrashing

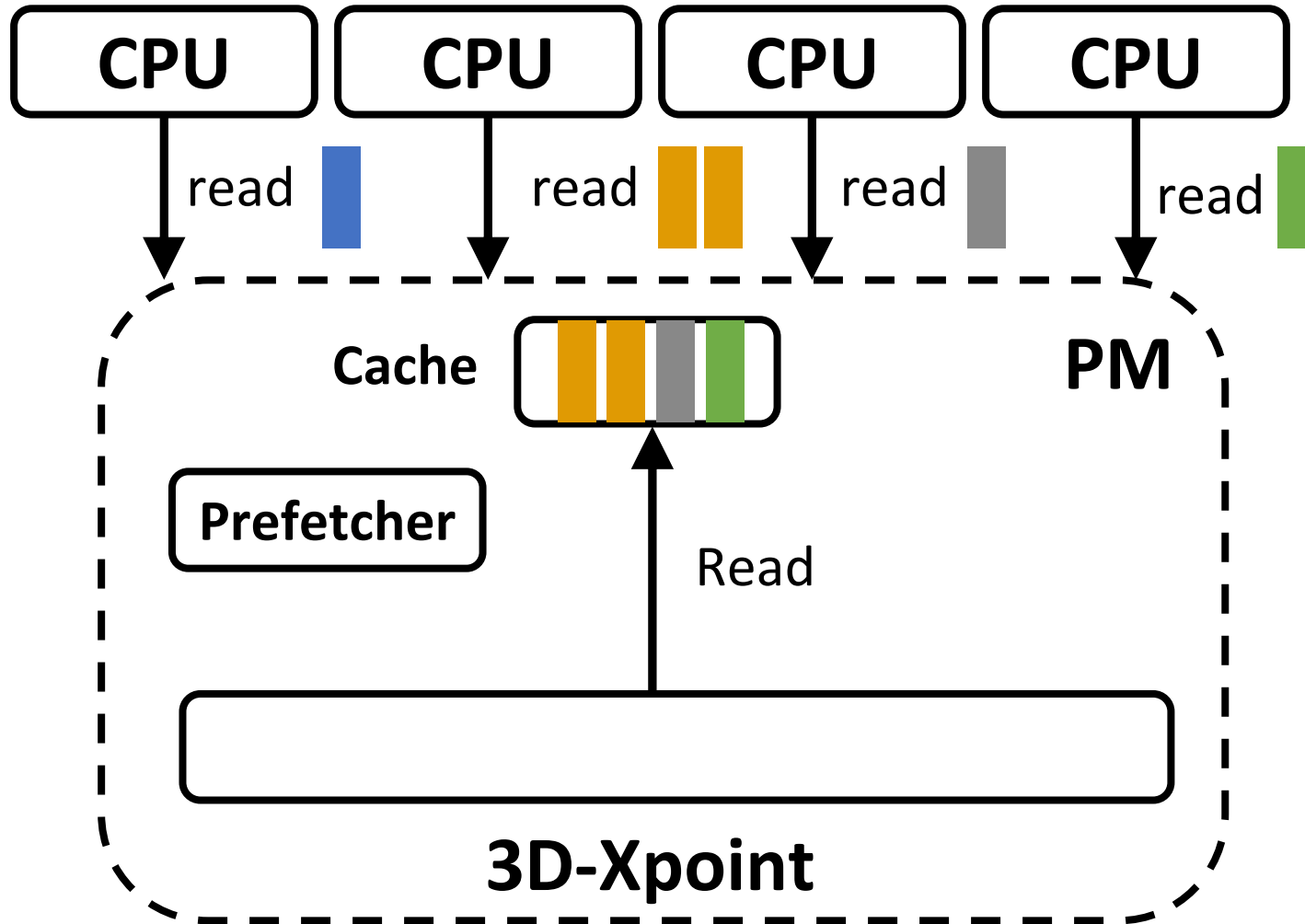
# PM cache thrashing due to concurrent access



Hide performance gap  
with caching & prefetching

Excessive concurrent access  
→ PM cache thrashing

# PM cache thrashing due to concurrent access

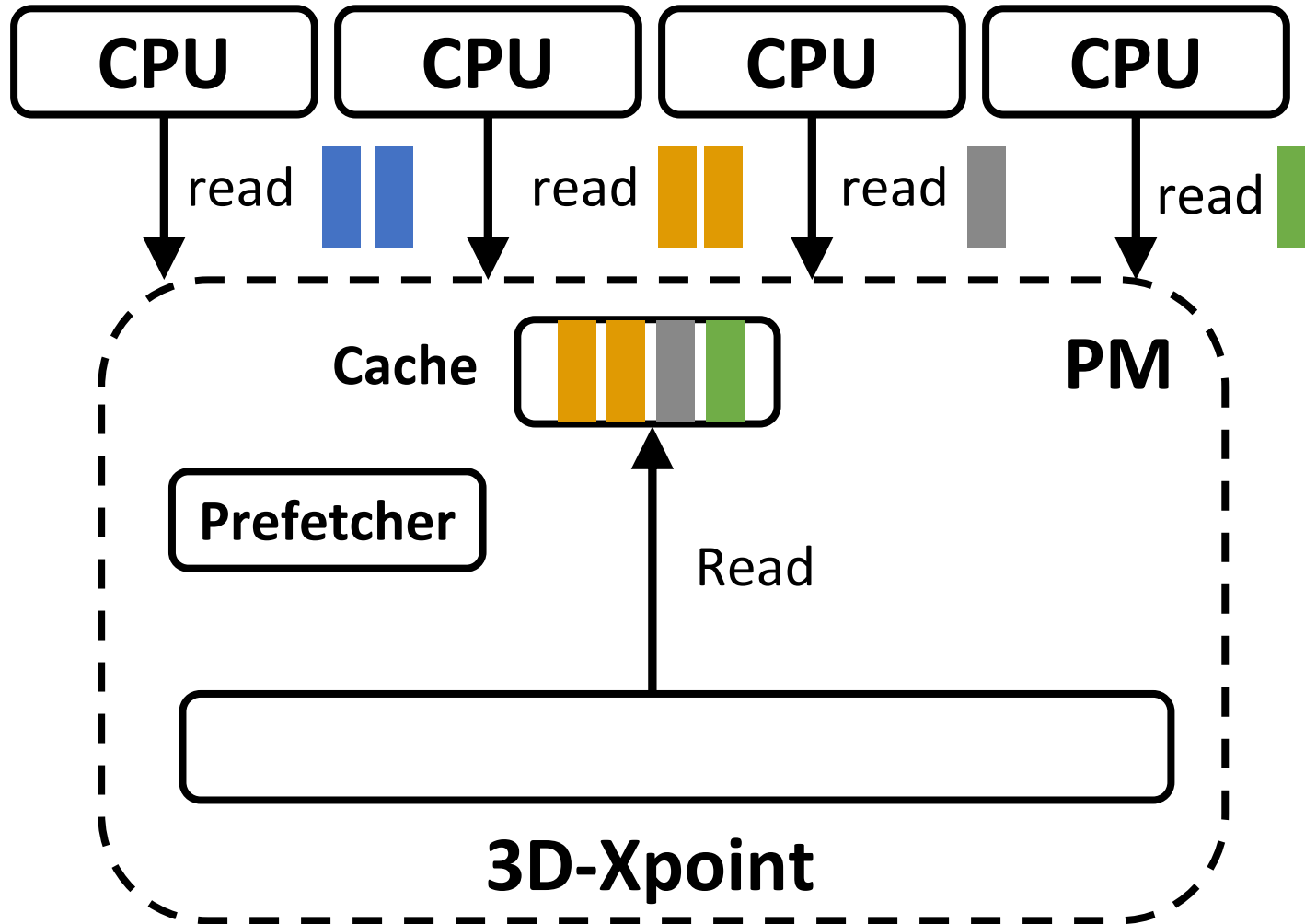


Hide performance gap  
with caching & prefetching

Excessive concurrent access  
→ PM cache thrashing



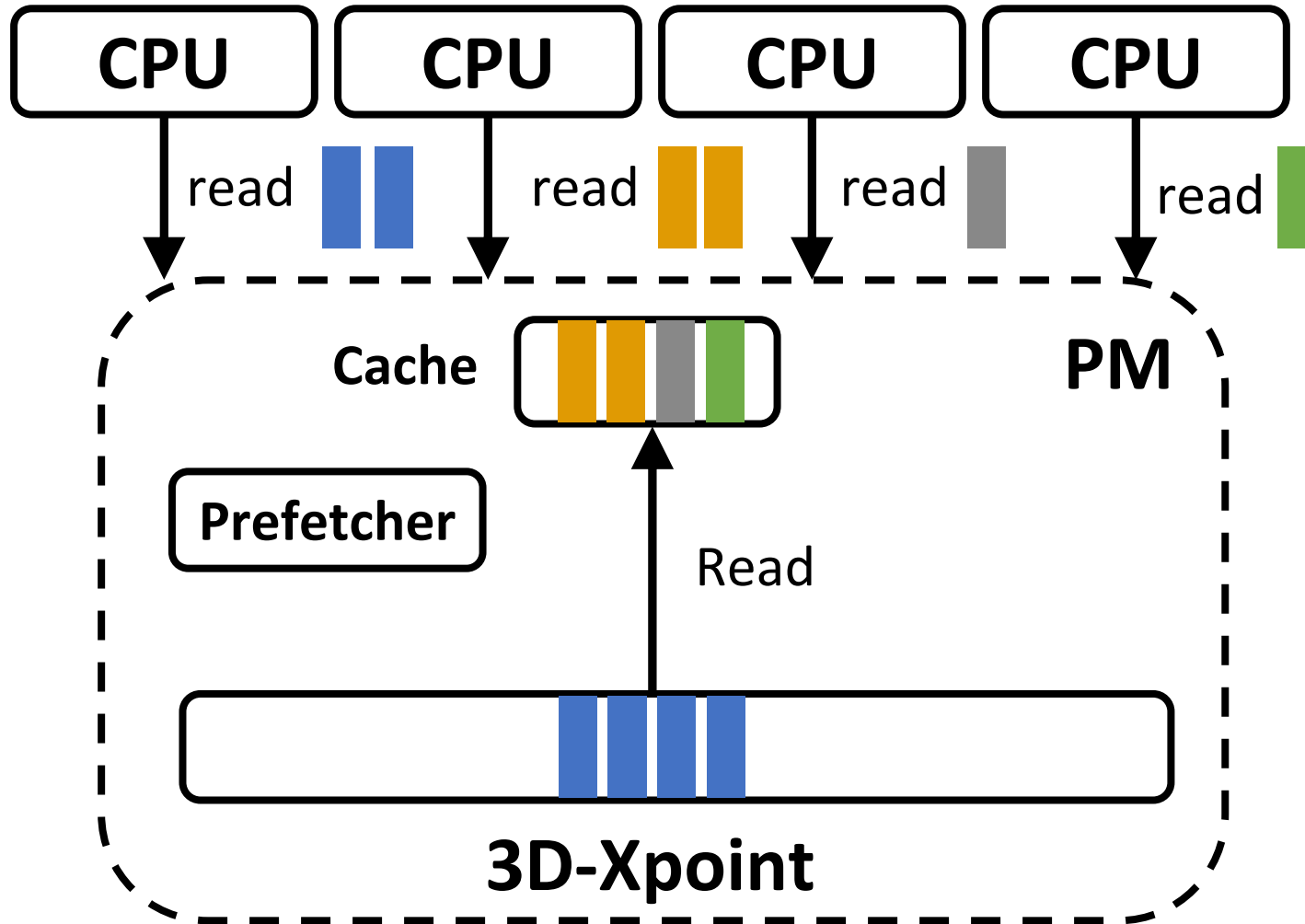
# PM cache thrashing due to concurrent access



Hide performance gap  
with caching & prefetching

Excessive concurrent access  
→ PM cache thrashing

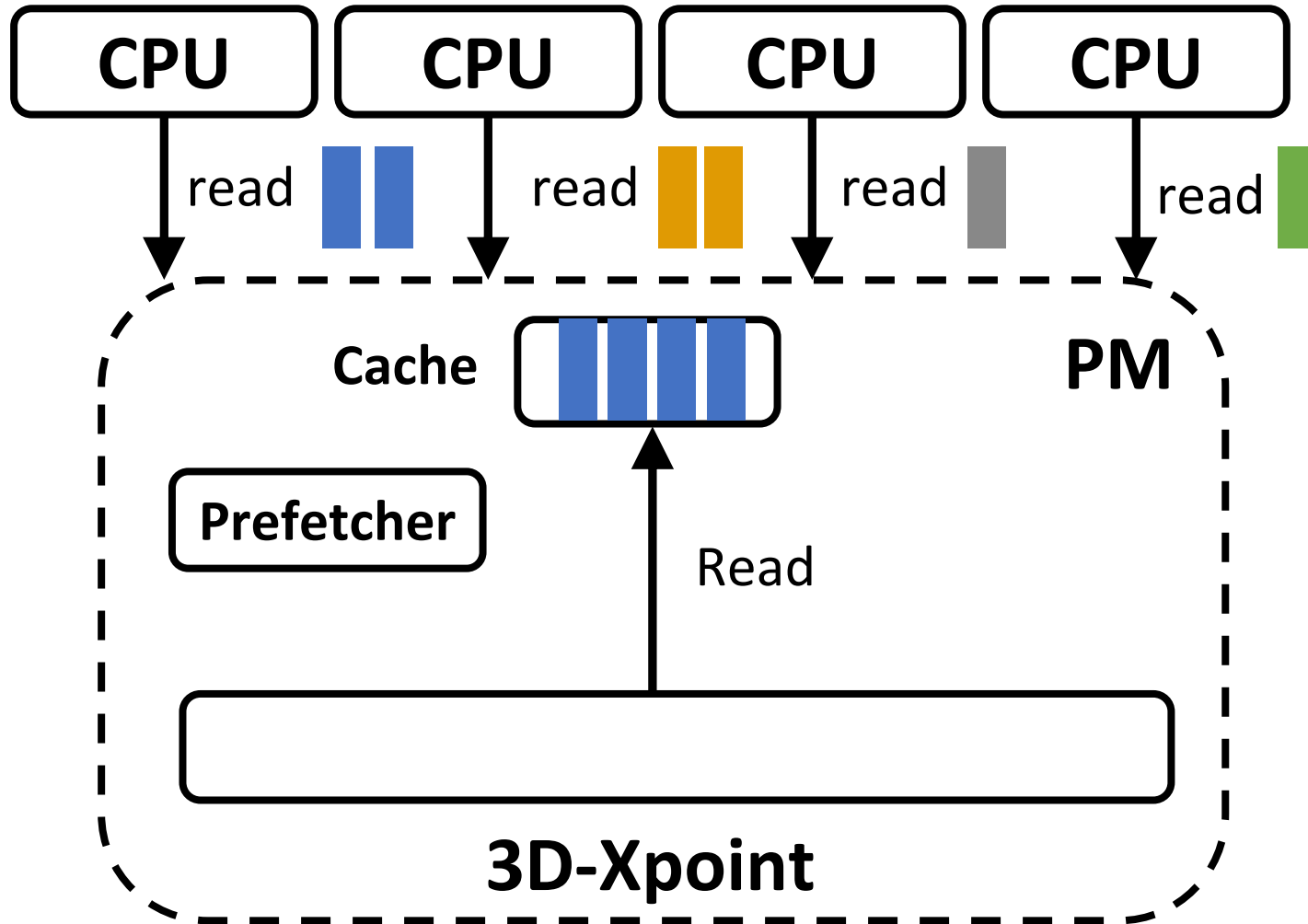
# PM cache thrashing due to concurrent access



Hide performance gap  
with caching & prefetching

Excessive concurrent access  
→ PM cache thrashing

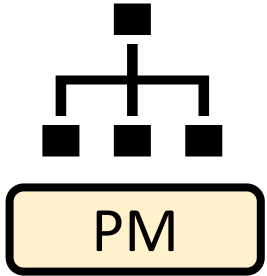
# PM cache thrashing due to concurrent access



Hide performance gap  
with caching & prefetching

Excessive concurrent access  
→ PM cache thrashing

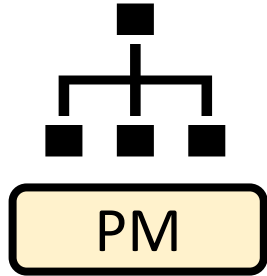
# PM performance analysis



**Issue:** Excessive concurrent access → PM performance collapse

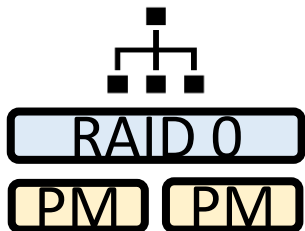
**Insight:** Control concurrent PM access for maximal performance

# PM performance analysis



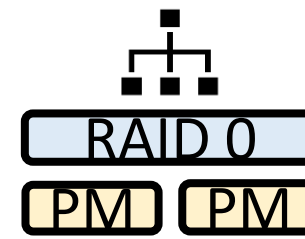
**Issue:** Excessive concurrent access → PM performance collapse

**Insight:** Control concurrent PM access for maximal performance

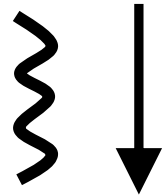


**Issue:** Inefficient remote PM access

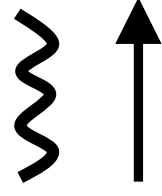
# I/O operations in a PM file system



write syscall

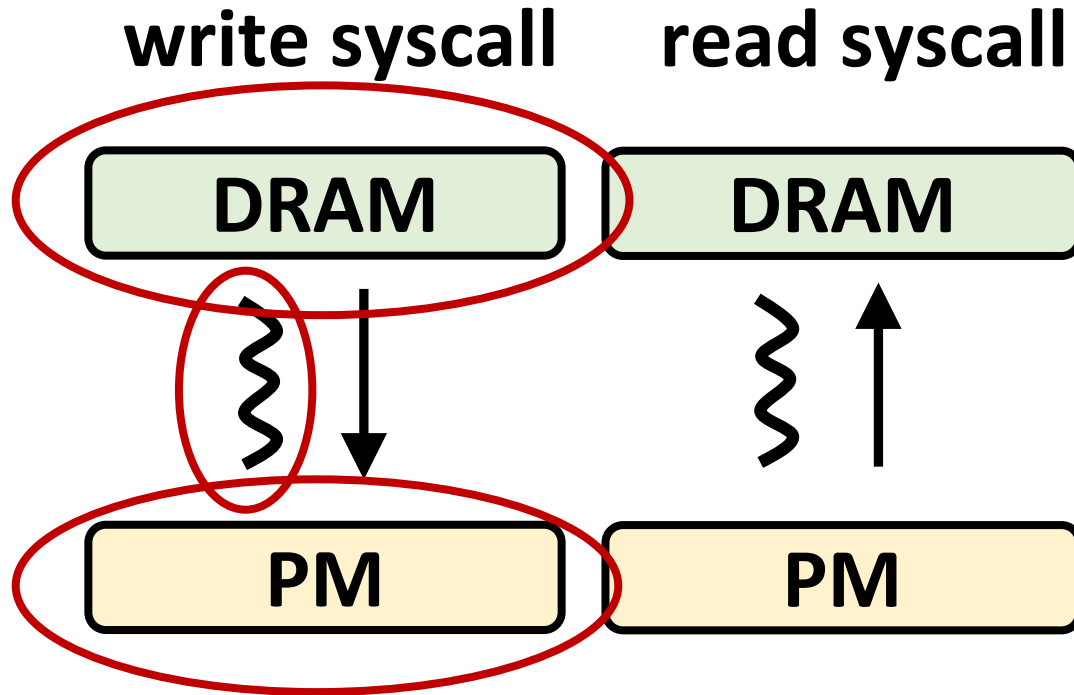
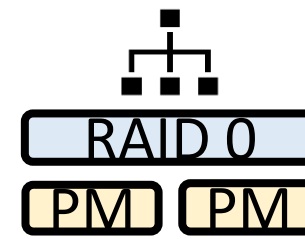


read syscall



Data transfer between DRAM and PM

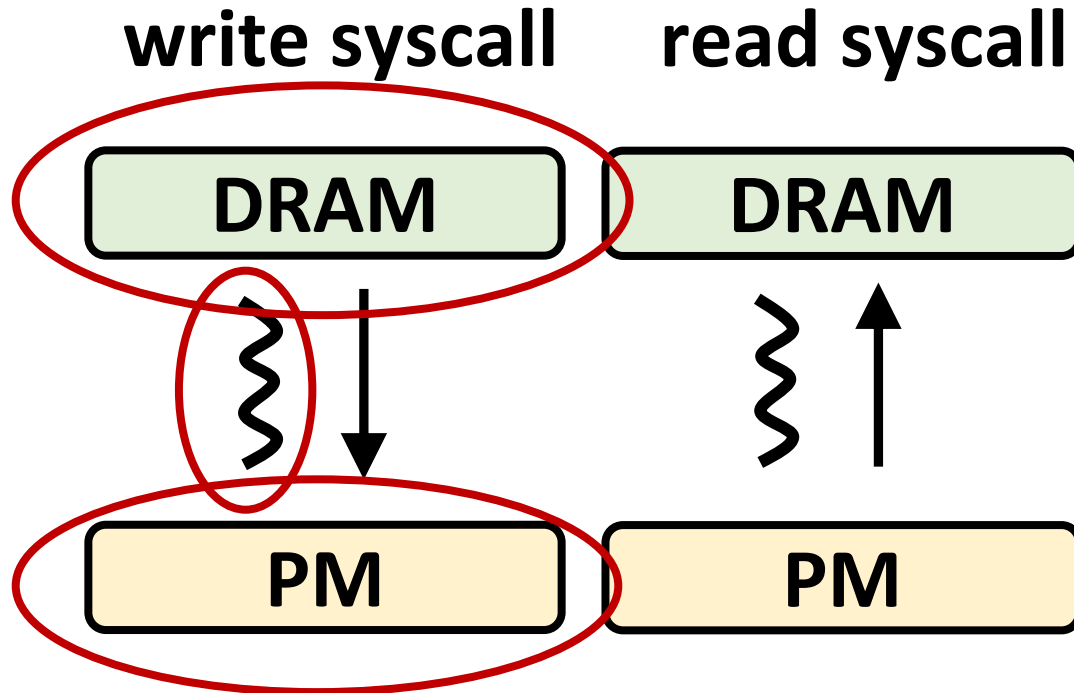
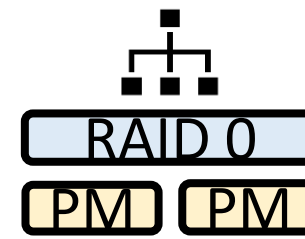
# I/O operations in a PM file system



Data transfer between DRAM and PM

Components: DRAM, PM, and thread

# I/O operations in a PM file system



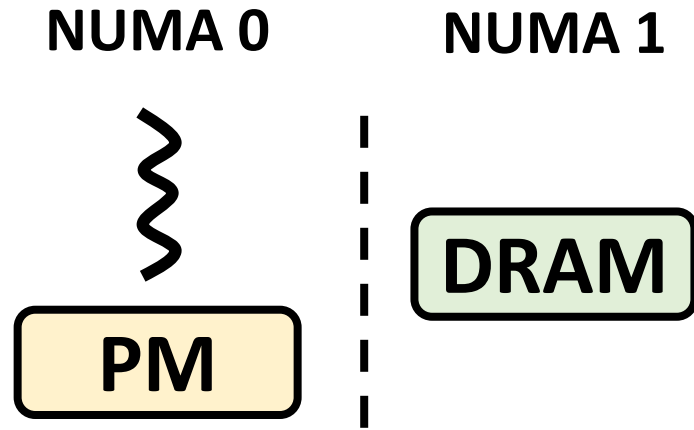
Data transfer between DRAM and PM

Components: DRAM, PM, and thread

How does the NUMA placement of the components affect performance?

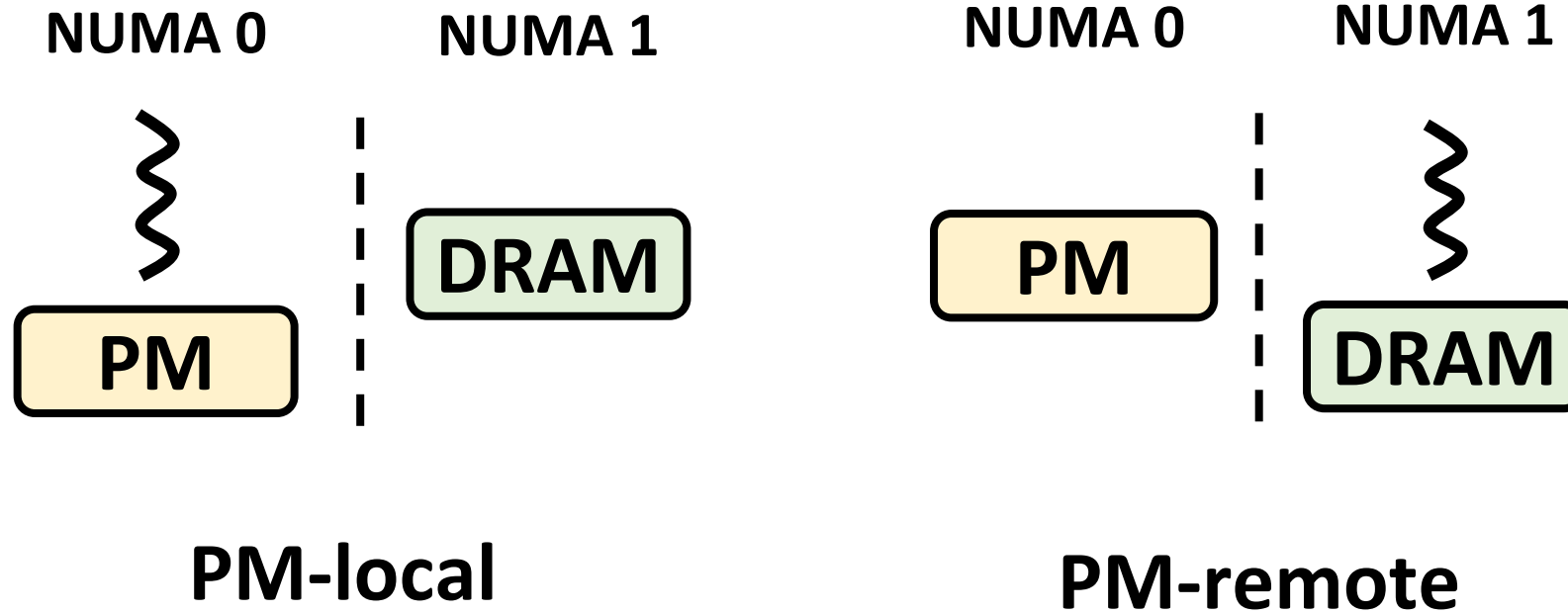


# NUMA placement setup

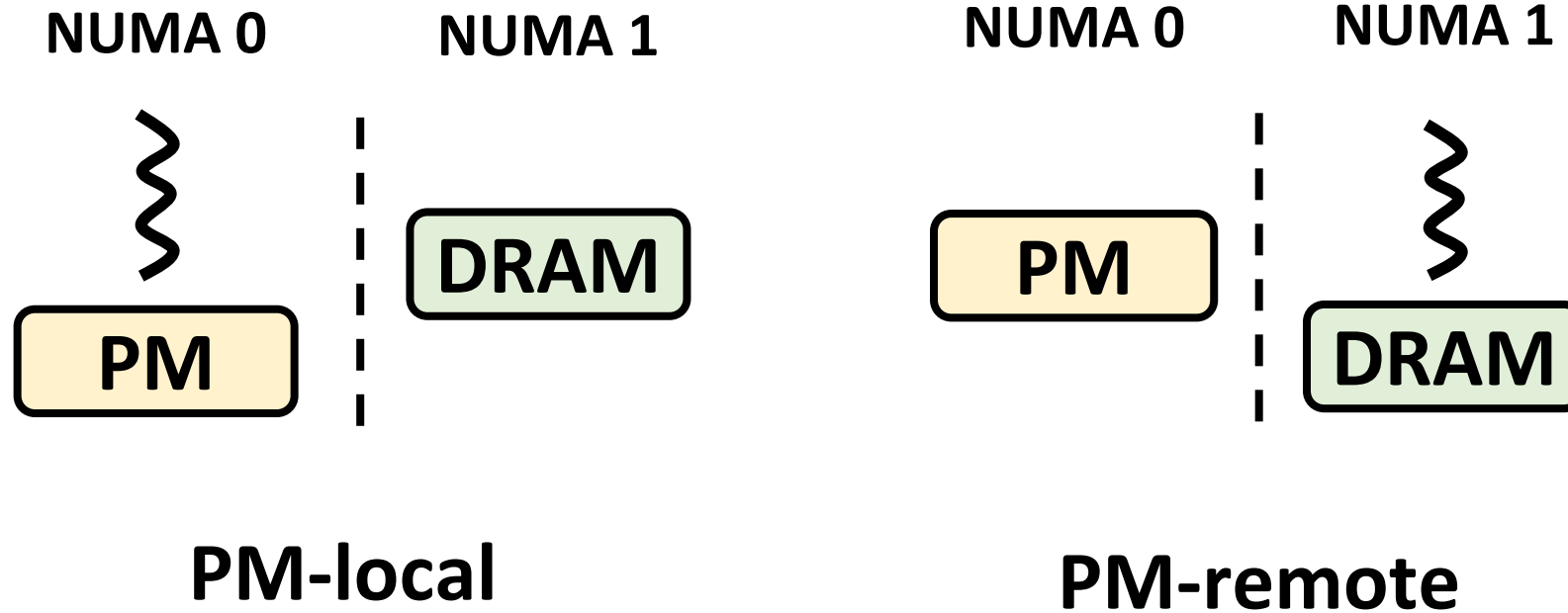


**PM-local**

# NUMA placement setup



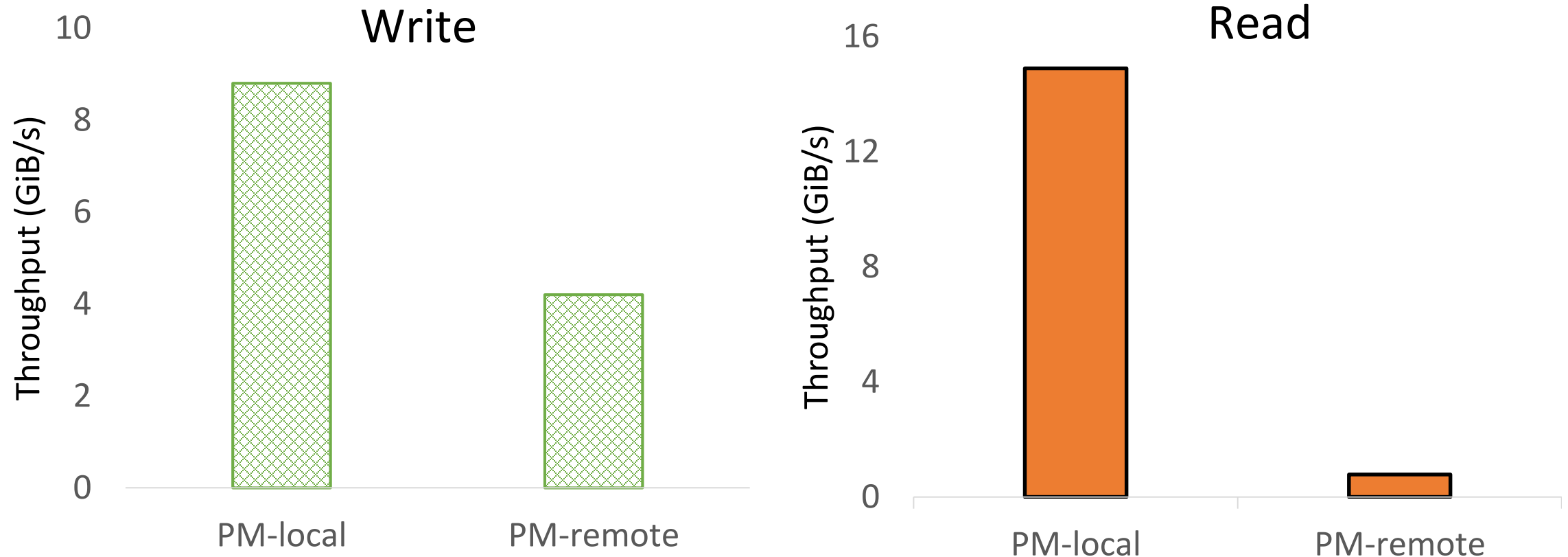
# NUMA placement setup



**Same Task:** copying data between PM in NUMA 0 and DRAM in NUMA 1

# Local PM access outperforms remote PM access

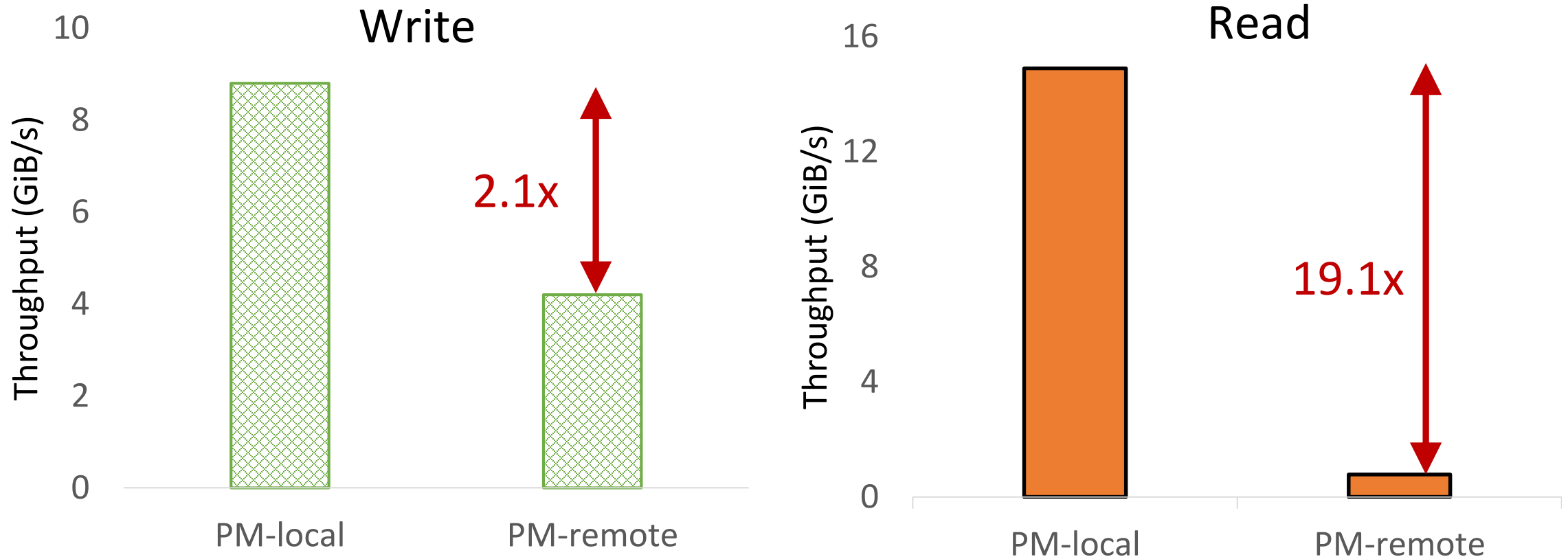
Workload: FIO: each thread writes/reads 2MB data in a private file



**Same Task:** copying data between PM in NUMA 0 and DRAM in NUMA 1

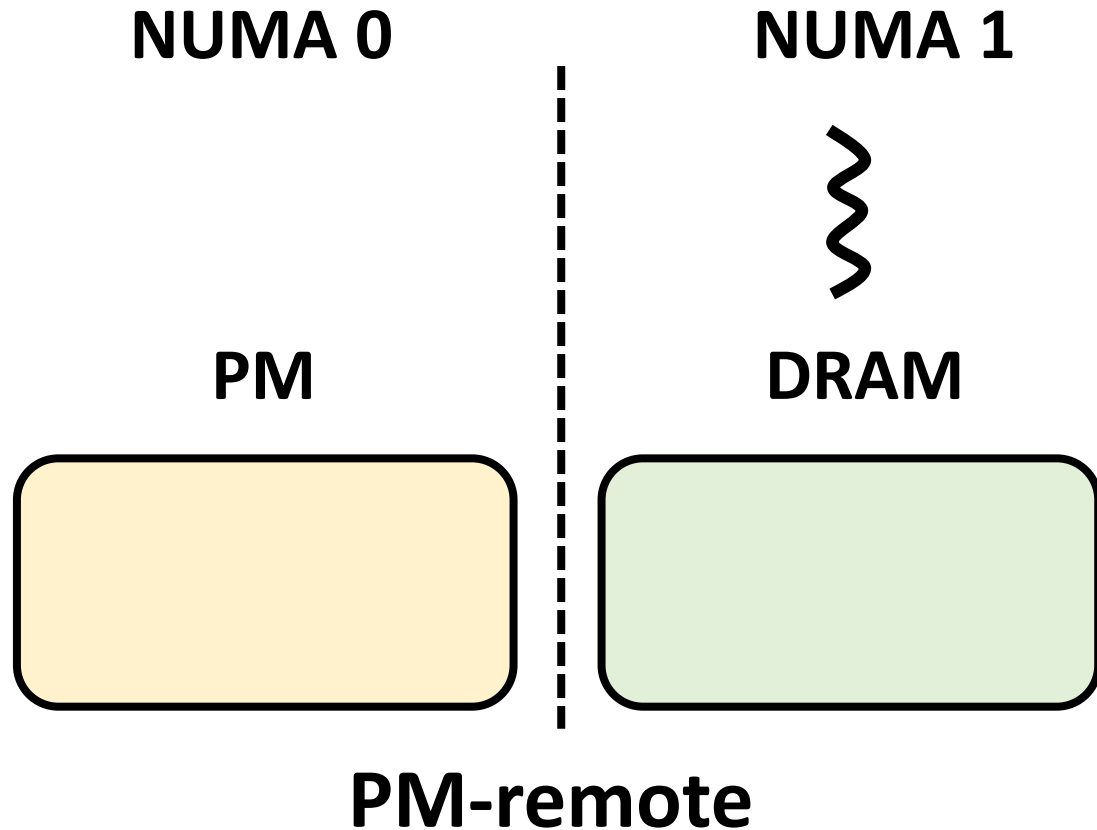
# Local PM access outperforms remote PM access

Workload: FIO: each thread writes/reads 2MB data in a private file



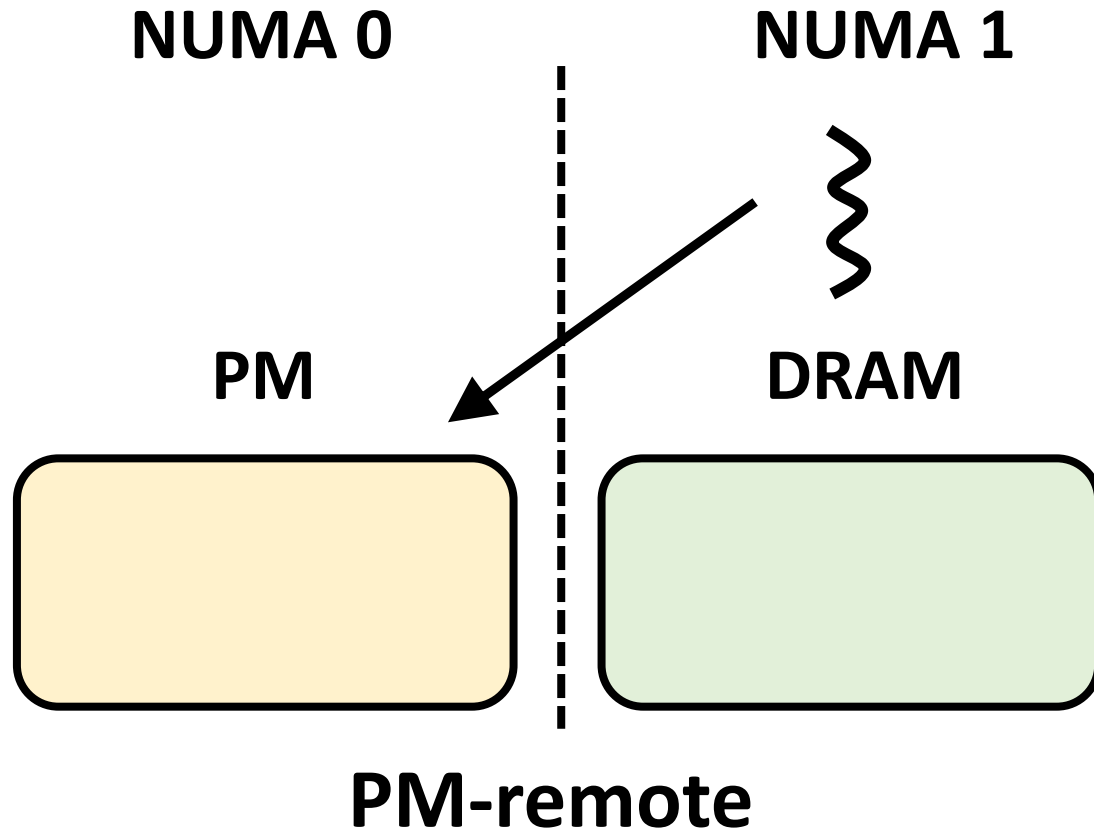
**Same Task:** copying data between PM in NUMA 0 and DRAM in NUMA 1

# Directory coherence → slow remote PM access



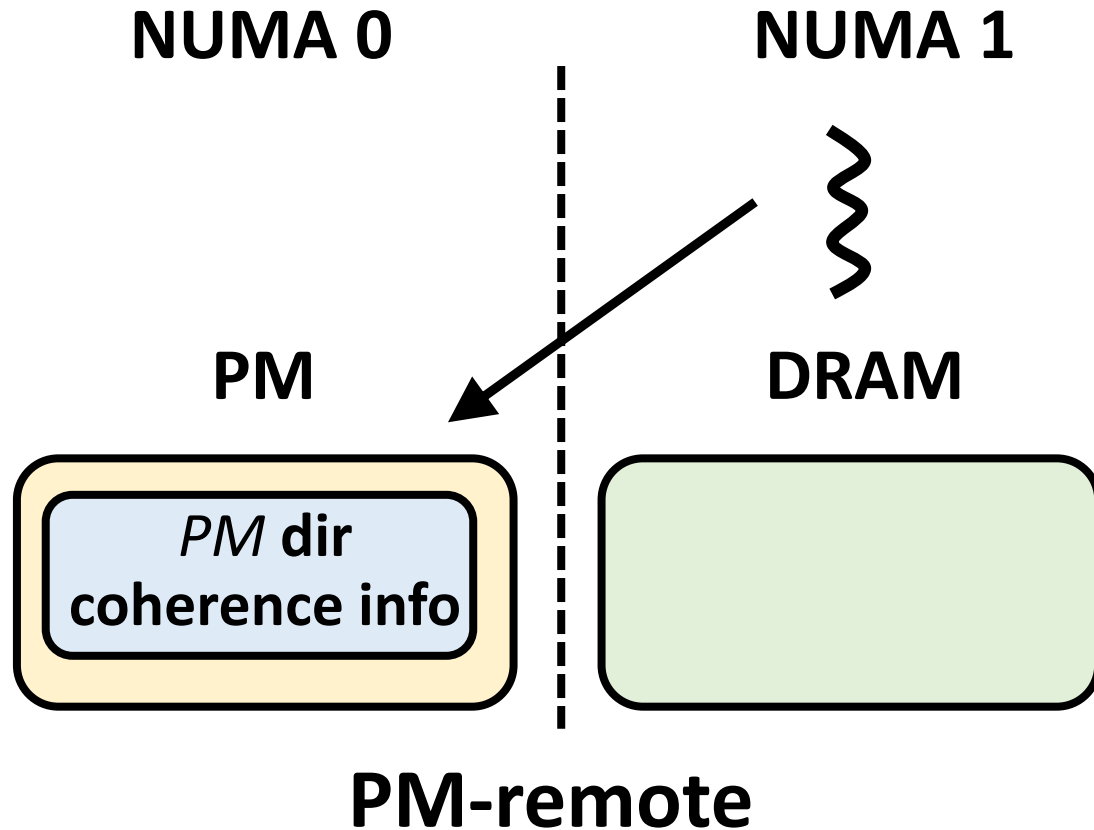
Directory coherence info maintained in memory

# Directory coherence → slow remote PM access



Directory coherence info maintained in memory

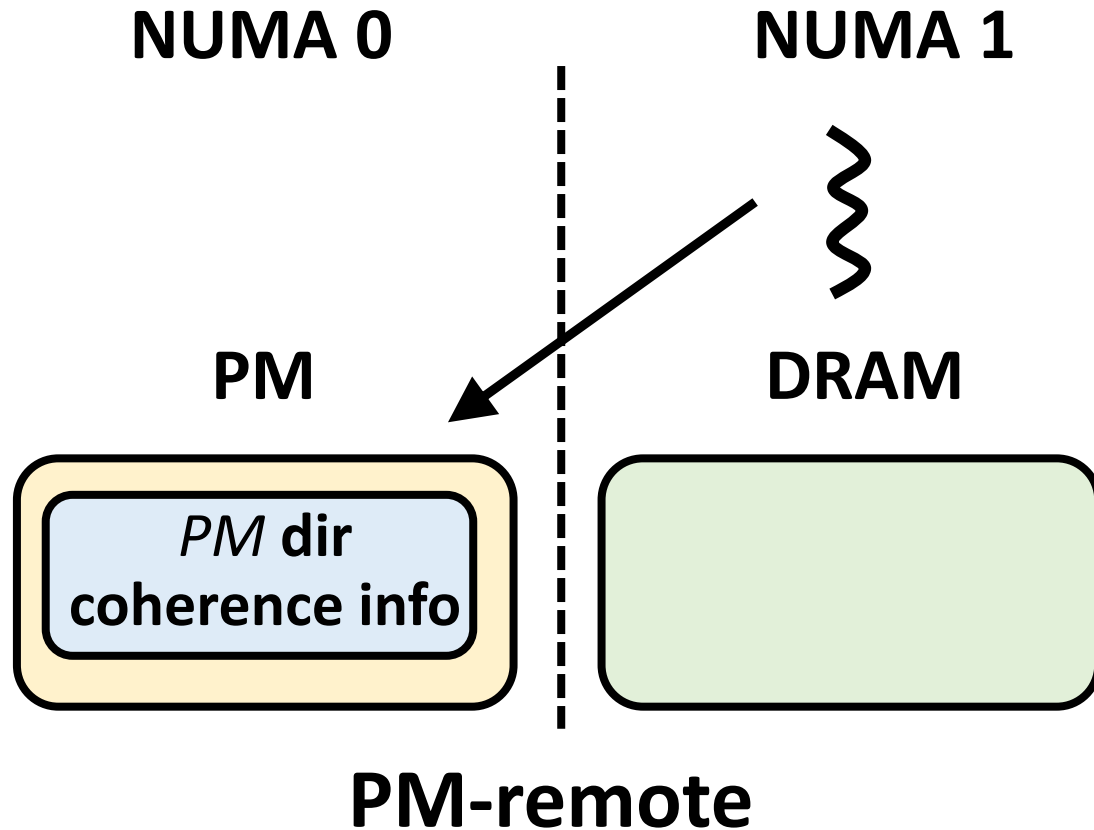
# Directory coherence → slow remote PM access



Directory coherence info maintained in memory



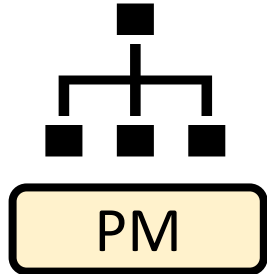
# Directory coherence → slow remote PM access



Directory coherence info maintained in memory

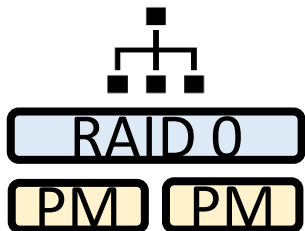
Slower PM performance  
→ Slower remote PM access

# PM performance analysis



**Issue:** Excessive concurrent access → PM performance collapse

**Insight:** Control concurrent PM access for maximal performance



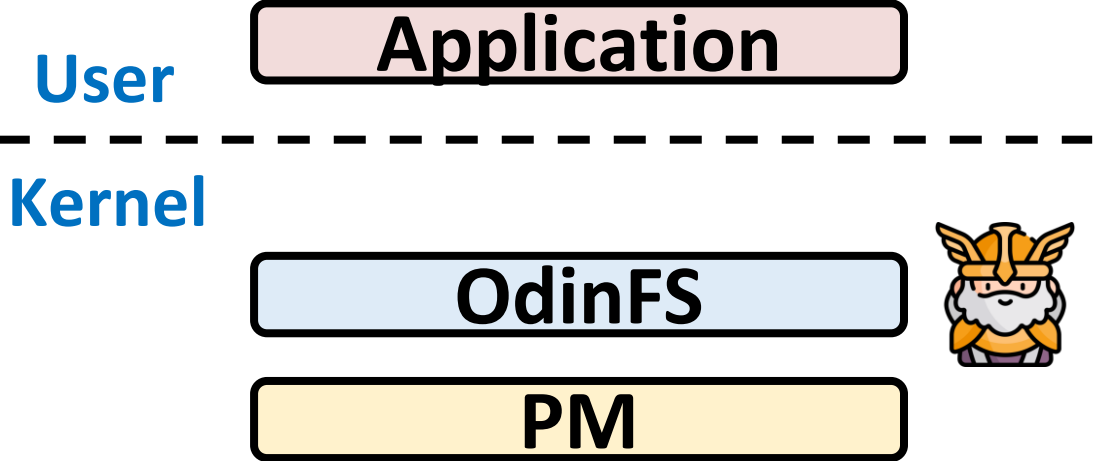
**Issue:** Inefficient remote PM access

**Insight:** Perform localized PM access to avoid PM NUMA impact

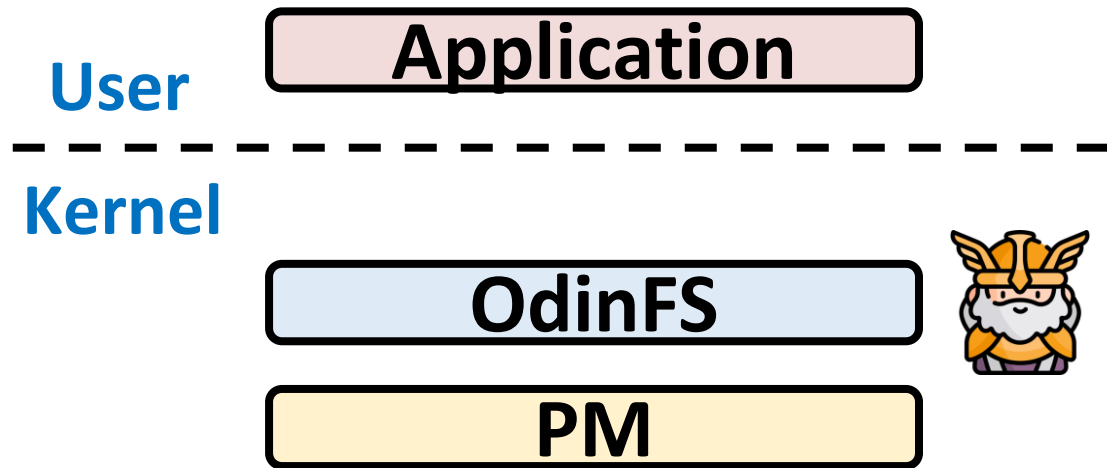
# OdinFS

File system maximizes PM performance  
via opportunistic delegation

# What is OdinFS?

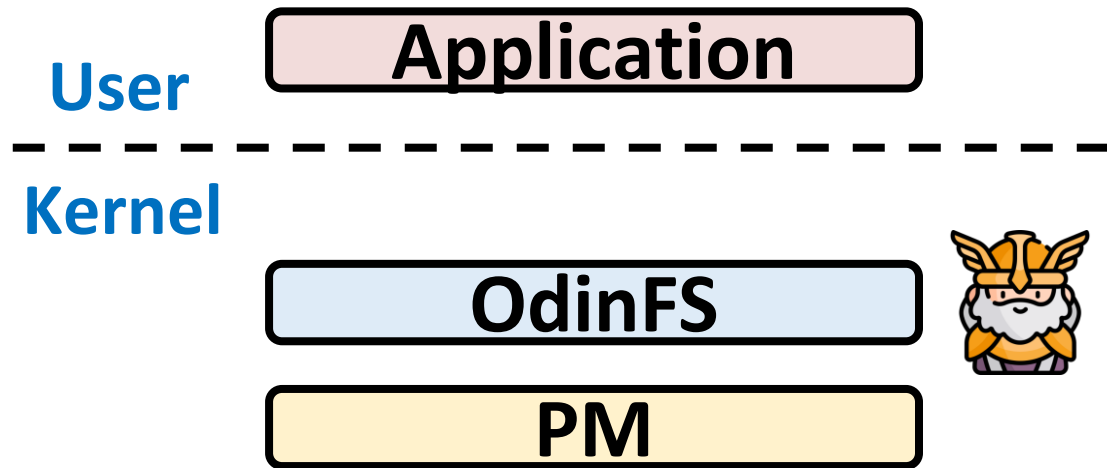


# What is OdinFS?



In-kernel file system

# What is OdinFS?



In-kernel file system

Fully POSIX compliant

# OdinFS design overview

## Limit concurrent access

- Preserves maximal PM performance within a NUMA node

## Always localized PM access

- Minimizes PM NUMA impact and efficient use of remote PM

# OdinFS design overview

## Limit concurrent access

- Preserves maximal PM performance within a NUMA node

## Always localized PM access

- Minimizes PM NUMA impact and efficient use of remote PM

## Efficient use of the aggregated PM bandwidth

- Applications on a single NUMA node can benefit



# OdinFS design overview

Limit concurrent access

→ Preserves maximal PM performance within a NUMA node

Always localized PM access

→ Minimizes PM NUMA impact and efficient use of remote PM

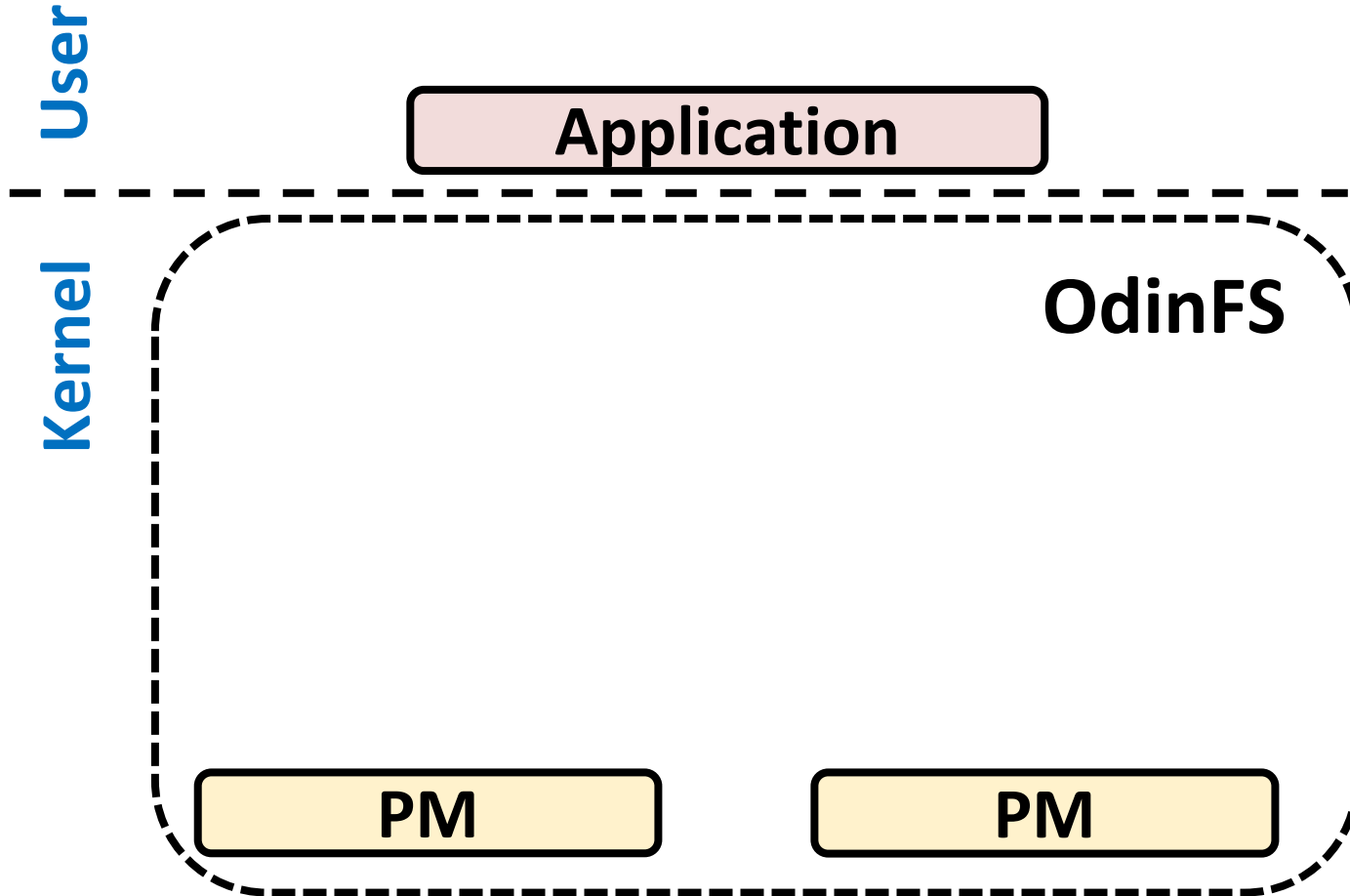
Efficient use of the aggregated PM bandwidth

→ Applications on a single NUMA node can benefit

Key insight: **Decouple** PM access from application threads to achieve the above goals **simultaneously**

# Decouple PM access from application threads

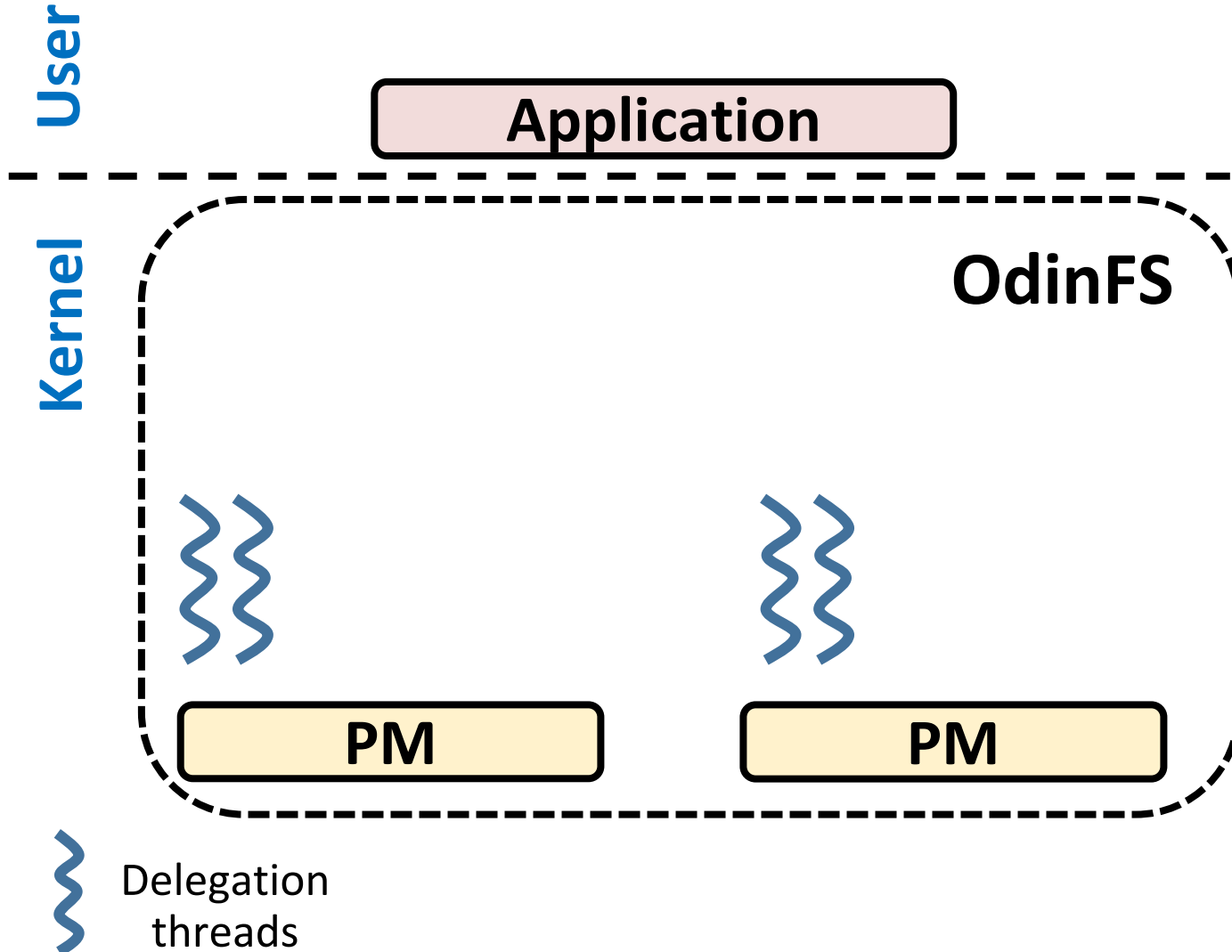
Decouple PM access from application threads



Delegation threads

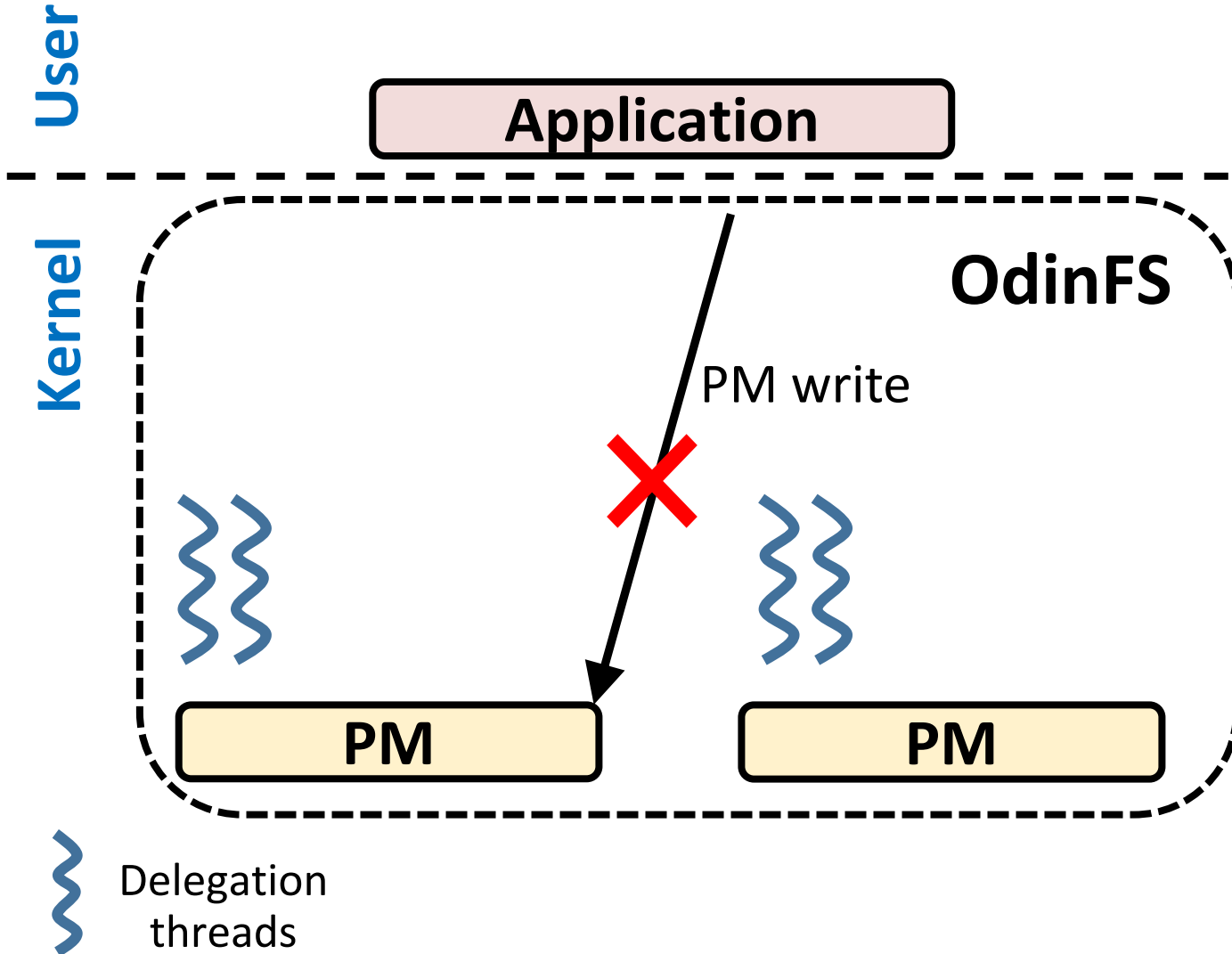
# Decouple PM access from application threads

Decouple PM access from application threads



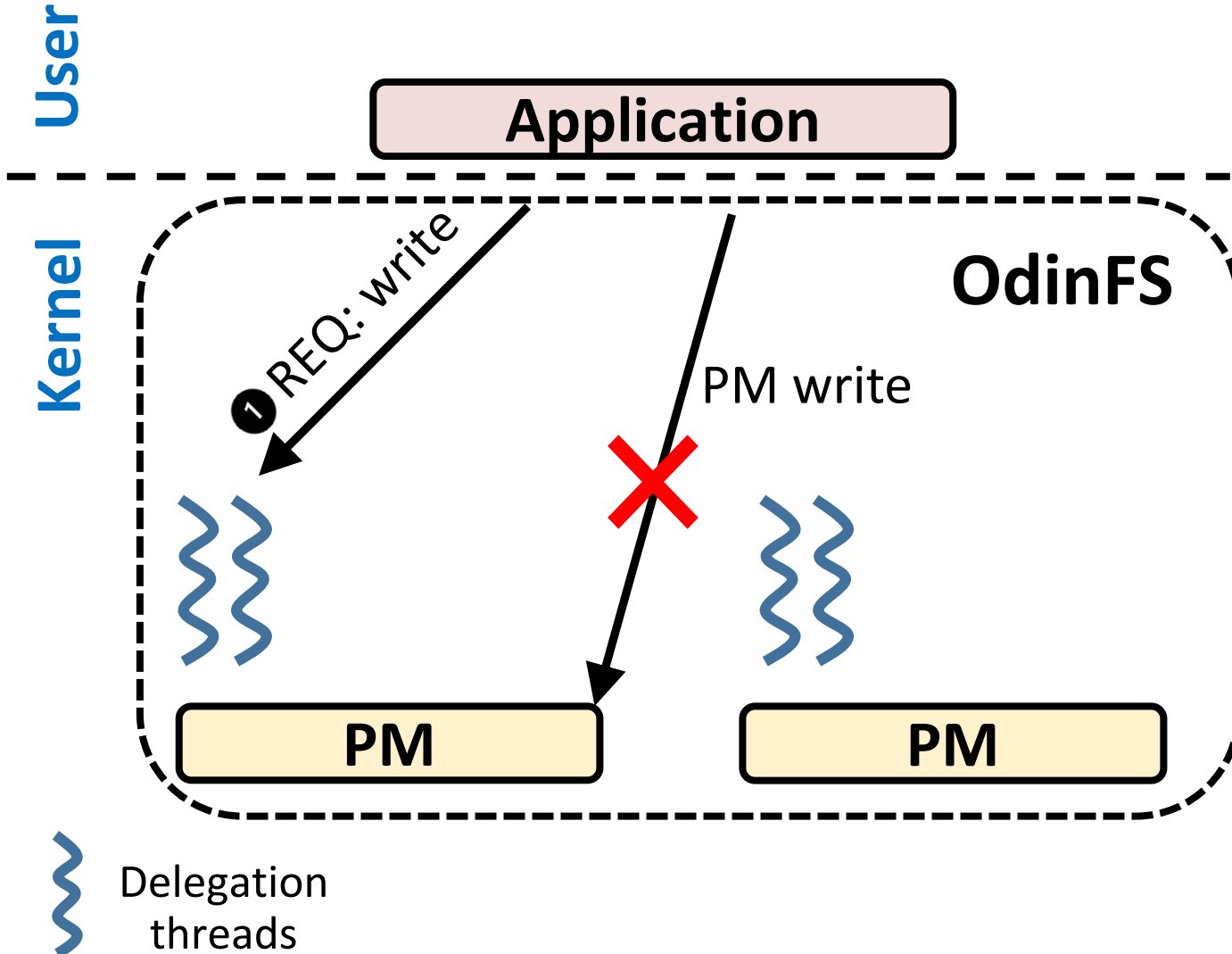
# Decouple PM access from application threads

Decouple PM access from application threads



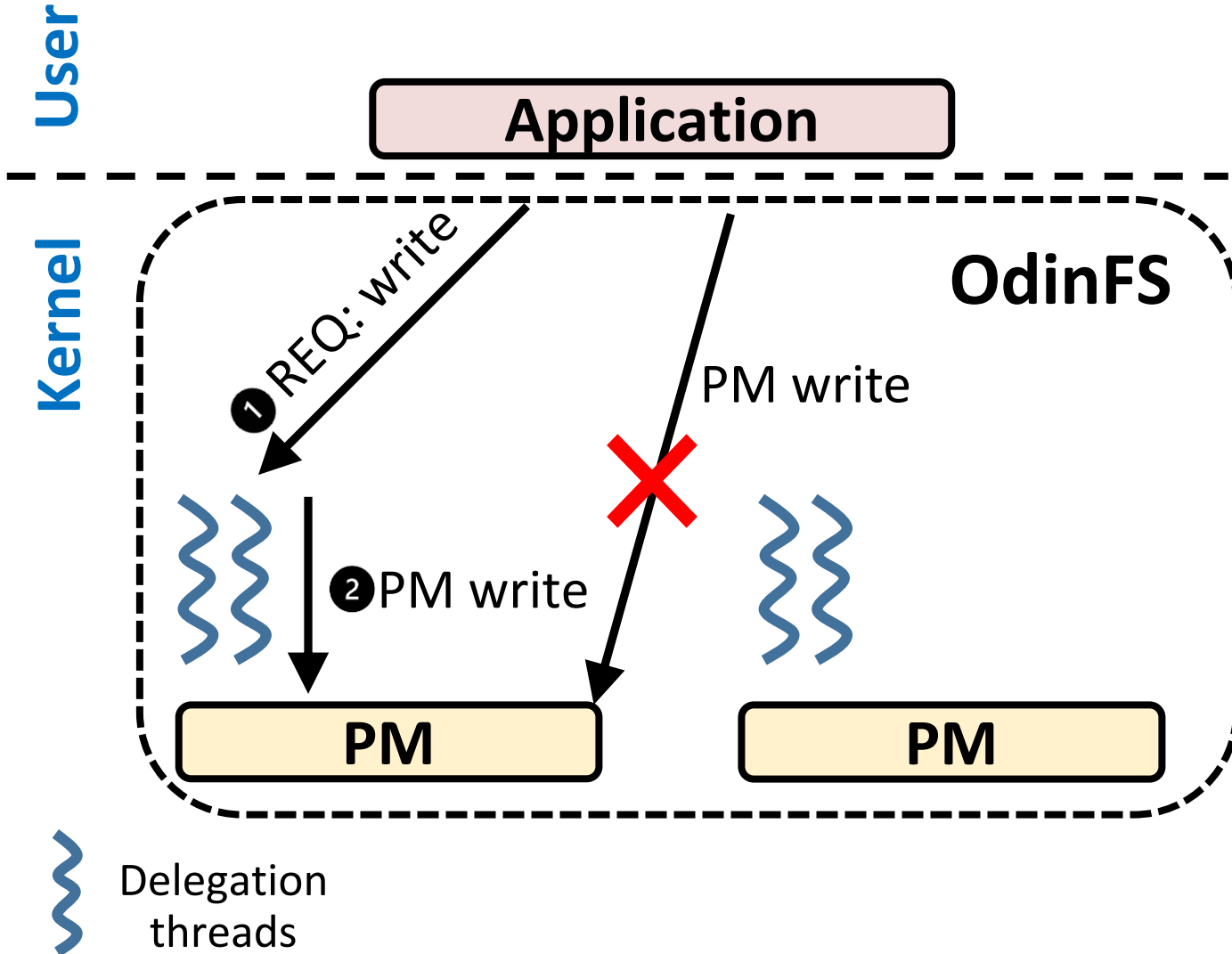
# Decouple PM access from application threads

Decouple PM access from application threads



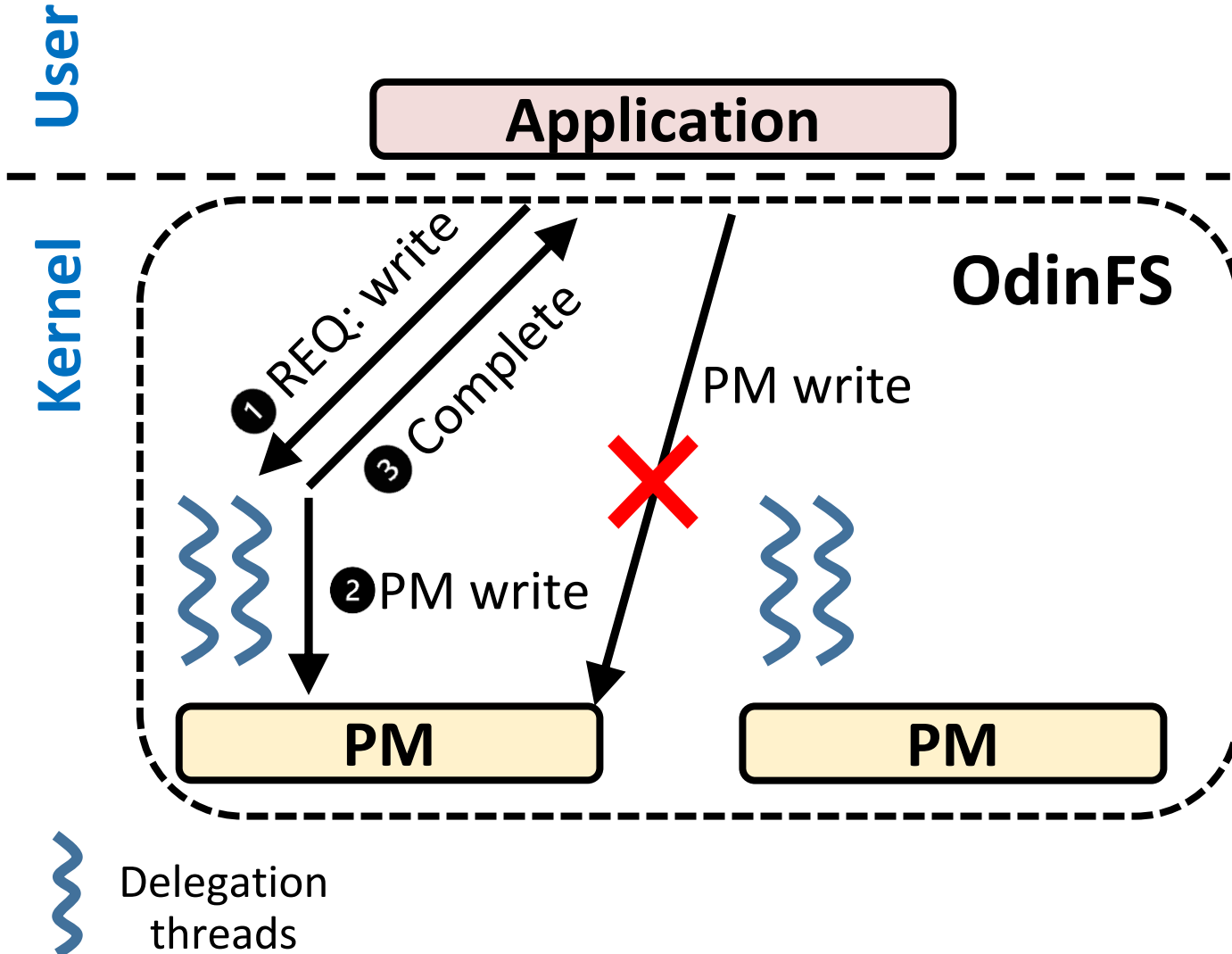
# Decouple PM access from application threads

Decouple PM access from application threads

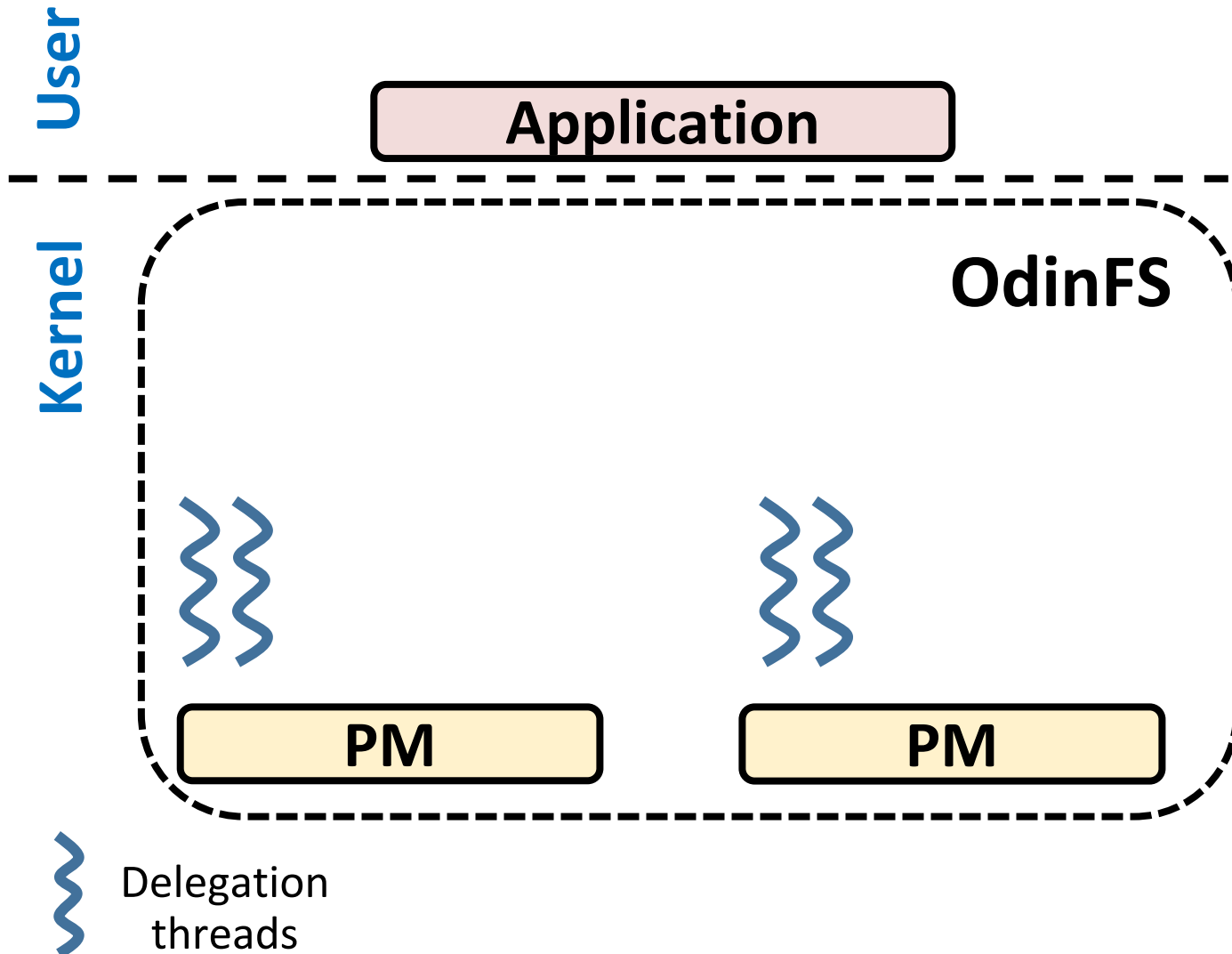


# Decouple PM access from application threads

Decouple PM access from application threads



# Delegation enables controlled and localized access

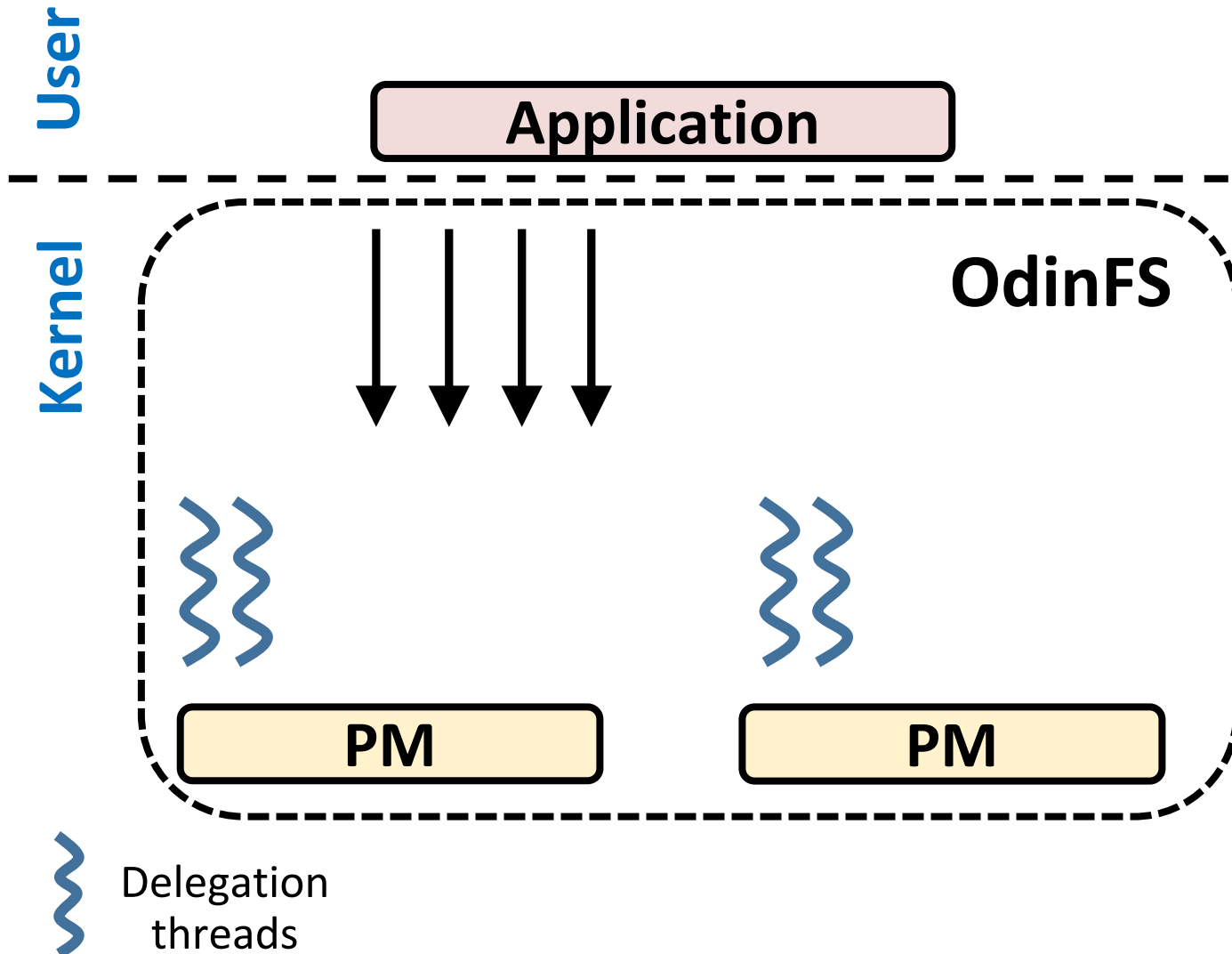


Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access



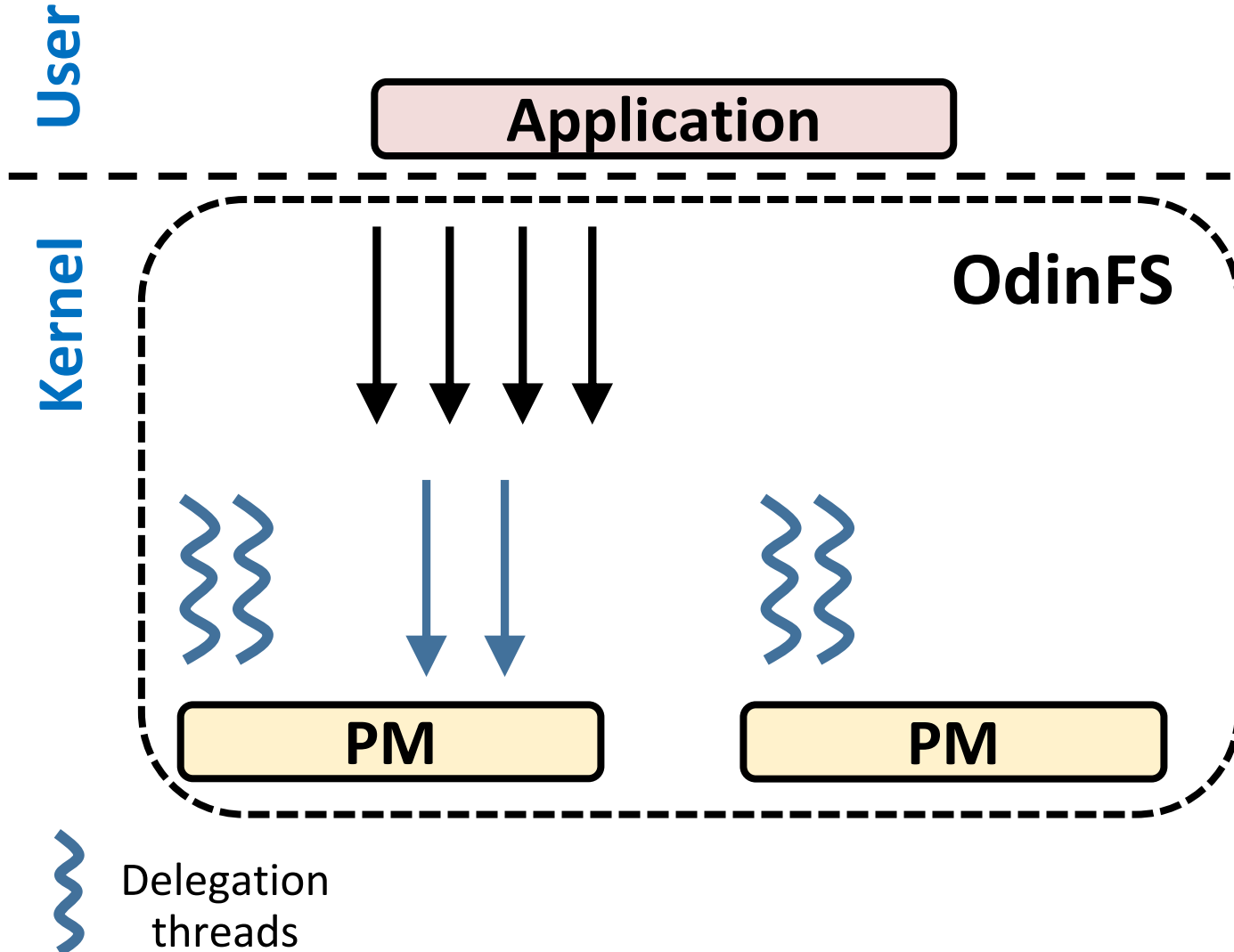
# Delegation enables controlled and localized access



Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access

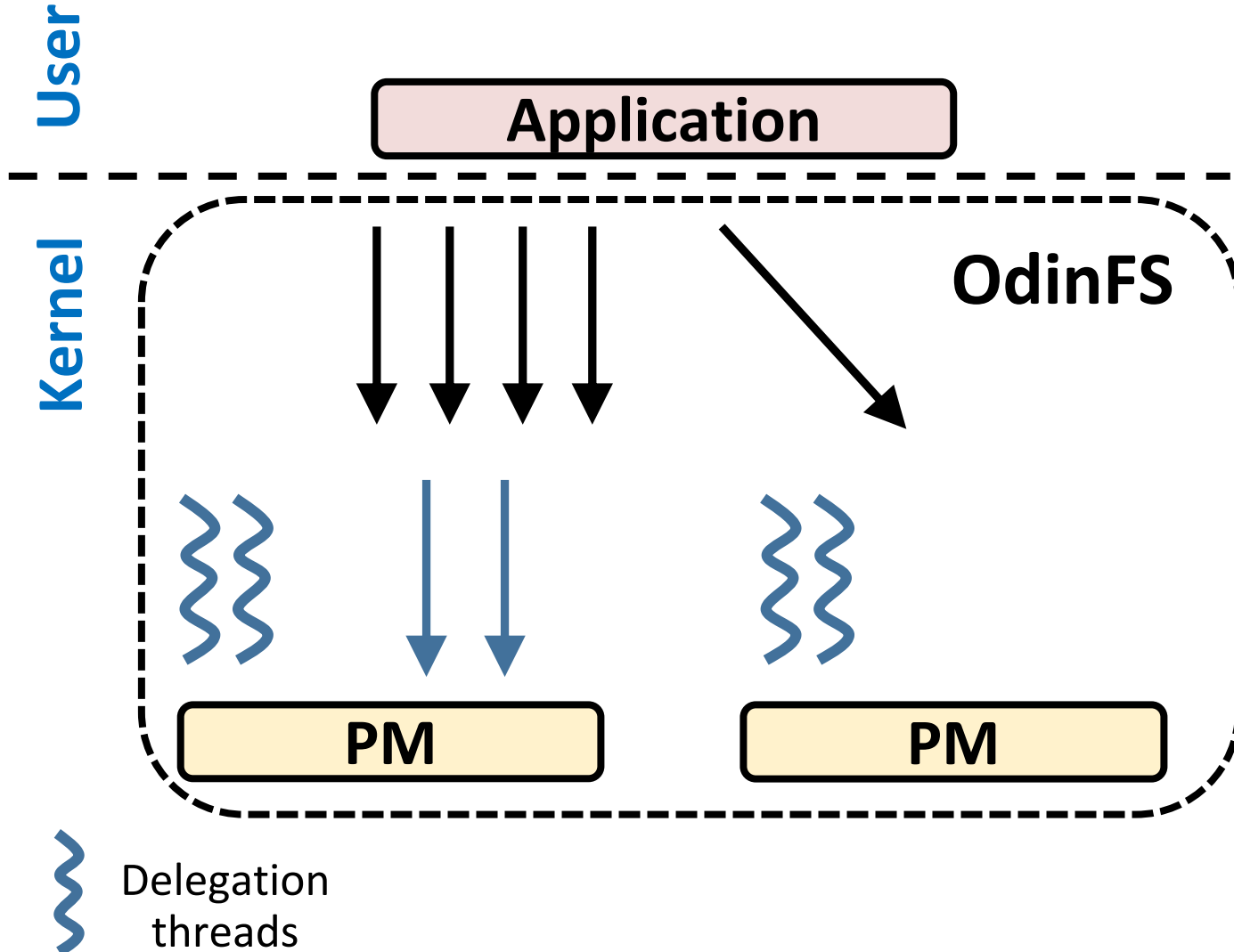
# Delegation enables controlled and localized access



Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access

# Delegation enables controlled and localized access

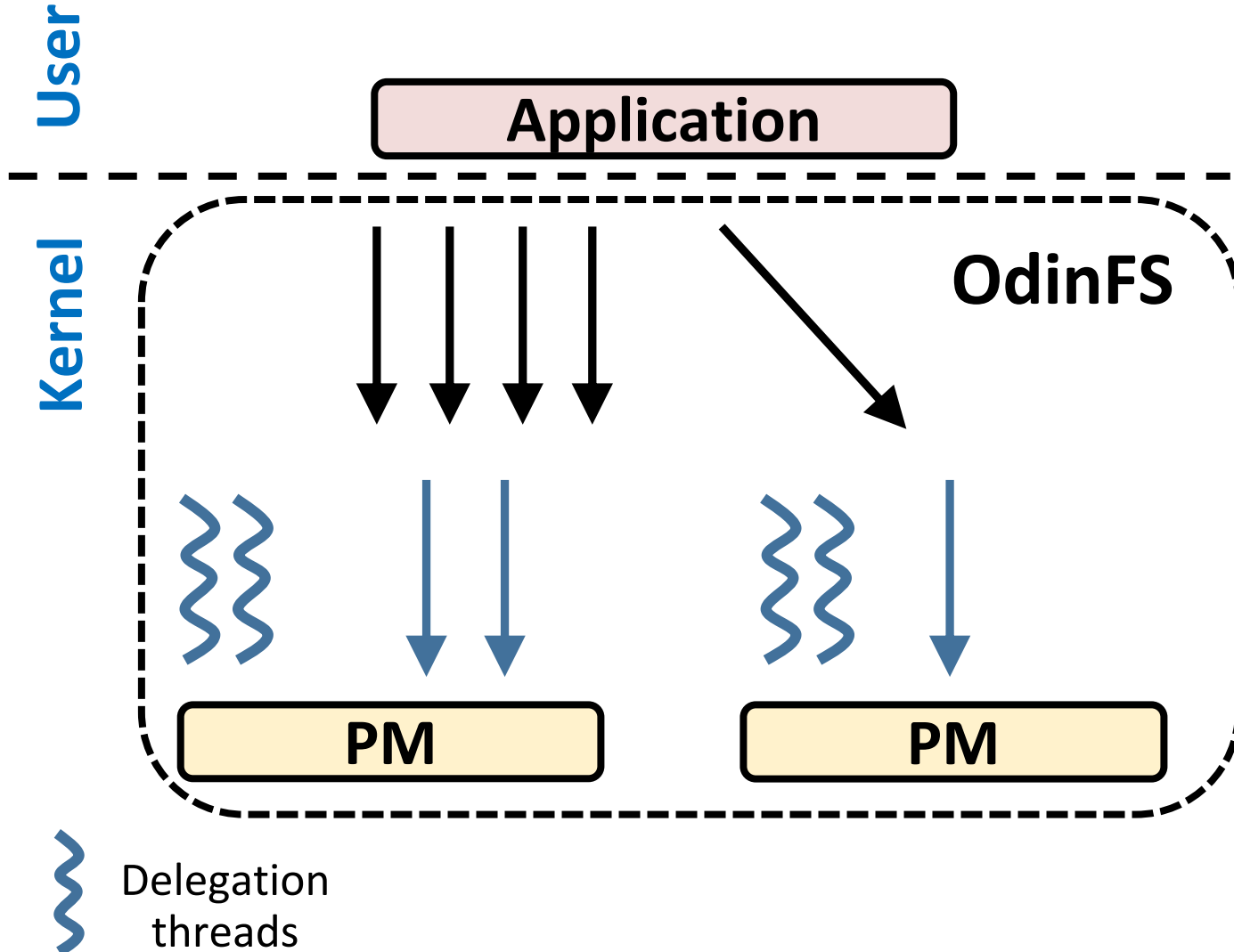


Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access

Delegation threads always perform **localized** PM access

# Delegation enables controlled and localized access

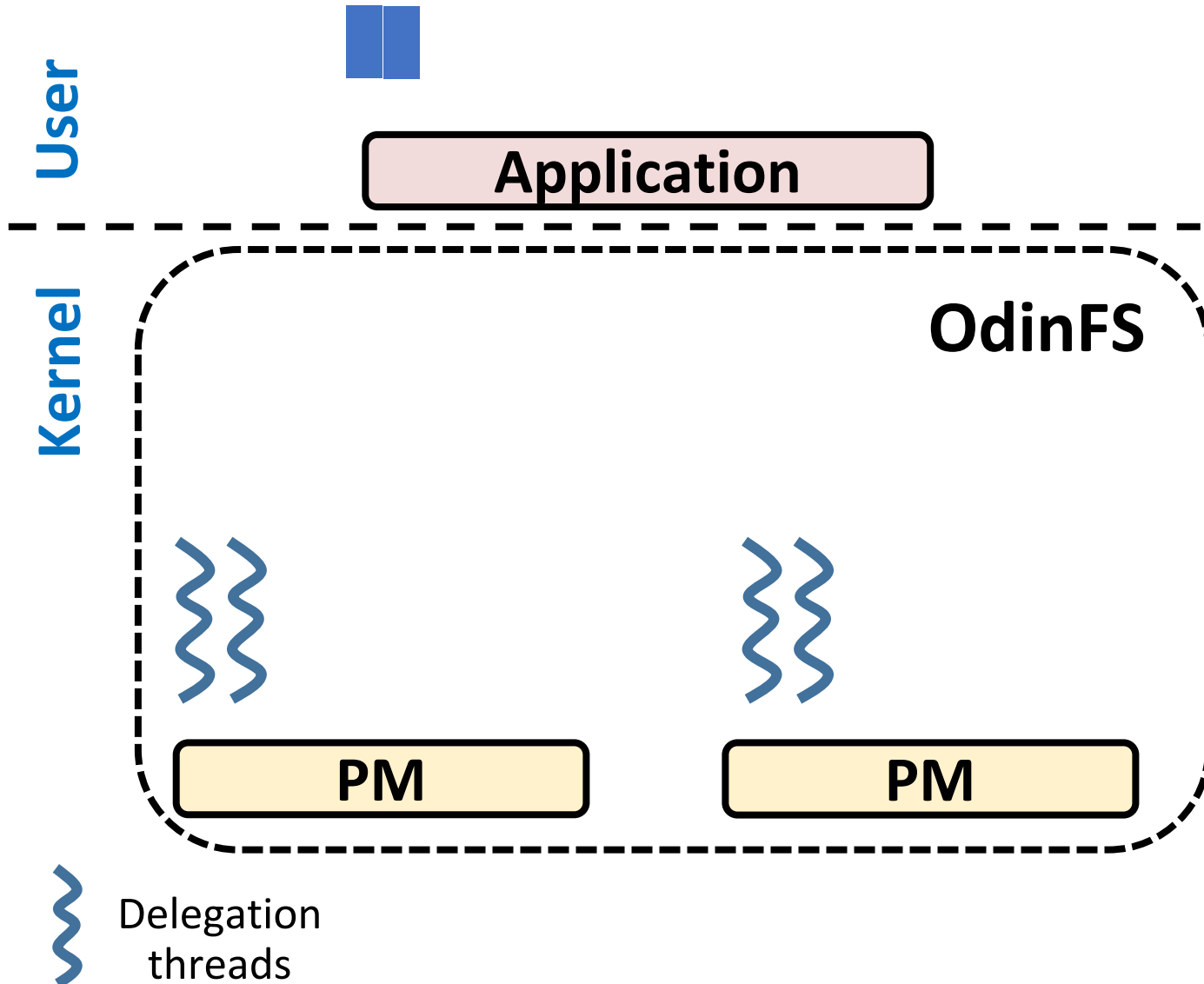


Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access

Delegation threads always perform **localized** PM access

# Efficiently utilize aggregated PM bandwidth



Decouple PM access from application threads

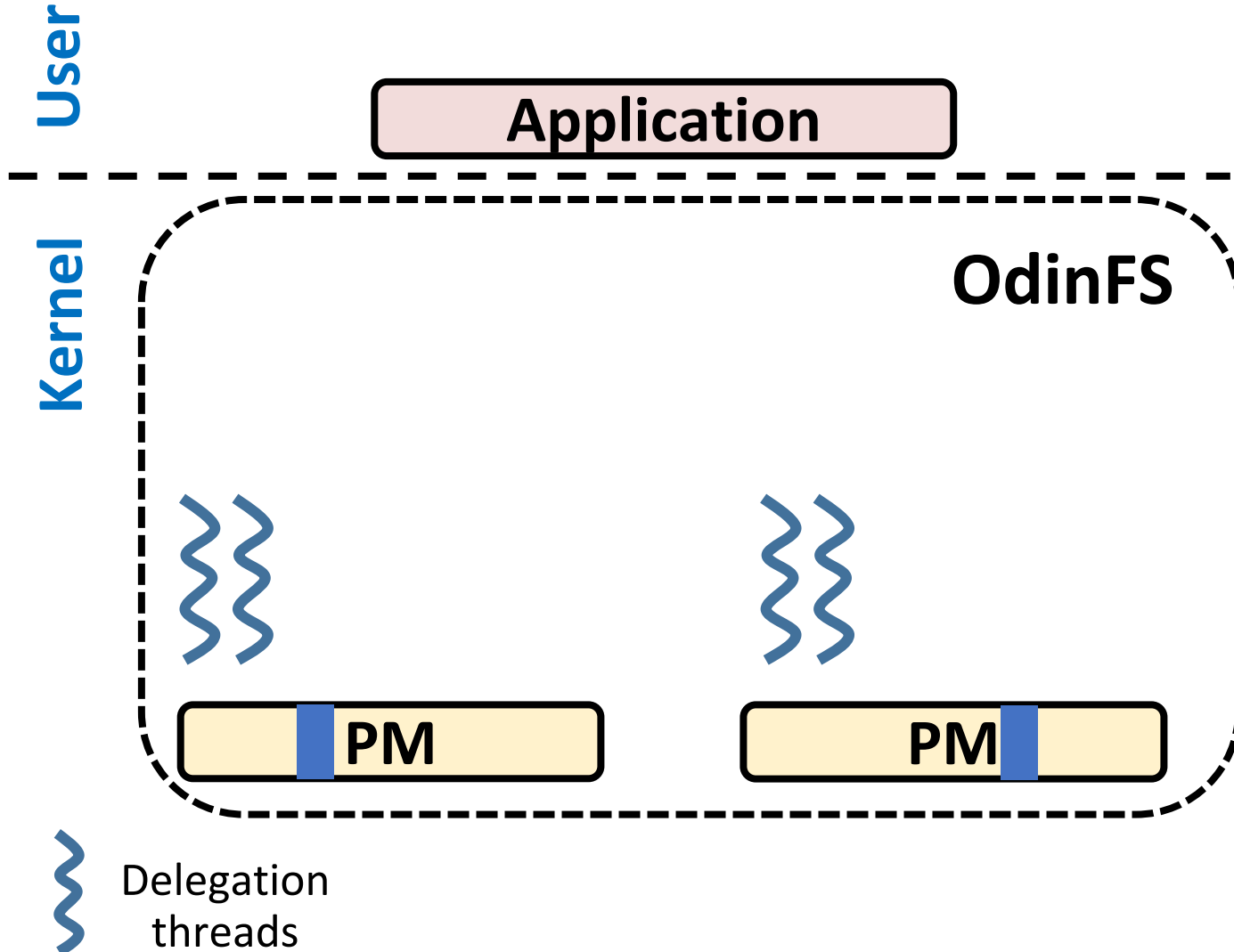
Fixed number of delegation threads **limit** concurrent access

Delegation threads always perform **localized** PM access

Utilize **aggregated** bandwidth

– Stripe file across NUMA nodes

# Efficiently utilize aggregated PM bandwidth



Decouple PM access from application threads

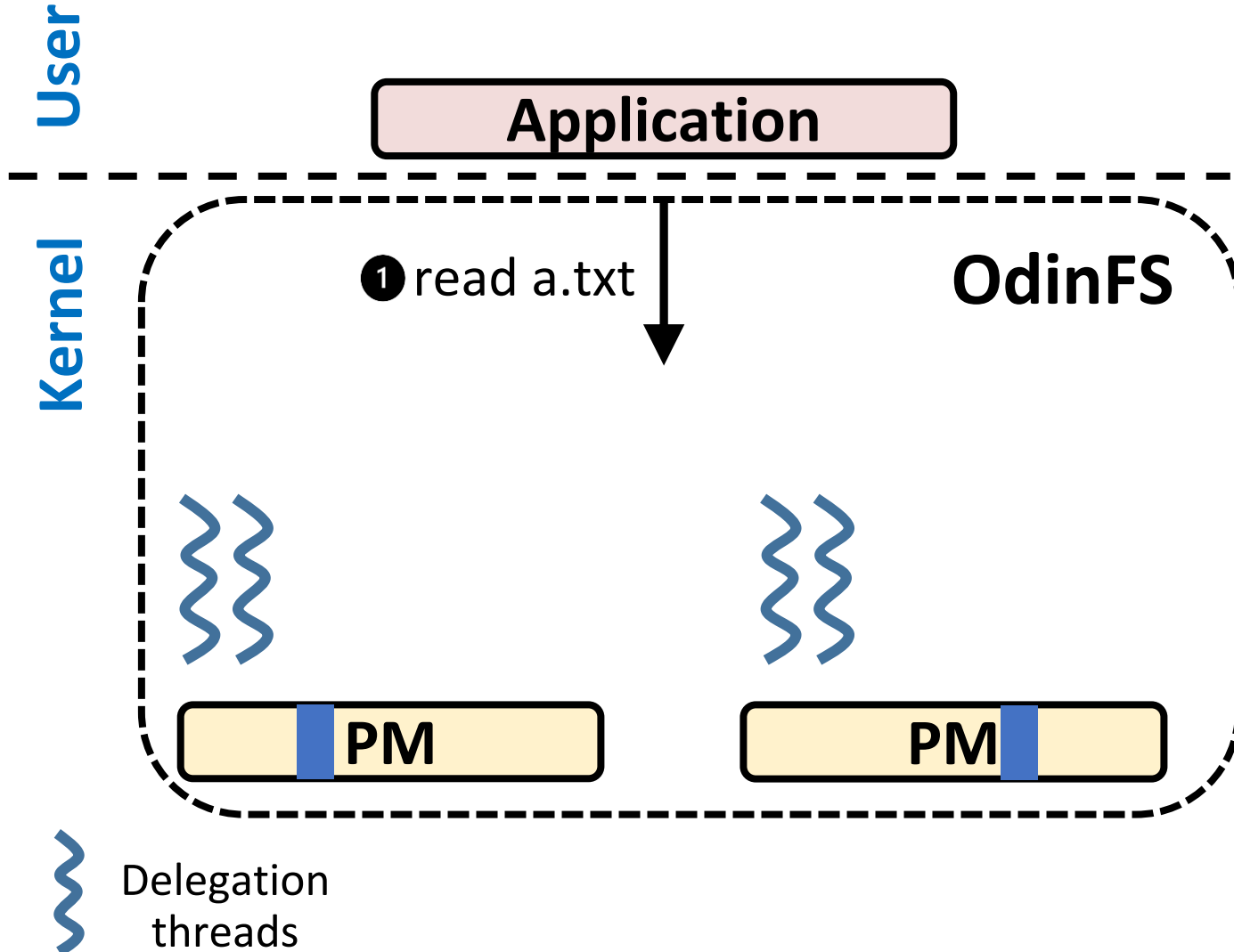
Fixed number of delegation threads **limit** concurrent access

Delegation threads always perform **localized** PM access

Utilize **aggregated** bandwidth

– Stripe file across NUMA nodes

# Efficiently utilize aggregated PM bandwidth



Decouple PM access from application threads

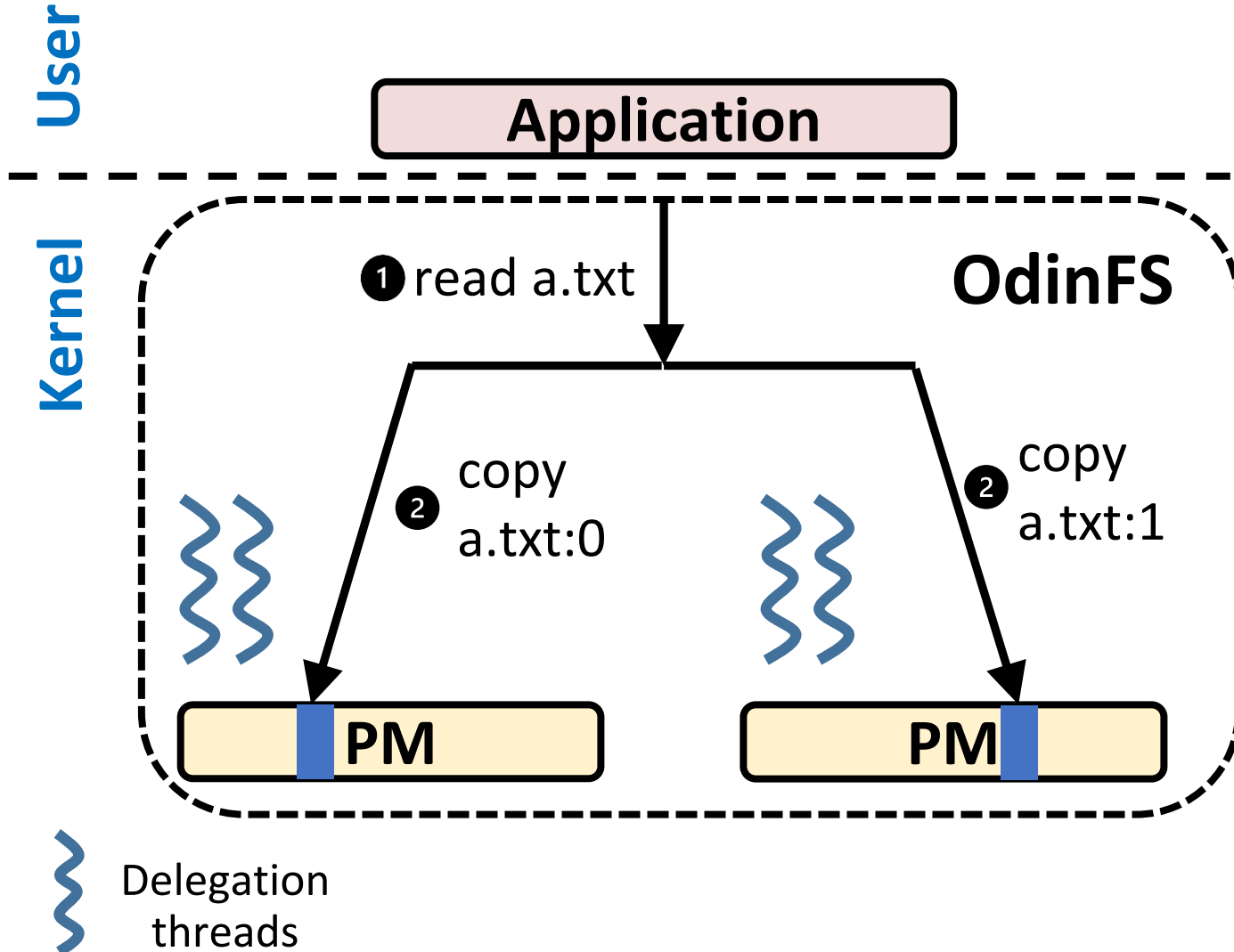
Fixed number of delegation threads **limit** concurrent access

Delegation threads always perform **localized** PM access

Utilize **aggregated** bandwidth

- Stripe file across NUMA nodes
- Transparent parallel PM access across NUMA nodes

# Efficiently utilize aggregated PM bandwidth



Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access

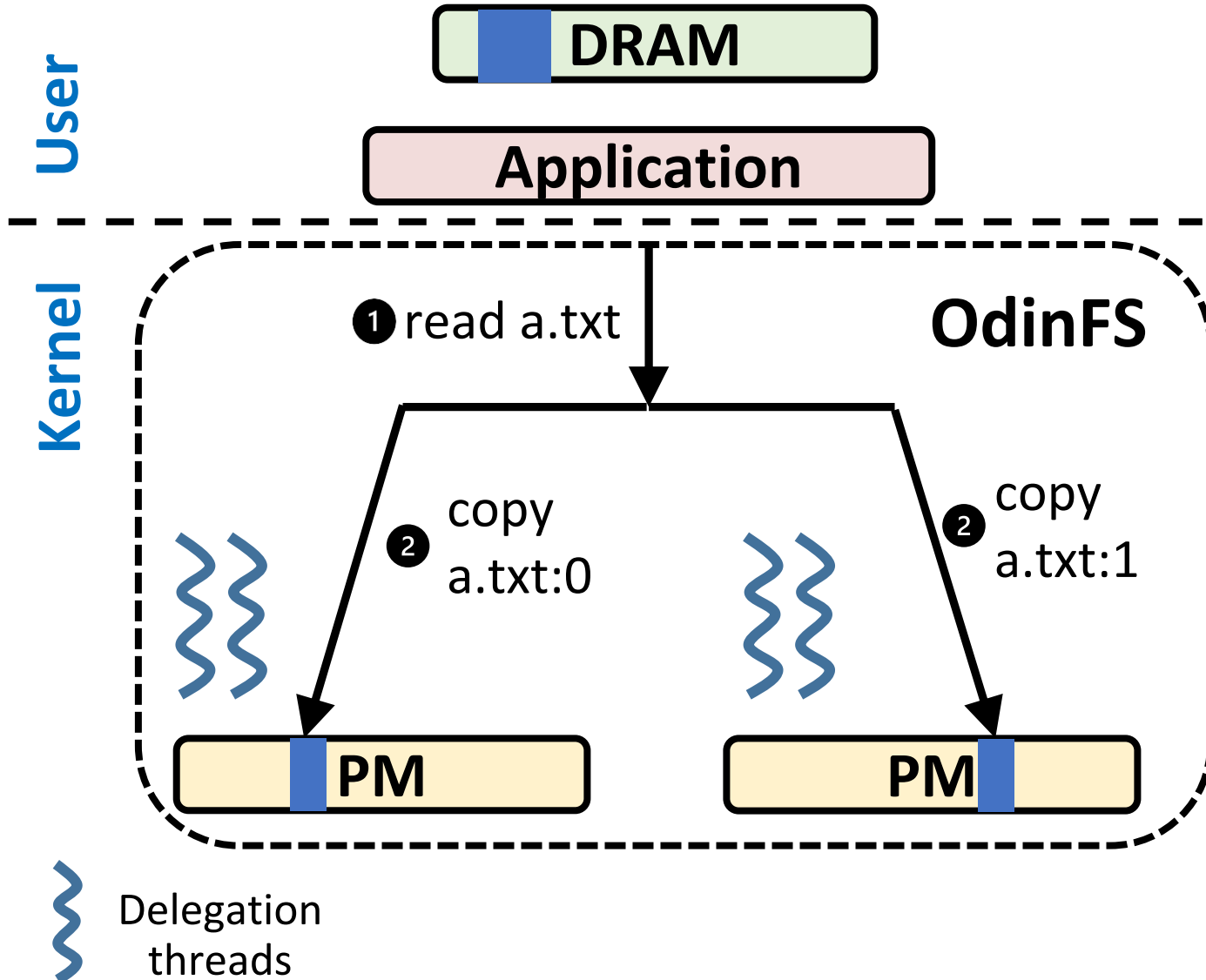
Delegation threads always perform **localized** PM access

Utilize **aggregated** bandwidth

- Stripe file across NUMA nodes
- Transparent parallel PM access across NUMA nodes



# Efficiently utilize aggregated PM bandwidth



Decouple PM access from application threads

Fixed number of delegation threads **limit** concurrent access

Delegation threads always perform **localized** PM access

Utilize **aggregated** bandwidth

- Stripe file across NUMA nodes
- Transparent parallel PM access across NUMA nodes

# OdinFS: Other design aspects

## Highly scalable PM file system

- **Maximize concurrent accesses** with range locks
- **Minimize synchronization overhead** with scalable data structures
- **Ensure crash consistency** despite concurrent access

# OdinFS: Other design aspects

## Highly scalable PM file system

- **Maximize concurrent accesses** with range locks
- **Minimize synchronization overhead** with scalable data structures
- **Ensure crash consistency** despite concurrent access

## Minimize delegation overhead

- **Opportunistic delegation** e.g., do not delegate small PM access
- **Adaptive spinning and parking** → Avoid wasting CPU cycles

# Performance Evaluation

Does OdinFS improve I/O performance

– Setup: 224-core eight-socket machine

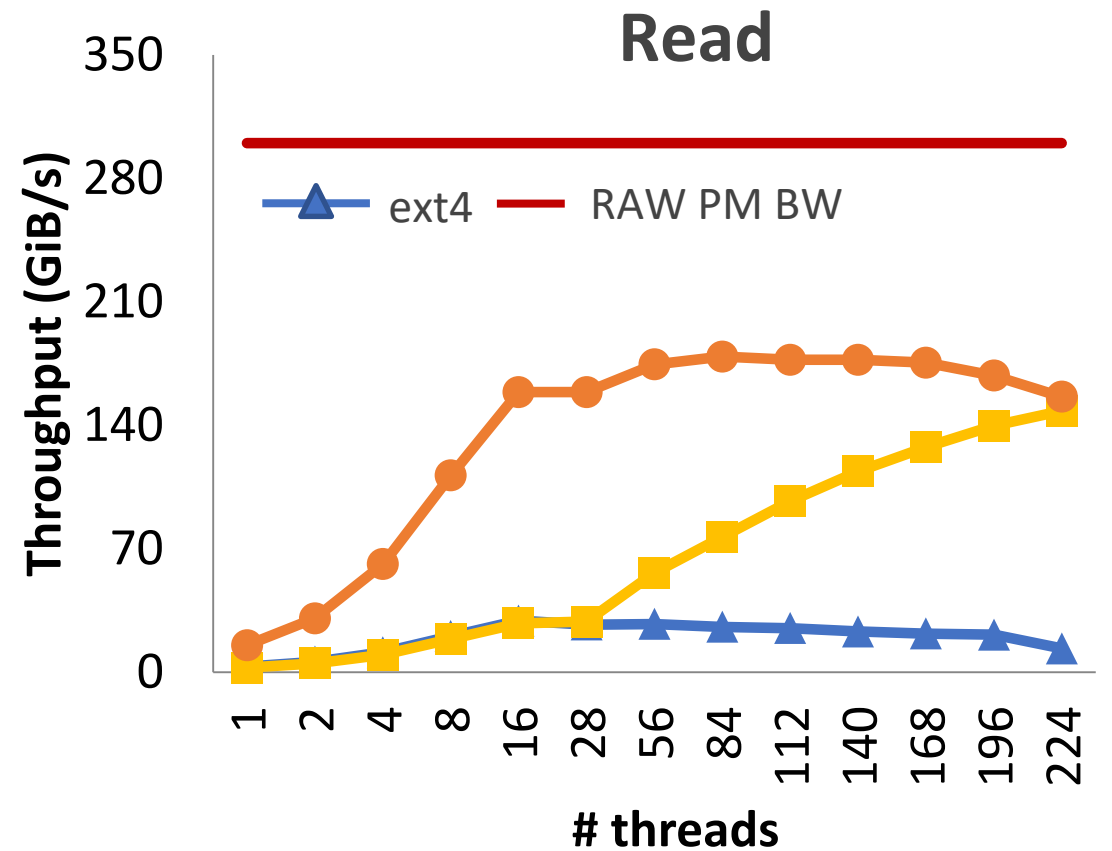
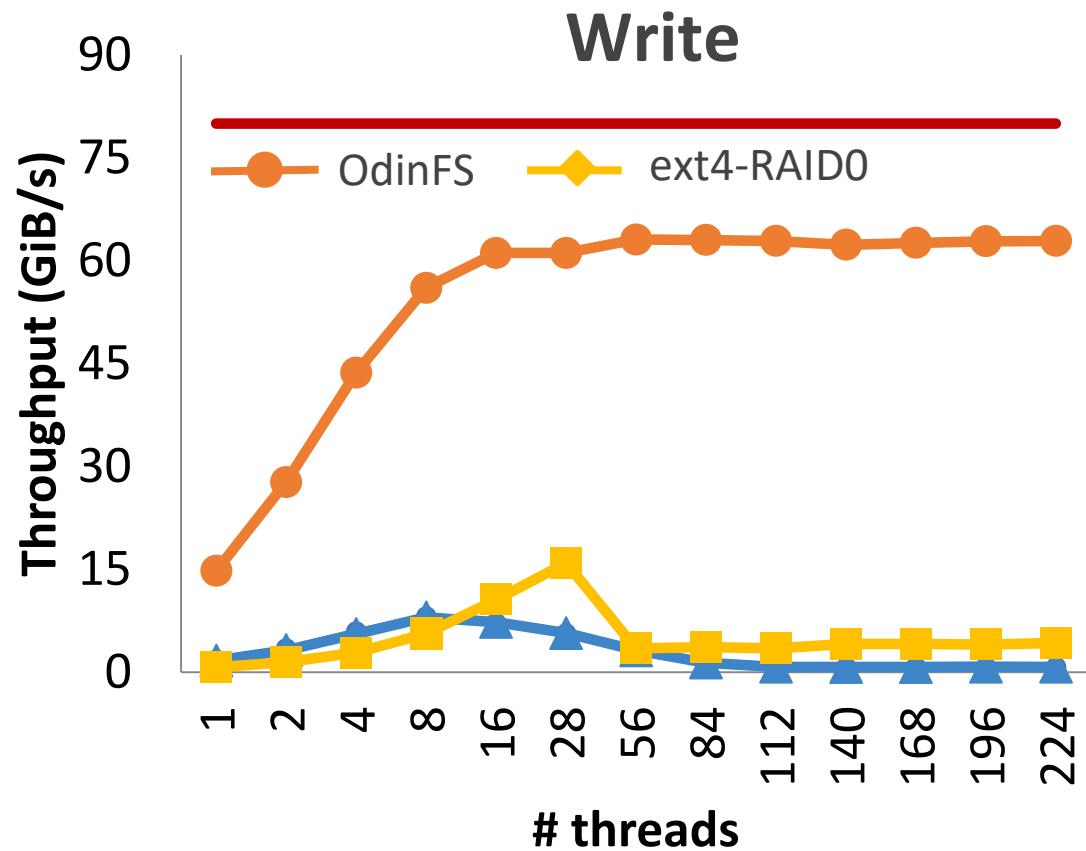
# Performance Evaluation

## Does OdinFS improve I/O performance

- Setup: 224-core eight-socket machine
- Microbenchmark (FIO)
- Marcobenchmark (Filebench)

# Microbenchmark: FIO

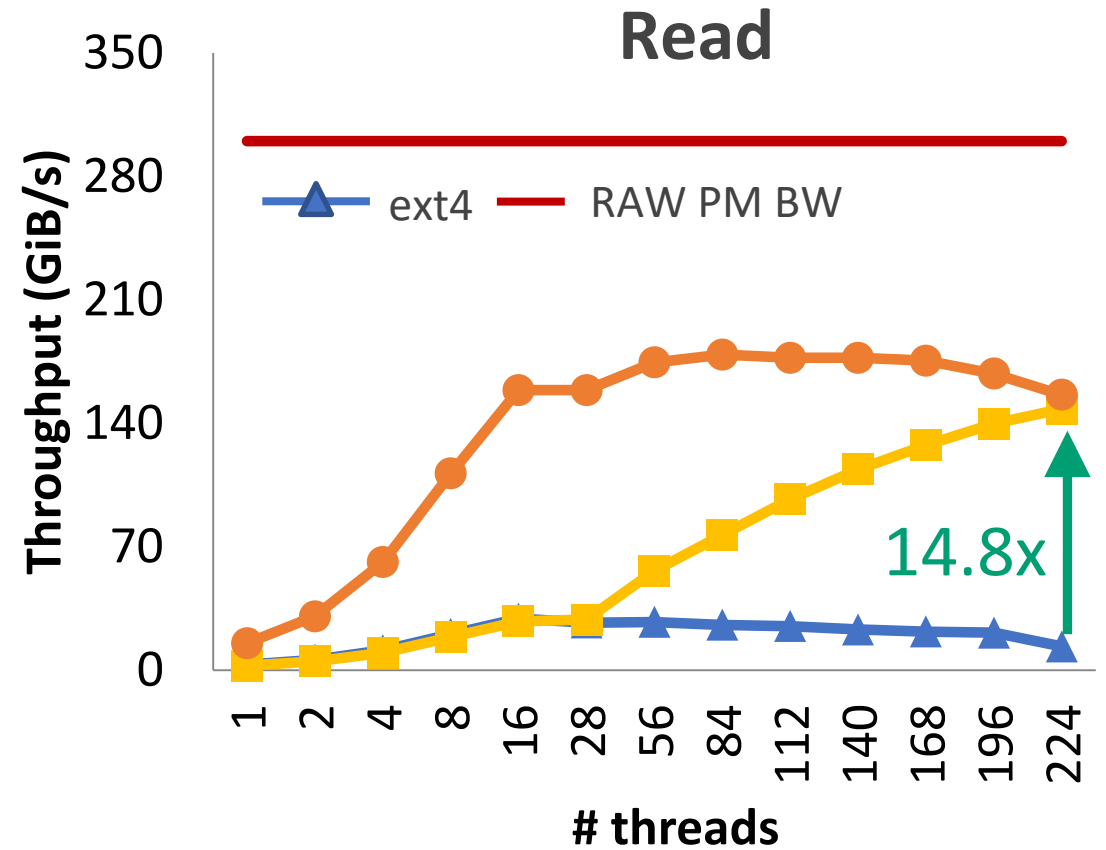
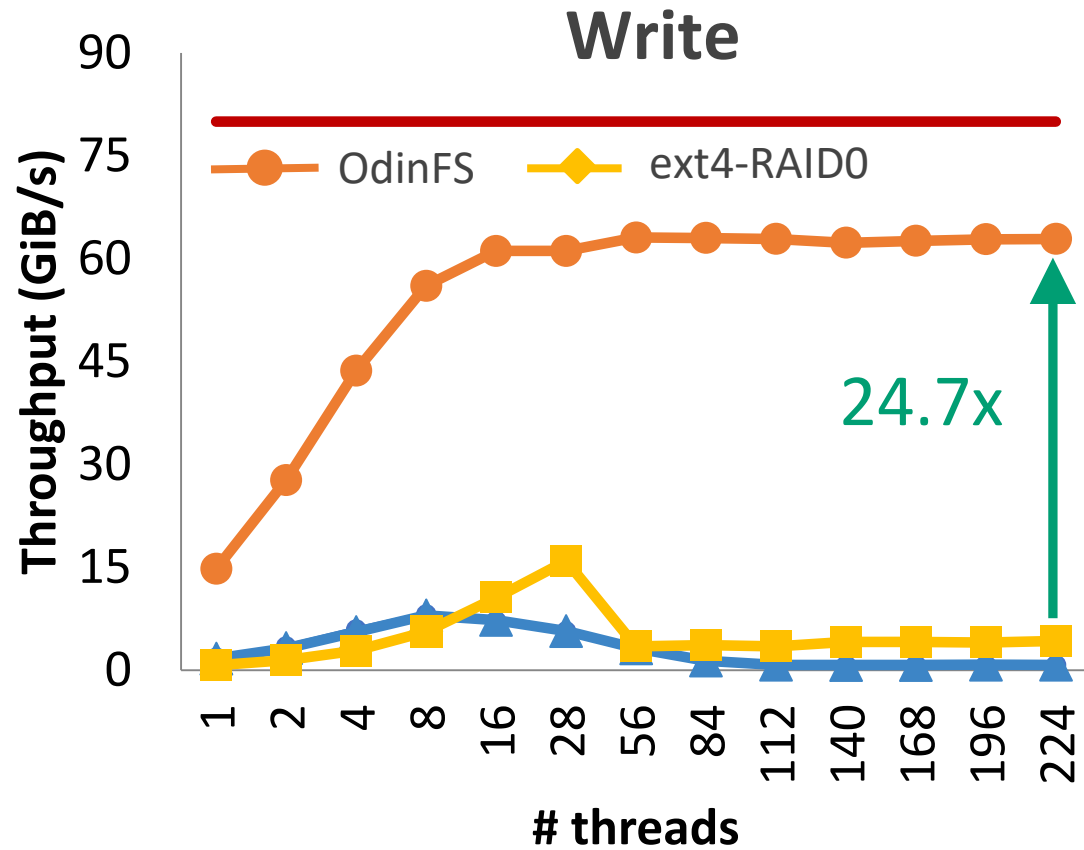
Workload: FIO: each thread writes/reads 2MB data in a private file



Setup: 224-core/8-socket machine

# Microbenchmark: FIO

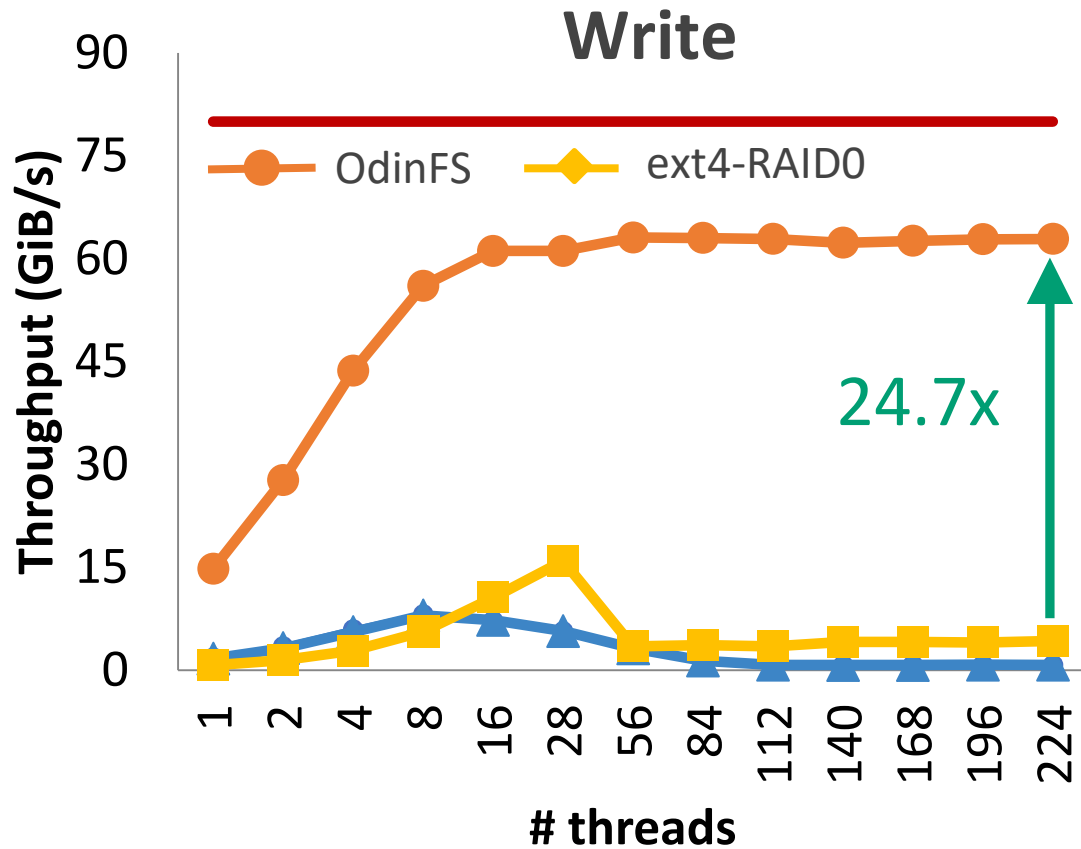
Workload: FIO: each thread writes/reads 2MB data in a private file



Setup: 224-core/8-socket machine

# Microbenchmark: FIO

Workload: FIO: each thread writes/reads 2MB data in a private file



Controlled concurrent access

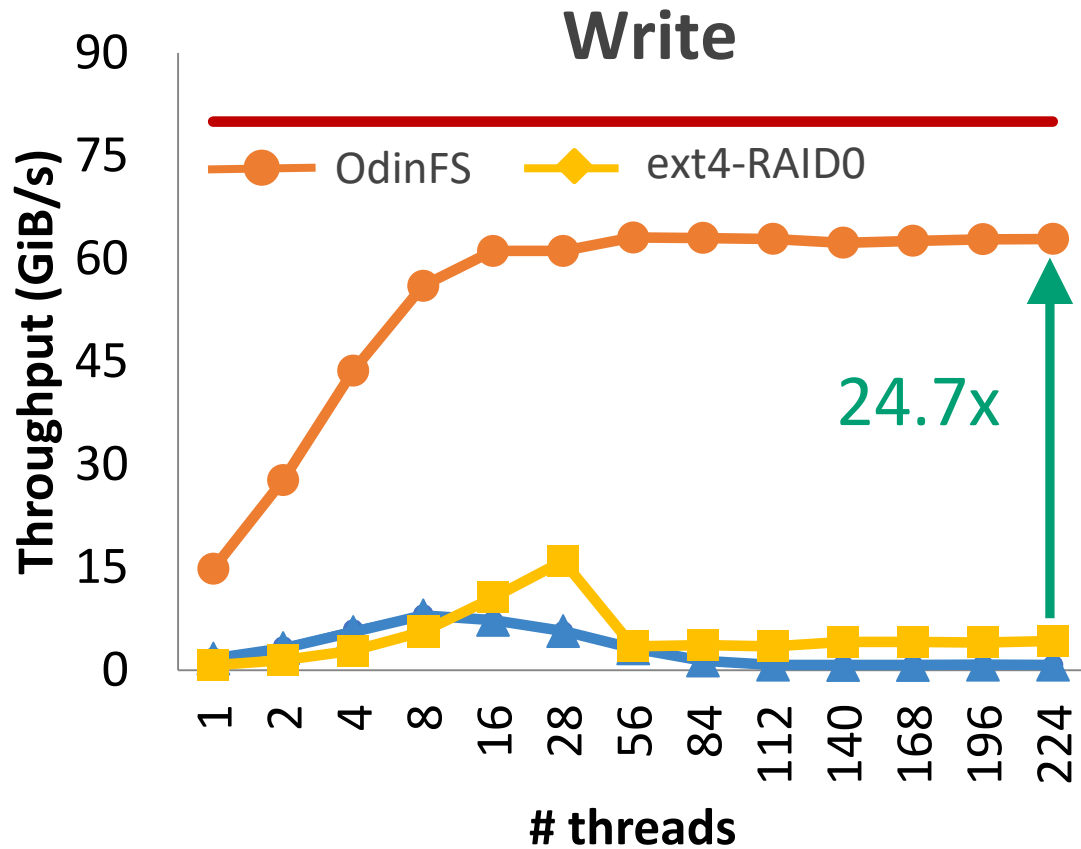
→ Maximize PM performance within one NUMA node

Setup: 224-core/8-socket machine



# Microbenchmark: FIO

Workload: FIO: each thread writes/reads 2MB data in a private file



Setup: 224-core/8-socket machine

## Controlled concurrent access

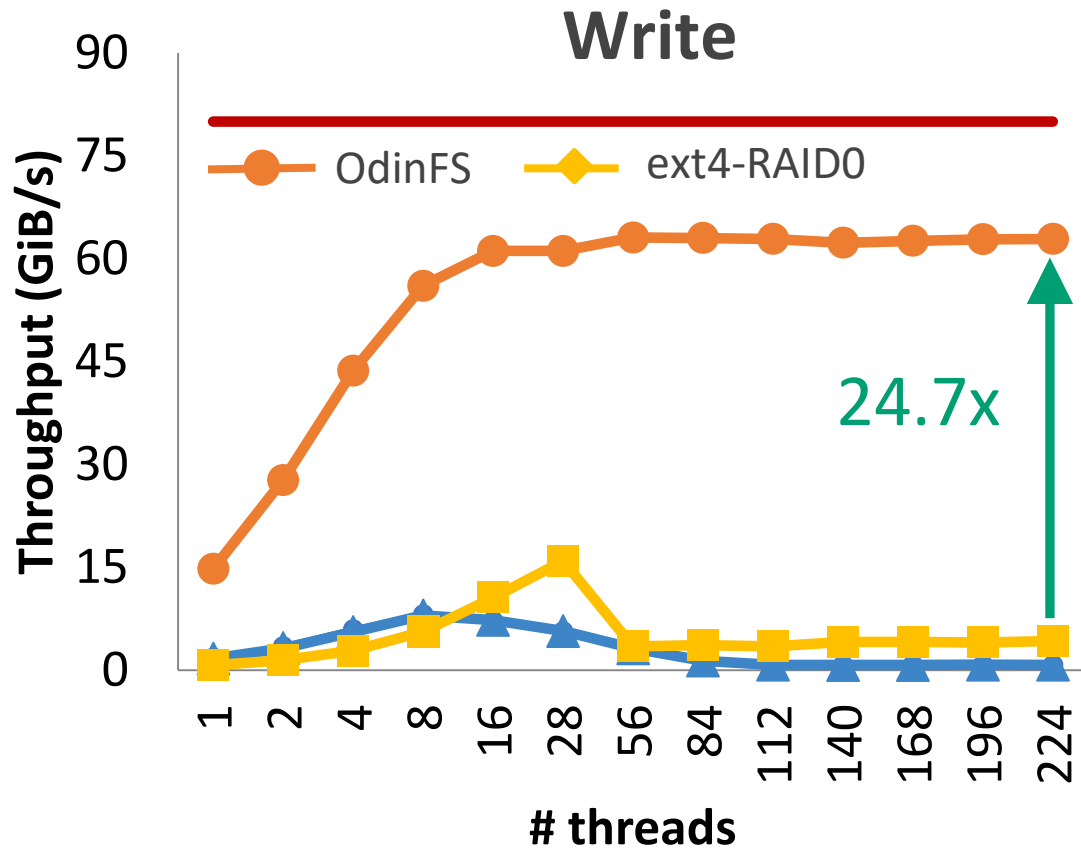
→ Maximize PM performance within one NUMA node

## Localized PM access

→ Minimize PM NUMA impact across NUMA nodes

# Microbenchmark: FIO

Workload: FIO: each thread writes/reads 2MB data in a private file



Setup: 224-core/8-socket machine

## Controlled concurrent access

→ Maximize PM performance within one NUMA node

## Localized PM access

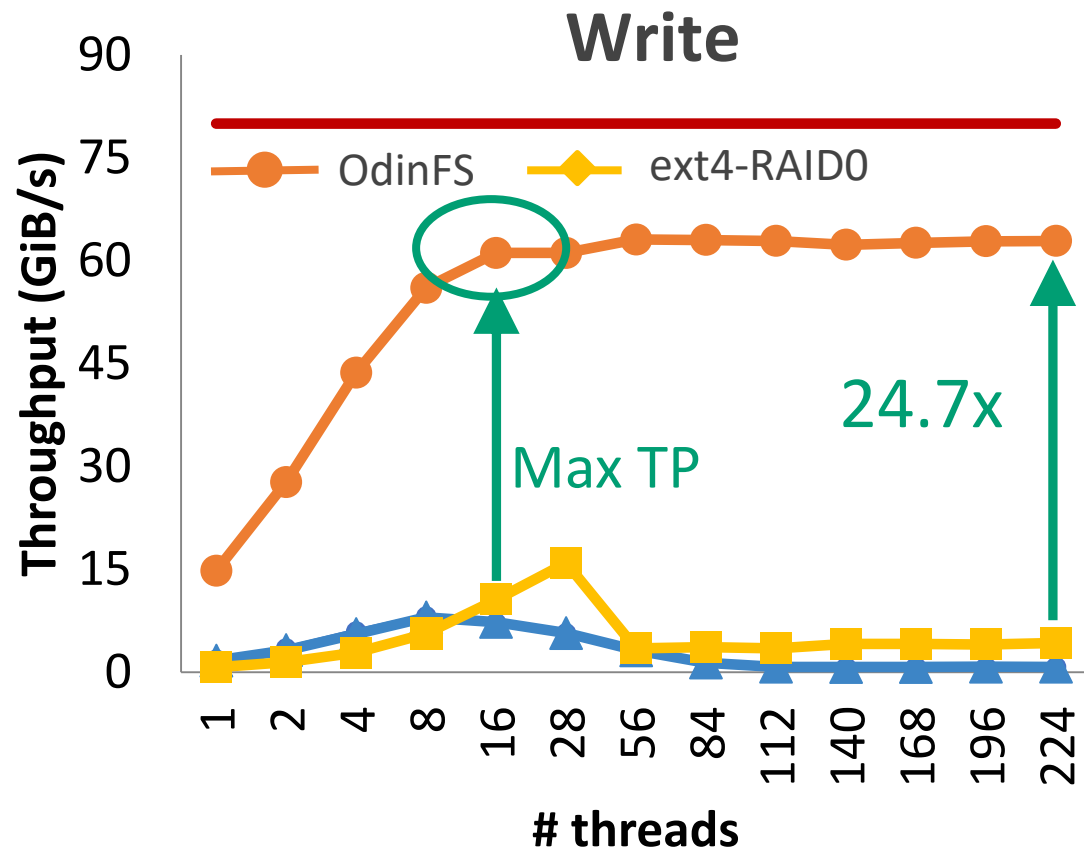
→ Minimize PM NUMA impact across NUMA nodes

## Parallel PM access

→ Efficiently utilize aggregated PM bandwidth

# Microbenchmark: FIO

Workload: FIO: each thread writes/reads 2MB data in a private file



Setup: 224-core/8-socket machine

## Controlled concurrent access

→ Maximize PM performance within one NUMA node

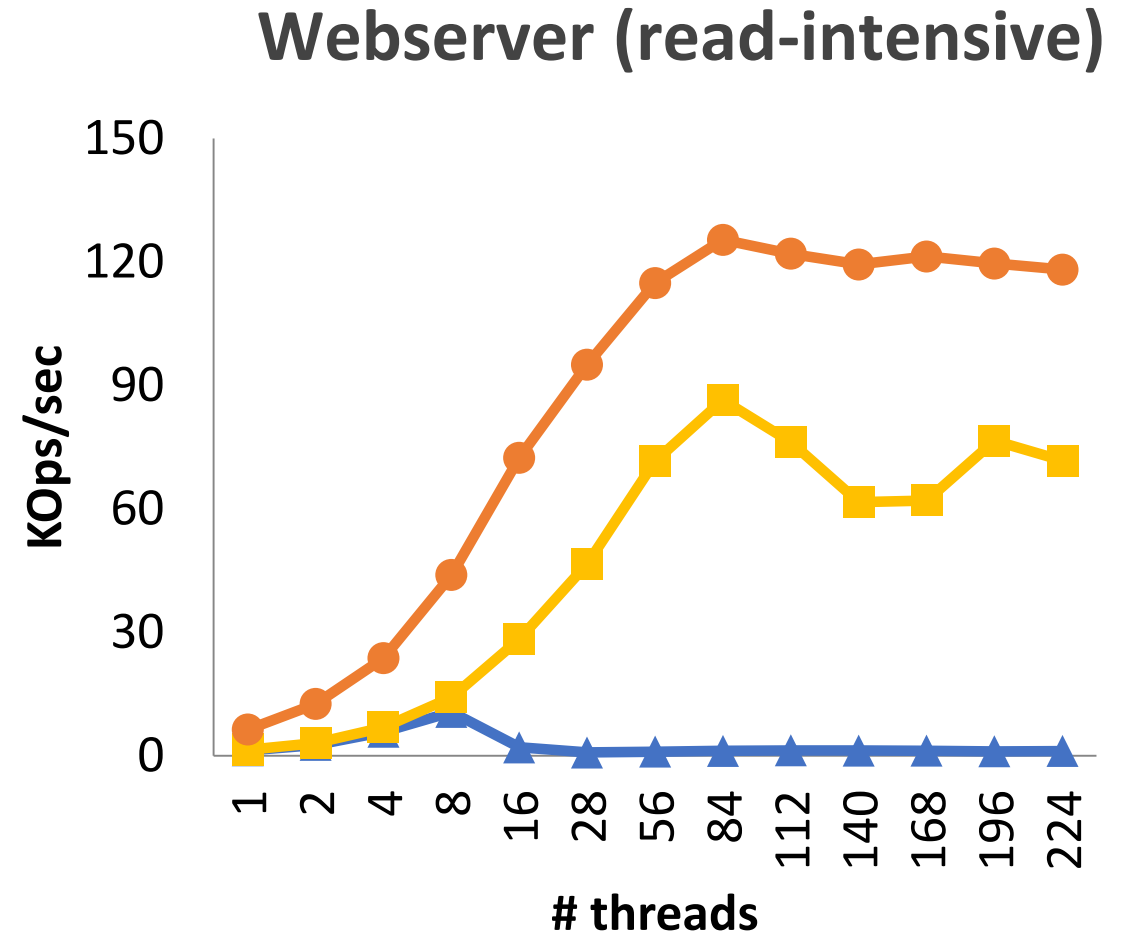
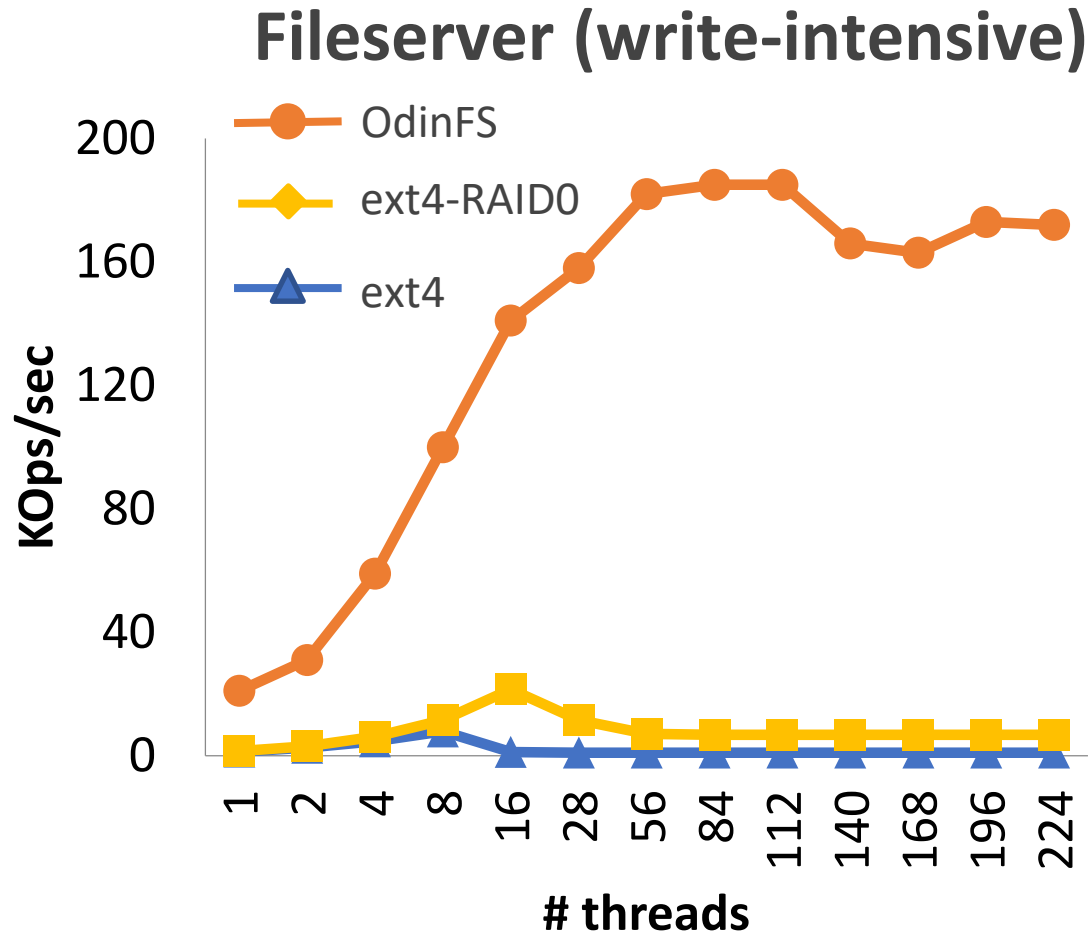
## Localized PM access

→ Minimize PM NUMA impact across NUMA nodes

## Parallel PM access

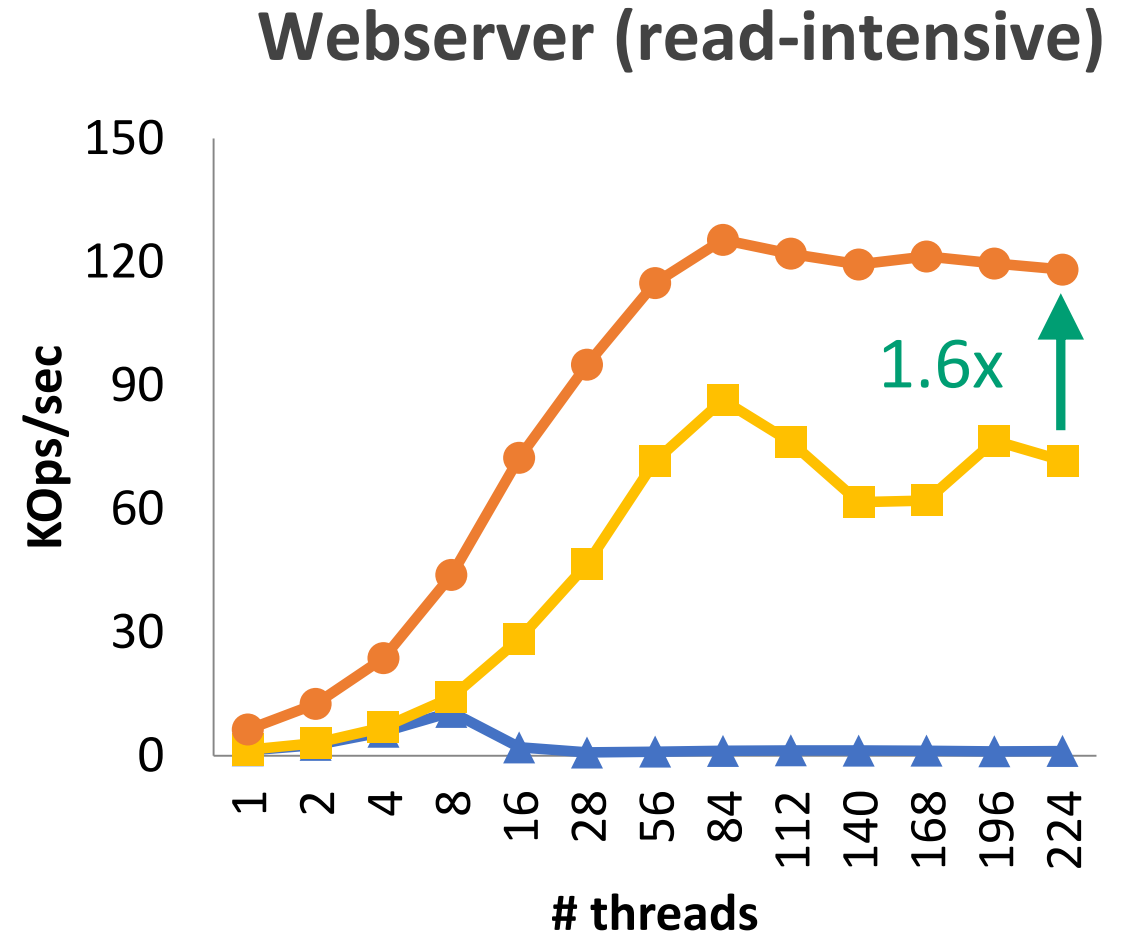
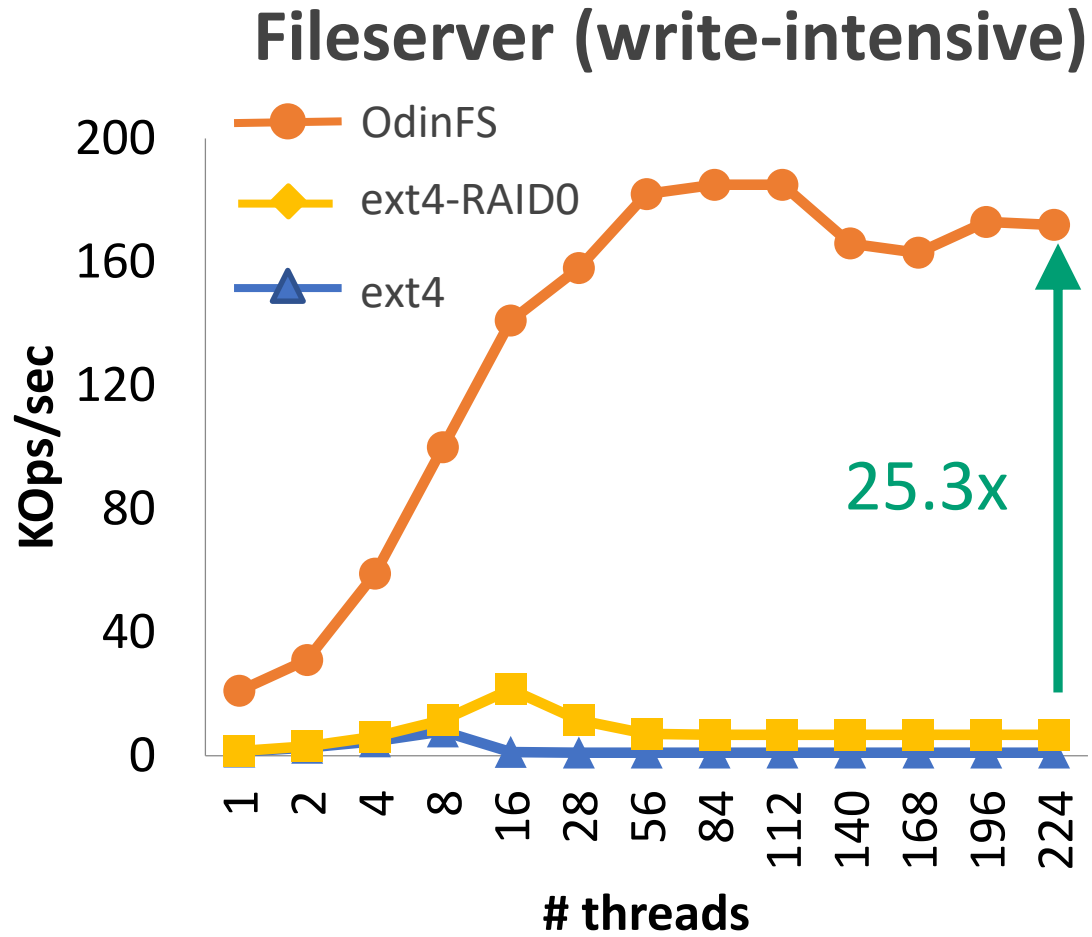
→ Efficiently utilize aggregated PM bandwidth

# Macrobenchmark: Filebench



Setup: 224-core/8-socket machine

# Macrobenchmark: Filebench



Setup: 224-core/8-socket machine

# Conclusion

Existing file systems cannot utilize PM efficiently

- **Uncontrolled** concurrent access
- **Inefficient** remote PM access
- Cannot efficiently leverage the **aggregated PM bandwidth**

# Conclusion

Existing file systems cannot utilize PM efficiently

- **Uncontrolled** concurrent access
- **Inefficient** remote PM access
- Cannot efficiently leverage the **aggregated PM bandwidth**

OdinFS: decouple PM access to maximize and scale performance

- **Controlled, localized, and parallel PM access**



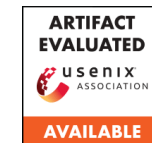
# Conclusion

Existing file systems cannot utilize PM efficiently

- **Uncontrolled** concurrent access
- **Inefficient** remote PM access
- Cannot efficiently leverage the **aggregated PM bandwidth**

OdinFS: decouple PM access to maximize and scale performance

- **Controlled, localized, and parallel PM access**
- **Publicly available:** <https://github.com/rs3lab/Odinfns>





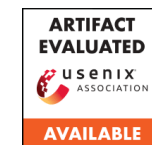
# Conclusion

Existing file systems cannot utilize PM efficiently

- **Uncontrolled** concurrent access
- **Inefficient** remote PM access
- Cannot efficiently leverage the **aggregated PM bandwidth**

OdinFS: decouple PM access to maximize and scale performance

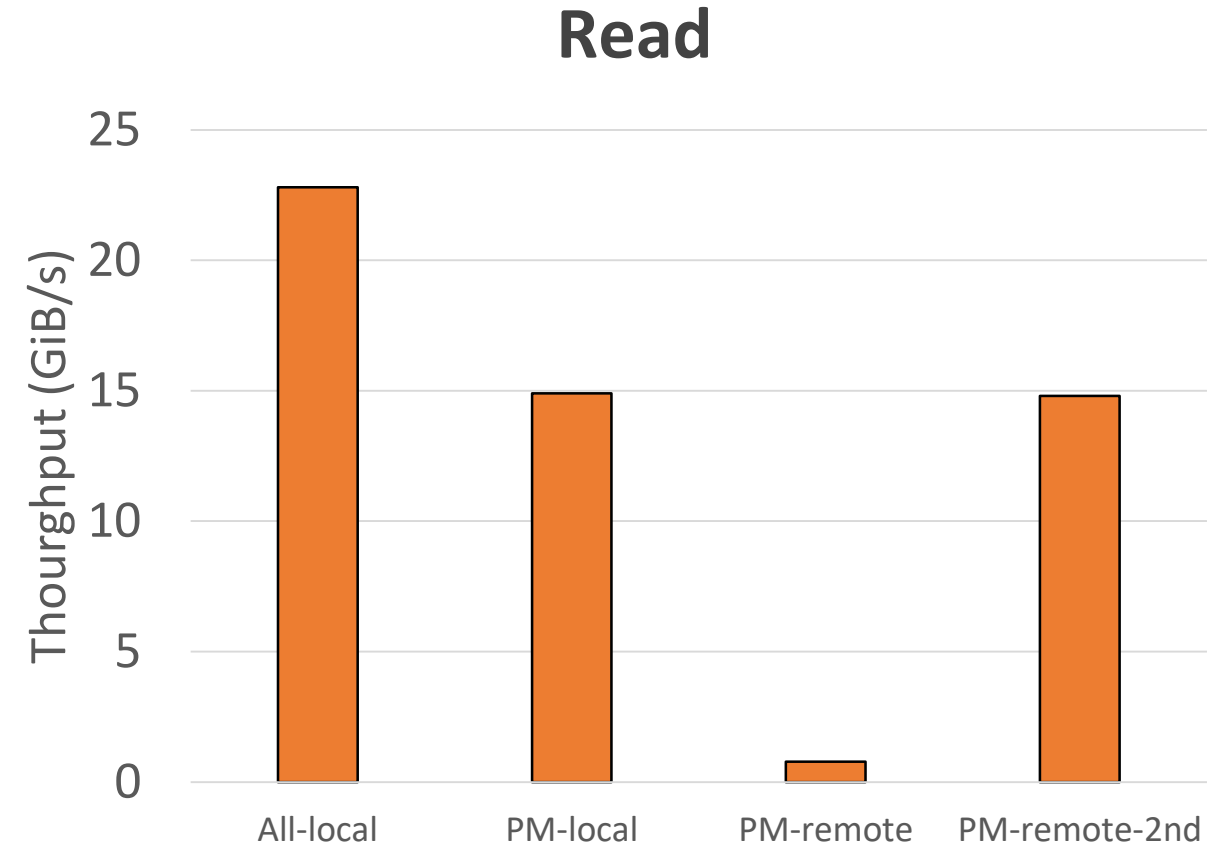
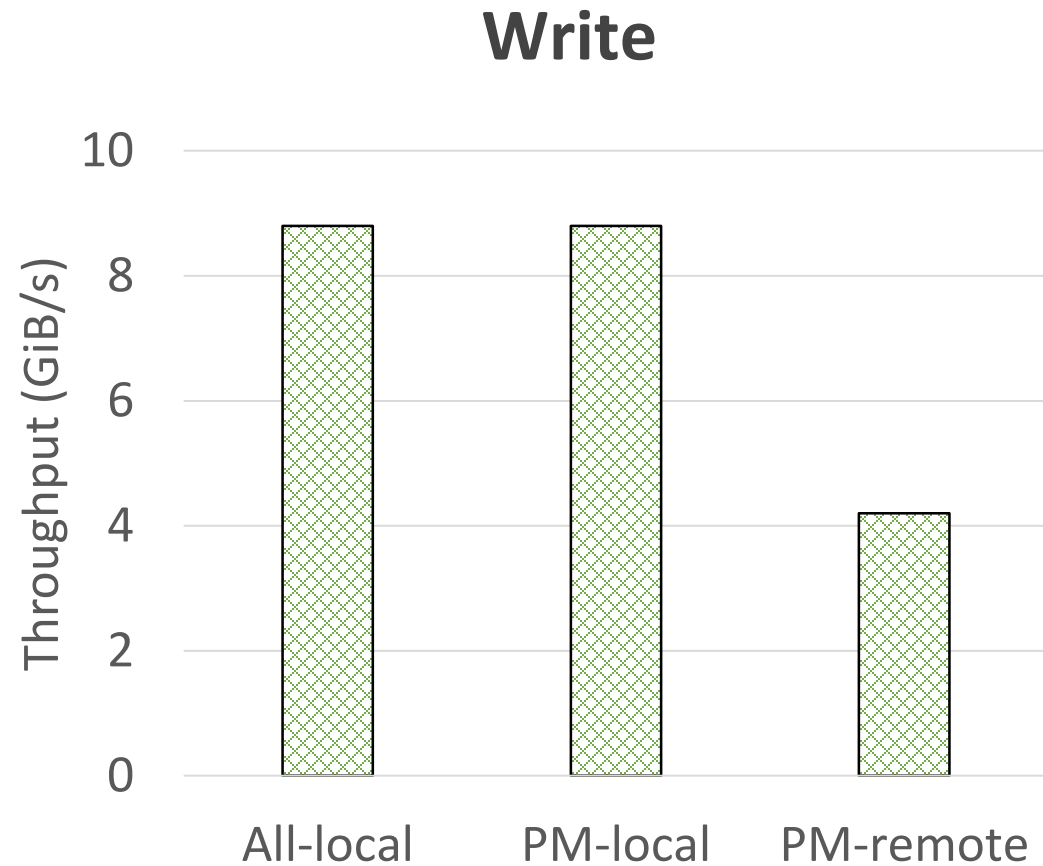
- **Controlled, localized, and parallel PM access**
- **Publicly available:** <https://github.com/rs3lab/Odinfs>



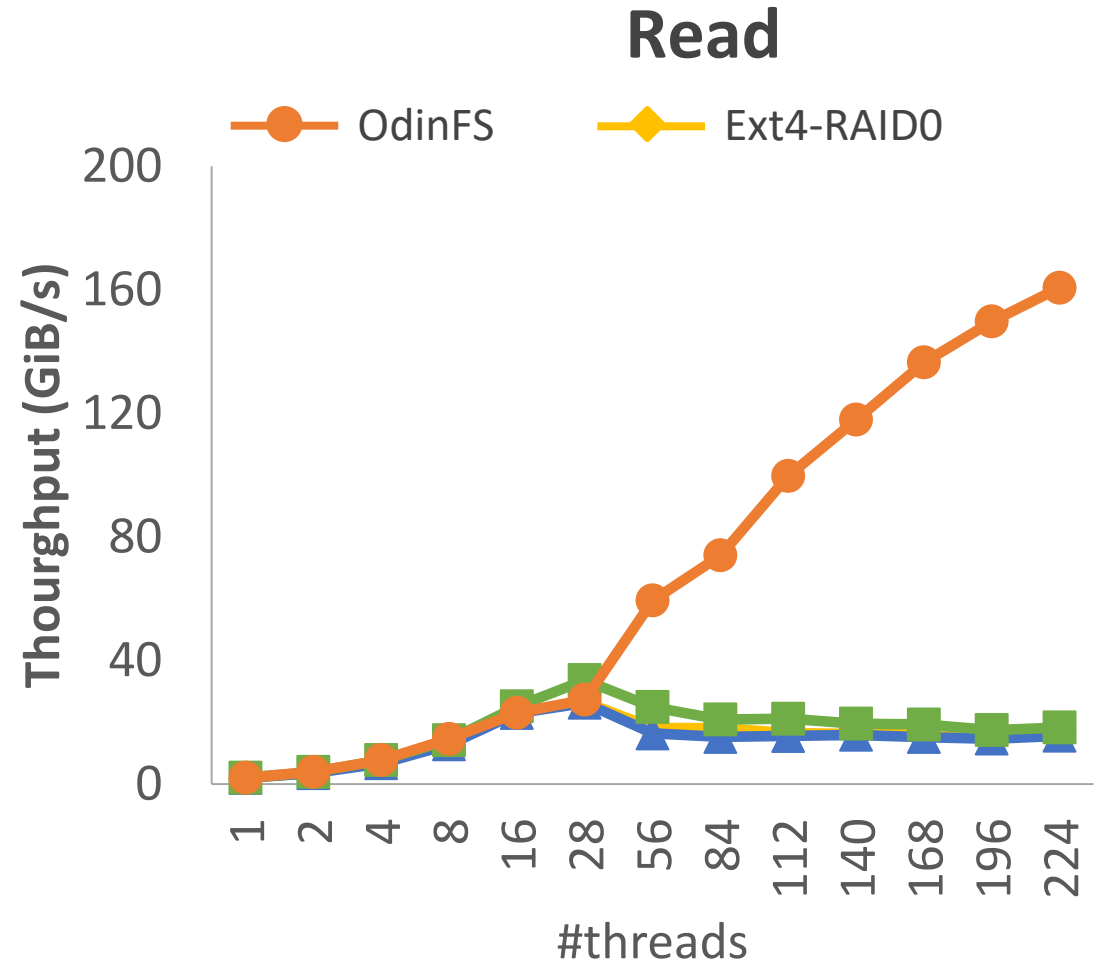
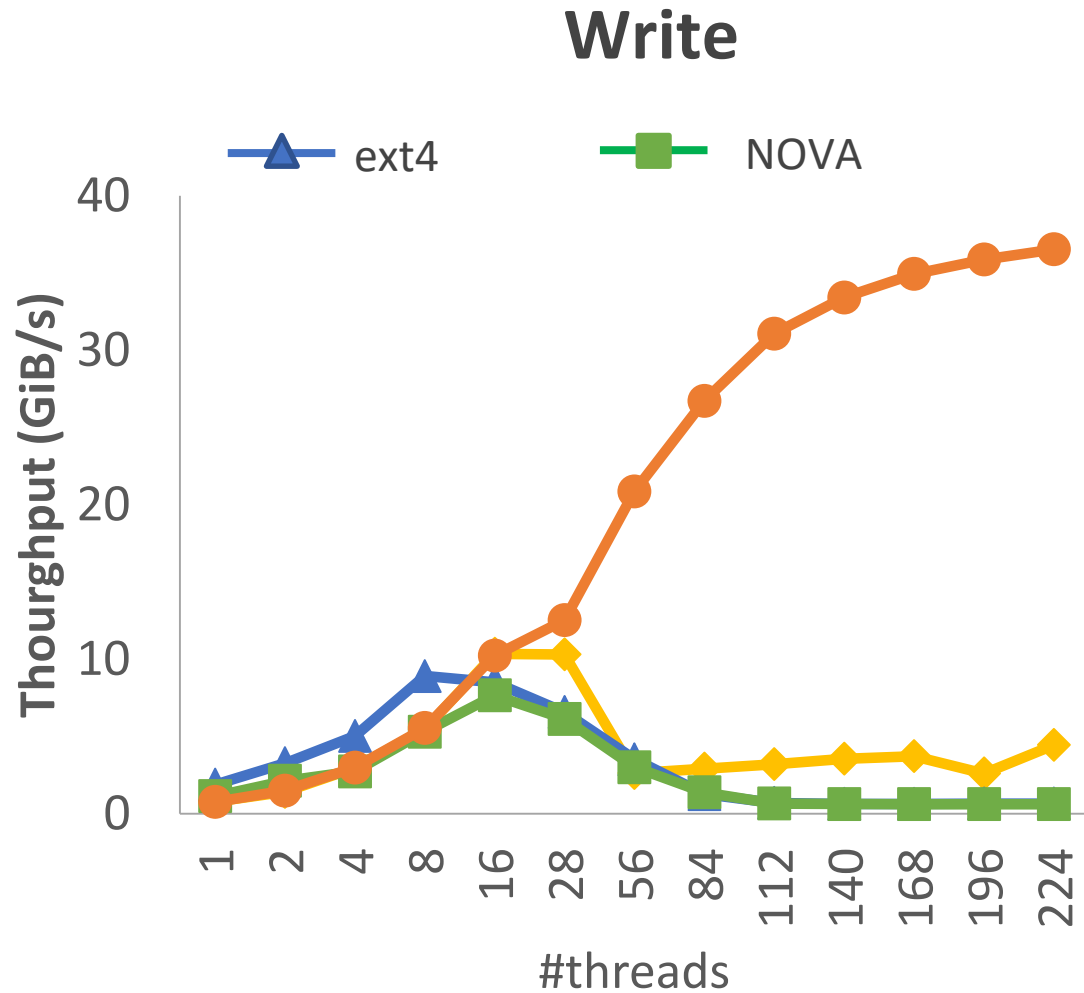
Thank you!



# PM performance under NUMA setup

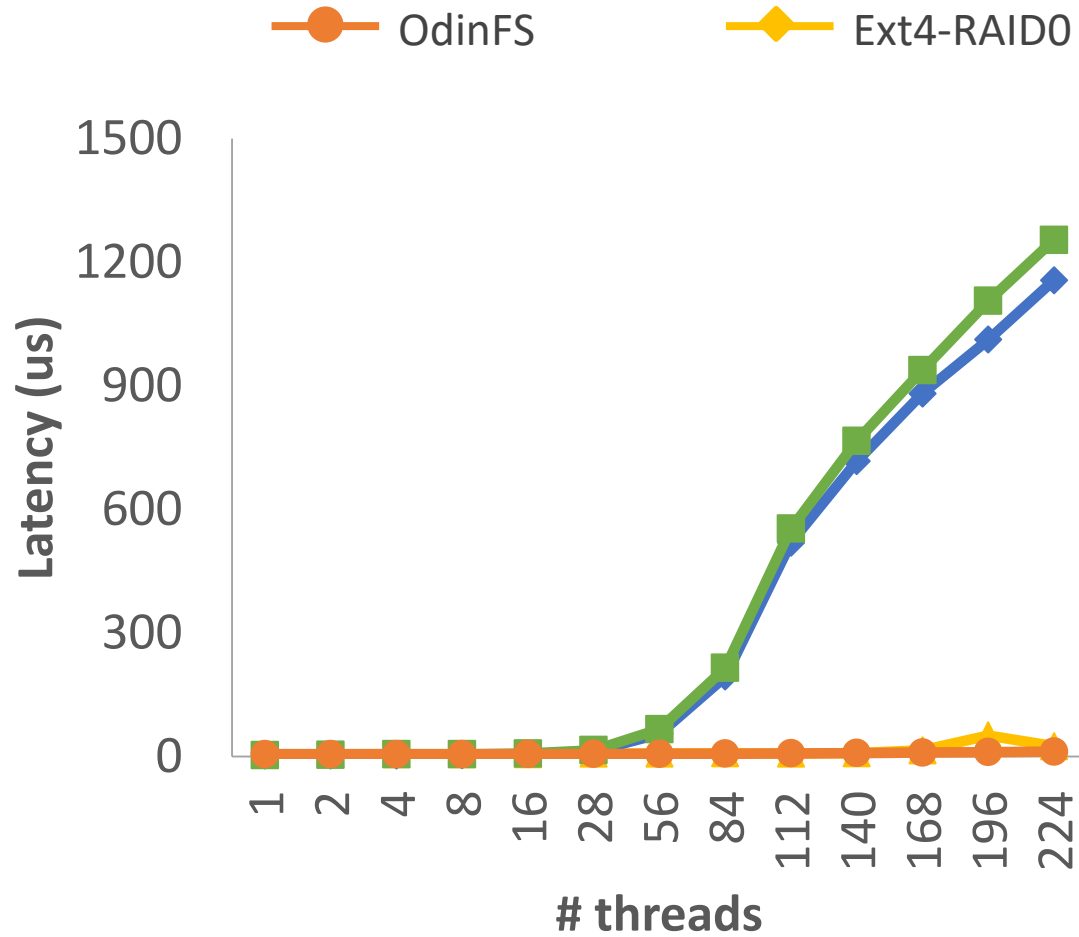


# FIO: 4K access size

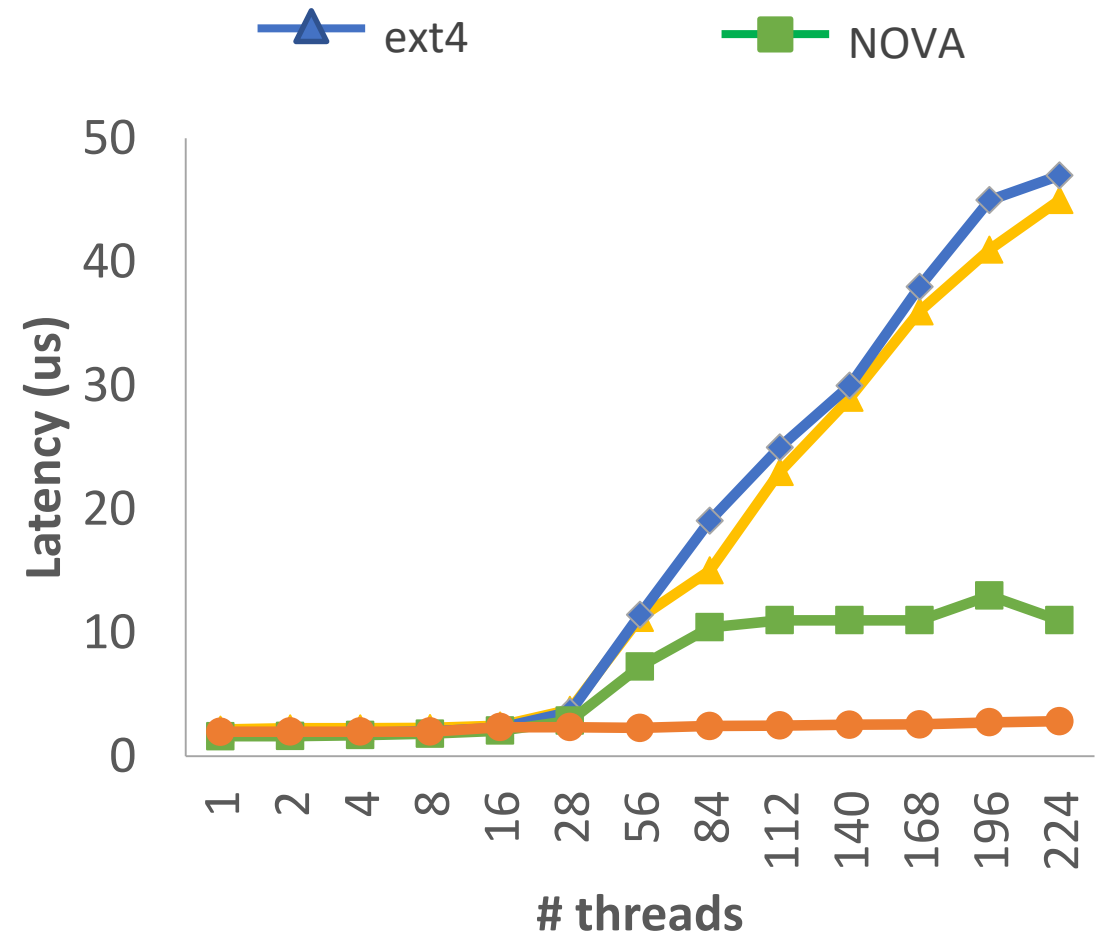


# FIO: Latency, 4K access size

## Write

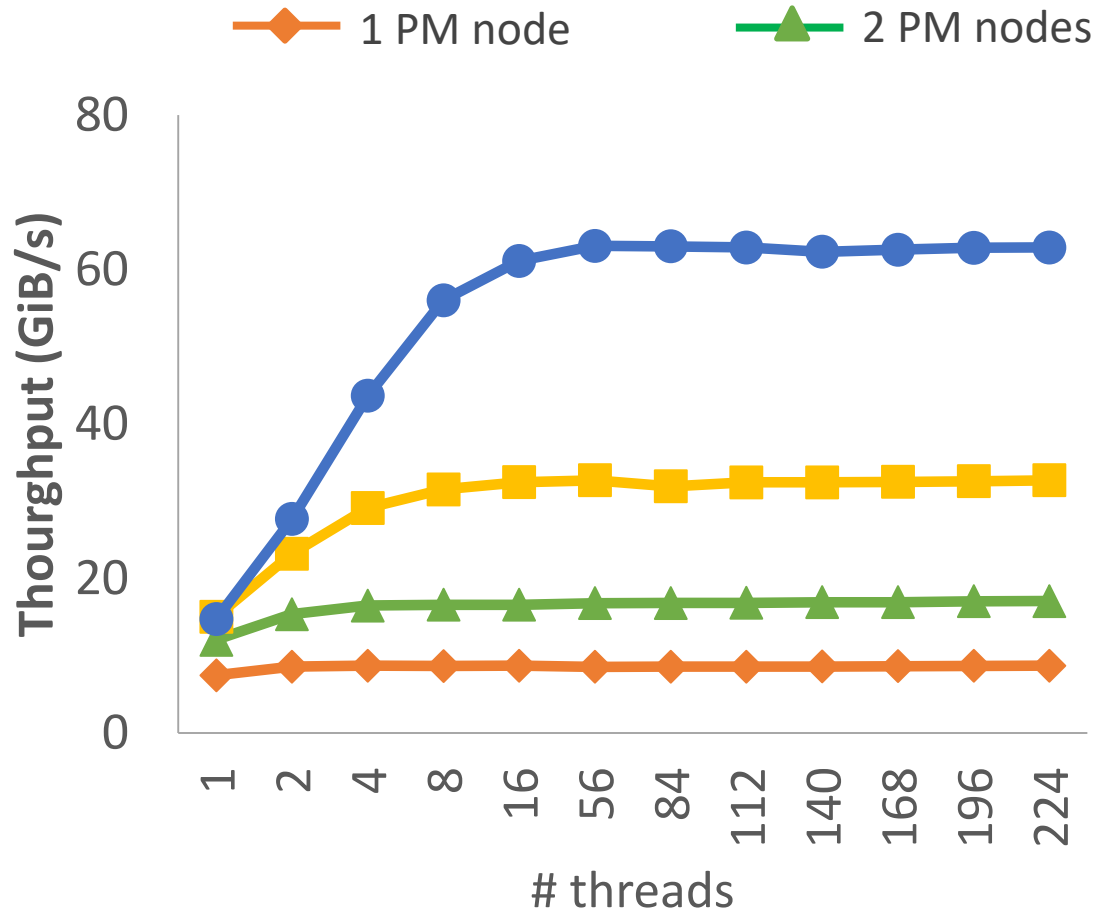


## Read

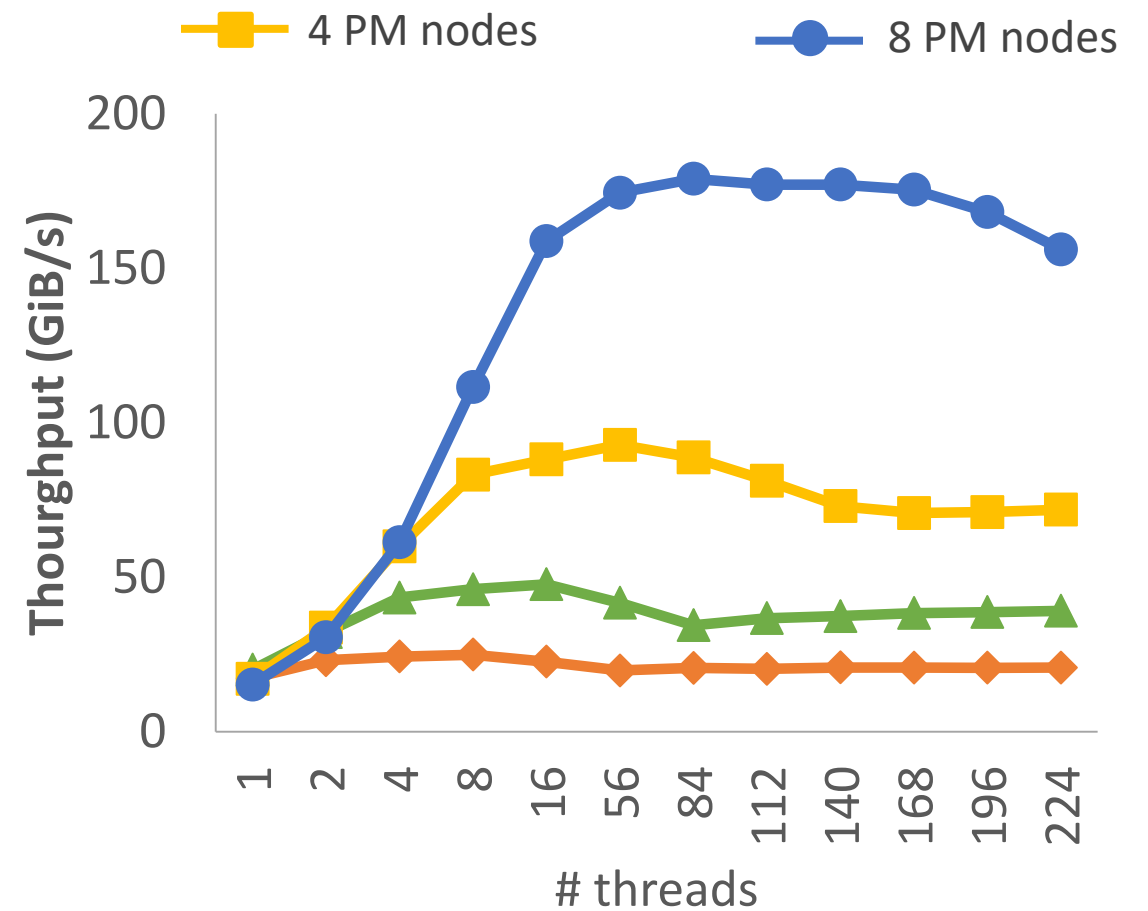


# OdinFS with different number of NUMA nodes

## Write



## Read



# PM NUMA Impact: Explanation

