A Parametric I/O Model for Modern Storage Devices

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presentation at DaMoN 2021

Modeling Performance

"Algorithm/Data Structure **X** has $O(f(N))$ performance, where N is the number of data pages on disk"

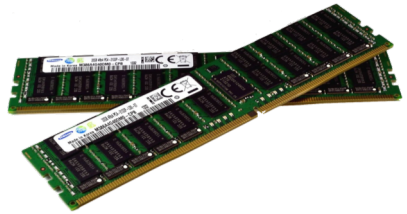
… is probably one of the most commonly read phrases in SIGMOD papers.


intel
Core™ i7

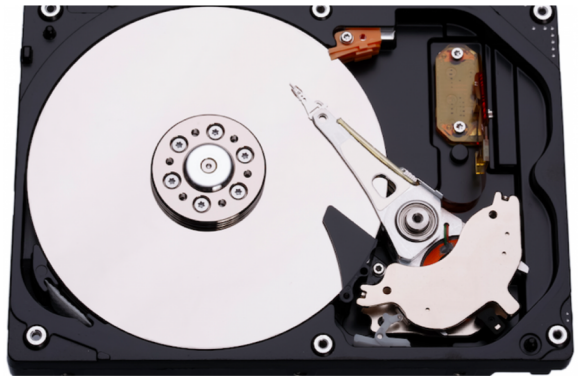

intel
Core™ i7

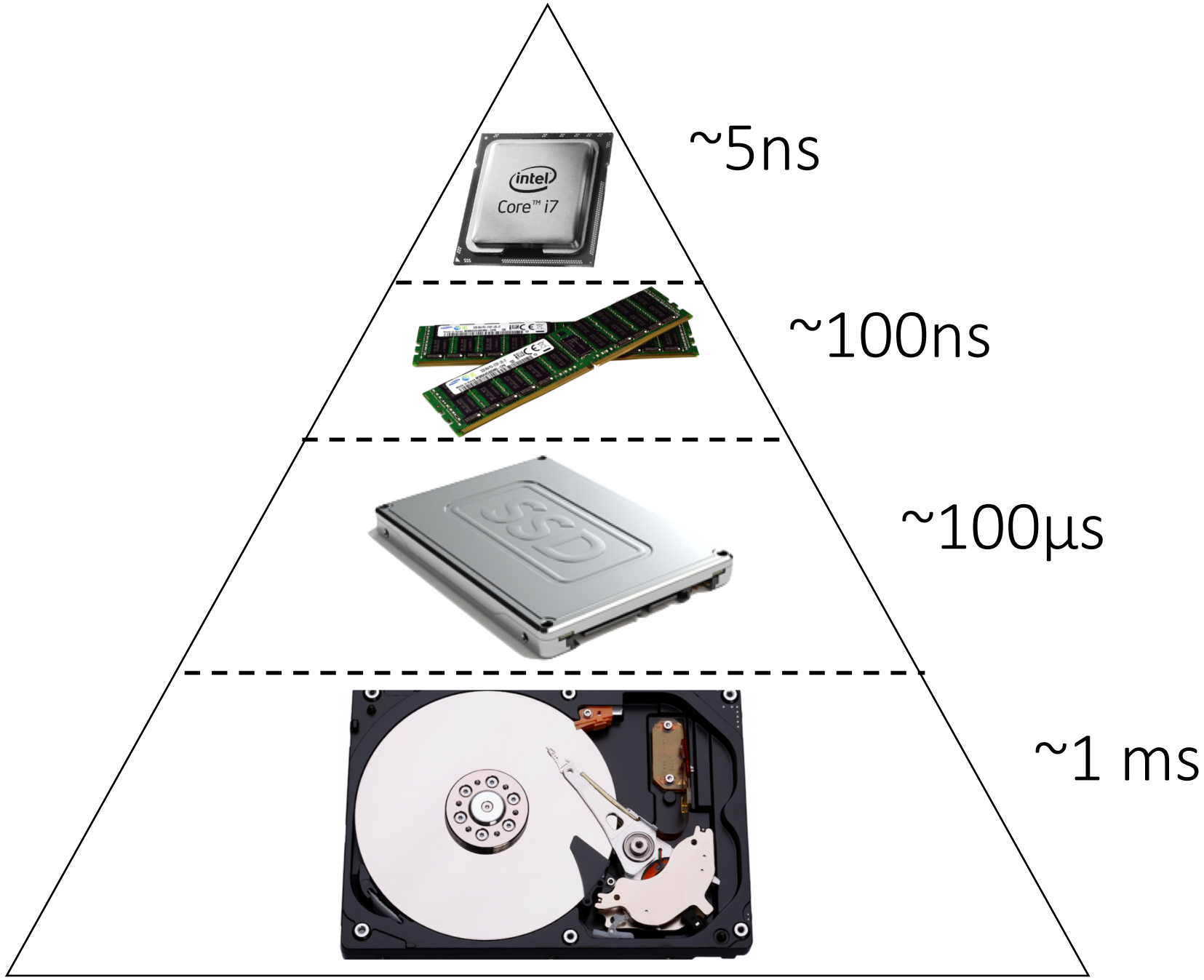

intel
Core™ i7
SSD

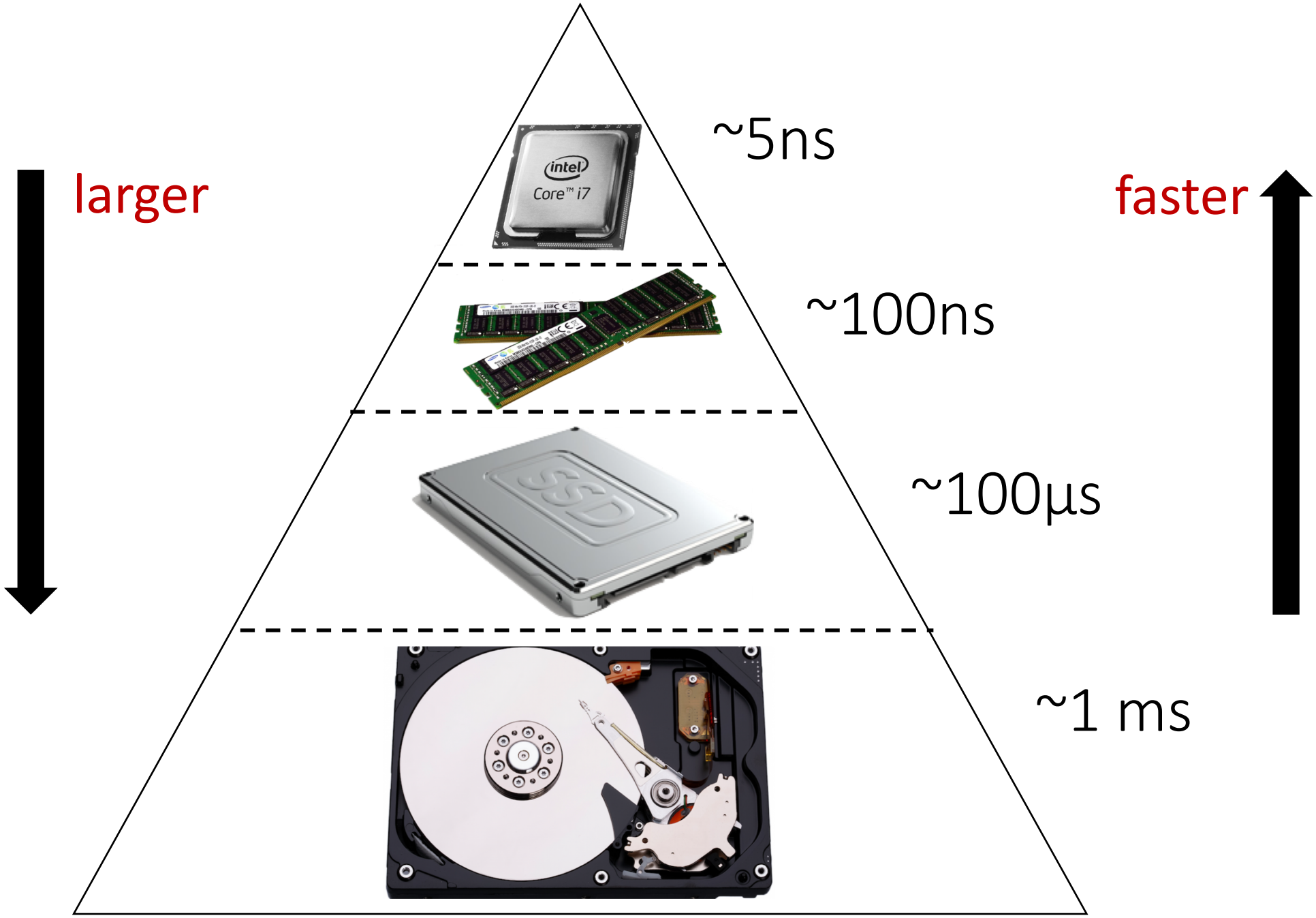

intel
Core™ i7



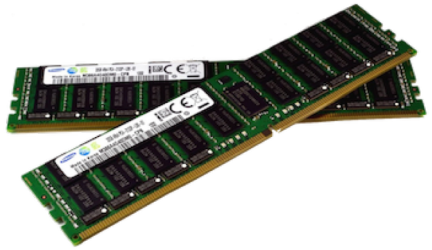

SSD




~5ns
~100ns
~100µs
~1 ms

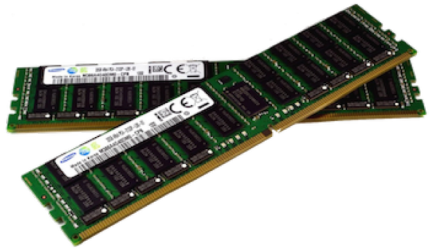

larger
faster
~5ns
~100ns
~100µs
~1 ms
intel
Core™ i7
SSD

Traditional I/O Model



Small, fast main memory
(size M)

Traditional I/O Model



Small, fast main memory
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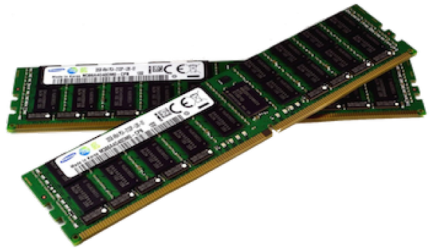
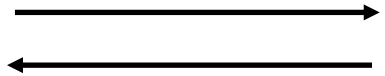
Large, slow external memory

Traditional I/O Model

One I/O at a time





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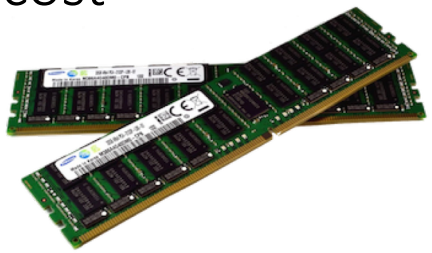
Traditional I/O Model

0 access cost



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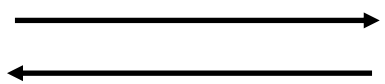

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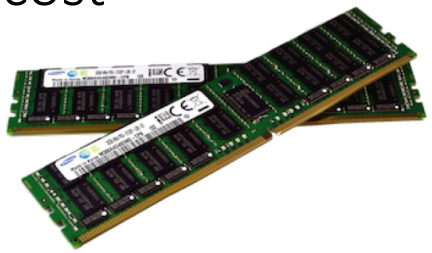


Small, fast main memory
(size M)

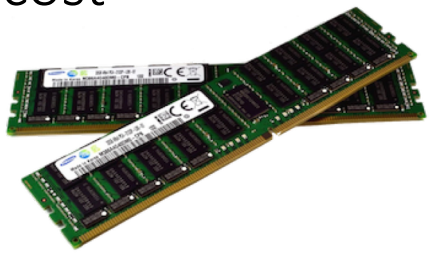
Transfer cost
1 unit

Large, slow external memory

Traditional I/O Model

total cost ≅ total # reads/writes to disk

0 access cost



Small, fast main memory
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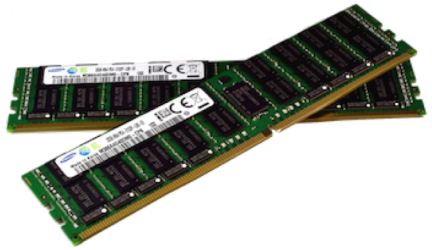
Large, slow external memory

Traditional I/O Model

Two (outdated) assumptions

- ✓ **Symmetric** cost for **Read & Write** to disk
- ✓ **One I/O** at a time



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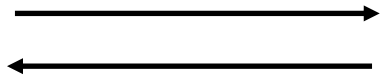
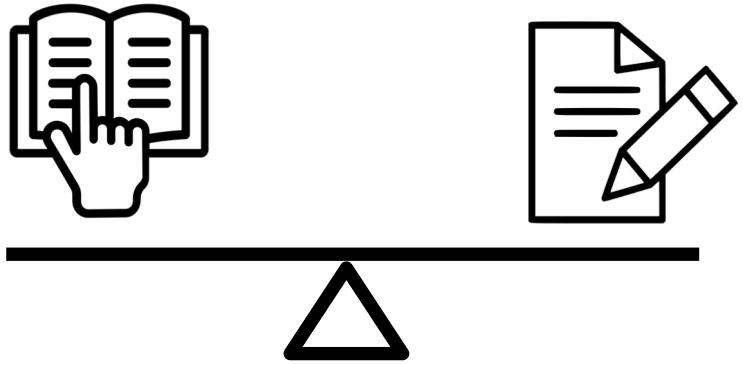


Large, slow external memory

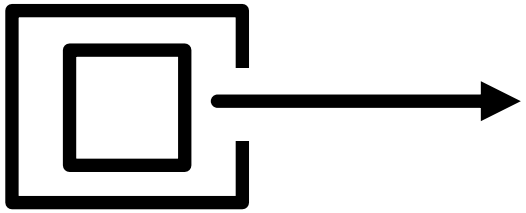
Hard Disk Drives

Hard Disk Drives

Two assumptions of the Traditional I/O Model



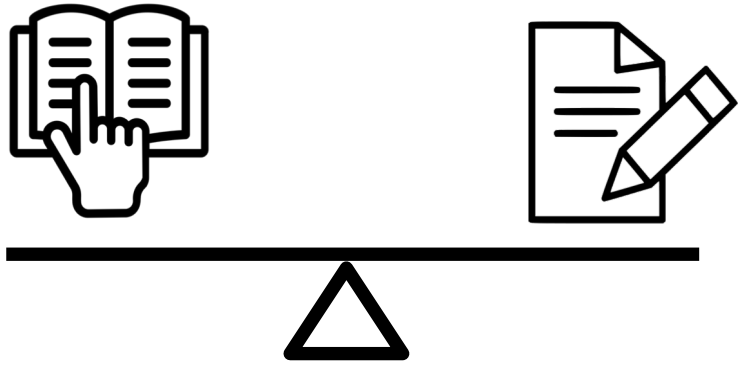
Symmetric cost for **Read & Write** to disk



One I/O at a time

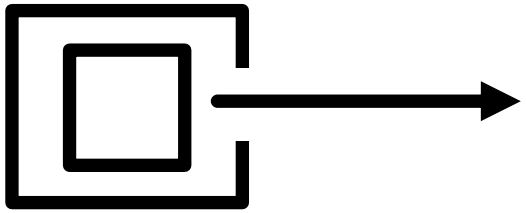
Hard Disk Drives

Two assumptions of the Traditional I/O Model



Symmetric cost for **Read & Write** to disk

✓



One I/O at a time

✓

"Tape is Dead. Disk is Tape.

Flash is Disk."

- Jim Gray

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Device	Size	Seq B/W	Time to read
HDD 1980	100 MB	1.2 MB/s	~ 1 min
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HDDs are moving deeper in the memory hierarchy, and new algorithms are designed for new faster storage devices

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How do these modern storage devices perform?

Solid-State Disk (SSD)

No mechanical movement

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No mechanical movement

Fast access, High chip density, Low energy consumption

Solid-State Disk (SSD)

- ✓ SATA SSD

Solid-State Disk (SSD)

- ✓ SATA SSD
- ✓ PCIe SSD

Solid-State Disk (SSD)

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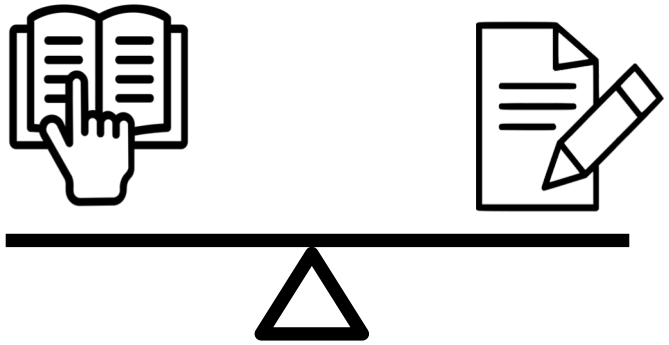
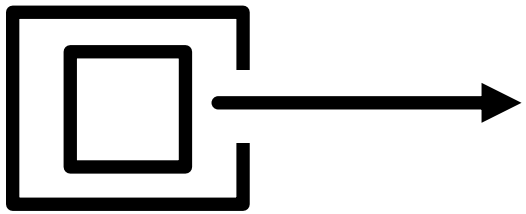
- ✓ PCIe SSD
- ✓ Optane SSD

Modern Storage Devices

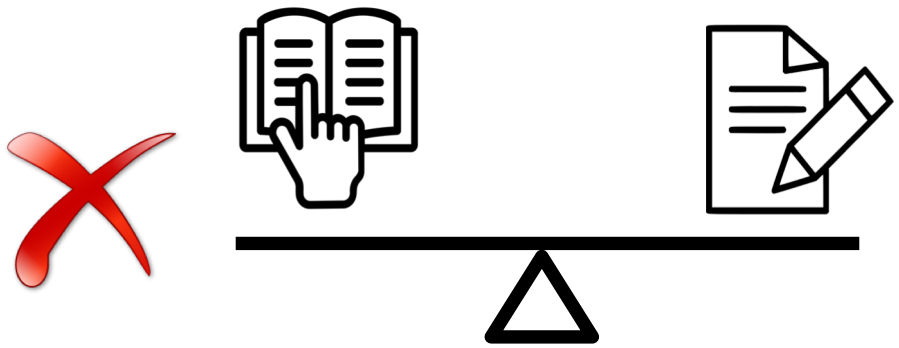


Symmetric cost for Read & Write



One I/O at a time

Modern Storage Devices



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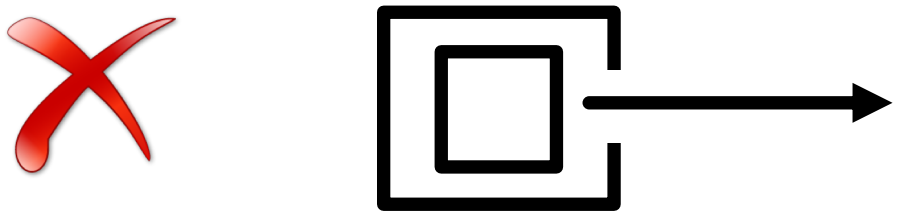

One I/O at a time

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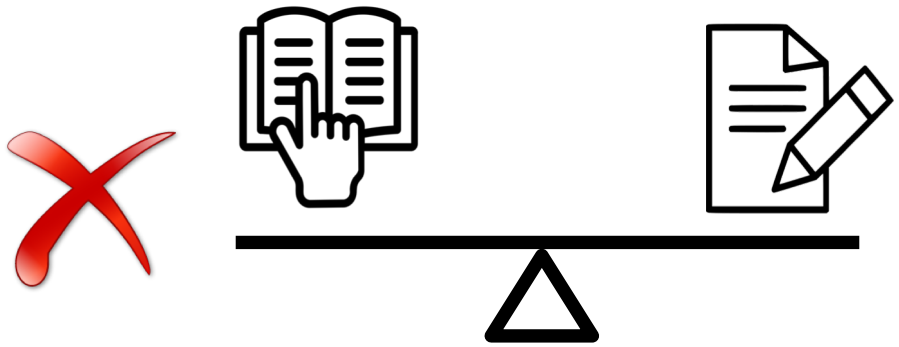

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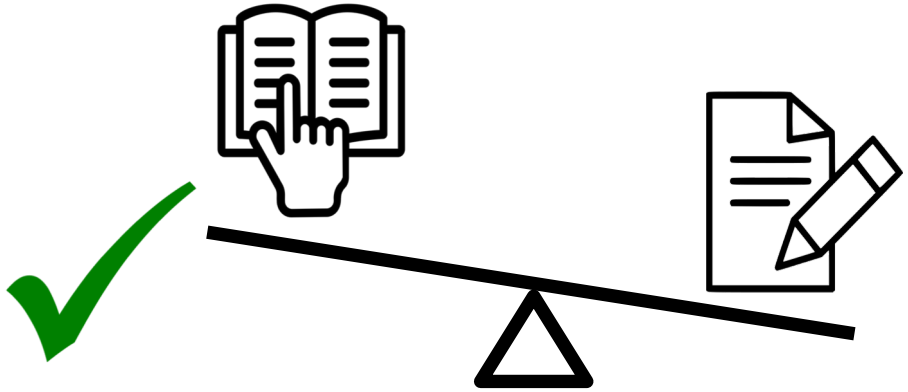
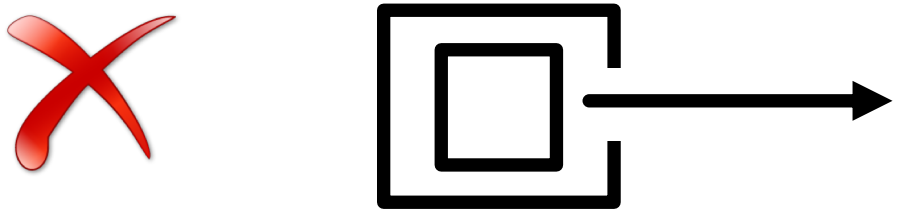
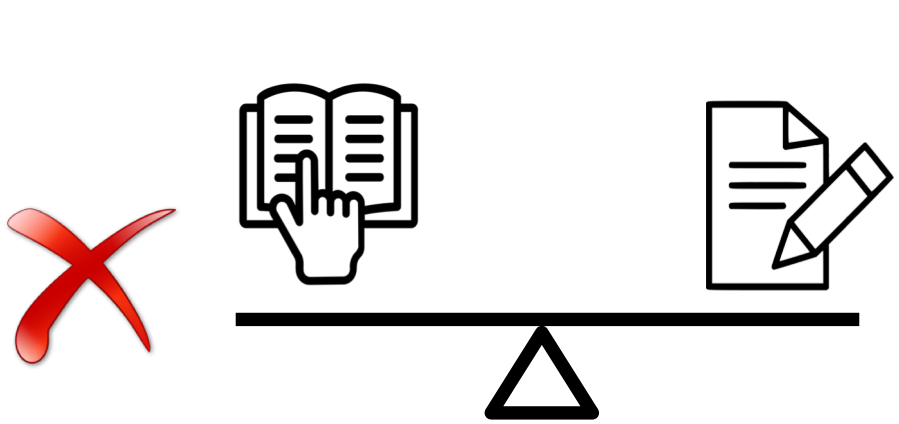


Read/Write Asymmetry

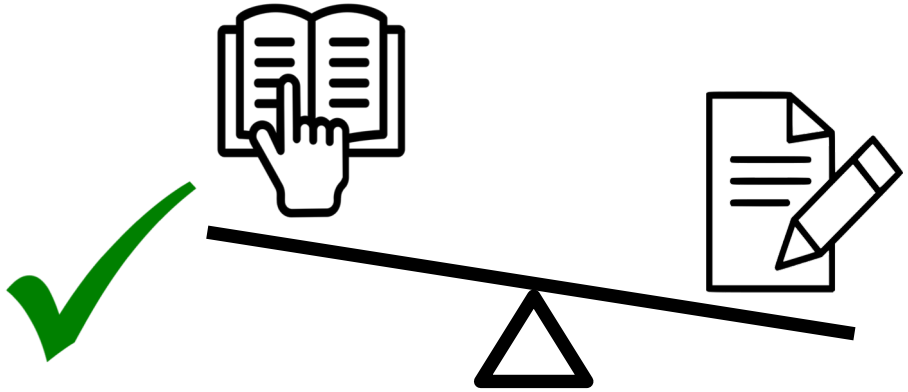


One I/O at a time

Modern Storage Devices



Symmetric cost for Read & Write



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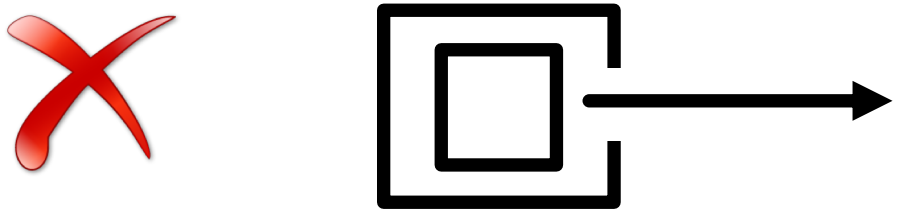

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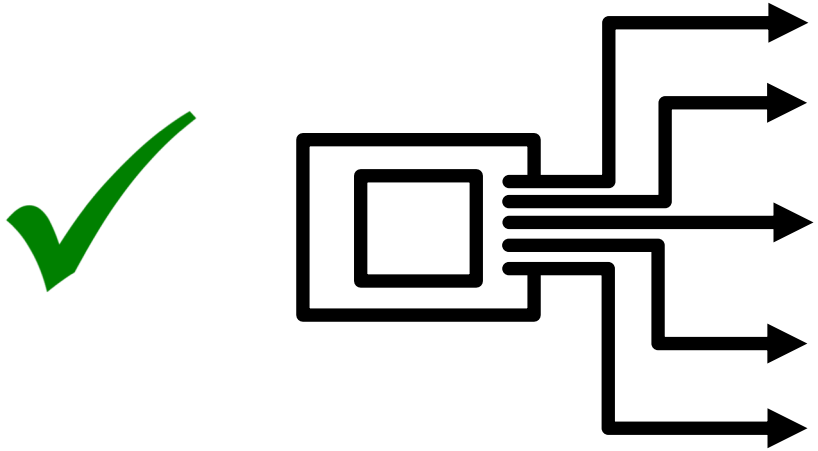


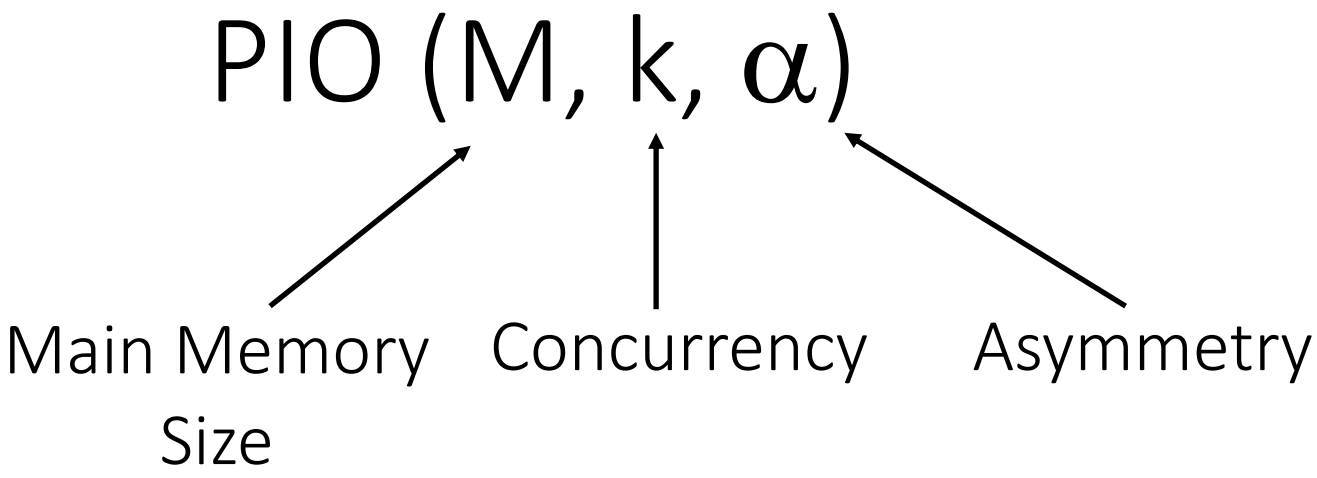
Concurrency

How should the I/O model be adapted in light of

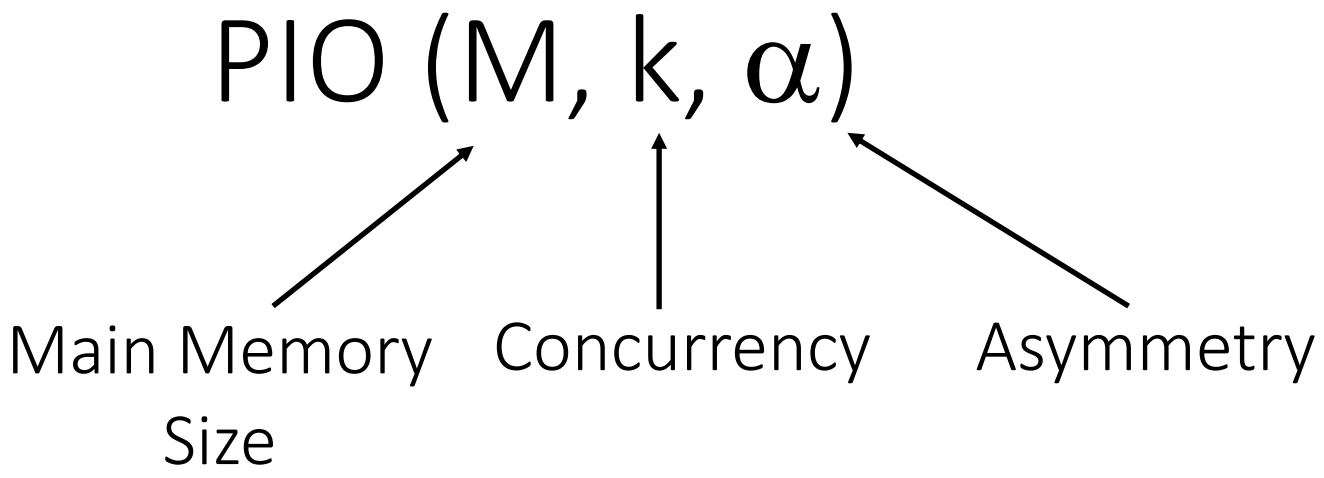
read/write asymmetry and concurrency?

Parametric I/O Model

Parametric I/O Model

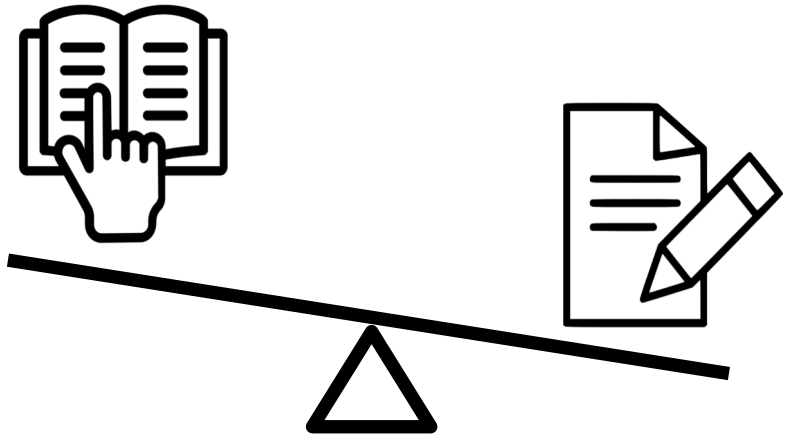


Parametric I/O Model



PIO*(M, k_r, k_w, α)** *assumes a fast main memory with capacity M, and storage of unbounded capacity that has* ***read/write asymmetry α*, and* ***read (write) concurrency*** k_r (k_w).

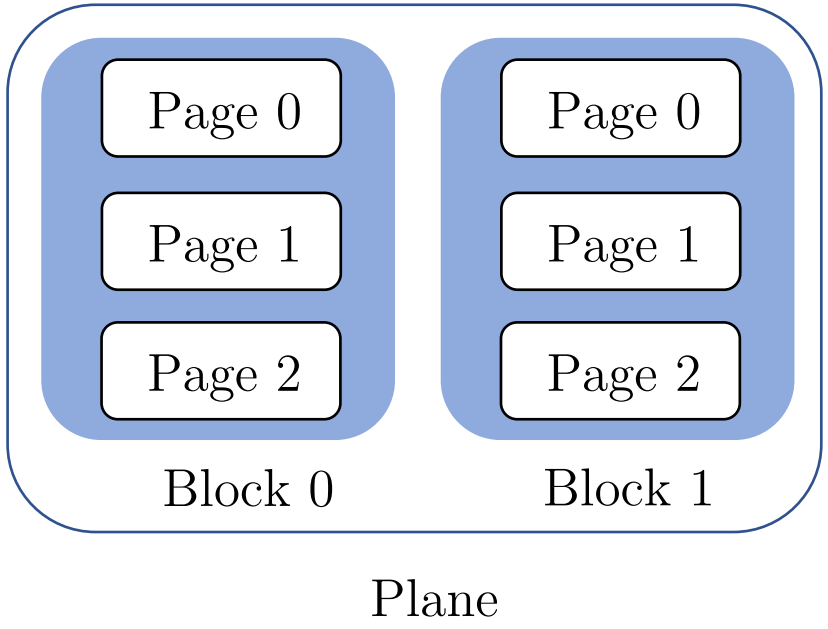
Read/Write Asymmetry



Writes in SSD

Out-of-place updates cause invalidation

Invalidation causes garbage collection.



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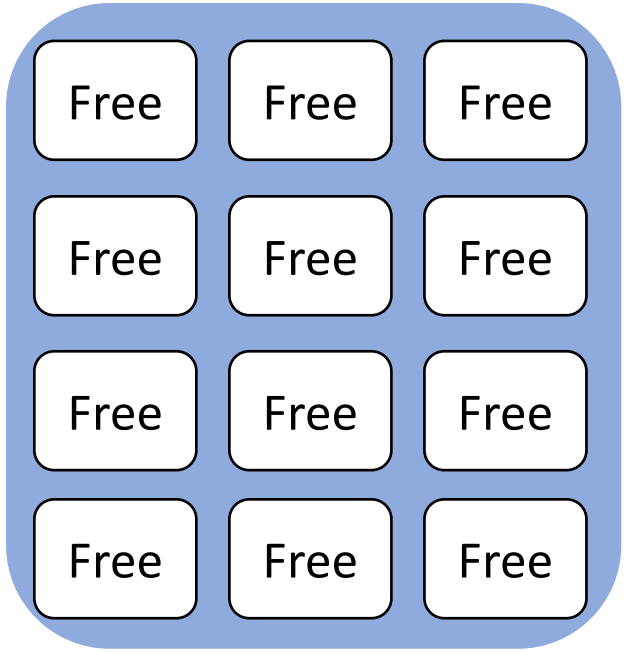

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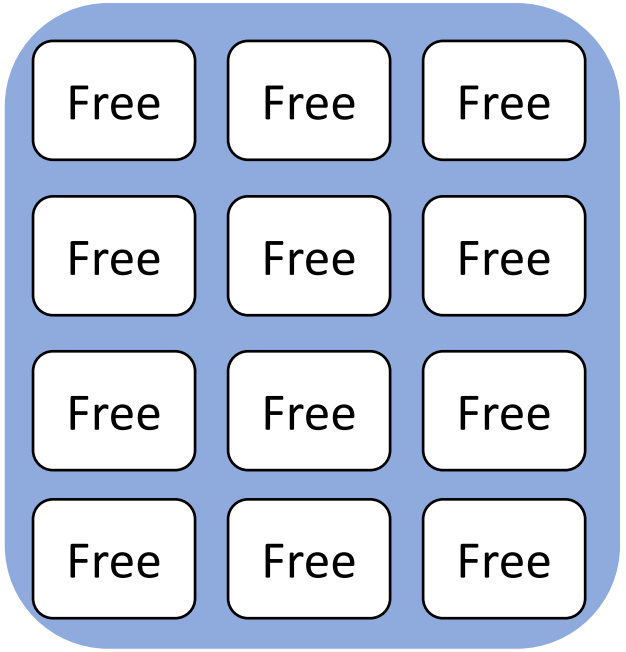
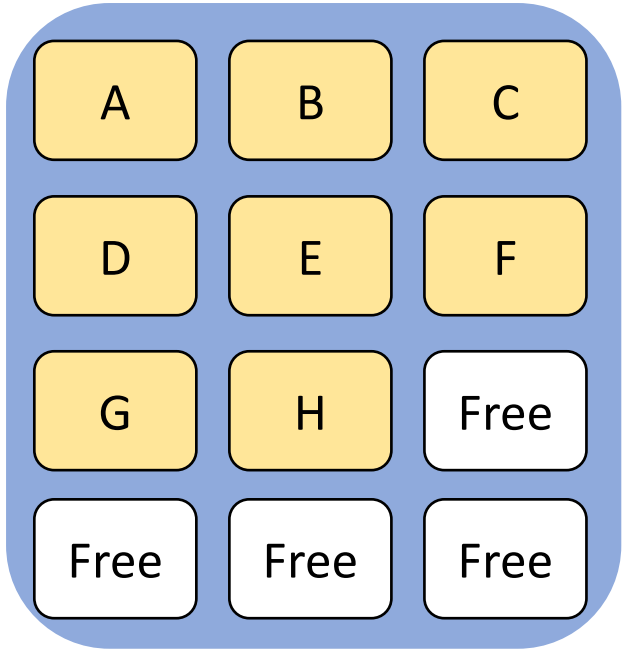


Block 1

Writes in SSD



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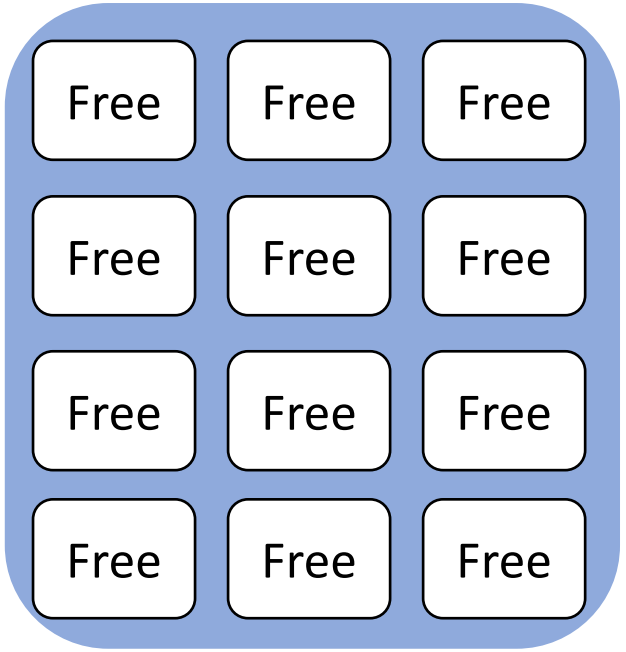


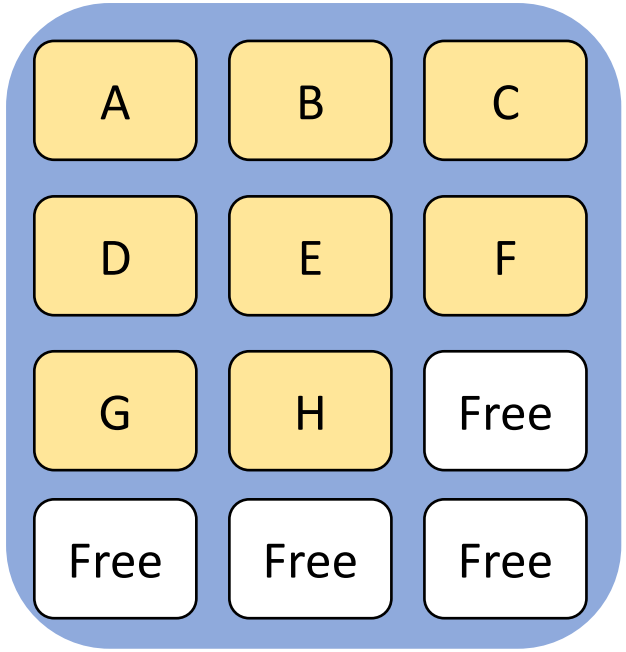
Block 1

Writing in a free page isn't costly!

Writes in SSD

Update

A, B, C, D



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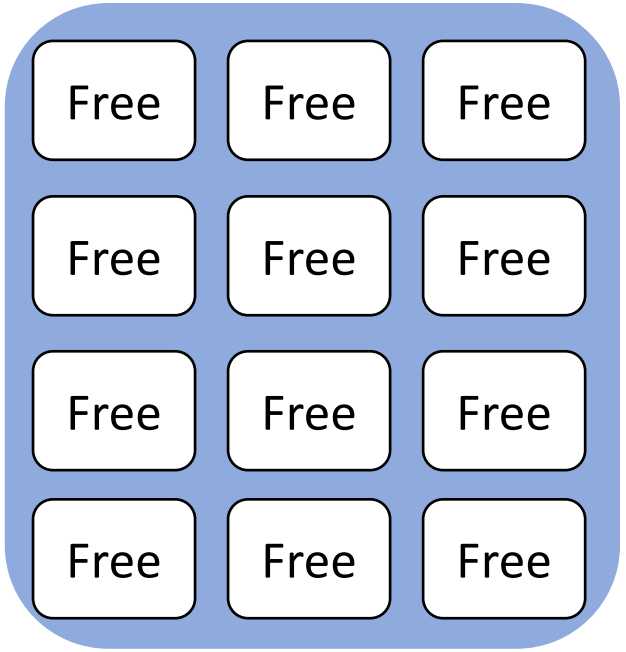

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Writes in SSD

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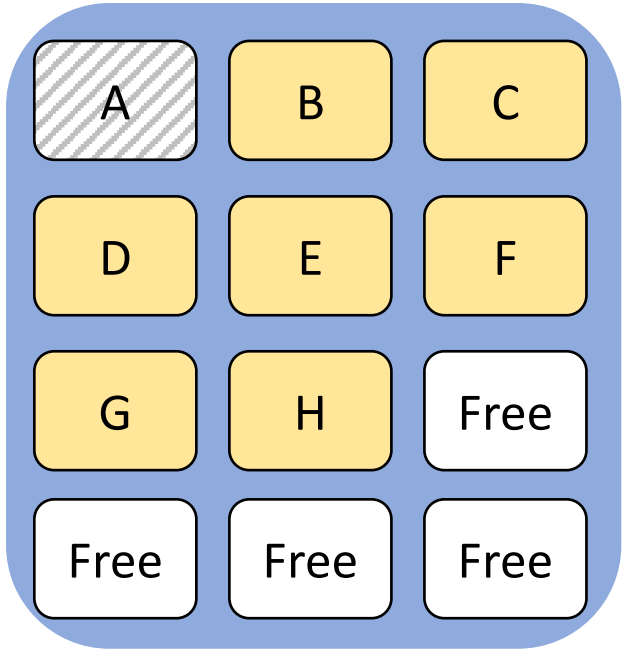

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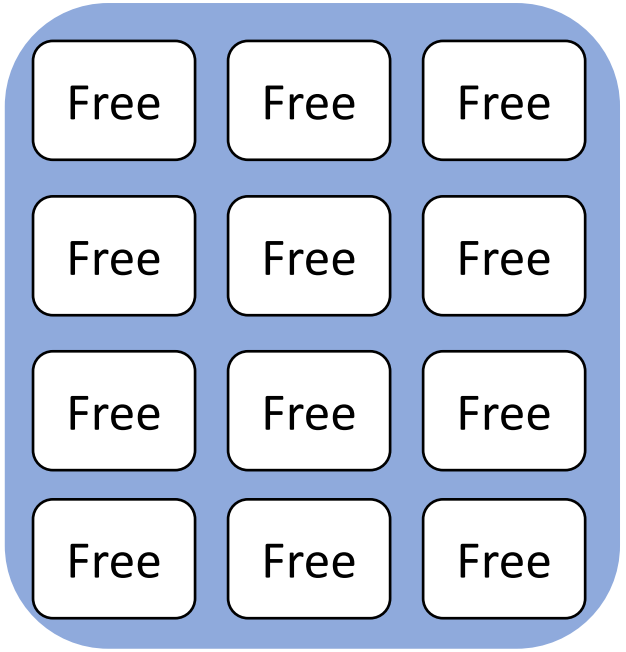

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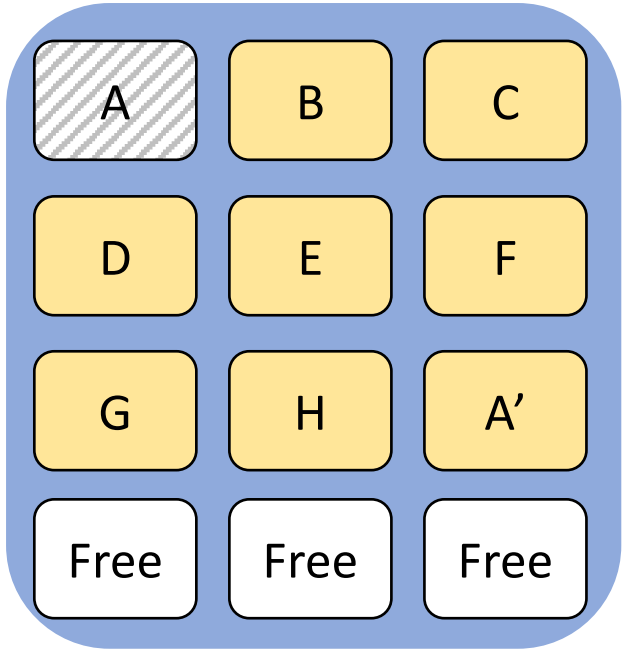

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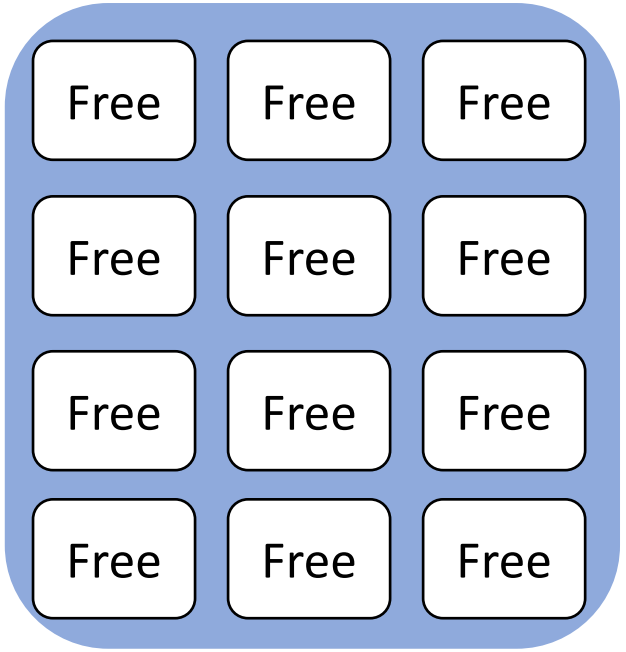

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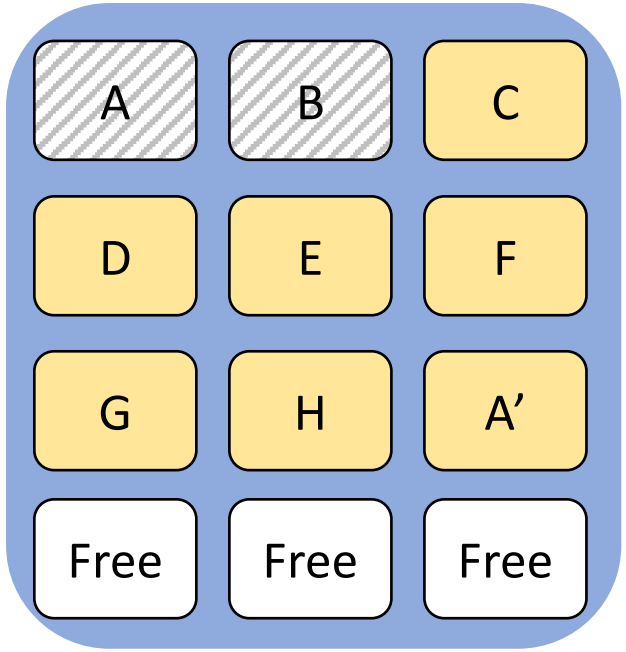

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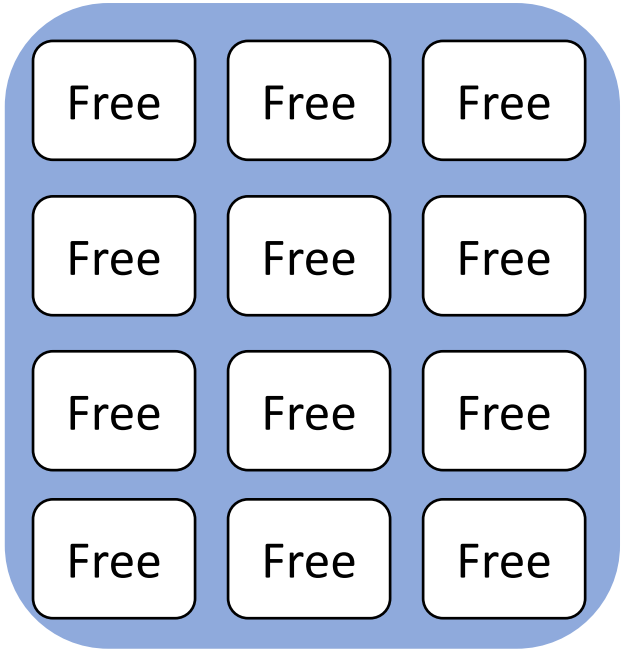

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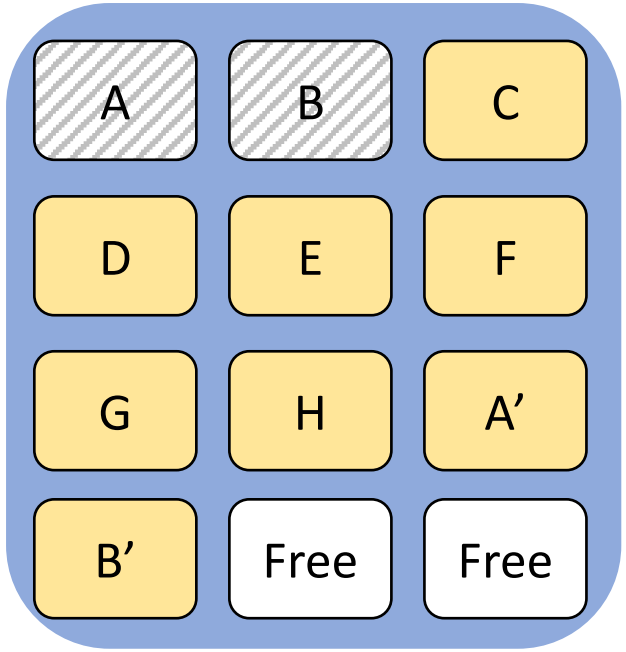

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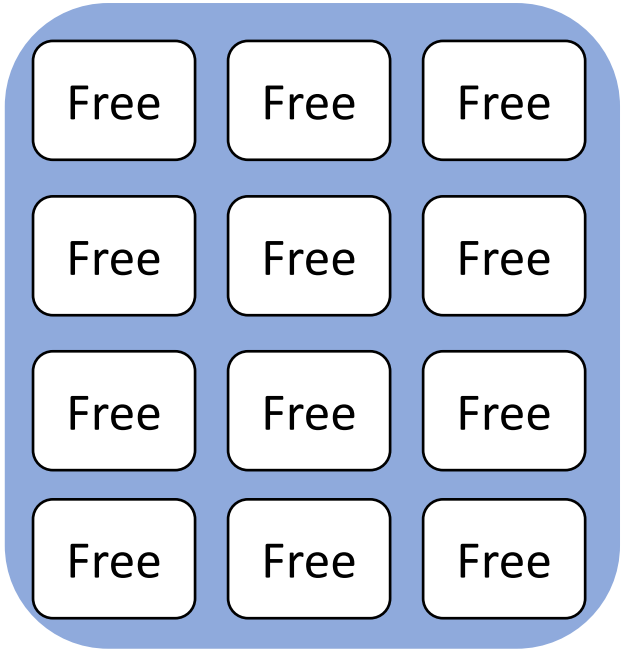

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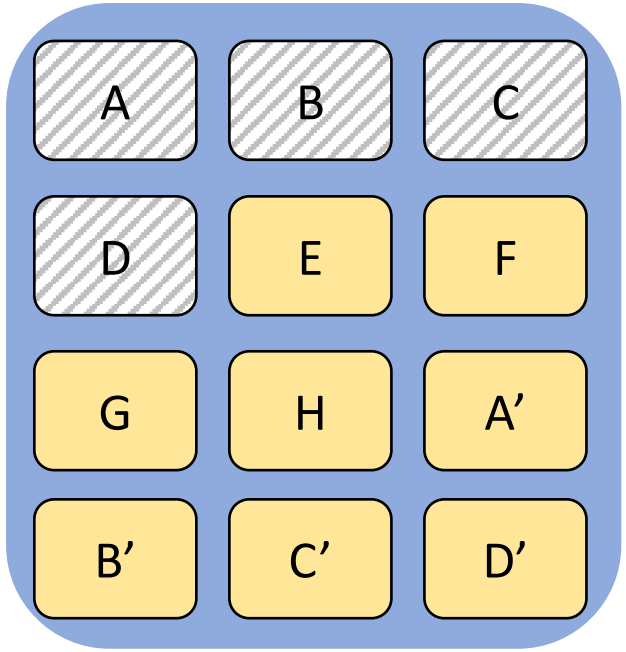

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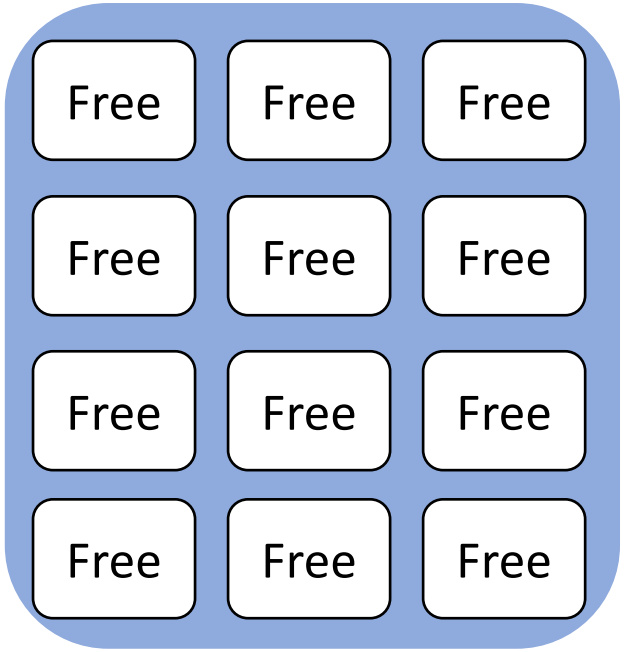
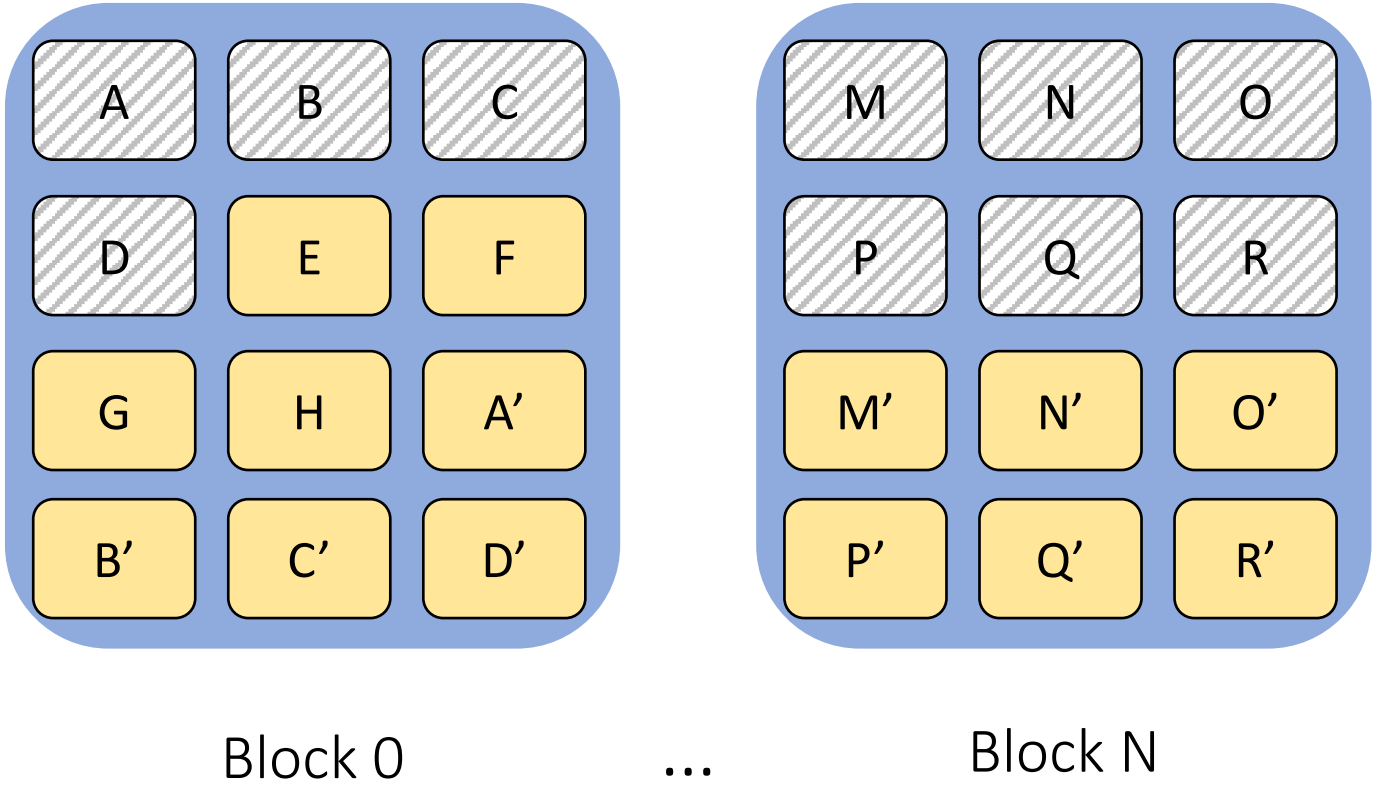


Block 1

Not all updates are costly!

Writes in SSD

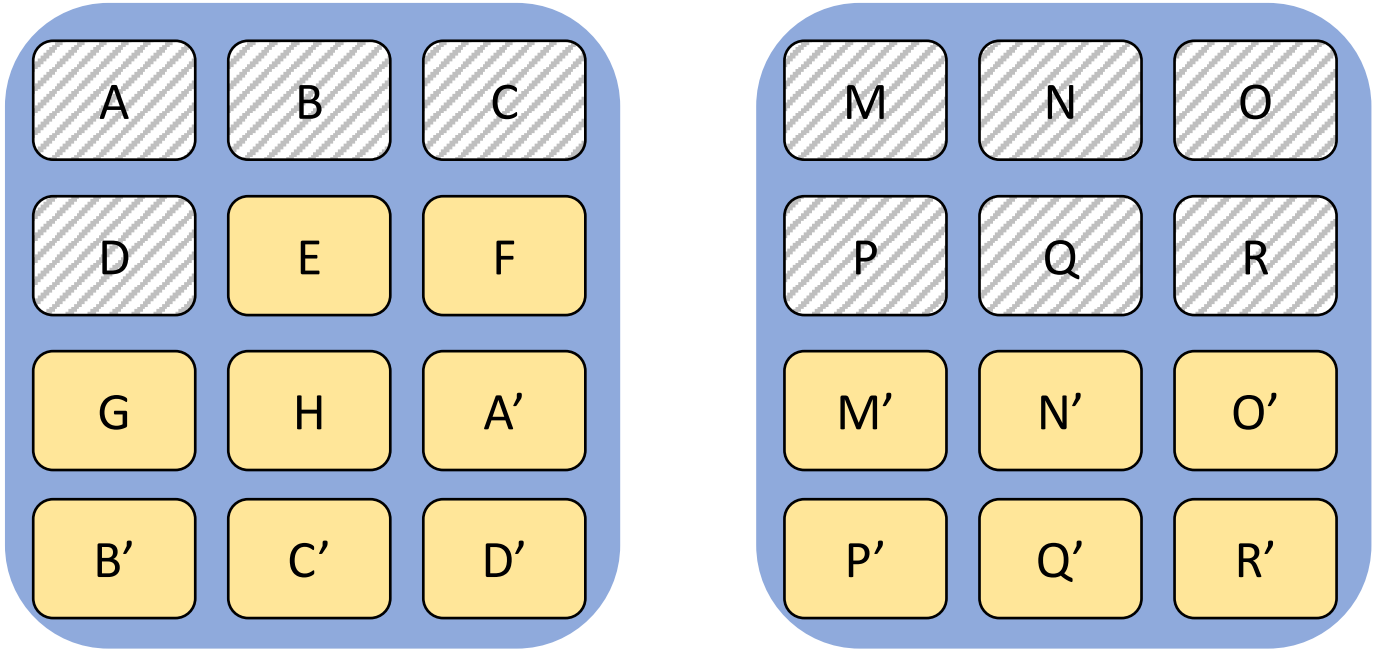
What if there is no space?



Writes in SSD

What if there is no space?

Garbage Collection!



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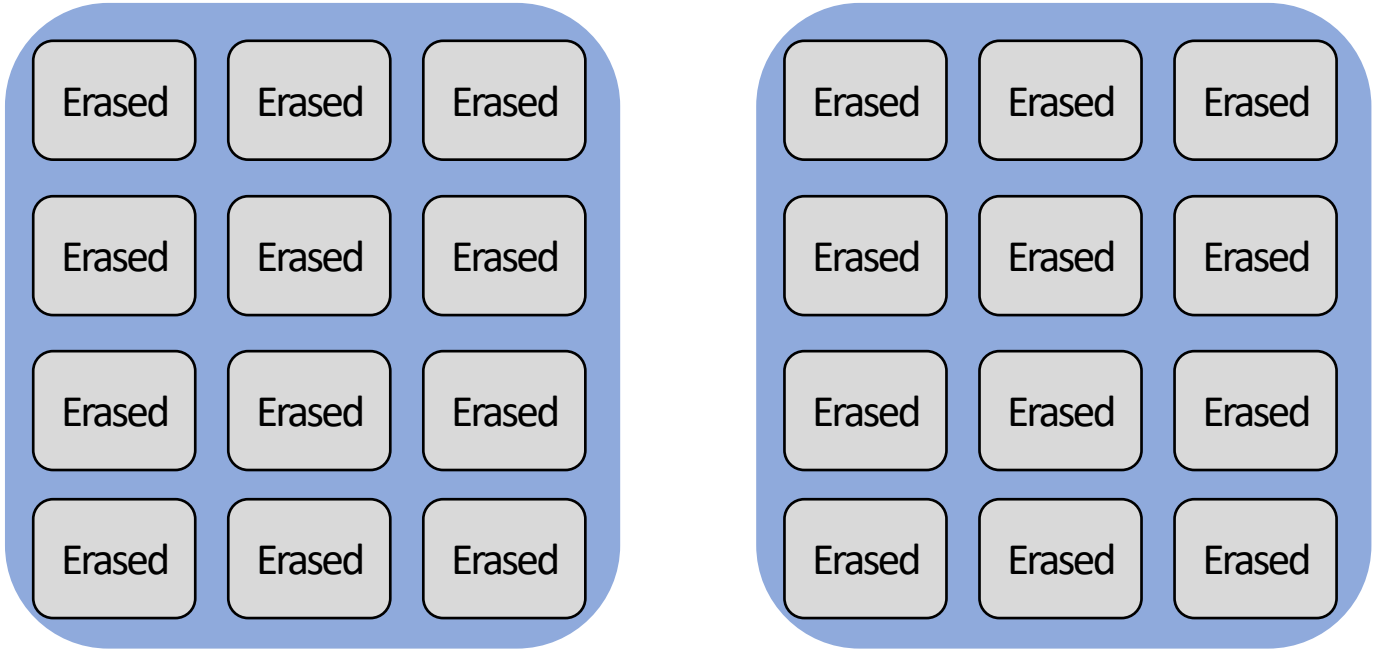
What if there is no space?

Garbage Collection!



Valid pages:

E	F	G	H	A’	B’	C’	D’	M’	N’	O’	P’	Q’	R’

Writes in SSD

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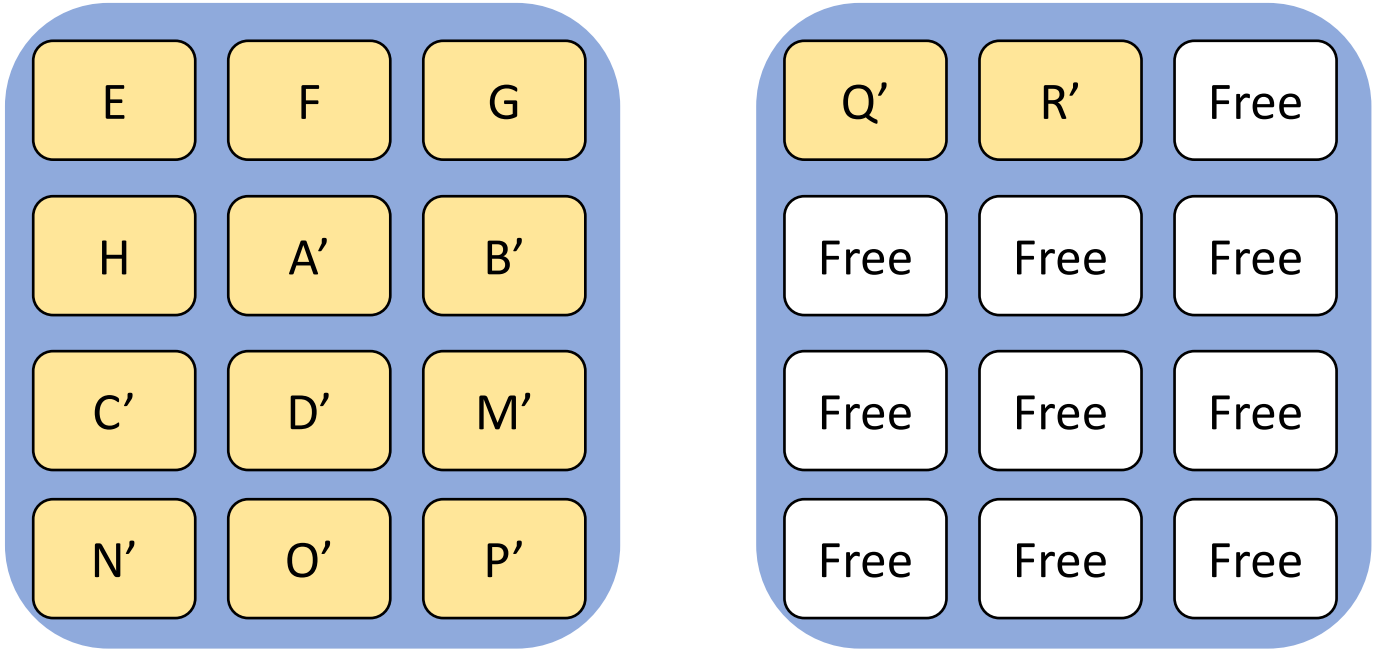

Writes in SSD

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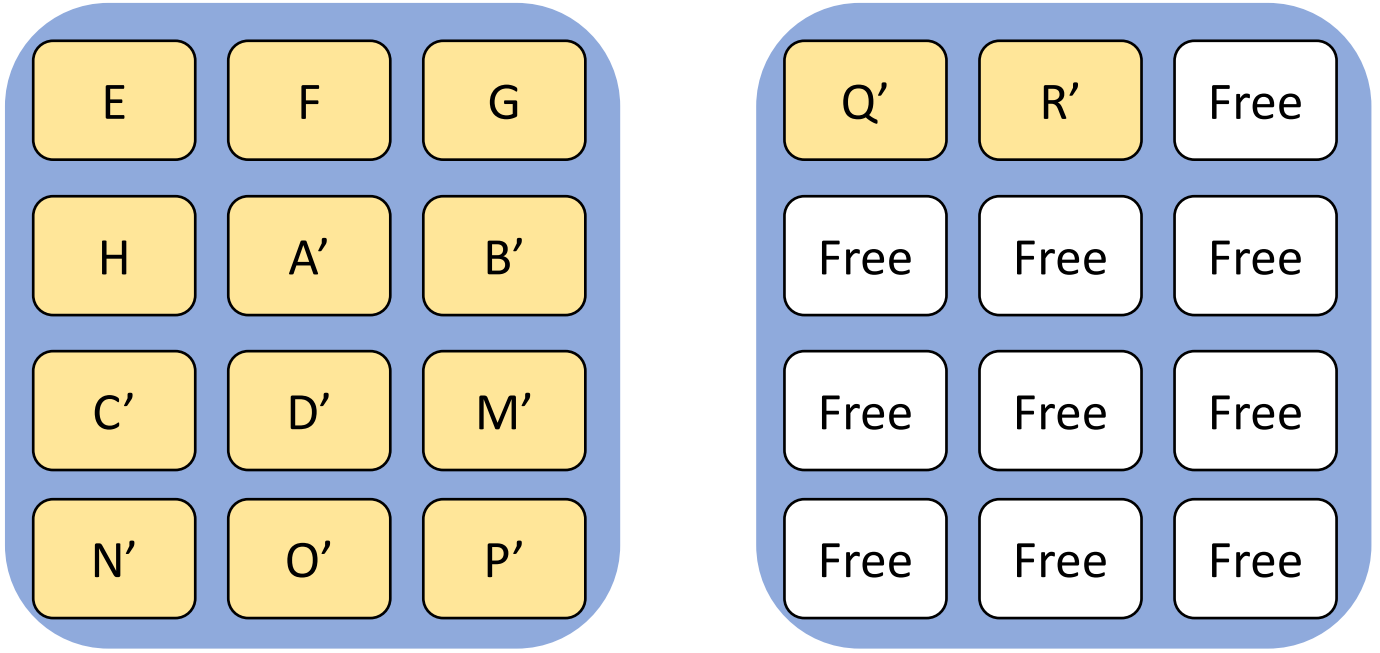

Higher average update cost (due to GC) → ***Read/Write asymmetry***

Read/Write Asymmetry - Example

Device	Advertised Rand Read IOPS	Advertised Rand Write IOPS	Advertised Asymmetry
PCIe D5-P4320	427k	36k	11.9
PCIe DC-P4500	626k	51k	12.3
PCIe P4510	465k	145k	3.2
SATA D3-S4610	92k	28k	3.3
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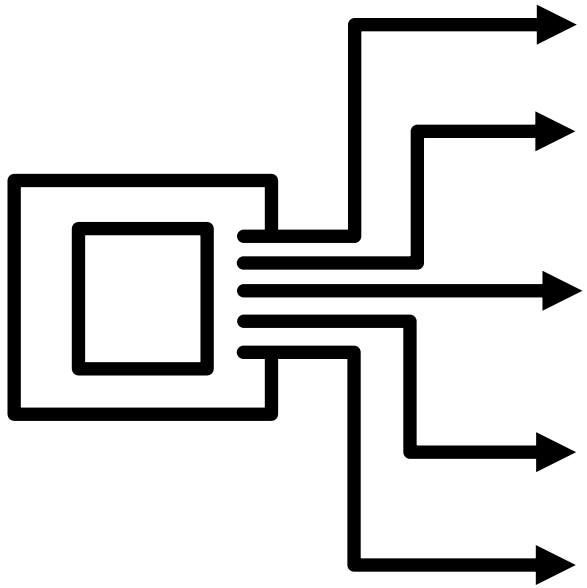
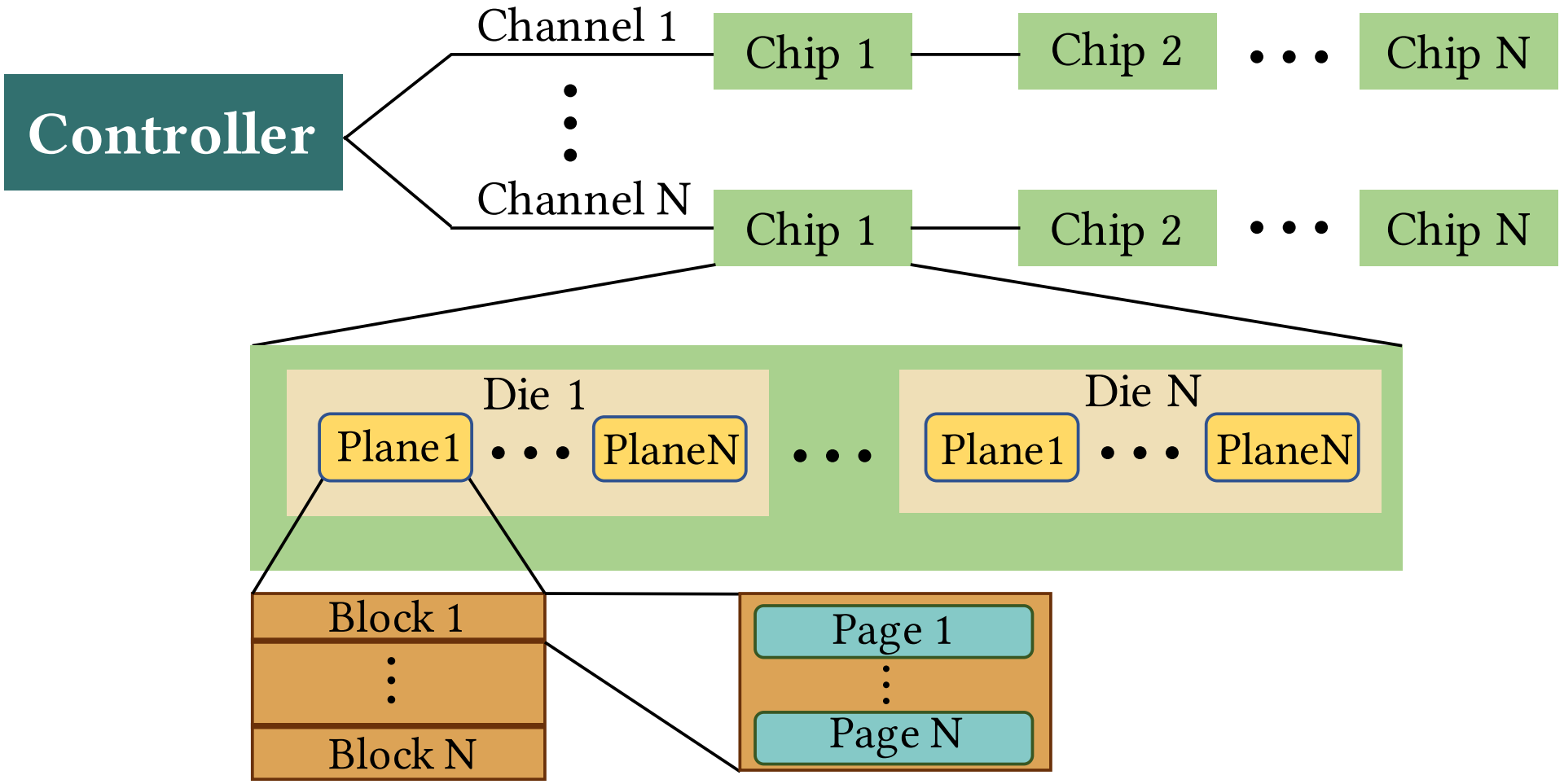
Concurrency



Internals of an SSD



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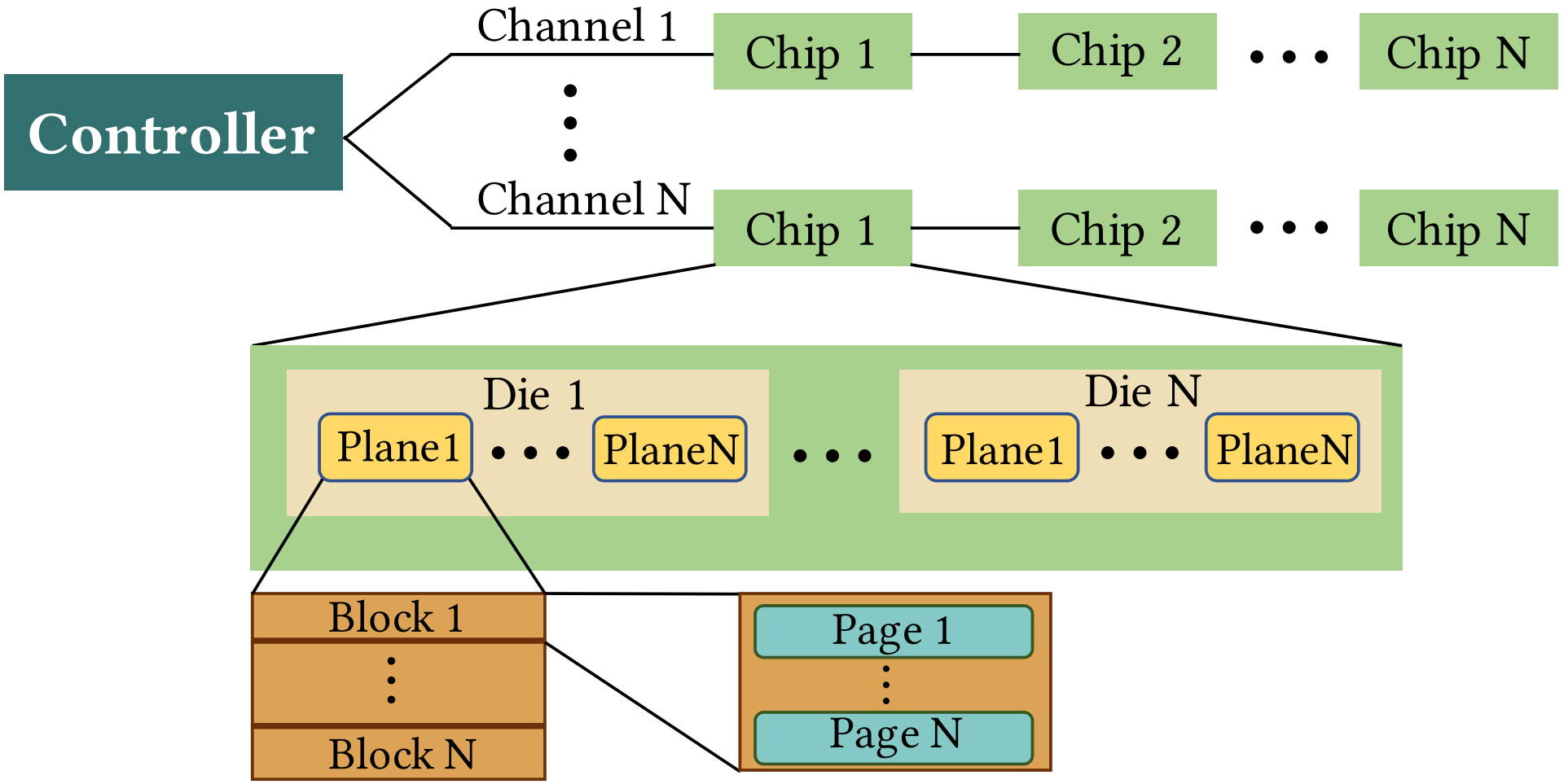
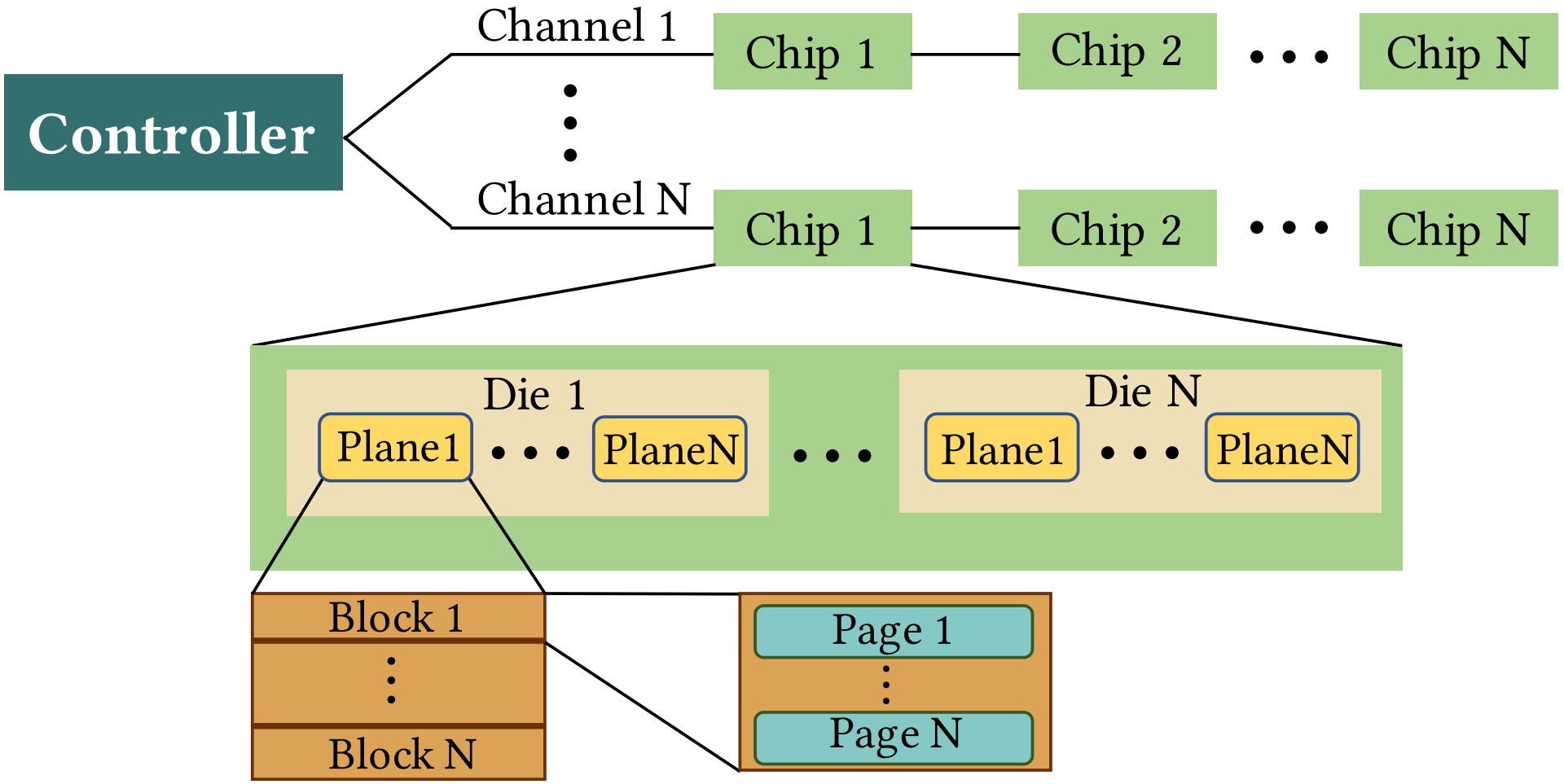


Parallelism at different levels (channel, chip, die, plane block, page)

Internals of an SSD



Essential to know the concurrency of a device!

How can we quantify

read/write asymmetry and concurrency?

Benchmarking

Benchmarking

Tools

- ✓ Custom micro-benchmarking
- ✓ Fio
- ✓ Intel's SPDK

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Setup

with and **without** FS

Benchmarking

Devices

- ✓ Optane SSD
- ✓ PCIe SSD **with** & **w/o** FS
- ✓ SATA SSD

Benchmarking

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- ✓ Optane SSD
- ✓ PCIe SSD **with** & **w/o** FS
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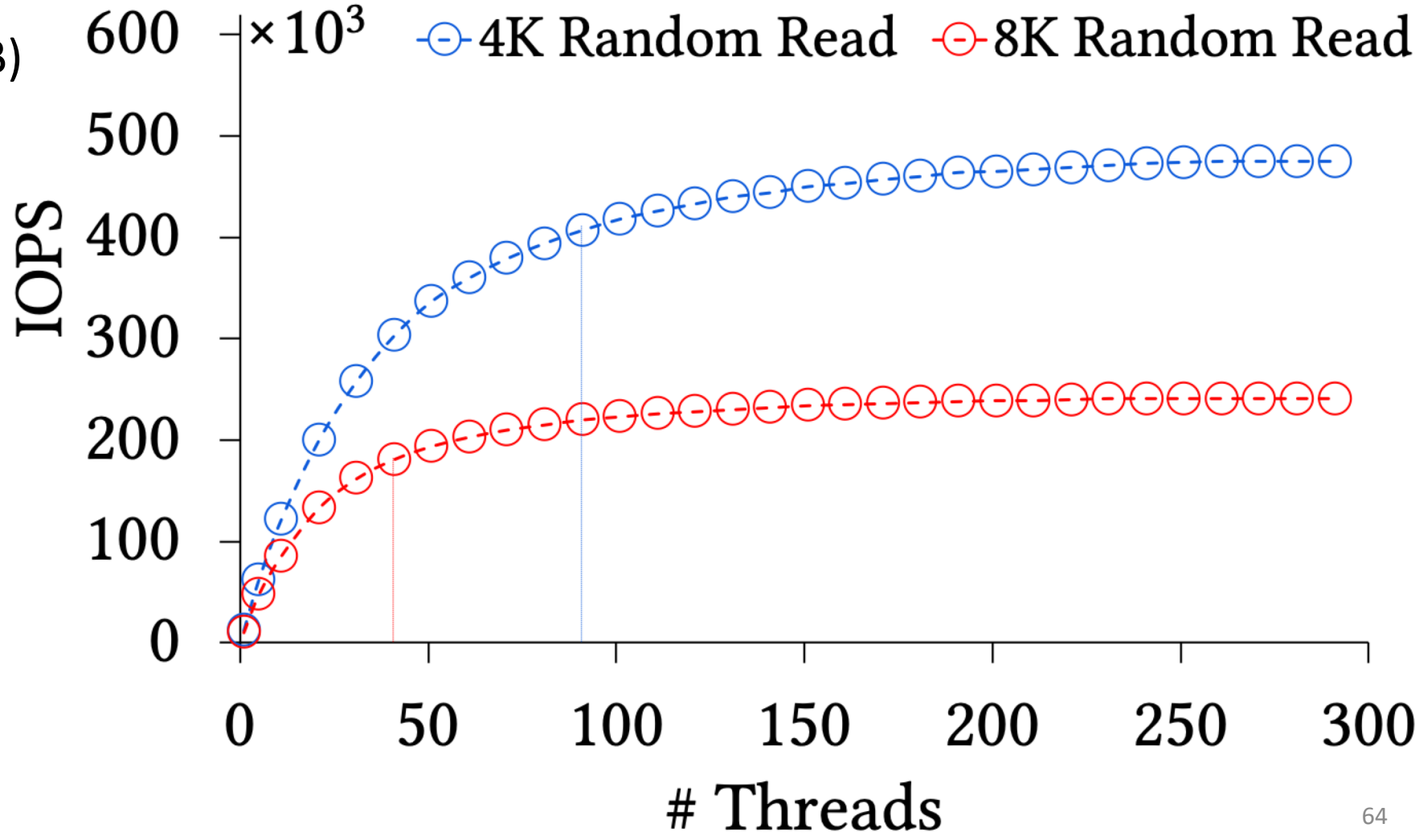
Setup

- ✓ Increase **#threads** issuing I/Os
- ✓ Report: **latency** and **throughput**

Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)



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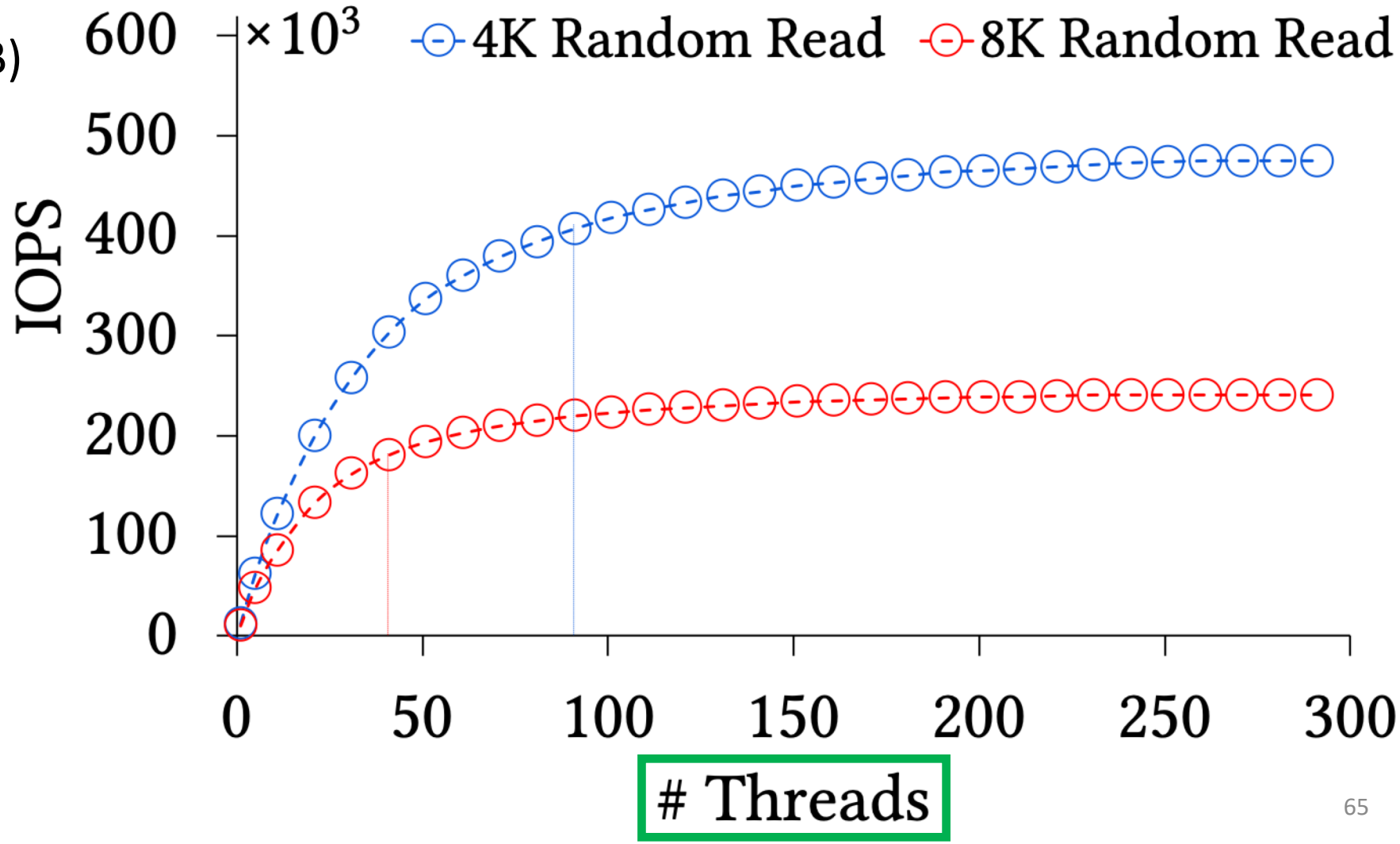

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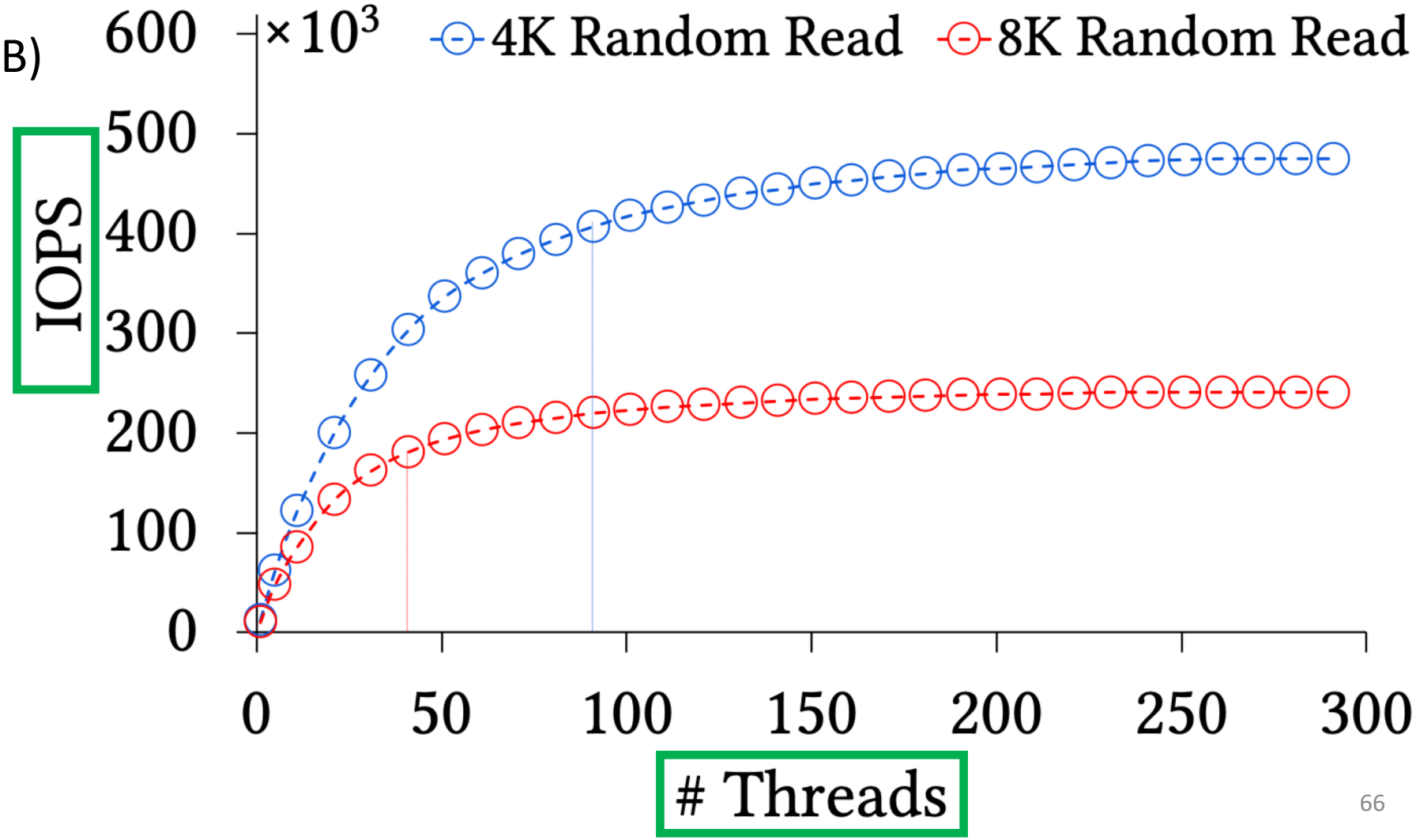

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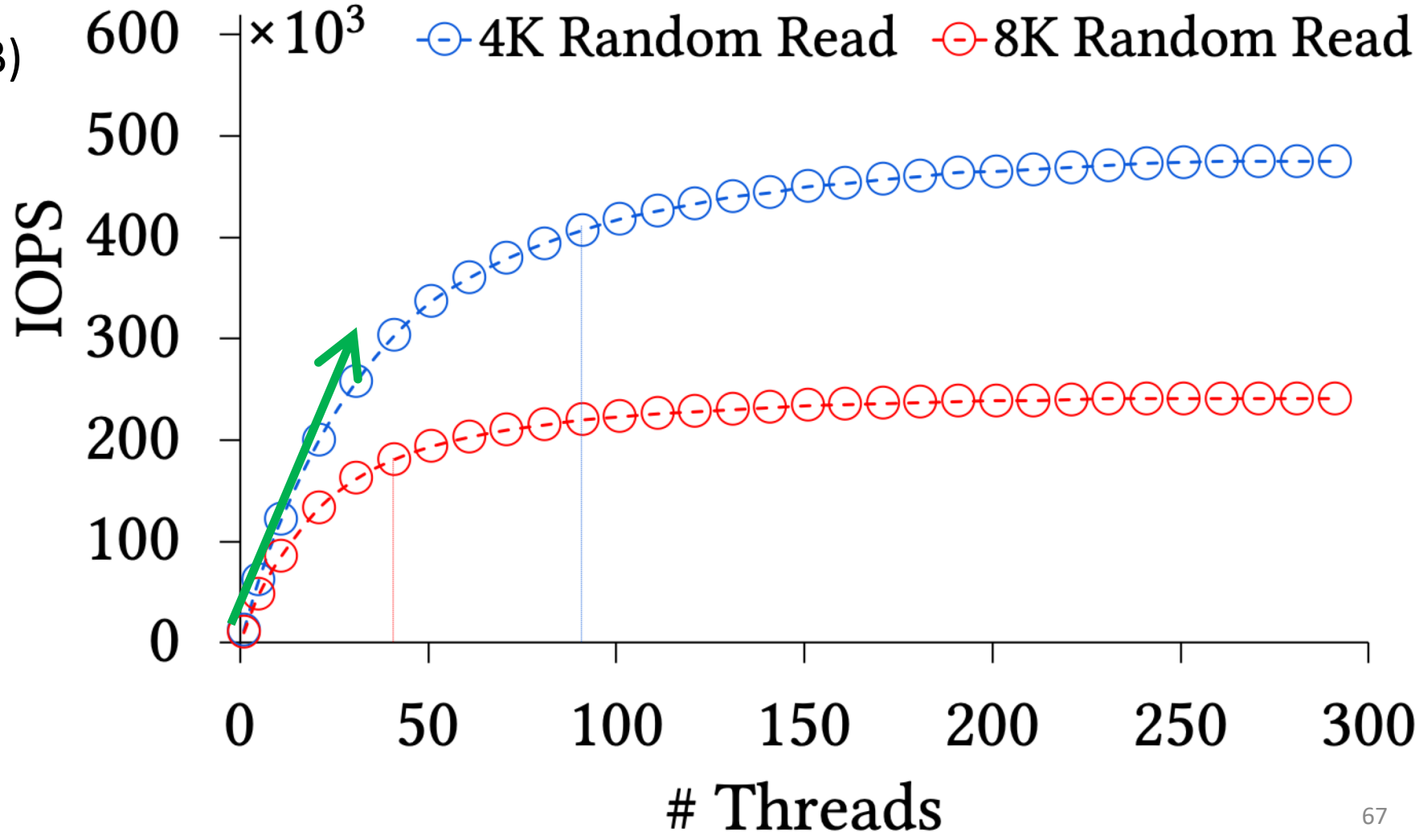

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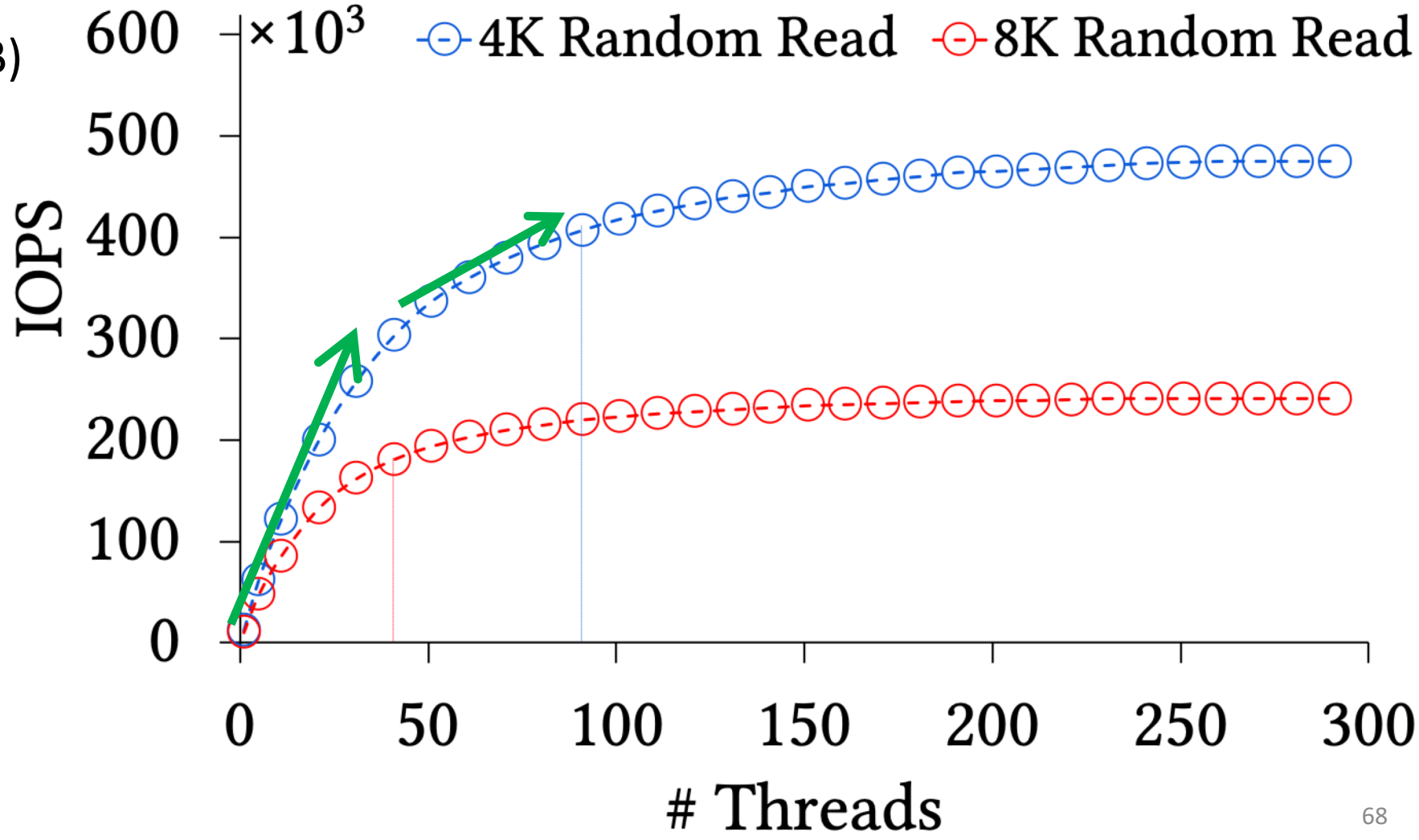

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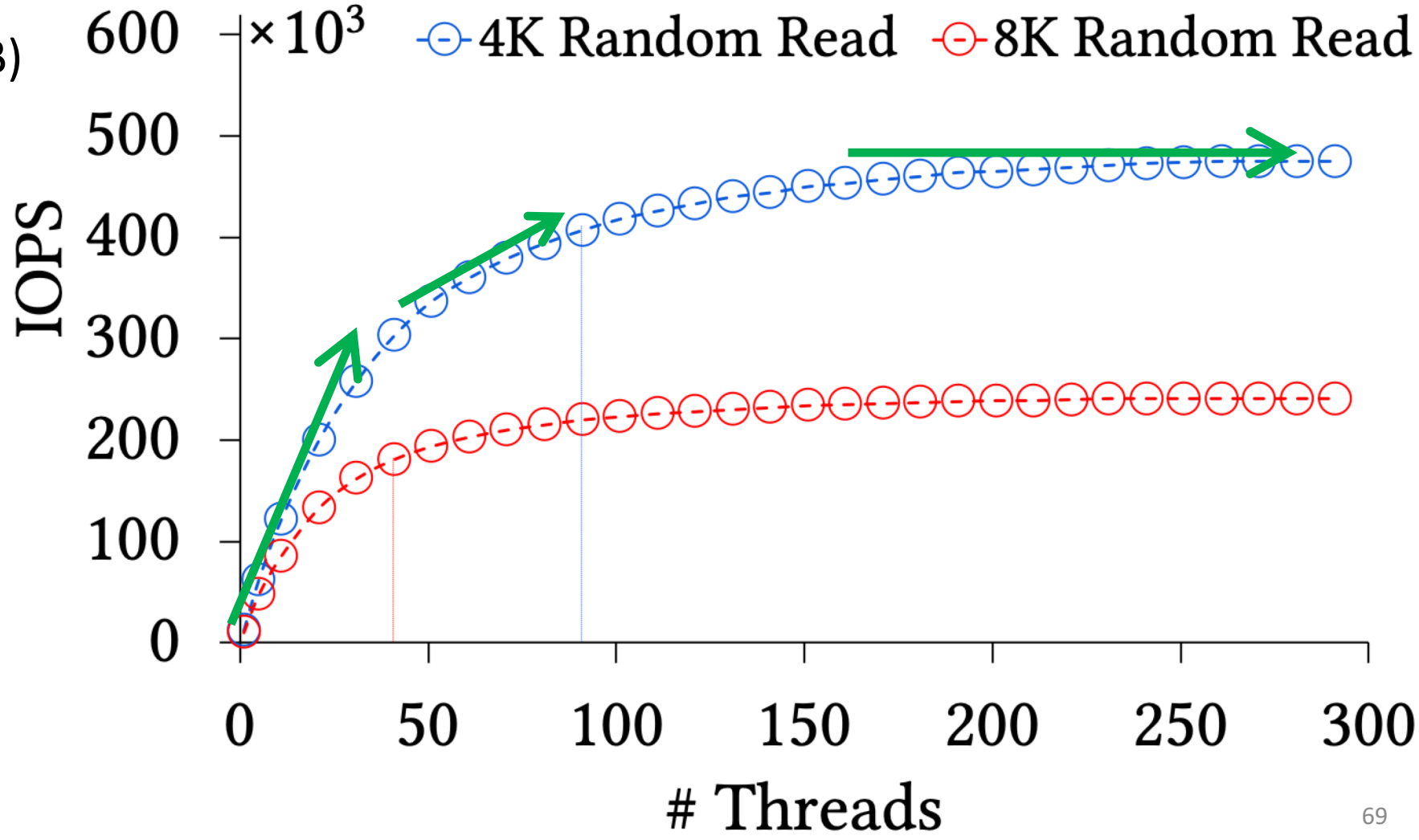

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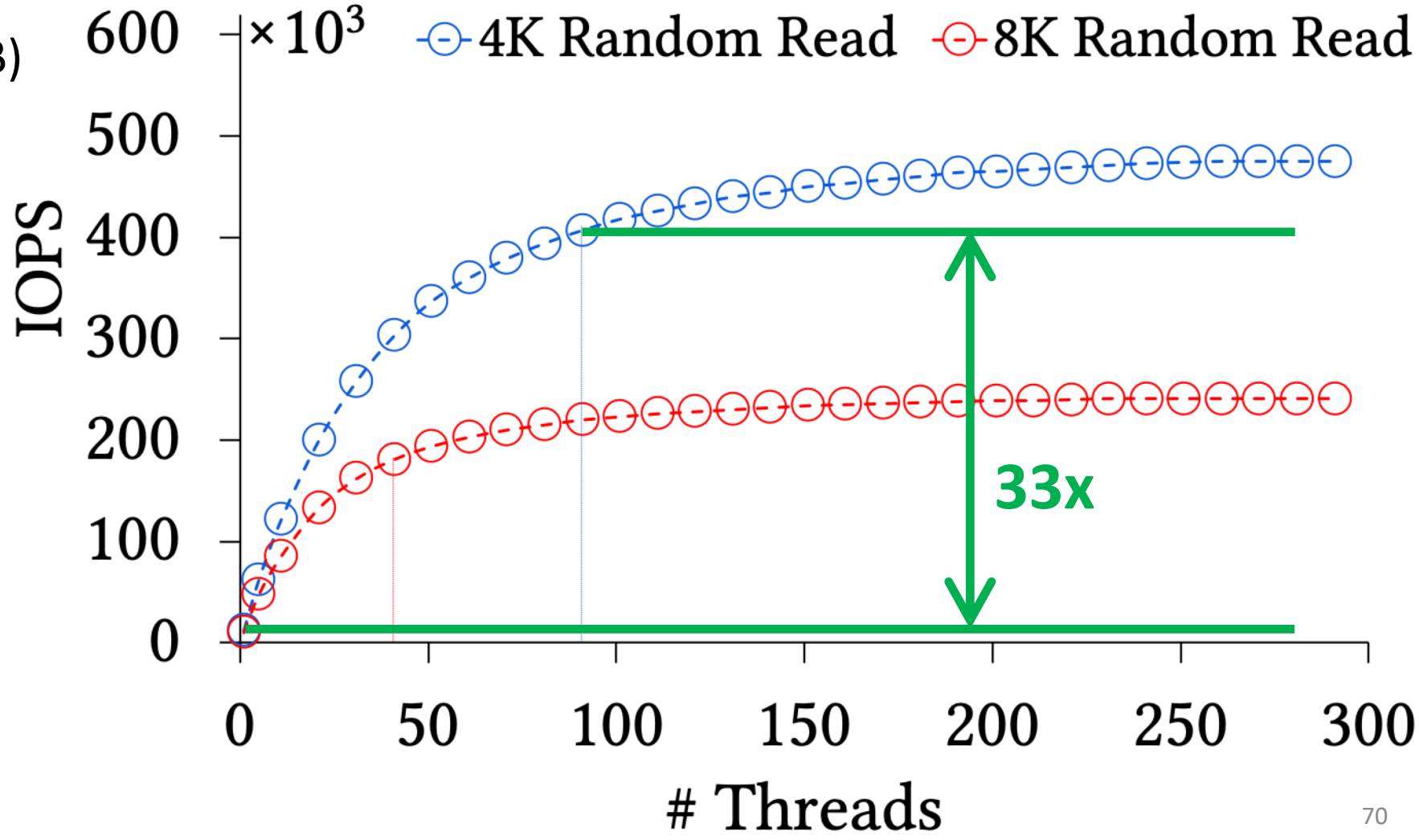

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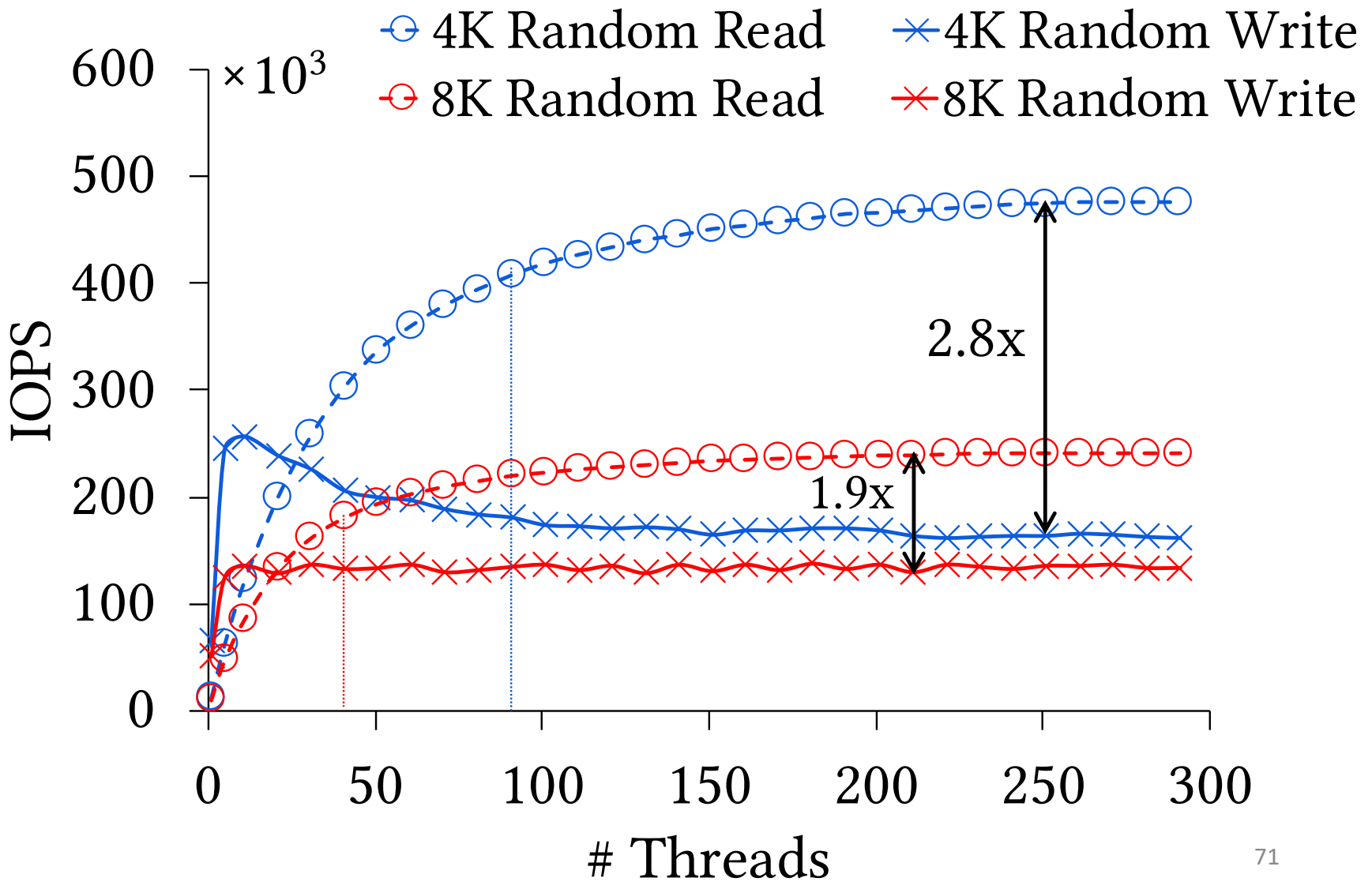

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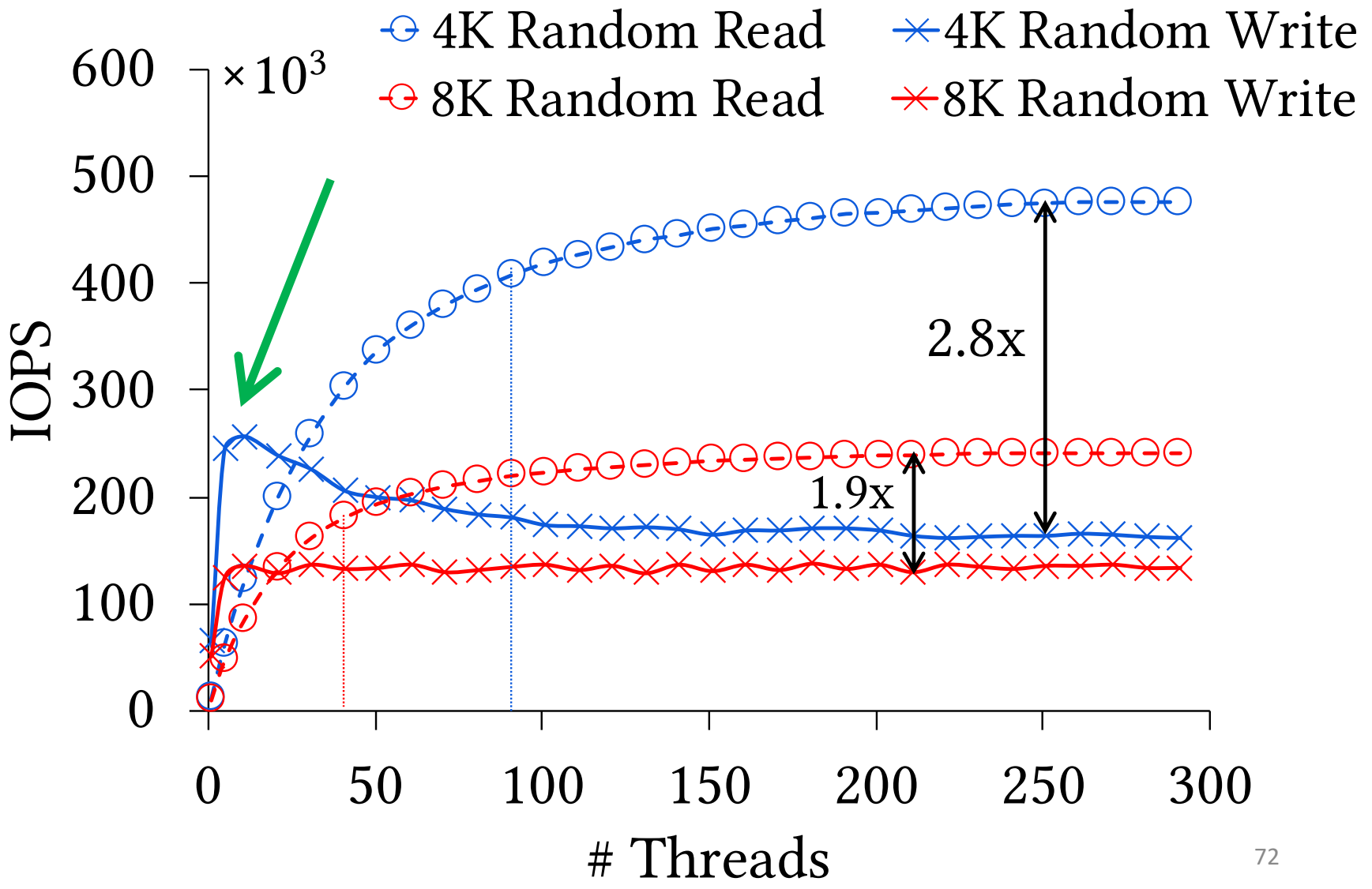

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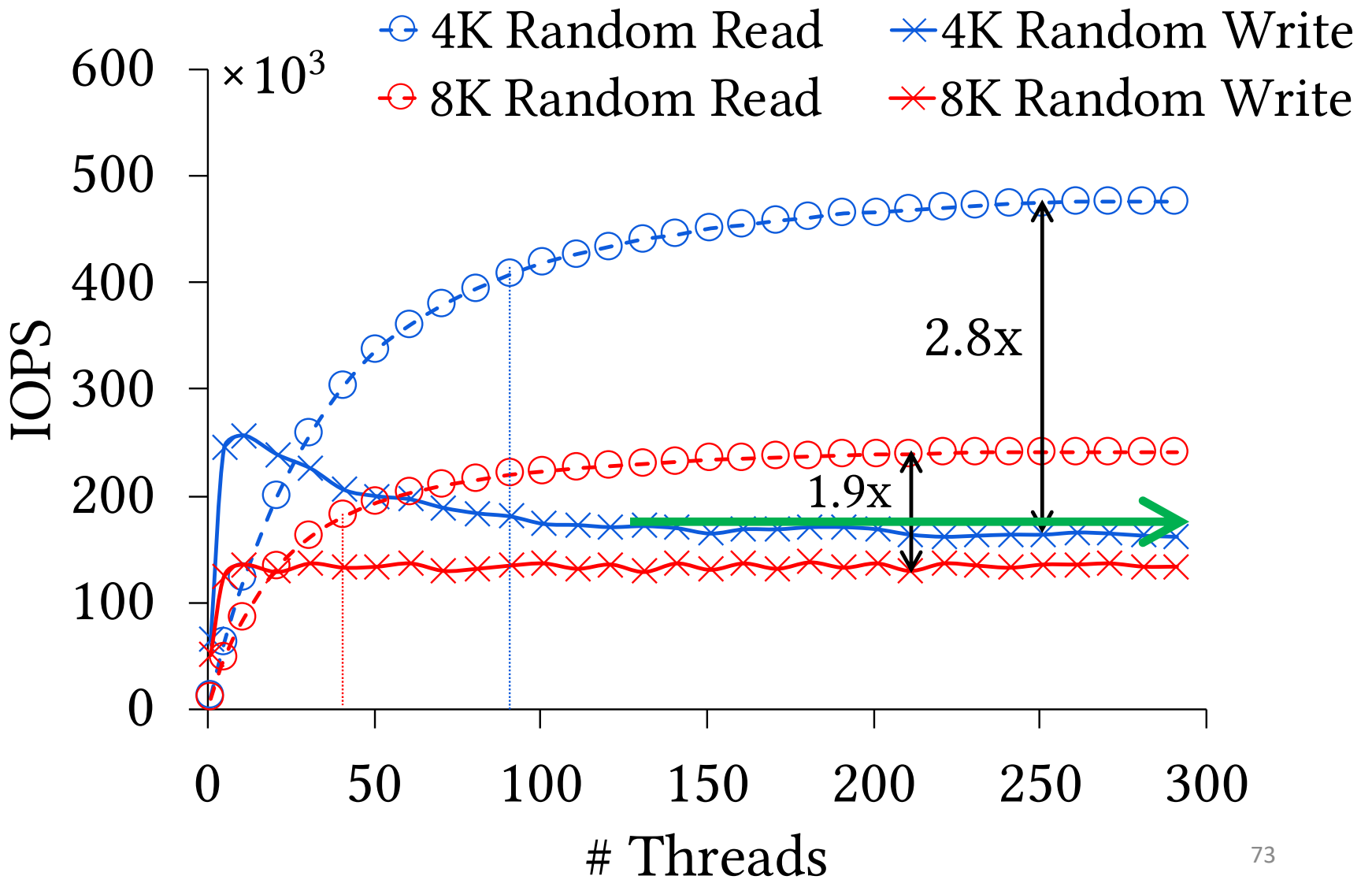


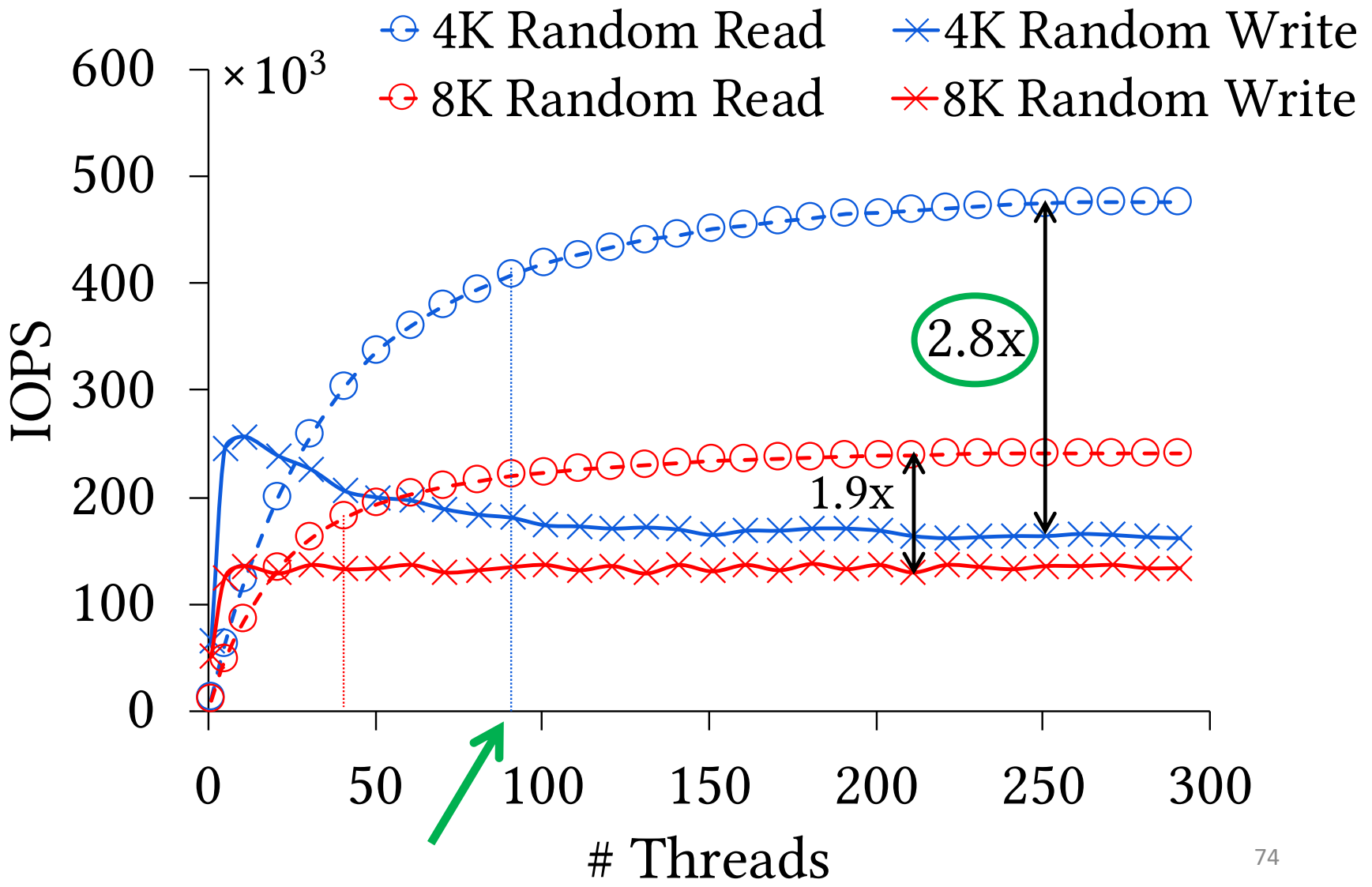
Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

For 4K random read,

Asymmetry: 2.8

Concurrency: 80



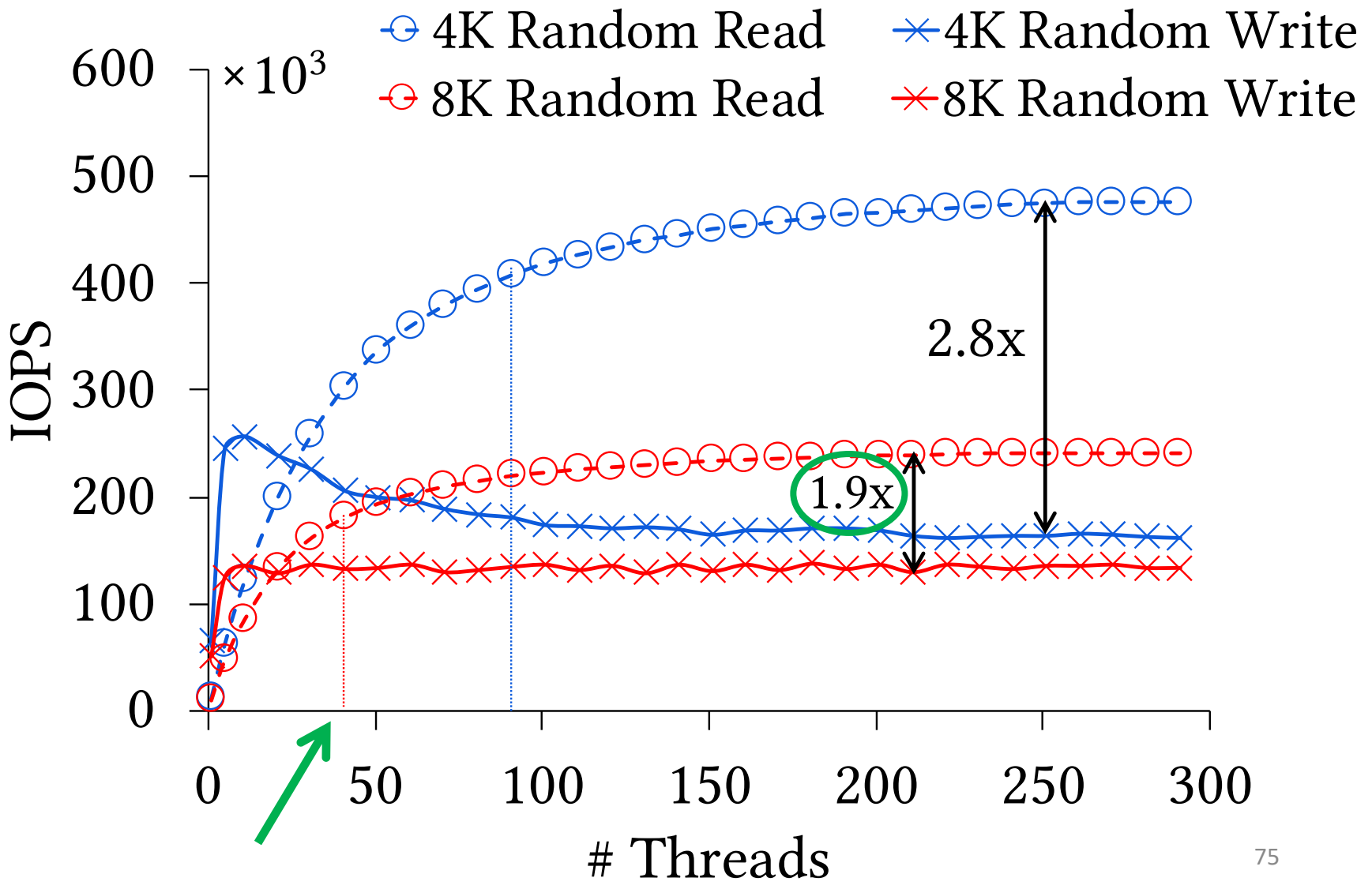
Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

For 8K random read,

Asymmetry: 1.9

Concurrency: 40



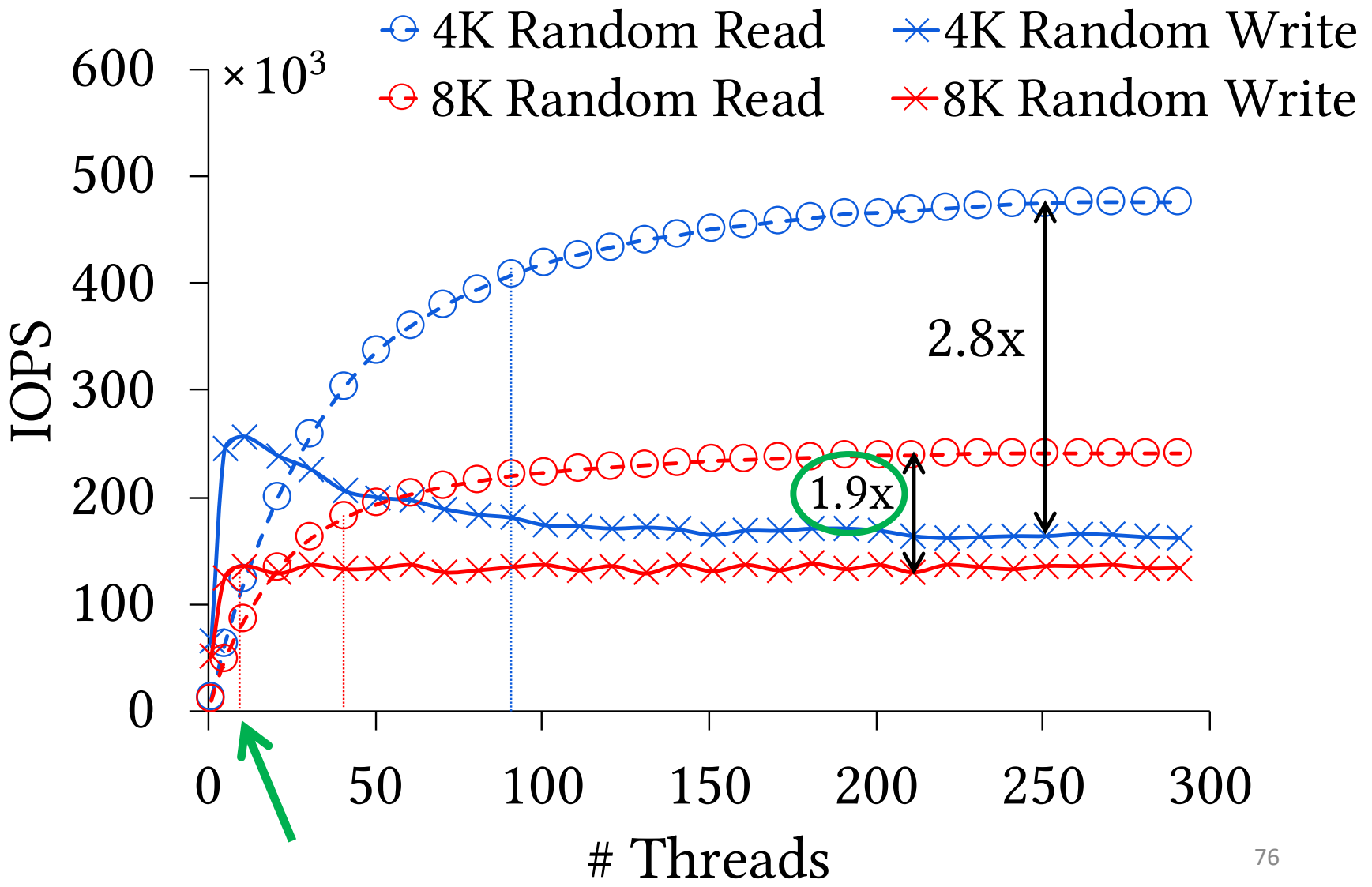
Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

For 8K random write,

Asymmetry: 1.9

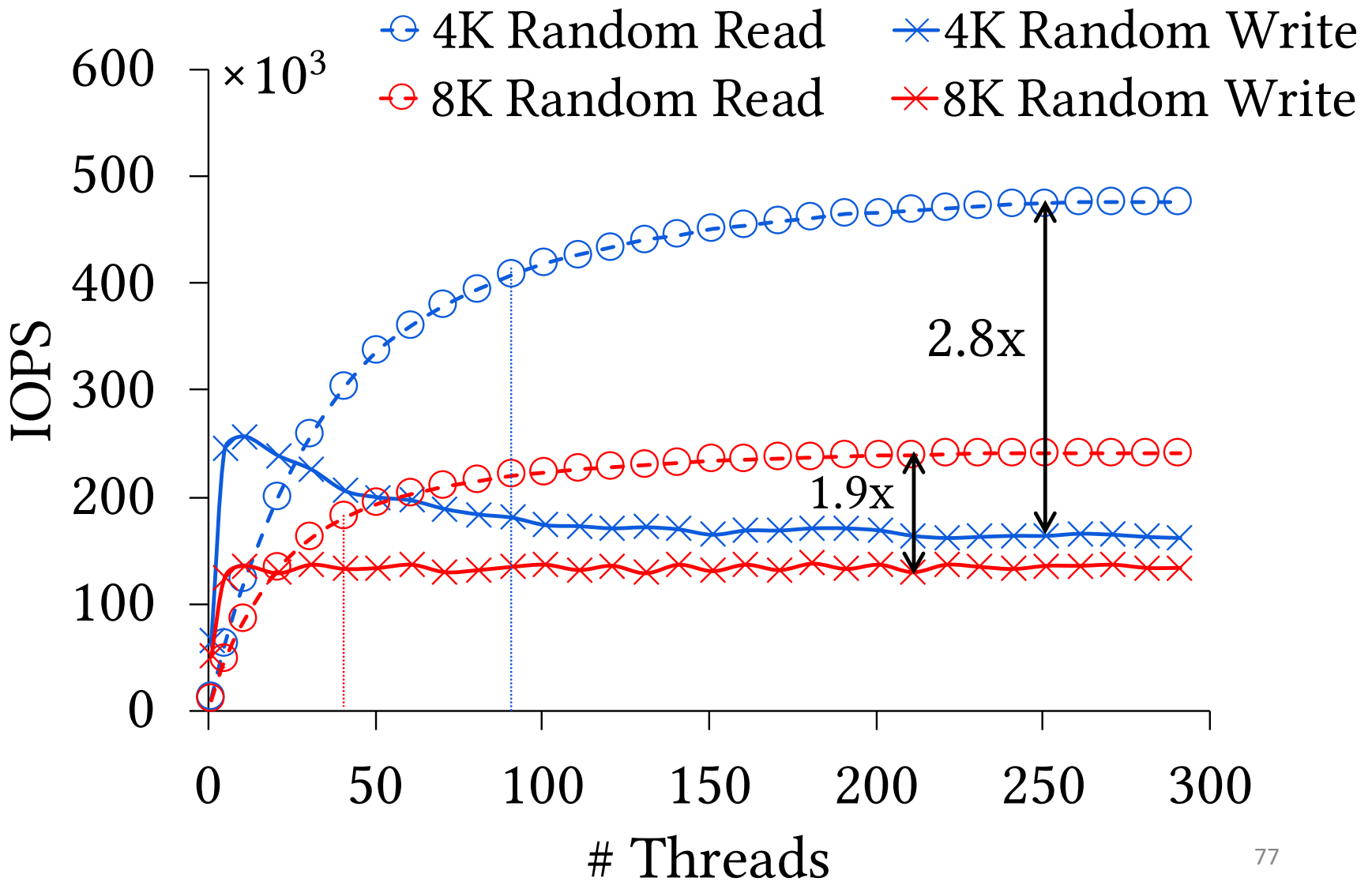
Concurrency: 7



Measuring Asymmetry/Concurrency (With FS)

Device
PCIe SSD - P4510 (1TB)

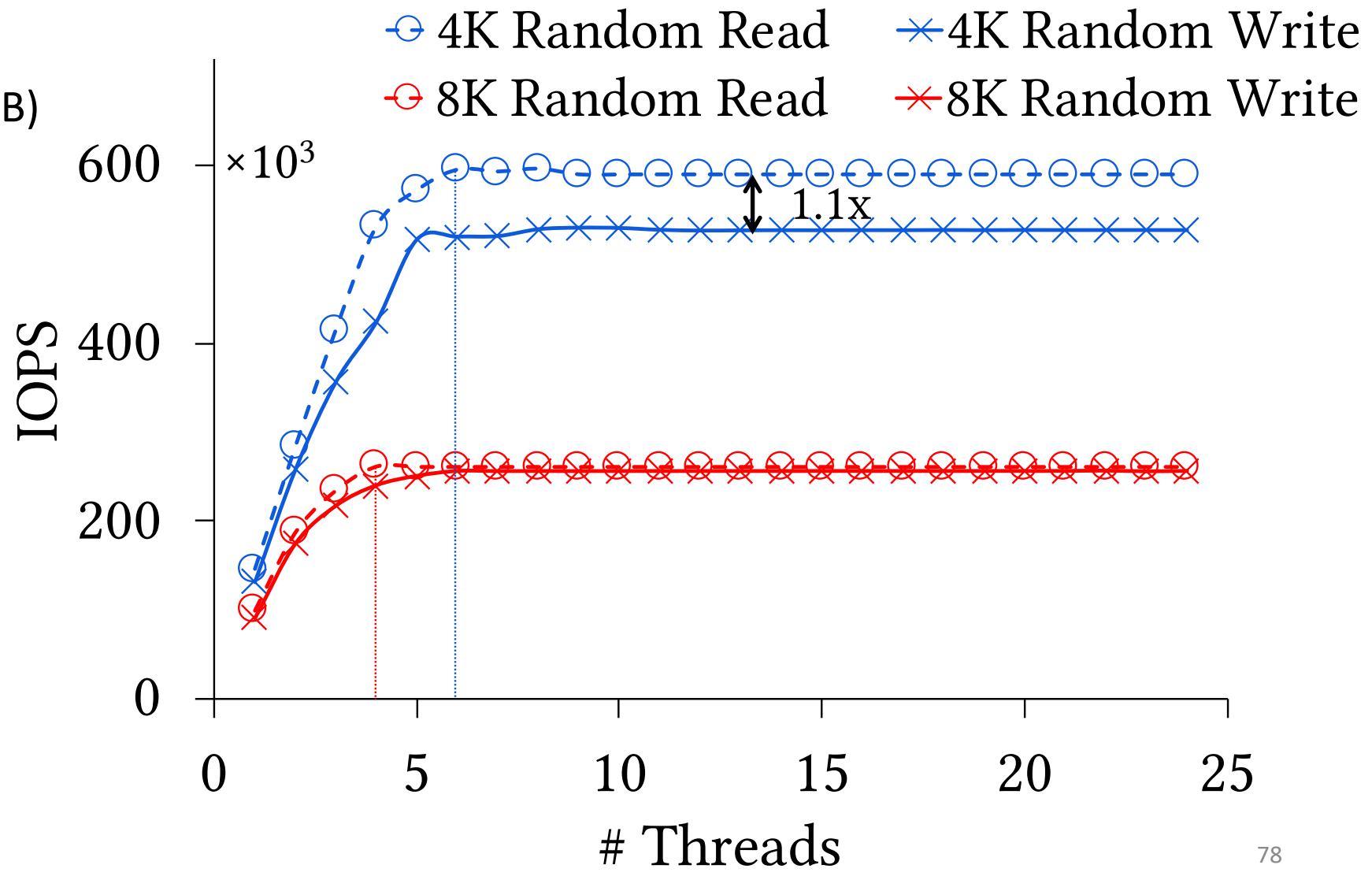
Asymmetry and concurrency depends on request type and access granularity.



Measuring Asymmetry/Concurrency (With FS)

Device

Optane SSD - P4800X (375GB)



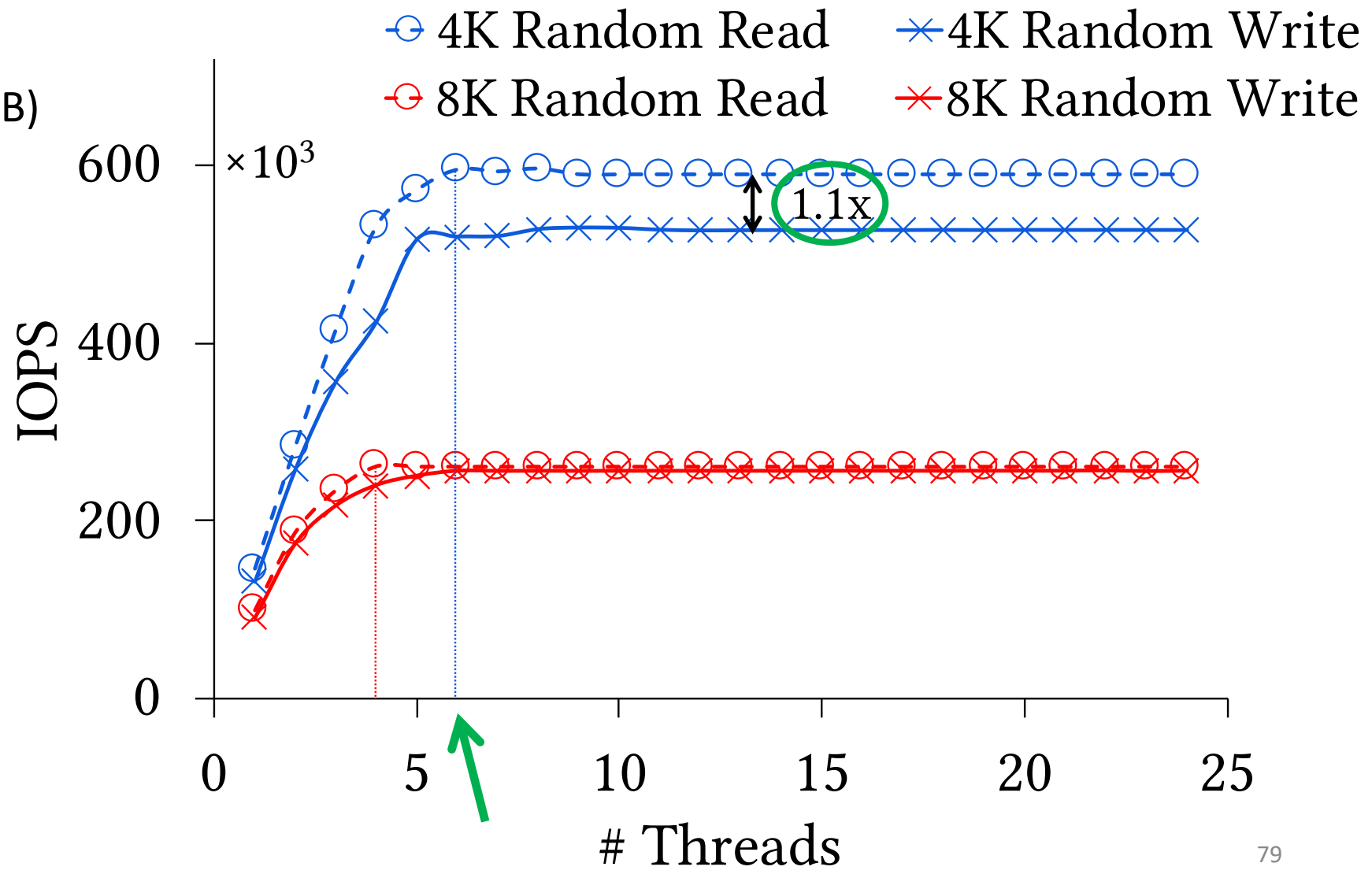
Measuring Asymmetry/Concurrency (With FS)

Device
Optane SSD - P4800X (375GB)

For 4K random read,

Asymmetry: 1.1

Concurrency: 6



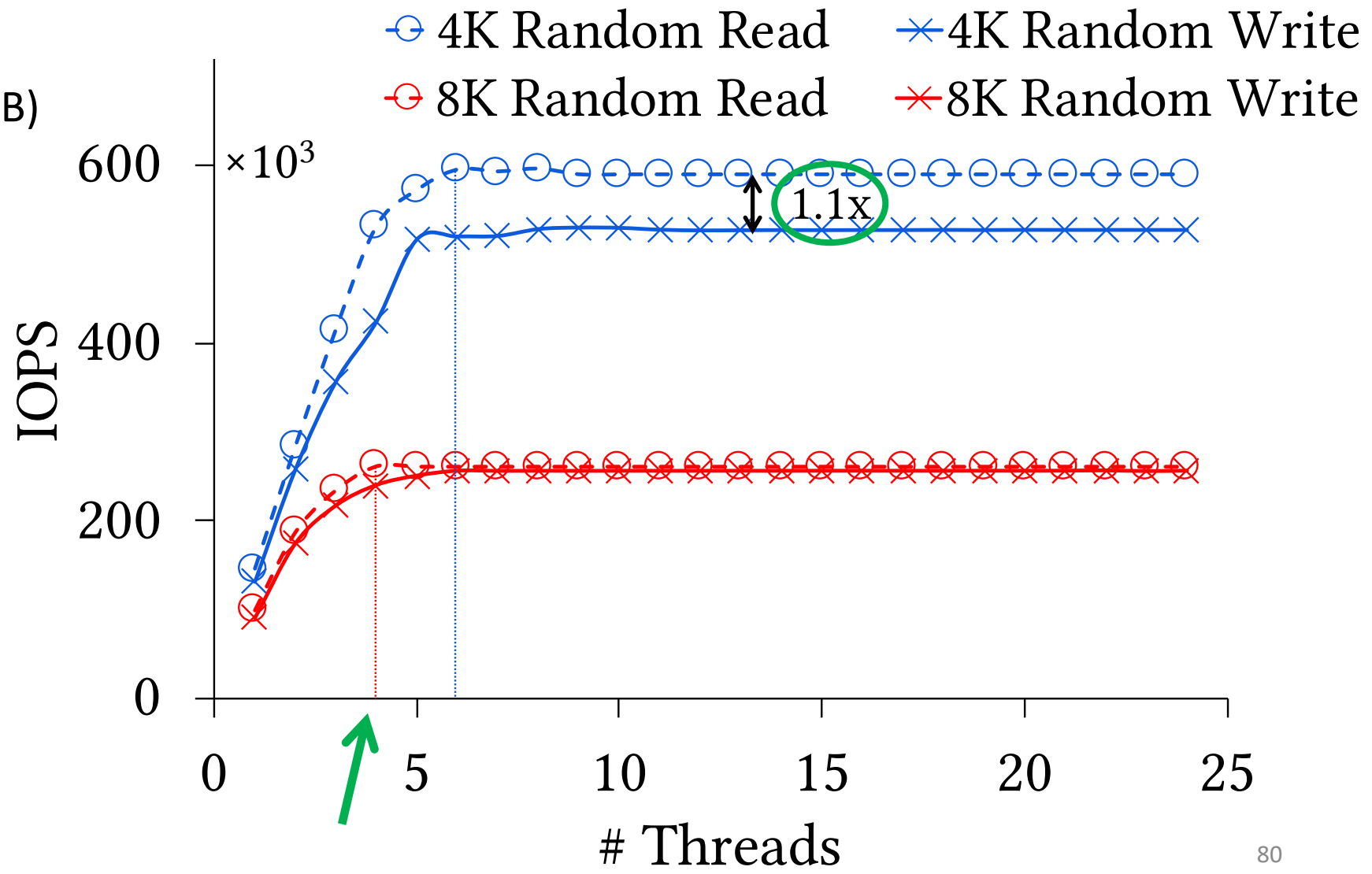
Measuring Asymmetry/Concurrency (With FS)

Device
Optane SSD - P4800X (375GB)

For 8K random read,

Asymmetry: 1.1

Concurrency: 4



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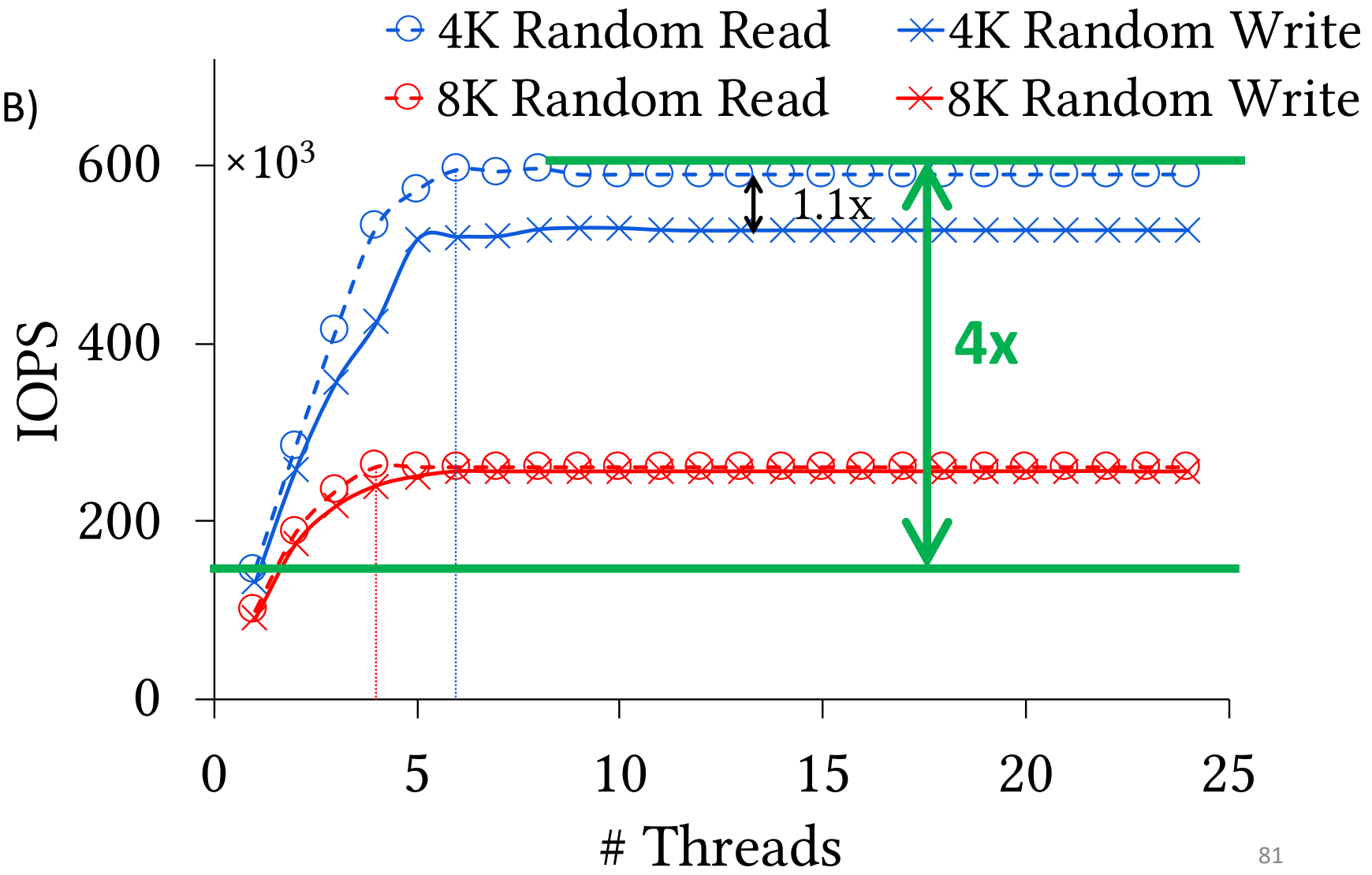
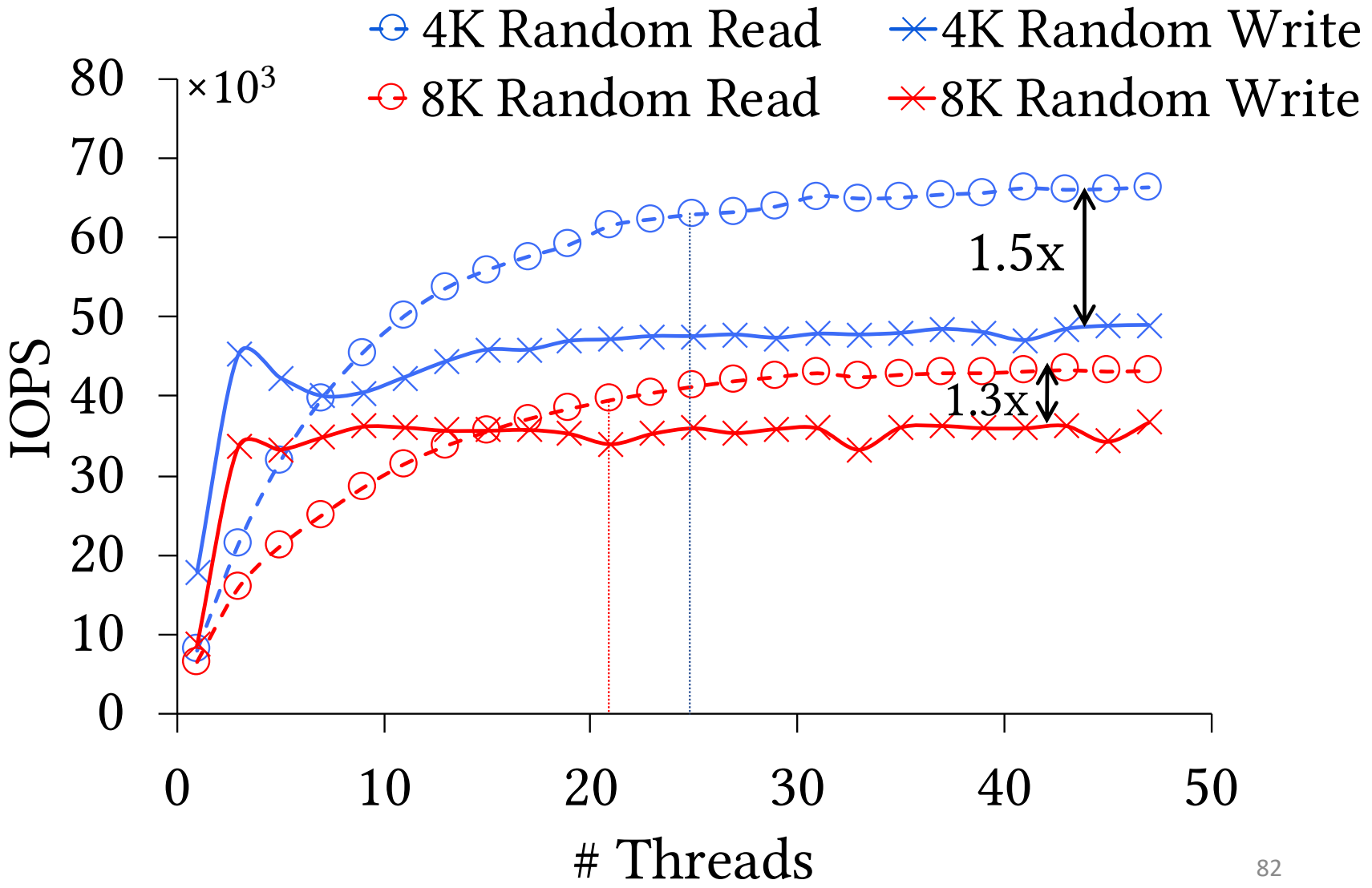


Measuring Asymmetry/Concurrency (With FS)

Device
SATA SSD - S4610 (240GB)



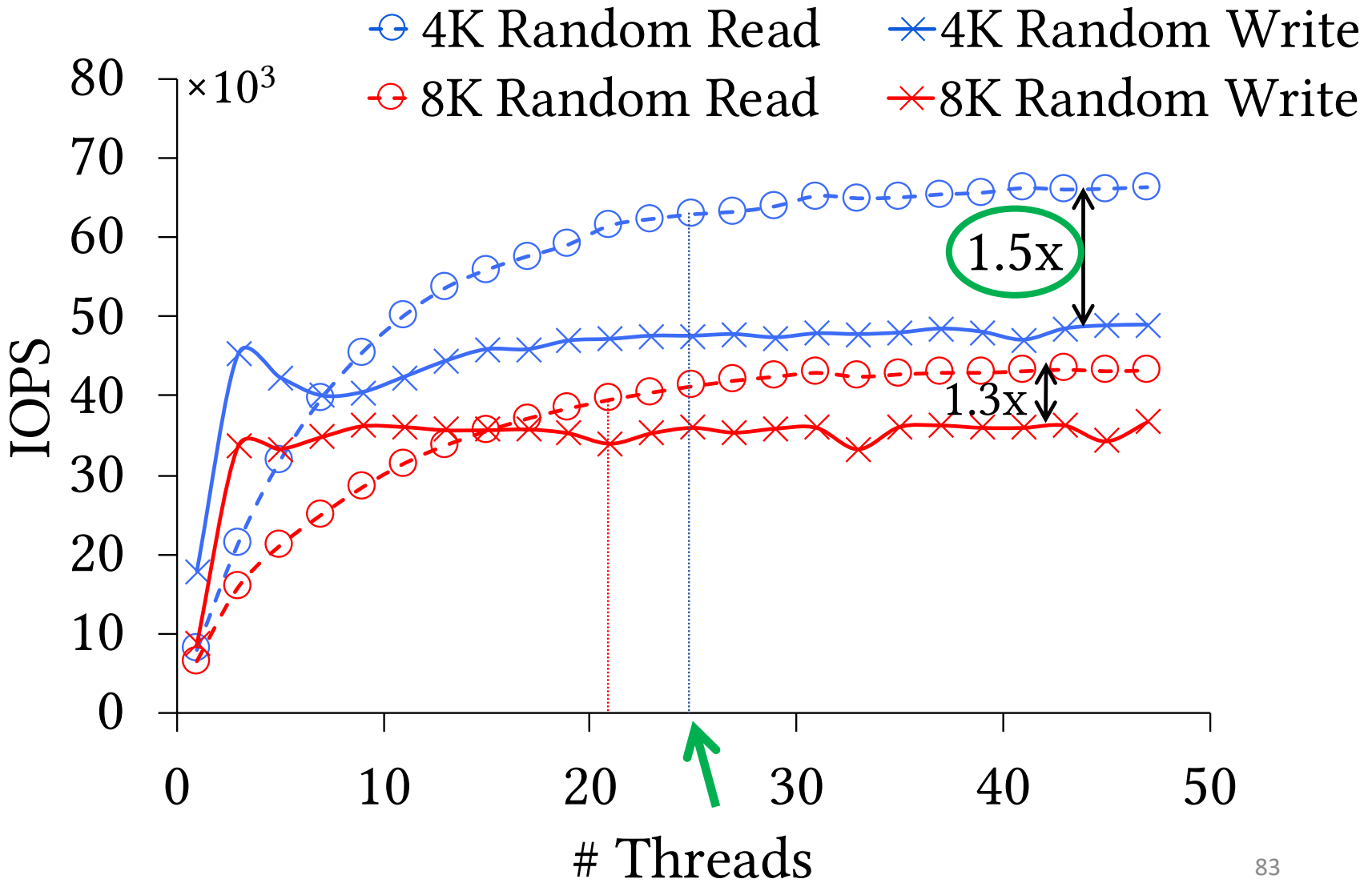
Measuring Asymmetry/Concurrency (With FS)

Device
SATA SSD - S4610 (240GB)

For 4K random read,

Asymmetry: 1.5

Concurrency: 25



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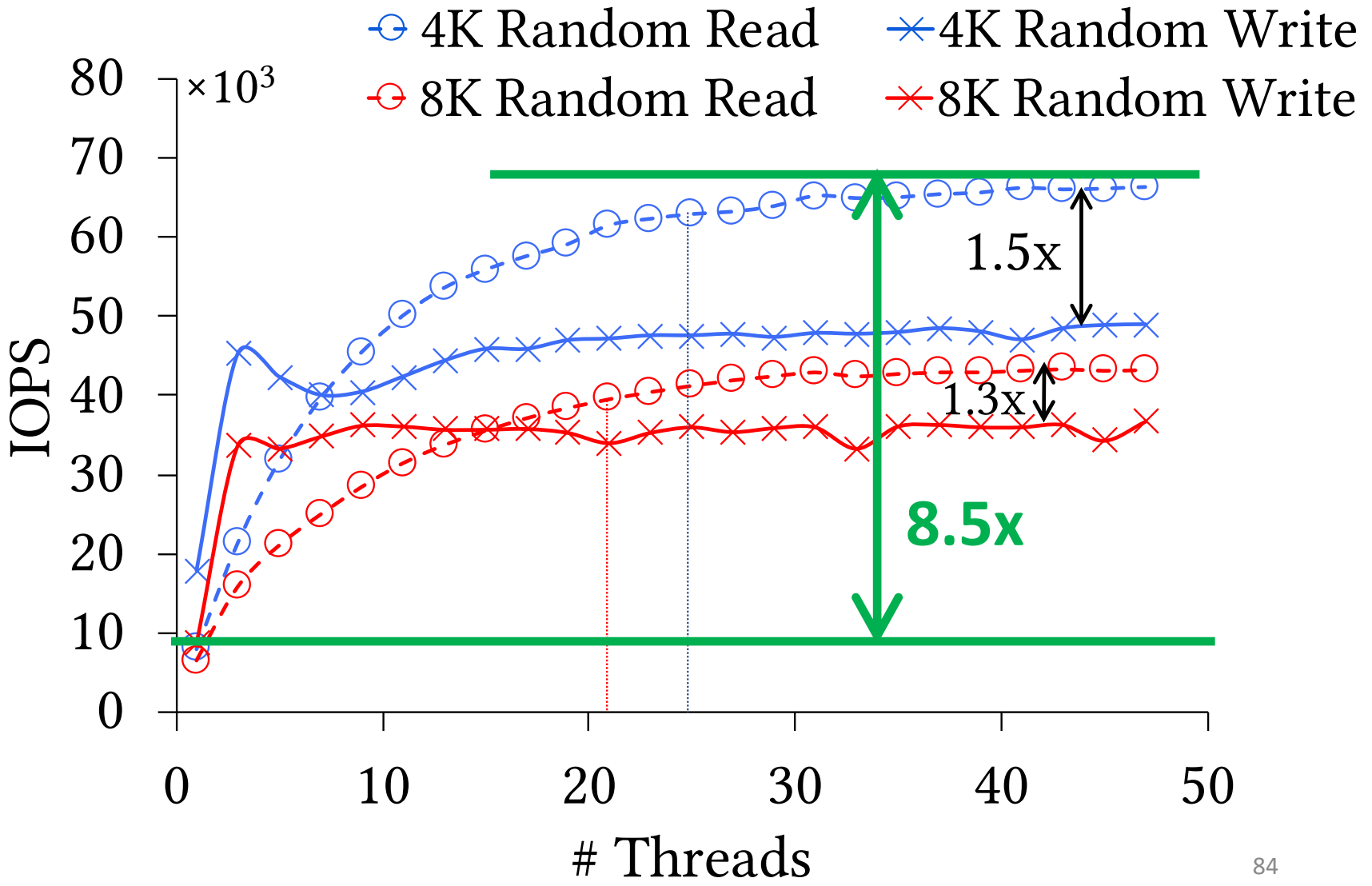
Asymmetry: 1.5

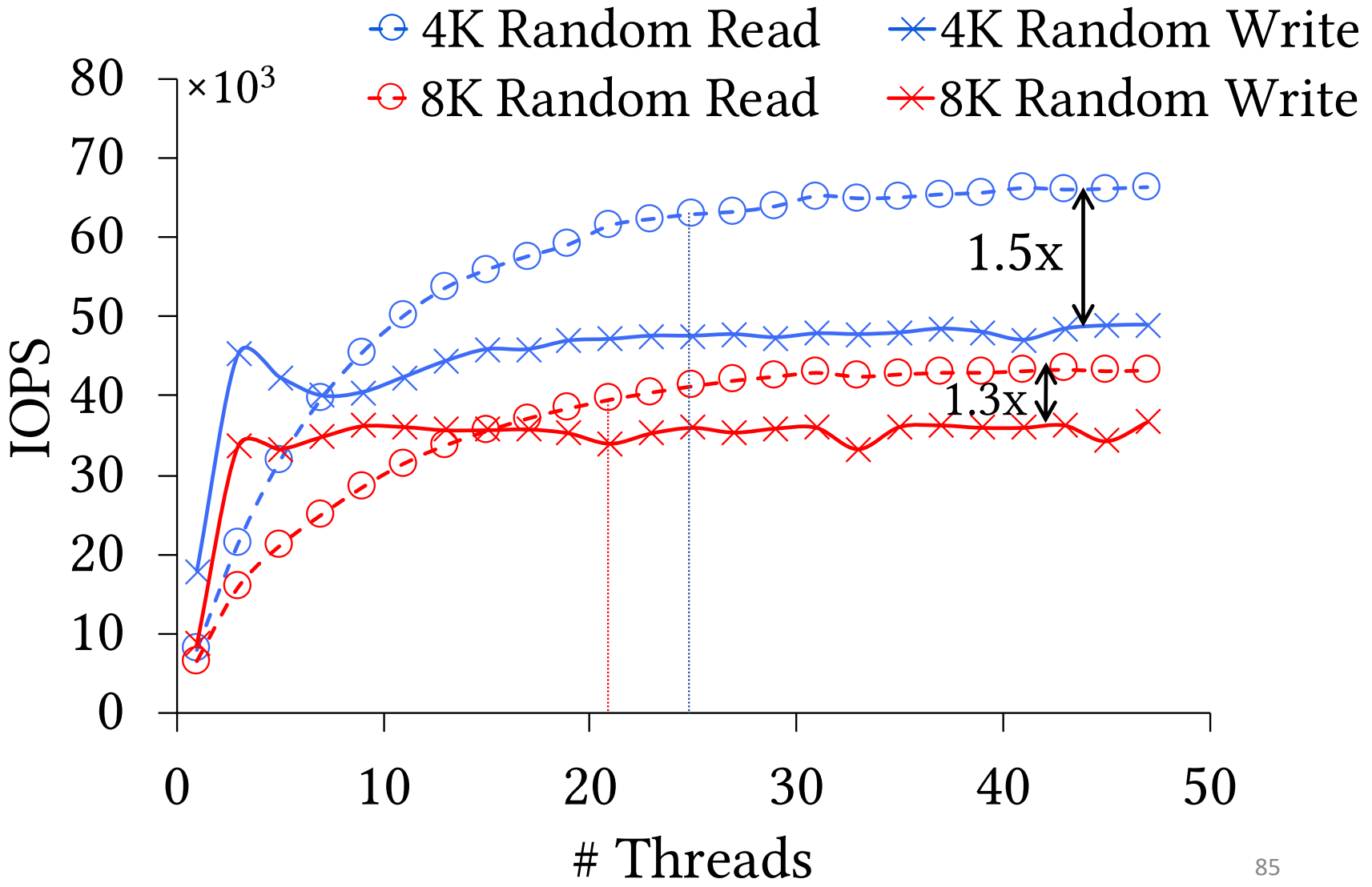
Concurrency: 25



Measuring Asymmetry/Concurrency (With FS)

Device
SATA SSD - S4610 (240GB)

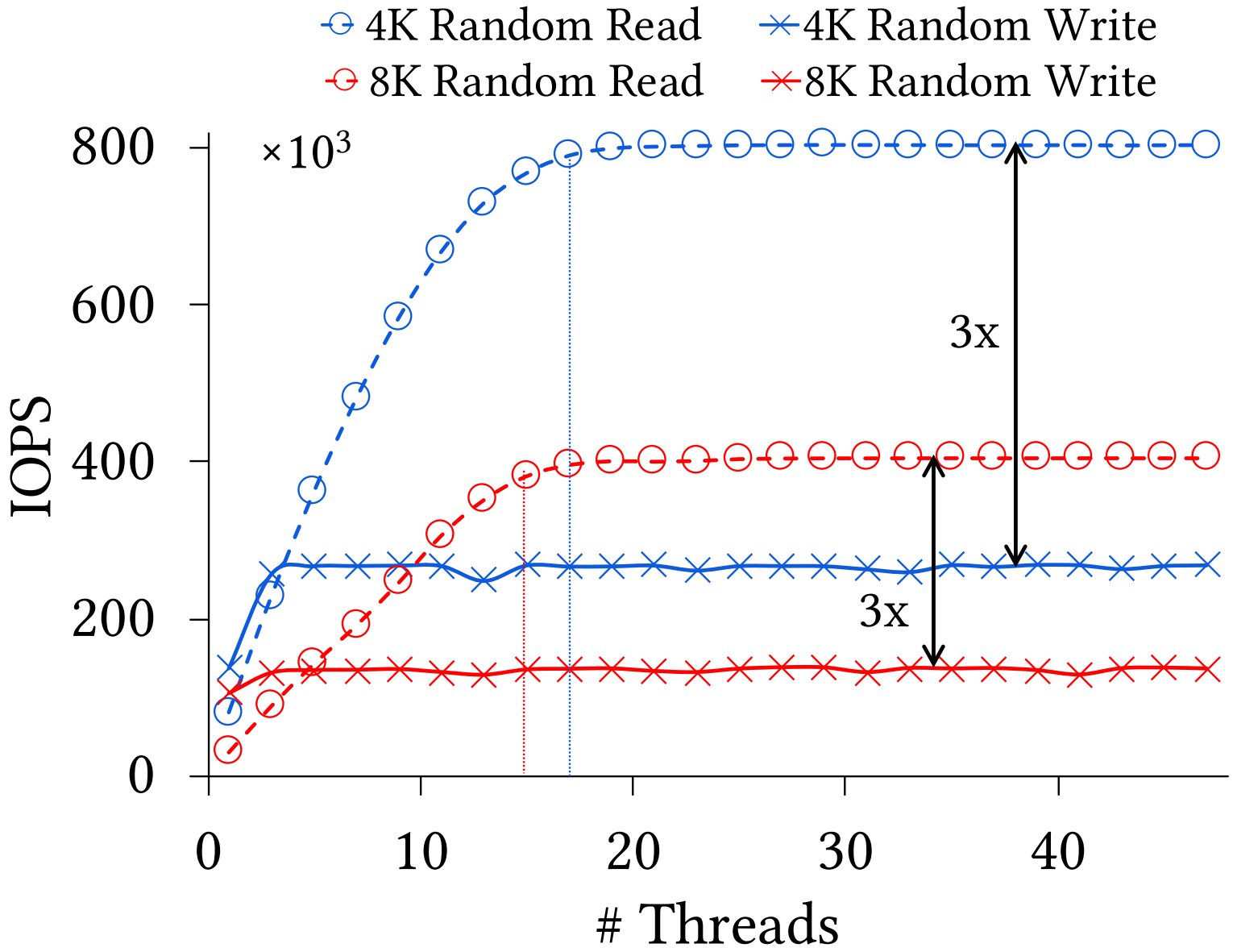
The impact of concurrency is high for any device.



Measuring Asymmetry/Concurrency (Without FS)

Device

PCIe SSD - P4510 (1TB)



Measuring Asymmetry/Concurrency (Without FS)

Device

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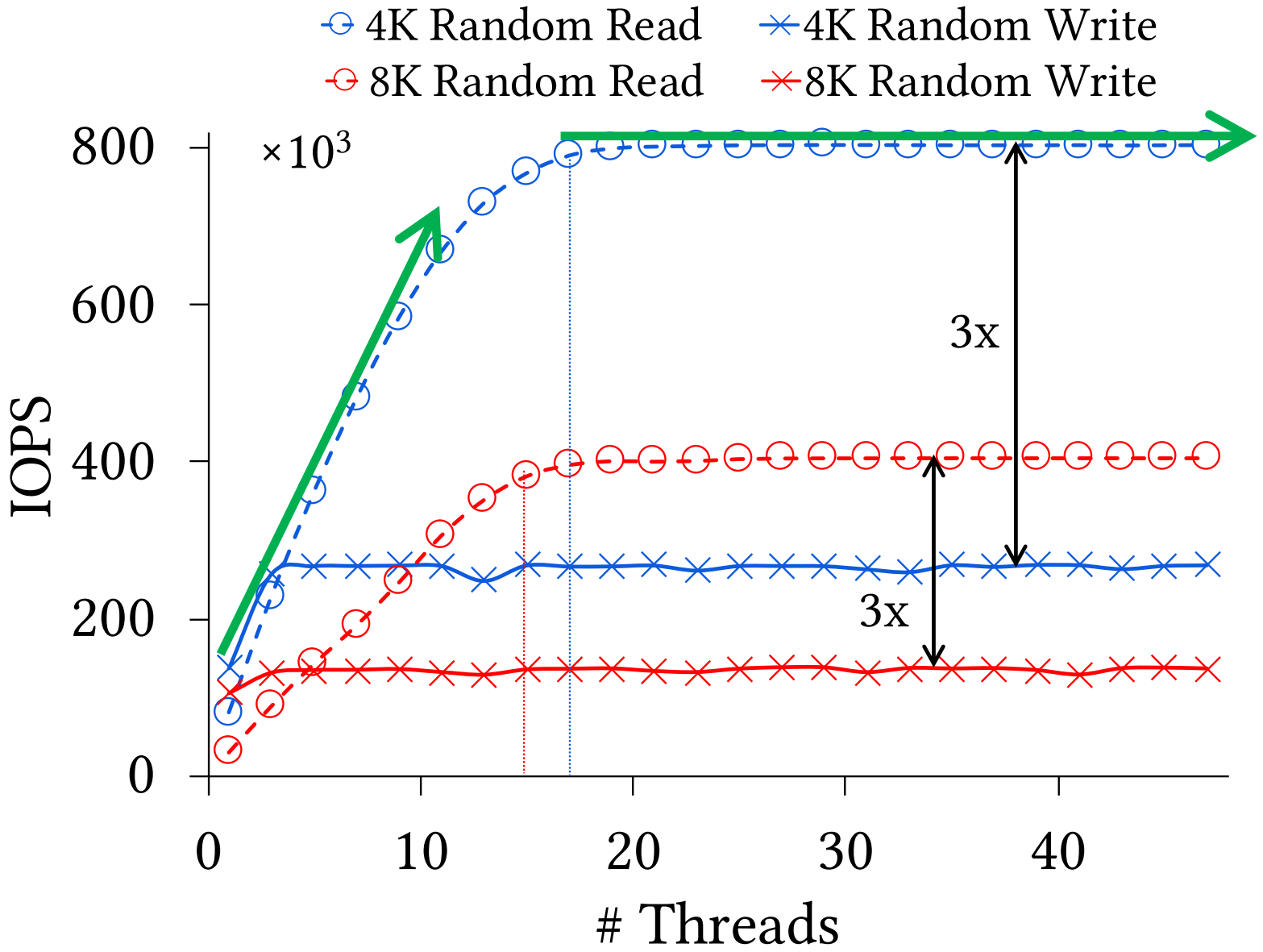

Measuring Asymmetry/Concurrency (Without FS)

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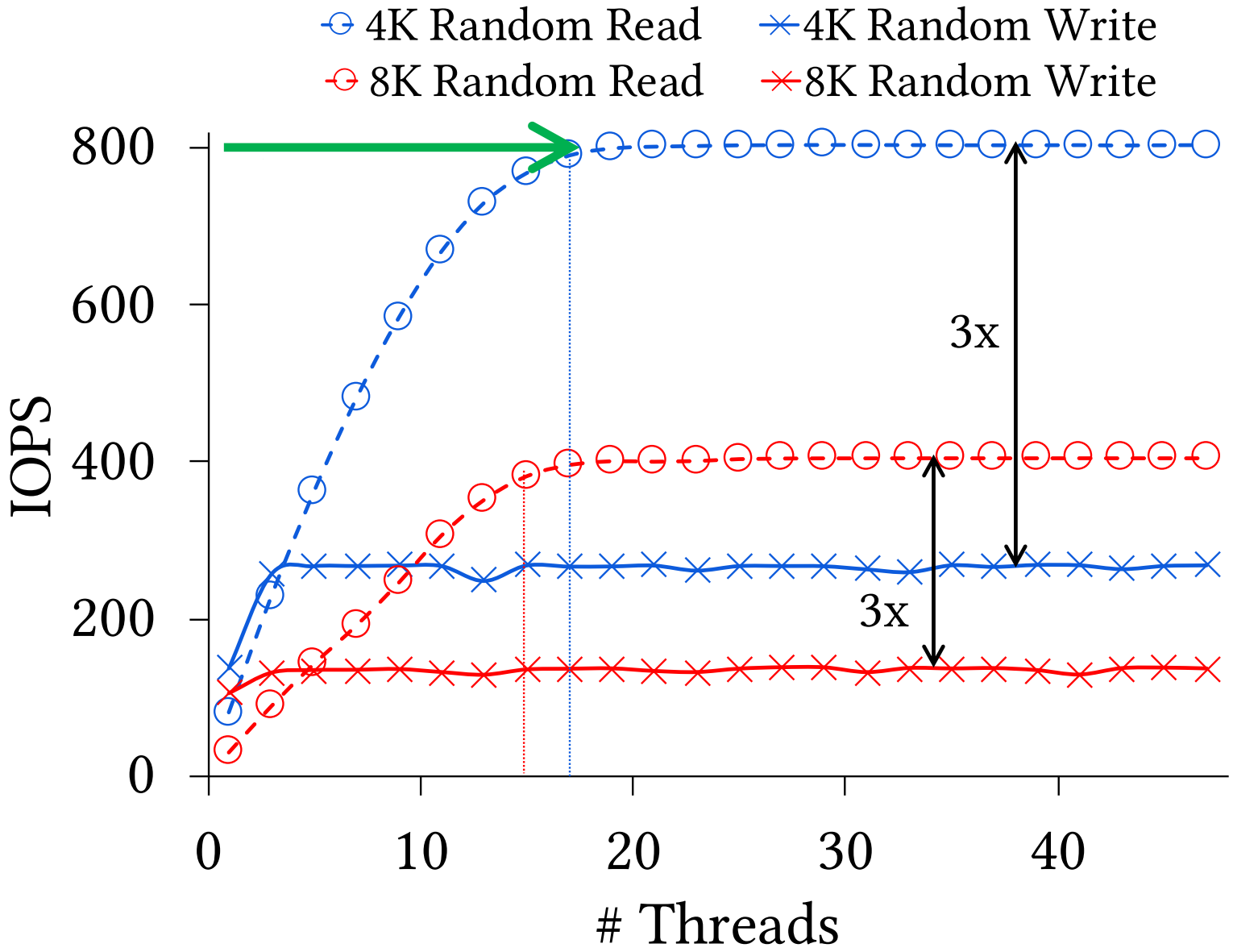


Measuring Asymmetry/Concurrency (Without FS)

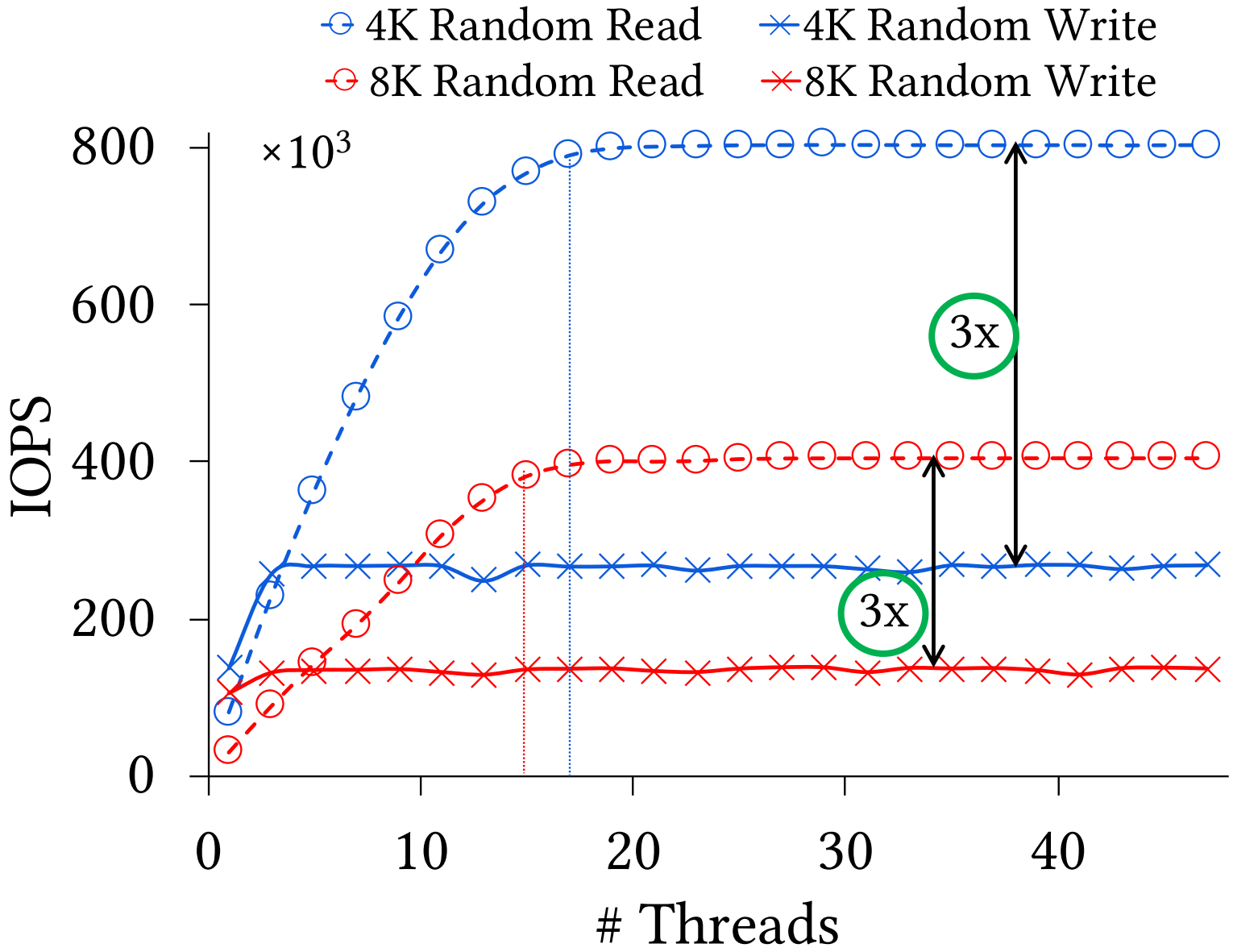
Device

PCIe SSD - P4510 (1TB)

For 4K random read,

Asymmetry: 3

Concurrency: 17

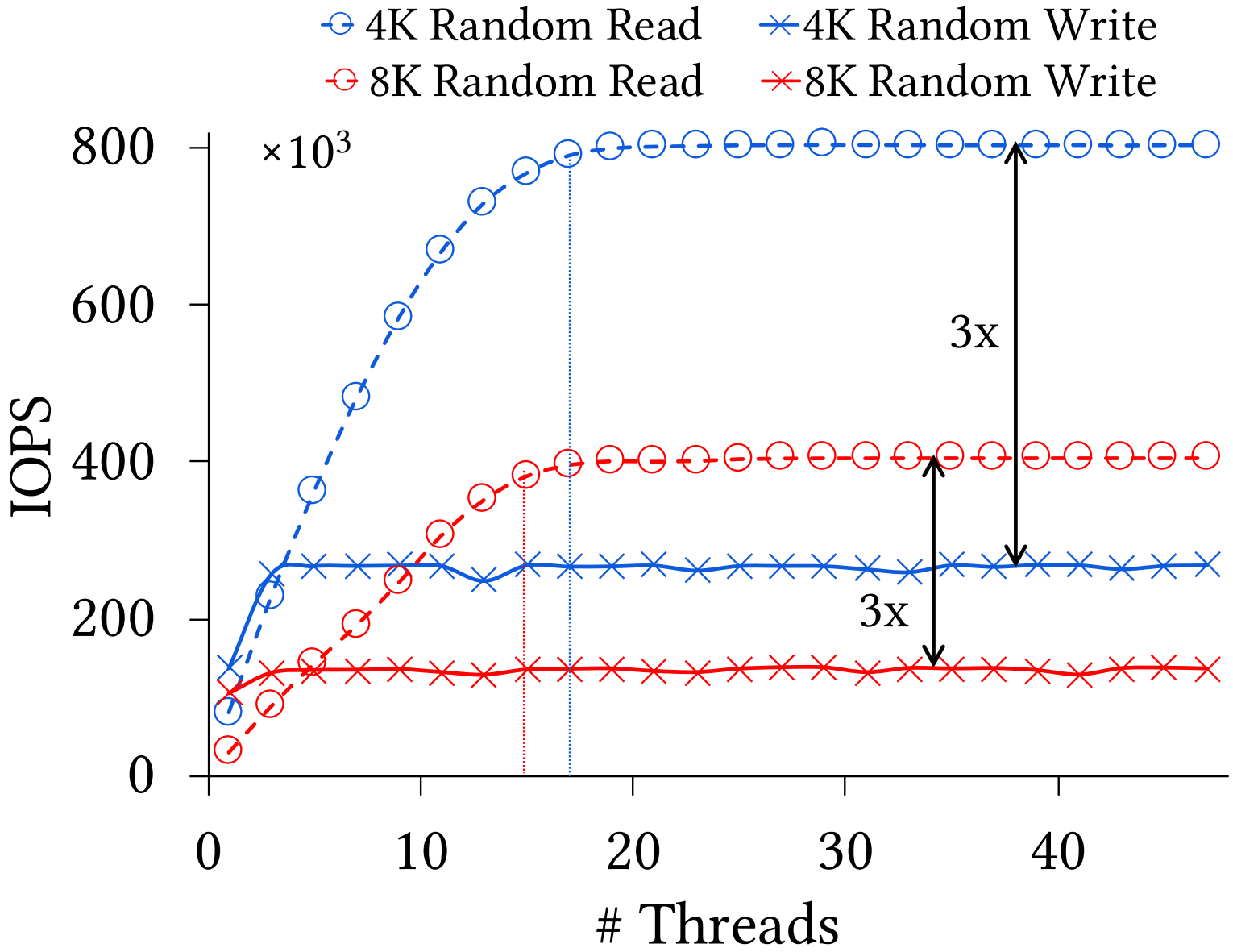


Measuring Asymmetry/Concurrency (Without FS)

Device

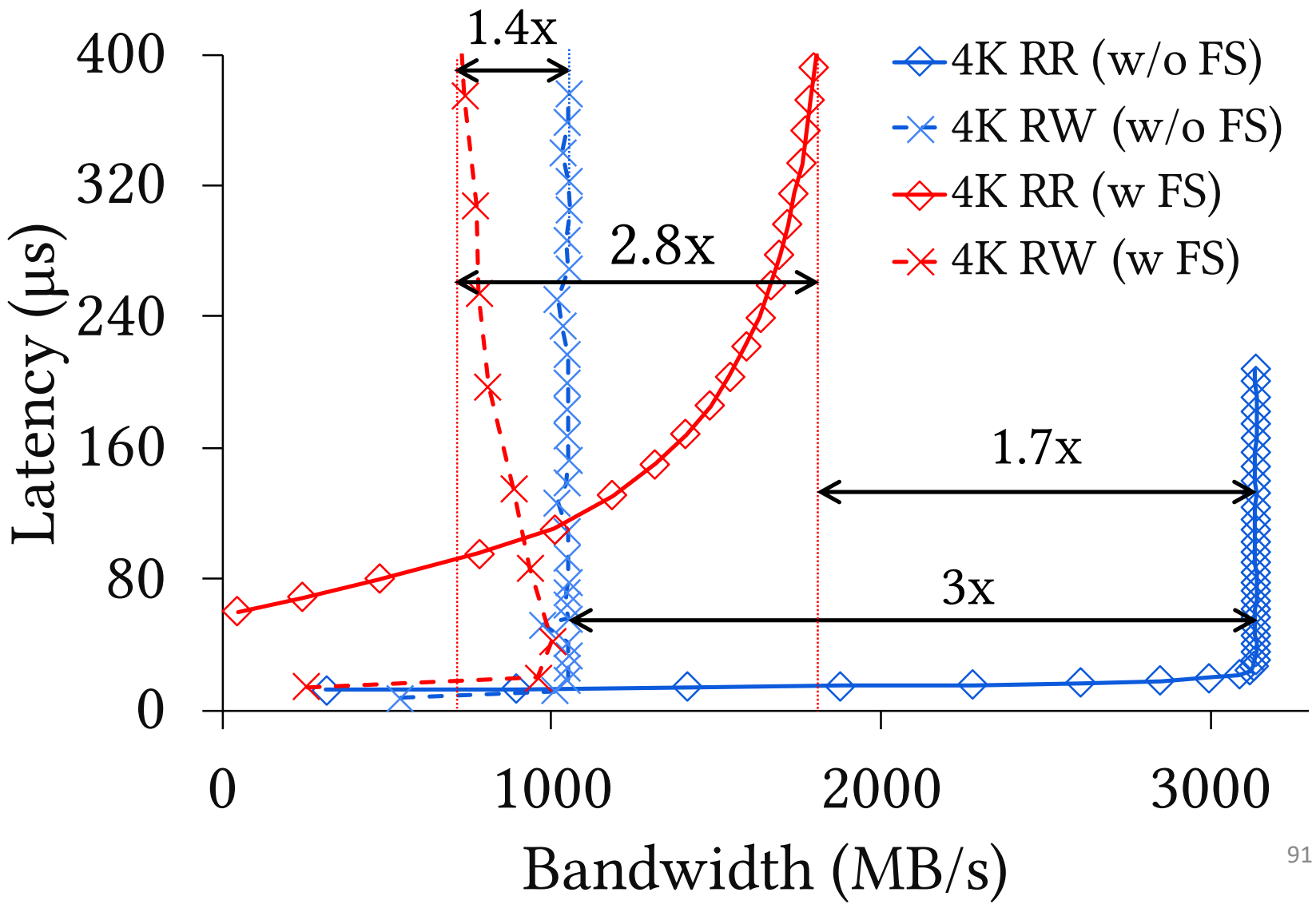
PCIe SSD - P4510 (1TB)

The observed α and k depends on the presence of the FS.



Impact of the File System

Device
PCIe SSD - P4510 (1TB)



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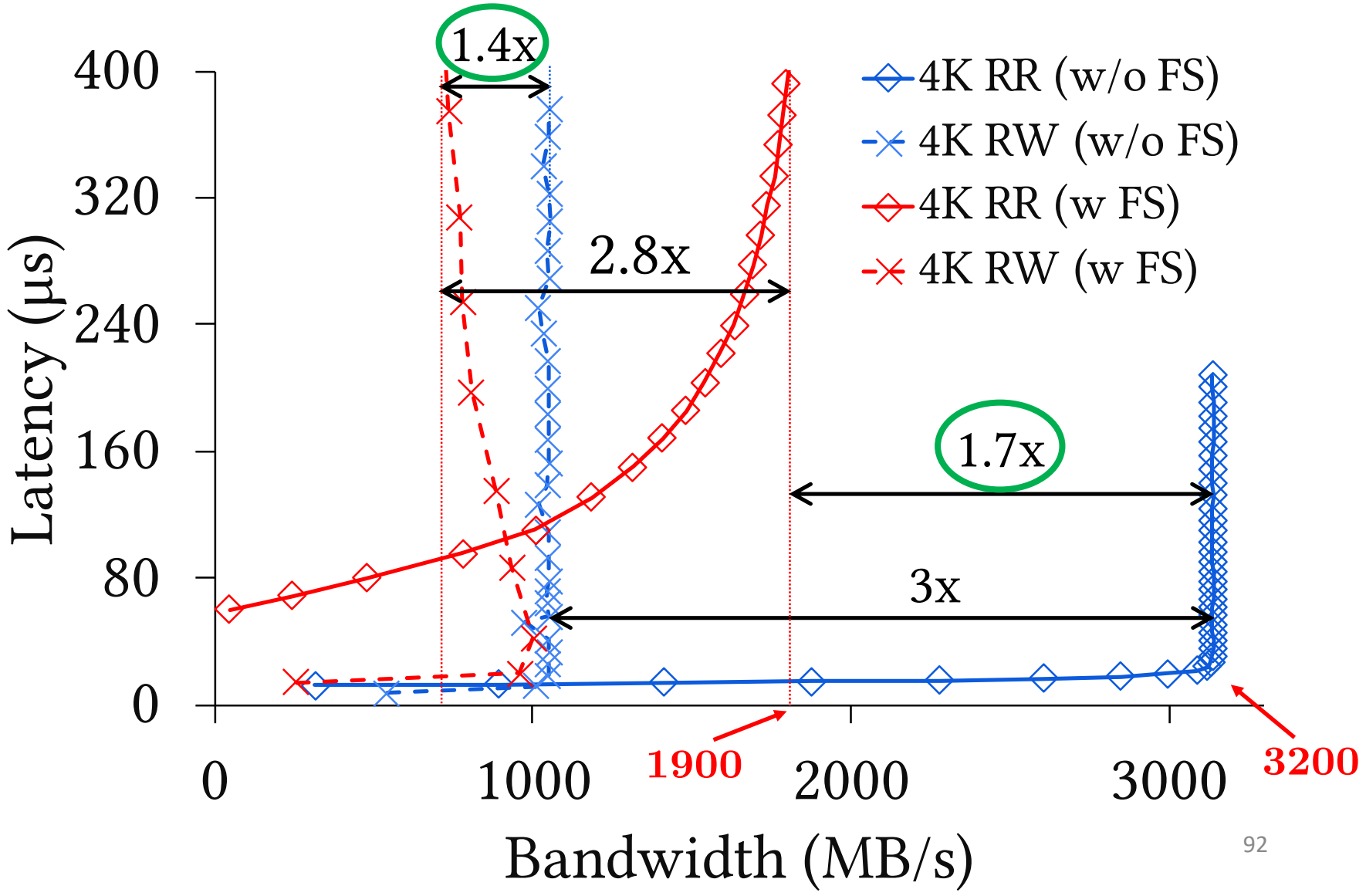

Impact of the File System

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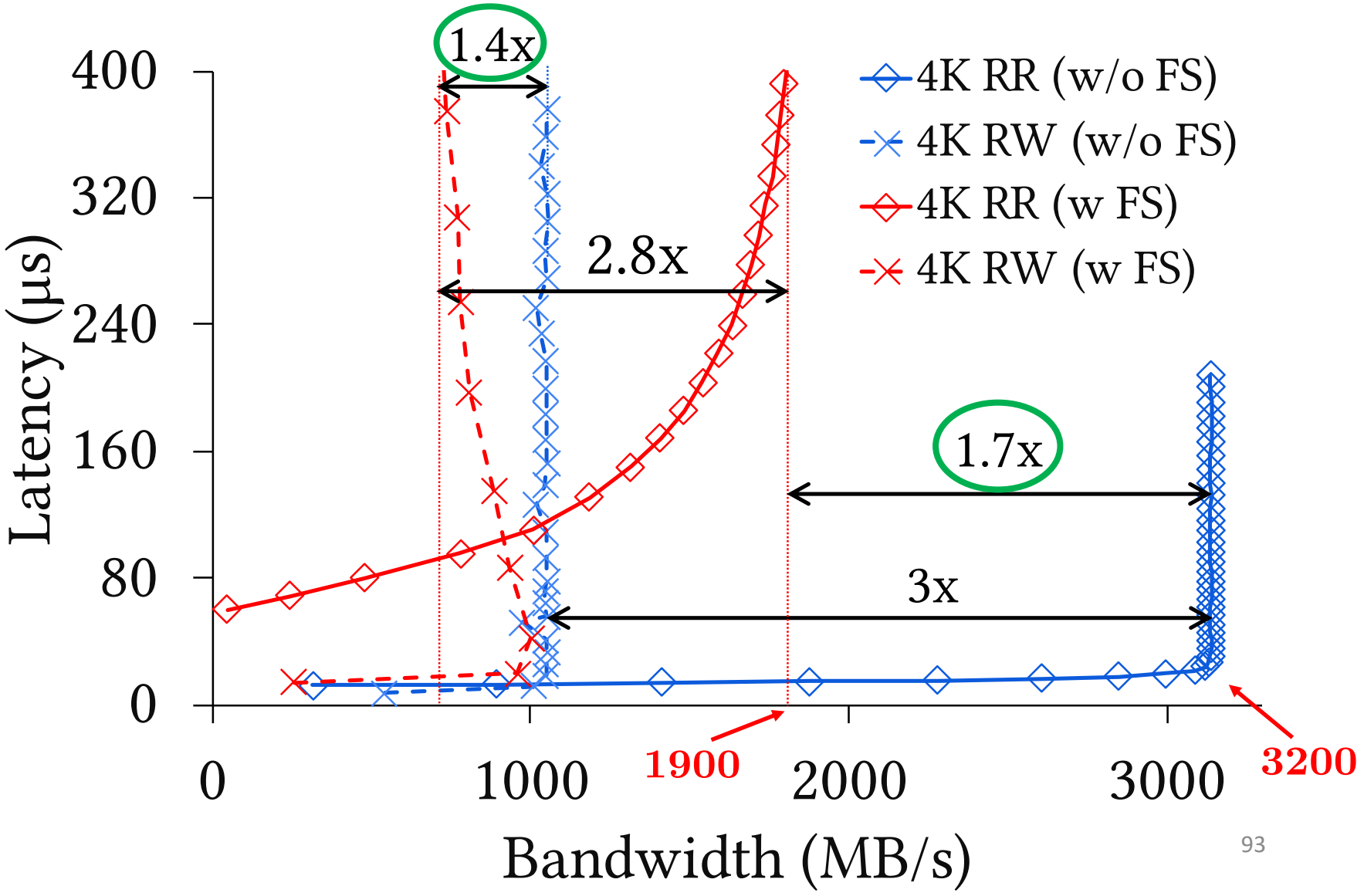
PCIe SSD - P4510 (1TB)

FS affects α and k.

Much stable &

increased bandwidth

w/o the file system.



Empirical Asymmetry and Concurrency

Devices	4KB			8KB		
	α	k_r	k_w	α	k_r	k_w
Optane SSD	1.1	6	5	1.0	4	4
PCIe SSD (with FS)	2.8	80	8	1.9	40	7
PCIe SSD (w/o FS)	3.0	16	6	3.0	15	4
SATA SSD	1.5	25	9	1.3	21	5

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Performance Analysis following PIO (M, k, α)

Performance Analysis

We classify storage-intensive applications into three classes

- ✓ Batchable Writes
- ✓ Batchable Reads
- ✓ Batchable Reads and Writes

Batchable Writes

- ✓ Can exploit write concurrency (k_w) by batching writes

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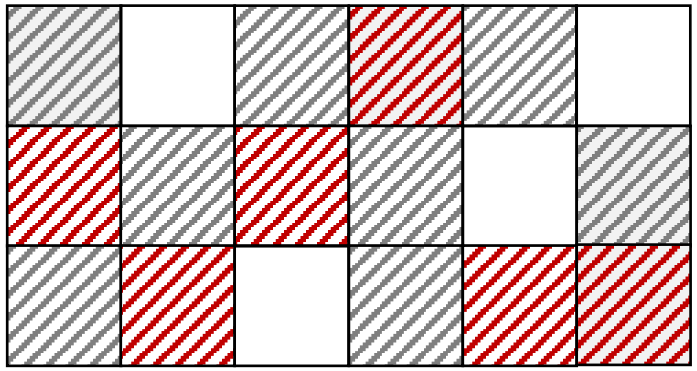
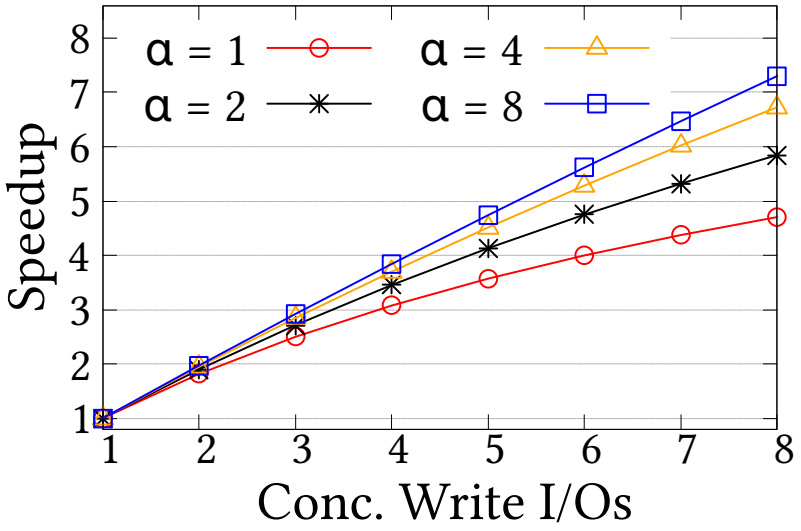
- ✓ Amortized cost per write following PIO is $\frac{\alpha}{k_w}$
- ✓ Example: DBMS bufferpool

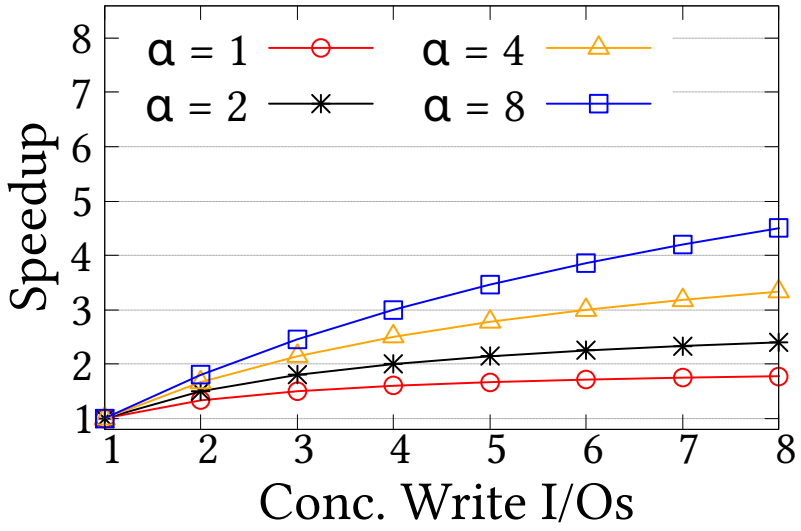


Batchable Writes

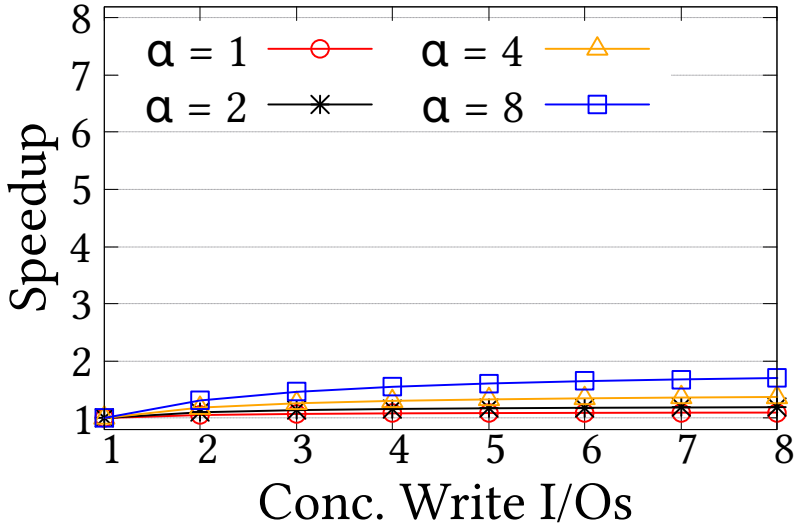
10% reads



50% reads

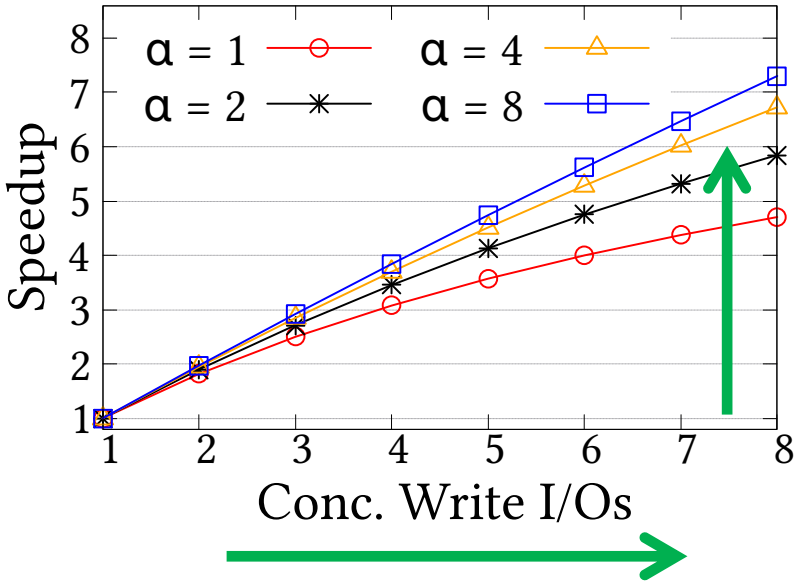


90% reads

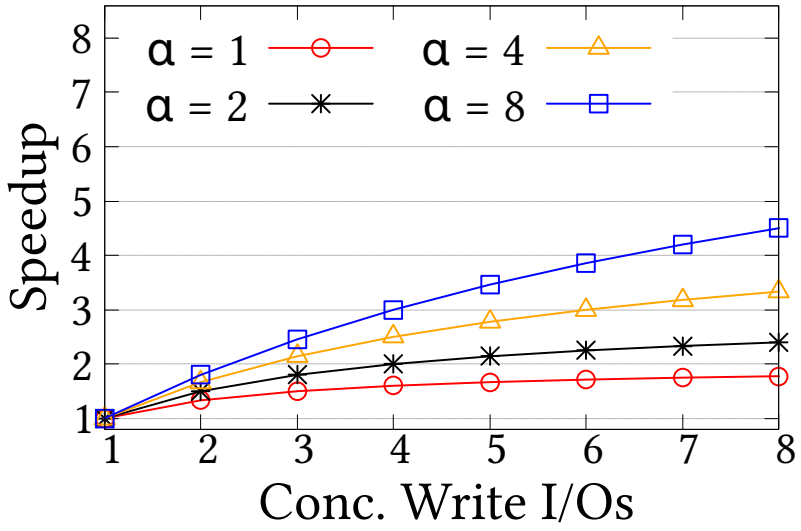


Batchable Writes

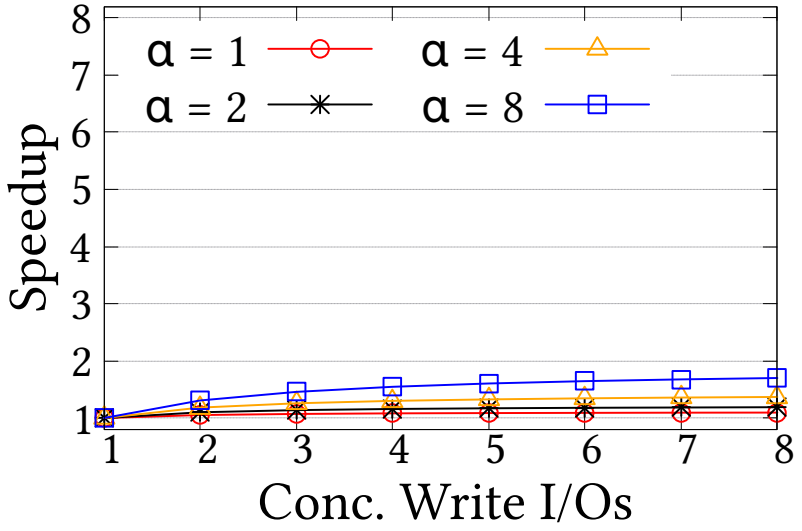
10% reads



50% reads



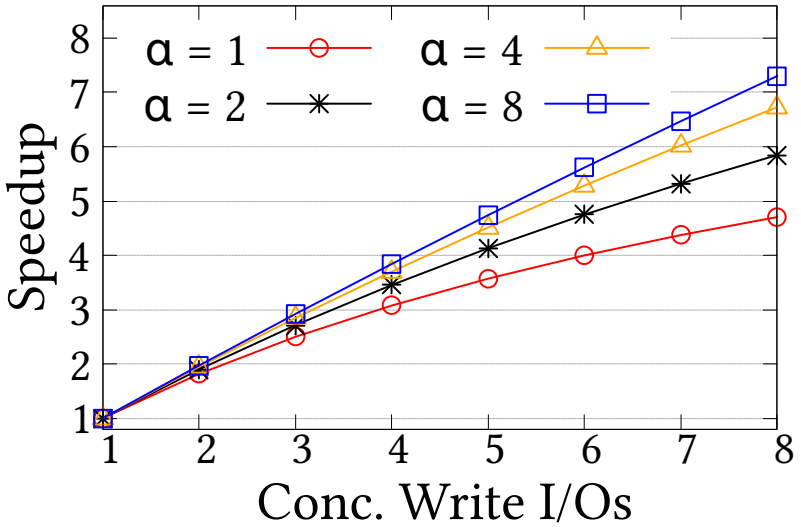
90% reads



Speedup increases with increasing concurrent I/Os

Batchable Writes

10% reads



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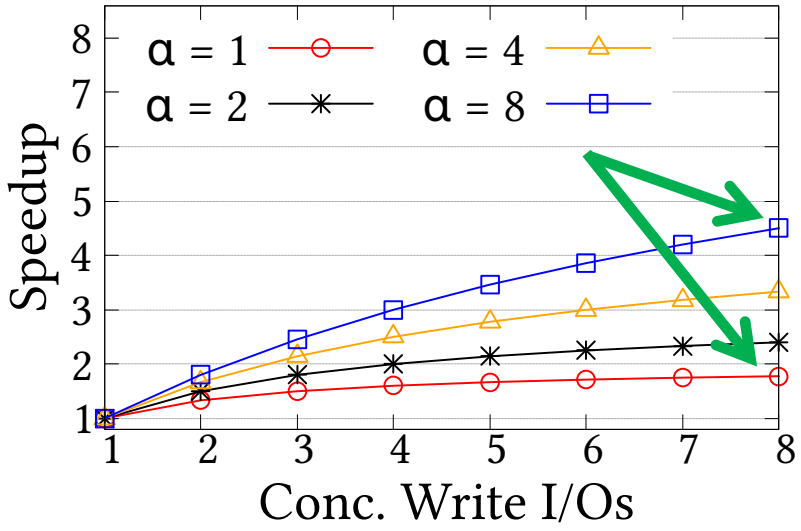

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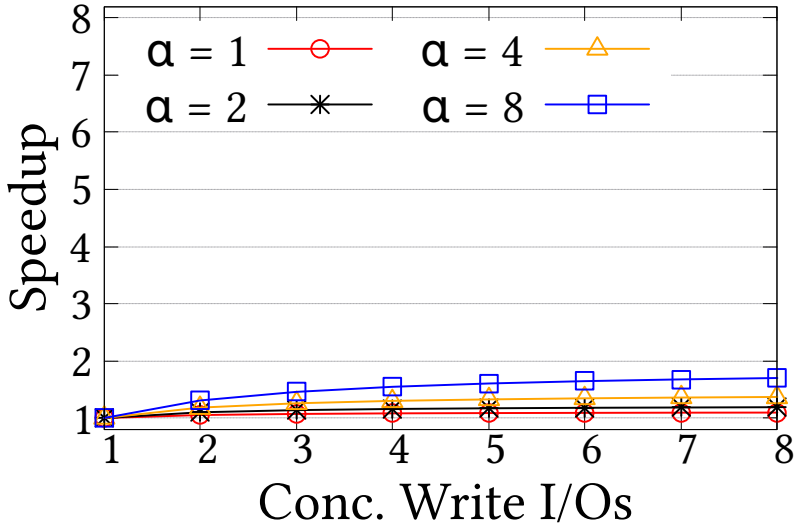

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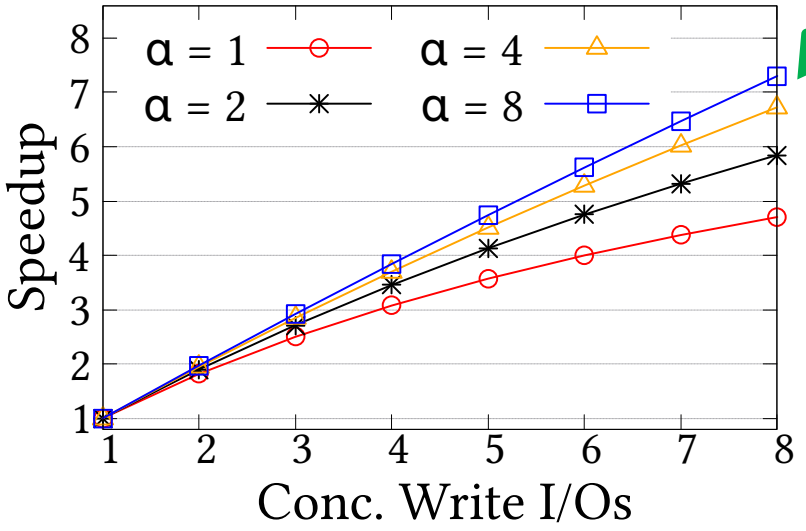

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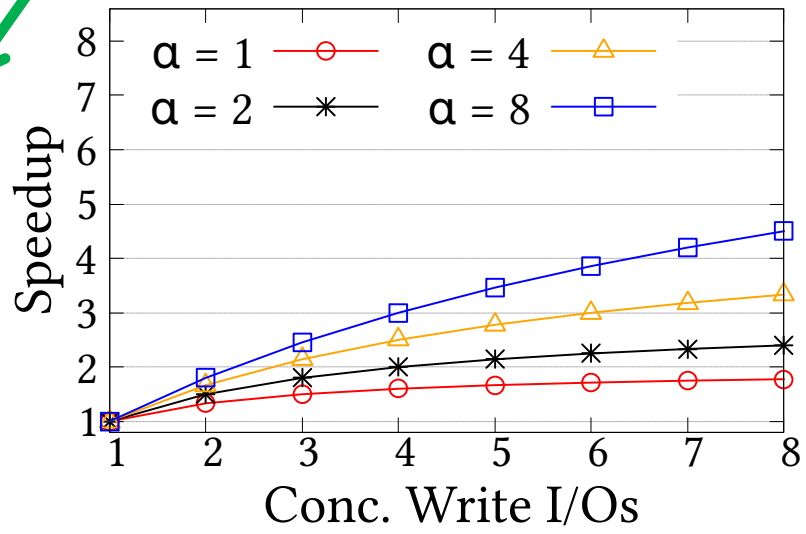

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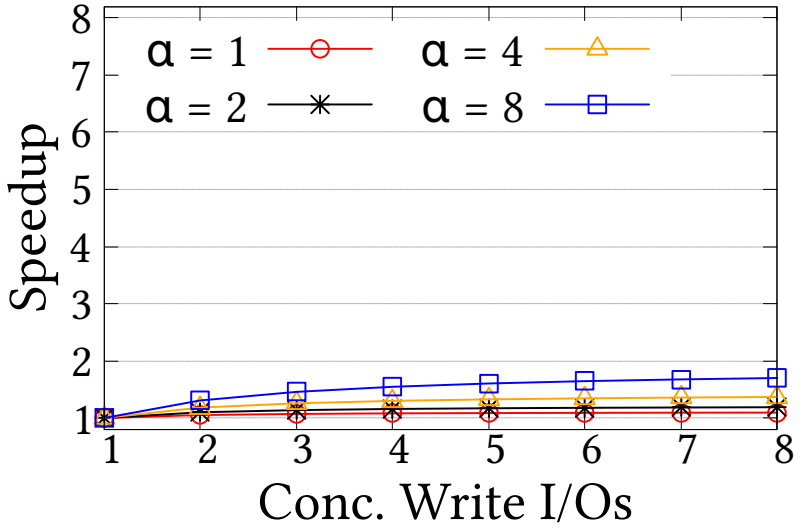

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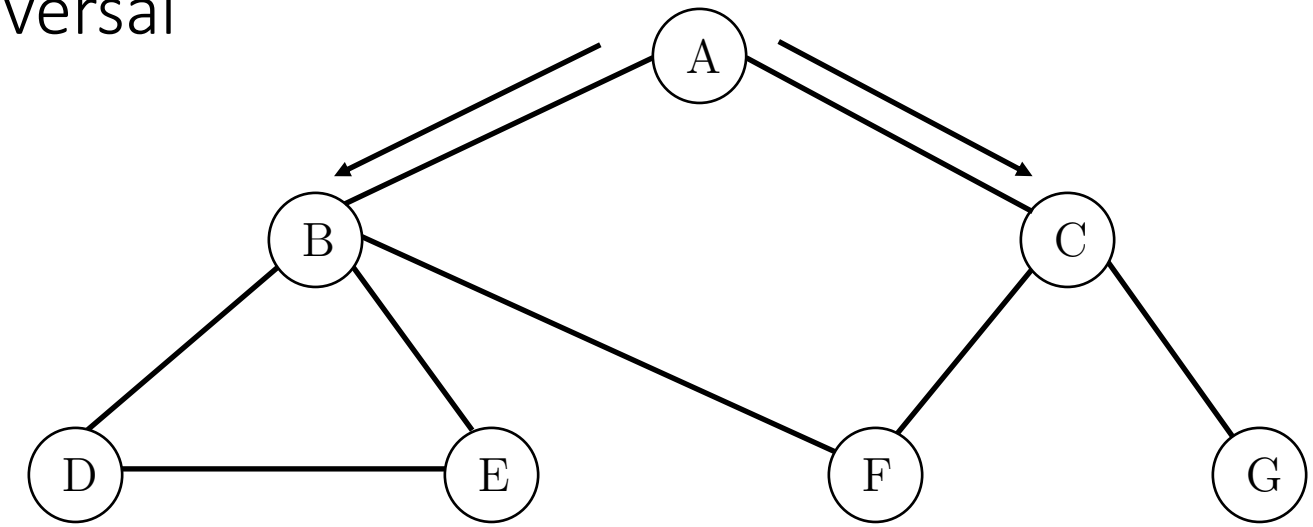

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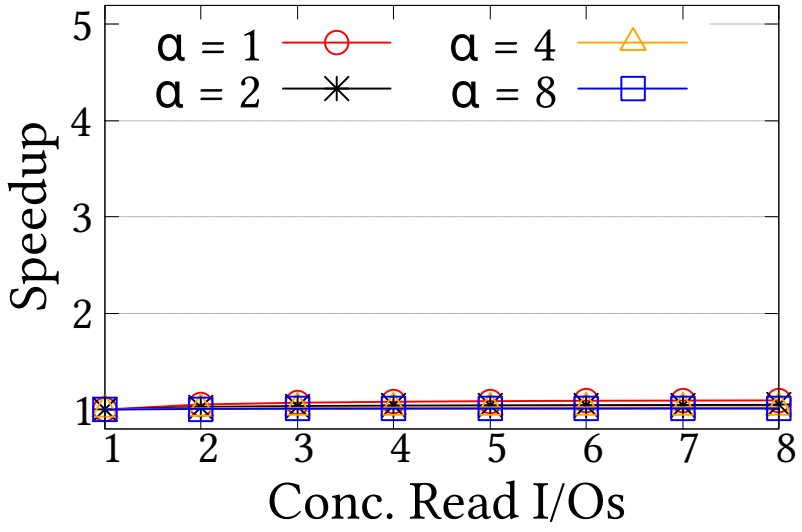

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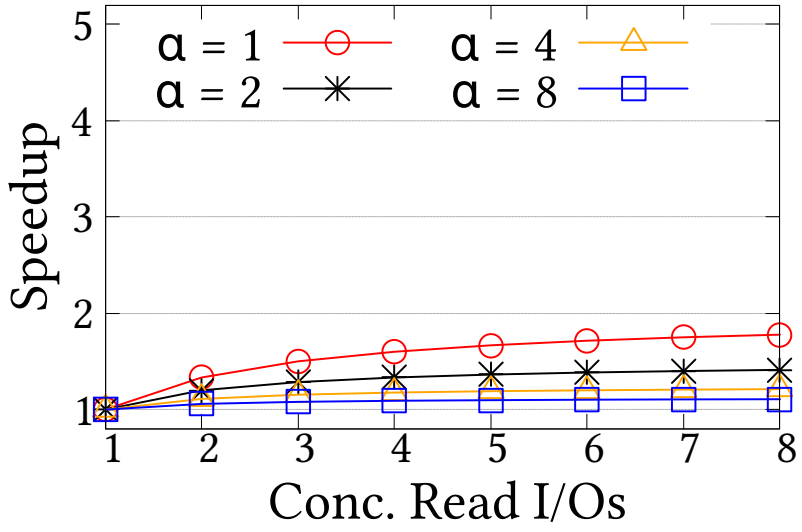

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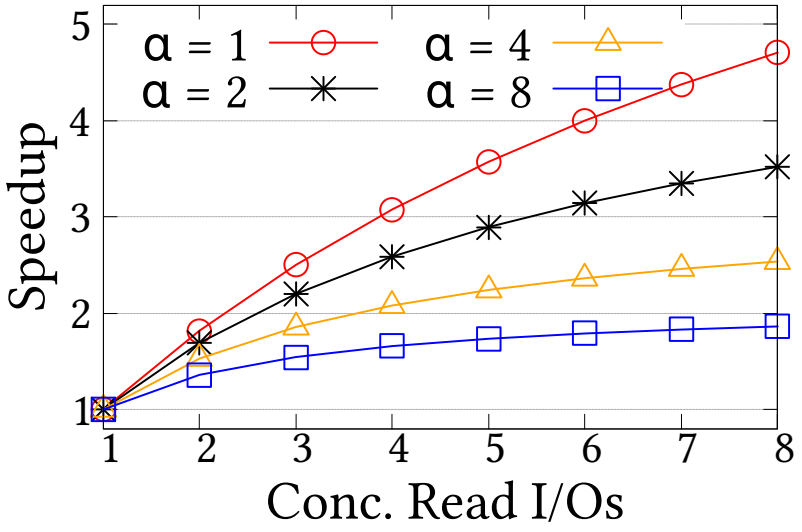

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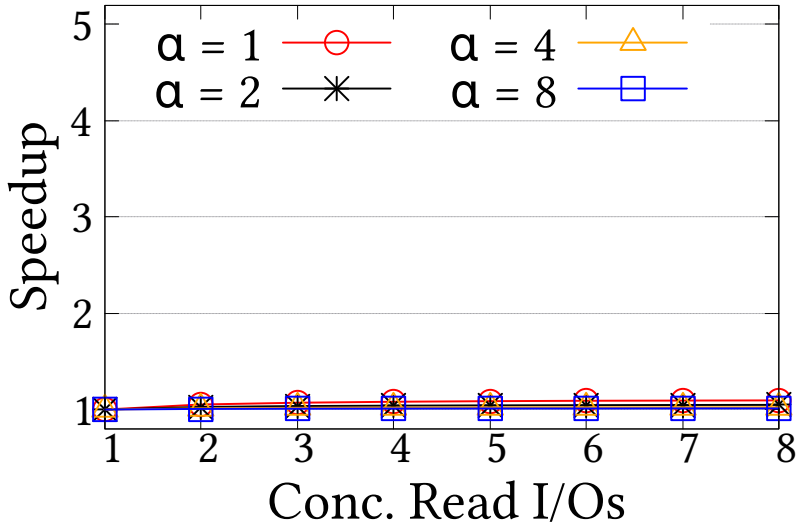

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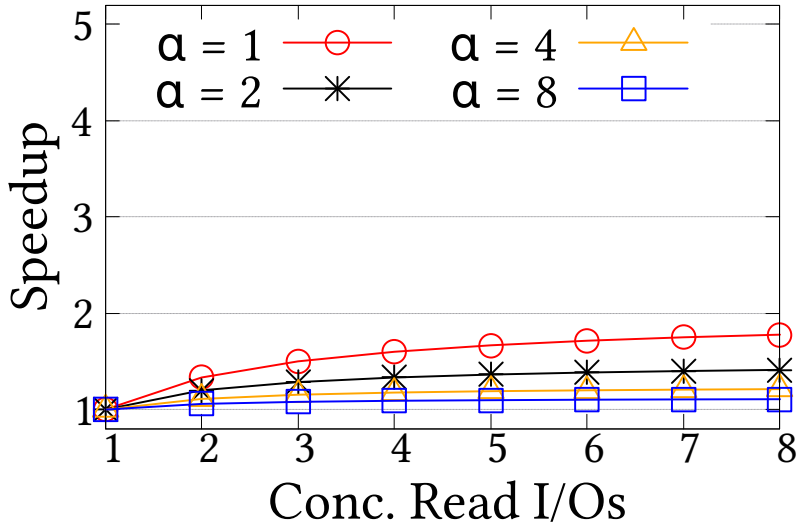

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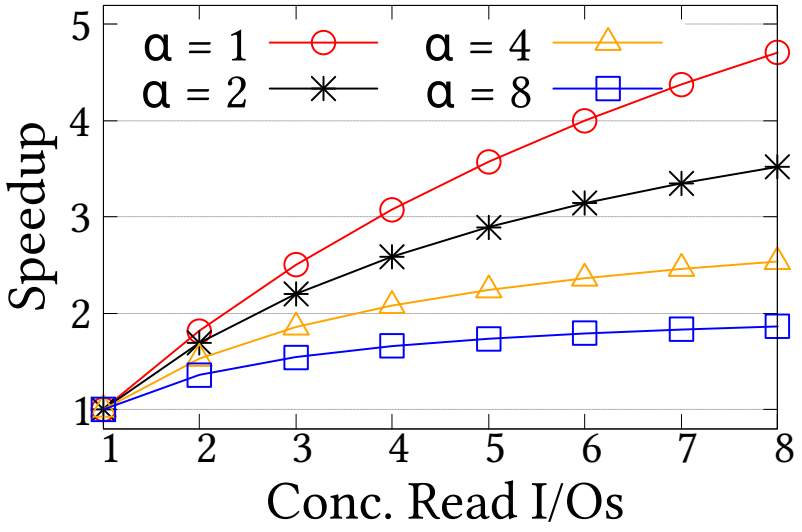

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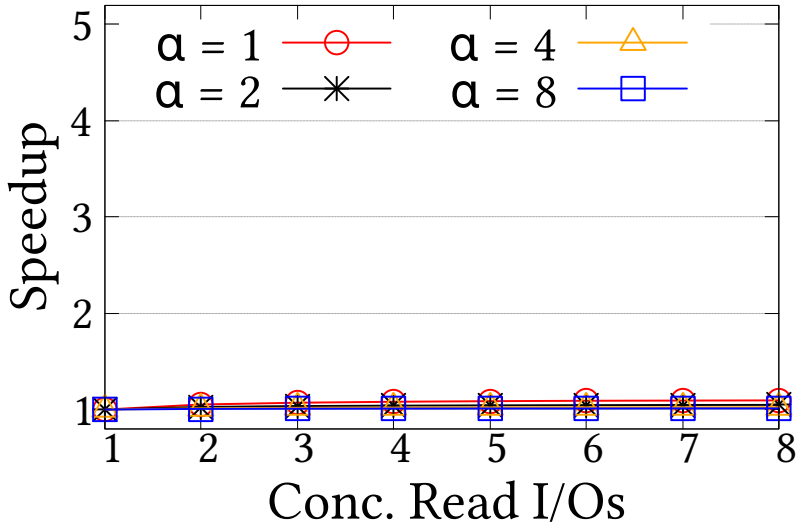

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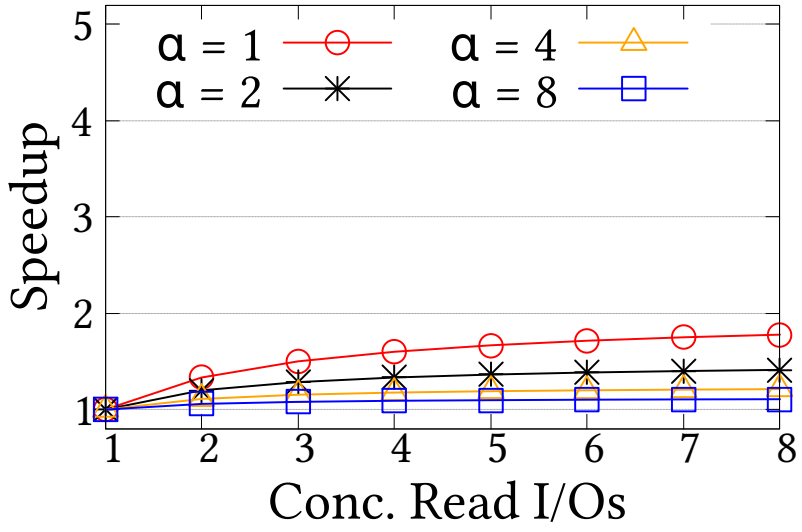

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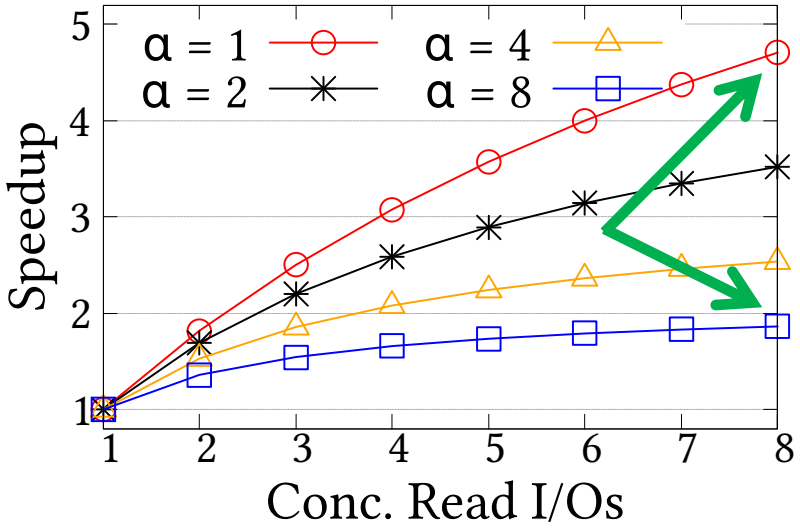

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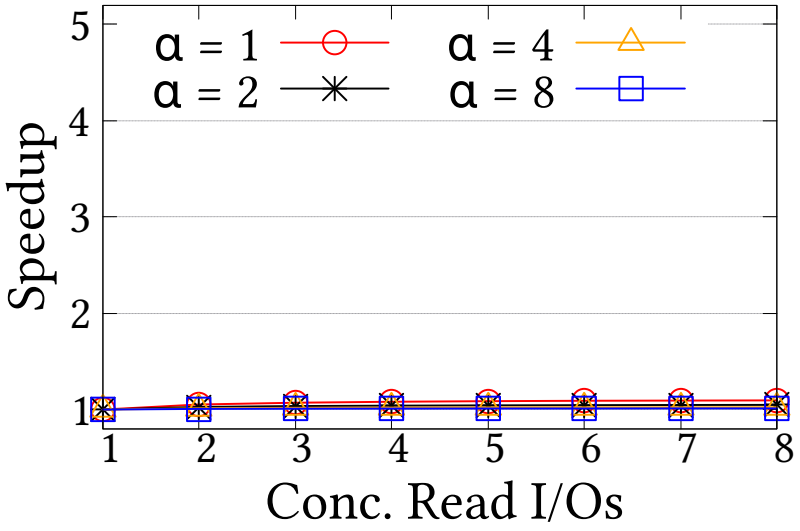

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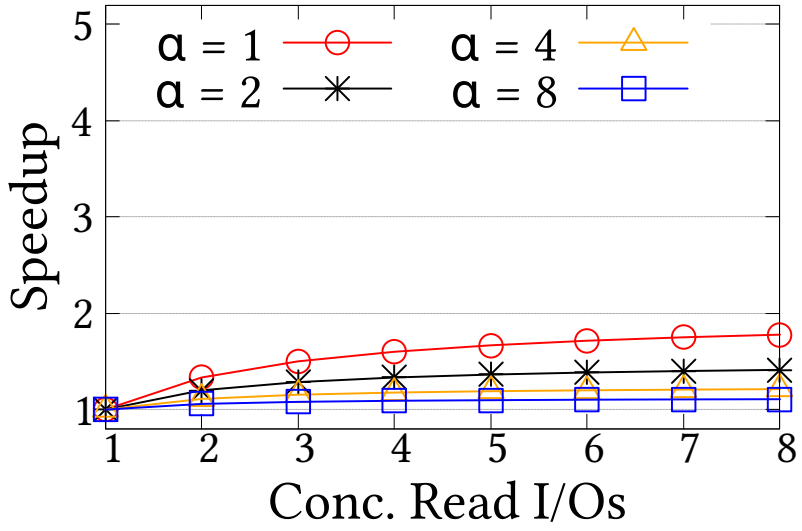

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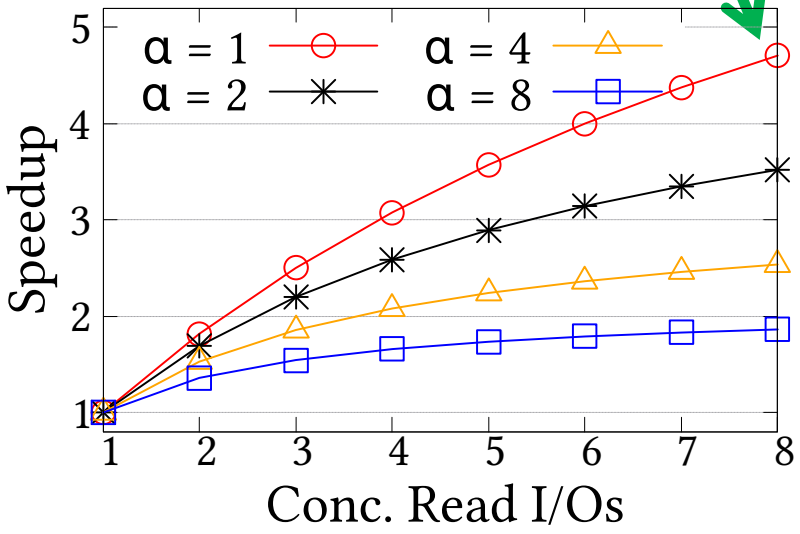

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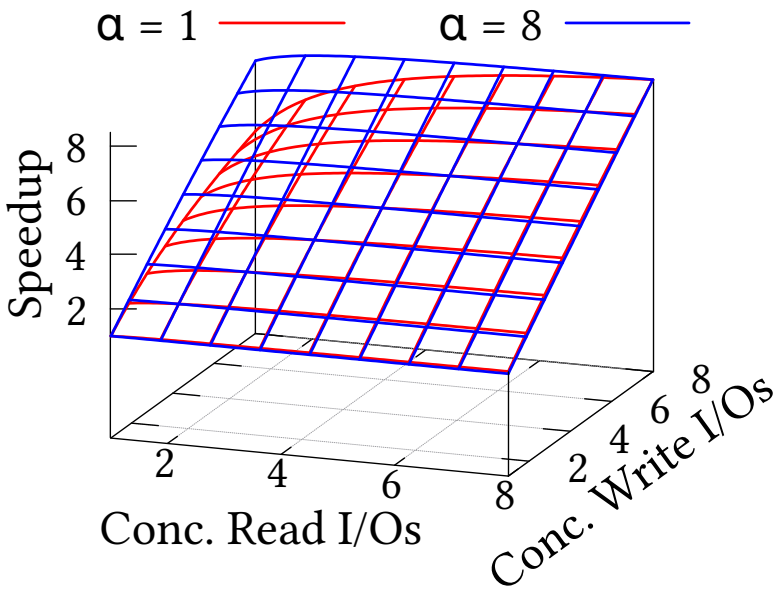

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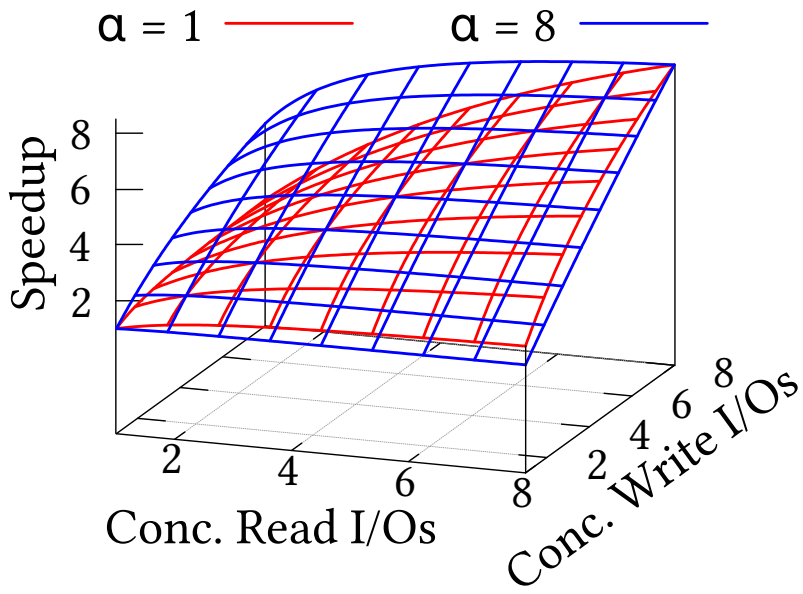

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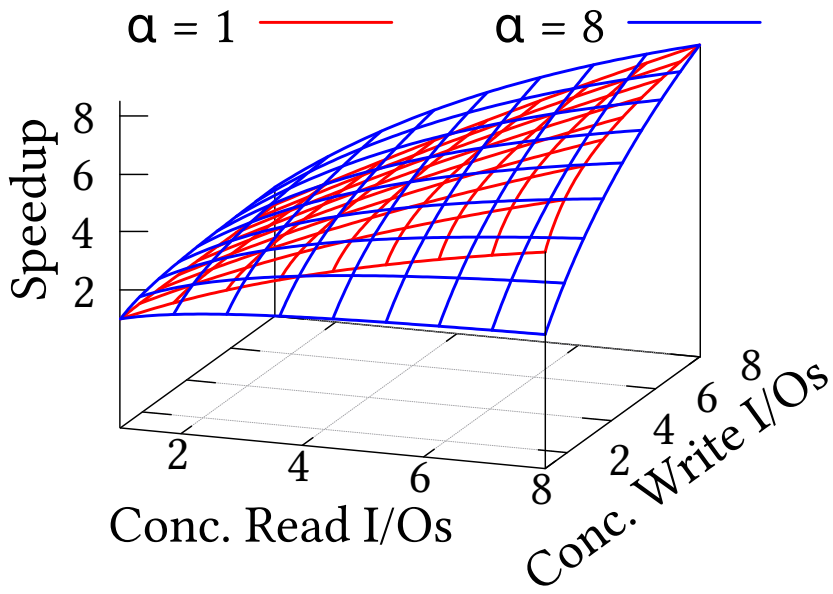

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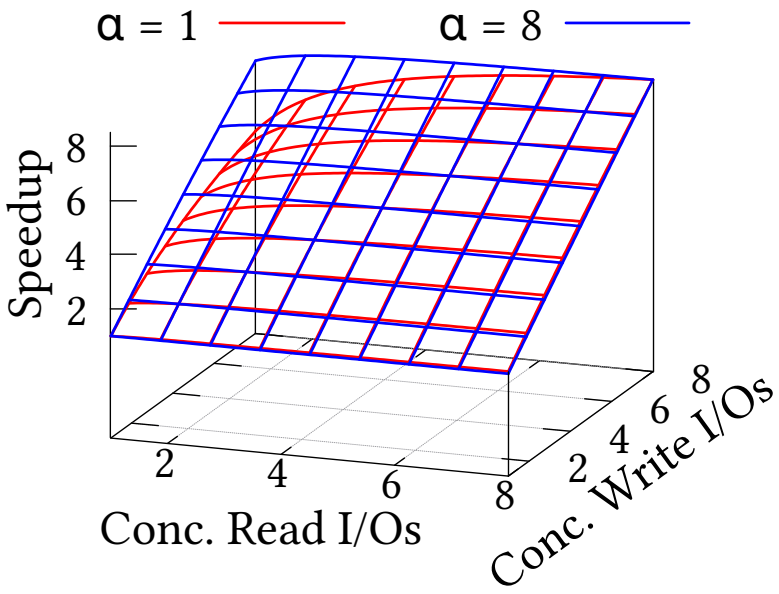

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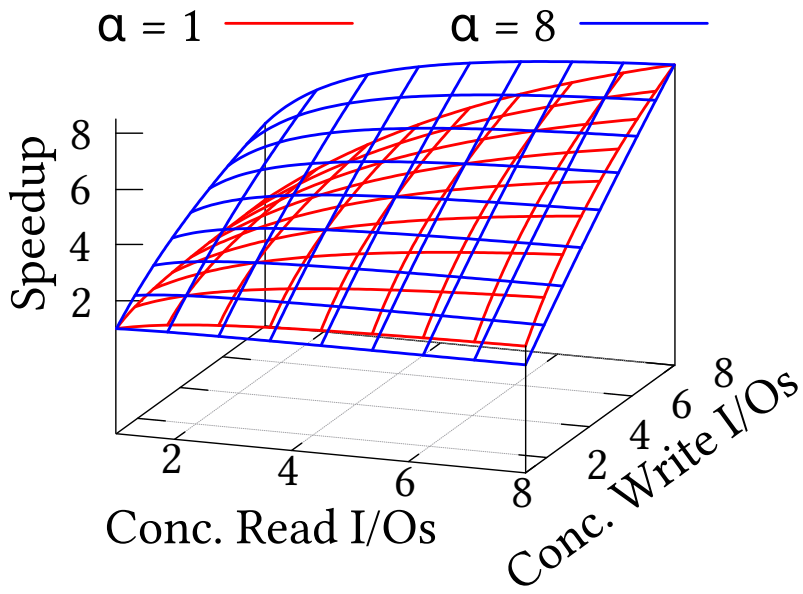

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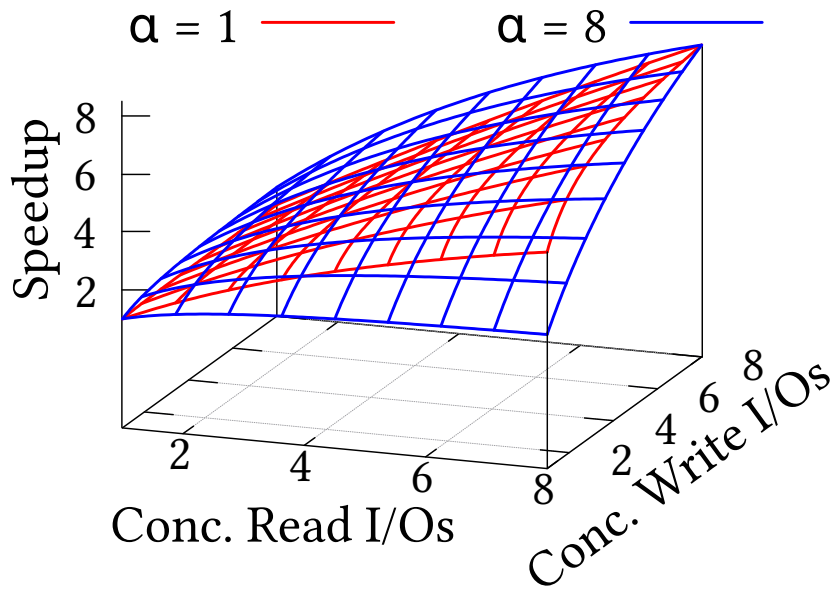

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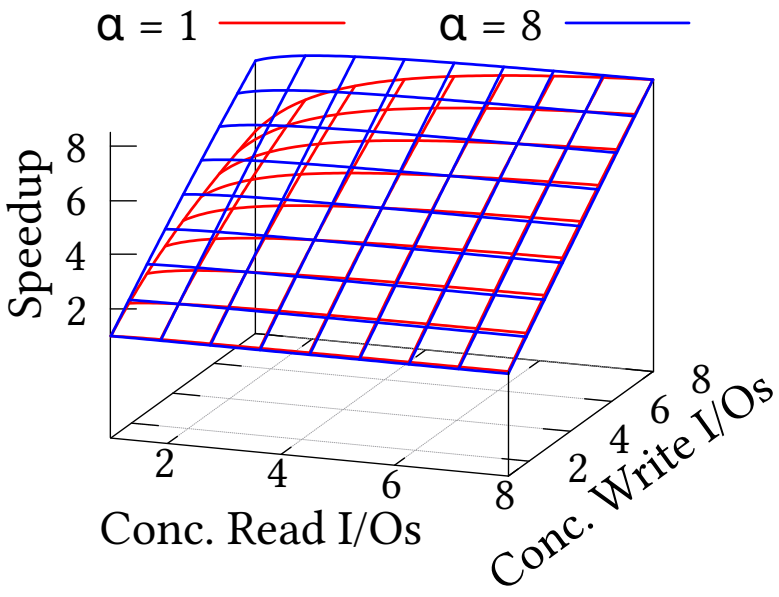

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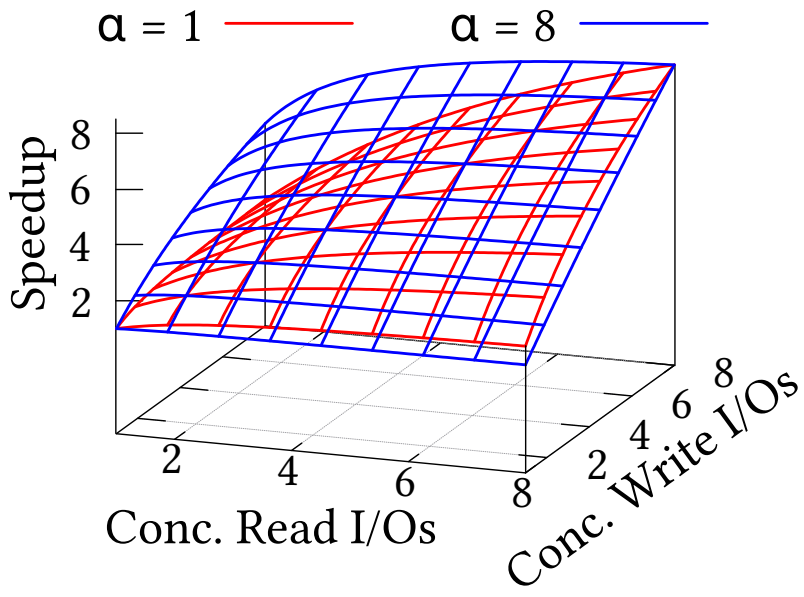

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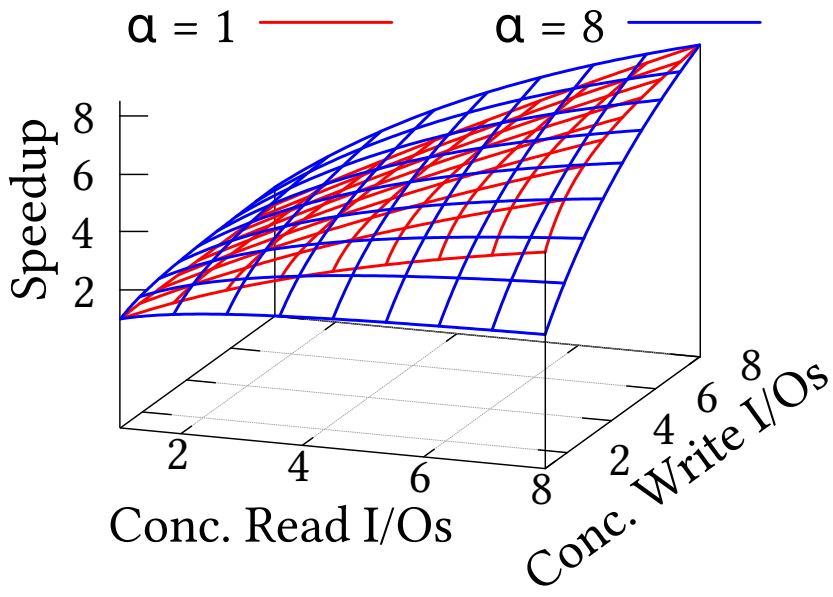

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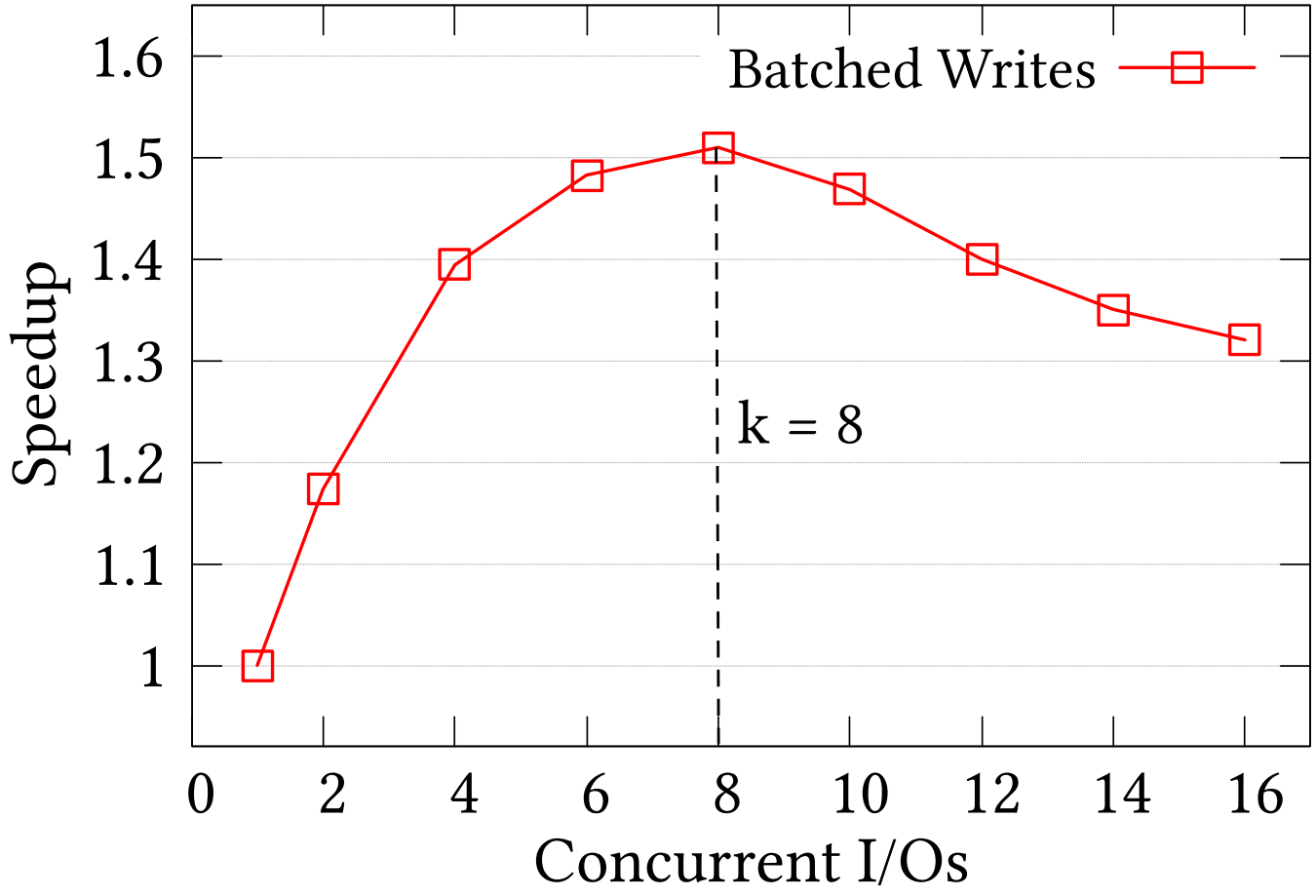
Impact of utilizing write concurrency is higher

Importance of using Proper k

Sample application: batchable writes



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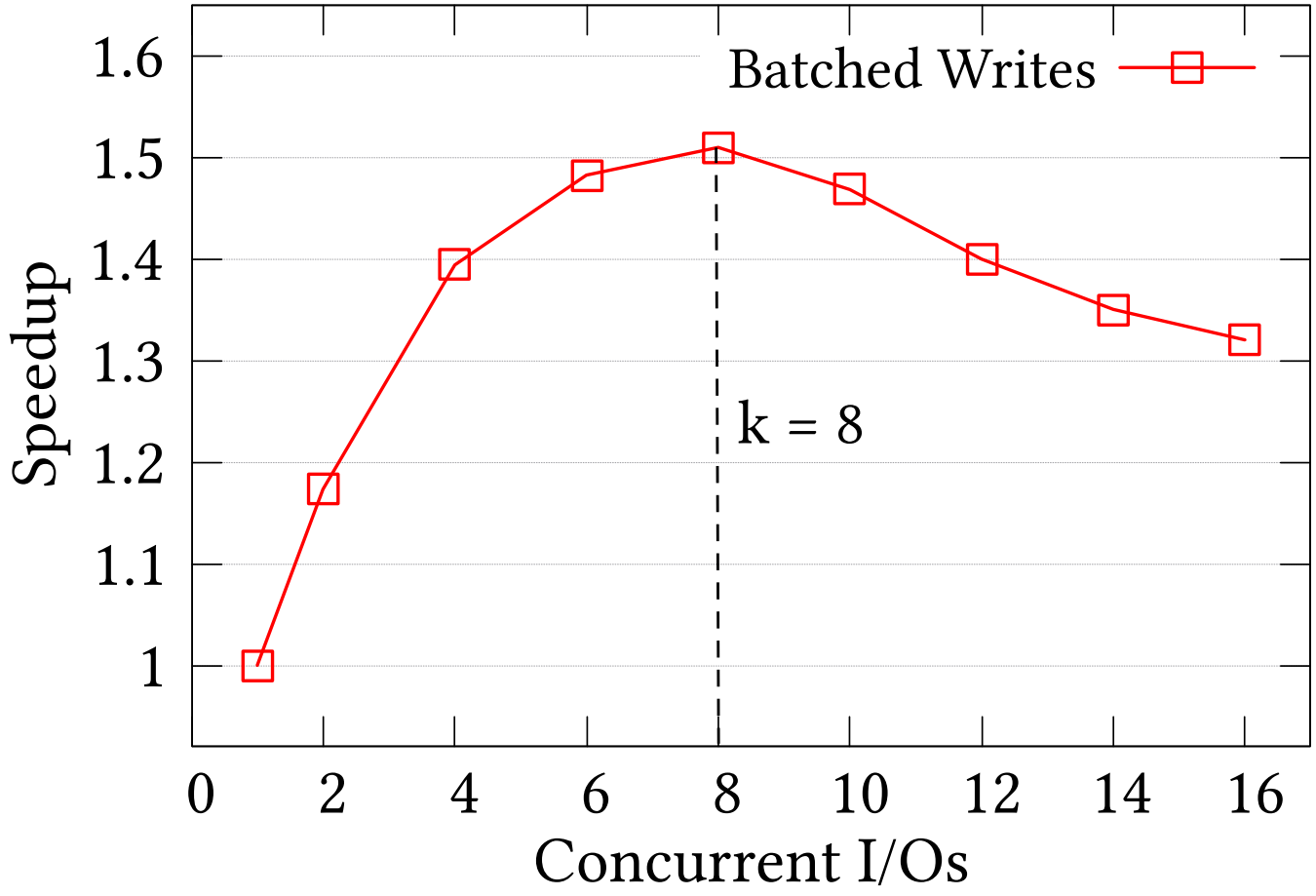
We use PCIe SSD ($k_w = 8$) to run this concurrency-aware application



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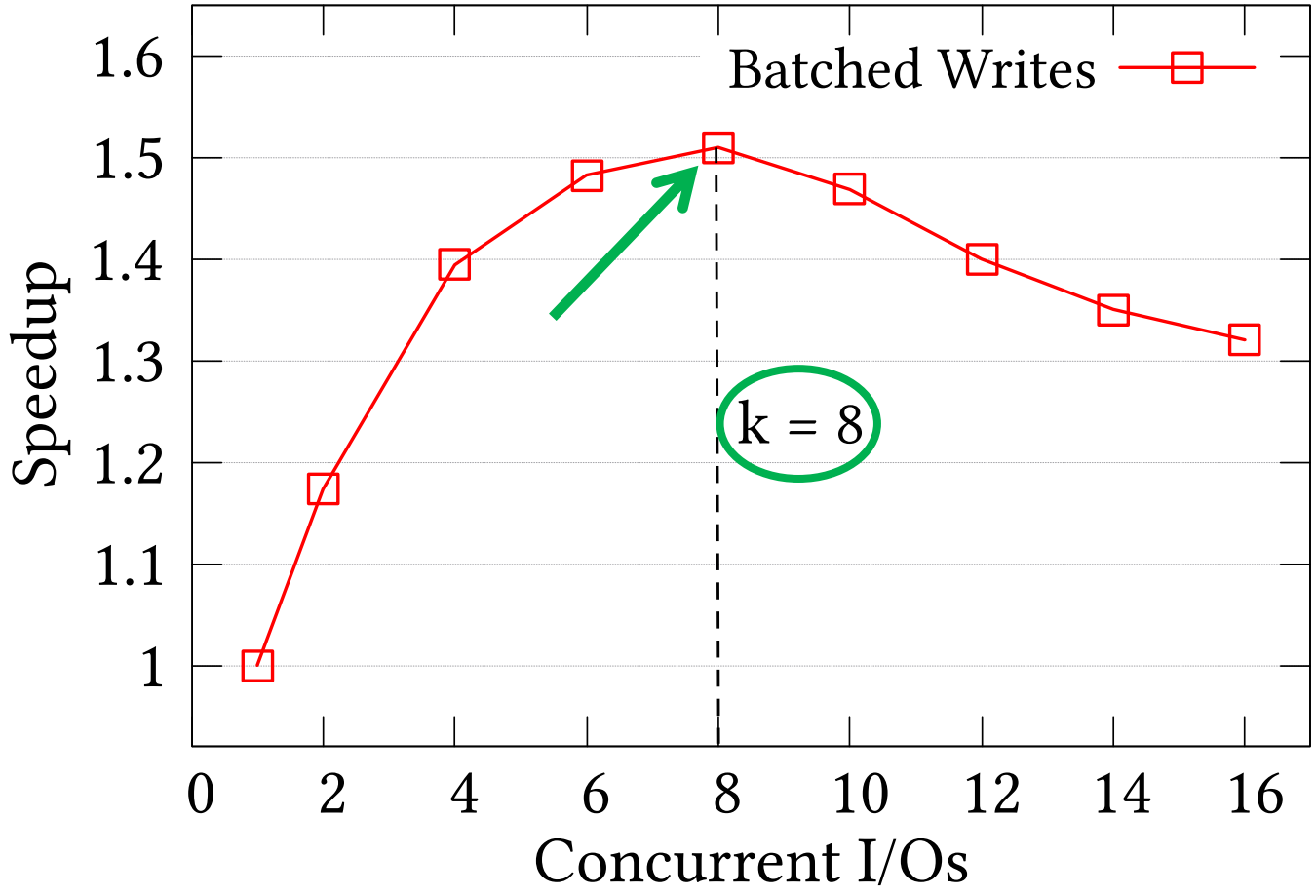
Optimal speedup at the device concurrency.



Guidelines for Algorithm Design

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Know Thy Device

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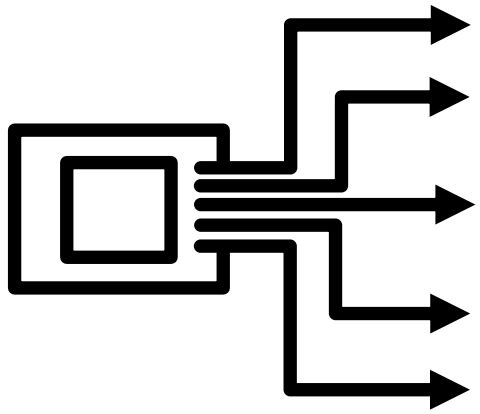

Exploit concurrency
(with care)

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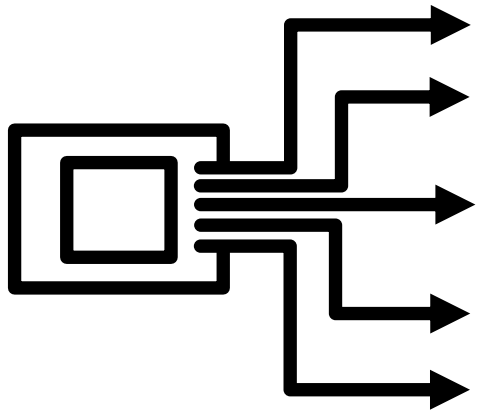

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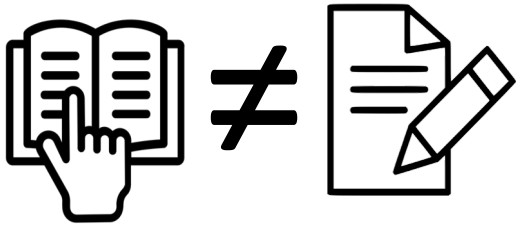

Treat read and write differently.

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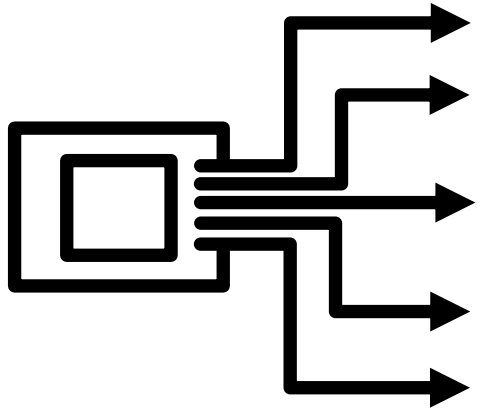

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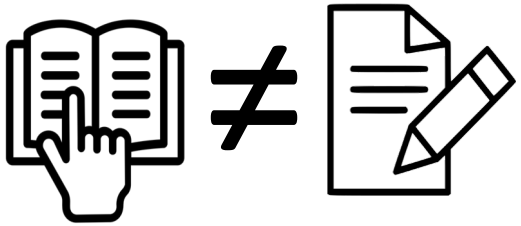

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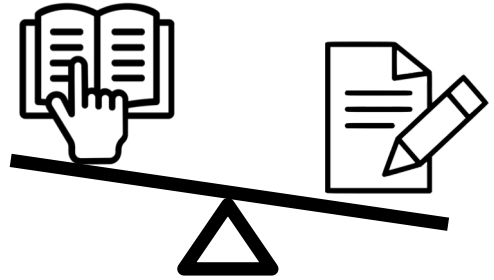
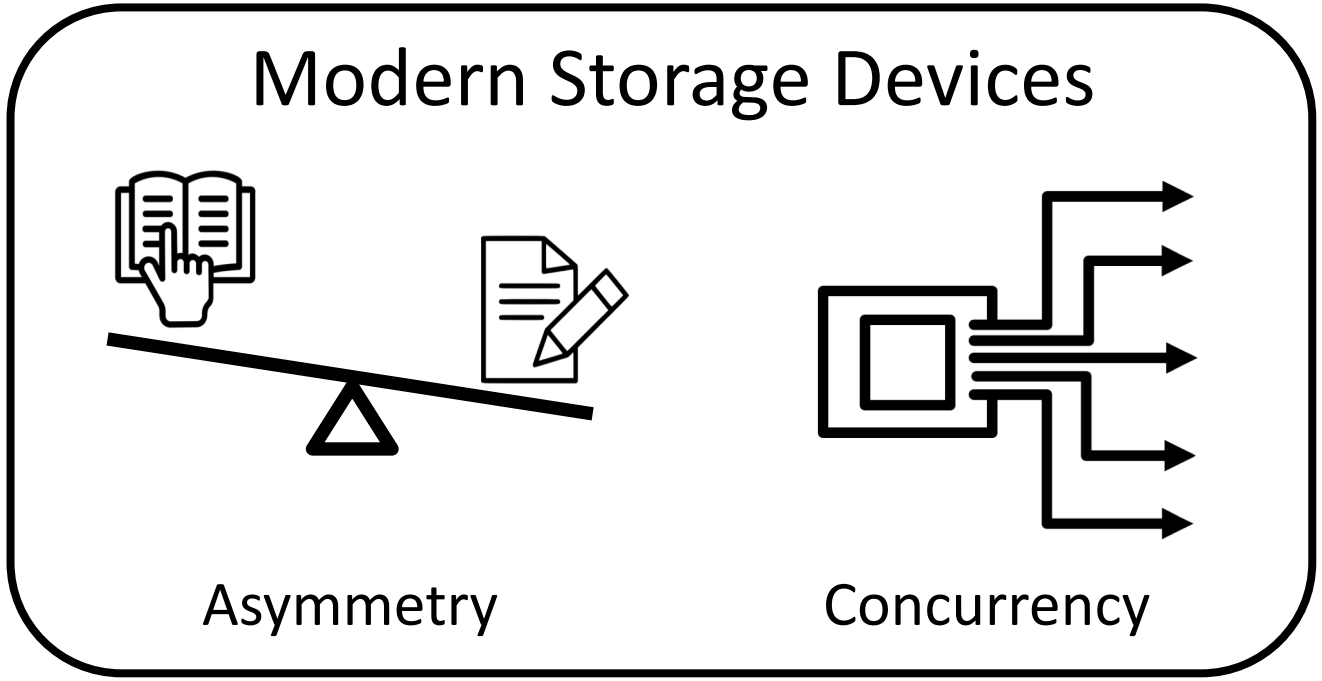


α controls performance

Conclusion & Future Work



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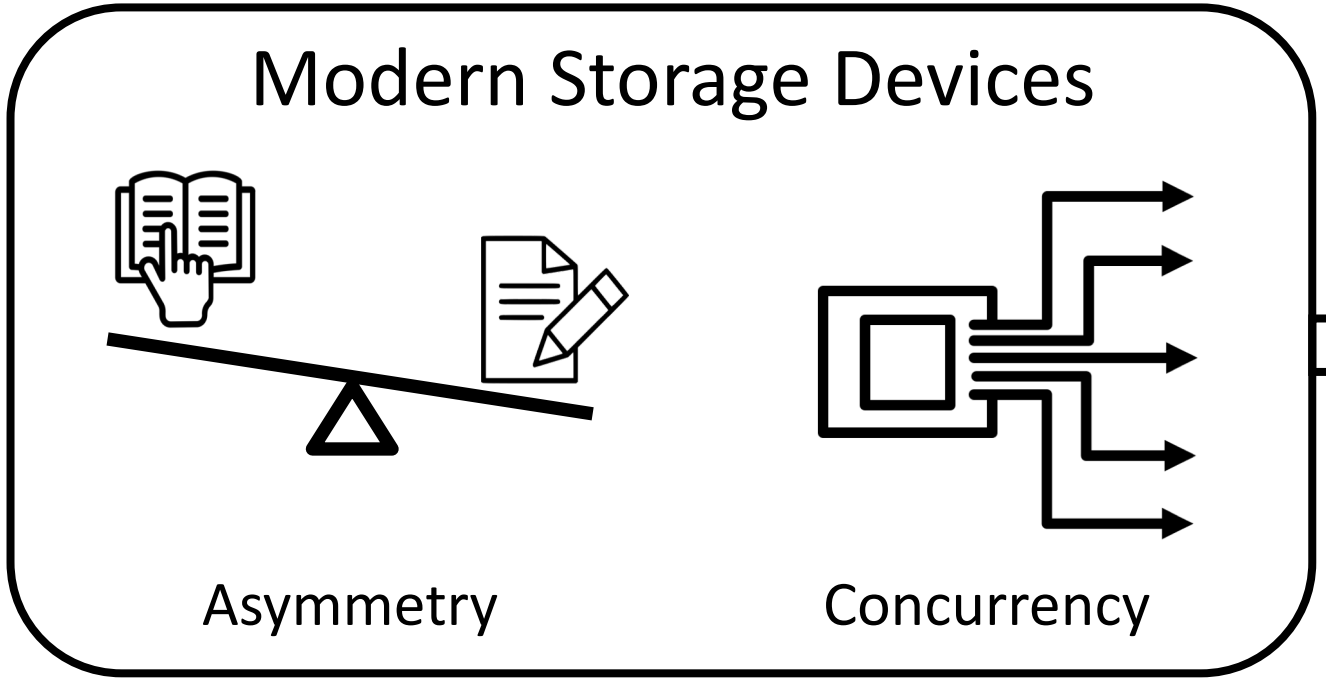

Need for a new parametric I/O model

PIO (M, k, α)

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… not simply an engineering optimization

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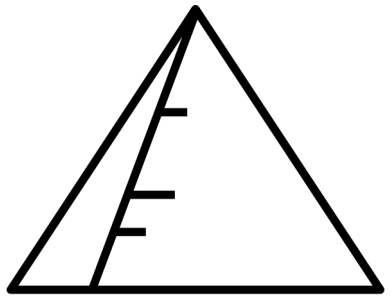

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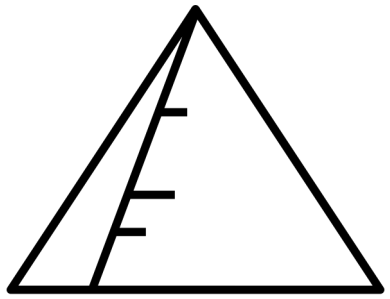
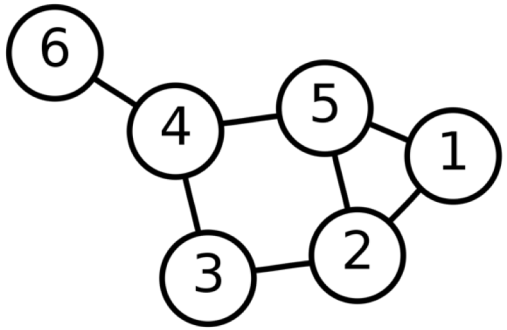


graph traversal algorithms



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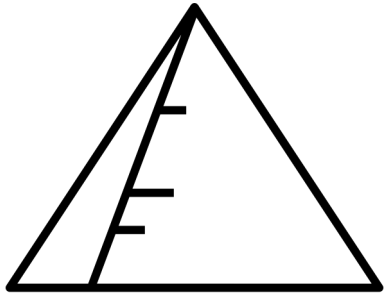

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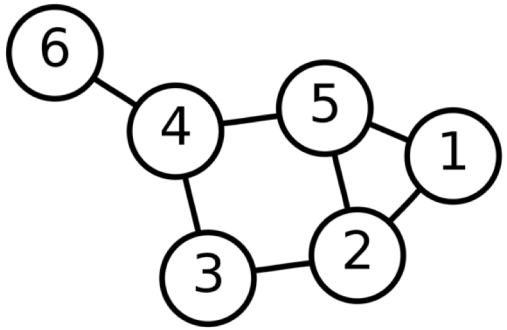
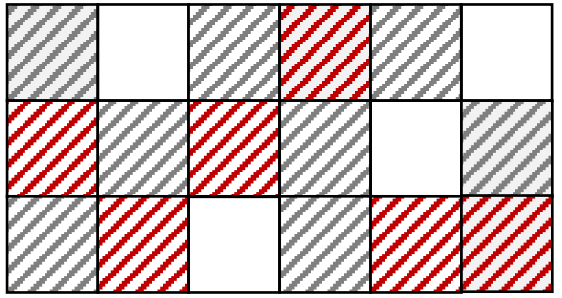


bufferpool management



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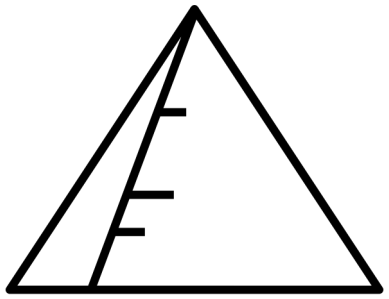
Stay Tuned!

index structures



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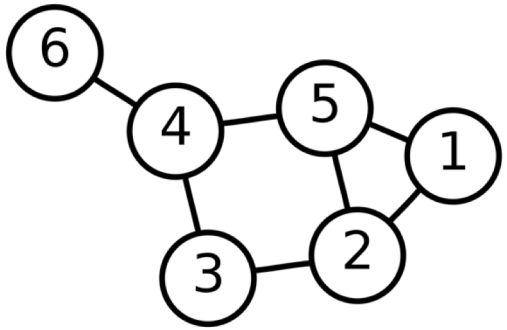

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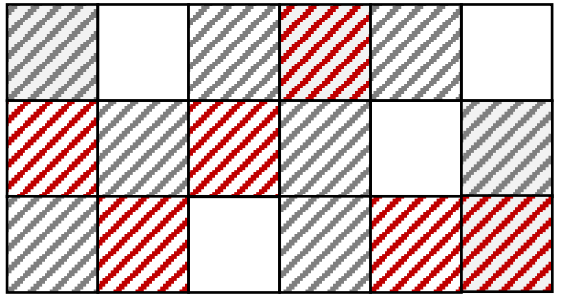

Thank You!

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