A Parametric I/O Model for Modern Storage Devices

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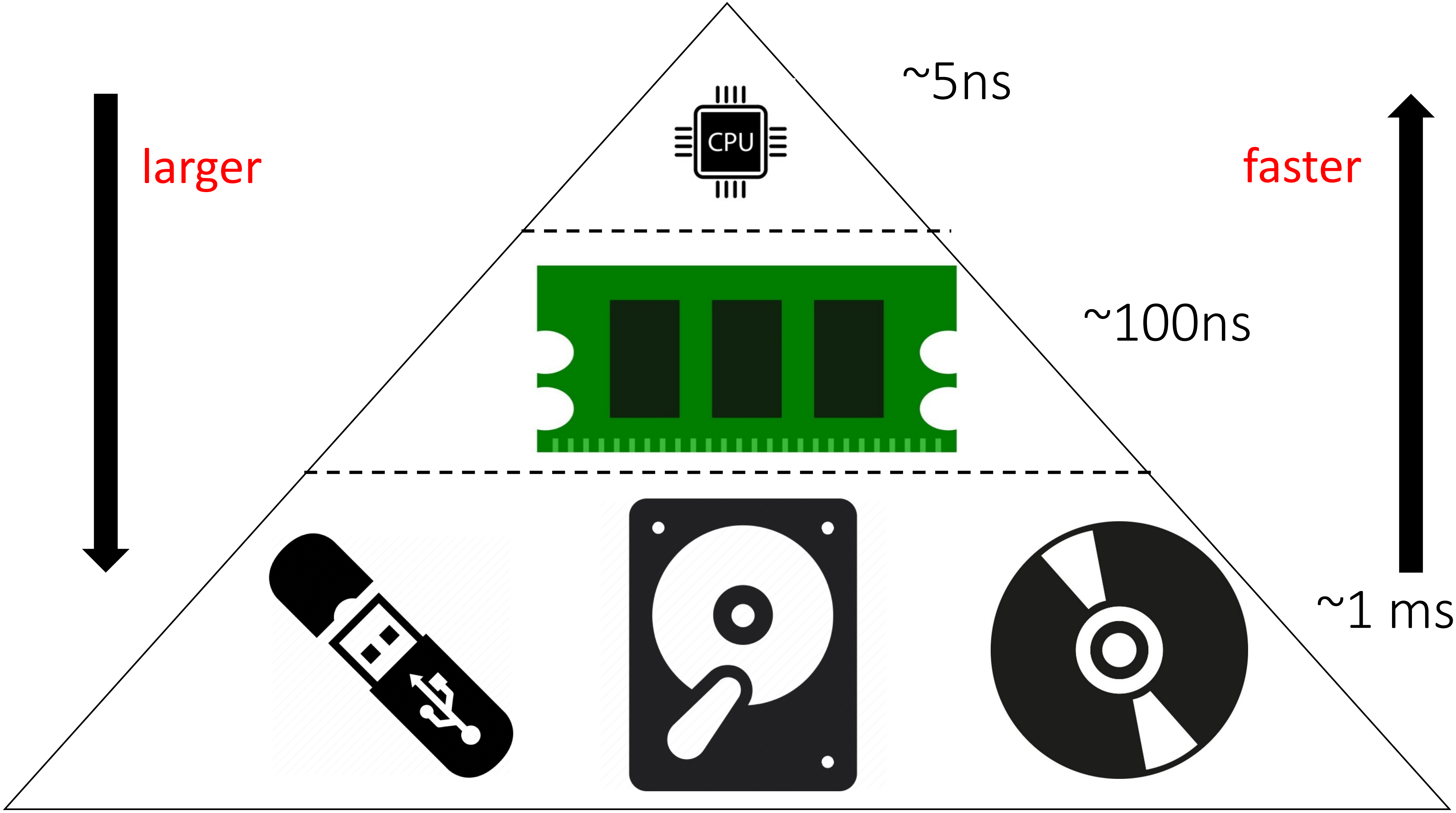
presentation at DaMoN 2021

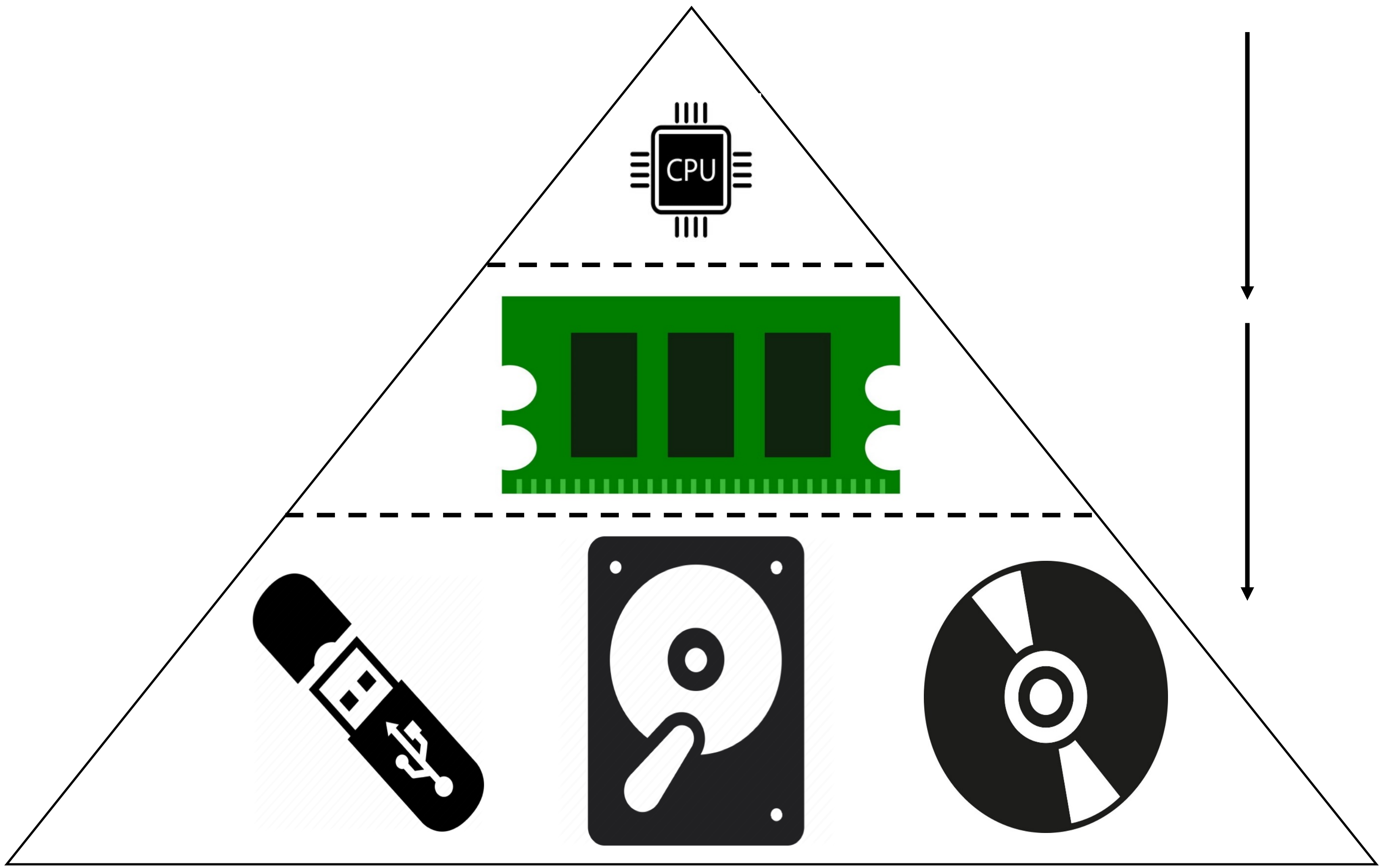
Modeling Performance

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

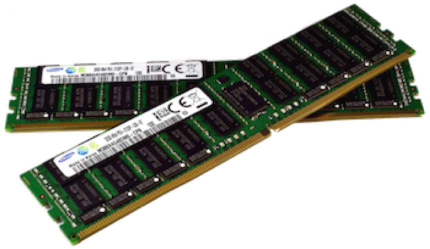
… is probably one of the most commonly read phrases in SIGMOD papers.


larger
CPU
~5ns
~100ns
~1 ms
faster

Memory Hierarchy

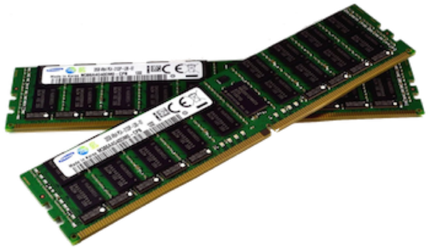


Traditional I/O Model



Small, fast main memory
(size M)

Traditional I/O Model

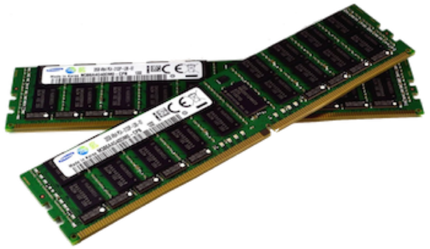


Small, fast main memory
(size M)

Large, slow external memory

Traditional I/O Model

One I/O at a time

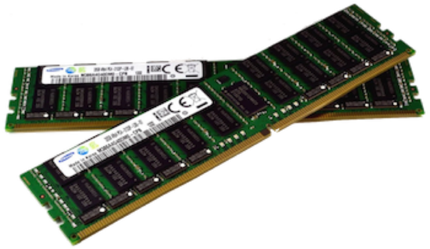


Small, fast main memory
(size M)

Large, slow external memory

Traditional I/O Model

0 access cost



Small, fast main memory
(size M)

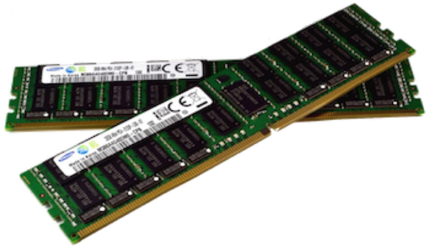
Large, slow external memory

Traditional I/O Model

Transfer cost

1 unit

0 access cost



Small, fast main memory

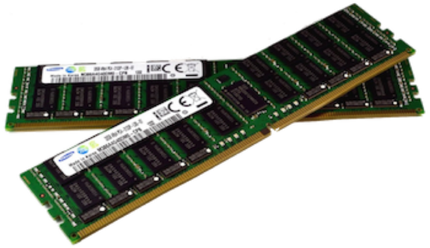
(size M)

Large, slow external memory

Traditional I/O Model

total cost $\simeq$ total # reads/writes to disk

0 access cost



Small, fast main memory
(size M)

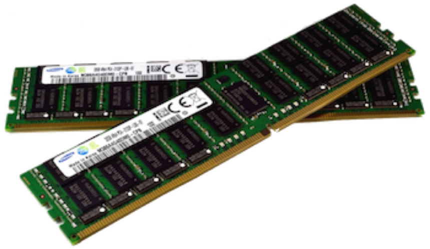
Transfer cost
1 unit

Large, slow external memory

Traditional I/O Model

Two (outdated) assumptions

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



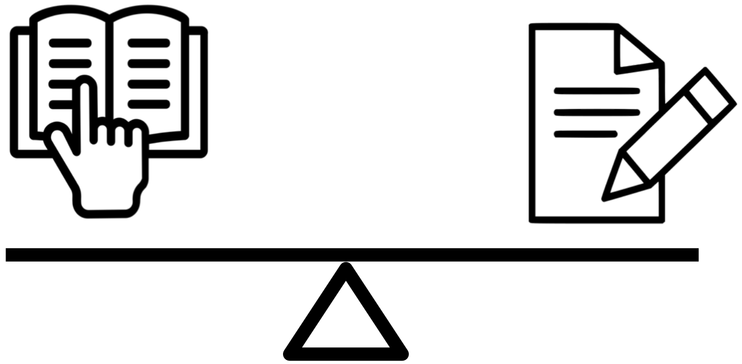
Small, fast main memory
(size M)

Large, slow external memory

Hard Disk Drives

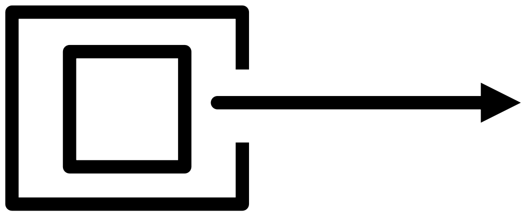
Hard Disk Drives

Two assumptions of Traditional I/O Model



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

✓



One I/O at a time

✓

HDD Stopped Evolving

- Generally, the slowest component
- Slowest increase in performance

Device	Size	Seq B/W	Time to read
HDD 1980	100 MB	1.2 MB/s	~ 1 min
HDD 2020	4 TB	125 MB/s	~ 9 hours

HDDs are moving deeper in the memory hierarchy, and new algorithms are designed for new faster storage devices

How do these modern storage devices perform?

Solid State Drives & NVMs

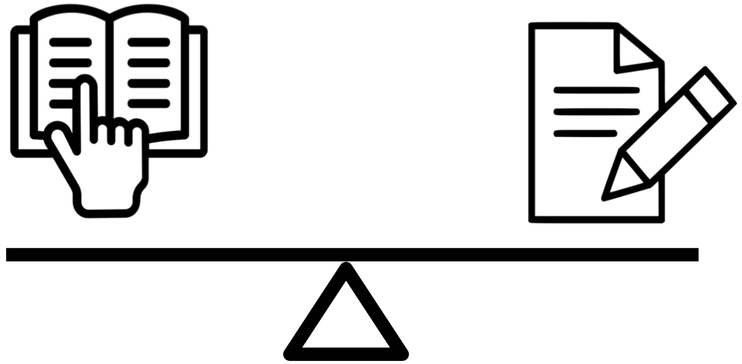
SSDs

- SATA SSDs
- PCIe SSDs (NVMe SSDs)
- Zoned SSDs
- Open SSDs

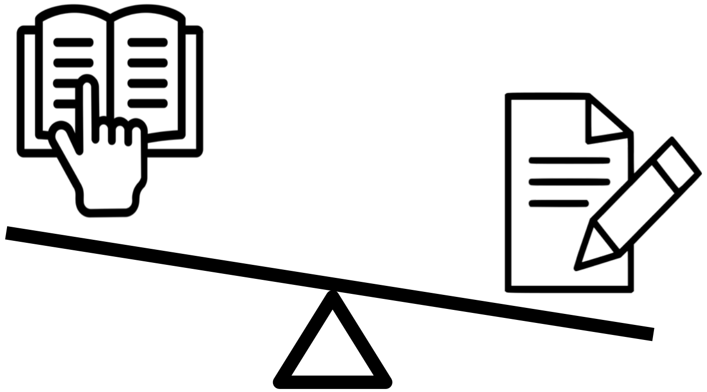
NVMs

- PCM
- MRAM
- STT-RAM
- 3D Xpoint (Intel's Optane)

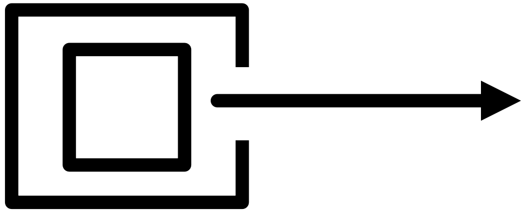
Modern Storage Devices



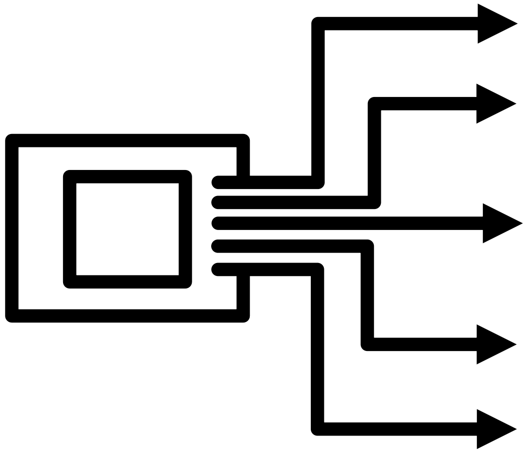
Symmetric cost for Read & Write



Read/Write Asymmetry

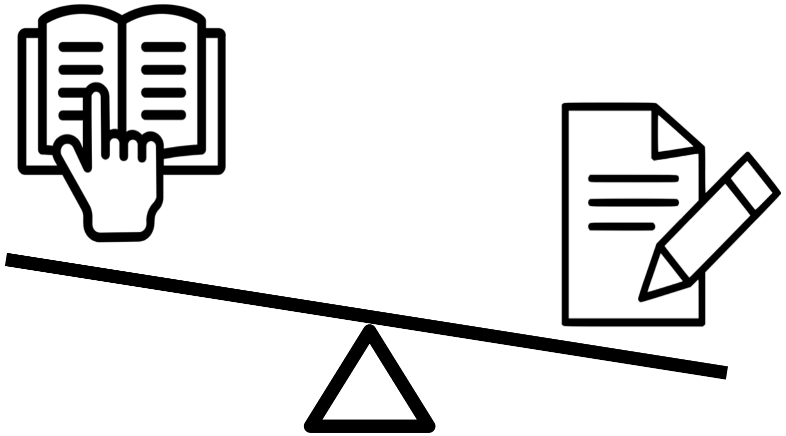


One I/O at a time



Concurrency

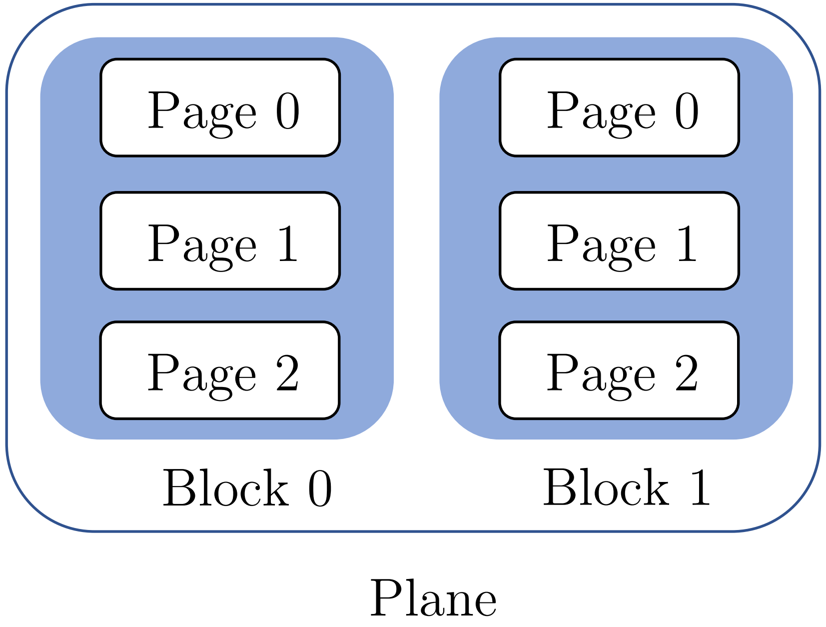
Read/Write Asymmetry



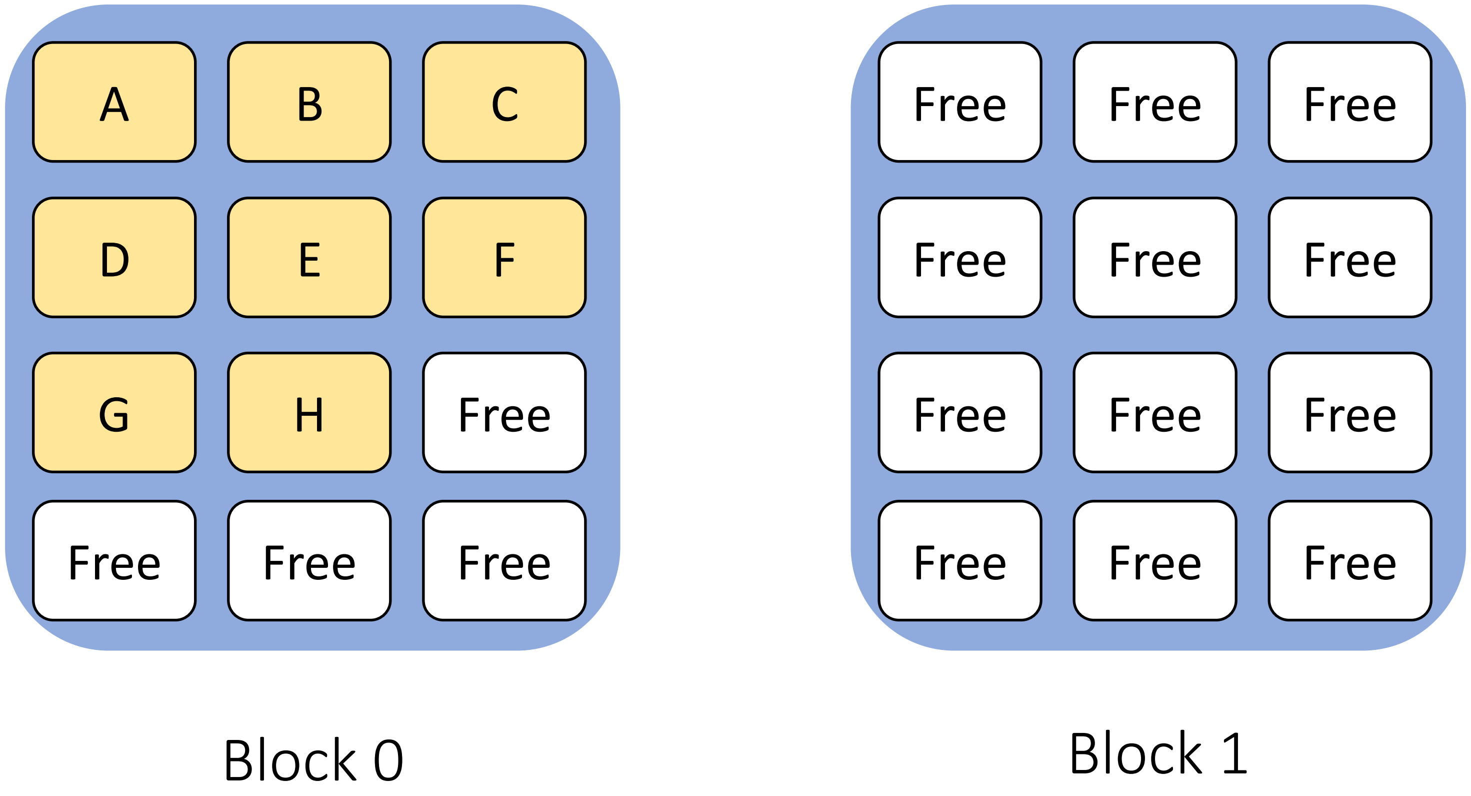
Writes in SSD

Out-of-place updates cause invalidation

Invalidation causes **garbage collection**



Writes in SSD

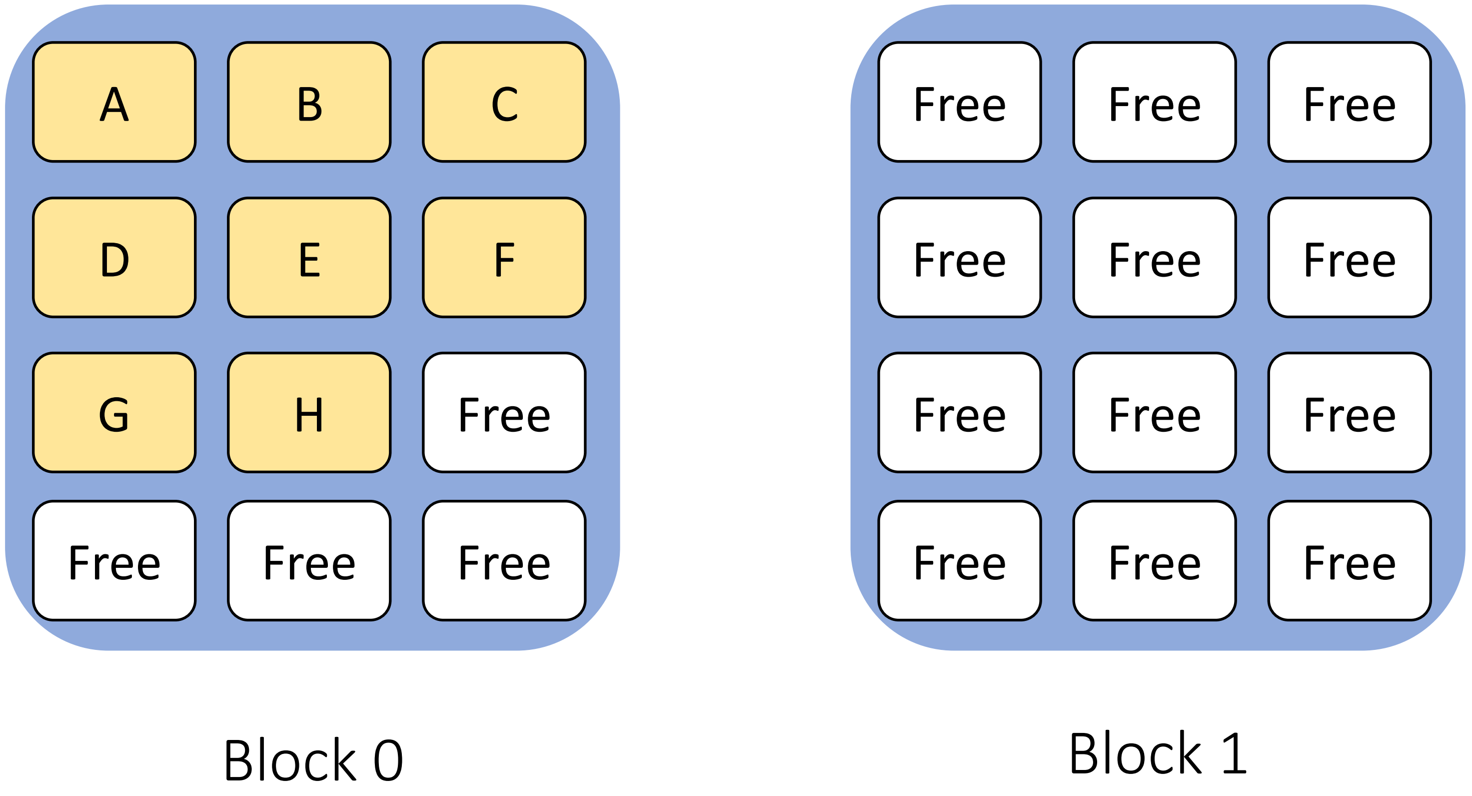


Writing in a free page isn't costly!

Writes in SSD

Update

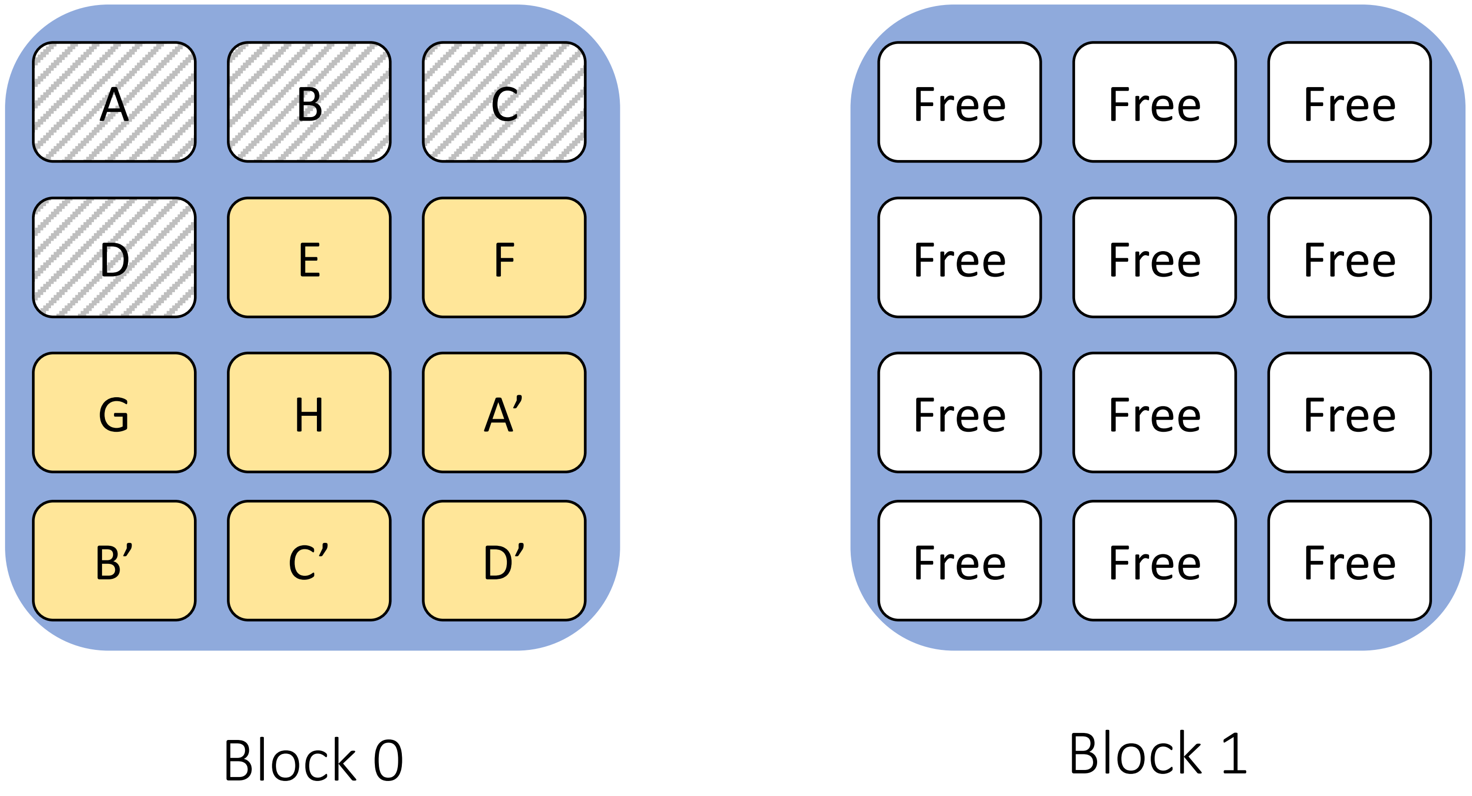
A, B, C, D



Writes in SSD

Update

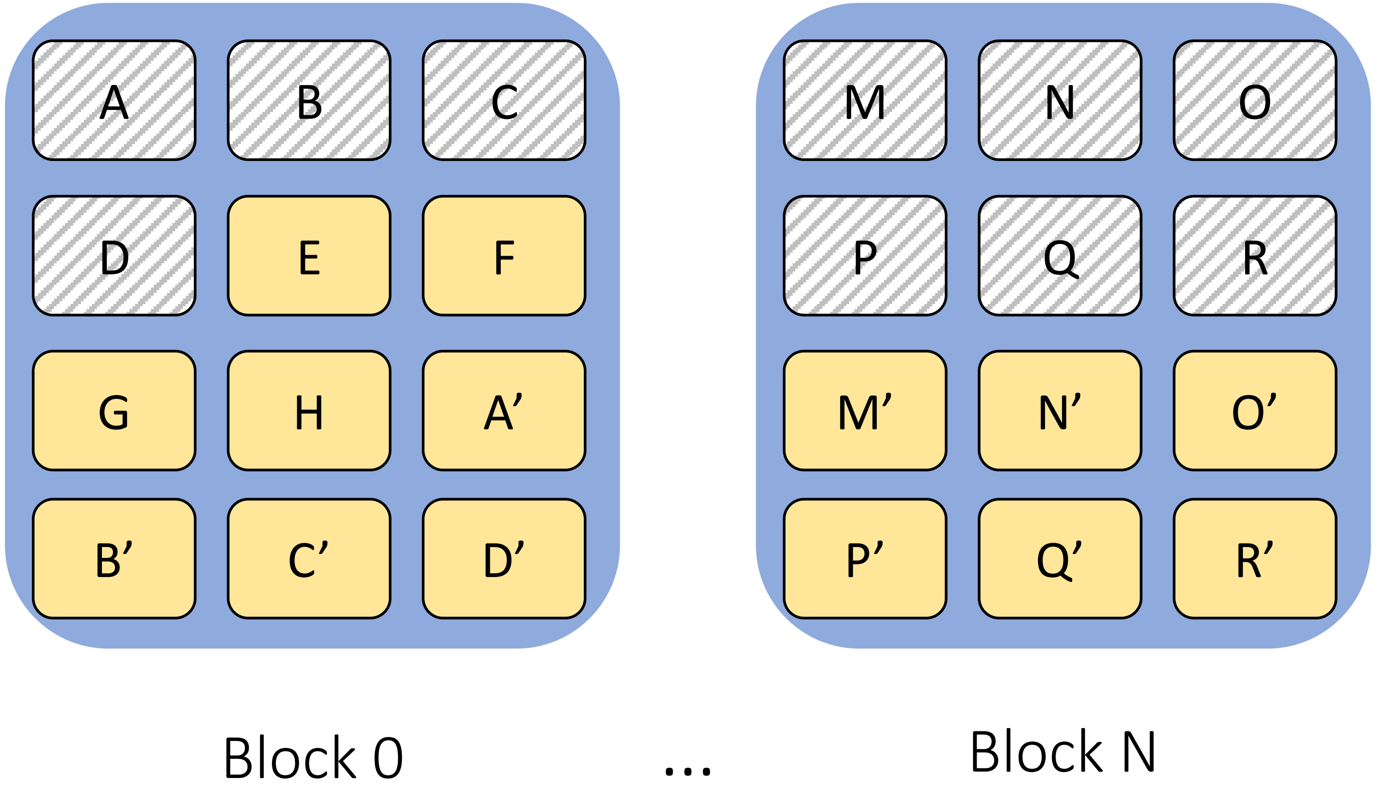
A, B, C, D



Not all updates are costly!

Writes in SSD

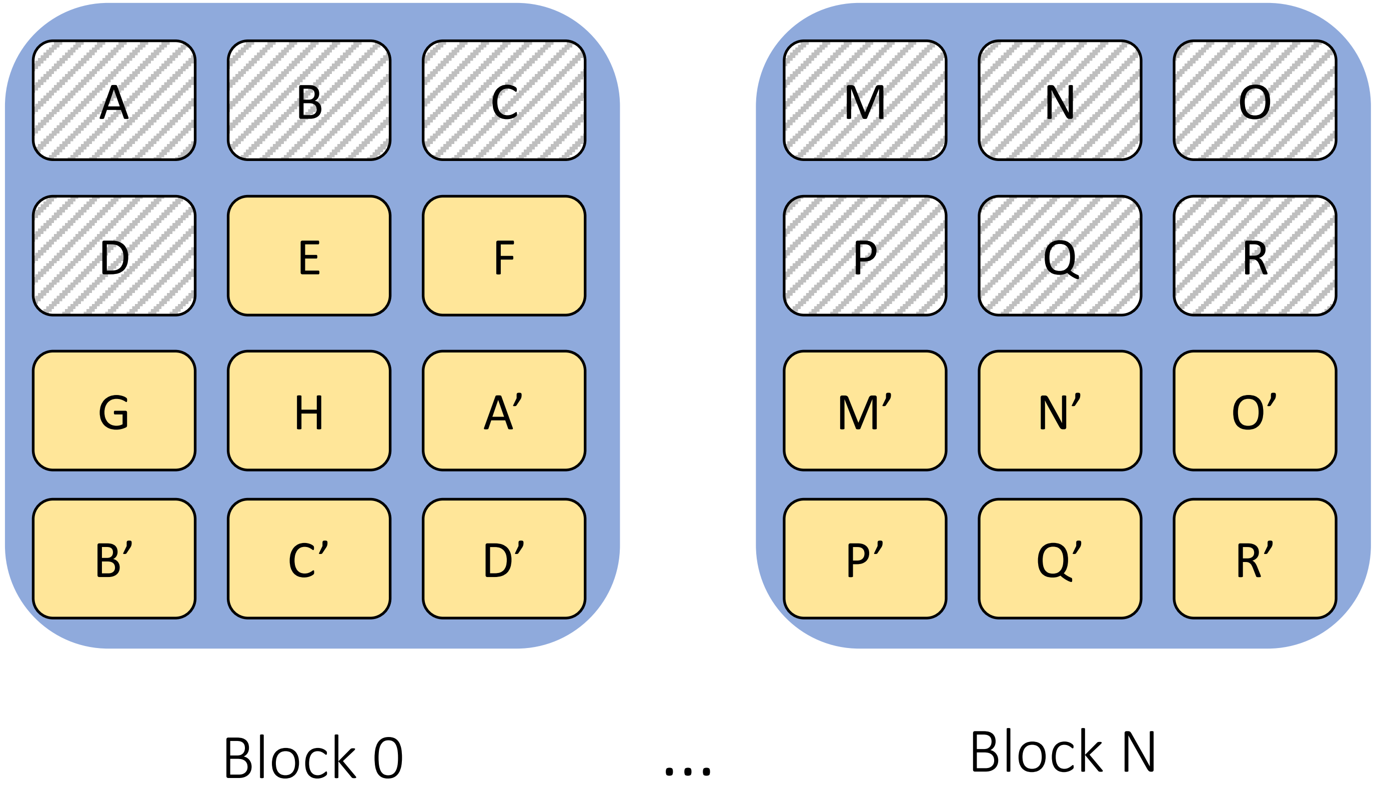
What if there is no space?



Writes in SSD

What if there is no space?

Garbage Collection!



Writes in SSD

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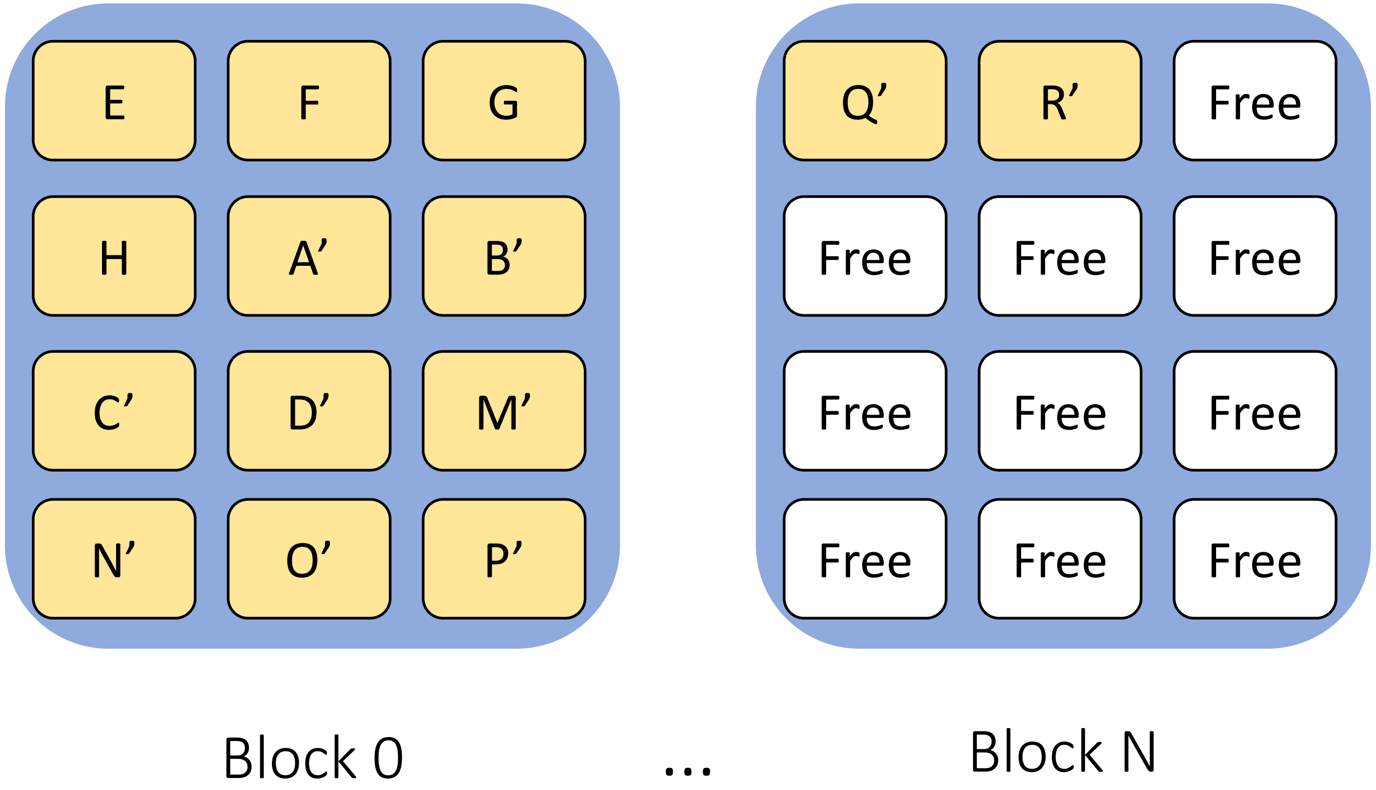
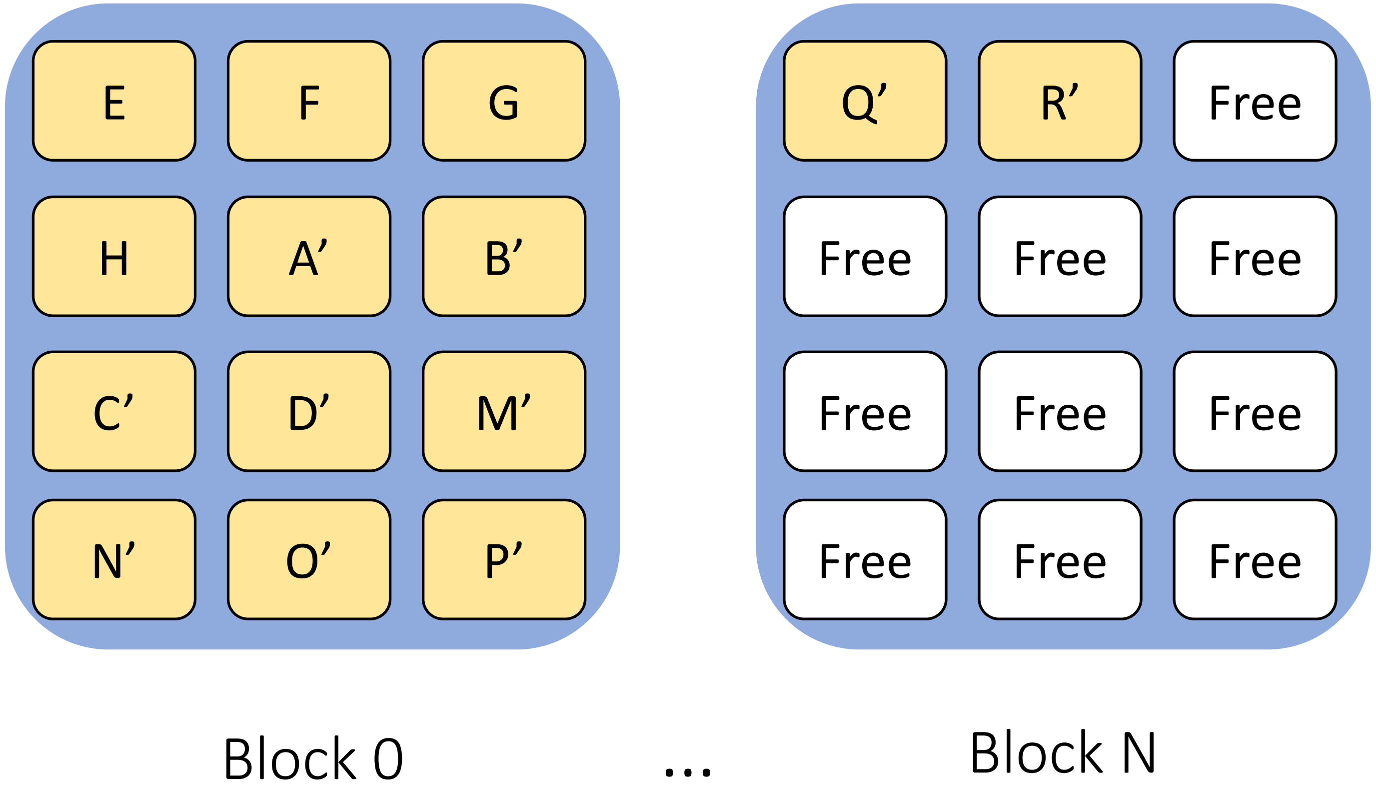


Writes in SSD

What if there is no space?

Garbage Collection!

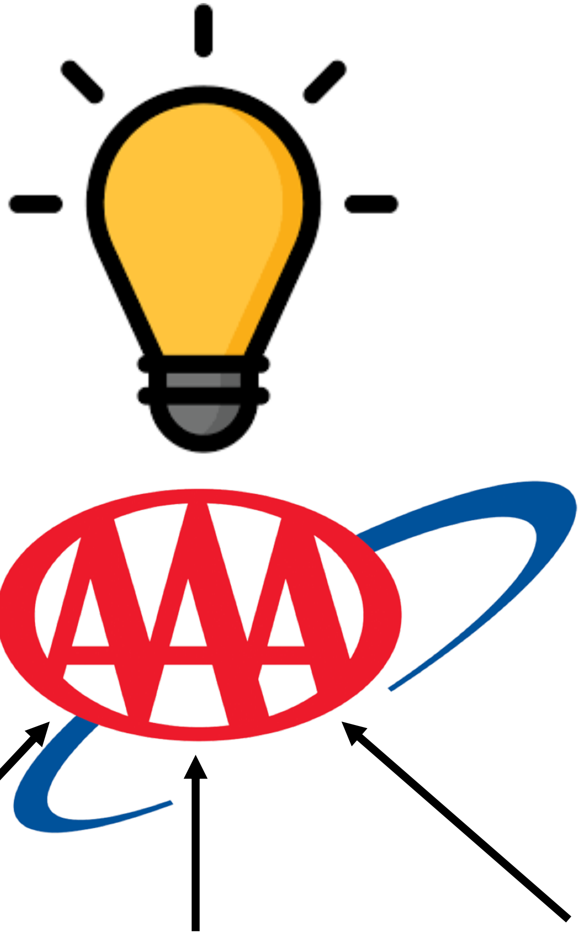


Higher average update cost (due to GC) → ***Read/Write asymmetry***

Read/Write Asymmetry - Example

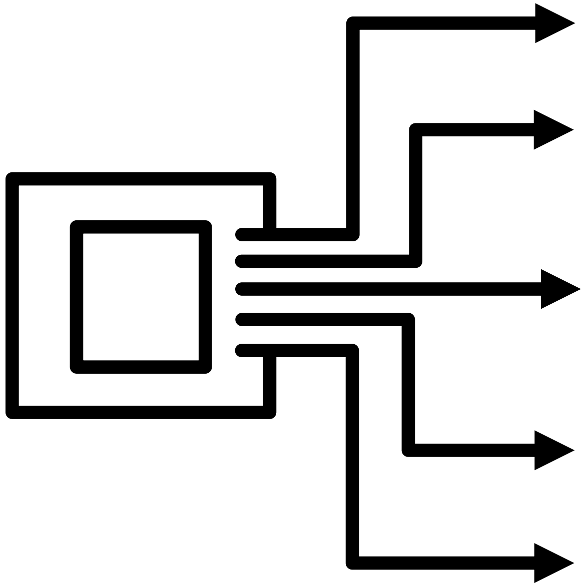
Intel Device	Advertised Random Read IOPS	Advertised Random Write IOPS	Advertised Asymmetry
D5-P4320	427k	36k	11.9
DC-P4500	626k	51k	12.3
DC-P4610	643k	199k	3.2
Optane 900P	550k	500k	1.1
Optane H10	330k	250k	1.3

Read/Write Asymmetry

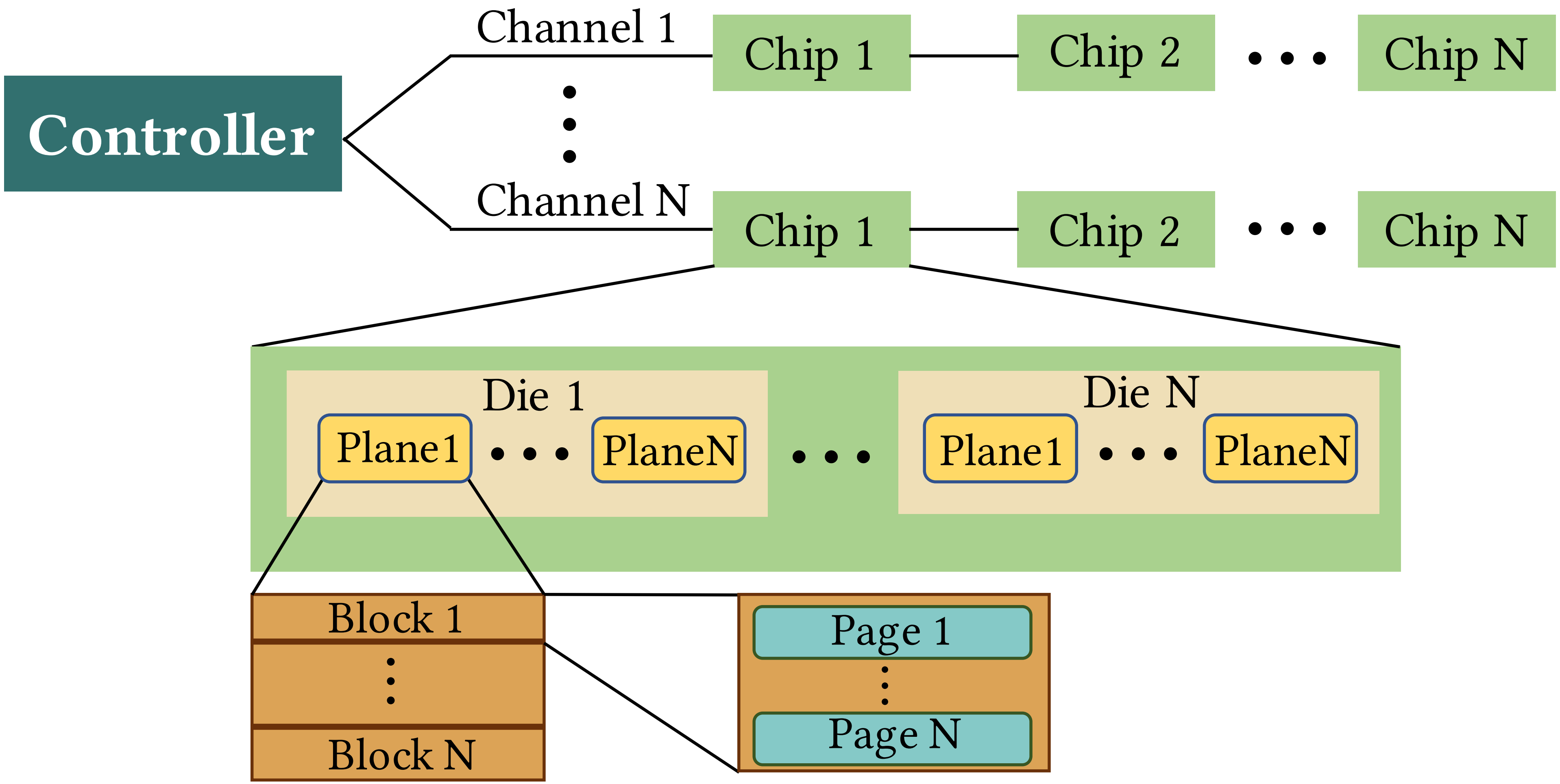


Asymmetry-Aware Algorithms

Concurrency

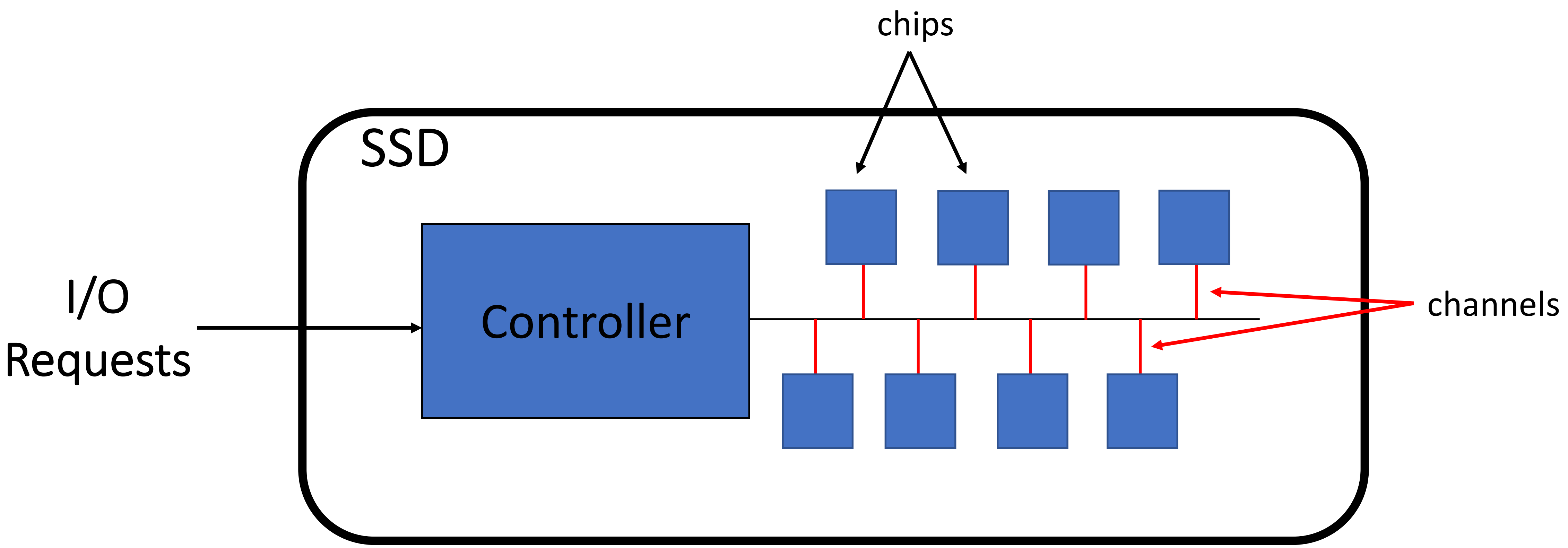


Internals of an SSD



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

Concurrency in SSD (simplified)



Benchmarking

Benchmarking

Tools

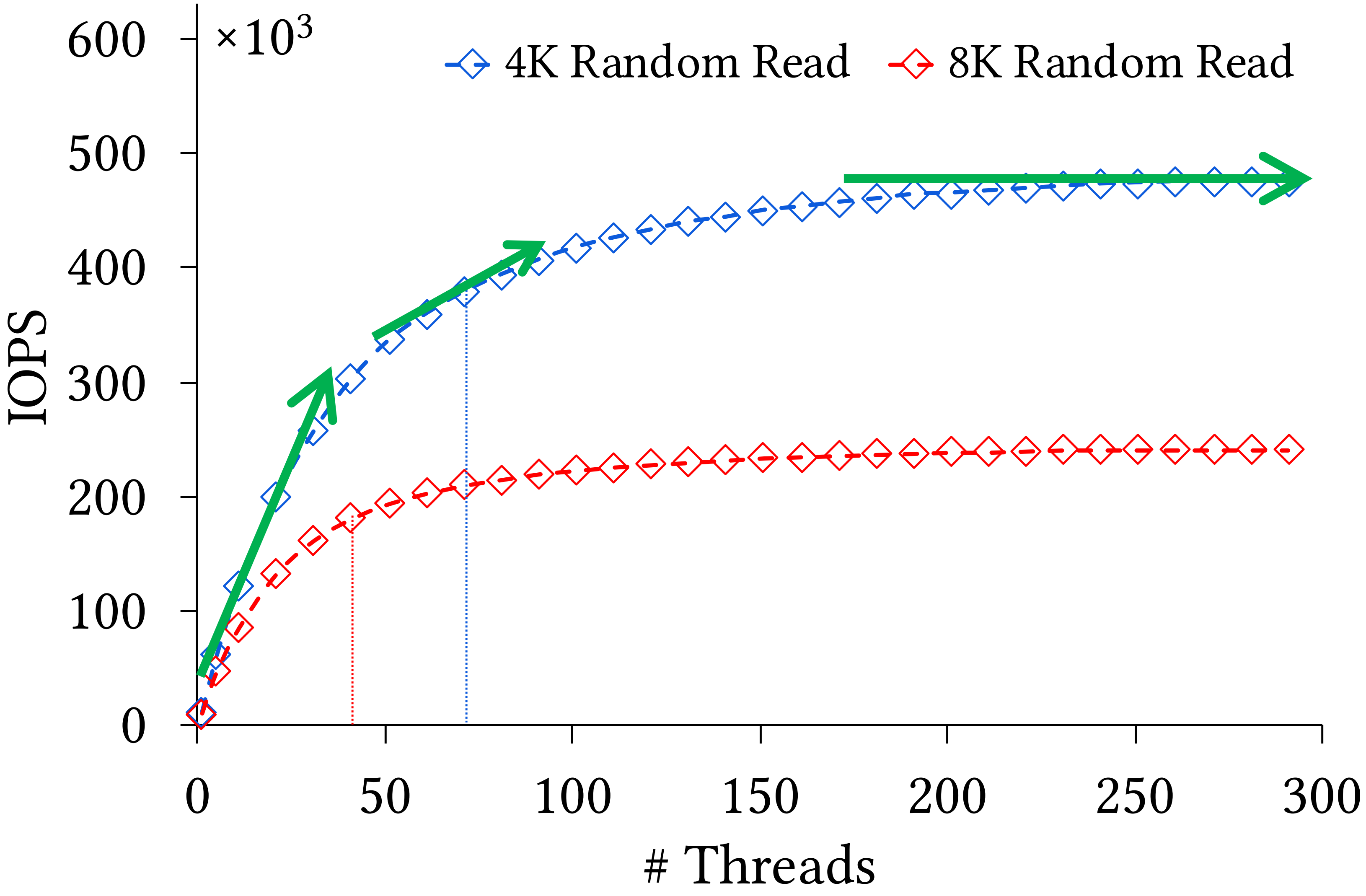
- Custom micro-benchmarking infrastructure
- fio
- Intel’s SPDK

Setup

- With File System
- Without File System

Measuring Asymmetry/Concurrency (With FS)

Device: Dell P4510 (1TB)



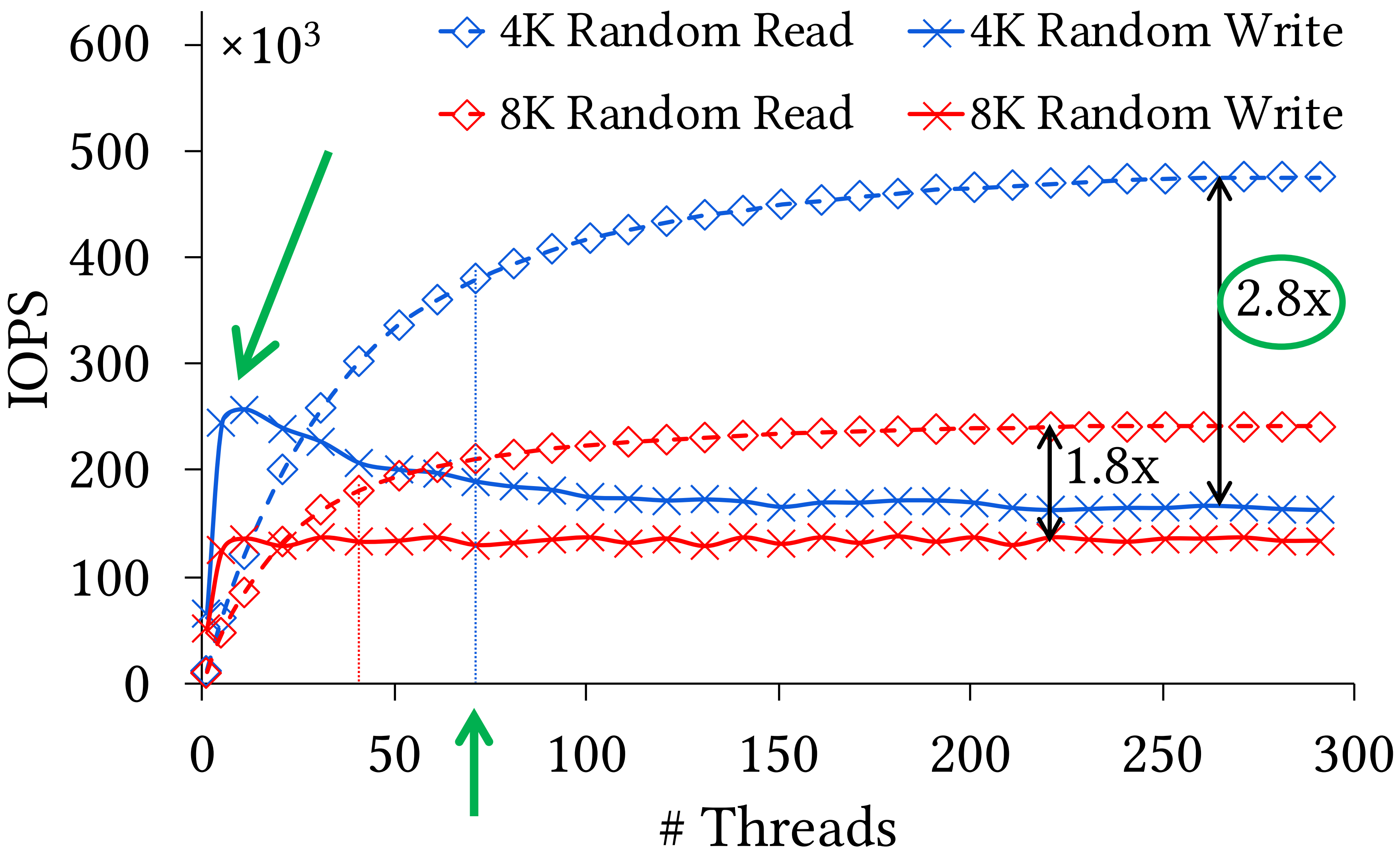
Measuring Asymmetry/Concurrency (With FS)

Device: Dell P4510 (1TB)

For 4K random read,

Asymmetry: 2.8

Concurrency: 70



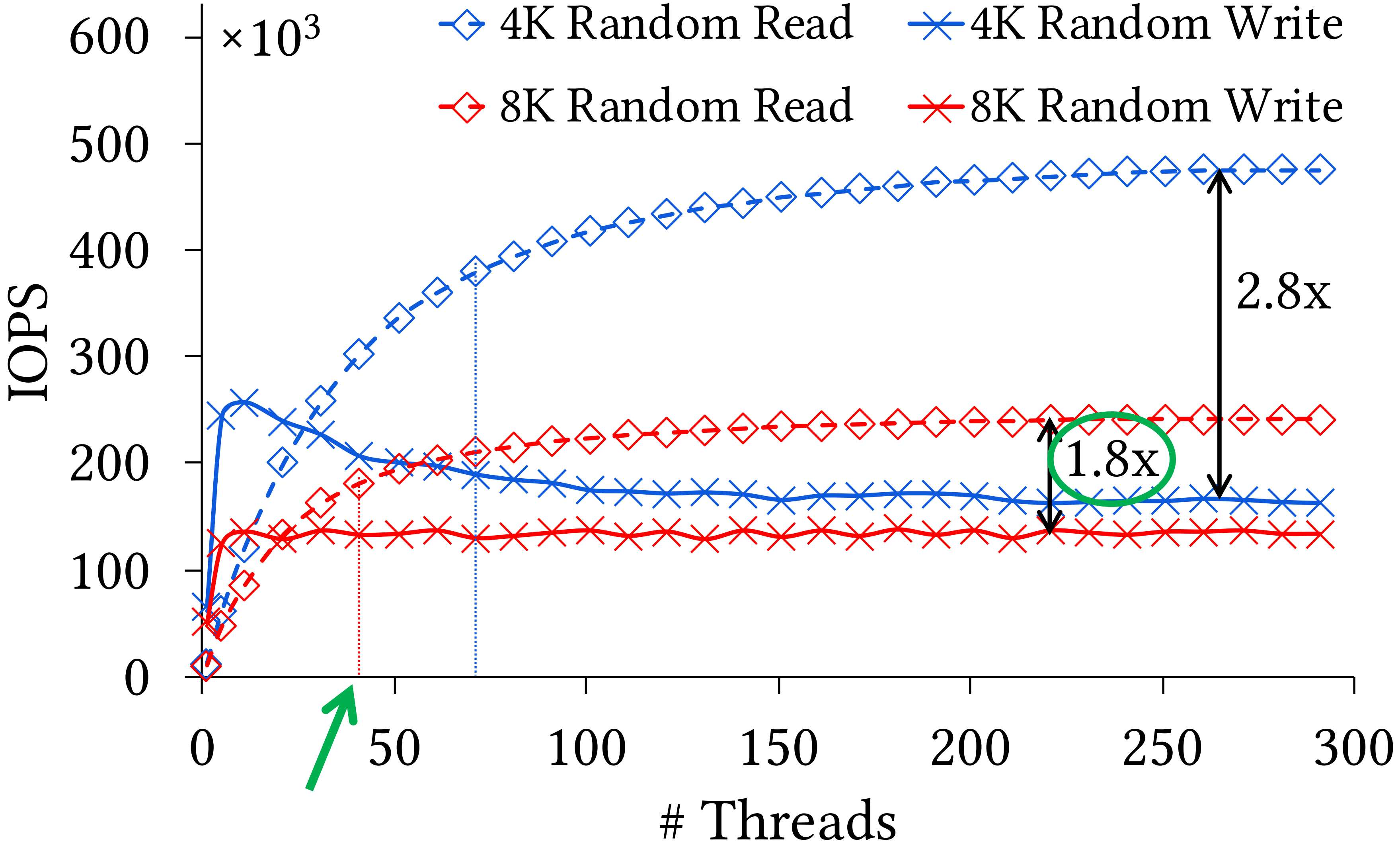
Measuring Asymmetry/Concurrency (With FS)

Device: Dell P4510 (1TB)

For 8K random write,

Asymmetry: 1.8

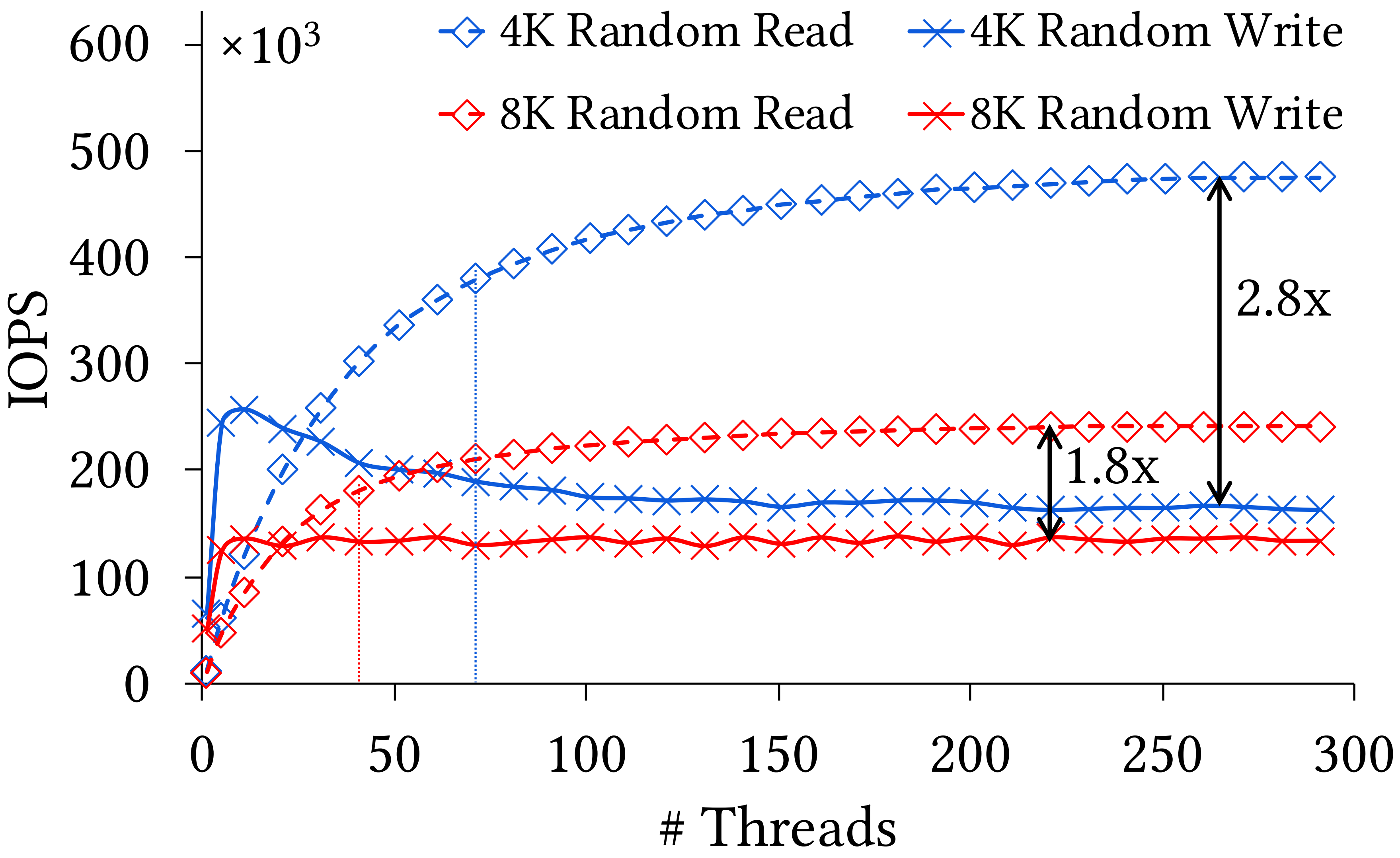
Concurrency: 10



Measuring Asymmetry/Concurrency (With FS)

Device: Dell P4510 (1TB)

Asymmetry and concurrency depends on request type and access granularity



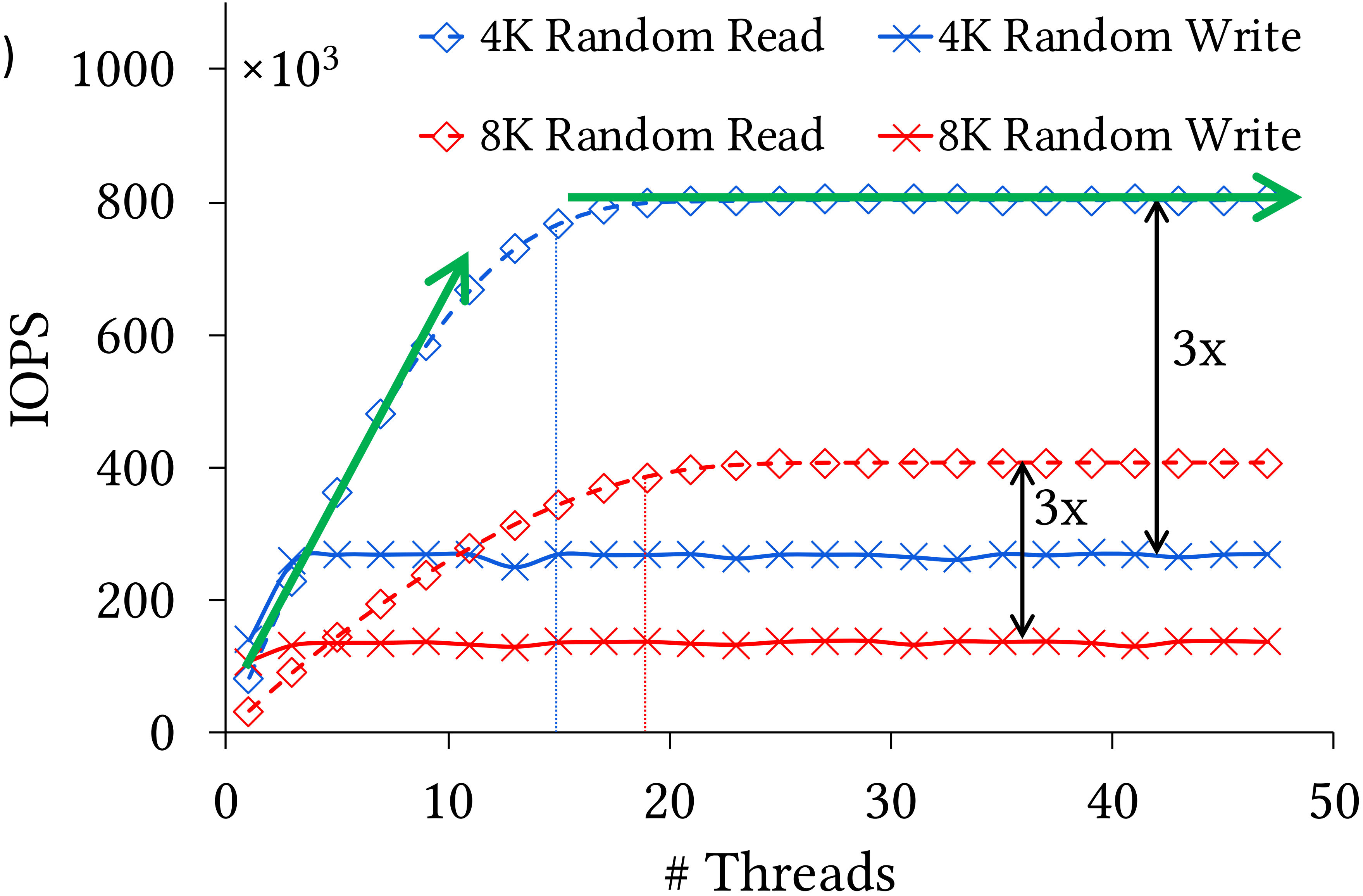
Measuring Asymmetry/Concurrency (Without FS)

Device: Dell P4510 (1TB)

For 4K random reads,

Asymmetry: 3

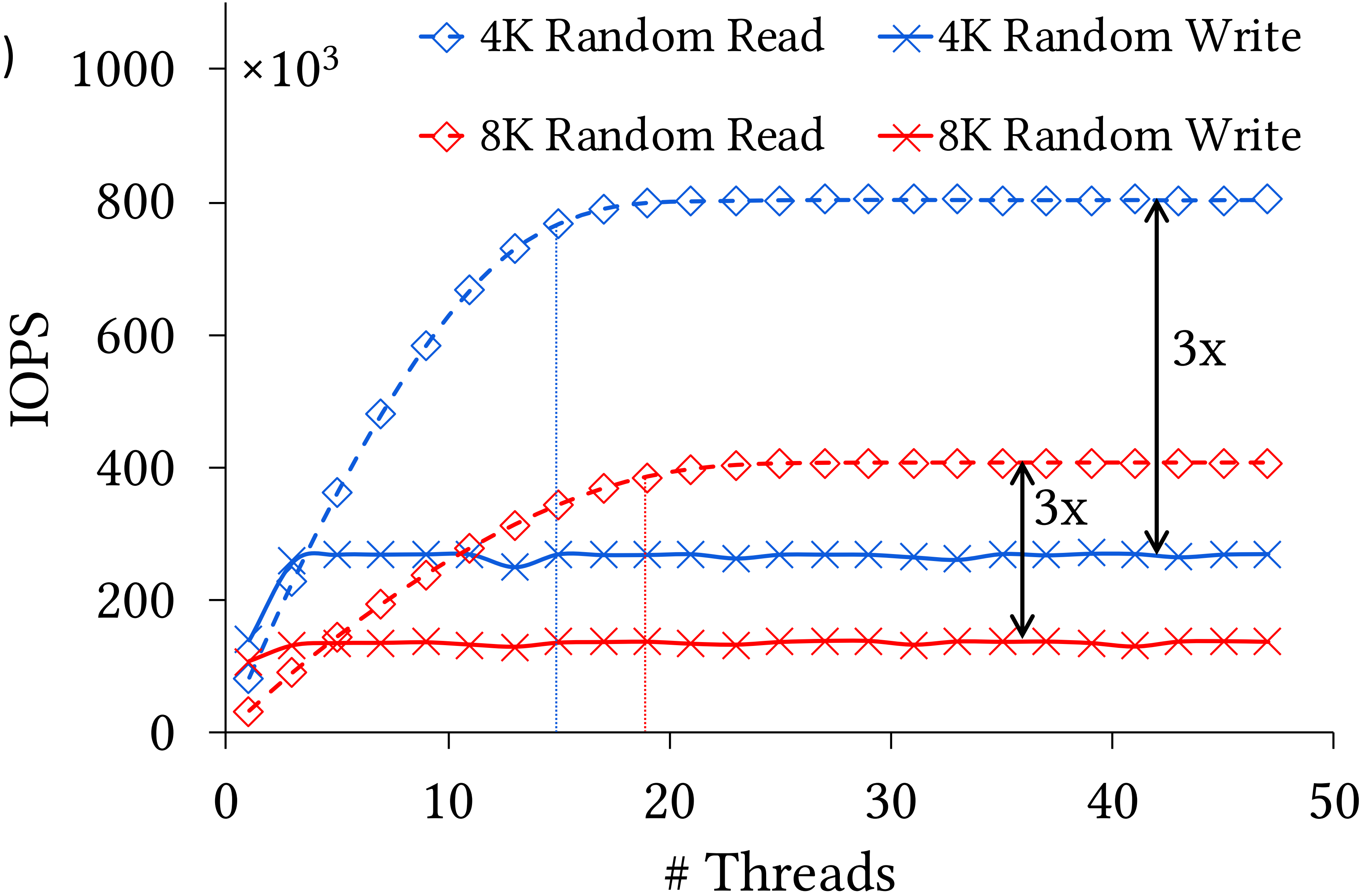
Concurrency: 14



Measuring Asymmetry/Concurrency (Without FS)

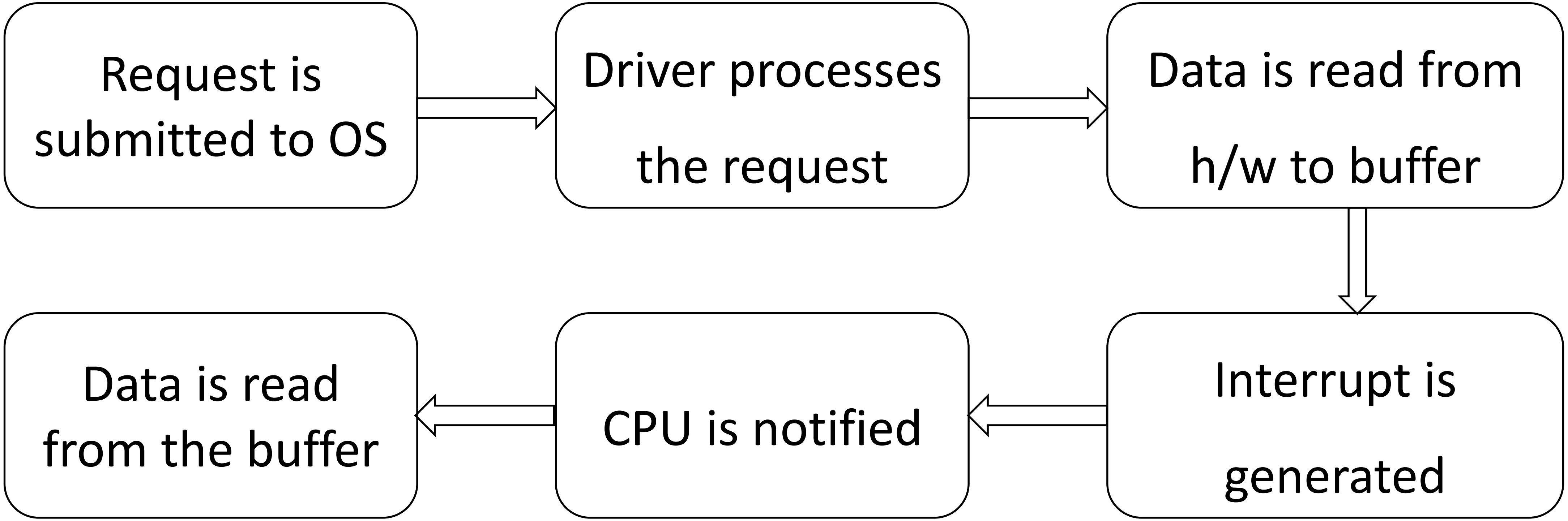
Device: Dell P4510 (1TB)

Much stable performance without the file system!



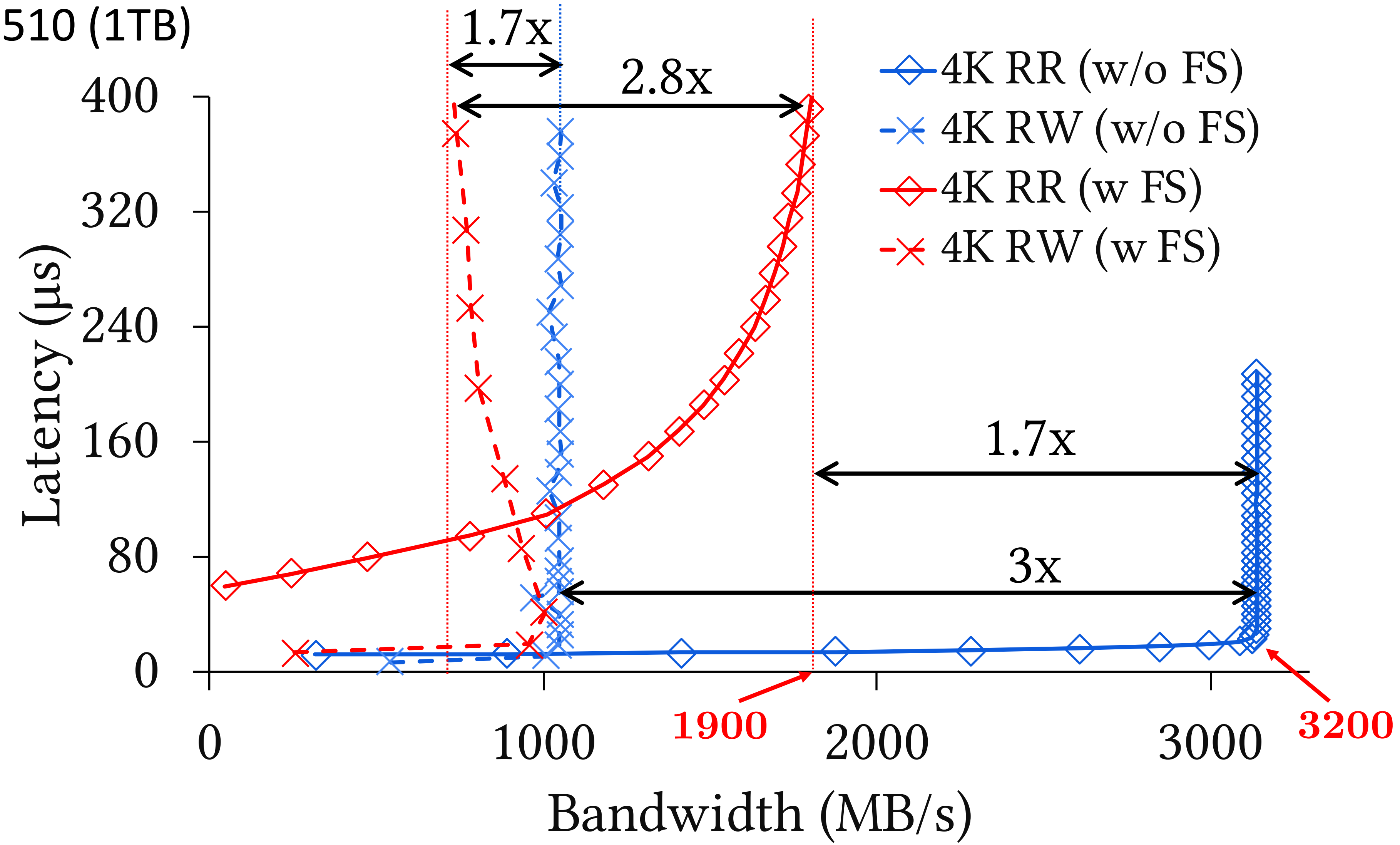
Can the File System be the Bottleneck?

Interrupt-based model



Can the File System be the Bottleneck?

Device: Dell P4510 (1TB)

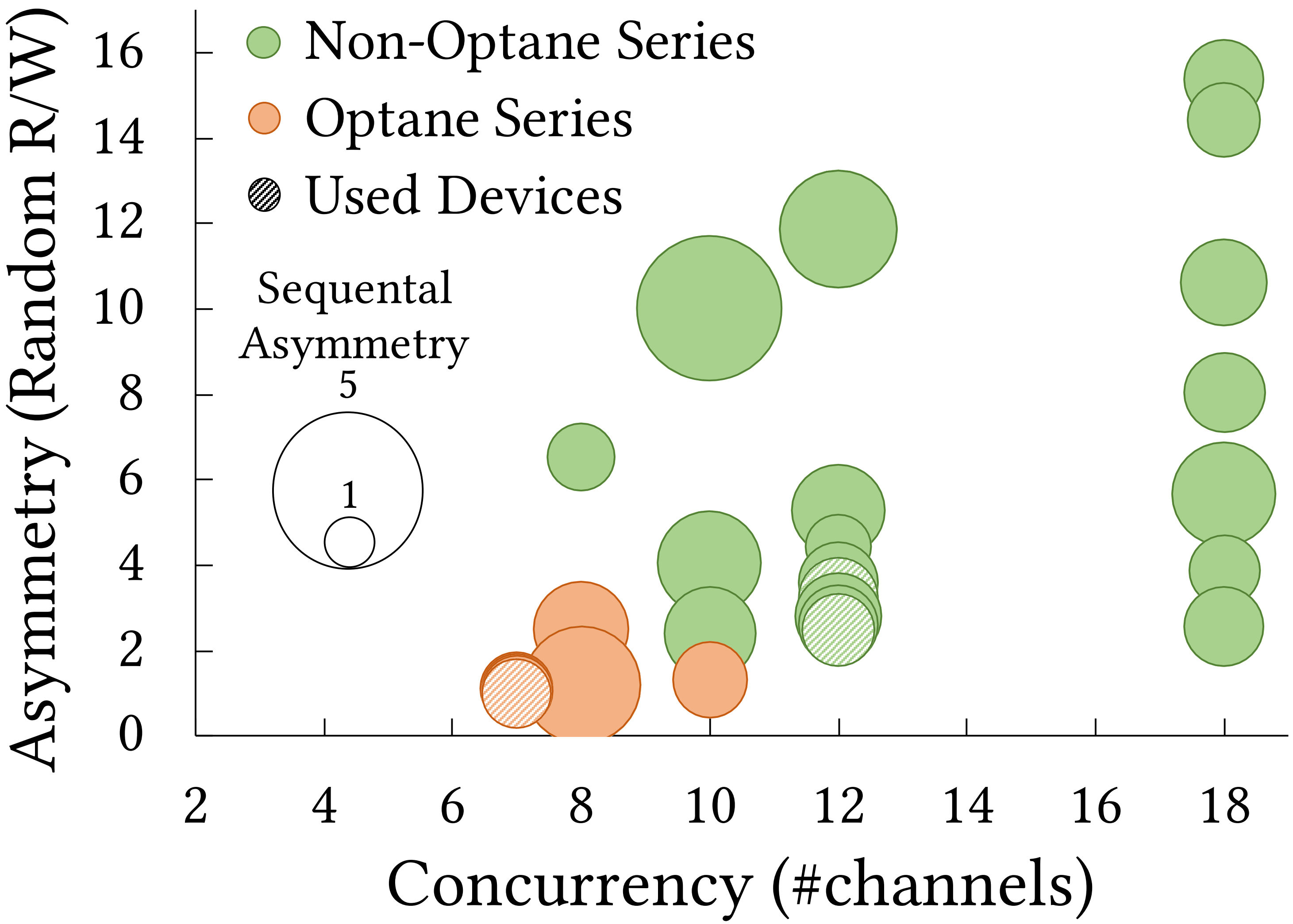


Measuring Asymmetry/Concurrency

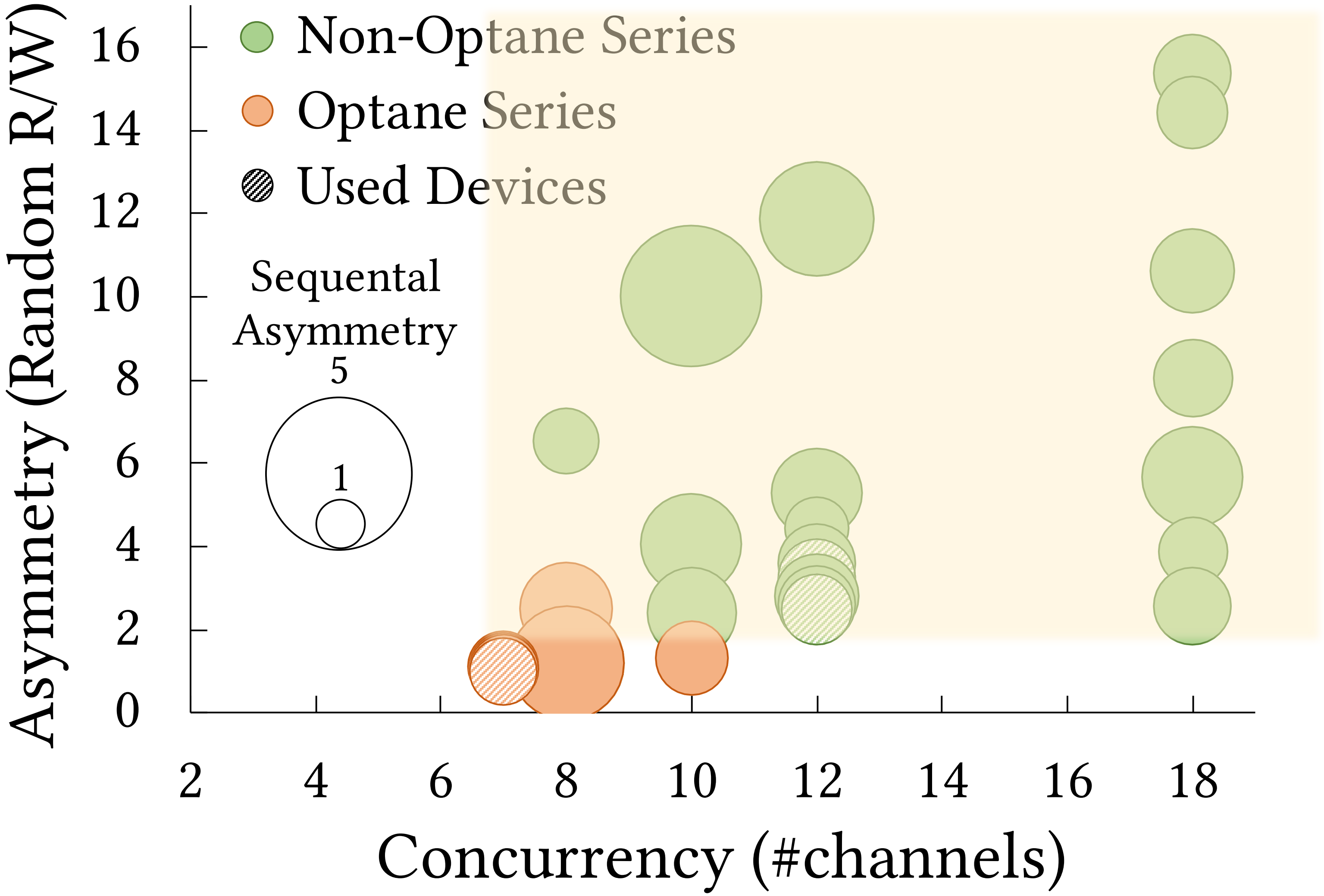
Table 2: Empirical *Asymmetry* and *Concurrency*.

	4KB			8KB		
Device	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
Virtual SSD	2.0	11	19	1.9	6	10

Modern Storage Devices



Modern Storage Devices



Most devices have high asymmetry

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

read/write asymmetry and **concurrency**?

Parametric I/O Model

PIO (M, k, α)

Main Memory Size — Concurrency — Asymmetry

$\boldsymbol{PIO(M, k_r, k_w, \alpha)}$ *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).

Performance Analysis

We classify storage-intensive applications into four classes

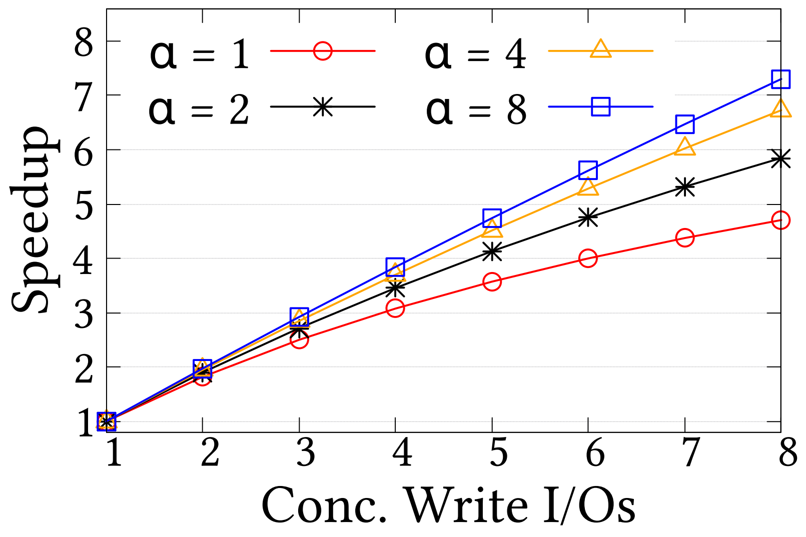
- Unbatchable Reads, Unbatchable Writes
- Unbatchable Reads, Batchable Writes
- Batchable Reads, Unbatchable Writes
- Batchable Reads, Batchable Writes

Unbatchable Reads, Batchable Writes

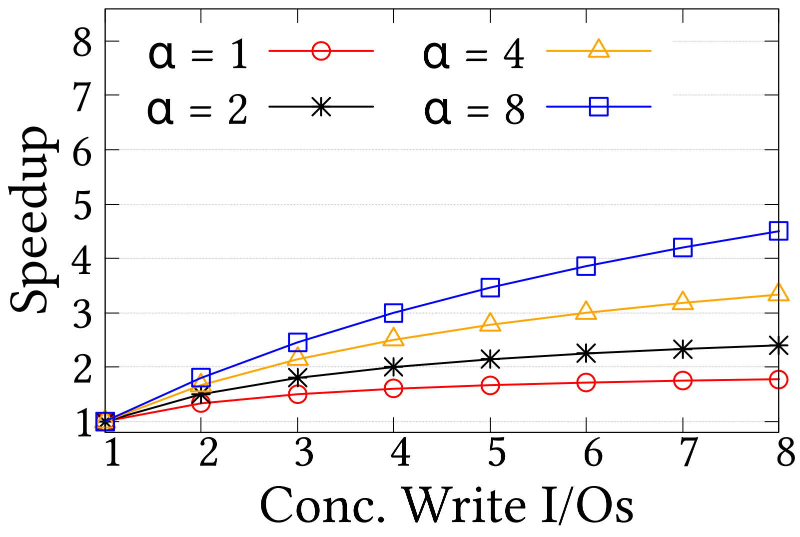
- Can exploit write concurrency (k_w) by batching writes
- Amortized cost per write following PIO is $\frac{\alpha}{k_w}$
- Example: DBMS bufferpool

Unbatchable Reads, Batchable Writes

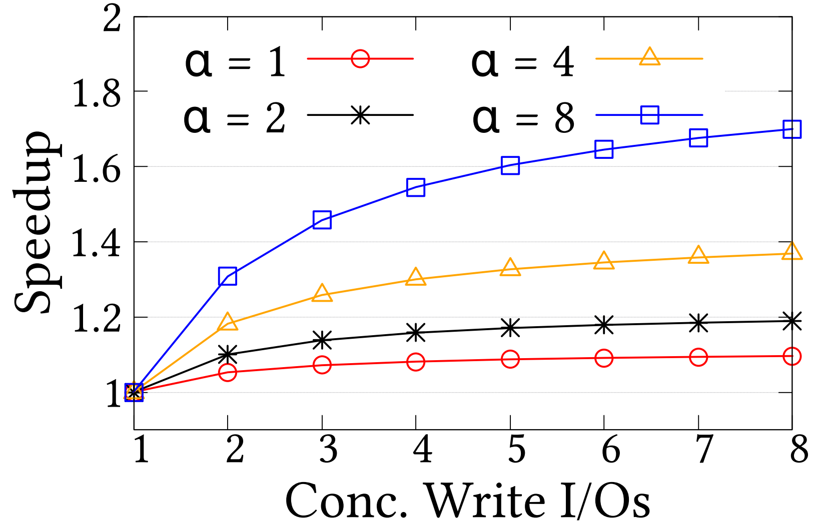
10% reads



50% reads



90% reads



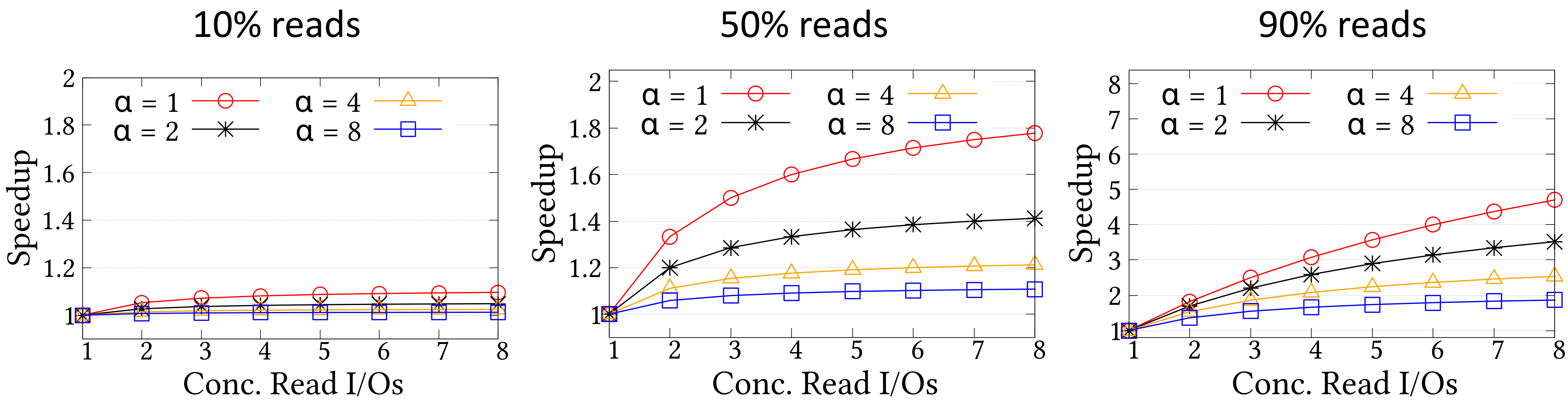
Speedup increases with increasing concurrent I/Os

Speedup depends on asymmetry – gain is ***higher*** for a device with ***higher*** asymmetry

Batchable Reads, Unbatchable Writes

- Can exploit read concurrency (k_r) by batching read
- Amortized cost per read following PIO is $\frac{1}{k_r}$
- Example: Graph traversal

Batchable Reads, Unbatchable Writes



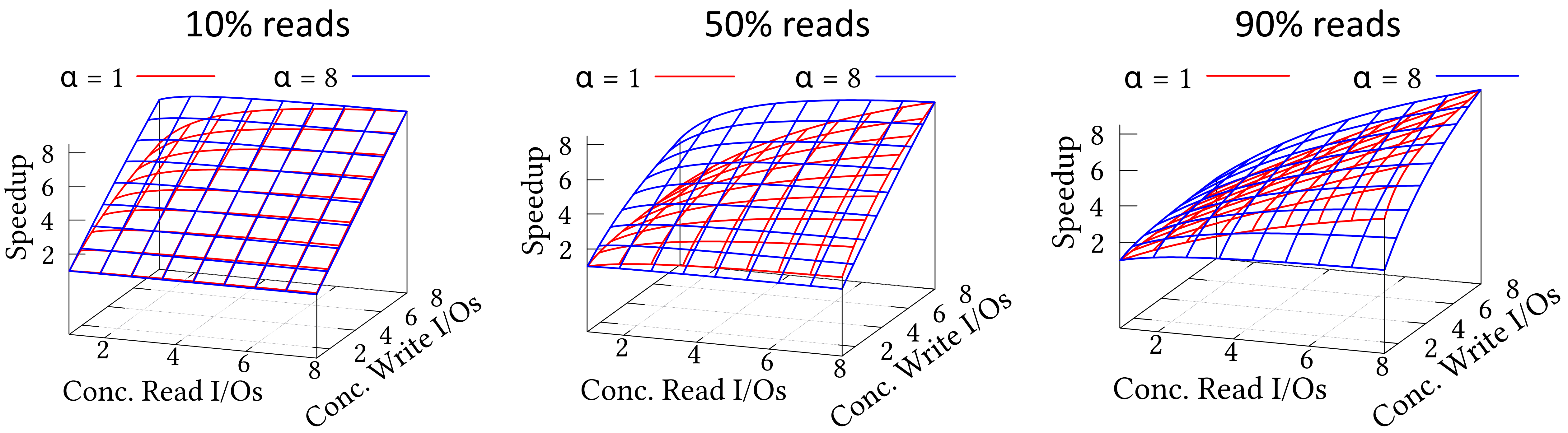
Speedup increases with increasing concurrent I/Os

Speedup depends on asymmetry – gain is ***higher*** for a device with ***lower*** asymmetry

Batchable Reads, Unbatchable Writes

- Can exploit both read and write concurrency $(k_r\,,\,k_w)$
- Amortized cost per read following PIO is $\frac{1}{k_r}$
- Amortized cost per write following PIO is $\frac{\alpha}{k_w}$
- Example: LSM compaction

Batchable Reads, Batchable Writes



Speedup increases with increasing concurrent I/Os, and depends on asymmetry

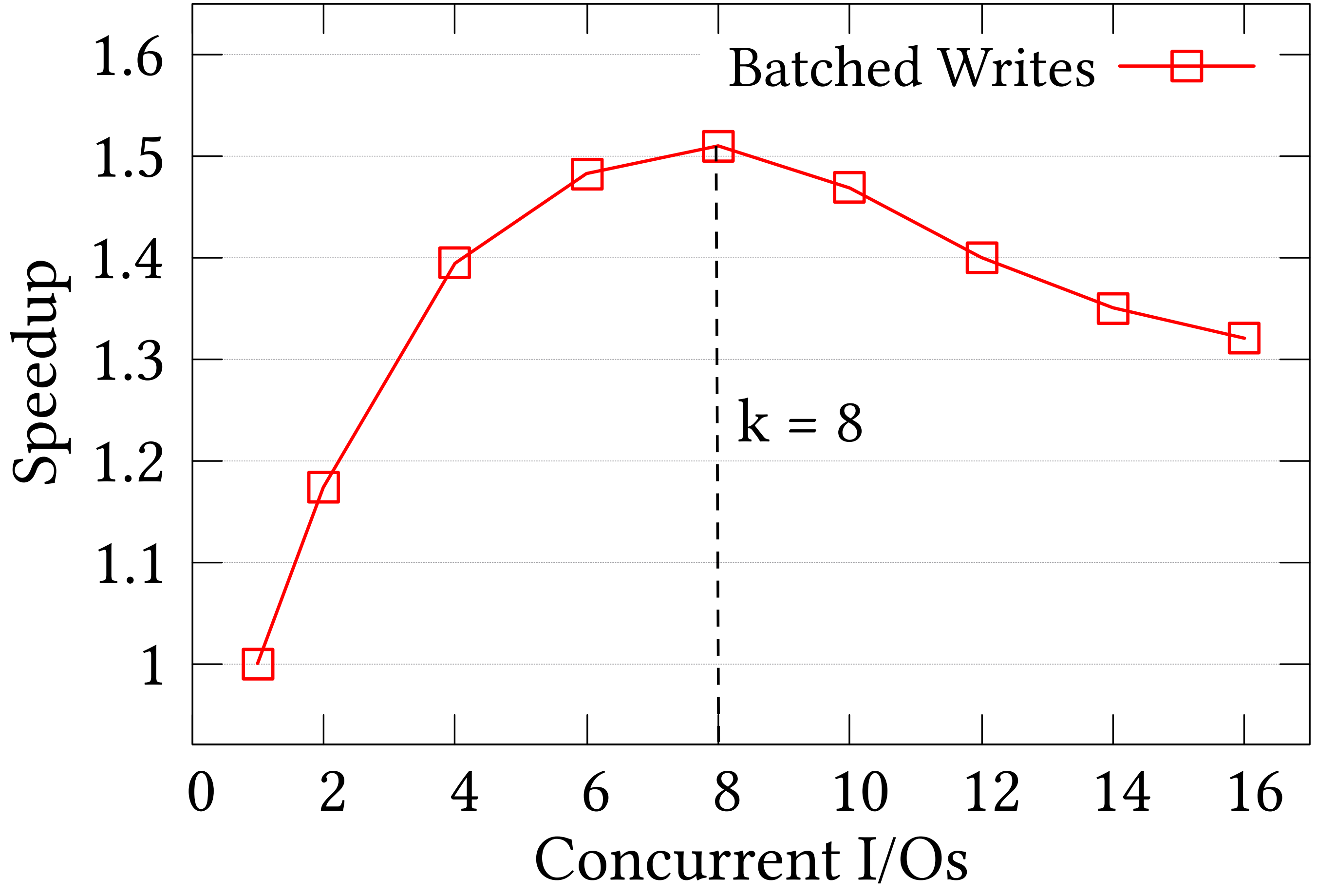
Impact of utilizing write concurrency is higher than utilizing read concurrency

Importance of using Proper k

A sample application with unbatchable reads and batchable writes

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

Optimal speedup at the device concurrency.



Guidelines for Algorithm Design

Know Thy Device

Exploit Device Concurrency

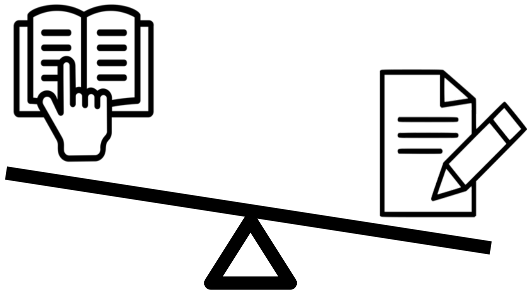
Use Concurrency with Care

It is suboptimal to treat a read and a write equally for a device with asymmetry

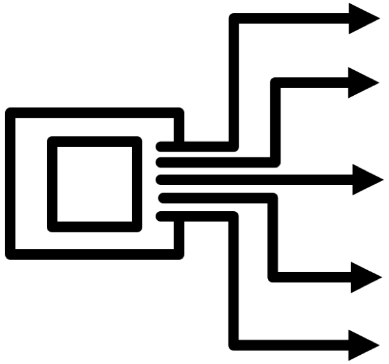
Asymmetry Controls Performance

Conclusion

Modern Storage Devices



Read/Write Asymmetry



Concurrency

Need for a new parametric I/O model

PIO (M, k, α)

Benefits of PIO (M, k, α)

- algorithms tailored to new devices
- Can capture ***any*** new device

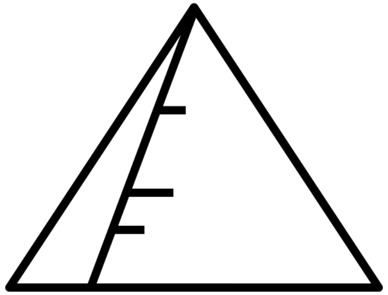
Prerequisite: quantify ***k*** and ***α***

Make *asymmetry and concurrency* part of *algorithm design*

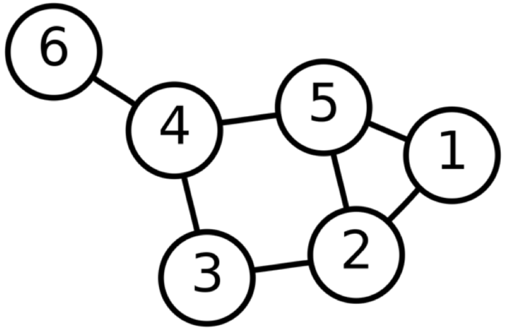
… not simply an engineering optimization

Build algorithms/data structures for storage devices
with asymmetry α and concurrency k

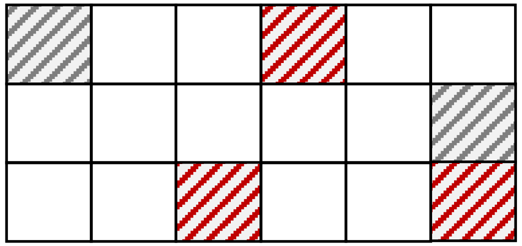
index structures



graph traversal algorithms



bufferpool management



Thank You!

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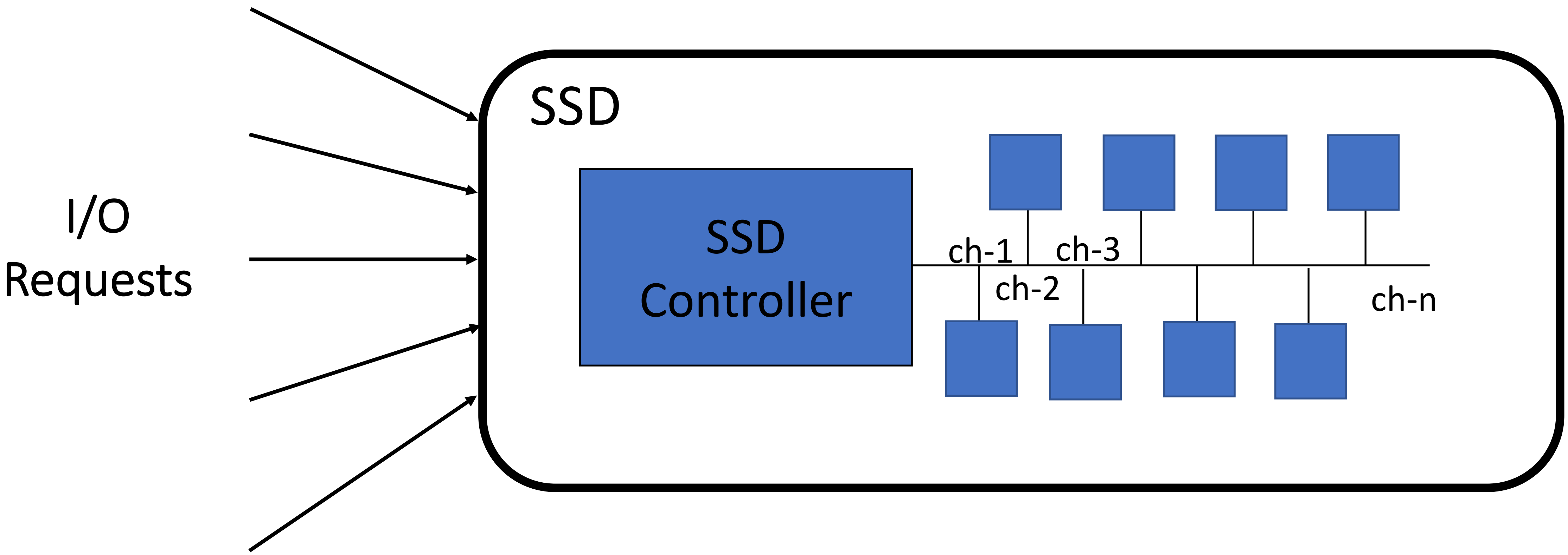
Backup Slides

Expected Parallelism



How many of the channels will be occupied for uniform distribution?

Expected Parallelism

E_n = expected number of empty channels after n I/Os are uniformly distributed

We use E_{n-1} and consider where the n^{th} I/O will be routed

it will be on an empty channel reducing them

with probability

$$E_n = \frac{E_{n-1}}{n}(E_{n-1} - 1) + \left(1 - \frac{E_{n-1}}{n}\right)E_{n-1} = \frac{n-1}{n}E_{n-1}$$

with probability

it will be on a non-empty channel

Since $E_0 = n$; $\quad E_n = \left(\frac{n-1}{n}\right)^n n$

Fraction of empty channels $= {}^{E_n}/_{n} = \left(1 - \frac{1}{n}\right)^n \approx \frac{1}{e}$

So, on average $\left(1 - \frac{1}{e}\right)$ = **63.2%** channels will be accessed in parallel

Unbatchable Reads, Batchable Writes