22nd USENIX Conference on File and Storage Technologies (FAST '24)

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We Ain't Afraid of No File Fragmentation: Causes and Prevention of Its Performance Impact on Modern Flash SSDs

Yuhun Jun[1,2], Shinhyun Park[1], Jeong-Uk Kang[2], Sang-Hoon Kim[3] and Euiseong Seo[1]

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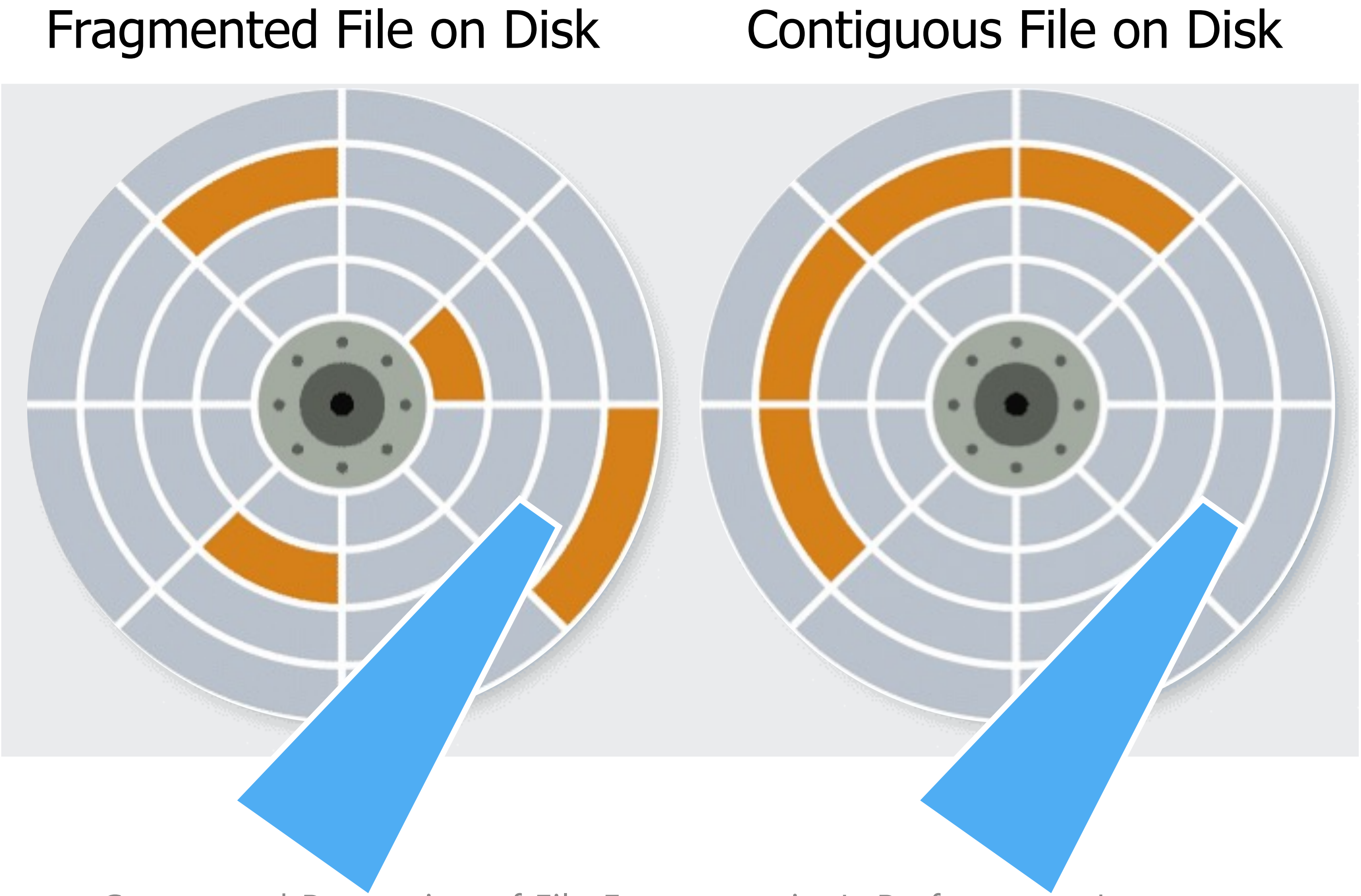
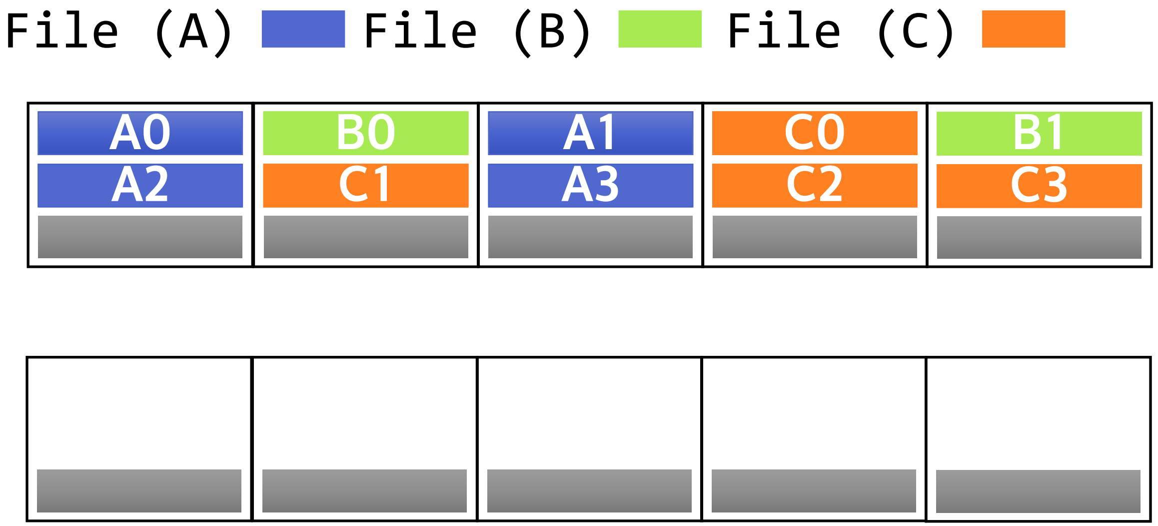
File Fragmentation

- Non-contiguously stored file ➔ Degraded read performance



File Fragmentation

- To recover, costly defragmentation should be performed

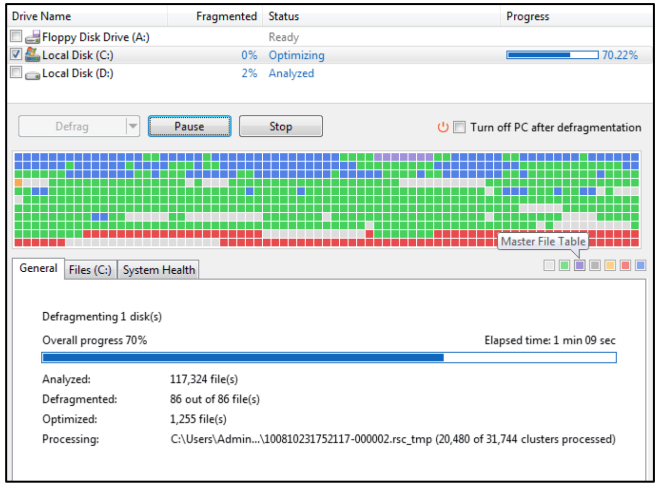


File (A) 🟦 File (B) 🟩 File (C) 🟧

Fragmented file

A0	B0	A1	C0	B1
A2	C1	A3	C2	C3

Defragmented file



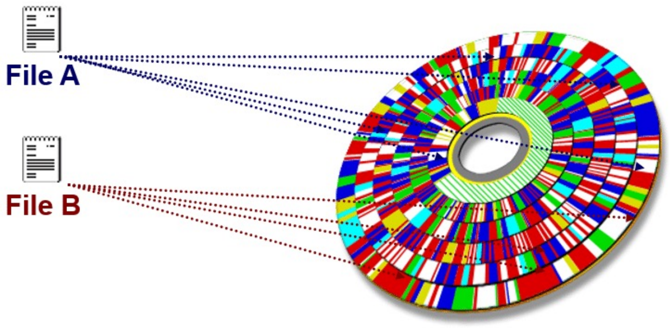
Drive Name	Fragmented	Status	Progress
☐ Floppy Disk Drive (A:)		Ready	
☑ Local Disk (C:)	0%	Optimizing	70.22%
☐ Local Disk (D:)	2%	Analyzed	

☐ Turn off PC after defragmentation

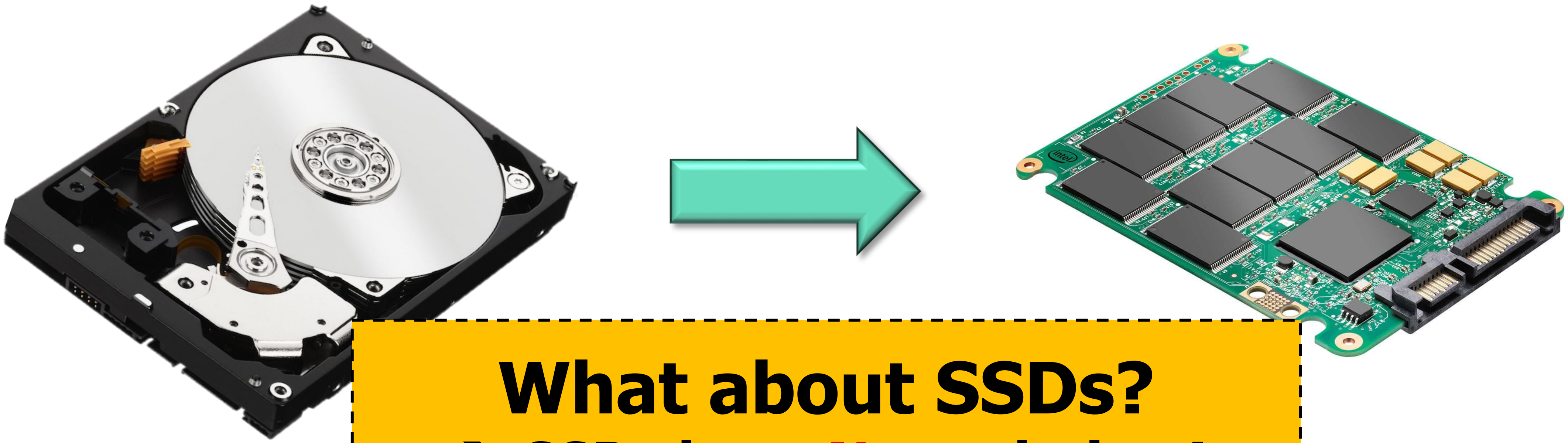
Defragmenting 1 disk(s)

Overall progress 70% Elapsed time: 1 min 09 sec

Analyzed: 117,324 file(s)
Defragmented: 86 out of 86 file(s)
Optimized: 1,255 file(s)
Processing: C:\Users\Admin...\100810231752117-000002.rsc_tmp (20,480 of 31,744 clusters processed)



File Fragmentation



What about SSDs?

➔ SSDs have No seek time!

➔ No performance drop?

File Fragmentation in SSD-Era

- Even in SSDs, still performance degradation occurs (observed reduction of 2x to 5x) *

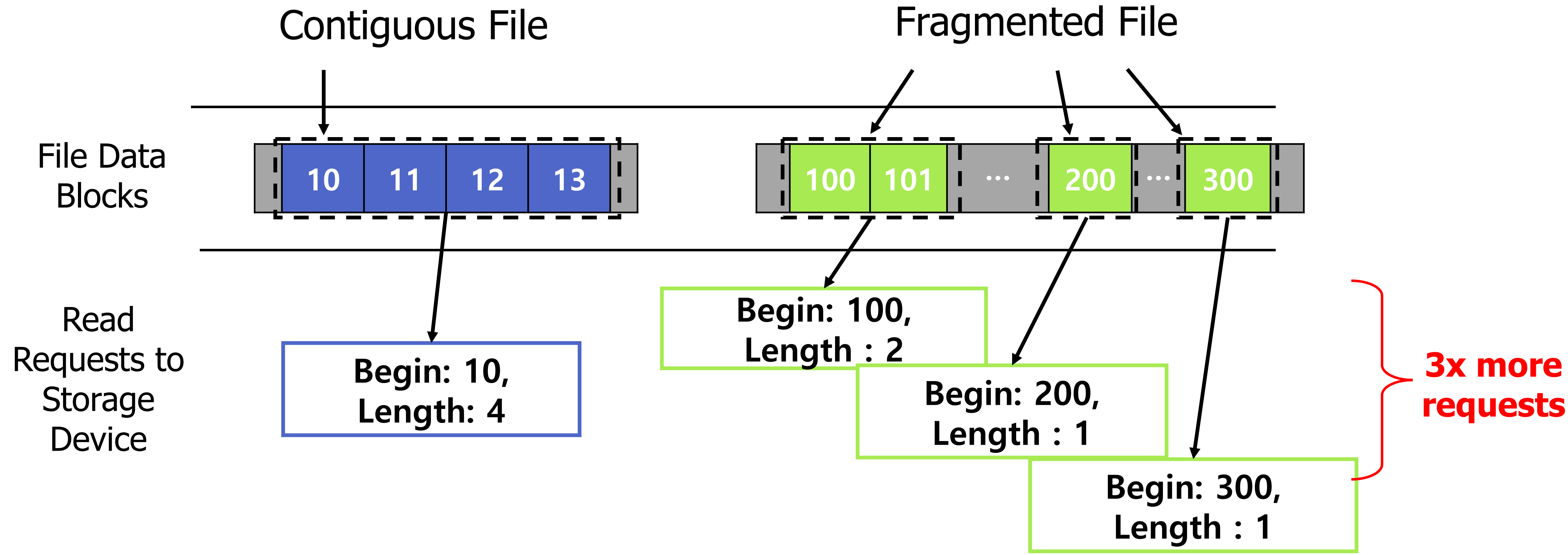
  * Conway *et al*. File systems fated for senescence? nonsense, says science!(FAST ’ 17).
  * Kadekodi *et al*. Geriatrix: Aging what you see and what you don't see. A file system aging approach for modern storage systems (ATC ’ 18).
  * Conway *et al*. Filesystem Aging: It’ s more usage than fullness (Hotstorage ’ 19).

- ***Request splitting*** caused by fragmentation increases kernel I/O stack overhead **

  ** Park and Eom. Fragpicker: A new defragmentation tool for modern storage devices (SOSP ’ 21)

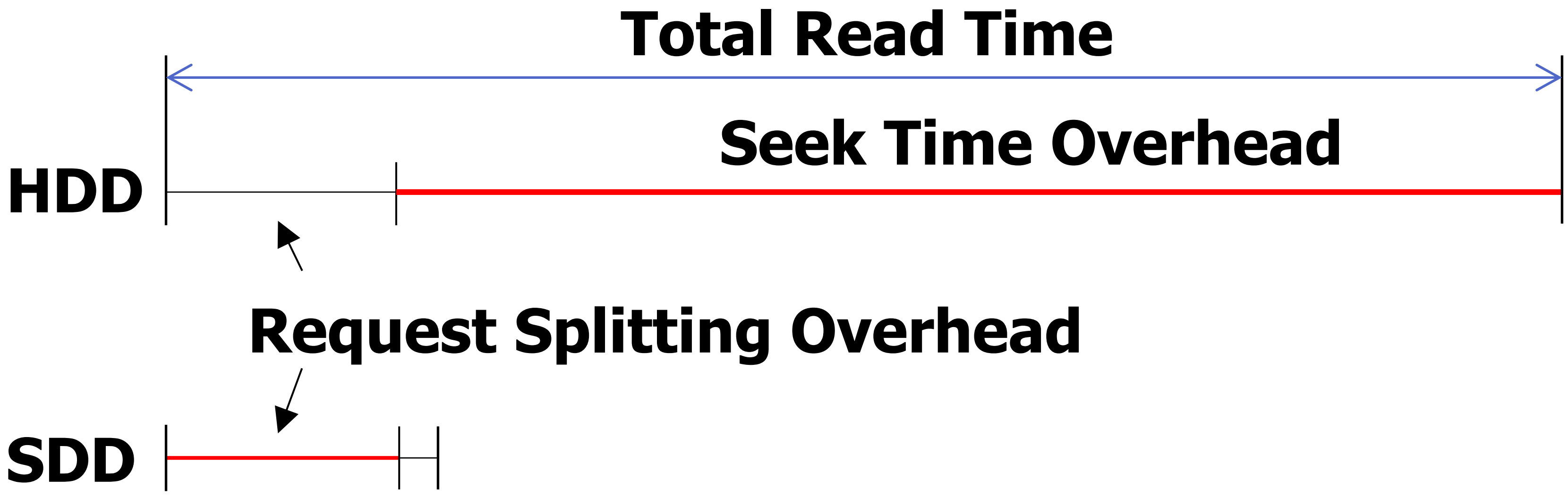
File Fragmentation in SSD-Era

- ***Request splitting***



File Fragmentation in SSD-Era

- *Request splitting*



File Fragmentation in SSD-Era

- ***Request splitting***

In faster SSDs compared to HDDs
***Is request splitting* more evident ?**

Analysis of Request Splitting Overhead

- Does *request splitting* impact ramdisks more than SSDs?

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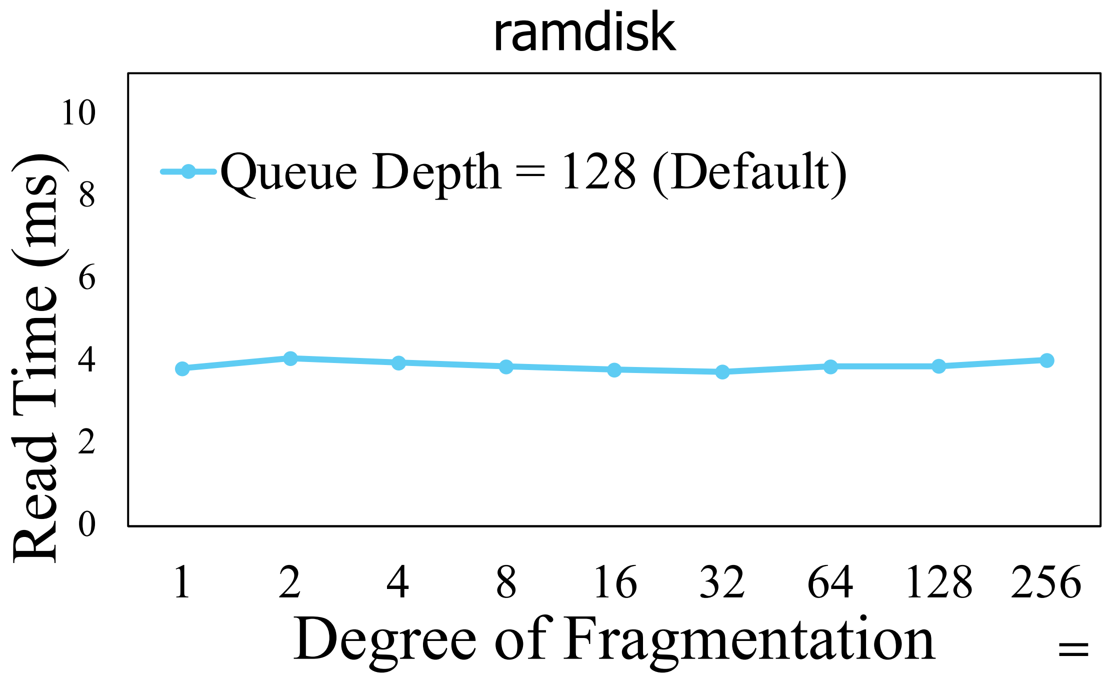
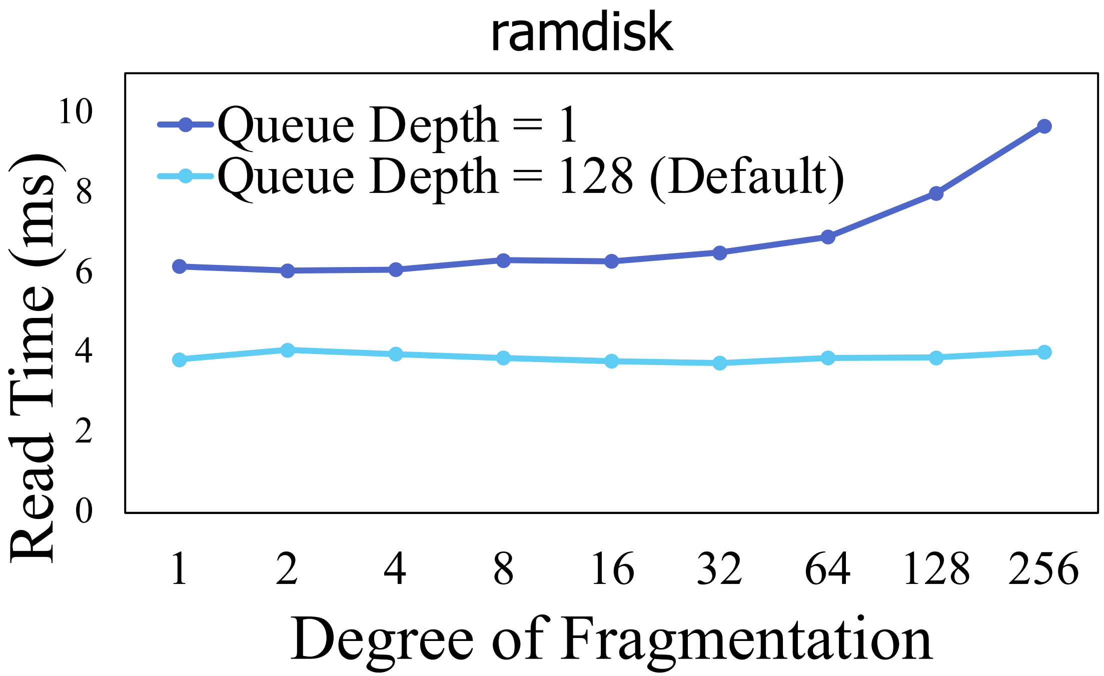


$$= \frac{\text{Actual Number of Extents of File}}{\text{Ideal Number of Extents of File (contiguous case)}}$$

Analysis of Request Splitting Overhead

- Does *request splitting* impact ramdisks more than SSDs?

→ Impact seen with forced queue depth of 1



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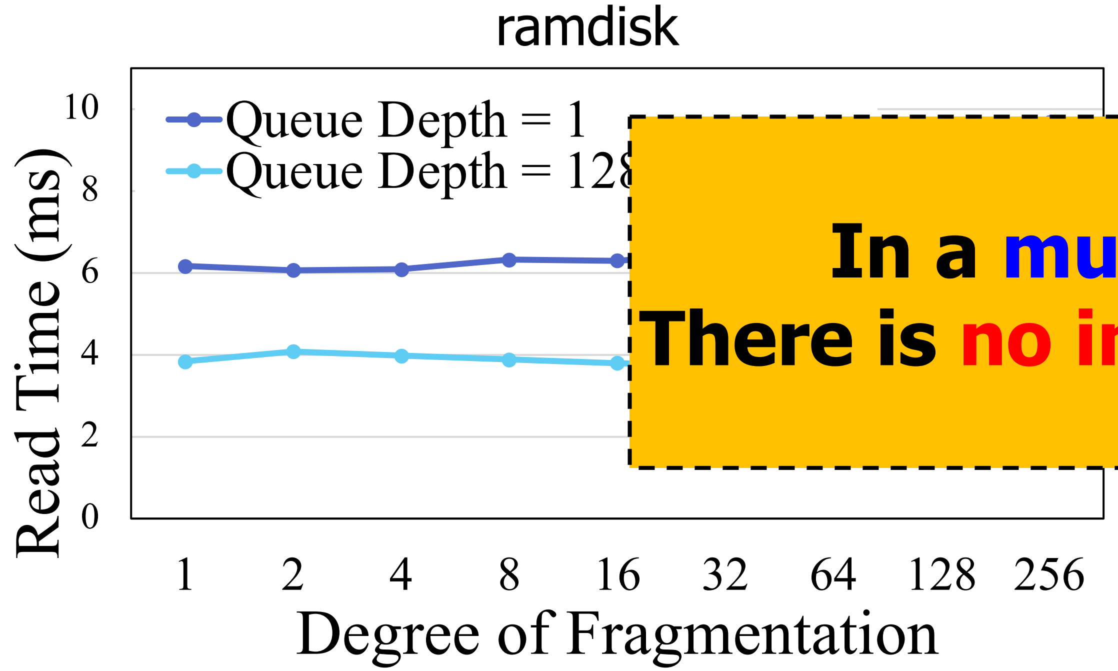
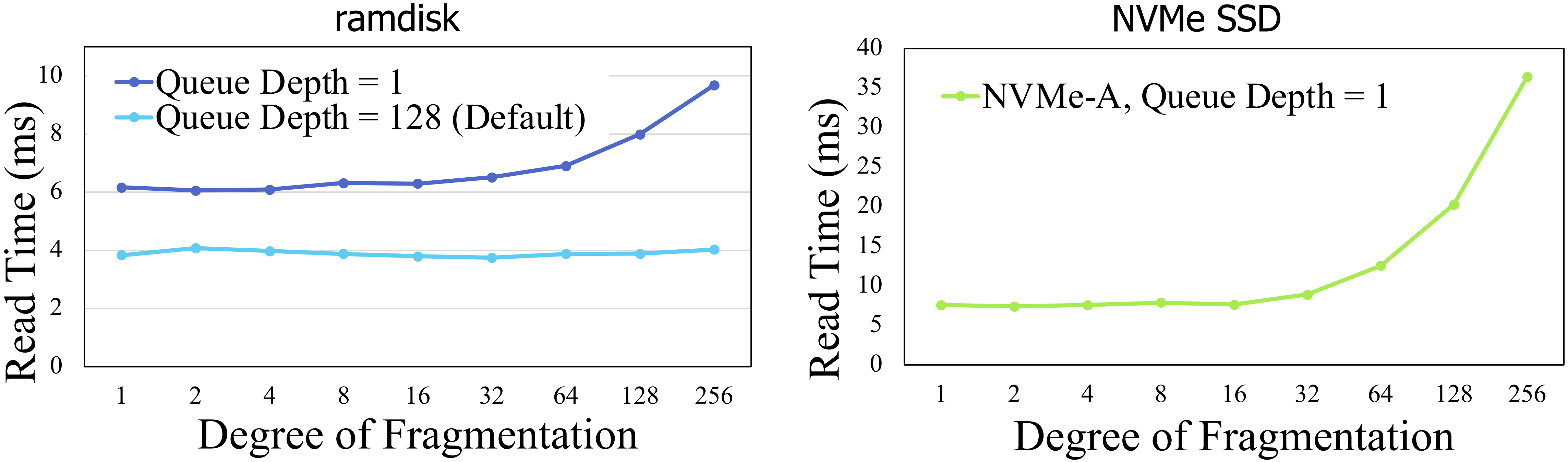


In a multi-queue environment,
There is no impact from request splitting.

Analysis of Request Splitting Overhead

- Does *request splitting* impact ramdisks more than SSDs?

→ Impact seen with forced queue depth of 1; No request splitting impact in multi-queue (default)



Analysis of Request Splitting Overhead

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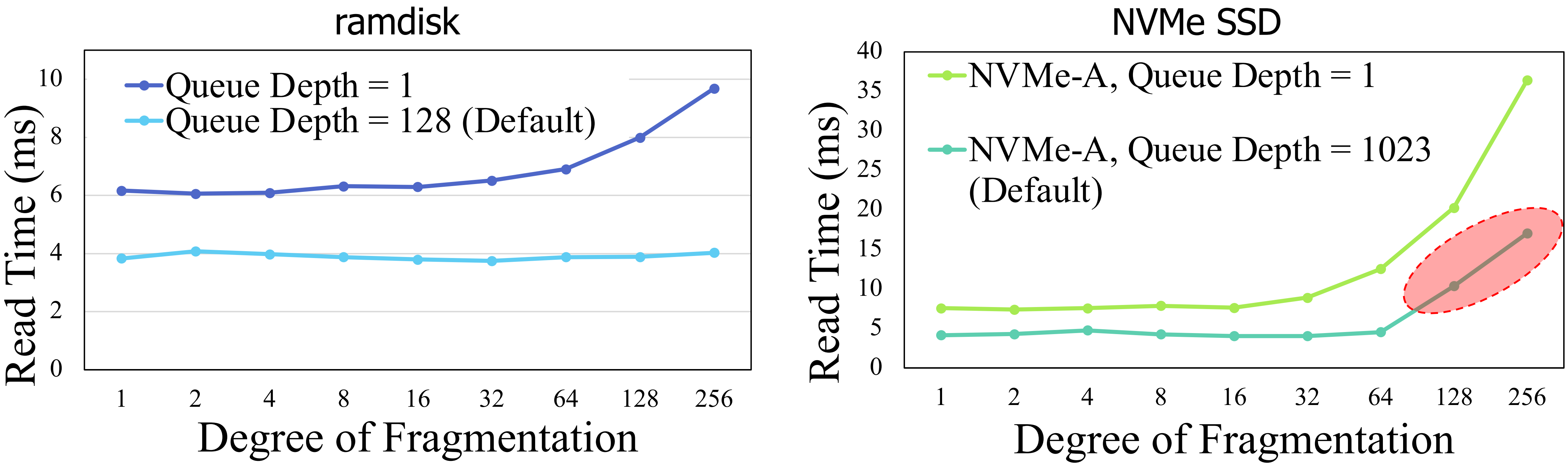
Commercial SSDs showed performance drop in fragmentation



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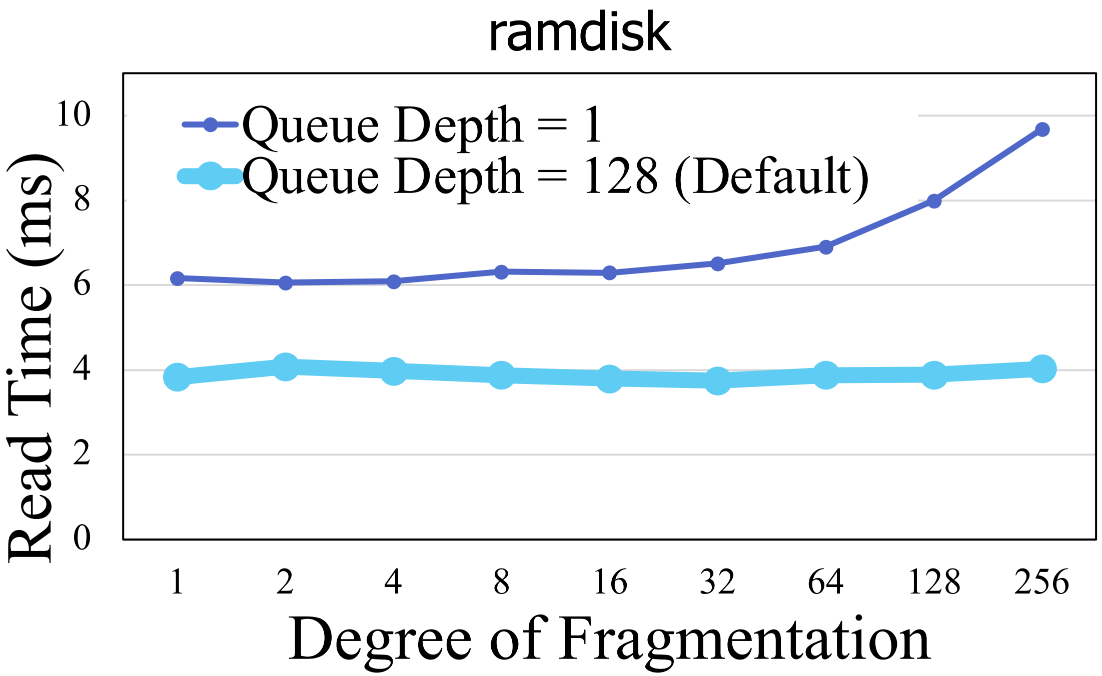
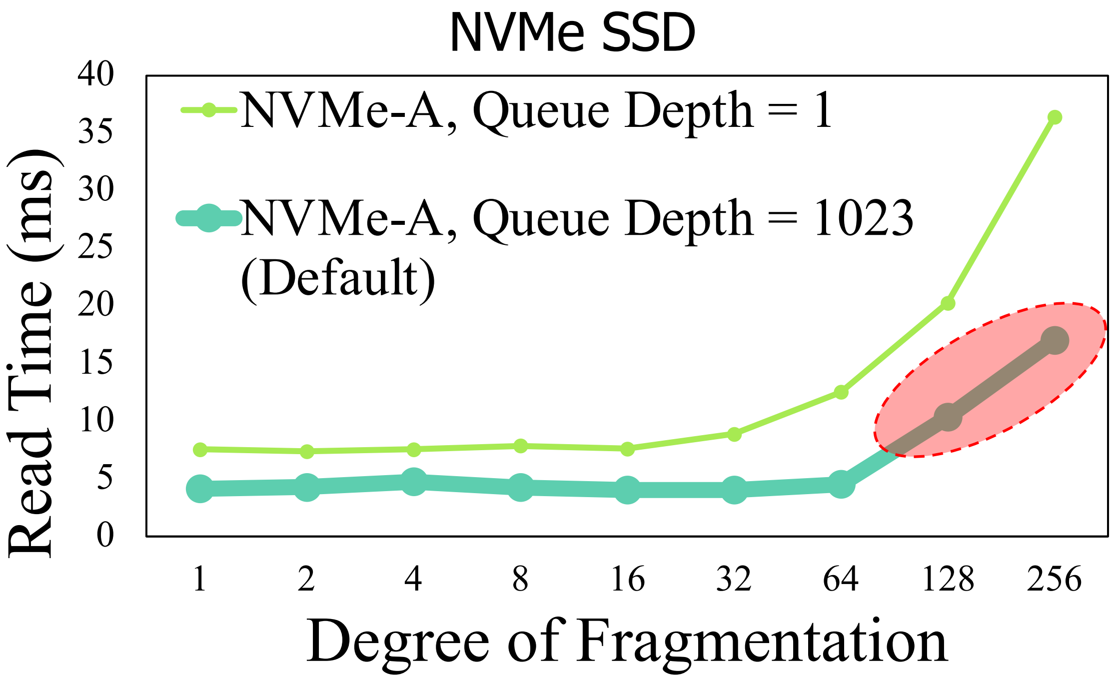
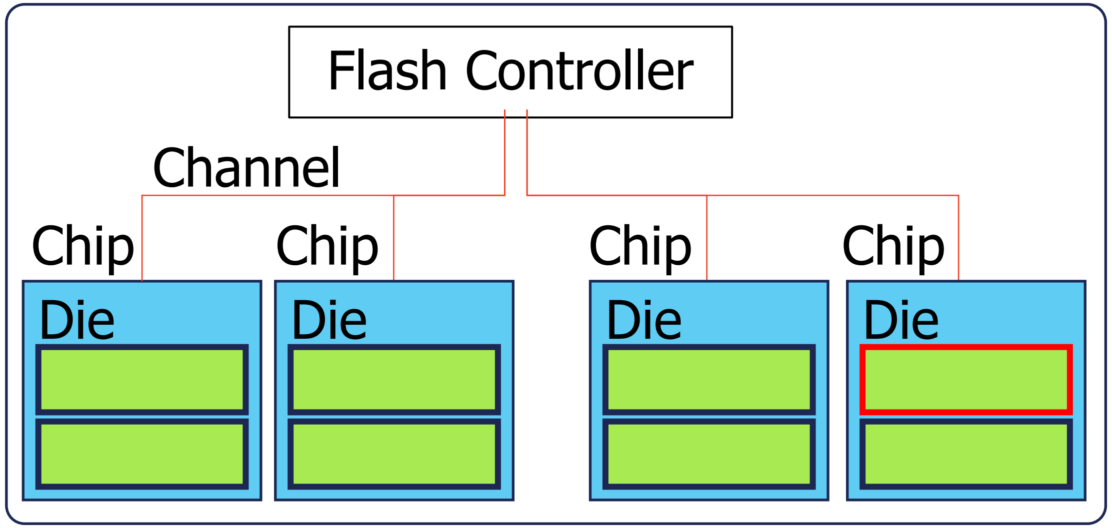




SSD Performance Background

- High performance from operating multiple NAND Flashes simultaneously



Structure of NAND Flash inside SSD
(2-Channel 2-chip 2-Die SSD Total 8-Dies in an SSD)

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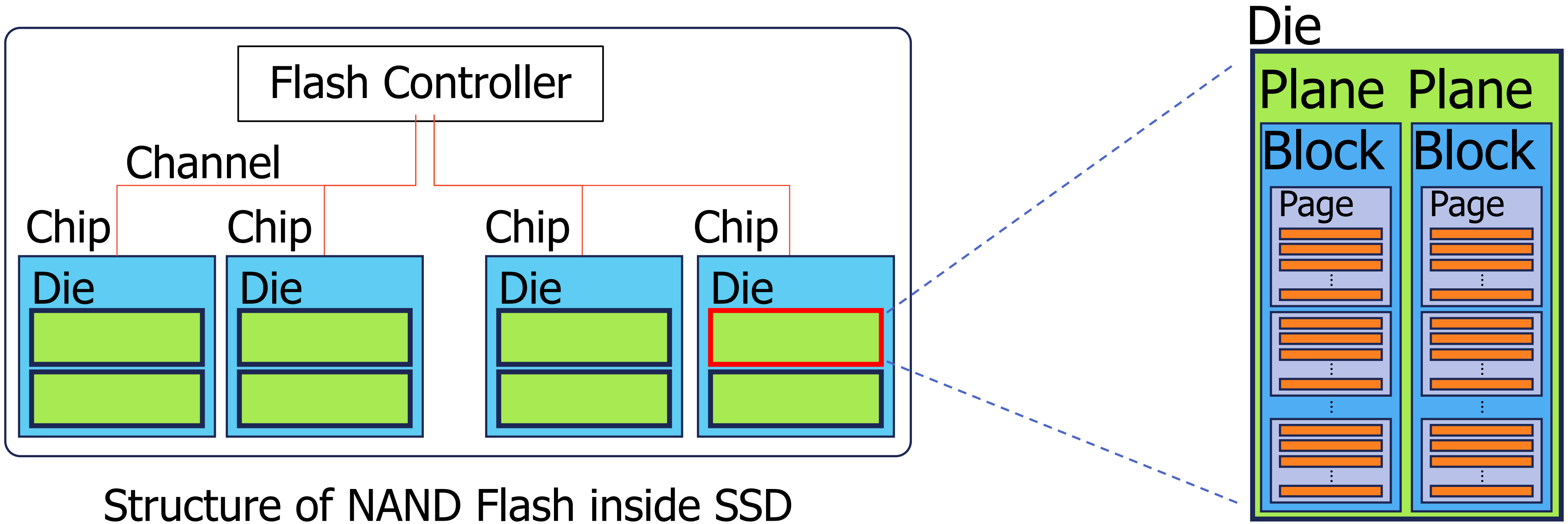
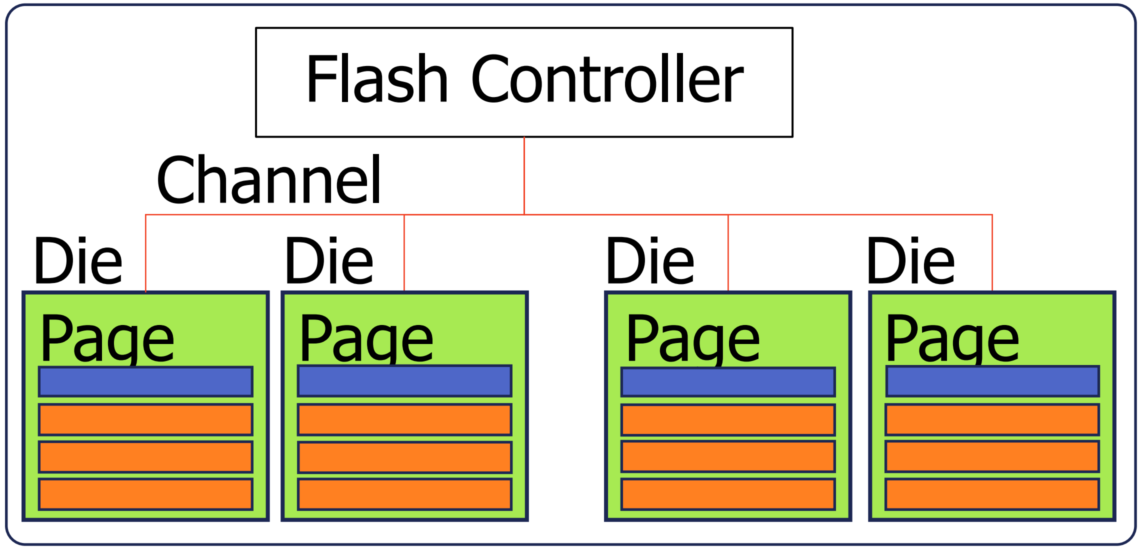


Structure of NAND Flash inside SSD
(2-Channel 2-chip 2-Die SSD Total 8-Dies in an SSD)

Page writing/reading suspends other operations issued to the same die

SSD Performance Background

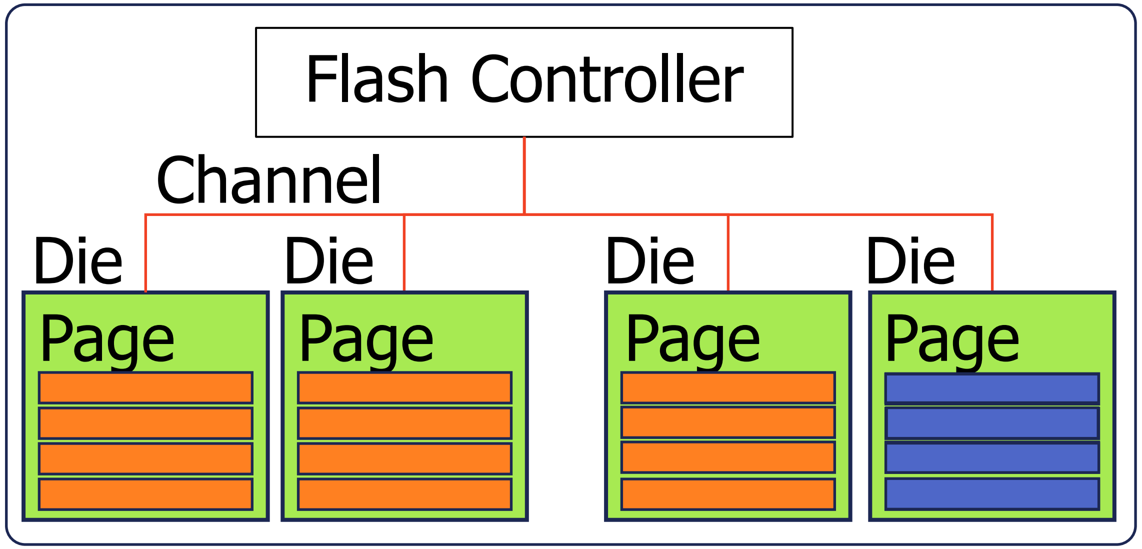
- High performance from operating multiple dies simultaneously
- For write and read operations, as many dies as possible should be utilized



Structure of NAND **dies** inside SSD
(2-Channel 2-Die SSD, Total 4-Dies in an SSD)

SSD Performance Background

- High performance from operating multiple dies simultaneously.
- For write and read operations, as many dies as possible should be activated
- Focusing on a single die during reading ➔ Reduced parallelism



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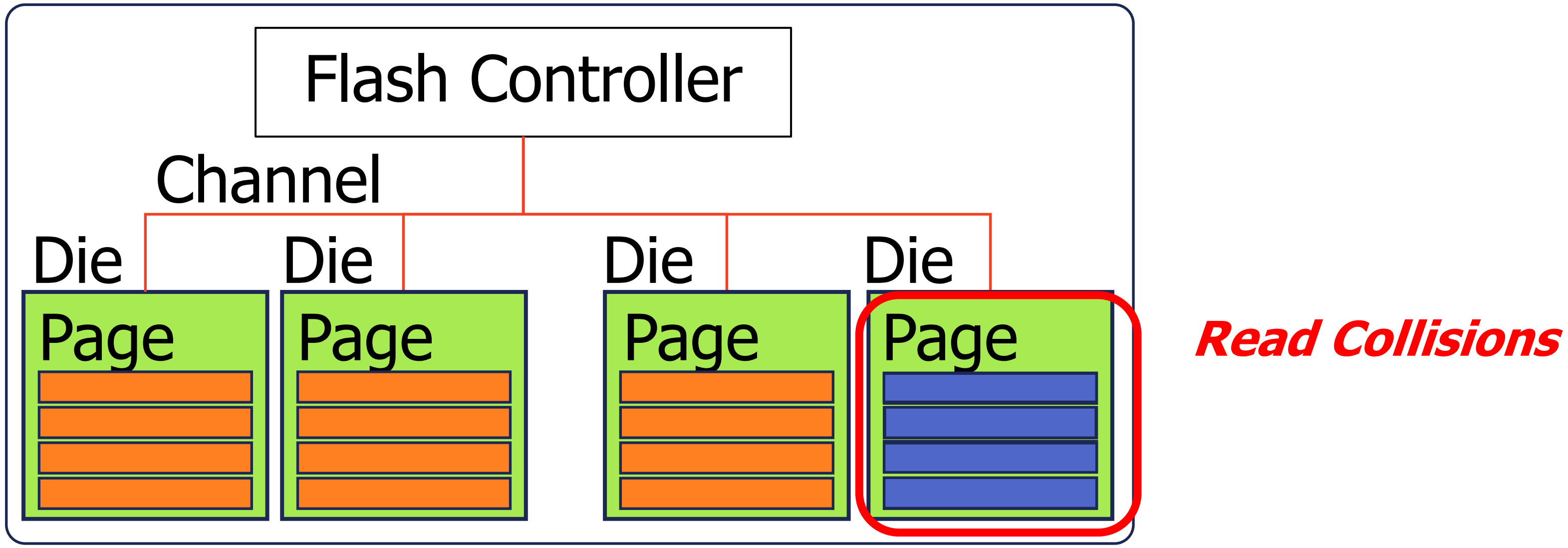
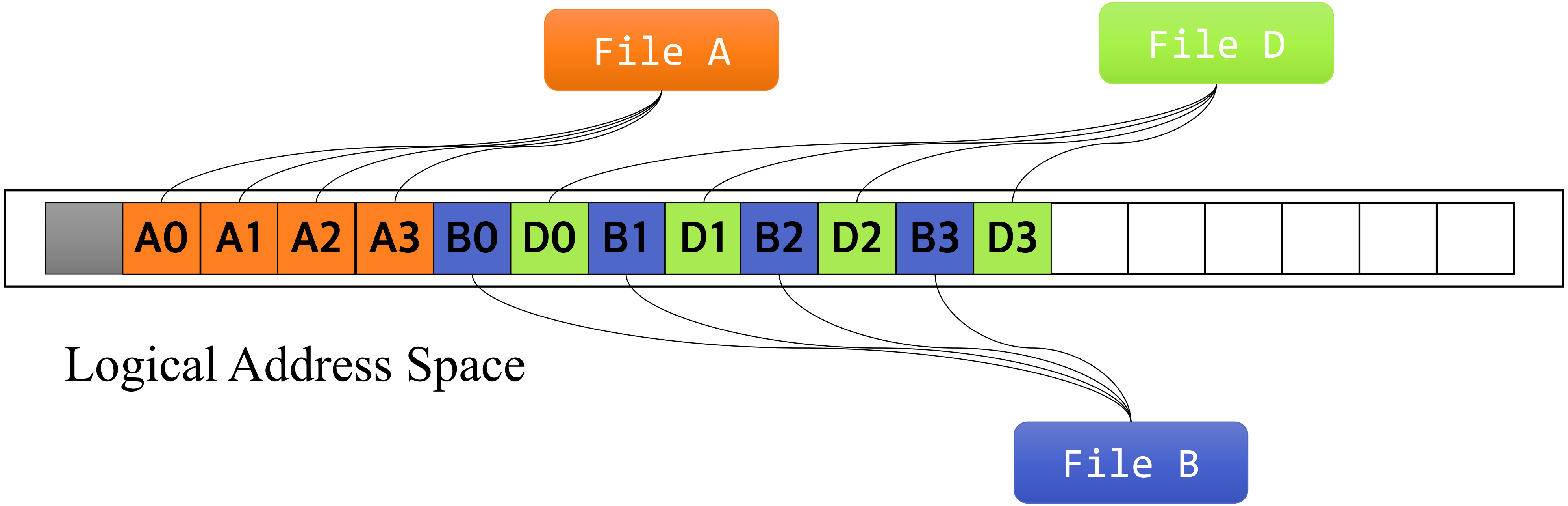


Structure of NAND **dies** inside SSD
(2-Channel 2-Die SSD, Total 4-Dies in an SSD)

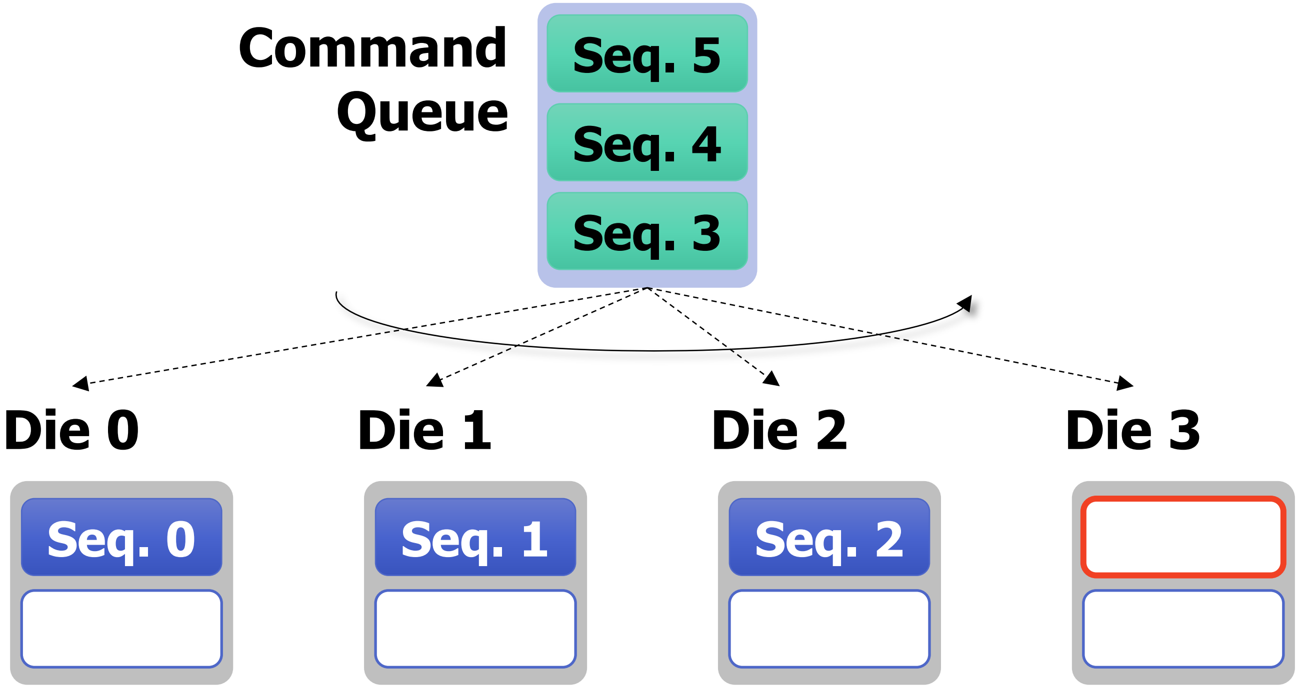
File Fragmentation Scenarios

- File fragmentation occurs when multiple files are appended in an alternating manner



Misaligned Die Allocation from Fragmentation

- Pages to be written are allocated from dies in a round-robin manner



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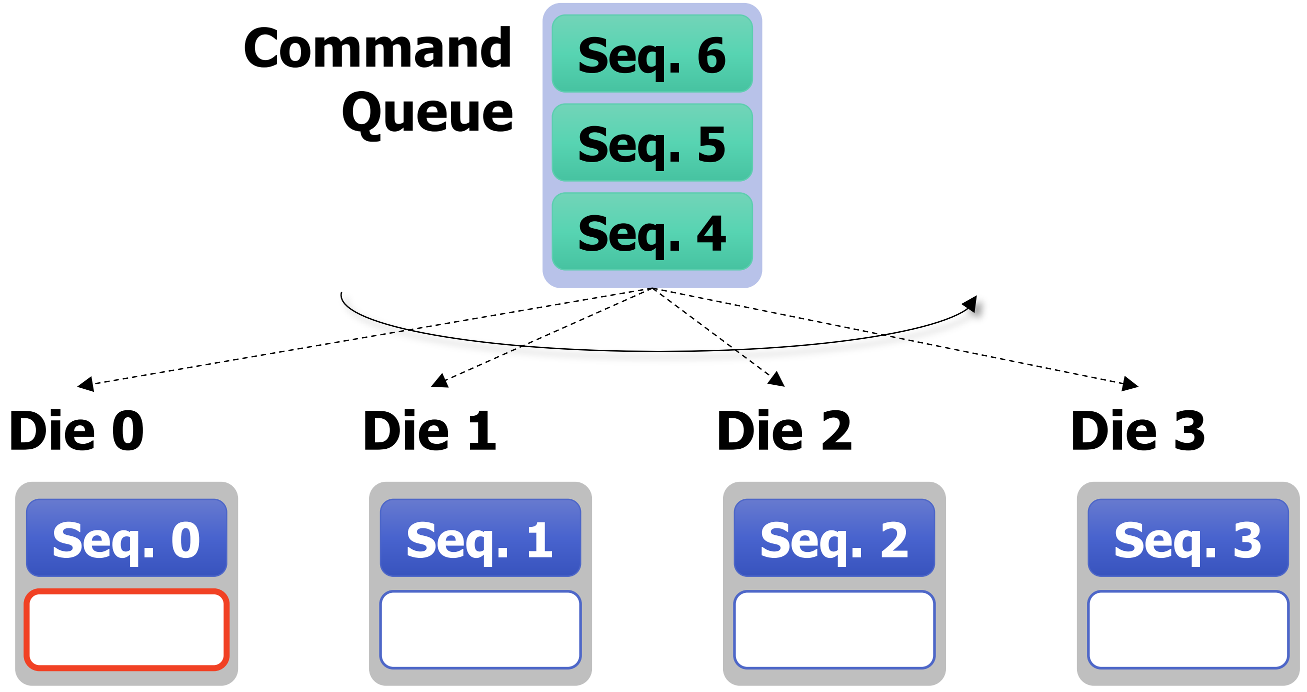

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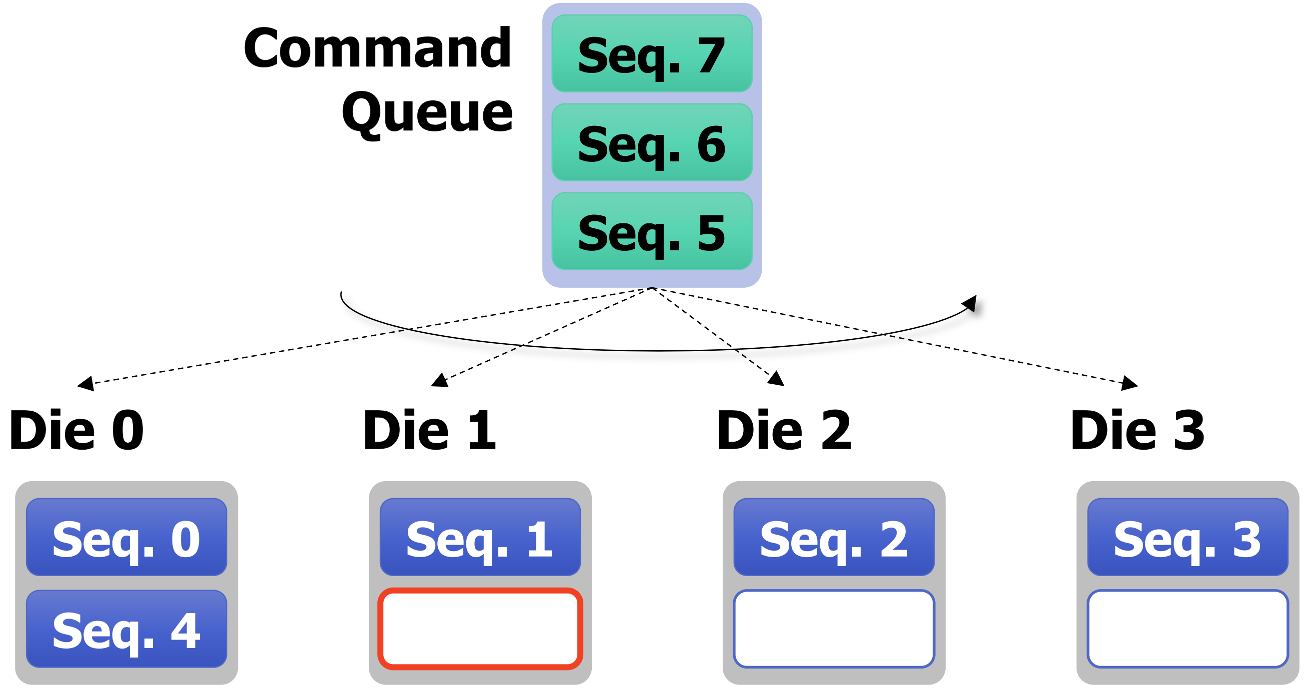

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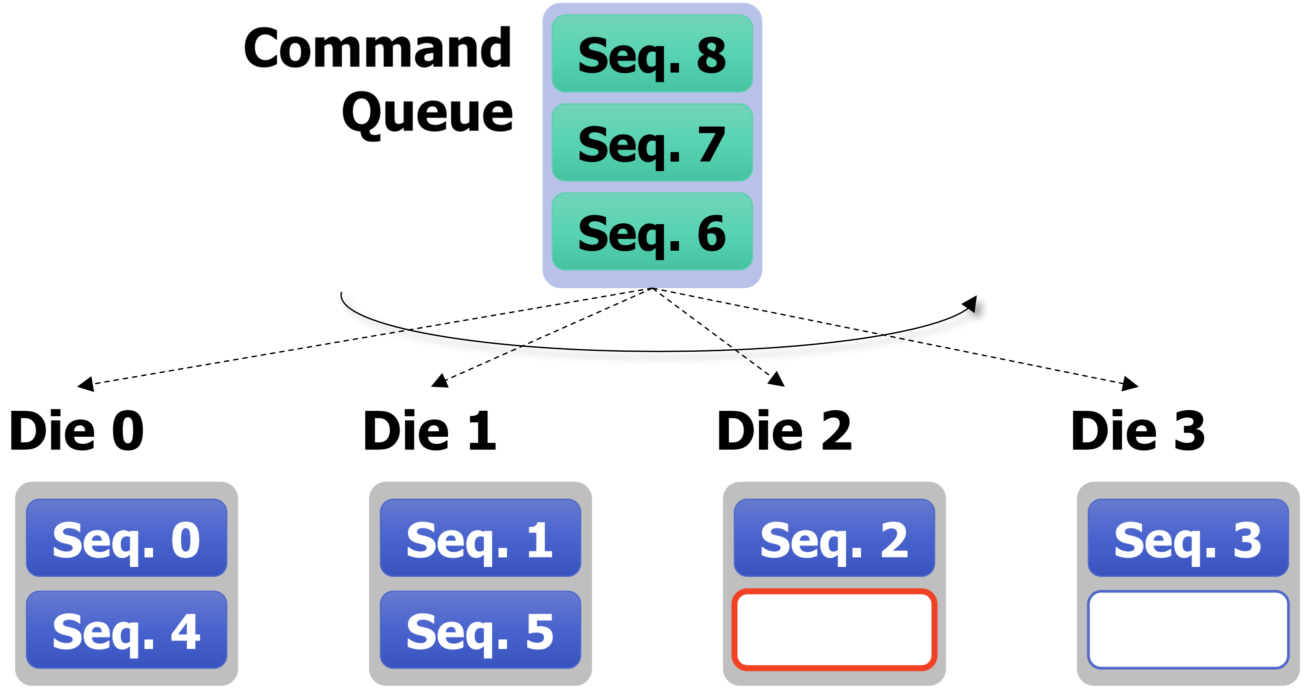
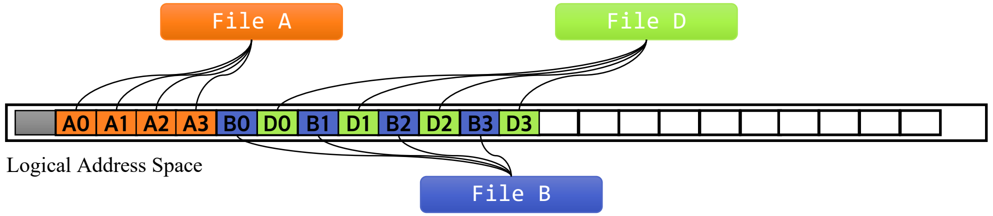
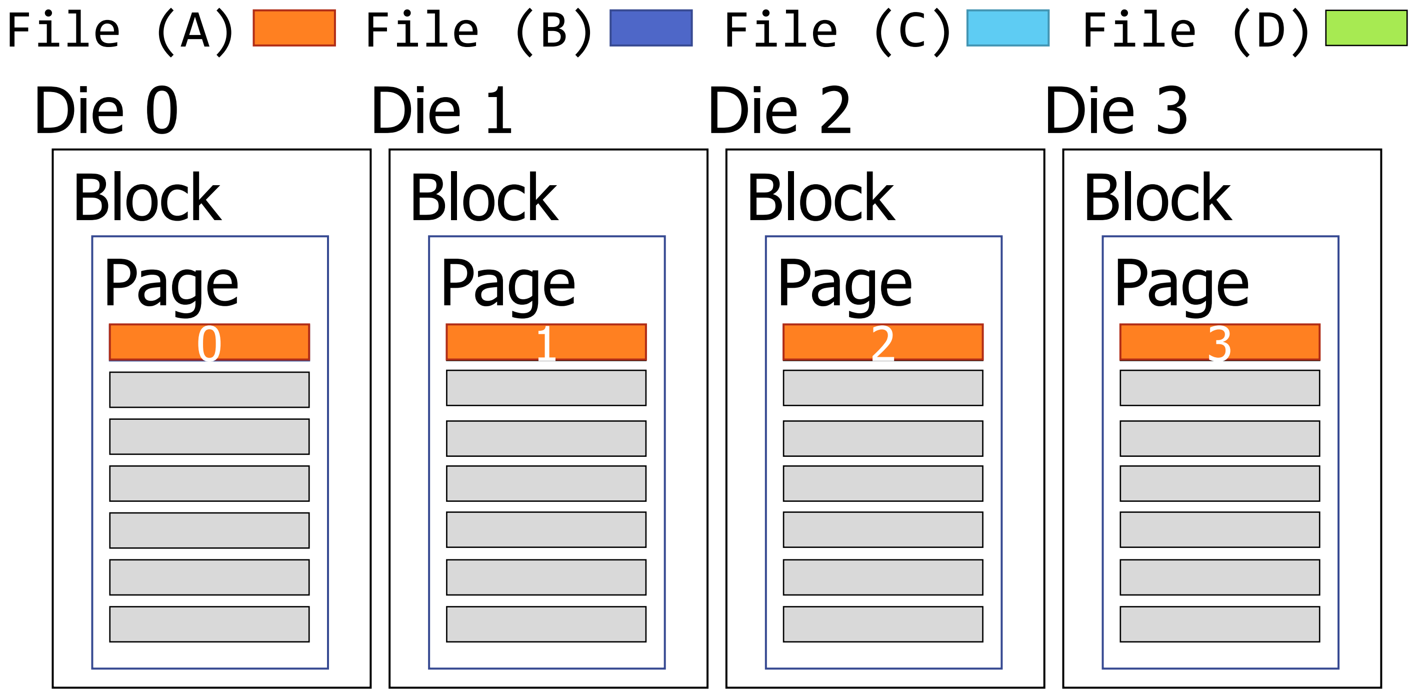


Misaligned Die Allocation from Fragmentation

- Alternating appends causes misaligned die allocation





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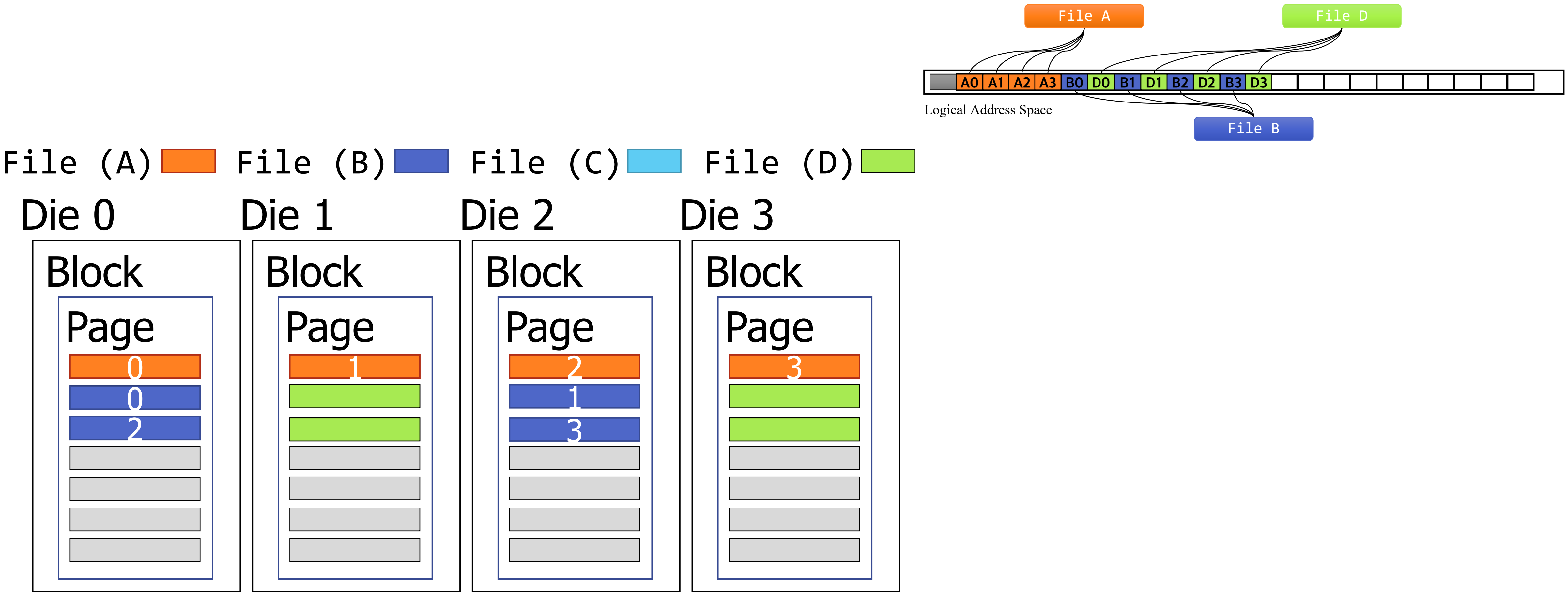

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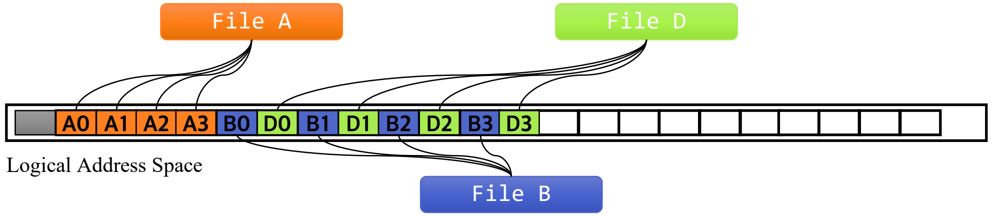

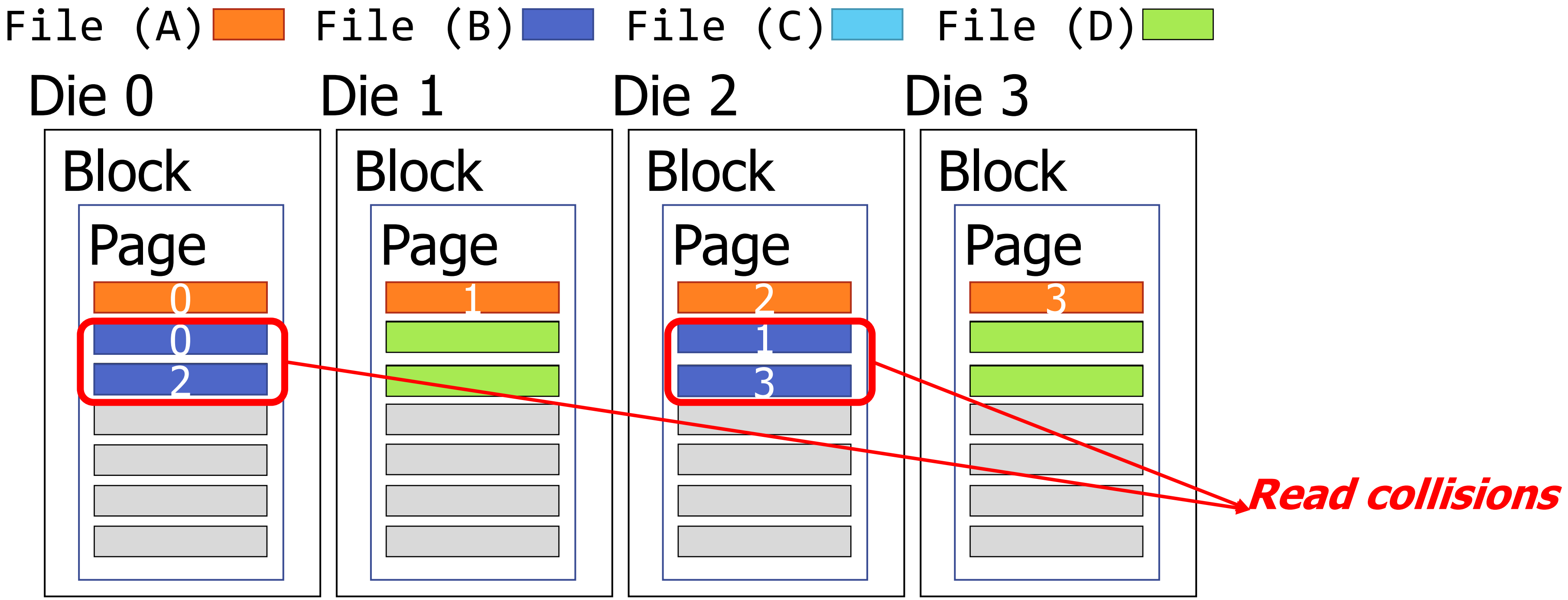

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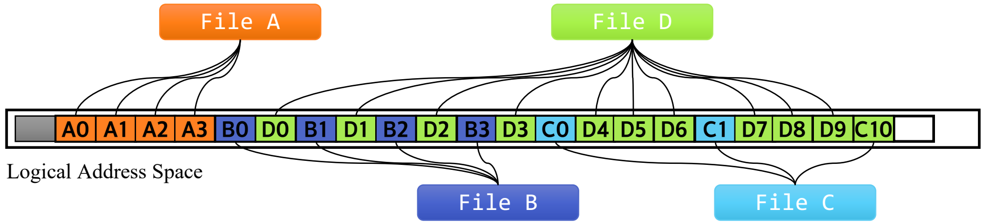
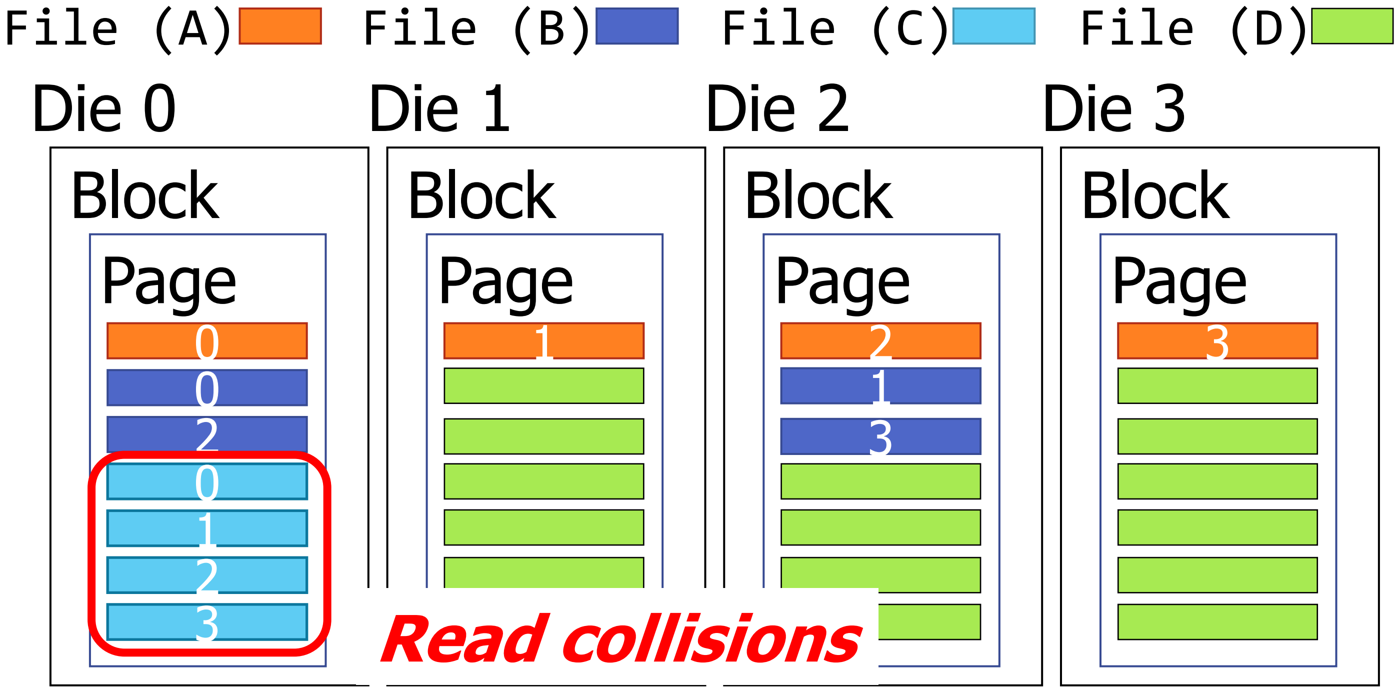
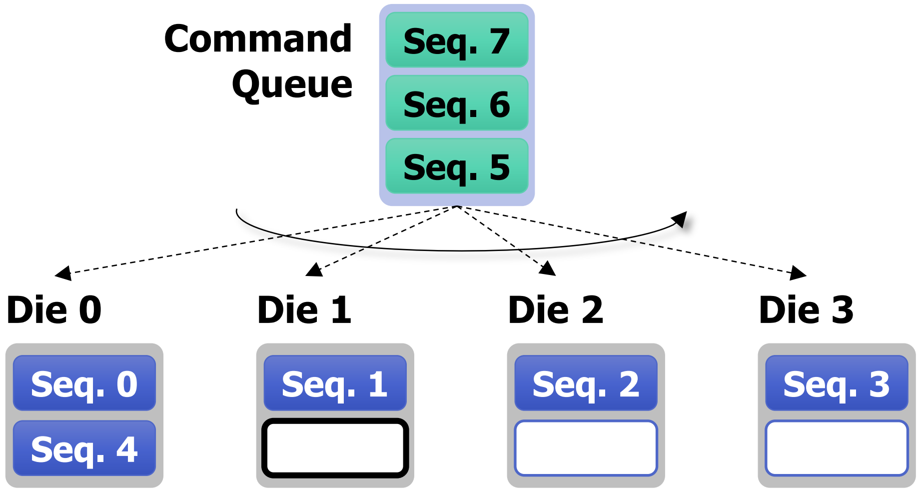




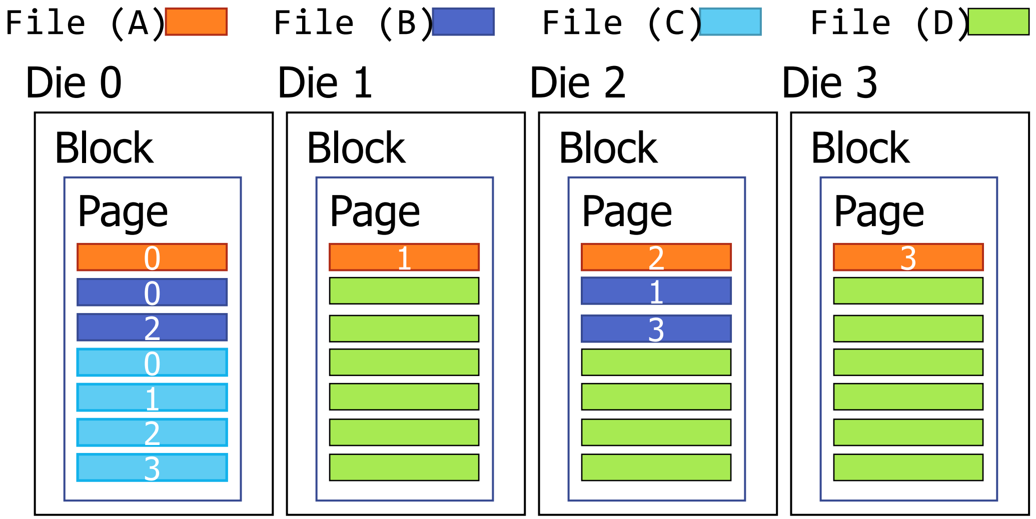
Read collisions

Misaligned Die Allocation from Fragmentation

- Alternating appends causes misaligned die allocation
  ➔ ***Read collisions***

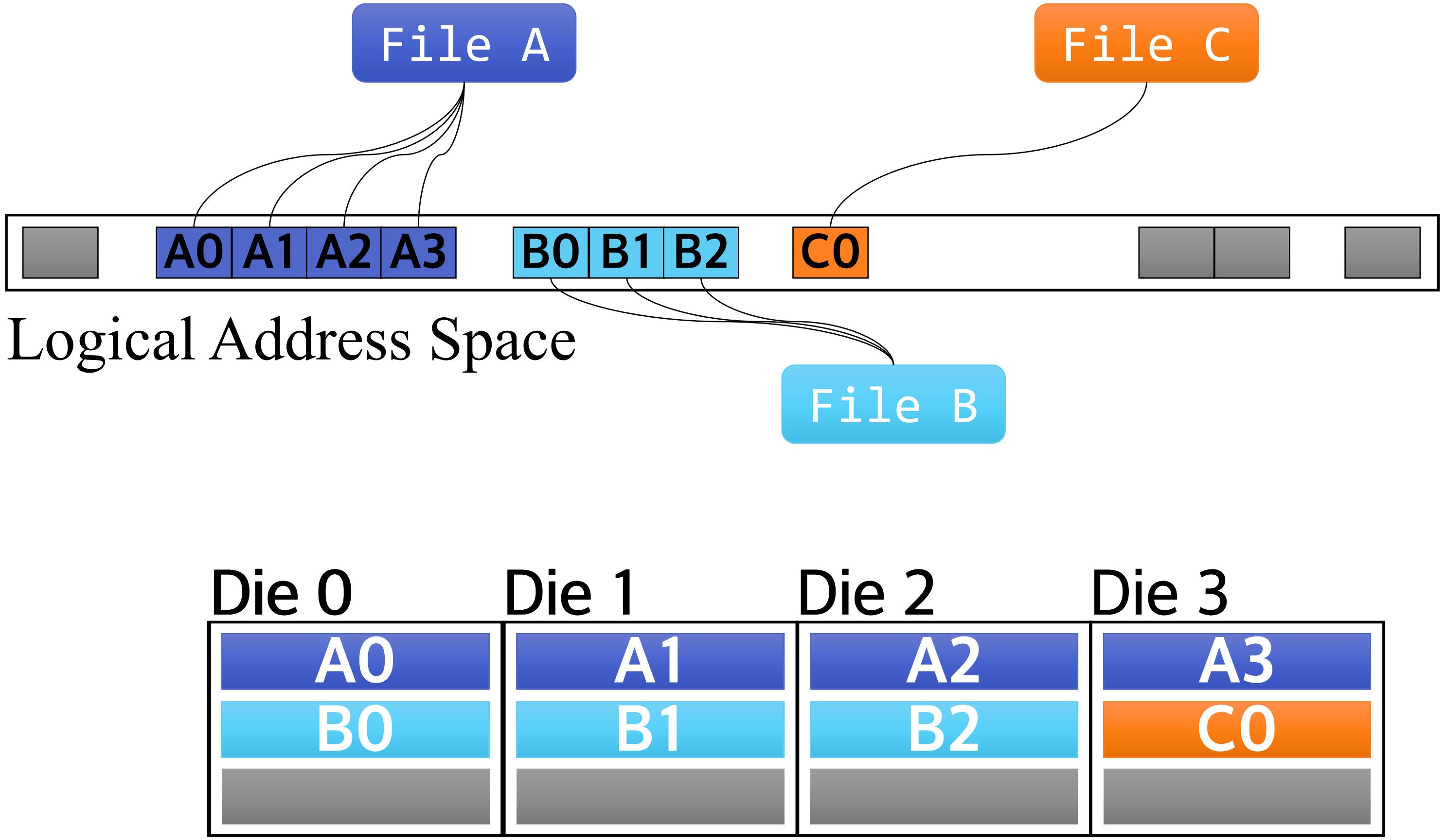


Die allocation in a round-robin manner



Concurrent writes to multiple files cause misaligned die allocation

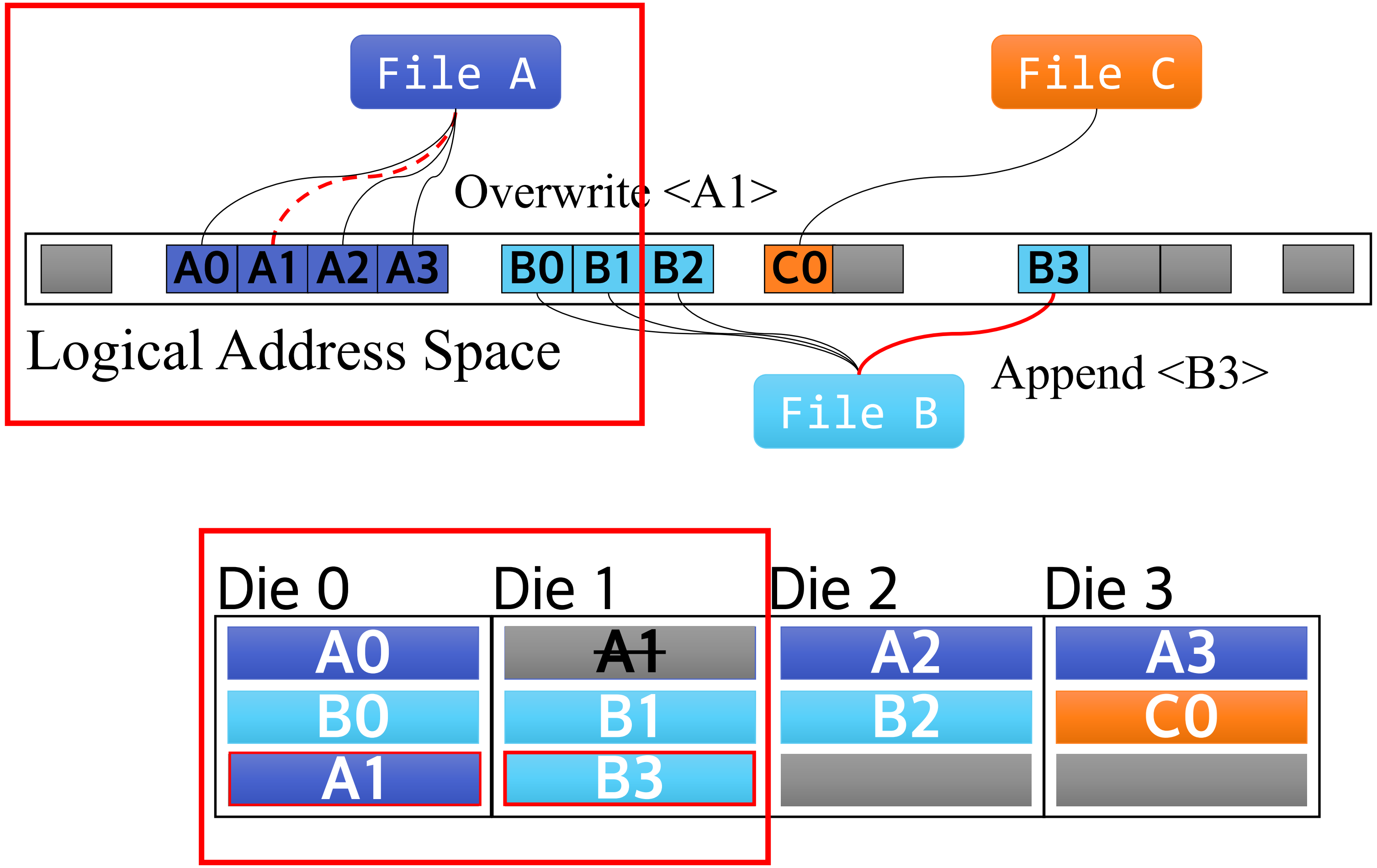
Misaligned Die Allocation from Overwrites



Die 0	Die 1	Die 2	Die 3
A0	A1	A2	A3
B0	B1	B2	C0

- File A Append <A0, A1, A2, A3>
- File B Append <B0, B1, B2>
- File C Append <C0>

Misaligned Die Allocation from Overwrites

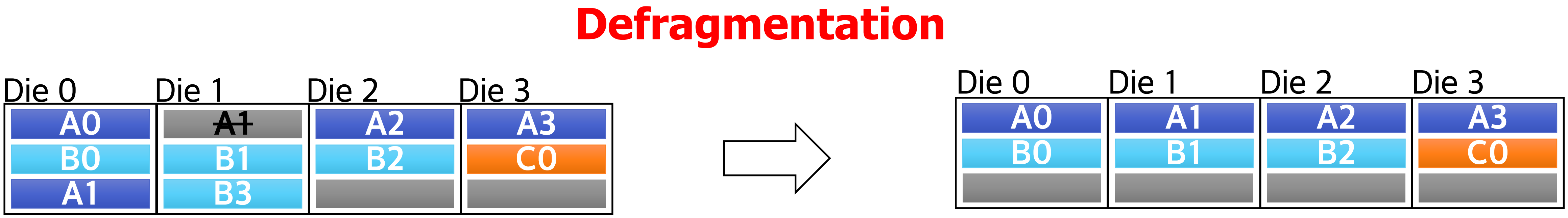


- File A Append <A0, A1, A2, A3>
- File B Append <B0, B1, B2>
- File C Append <C0>

- File A Overwrite <A1>
- File B Append <B3>

Conventional Approach

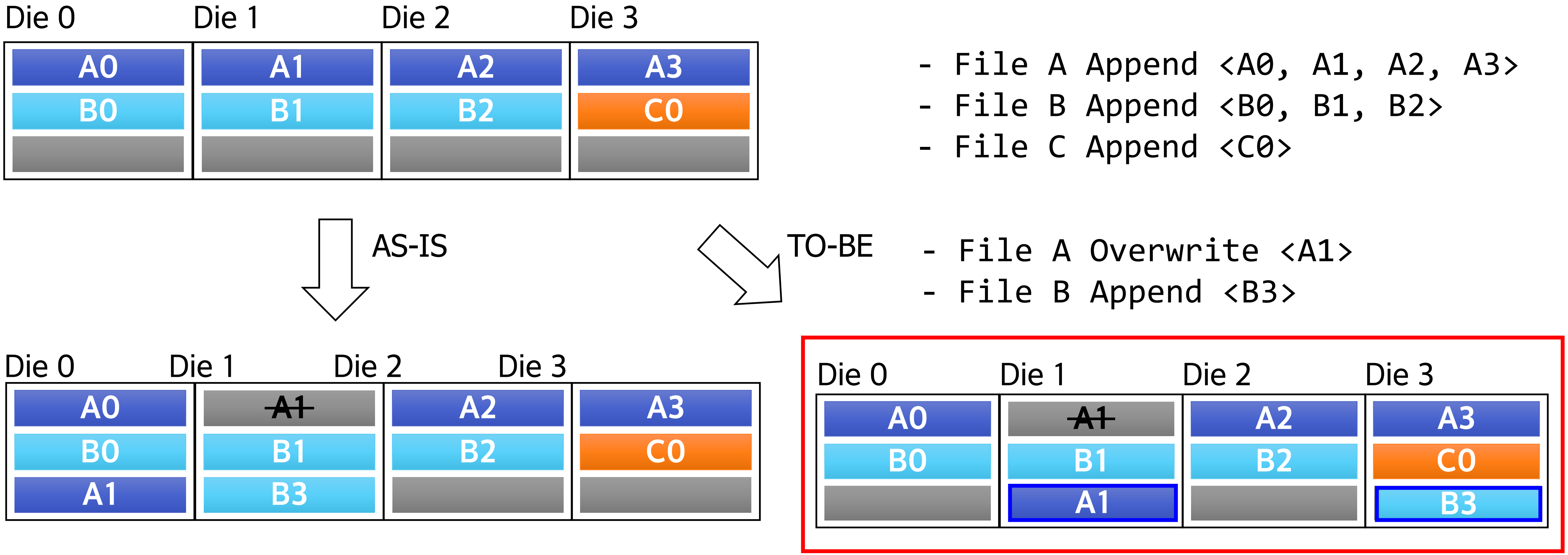
- Appends and overwrites lead to misaligned die allocation
- While defragmentation addresses this issue, it incurs significant costs



Reads and rewrites the entire file

Our Approach

- Prevents misaligned allocation on the fly



- File A Append <A0, A1, A2, A3>
- File B Append <B0, B1, B2>
- File C Append <C0>

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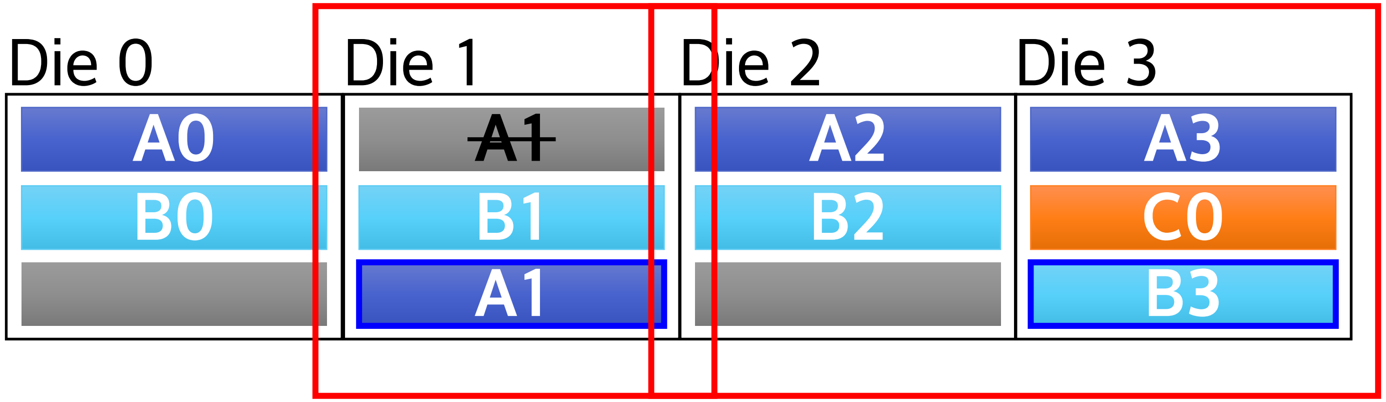
Our Approach

- Prevents misaligned allocation on the fly

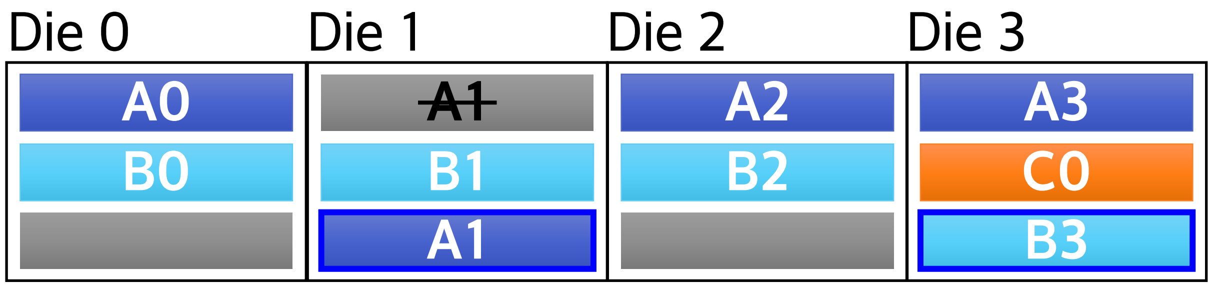
```
- File A Overwrite <A1>
- File B Append <B3>
```

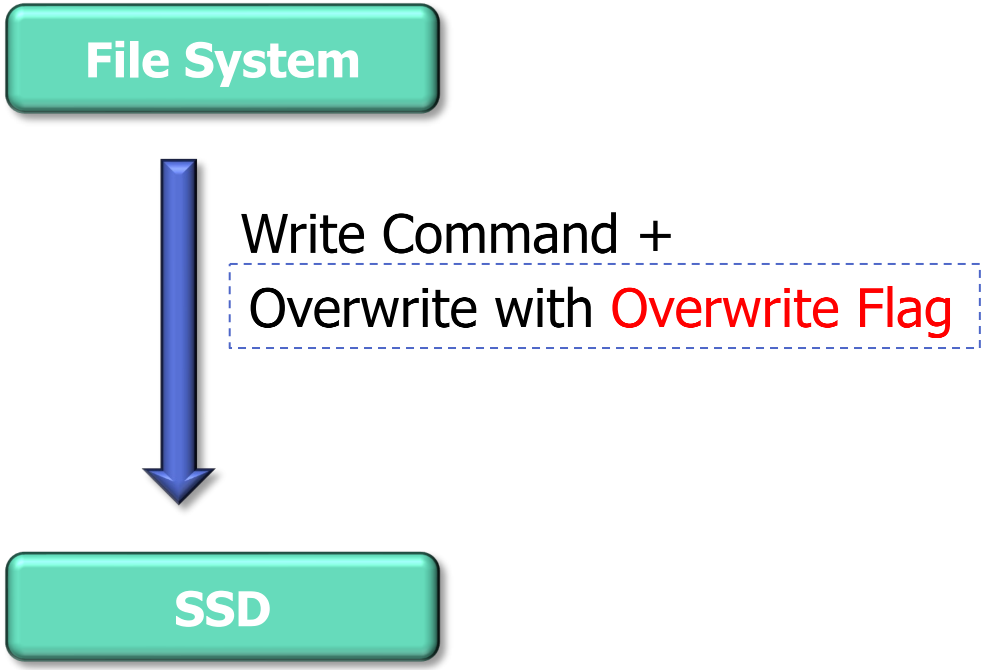


Our Approach

- File system provides file information to the SSD
- Overwrite to same die

`- File A Overwrite <A1> (with OW flag)`

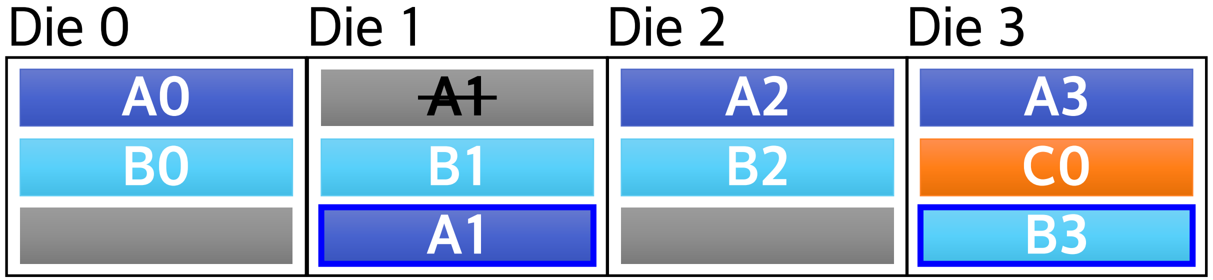




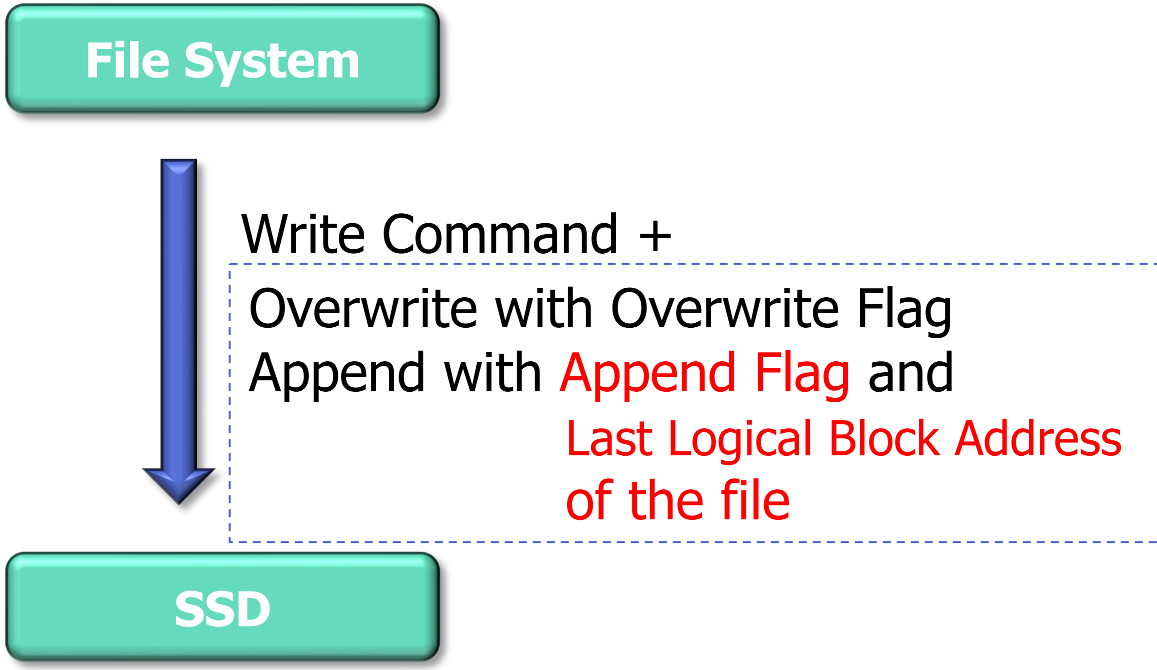
Our Approach

- File system provides file information to the SSD
- Overwrite to same die
- Append to the die next to last written one

```
- File A Overwrite <A1> (with OW flag)
- File B Append <B3> (with AP flag, B2)
```



Die 0	Die 1	Die 2	Die 3
A0	~~A1~~	A2	A3
B0	B1	B2	C0
	A1		B3



File System

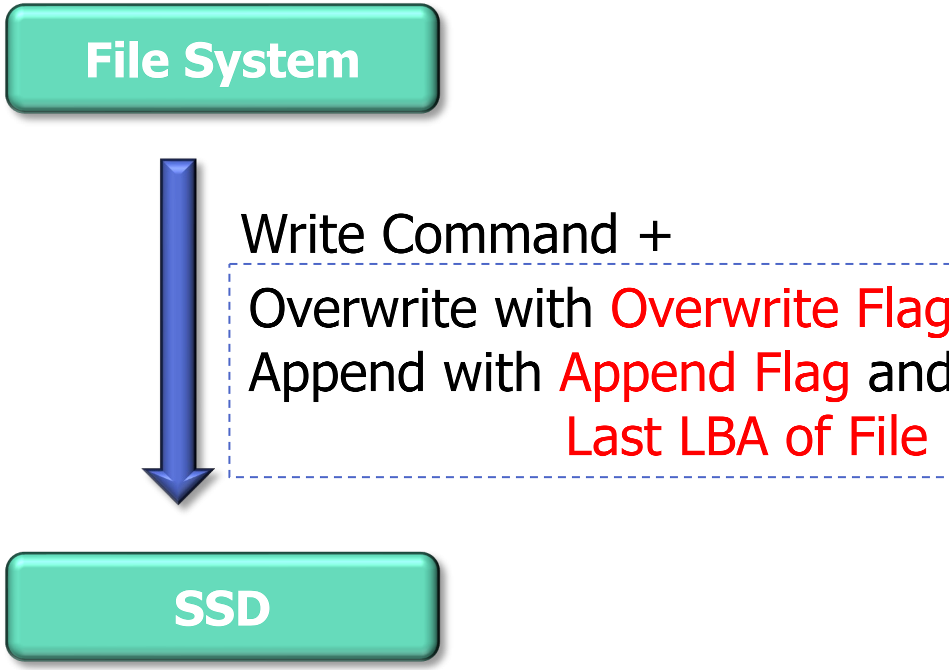
Write Command +

Overwrite with Overwrite Flag
Append with Append Flag and
Last Logical Block Address of the file

SSD

Our Approach

- The hints are sent through an unused field of the NVMe write command



File System

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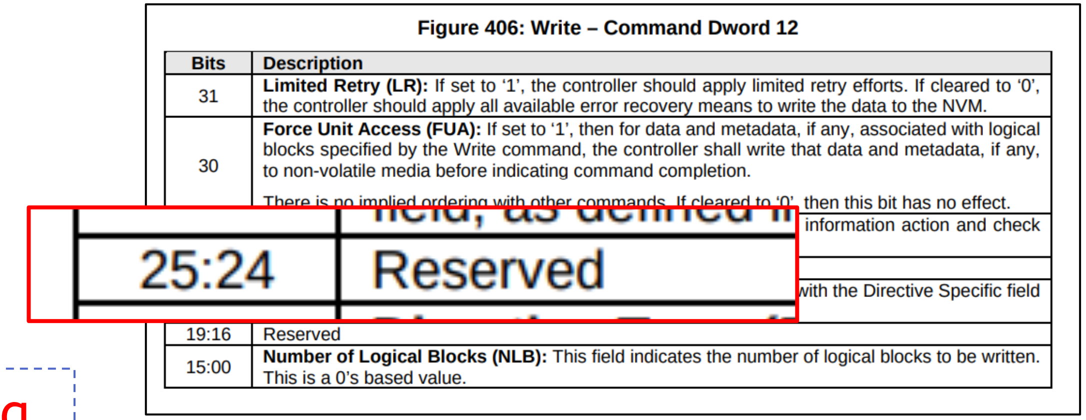


Figure 406: Write – Command Dword 12

Bits	Description
31	**Limited Retry (LR):** If set to '1', the controller should apply limited retry efforts. If cleared to '0', the controller should apply all available error recovery means to write the data to the NVM.
30	**Force Unit Access (FUA):** If set to '1', then for data and metadata, if any, associated with logical blocks specified by the Write command, the controller shall write that data and metadata, if any, to non-volatile media before indicating command completion. There is no implied ordering with other commands. If cleared to '0', then this bit has no effect.
	field, as defined in … information action and check
25:24	Reserved
	… with the Directive Specific field
19:16	Reserved
15:00	**Number of Logical Blocks (NLB):** This field indicates the number of logical blocks to be written. This is a 0's based value.

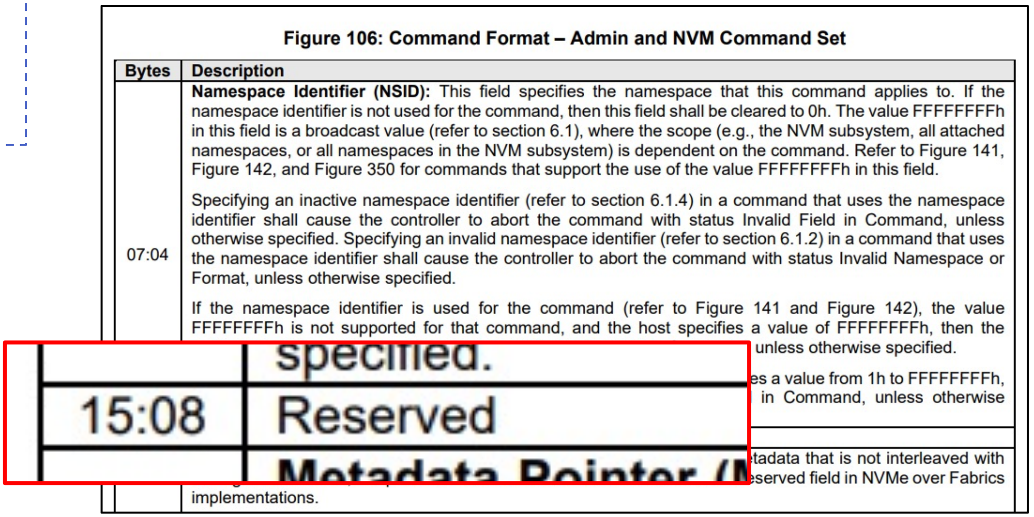
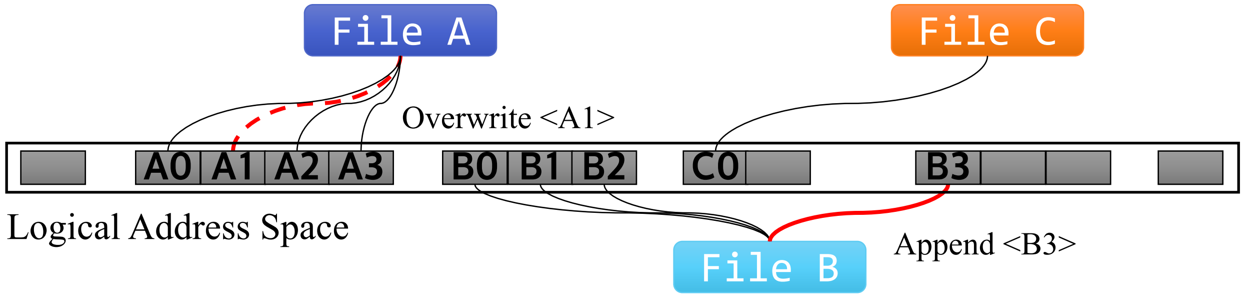


Figure 106: Command Format – Admin and NVM Command Set

Bytes	Description
07:04	**Namespace Identifier (NSID):** This field specifies the namespace that this command applies to. If the namespace identifier is not used for the command, then this field shall be cleared to 0h. The value FFFFFFFFh in this field is a broadcast value (refer to section 6.1), where the scope (e.g., the NVM subsystem, all attached namespaces, or all namespaces in the NVM subsystem) is dependent on the command. Refer to Figure 141, Figure 142, and Figure 350 for commands that support the use of the value FFFFFFFFh in this field. Specifying an inactive namespace identifier (refer to section 6.1.4) in a command that uses the namespace identifier shall cause the controller to abort the command with status Invalid Field in Command, unless otherwise specified. Specifying an invalid namespace identifier (refer to section 6.1.2) in a command that uses the namespace identifier shall cause the controller to abort the command with status Invalid Namespace or Format, unless otherwise specified. If the namespace identifier is used for the command (refer to Figure 141 and Figure 142), the value FFFFFFFFh is not supported for that command, and the host specifies a value of FFFFFFFFh, then the … unless otherwise specified. … es a value from 1h to FFFFFFFFh, … in Command, unless otherwise specified.
15:08	Reserved
	Metadata Pointer (M… … tadata that is not interleaved with … served field in NVMe over Fabrics implementations.

Our Approach

- Prevents misaligned allocation on the fly



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Die 0	Die 1	Die 2	Die 3
A0	~~A1~~	A2	A3
B0	B1	B2	C0
	A1		B3

- File A Overwrite <A1> (with OW flag)
- File B Append <B3> (with AP flag, B2)

Evaluation

- Environment

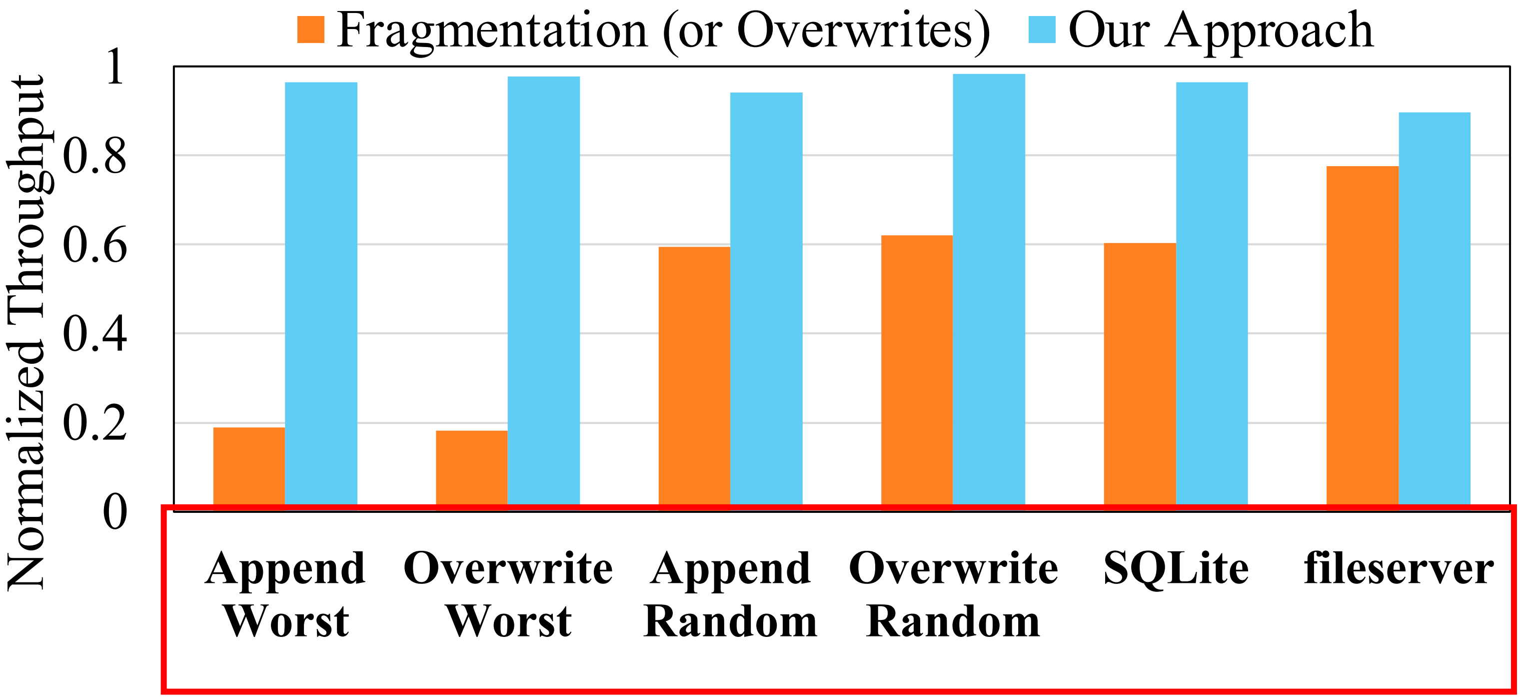
System Configuration	
Processor	Intel Xeon Gold 6138 2.0 GHz, 160-Core
Chipset	Intel C621
Memory	DDR4 2666 MHz, 32 GB x16
OS	Ubuntu 20.04 Server (kernel v5.15.0)
File system	Ext4

NVMeVirt Emulator [22]	
Interface	PCIe Gen 3 x4
Capacity	60 GB
Channel Count	4
Dies per Channel	2
Read/Write Unit Size	32 KB
Read Time	36 μs
Write Time	185 μs

- Our approach was validated using commodity SSDs (as detailed in the paper)
- Evaluation our approach with SSD emulator
  - Modified Ext4 and NVMe driver to transmit info through NVMe Write Command
  - NVMeVirt adjusts die allocation policy using this information

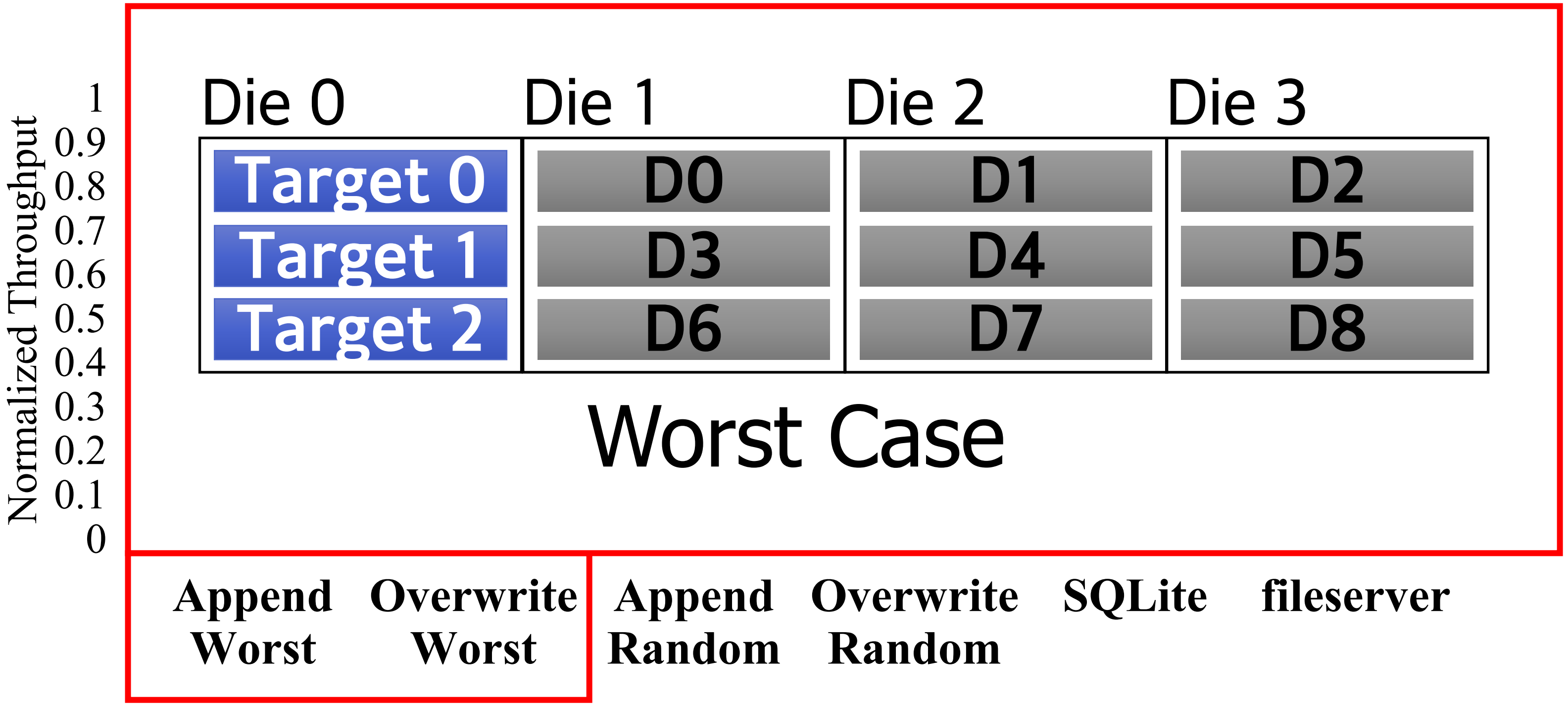
Evaluation

- Used hypothetical workloads, SQLite and Filebench



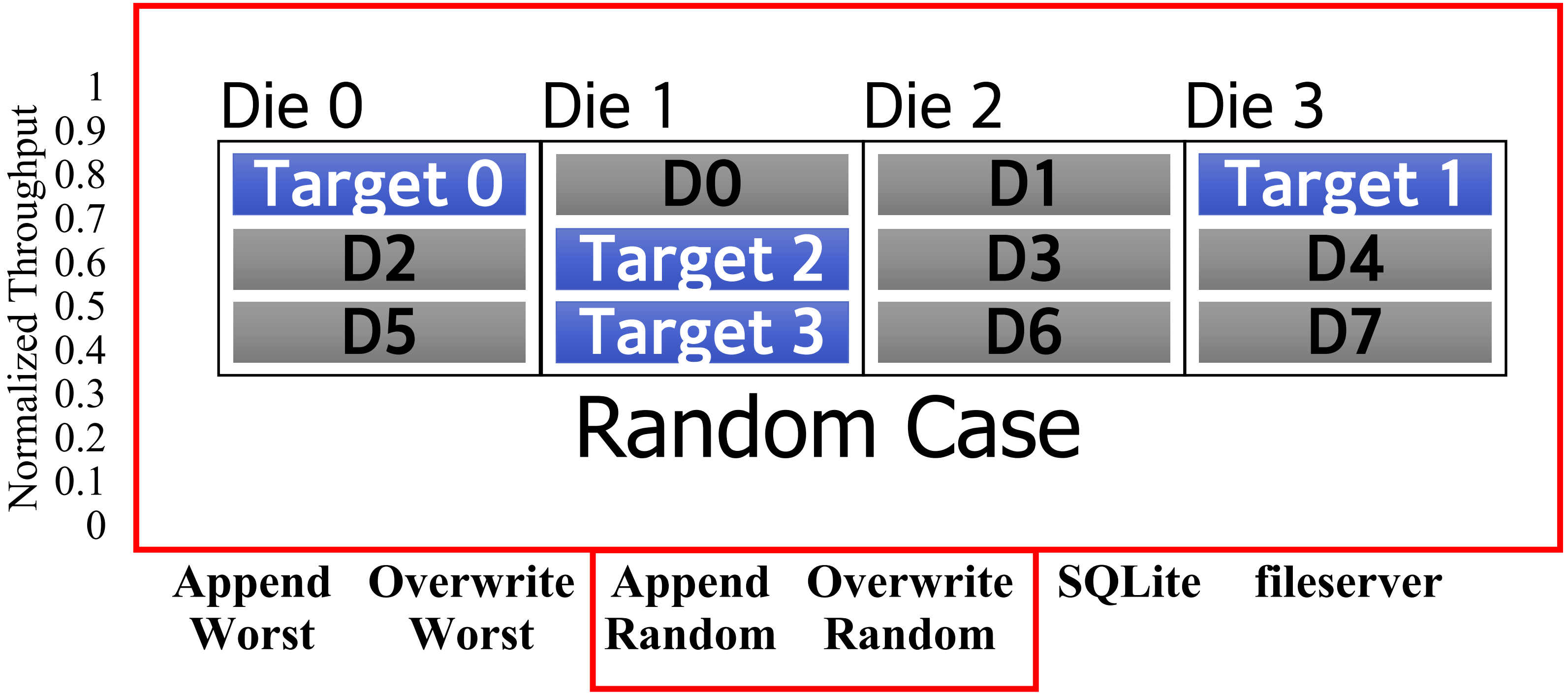
Evaluation

- Worst case of hypothetical workloads



Evaluation

- Random case of hypothetical workloads



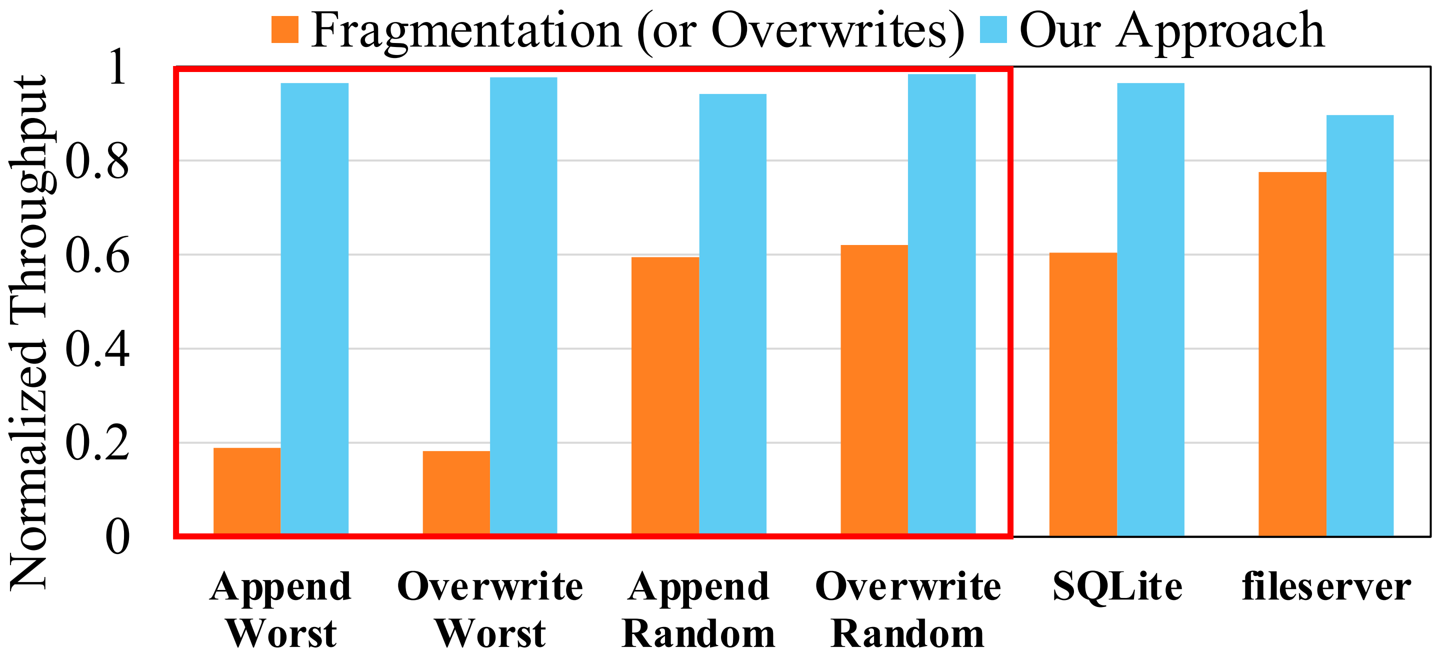
Evaluation

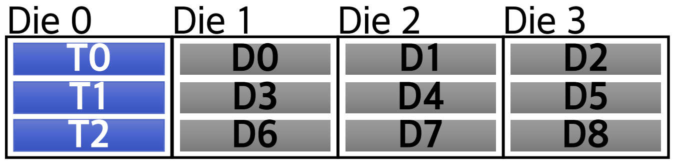
- In the worst case, 20% of contiguous file’s
- In the random case, 60% of contiguous file’s

➔ Improved to within 6%.

- In SQLite, 60% of contiguous file’s
- In fileserver, 77% of contiguous file’s

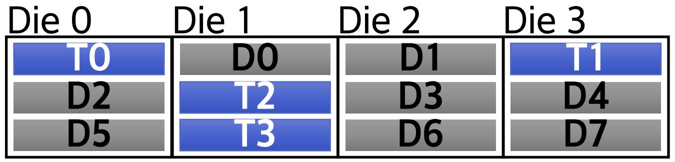
➔ Improved to within 10%.





Die 0	Die 1	Die 2	Die 3
T0	D0	D1	D2
T1	D3	D4	D5
T2	D6	D7	D8

Worst Case



Die 0	Die 1	Die 2	Die 3
T0	D0	D1	T1
D2	T2	D3	D4
D5	T3	D6	D7

Random Case

Evaluation

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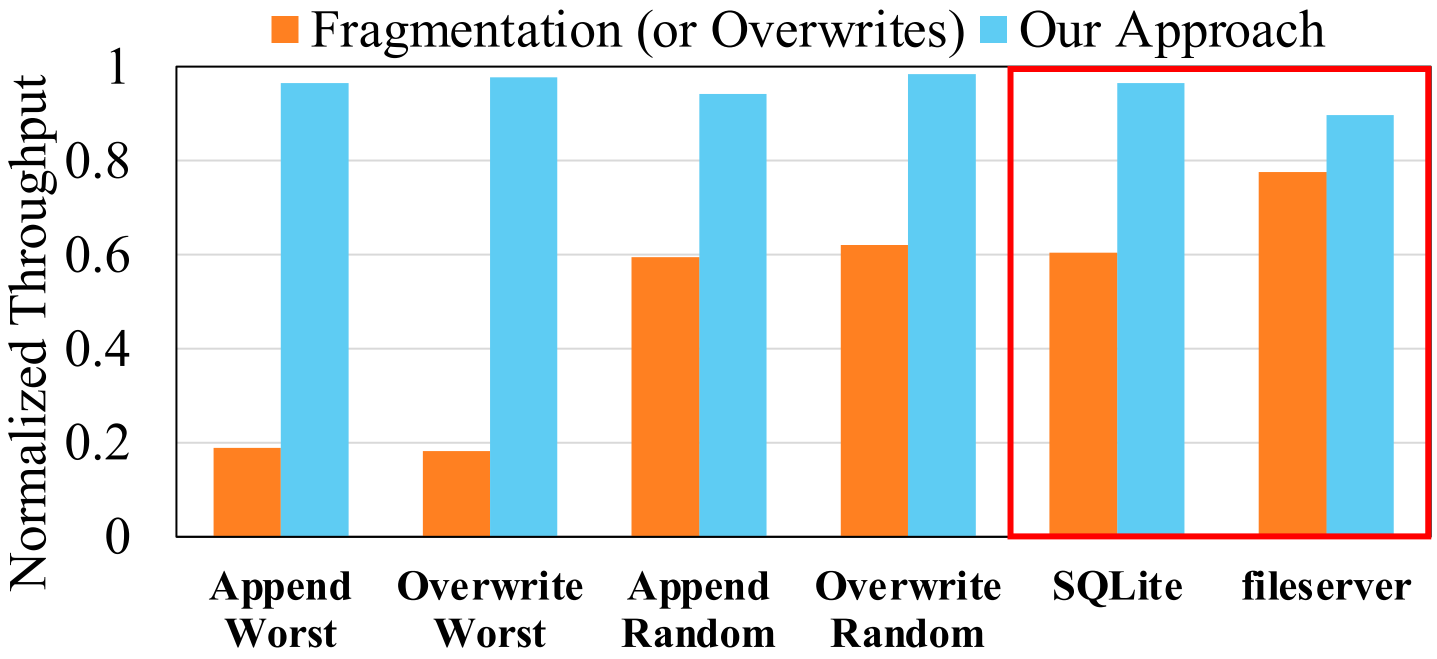

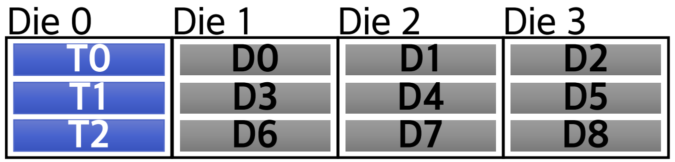

Die 0	Die 1	Die 2	Die 3
T0	D0	D1	D2
T1	D3	D4	D5
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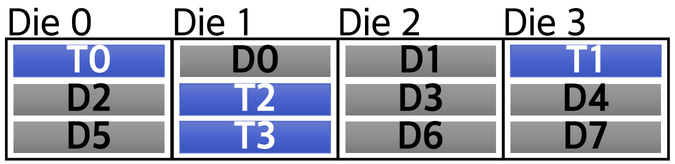
Worst Case



Die 0	Die 1	Die 2	Die 3
T0	D0	D1	T1
D2	T2	D3	D4
D5	T3	D6	D7

Random Case

Conclusion

- We identify the true cause of performance degradation due to file fragmentation
  - Request splitting overhead is concealed in a multi-queue environment
  - Primary cause is *read collisions due to misaligned die allocation*

- We proposed an approach to mitigate the misalignment
  - By providing filesystem information to the SSD,
    it maintains the proper die allocations even under adverse conditions
  - Addressing not only append write cases, but also overwrite cases

Thank you

Q&A