The Unwritten Contract of Solid State Drives

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Department of Computer Sciences, University of Wisconsin - Madison

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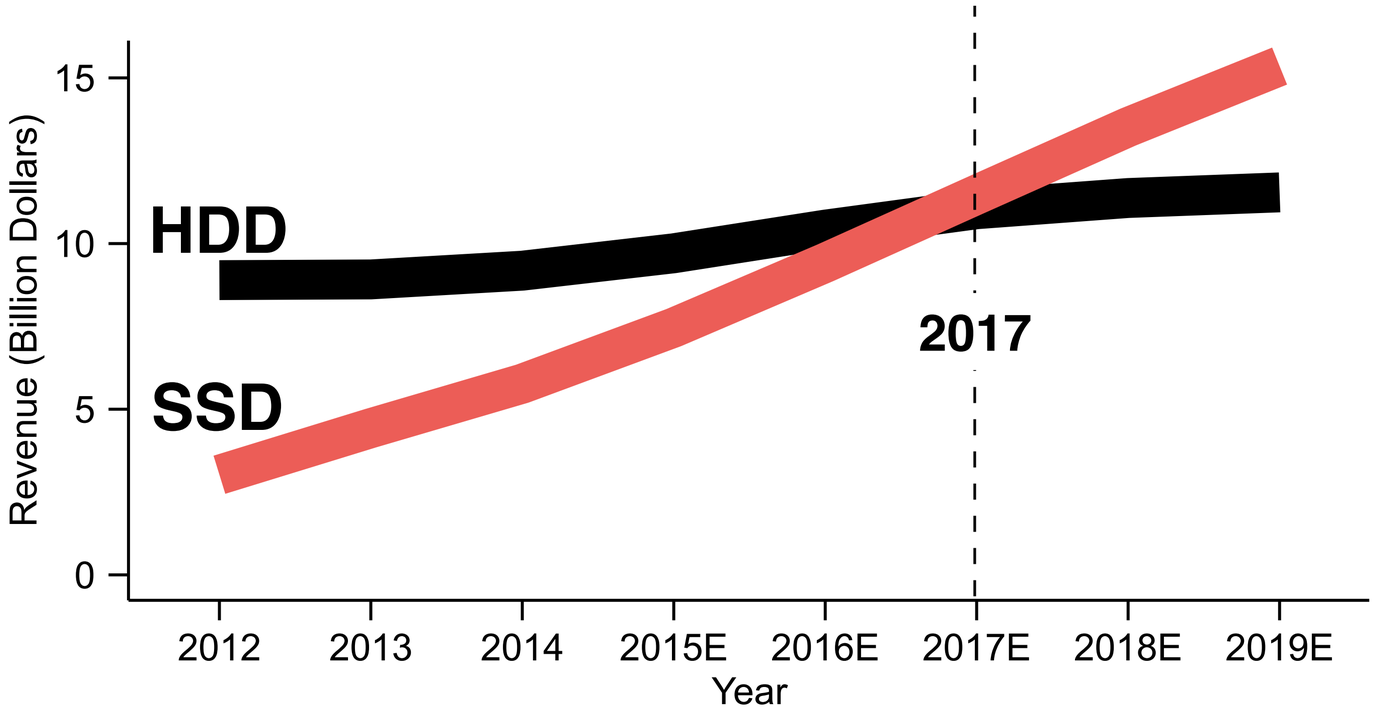
Enterprise SSD revenue is expected to exceed enterprise HDD in 2017



Source: Gartner, Stifel Estimates
https://www.theregister.co.uk/2016/01/07/gartner_enterprise_ssd_hdd_revenue_crossover_in_2017/

Storage stack is shifting from the HDD era to the SSD era

App

FS

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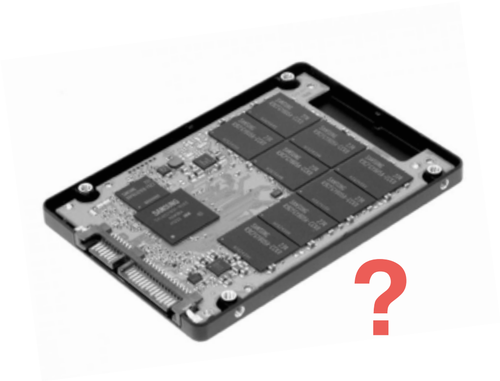

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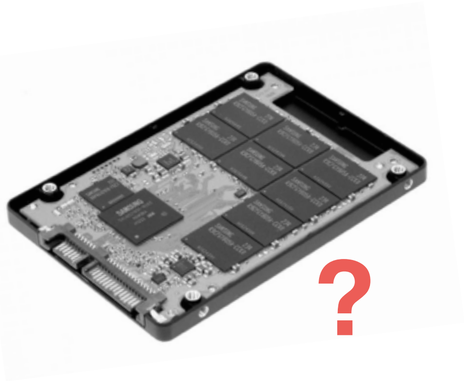

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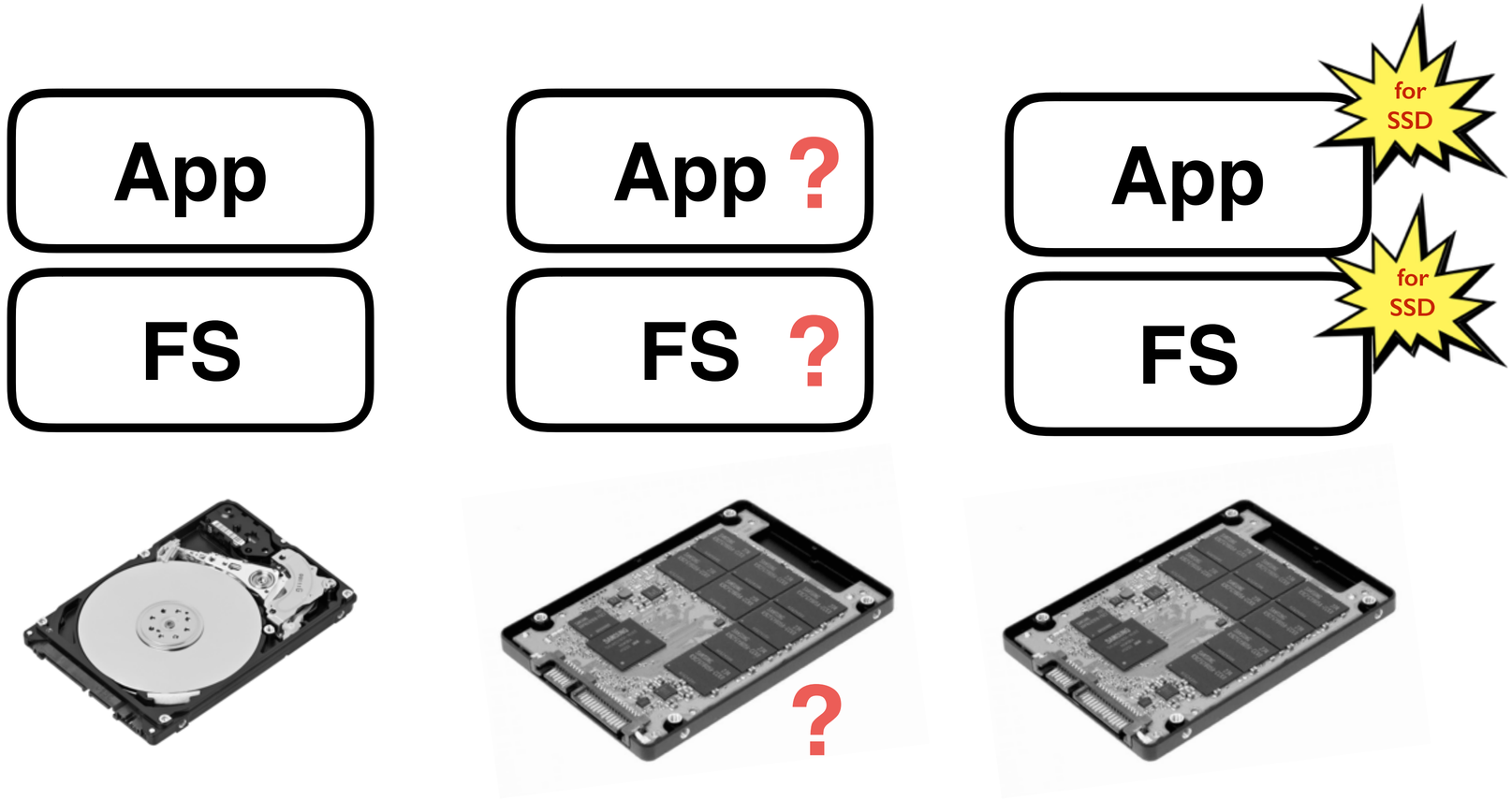

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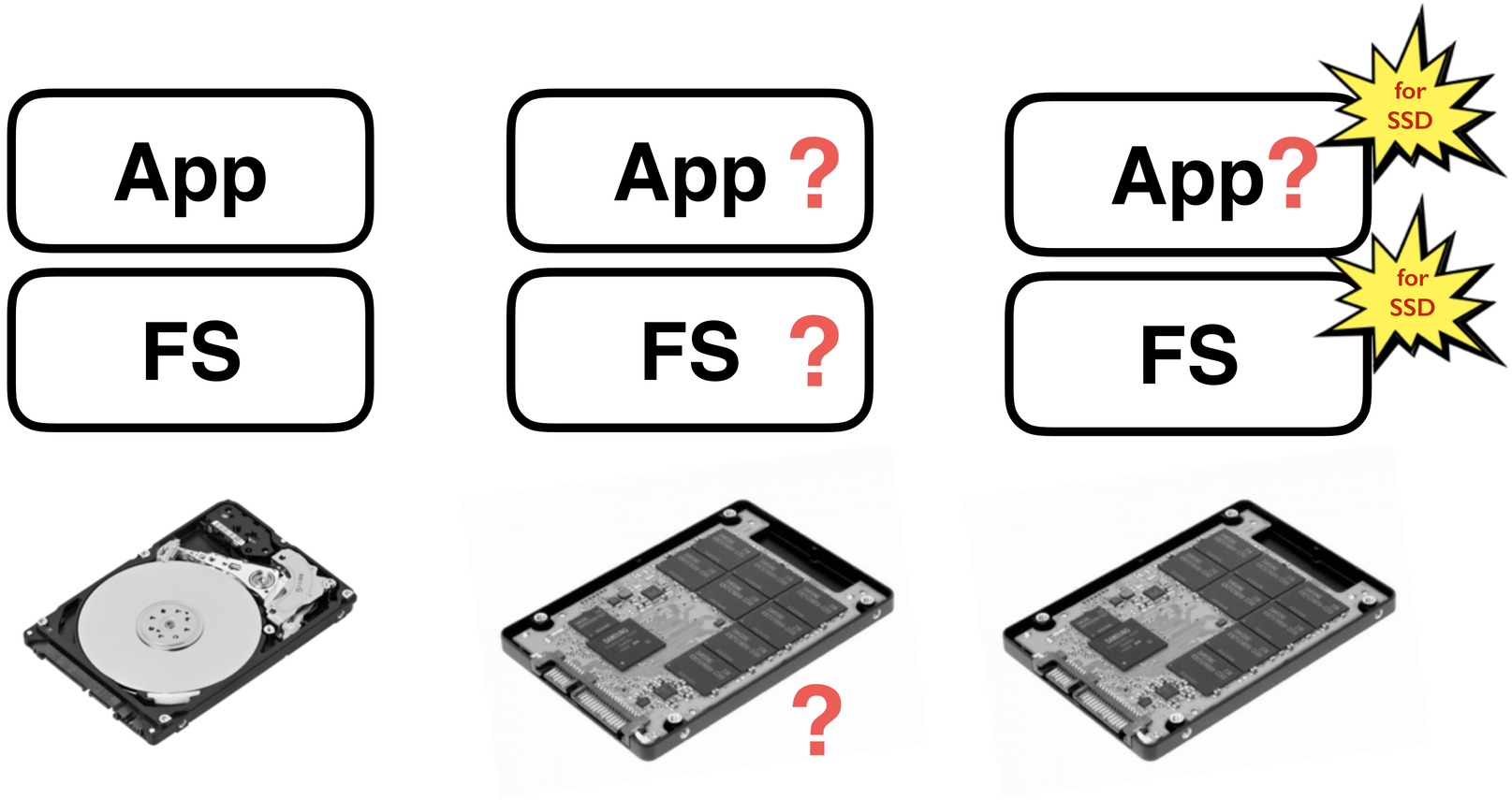

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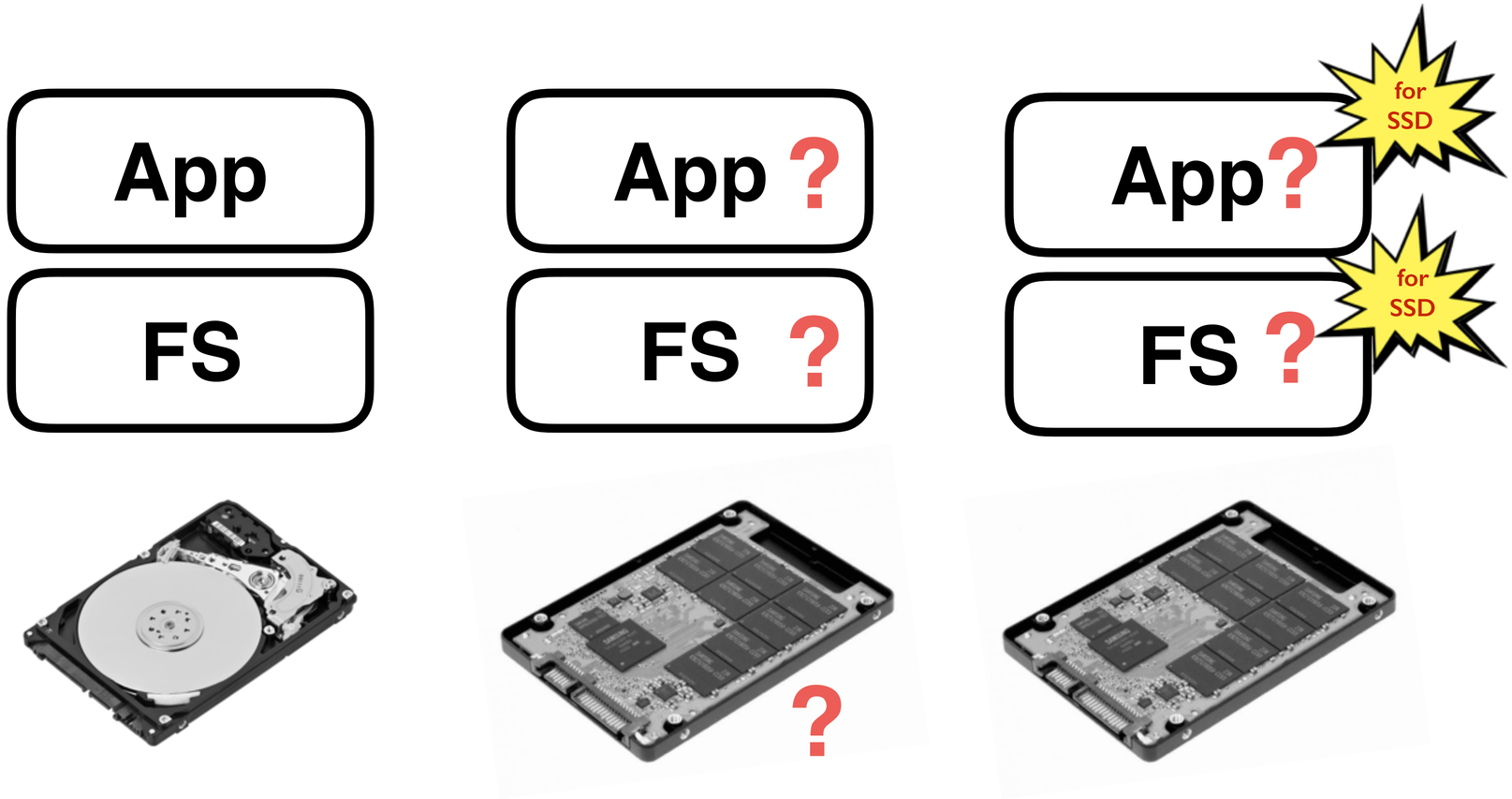

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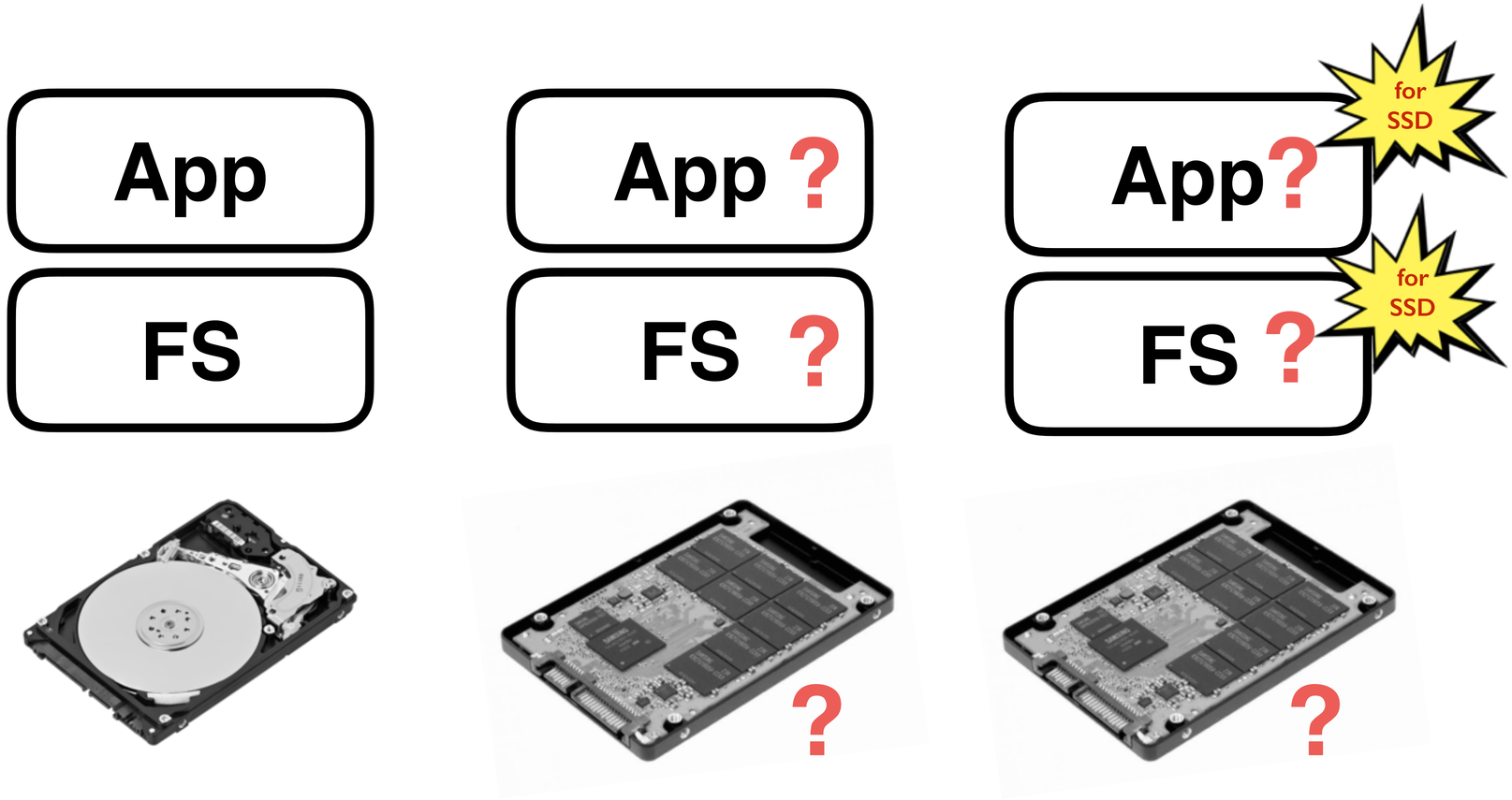

The consequences of misuses

http://crestingwave.com/sites/default/files/collateral/velobit_whitepaper_ssdperformancetips.pdf
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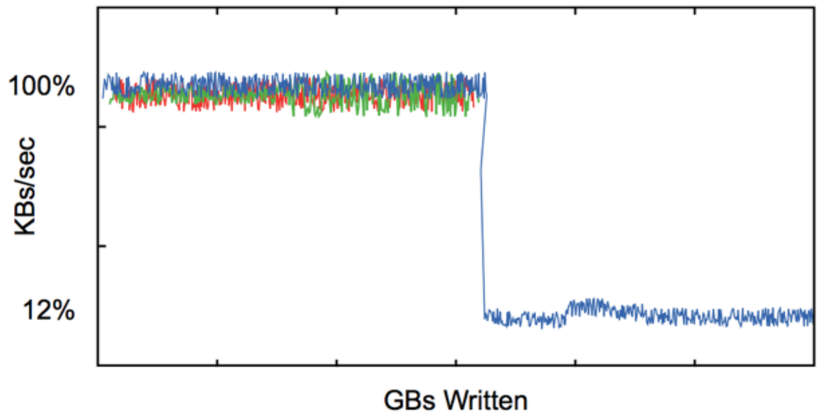

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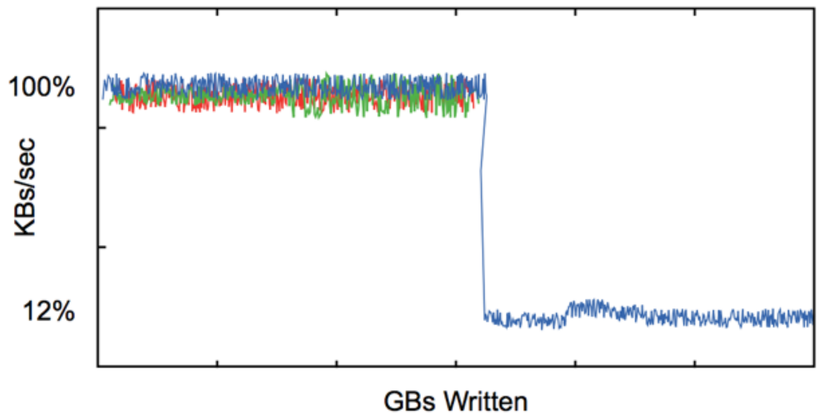
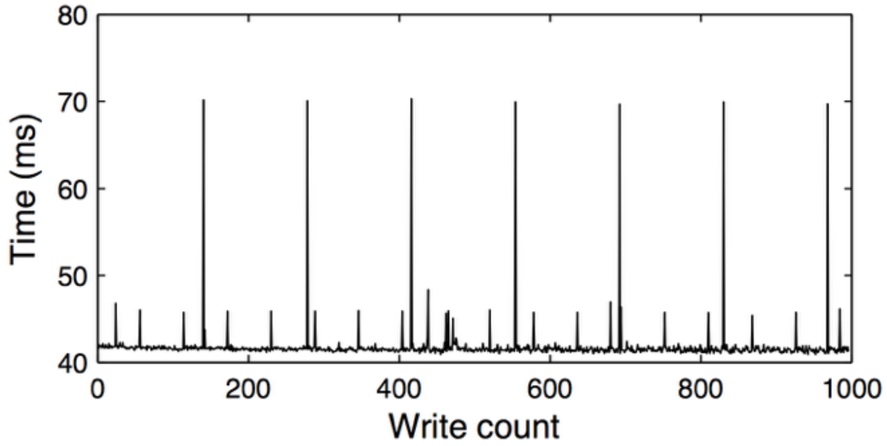


Performance fluctuation



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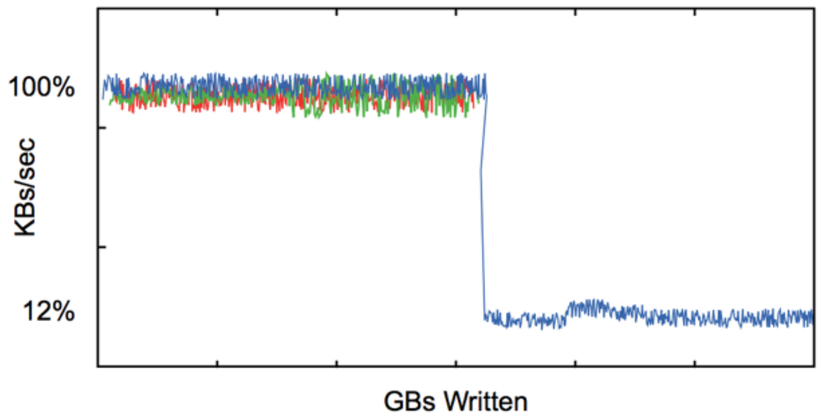

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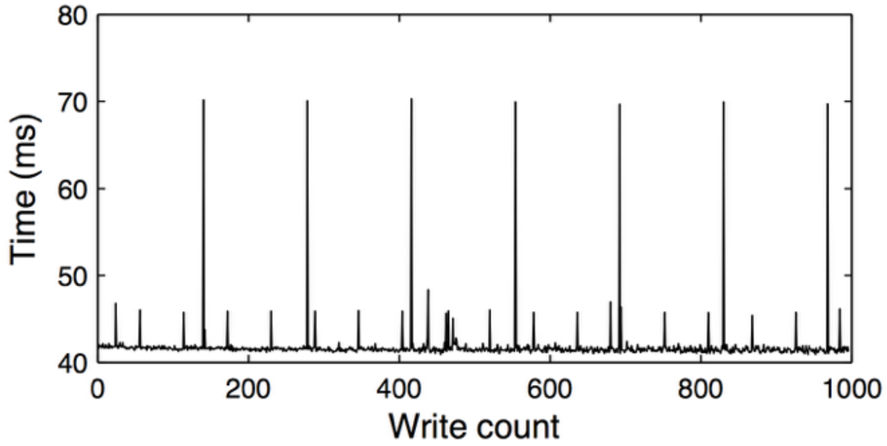

Early end of device life

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What is the right way to achieve high performance on SSDs?

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The **written** contract

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Example: SATA read command format

Register	7	6	5	4	3	2	1	0
Features(7:0)	Sector Count 7:0							
Features(15:8)	Sector Count 15:8							
Count(7:0)	TAG					Reserved		
Count(15:8)	PRIO(1:0)		Reserved					
LBA(7:0)	LBA 7:0							
LBA(31:24)	LBA 31:24							
LBA(15:8)	LBA 15:8							
LBA(39:32)	LBA 39:32							
LBA(23:16	LBA 23:16							
LBA(47:40)	LBA 47:40							
ICC	ICC(7:0)							
Device	FUA	1	Res	0	Reserved			
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Figure 205 – READ FPDMA QUEUED command definition

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Figure 205 – READ FPDMA QUEUED command definition

The **unwritten** contract

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Figure 205 – READ FPDMA QUEUED command definition

The **unwritten** contract

Rules

1. **Request Scale**
2. **Locality**
3. **Aligned Sequentiality**
4. **Grouping by Death Time**
5. **Uniform Data Lifetime**

Do the current apps/FSes comply with the unwritten contract of SSDs?

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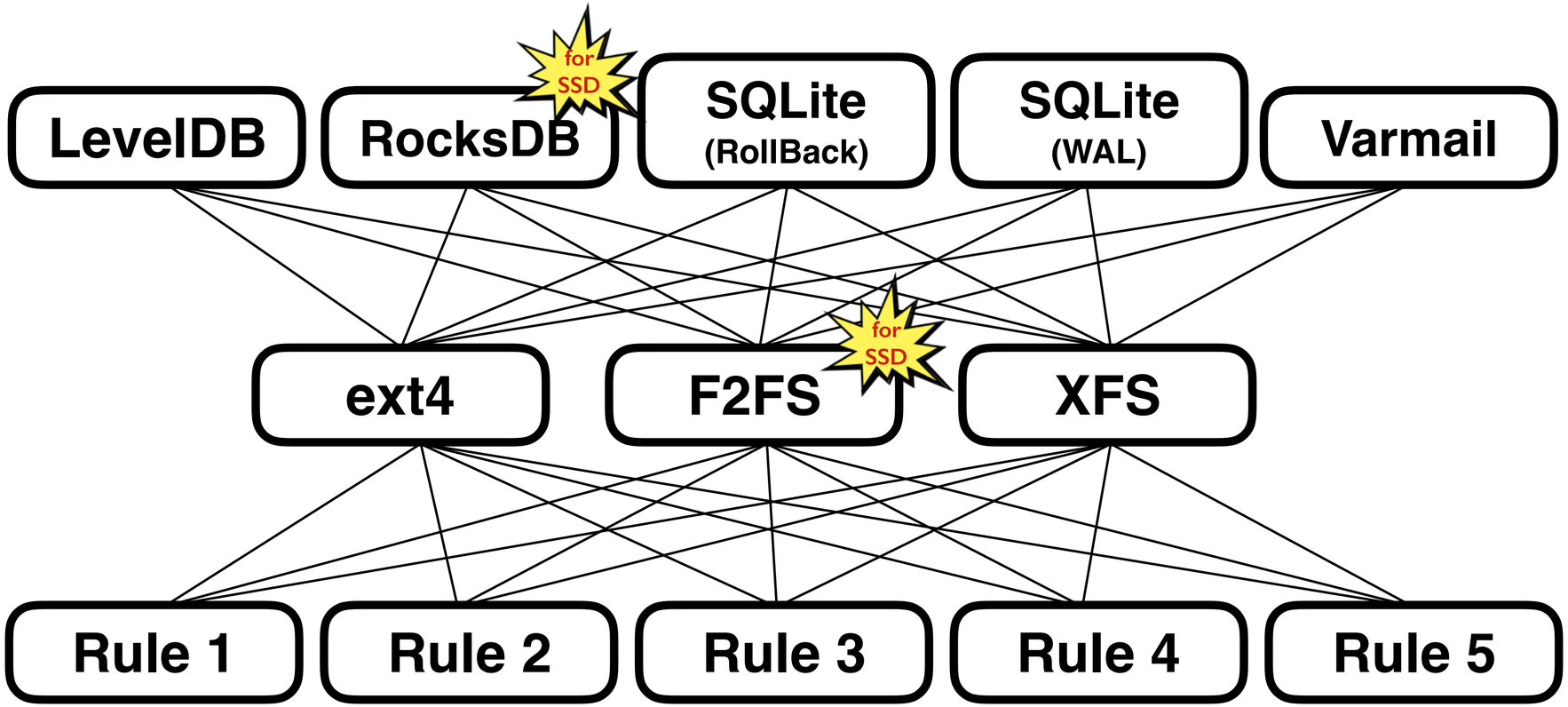

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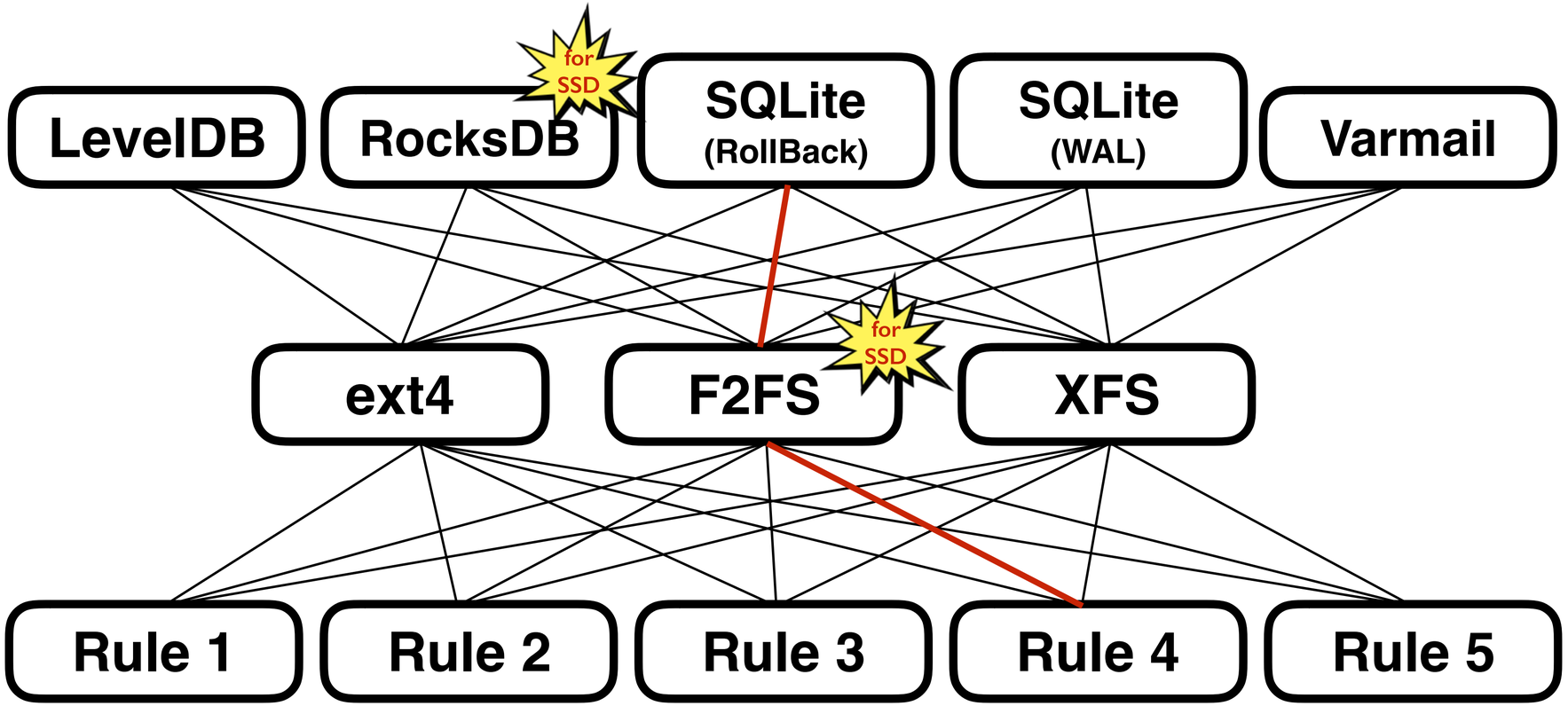

We made 24 observations, here are the 3 in this talk

- **Implementation of Linux limits performance**
- **F2FS incurs more GC overhead than ext4/XFS**
- **Application log structuring does not reduce GC**

Outline

- **Overview**
- SSD Unwritten Contract
- Violations of Unwritten Contract
  - Method
  - Observations
- Lessons Learned
- Conclusions

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- Overview
- **SSD Unwritten Contract**
- Violations of Unwritten Contract
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We summarize the unwritten contract from existing studies

Contract Rules

#1 Request Scale

#2 Locality

#3 Aligned Sequentiality

#4 Grouping by Death Time

#5 Uniform Data Lifetime

SSD Background

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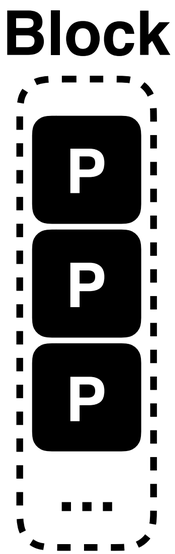

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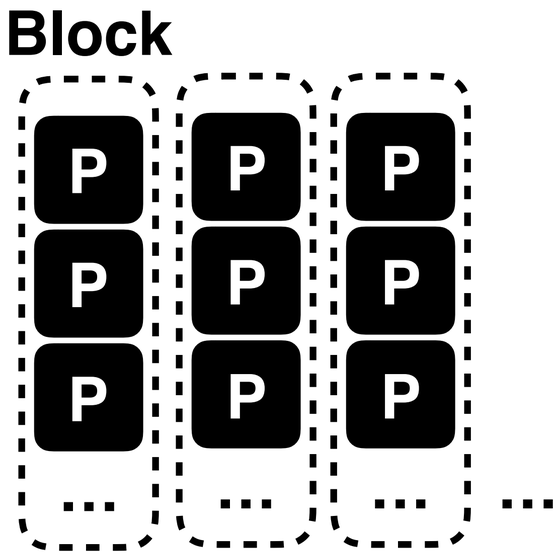

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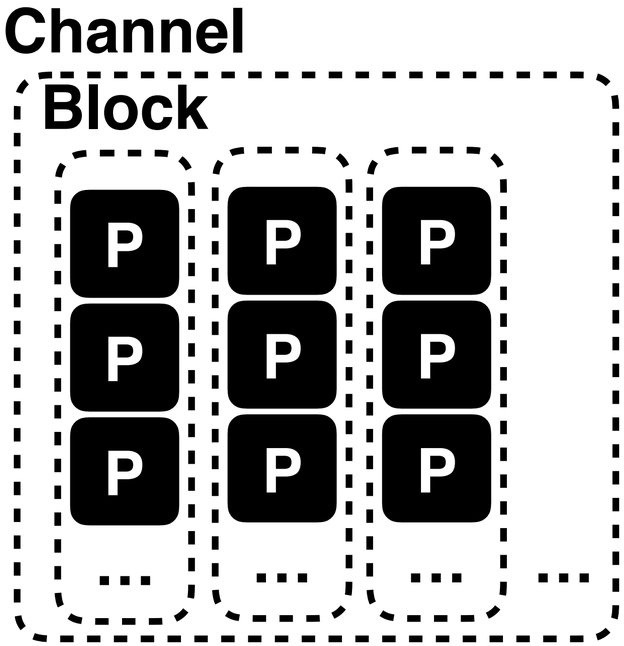

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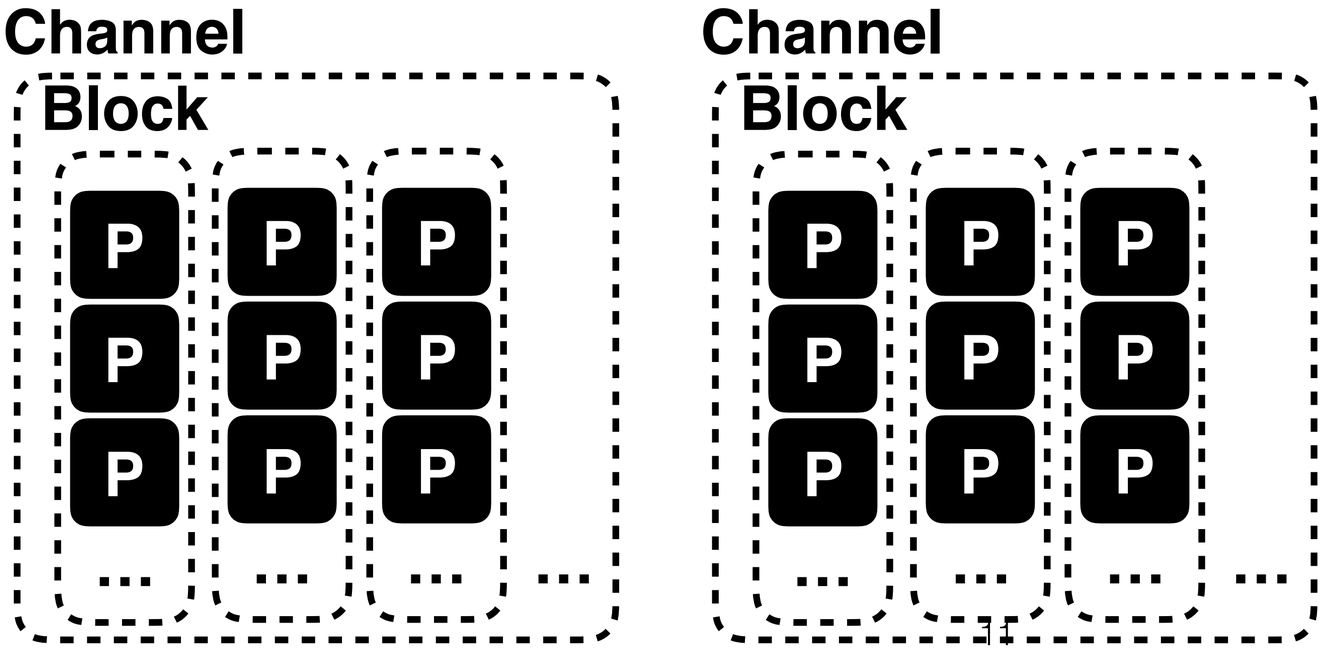

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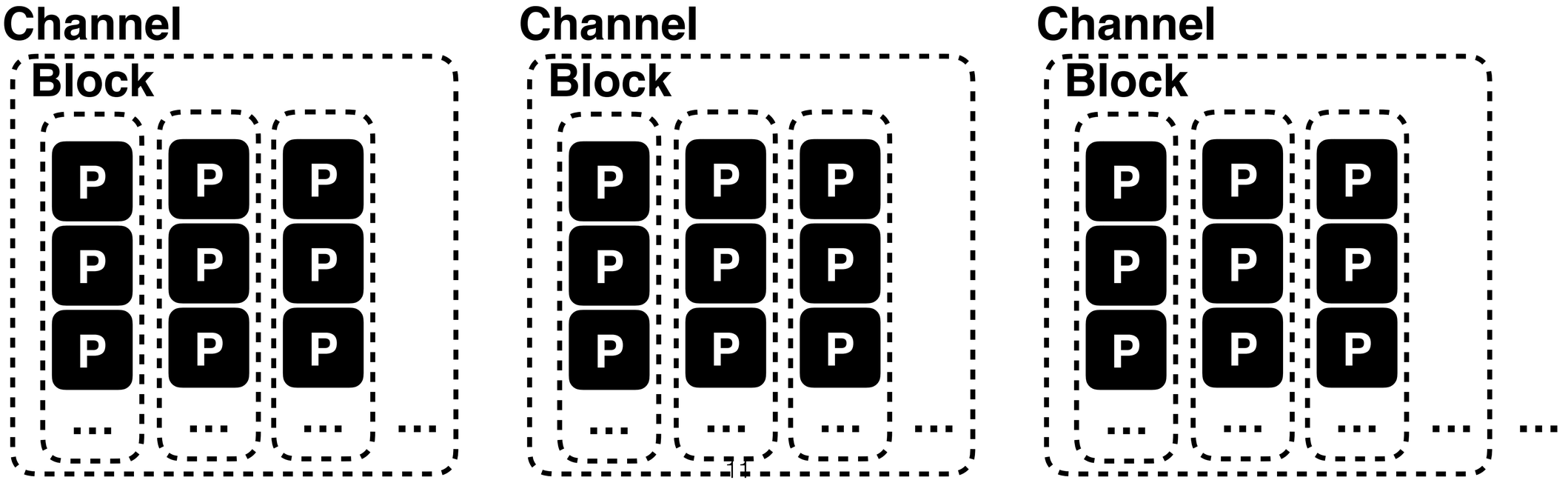

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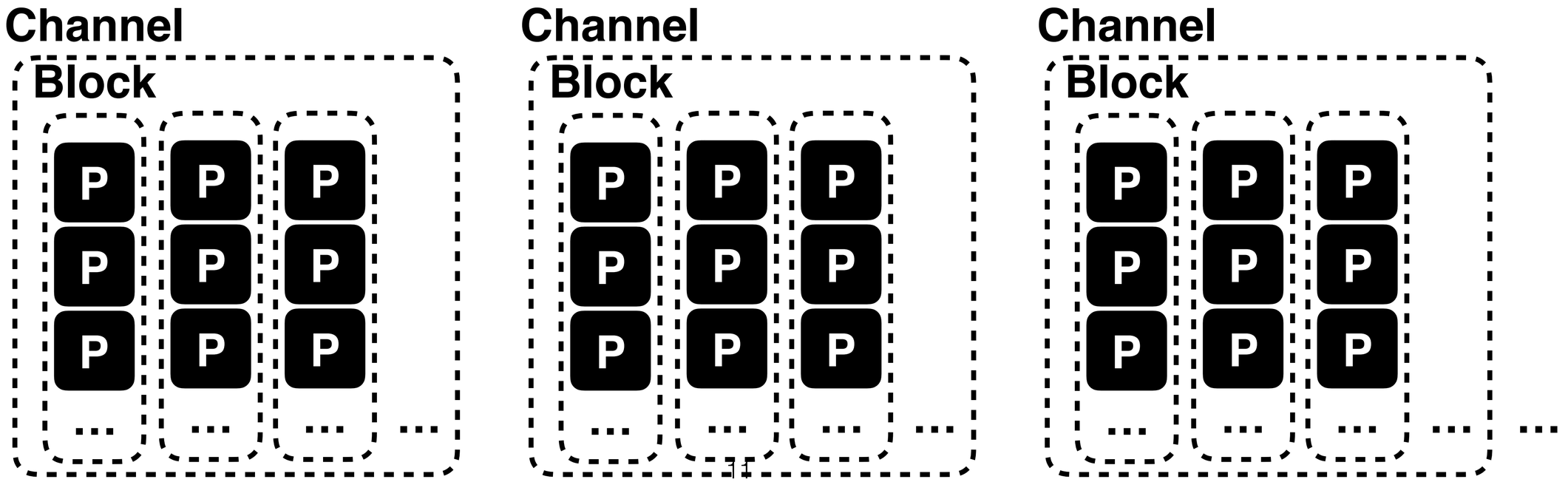

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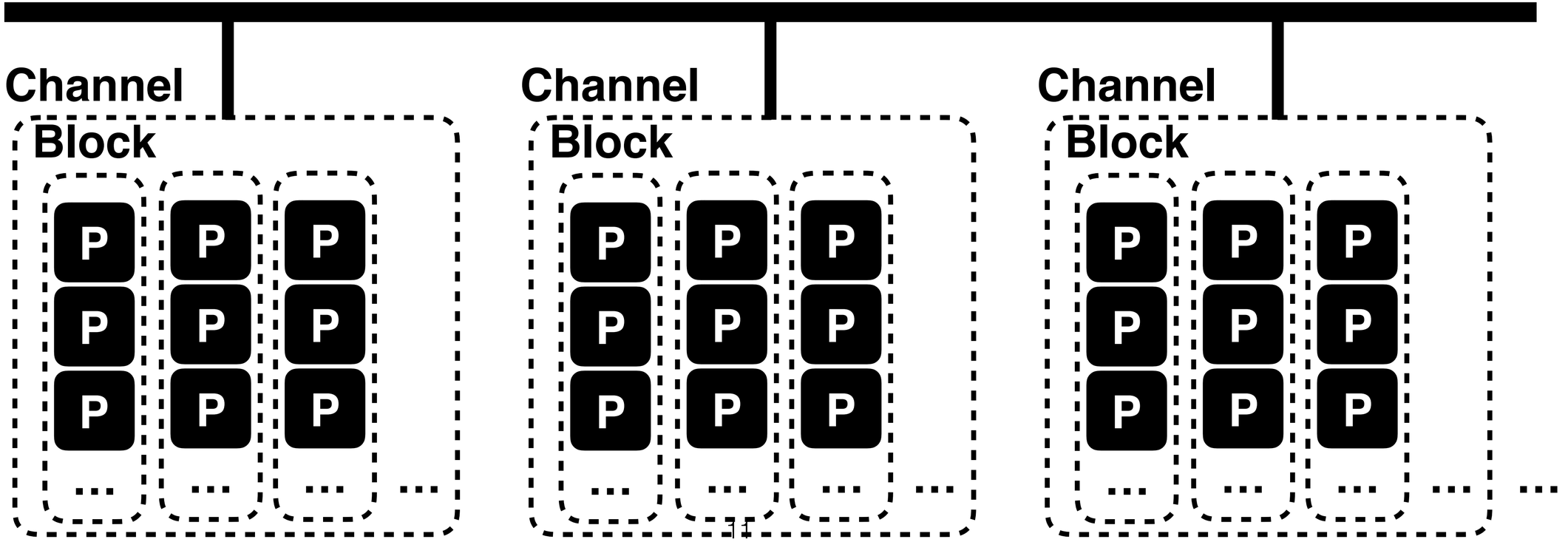

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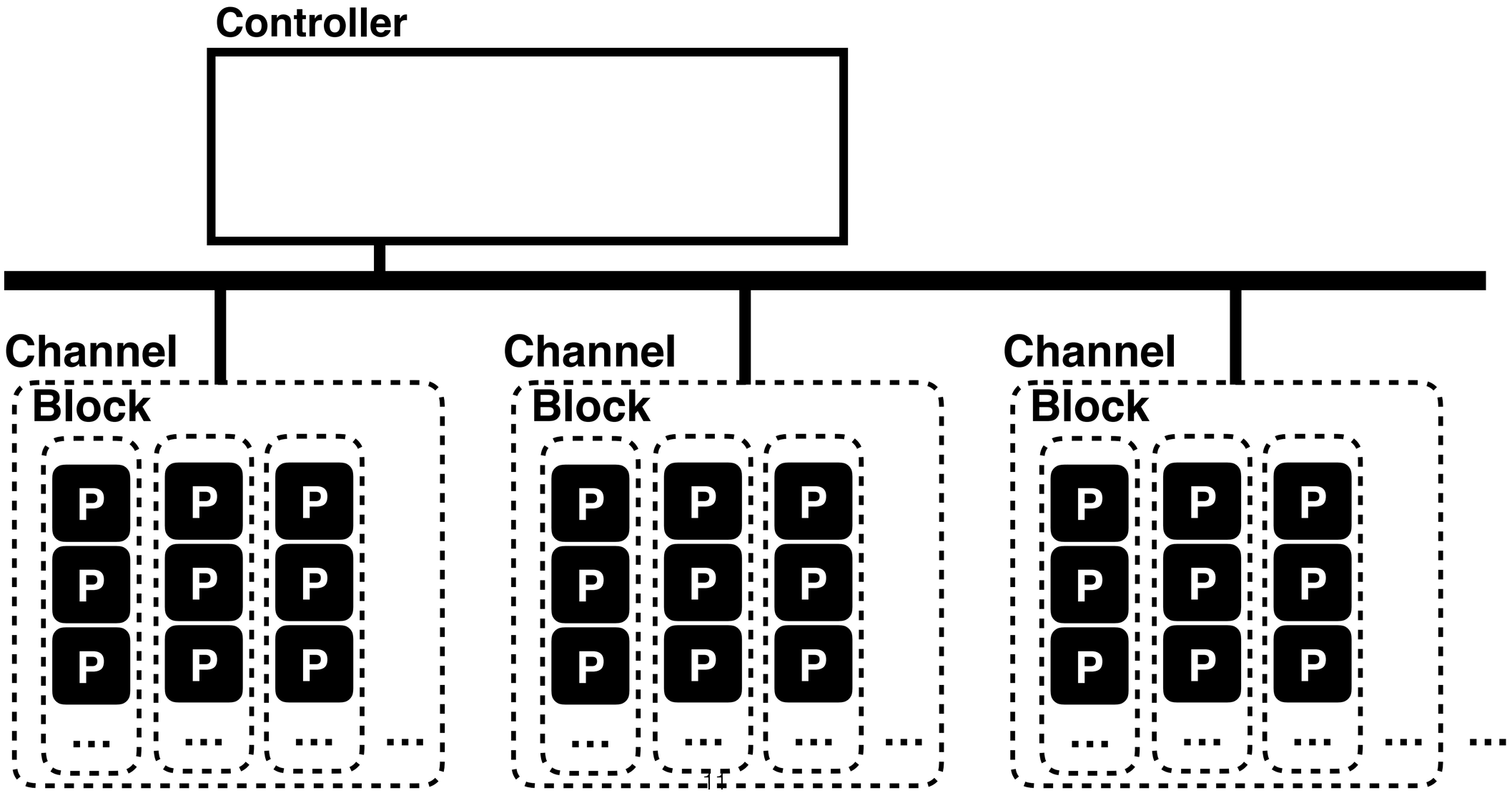

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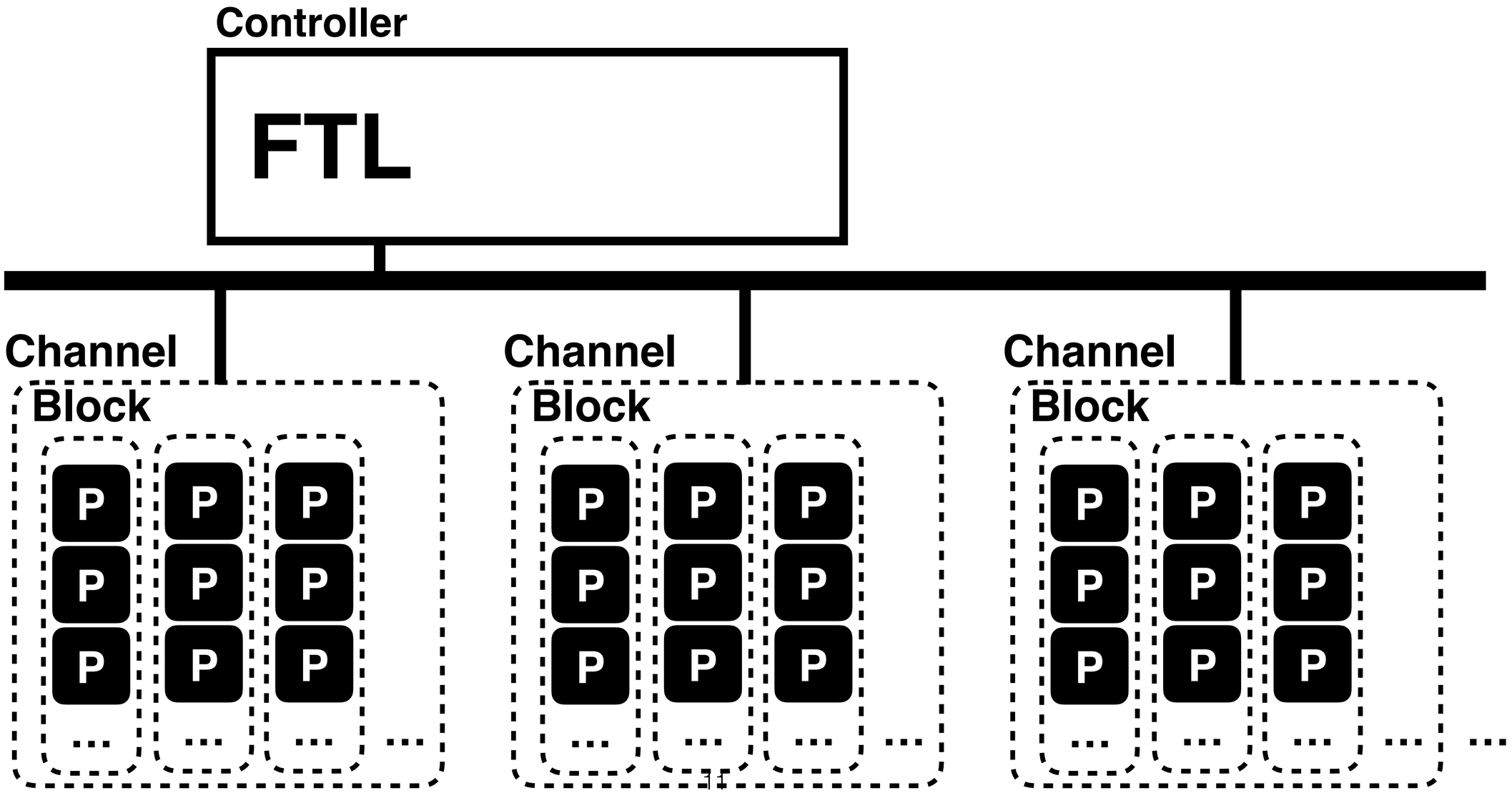

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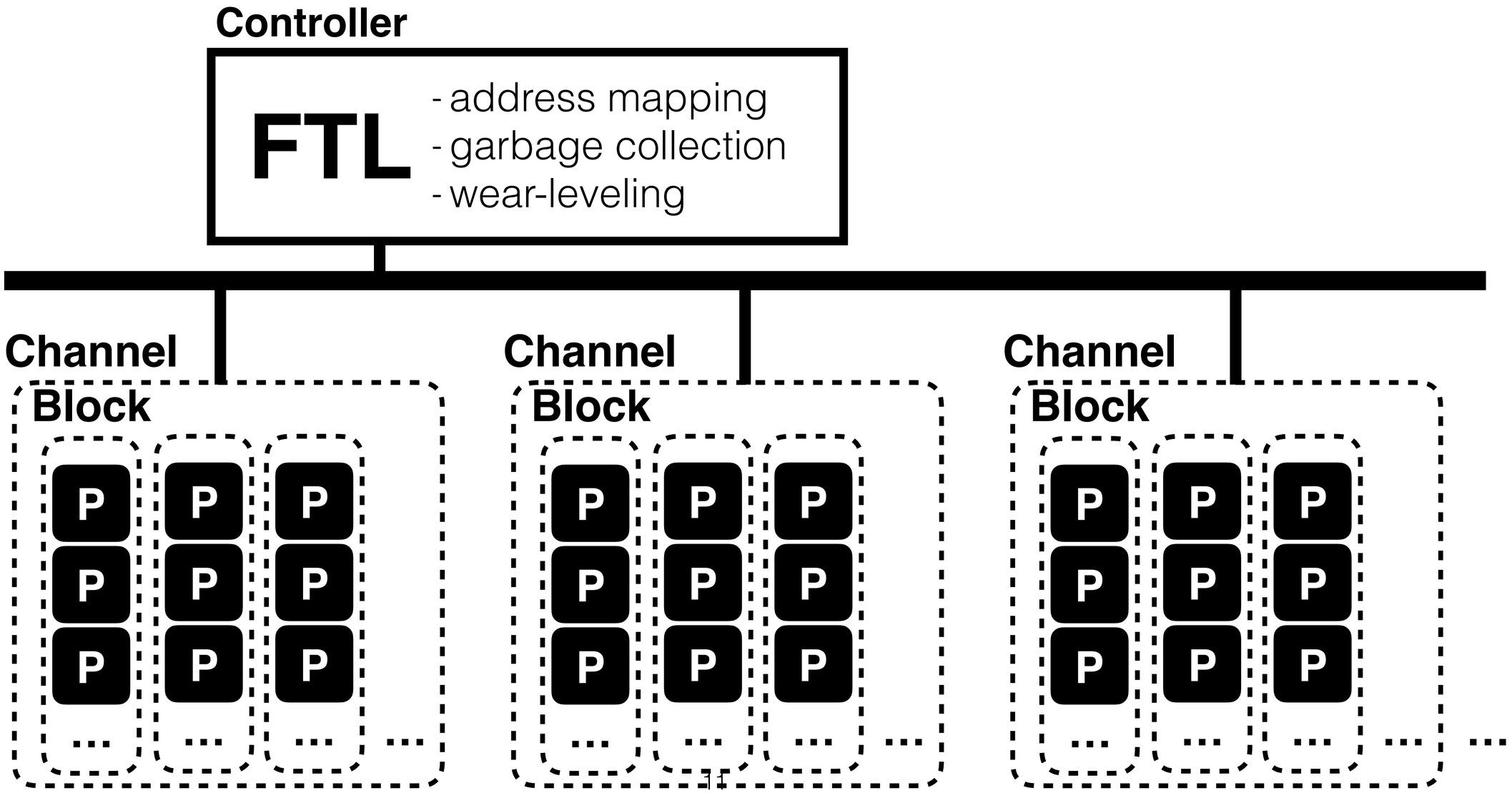

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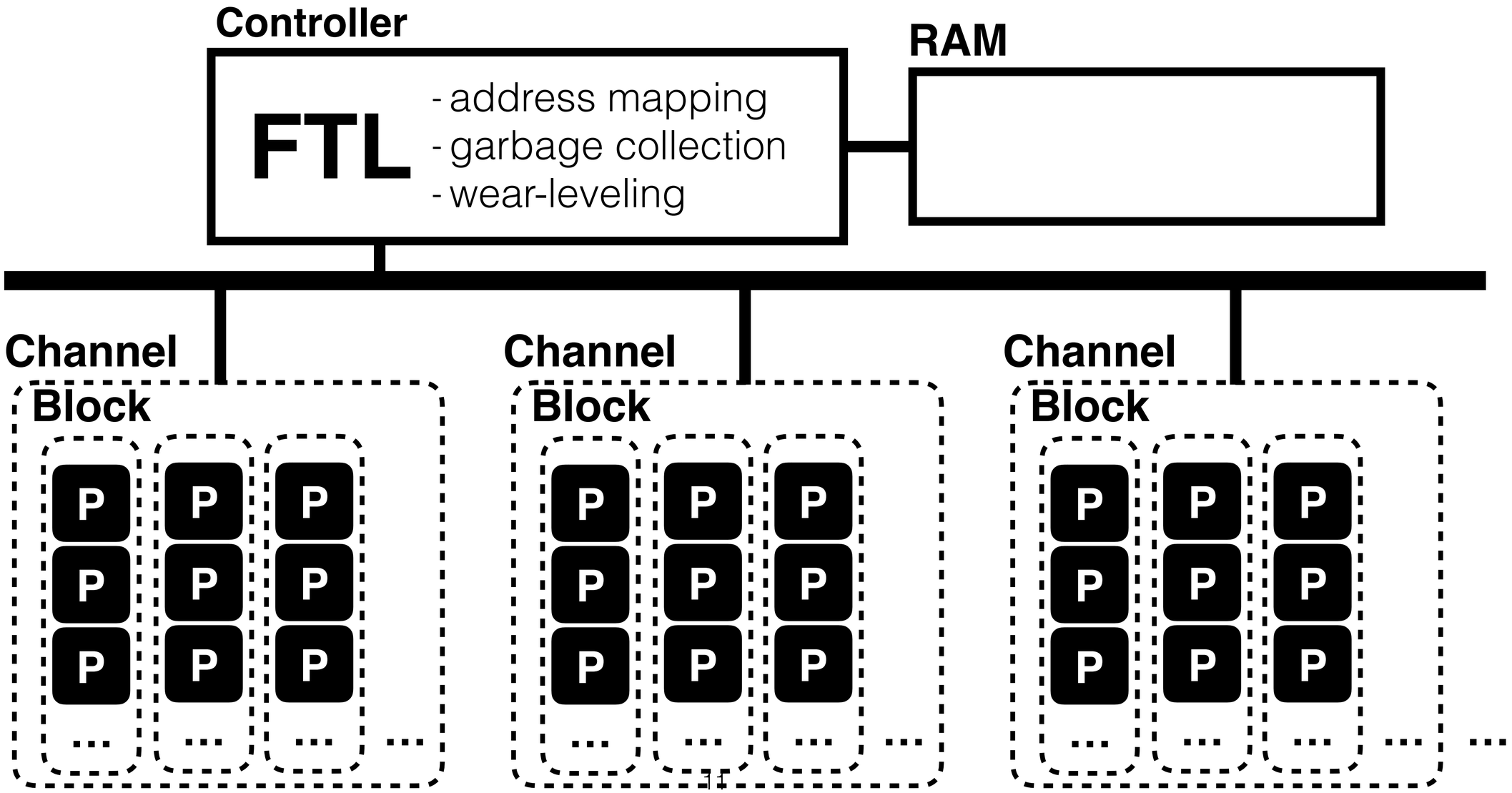

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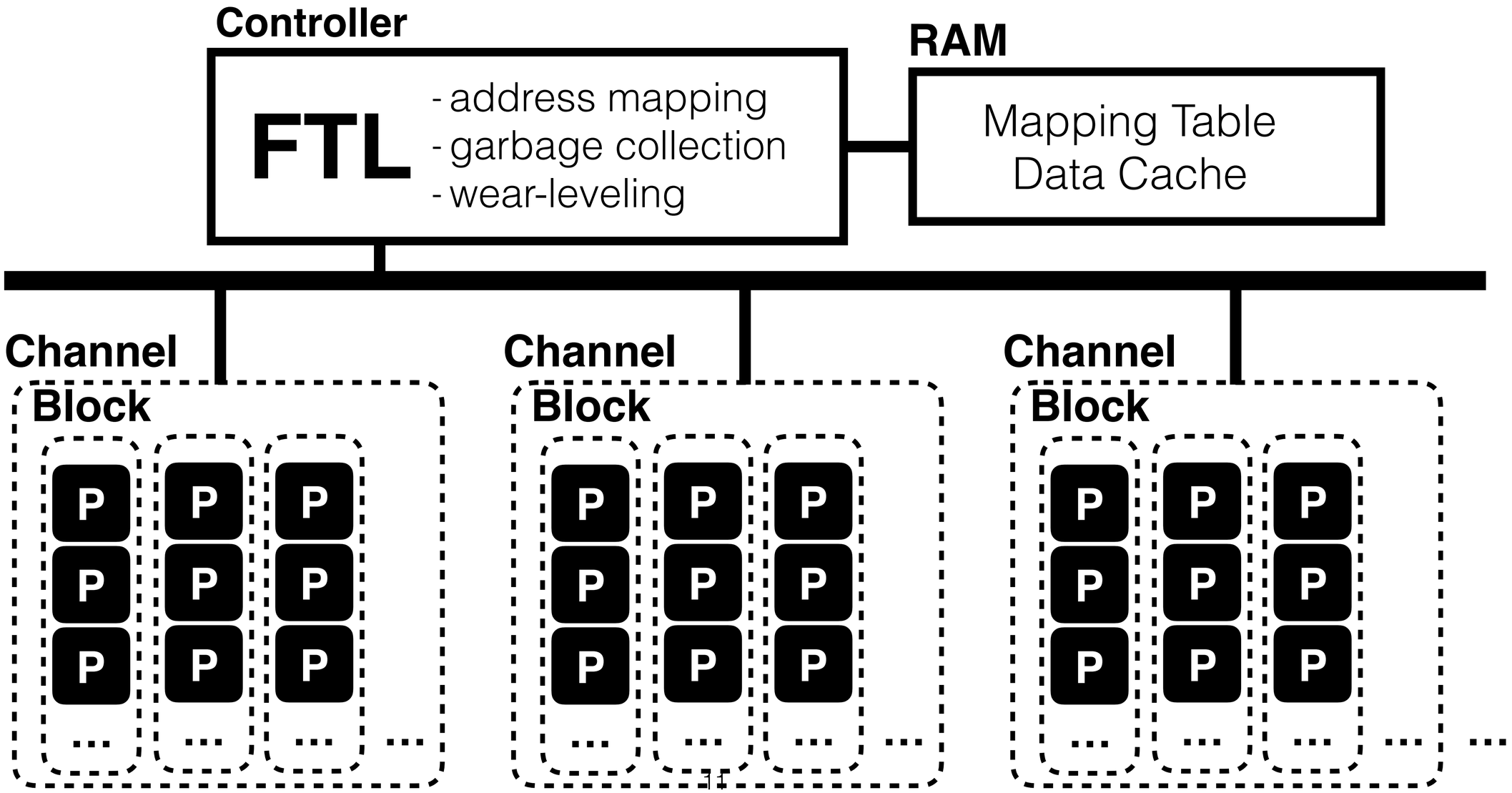

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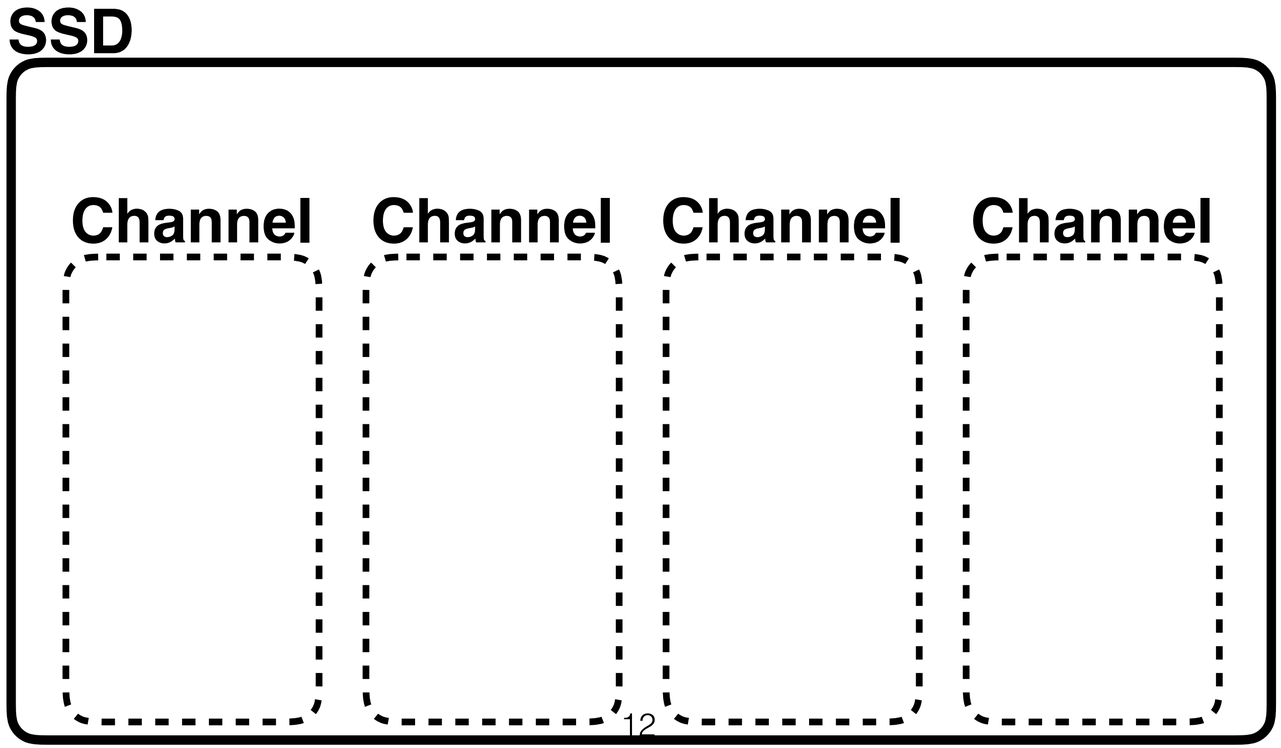

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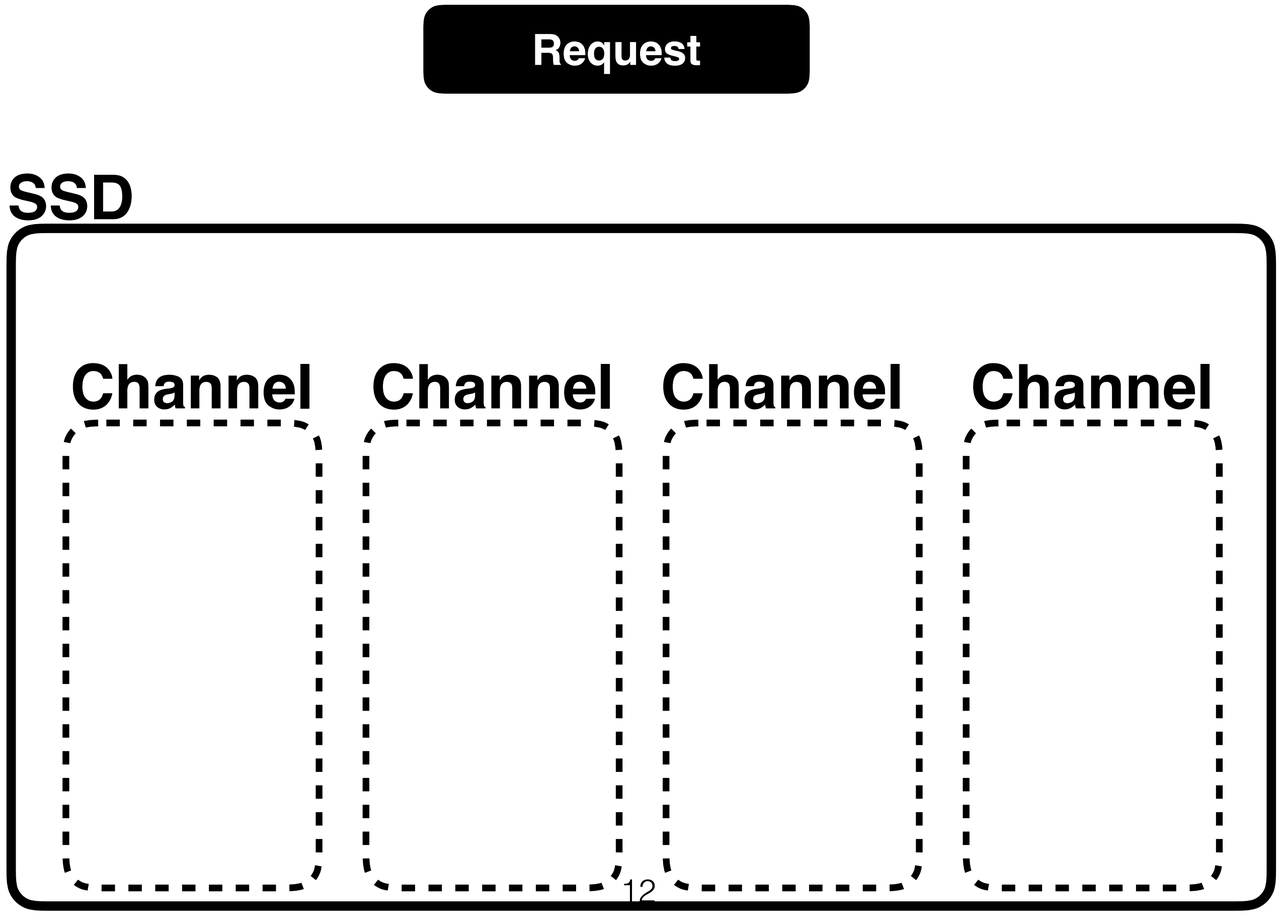

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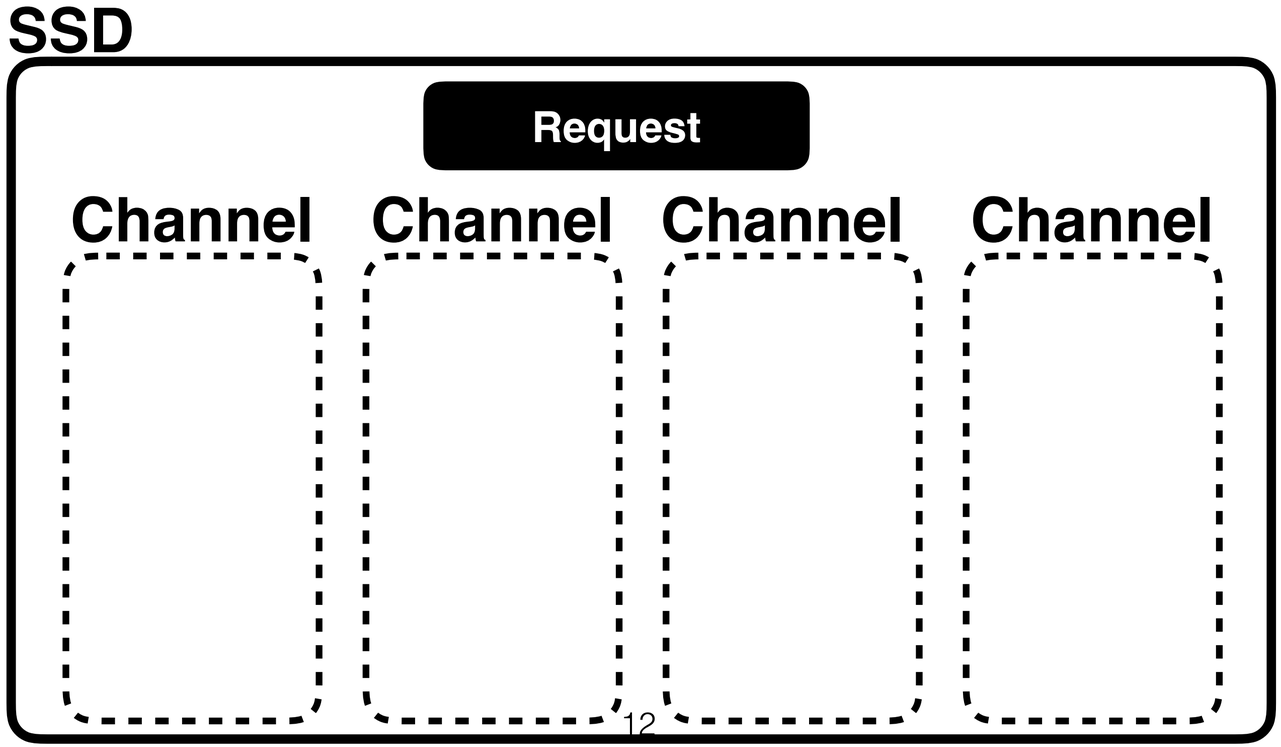

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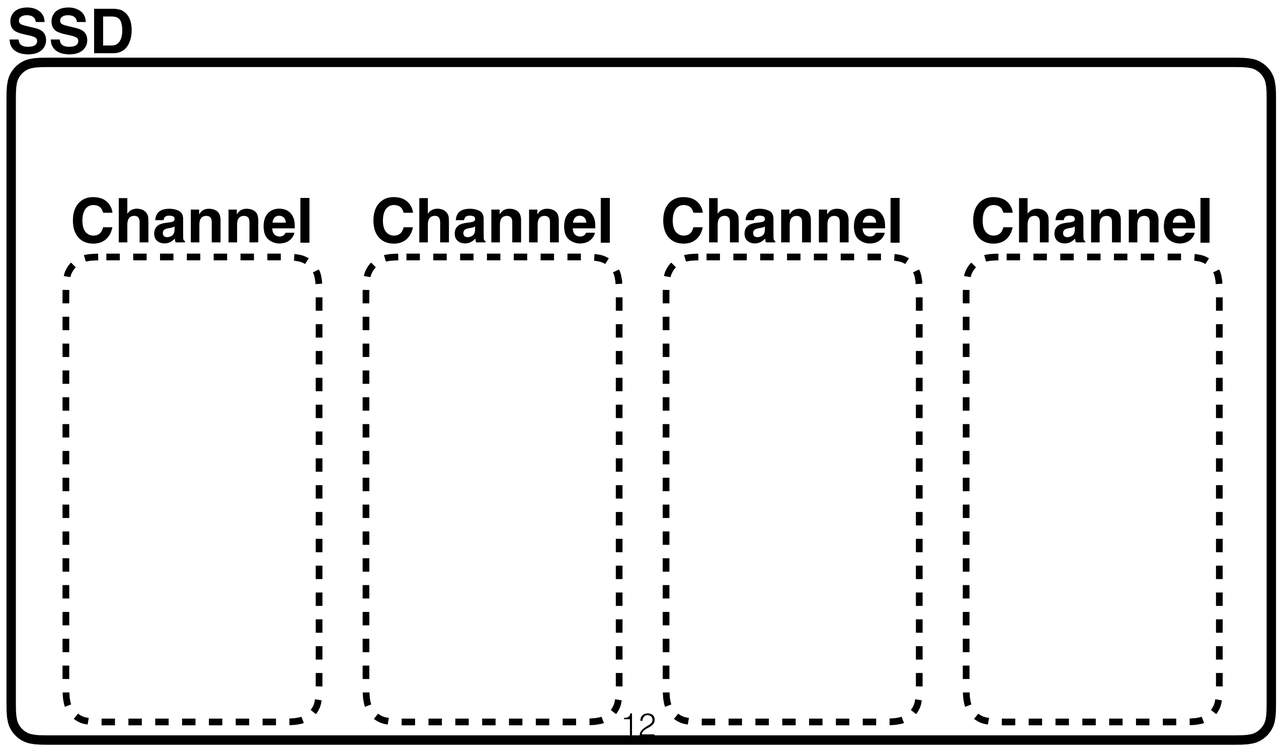

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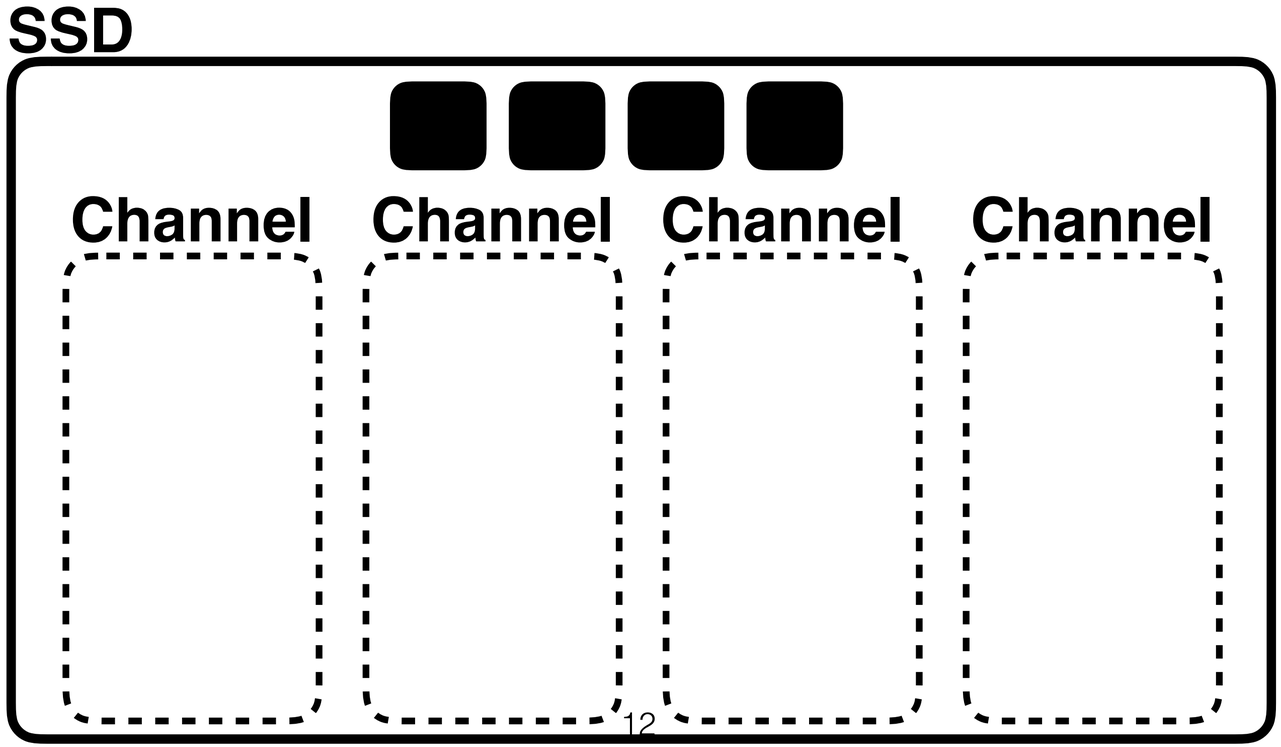

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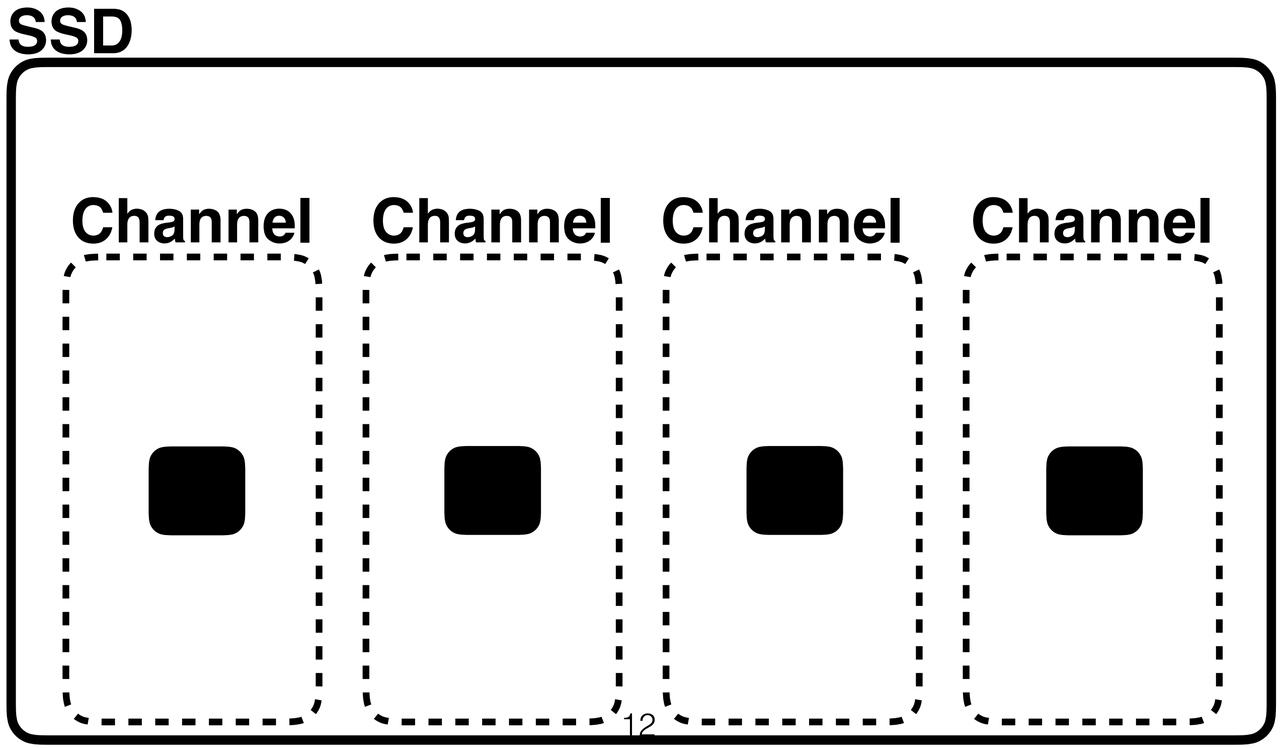

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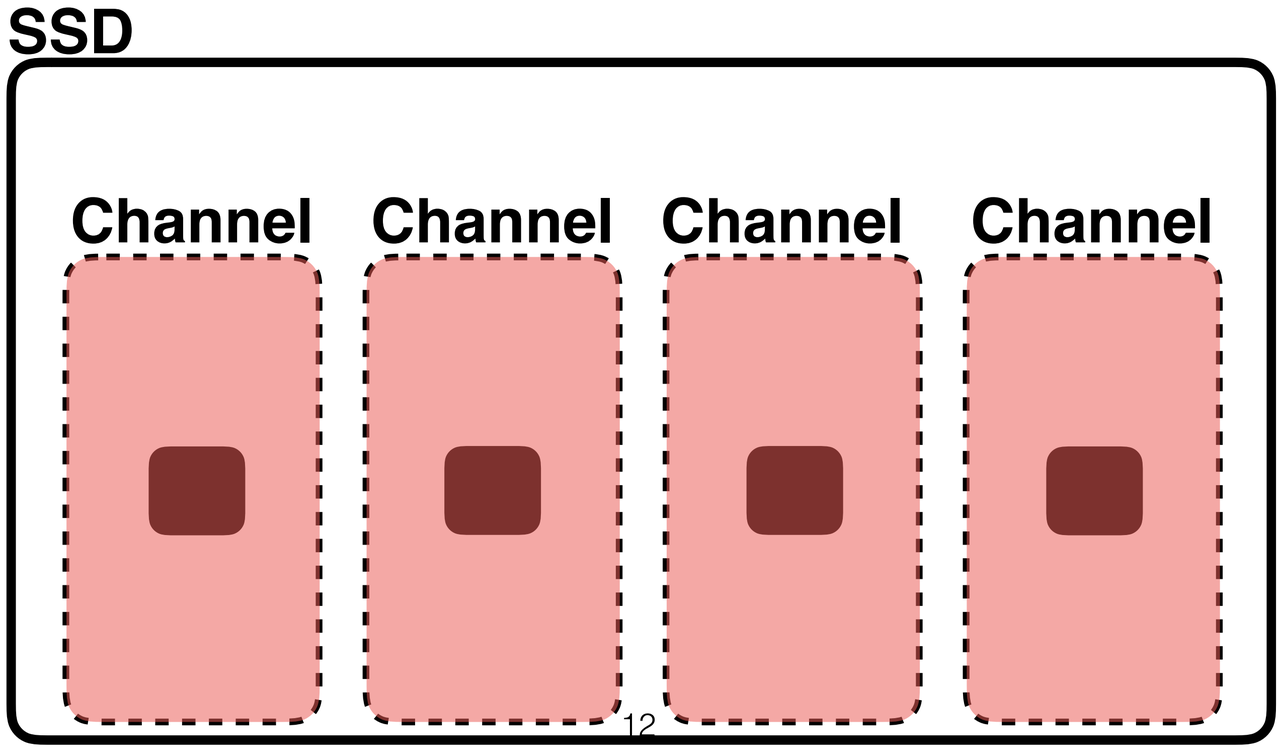

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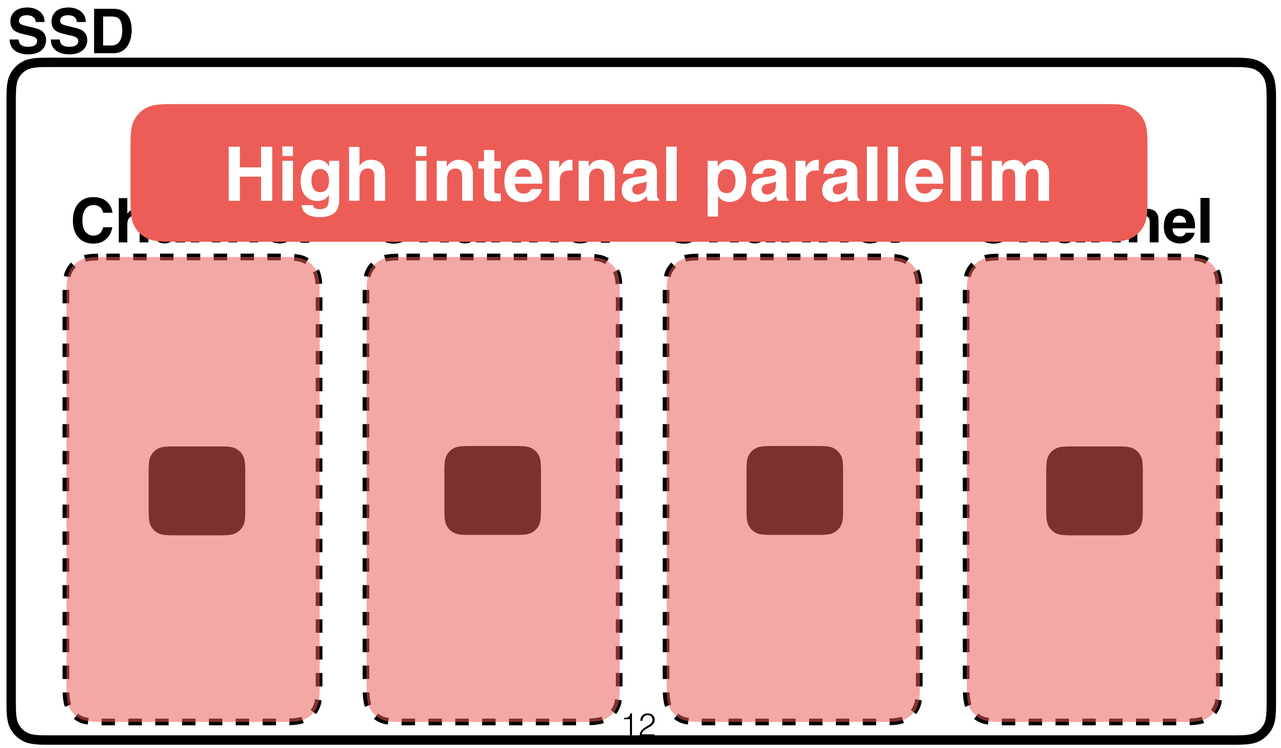

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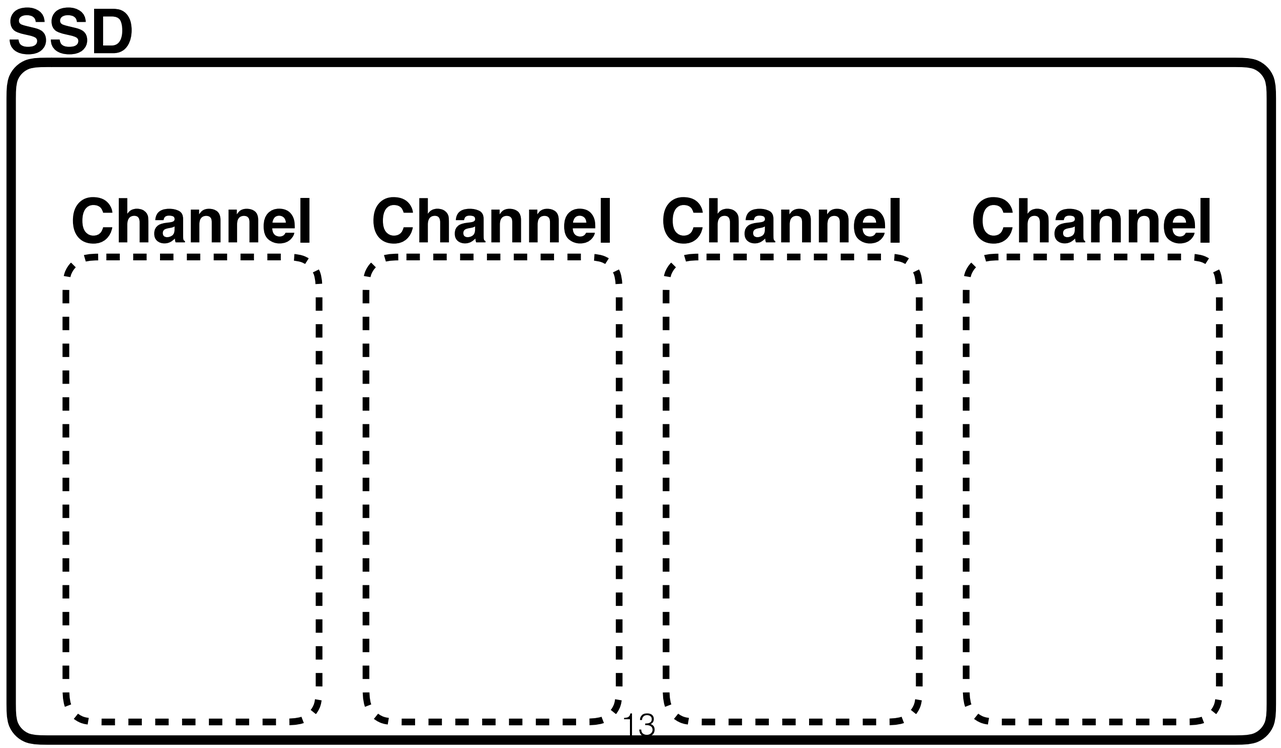
Violation

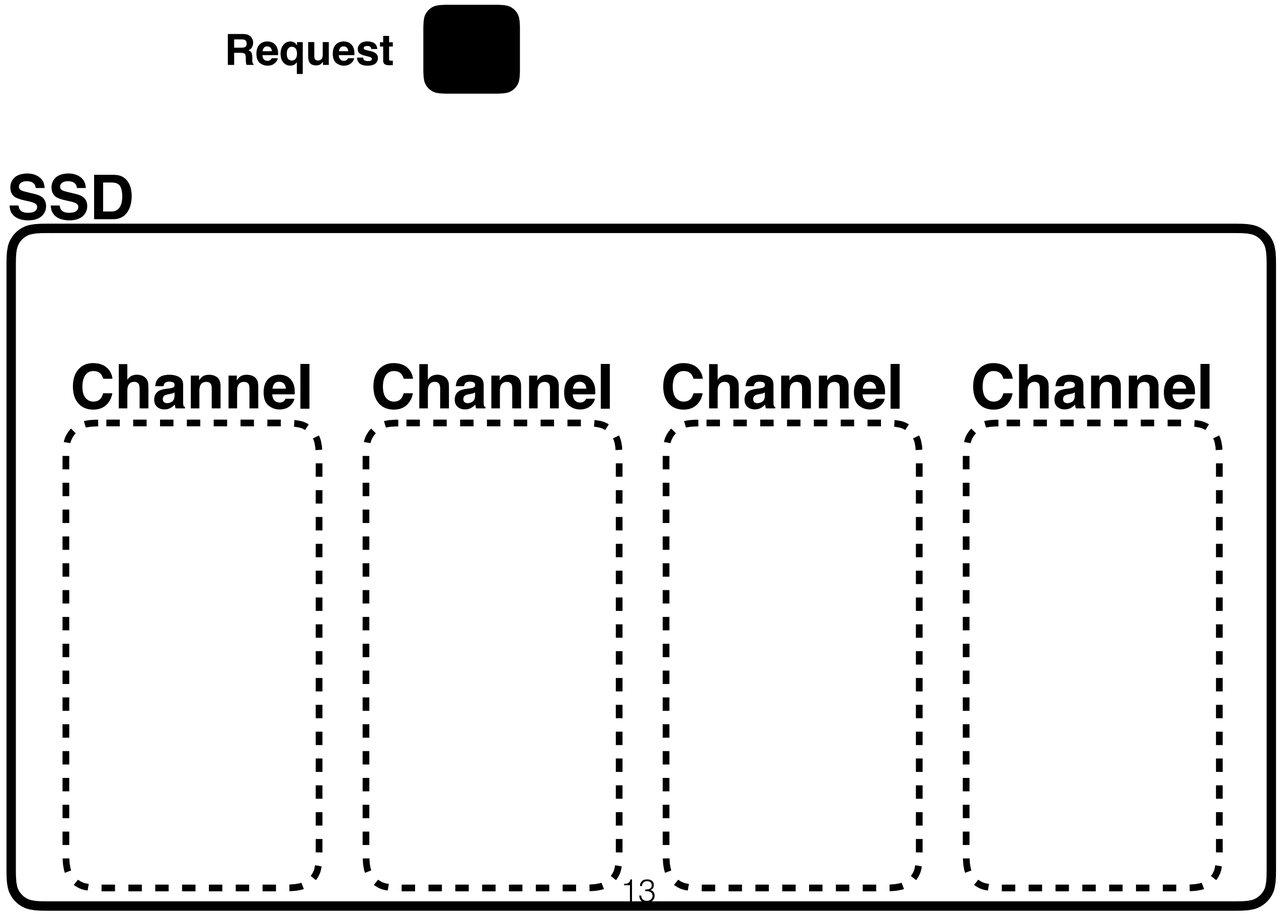
Rule #1: Request Scale

Violation



Rule #1: Request Scale

Violation



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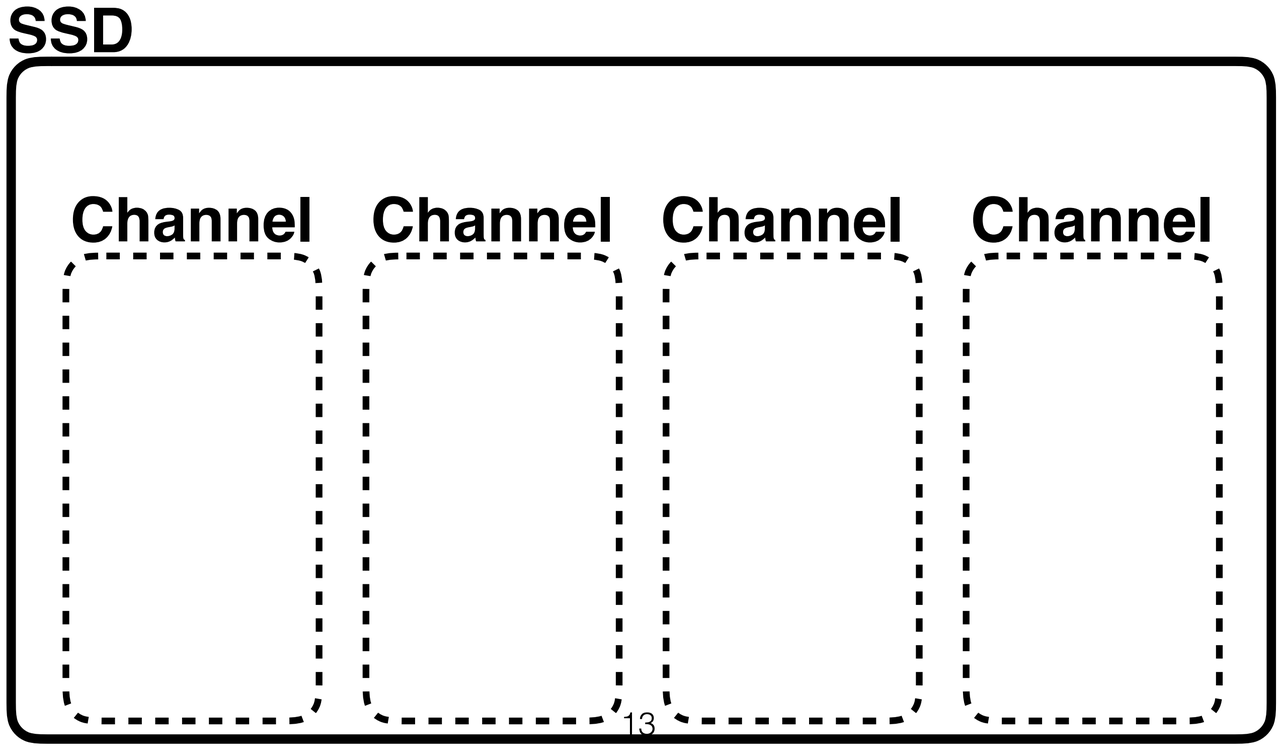
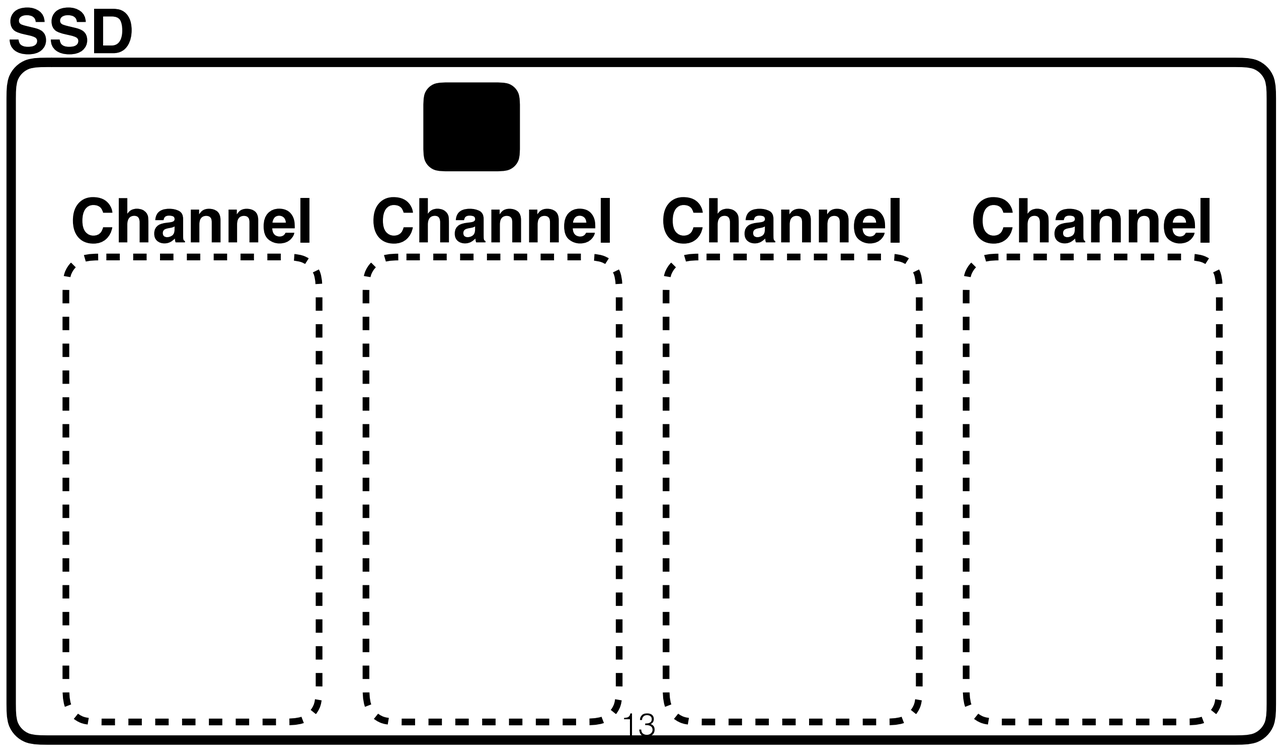


Rule #1: Request Scale

Violation



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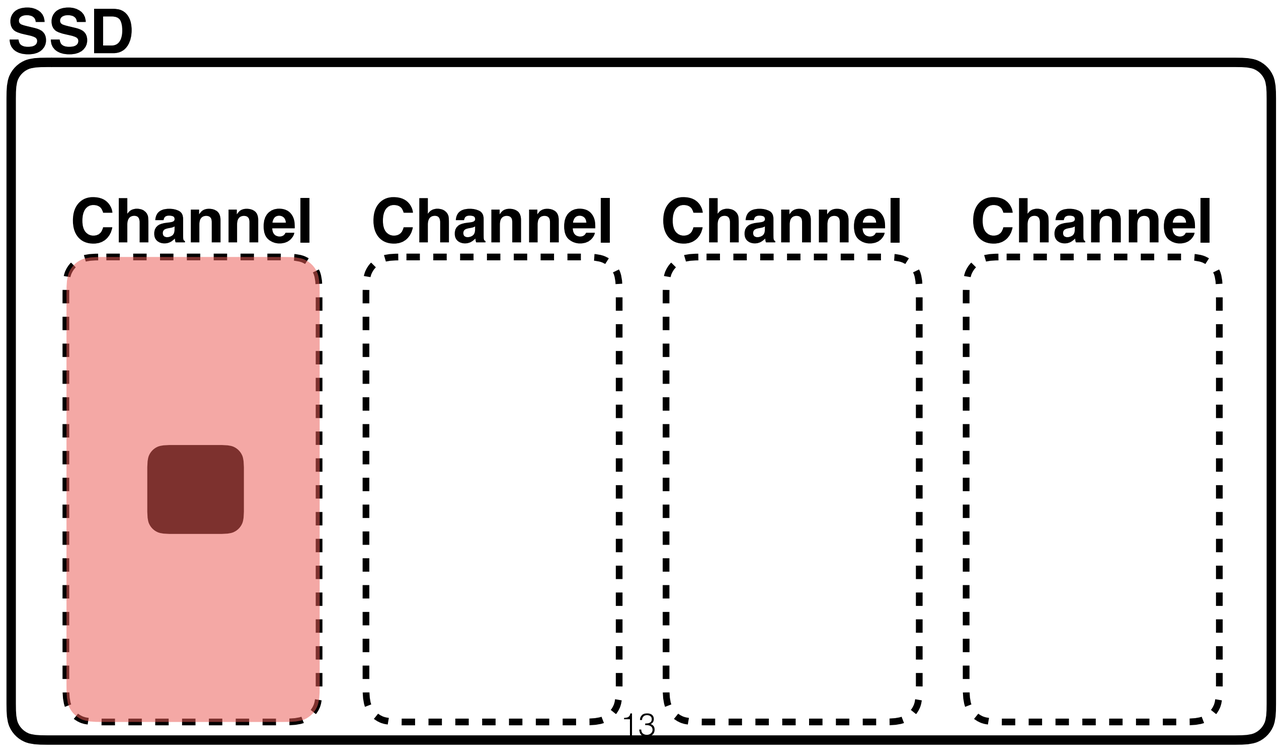
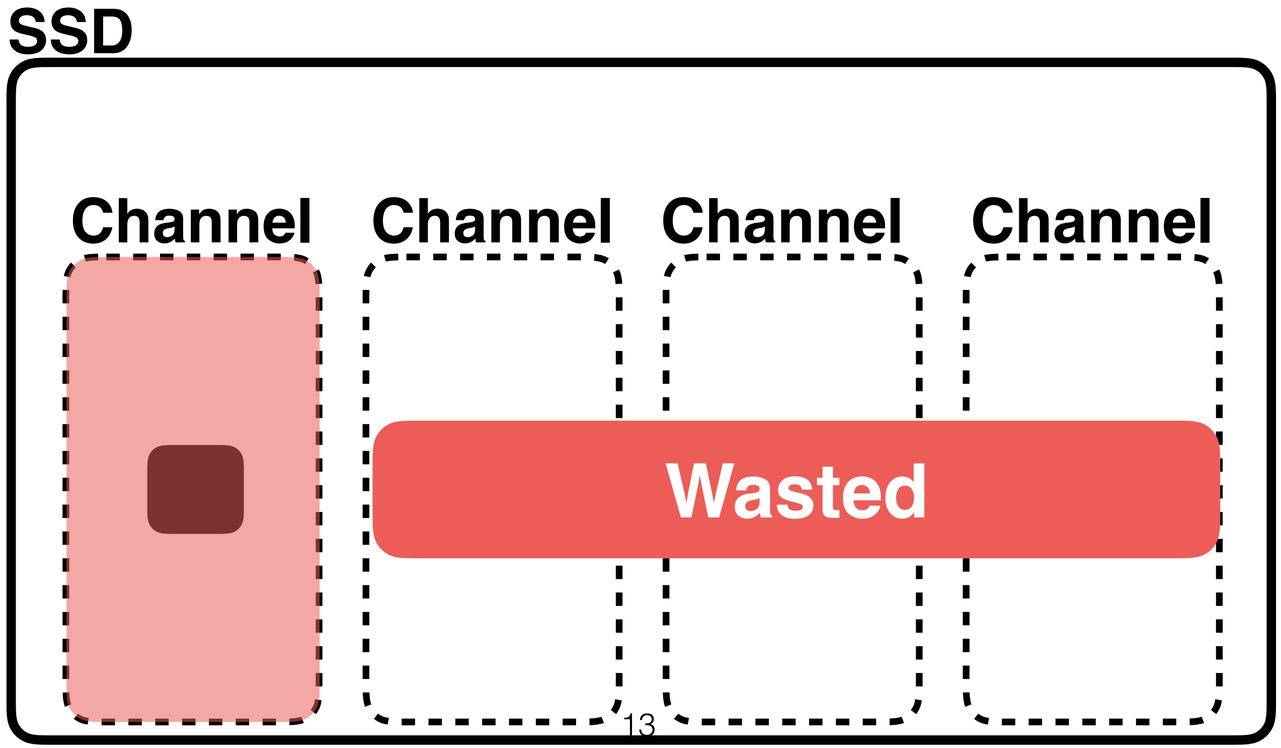
Violation



Rule #1: Request Scale

Violation

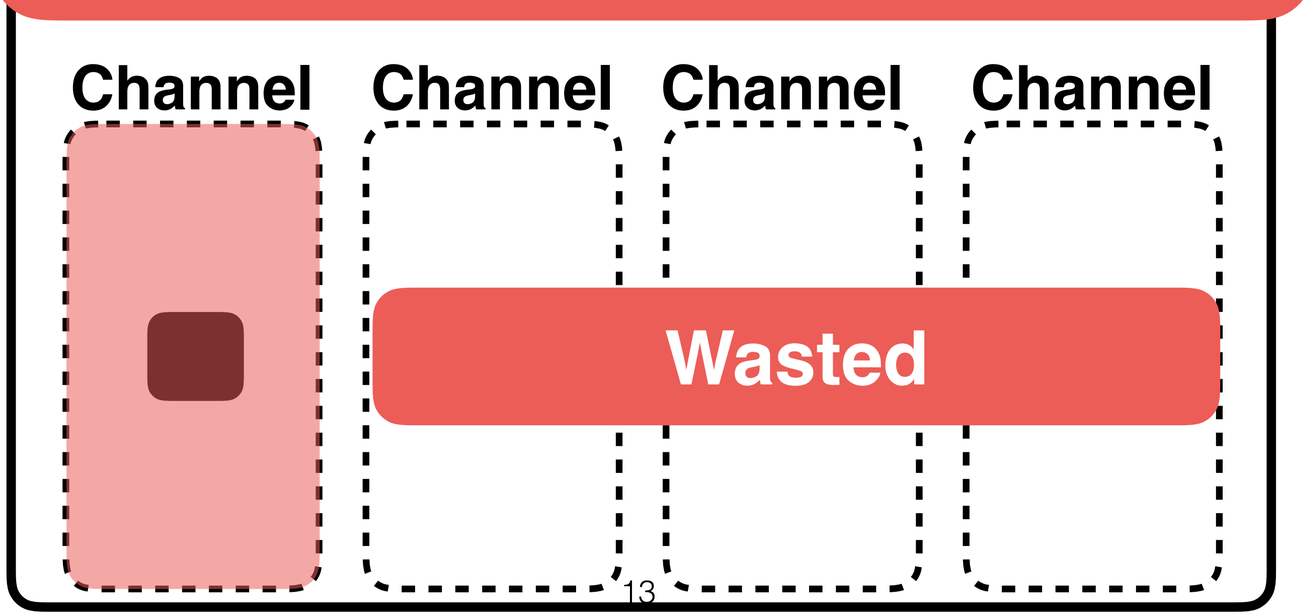


Rule #1: Request Scale

Violation

If you violate the rule:

- Low internal parallelism



Rule #1: Request Scale

Violation

If you violate the rule:

- Low internal parallelism

Performance impact:

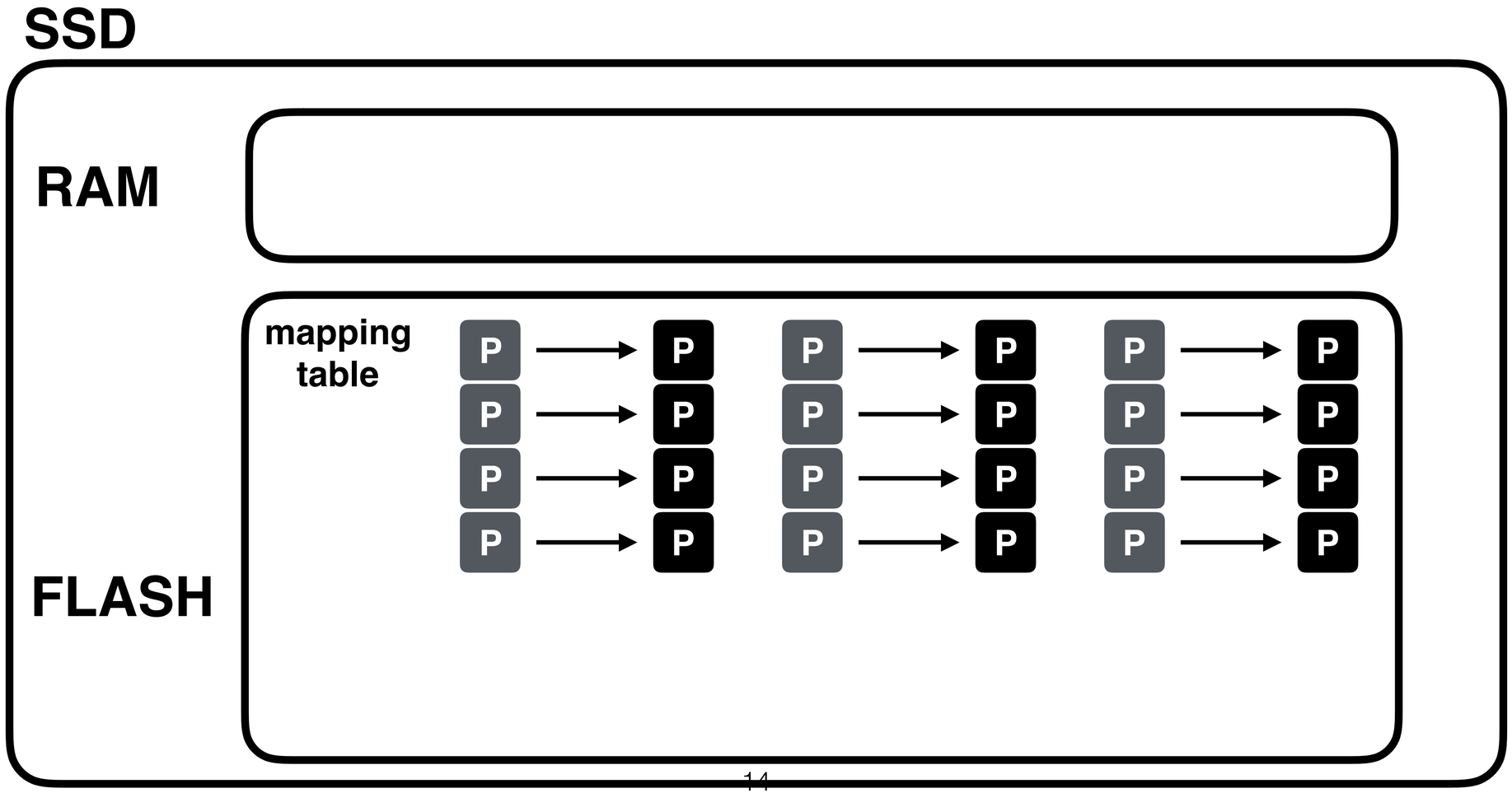
18x read bandwidth

10x write bandwidth

F. Chen, R. Lee, and X. Zhang. Essential Roles of Exploit- ing Internal Parallelism of Flash Memory Based Solid State Drives in High-speed Data Processing. In Proceedings of the 17th International Symposium on High Performance Com- puter Architecture (HPCA-11), pages 266–277, San Antonio, Texas, February 2011.

Rule 2: Locality

SSD clients should access with locality



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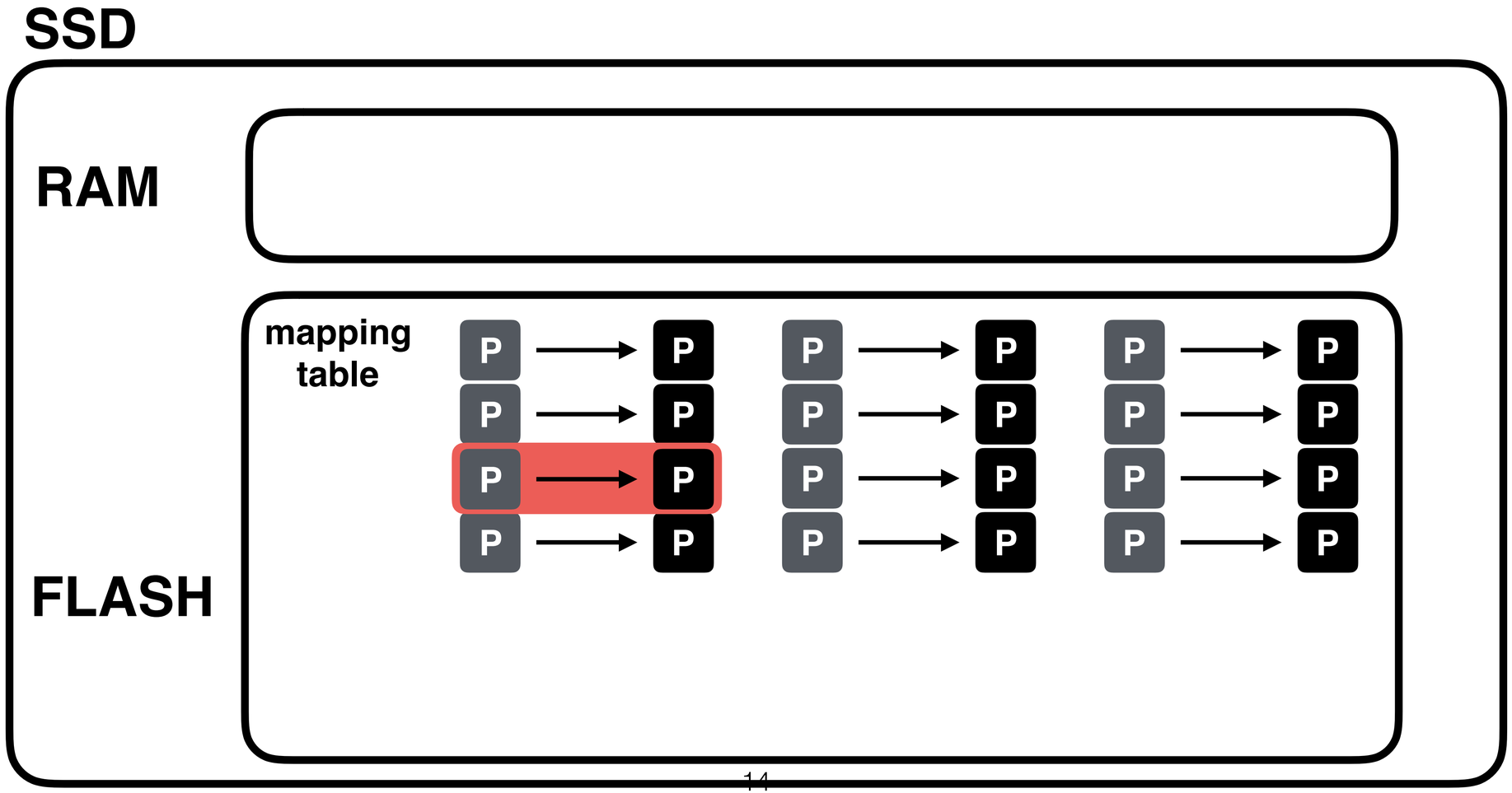

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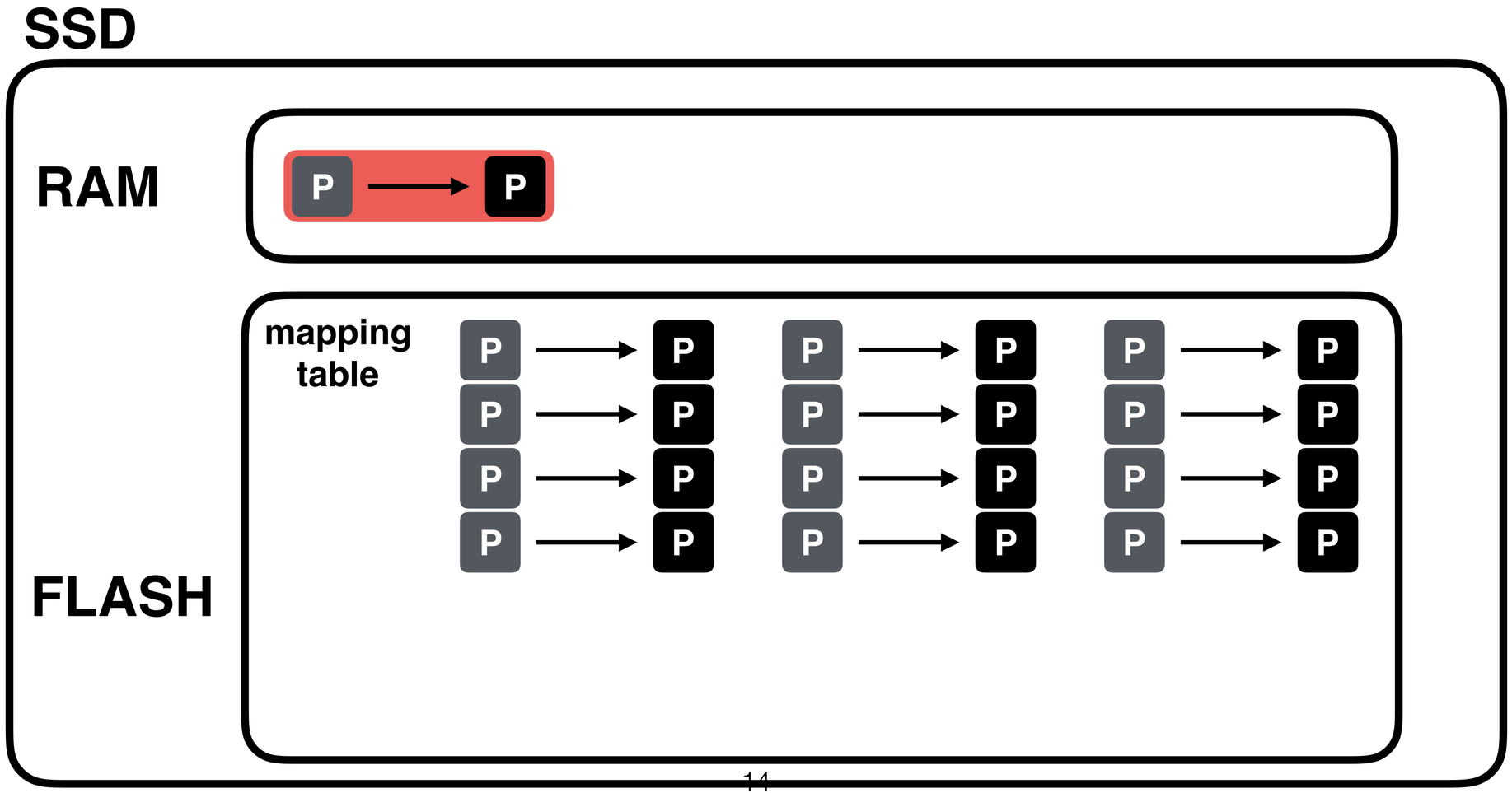

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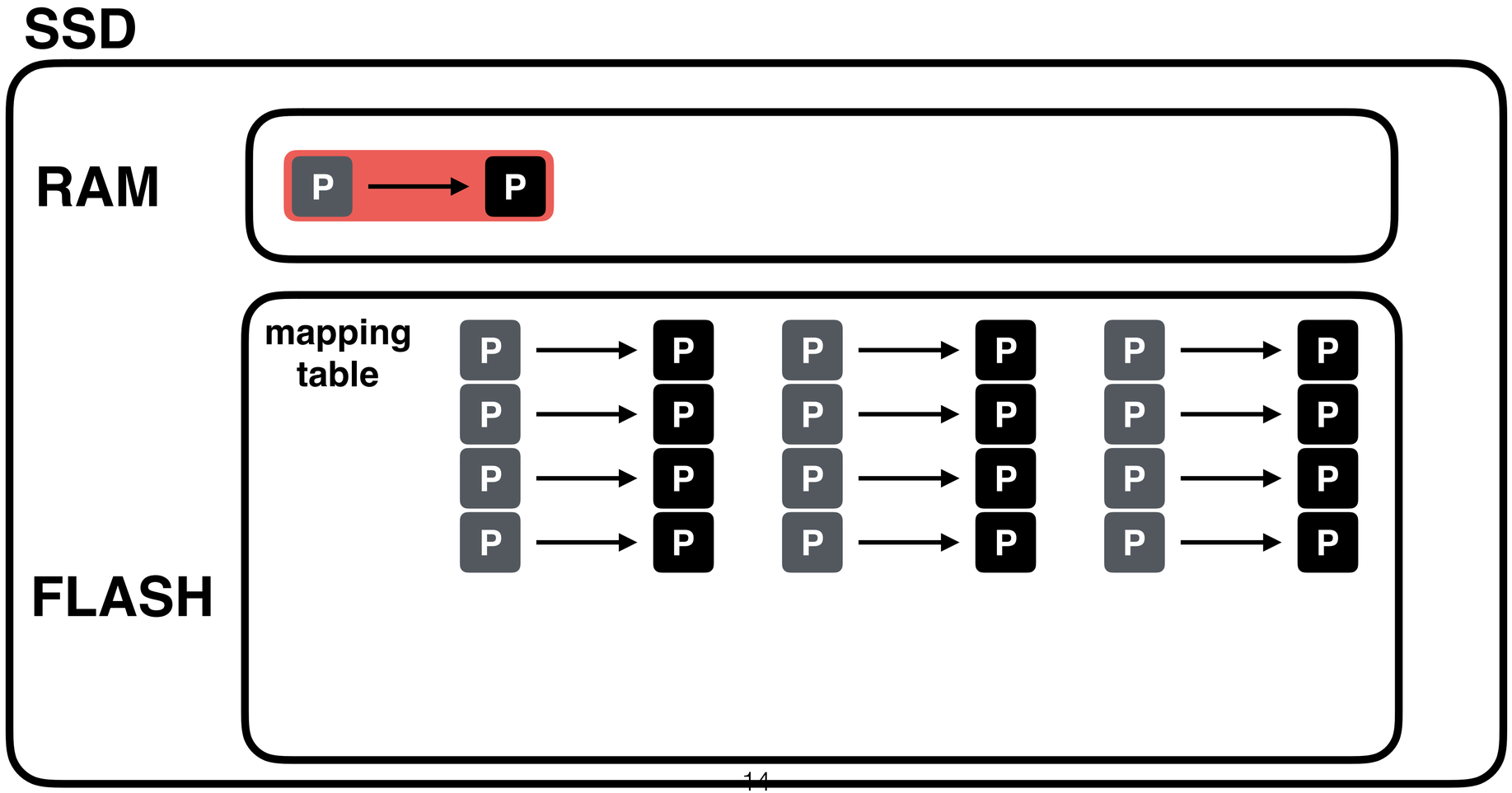

Rule 2: Locality Violation

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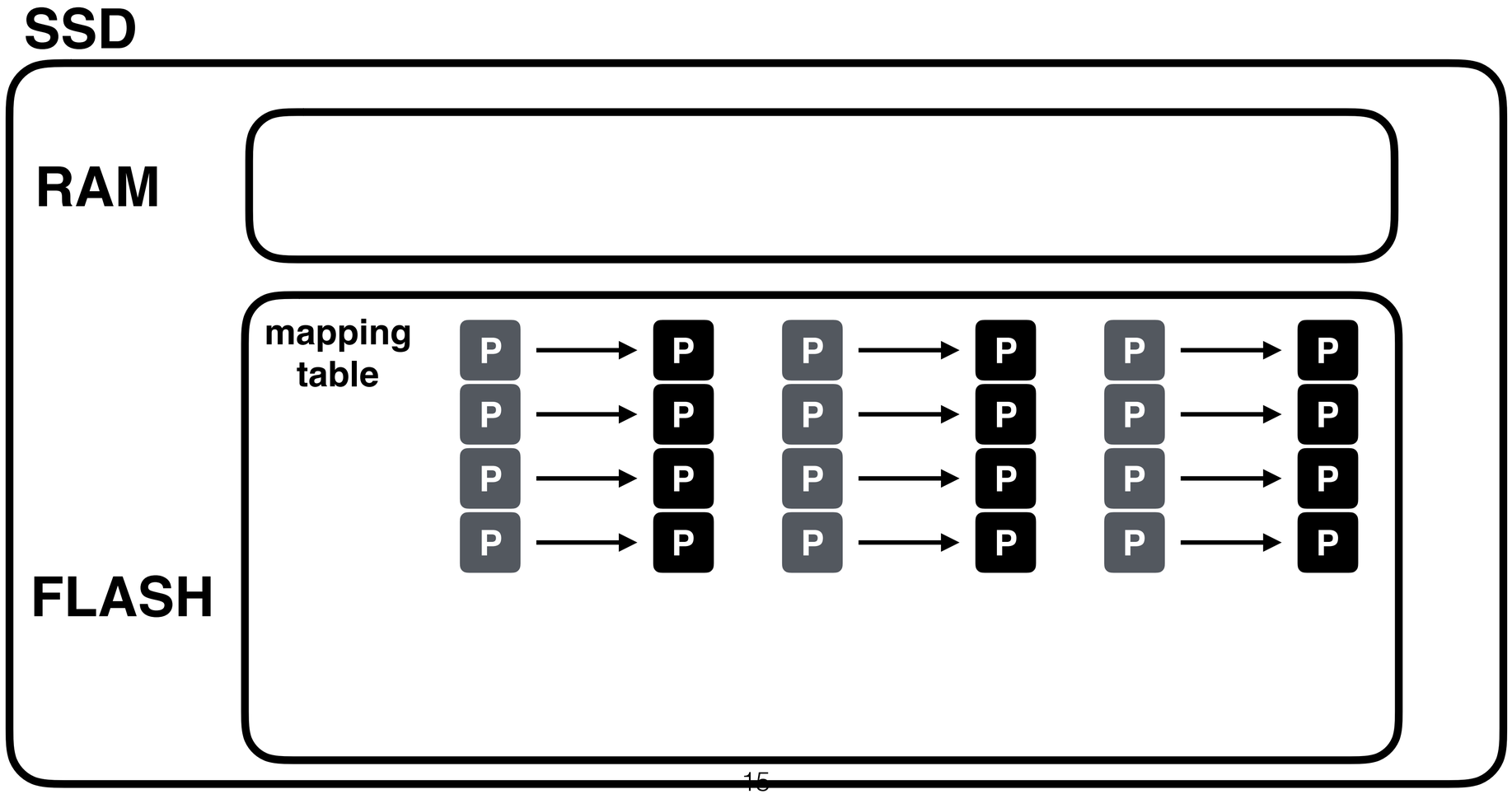

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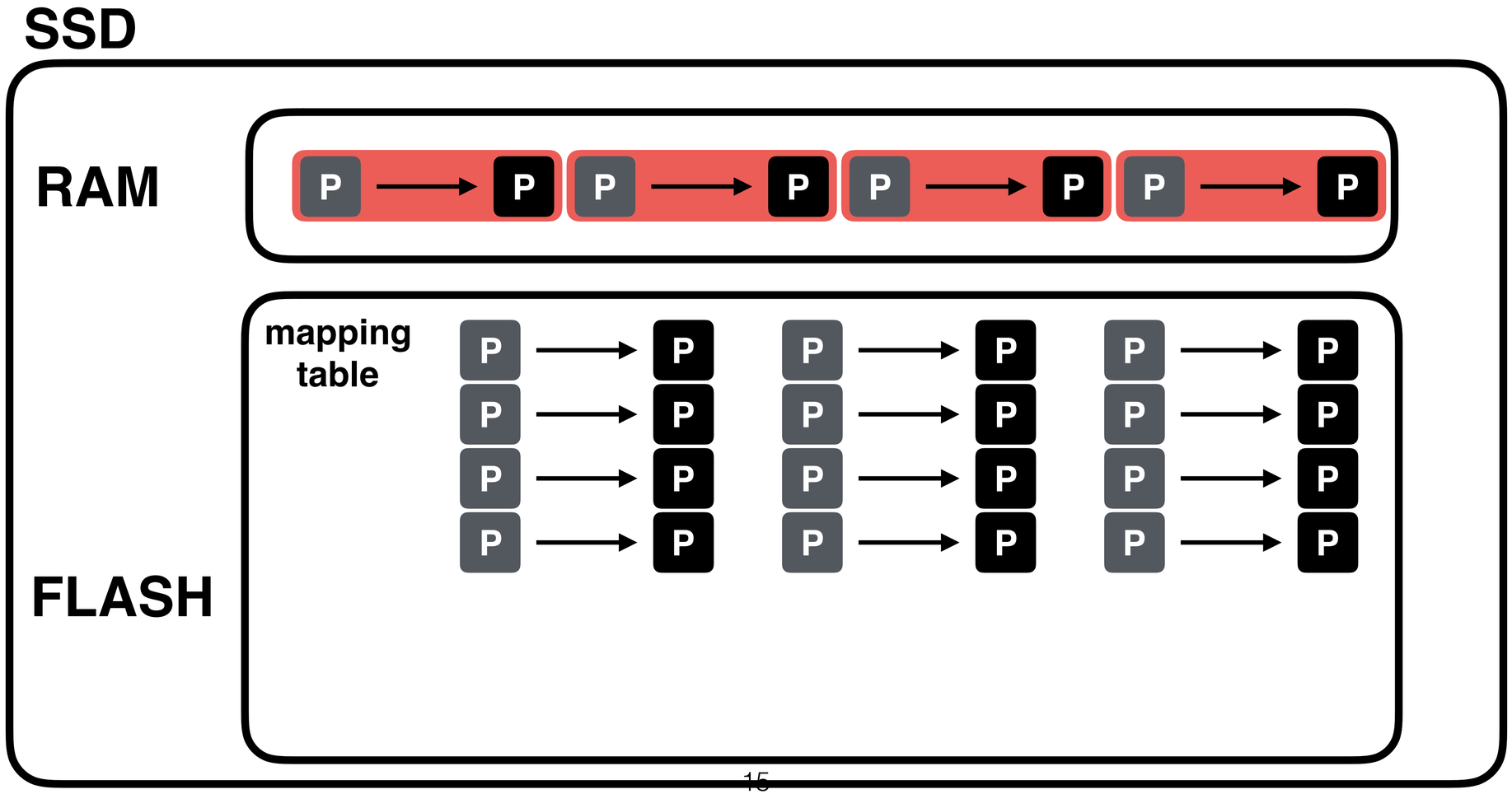

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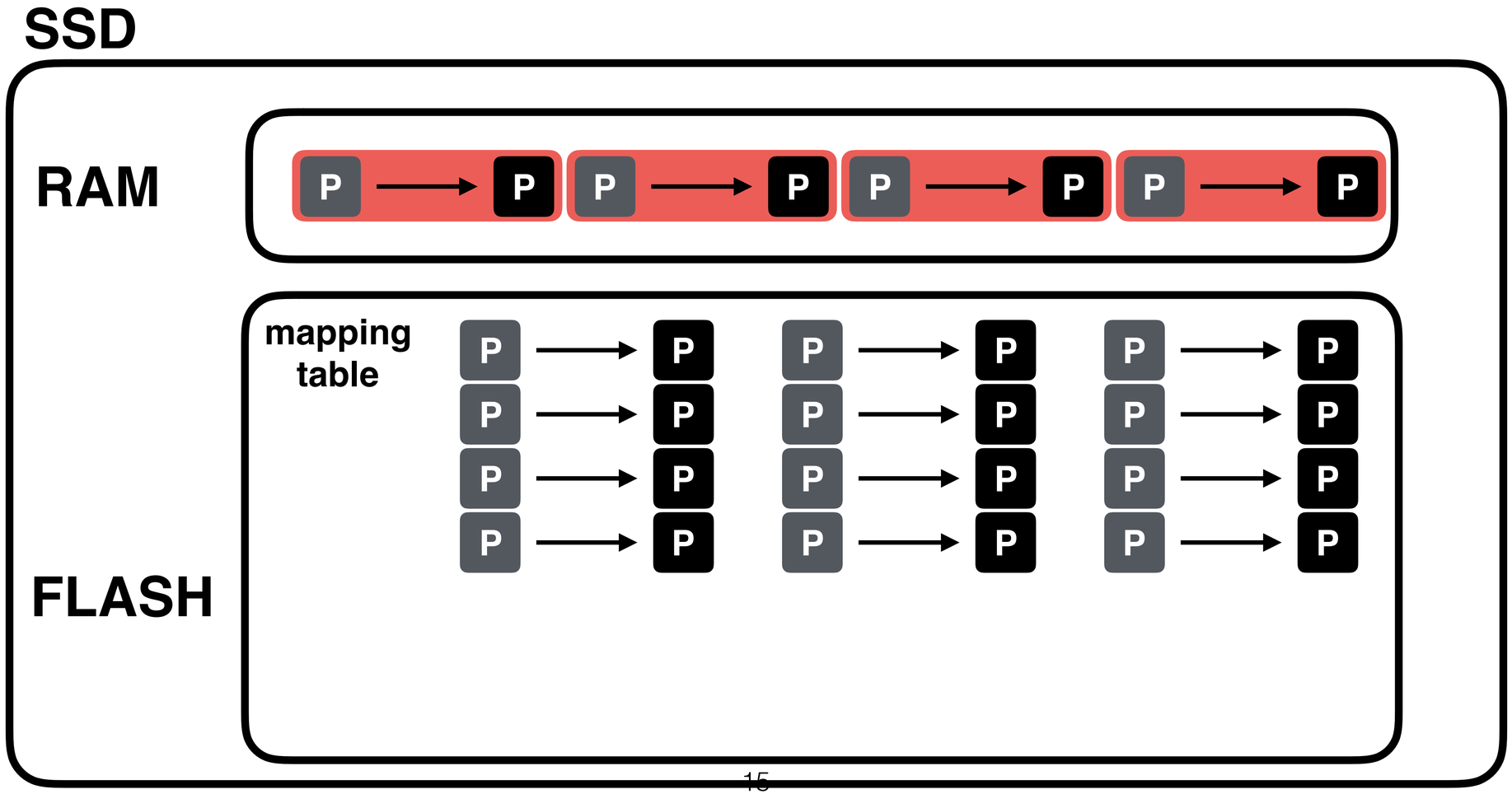

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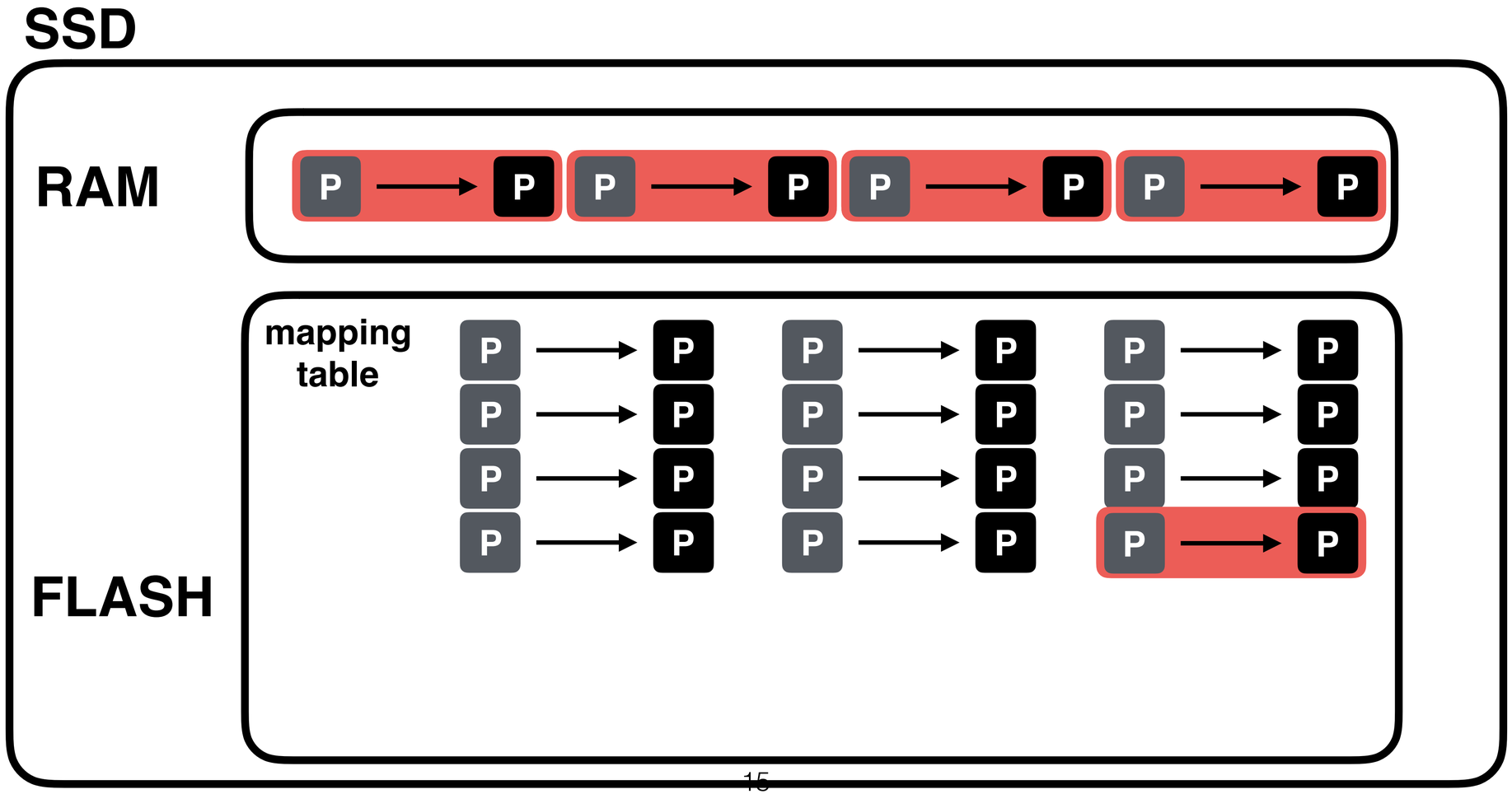

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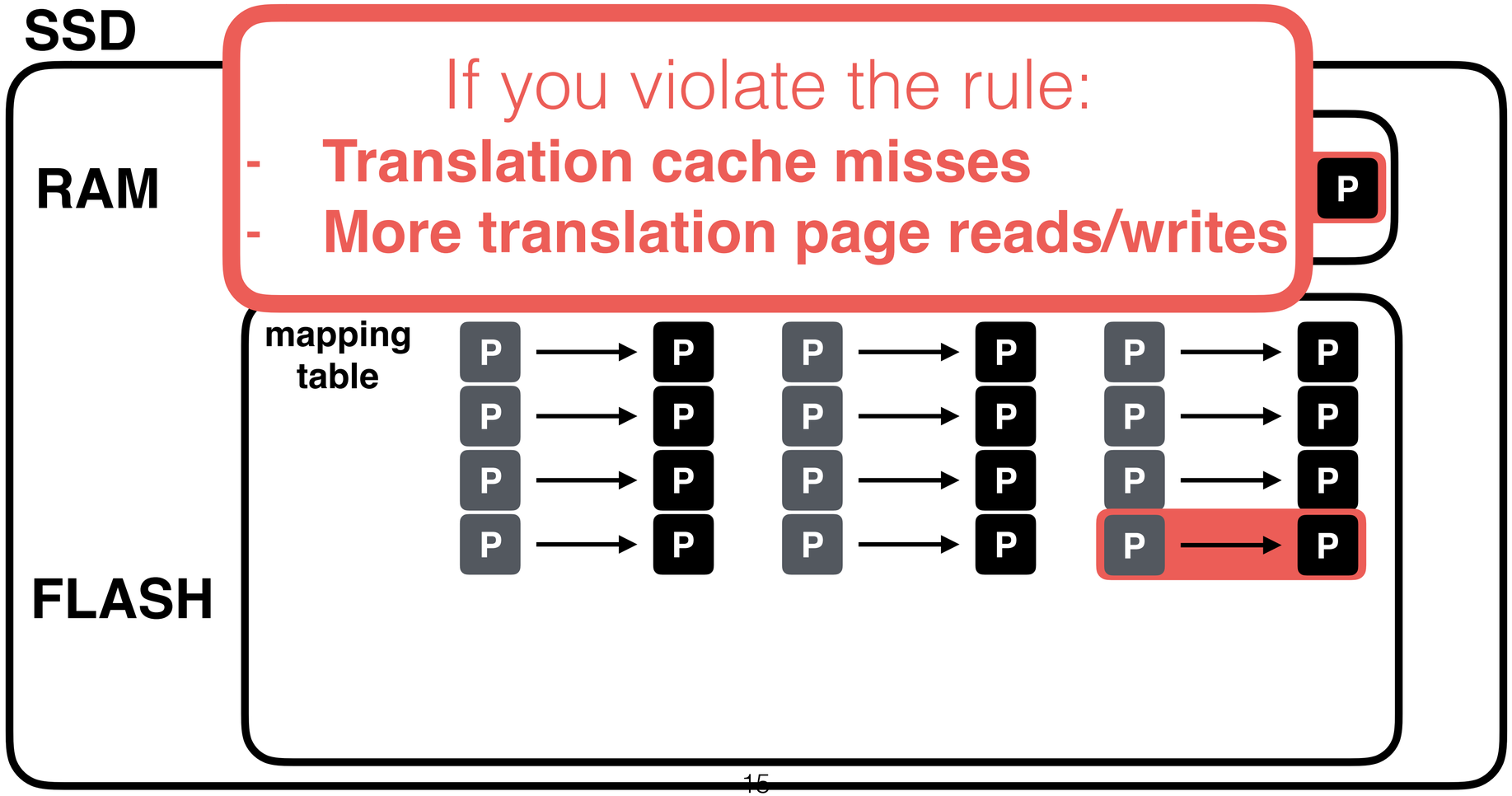

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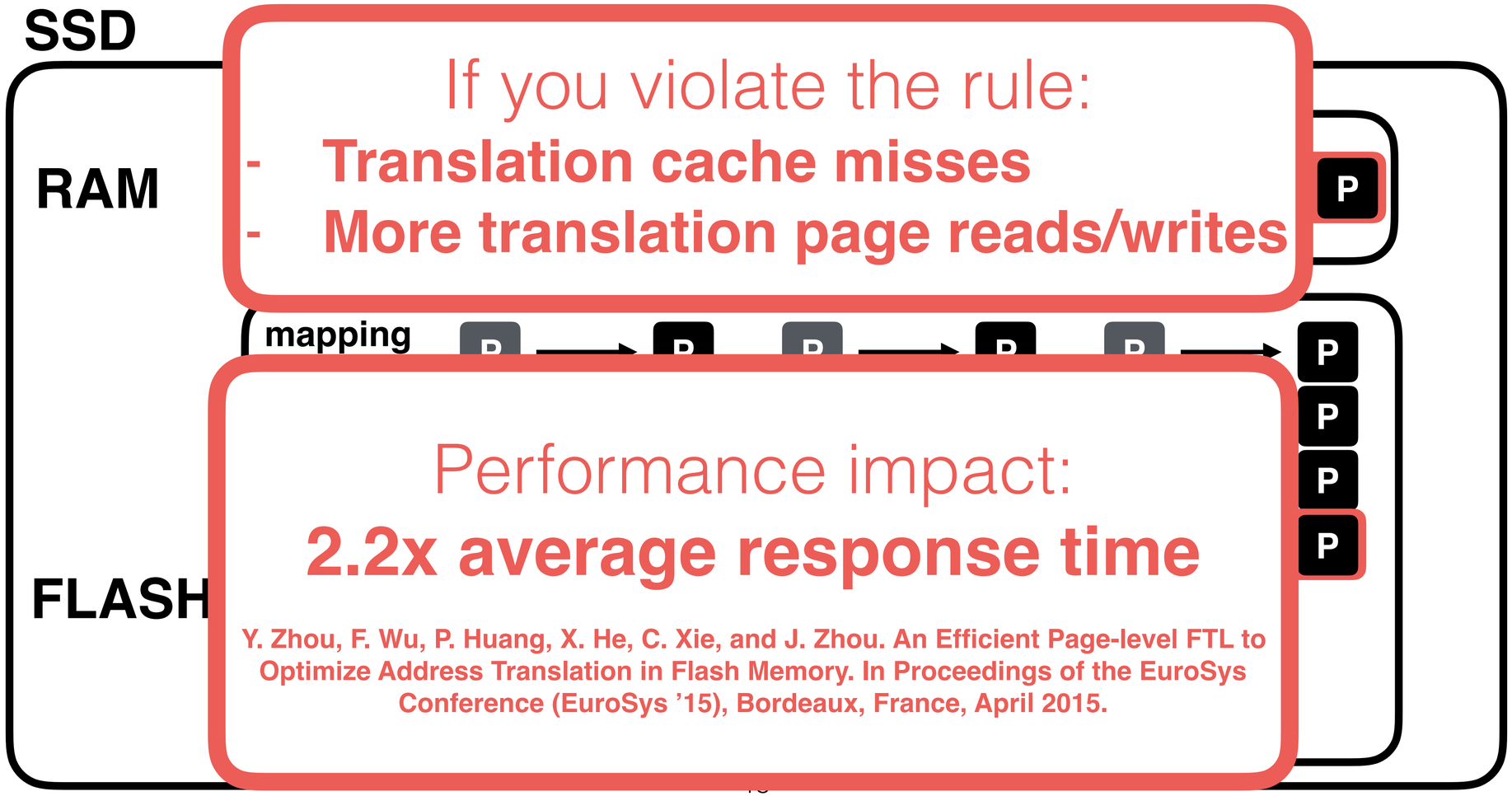

Rule 3: Aligned Sequentiality

1. Start writing at block boundary

2. Write sequentially

RAM

Page-leveling mapping
e.g., one entry covers 4KB

Block-leveling mapping
e.g., one entry covers 1MB

Rule 3: Aligned Sequentiality

1. Start writing at block boundary

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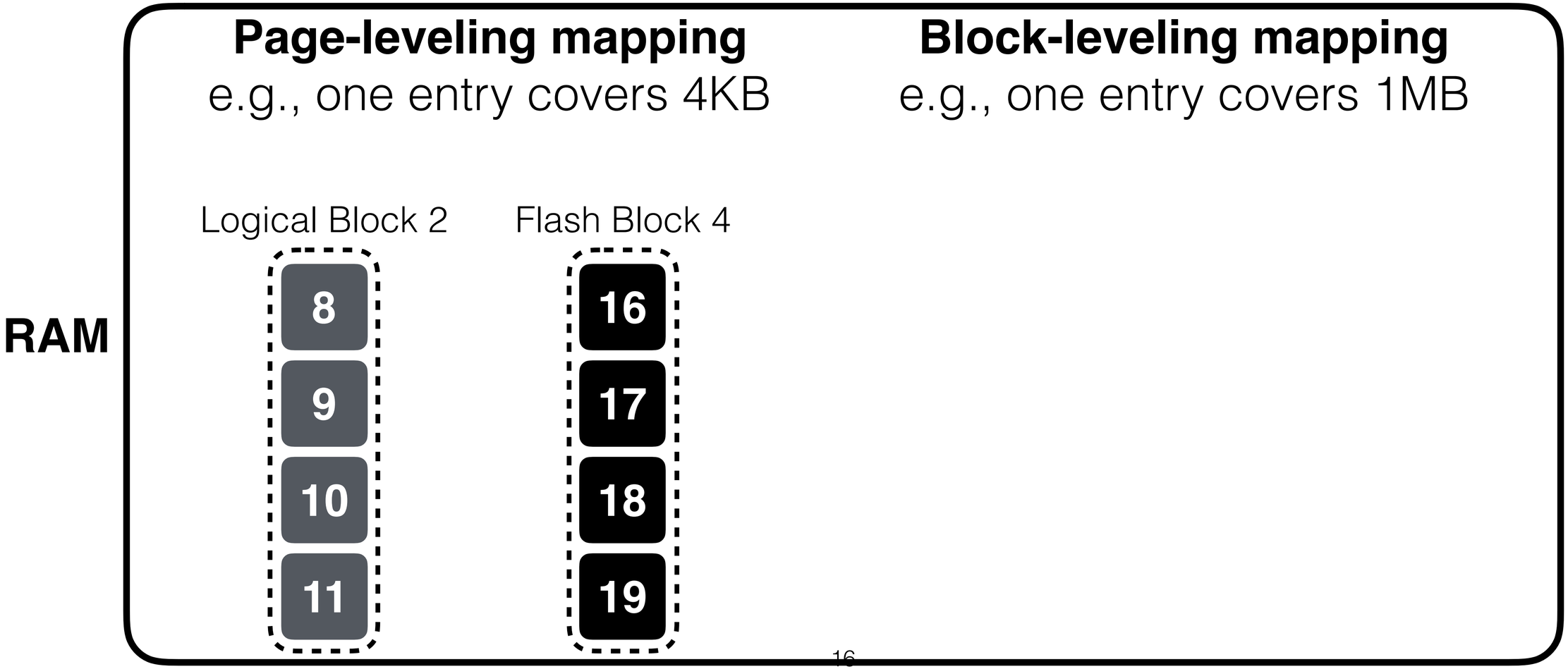

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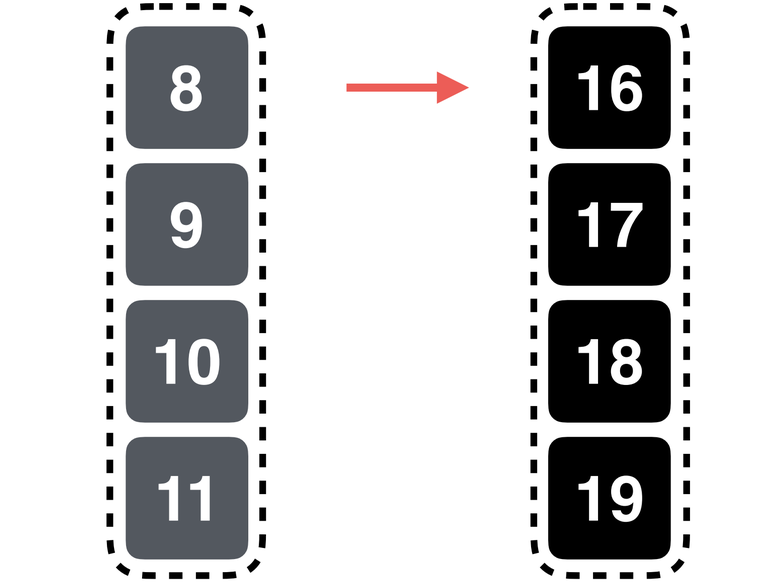

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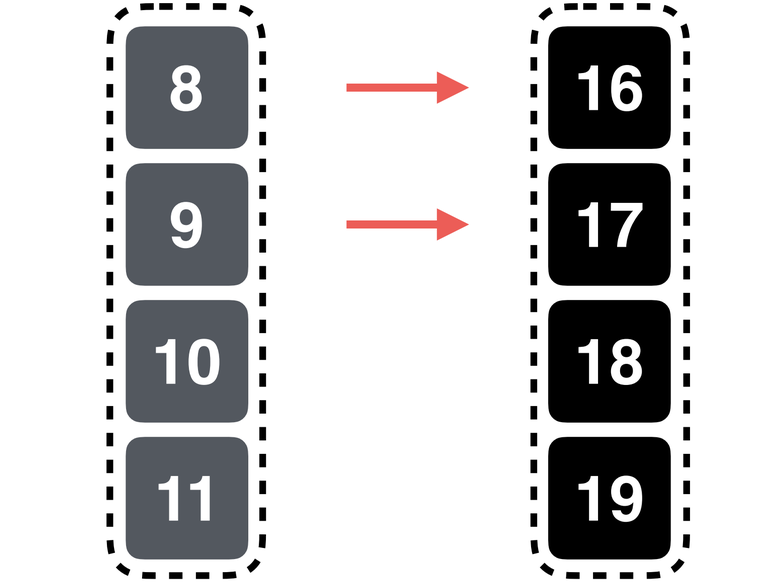

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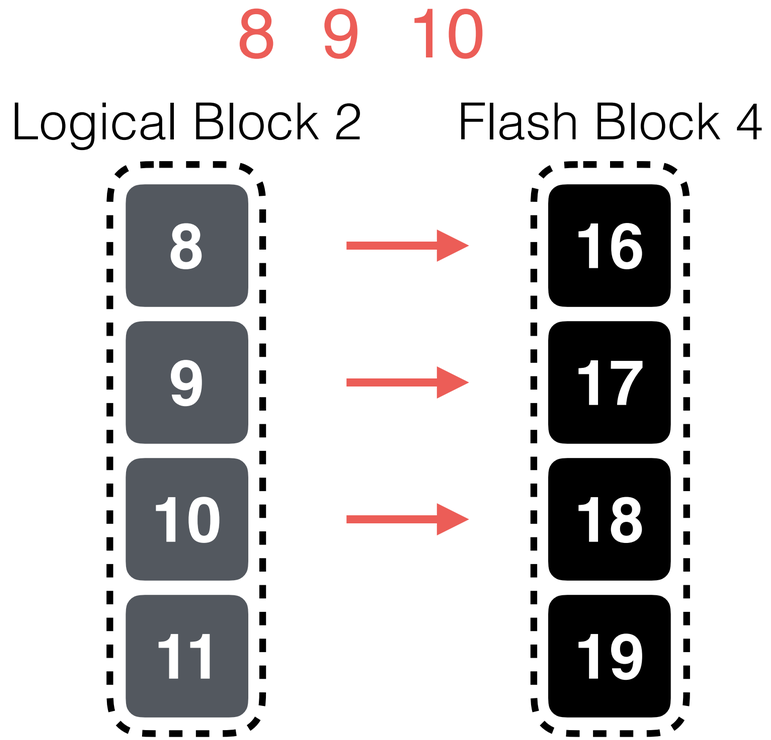

Block-leveling mapping

e.g., one entry covers 1MB

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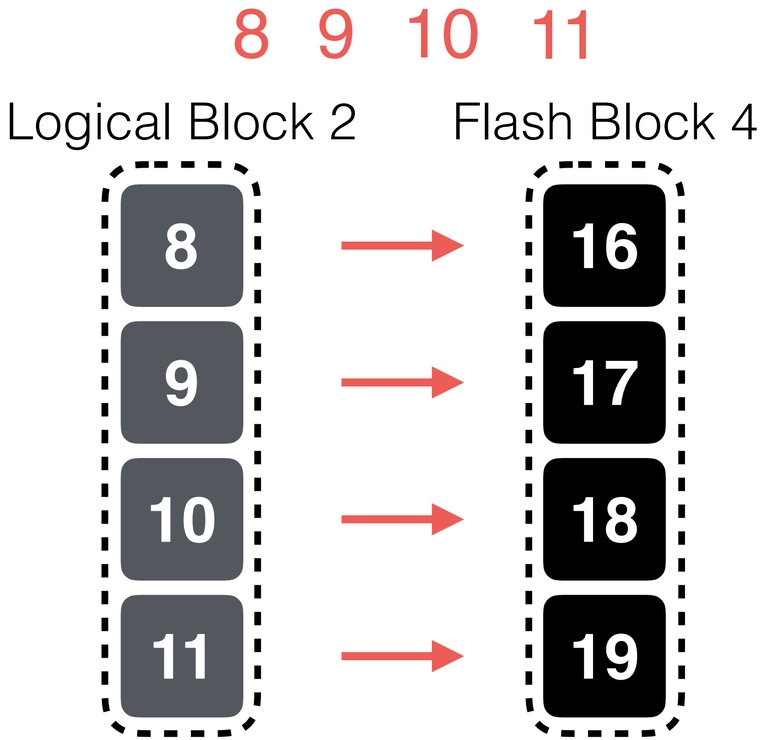
RAM

Page-leveling mapping

e.g., one entry covers 4KB



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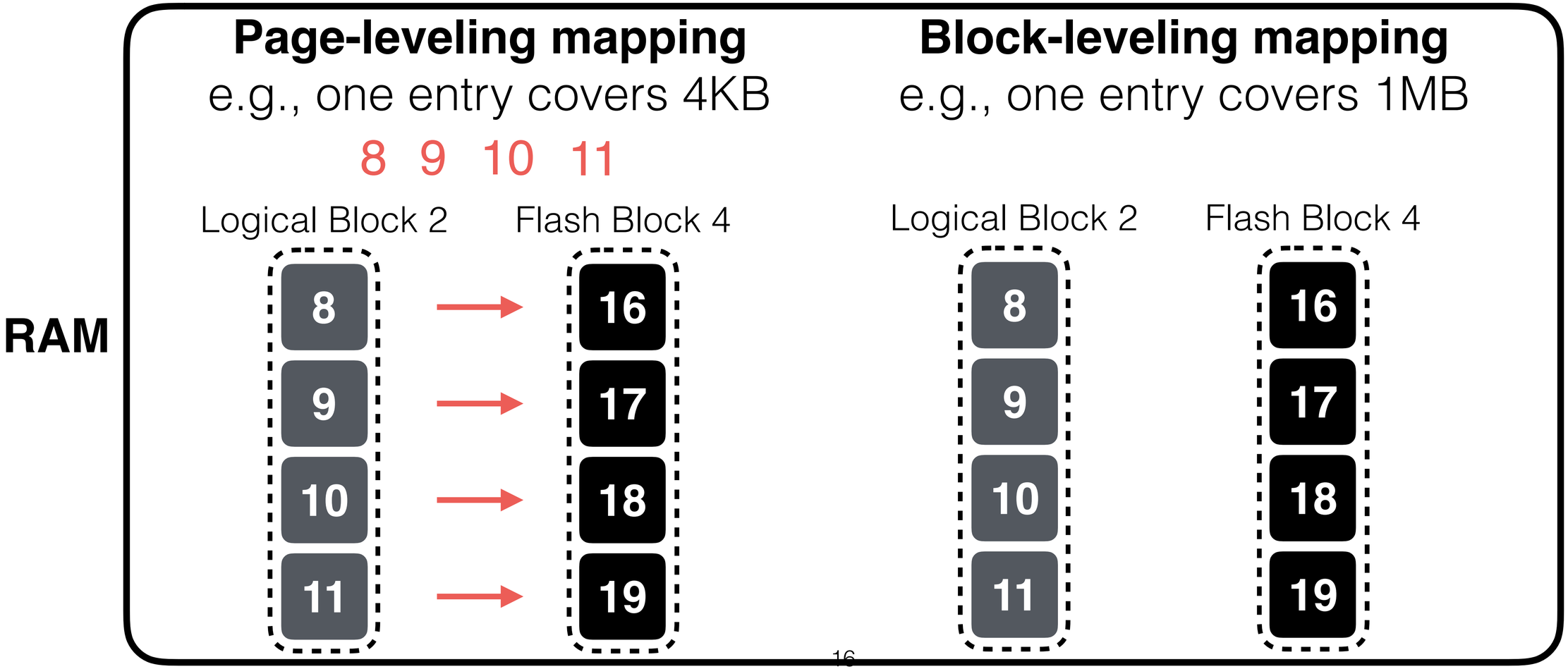

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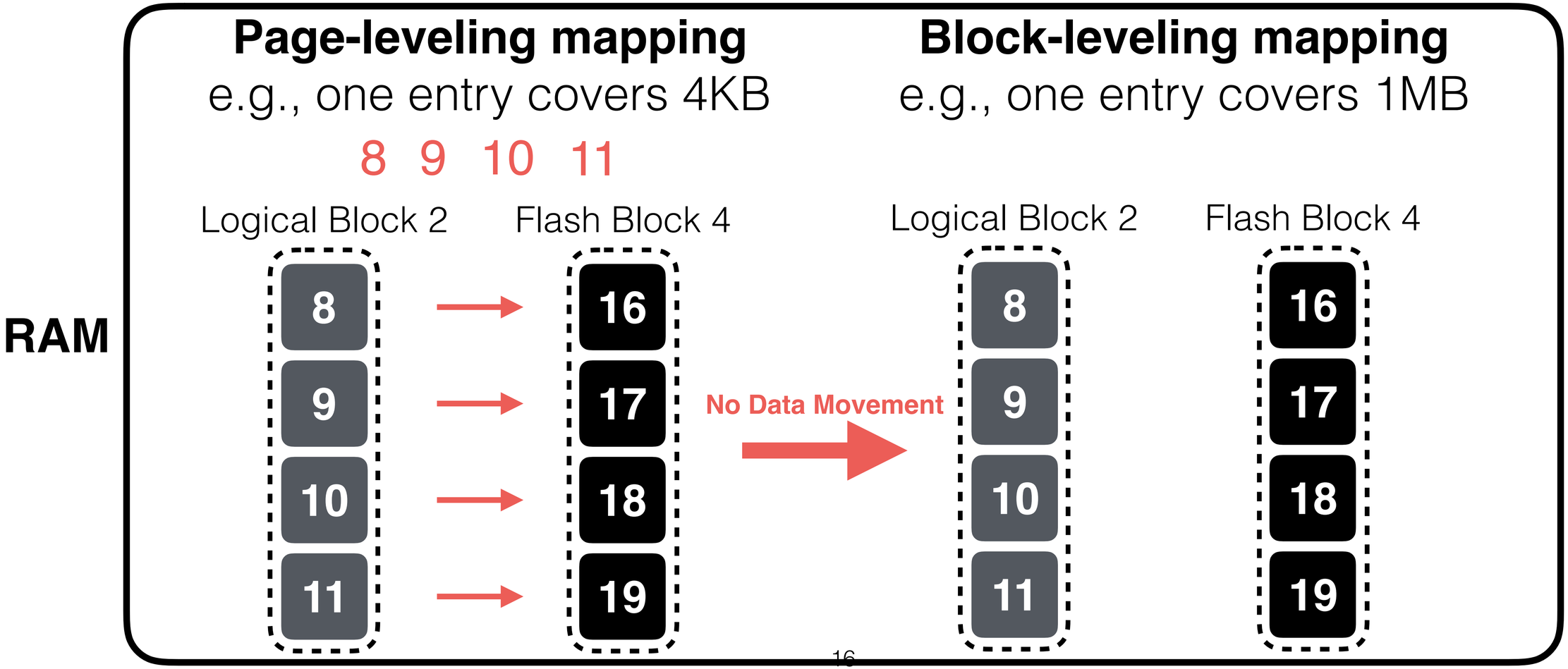

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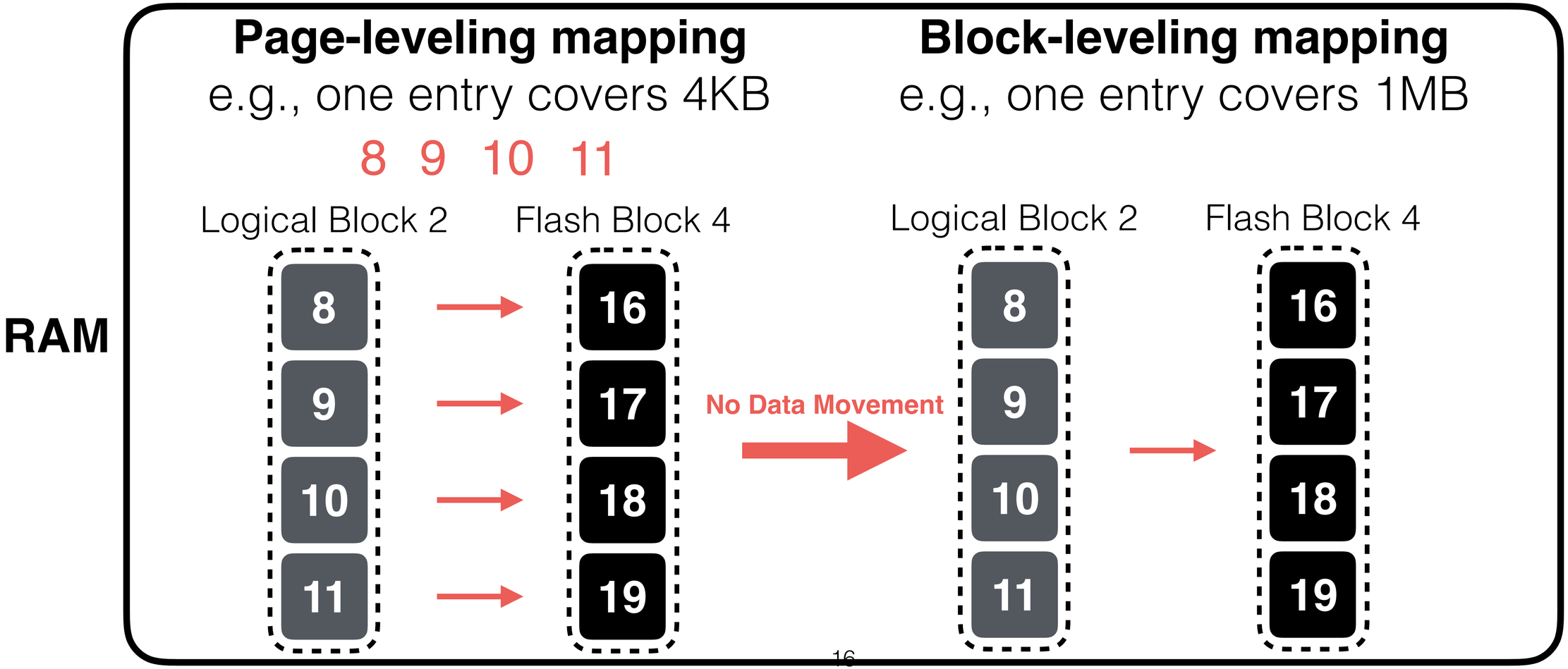

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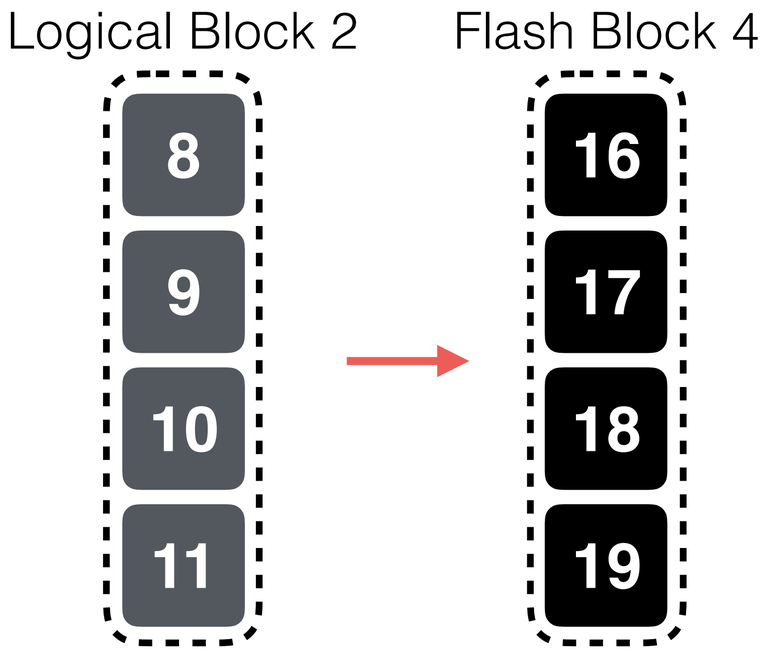
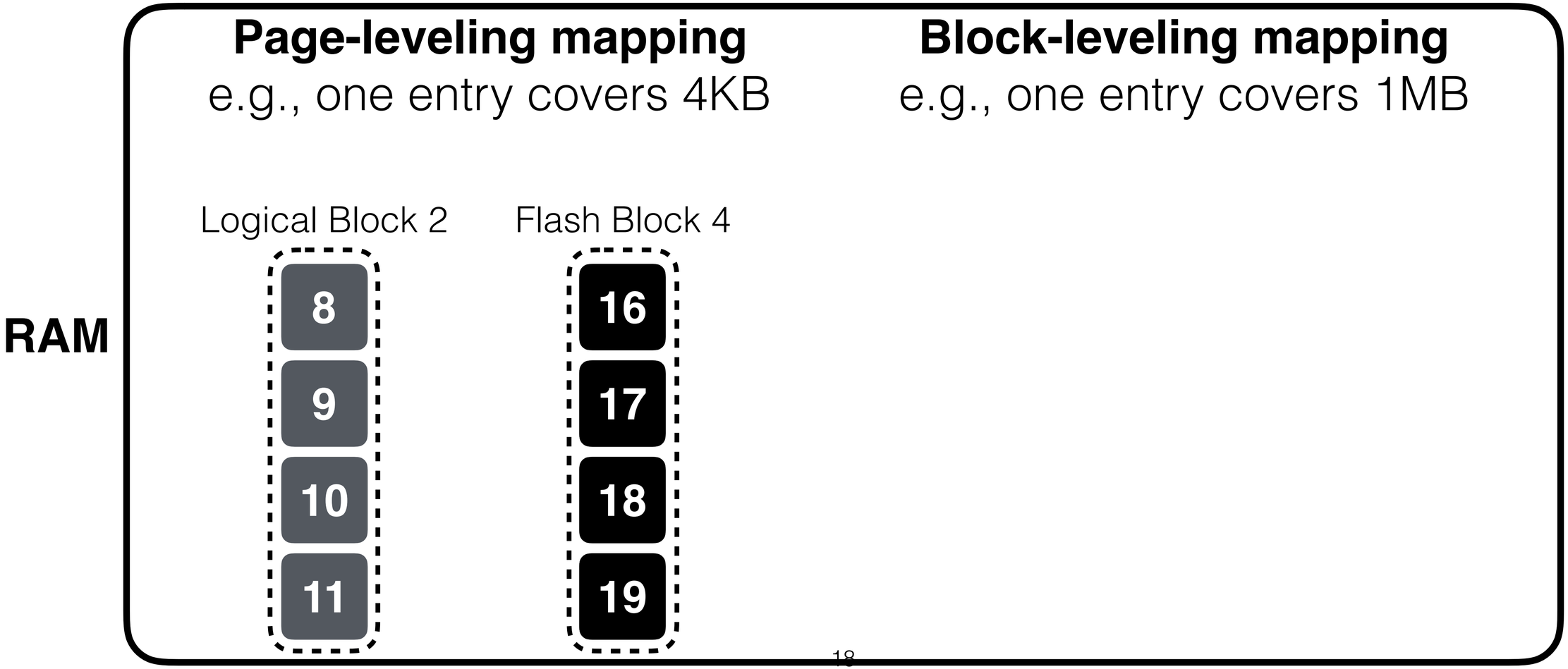


Rule 3: Aligned Sequentiality

Violation



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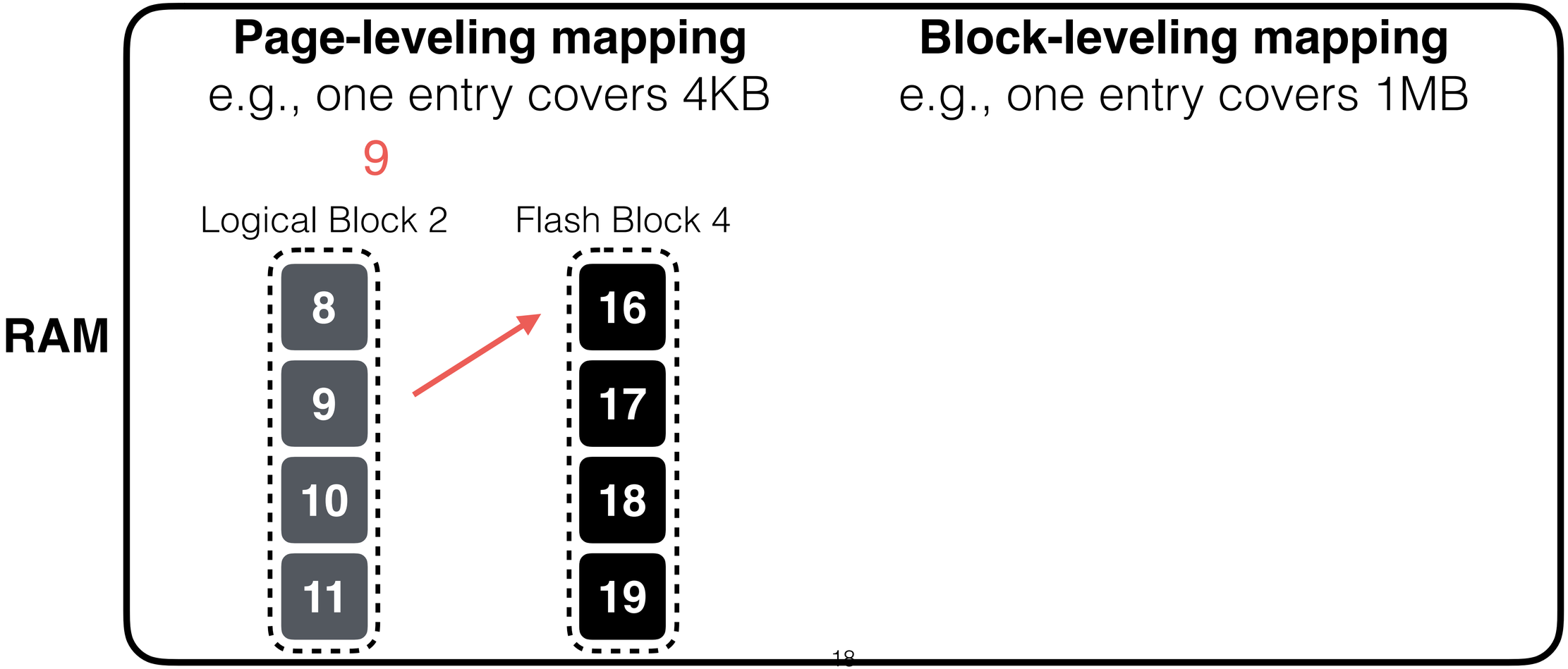
Violation



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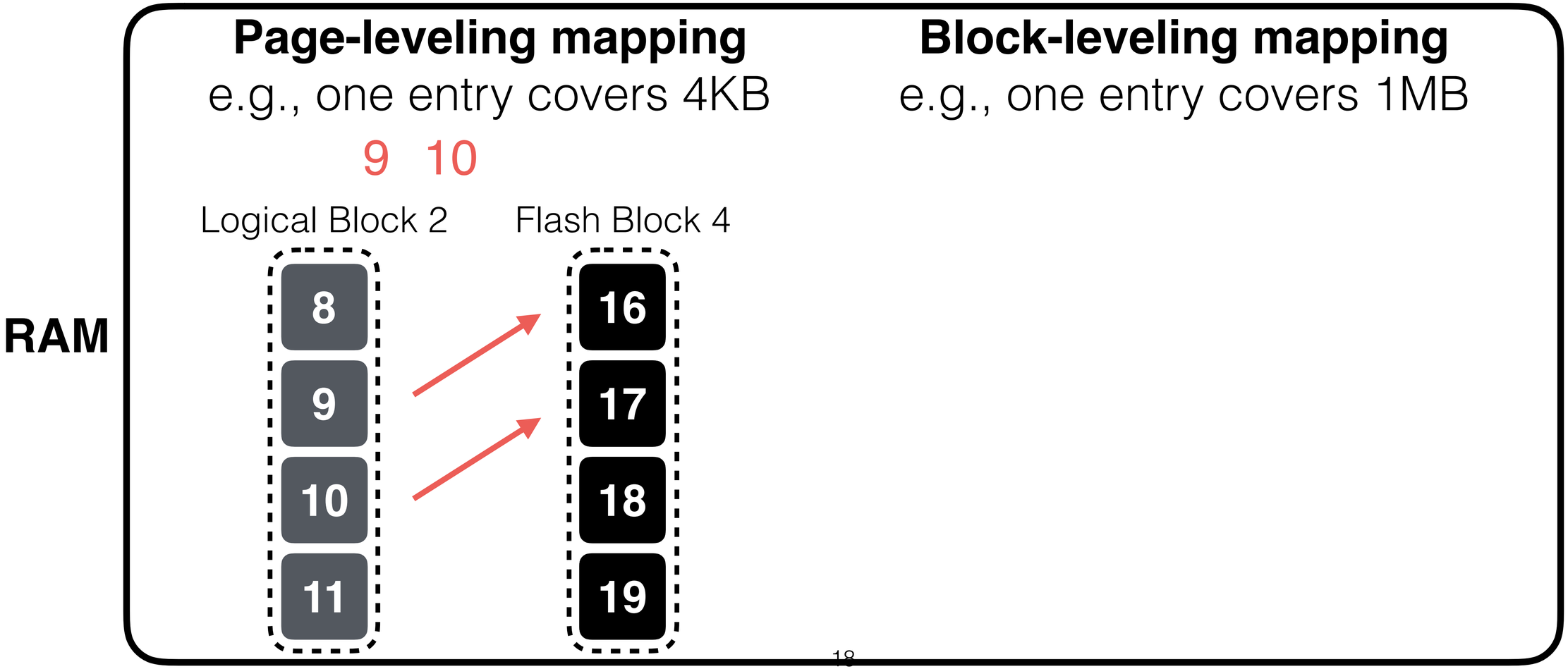

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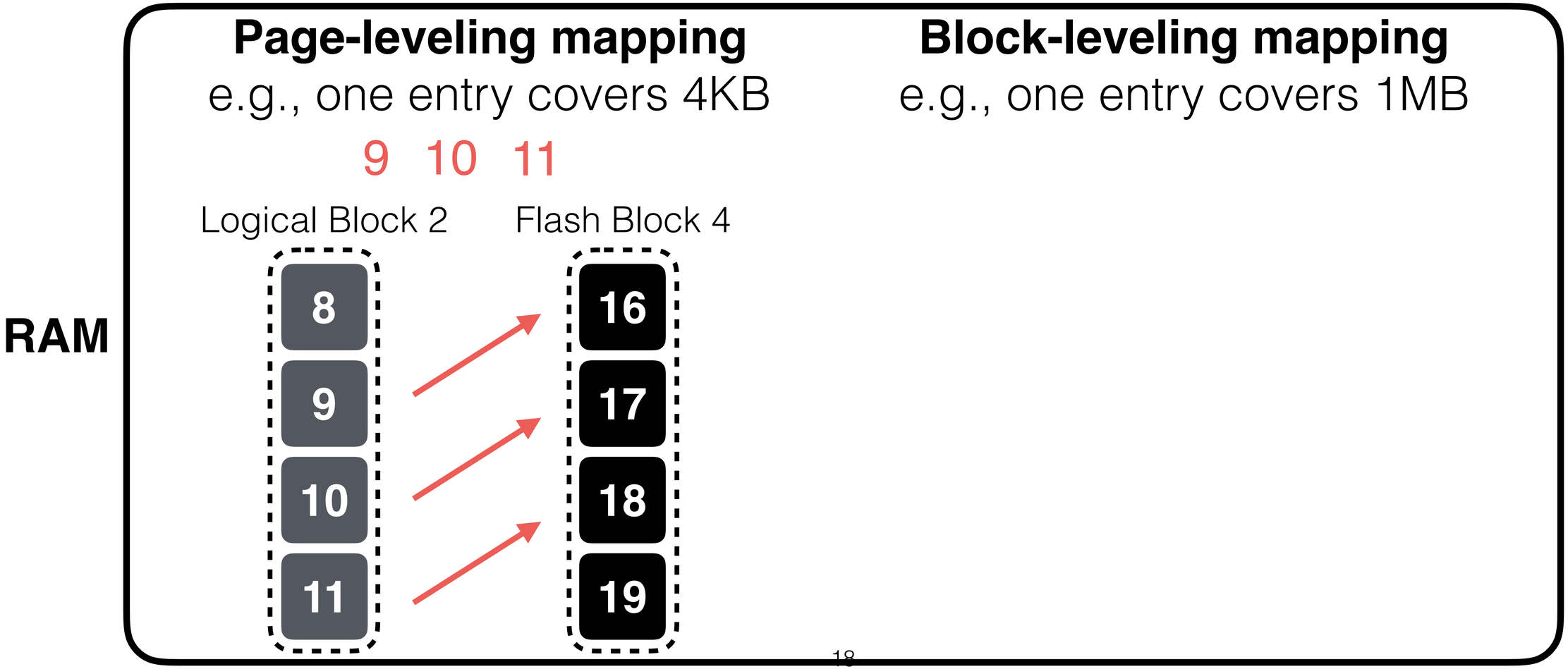
Violation



Rule 3: Aligned Sequentiality

Violation

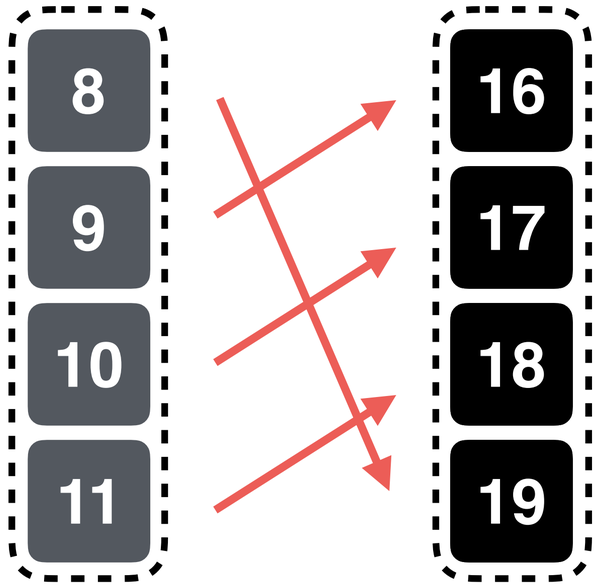
RAM

Page-leveling mapping

e.g., one entry covers 4KB

9 10 11 8

Logical Block 2 Flash Block 4

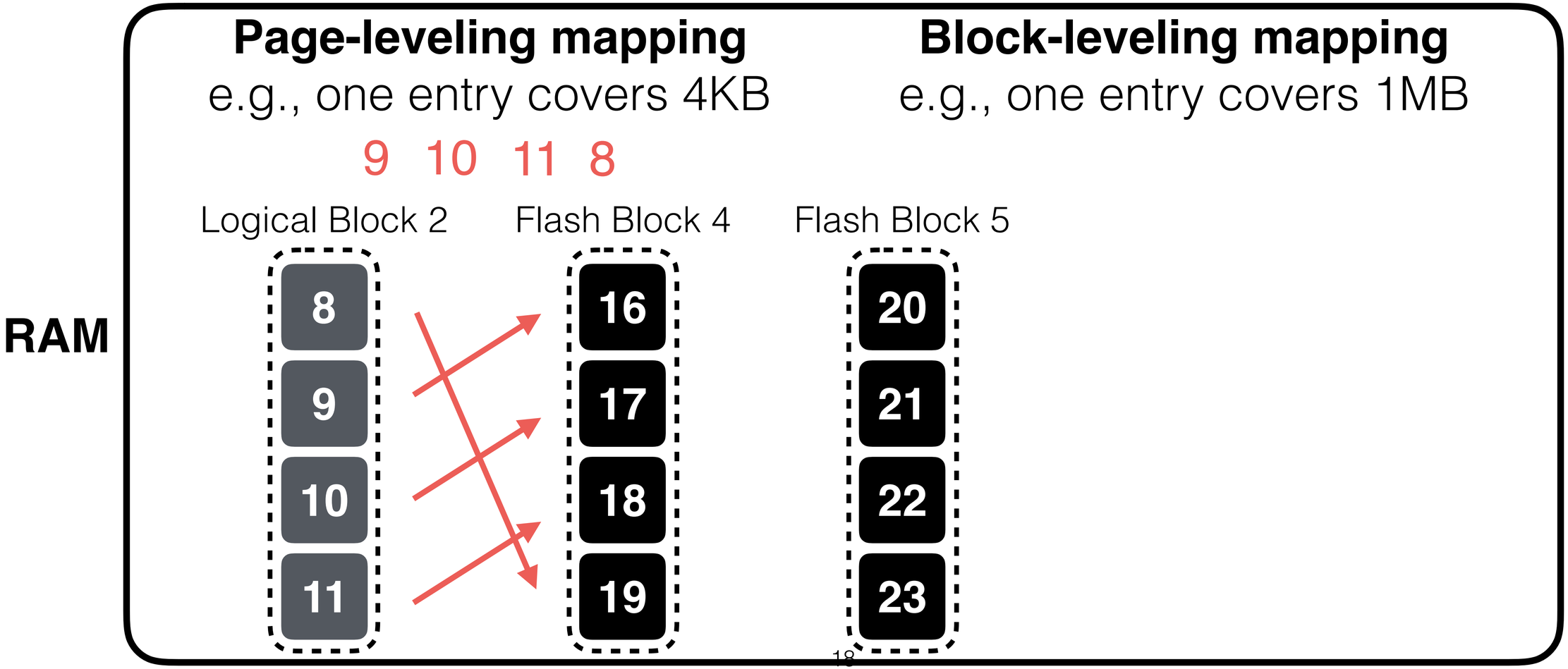


Block-leveling mapping

e.g., one entry covers 1MB

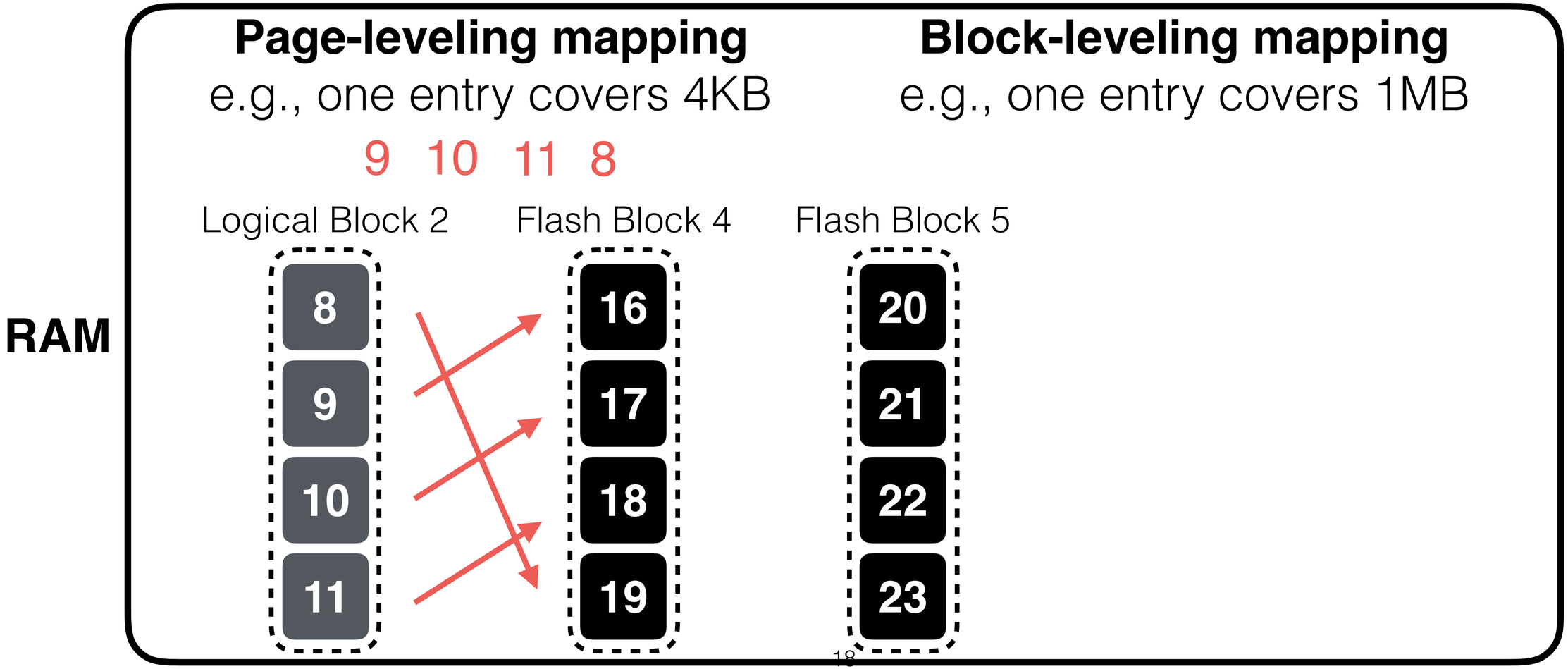
Rule 3: Aligned Sequentiality

Violation



Rule 3: Aligned Sequentiality

Violation



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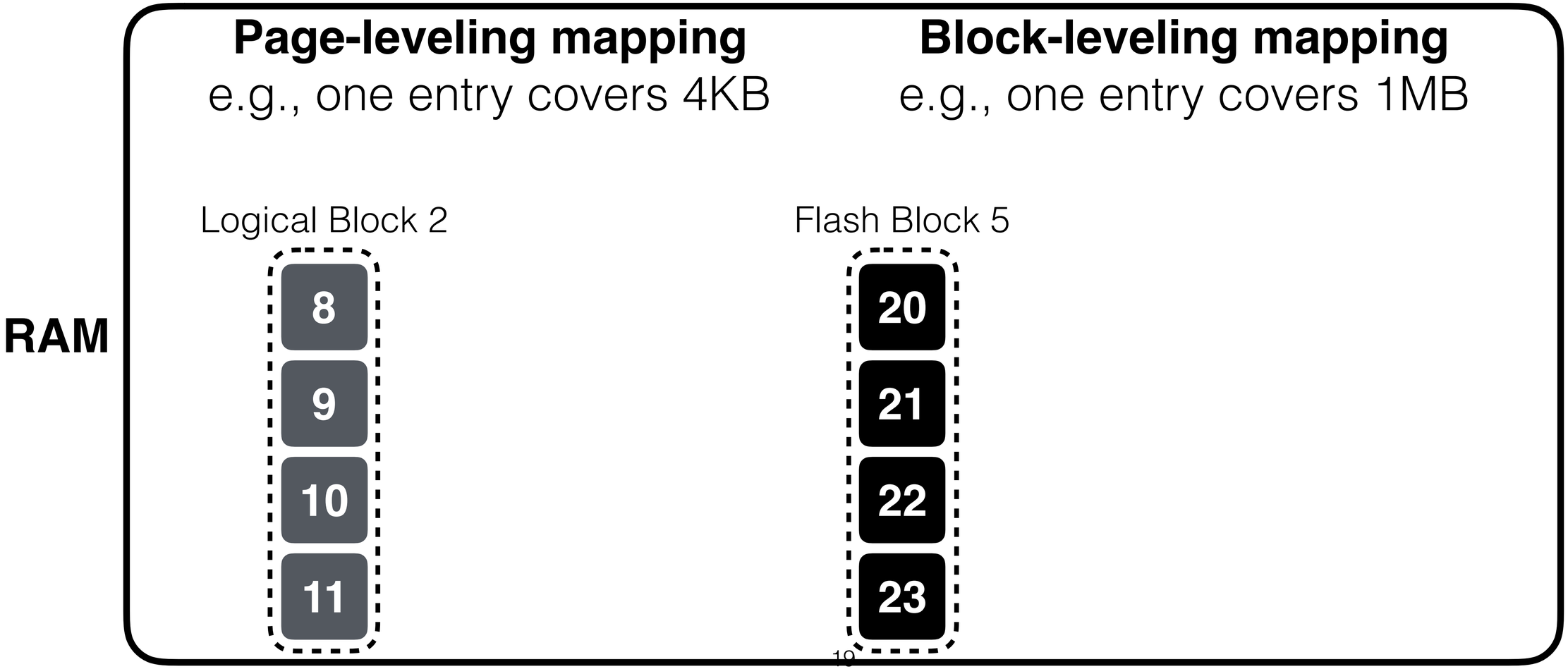

Rule 3: Aligned Sequentiality

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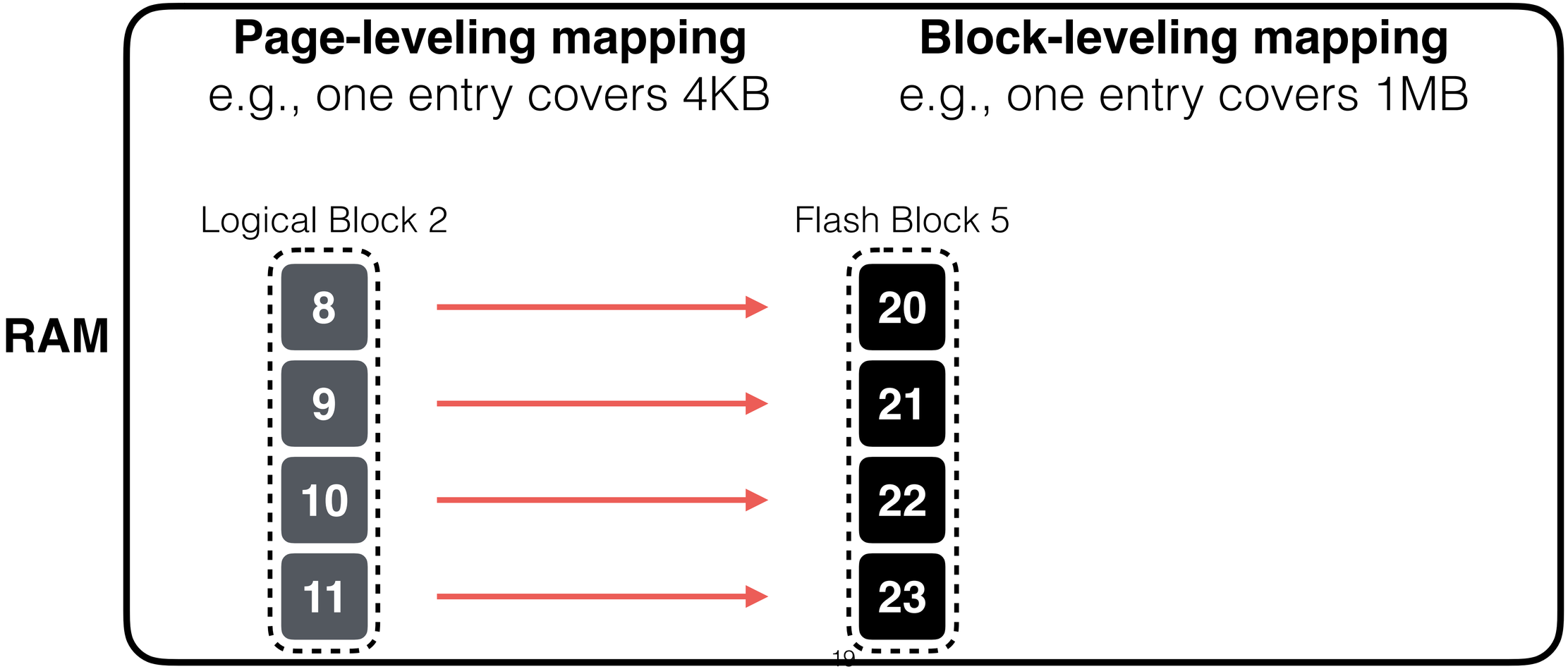

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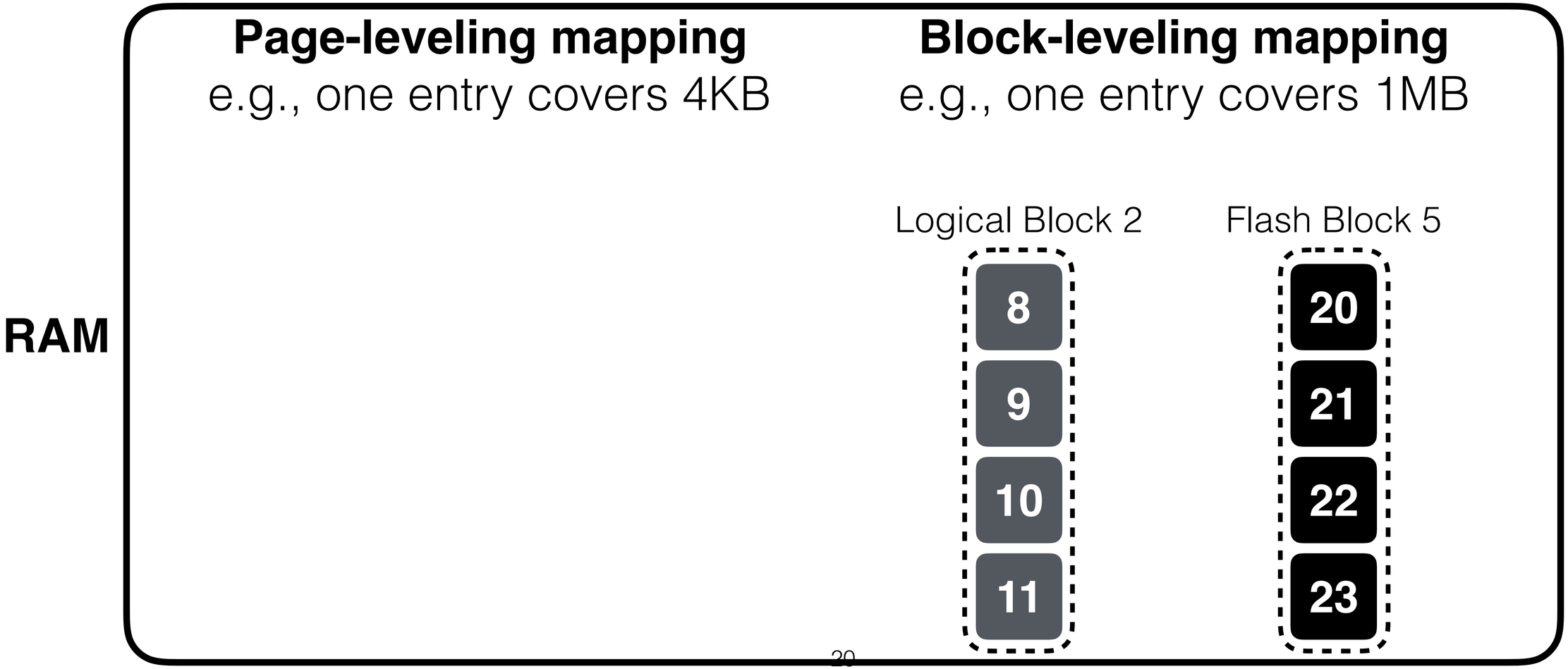
Violation



Rule 3: Aligned Sequentiality

Violation

RAM

Page-leveling mapping
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Block-leveling mapping
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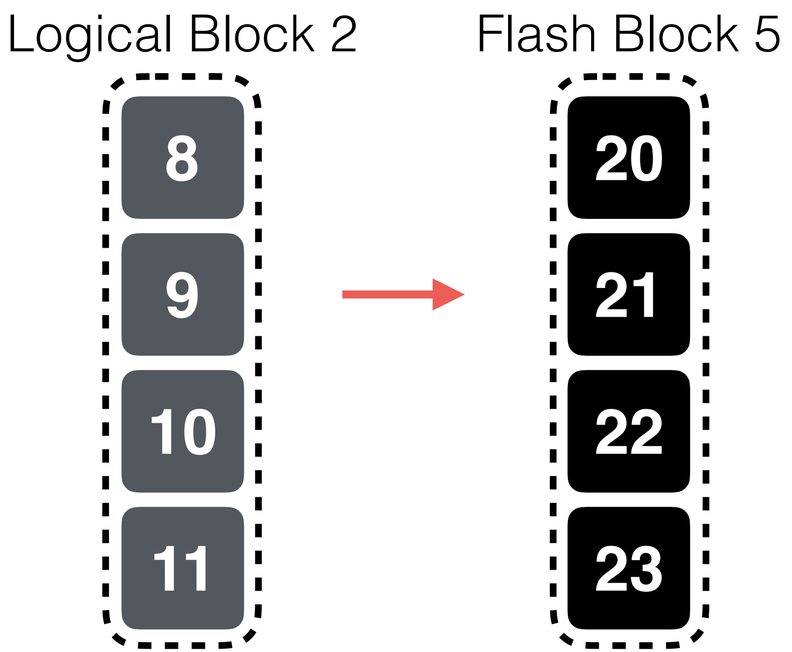


Rule 3: Aligned Sequentiality

Violation

If you violate the rule:

- **Performance penalty**
- **Write amplification**

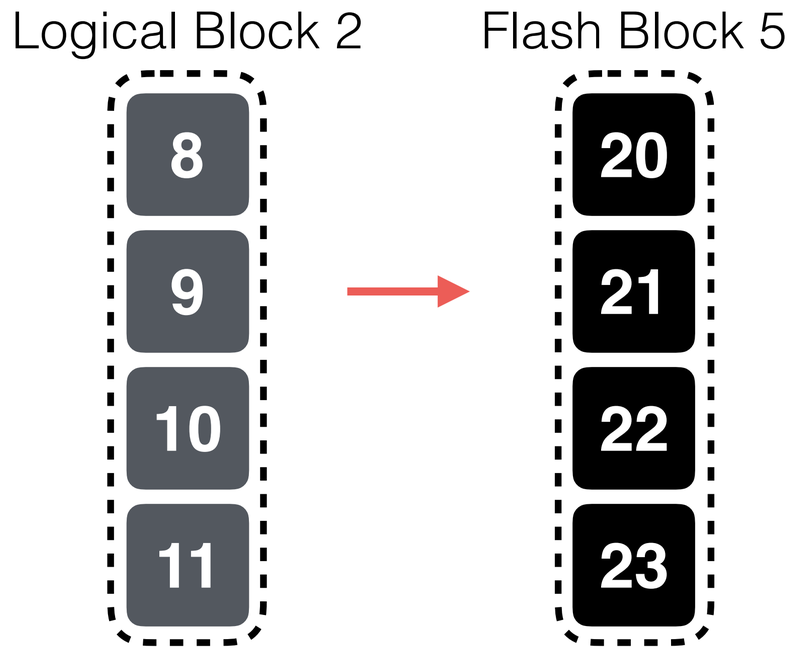
Page-l

e.g., one

apping

ers 1MB

RAM



Rule 3: Aligned Sequentiality

Violation

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Page-l

e.g., one

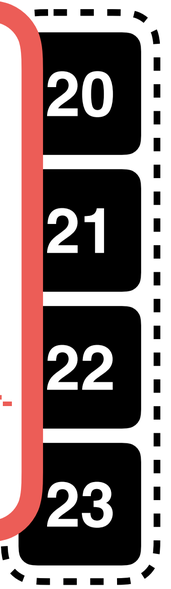
apping

ers 1MB

RAM

Logical Block 2

Flash Block 5



Performance impact:

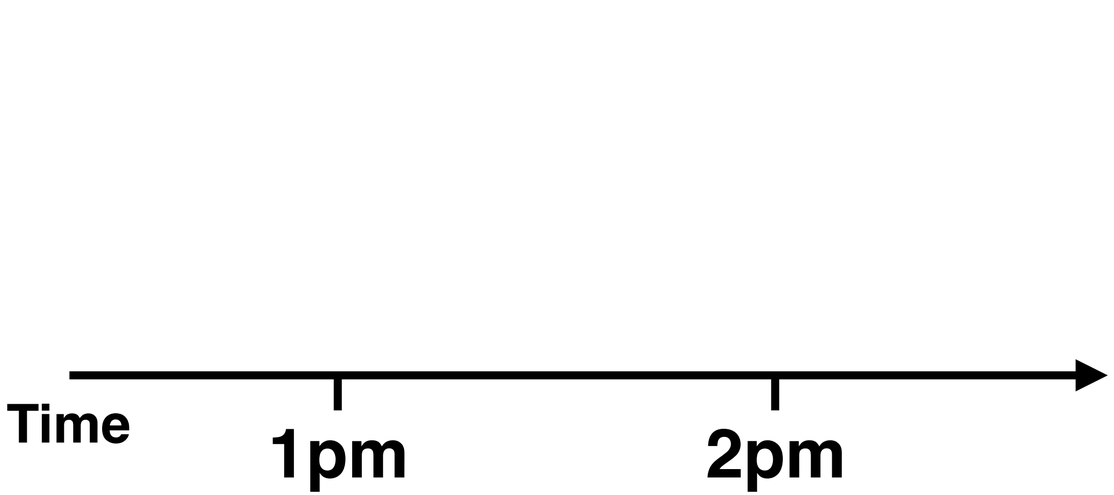
2.5x execution time

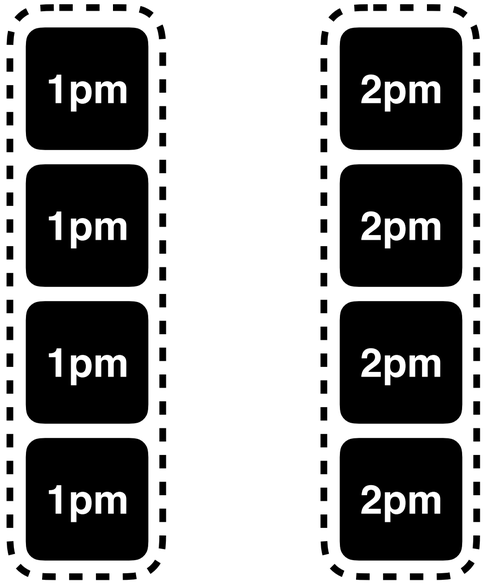
2.4x block erasure count

S.-W. Lee, D.-J. Park, T.-S. Chung, D.-H. Lee, S. Park, and H.- J. Song. A Log Buffer-based Flash Translation Layer Using Fully-associative Sector Translation. ACM Trans. Embed. Comput. Syst., 6(3), July 2007.

Rule 4: Grouping By Death Time

Data with similar death times should be placed in the same block.





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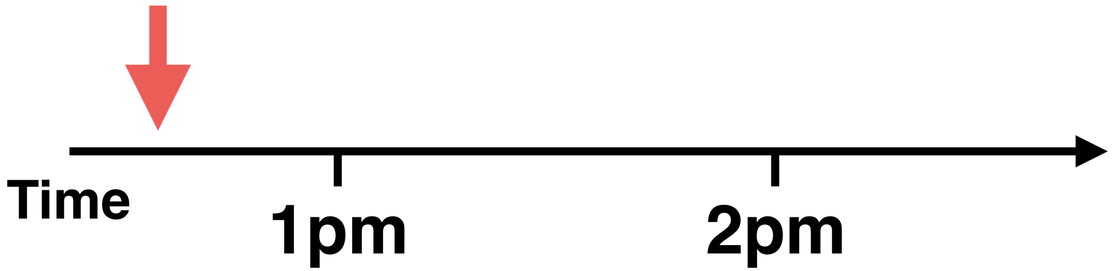

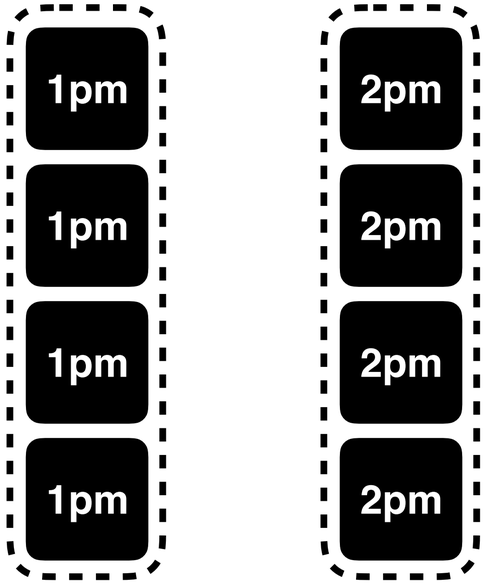

Rule 4: Grouping By Death Time

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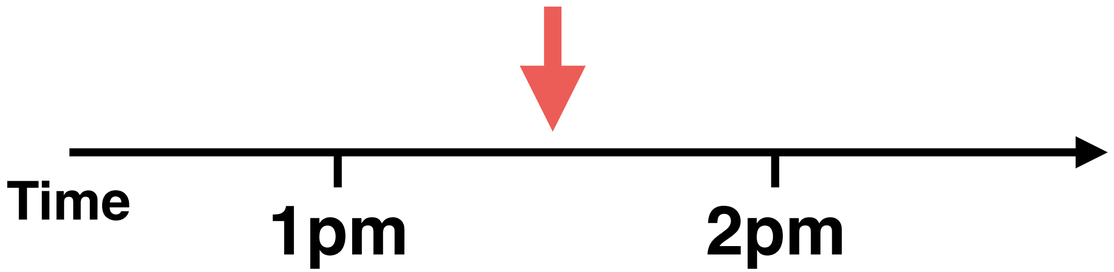

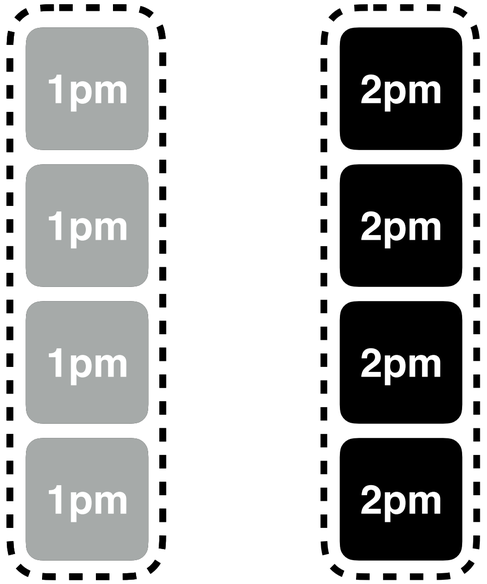

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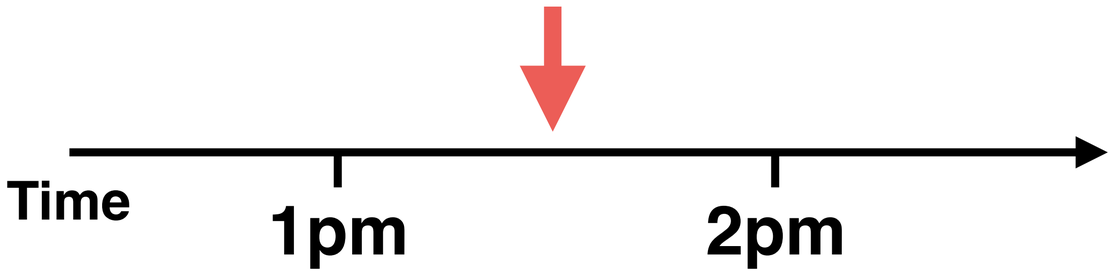

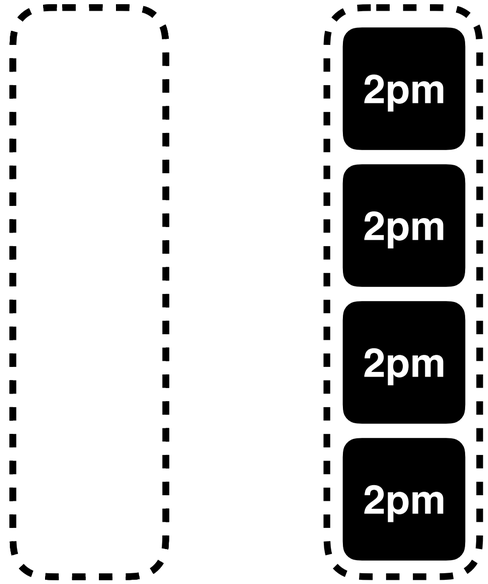

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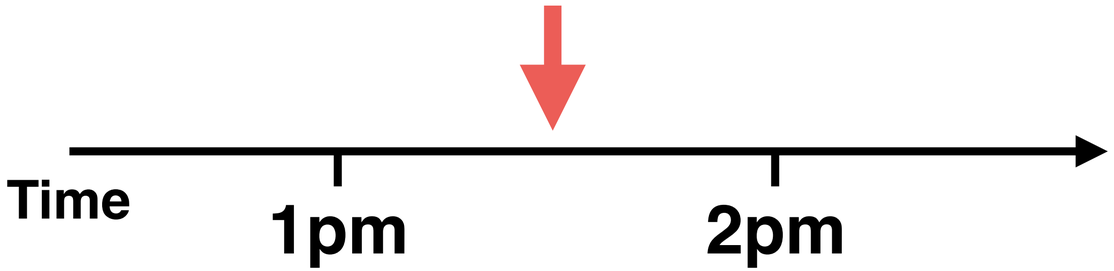
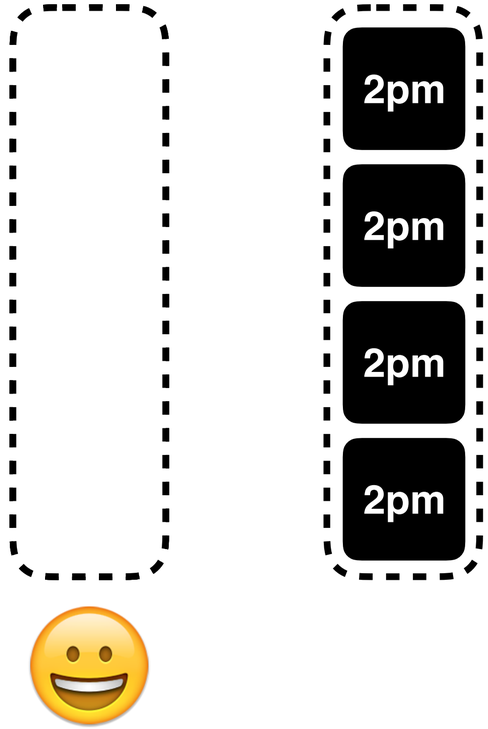
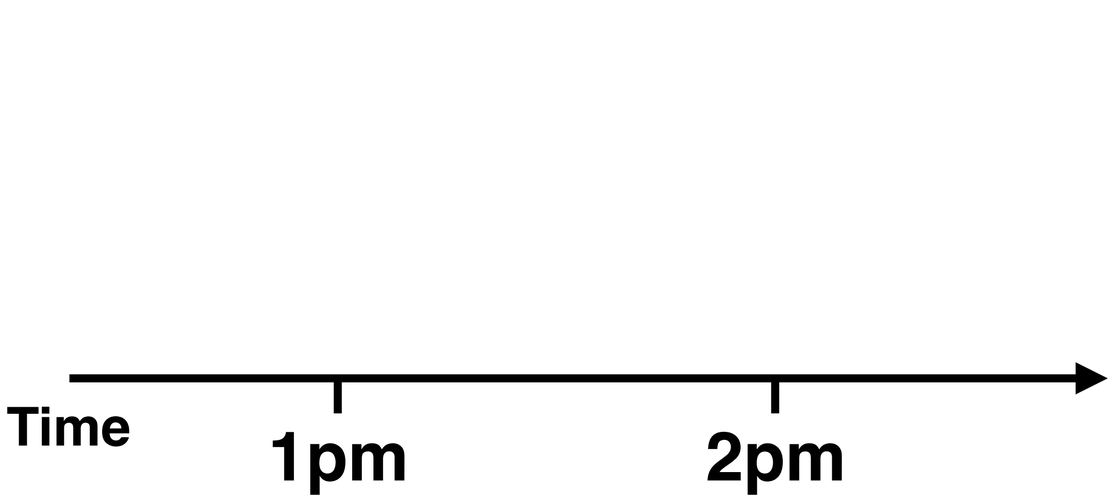
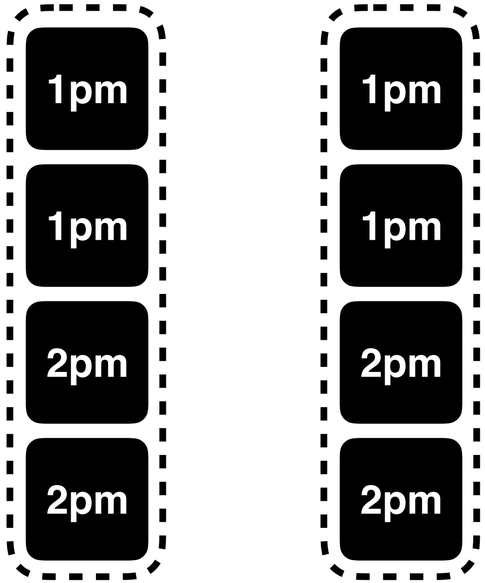




Rule 4: Grouping By Death Time

Violation





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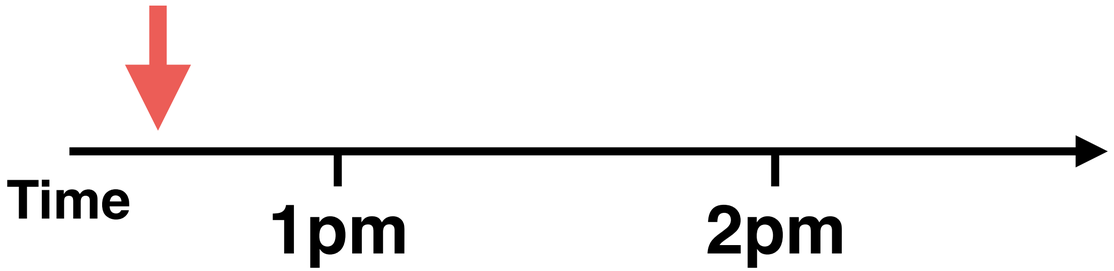

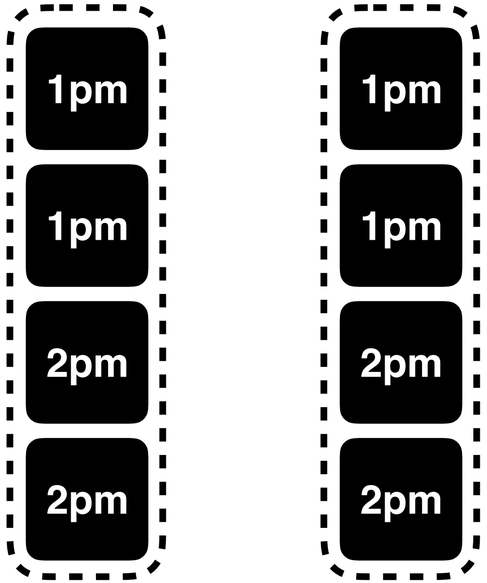

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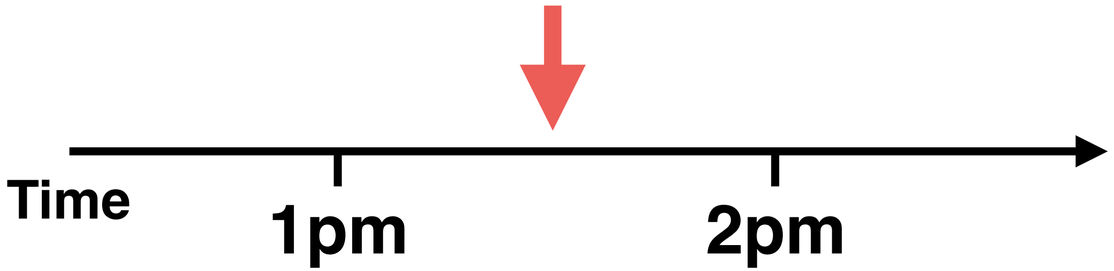

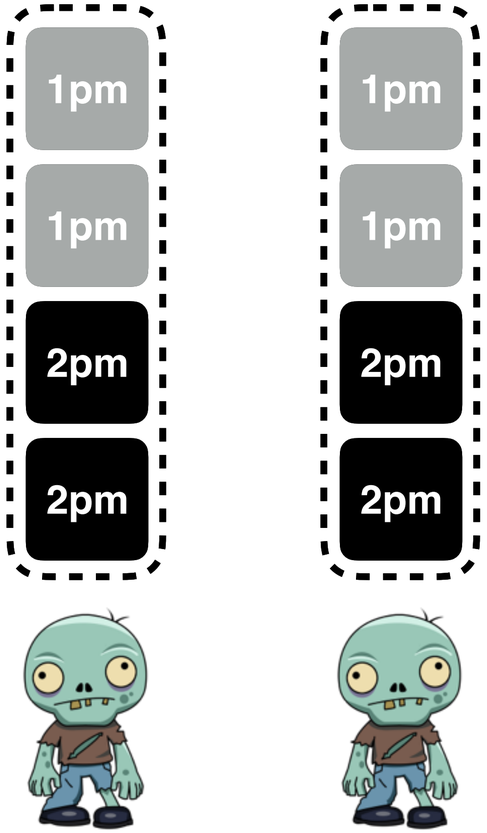

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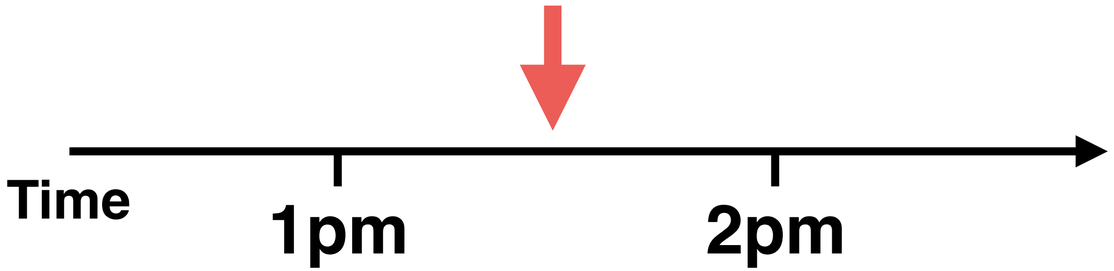

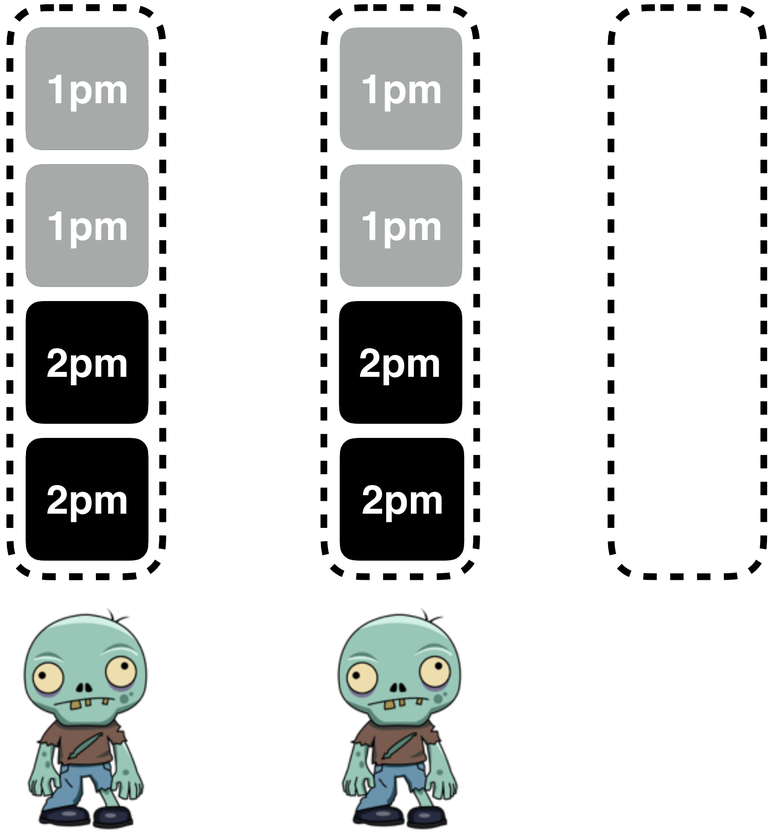

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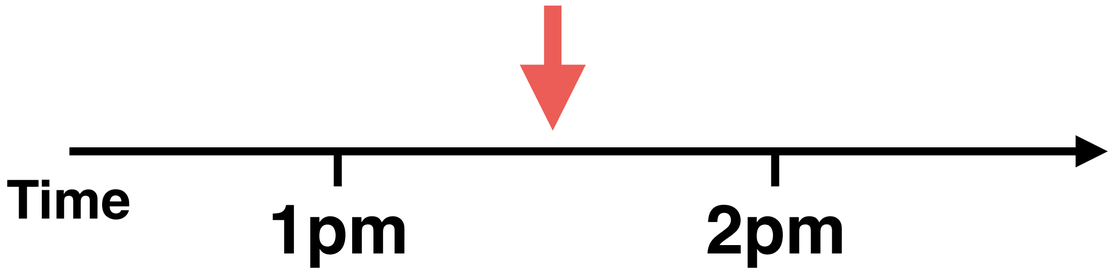

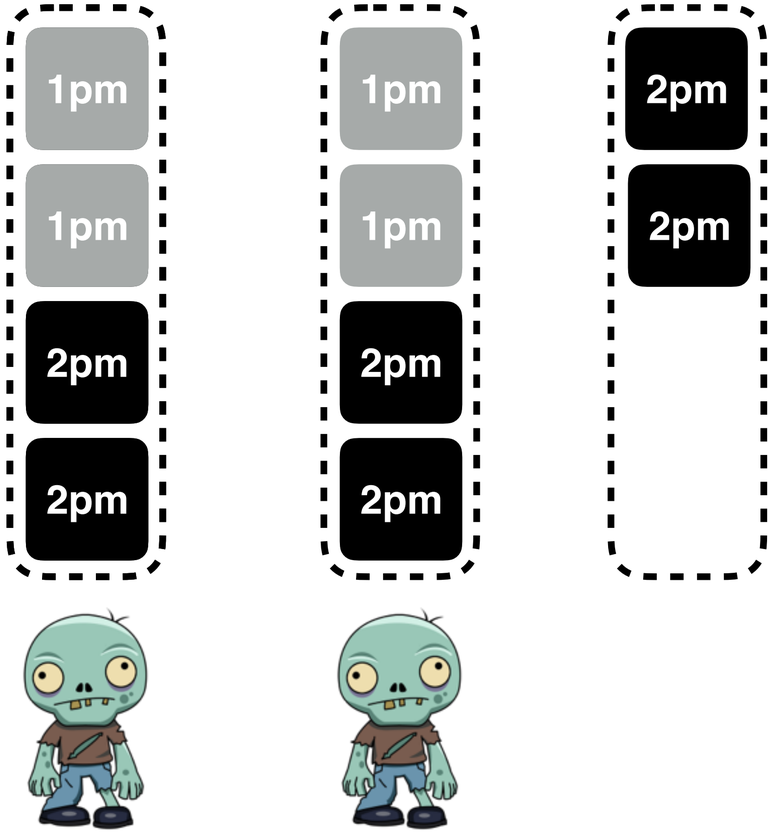

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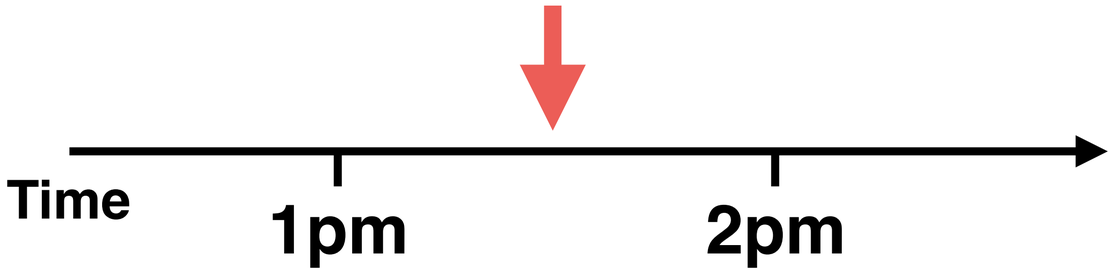

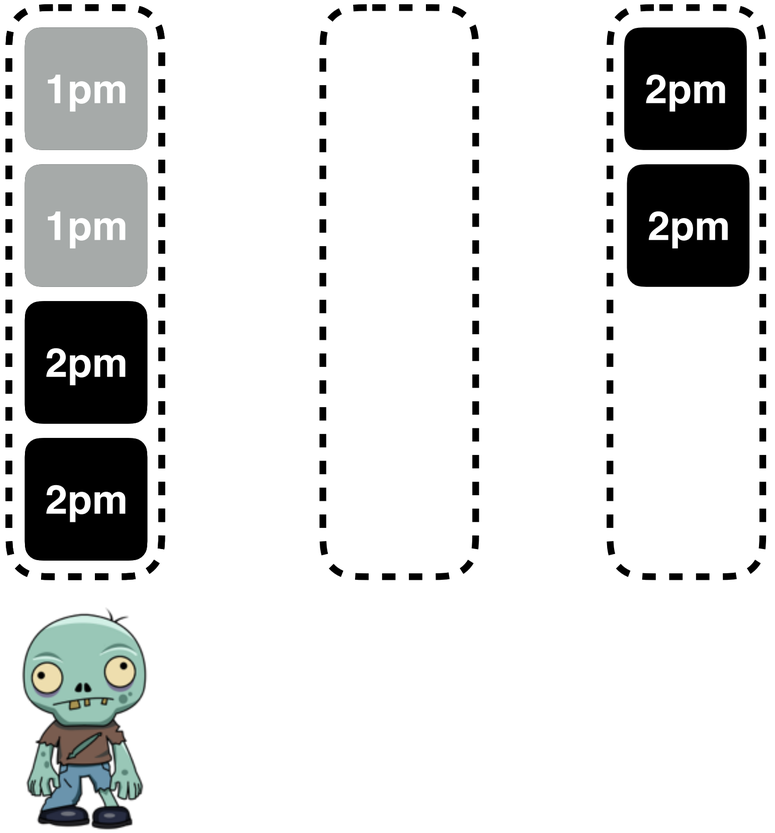

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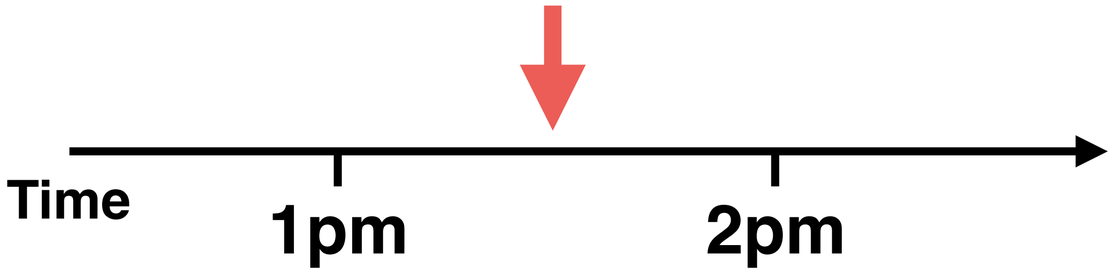
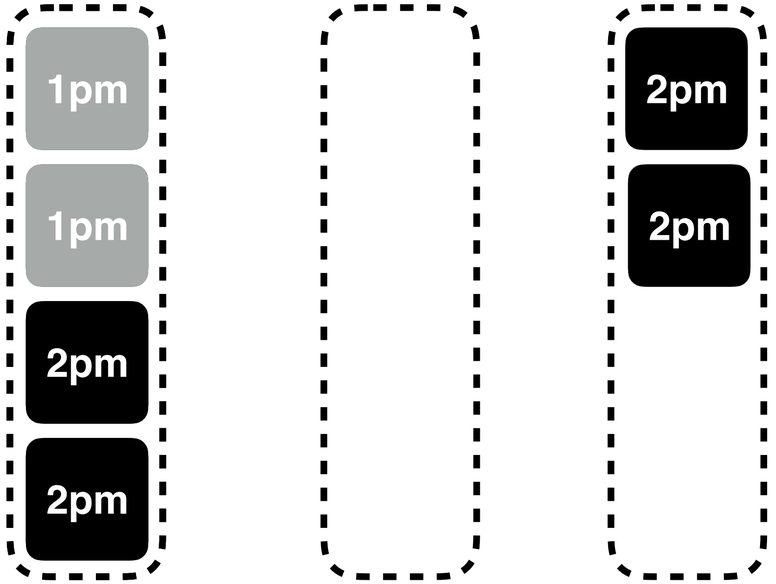


Data movement!!!



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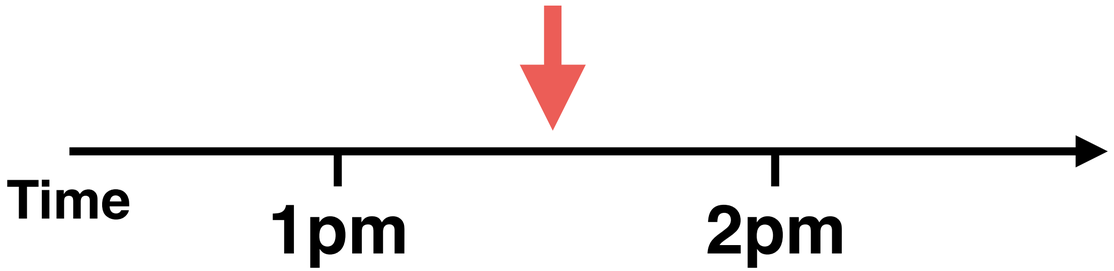
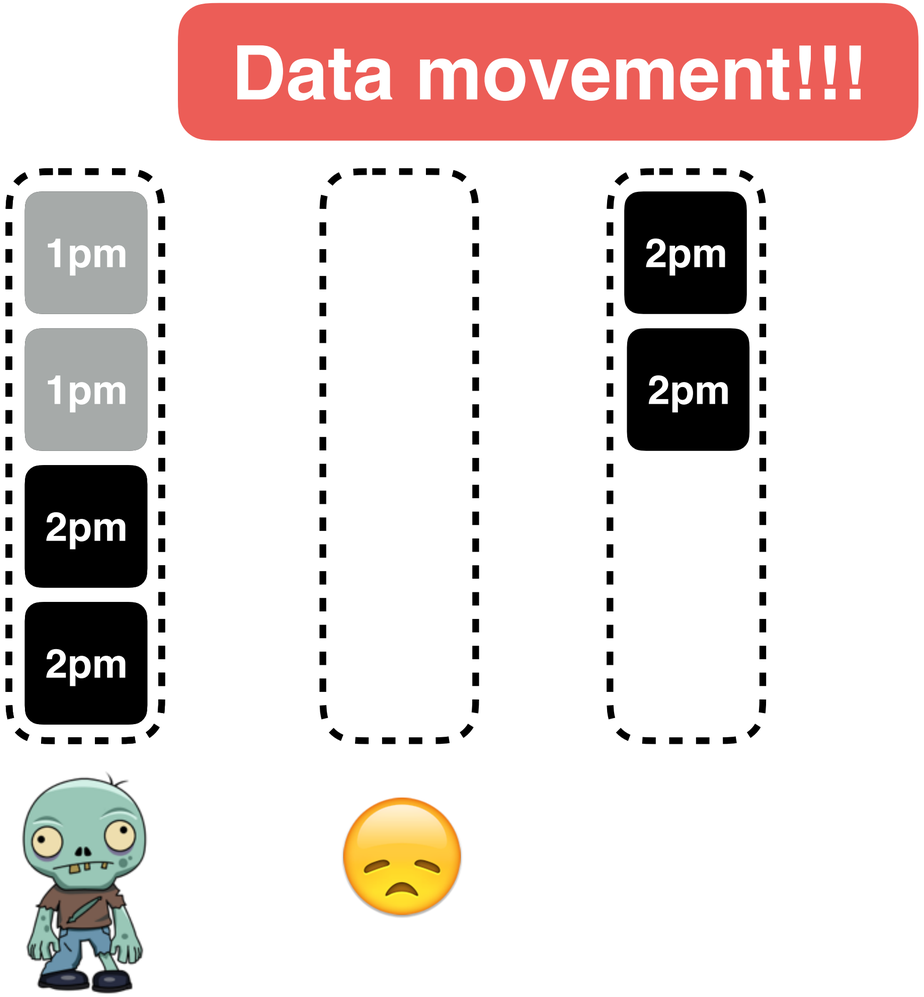


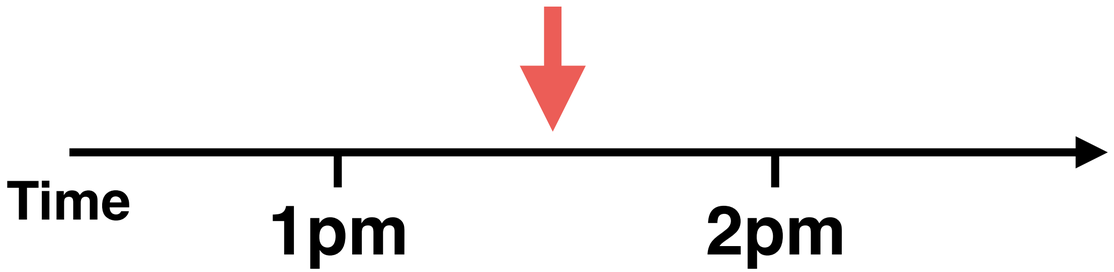


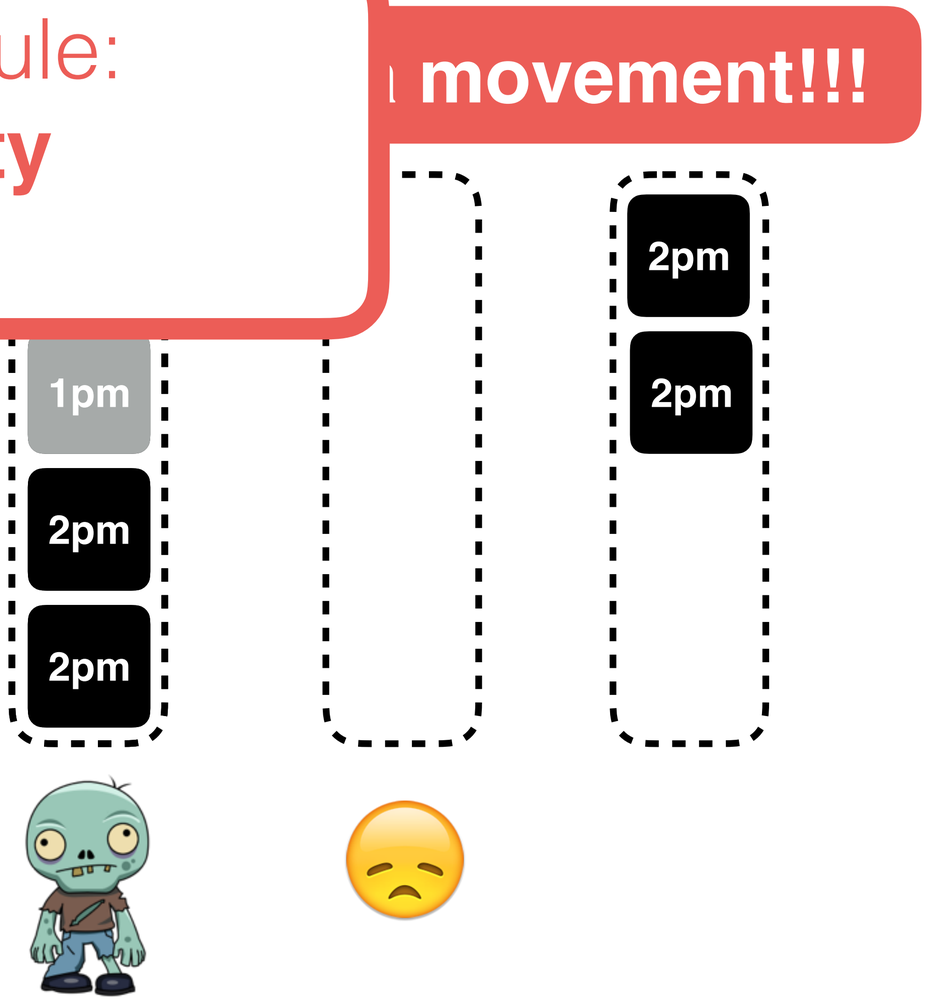
Rule 4: Grouping By Death Time

Violation

If you violate the rule:

- **Performance penalty**
- **Write amplification**





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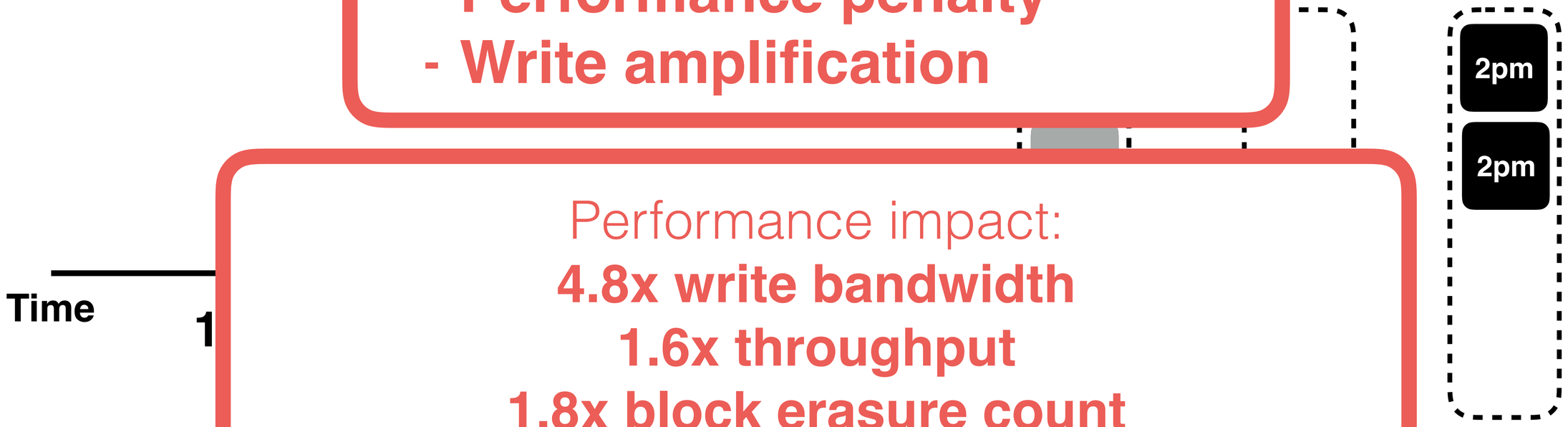
movement!!!



Performance impact:

4.8x write bandwidth

1.6x throughput

1.8x block erasure count

C. Lee, D. Sim, J.-Y. Hwang, and S. Cho. F2FS: A New File System for Flash Storage. In Proceedings of the 13th USENIX Conference on File and Storage Technologies (FAST '15), Santa Clara, California, February 2015.

J.-U. Kang, J. Hyun, H. Maeng, and S. Cho. The Multi- streamed Solid-State Drive. In 6th USENIX Workshop on Hot Topics in Storage and File Systems (HotStorage '14), Philadelphia, PA, June 2014.

. Y. Cheng, F. Douglis, P. Shilane, G. Wallace, P. Desnoyers, and K. Li. Erasing Belady's Limitations: In Search of Flash Cache Offline Optimality. In 2016 USENIX Annual Technical Conference (USENIX ATC 16), pages 379–392, Denver, CO, 2016. USENIX Association.

Rule 5: Uniform Data Lifetime

Clients of SSDs should create data with similar lifetimes

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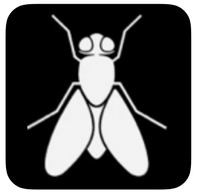
Lifetime



1 Day

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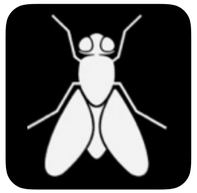

1 Day

SSD

Program Count: **0 0 0 0**

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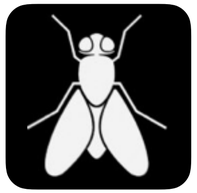

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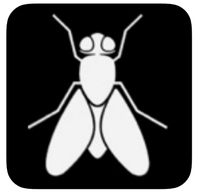

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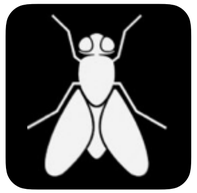

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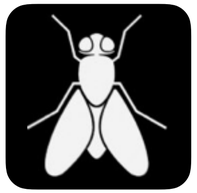

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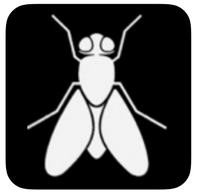

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SSD

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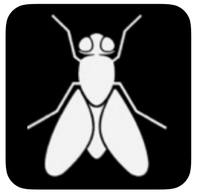

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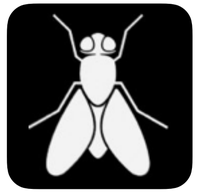

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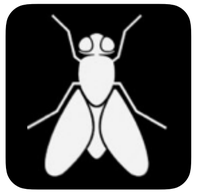

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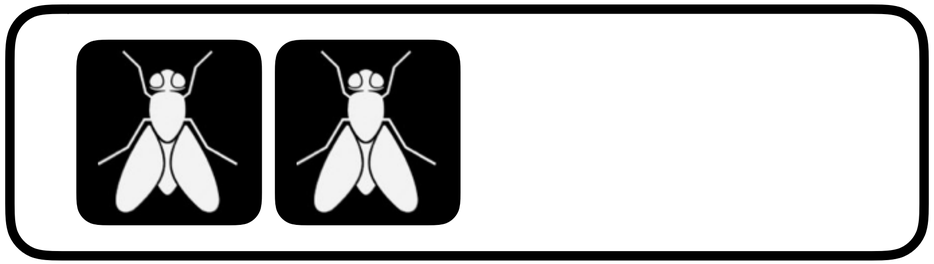

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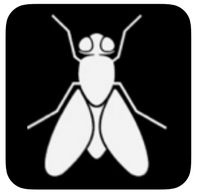

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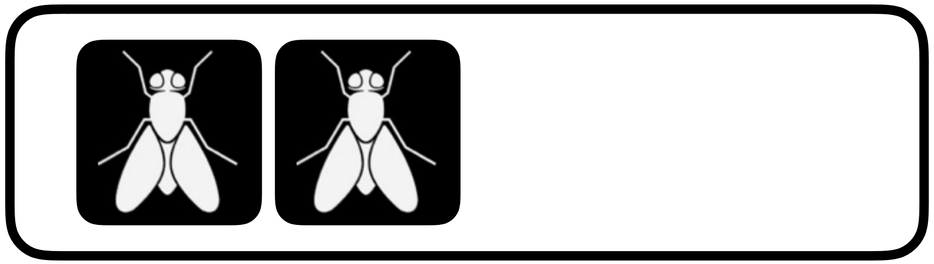

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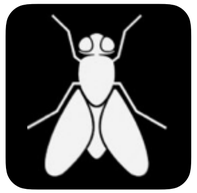

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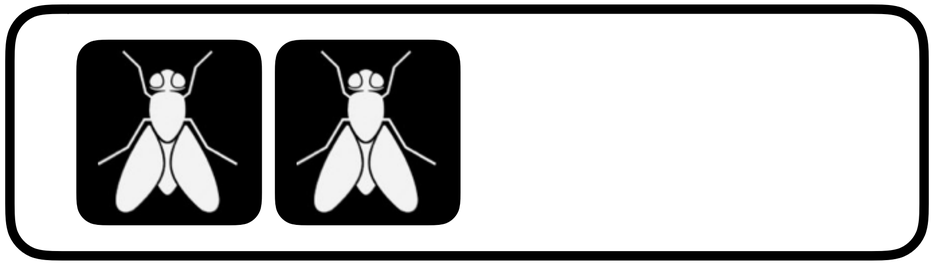
SSD



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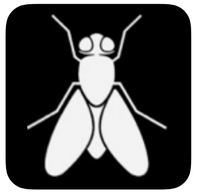

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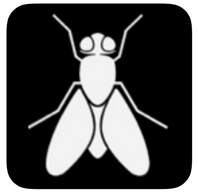
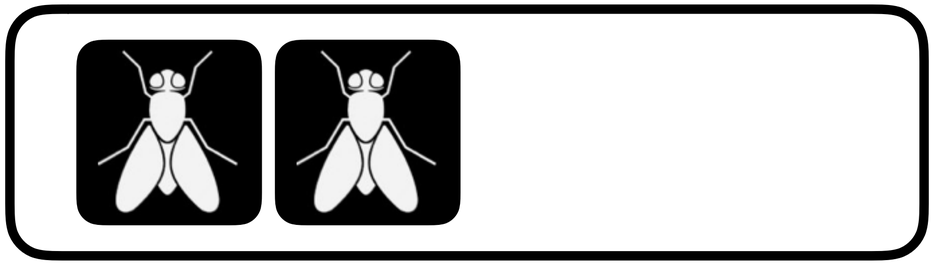


SSD

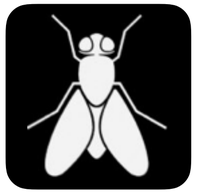


Program Count: **1 1 0 0**

Rule 5: Uniform Data Lifetime

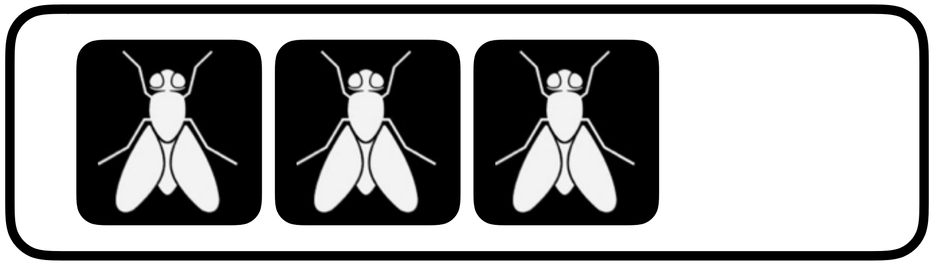
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD



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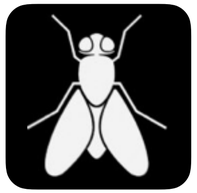
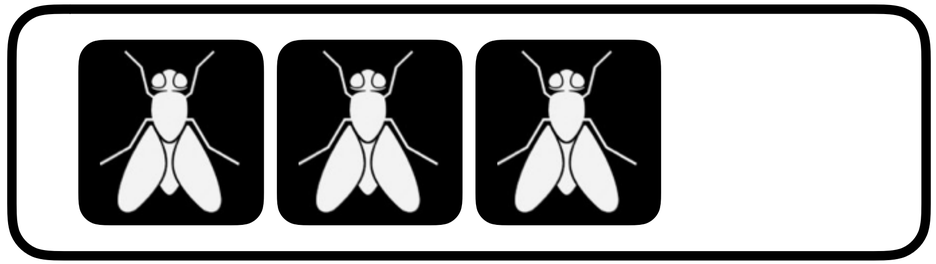


1 Day



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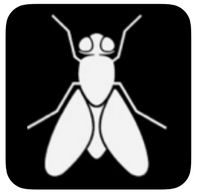

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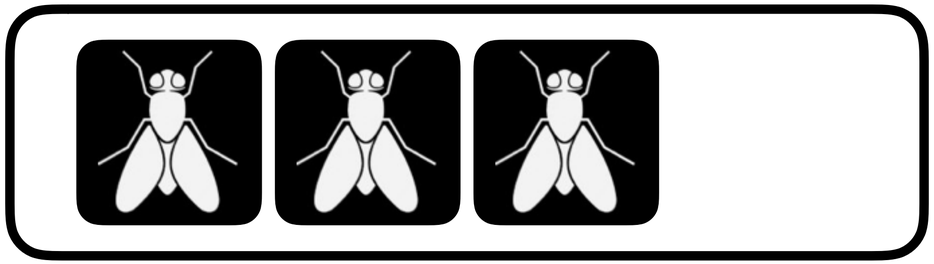

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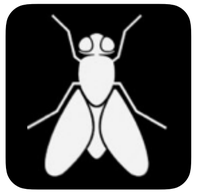

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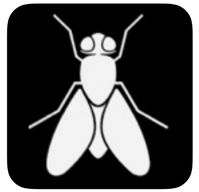
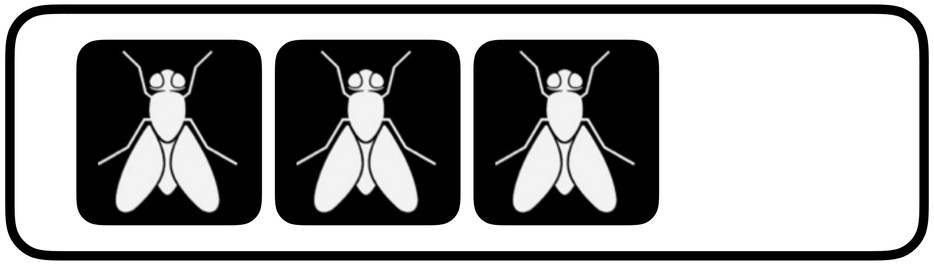


SSD



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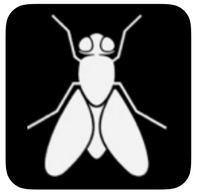

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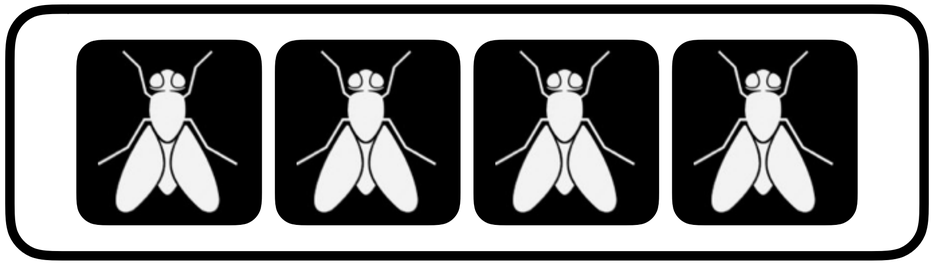

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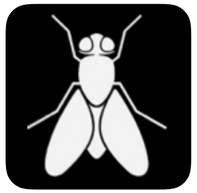

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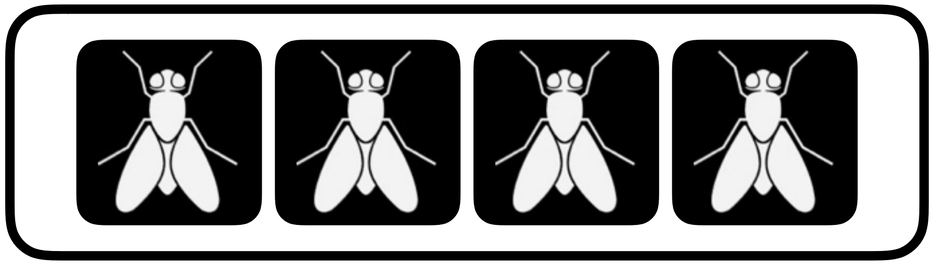

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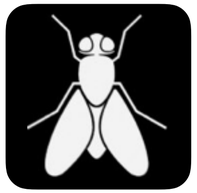

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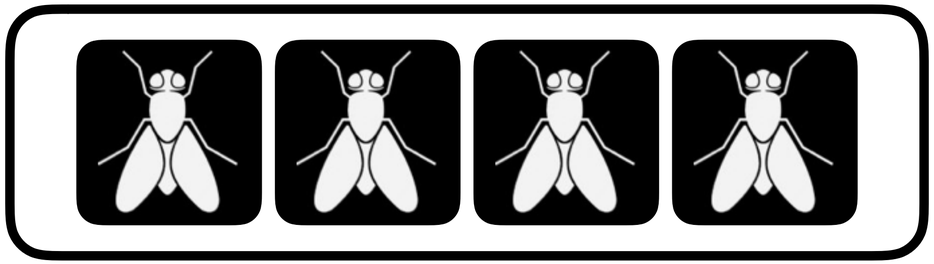

Program Count: **1 1 1 1**

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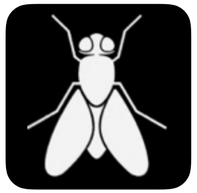

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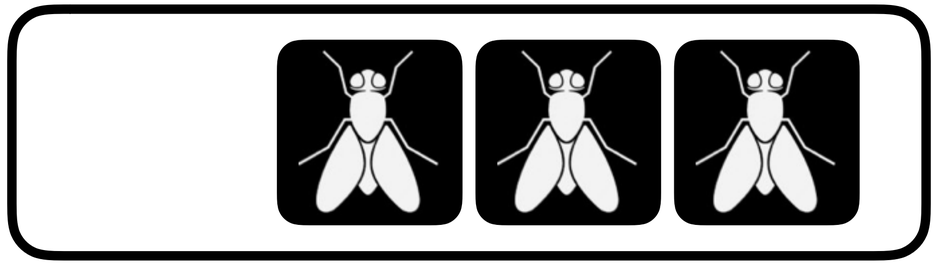

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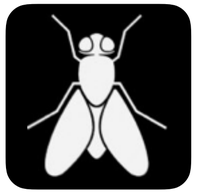

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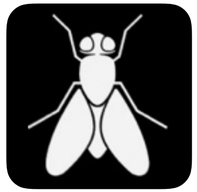
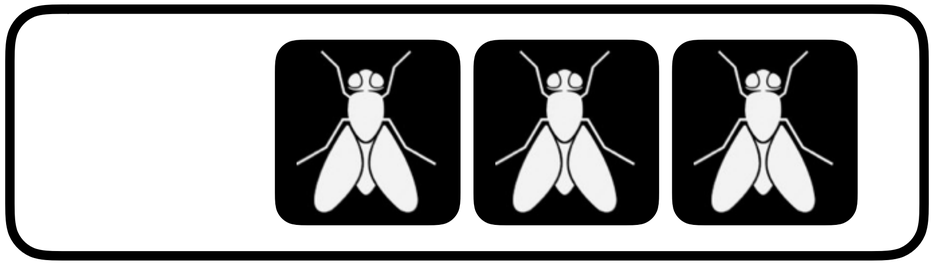


SSD



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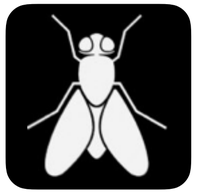

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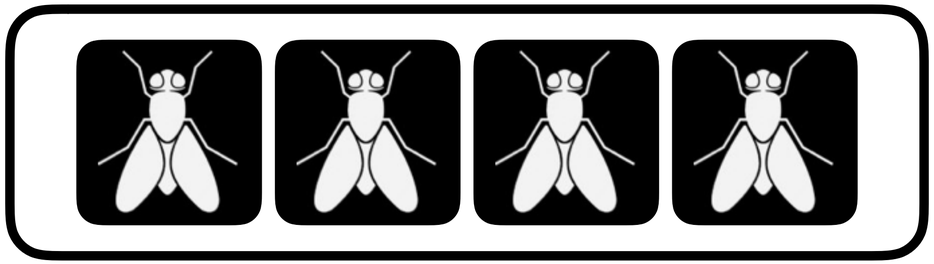

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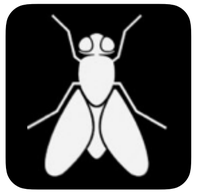

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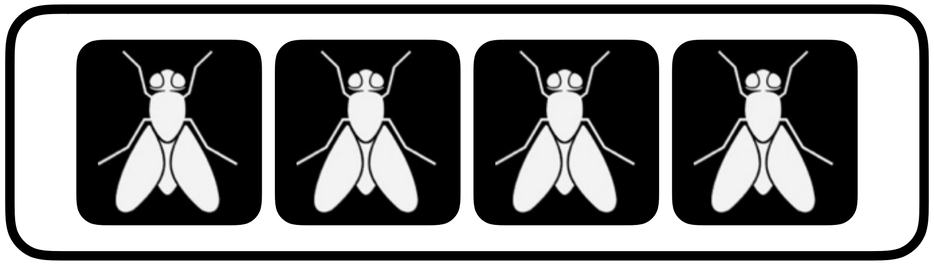

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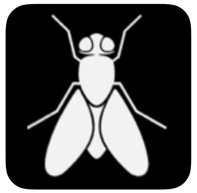
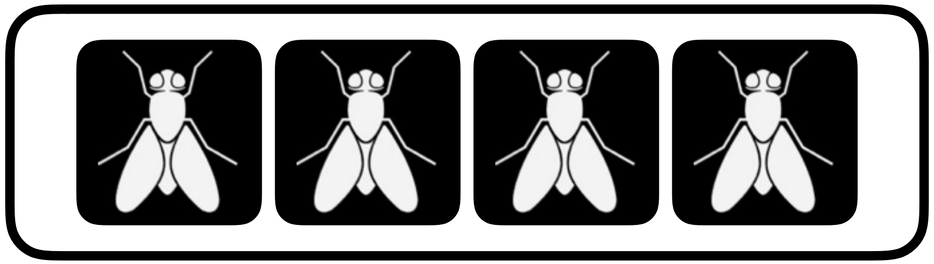


1 Day

SSD



Program Count: **2 1 1 1**

Rule 5: Uniform Data Lifetime

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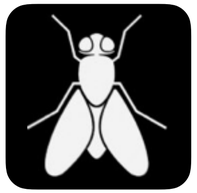
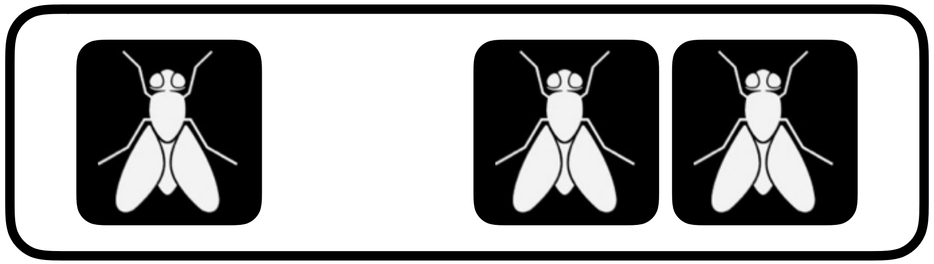


1 Day

SSD



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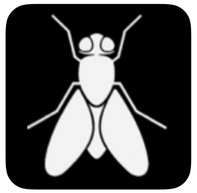
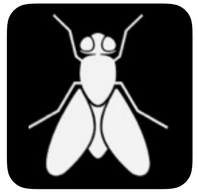
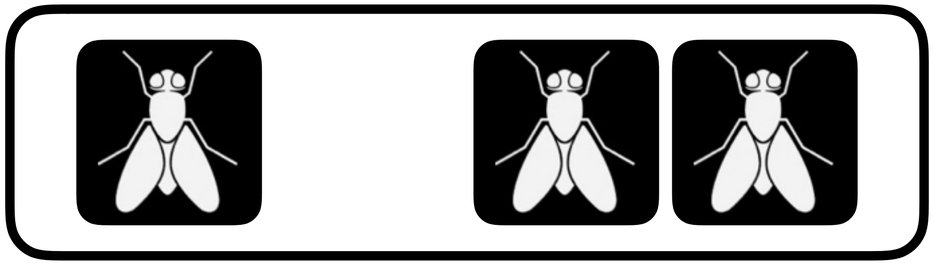


1 Day



SSD



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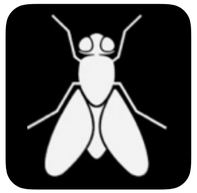

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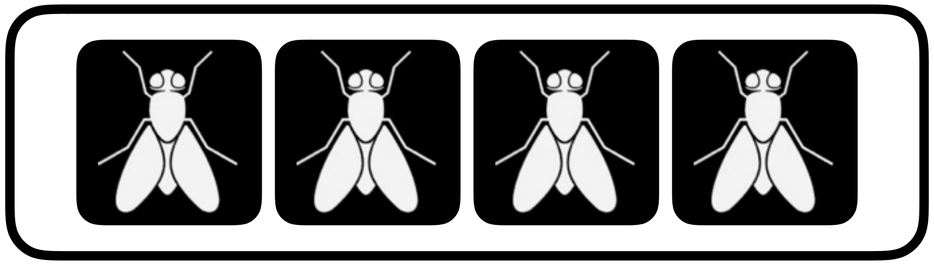

Program Count: **2** **1** **1** **1**

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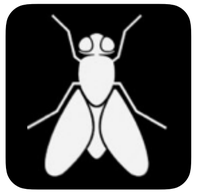

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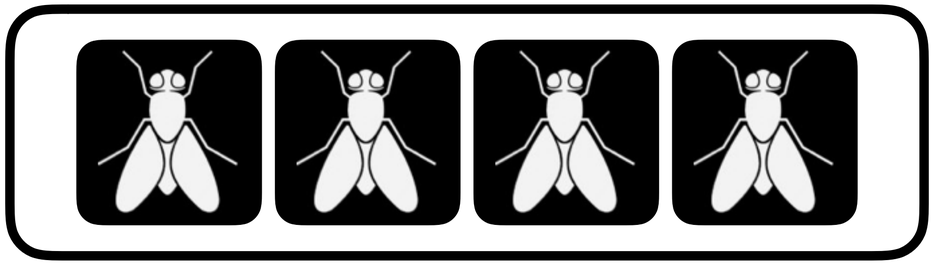

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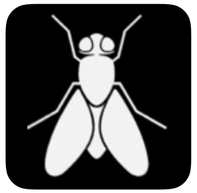

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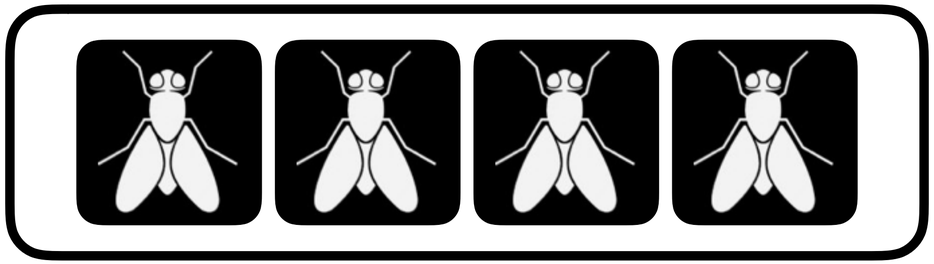

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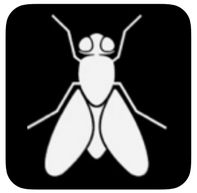

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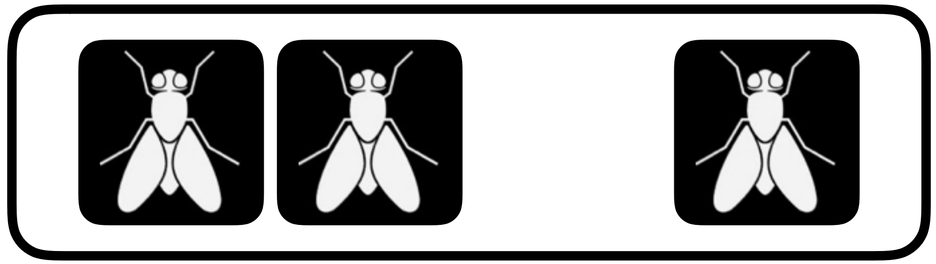

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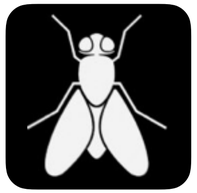

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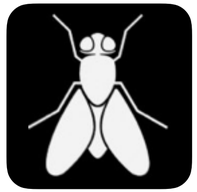

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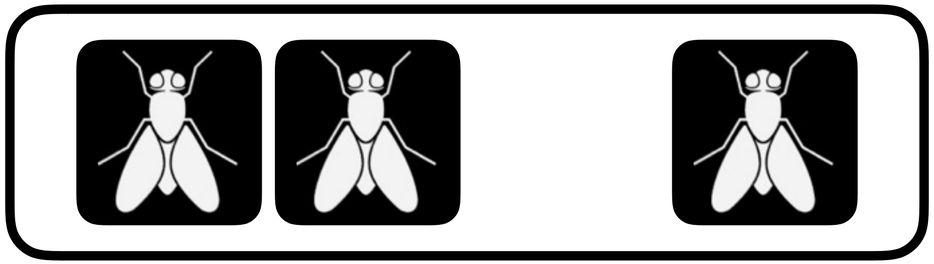

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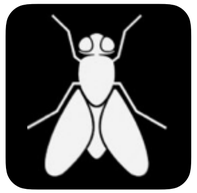

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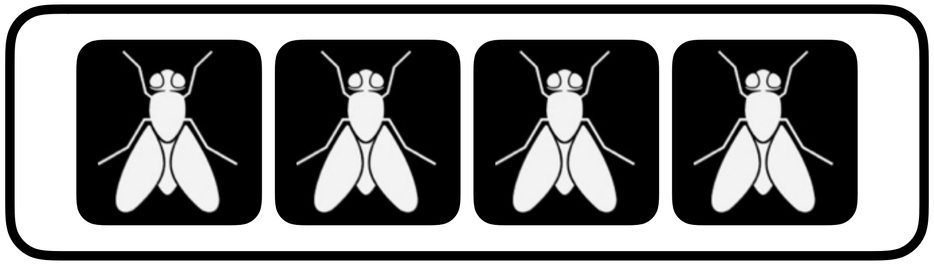

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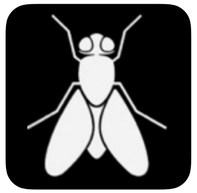
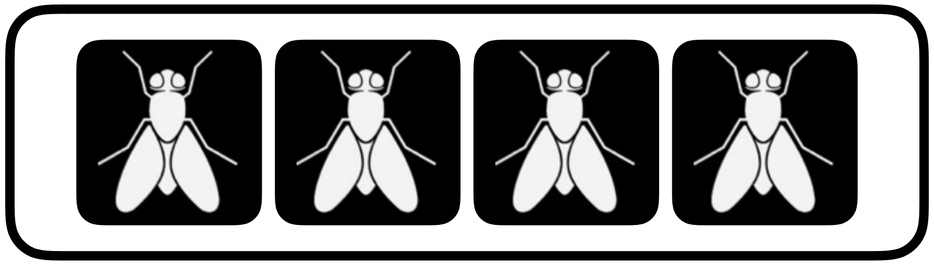


1 Day

SSD

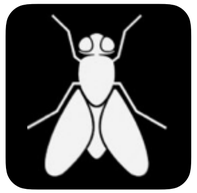


Program Count: **2** **2** **1**

Rule 5: Uniform Data Lifetime

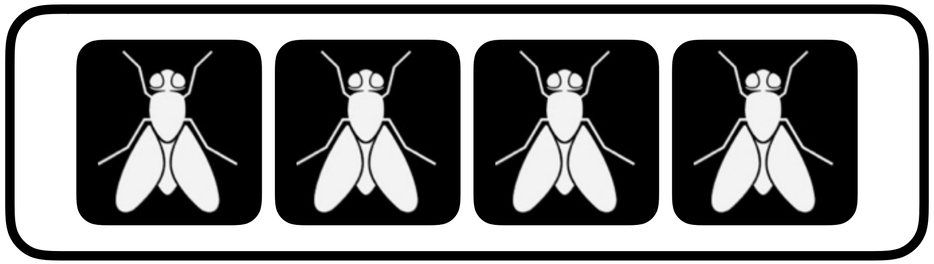
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD



Program Count: **2 2 2 1**

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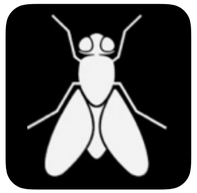
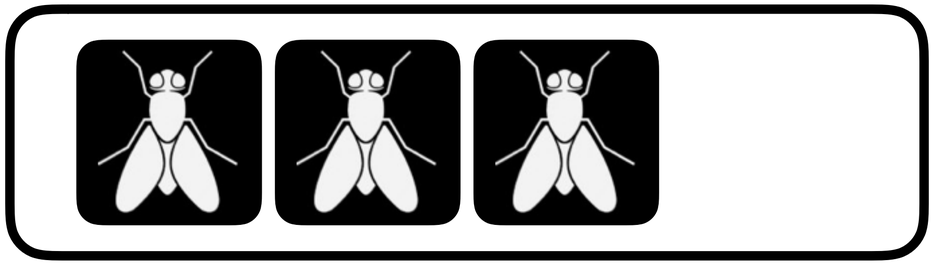


1 Day

SSD



Program Count: **2 2 2 1**

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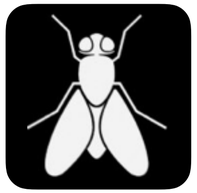
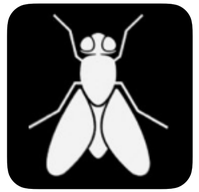
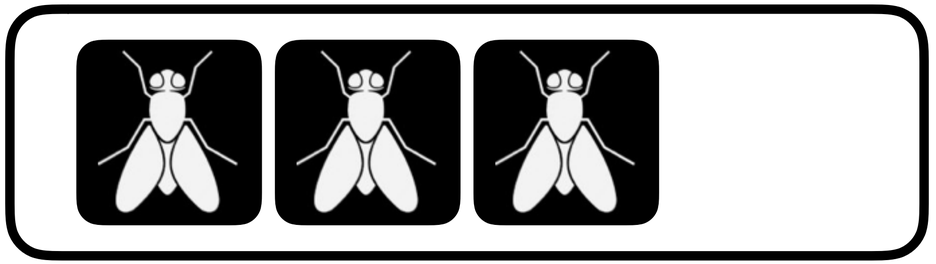


1 Day



SSD



Program Count: **2 2 2 1**

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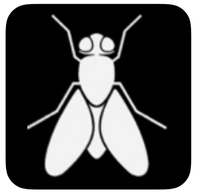
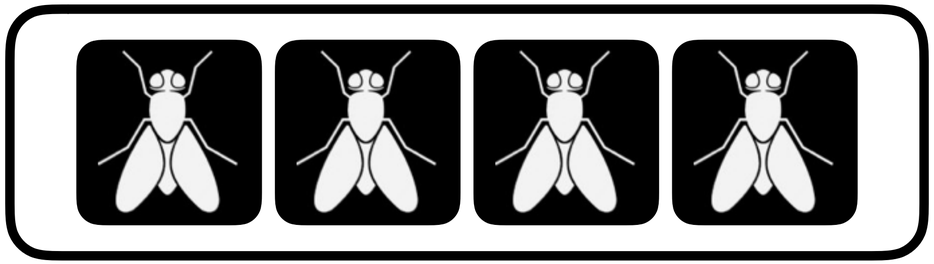


1 Day

SSD



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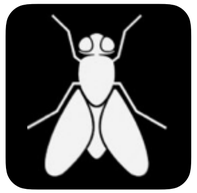
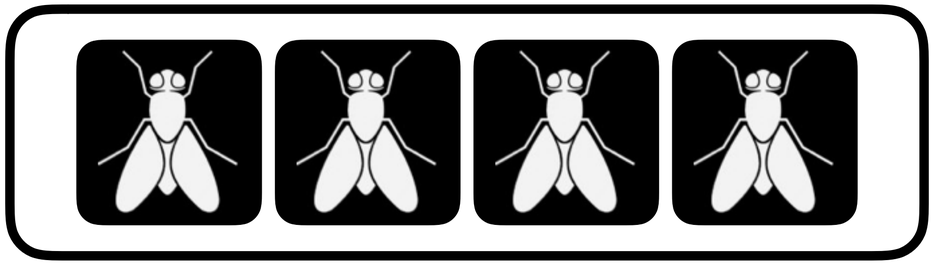


1 Day

SSD



Program Count: **2** **2** **2**

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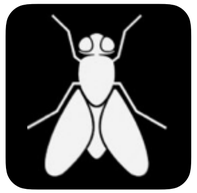
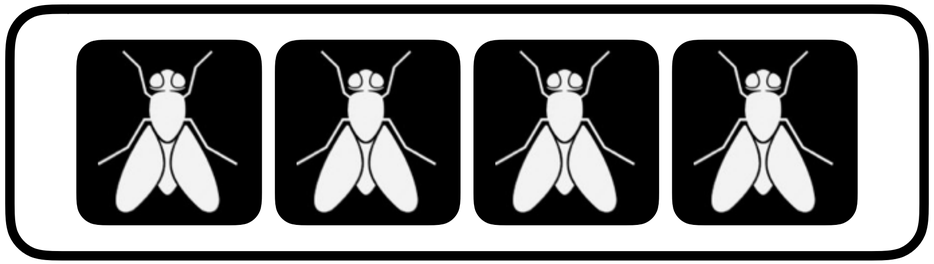


1 Day

SSD



Program Count: **2** **2** **2** **2**

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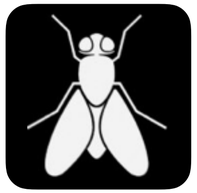

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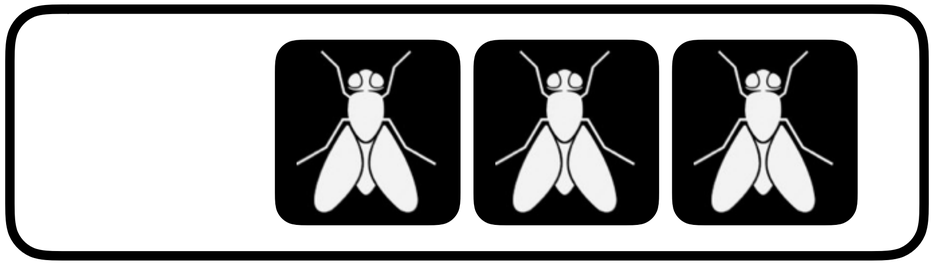
SSD



Program Count: **2** **2** **2** **2**

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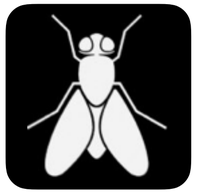
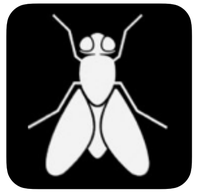
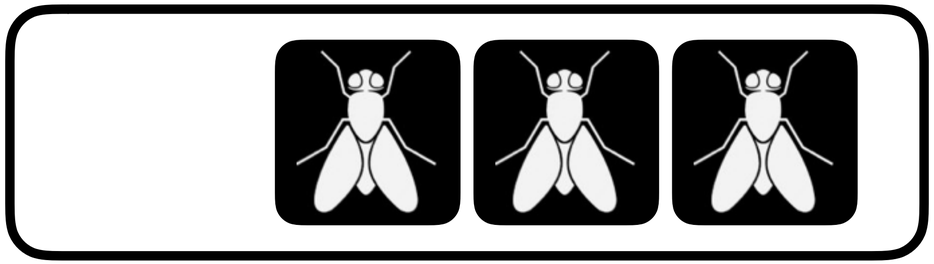
Lifetime



1 Day



SSD



Program Count: **2** **2** **2** **2**

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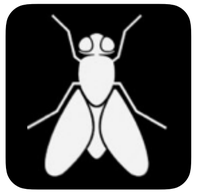
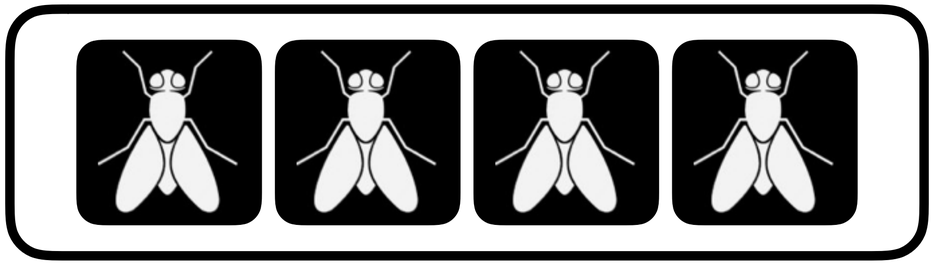


1 Day

SSD



Program Count: **2** **2** **2** **2**

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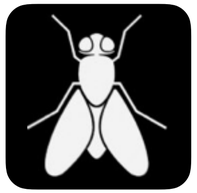
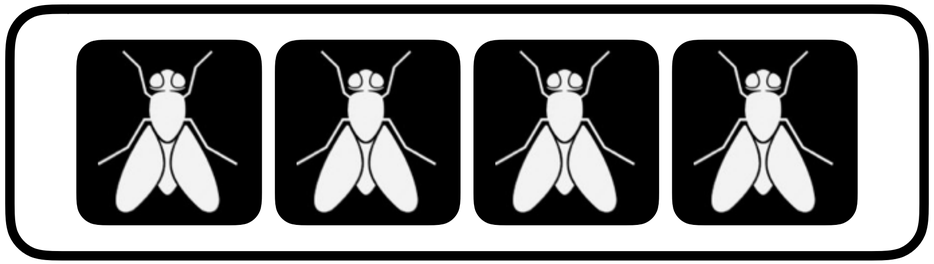


1 Day

SSD



Program Count: **2** **2** **2**

Rule 5: Uniform Data Lifetime

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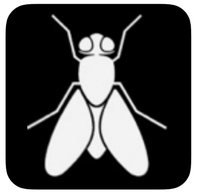
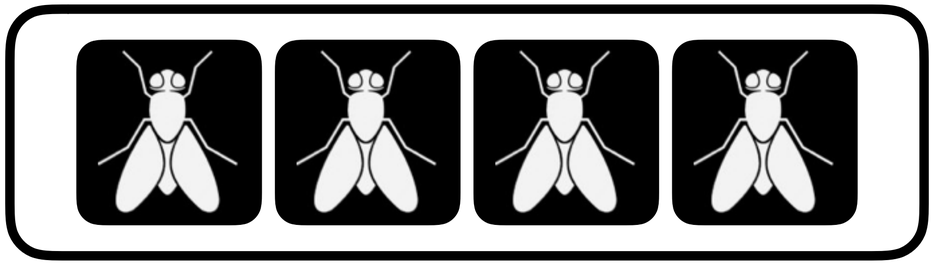
Lifetime



1 Day

SSD

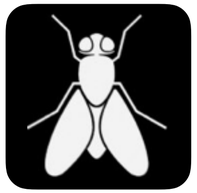


Program Count: **3** **2** **2** **2**

Rule 5: Uniform Data Lifetime

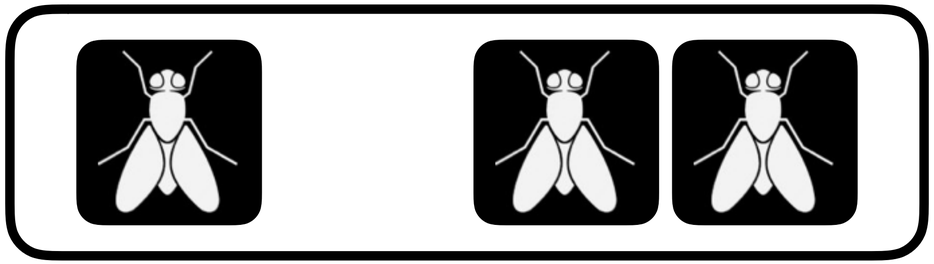
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD



Program Count: **3** **2** **2** **2**

Rule 5: Uniform Data Lifetime

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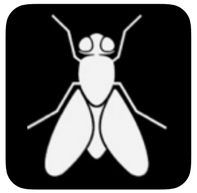
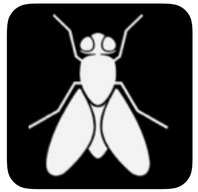
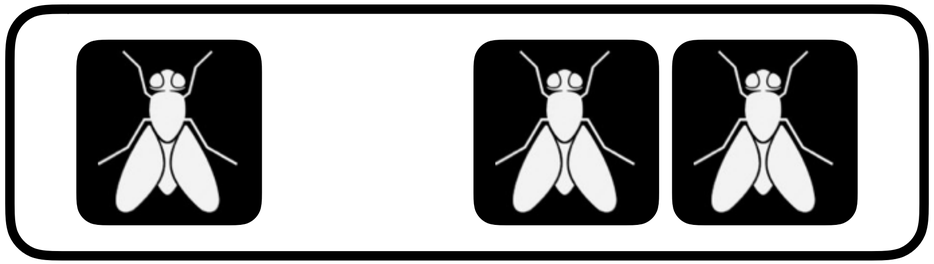
Lifetime



1 Day



SSD



Program Count: **3** **2** **2** **2**

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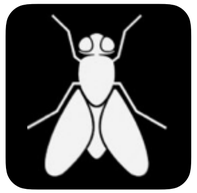
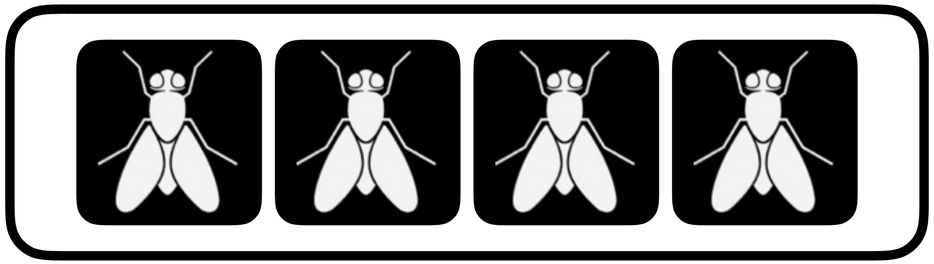
Lifetime



1 Day

SSD



Program Count: **3** **2** **2** **2**

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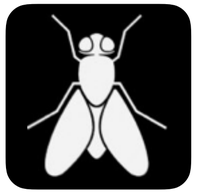

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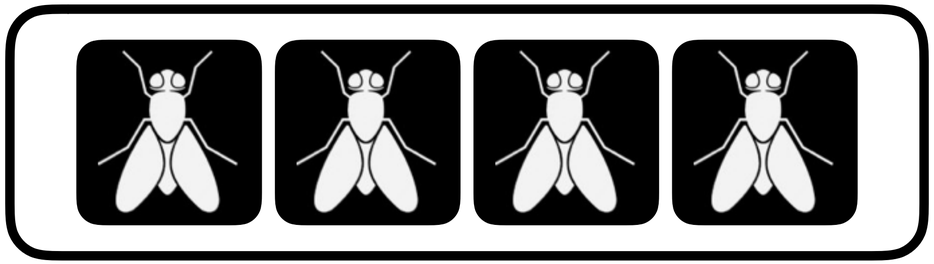
SSD



Program Count: **3** **2** **2**

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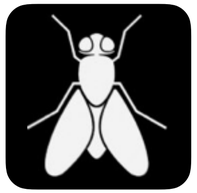

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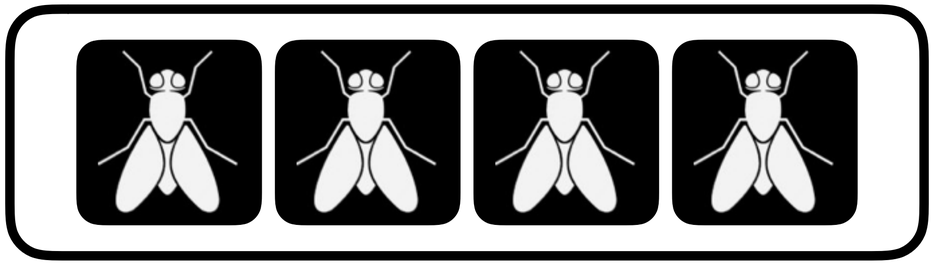
SSD



Program Count: **3** **3** **2** **2**

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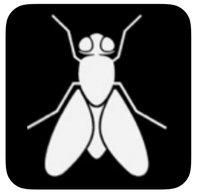
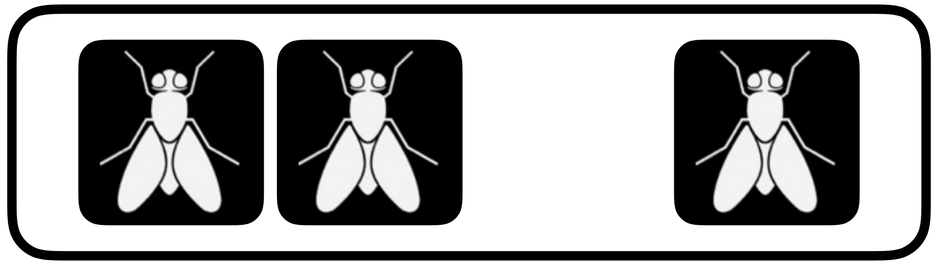


1 Day



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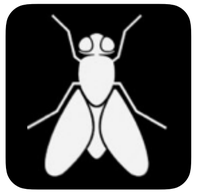

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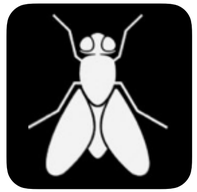
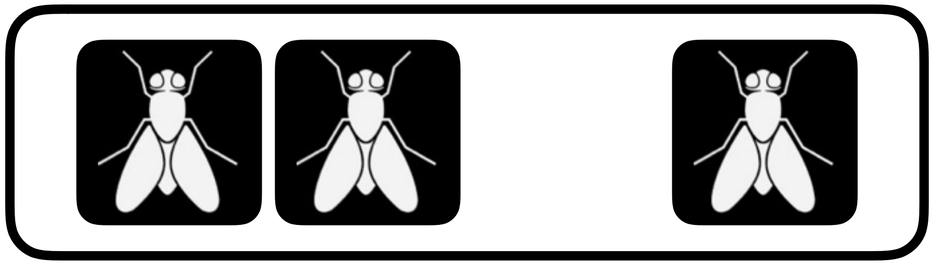


SSD



Program Count: 3 3 2 2

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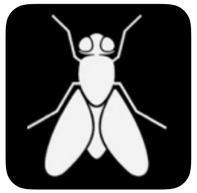
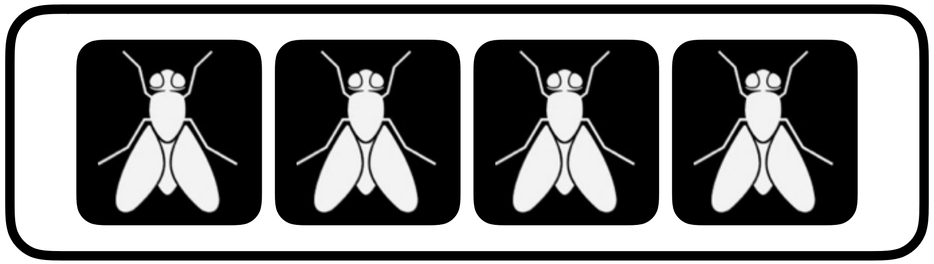
Lifetime



1 Day

SSD



Program Count: **3** **3** **2** **2**

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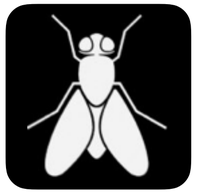

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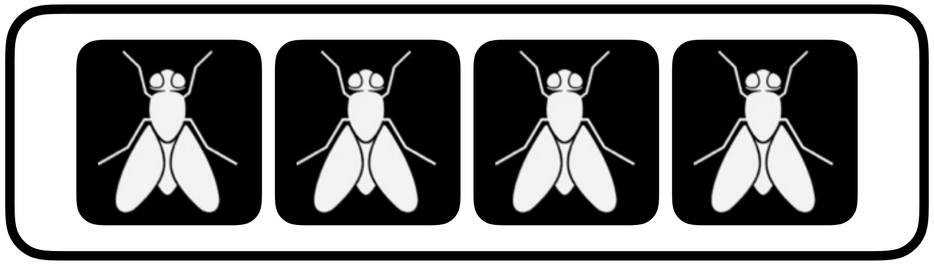
SSD



Program Count: **3** **3** **2**

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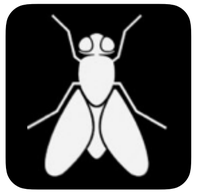
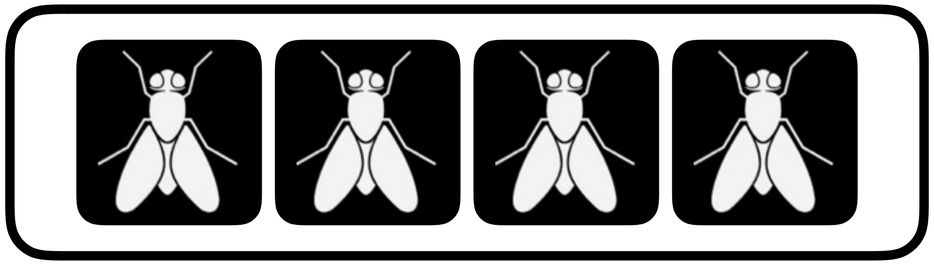
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD

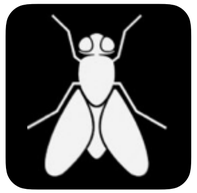


Program Count: **3** **3** **3** **2**

Rule 5: Uniform Data Lifetime

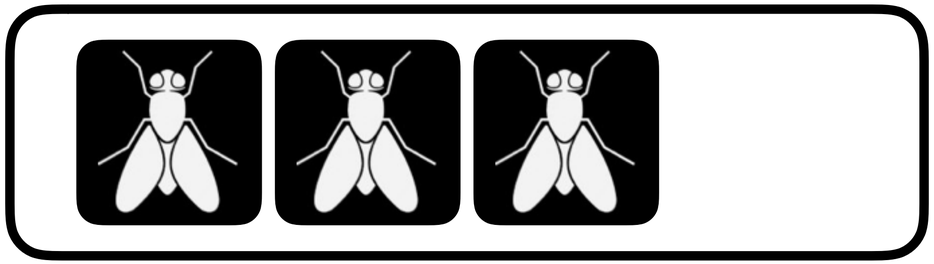
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD

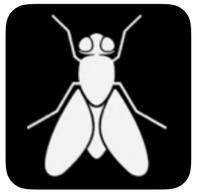


Program Count: **3** **3** **3** **2**

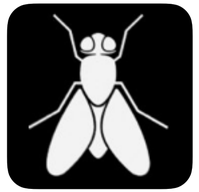
Rule 5: Uniform Data Lifetime

Clients of SSDs should create data with similar lifetimes

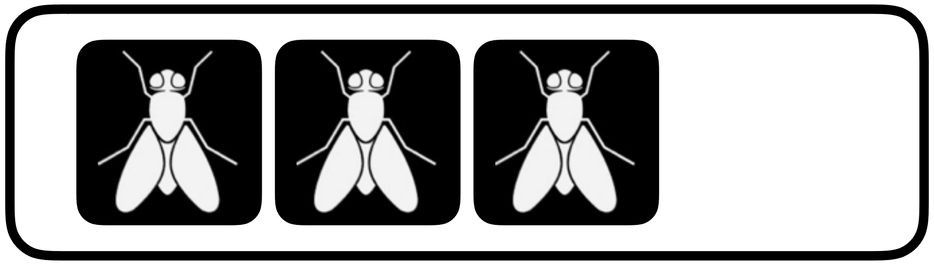
Lifetime



1 Day



SSD

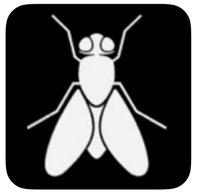


Program Count: **3** **3** **3** **2**

Rule 5: Uniform Data Lifetime

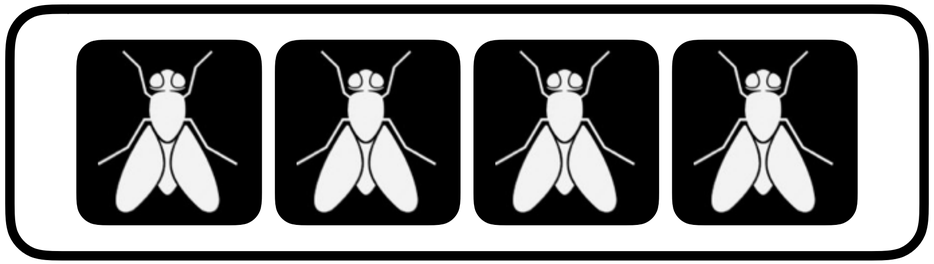
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD

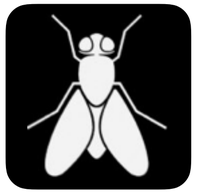


Program Count: **3** **3** **3** **2**

Rule 5: Uniform Data Lifetime

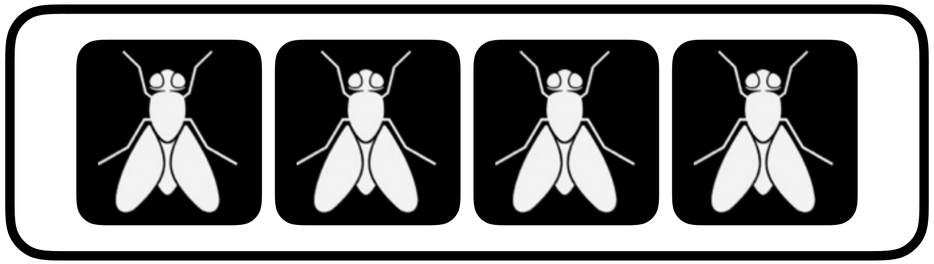
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD

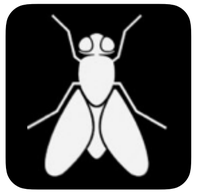


Program Count: **3** **3** **3**

Rule 5: Uniform Data Lifetime

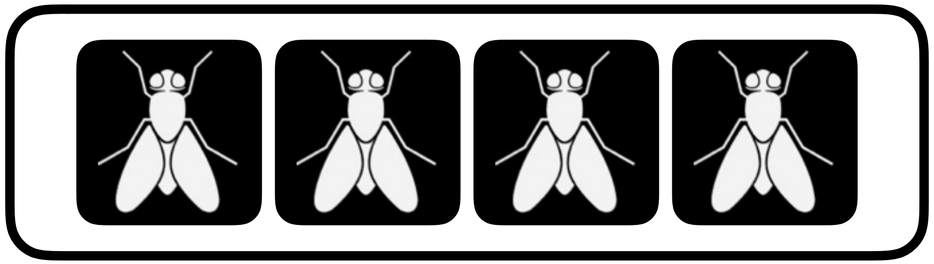
Clients of SSDs should create data with similar lifetimes

Lifetime



1 Day

SSD

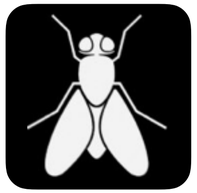


Program Count: **3** **3** **3** **3**

Rule 5: Uniform Data Lifetime

Clients of SSDs should create data with similar lifetimes

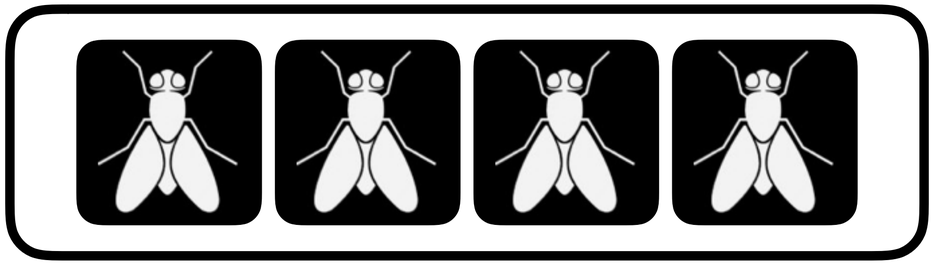
Lifetime



1 Day

No wear-leveling needed

SSD

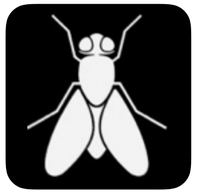


Program Count: **3** **3** **3** **3**

Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

1000 Years

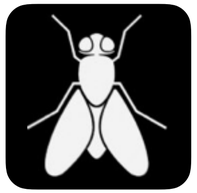
SSD

Program Count: **0** **0** **0** **0**

Rule 5: Uniform Data Lifetime

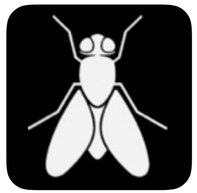
Violation

Lifetime



1 Day

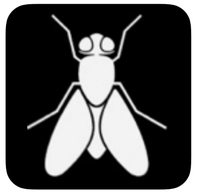
1000 Years



Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

1000 Years

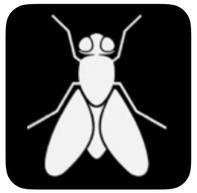
SSD

Program Count: **0** **0** **0** **0**

Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

1000 Years

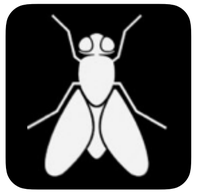
SSD

Program Count: **0** **0** **0**

Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

1000 Years

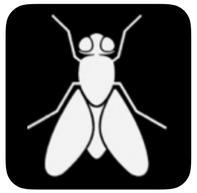
SSD

Program Count: **1 0 0 0**

Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

1000 Years

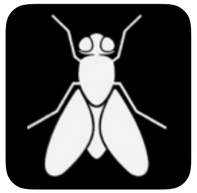
SSD

Program Count: 1 0 0 0

Rule 5: Uniform Data Lifetime

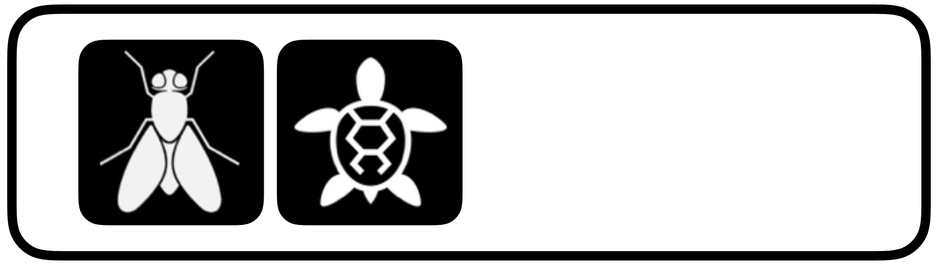
Violation

Lifetime



1 Day

1000 Years

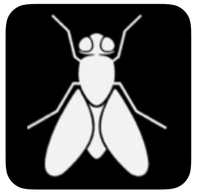


Program Count: 1 0 0 0

Rule 5: Uniform Data Lifetime

Violation

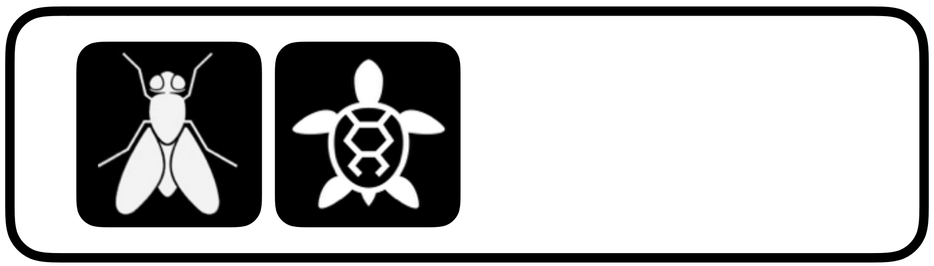
Lifetime



1 Day

1000 Years

SSD

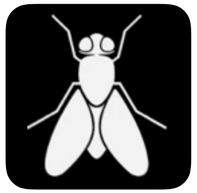


Program Count: **1** **0** **0**

Rule 5: Uniform Data Lifetime

Violation

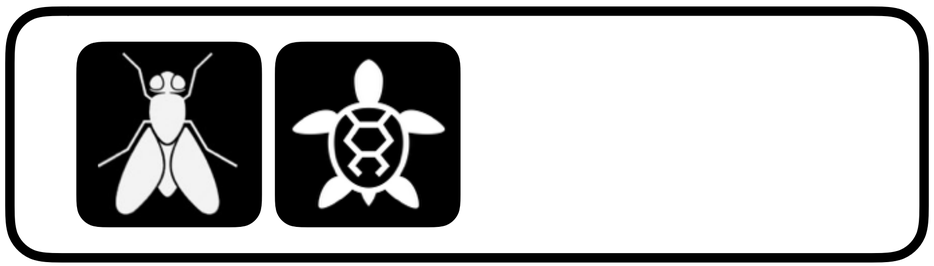
Lifetime



1 Day

1000 Years

SSD

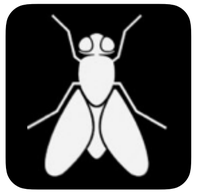


Program Count: 1 1 0 0

Rule 5: Uniform Data Lifetime

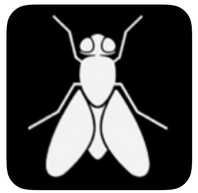
Violation

Lifetime

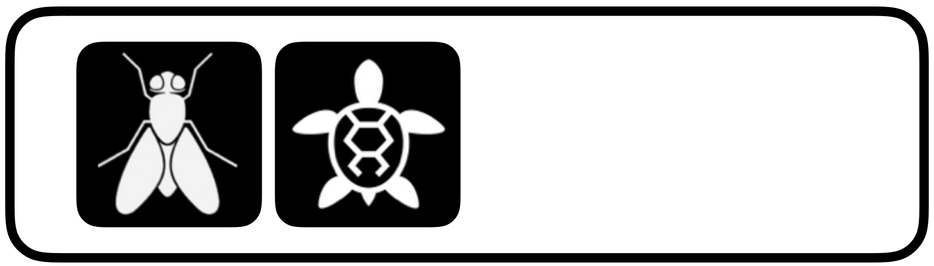


1 Day

1000 Years



SSD

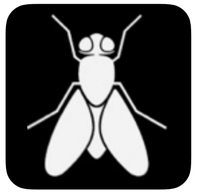


Program Count: 1 1 0 0

Rule 5: Uniform Data Lifetime

Violation

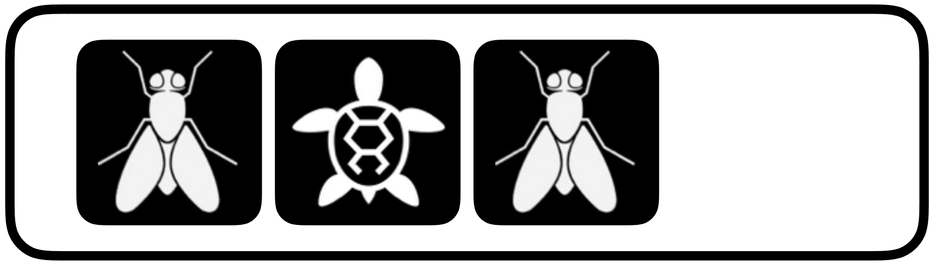
Lifetime



1 Day

1000 Years

SSD

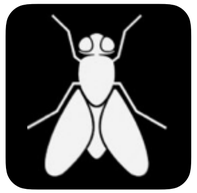


Program Count: 1 1 0 0

Rule 5: Uniform Data Lifetime

Violation

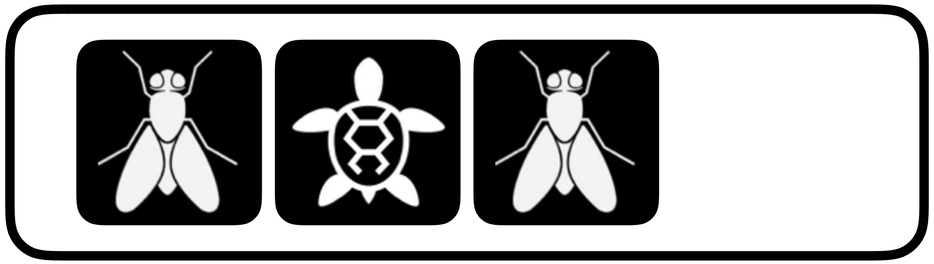
Lifetime



1 Day

1000 Years

SSD

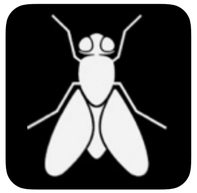


Program Count: **1** **1** **0**

Rule 5: Uniform Data Lifetime

Violation

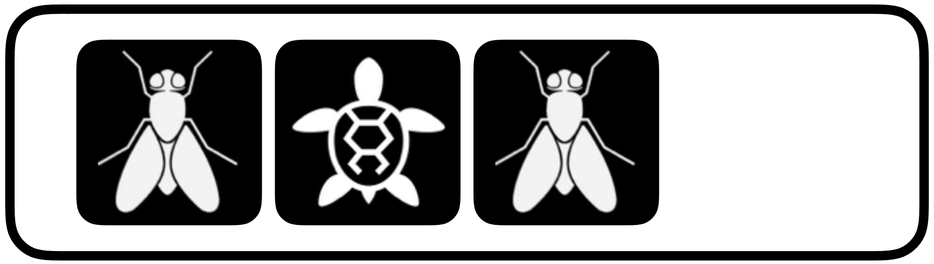
Lifetime



1 Day

1000 Years

SSD

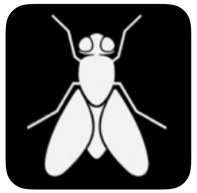


Program Count: **1 1 1 0**

Rule 5: Uniform Data Lifetime

Violation

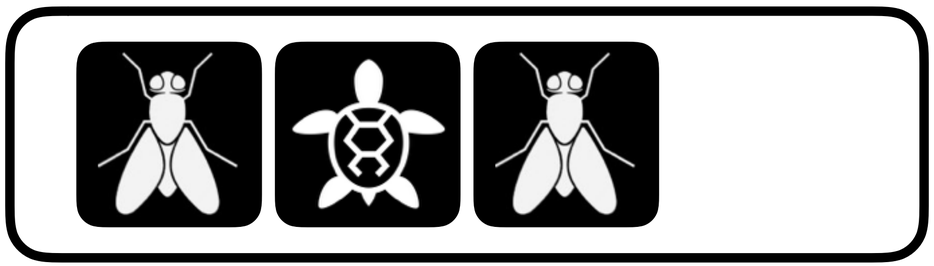
Lifetime



1 Day

1000 Years

SSD

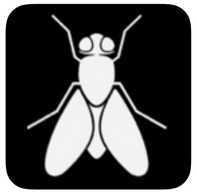


Program Count: 1 1 1 0

Rule 5: Uniform Data Lifetime

Violation

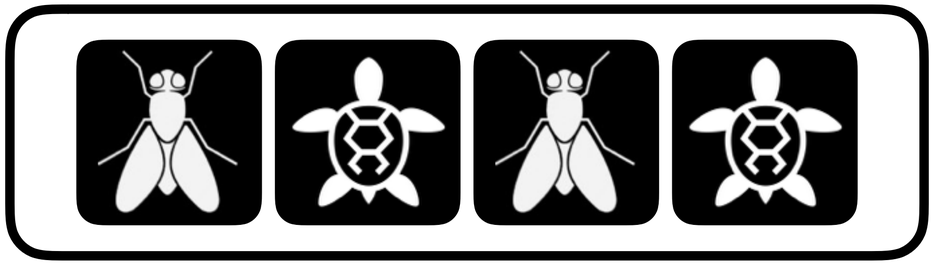
Lifetime



1 Day

1000 Years

SSD

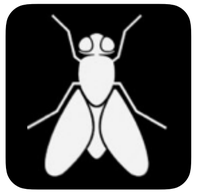


Program Count: **1 1 1 0**

Rule 5: Uniform Data Lifetime

Violation

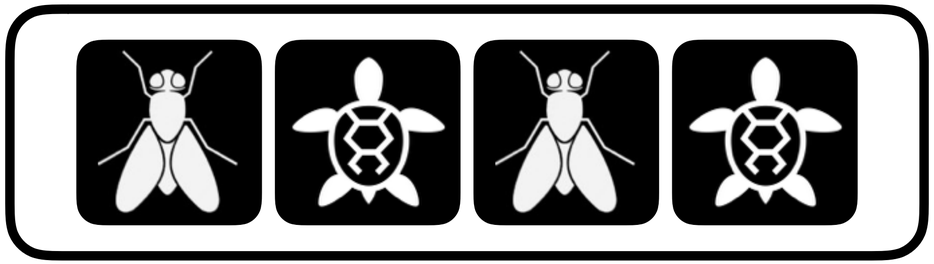
Lifetime



1 Day

1000 Years

SSD

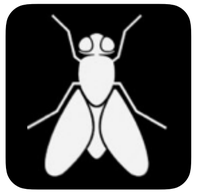


Program Count: 1 1 1

Rule 5: Uniform Data Lifetime

Violation

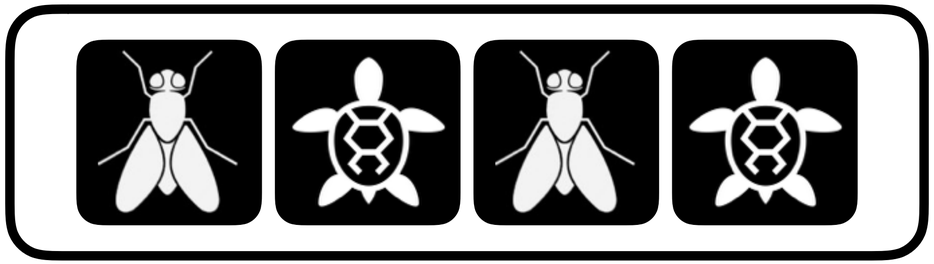
Lifetime



1 Day

1000 Years

SSD

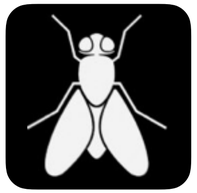


Program Count: 1 1 1 1

Rule 5: Uniform Data Lifetime

Violation

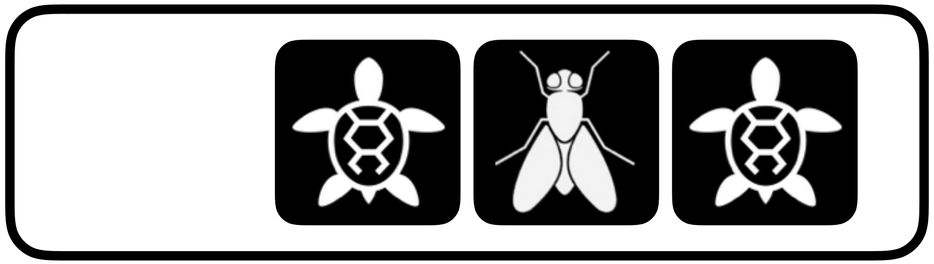
Lifetime



1 Day

1000 Years

SSD

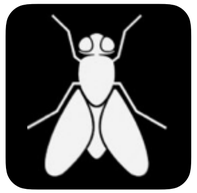


Program Count: 1 1 1 1

Rule 5: Uniform Data Lifetime

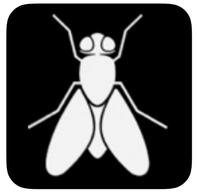
Violation

Lifetime

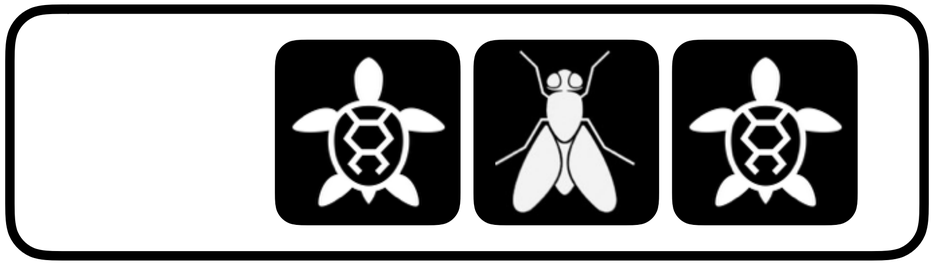


1 Day

1000 Years



SSD

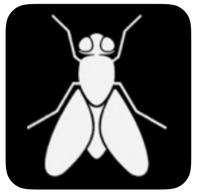


Program Count: 1 1 1 1

Rule 5: Uniform Data Lifetime

Violation

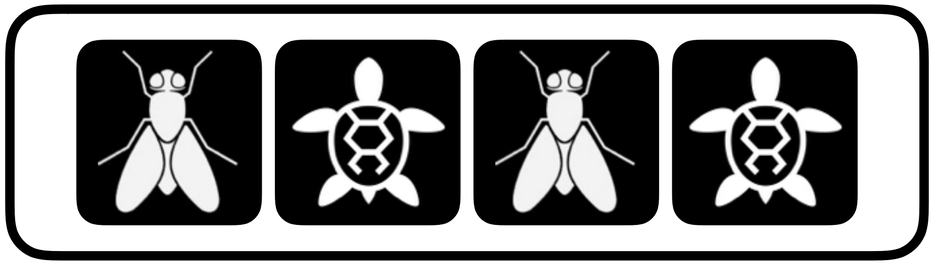
Lifetime



1 Day

1000 Years

SSD

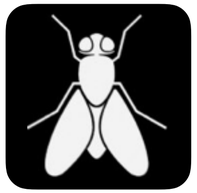


Program Count: 1 1 1 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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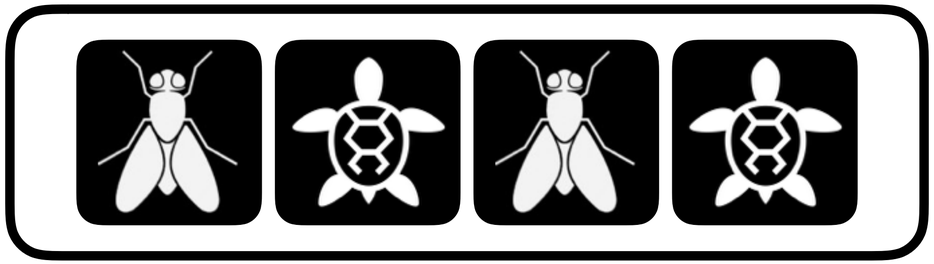
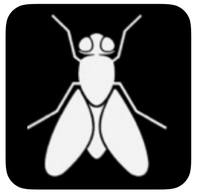


Program Count: 1 1 1

Rule 5: Uniform Data Lifetime

Violation

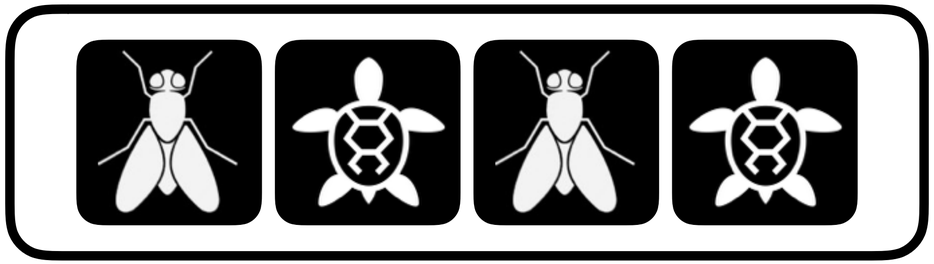
Lifetime



1 Day

1000 Years

SSD

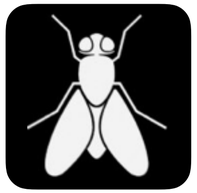


Program Count: 2 1 1 1

Rule 5: Uniform Data Lifetime

Violation

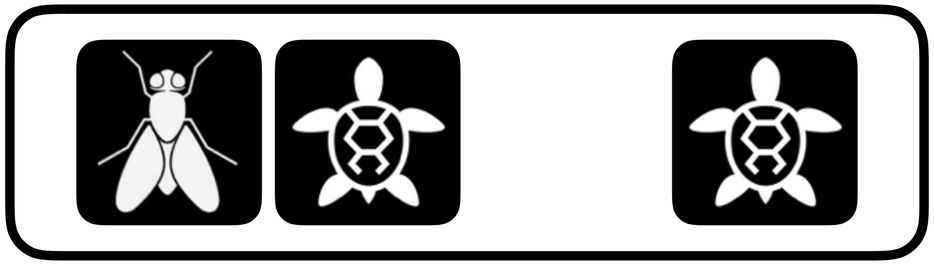
Lifetime



1 Day

1000 Years

SSD

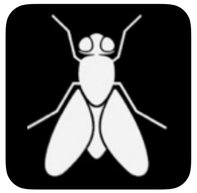


Program Count: 2 1 1 1

Rule 5: Uniform Data Lifetime

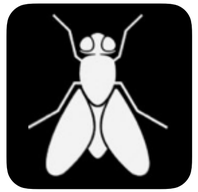
Violation

Lifetime

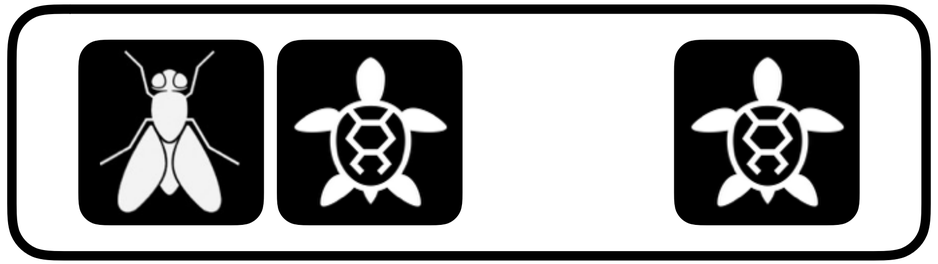


1 Day

1000 Years



SSD

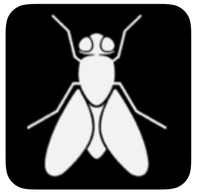


Program Count: 2 1 1 1

Rule 5: Uniform Data Lifetime

Violation

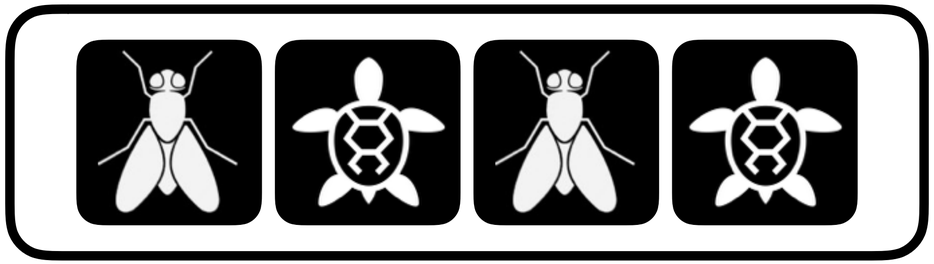
Lifetime



1 Day

1000 Years

SSD

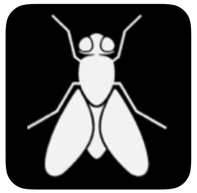


Program Count: 2 1 1 1

Rule 5: Uniform Data Lifetime

Violation

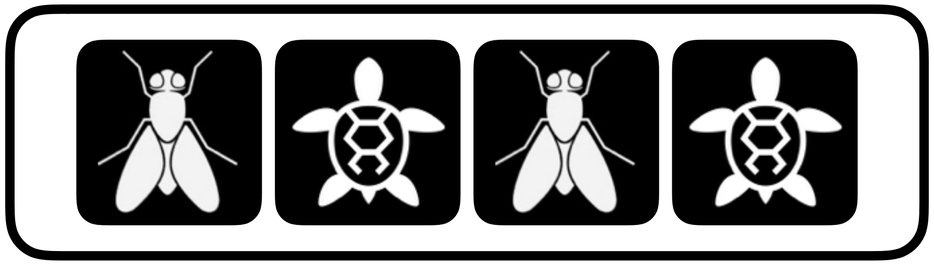
Lifetime



1 Day

1000 Years

SSD

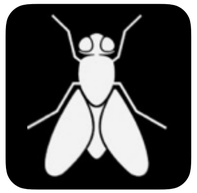


Program Count: 2 1 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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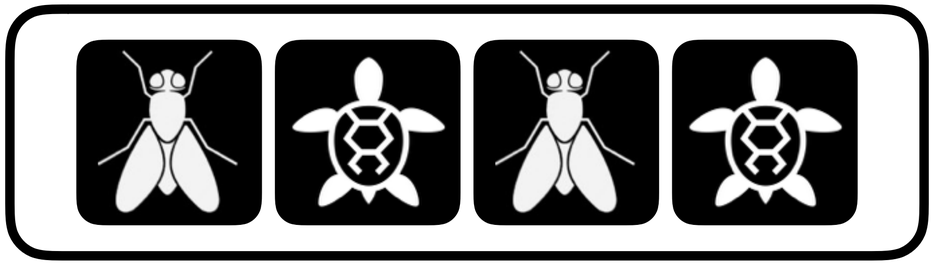
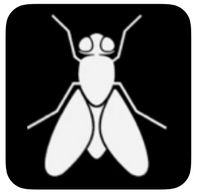


Program Count: 2 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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1000 Years

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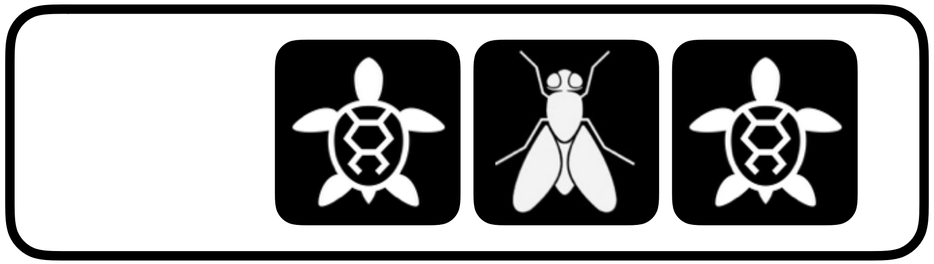
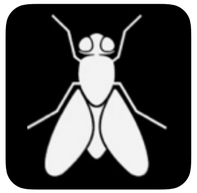


Program Count: 2 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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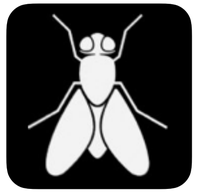
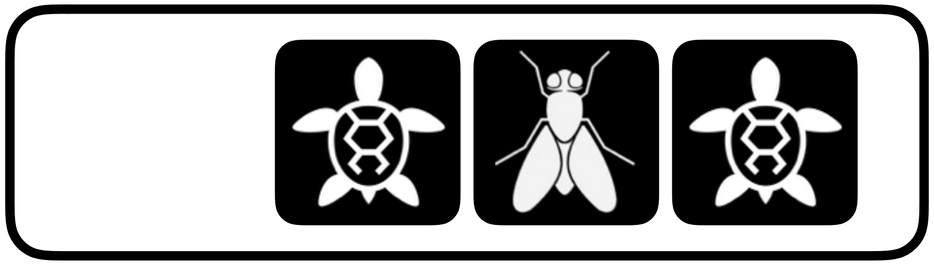
1000 Years



SSD

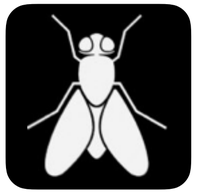


Program Count: 2 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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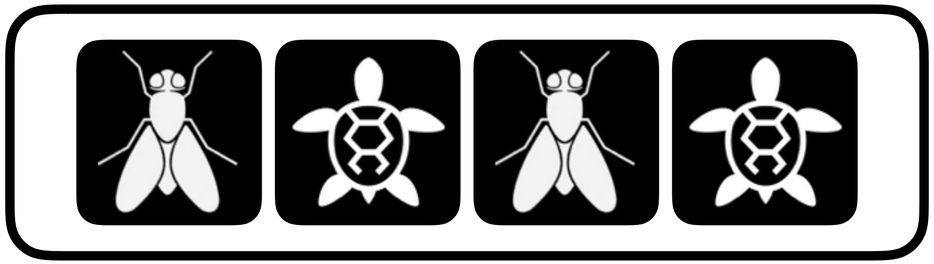
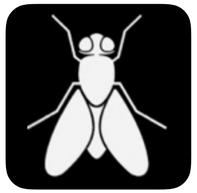


Program Count: 2 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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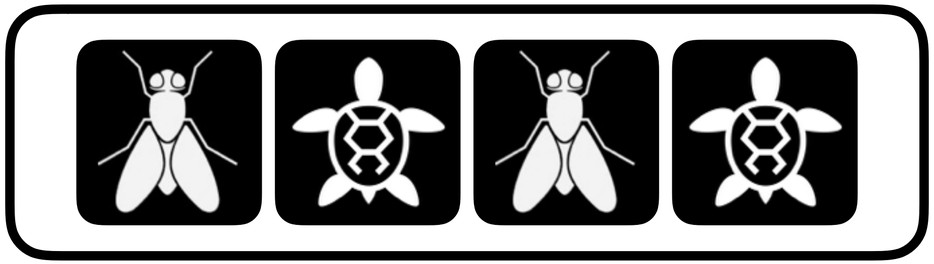
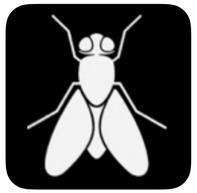


Program Count: 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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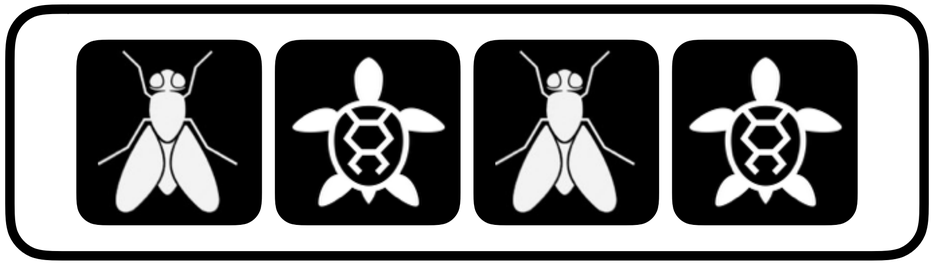
1000 Years

SSD

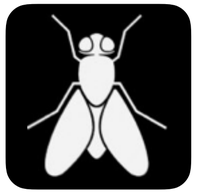


Program Count: 3 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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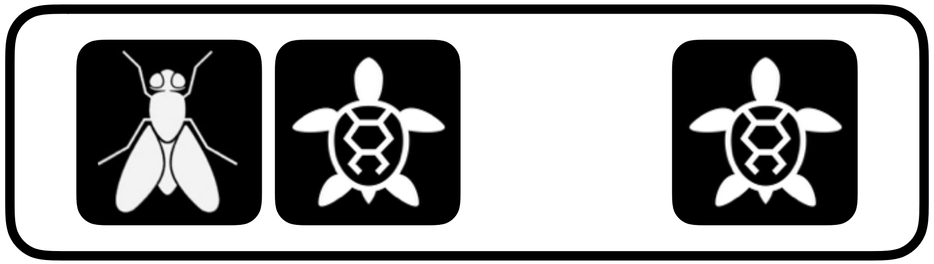
1000 Years

SSD

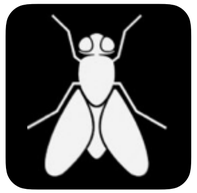


Program Count: 3 1 2 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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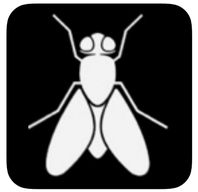

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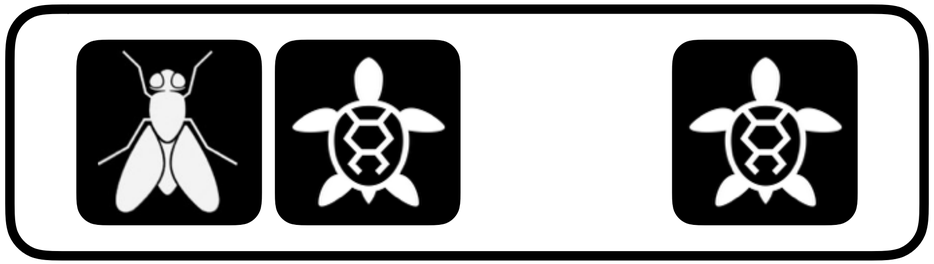

Program Count: 3 1 2 1

Rule 5: Uniform Data Lifetime

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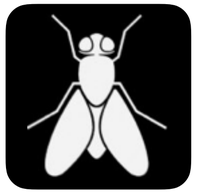

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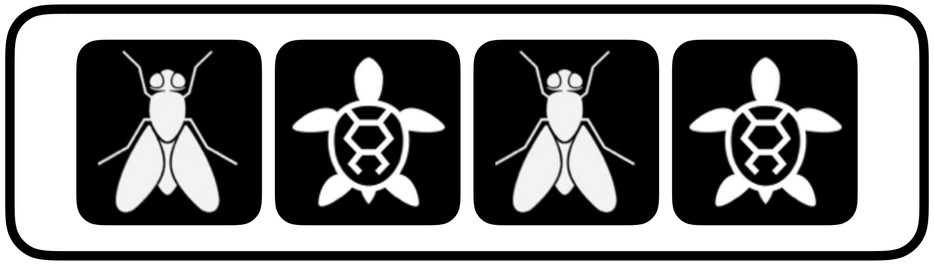

Program Count: 3 1 2 1

Rule 5: Uniform Data Lifetime

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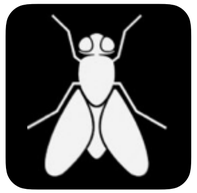

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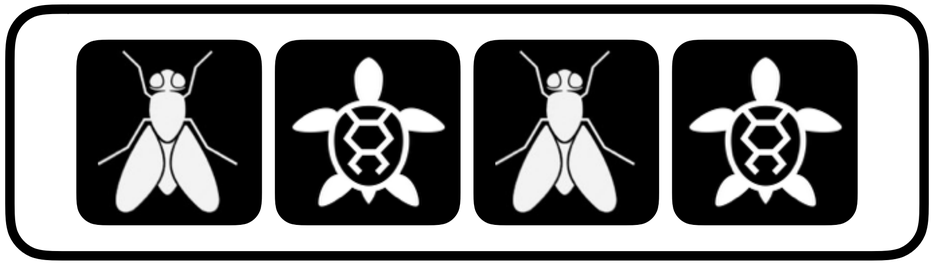
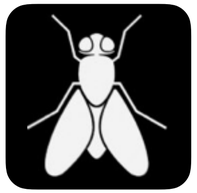


Program Count: 3 1 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



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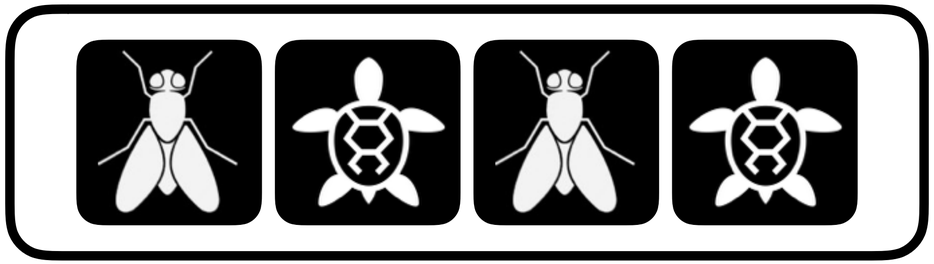
1000 Years

SSD



Program Count: 3 1 3 1

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Violation

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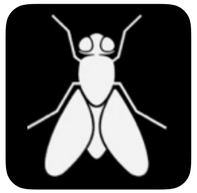

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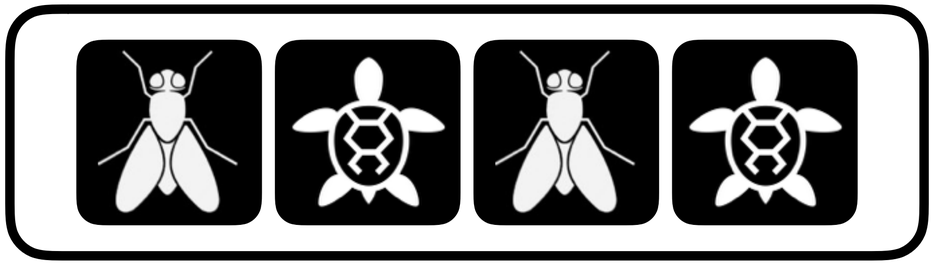

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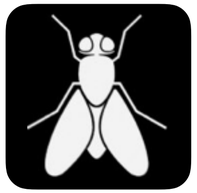
Rule 5: Uniform Data Lifetime

Violation

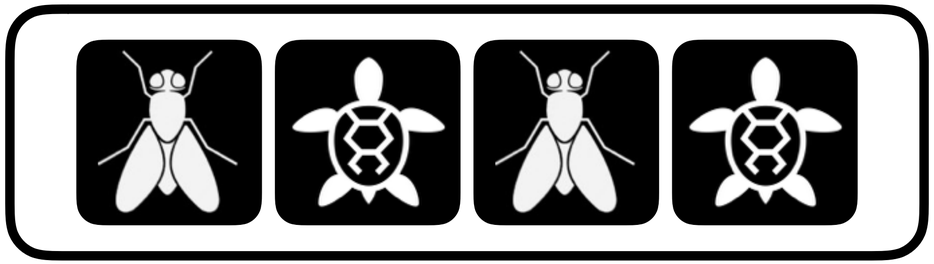
Lifetime



1 Day

1000 Years

SSD

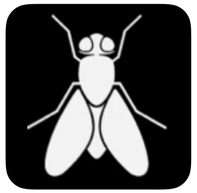


Program Count: 365*1000 1 365*1000 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime

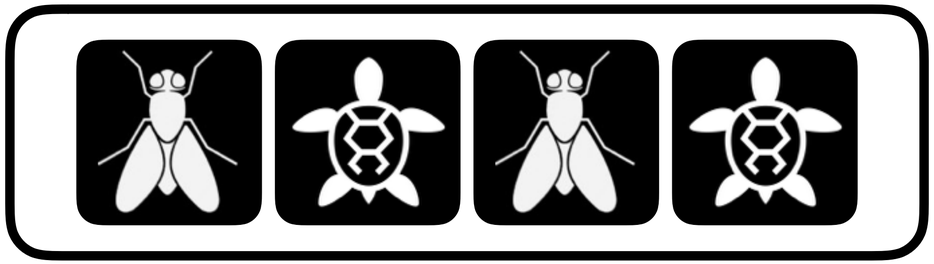


1 Day

1000 Years

Frequent wear-leveling needed!!!

SSD

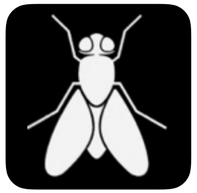


Program Count: 365*1000 1 365*1000 1

Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

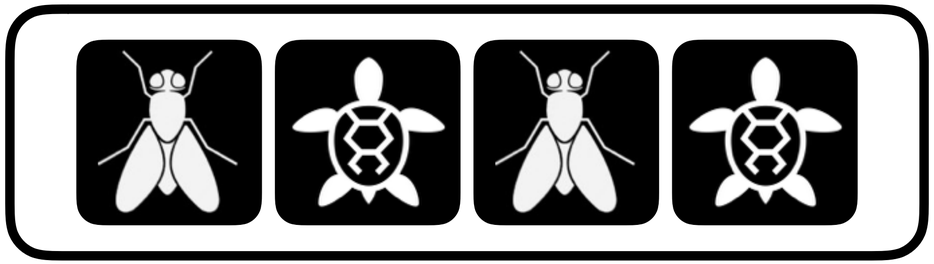
1000 Years

If you violate the rule:

- **Performance penalty**
- **Write amplification**

Frequent wear-leveling needed!!!

SSD

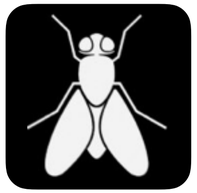


Program Count: **365*1000** **1** **365*1000** **1**

Rule 5: Uniform Data Lifetime

Violation

Lifetime



1 Day

1000 Year

If you violate the rule:

- **Performance penalty**
- **Write amplification**

Performance impact:

1.6x write latency

S. Boboila and P. Desnoyers. Write Endurance in Flash Drives: Measurements and Analysis. In Proceedings of the 8th USENIX Symposium on File and Storage Technologies (FAST '10), San Jose, California, February 2010.

Program Count:

A FTL often has a subset of rules

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Rules

#1 Request Scale

#2 Locality

#3 Aligned Sequentiality

#4 Grouping by Death Time

#5 Uniform Data Lifetime

A FTL often has a subset of rules

Page-level Mapping FTL

Rules

#1 Request Scale

#2 Locality

#3 Aligned Sequentiality

#4 Grouping by Death Time

#5 Uniform Data Lifetime

A FTL often has a subset of rules

Rules	Page-level Mapping FTL
	Immediate
#1 Request Scale	**x**
#2 Locality	**x**
#3 Aligned Sequentiality	
#4 Grouping by Death Time	
#5 Uniform Data Lifetime	

A FTL often has a subset of rules

	Page-level Mapping FTL	
Rules	**Immediate**	**Sustainable**
#1 Request Scale	**x**	**x**
#2 Locality	**x**	**x**
#3 Aligned Sequentiality		
#4 Grouping by Death Time		**x**
#5 Uniform Data Lifetime		**x**

A FTL often has a subset of rules

	Page-level Mapping FTL		Hybrid Mapping FTL
Rules	**Immediate**	**Sustainable**	
#1 Request Scale	**x**	**x**	
#2 Locality	**x**	**x**	
#3 Aligned Sequentiality			
#4 Grouping by Death Time		**x**	
#5 Uniform Data Lifetime		**x**	

A FTL often has a subset of rules

	Page-level Mapping FTL		Hybrid Mapping FTL
Rules	**Immediate**	**Sustainable**	**Immediate**
#1 Request Scale	**x**	**x**	**x**
#2 Locality	**x**	**x**	
#3 Aligned Sequentiality			
#4 Grouping by Death Time		**x**	
#5 Uniform Data Lifetime		**x**	

A FTL often has a subset of rules

	Page-level Mapping FTL		Hybrid Mapping FTL	
Rules	**Immediate**	**Sustainable**	**Immediate**	**Sustainable**
#1 Request Scale	**x**	**x**	**x**	**x**
#2 Locality	**x**	**x**		
#3 Aligned Sequentiality				**x**
#4 Grouping by Death Time		**x**		
#5 Uniform Data Lifetime		**x**		**x**

Do applications/file systems comply with the unwritten contract?

Outline

- Overview
- SSD Unwritten Contract
- **Violations of Unwritten Contract**
  - Method
  - Observations
- Lessons Learned
- Conclusions

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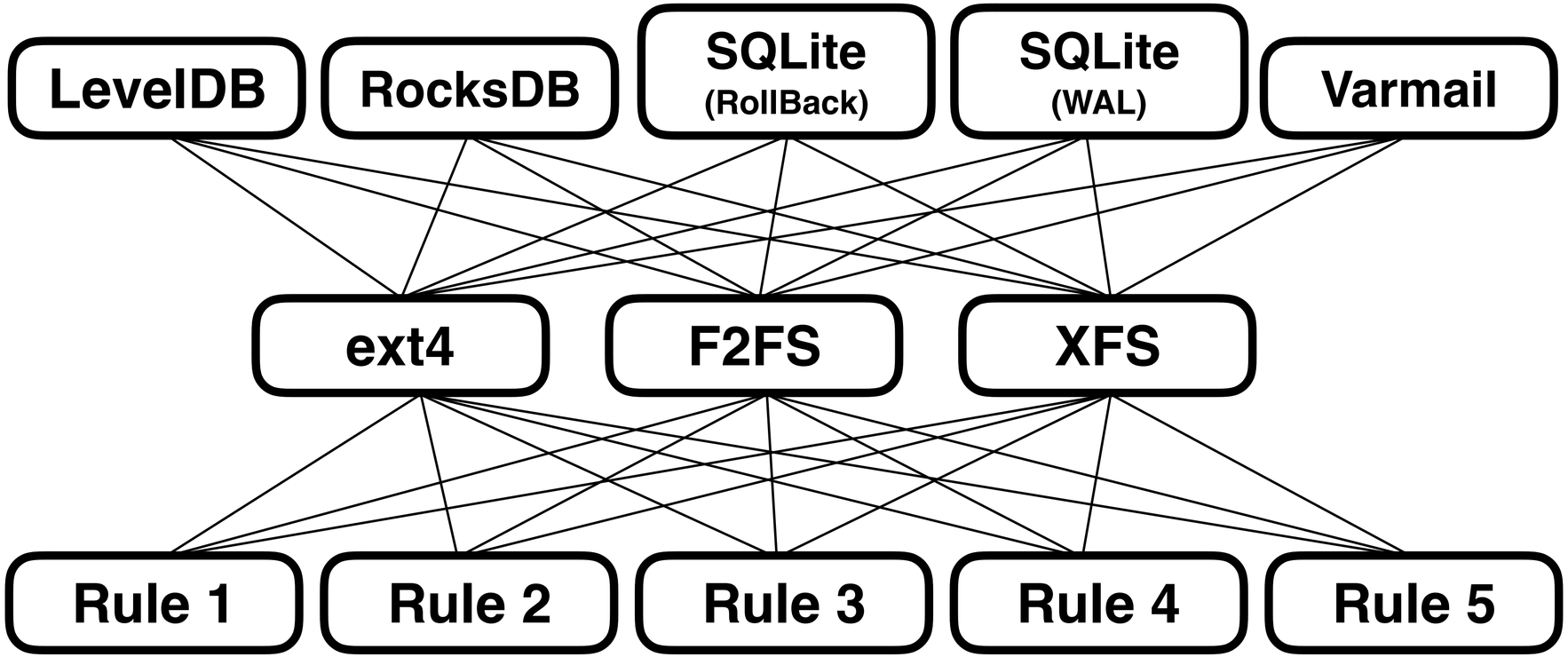
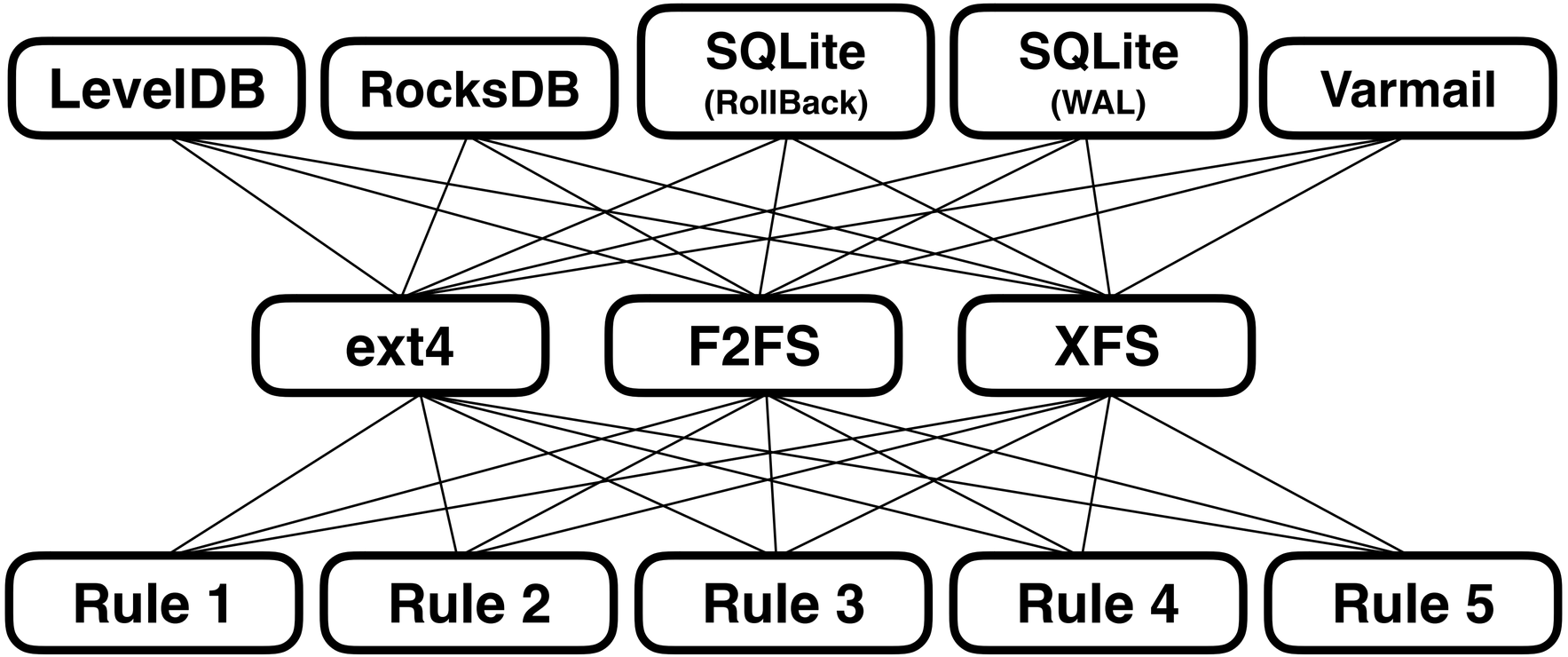
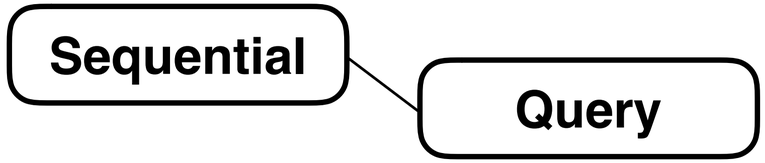
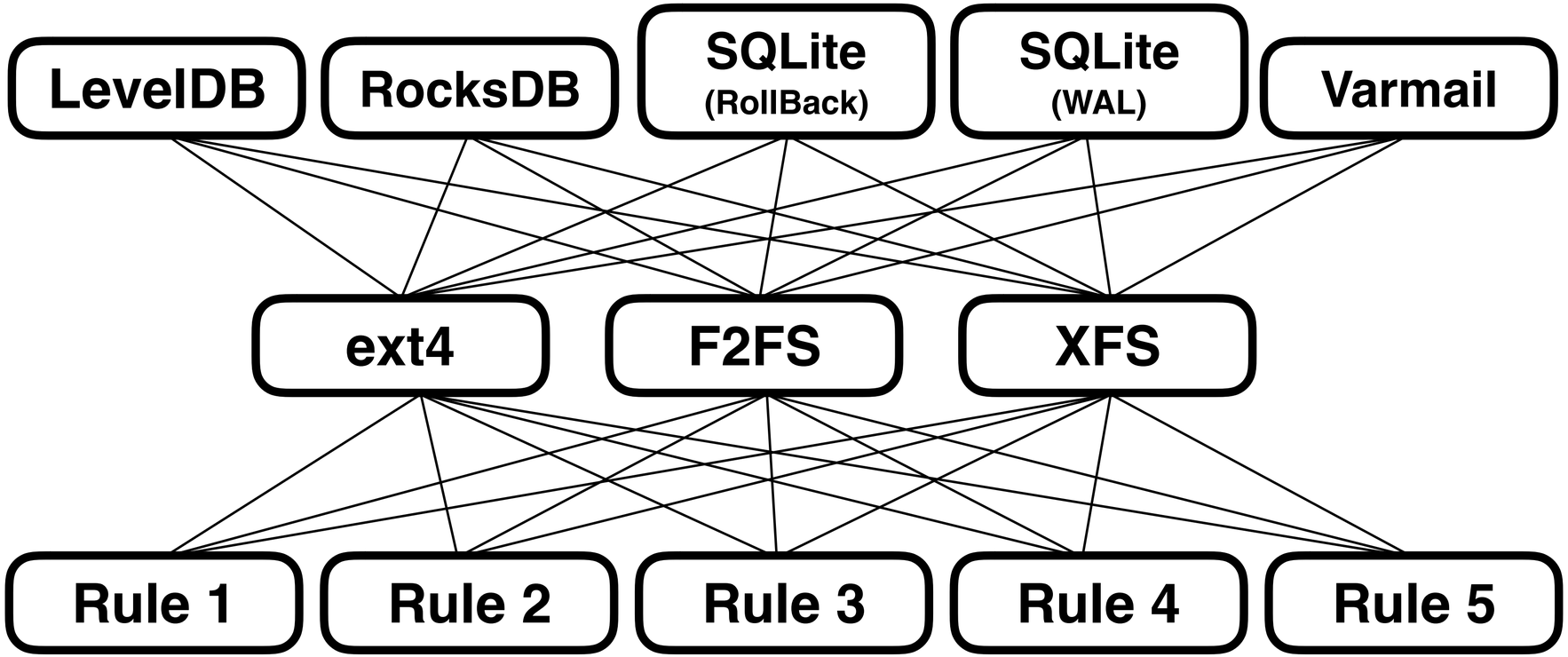

LevelDB
RocksDB
SQLite
(RollBack)
SQLite
(WAL)
Varmail
ext4
F2FS
XFS
Rule 1
Rule 2
Rule 3
Rule 4
Rule 5

Database Operations:

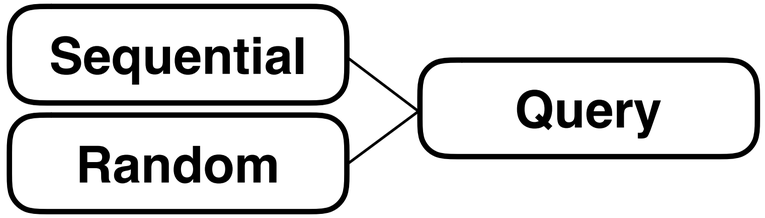


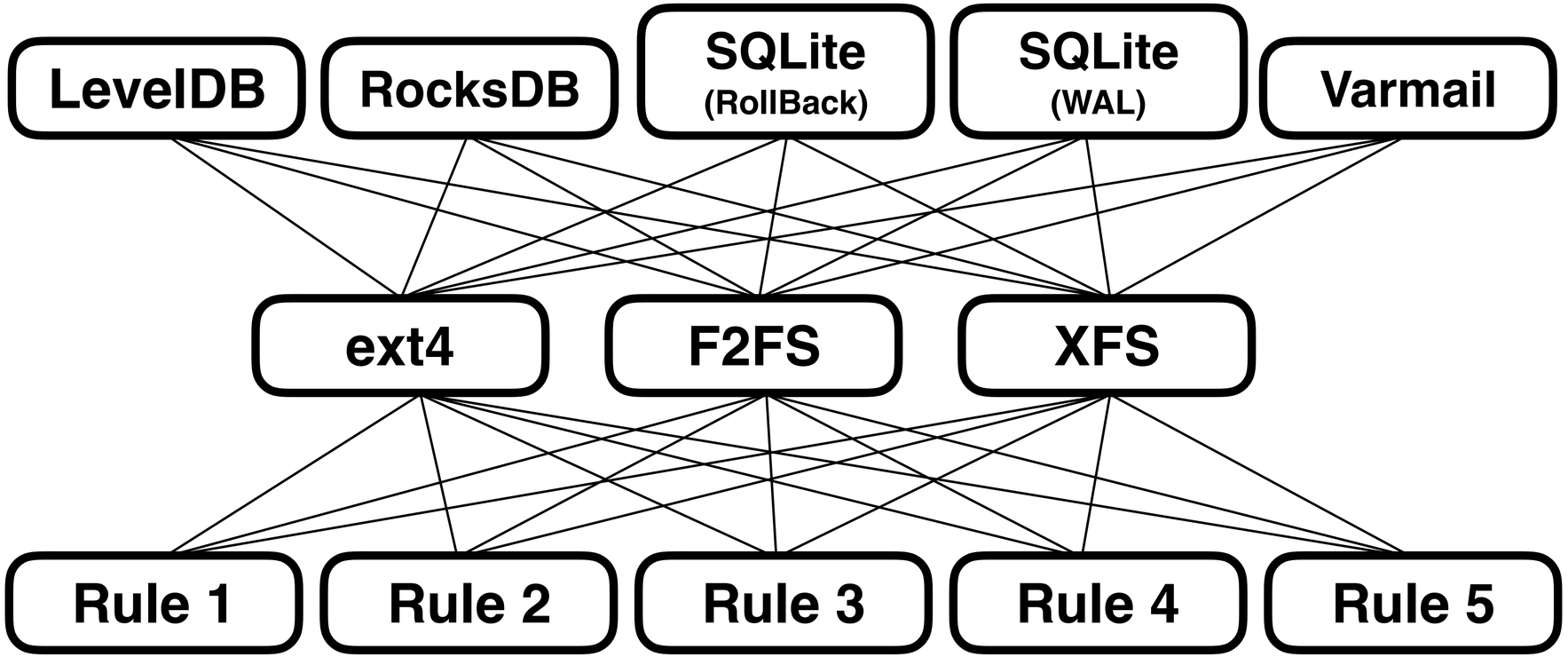
Database Operations:





Database Operations:





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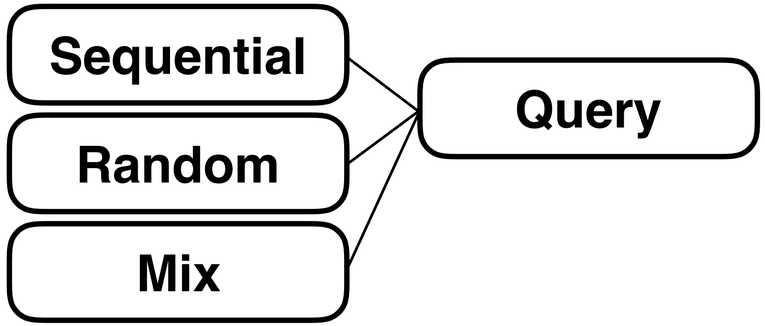

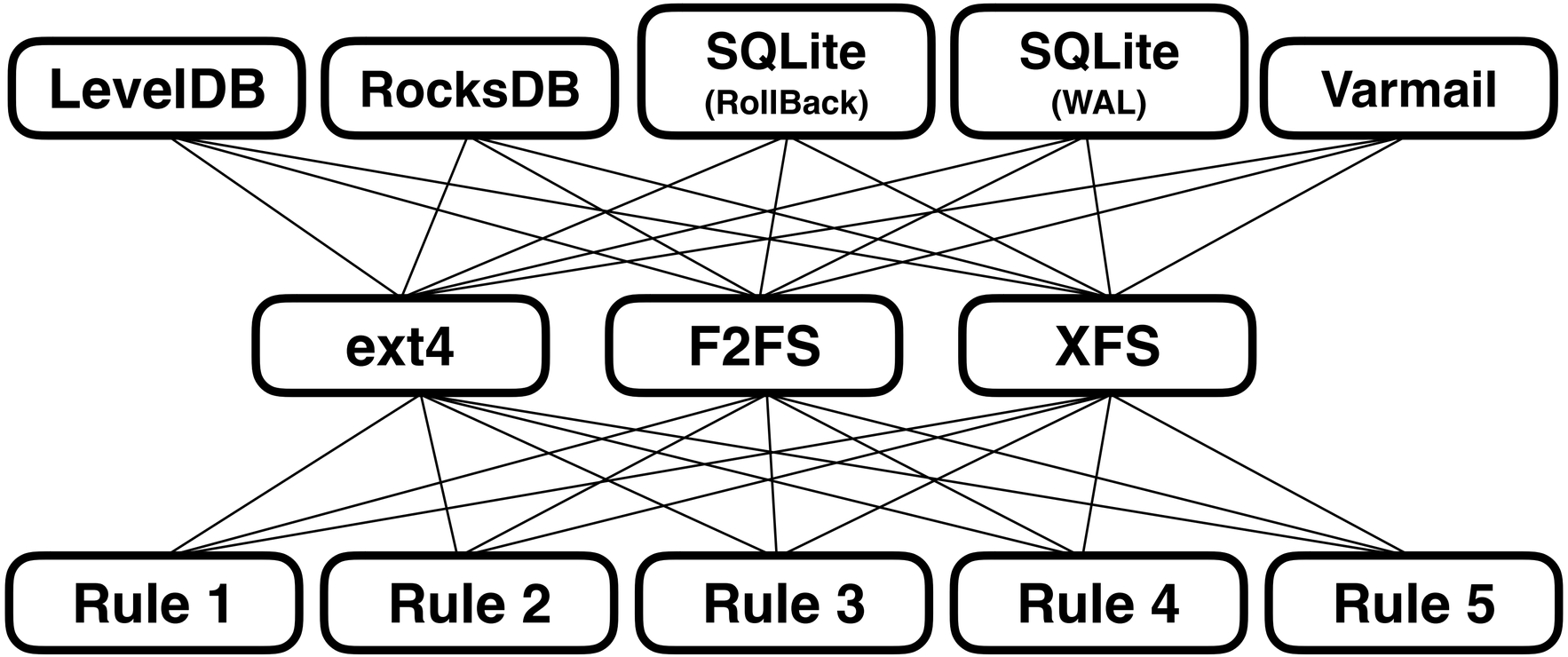

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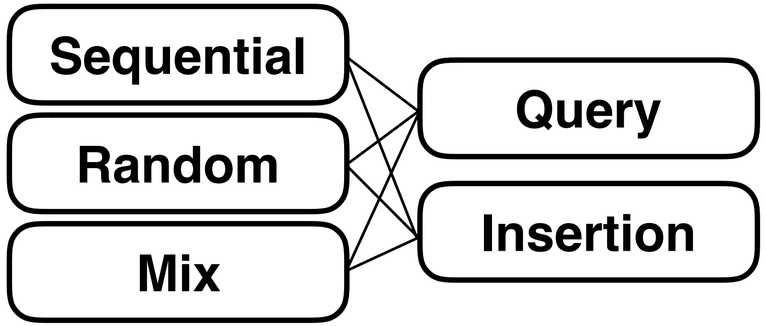

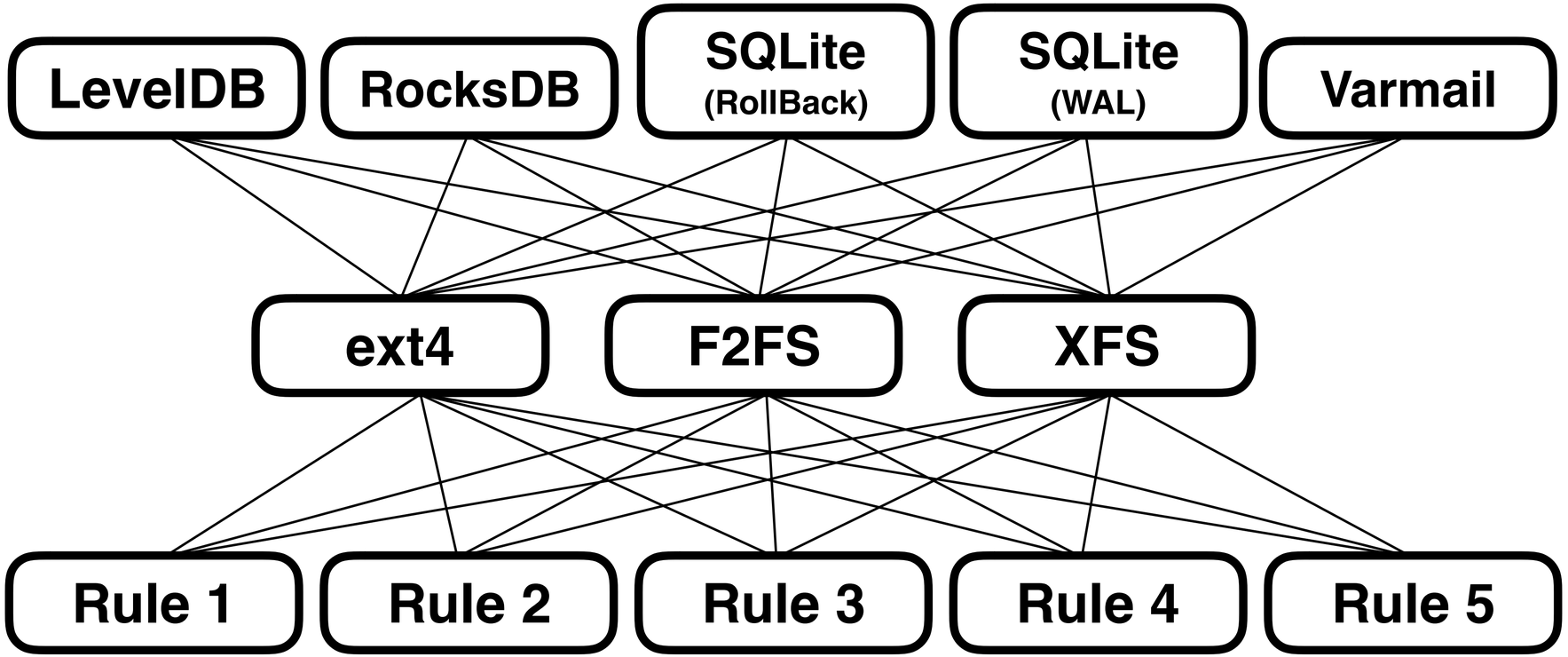

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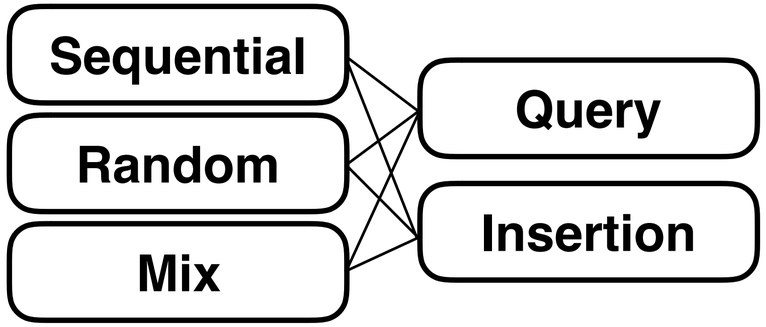
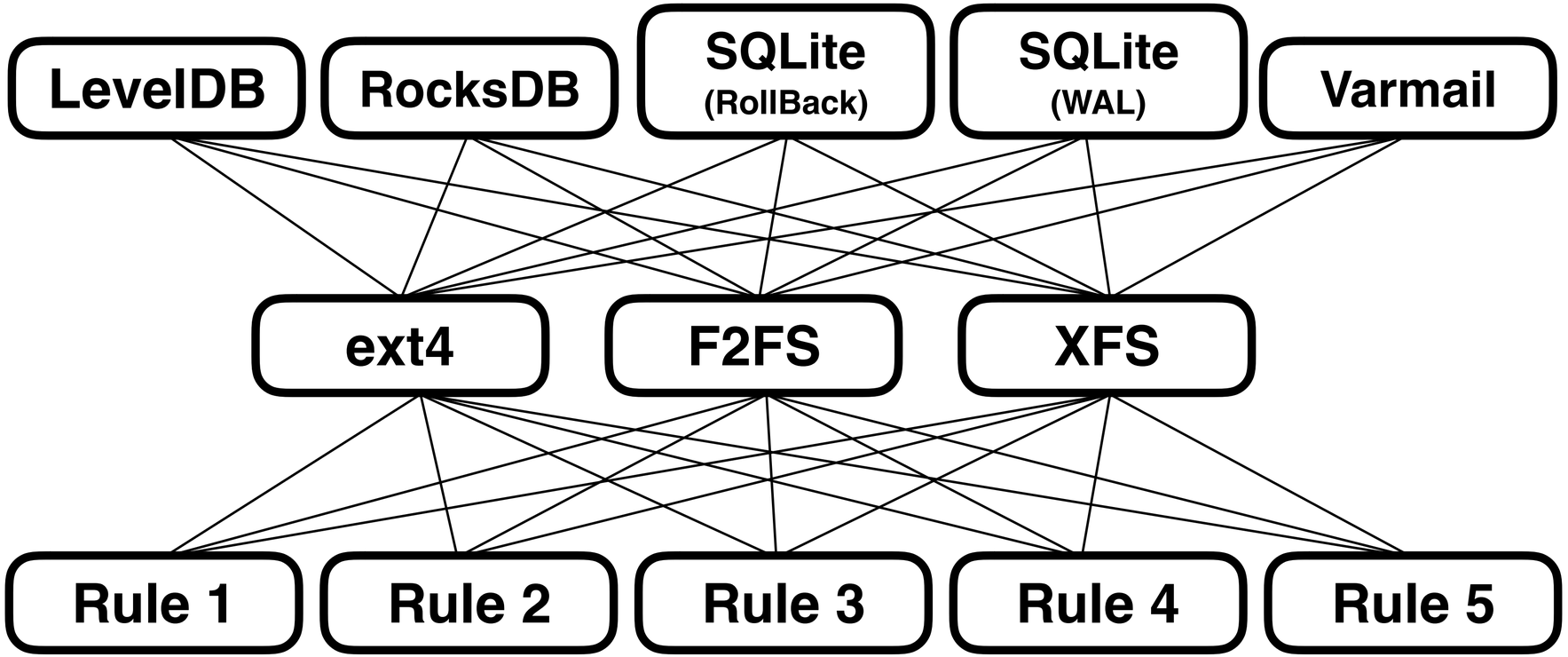
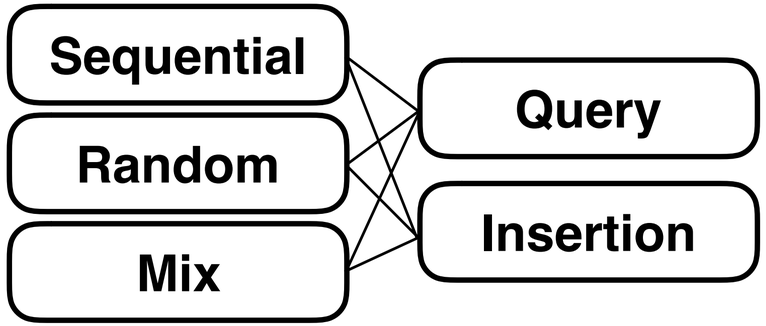


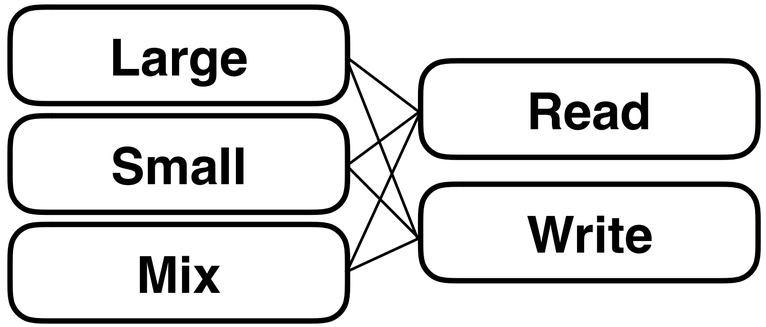
Varmail Operations:

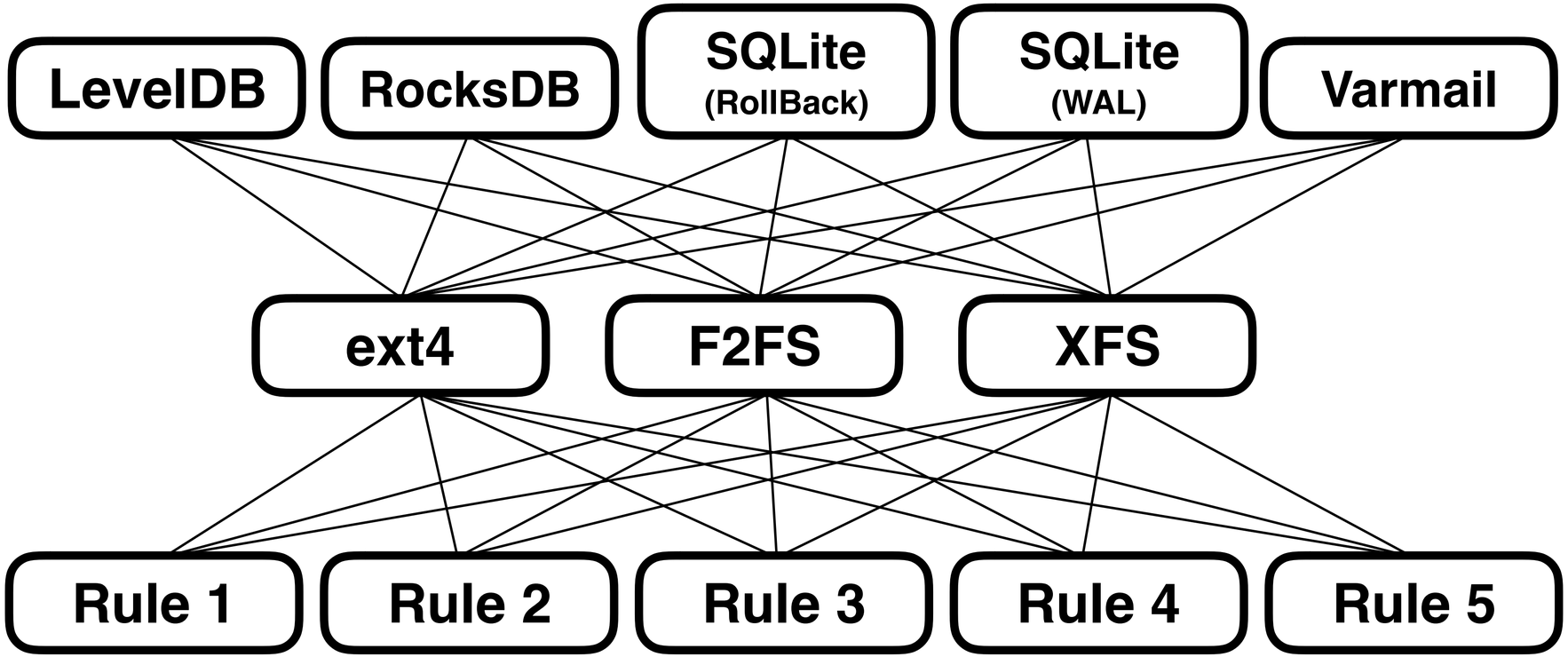


Database Operations:



Varmail Operations:





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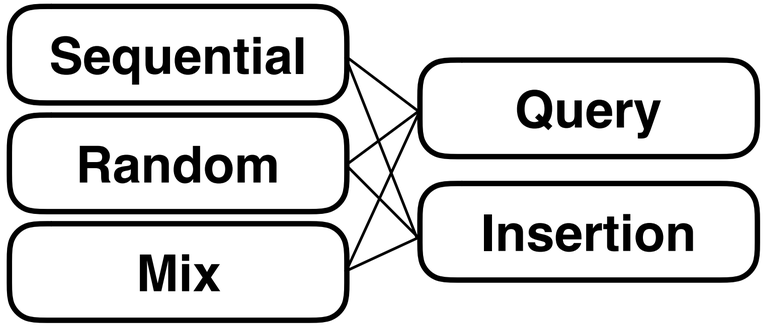

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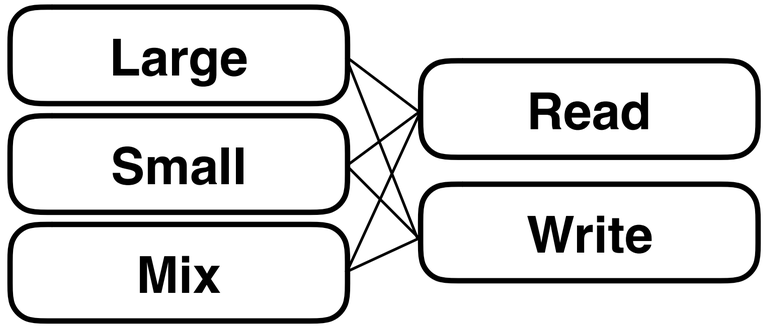

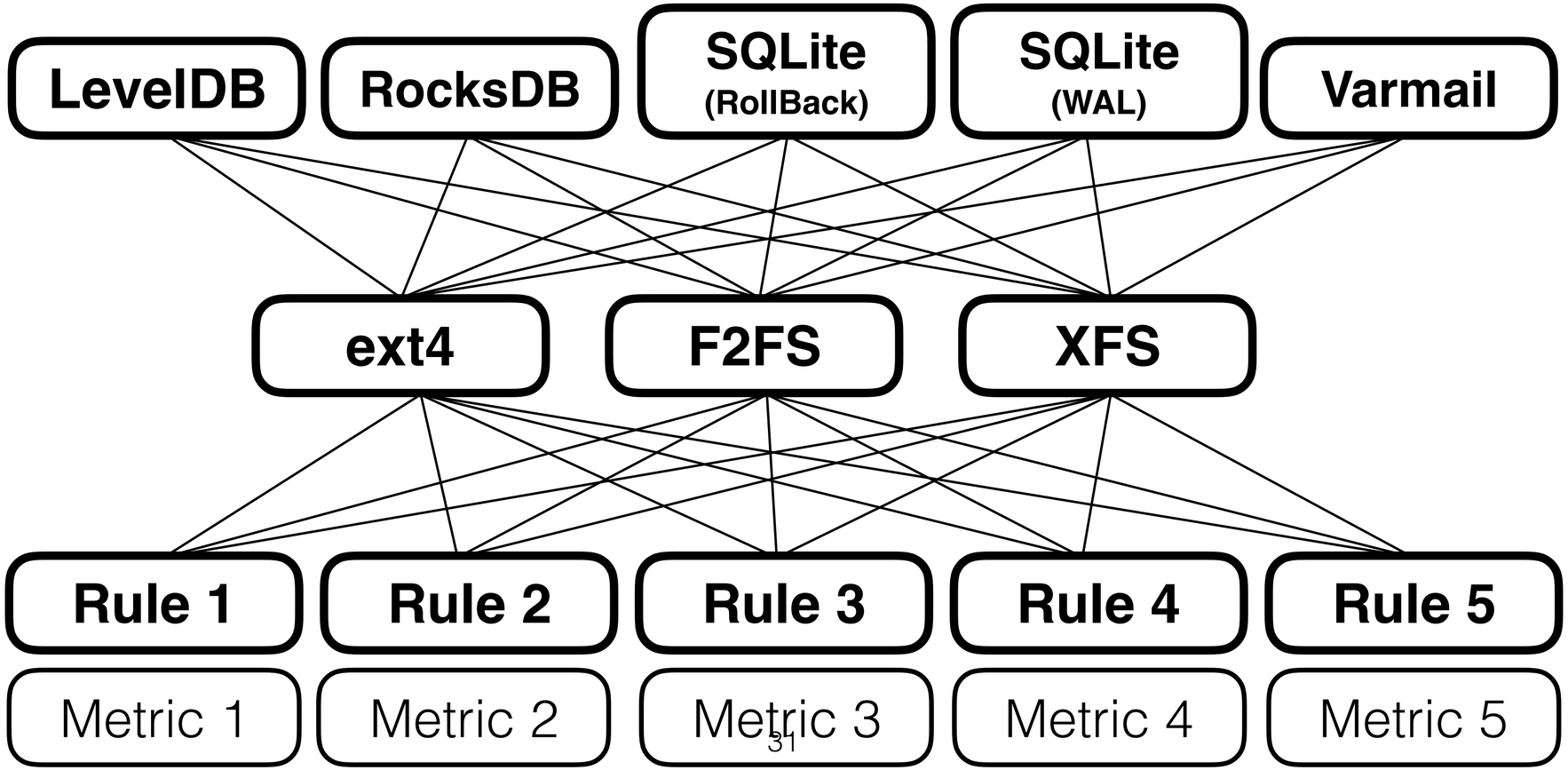

We conduct vertical analysis to find violations of SSD contract.

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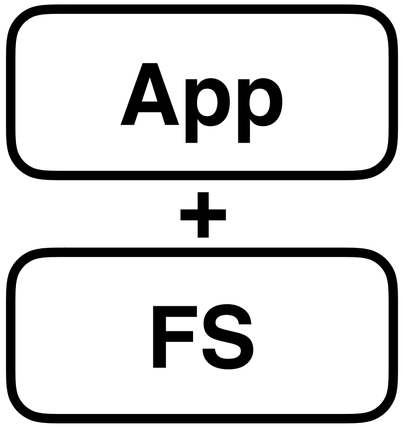

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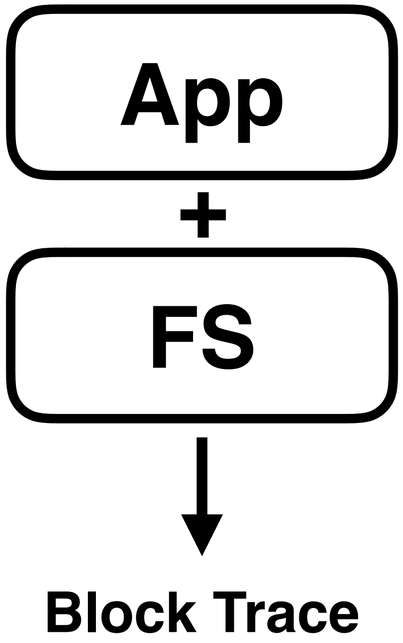

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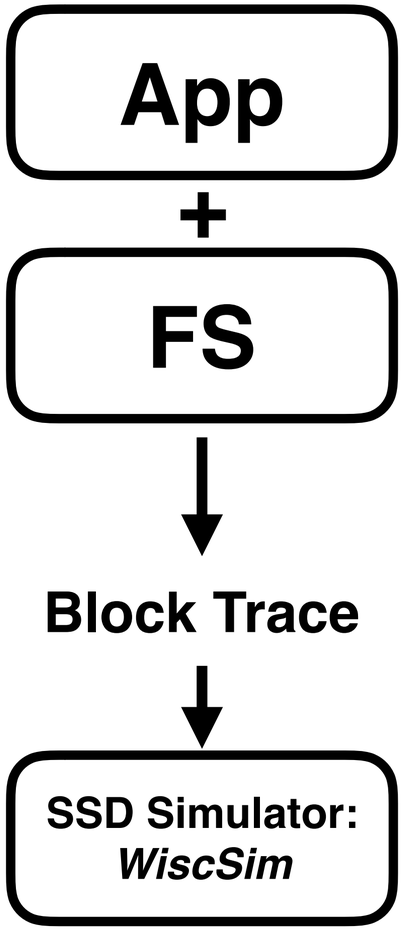

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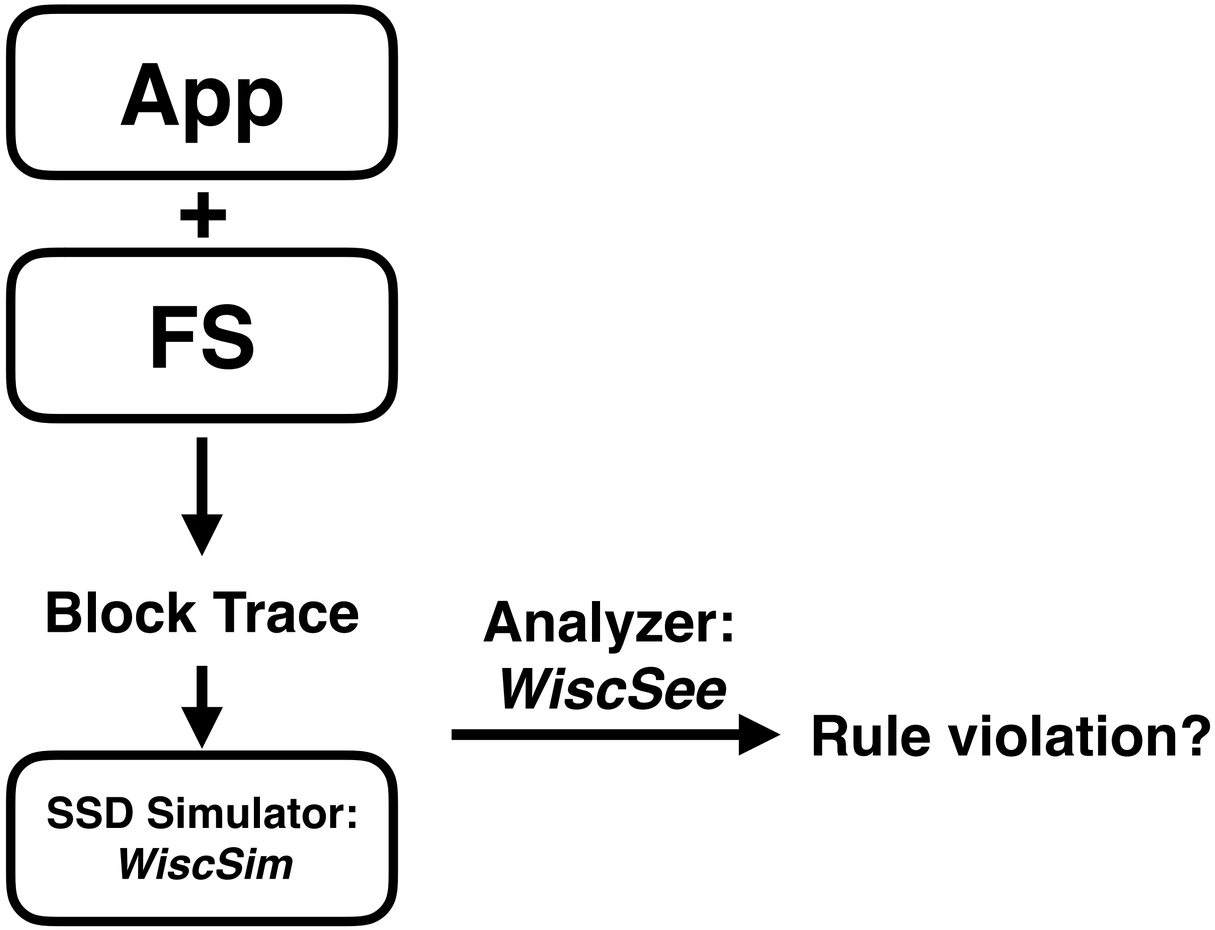

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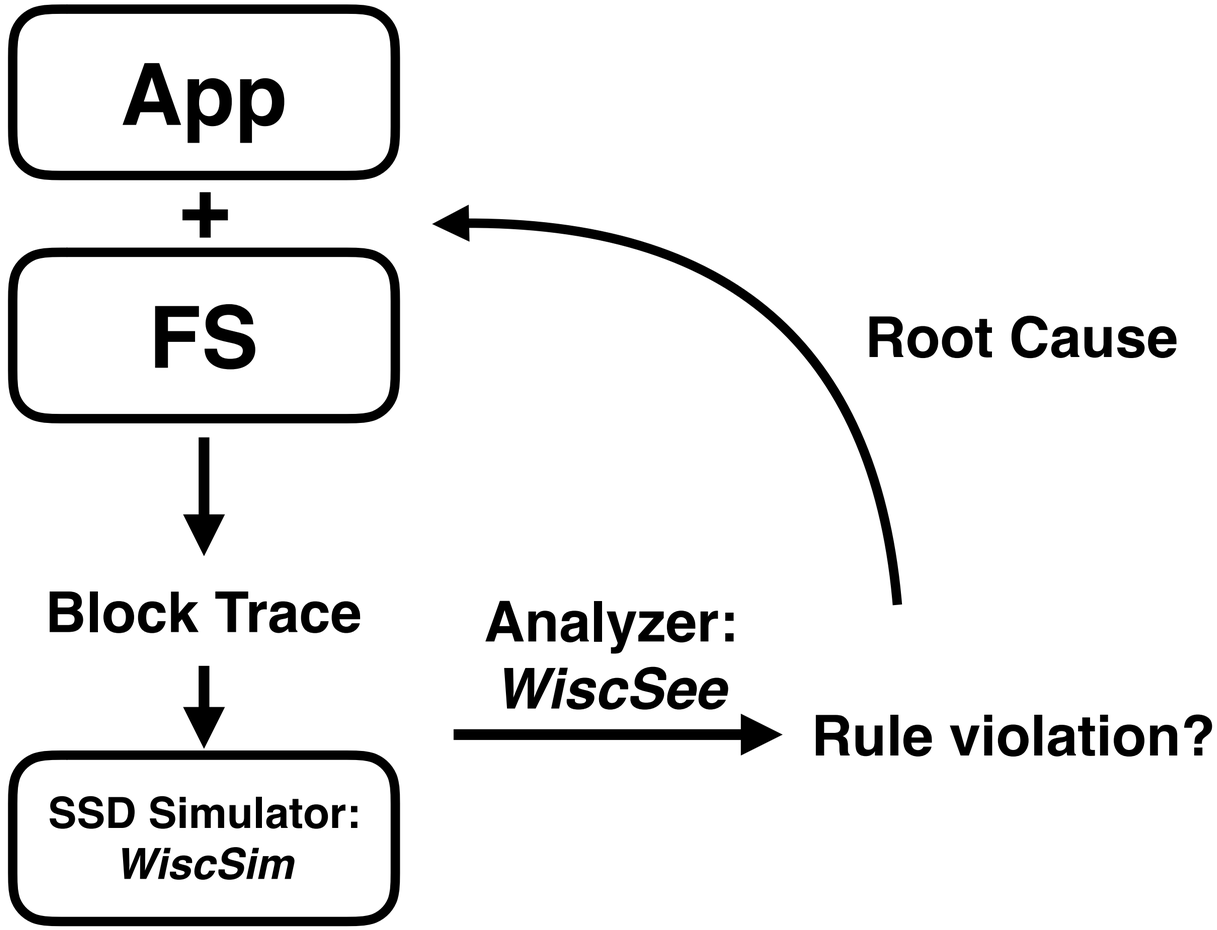

Outline

- Overview
- SSD Unwritten Contract
- Violations of Unwritten Contract
  - Method
  - **Observations**
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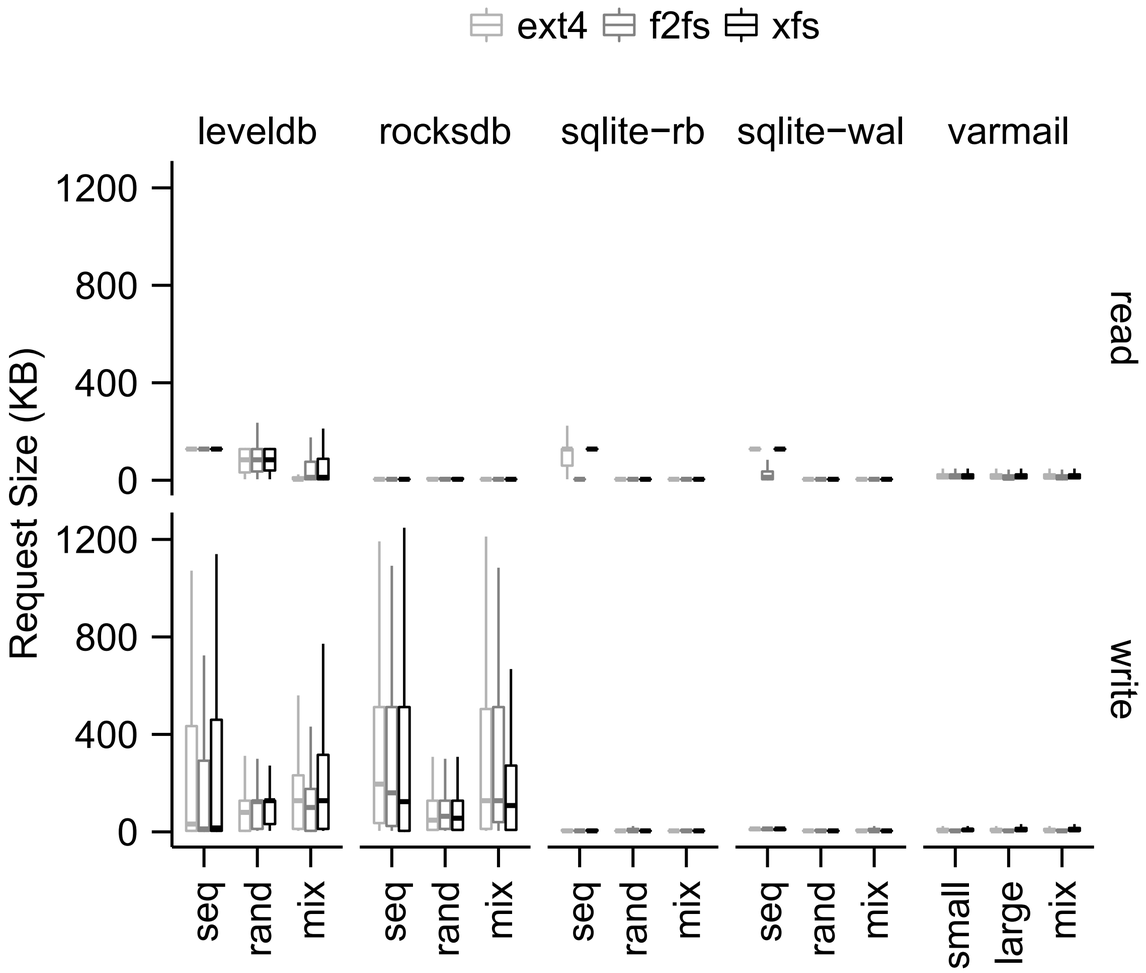
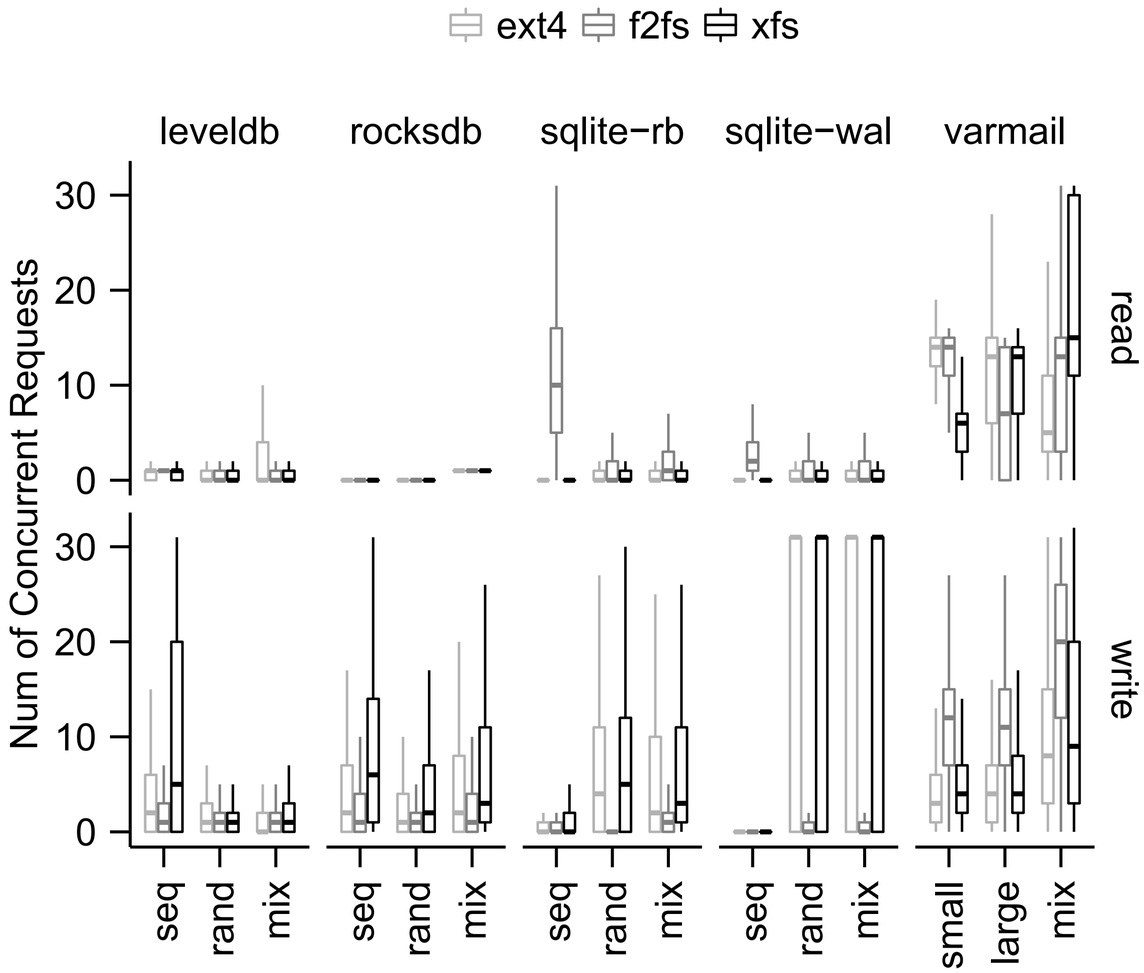
Observations

- Rule 1: Request Scale
- Implementation of Linux limits performance
- Rule 3: Grouping by Death Time
  - F2FS incurs more GC overhead than ext4/XFS
  - Application log structuring does not reduce GC

We evaluate request scale by request size and number of concurrent requests





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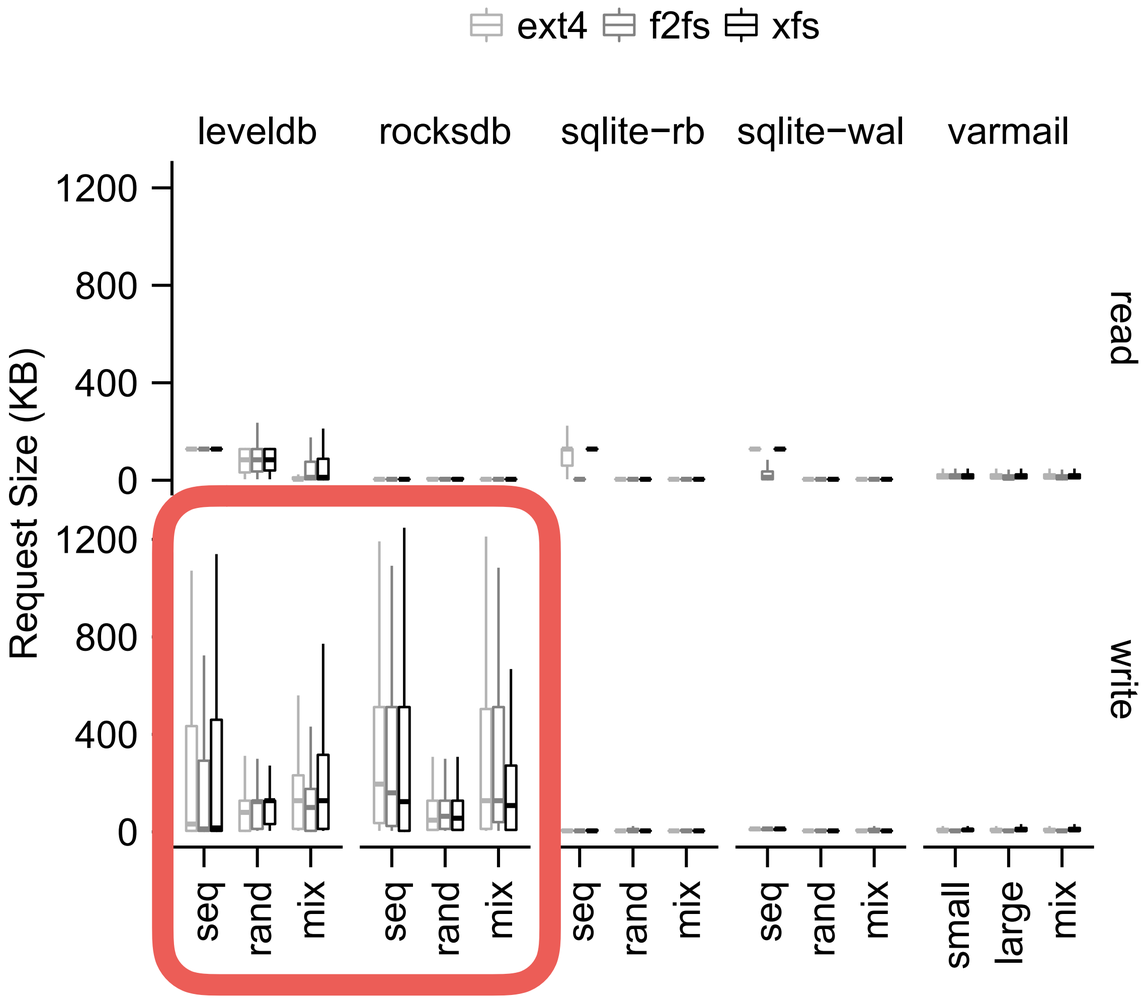

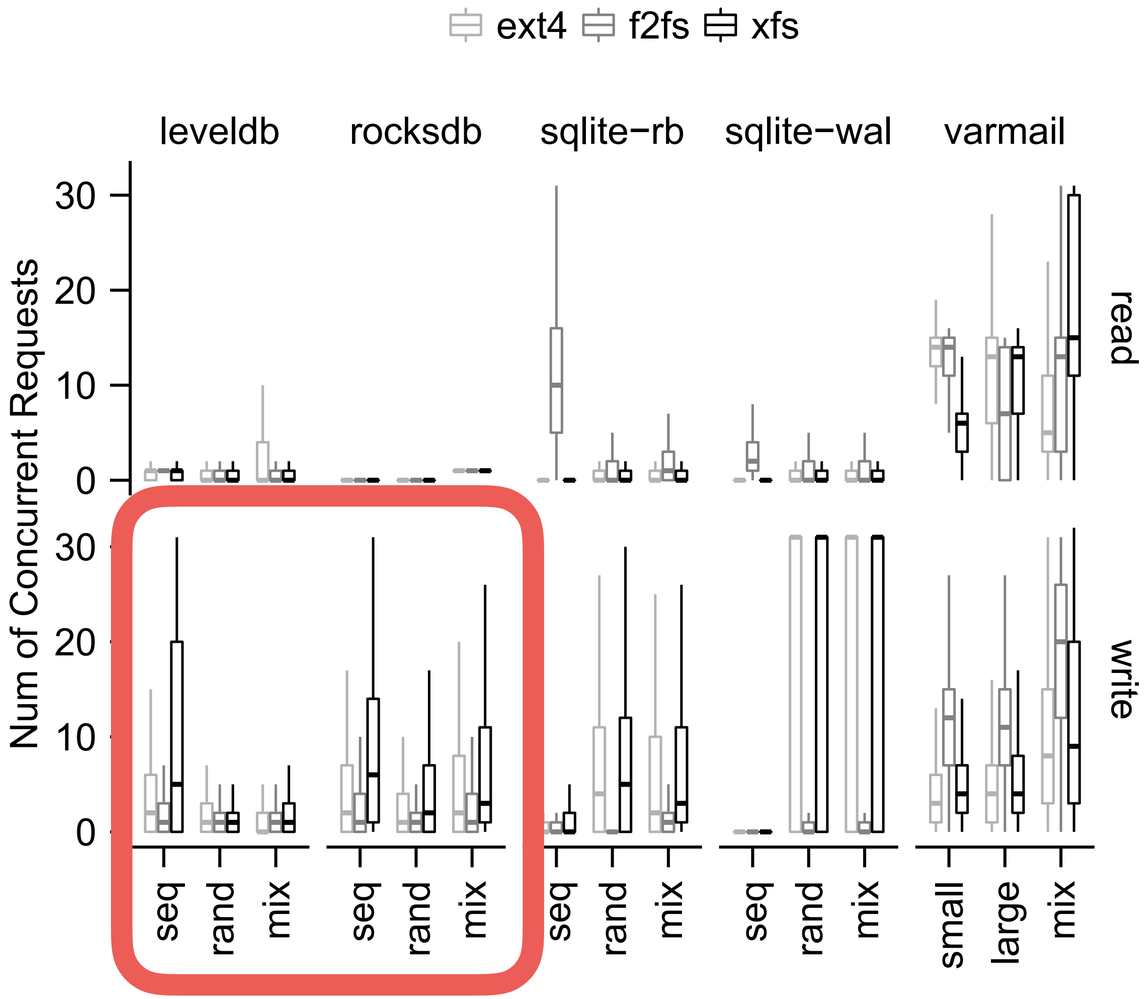

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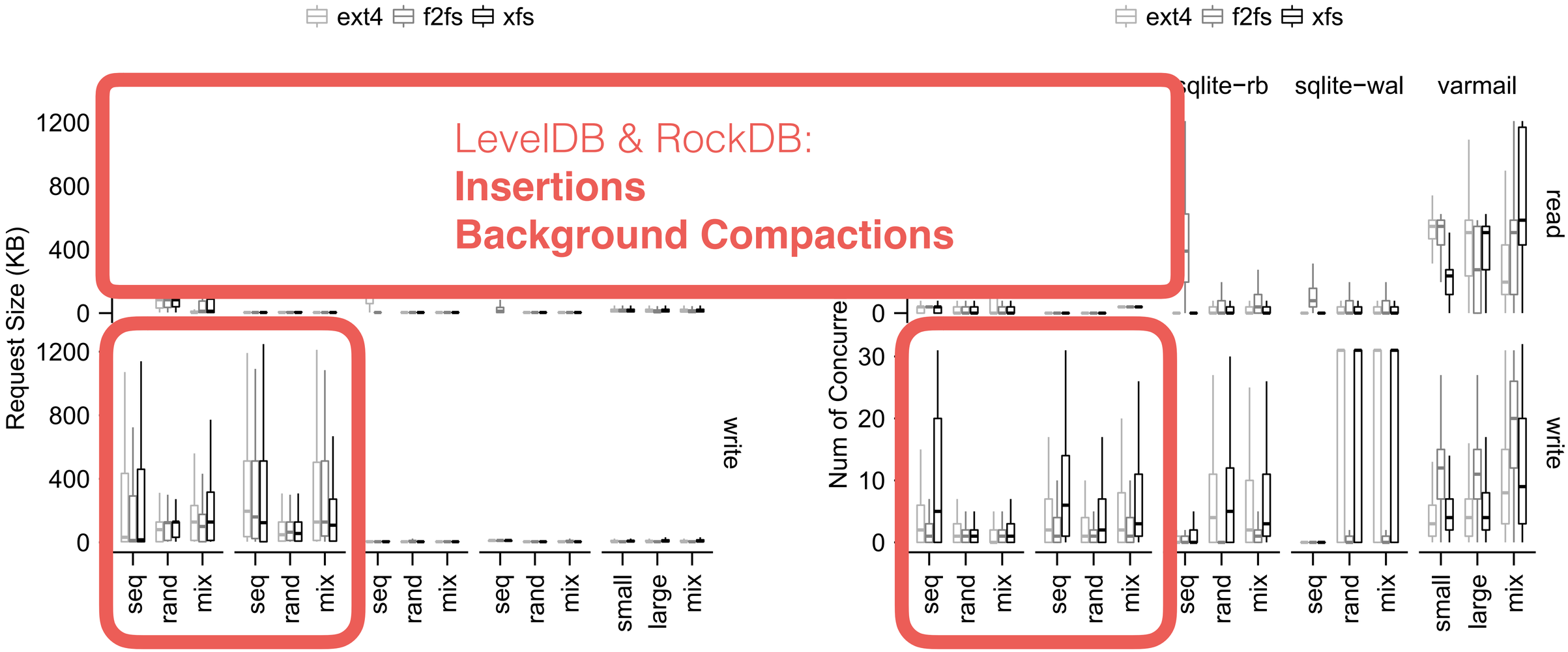

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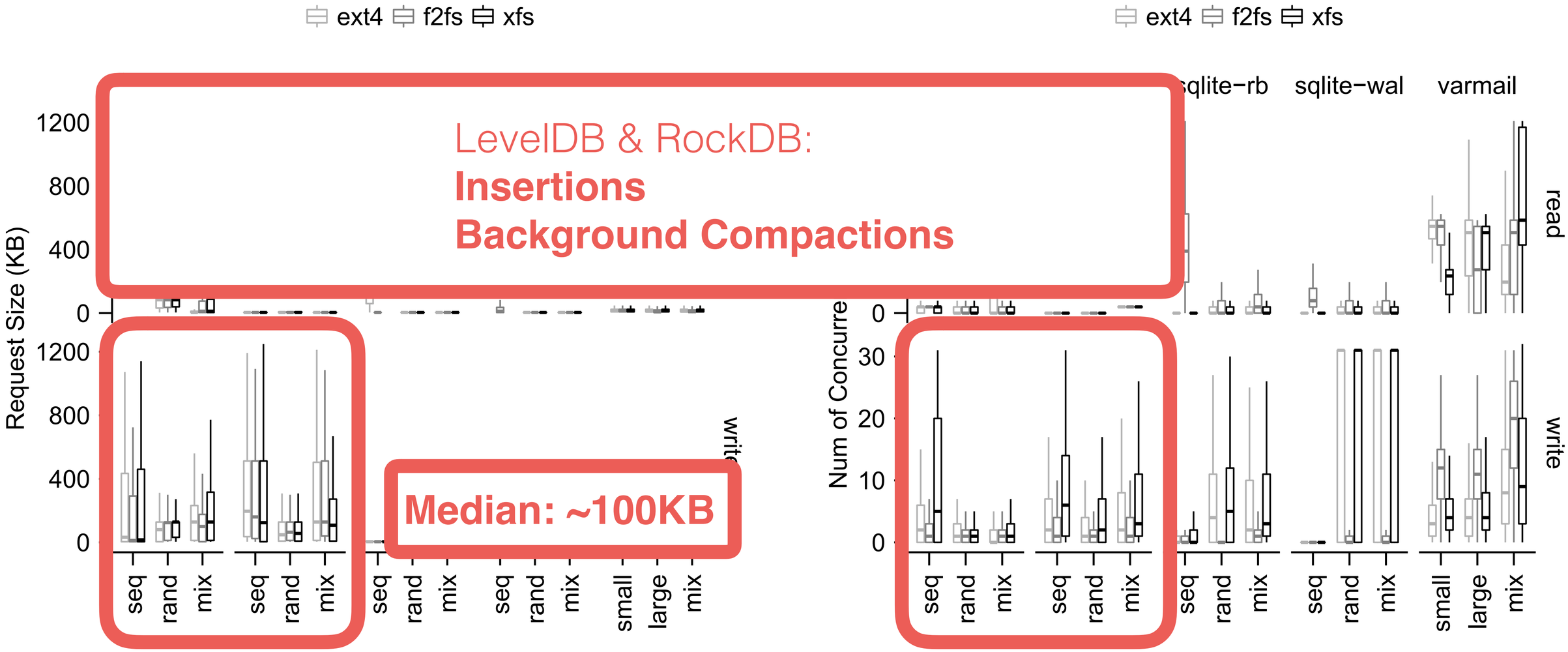

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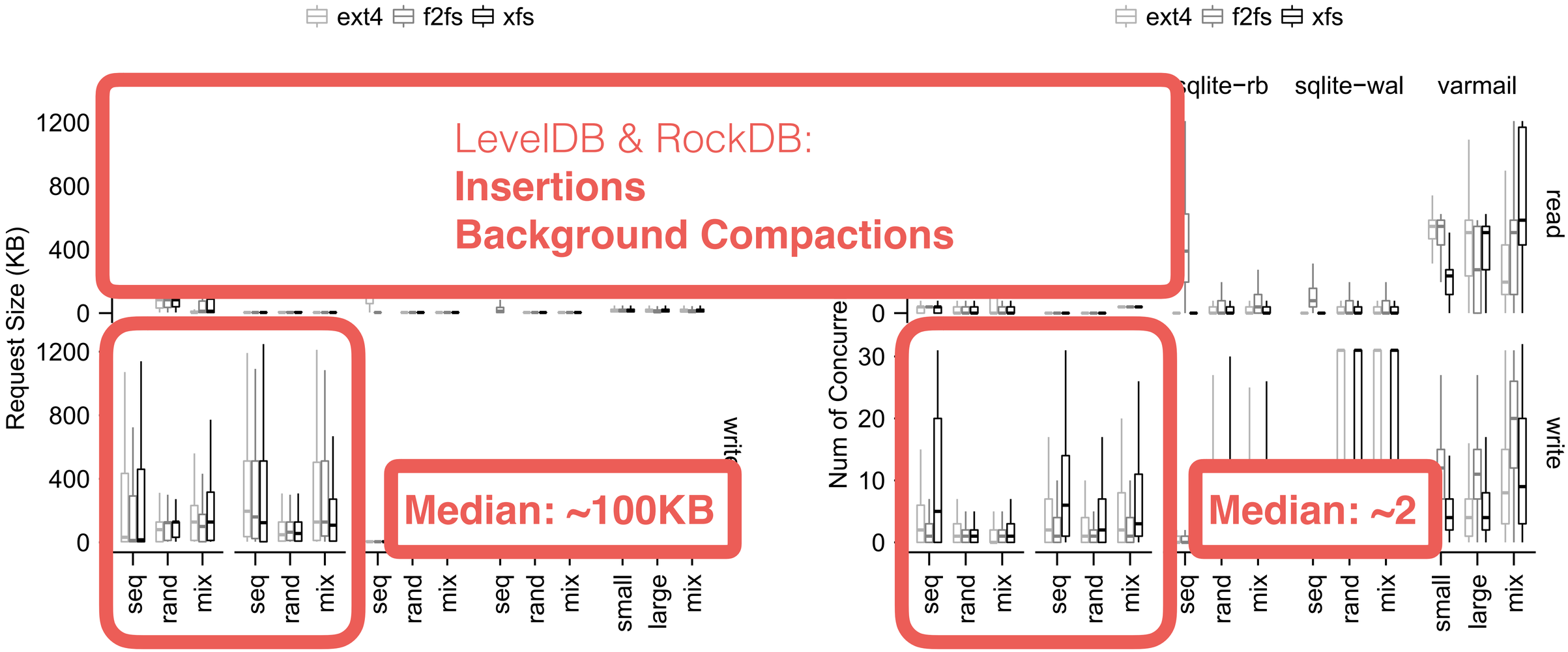
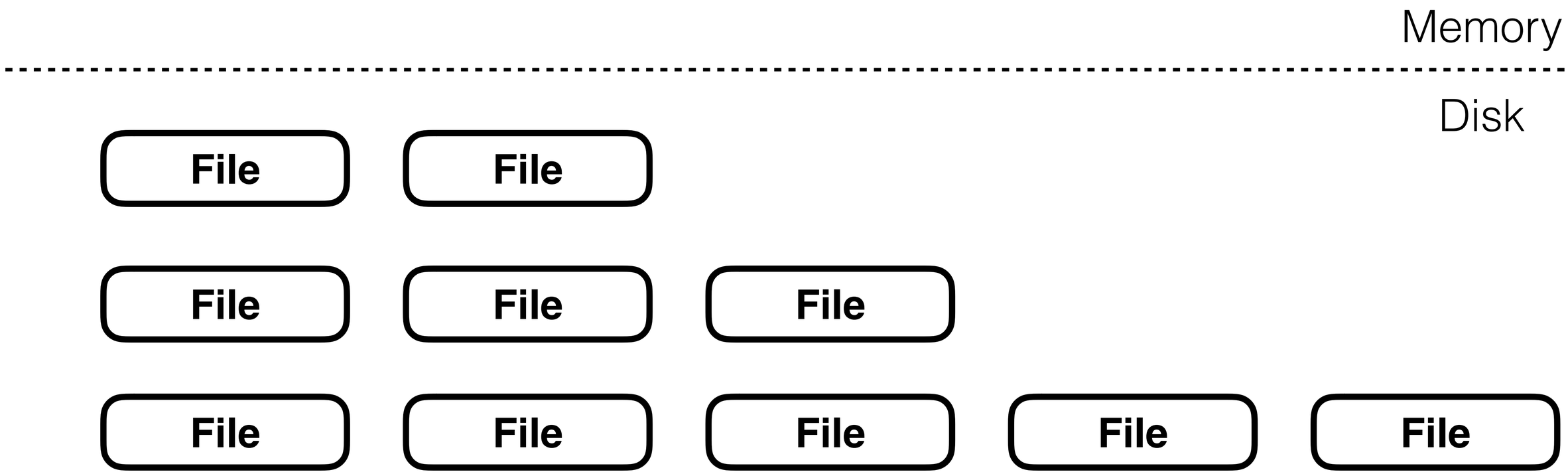


LevelDB & RocksDB Background



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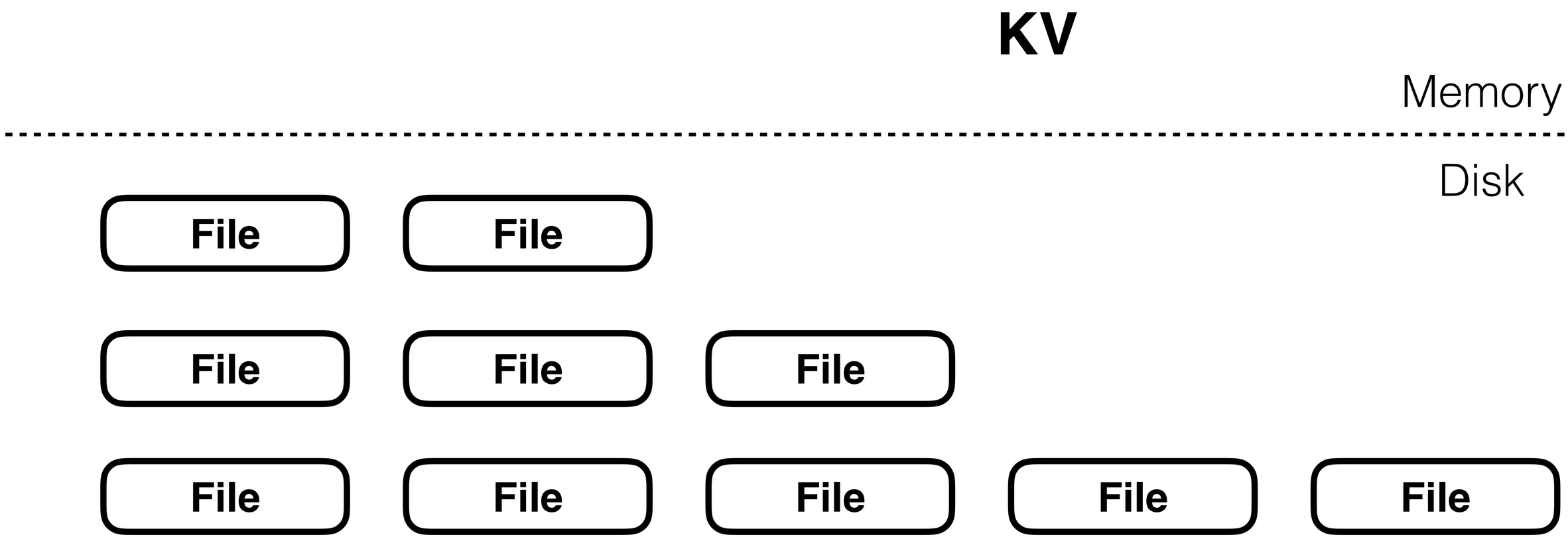

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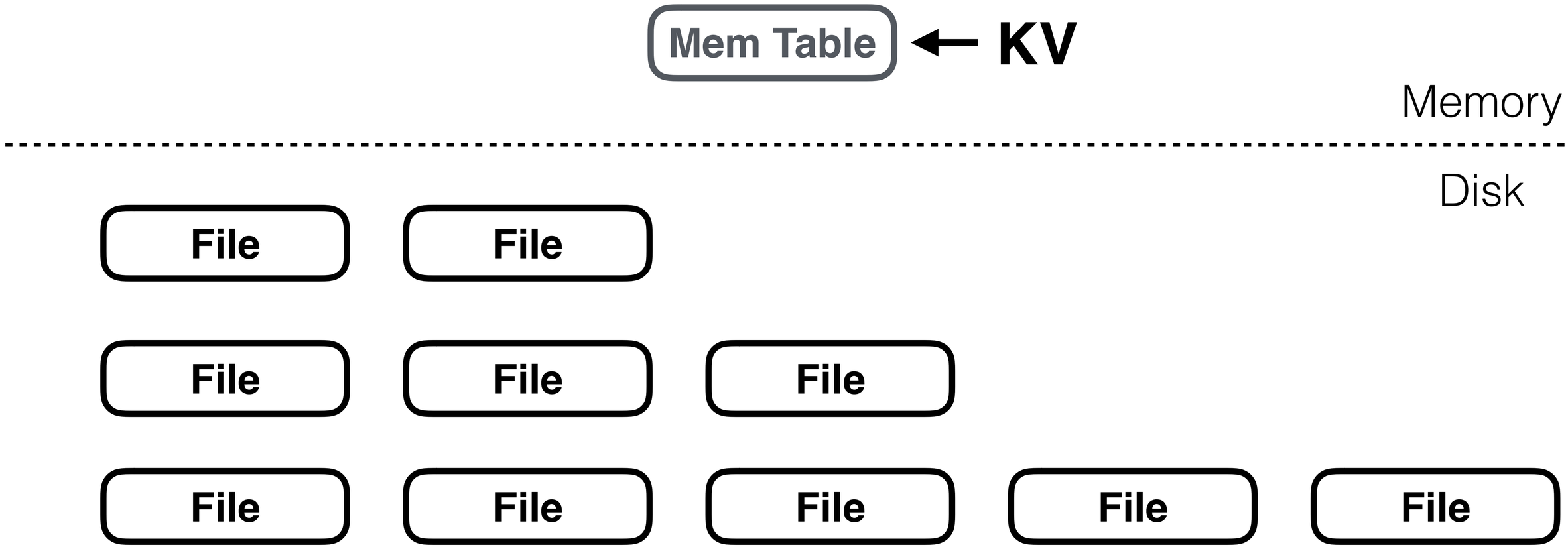

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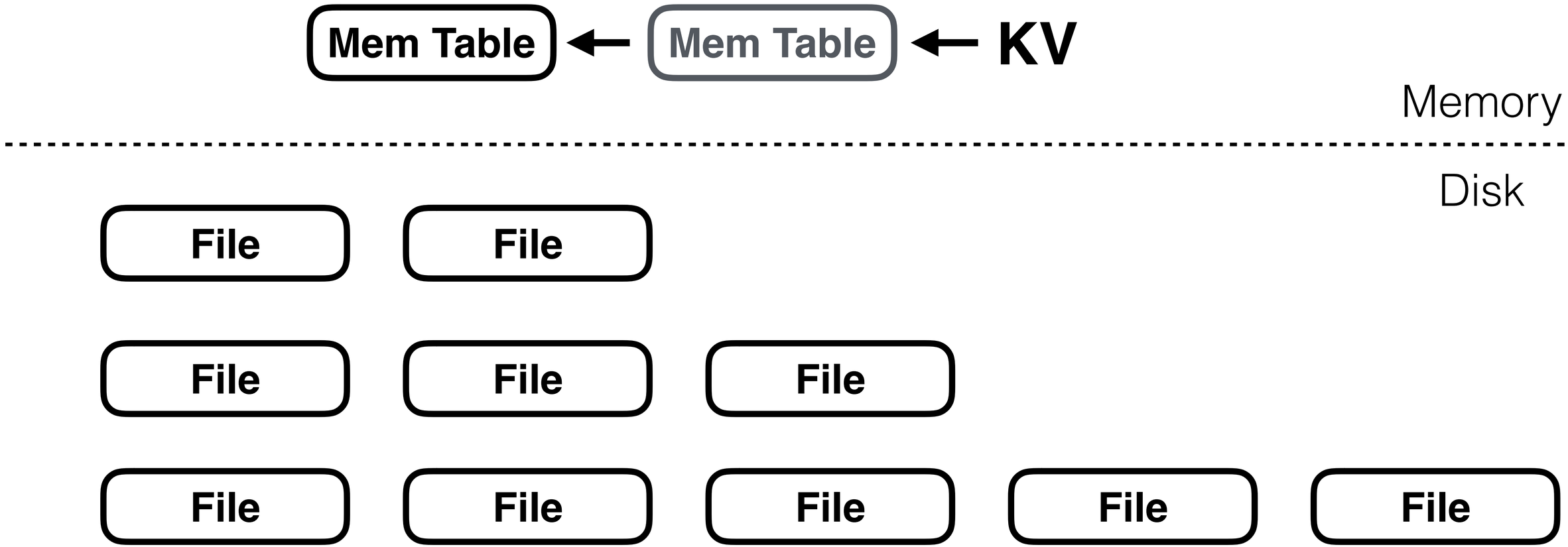

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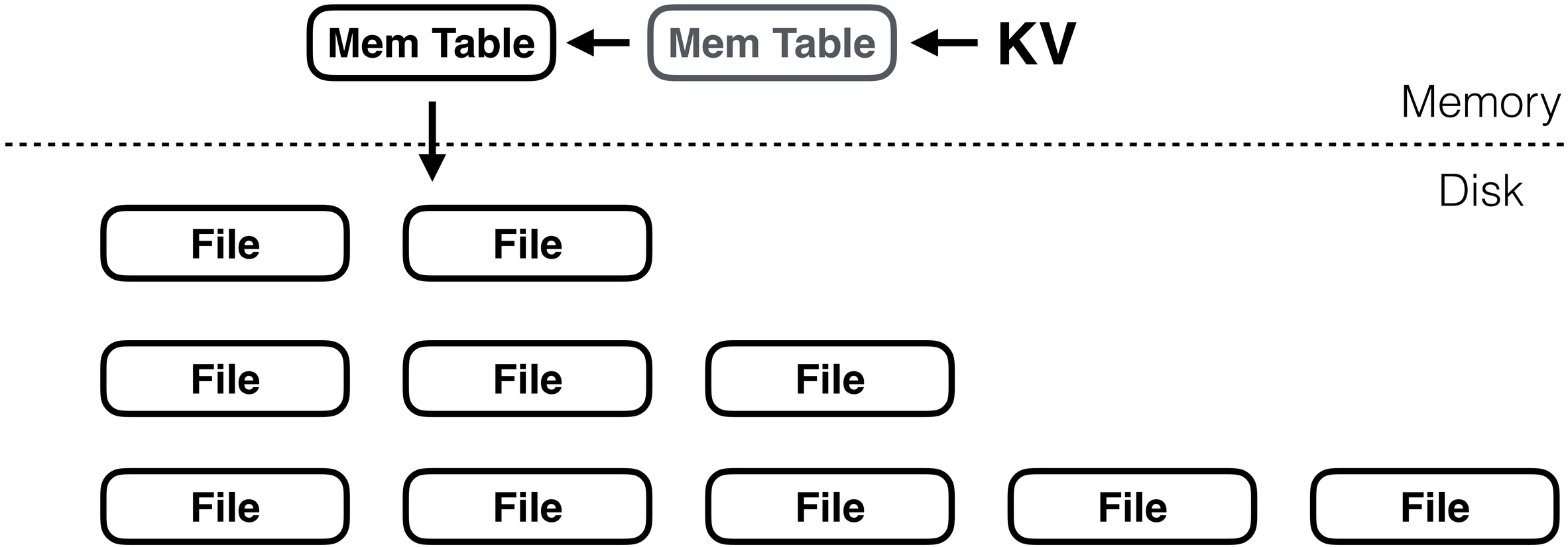
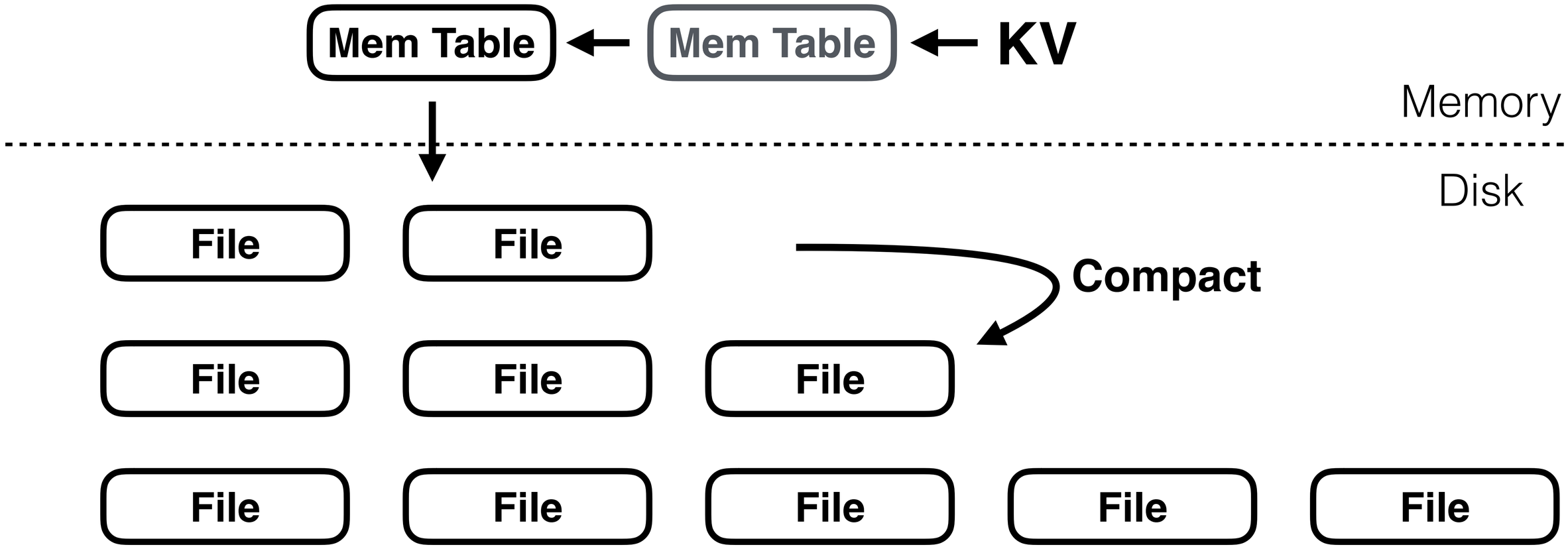
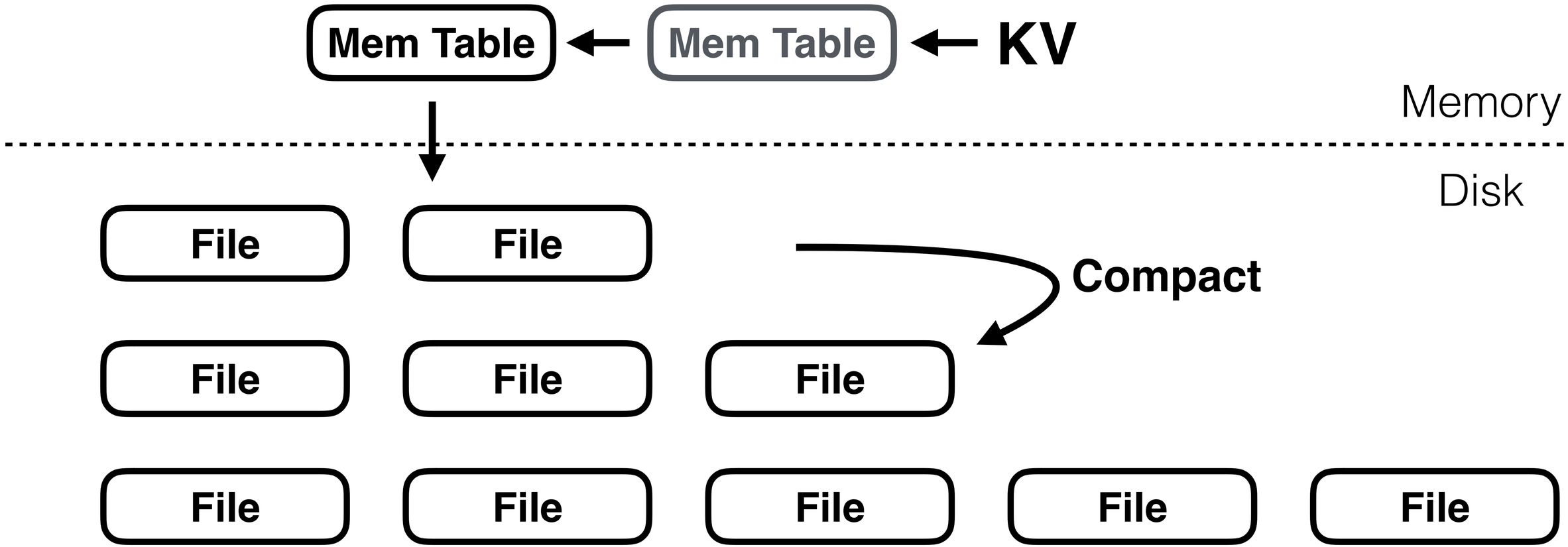


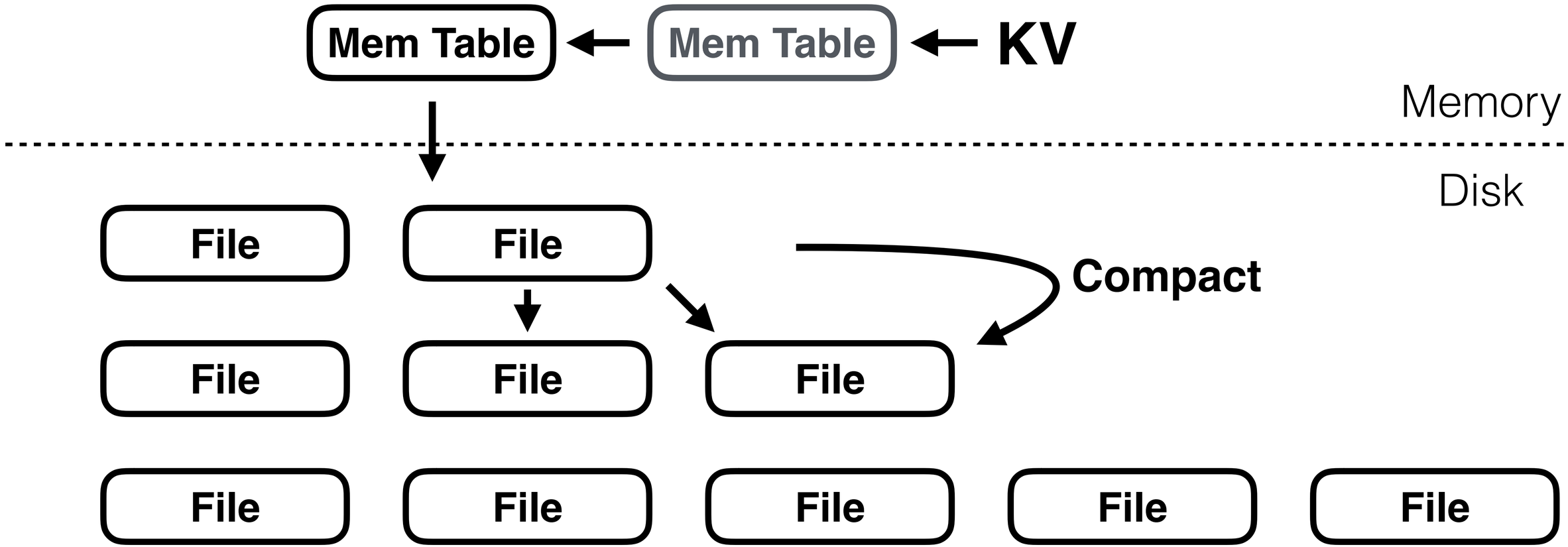
LevelDB & RocksDB Background



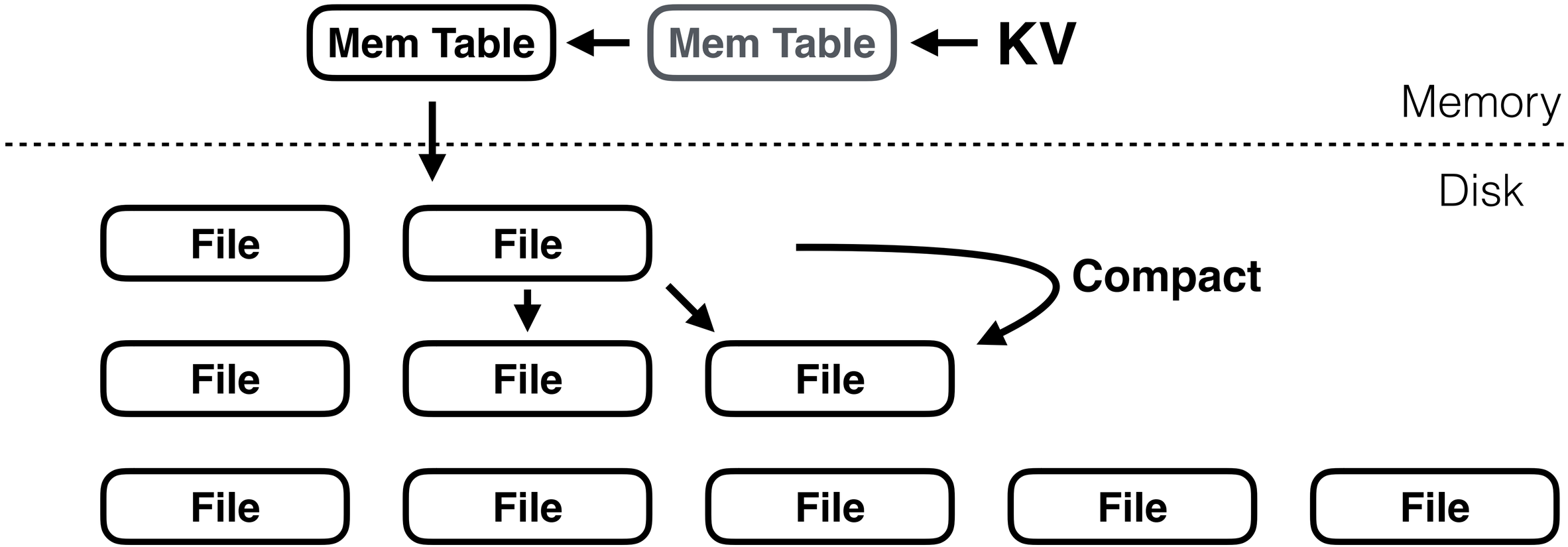
LevelDB & RocksDB Background



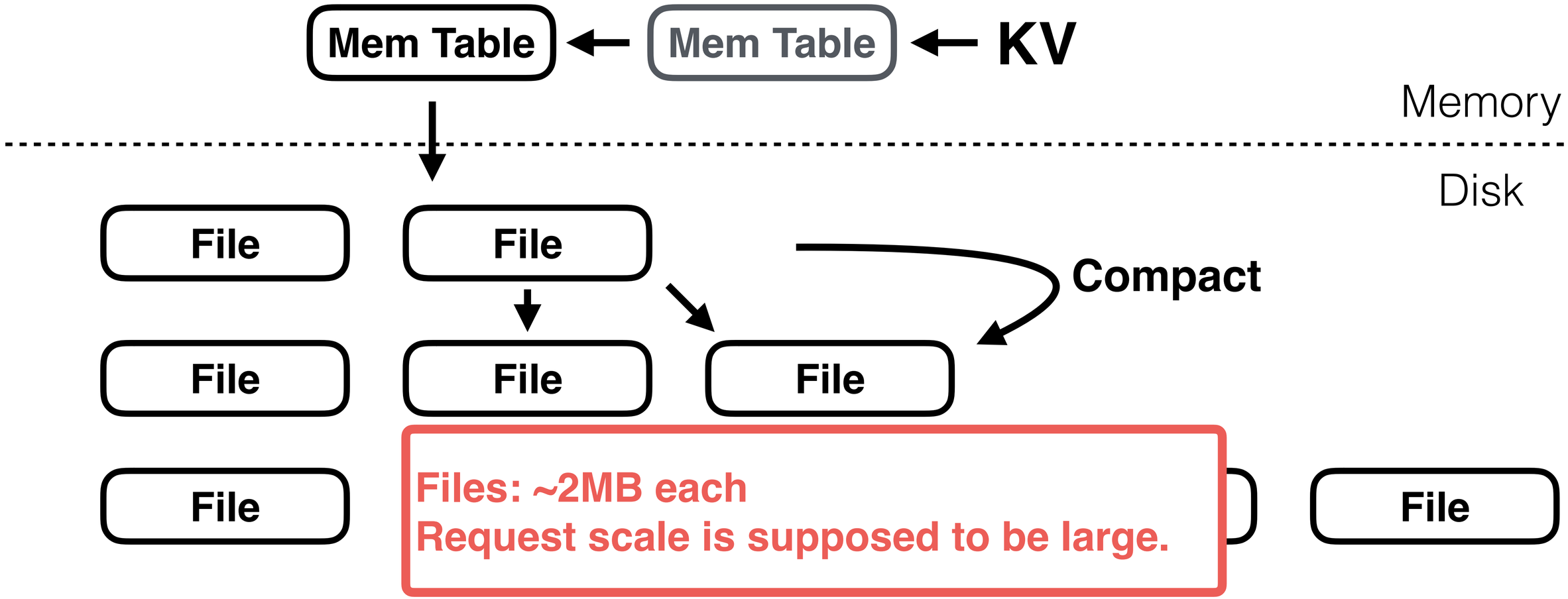
LevelDB & RocksDB Background



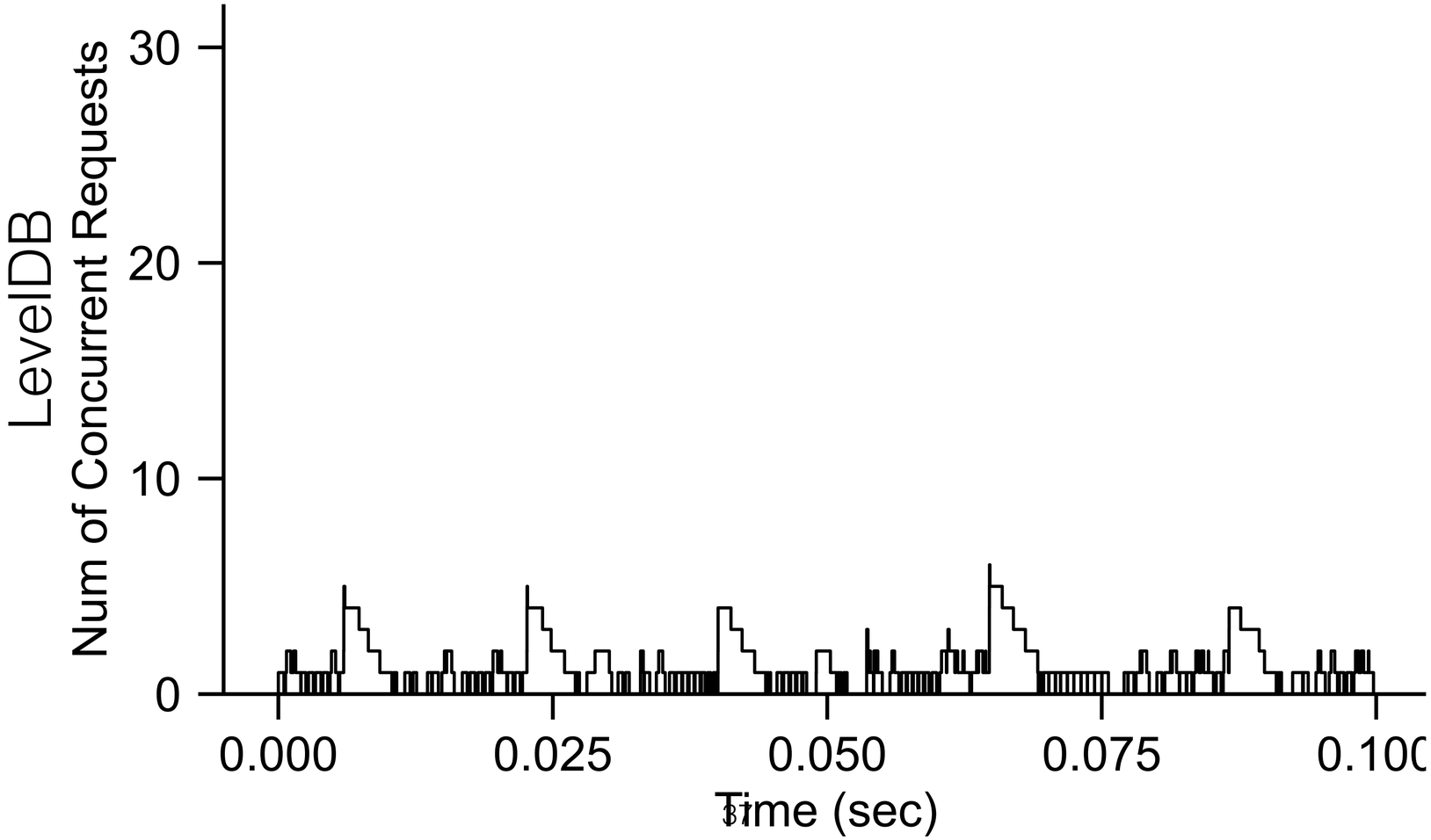
LevelDB & RocksDB Background



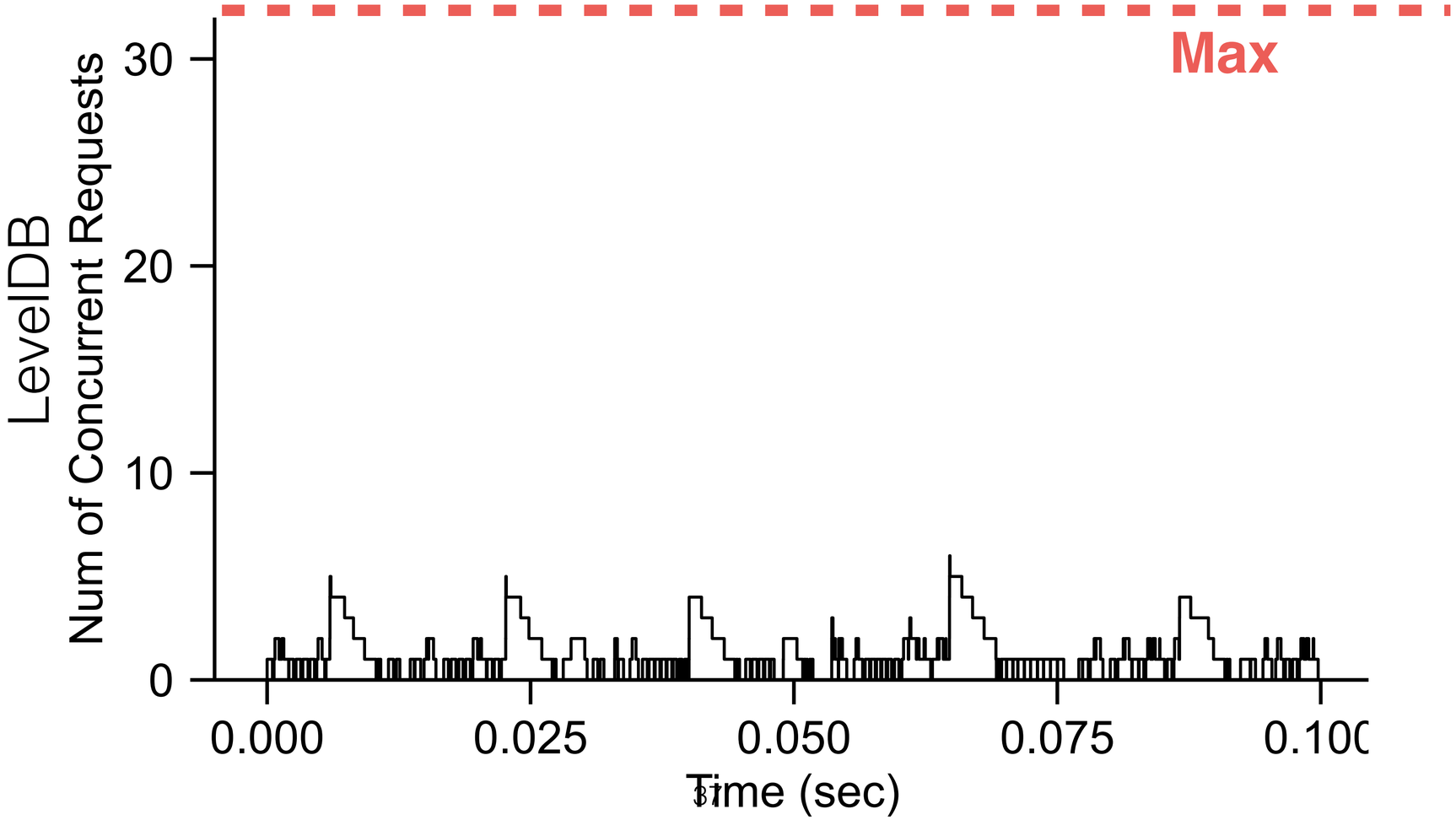
LevelDB & RocksDB Background



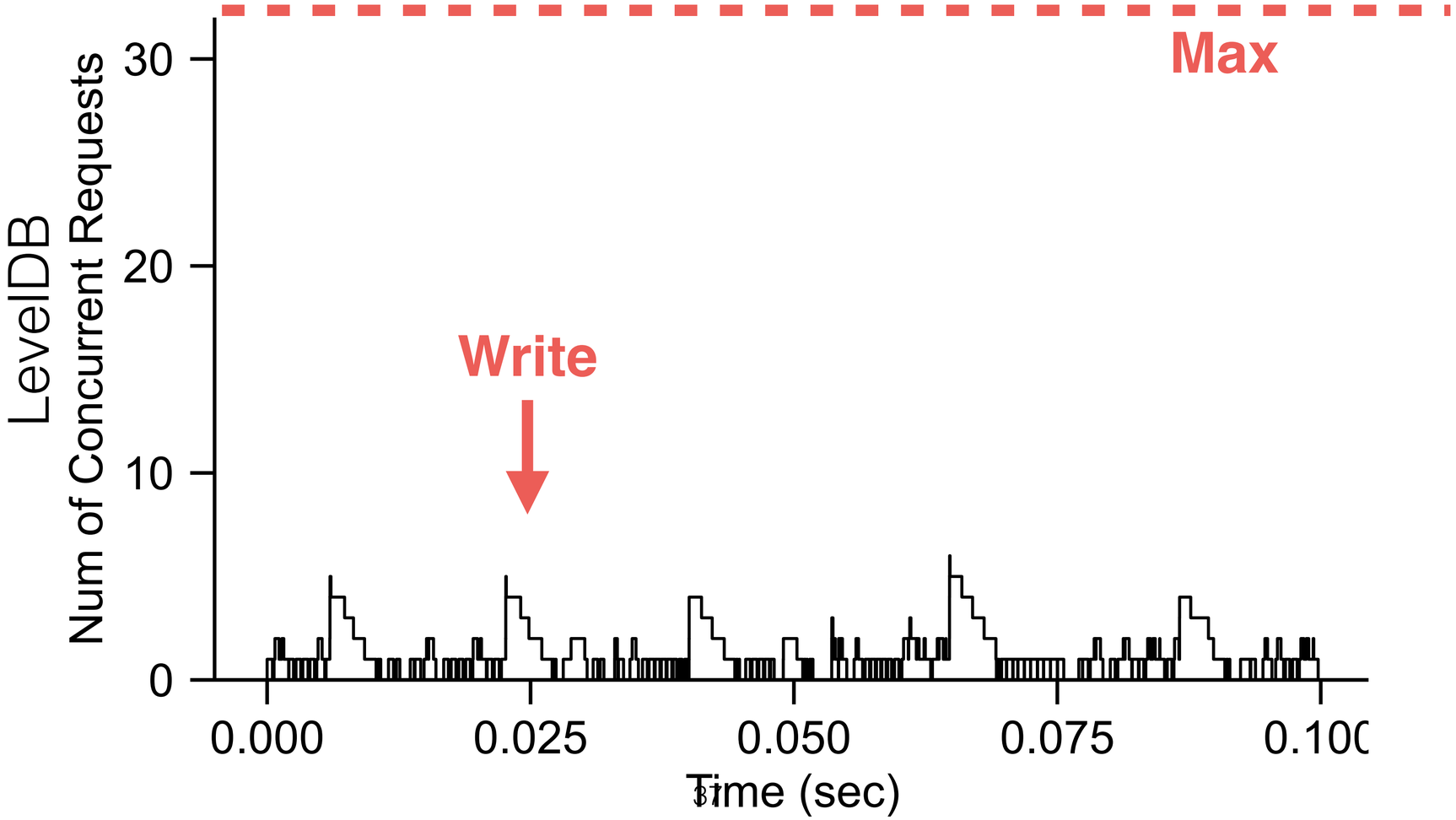
Num of concurrent requests is low during compaction



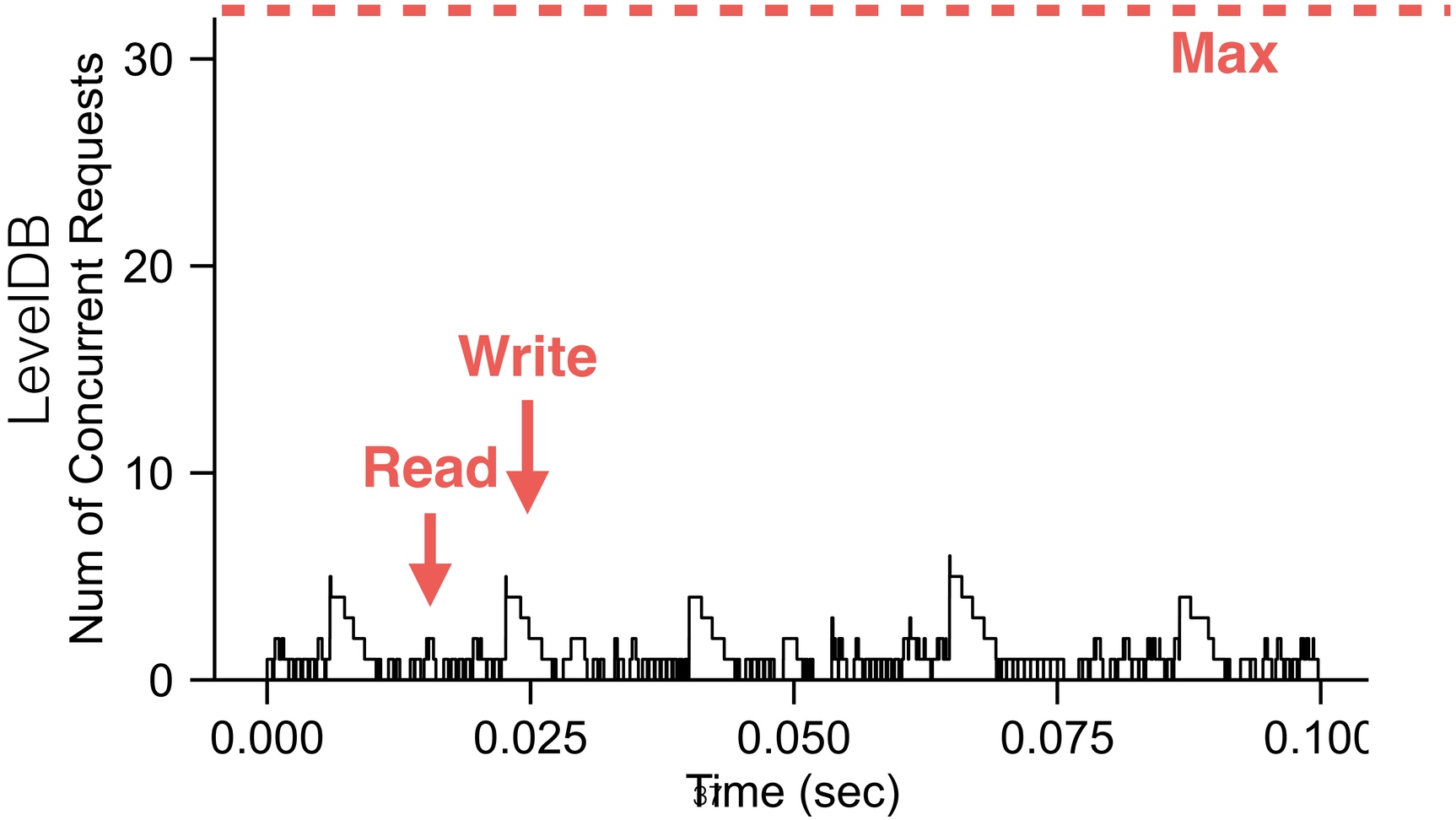
Num of concurrent requests is low during compaction



Num of concurrent requests is low during compaction



Num of concurrent requests is low during compaction



Page cache implementation splits and serializes user requests

App

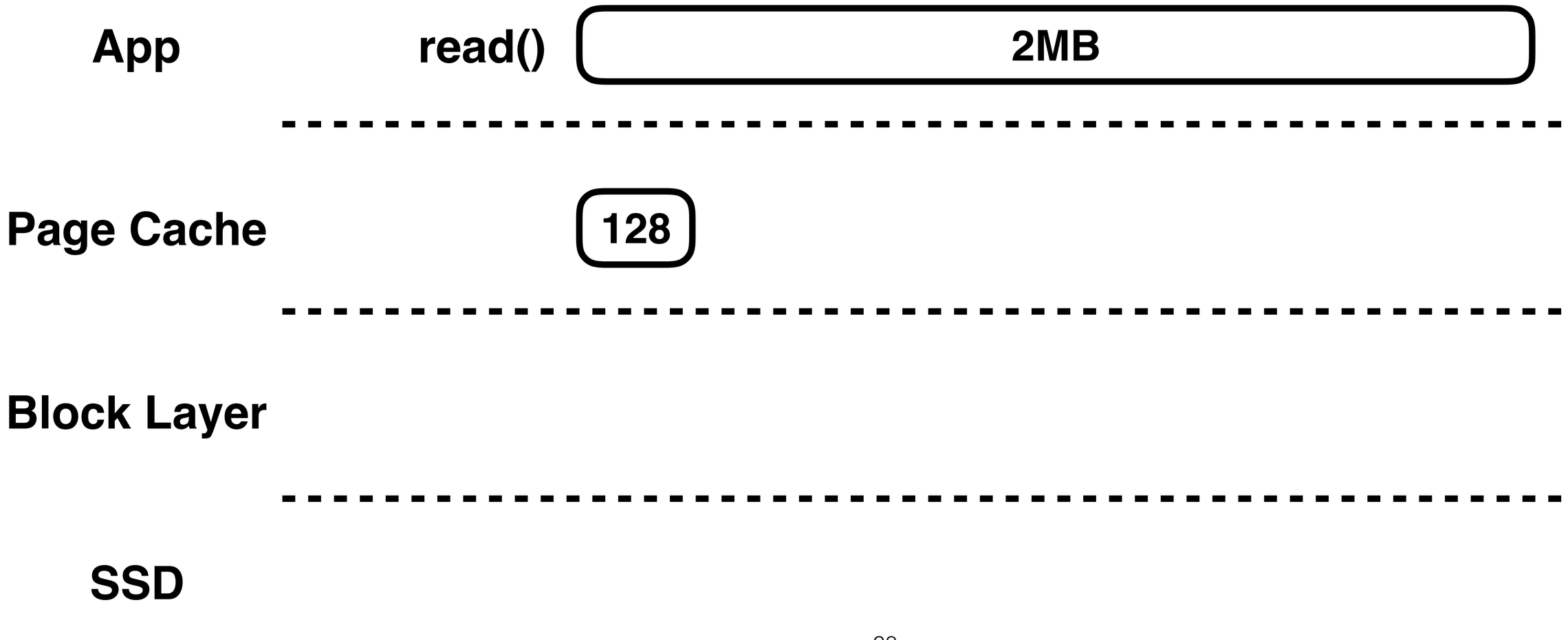
Page Cache

Block Layer

SSD

Page cache implementation splits and serializes user requests

Page cache implementation splits and serializes user requests



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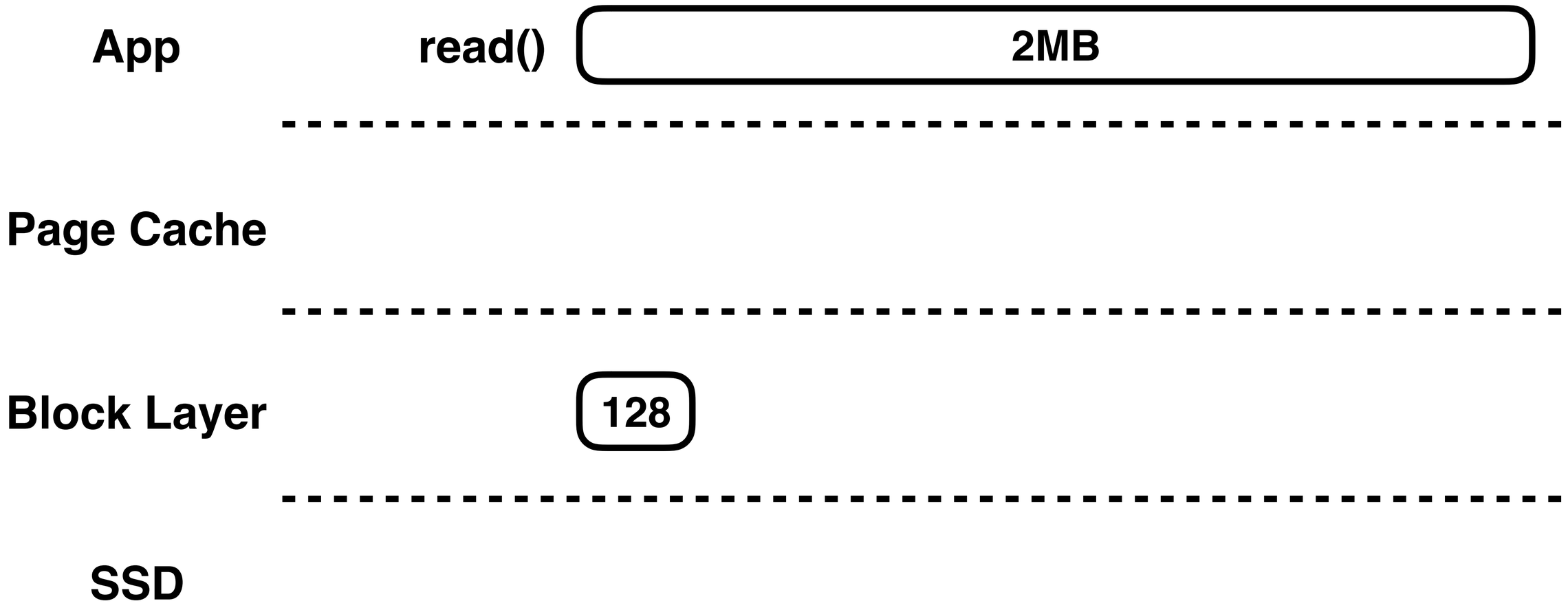

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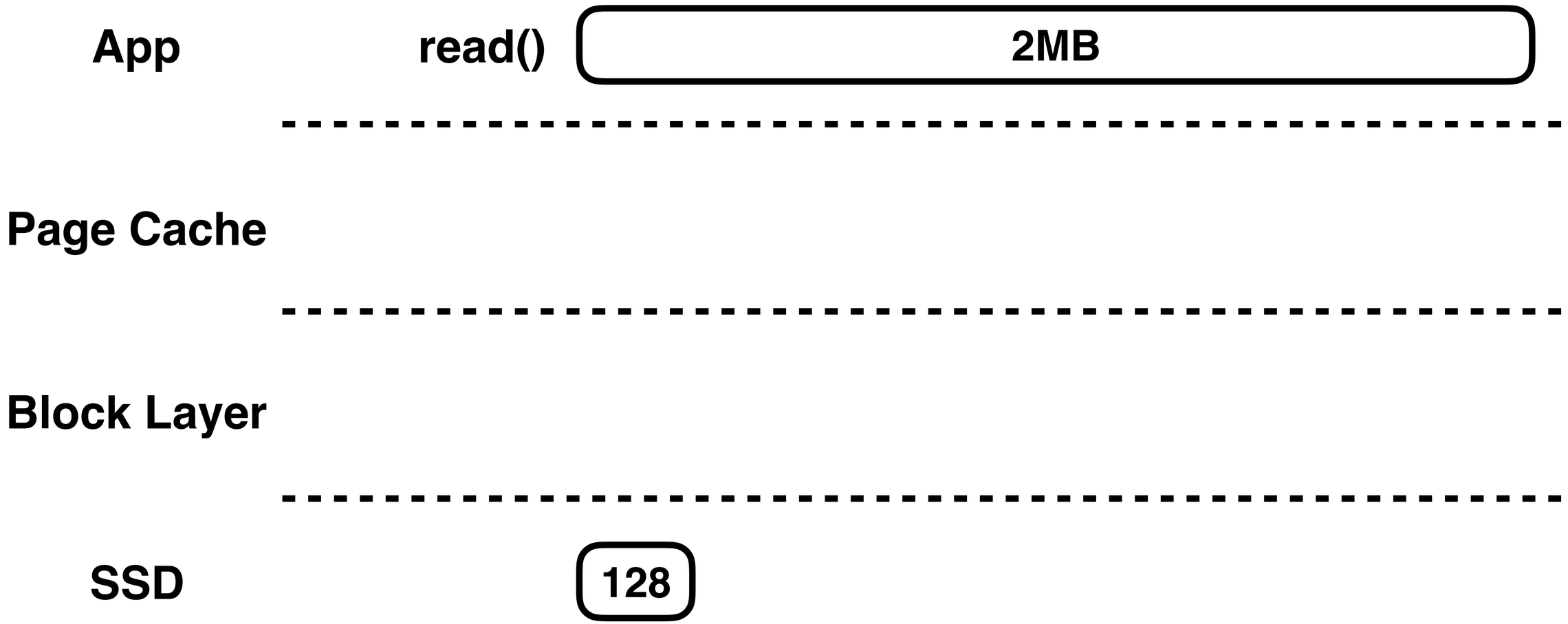

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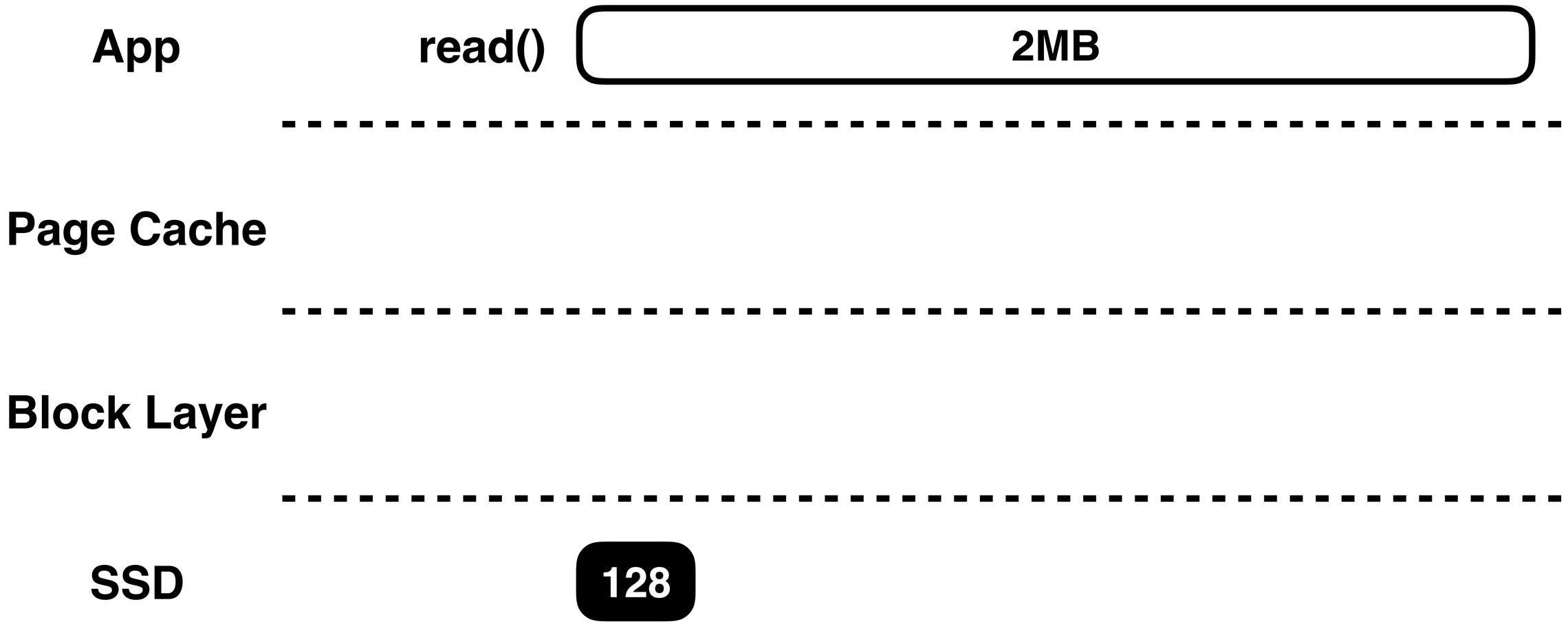

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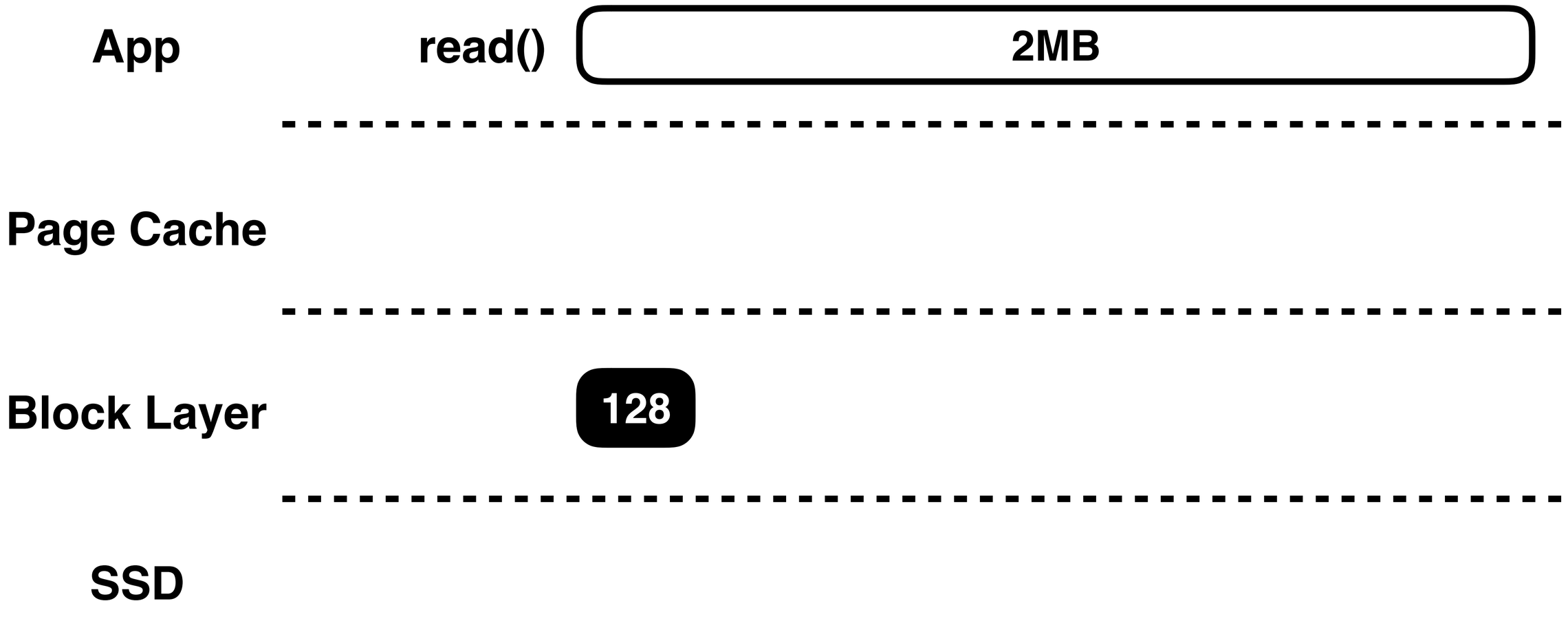

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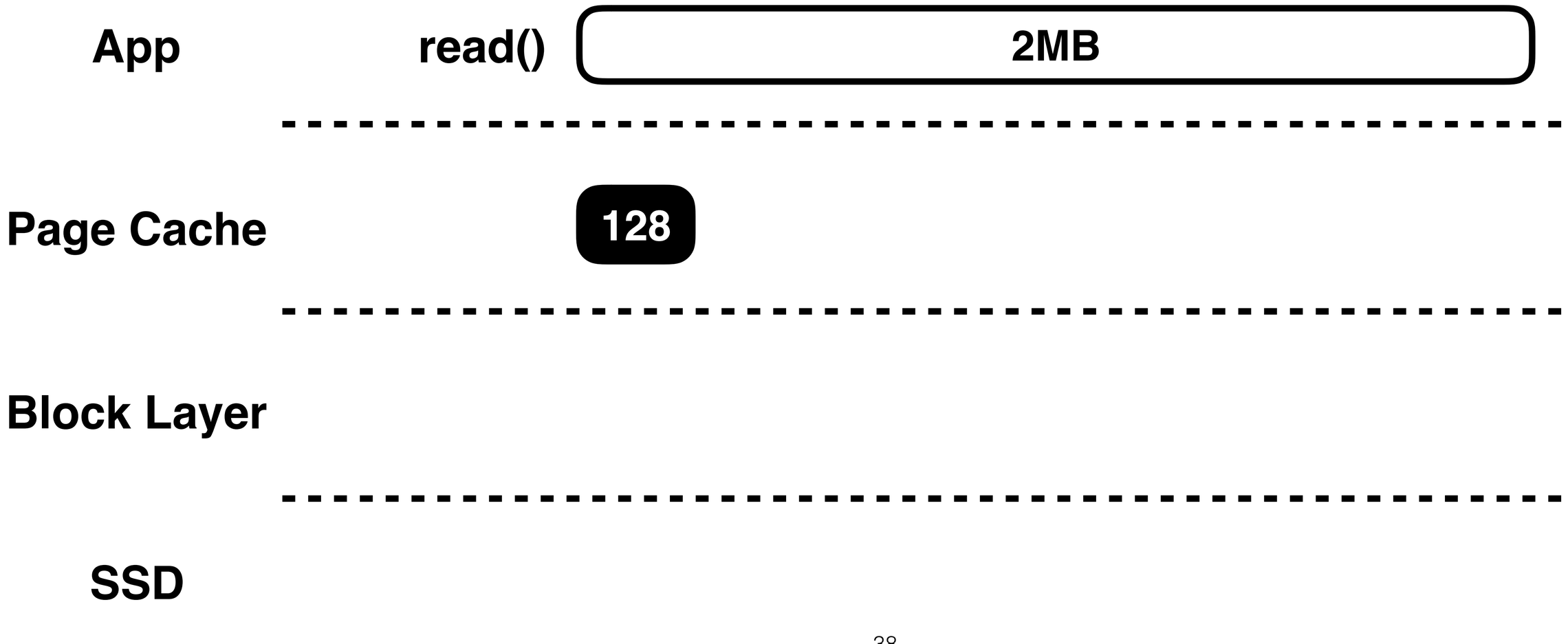

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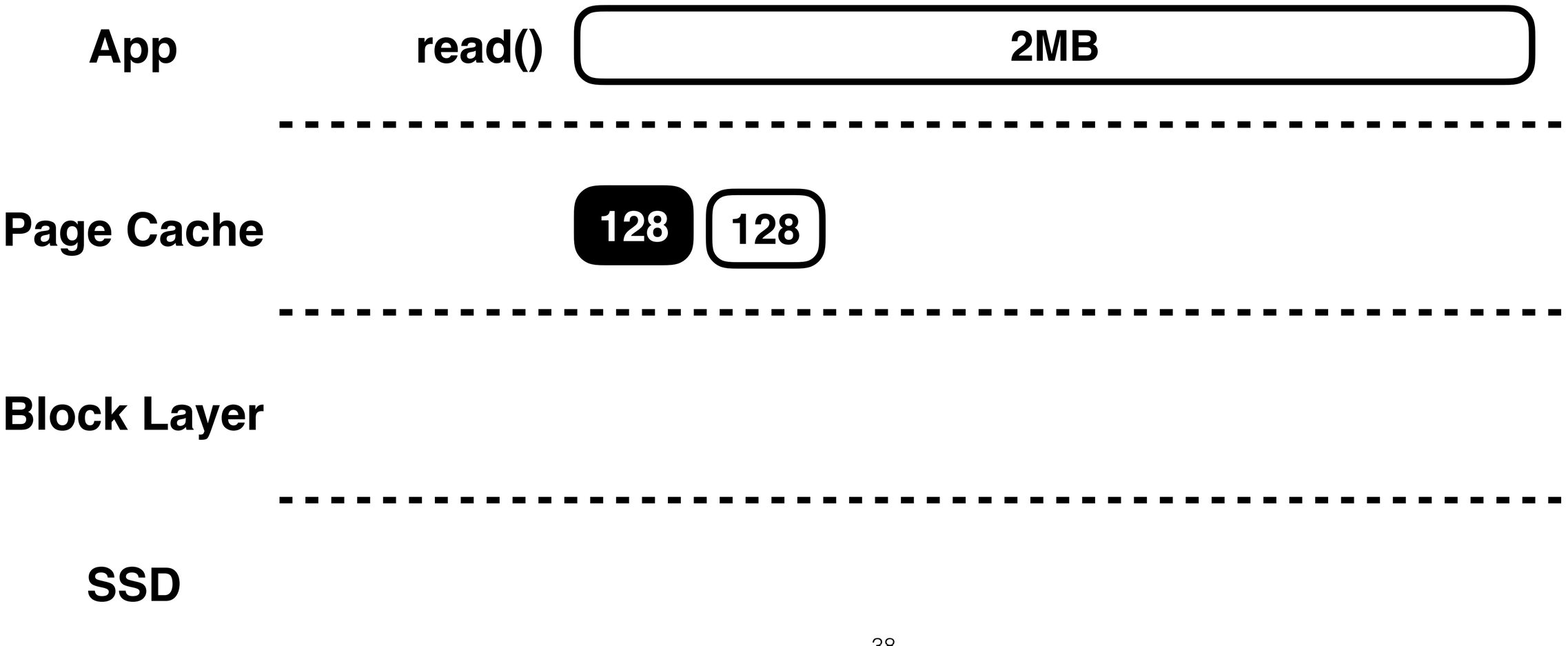

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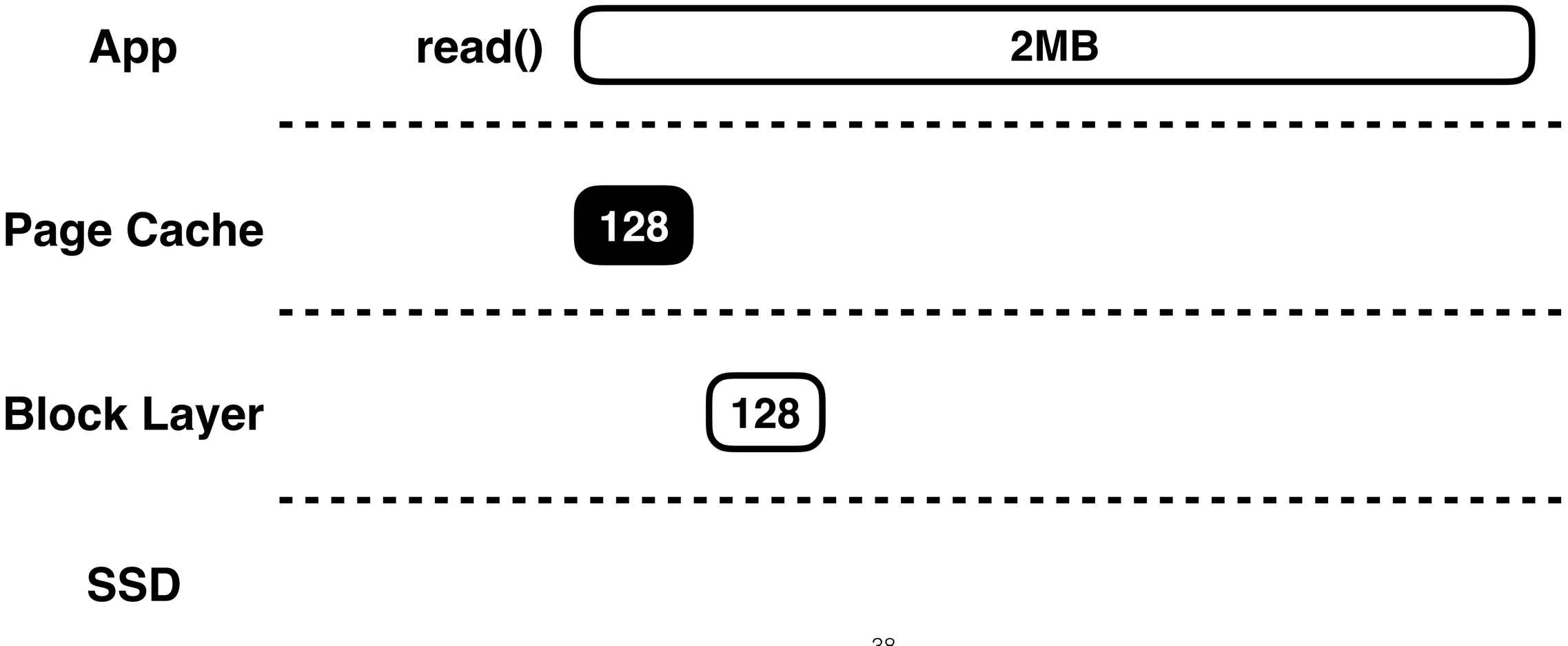

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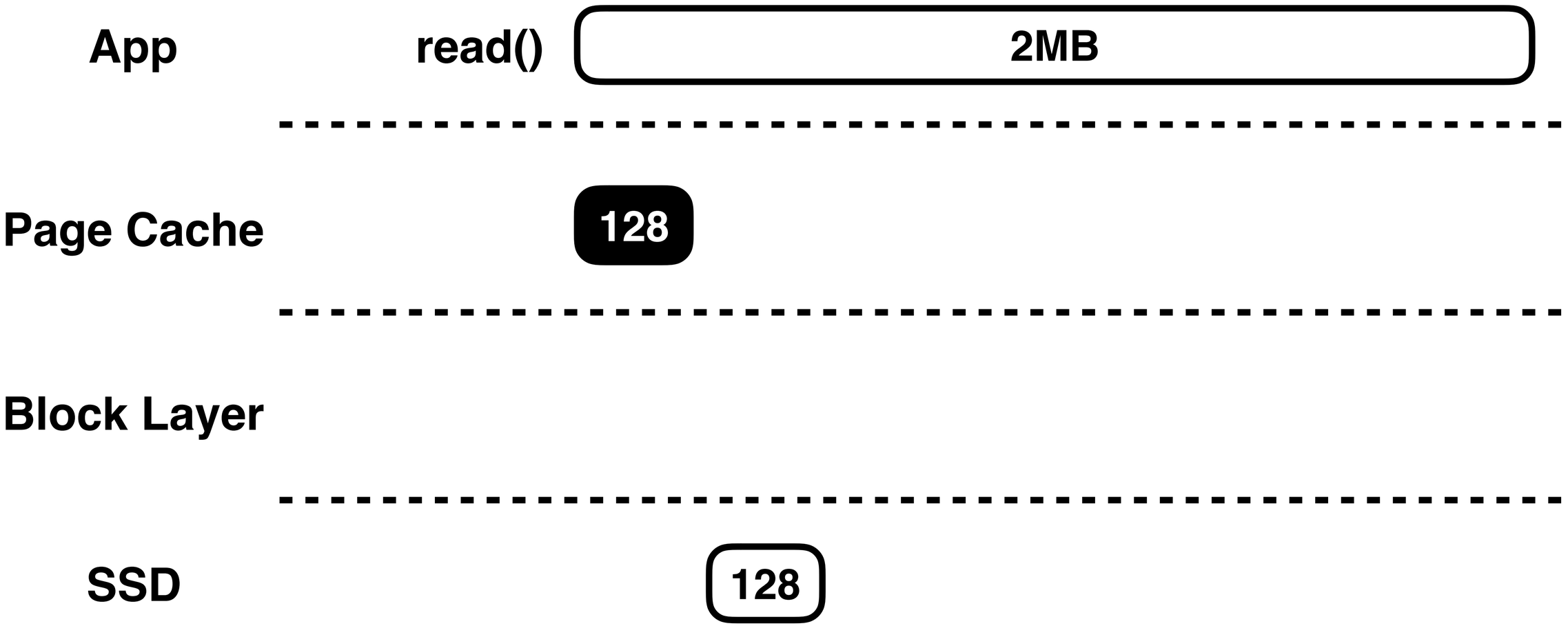

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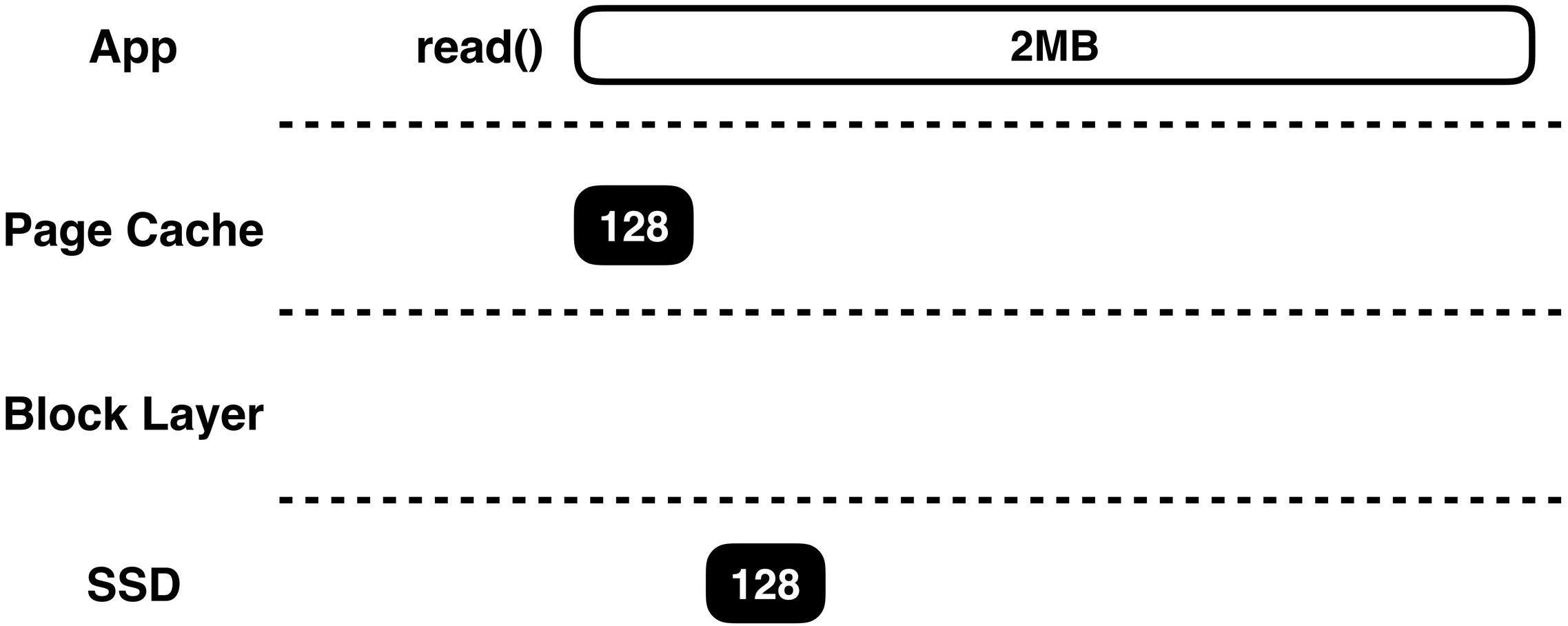

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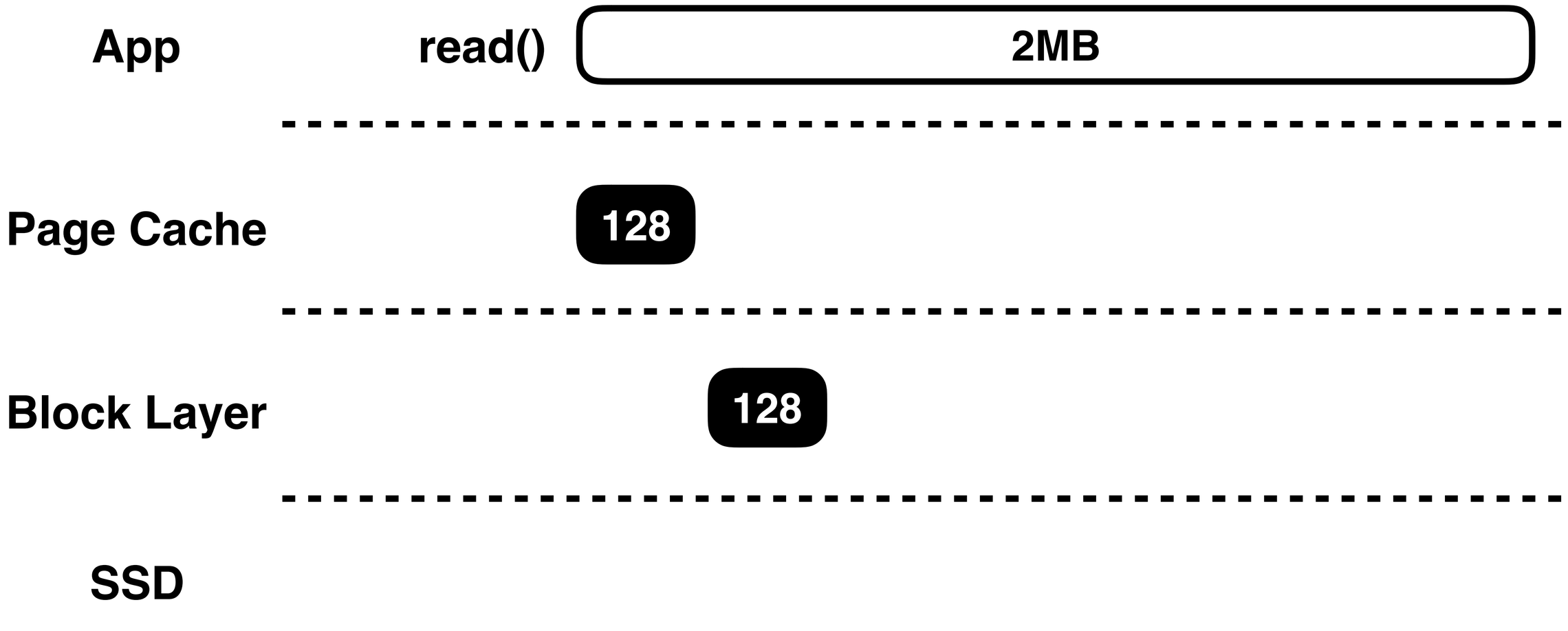

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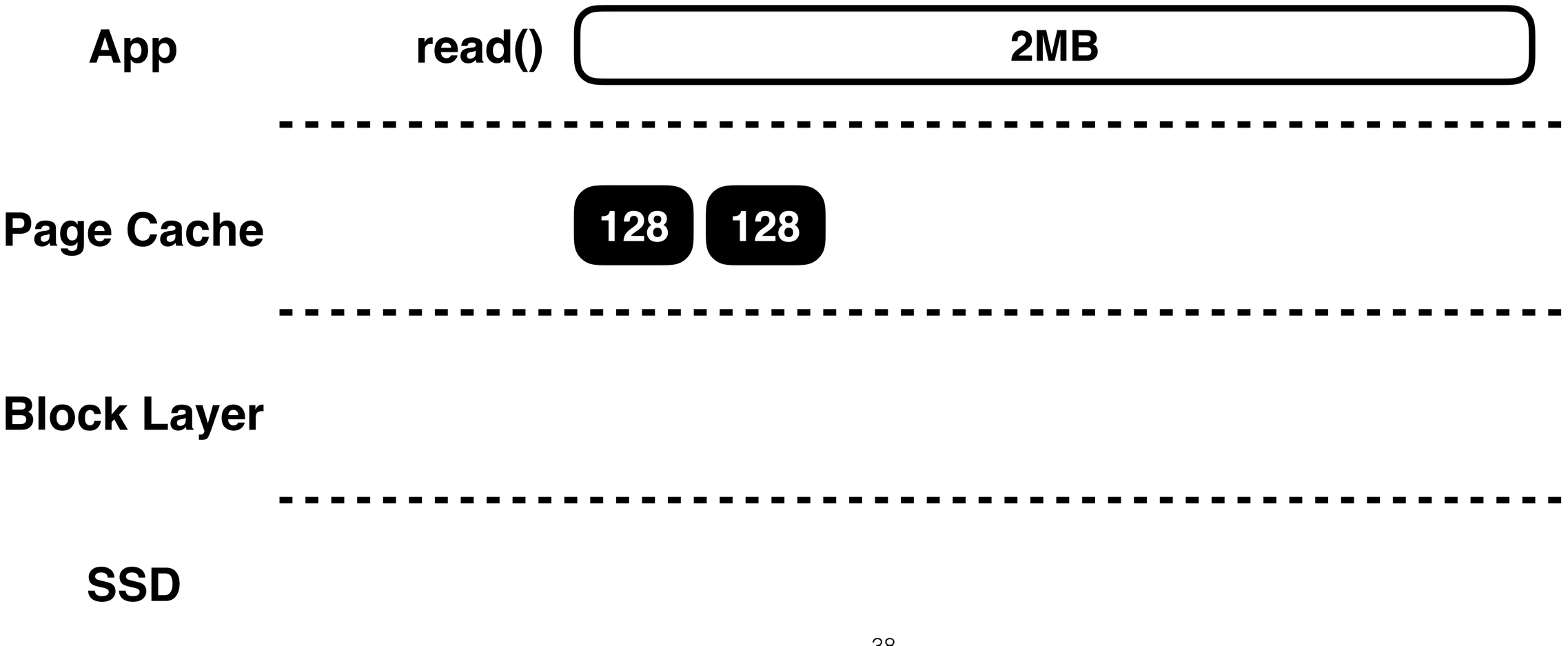

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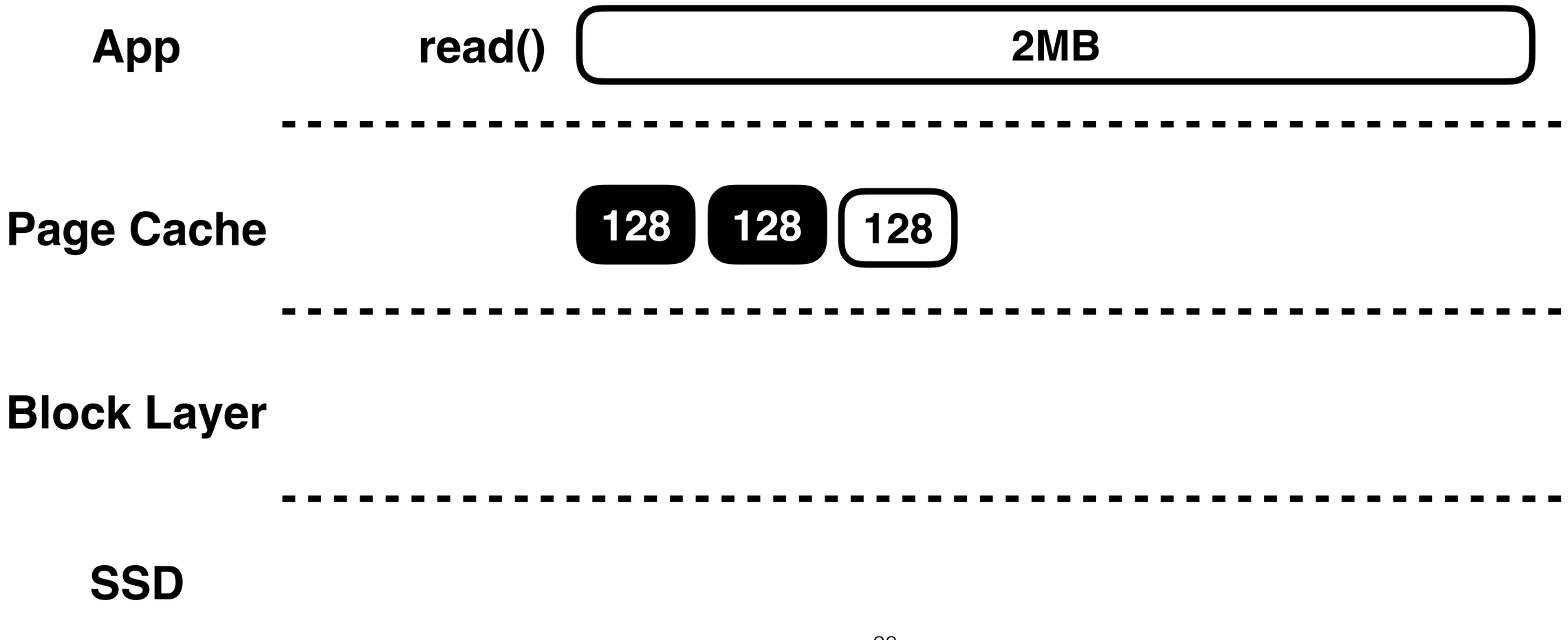

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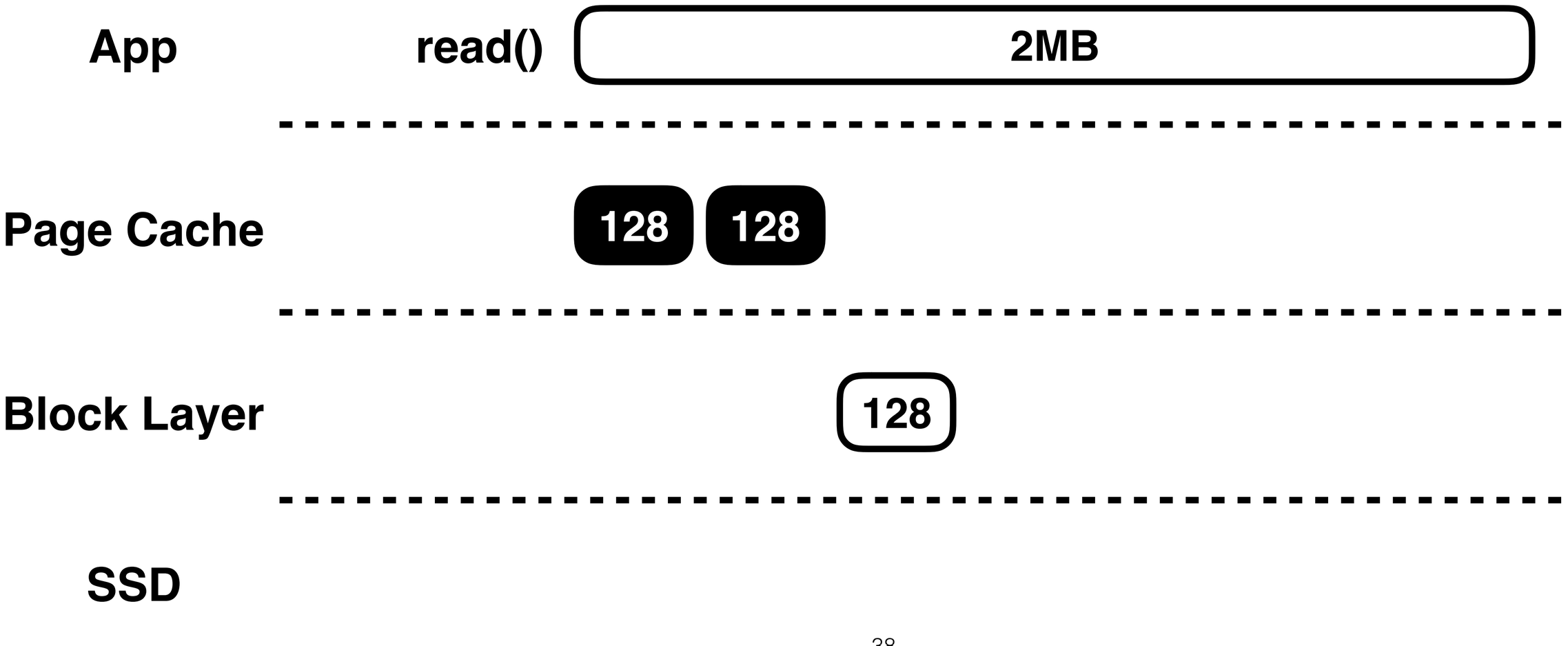

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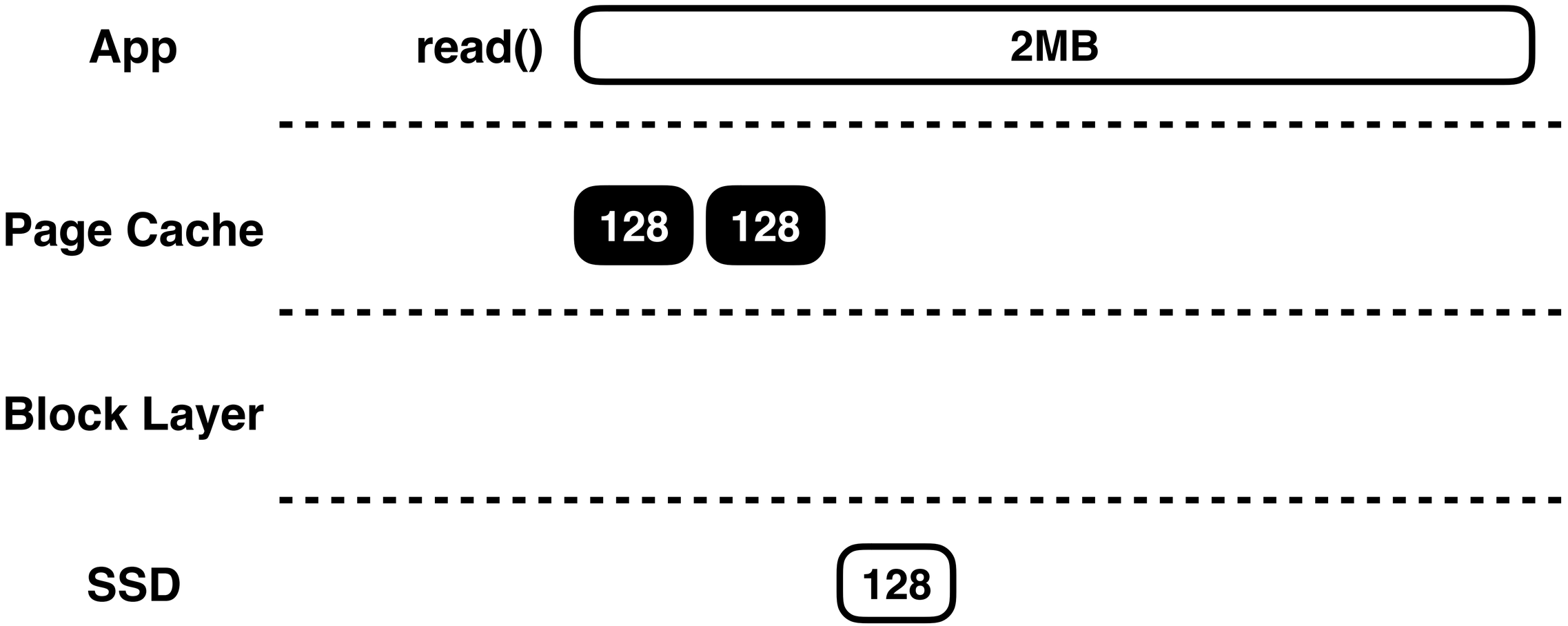

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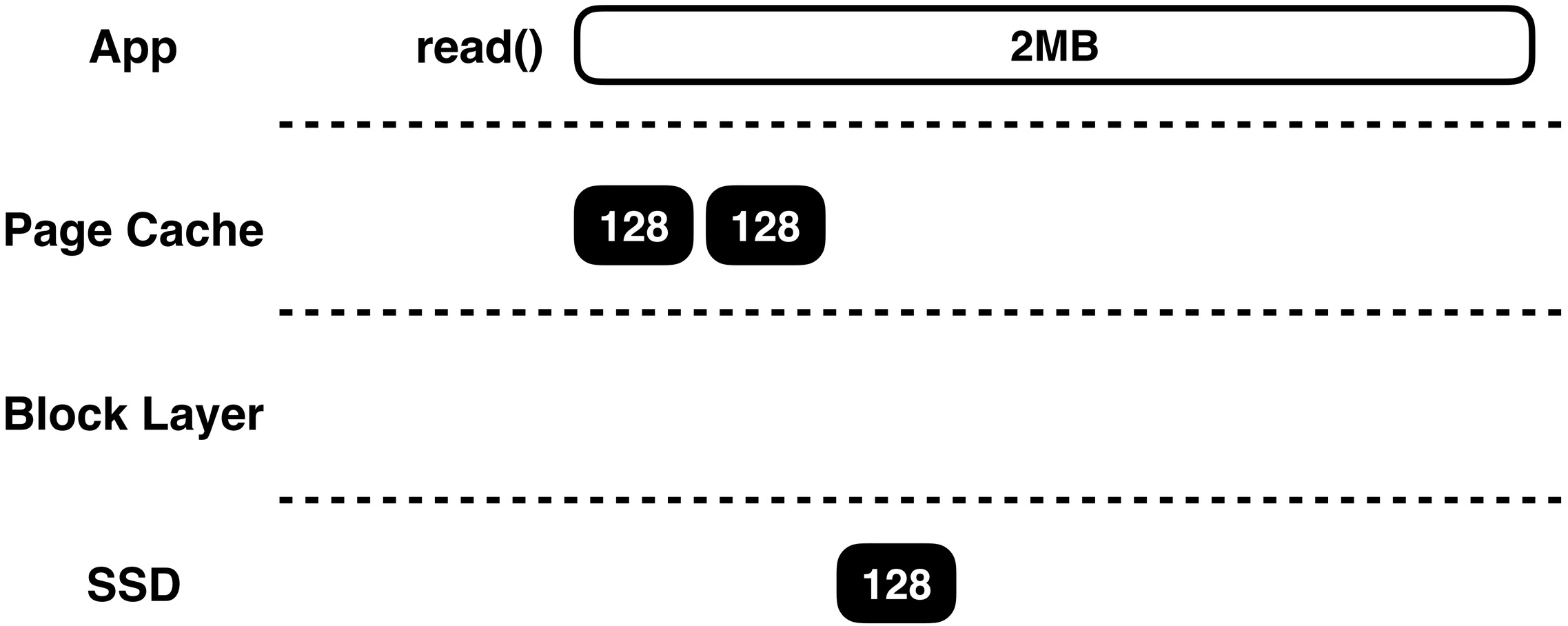

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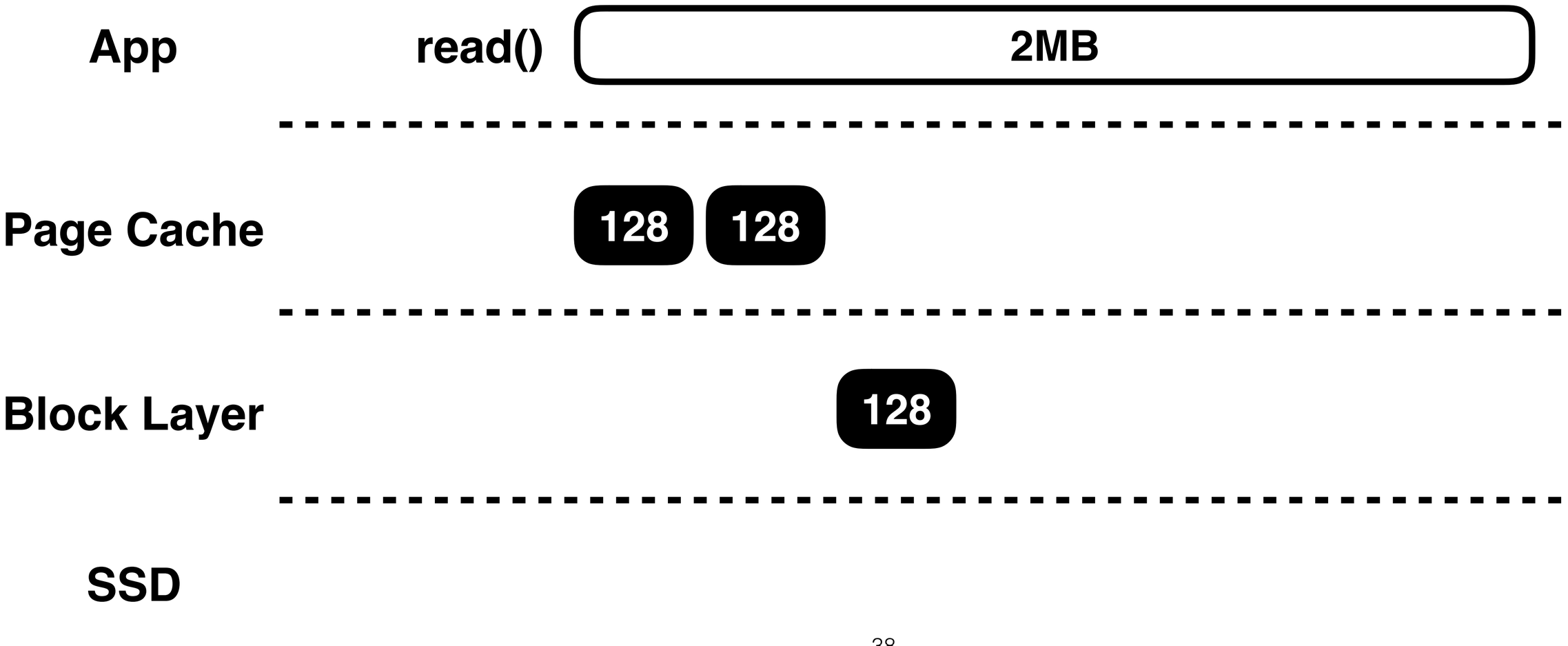

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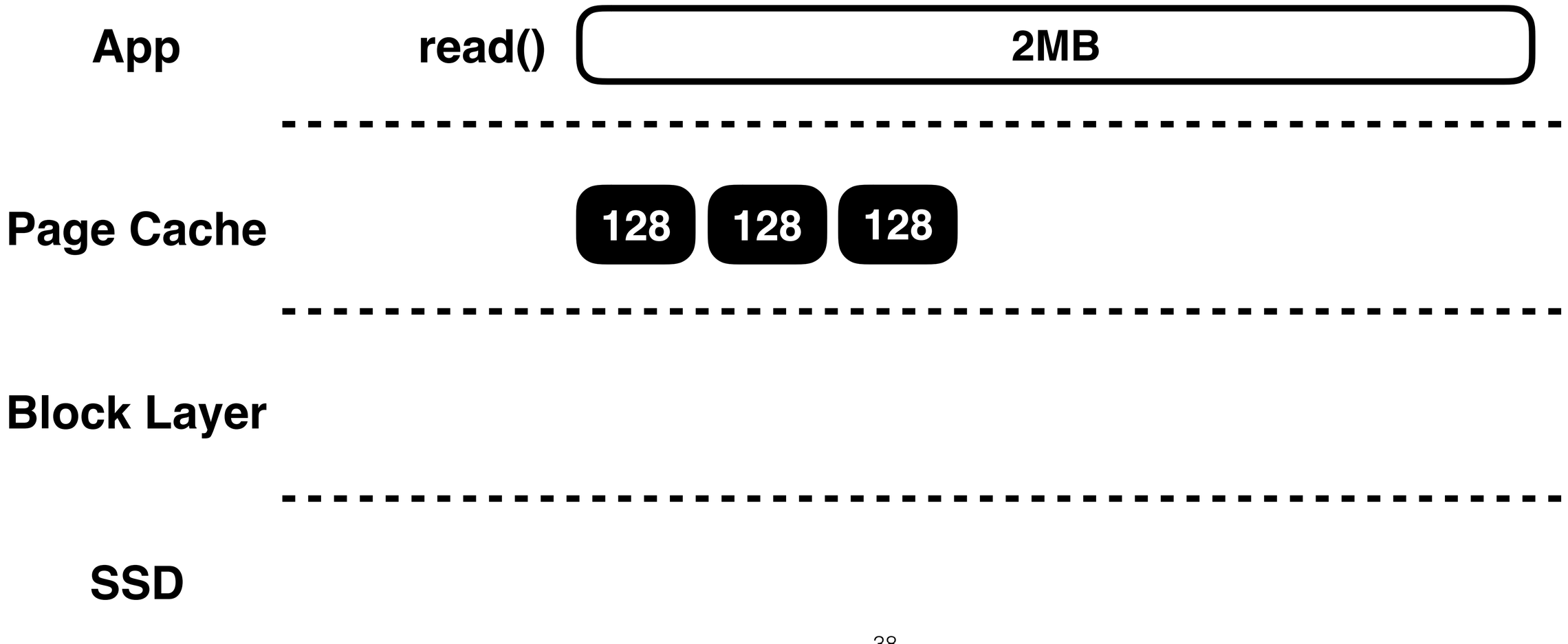

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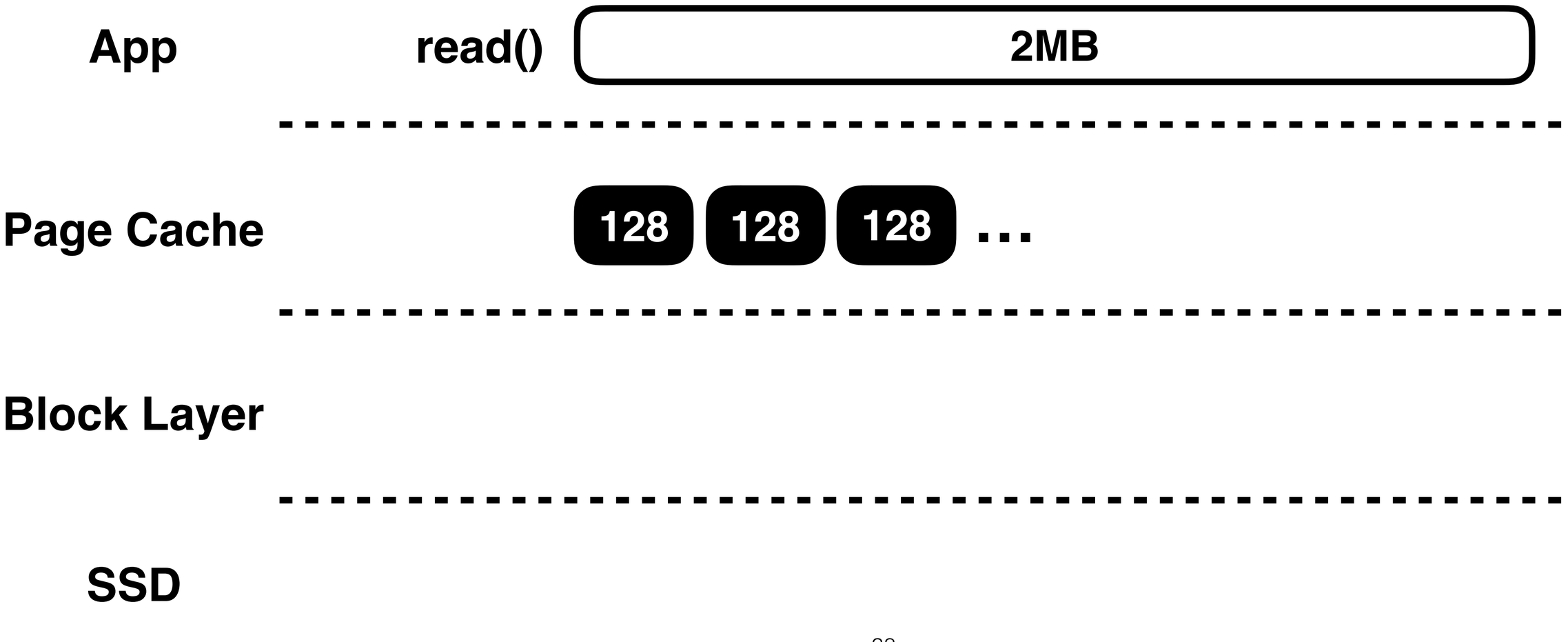

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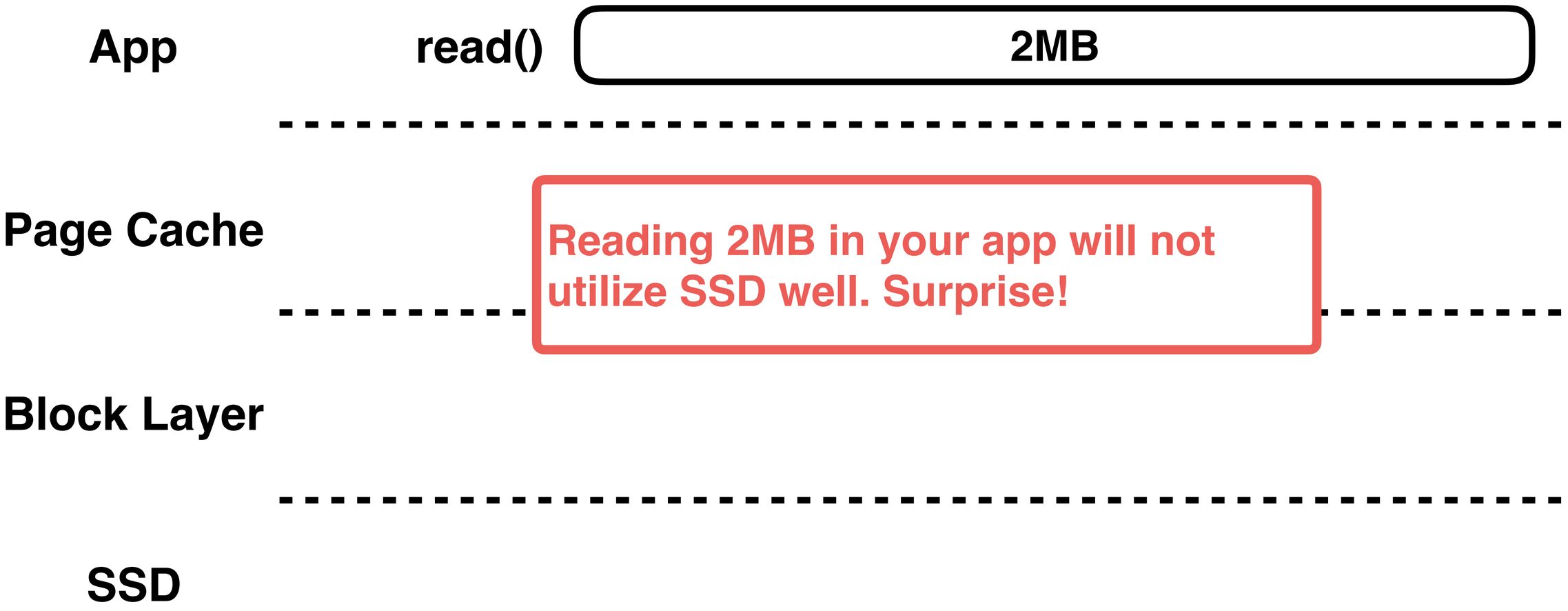


Page cache implementation splits and serializes user requests

App

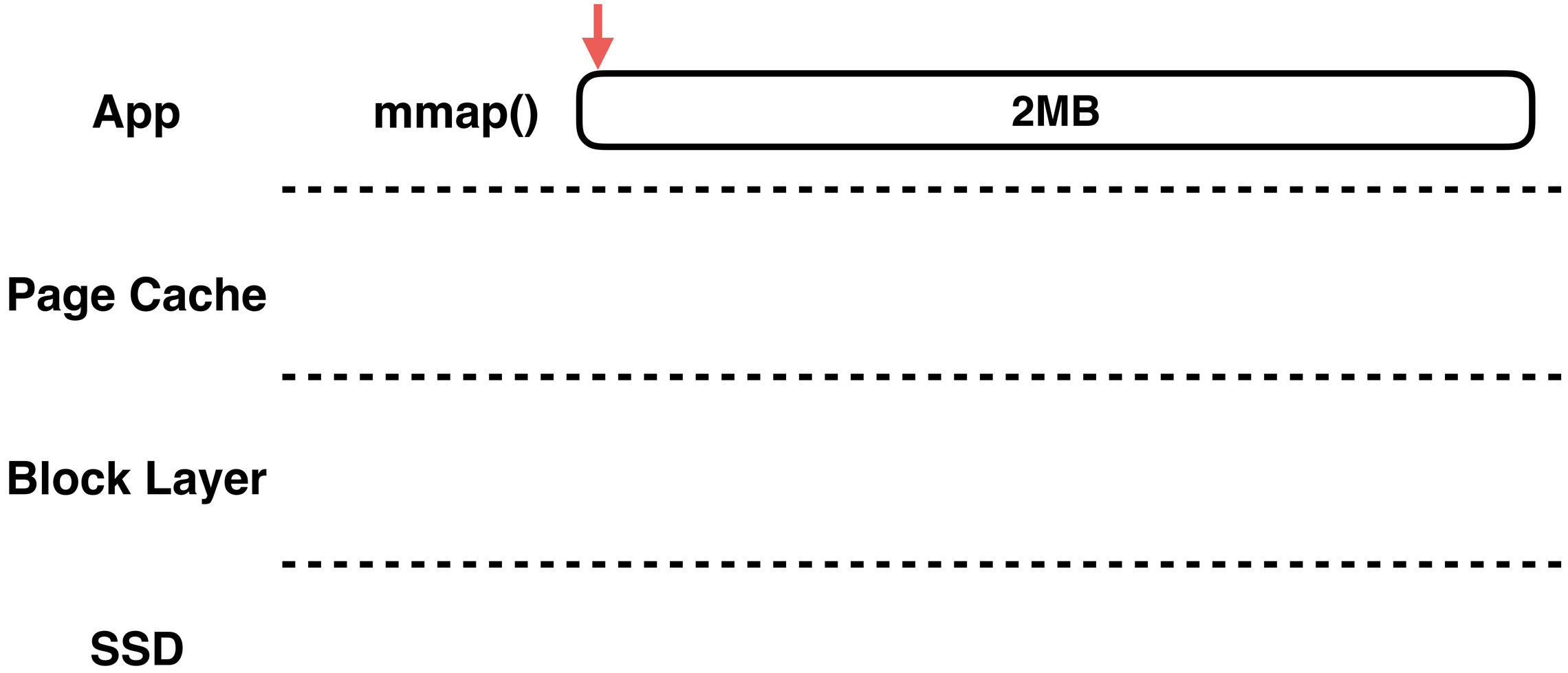
Page Cache

Block Layer

SSD

Page cache implementation splits and serializes user requests

Page cache implementation splits and serializes user requests



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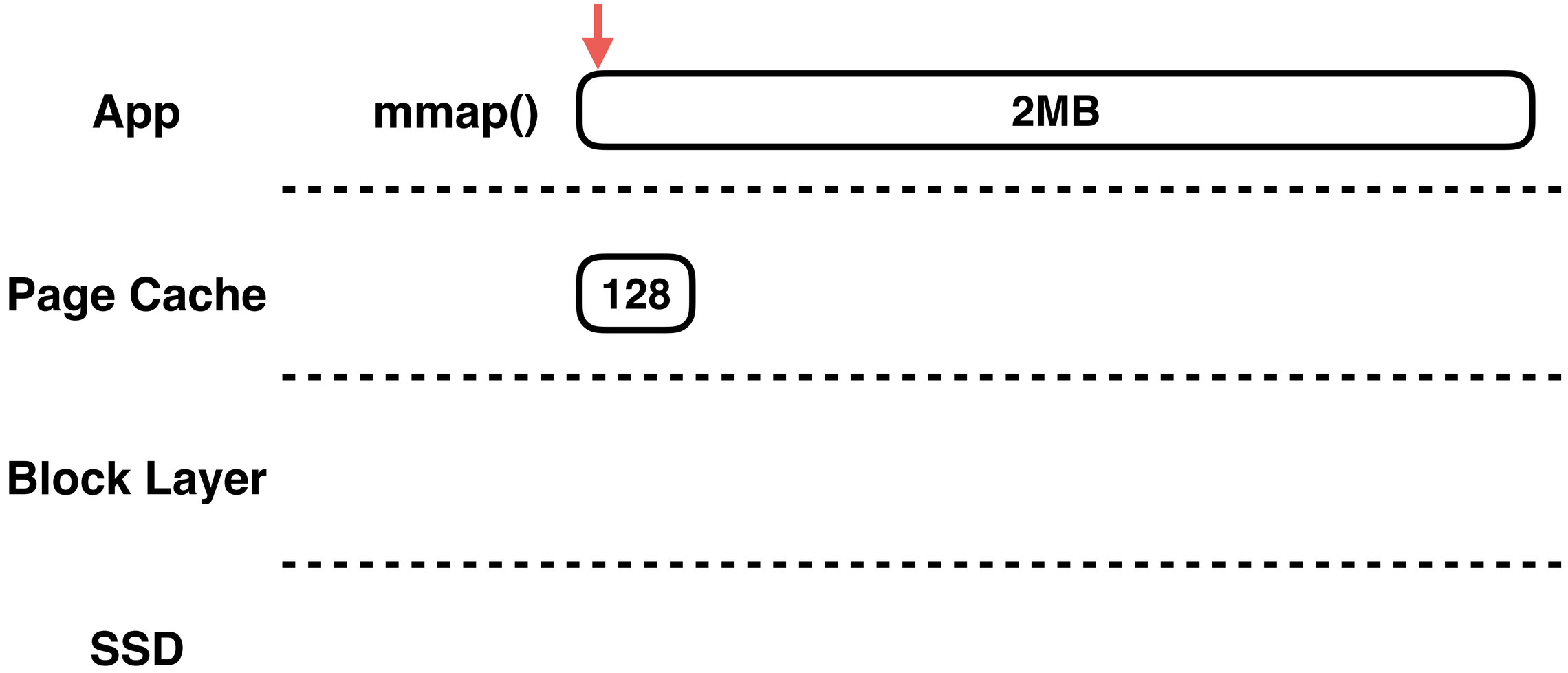

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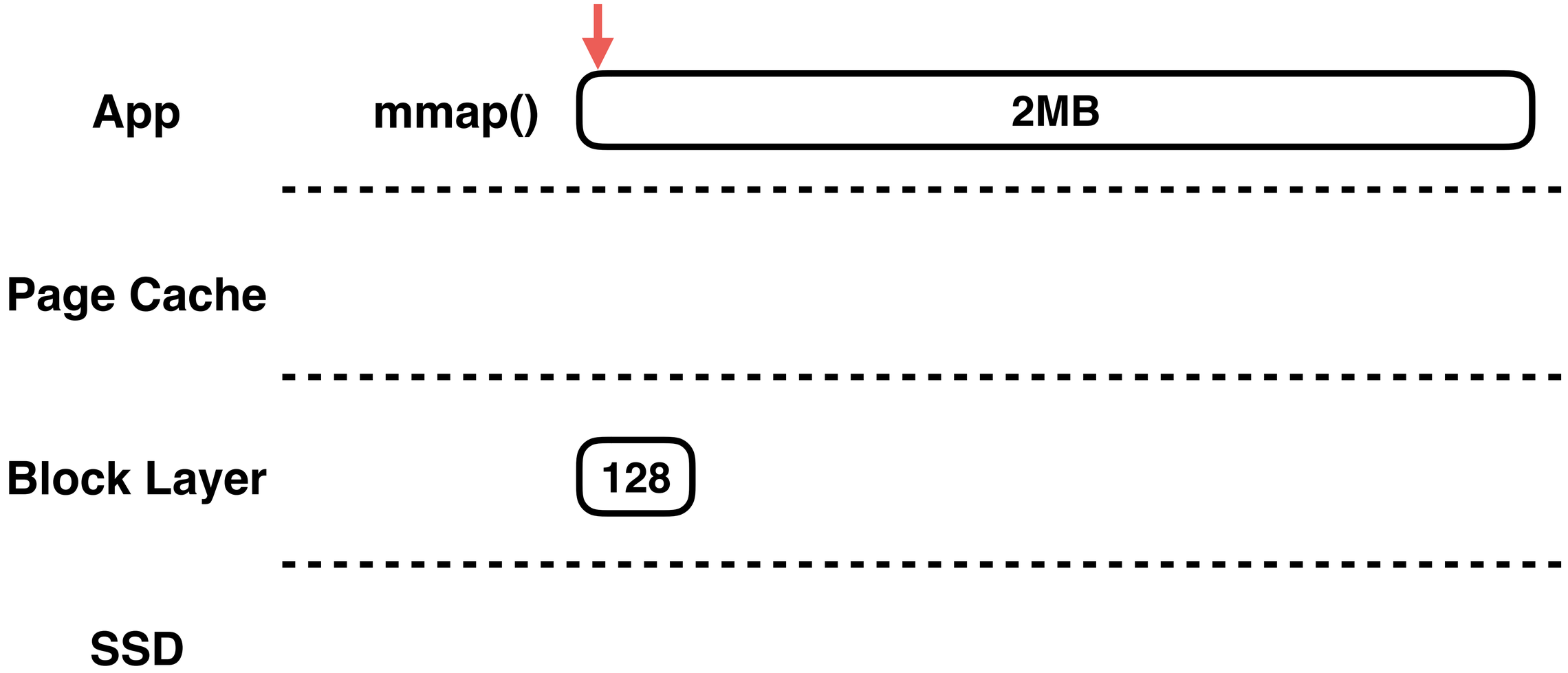

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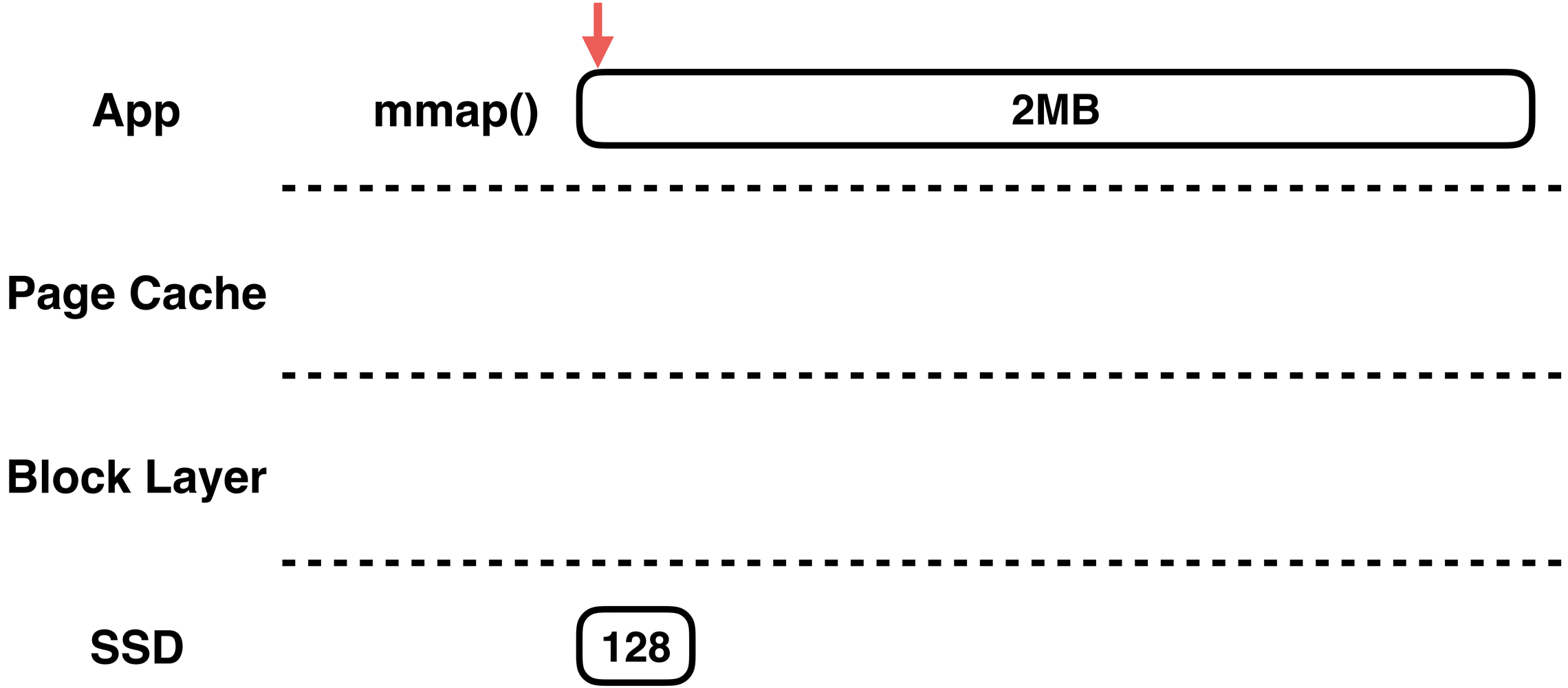

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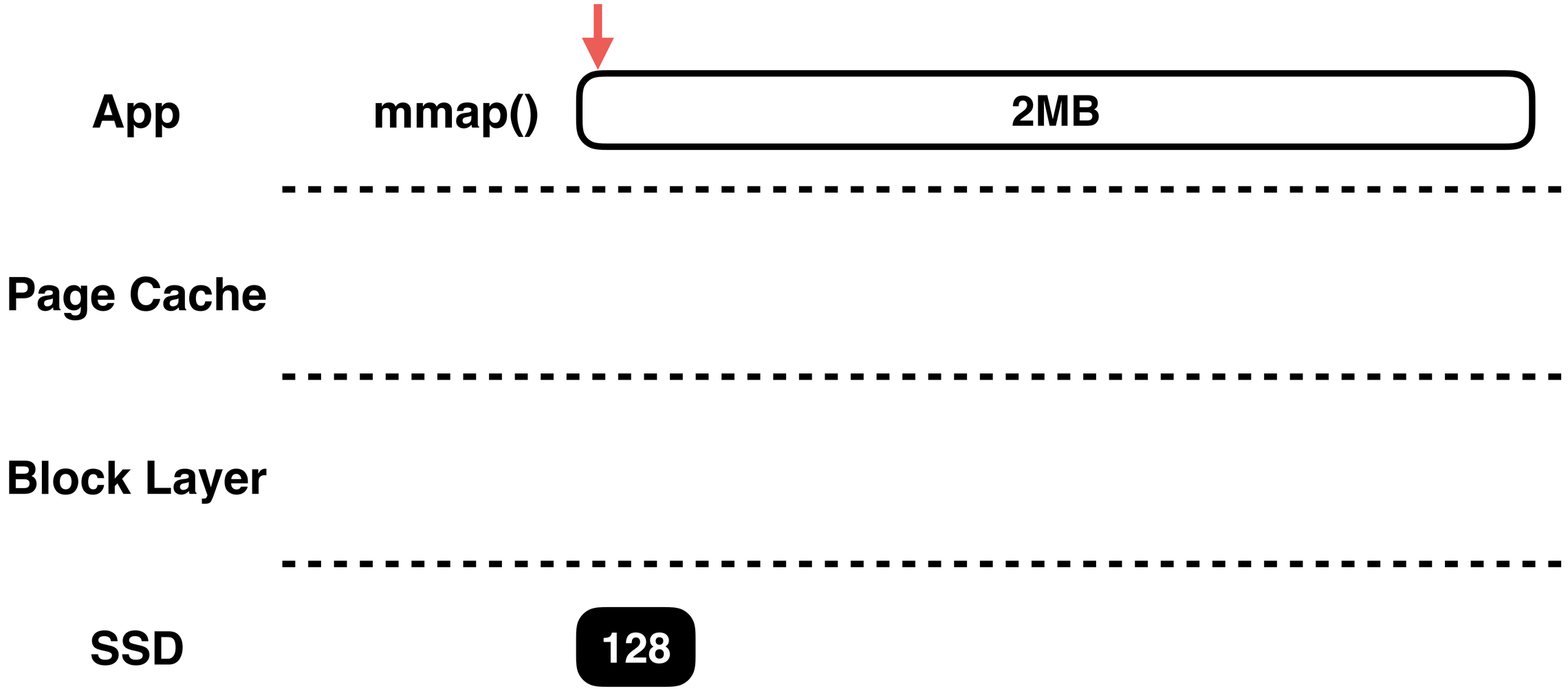

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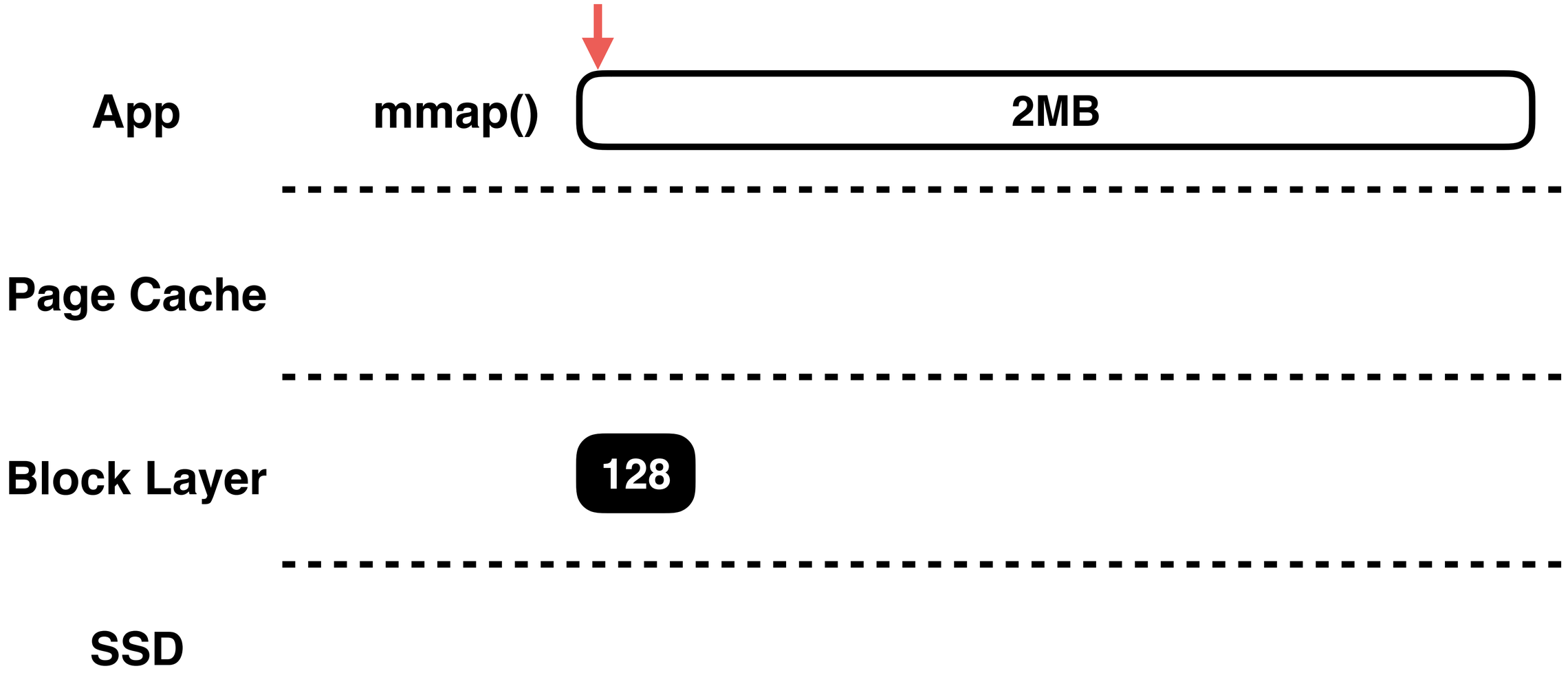

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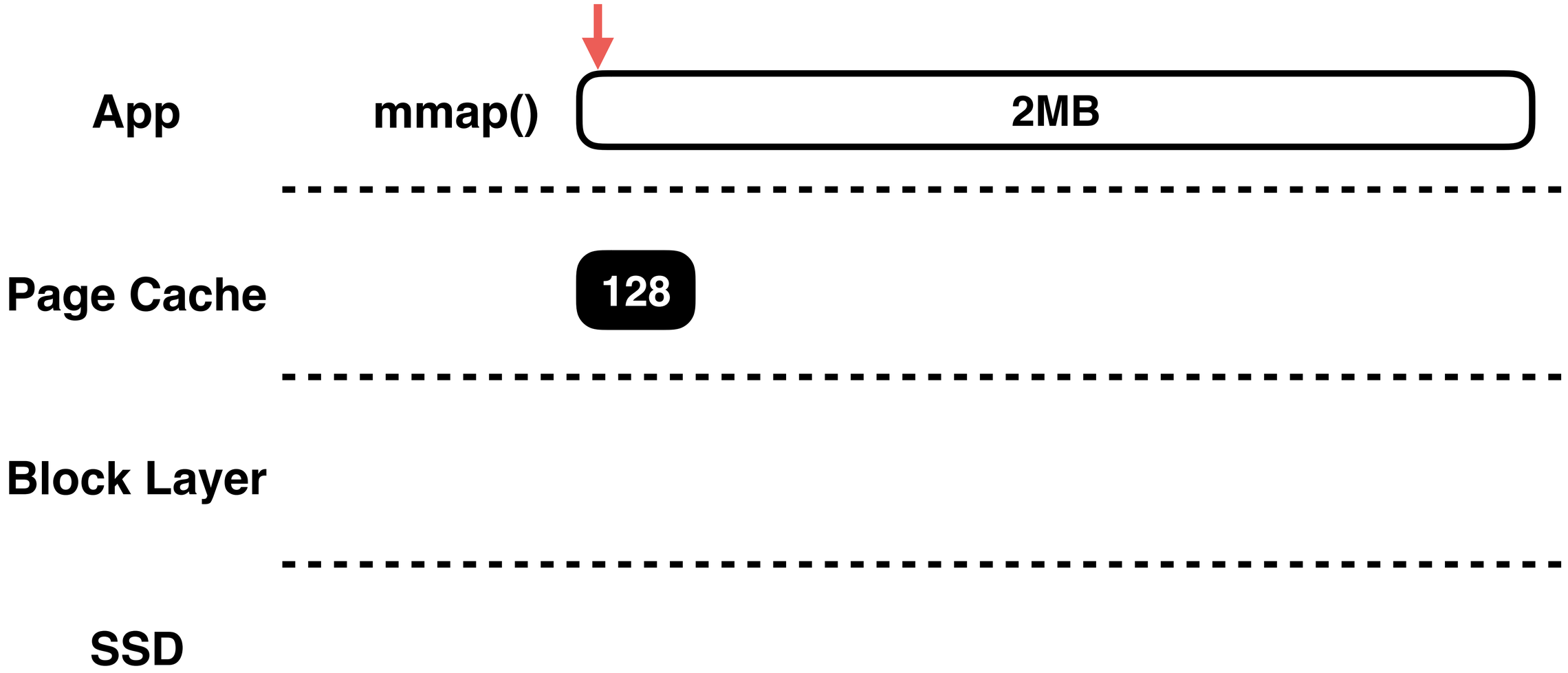

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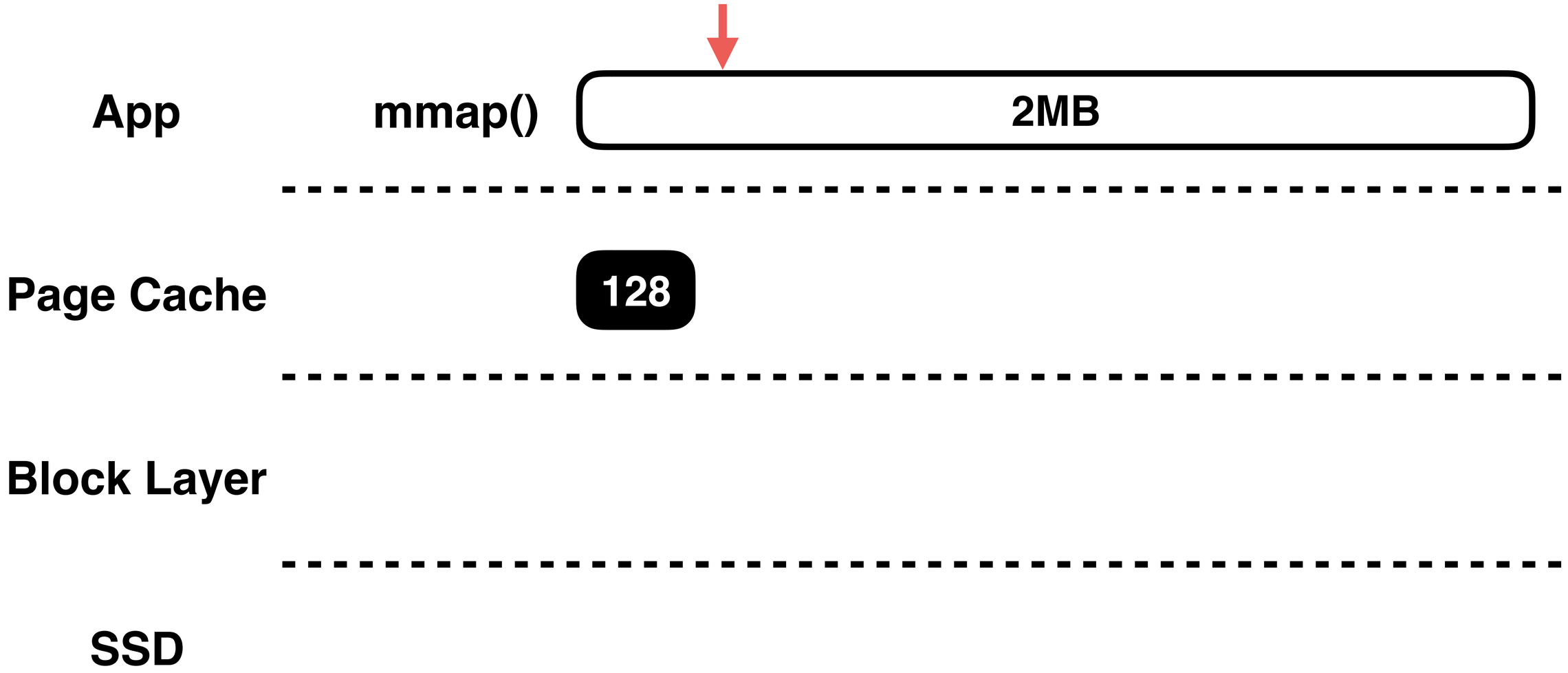

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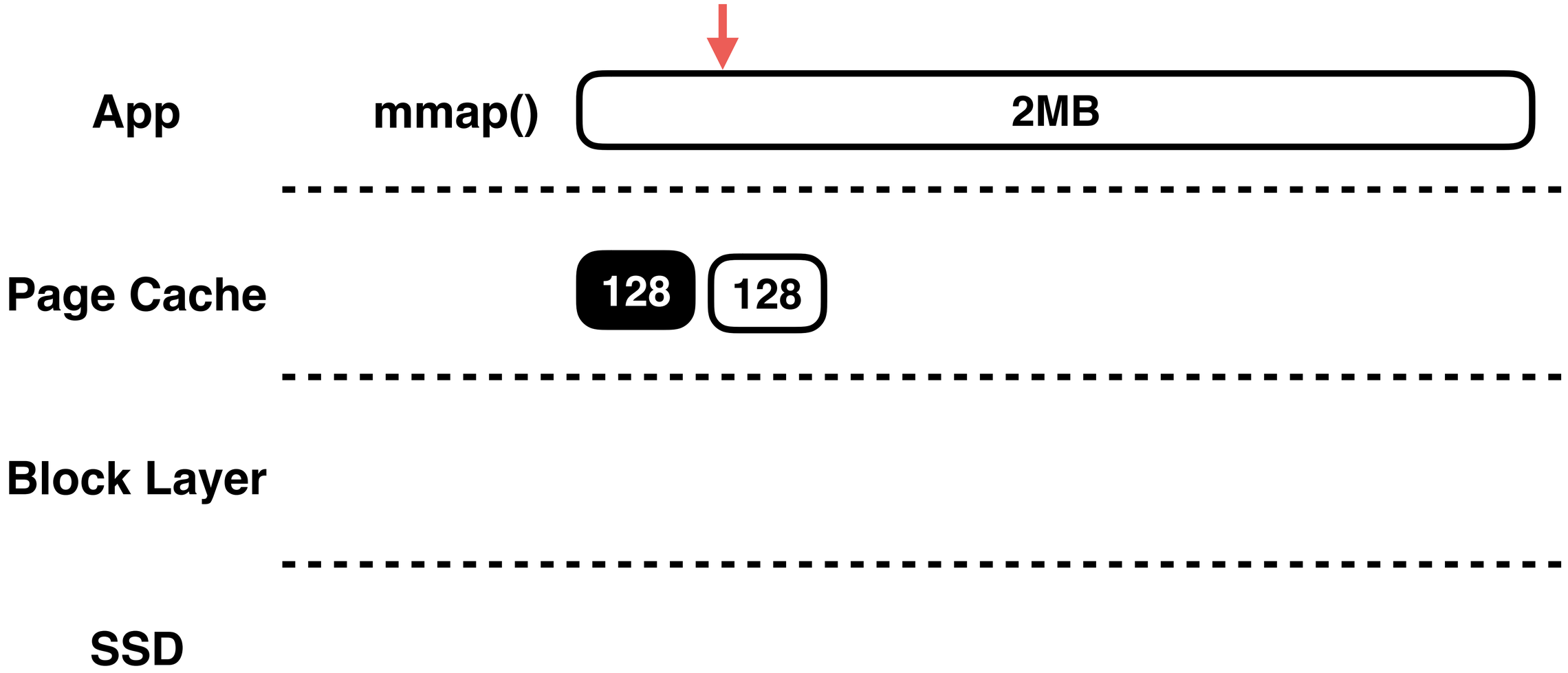

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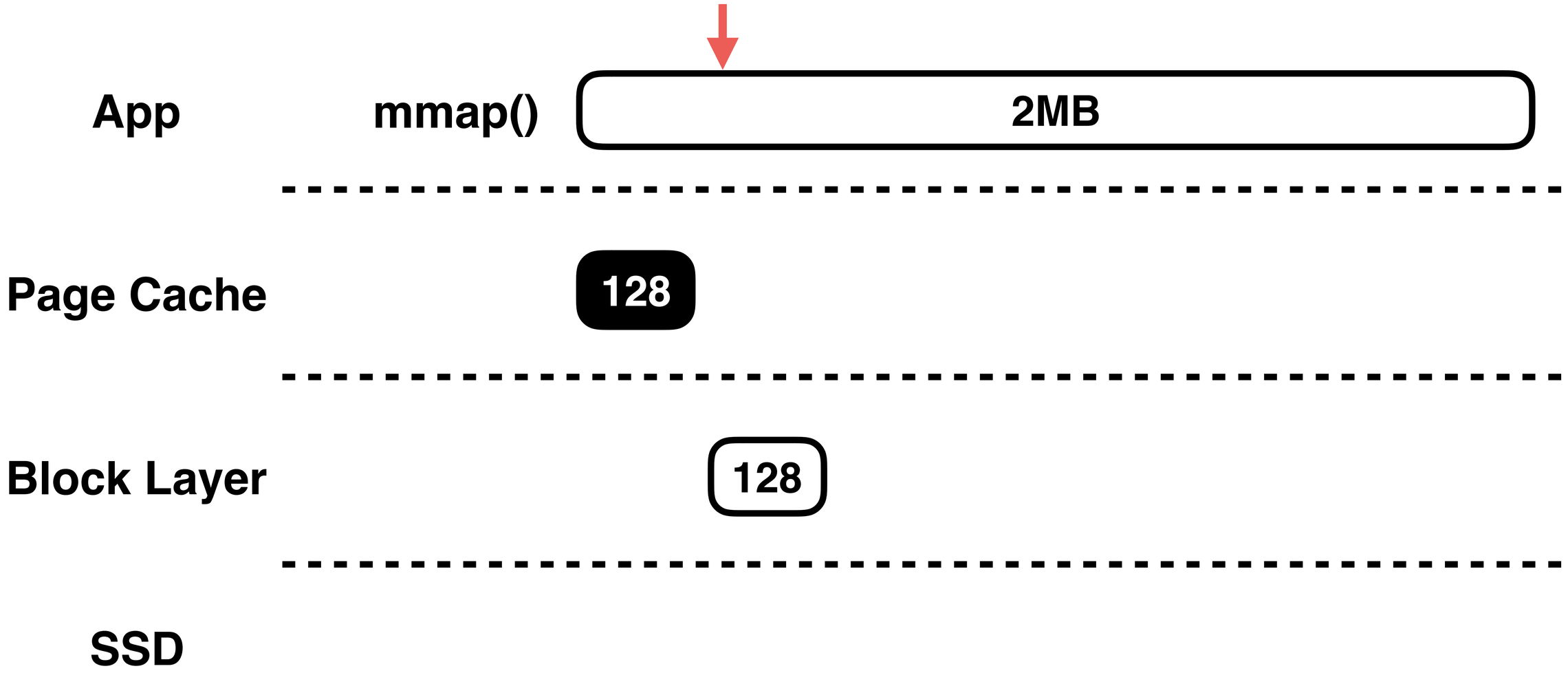

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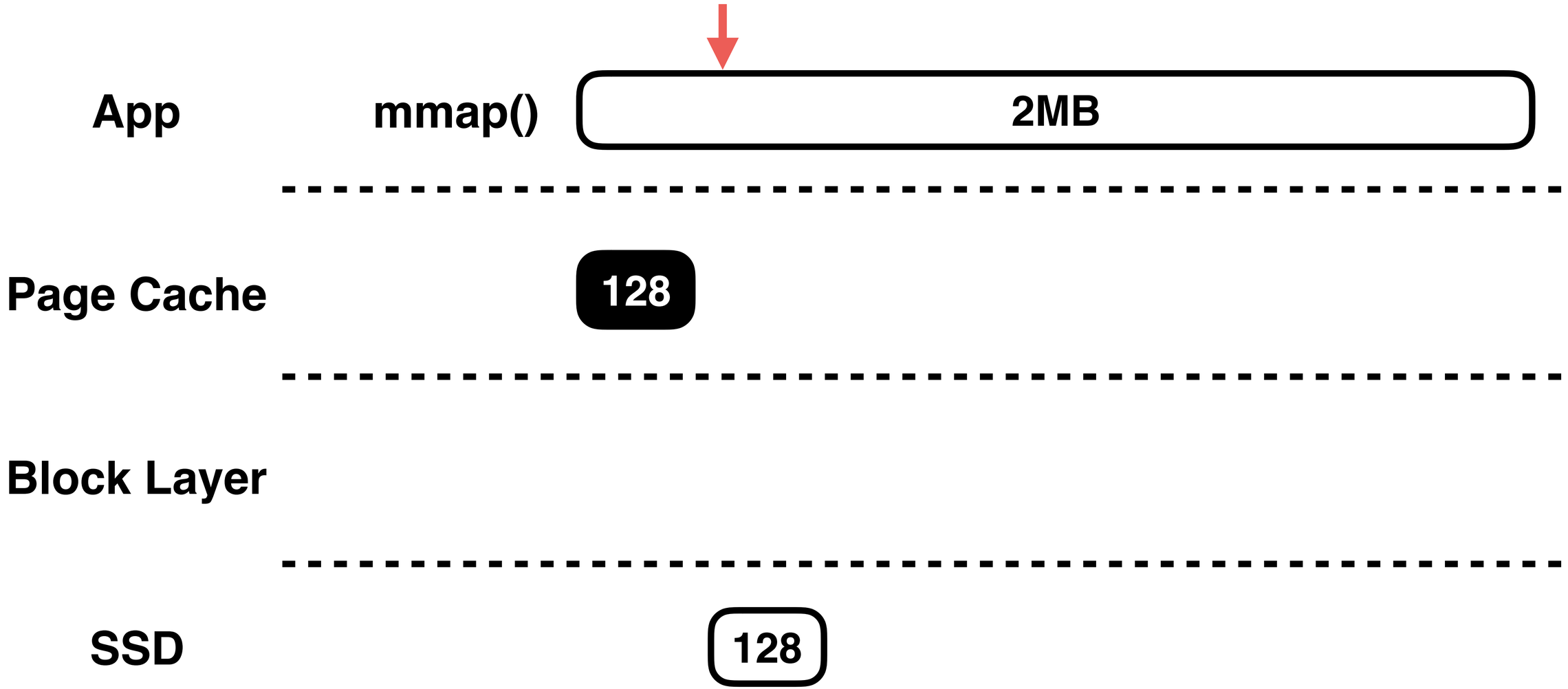

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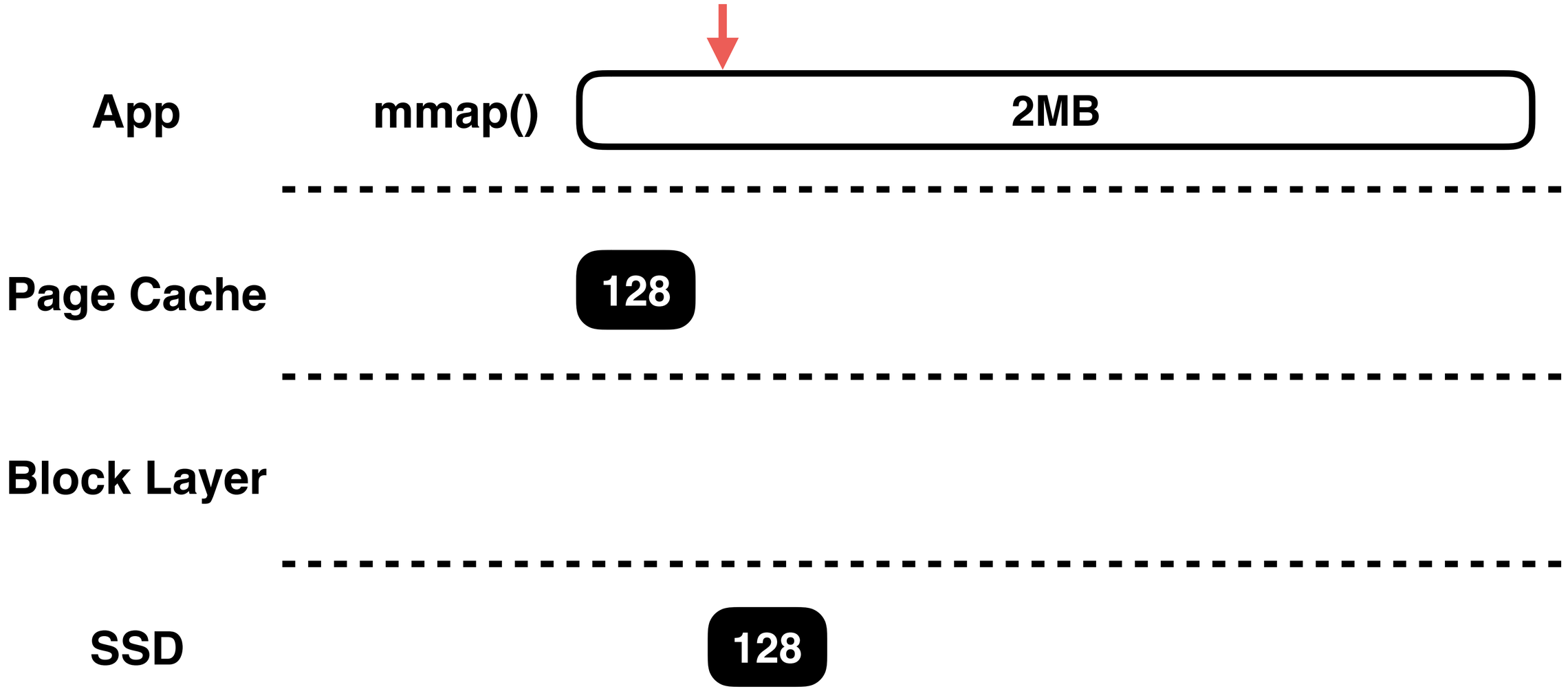

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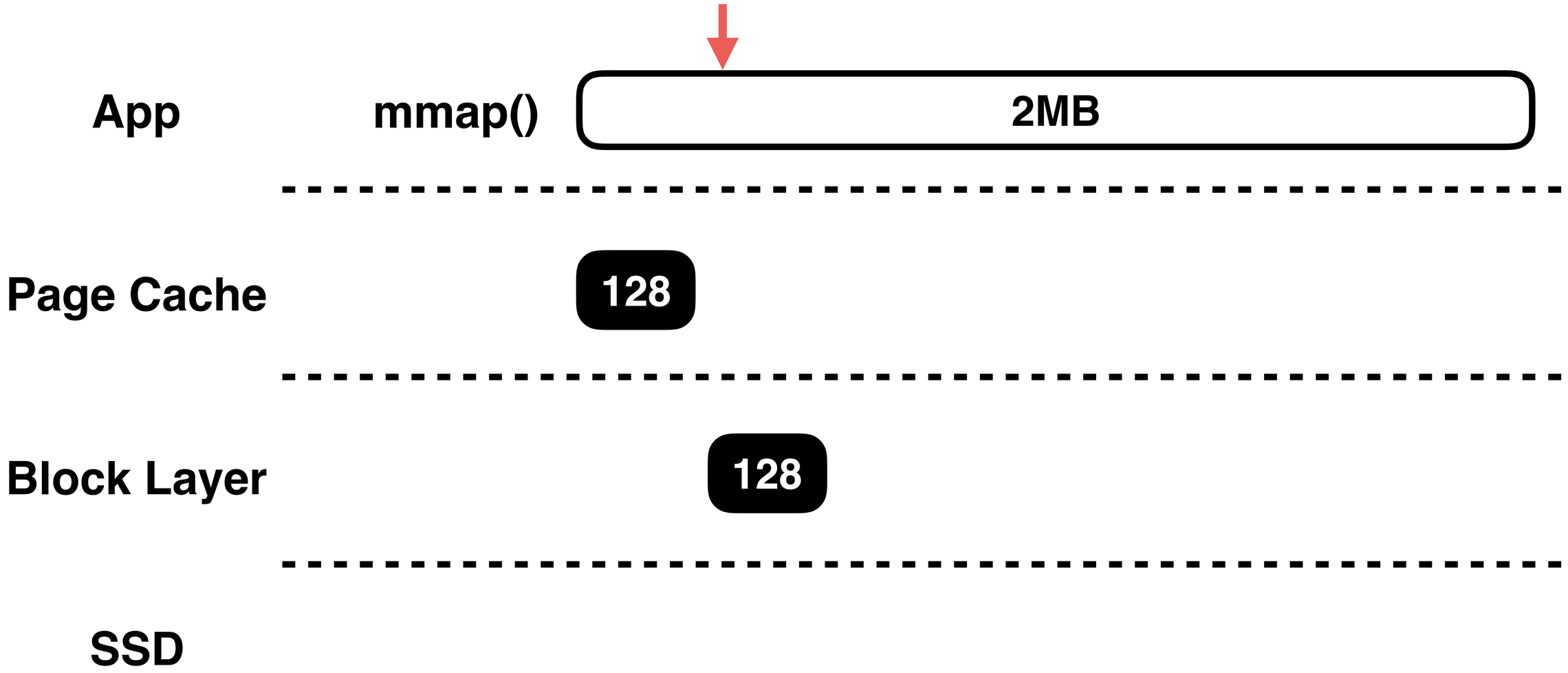

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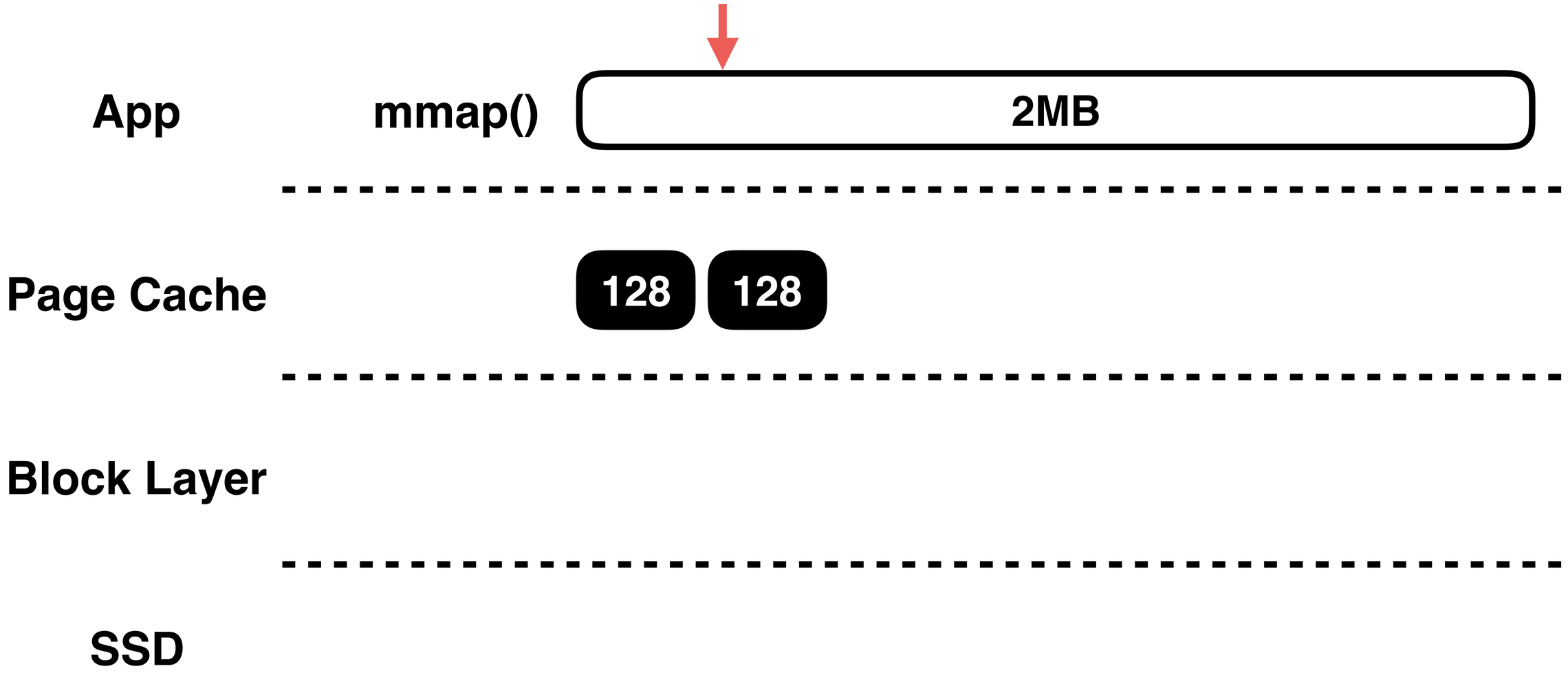

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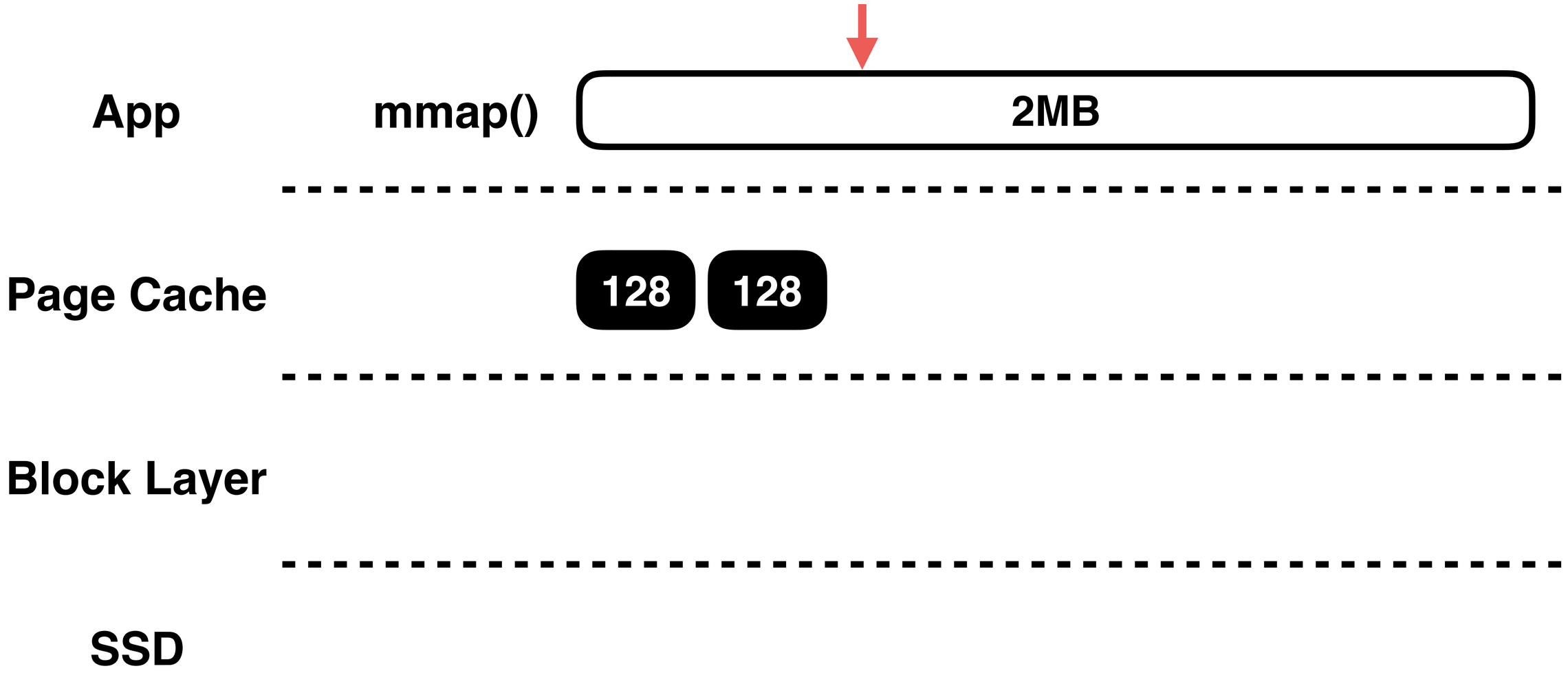

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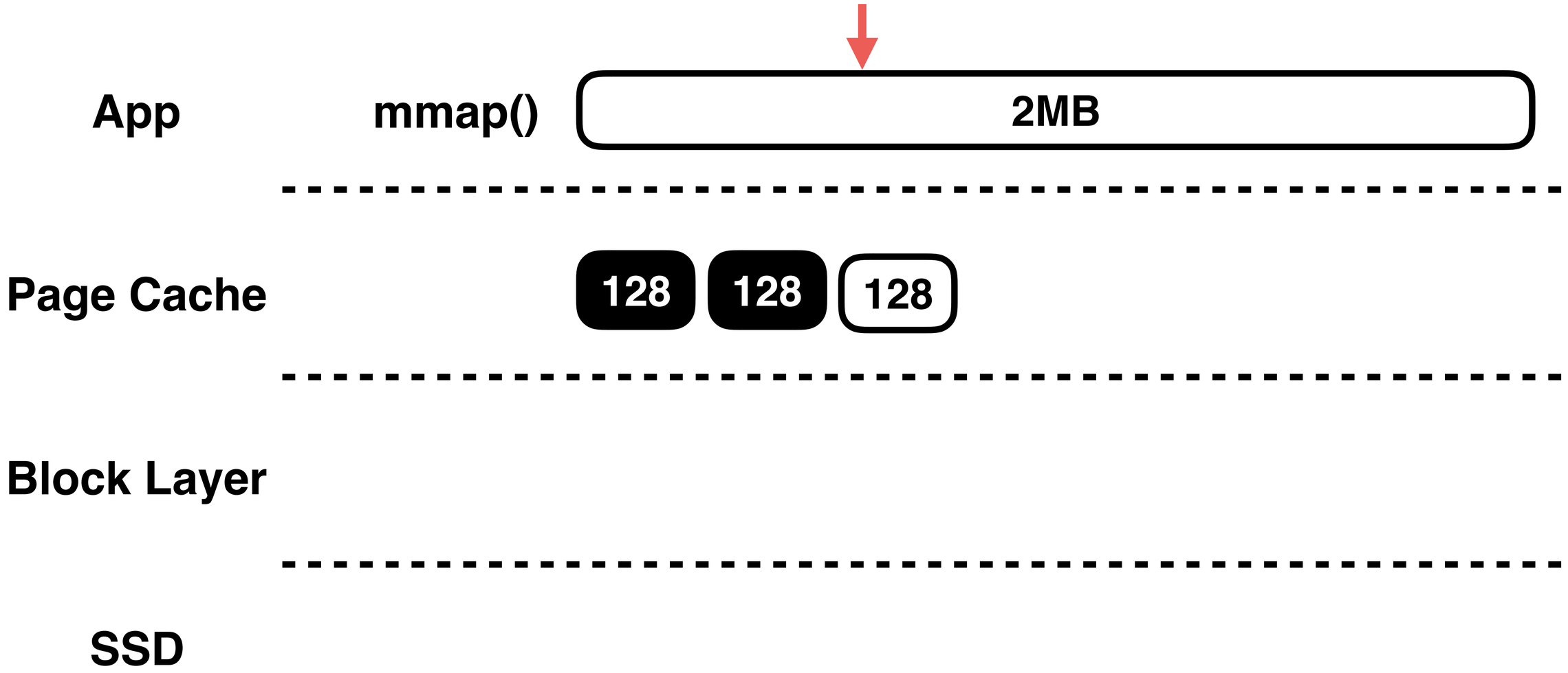

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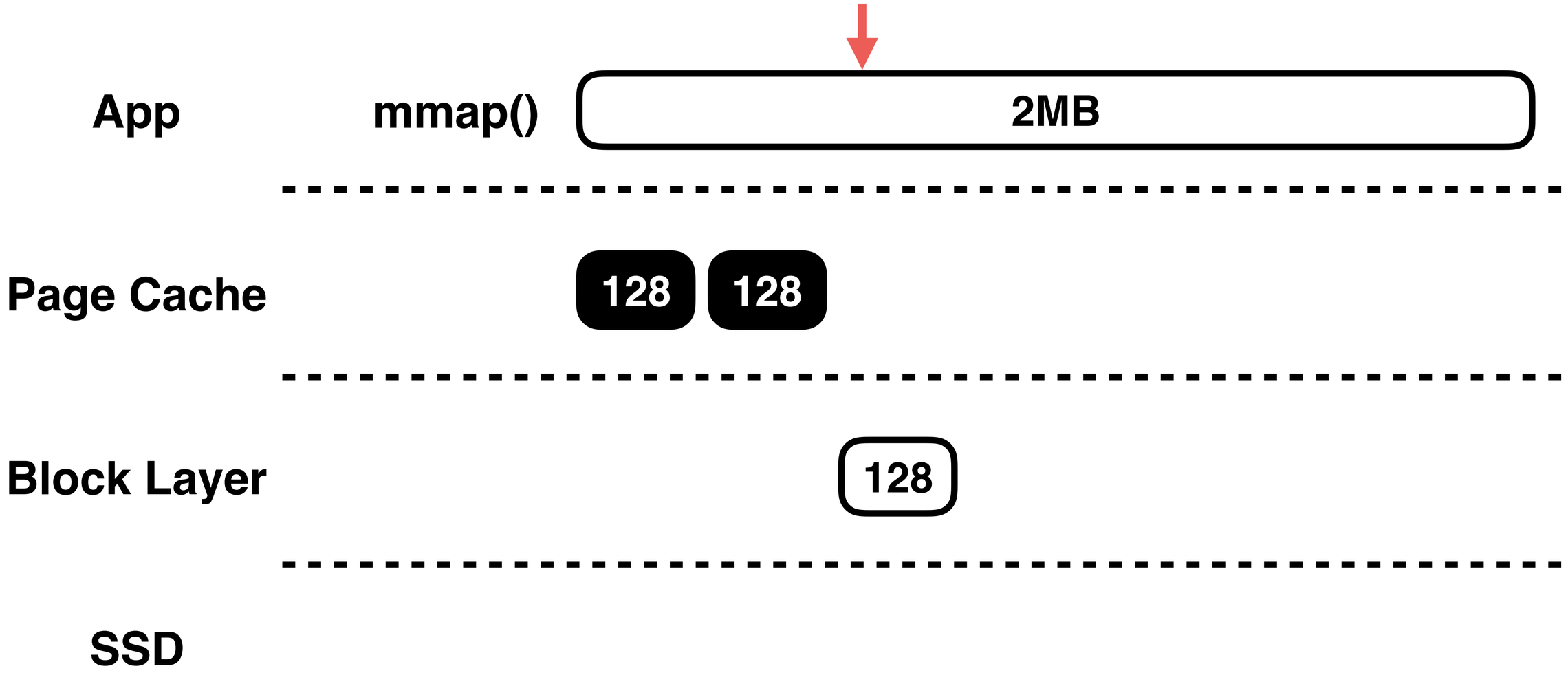

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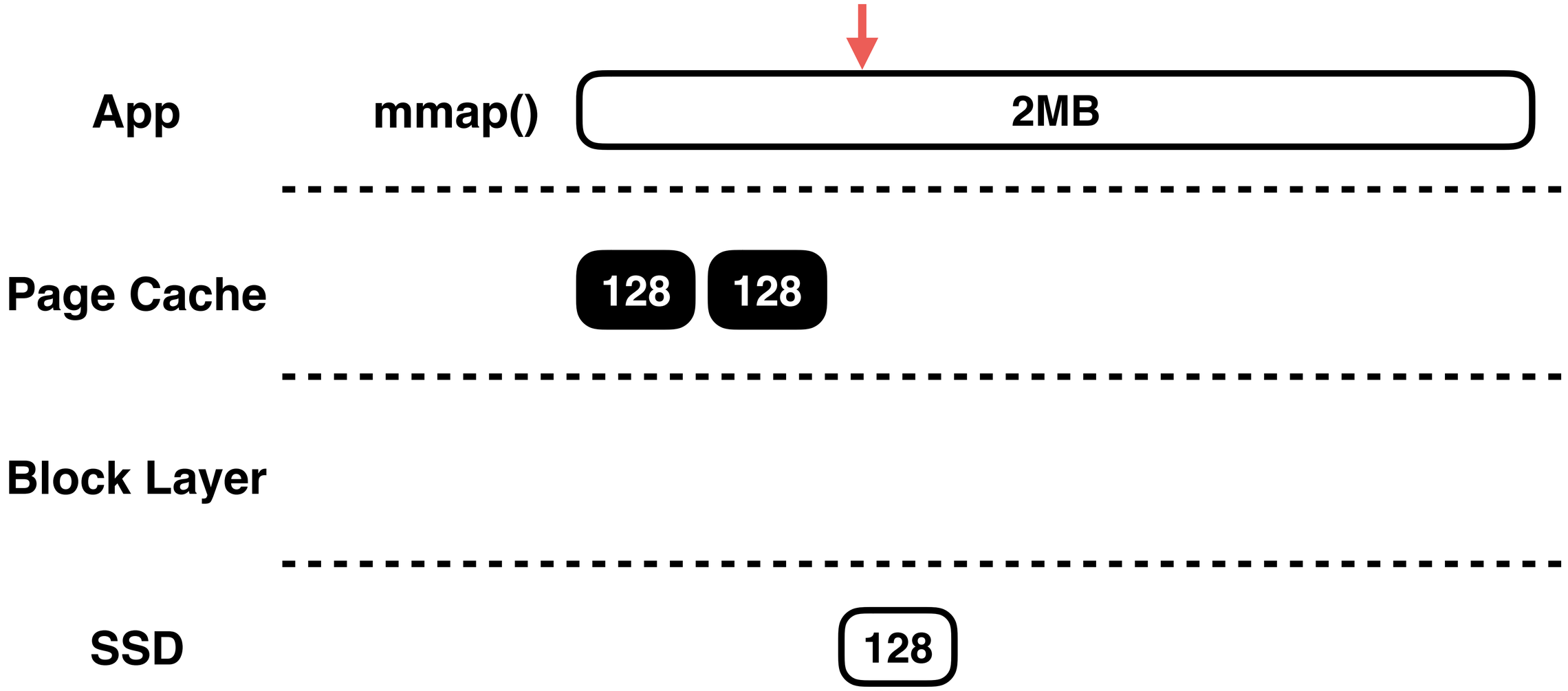

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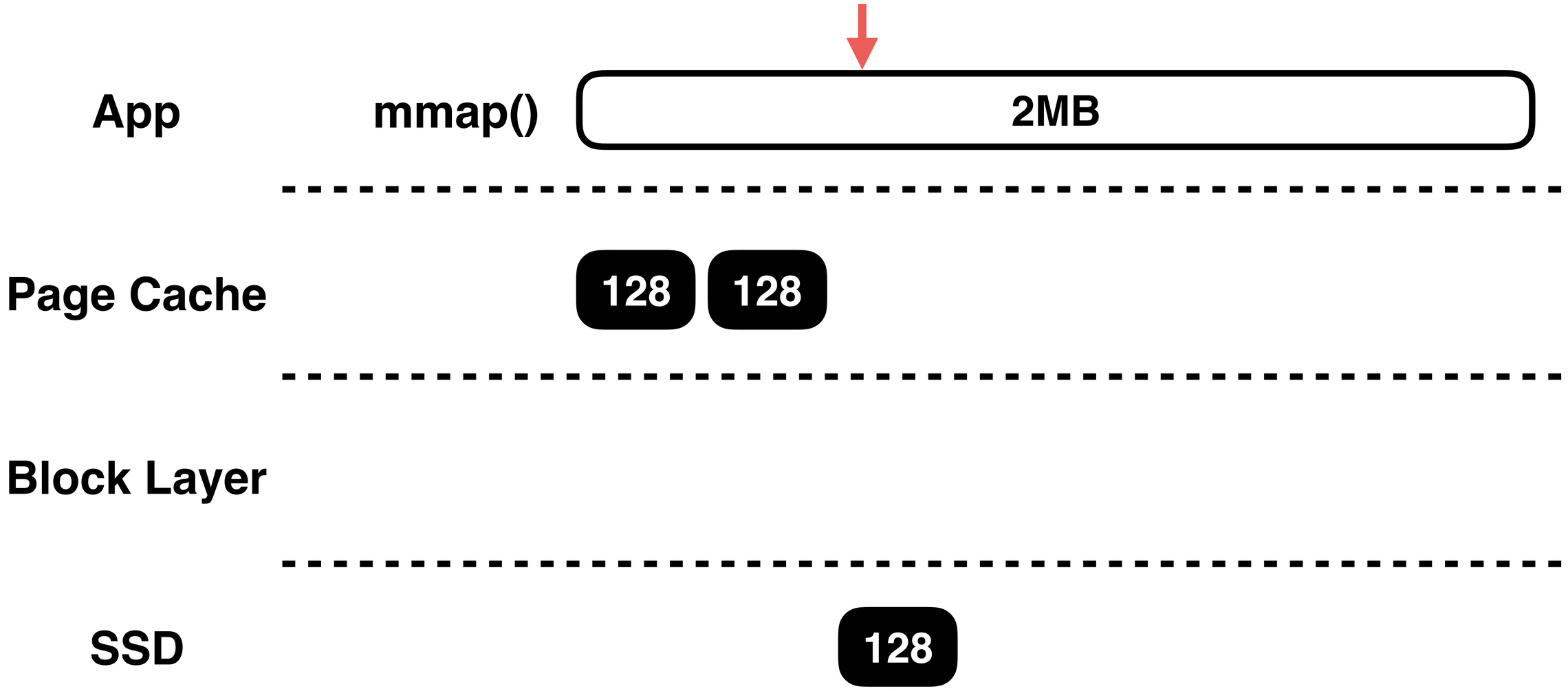

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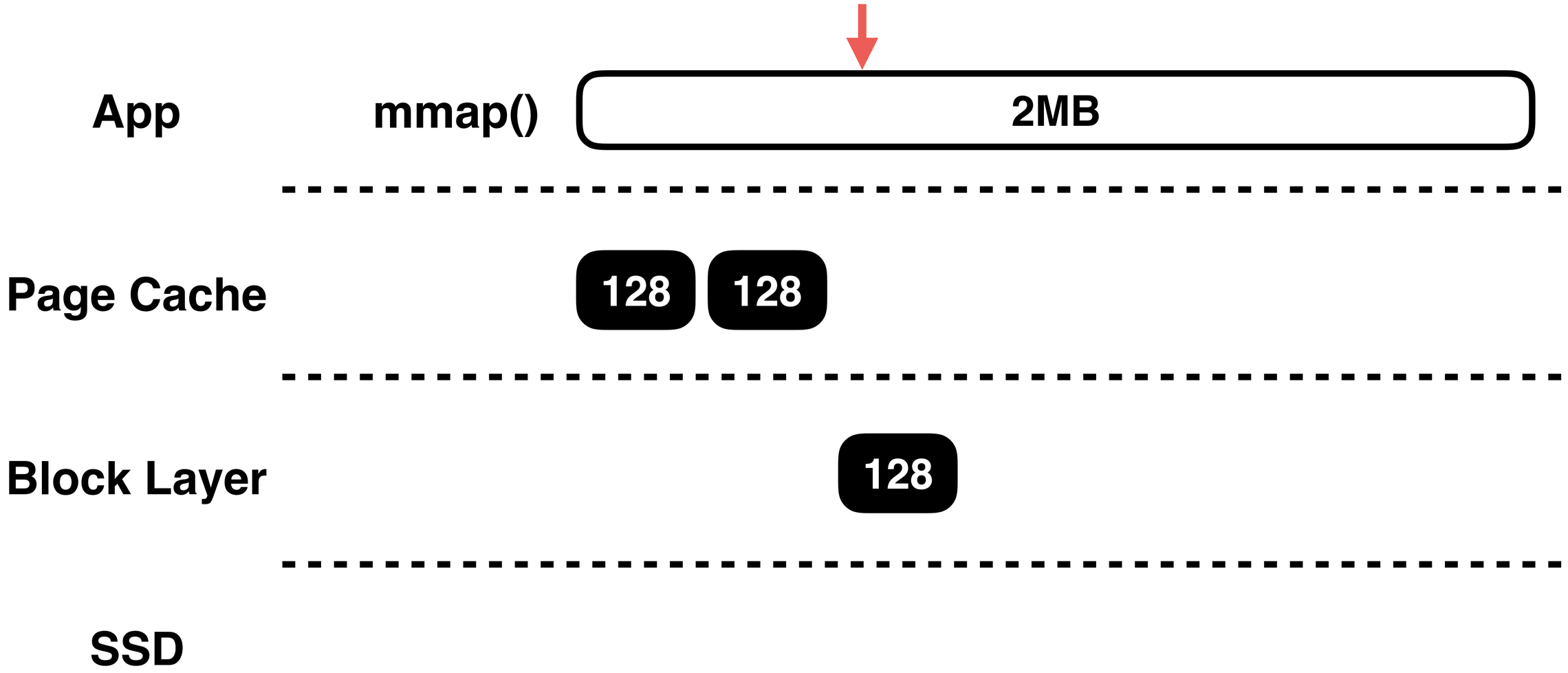

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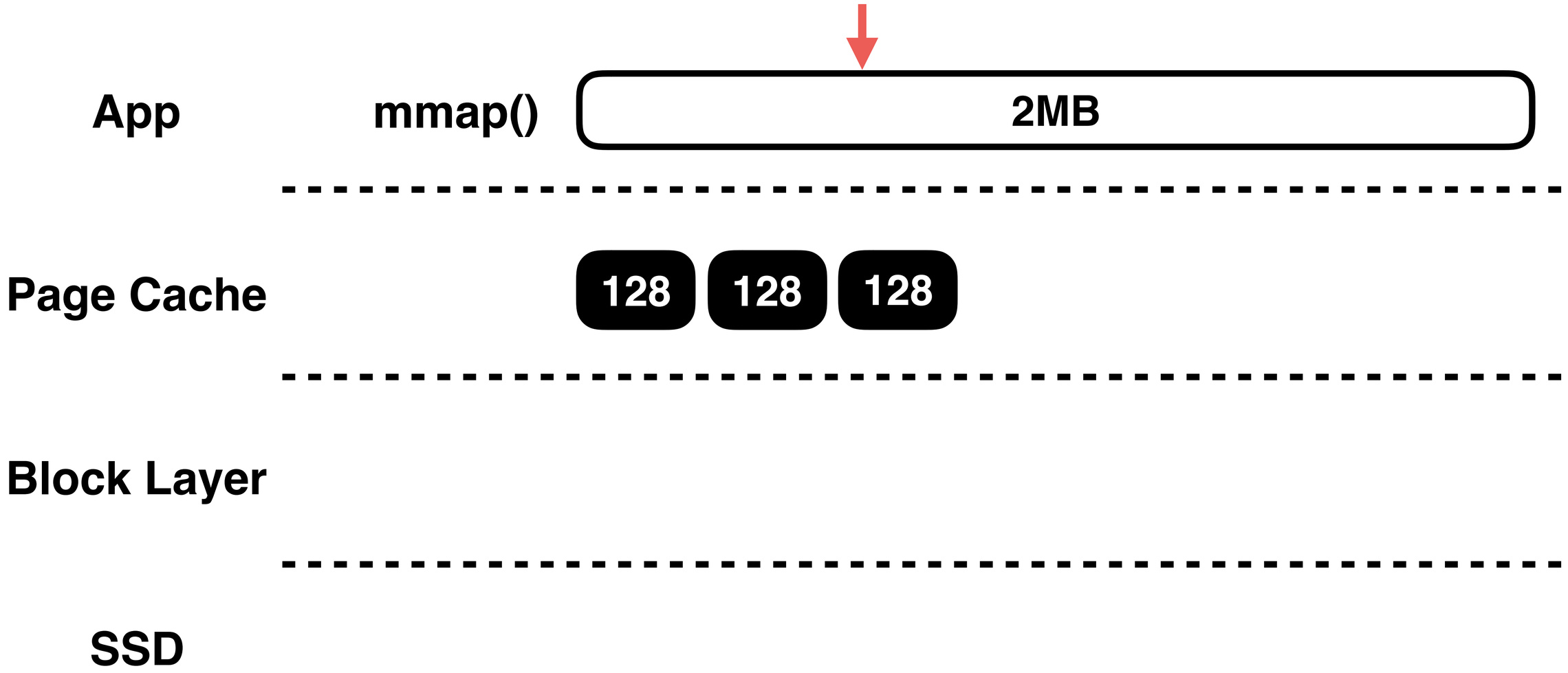

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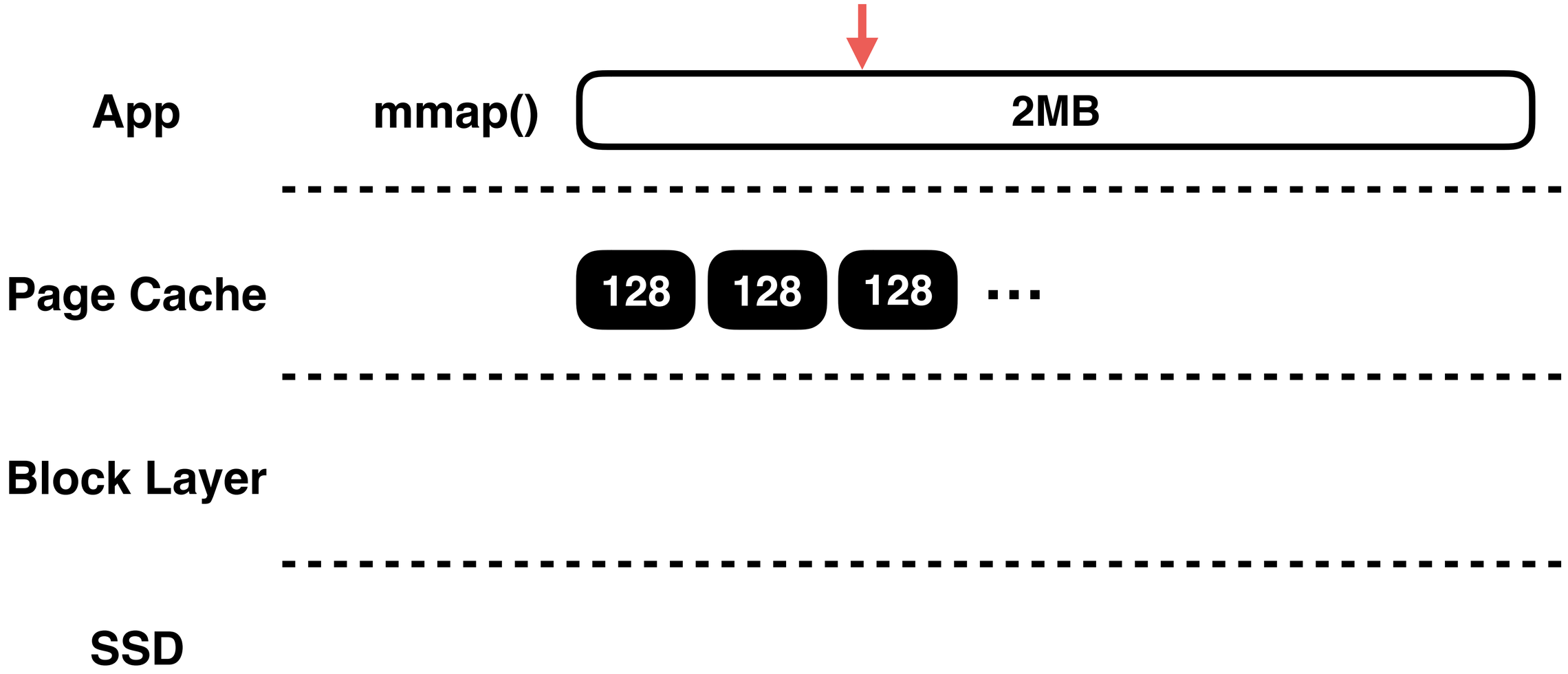

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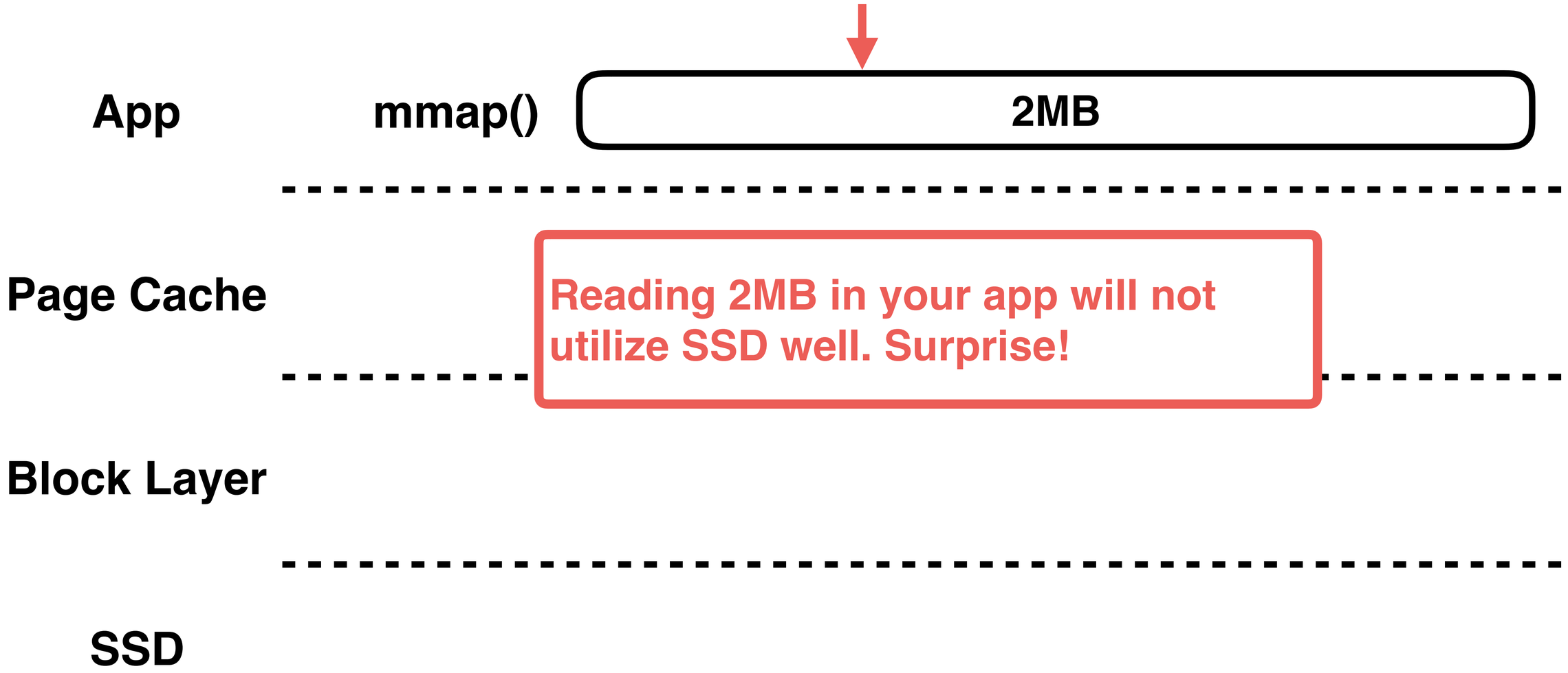

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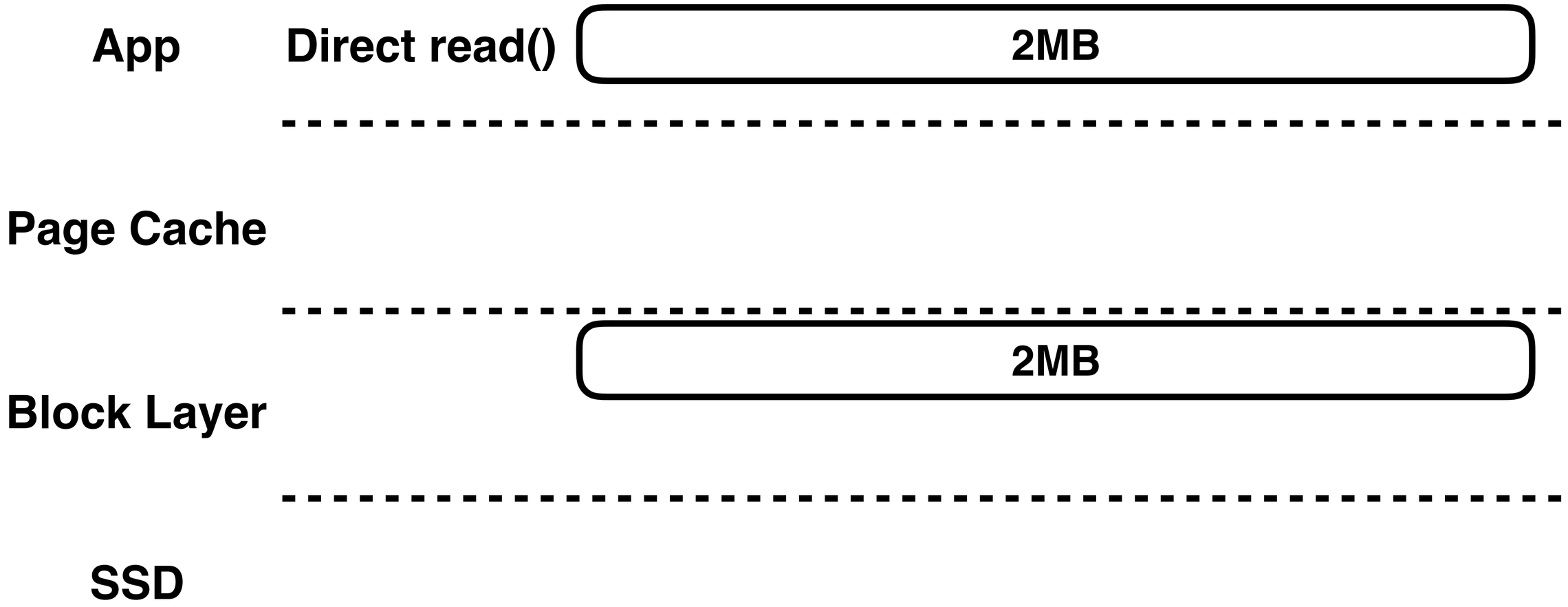

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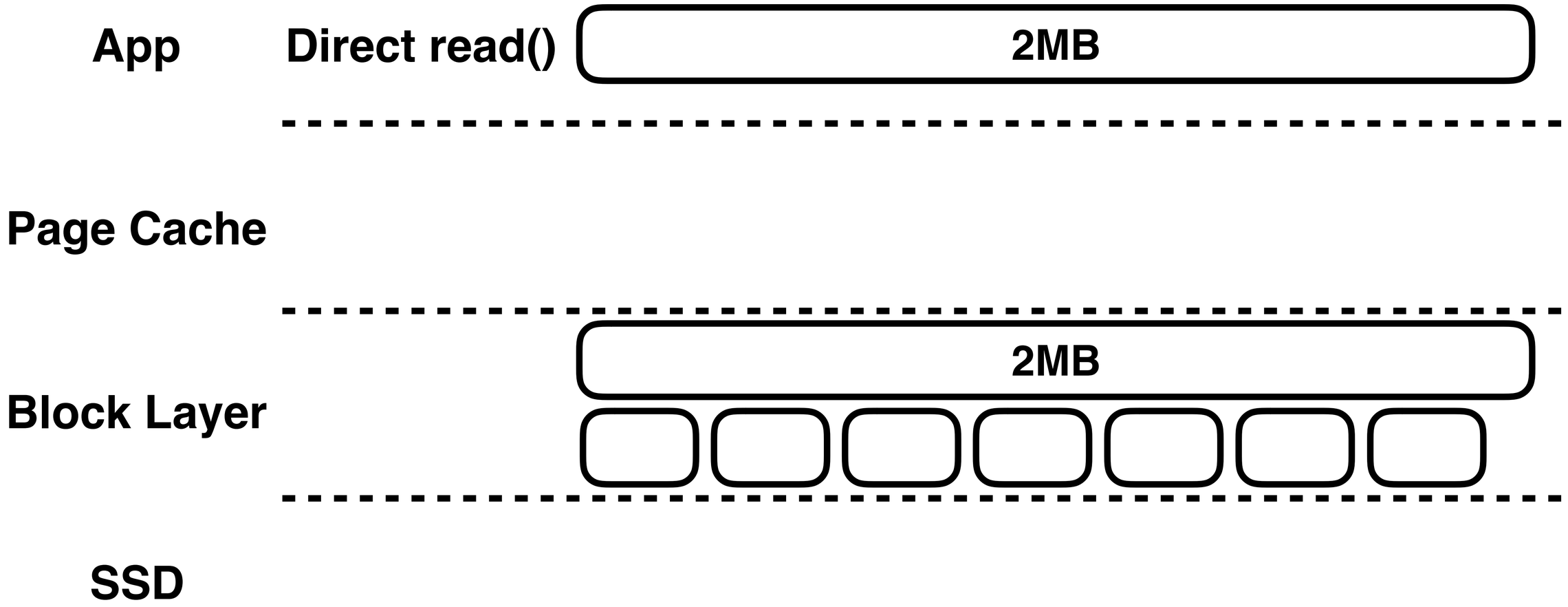

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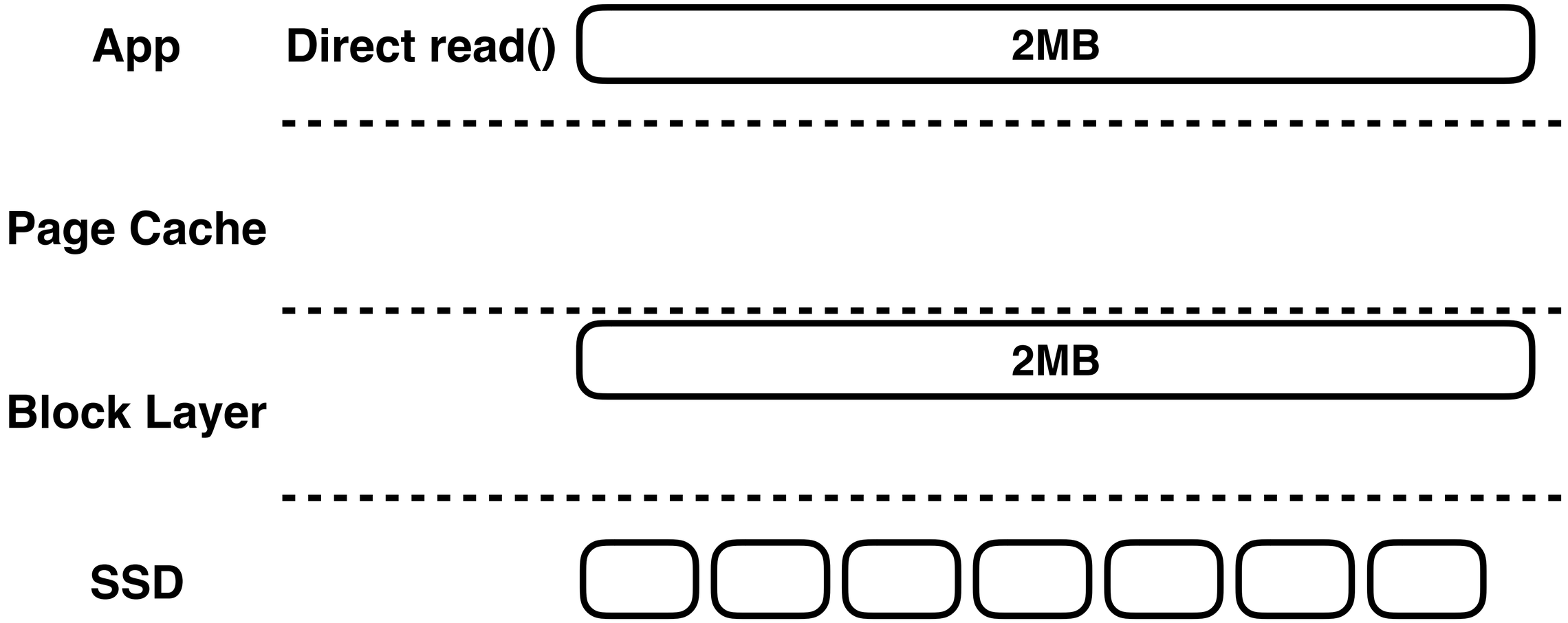

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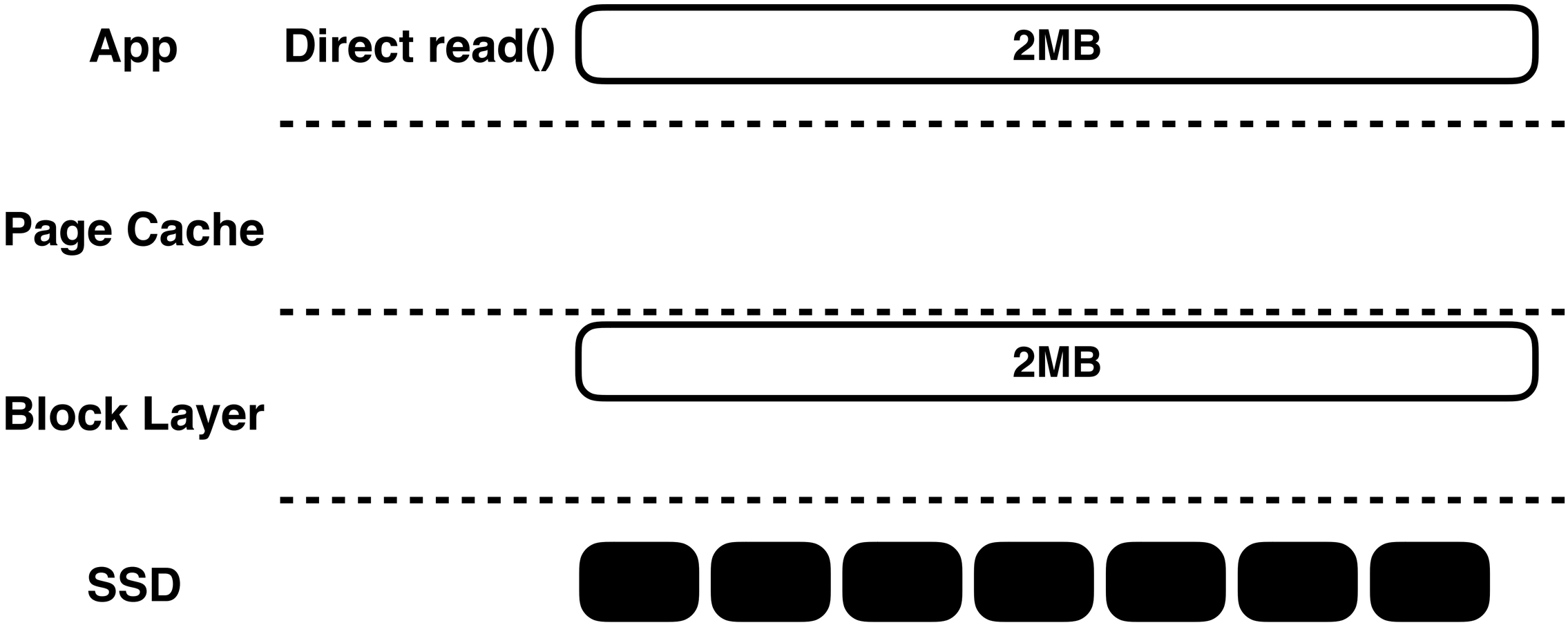

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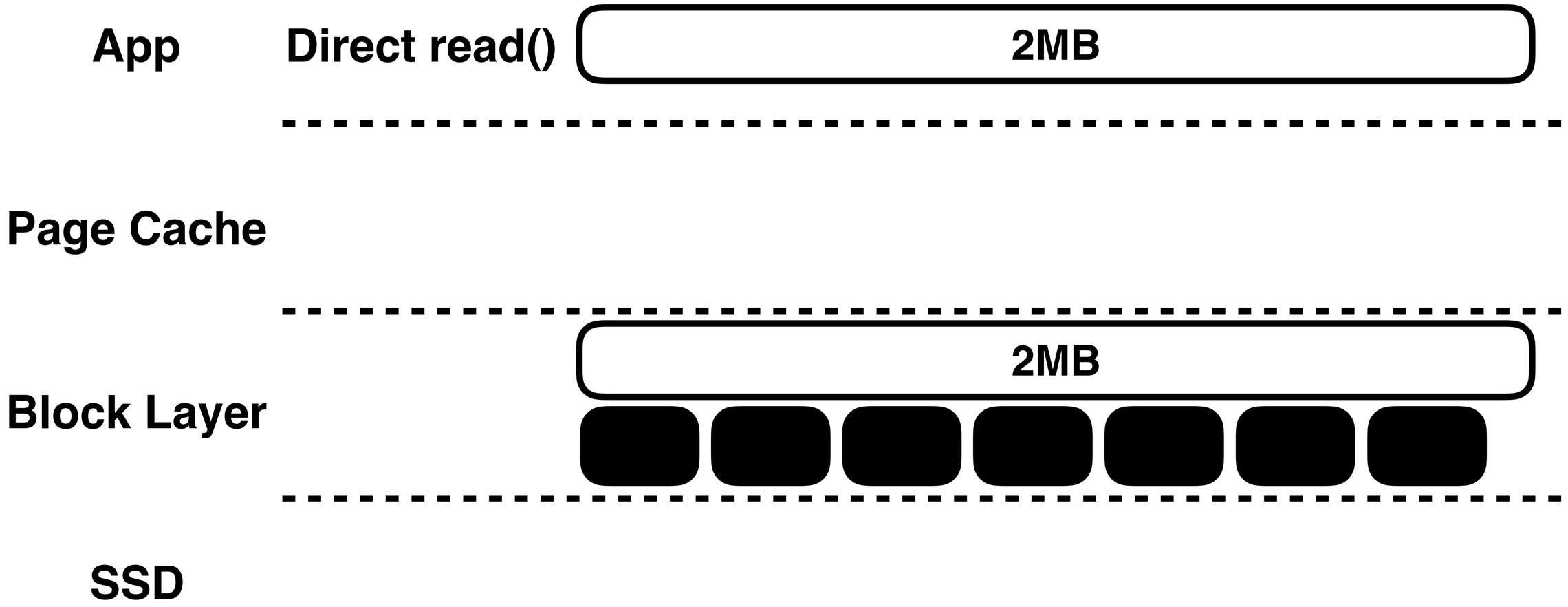

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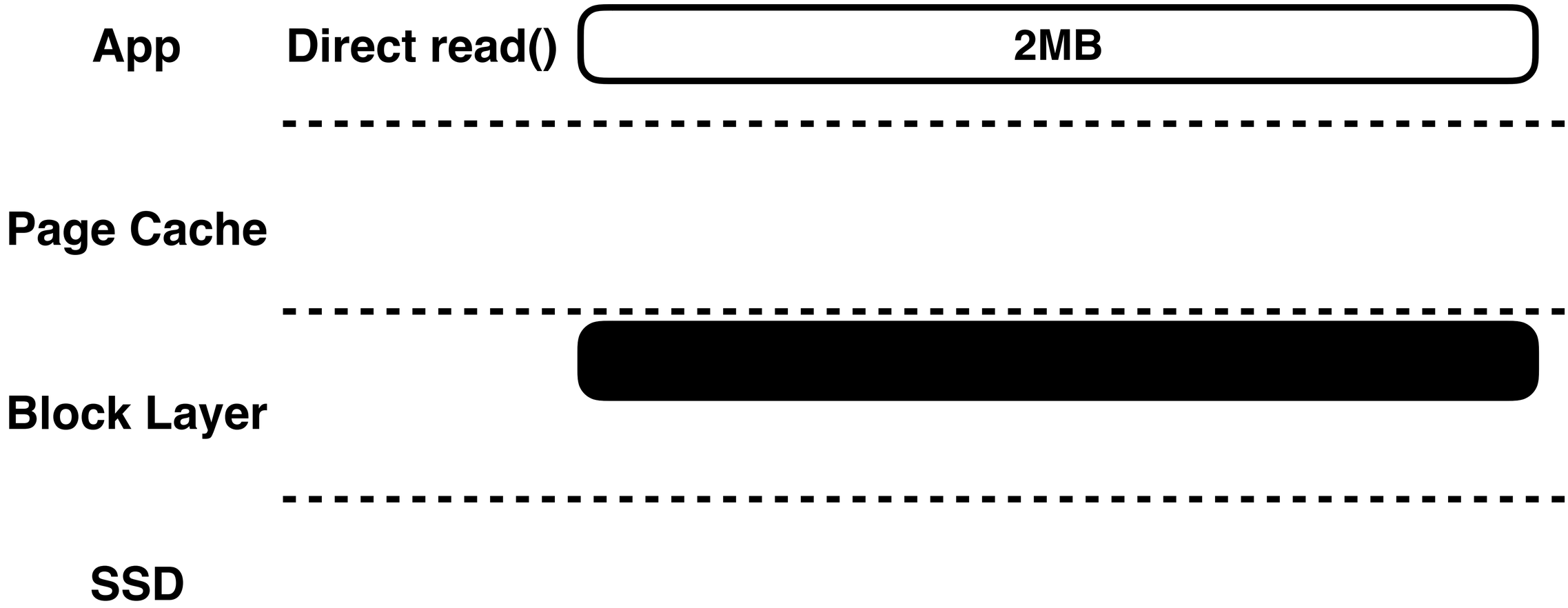

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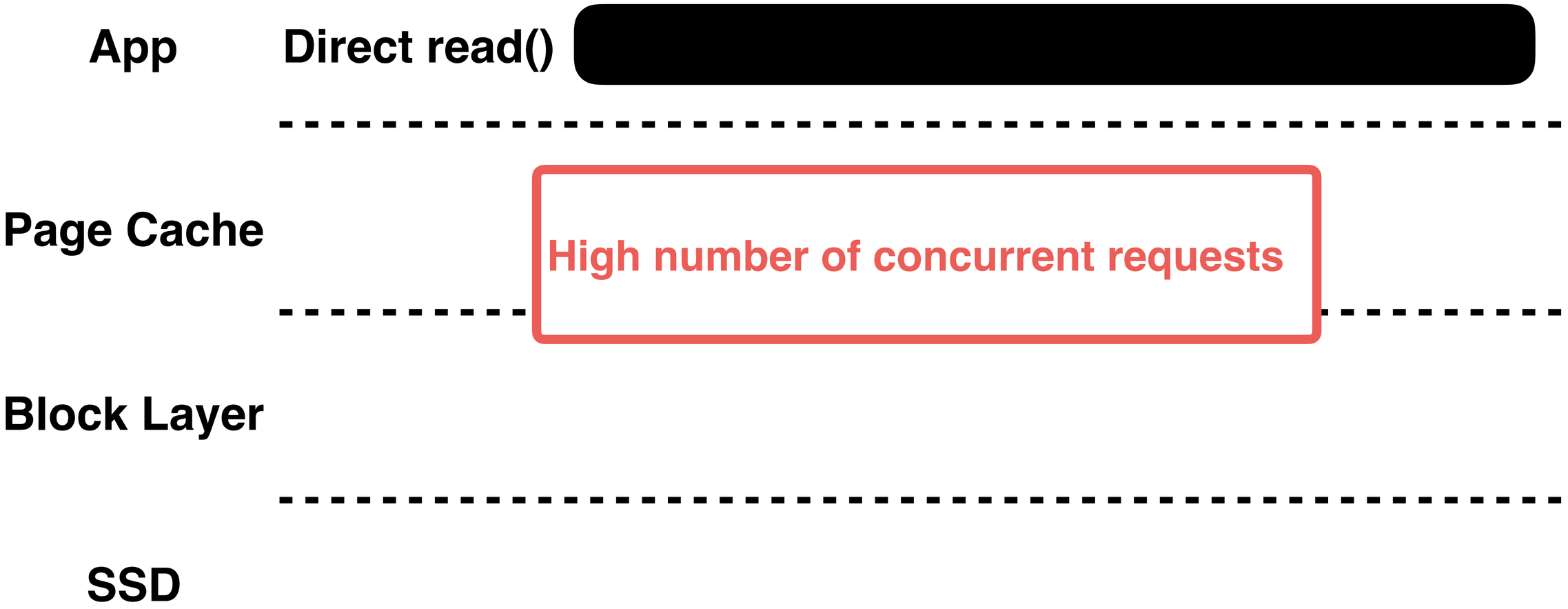

Remedies?

- Increase *read_ahead_kb*
  - It forces other applications to read potentially useless data
  - It is limited by hard-coded bound “2MB”
- Use multiple threads OR async I/O
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Problem to fix:
Large read is throttled by small prefetching(readahead)

A File System Summary for Request Scale

- ext4 & XFS have very similar request scale
- F2FS is very different to ext4 and XFS
  - F2FS could break data structures of applications
  - F2FS boosts request scale by delaying discards

Observations

- Rule 1: Request Scale
- Implementation of Linux limits performance
- Rule 3: Grouping by Death Time
  - F2FS incurs more GC overhead than ext4/XFS
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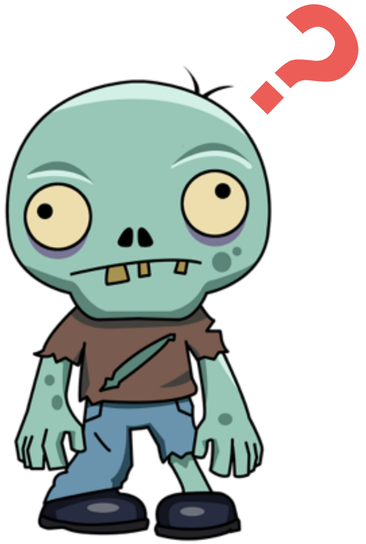

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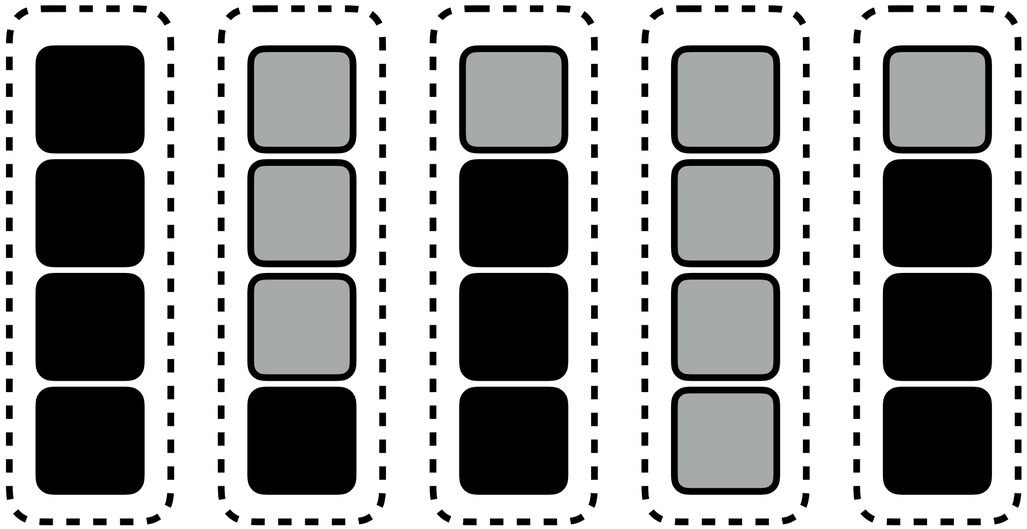

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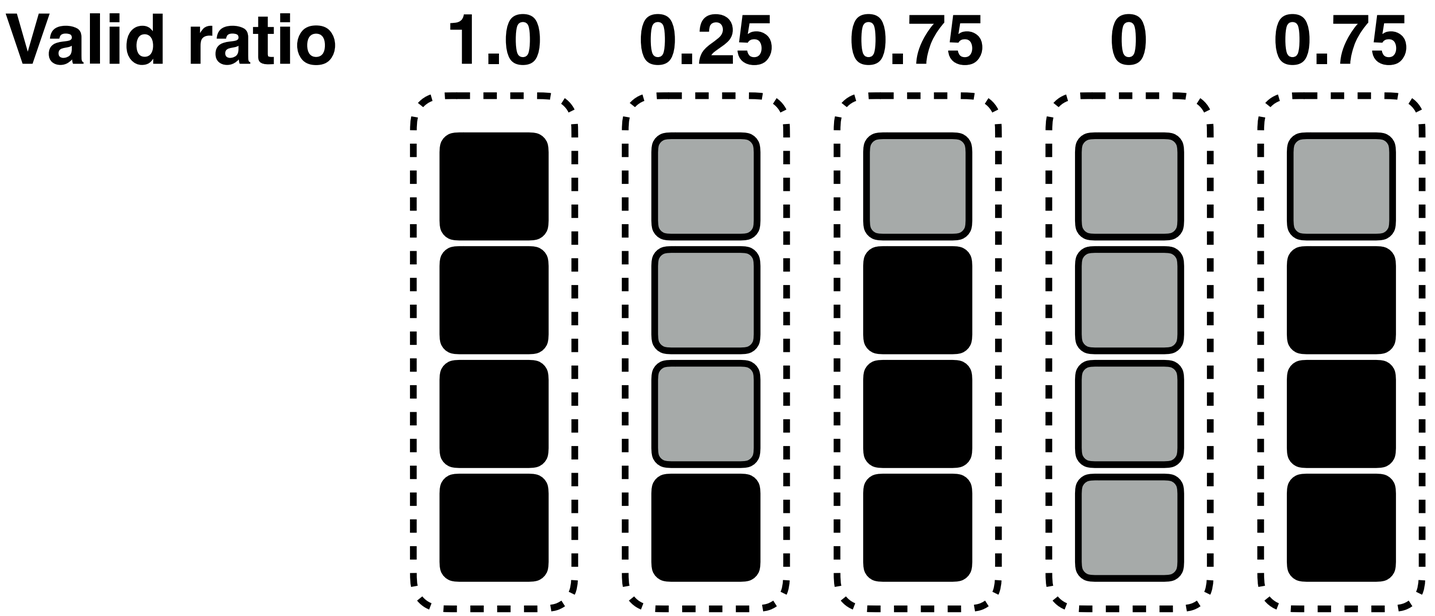

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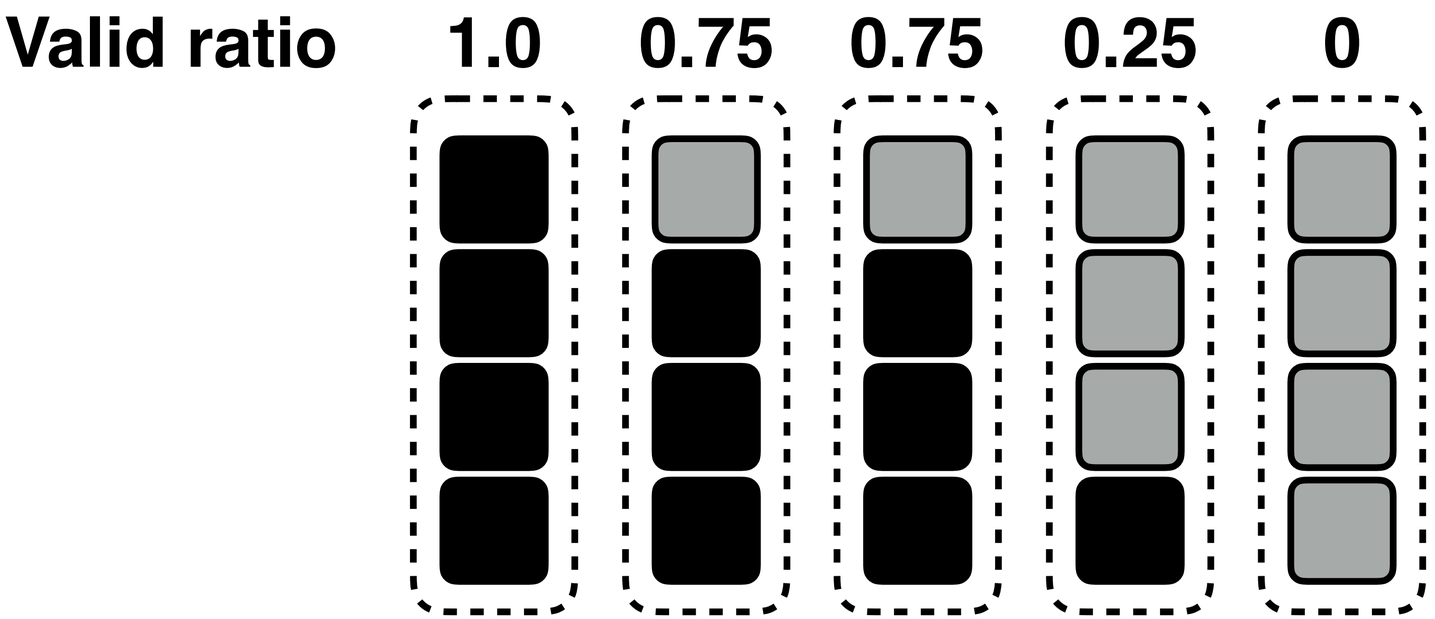

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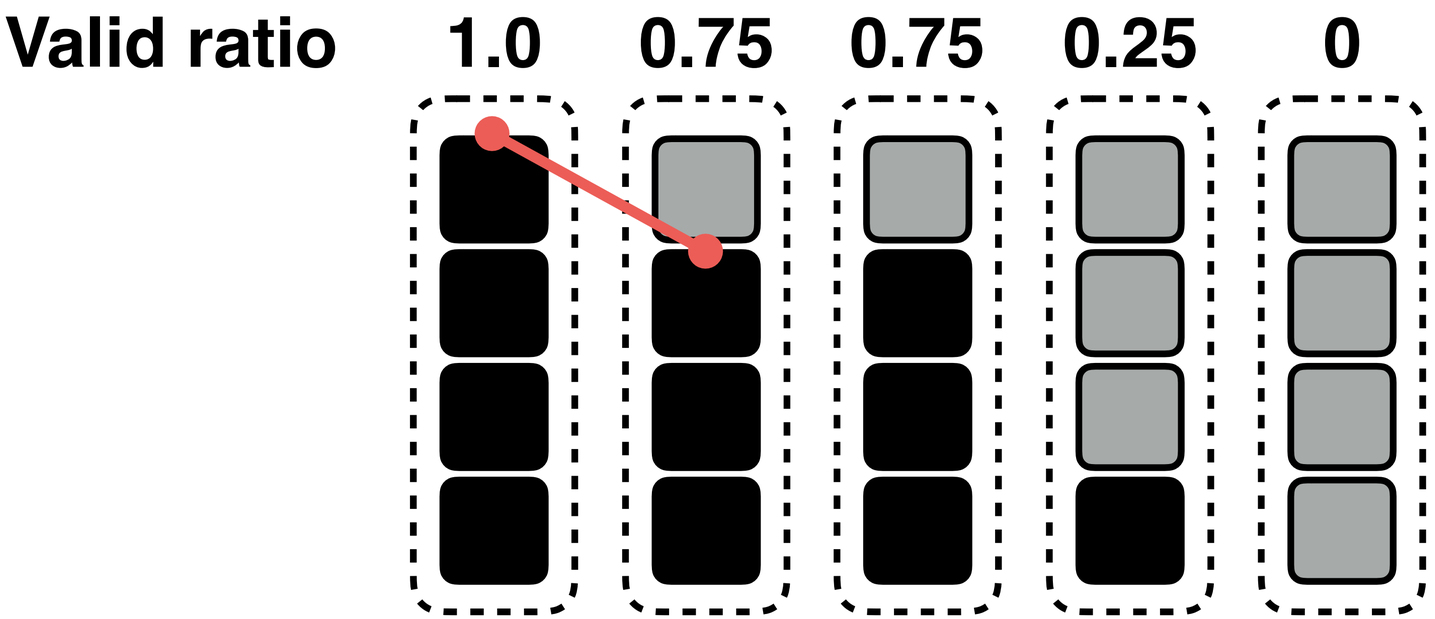

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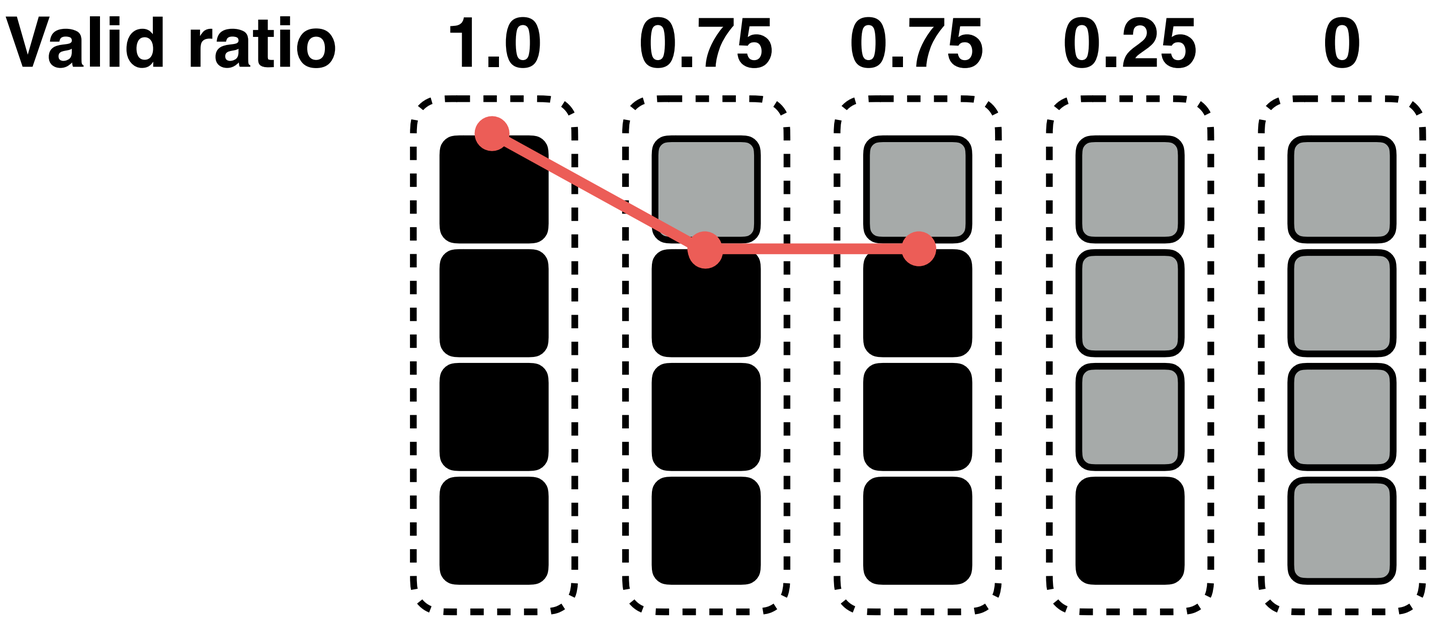

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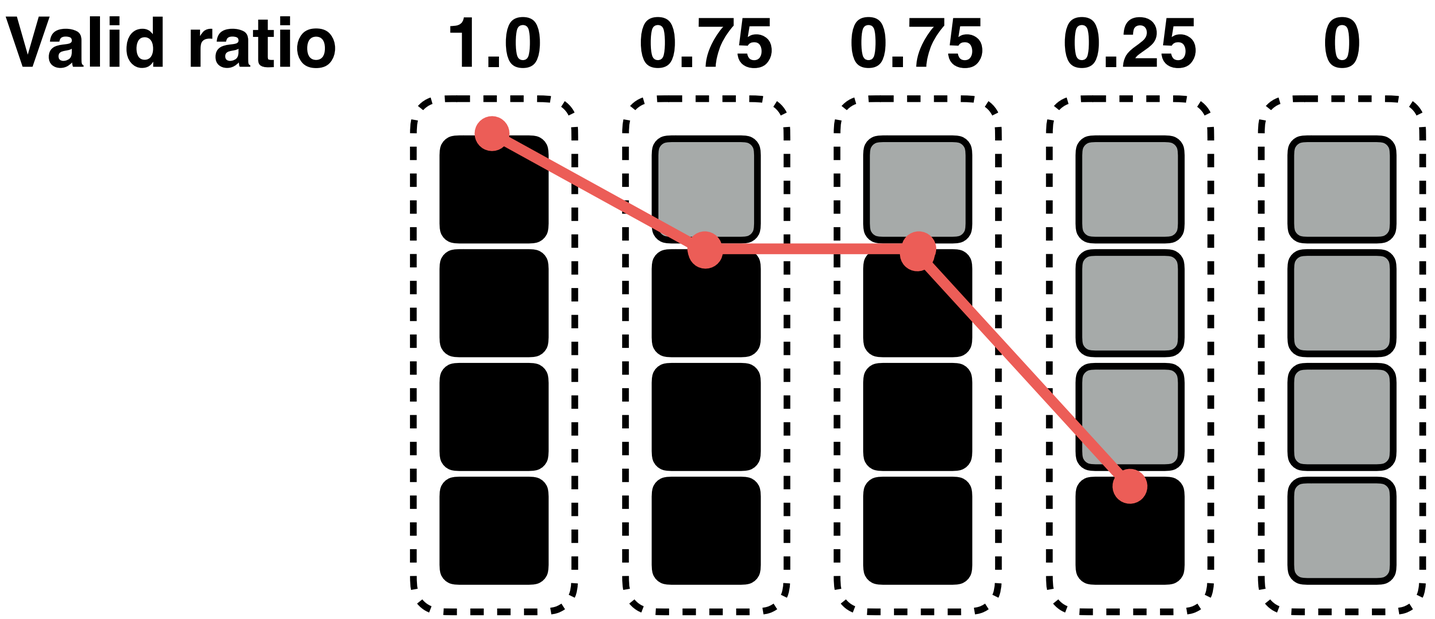

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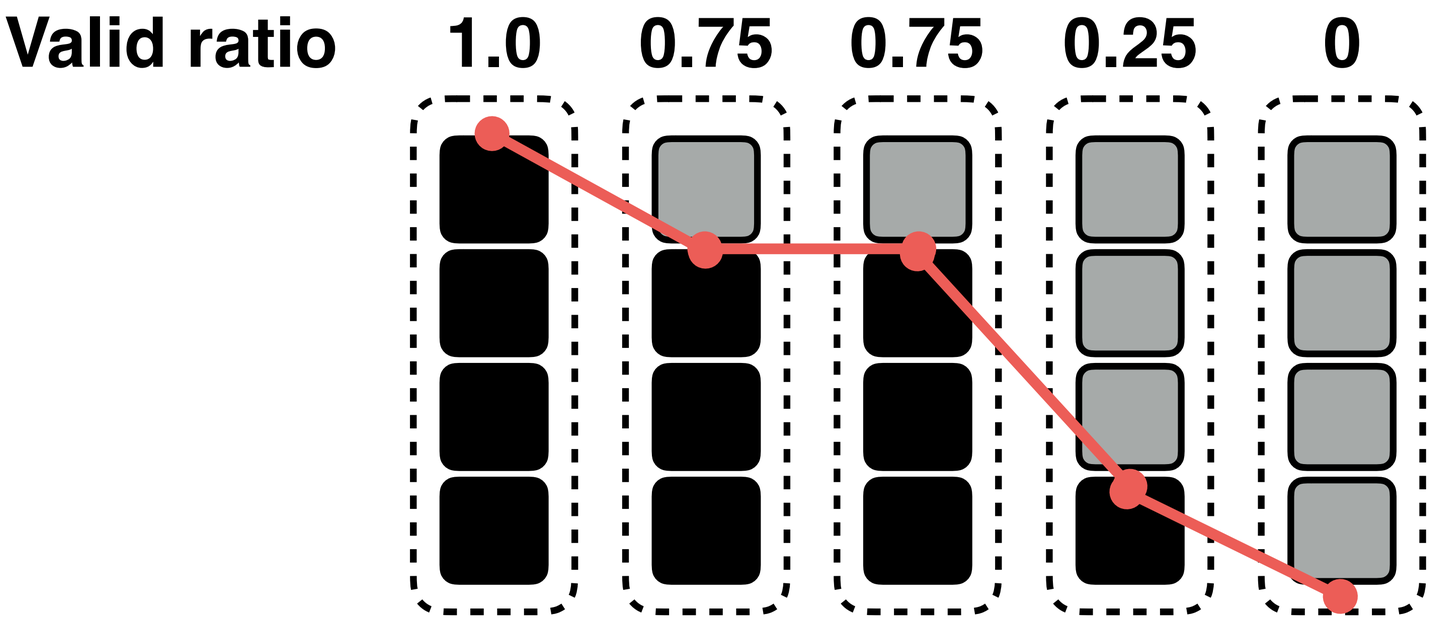

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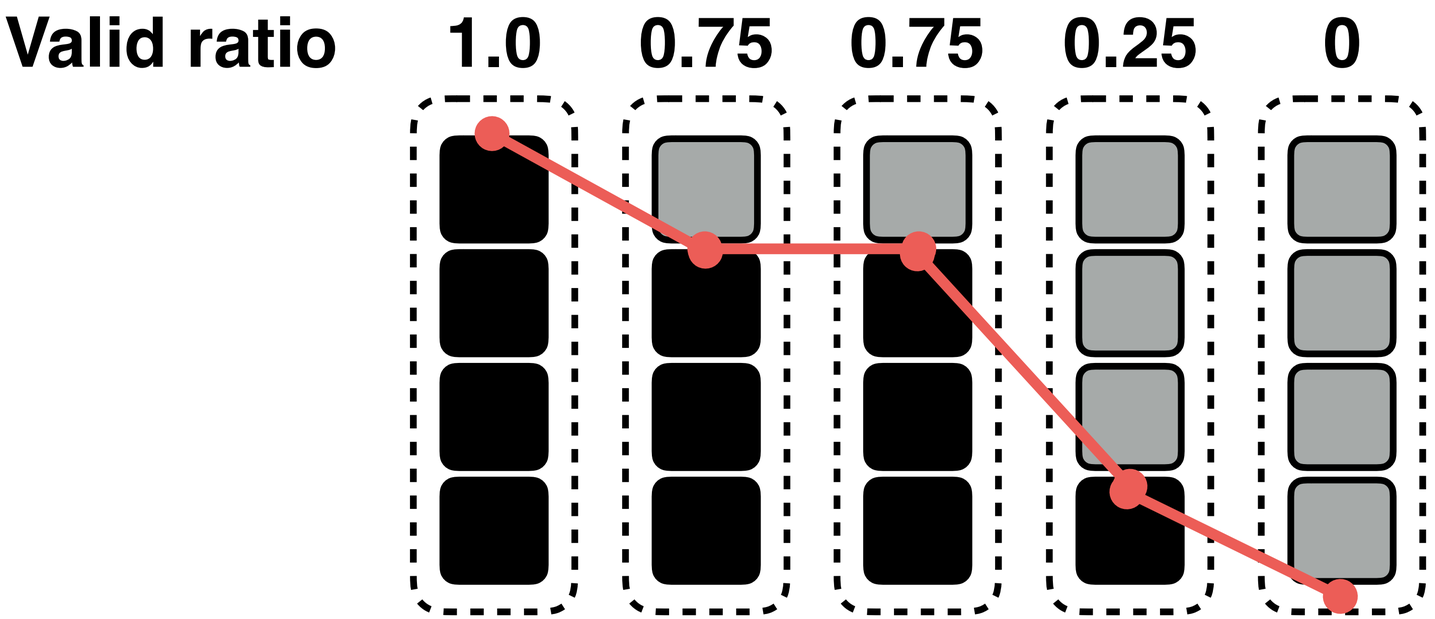

Zombie blocks are the blocks with partially valid pages.

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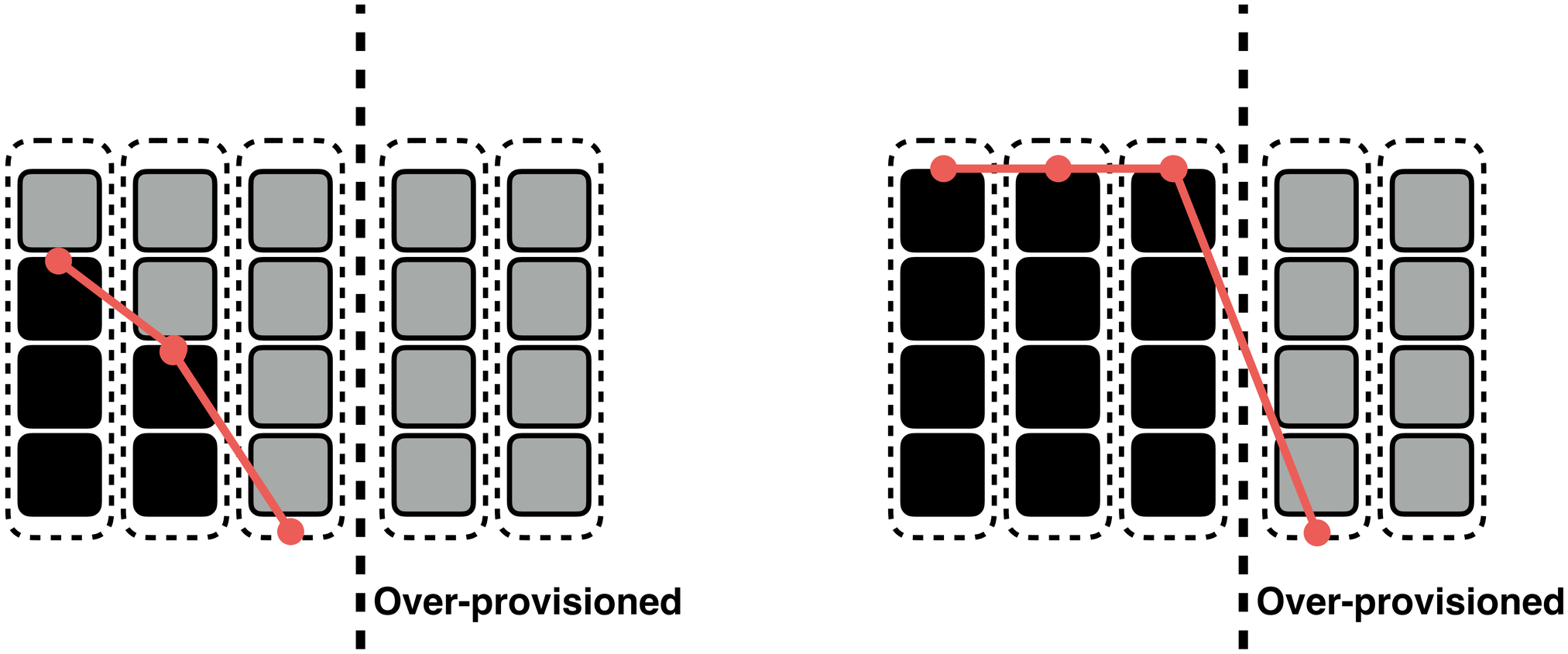

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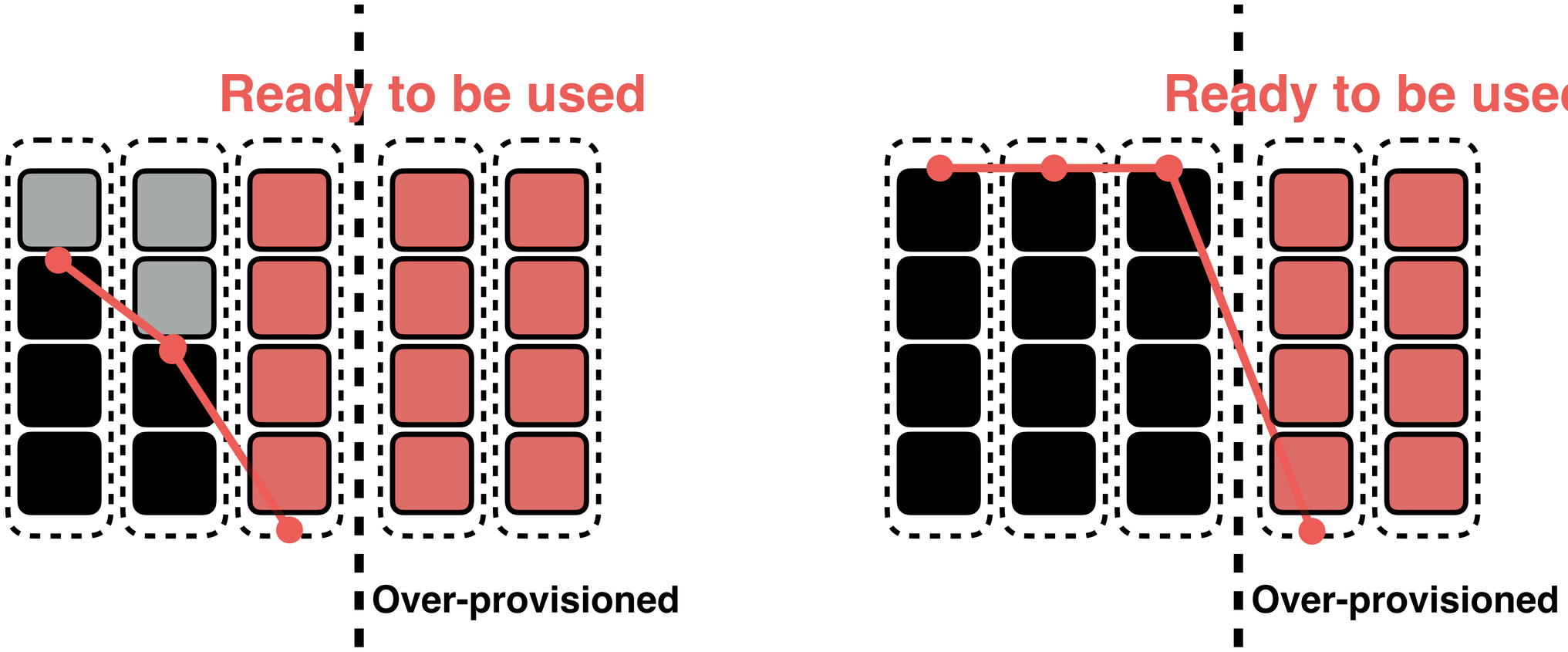

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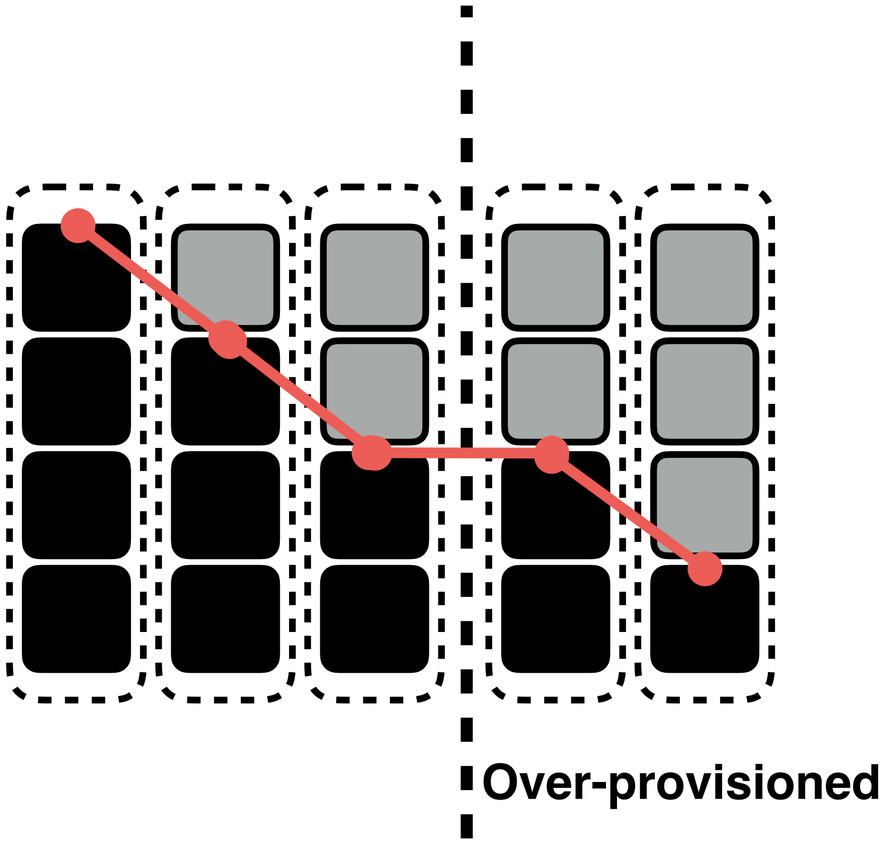

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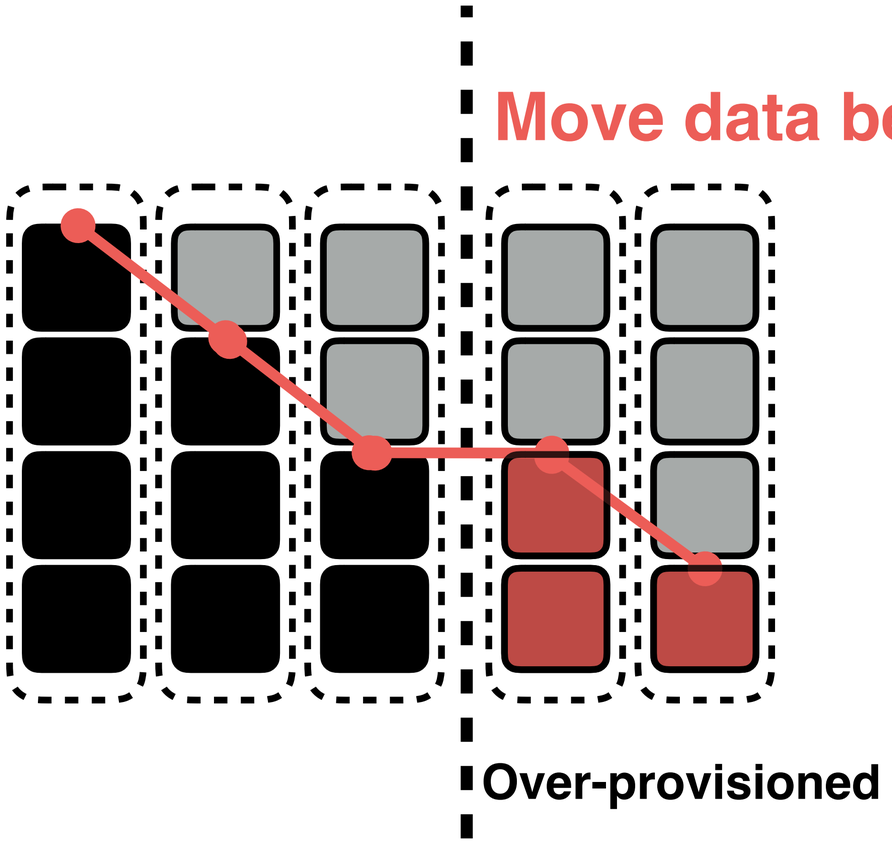

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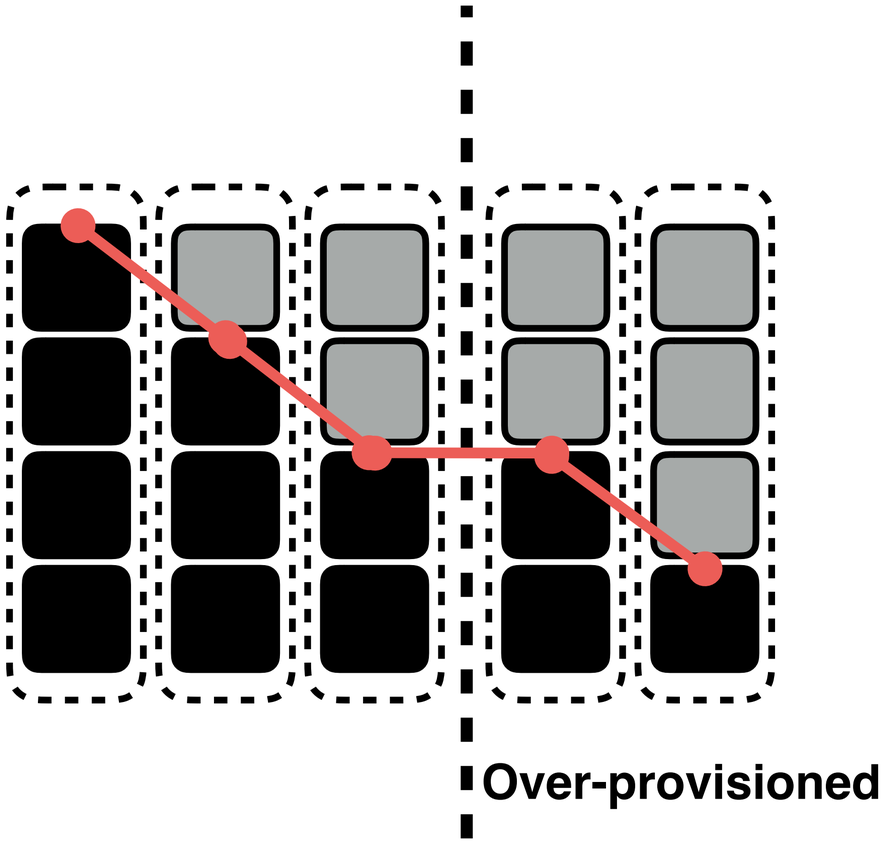

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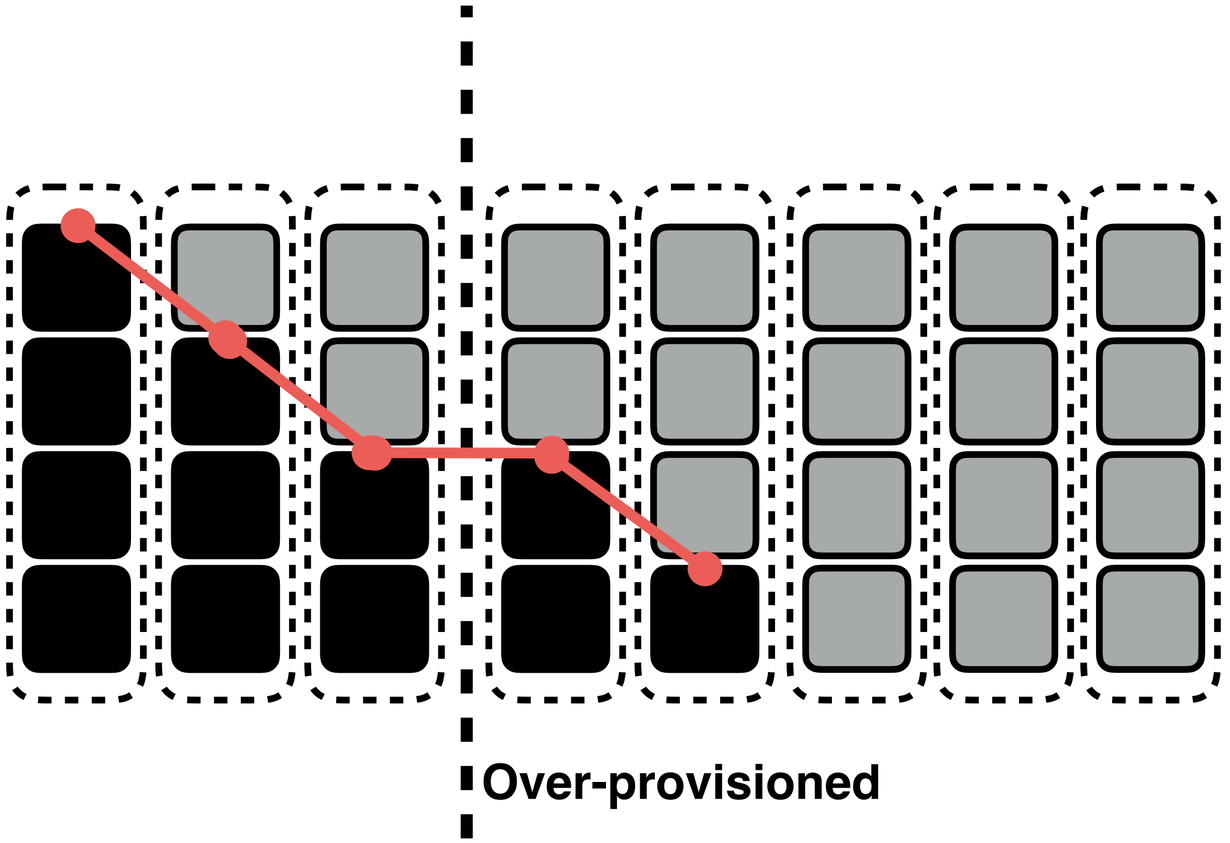
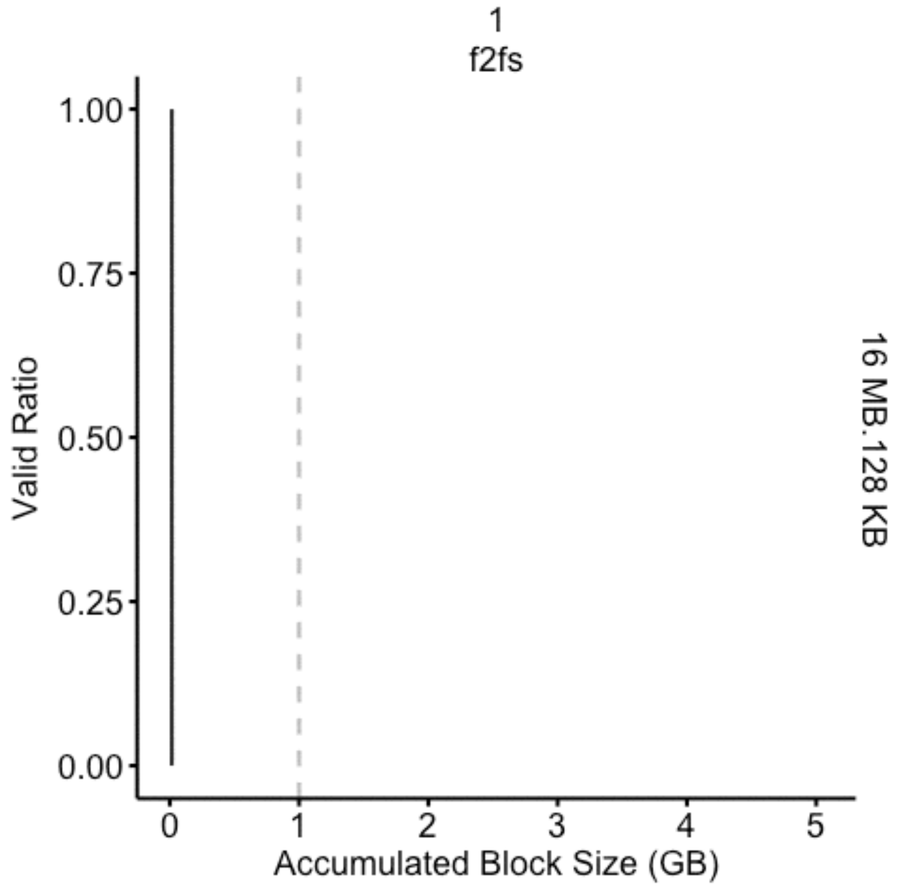


We use stable zombie curves to characterize workloads



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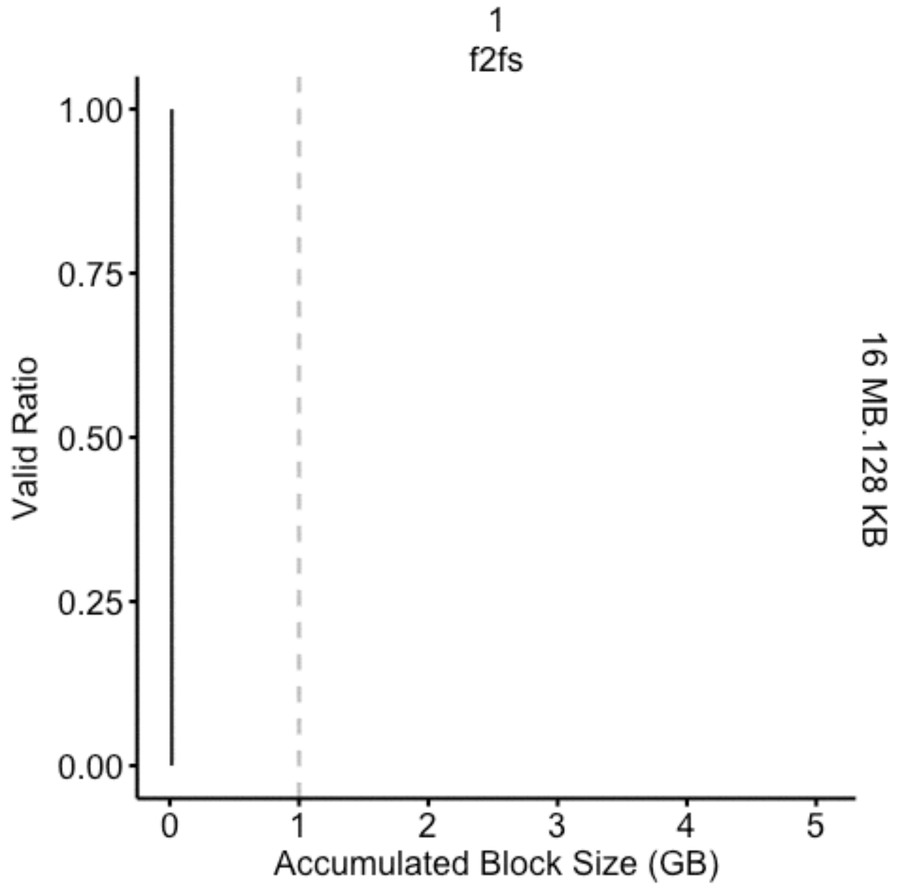

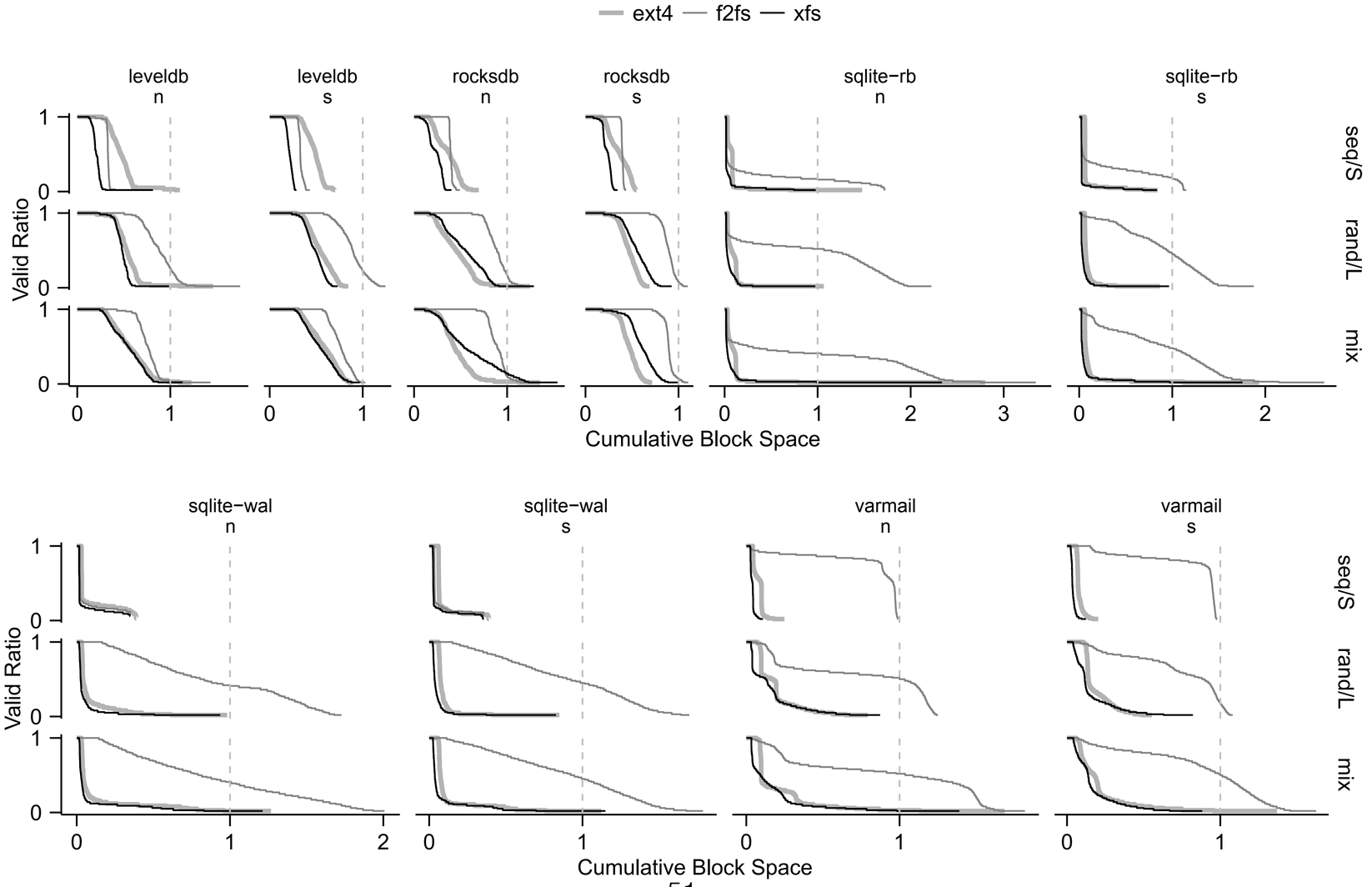
ext4
f2fs
xfs
leveldb n
leveldb s
rocksdb n
rocksdb s
sqlite−rb n
sqlite−rb s
sqlite−wal n
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varmail n
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seq/S
rand/L
mix
Valid Ratio
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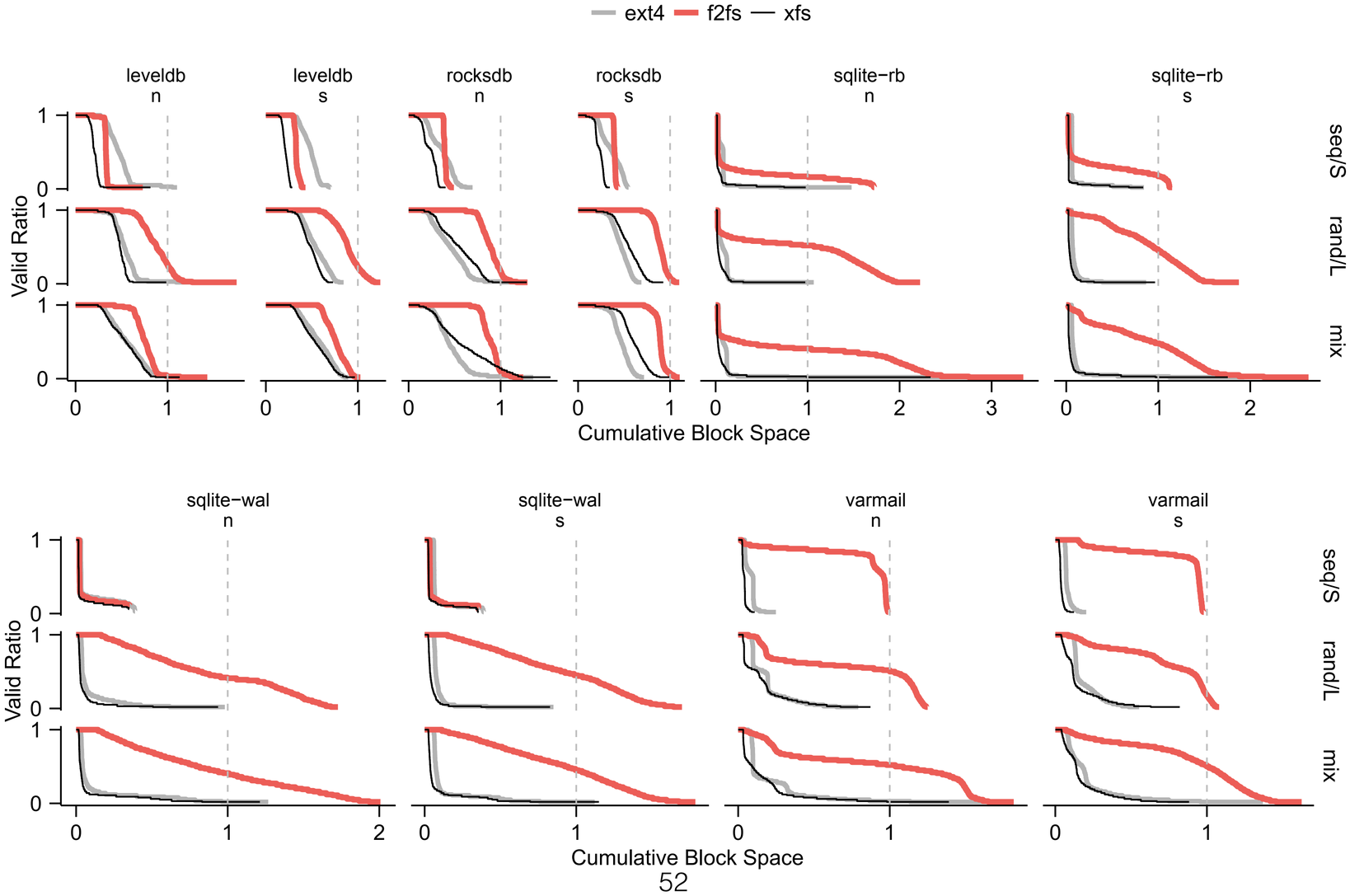

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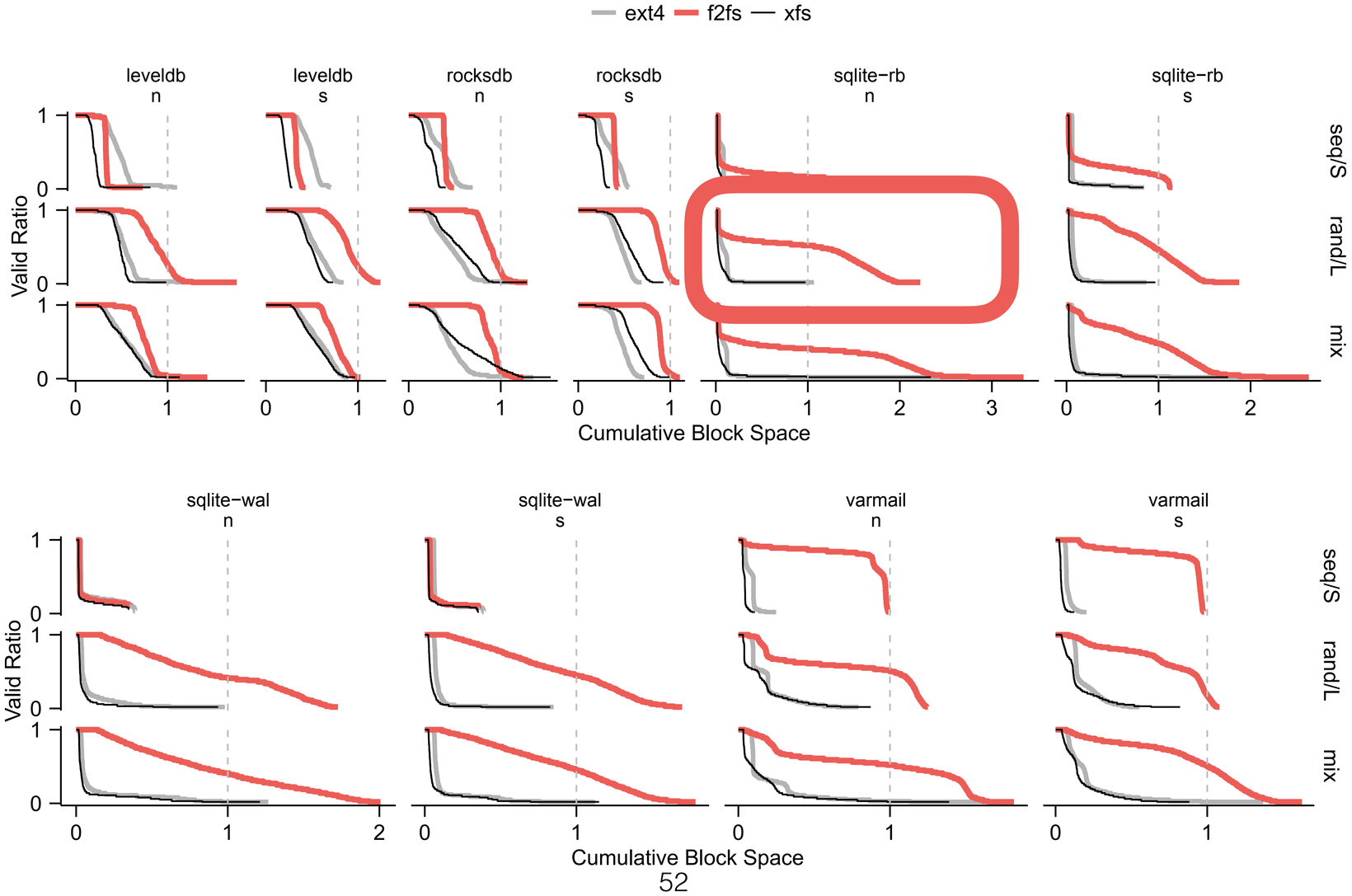
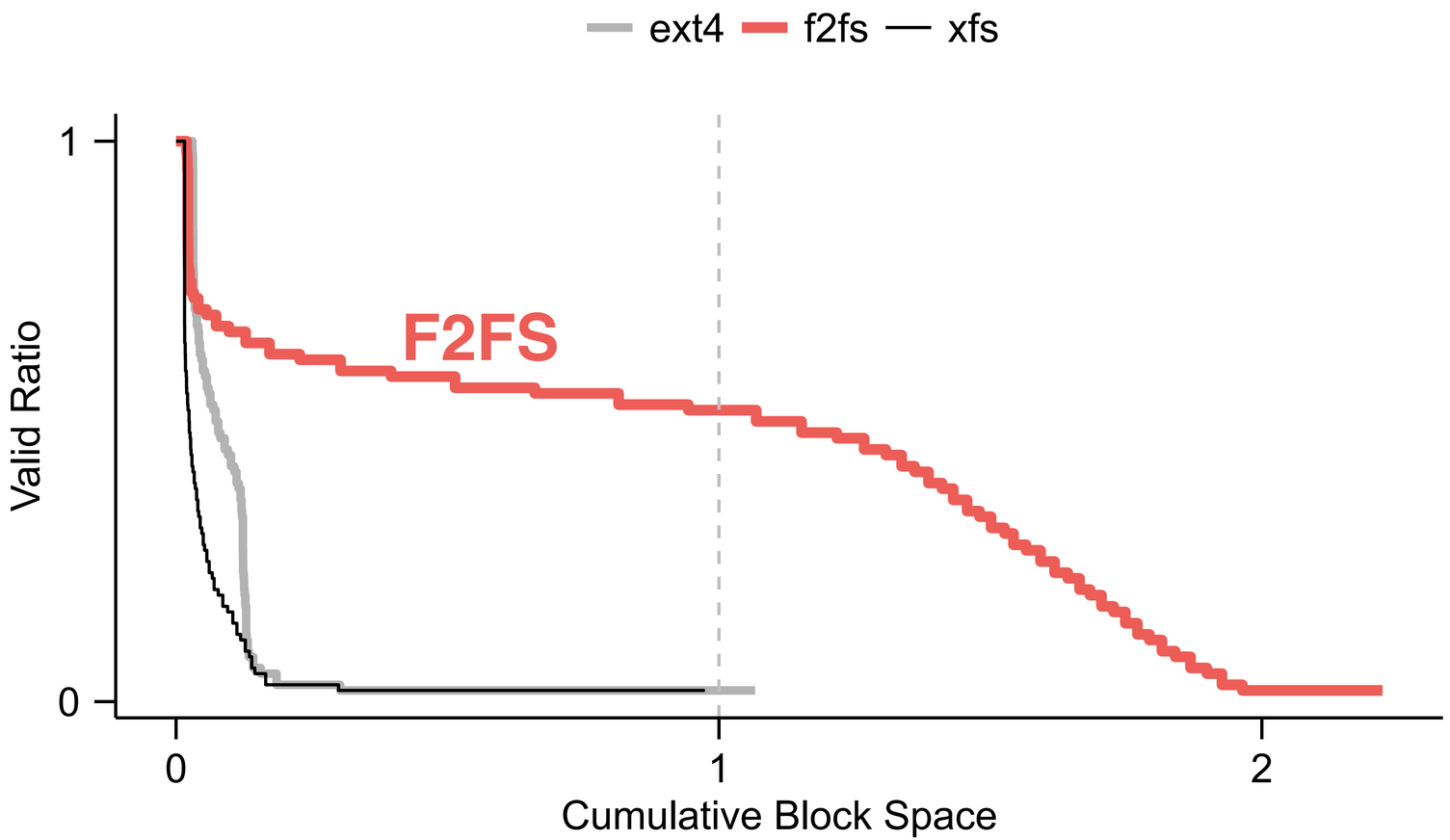


Random Insertions to SQLite-RollBack



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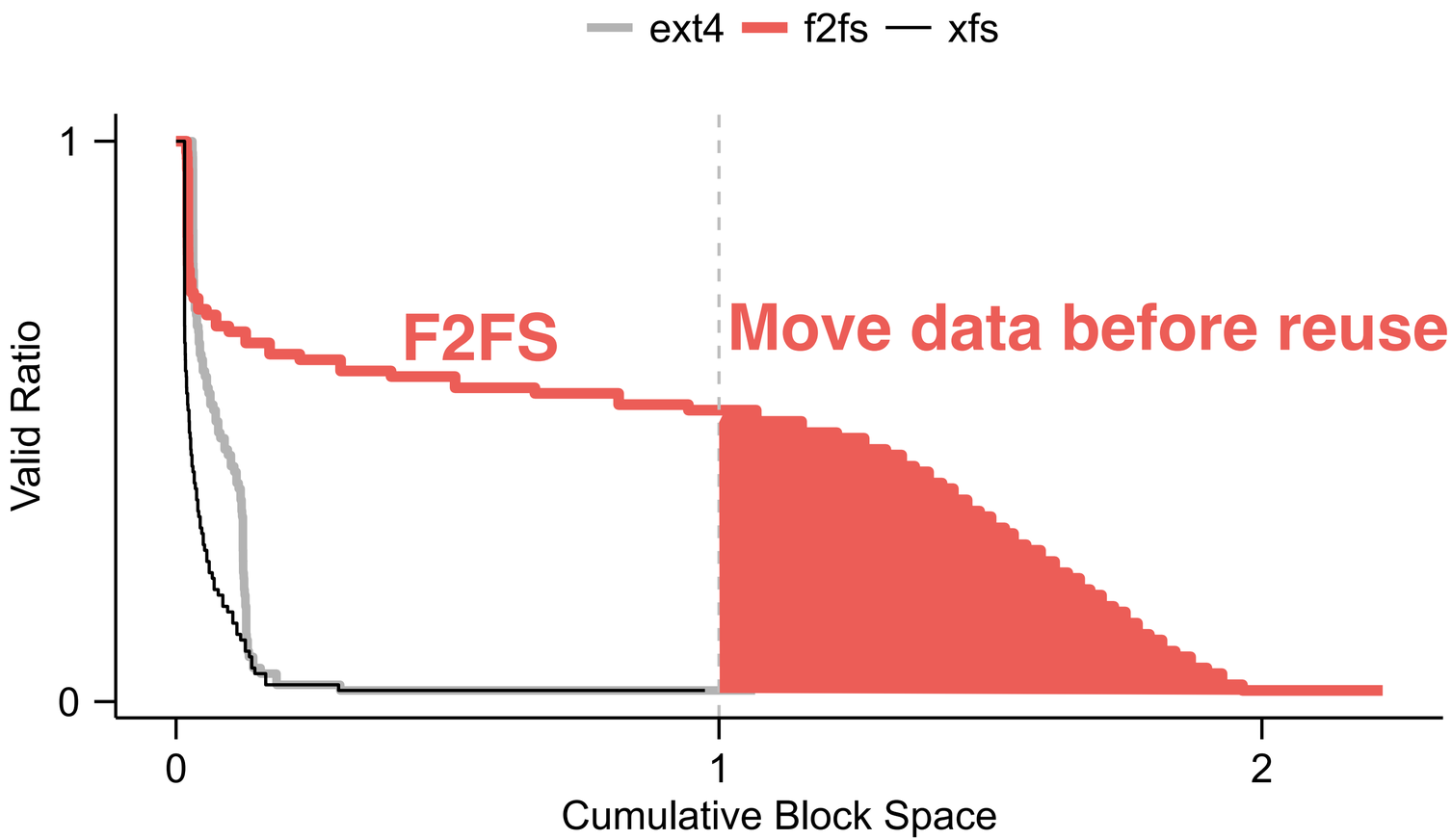

How SQLite-RollBack commit works?

Memory

SSD

Database

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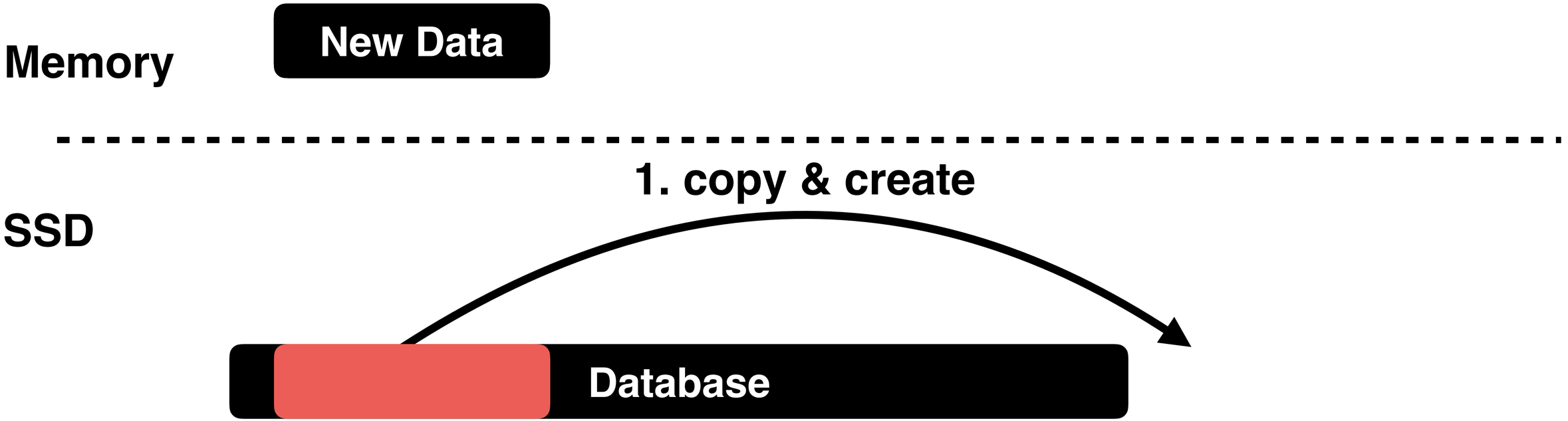

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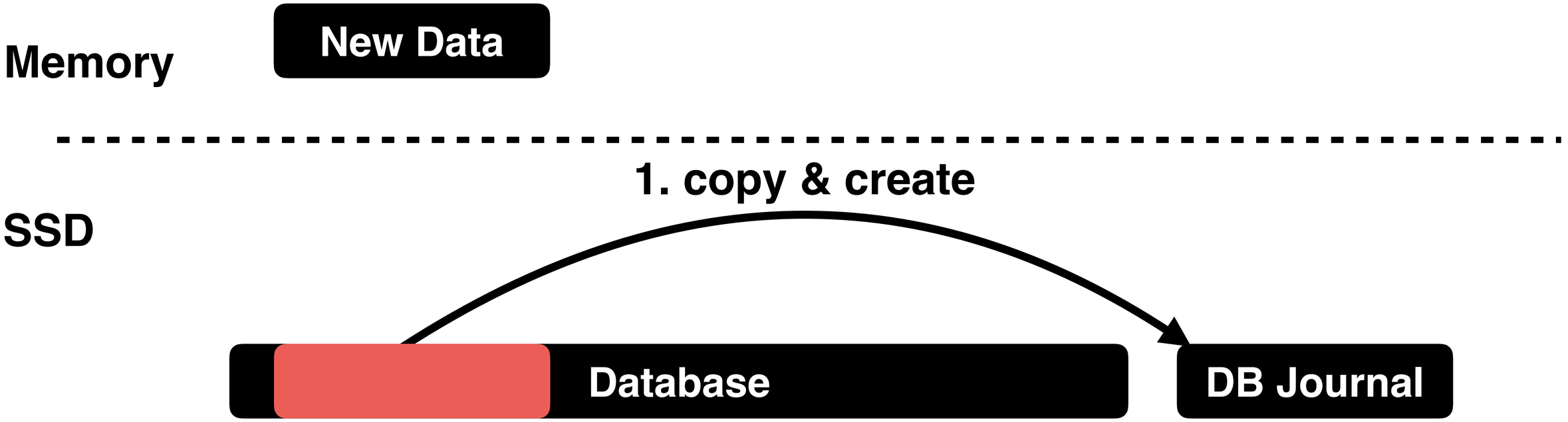

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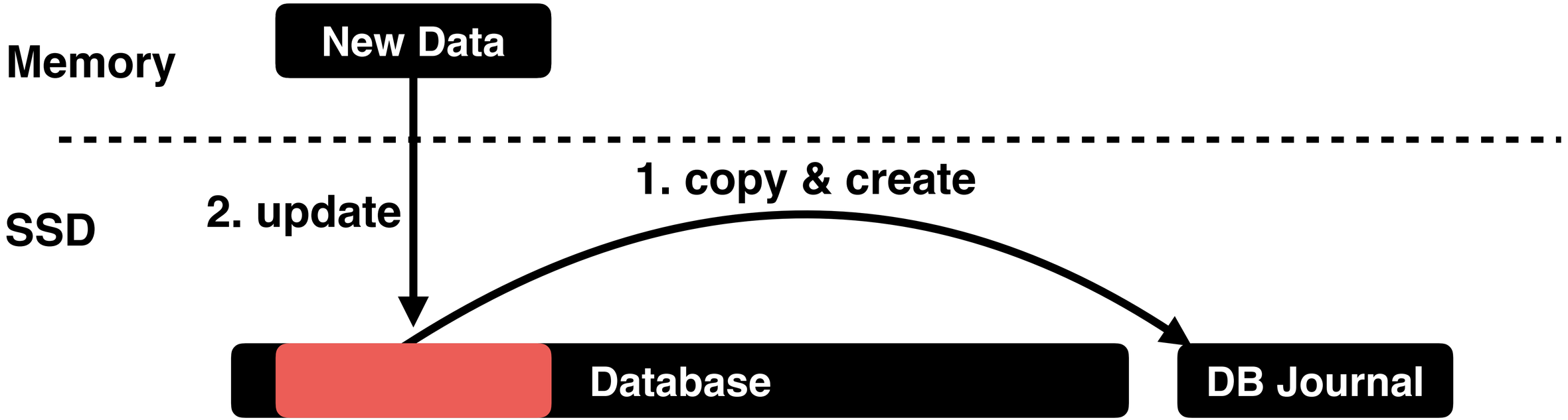

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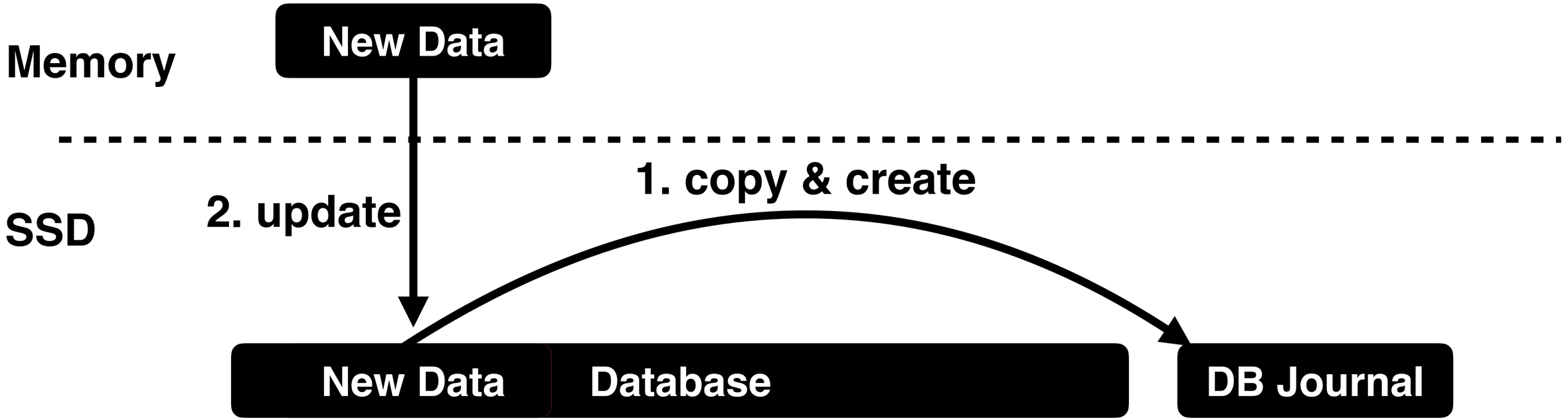

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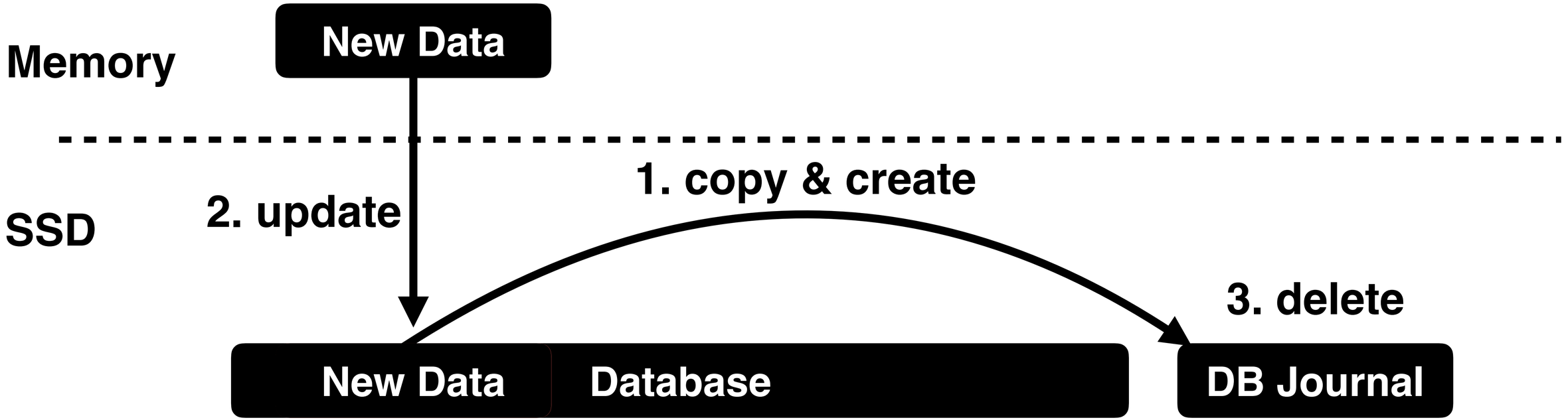

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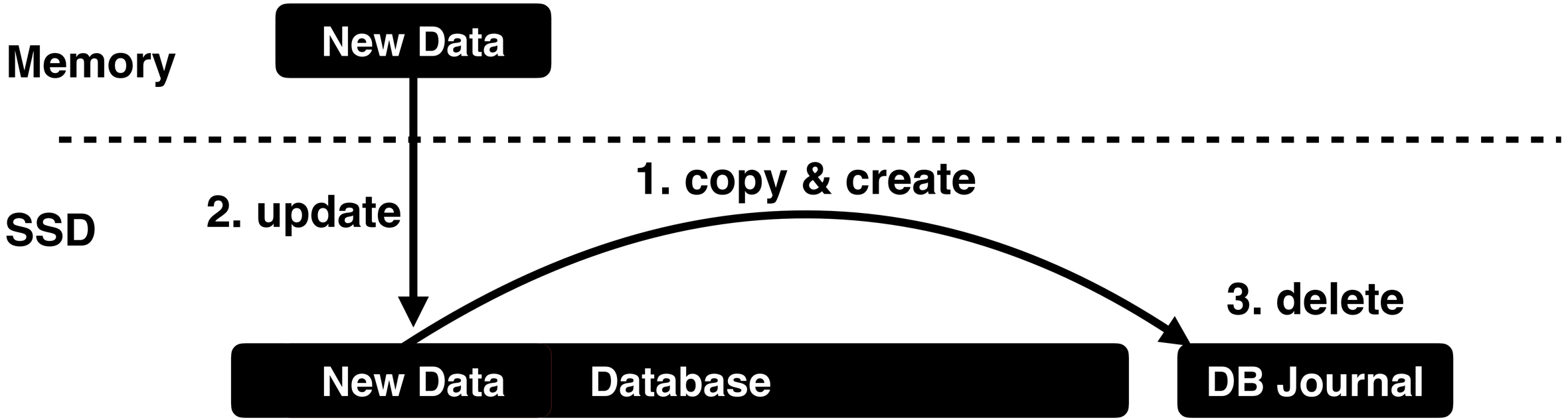

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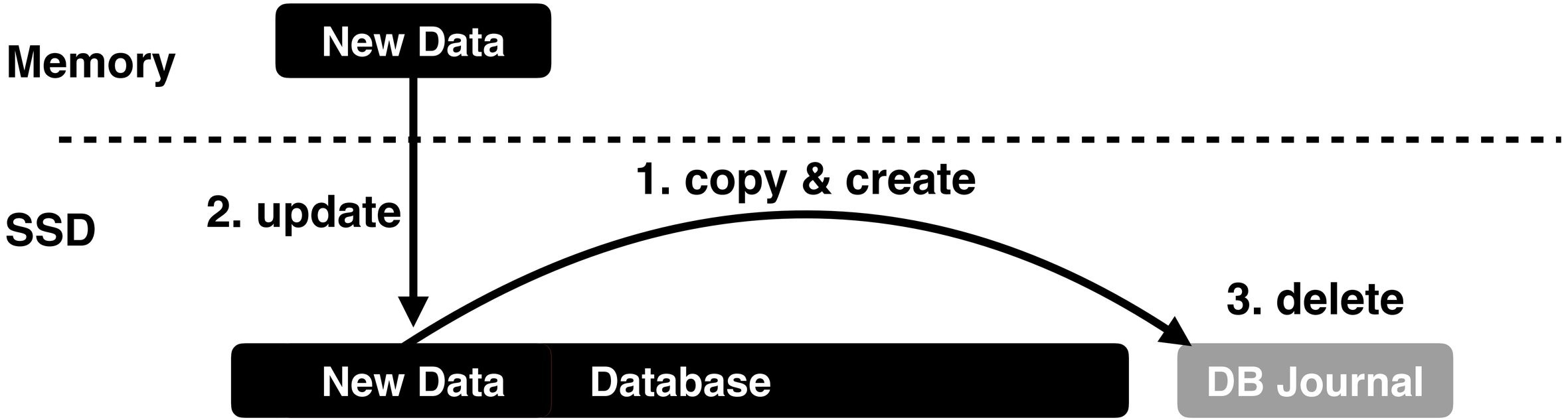

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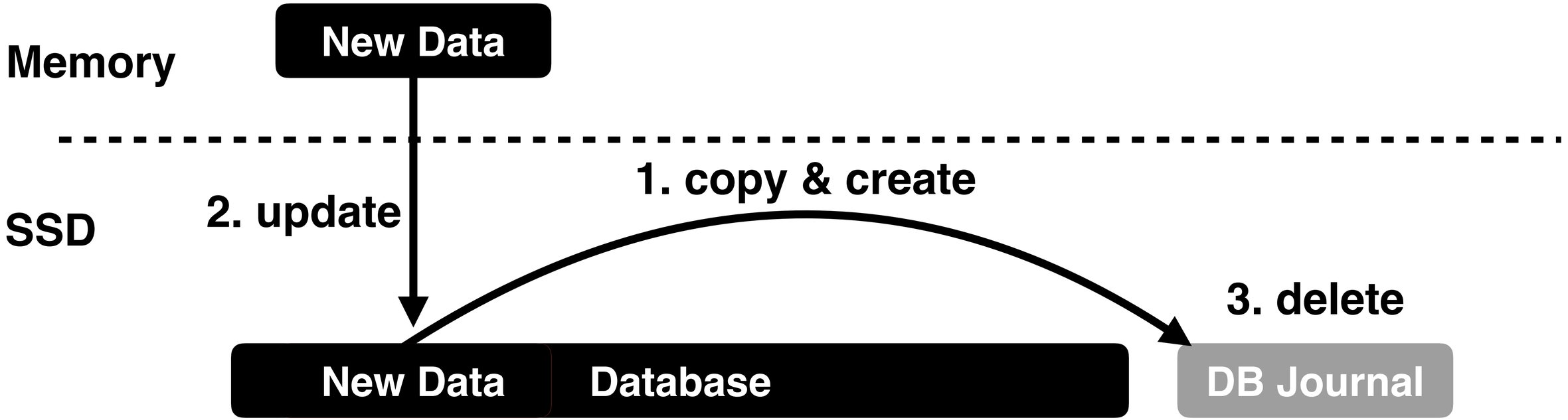
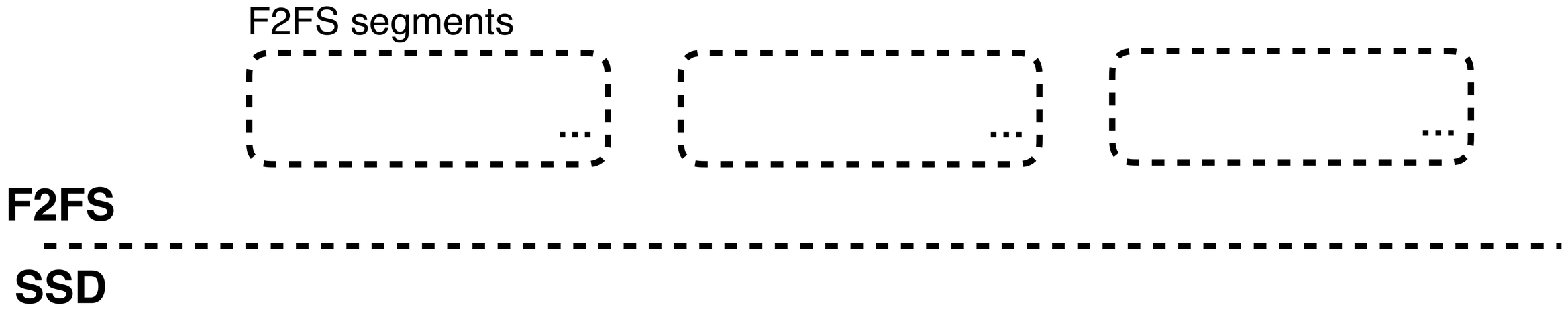


Small DB journal file is frequently created and deleted.

F2FS delays discarding DB journal files; DB journal files are considered valid for a long time inside SSD



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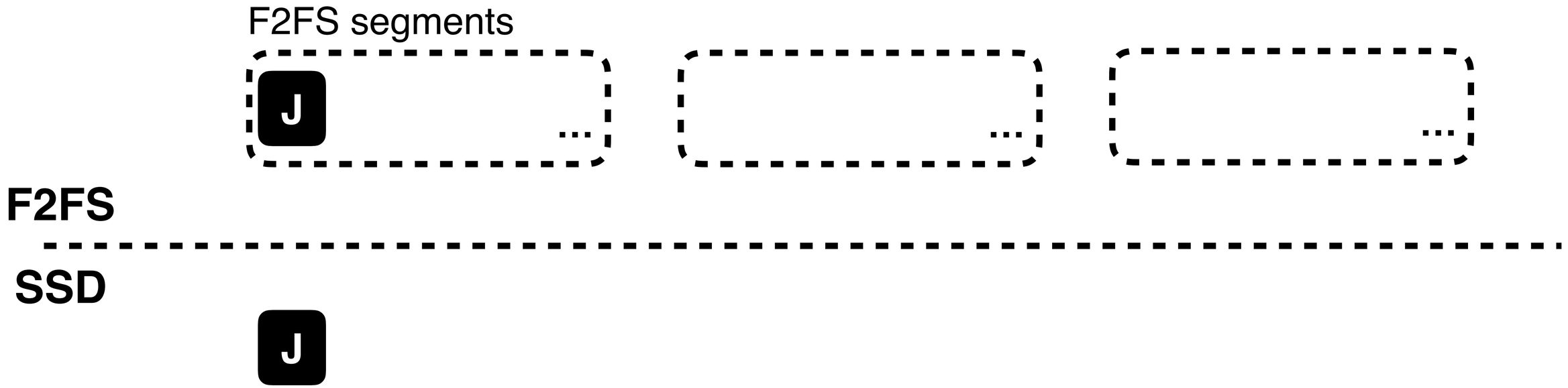

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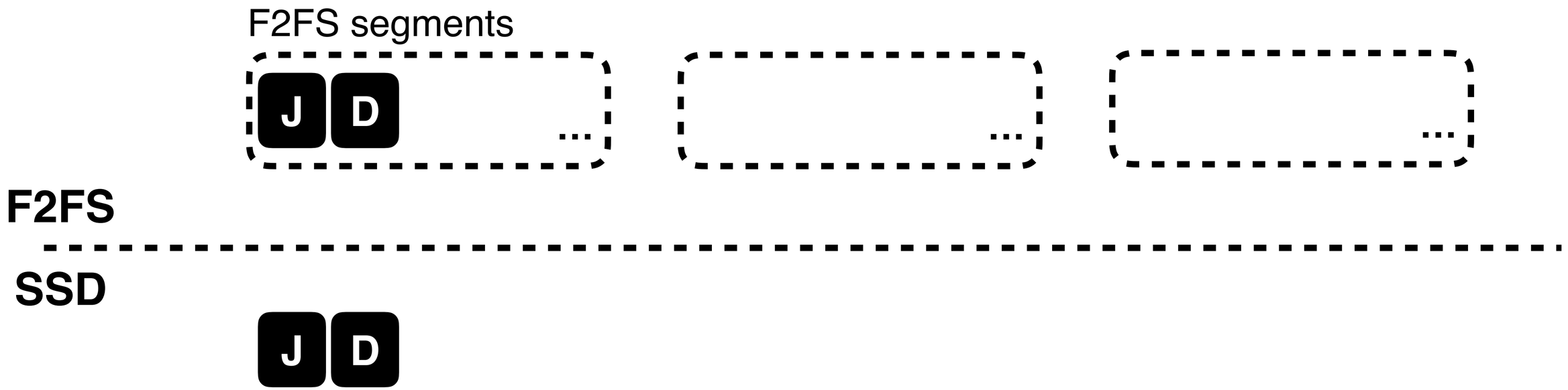

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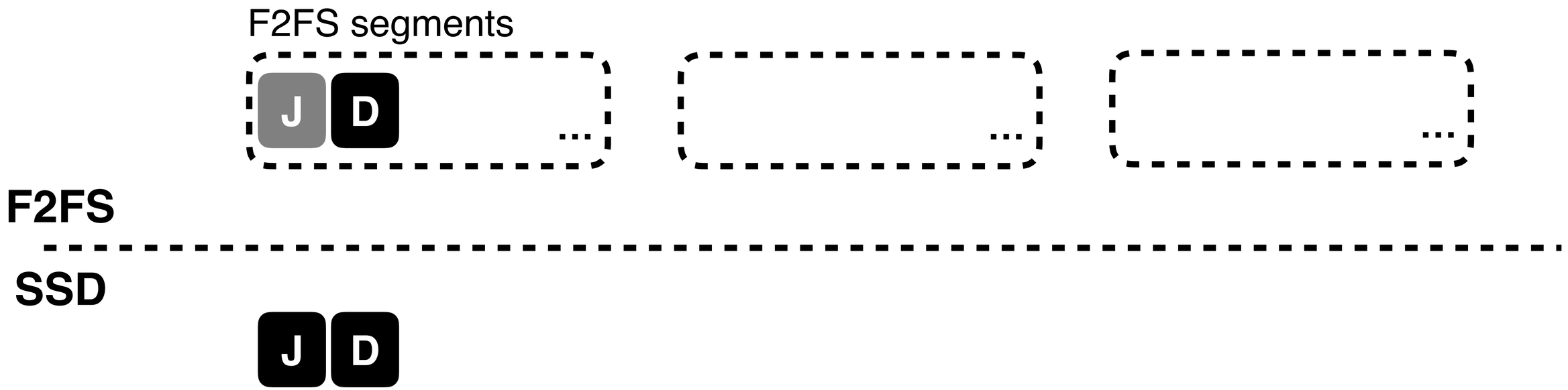

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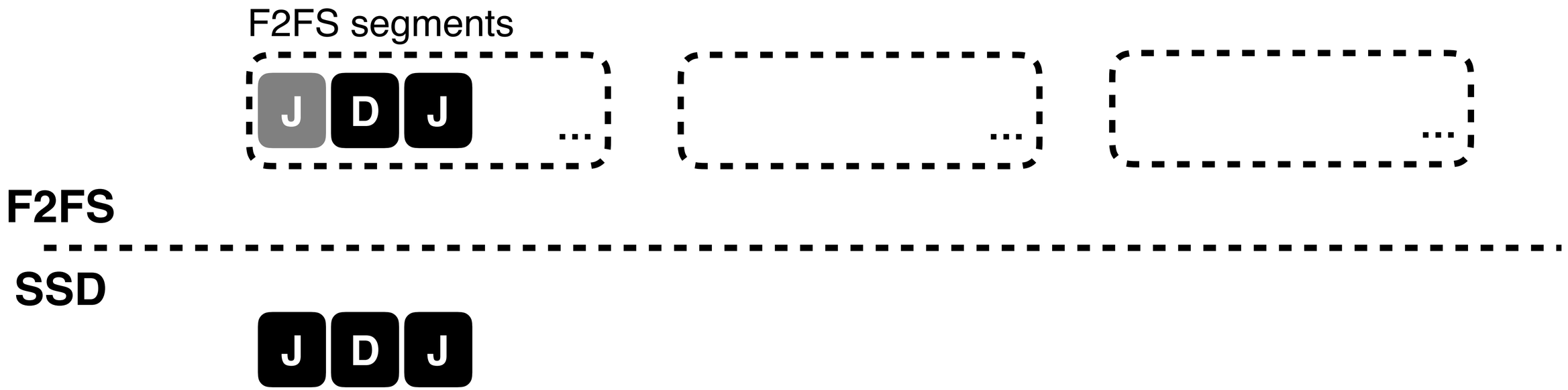

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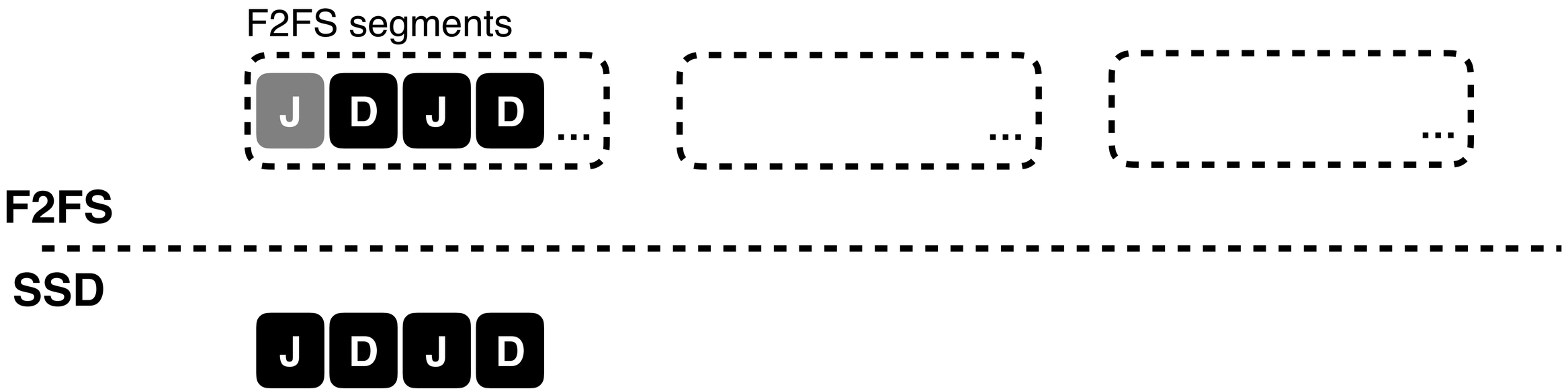

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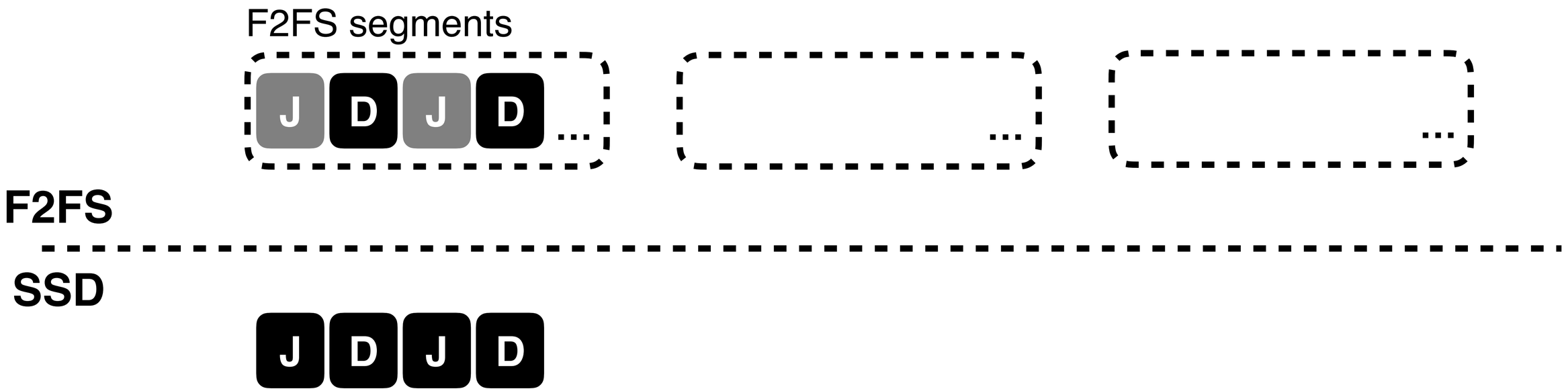

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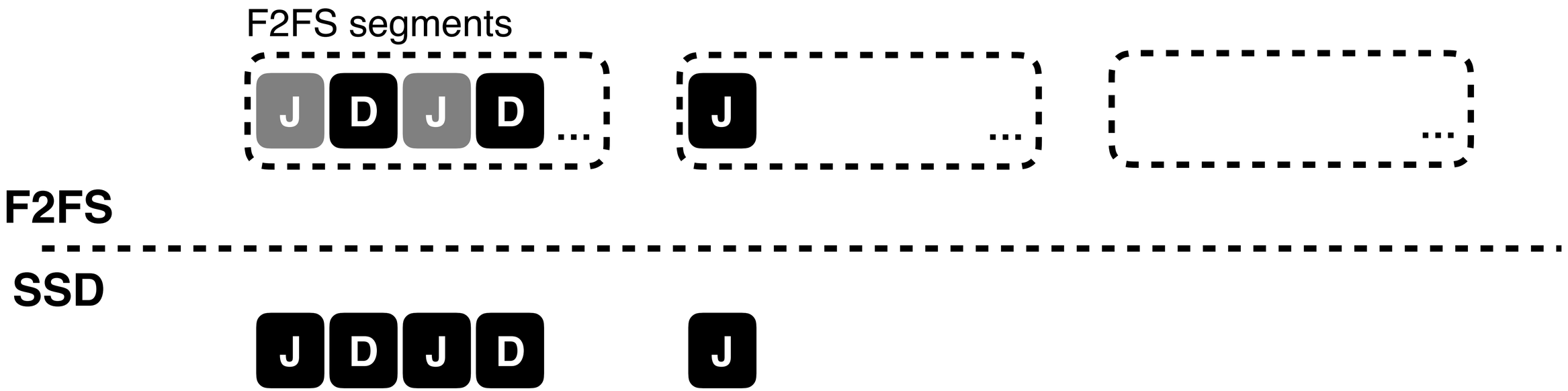

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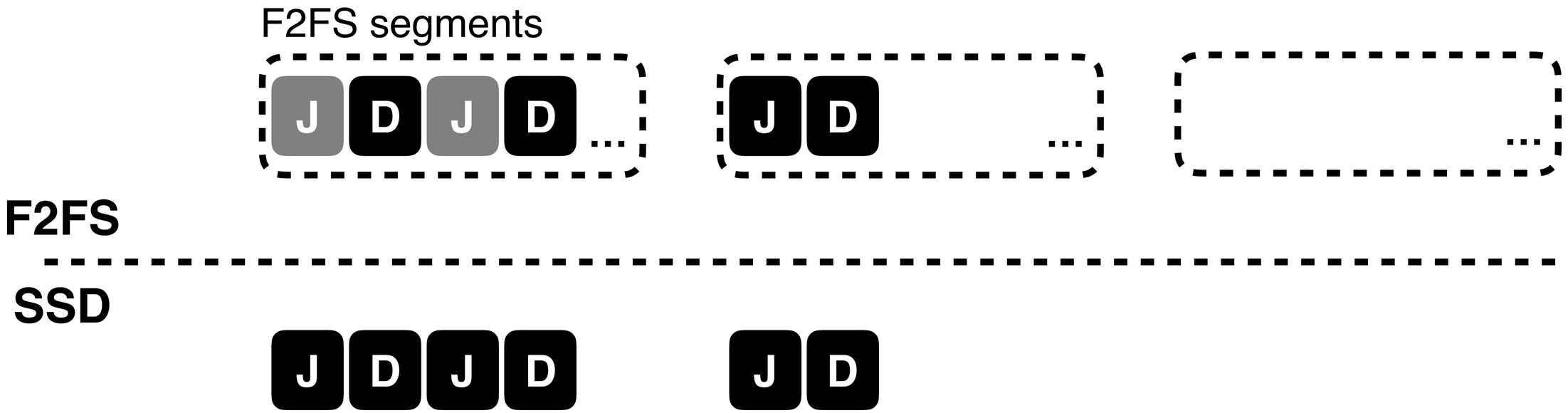

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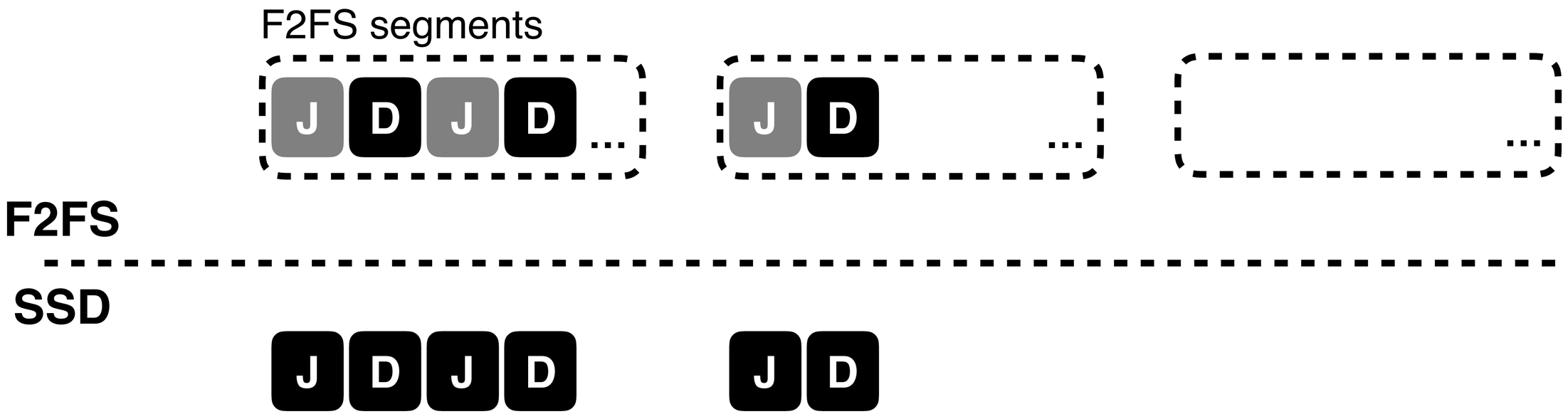

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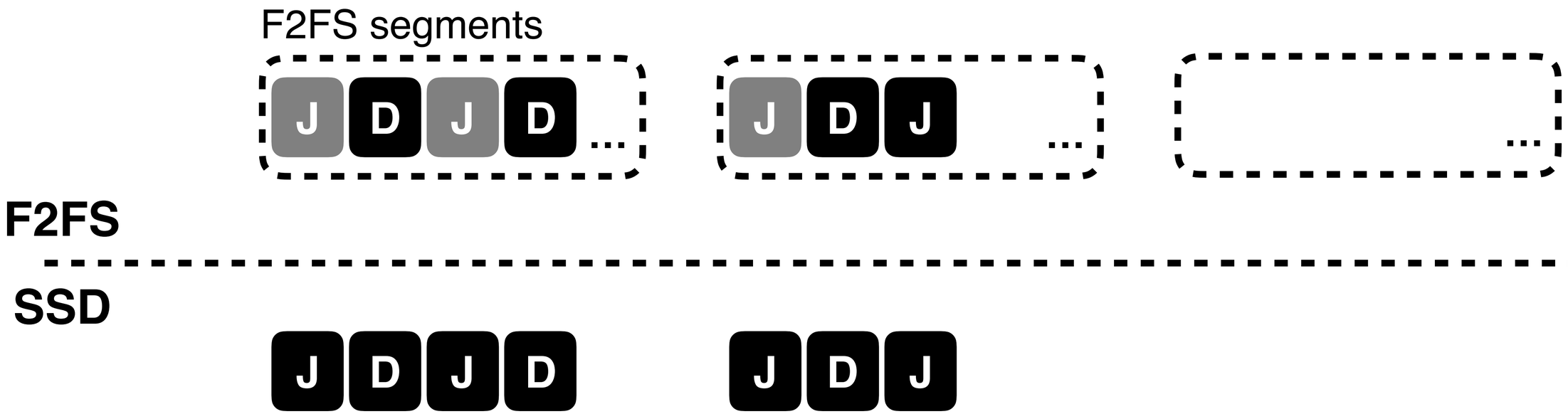

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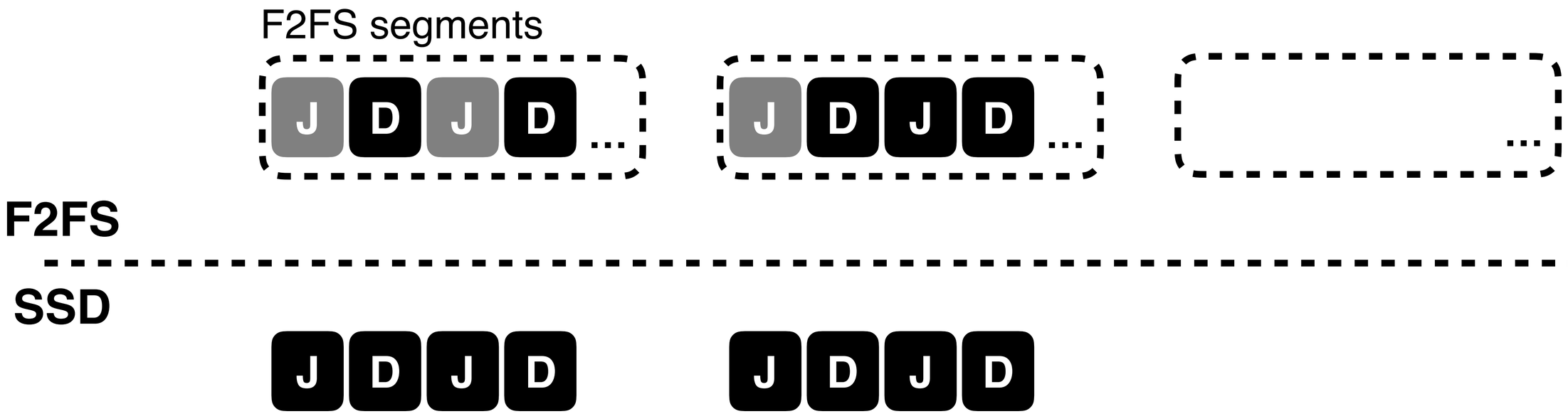

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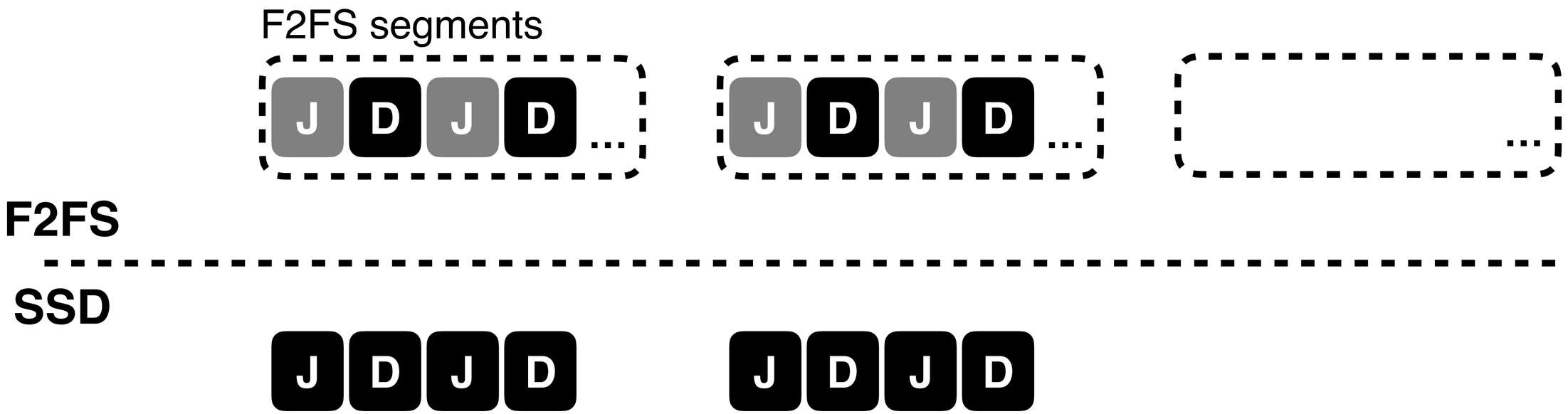

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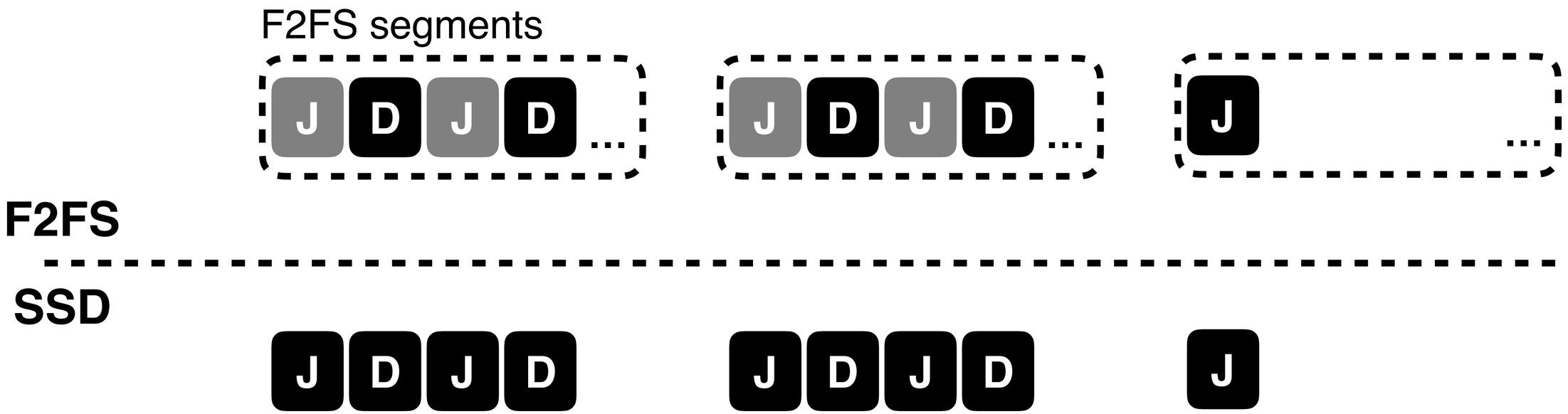

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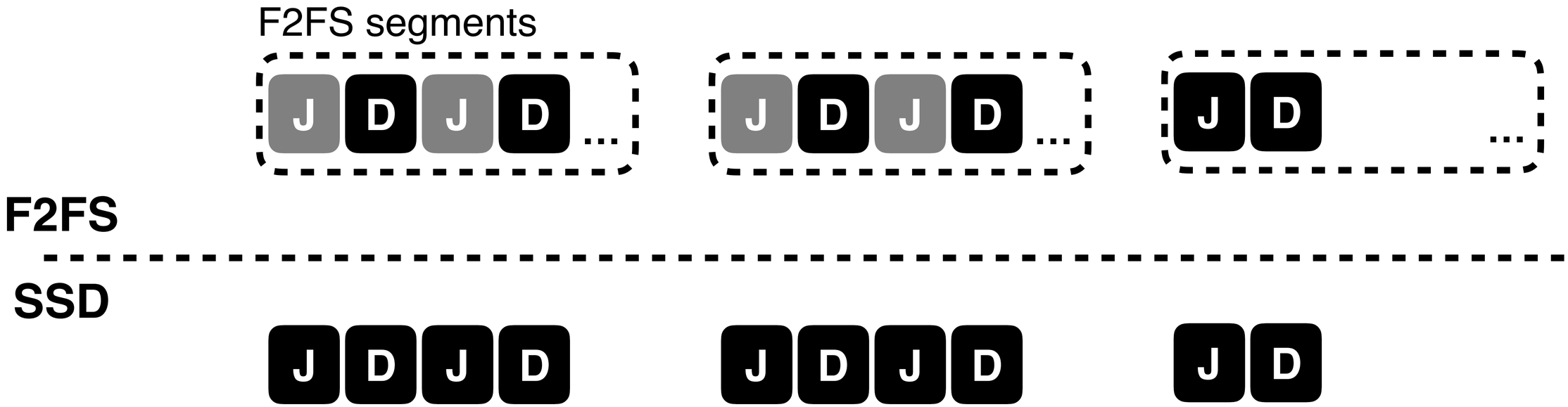

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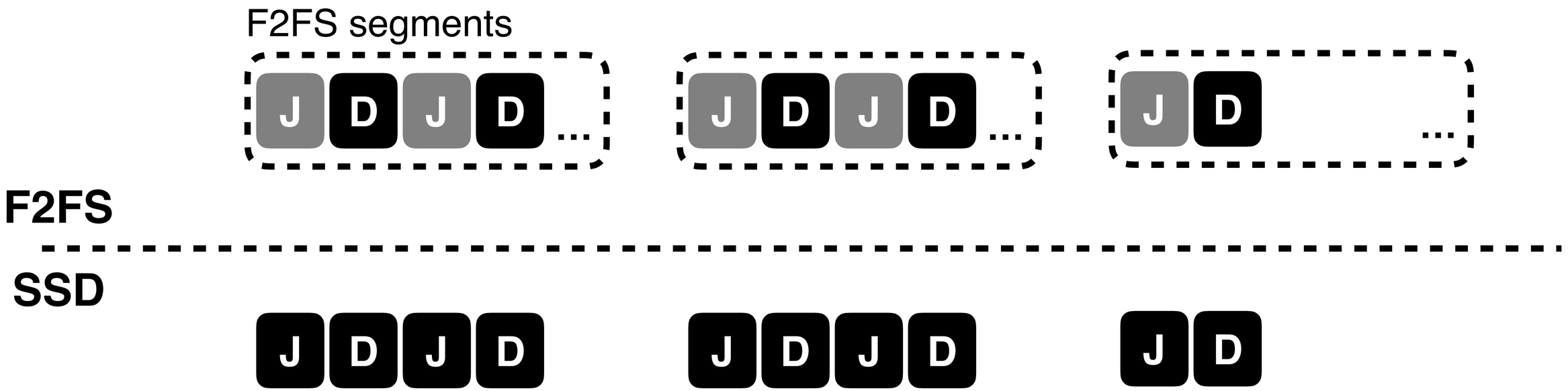

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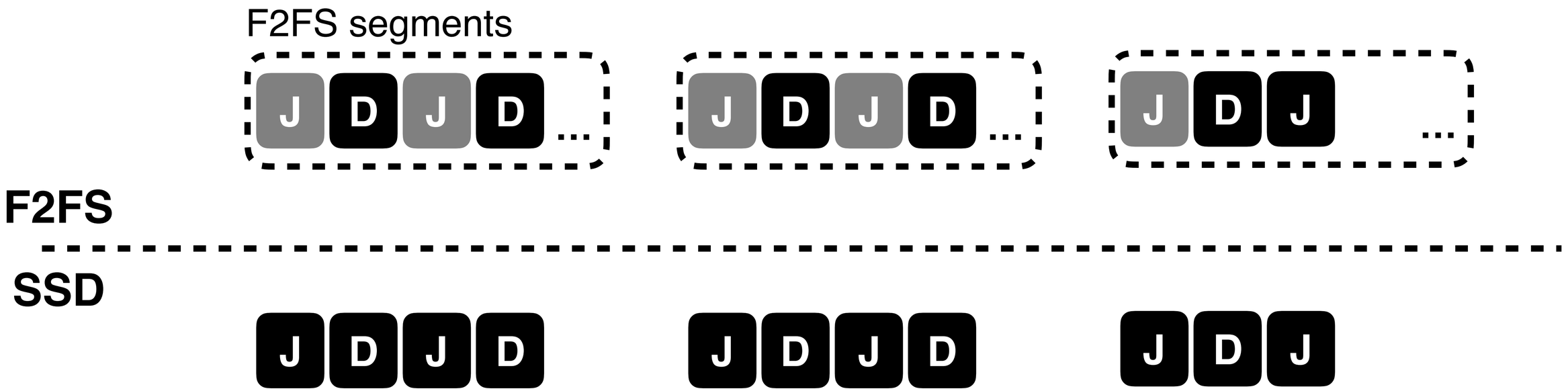

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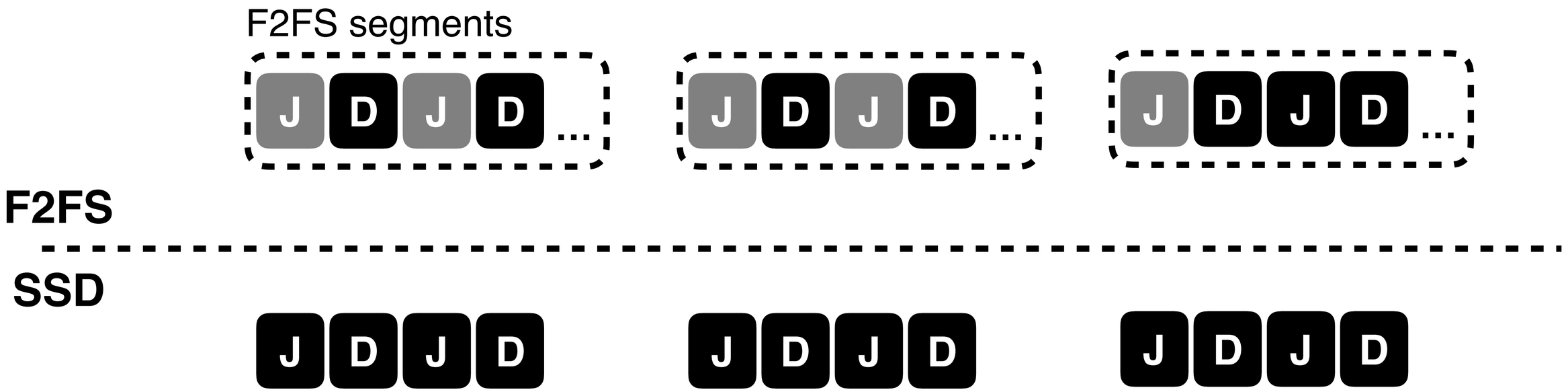

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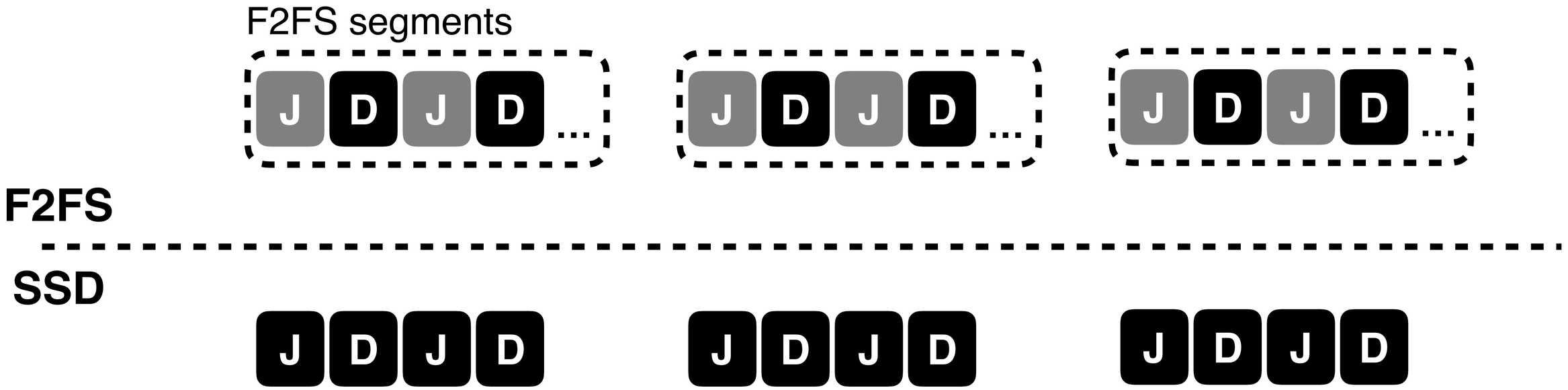

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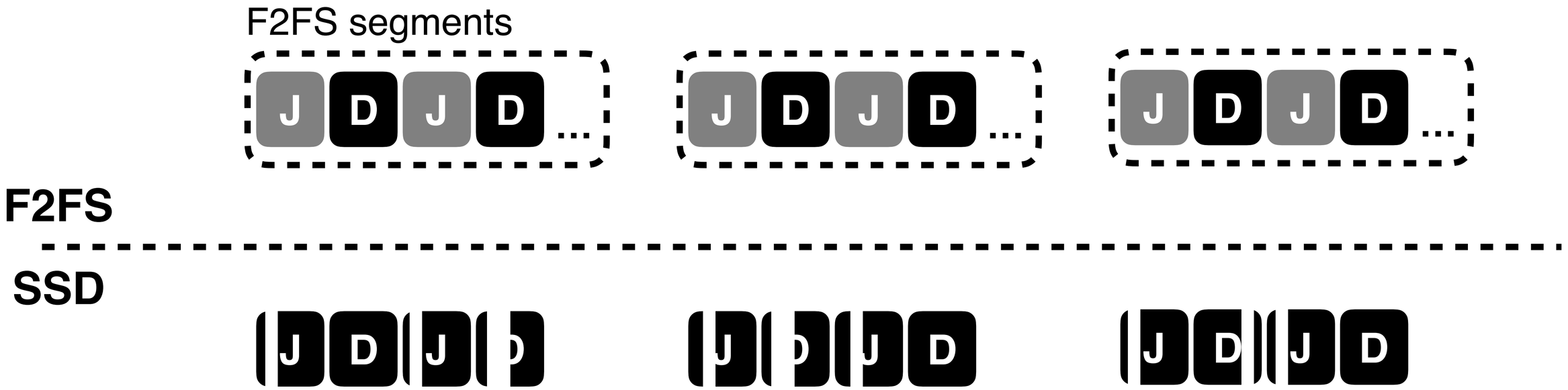

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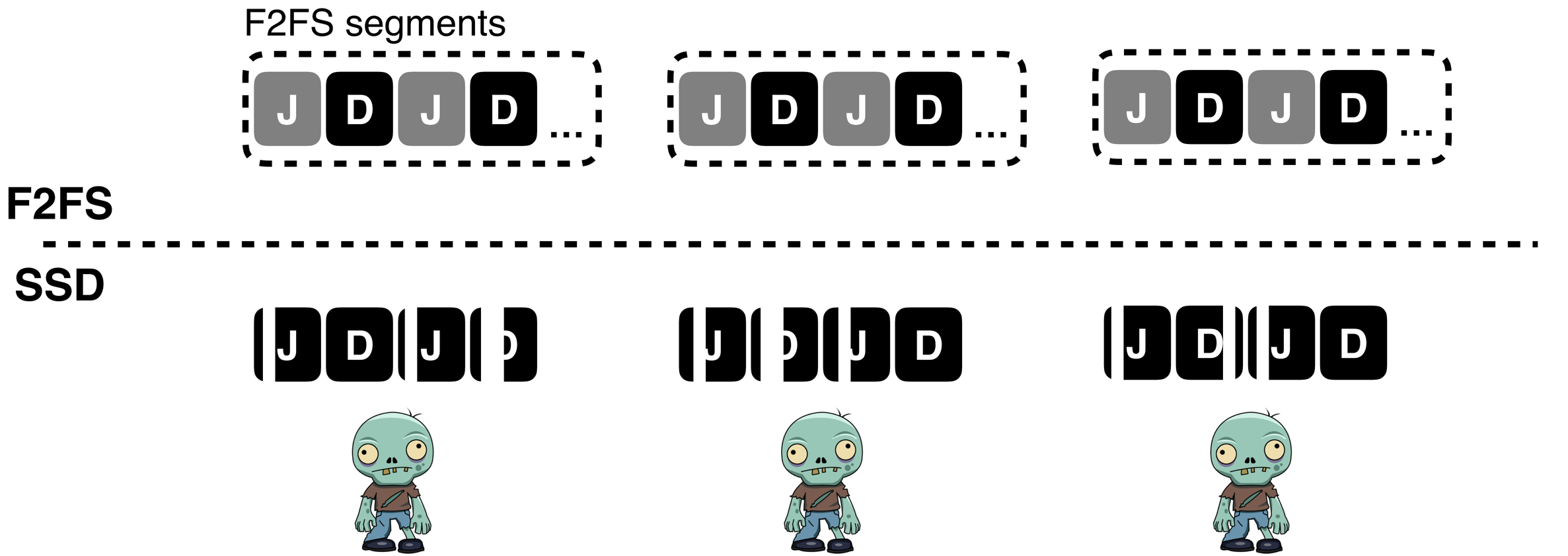

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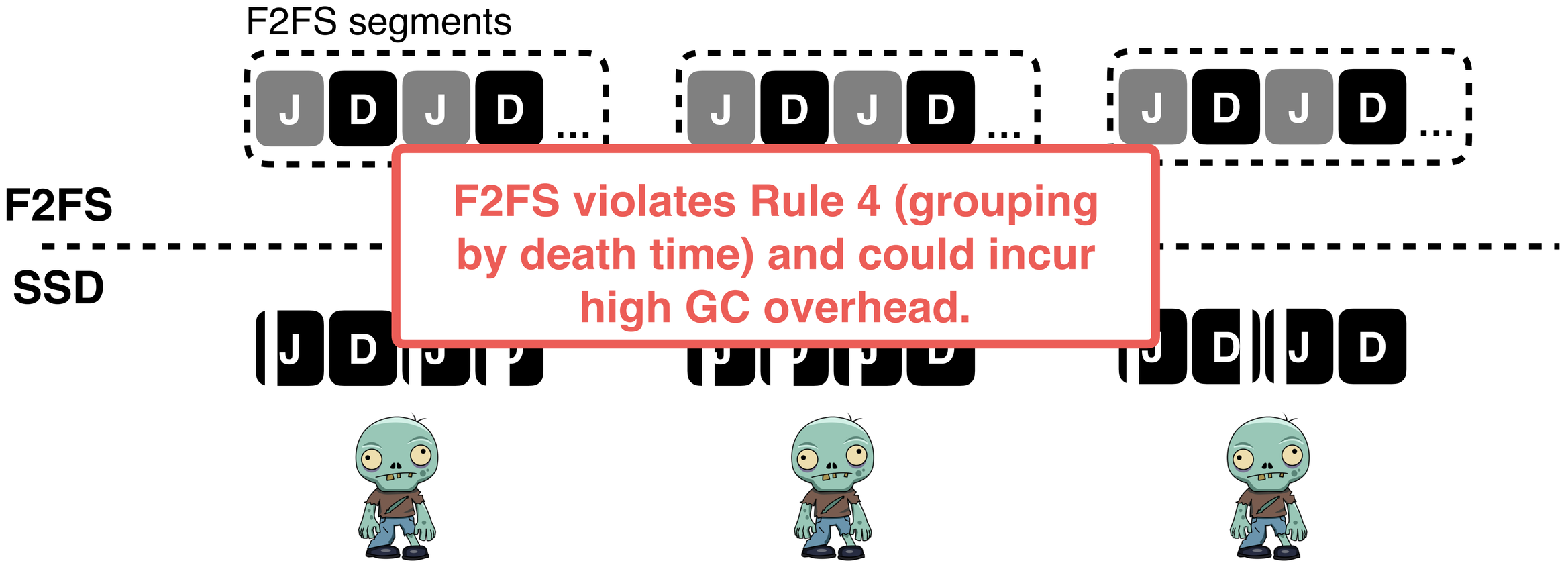

Observations

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  - Implementation of Linux limits performance
- Rule 3: Grouping by Death Time
  - F2FS incurs more GC overhead than ext4/XFS
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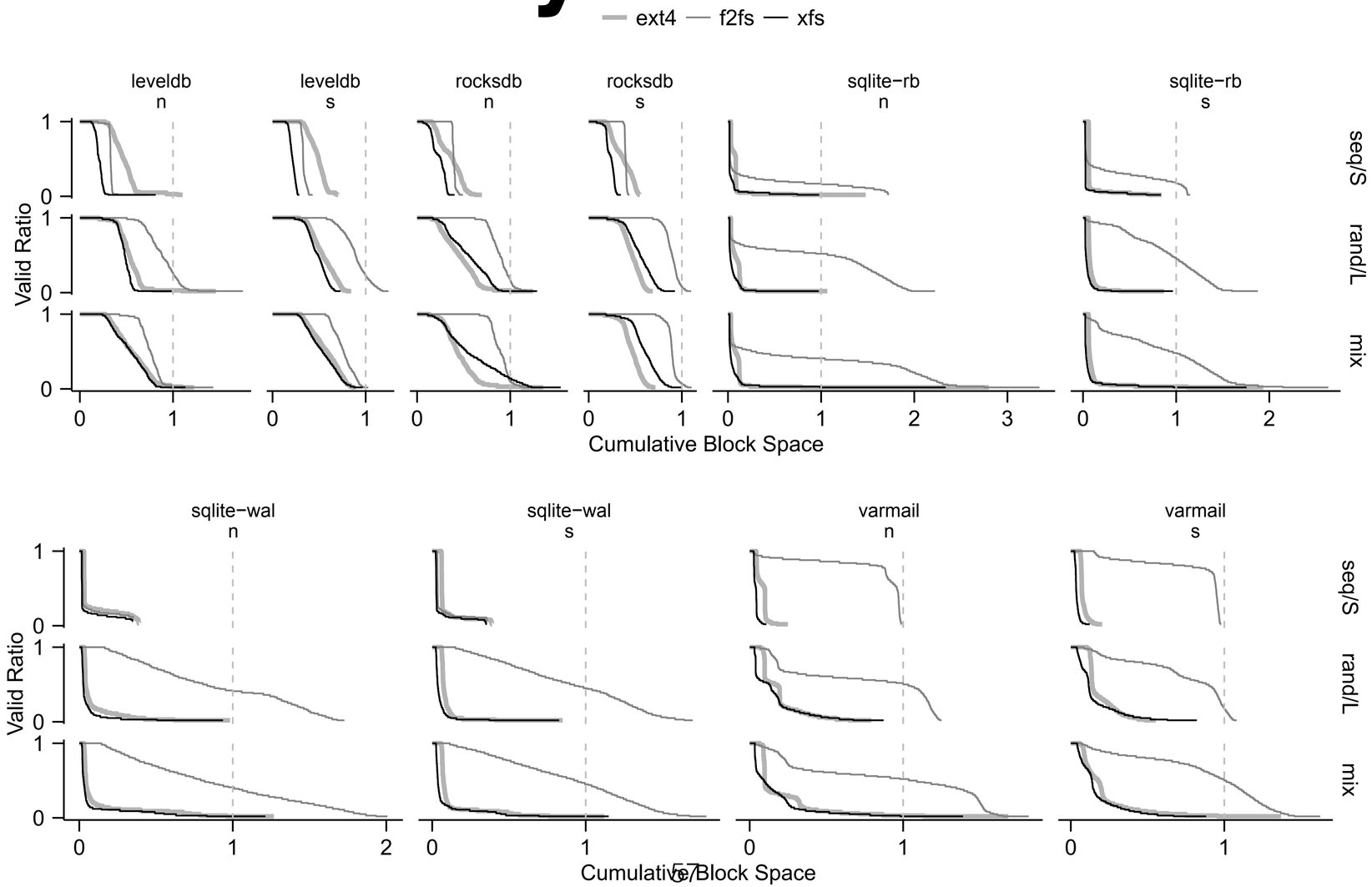
LevelDB & RocksDB often incur many zombie blocks



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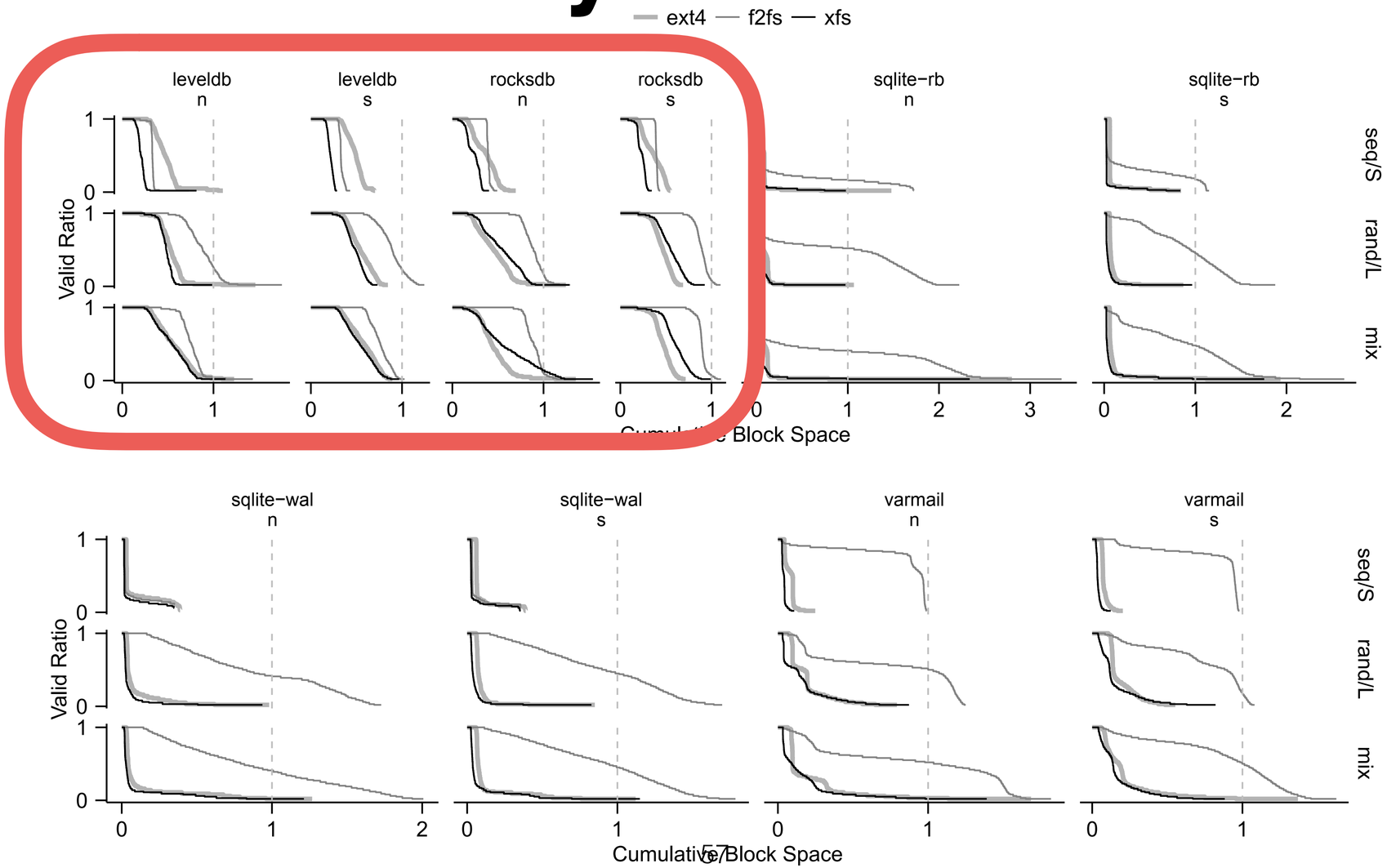

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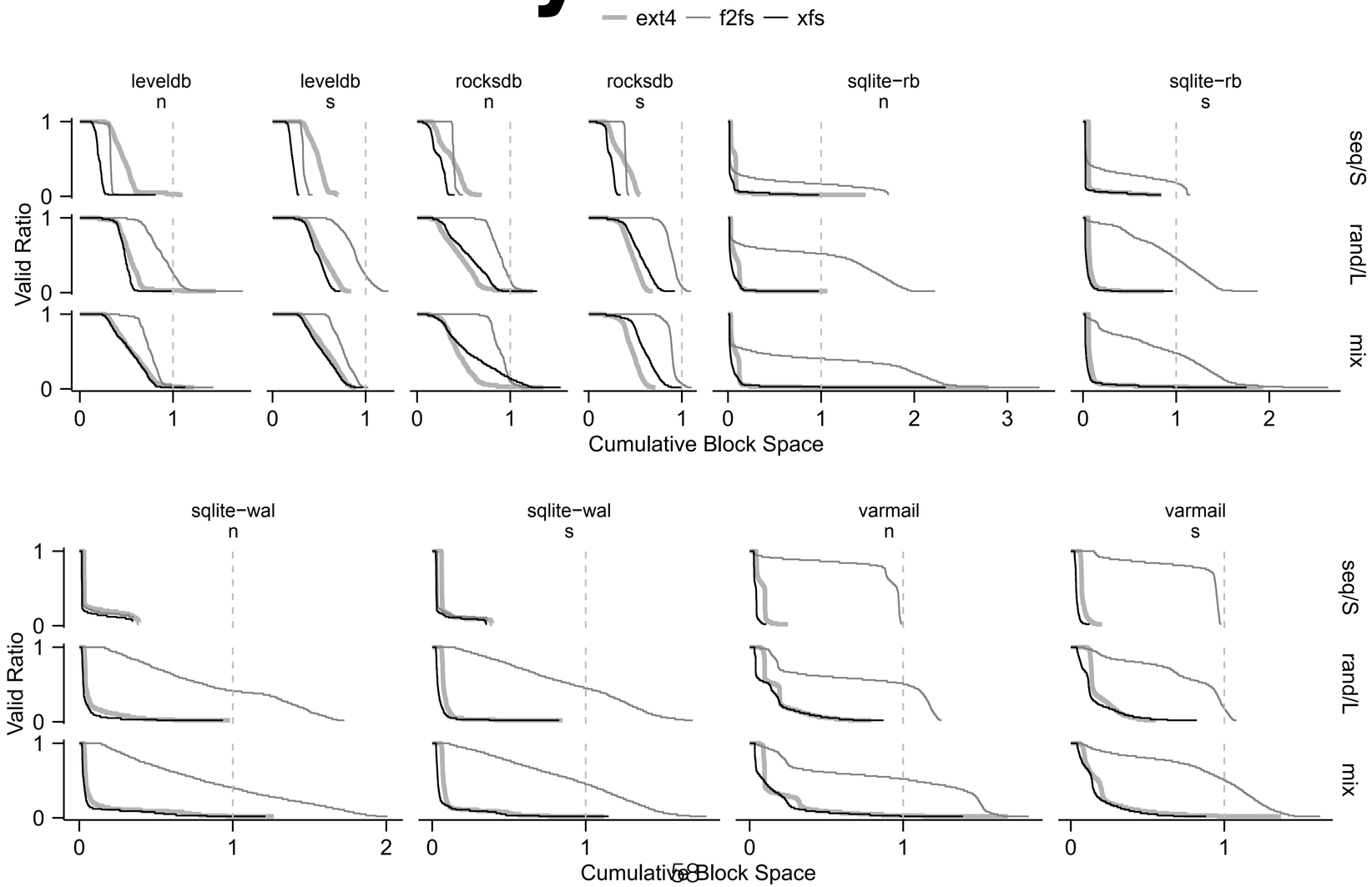

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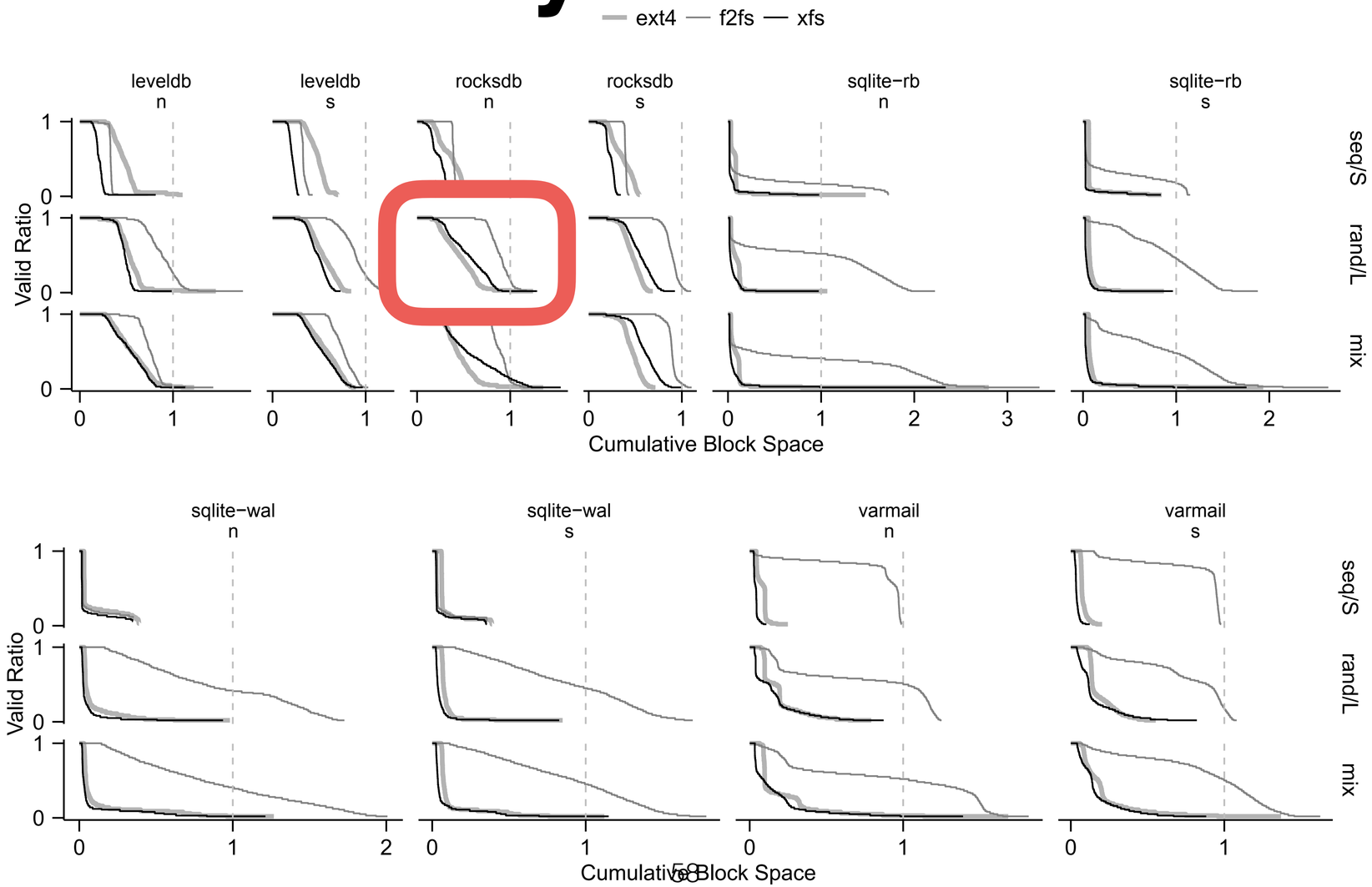
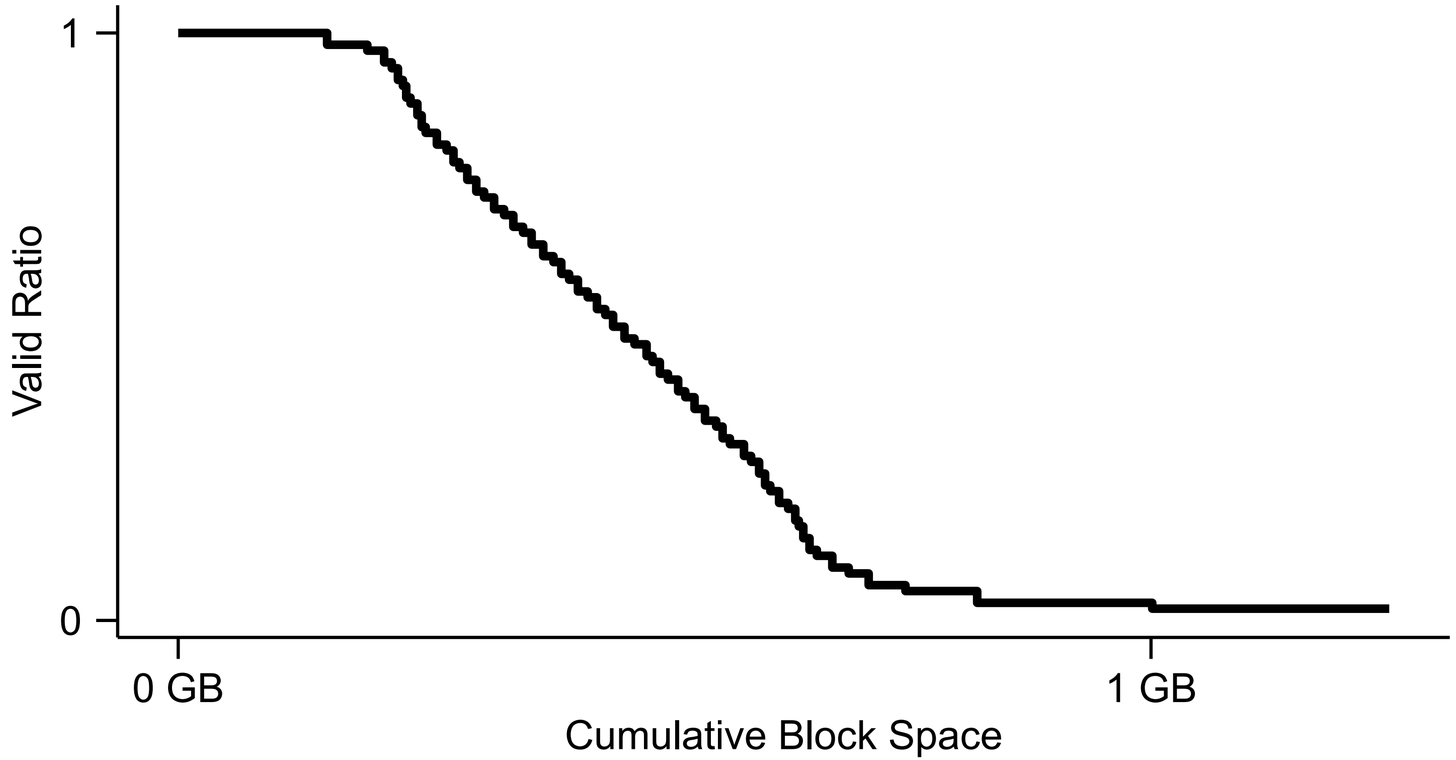


RocksDB Random Insertions on ext4



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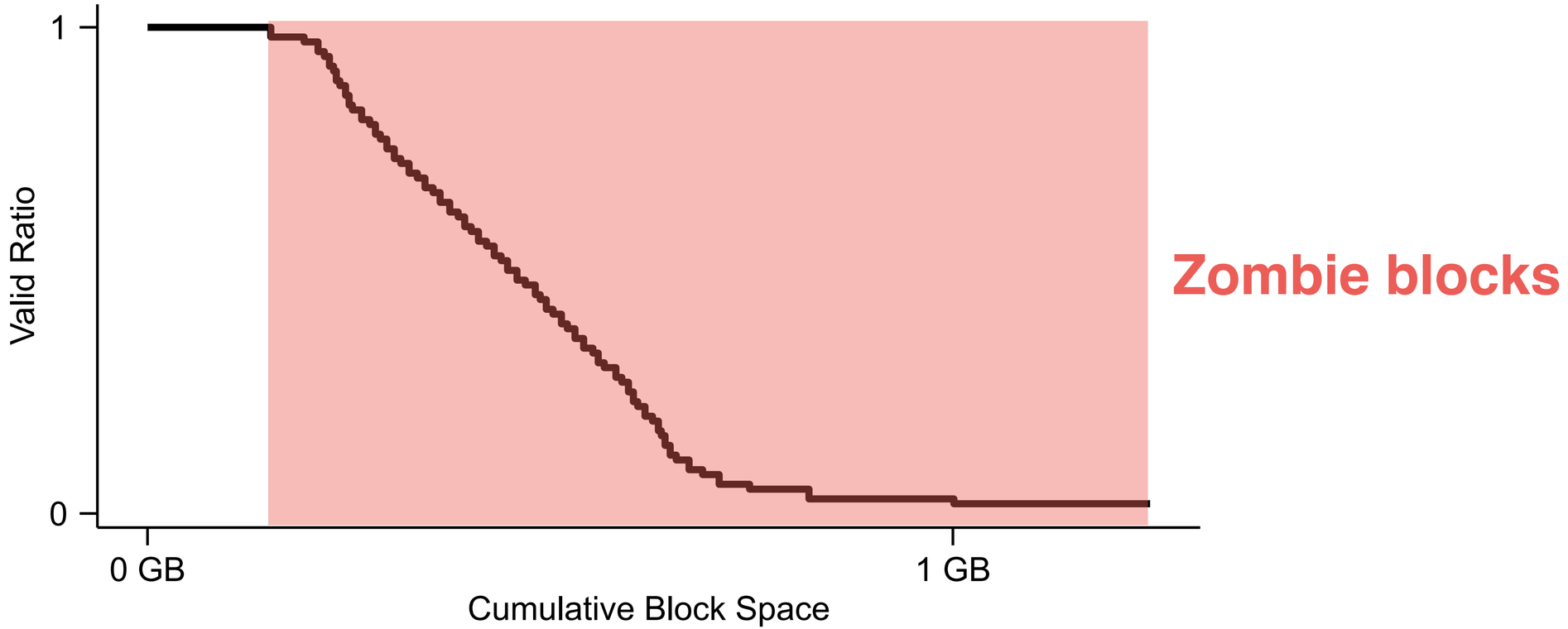
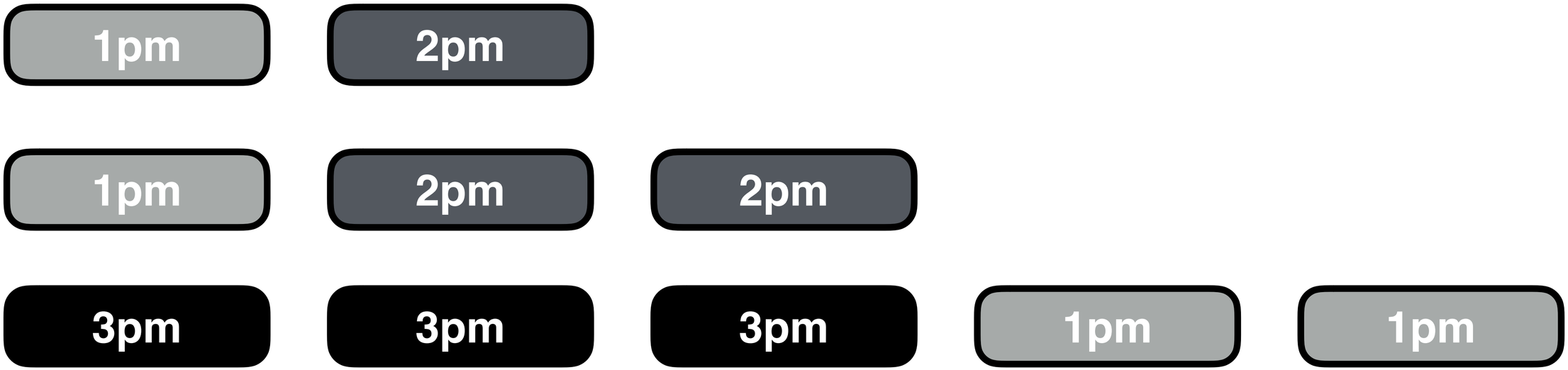


LevelDB & RocksDB files have different death times



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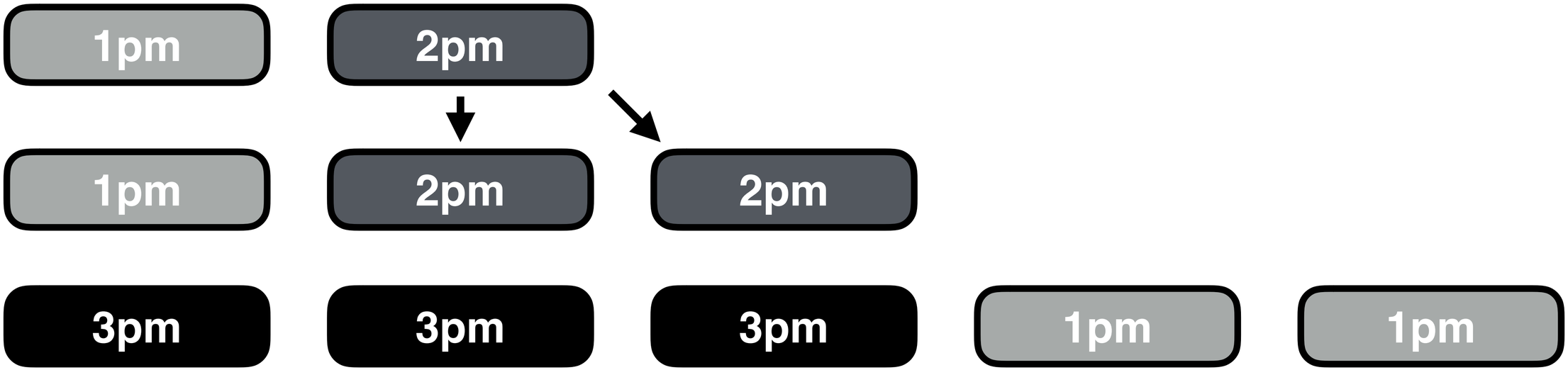

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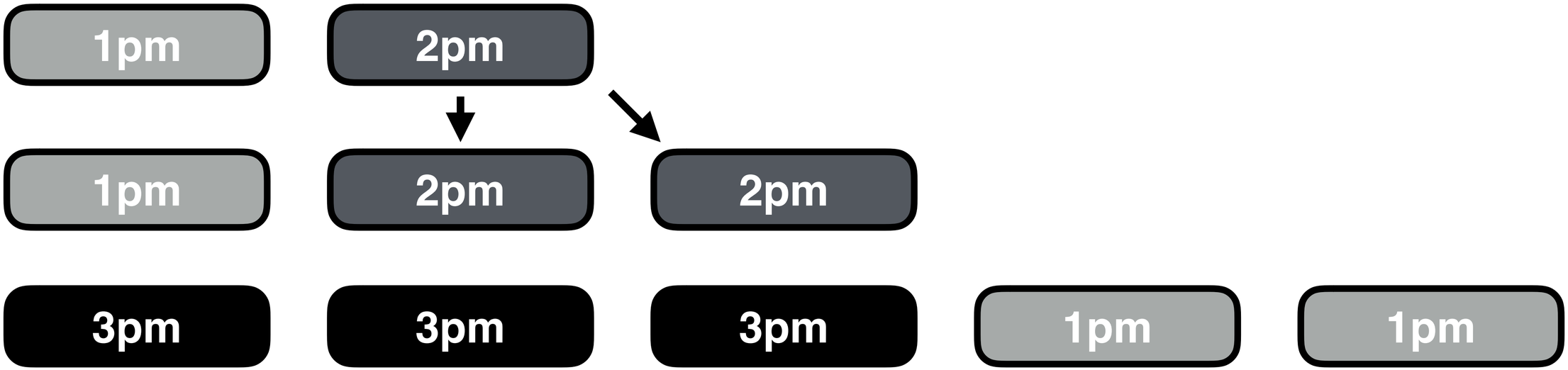
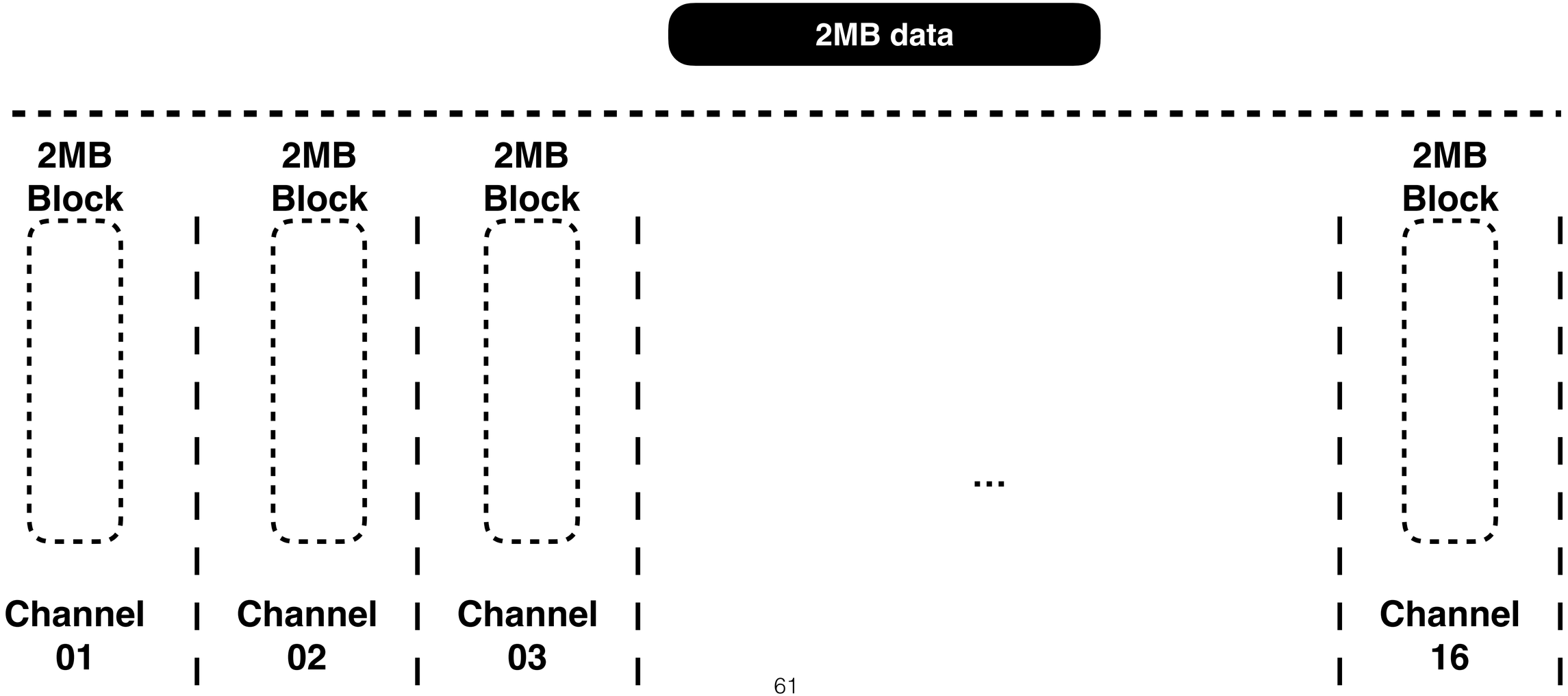


Data of different files is mixed to the same blocks



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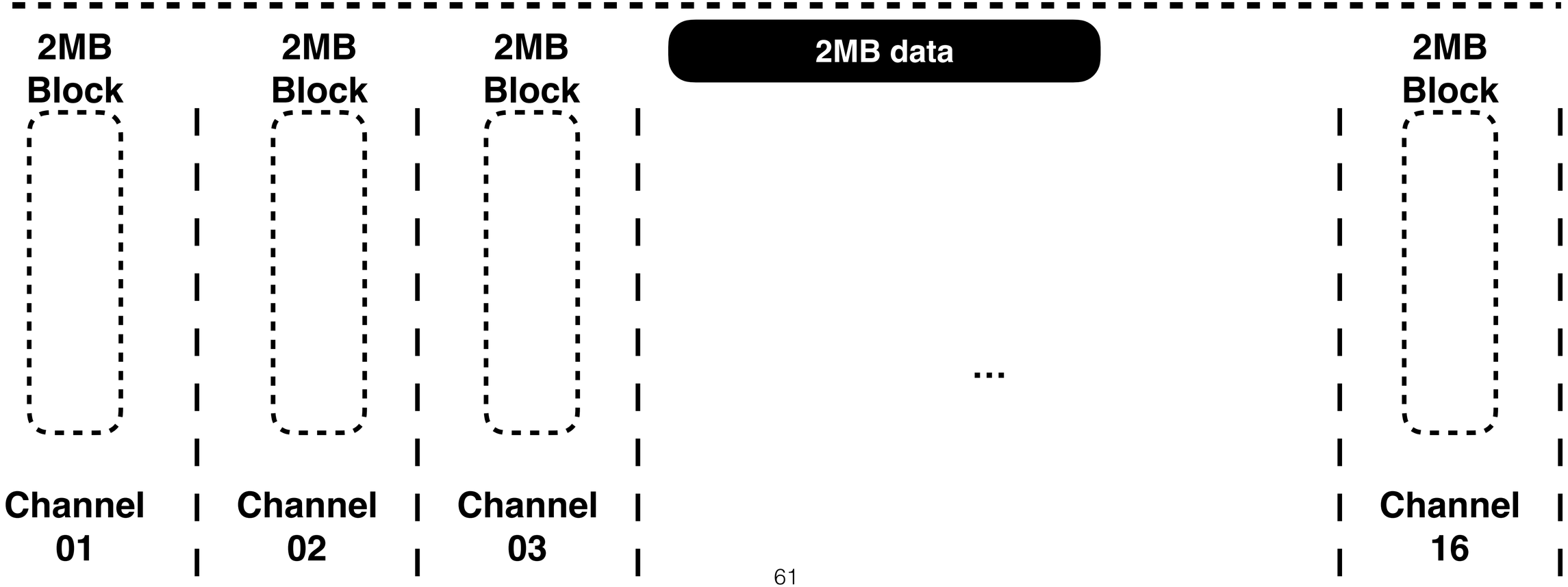

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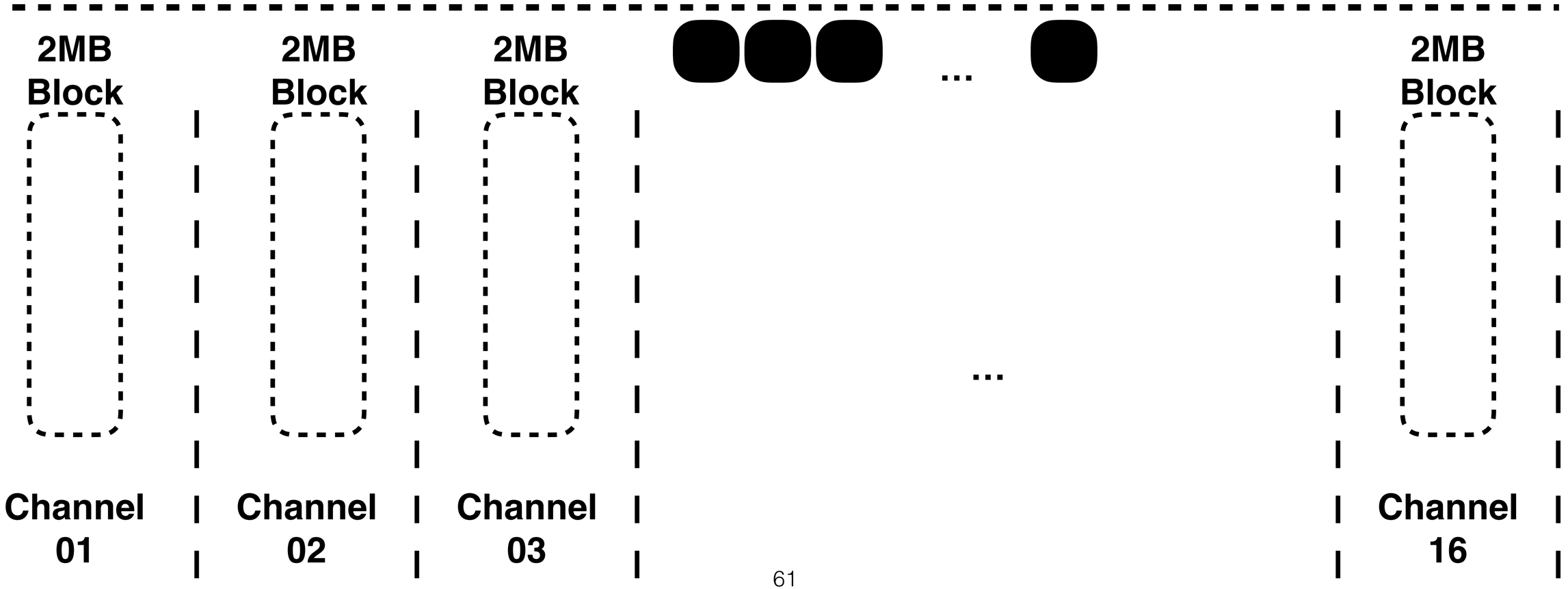

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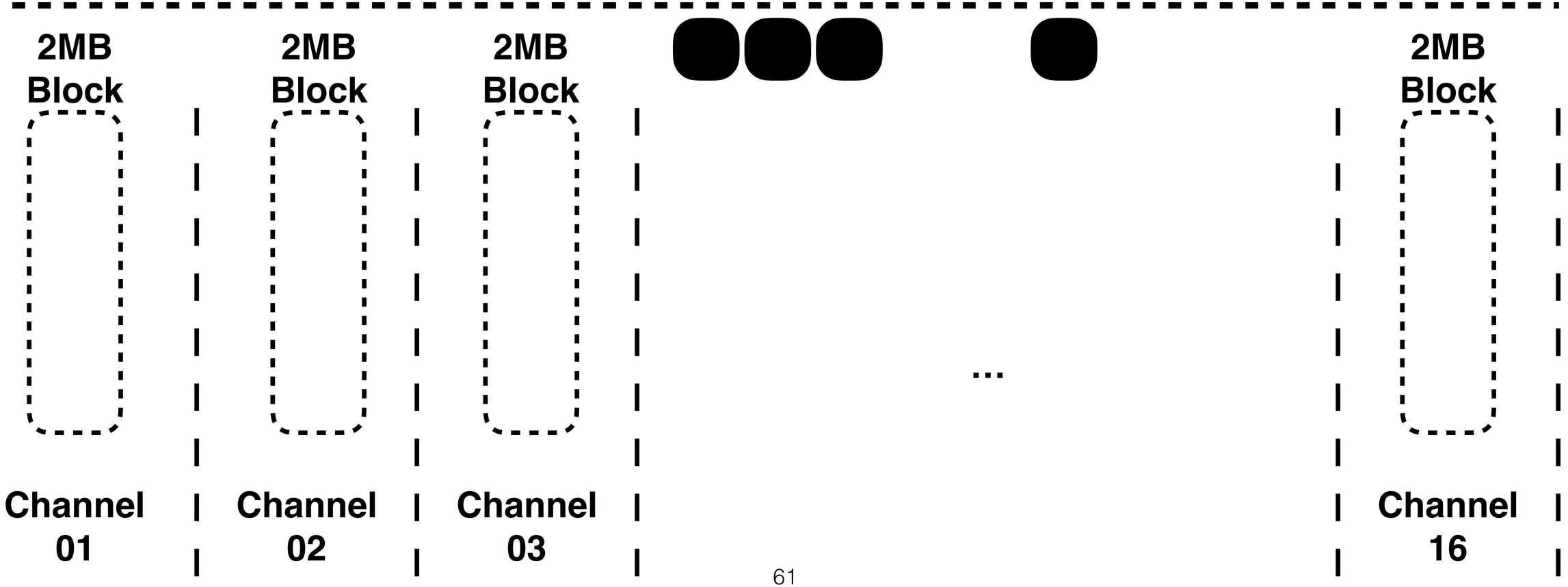

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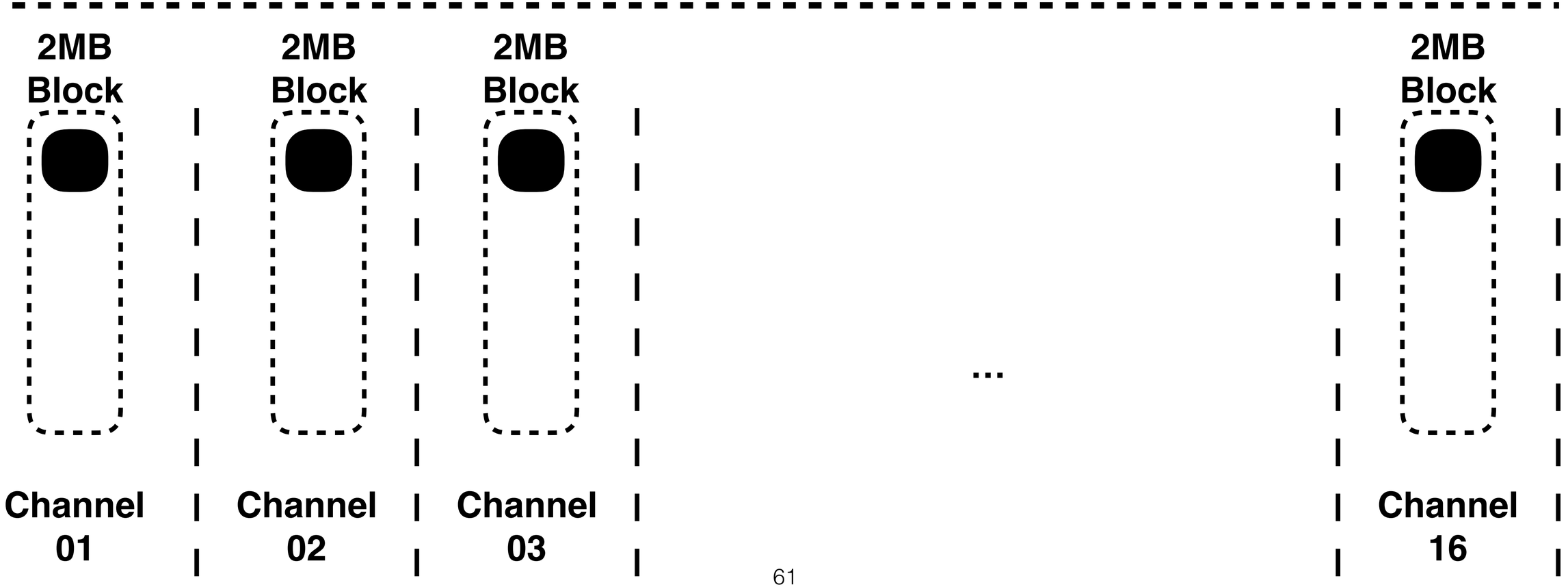

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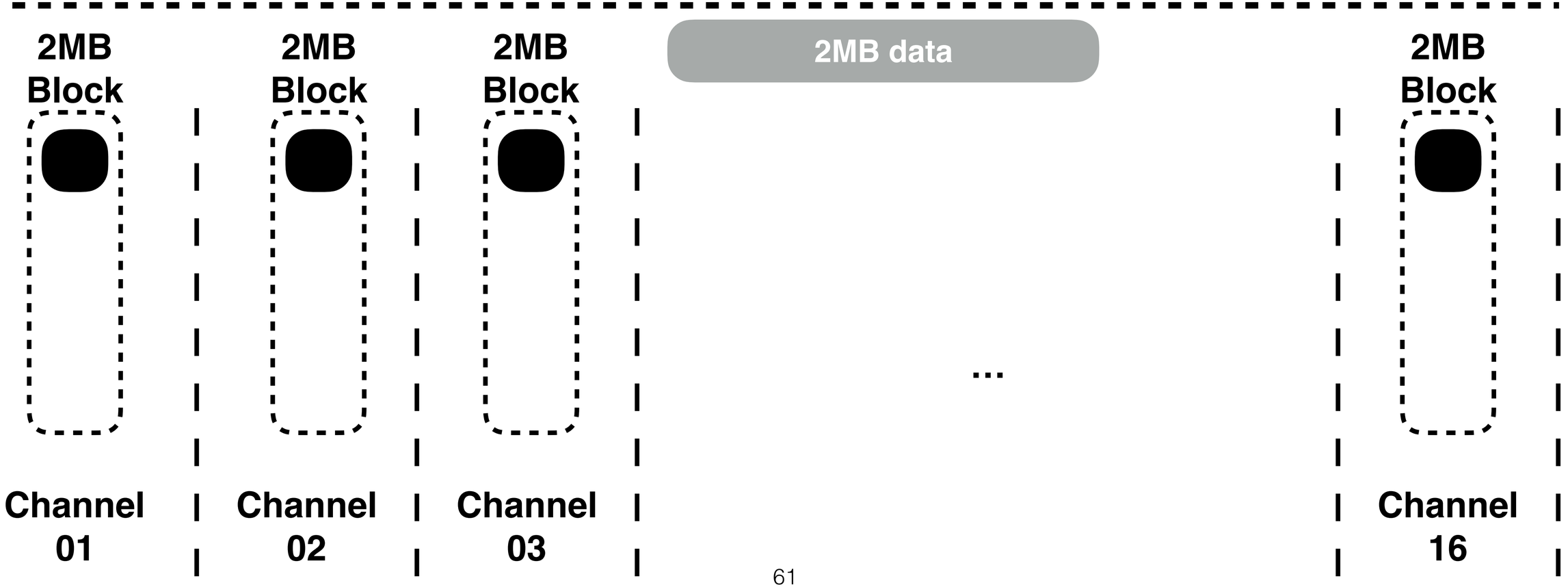

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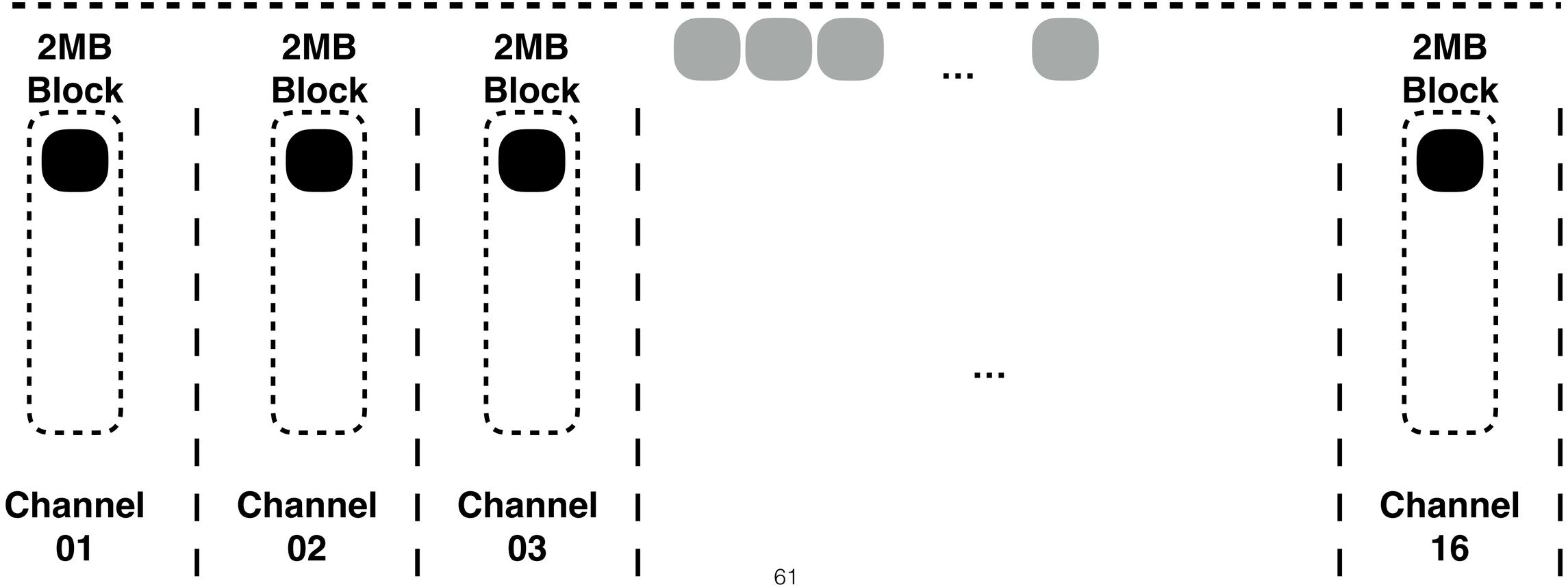

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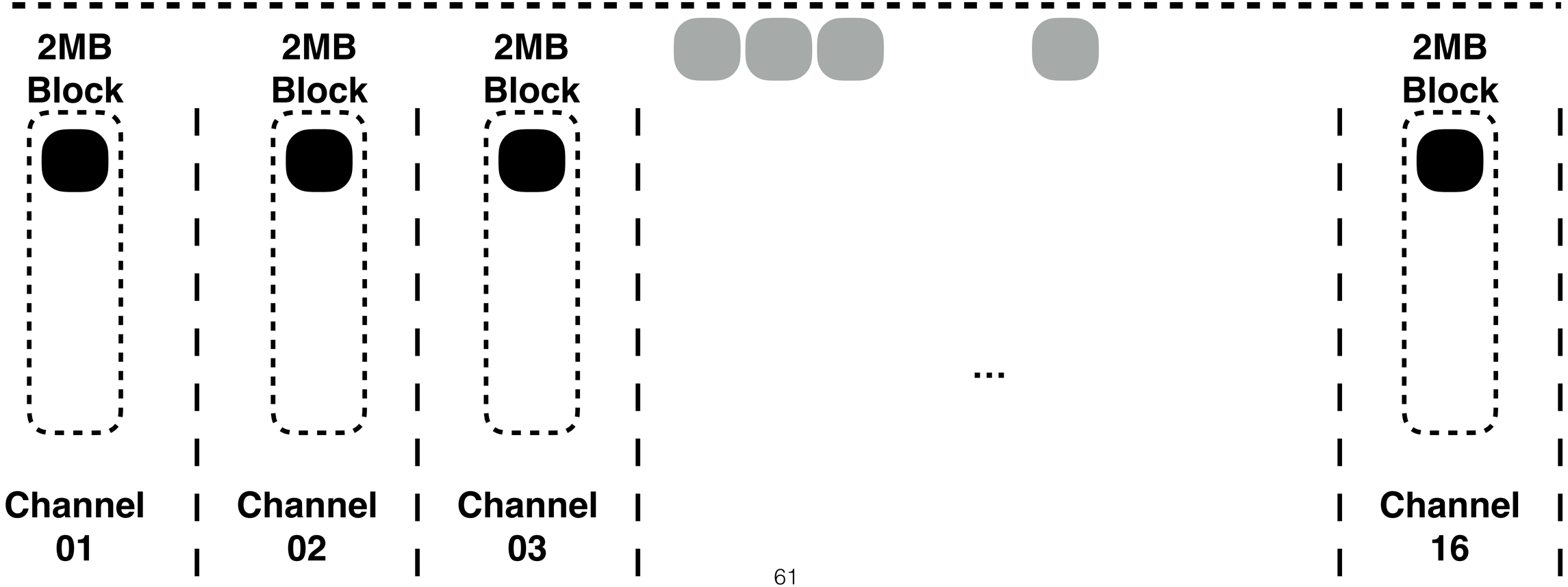

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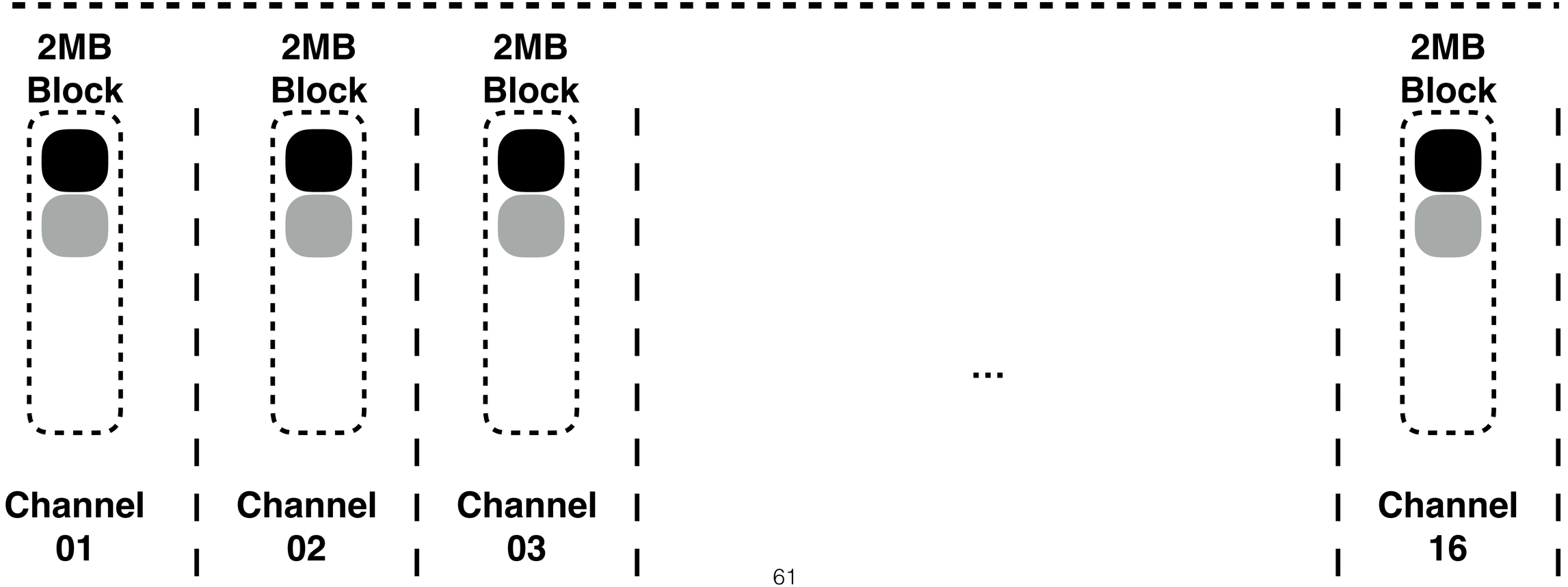

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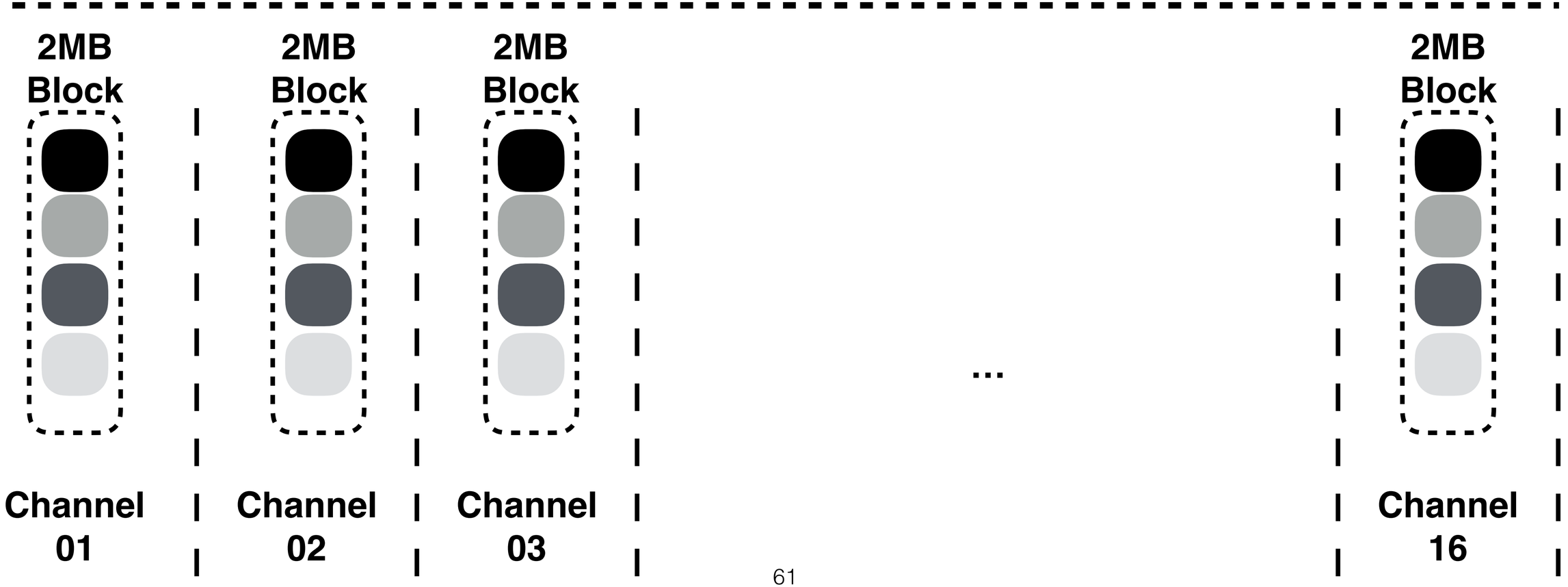

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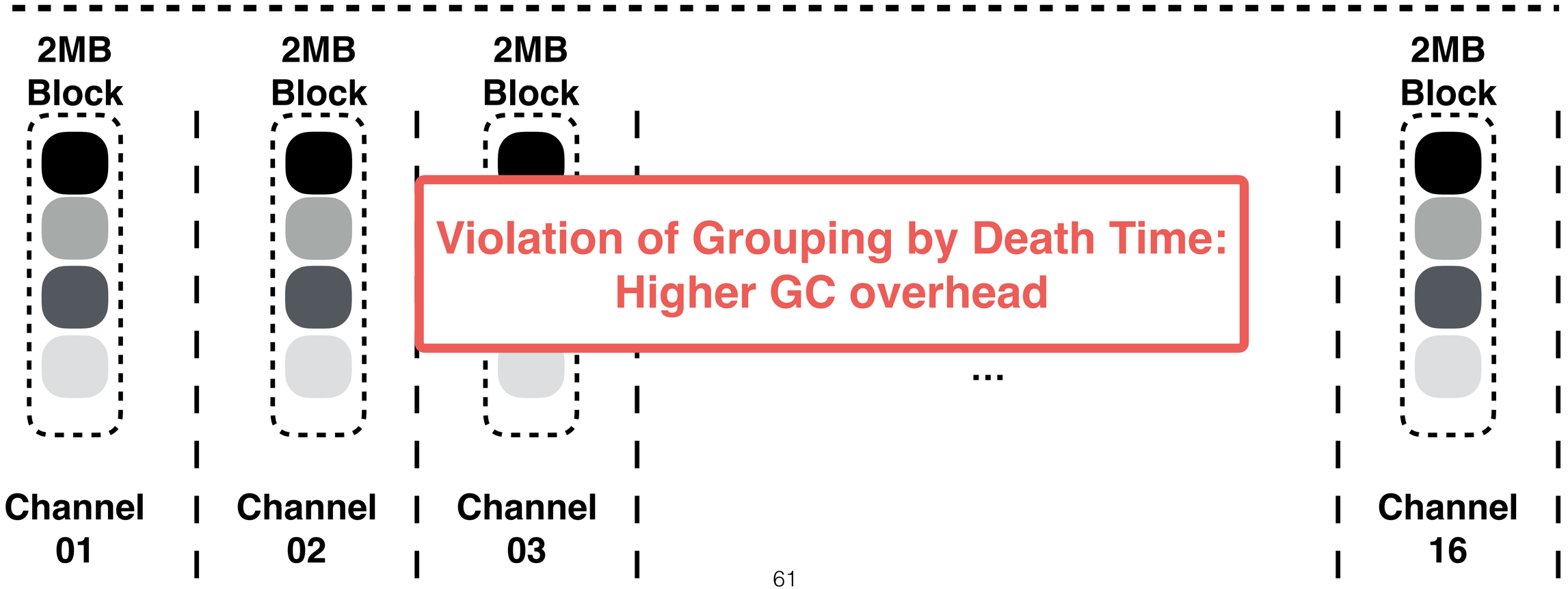

A File System Summary for Grouping by Death Time

- Immediate discarding reduces GC overhead
- All file systems violate the rule
  - XFS violates the least
  - ext4 violates due partially to HDD optimizations
  - F2FS violates the most (delayed discards + IPU)
- F2FS creates another layer of problems
  - Now you have to group data to different F2FS segments by death time, in order to reduce F2FS GC
  - F2FS does not group file data (except for mp3, avi etc.)
  - F2FS will have zombie segments
- Stacking logs may be problematic because of uncoordinated GCs across layers

Lessons Learned

- **The SSD contract is multi-dimensional.**
  - We need more sophisticated tools to analyze workloads.
  - Optimizing for one dimension is not enough.
- **Although not perfect, ext4/XFS perform well upon SSDs.**
- **Myths spread if the unwritten contract is not clarified.**

Myth: random writes increase GC overhead

- Pessimistic views have spread
- Systems are designed based on such views
- However, random writes are irrelevant to GC

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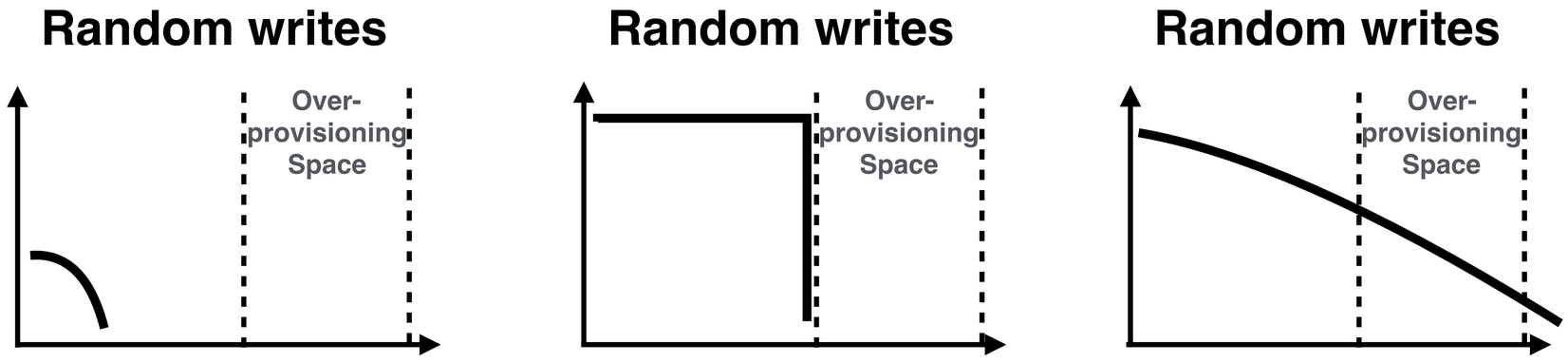

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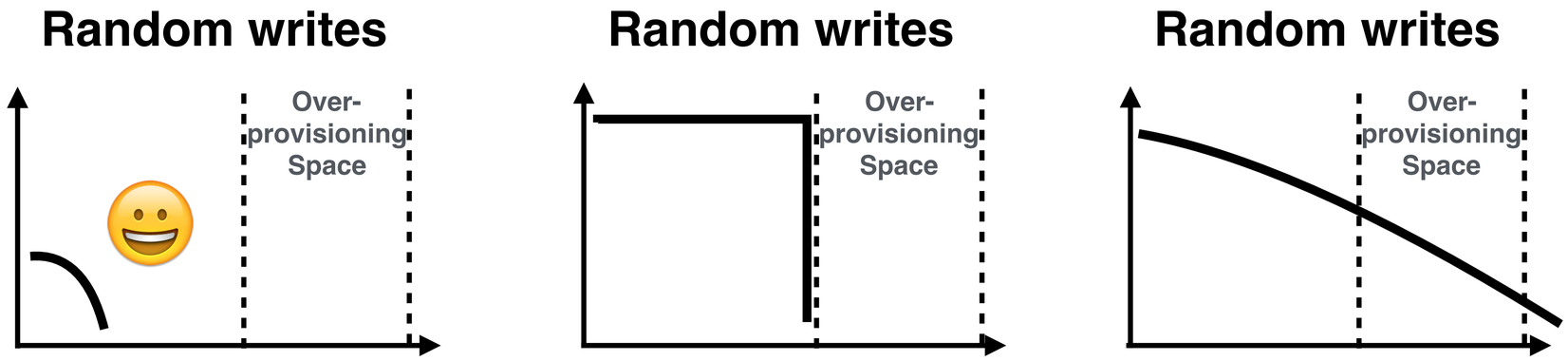

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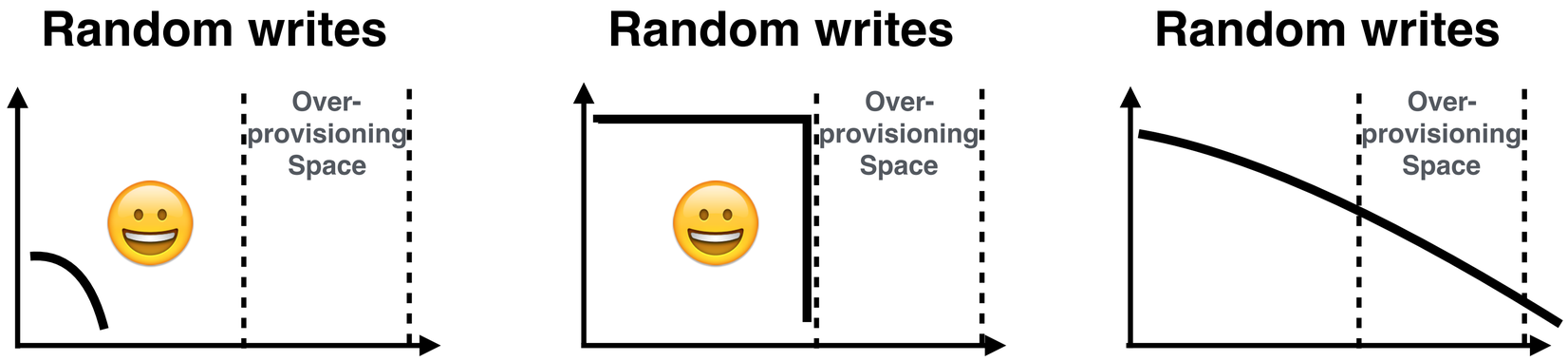

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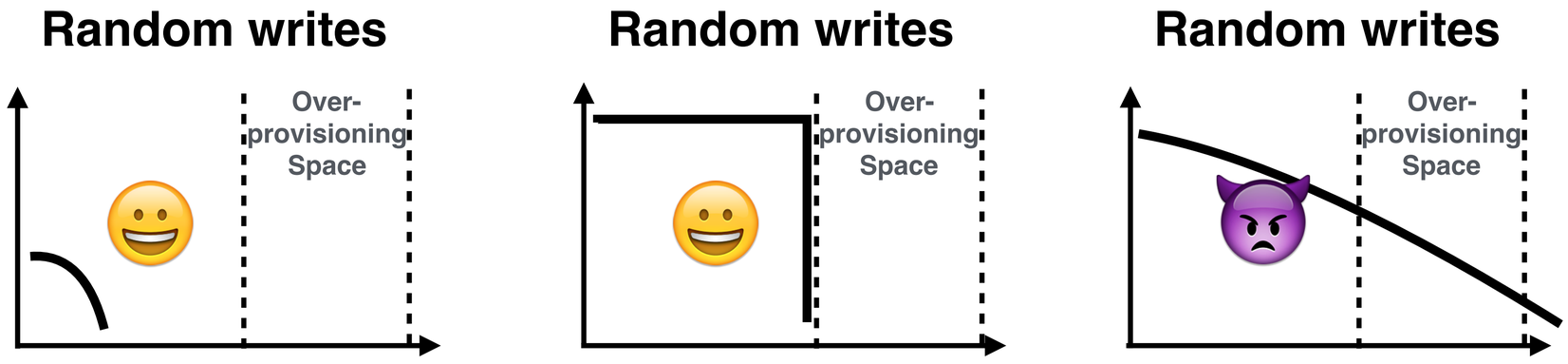

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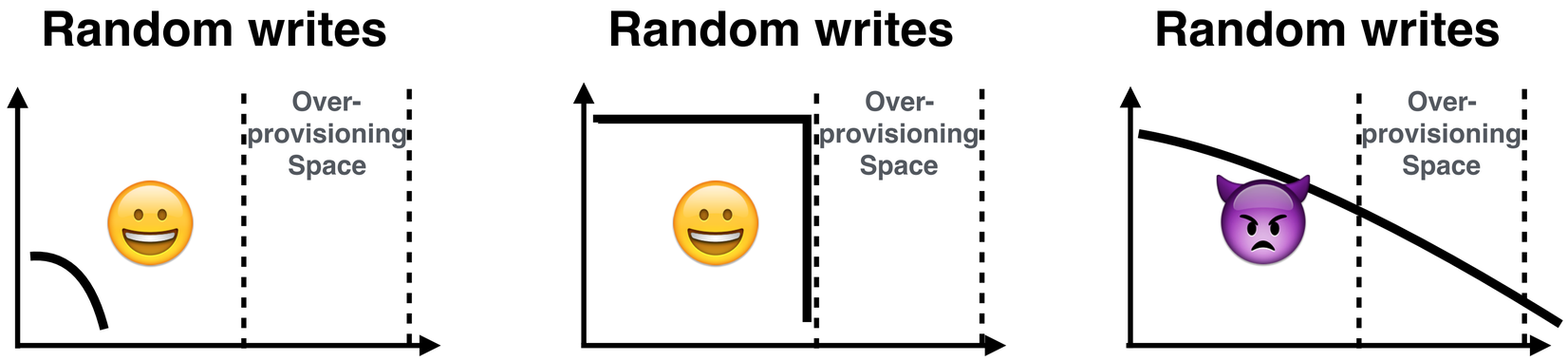

Stop using “random writes” to discuss GC

Conclusions

- We reveal the five rules of SSD unwritten contract
- We conduct vertical analysis of applications, file systems and FTLs
- We design tools for SSD workload analysis
- Our rules guide future workload analysis and system designs

WiscSee (analyzer) and WiscSim (SSD simulator) will be available at:
http://research.cs.wisc.edu/adsl/Software/wiscsee