Optimistic Crash Consistency

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CS 736 Graduate Operating Systems

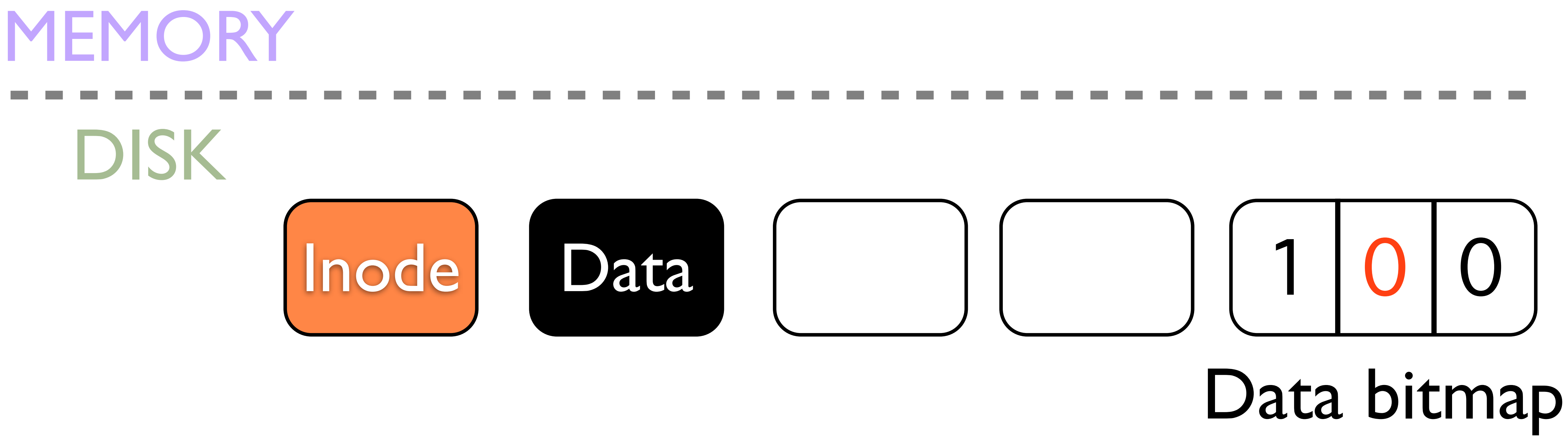
The Crash Consistency Problem

A single file-system operation updates multiple on-disk data structures

The system may crash in the middle of updating these structures

This leaves the file-system partially (incorrectly) updated

An Example



MEMORY

DISK

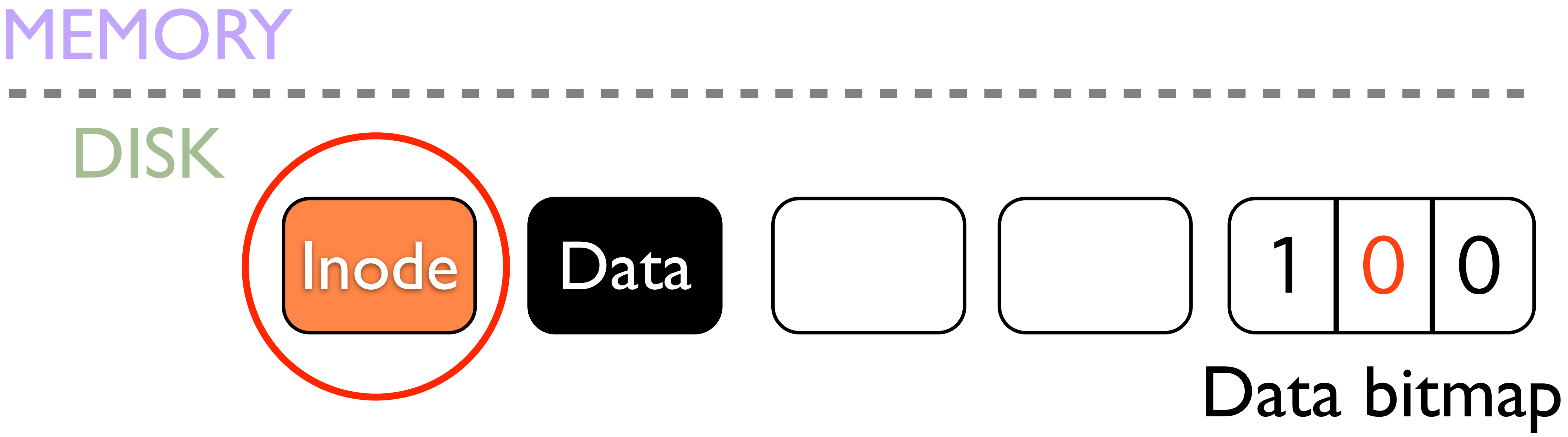
Inode

Data

1 0 0

Data bitmap

An Example



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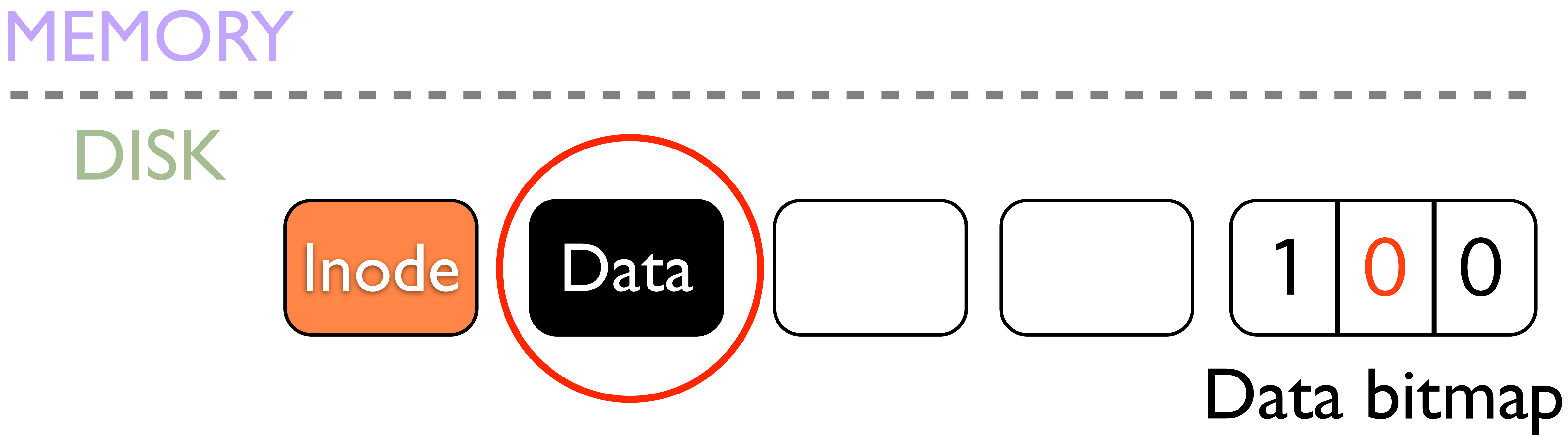

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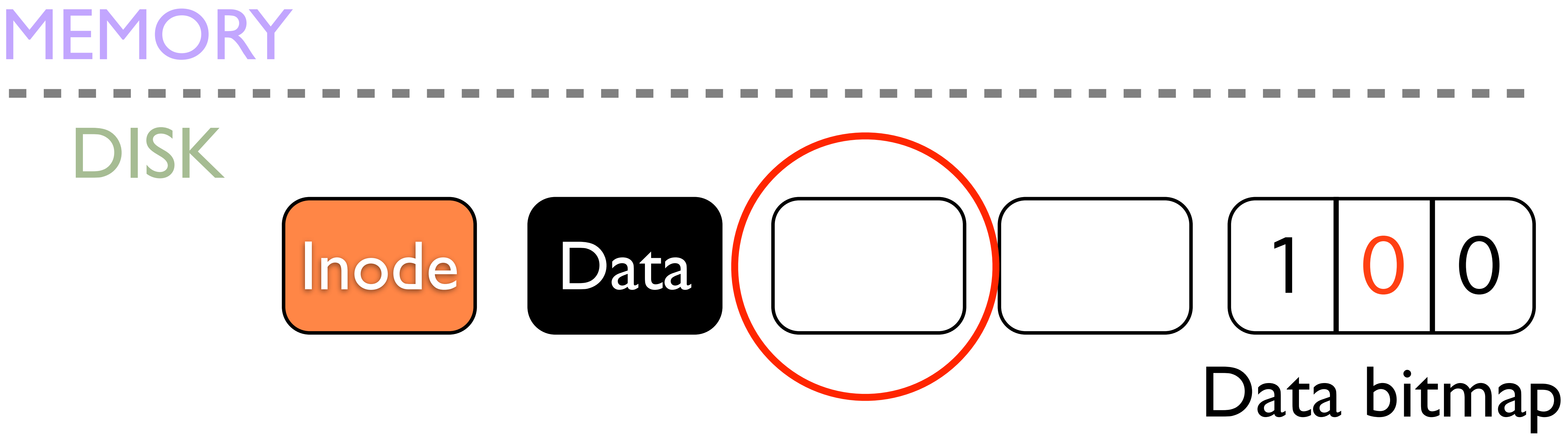

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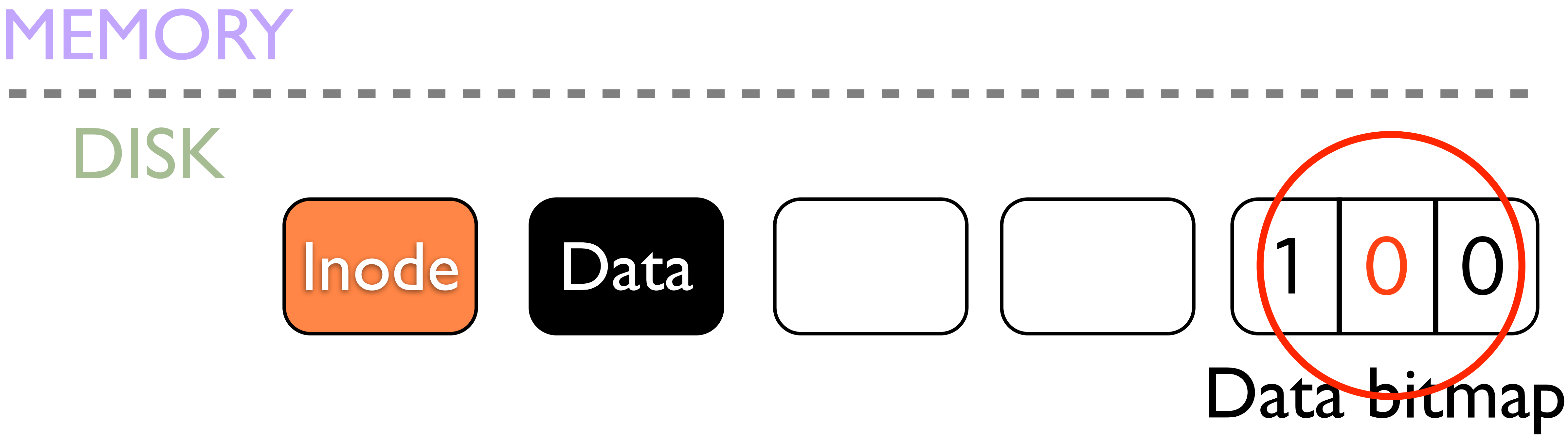

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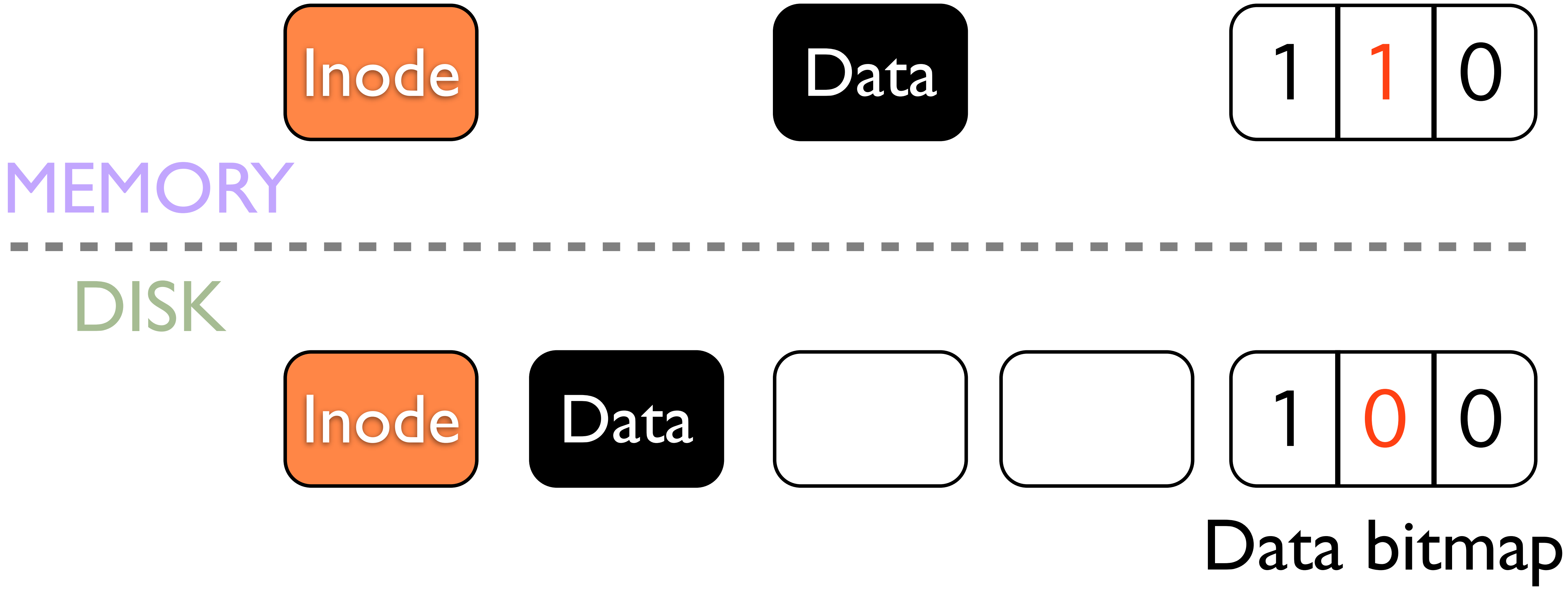

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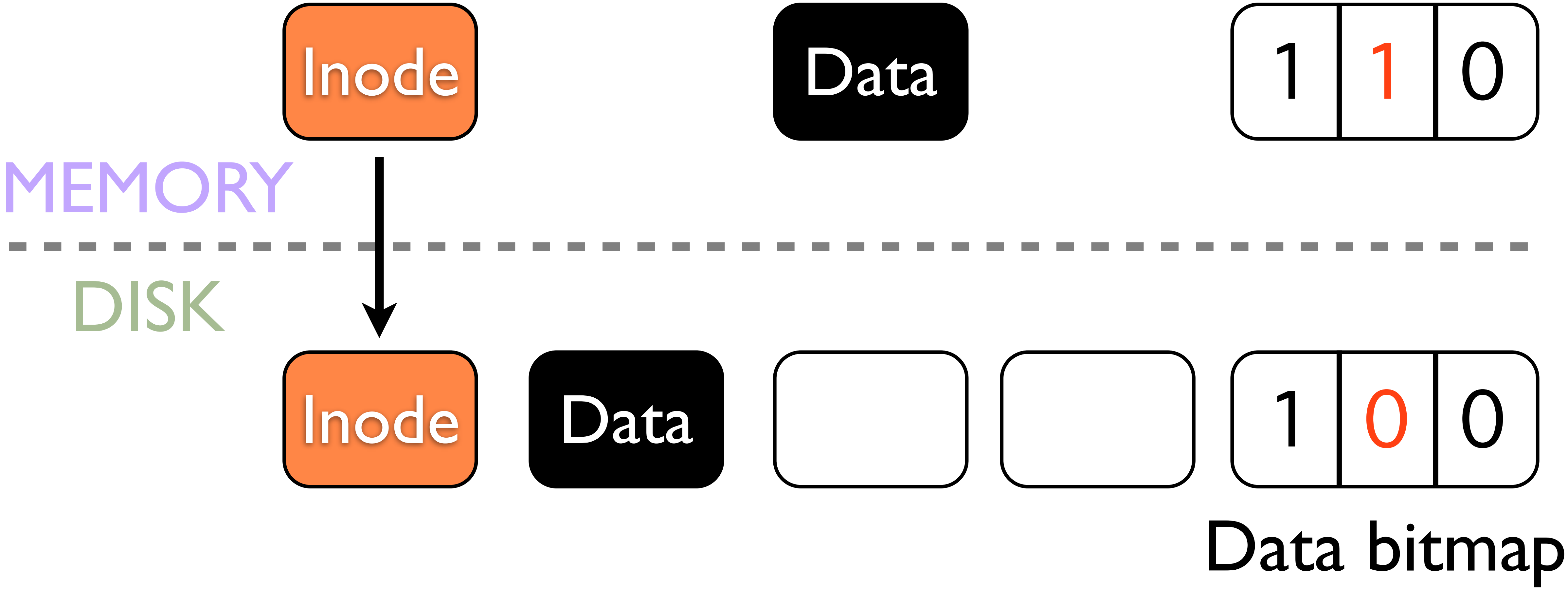

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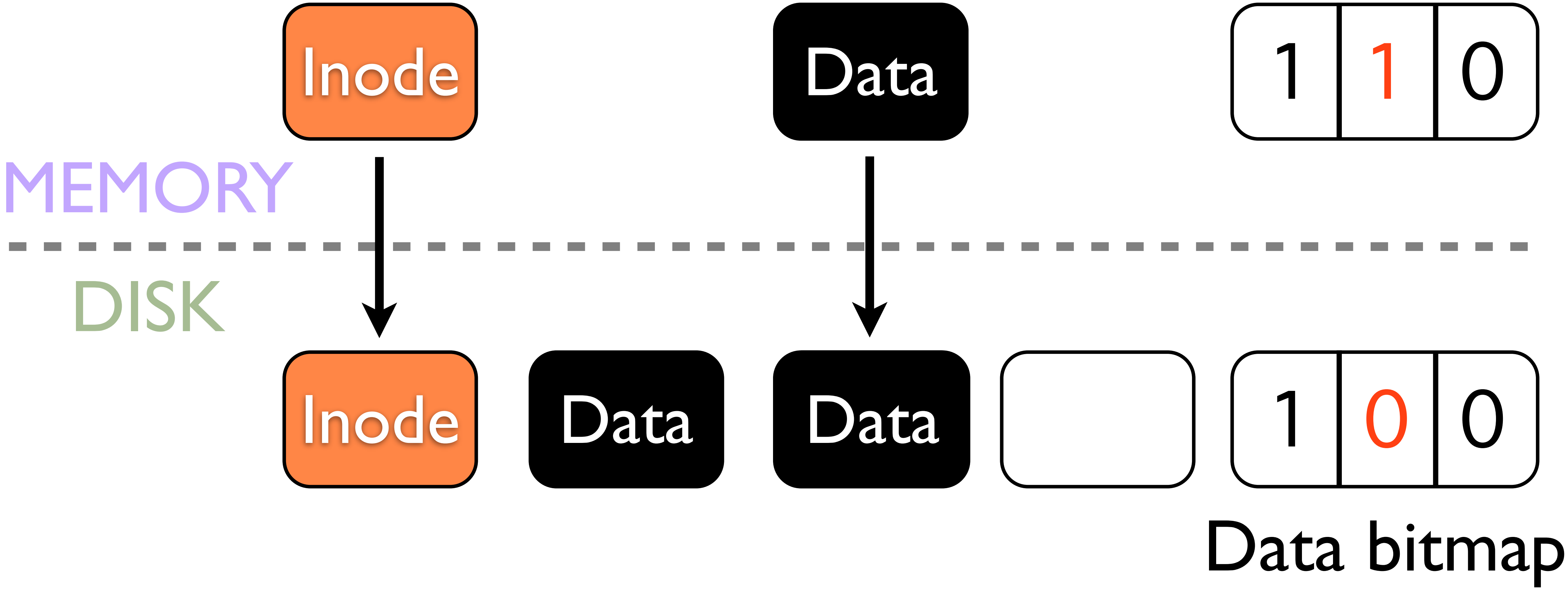

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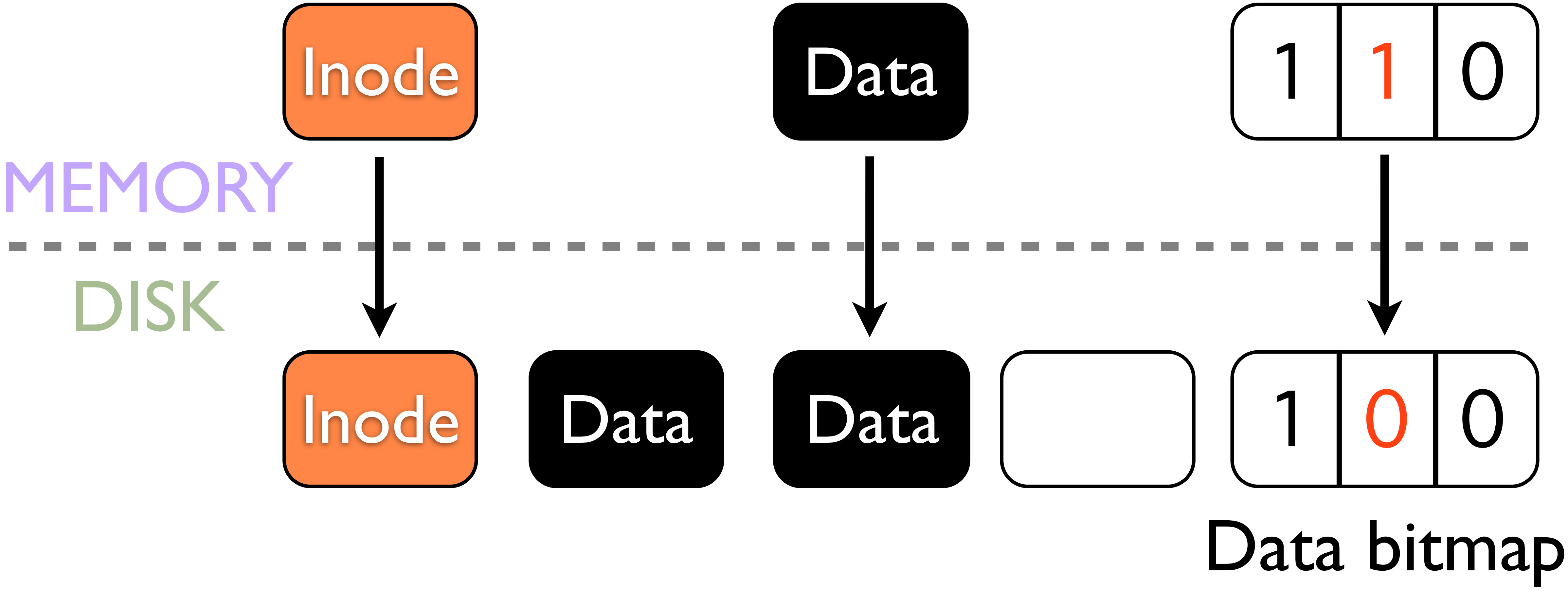

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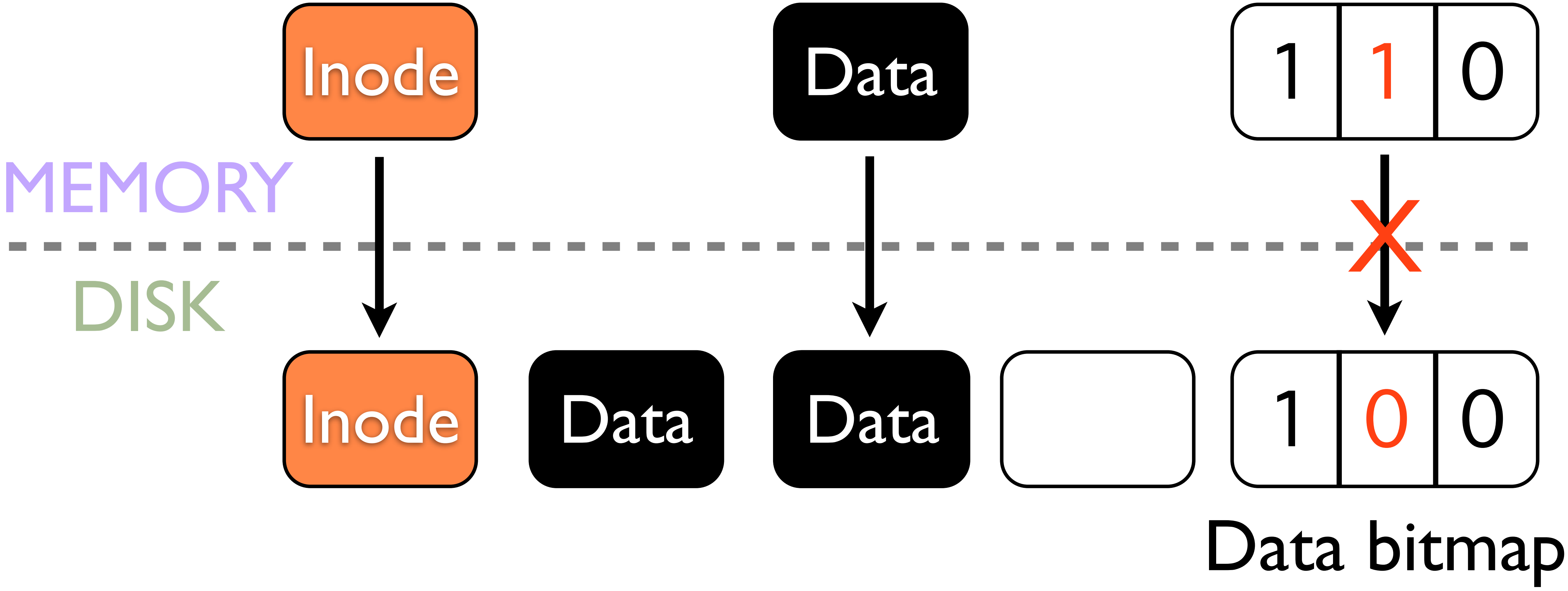

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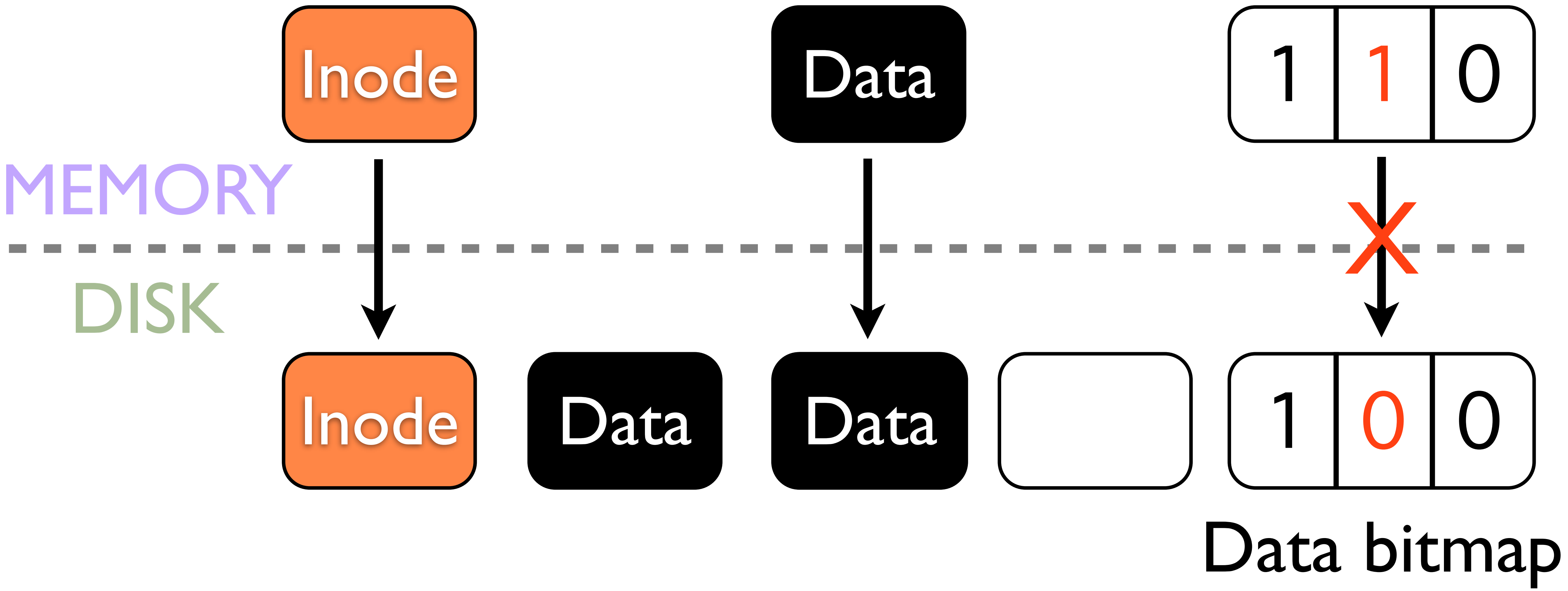

Problem: upon a crash, data structures on disk are partially updated

Current Solutions to Crash Consistency

Current Solutions to Crash Consistency

File-system check [McKusick84]

Journaling [Hagmann87]

Log structured file system [Rosenblum92]

Copy-on-write file system [Hitz94]

Soft Updates [Ganger94]

Journaling

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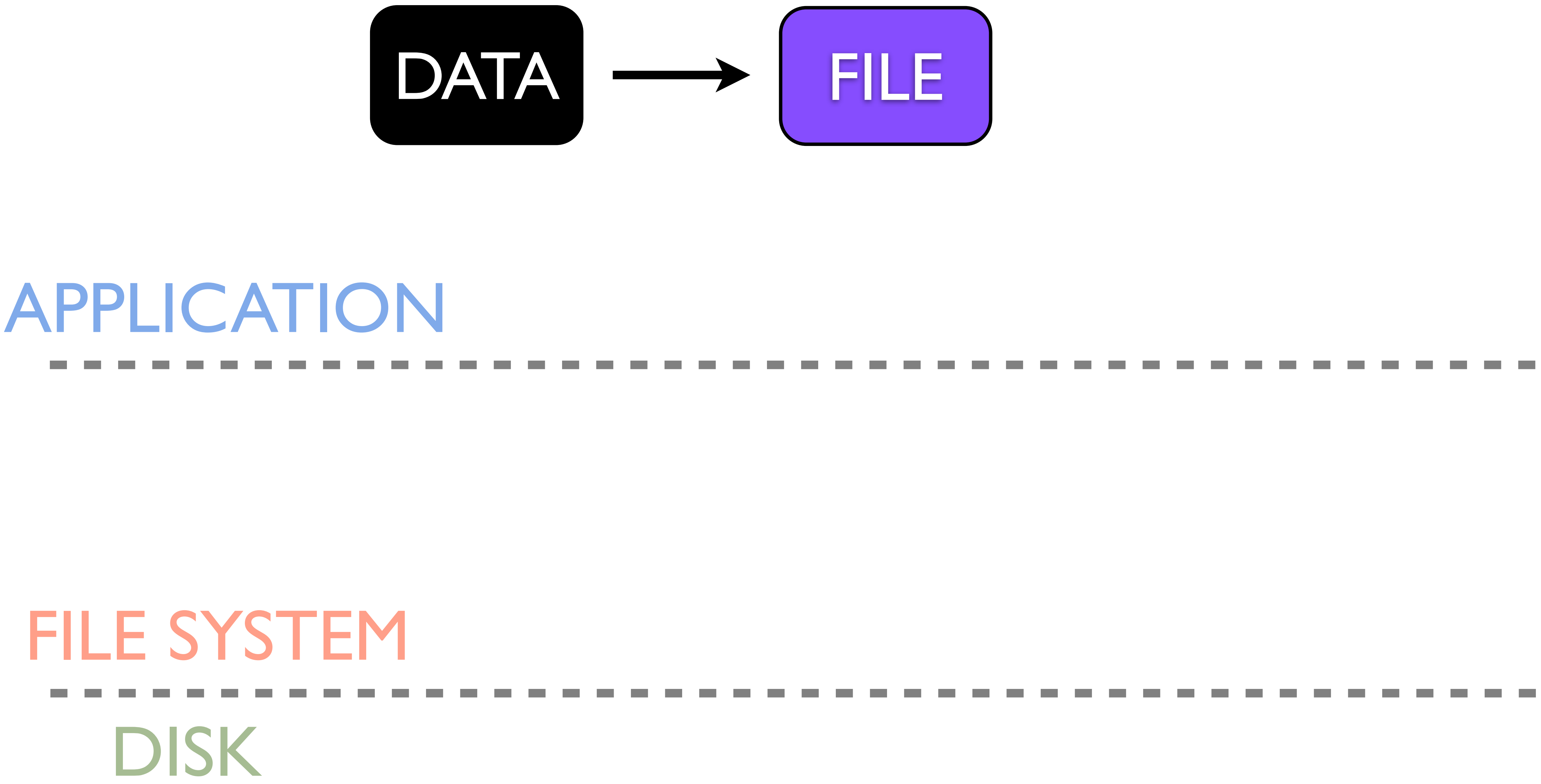


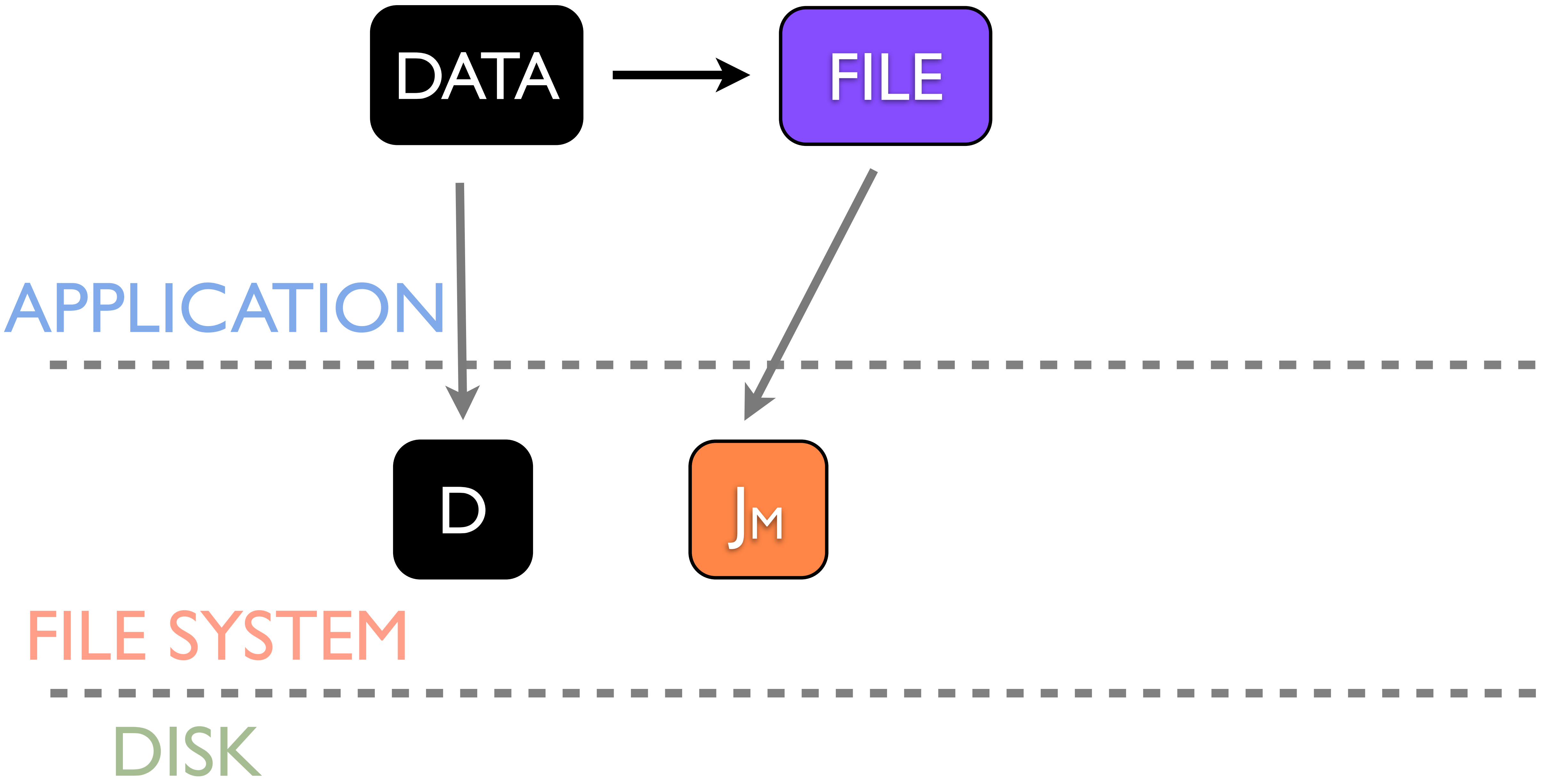
DATA → FILE

APPLICATION

FILE SYSTEM

DISK

Journaling: an example



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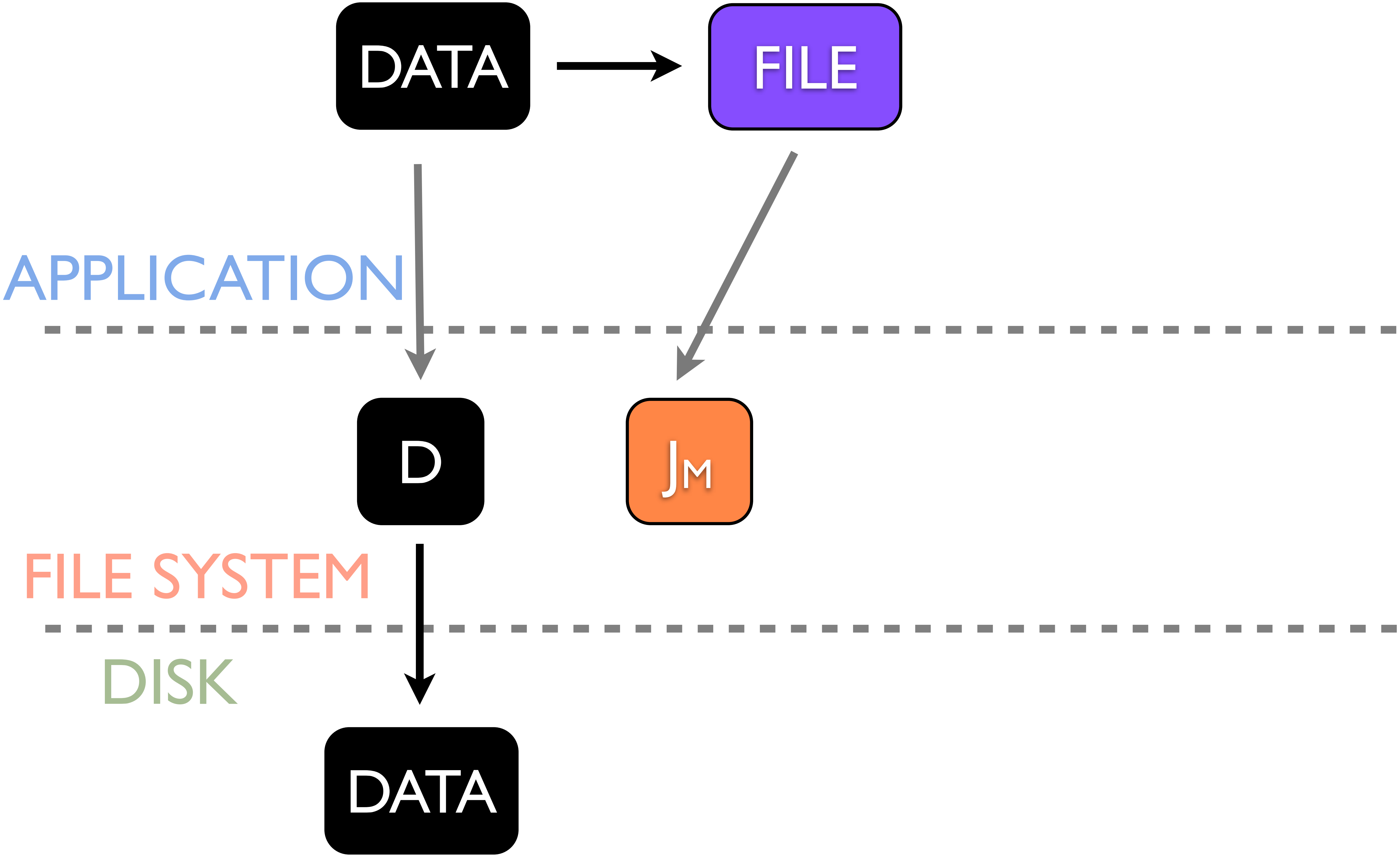

DATA

FILE

APPLICATION

D

JM

FILE SYSTEM

DISK

DATA

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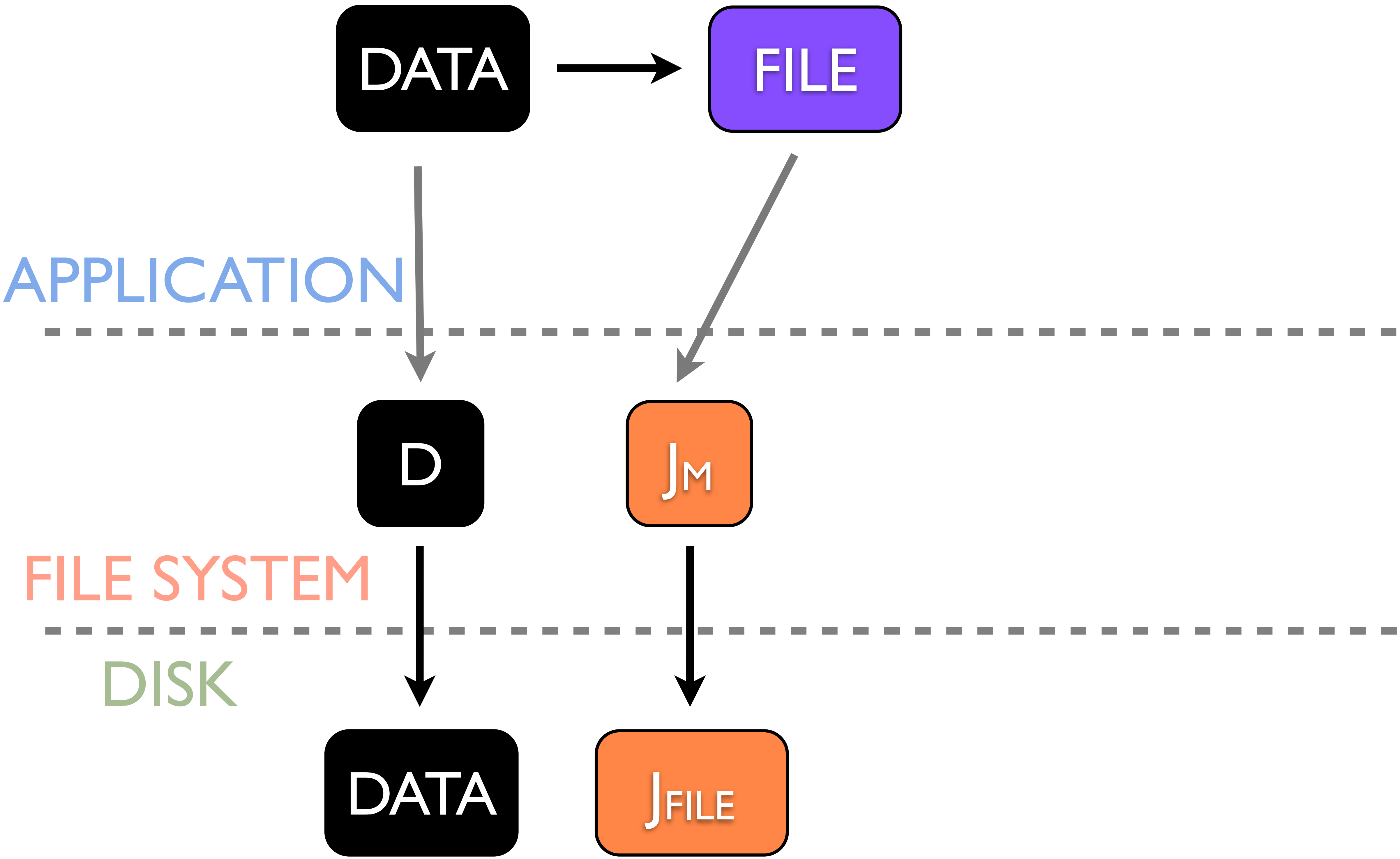

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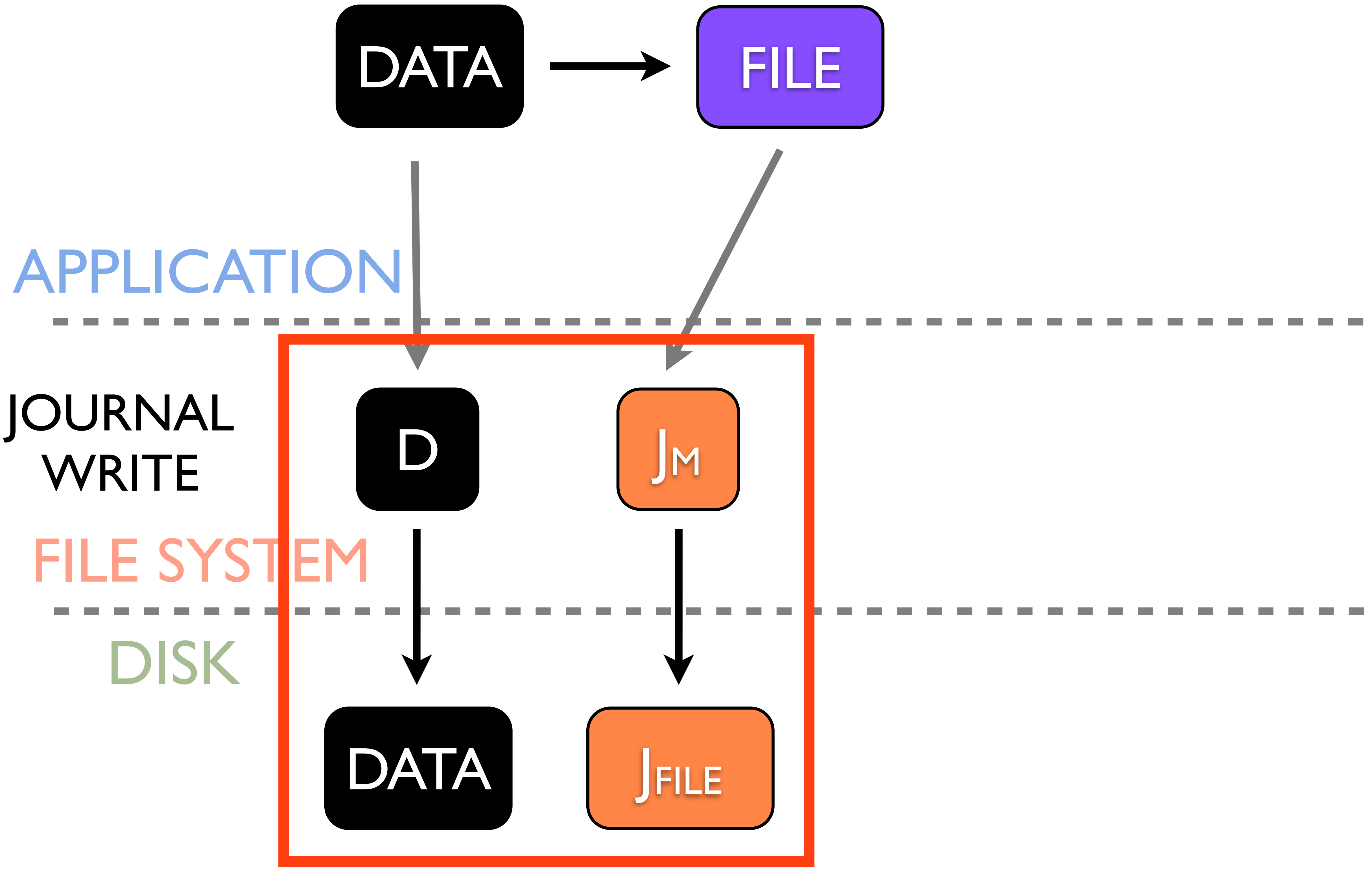

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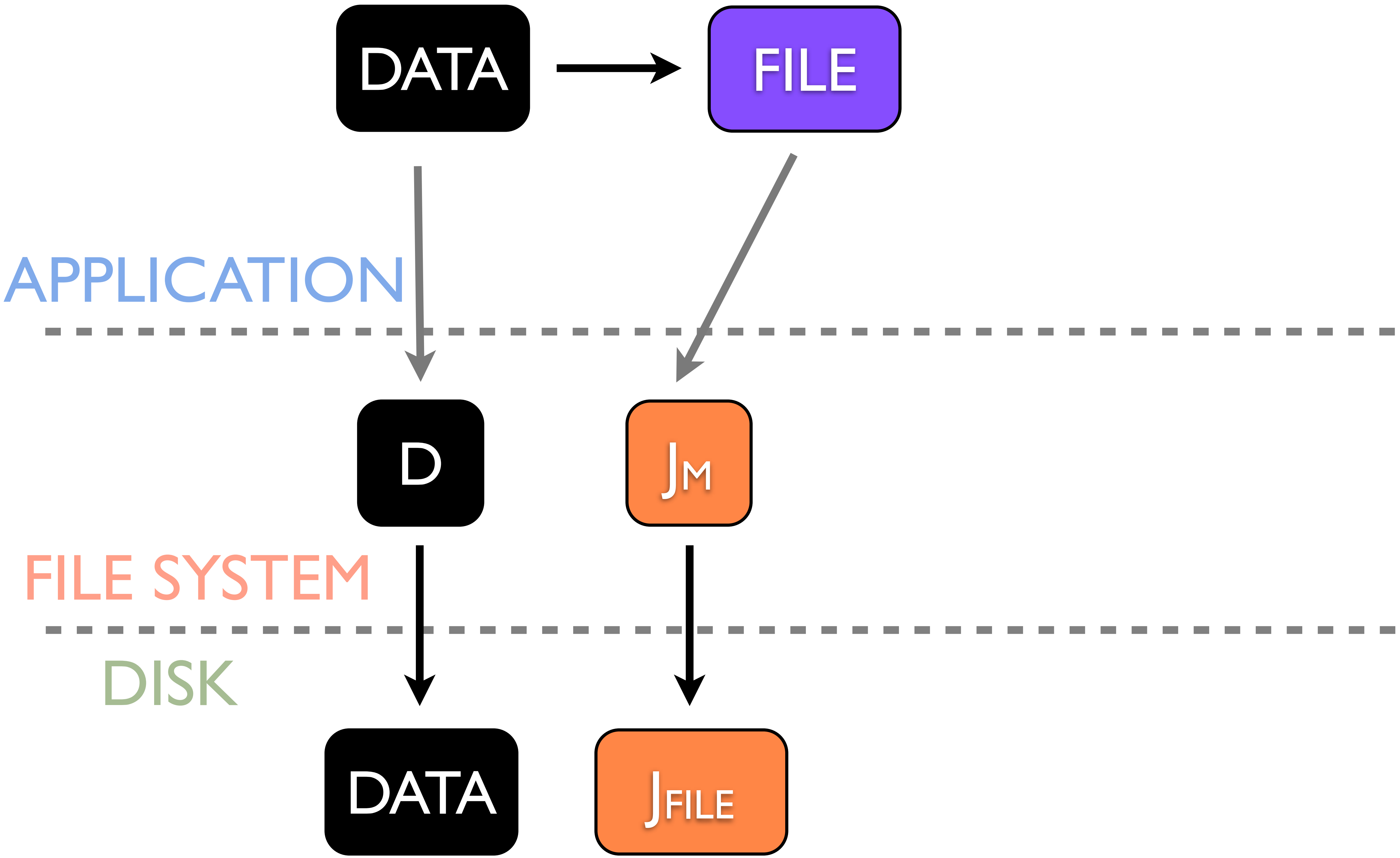

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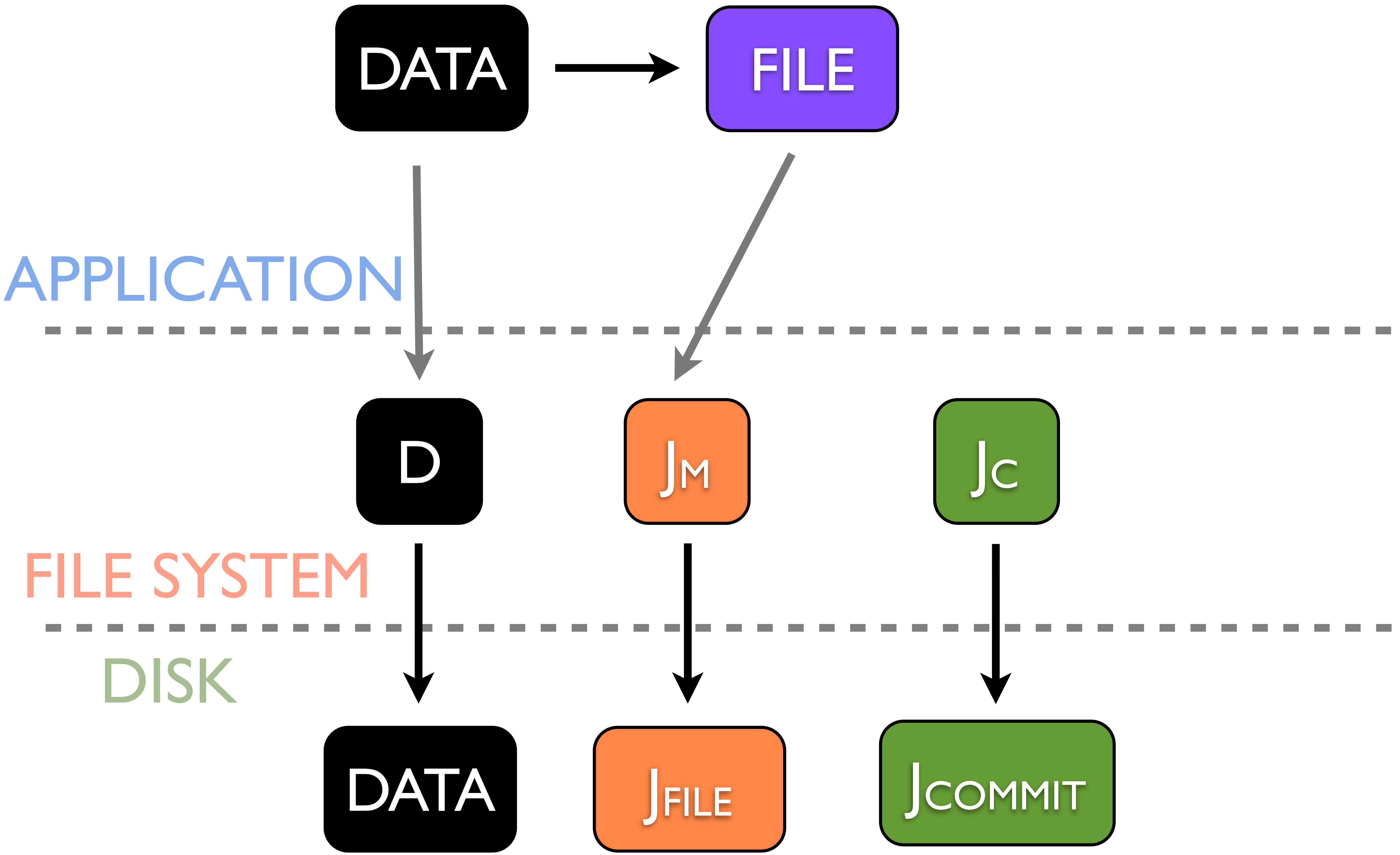

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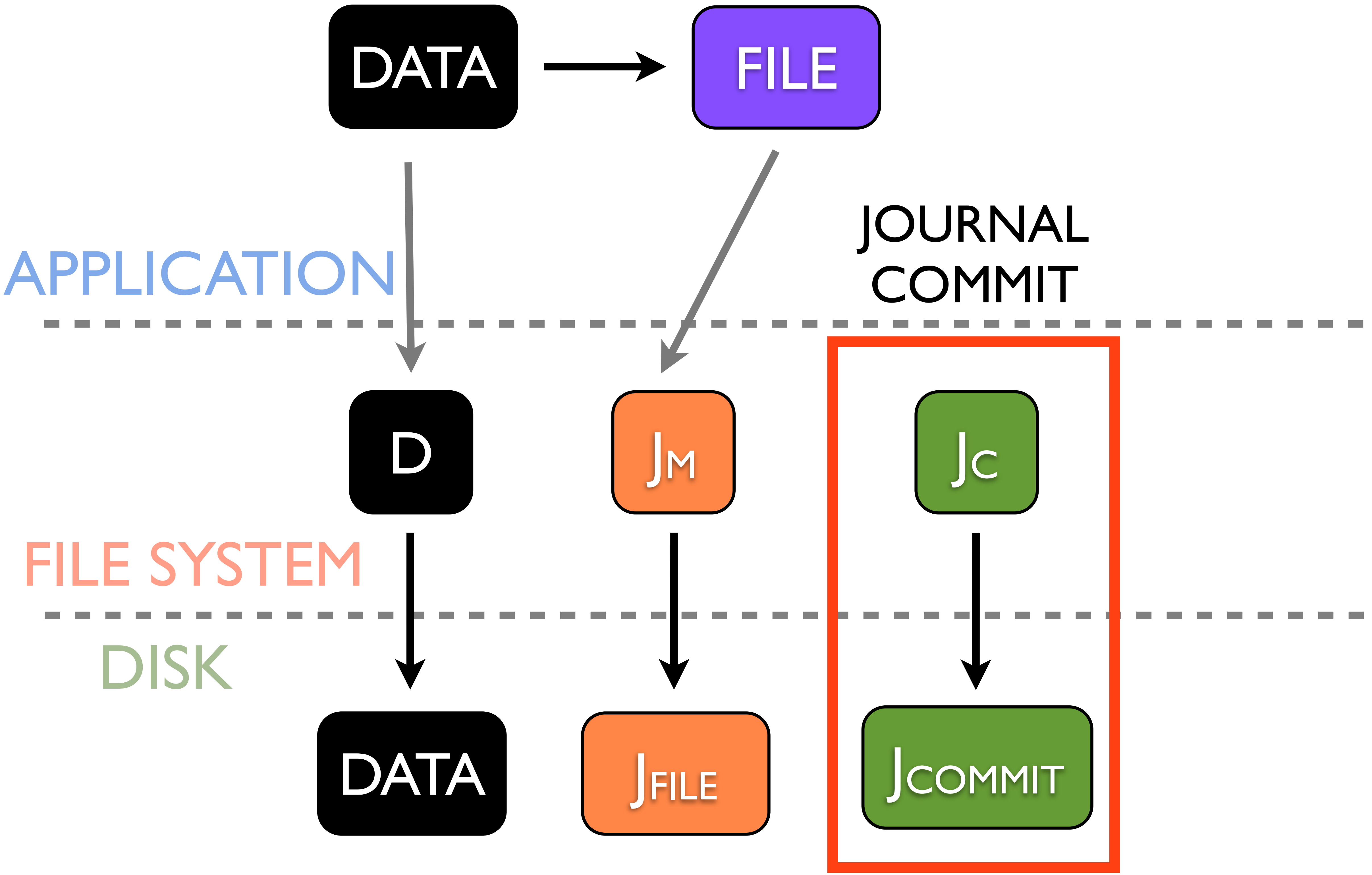

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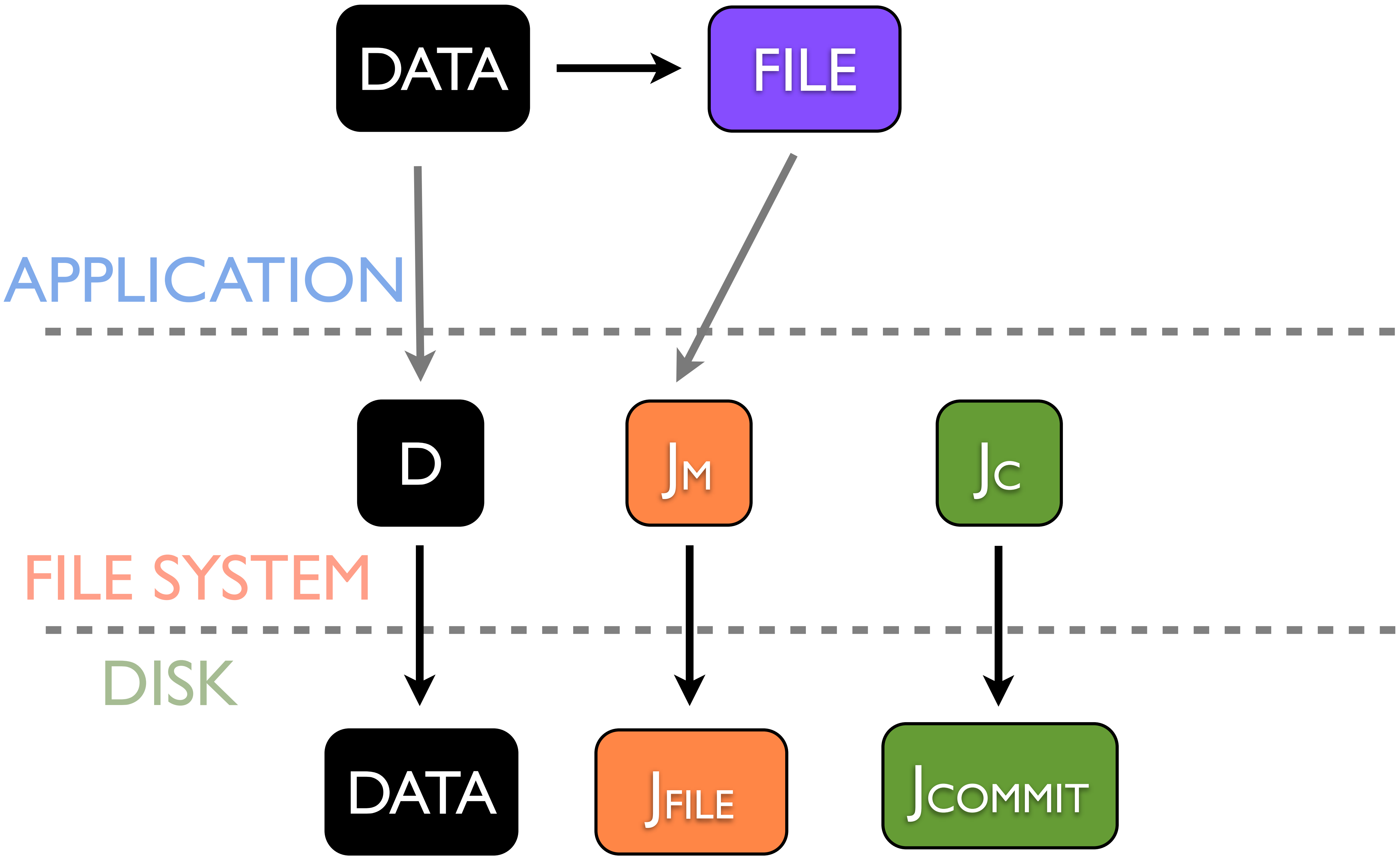

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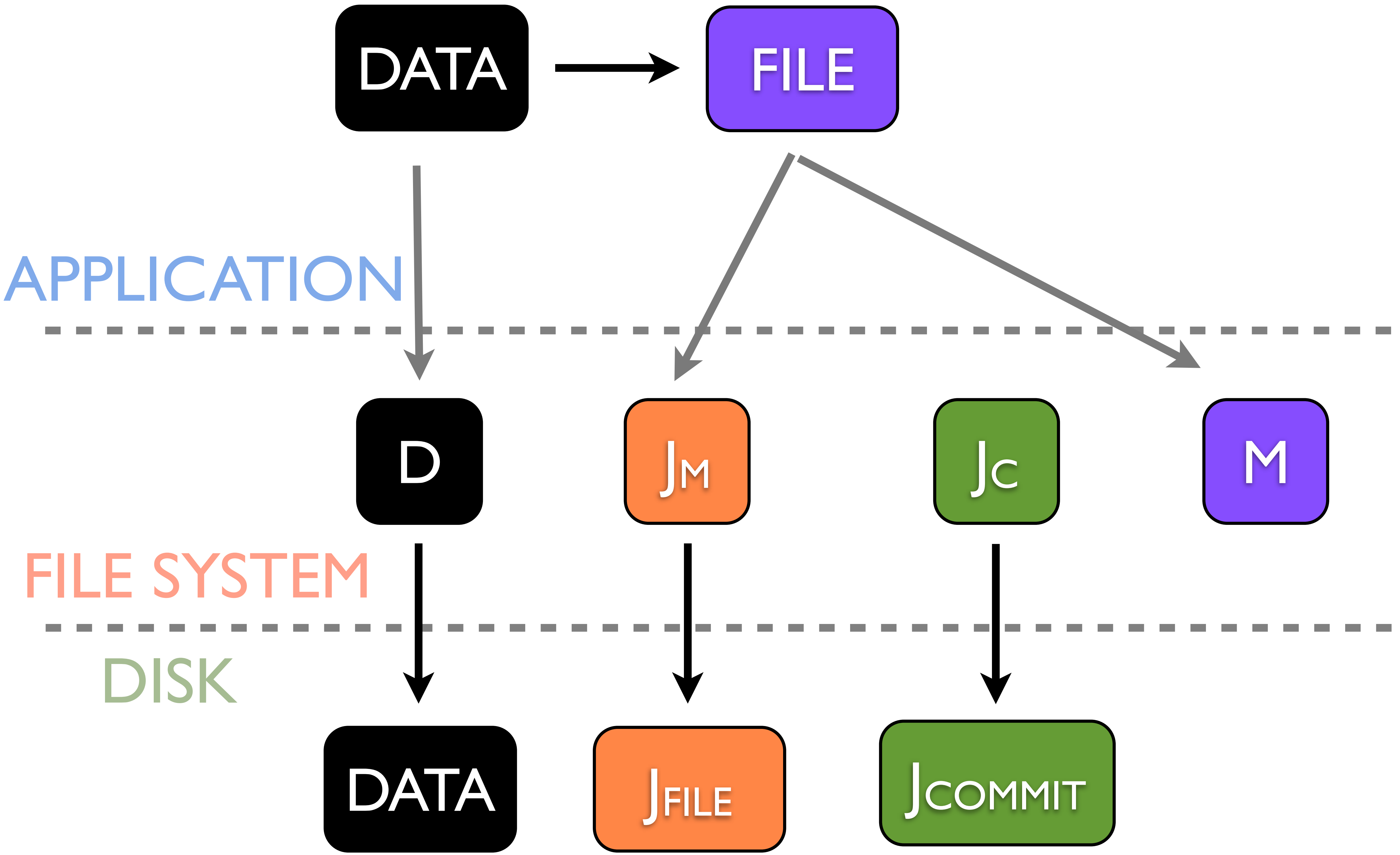

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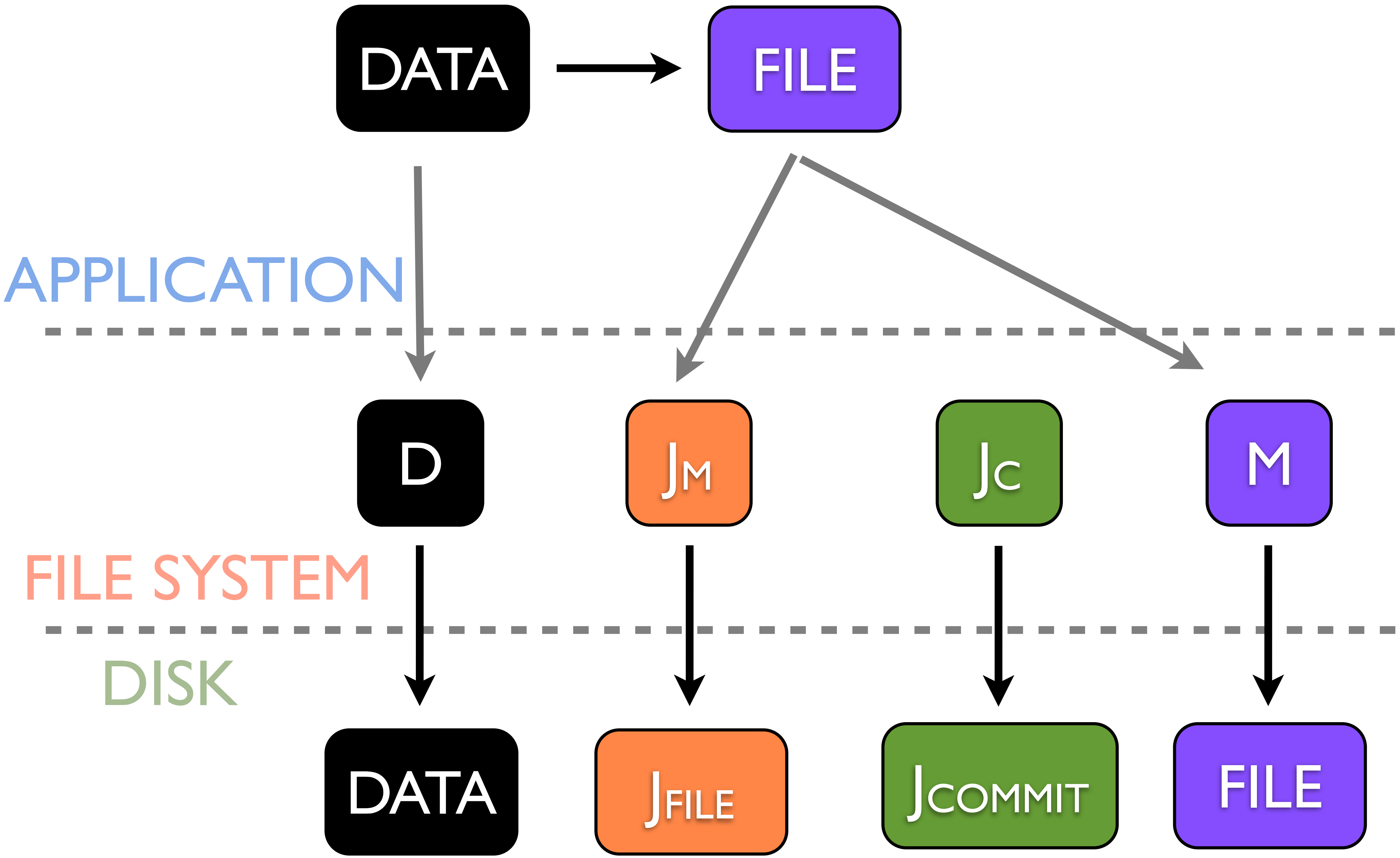

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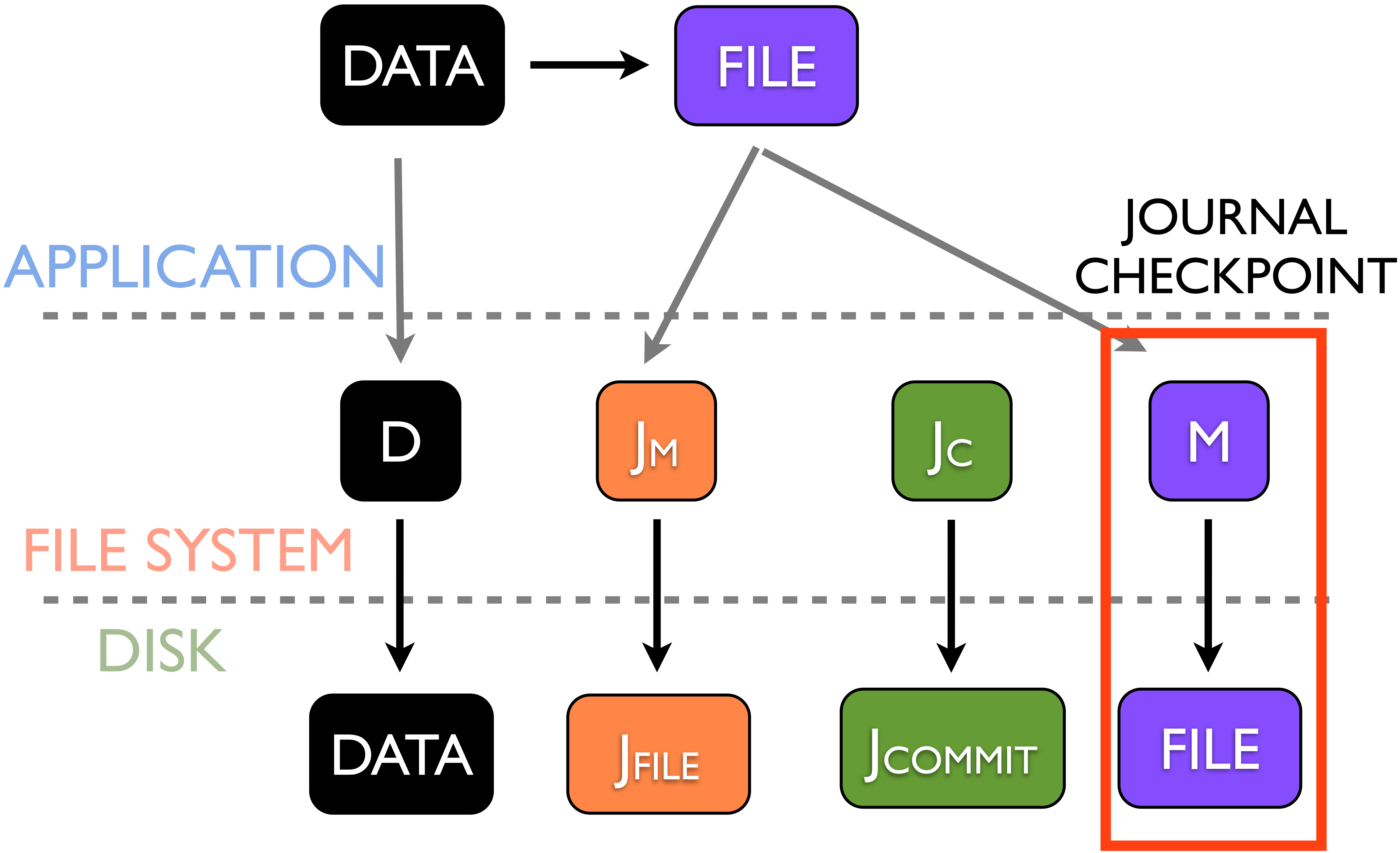


Ordered Writes

Journaling is built upon writing to disk in the correct order:

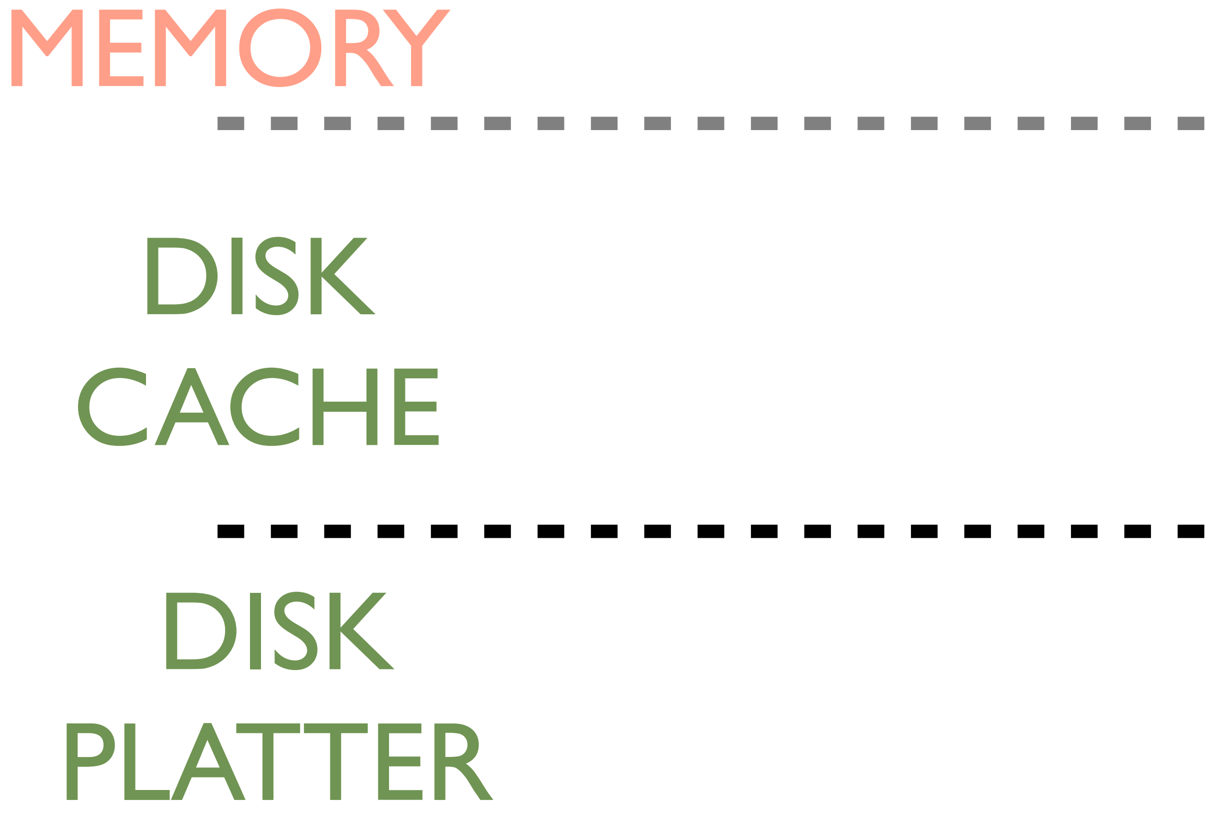
- Journal Writes
- Journal Commit
- Journal Checkpointing

Ex: if checkpointing happens before commit and transaction fails, file system is corrupted

Ordering Writes in Disks

Modern disk drives have on-board RAM caches

Writes are first buffered, then destaged to the non-volatile platter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DISK CACHE

DISK PLATTER

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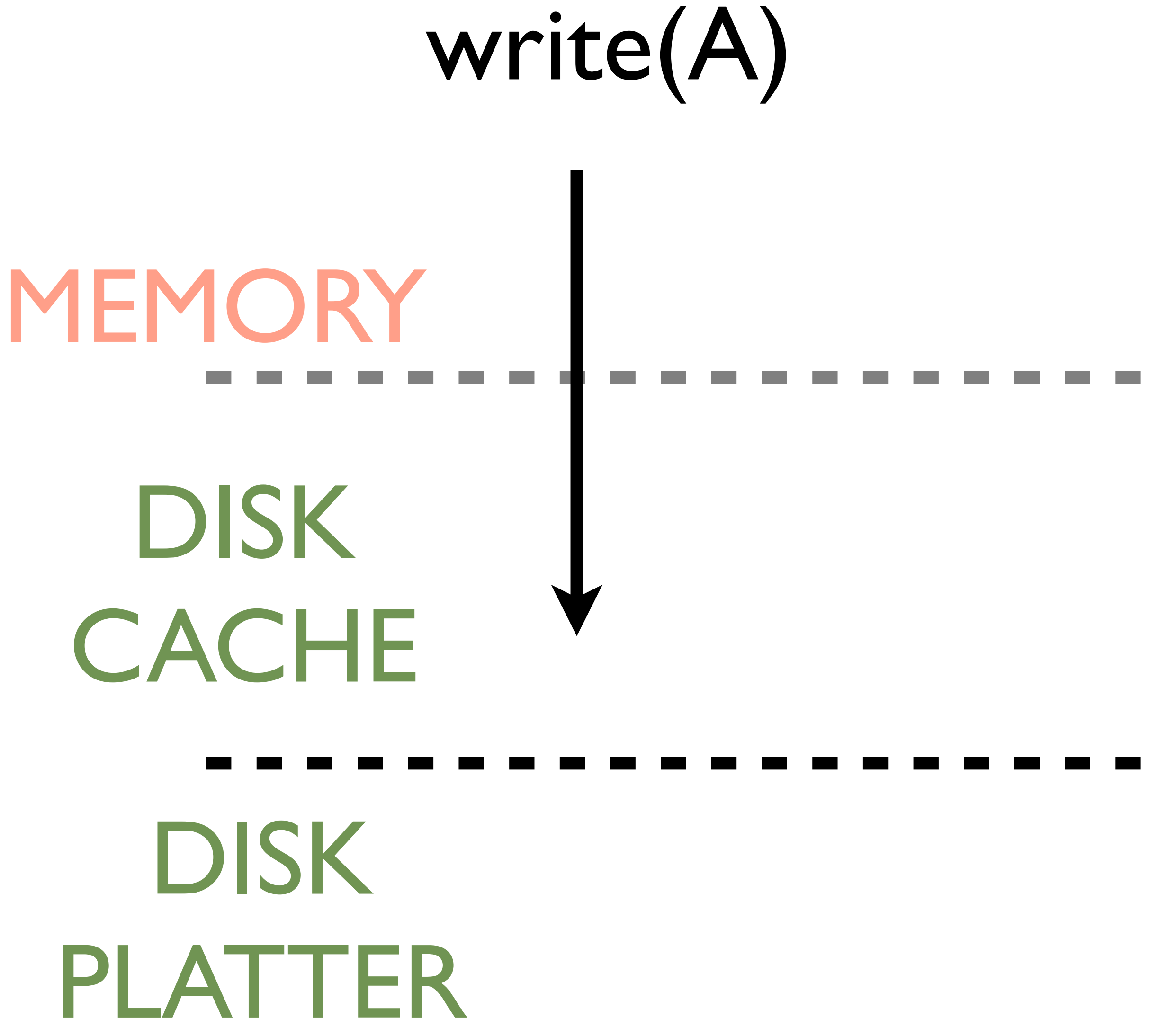

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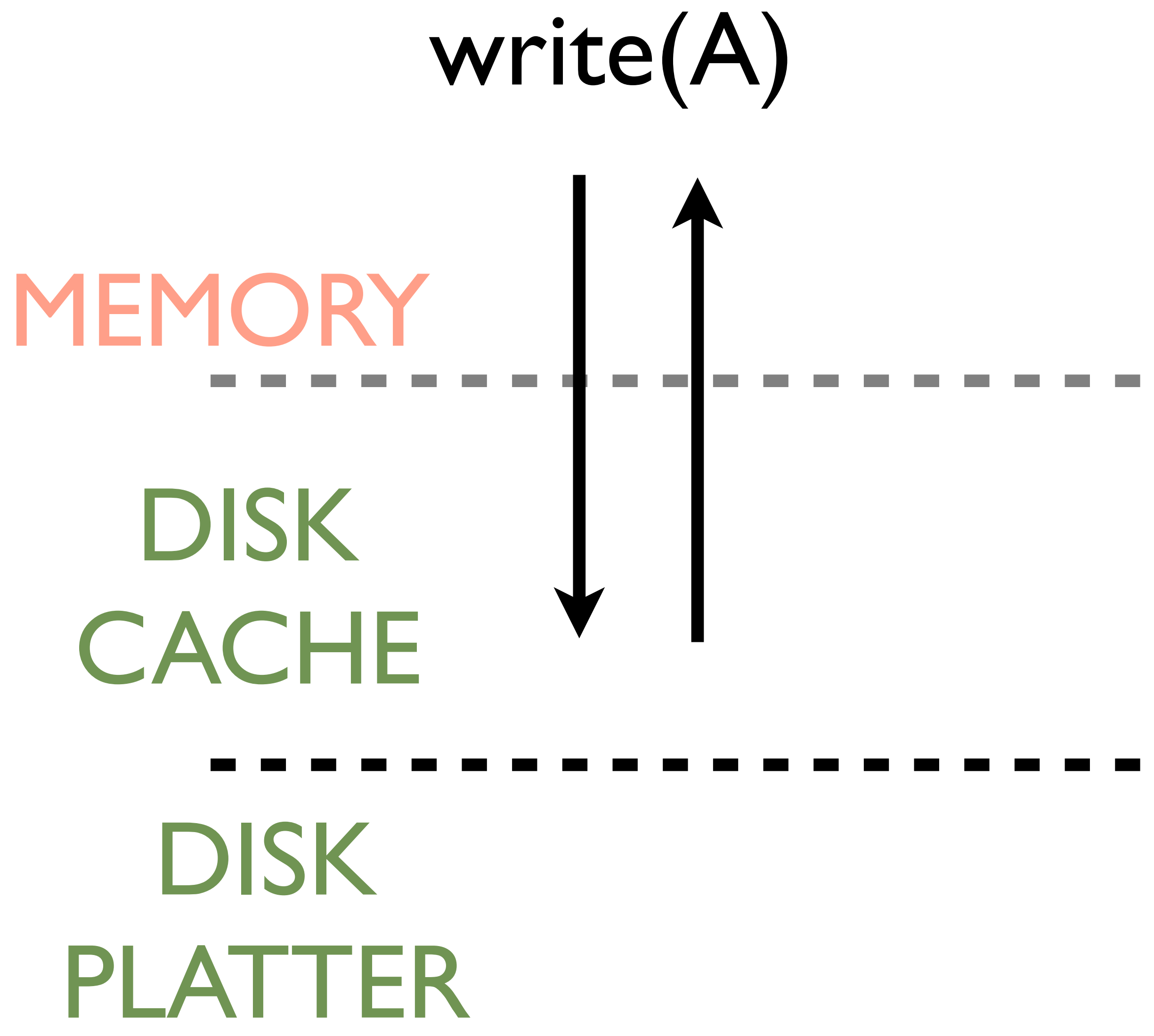

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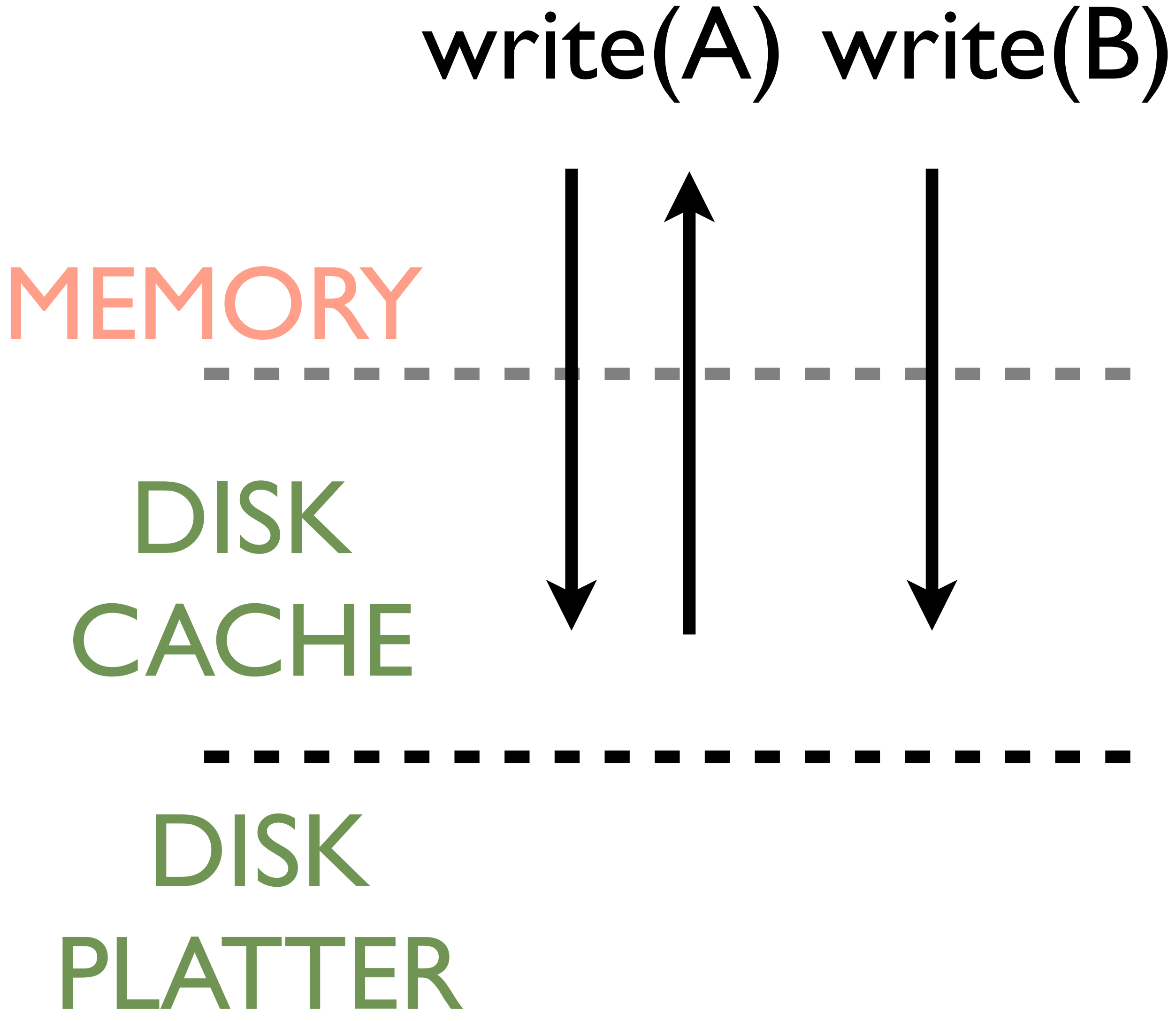

write(A) write(B)

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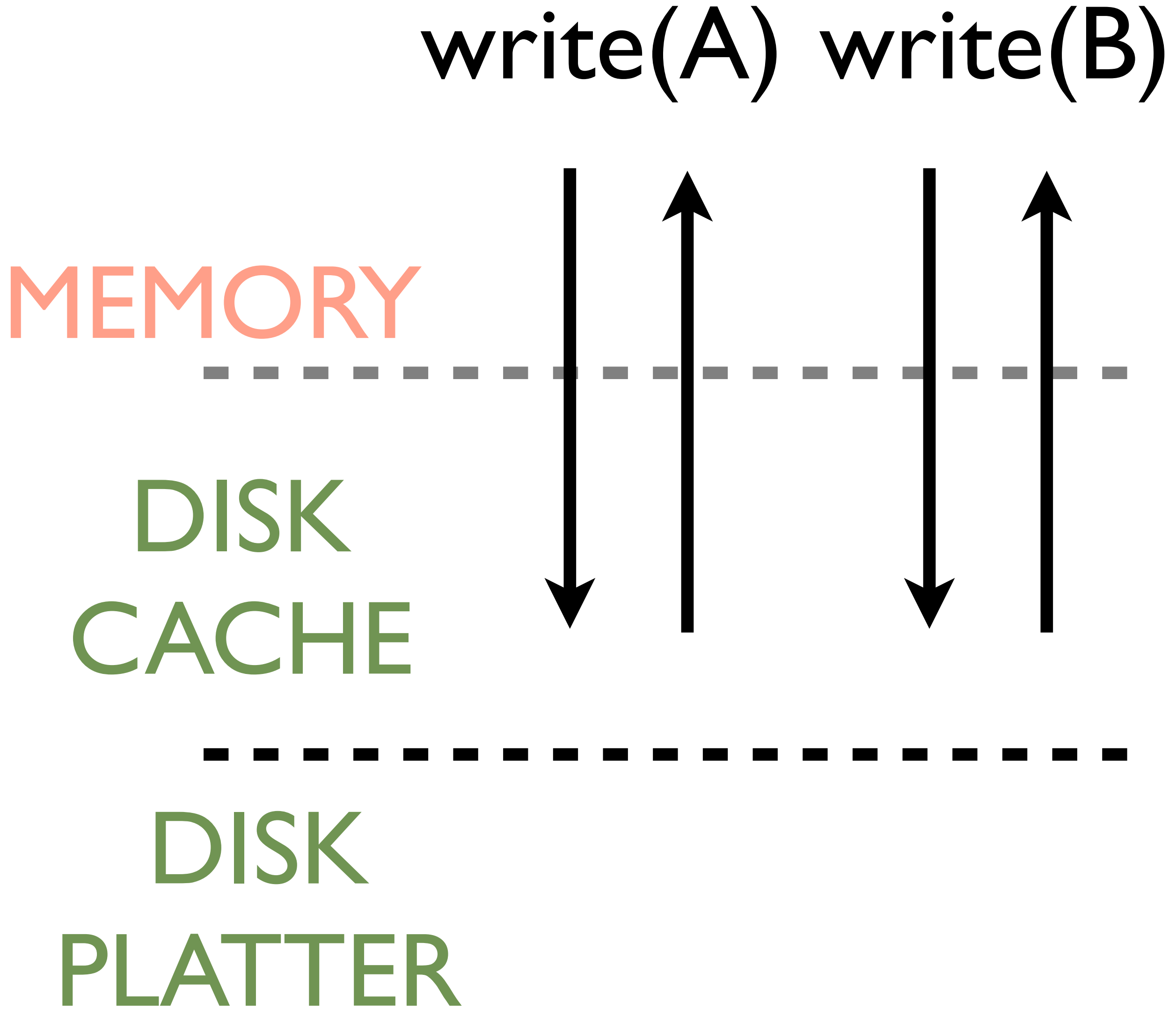

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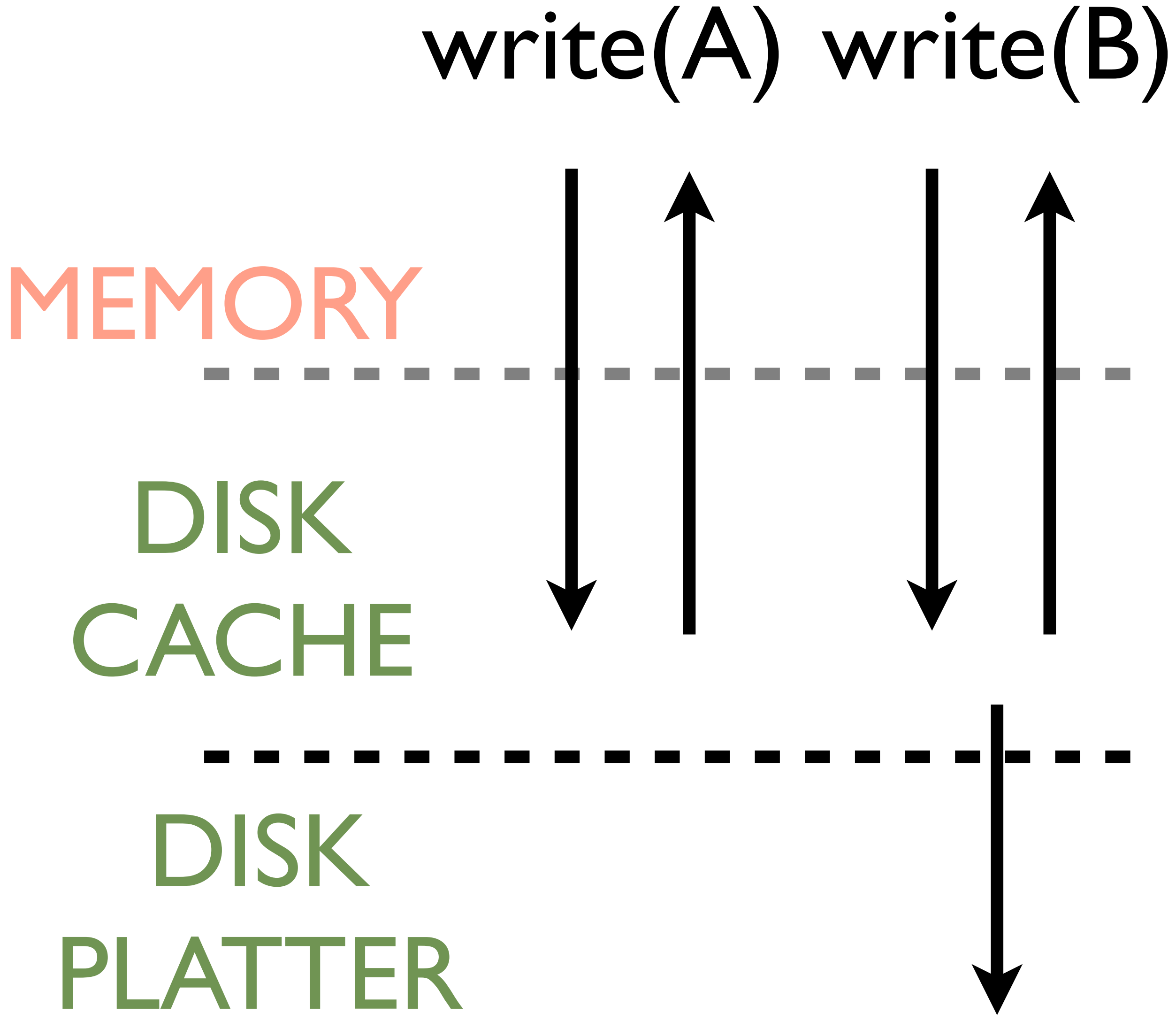

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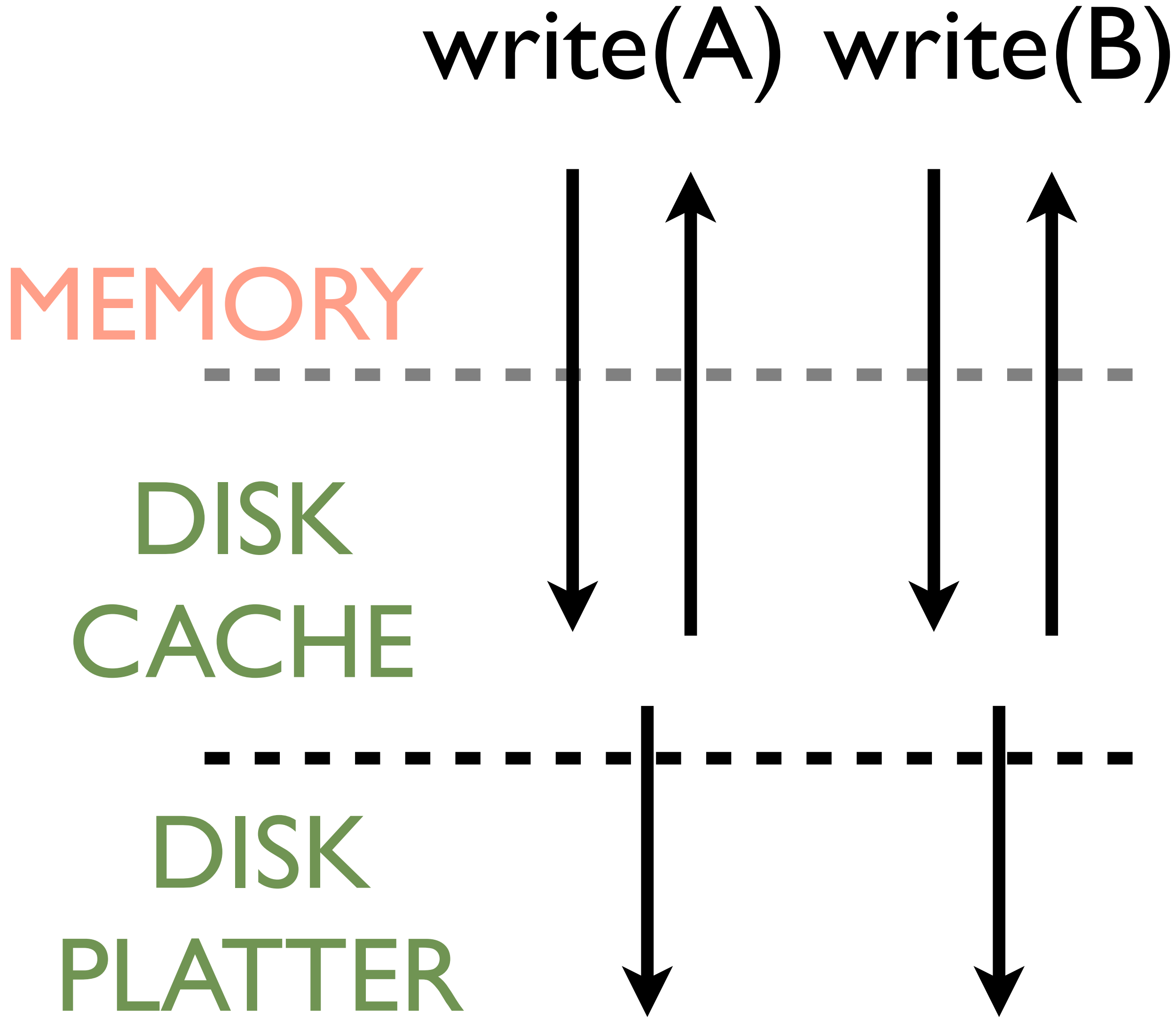
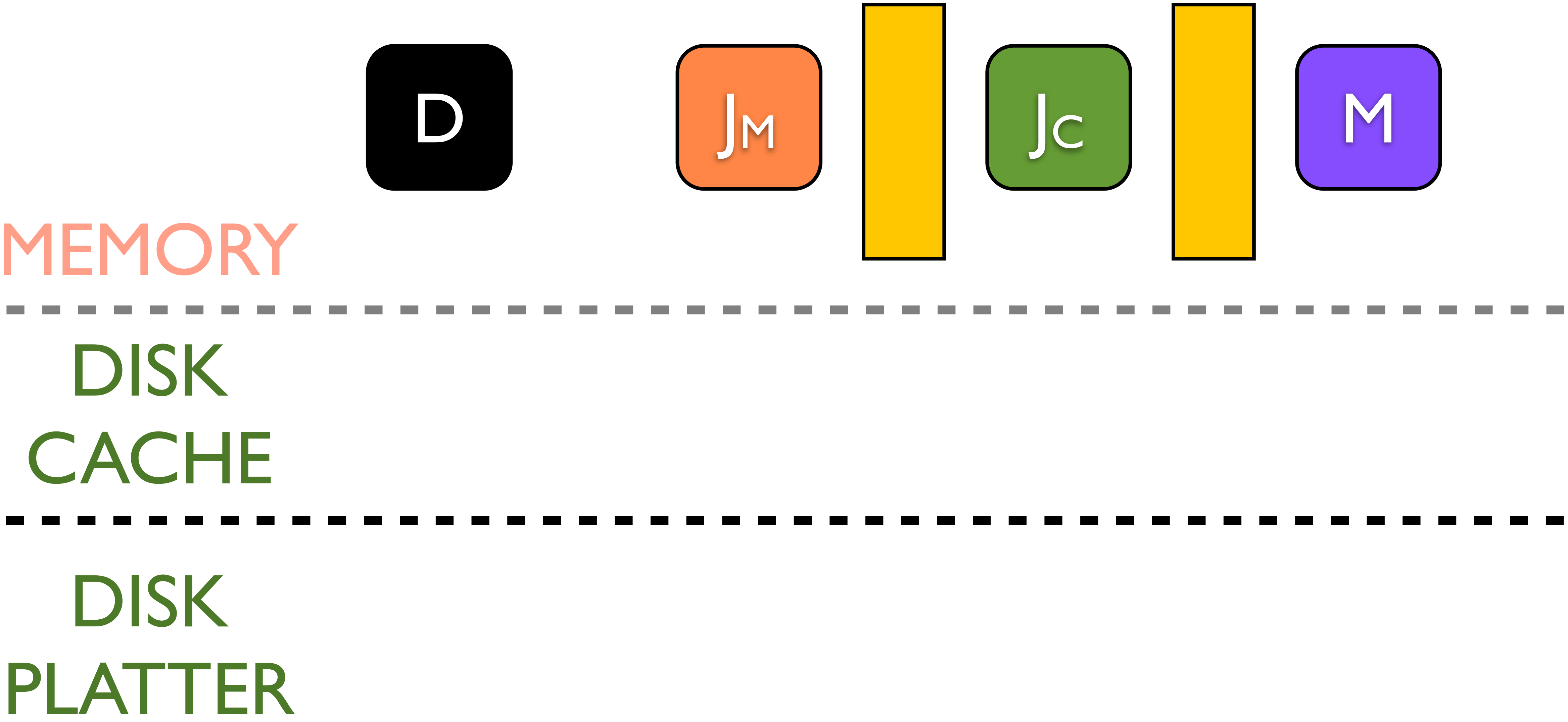


Using Flushes to Order Writes



D

J_M

J_C

M

MEMORY

DISK CACHE

DISK PLATTER

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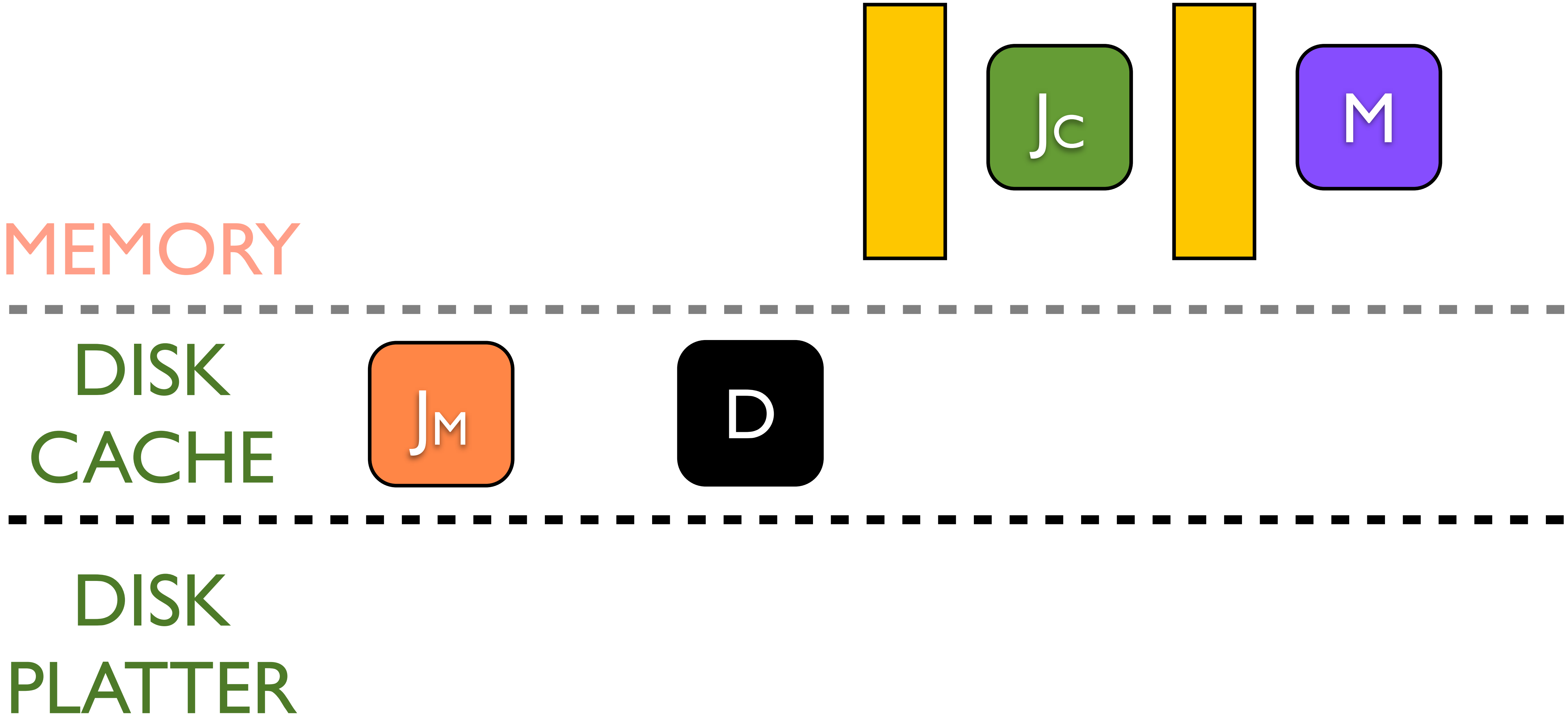

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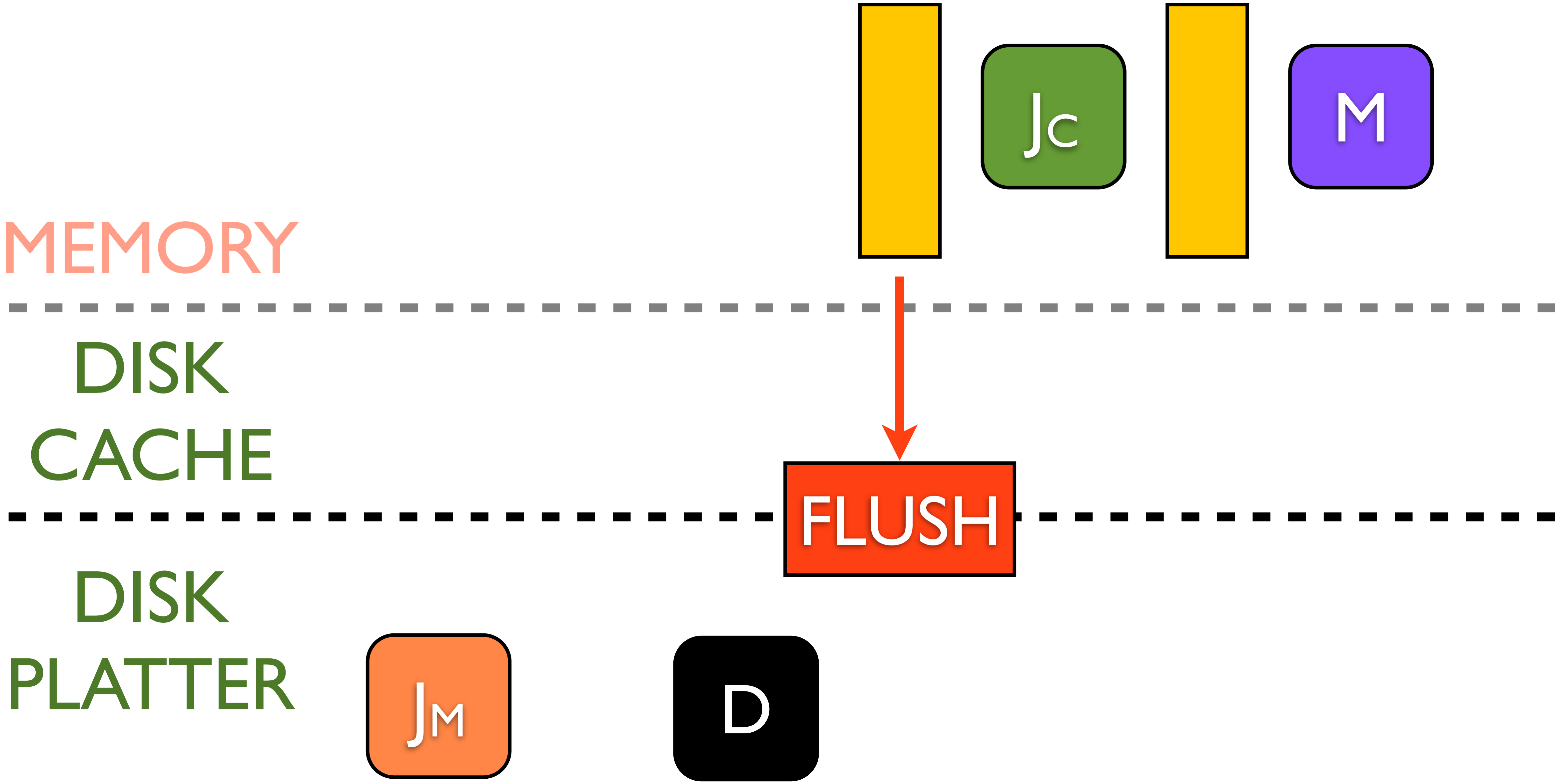

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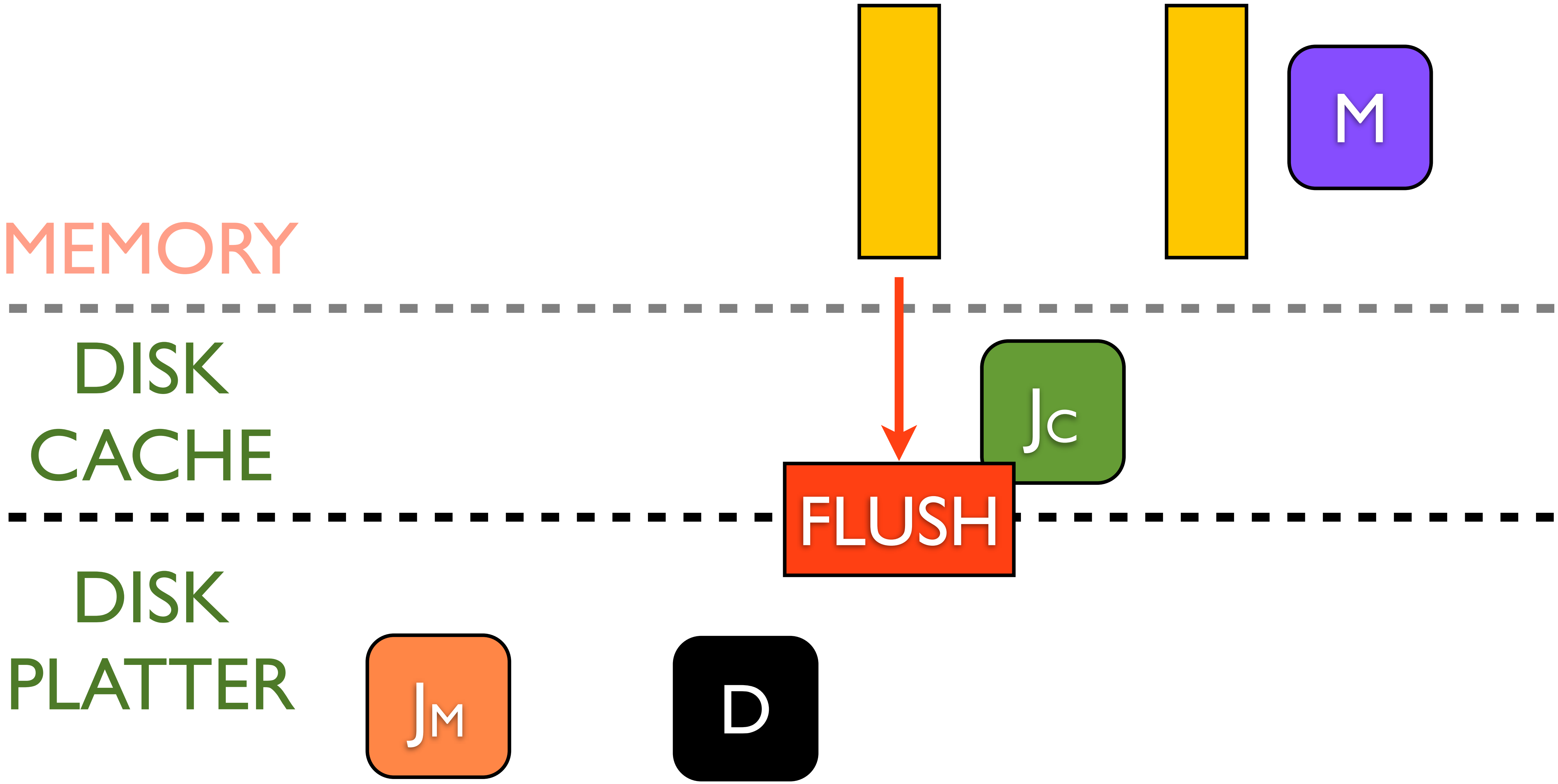

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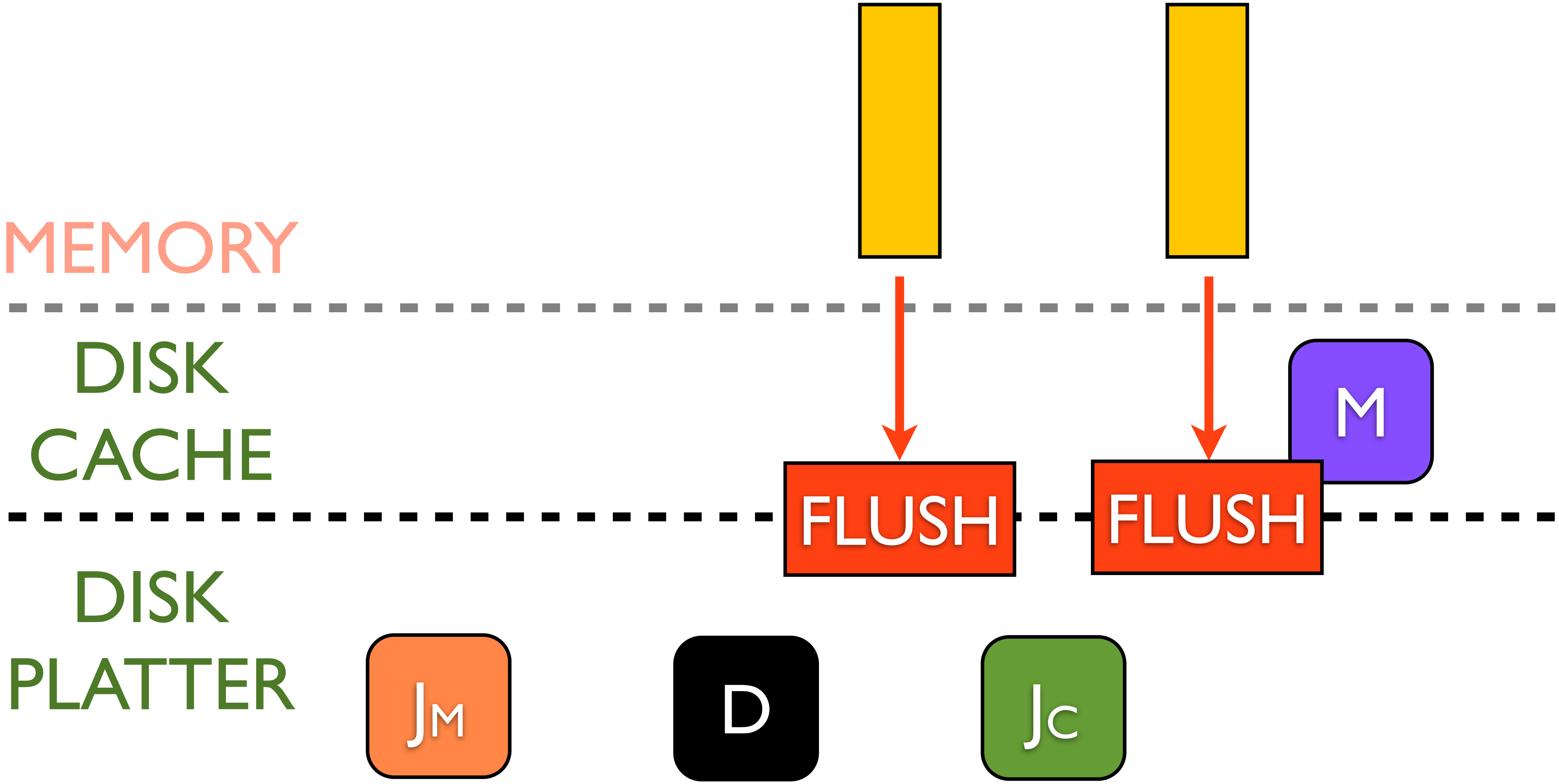

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Maintain consistency using flushes

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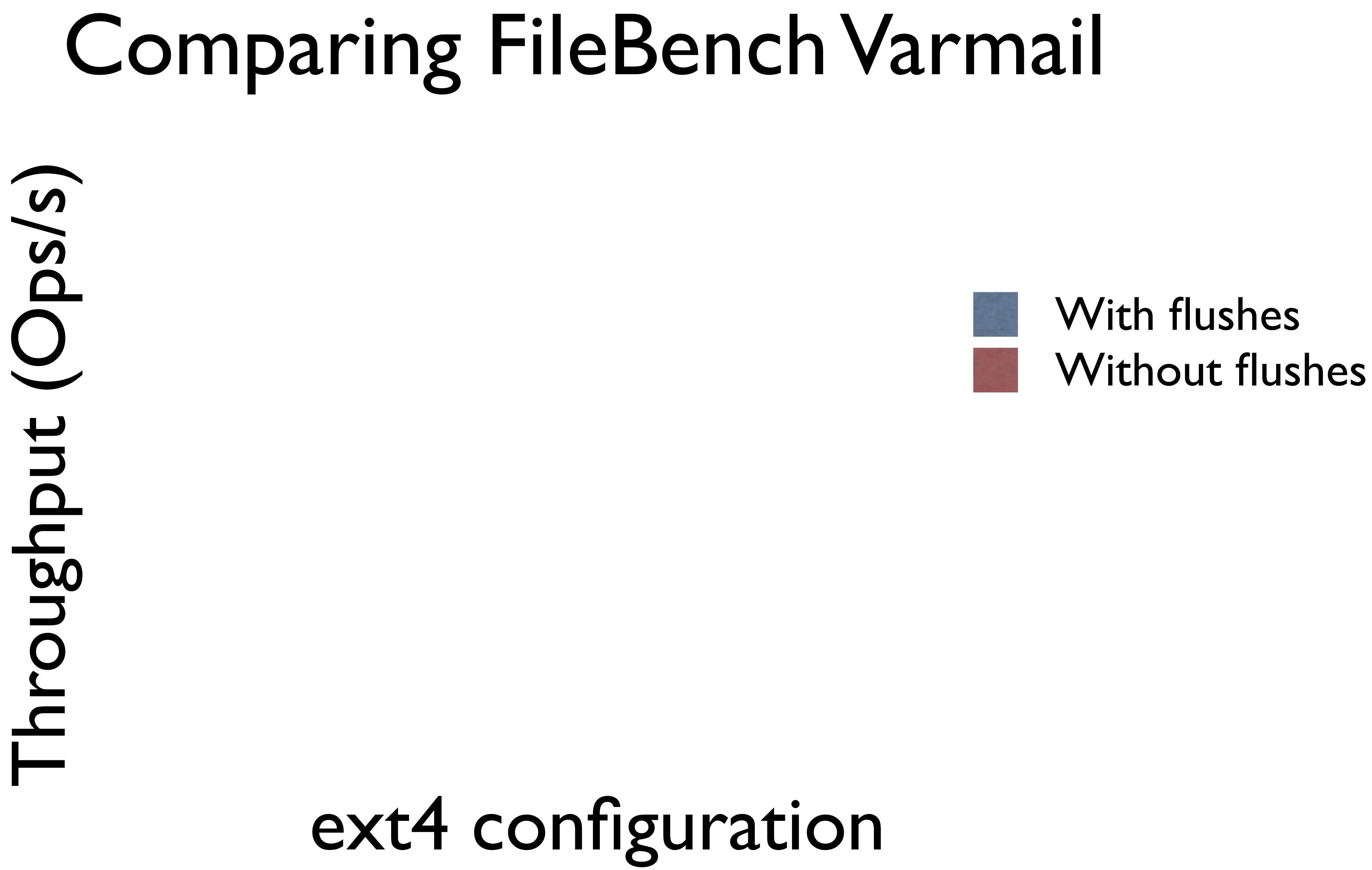
Do extra work during normal runtime

Maintain consistency using flushes

If crash does not happen, flushes are not actually needed

Flushing Performance Impact


Comparing FileBench Varmail

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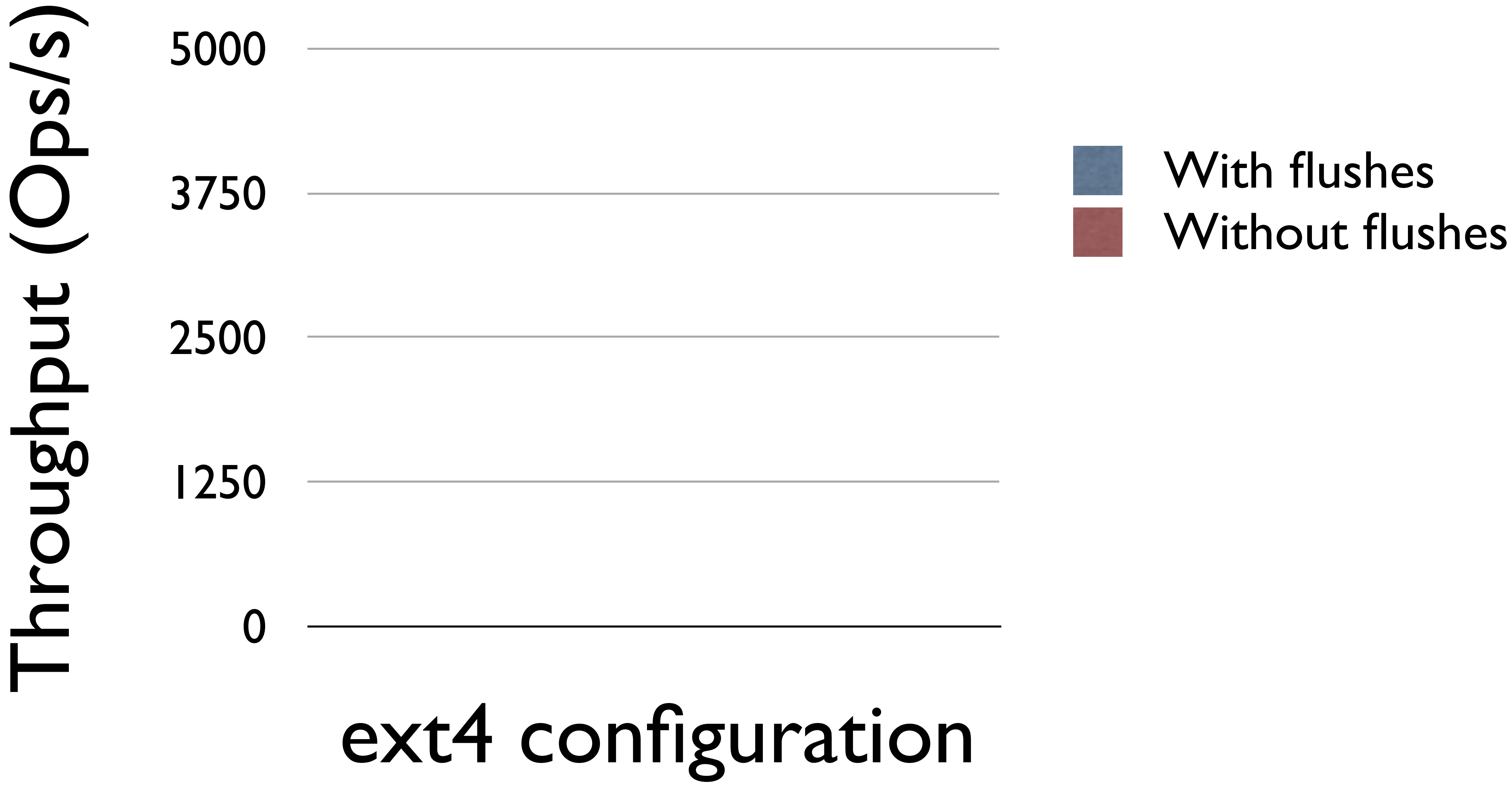

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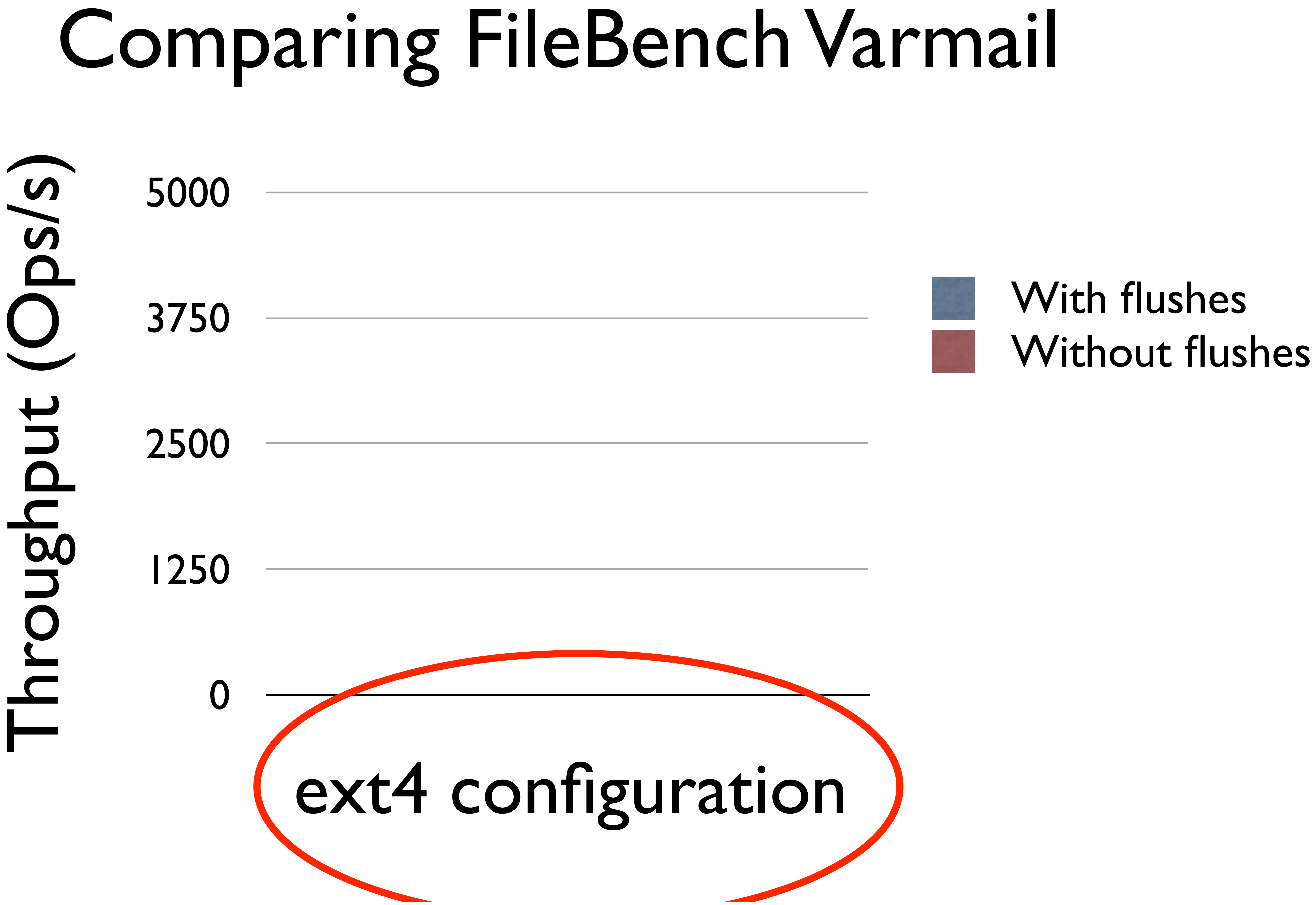

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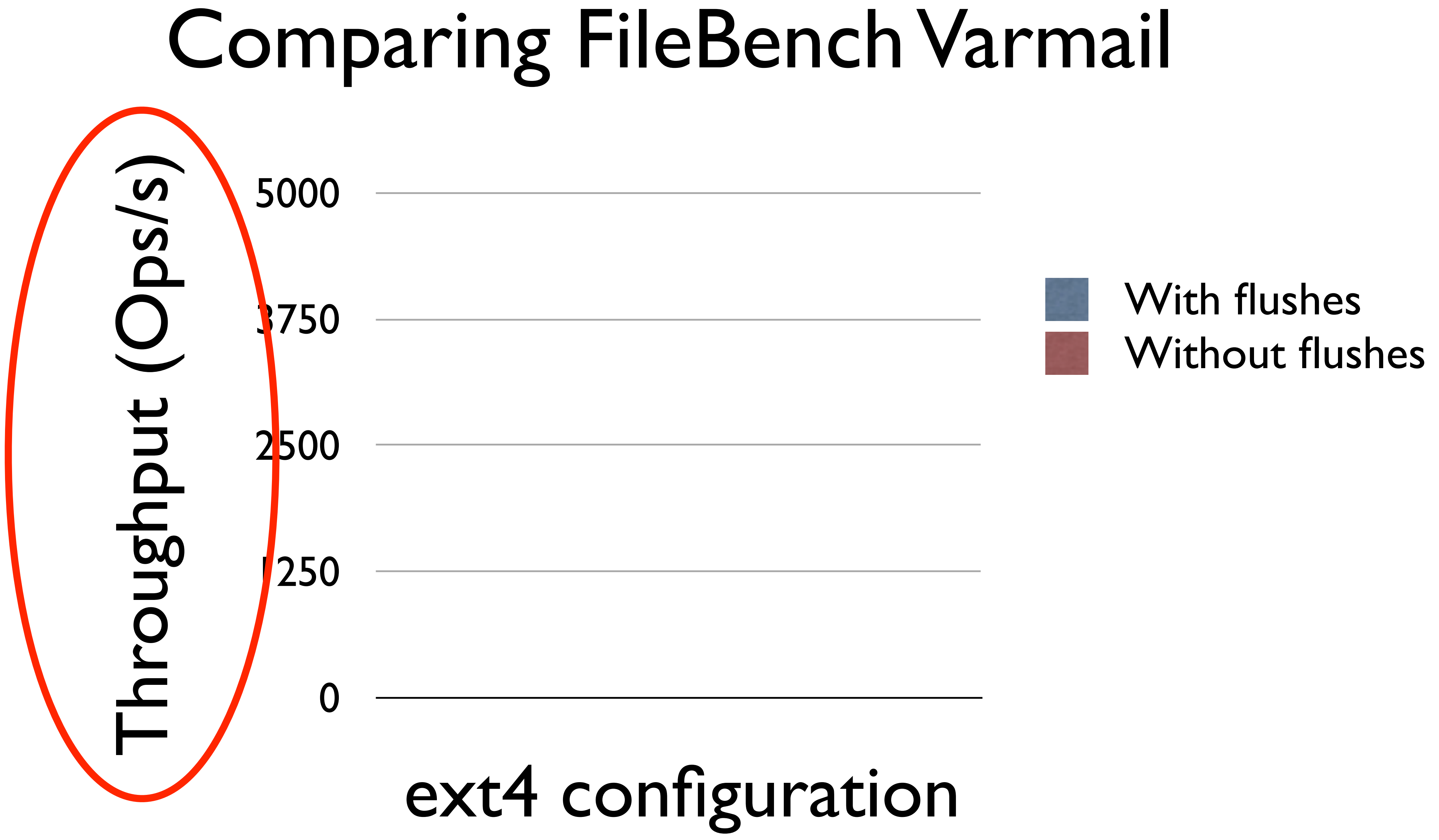

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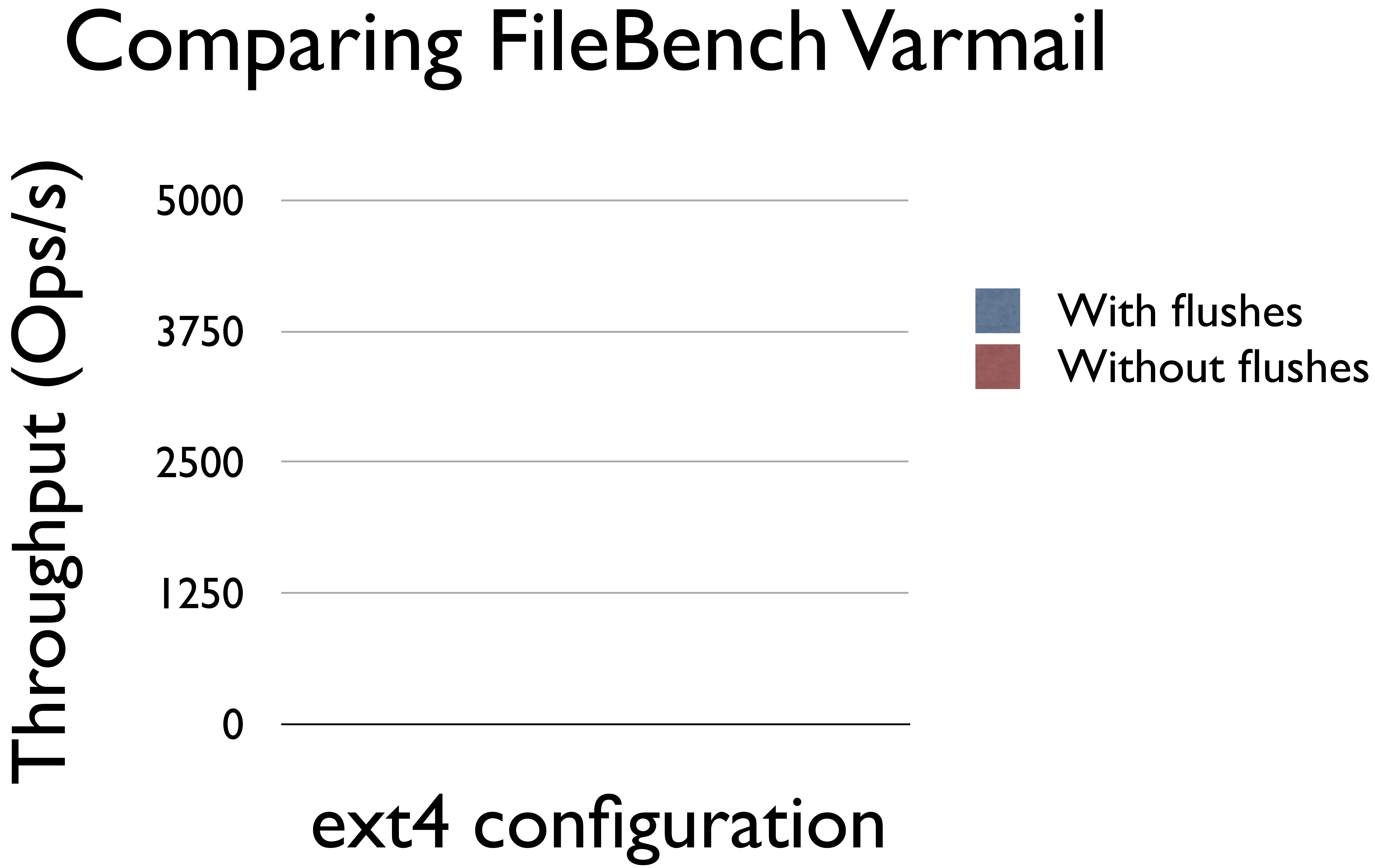

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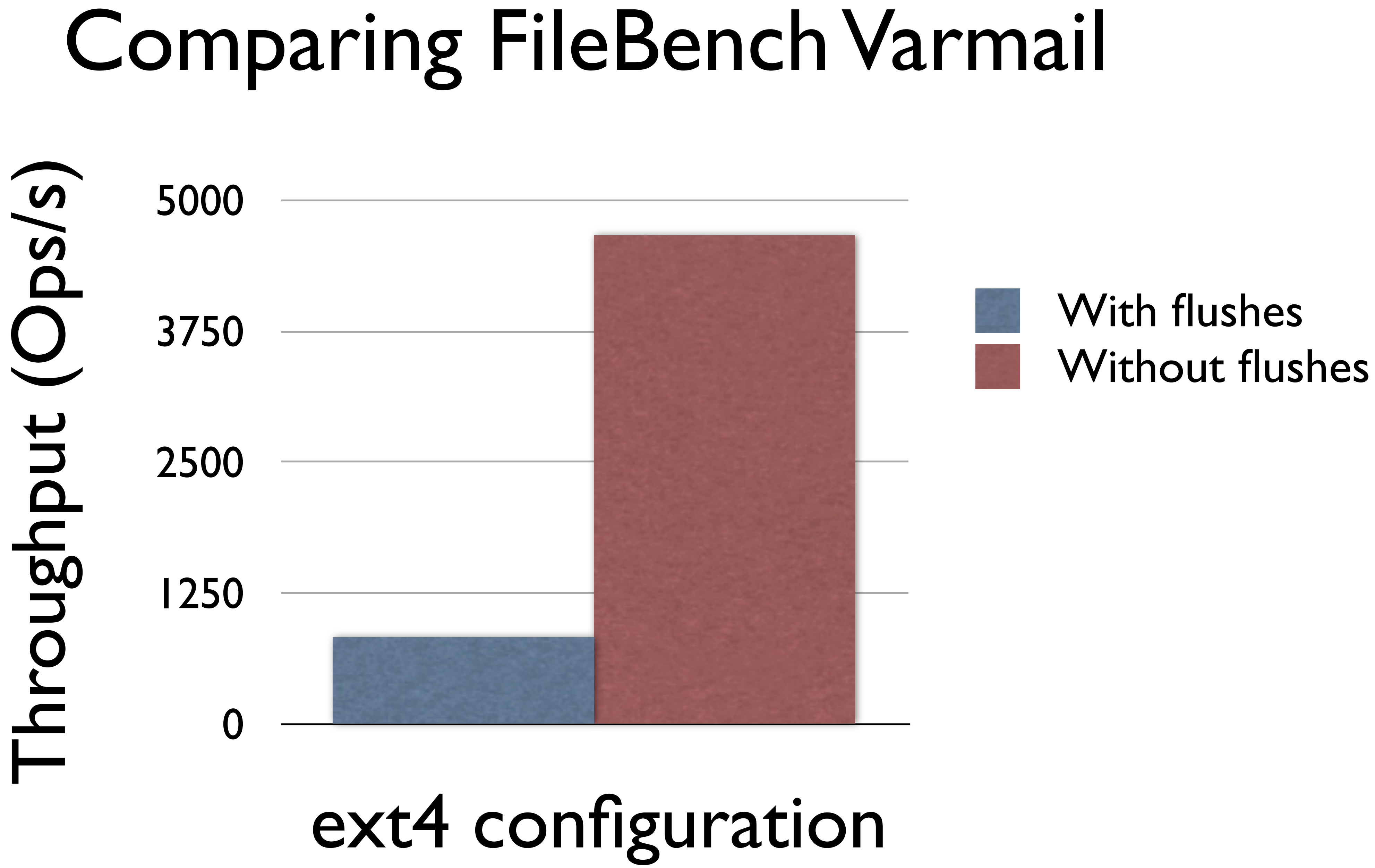

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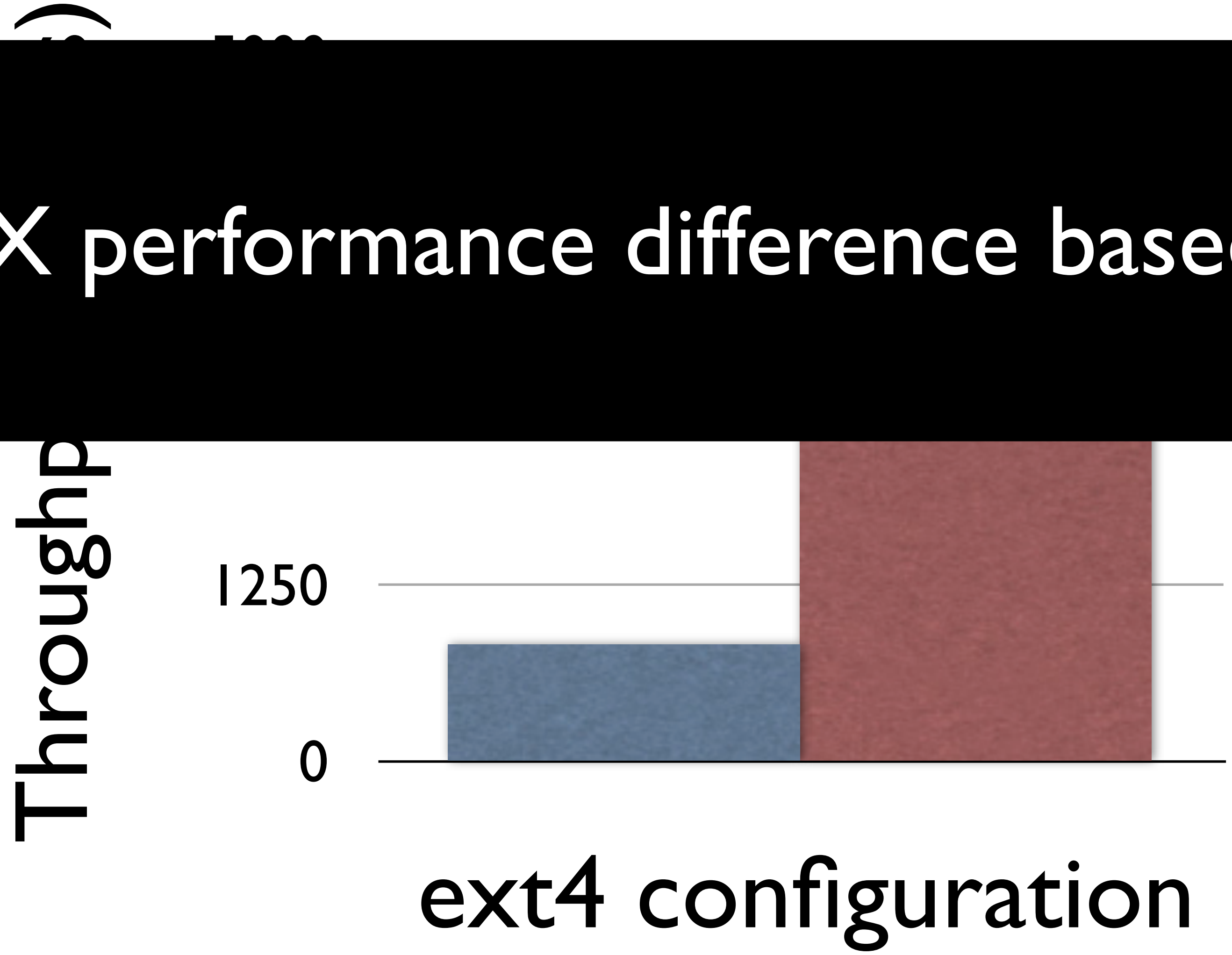

~ 5X performance difference based on flushing!

Journaling
Without Flushes

Journaling Without Flushes

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The Ts'o Hypothesis

Kernel developer Ted Ts'o hypothesized on why inconsistency does not occur:

> "I suspect the real reason why we get away with it so much with ext3 is that the journal is usually contiguous on disk, hence, when you write to the journal, it's highly unlikely that commit block will be written and the blocks before the commit block have not. ... The most important reason, though, is that the blocks which are dirty don't get flushed out to disk right away!"

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Re-ordering does not happen due to layout and checkpointing delay

Probabilistic Crash Consistency

We set out to investigate the Ts'o hypothesis

- Given a workload, what is the risk of causing inconsistency upon crash?
- What are the factors which that contribute to the risk?

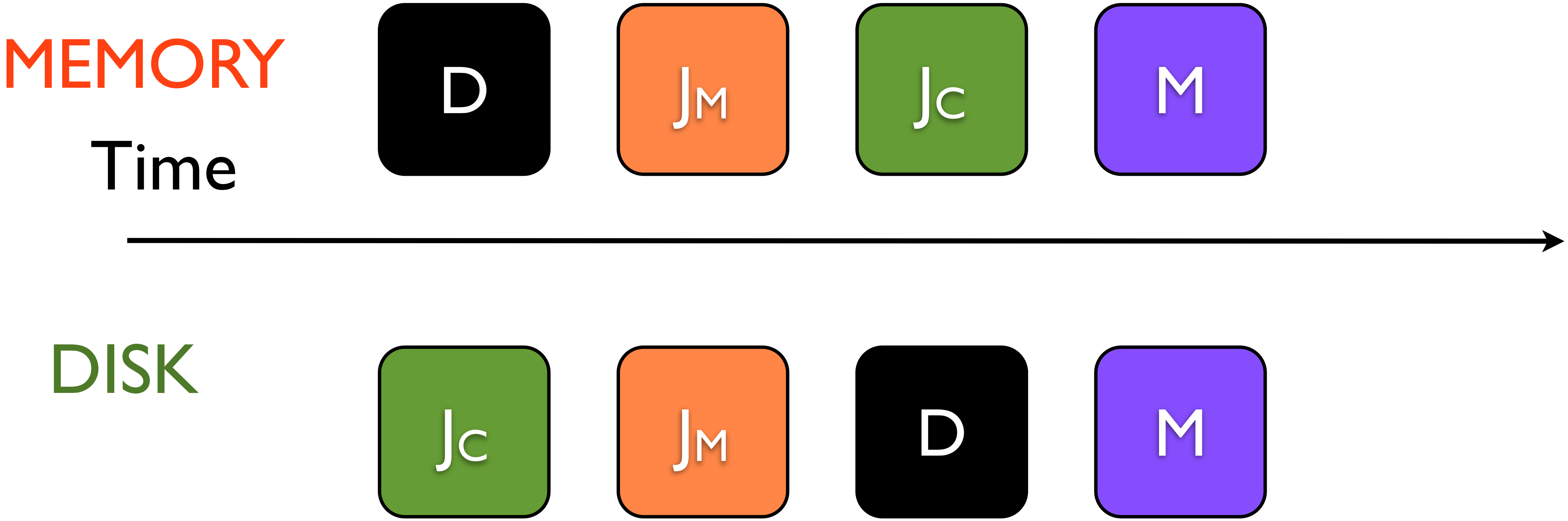
Probabilistic Crash Consistency

We ran different workloads on ext4 without flushes

We collected the traces at the disk level

We ran them on DiskSim simulator

Probabilistic Crash Consistency



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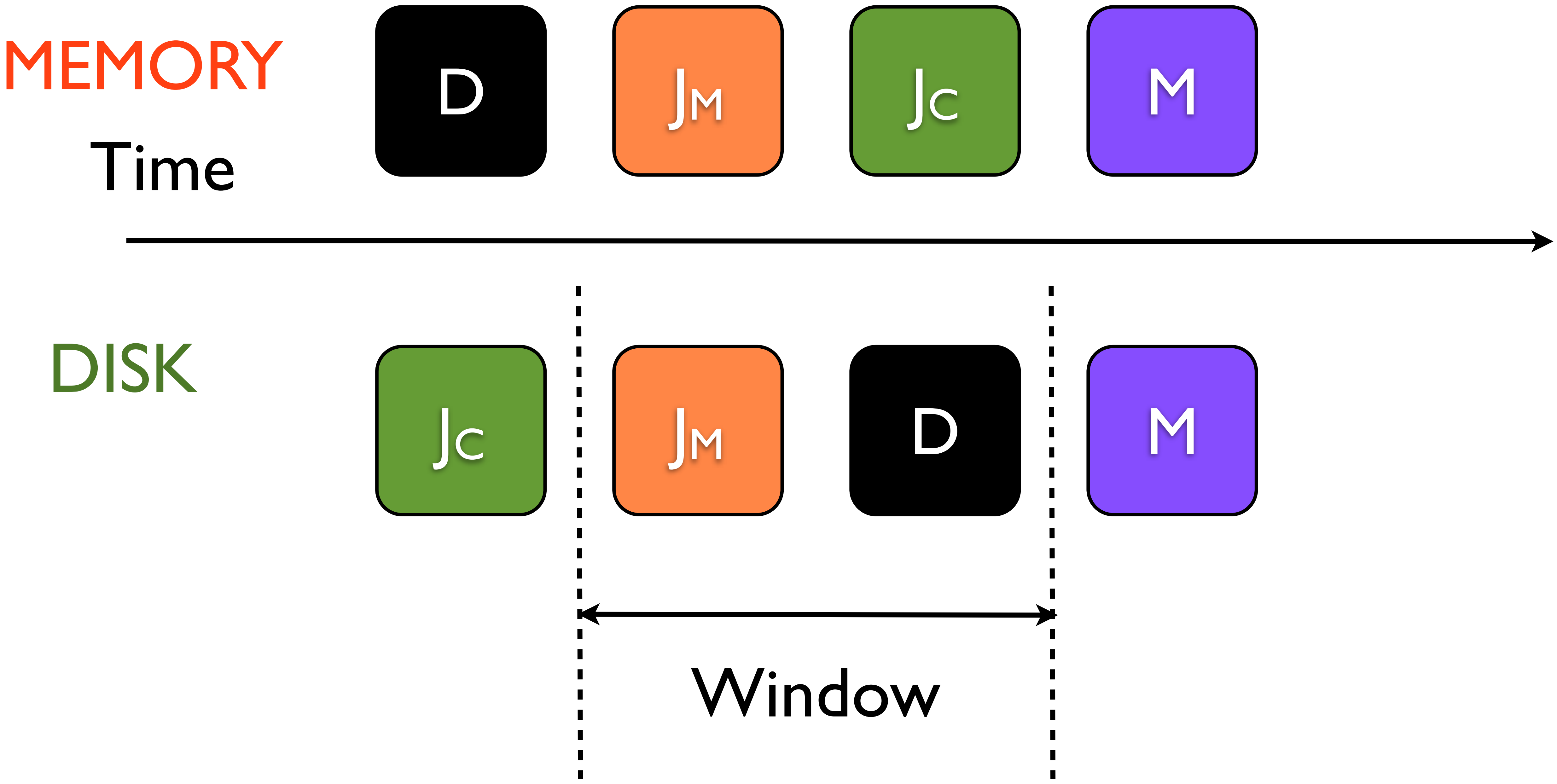

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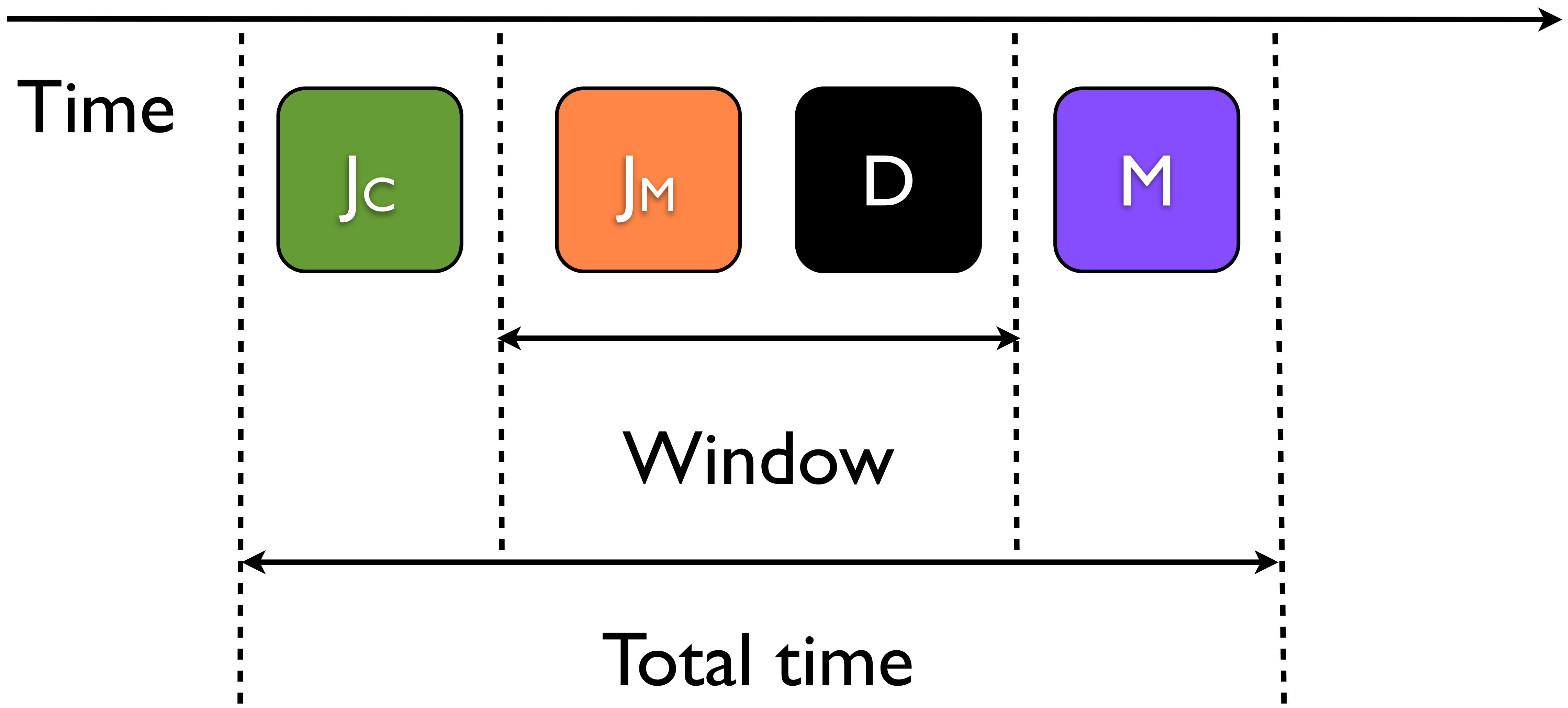

Time

JC

JM

D

M

Window

Total time

P-inconsistency = Total time in window(s) / Total time

Types of Re-ordering

Correct Order	D	JM	JC	M

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Early Commit	D	JC	JM	M
	JC	D	JM	M

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Correct Order	D	JM	JC	M
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Early Checkpoint	D	JM	M	JC
	D	M	JM	JC
	M	D	JM	JC

Types of Re-ordering

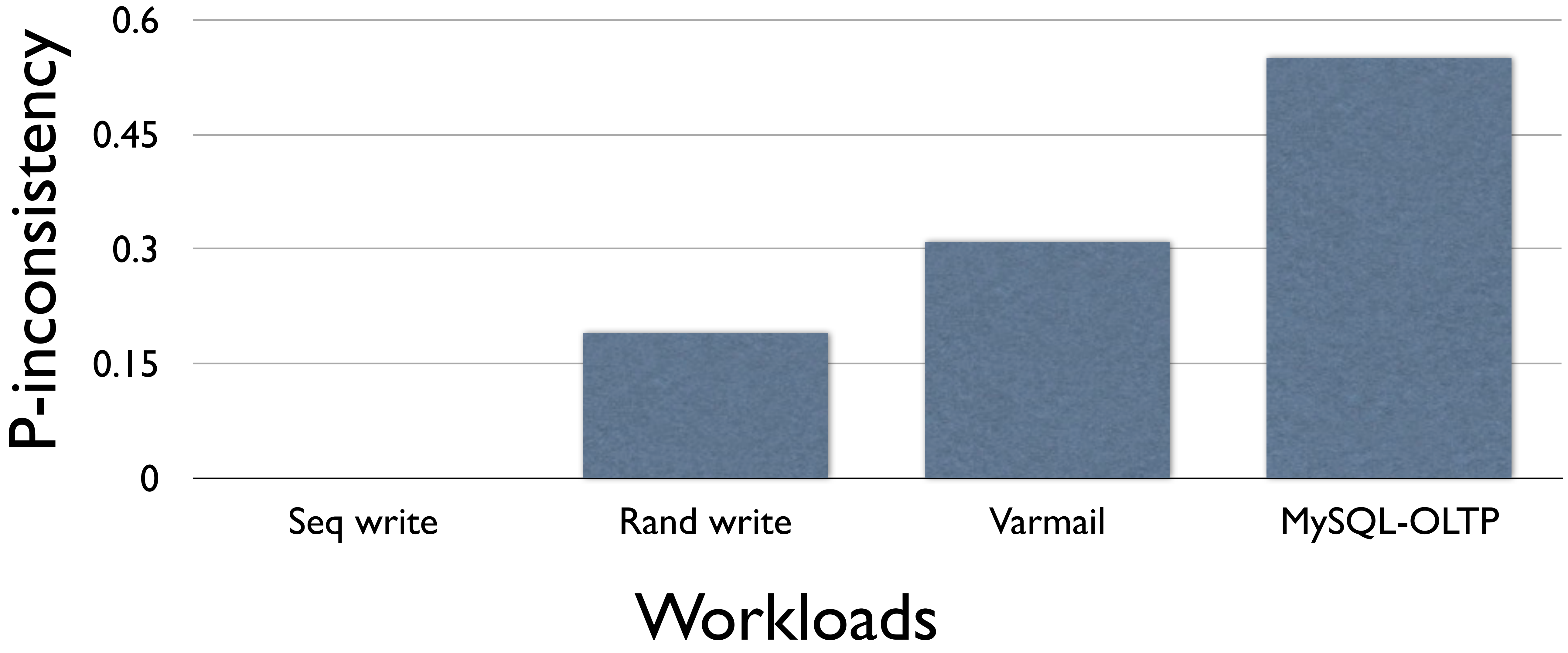
Correct Order	D	J_M	J_C	M
Early Commit	D J_C	J_C D	J_M J_M	M M
Early Checkpoint	D D M	J_M M D	M J_M J_M	J_C J_C J_C
Transaction Misorder		J_{Ci}	J_{Ci-1}	

Probabilistic Crash Consistency

We analyzed different workloads using this framework

Calculated p-inconsistency and investigated the factors contributing to p-inconsistency

Results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Seq write
Rand write
Varmail
MySQL-OLTP
Workloads

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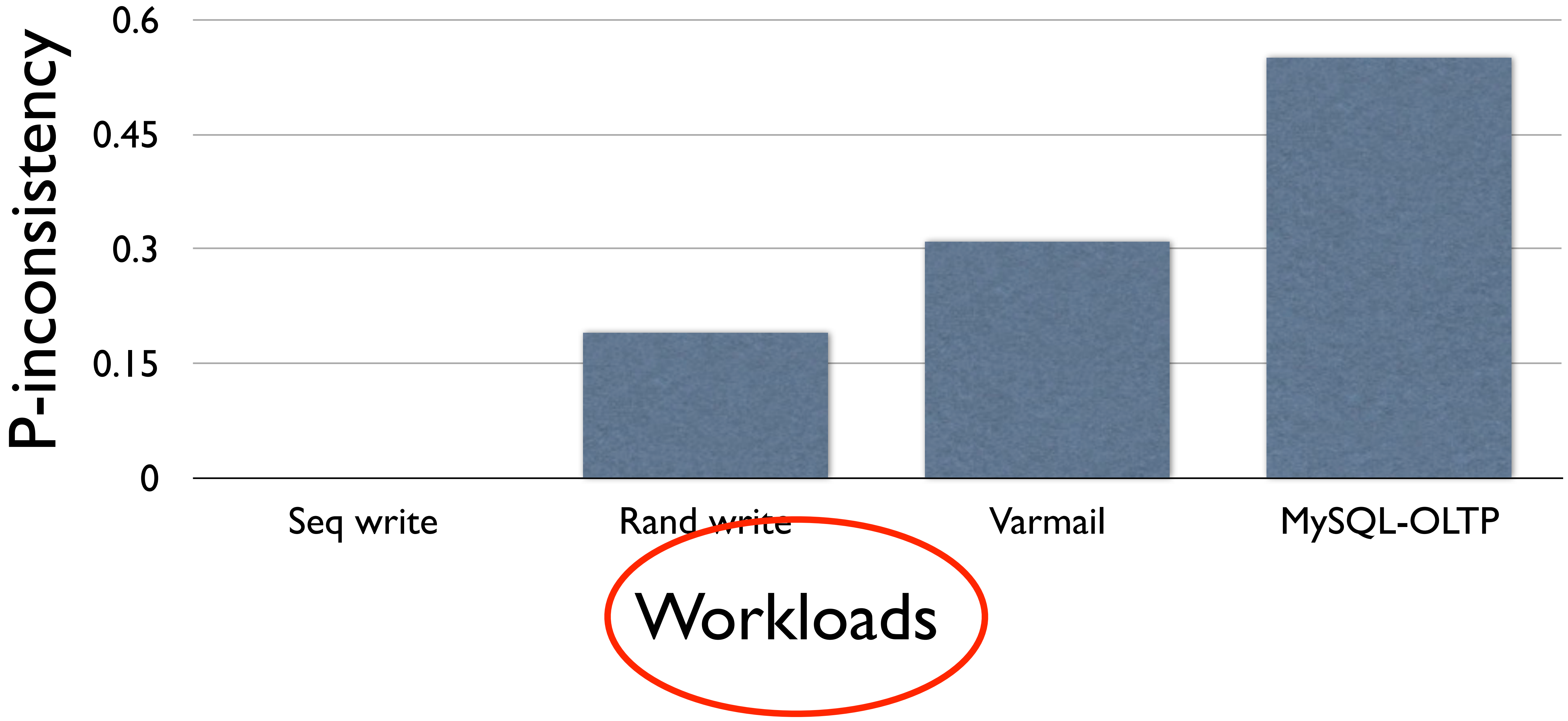
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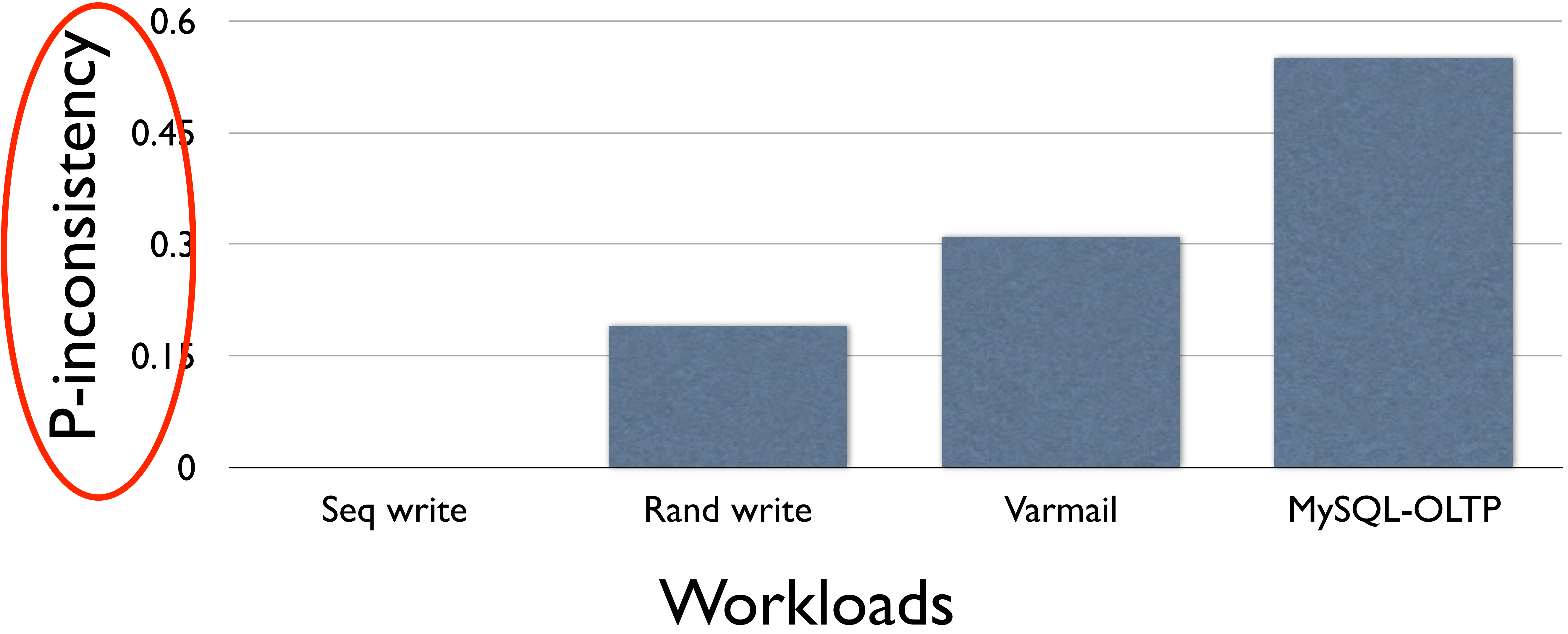
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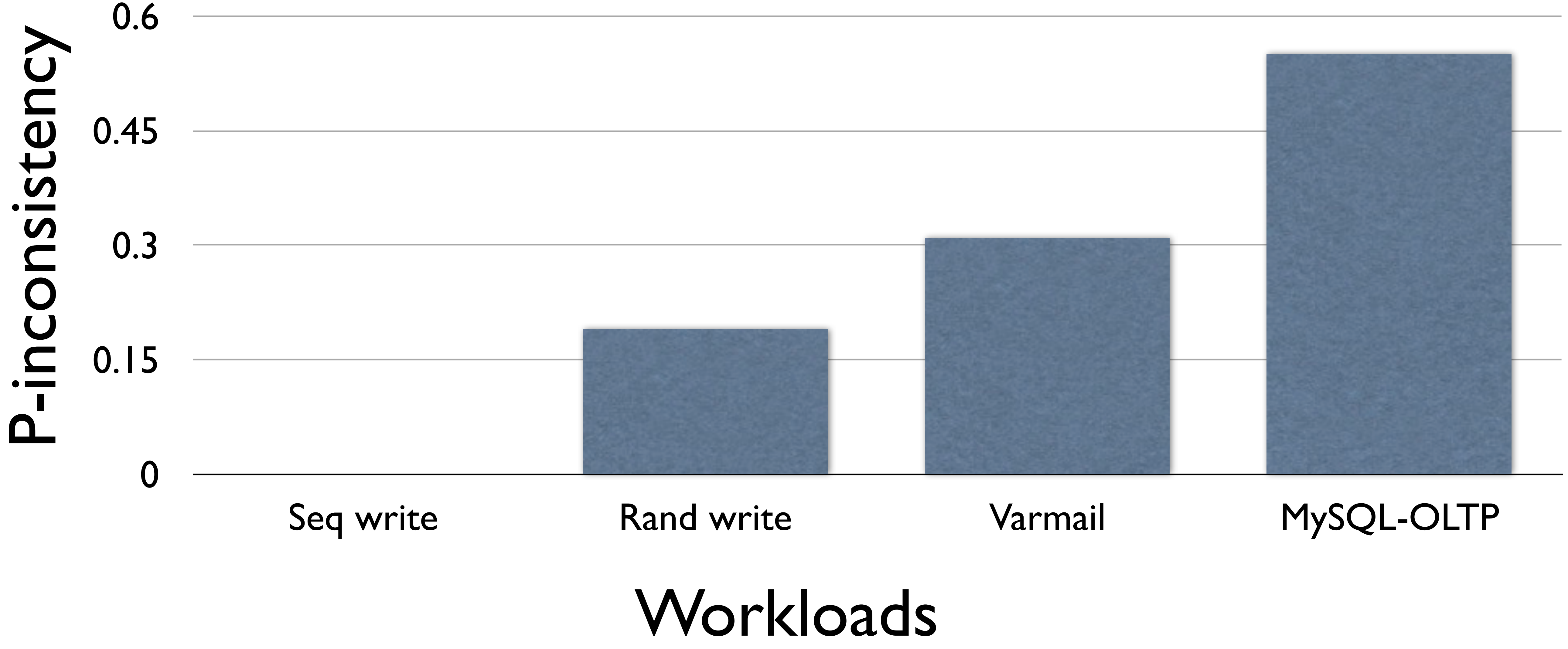
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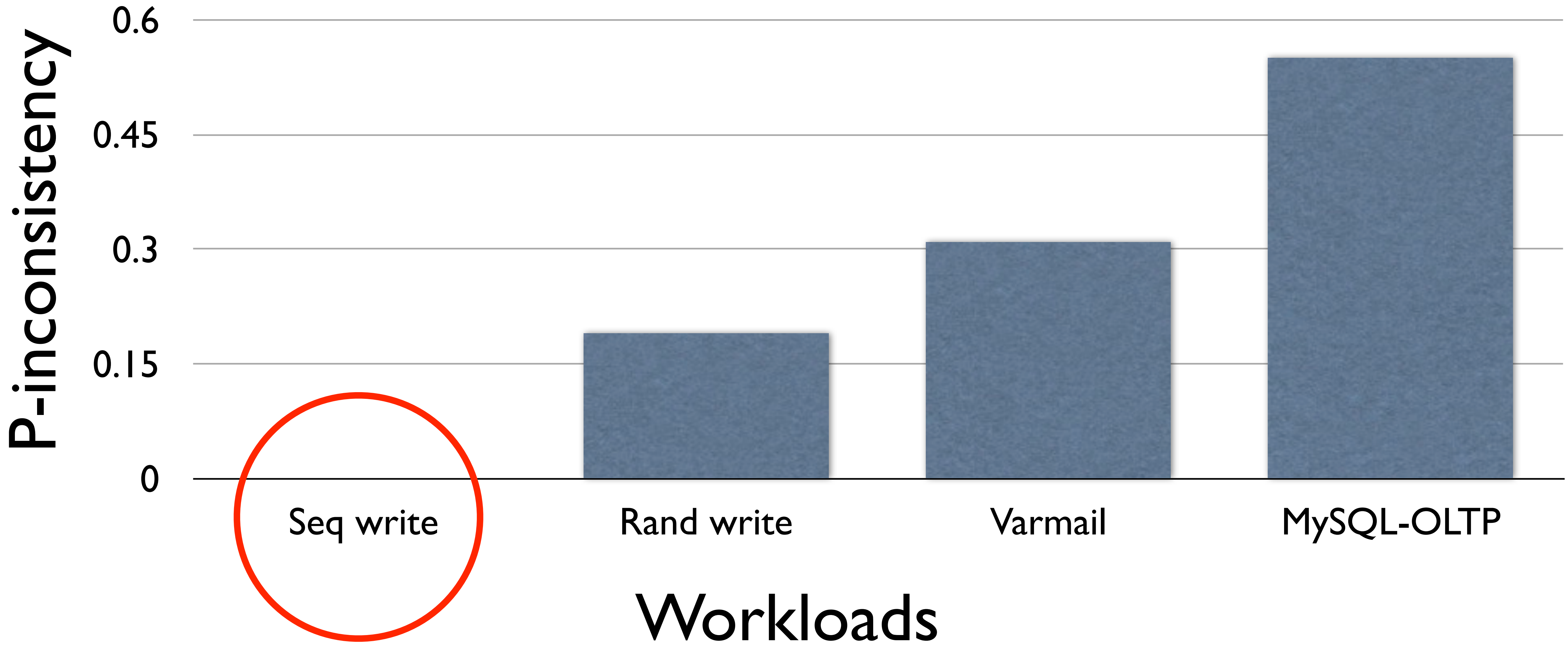
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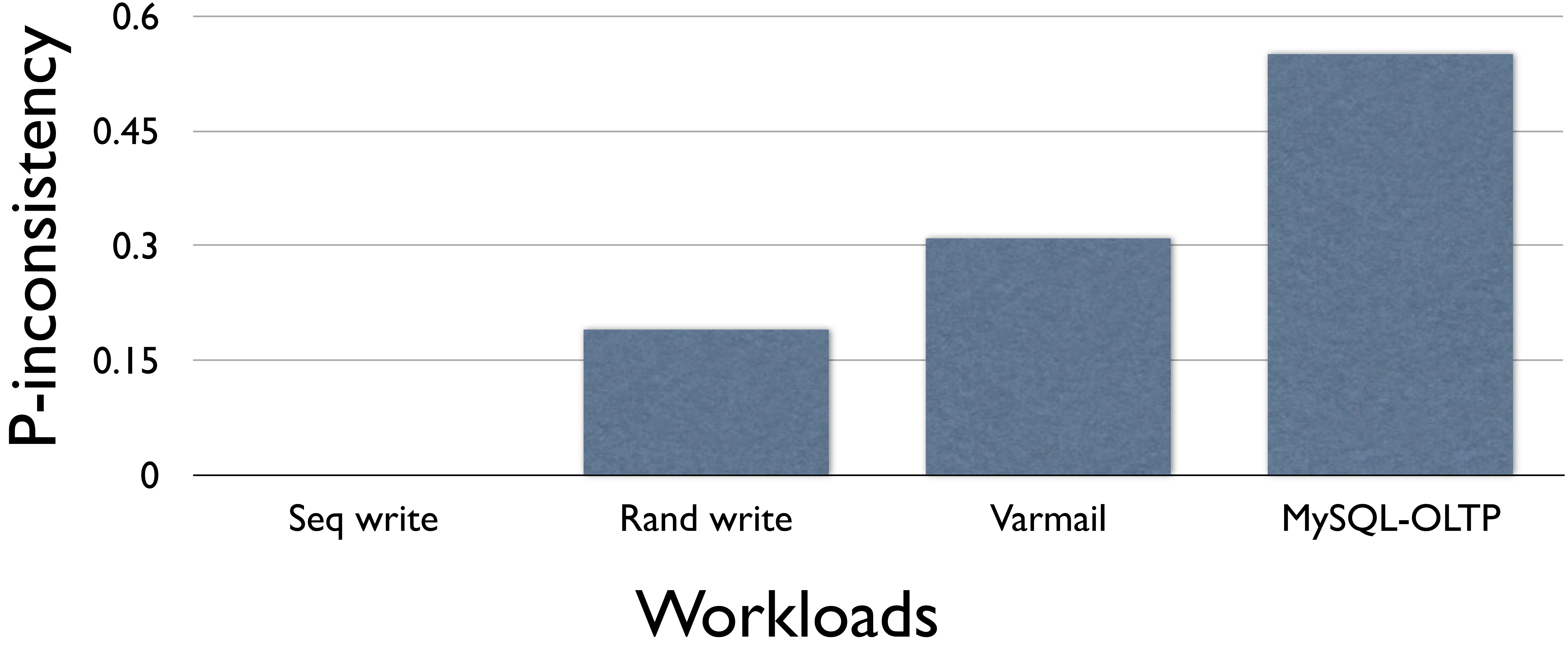
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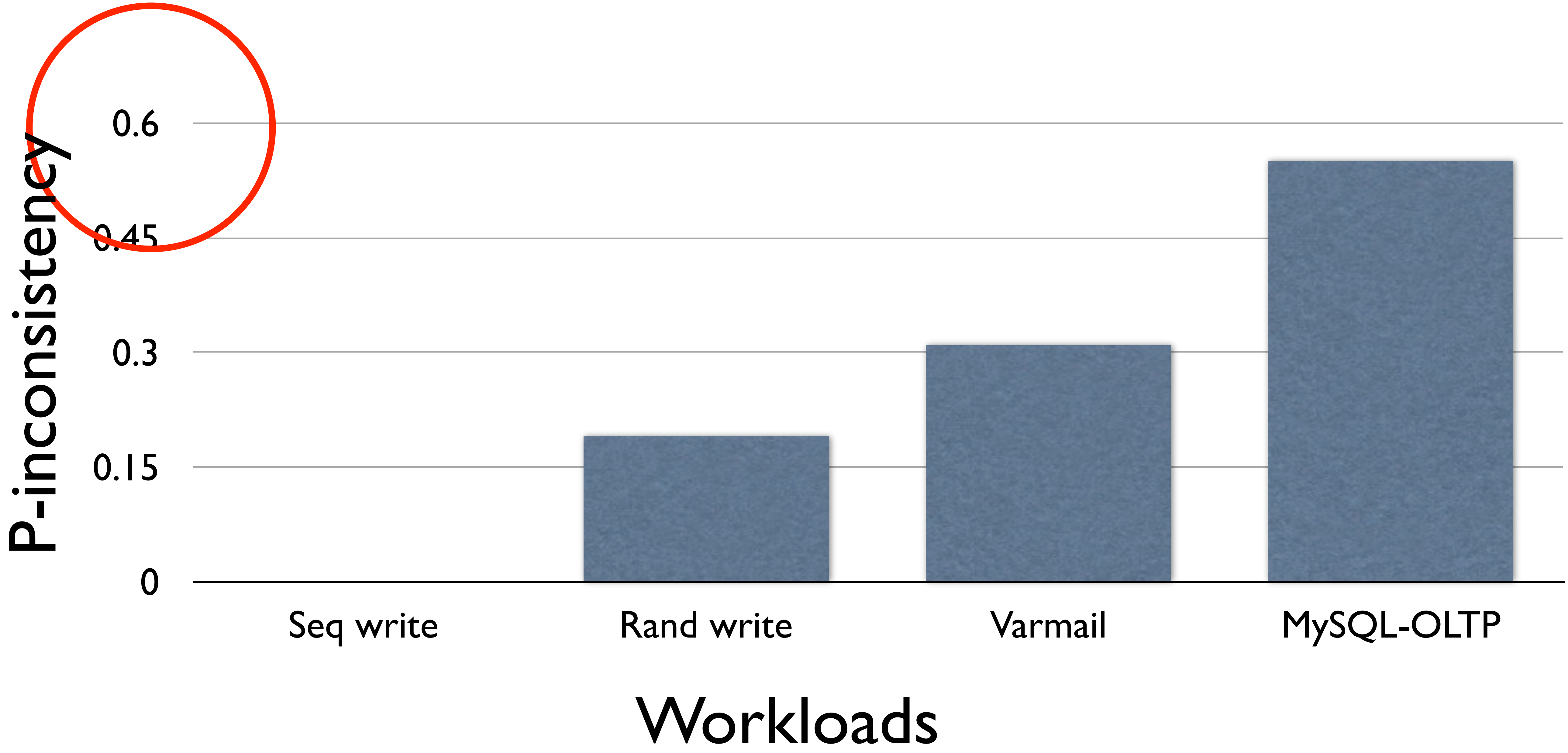
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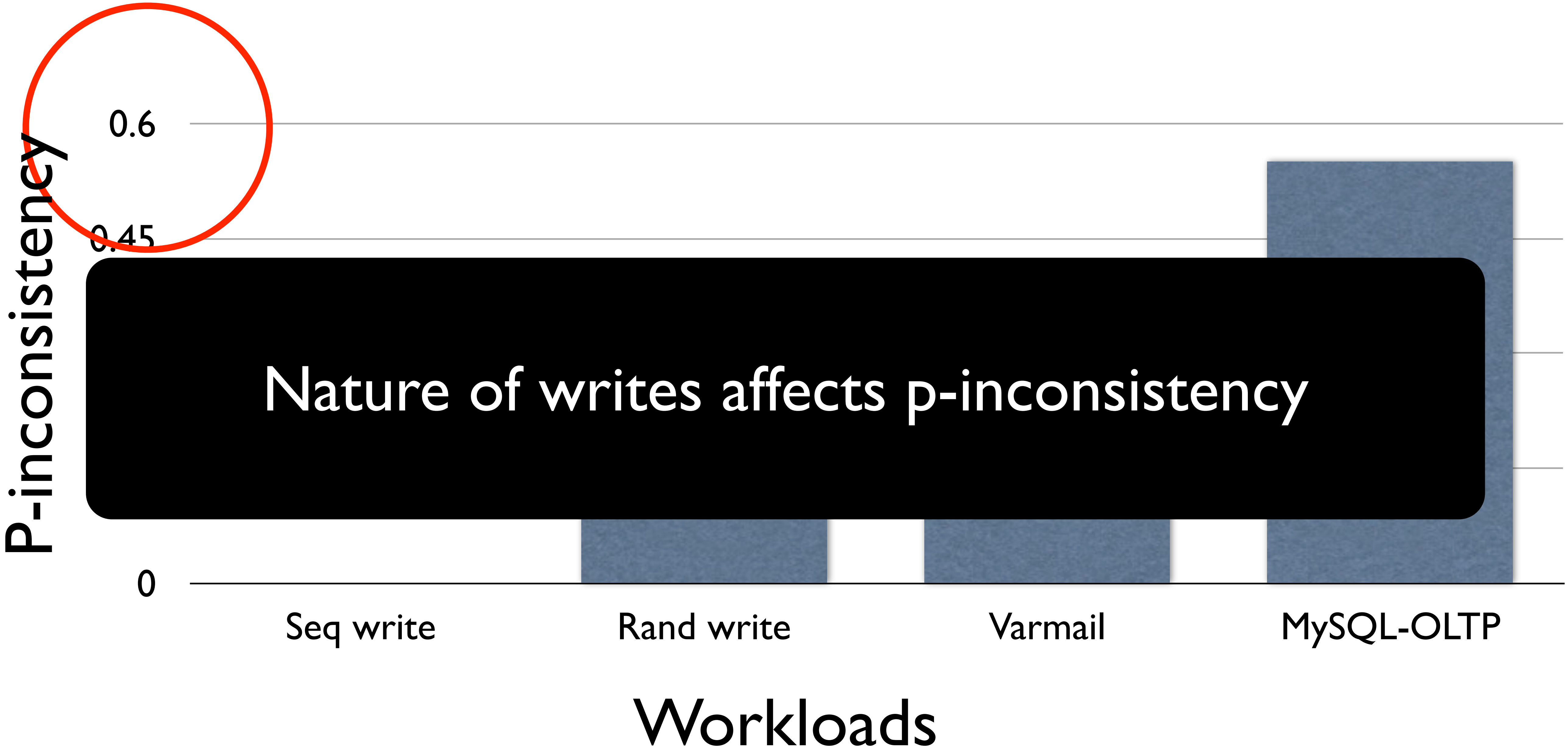
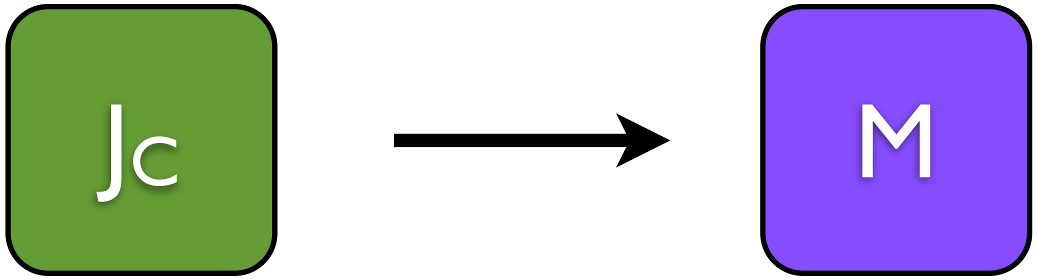


Nature of writes affects p-inconsistency

Some orderings hold in practice without flushes

Some orderings hold in practice without flushes

Checkpoint related re-orderings occurred very rarely in the workloads



- Due to the delay (~5-30 s) between committing and checkpointing a transaction

Some orderings hold in practice without flushes

If we extend that to all orderings, we get consistency without flushes

Optimistic Crash Consistency

Optimistic Crash Consistency

Optimistic commit protocol that provides consistency without flushes

Why “optimistic”?

Assume that crashes rarely happen

Eliminate flushes from runtime code

When crash happens, recover using appropriate mechanisms

Trade “freshness” for performance

Some data may be lost on a crash

Freshness

Freshness

Another aspect of crash consistency

Freshness

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After a crash, what consistent state does the system recover to?

- An empty file system is consistent

Freshness

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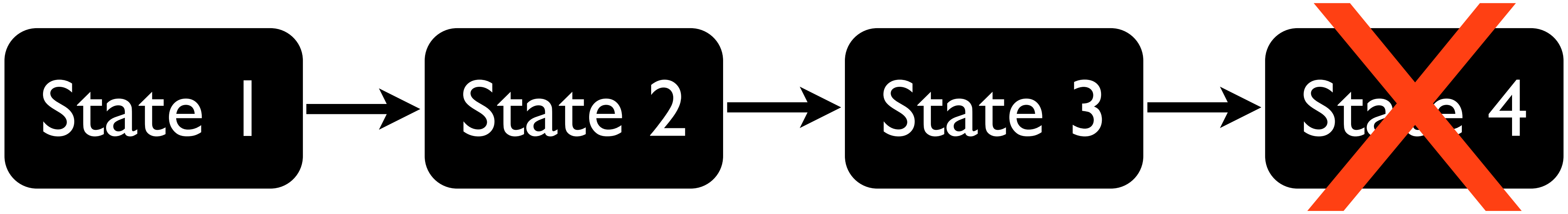

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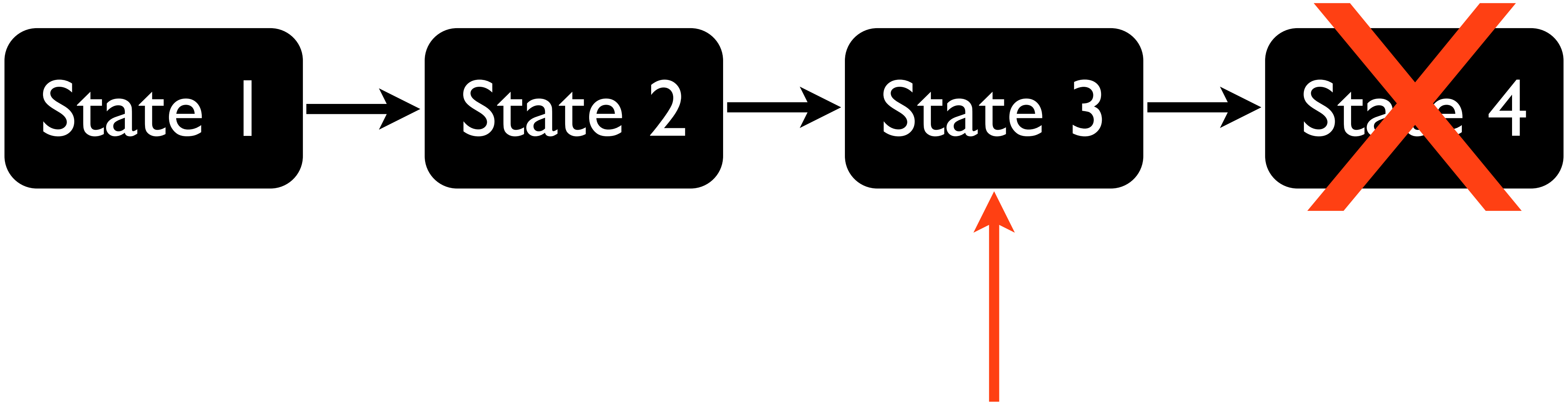

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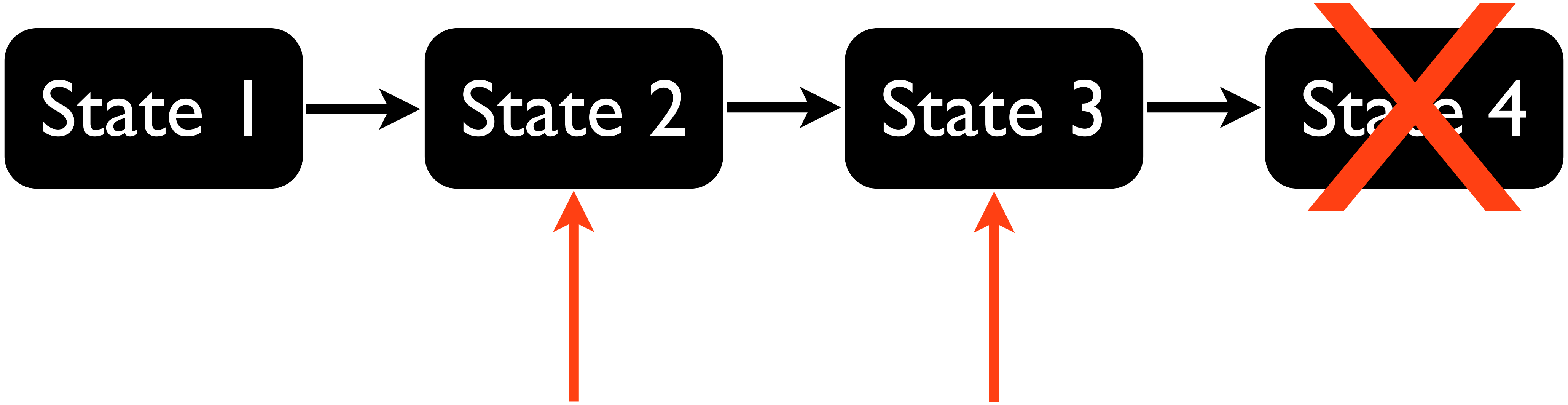


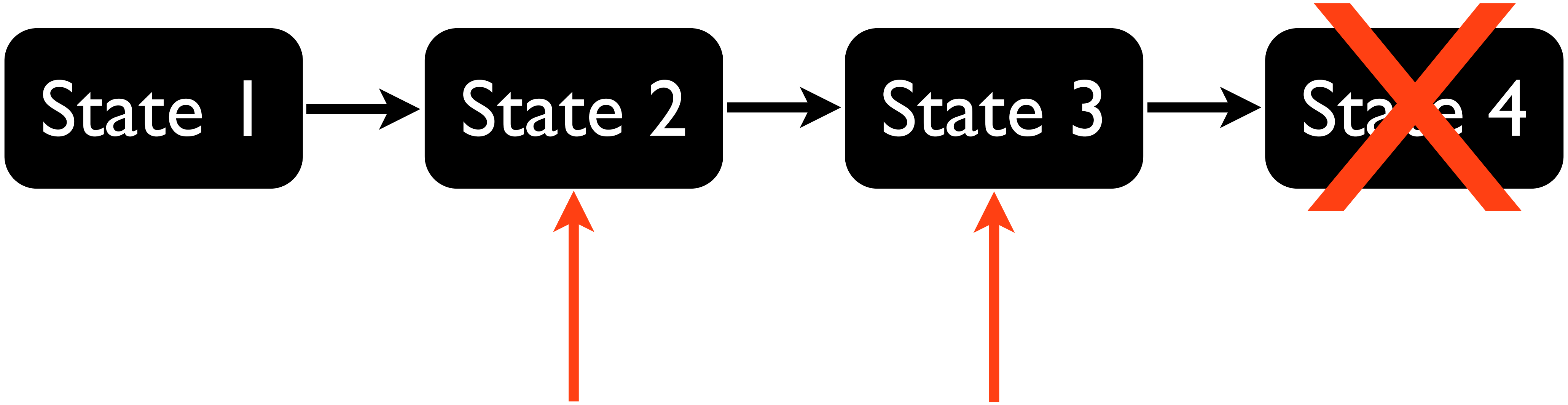
Freshness

Another aspect of crash consistency

After a crash, what consistent state does the system recover to?

- An empty file system is consistent

Many applications can tolerate stale but consistent data [Keeton04, Cipar12]



Optimistic Crash Consistency

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It changes the ACID model: only eventual durability is provided

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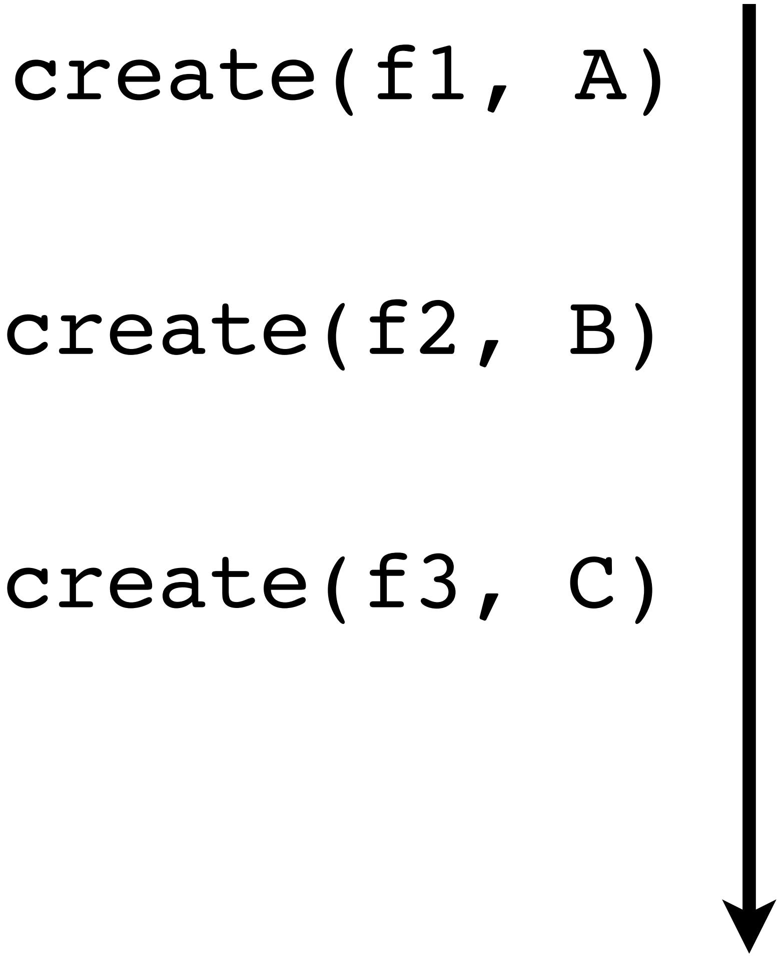
It changes the ACID model: only eventual durability is provided

We split the `fsync()` imperative into two:

- `osync()` for ordering
- `dsync()` for durability

nosync, fsync and osync

nosync, fsync and osync

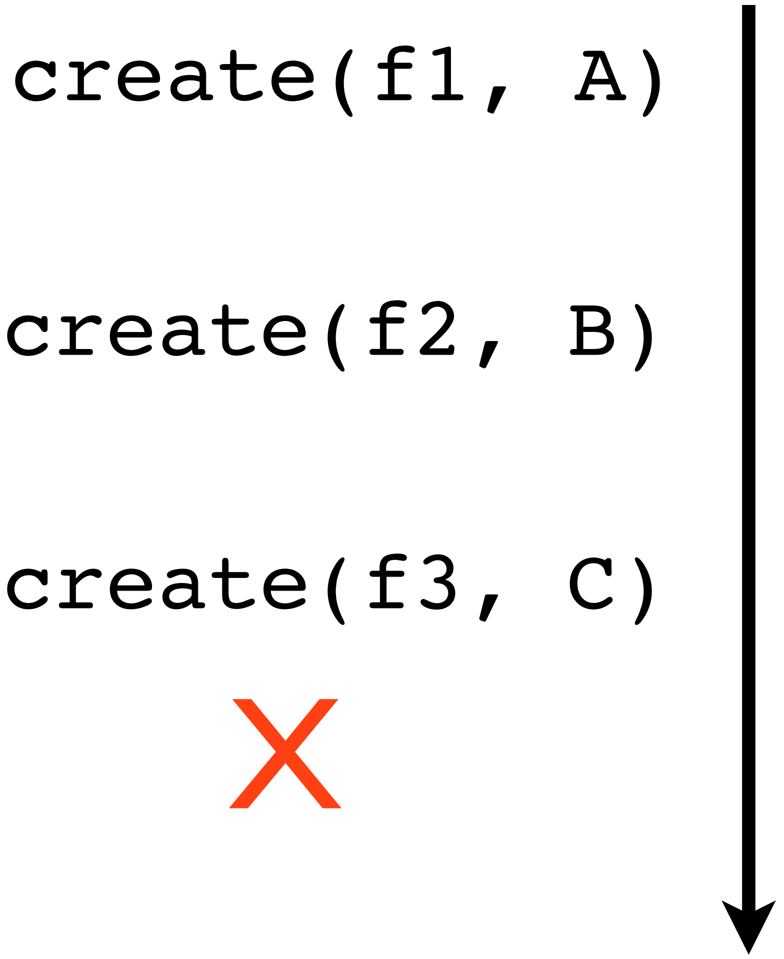


```
create(f1, A)

create(f2, B)

create(f3, C)
```

nosync, fsync and osync



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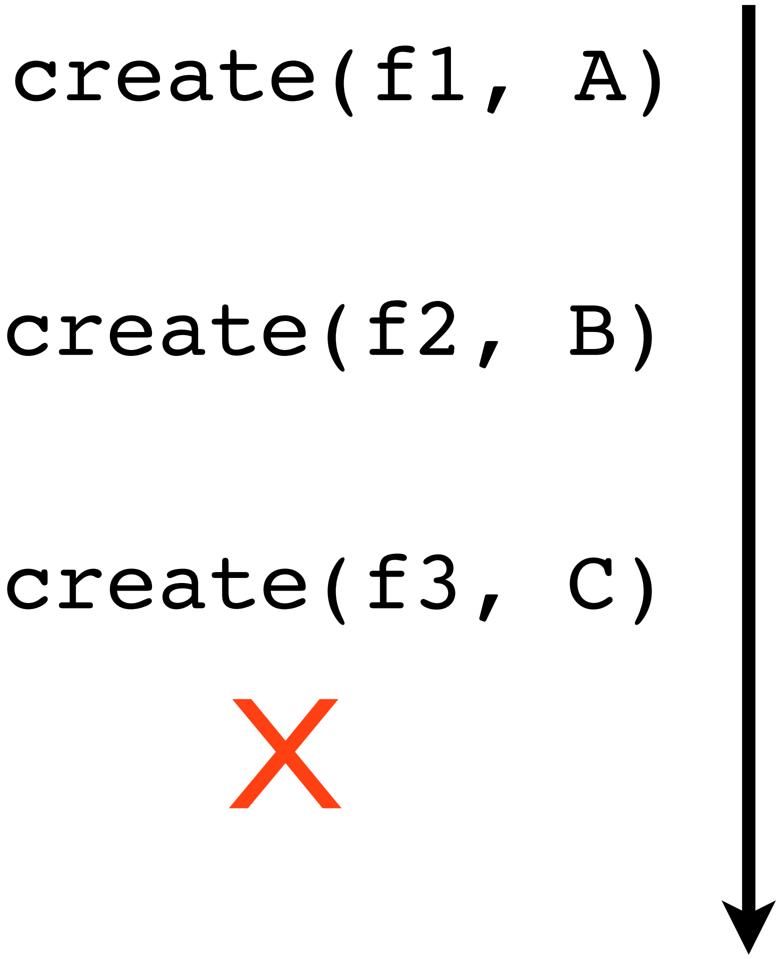

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X

Possible states

(ϕ, ϕ, ϕ) (A, ϕ, ϕ)

(ϕ, ϕ, C) (ϕ, B, ϕ)

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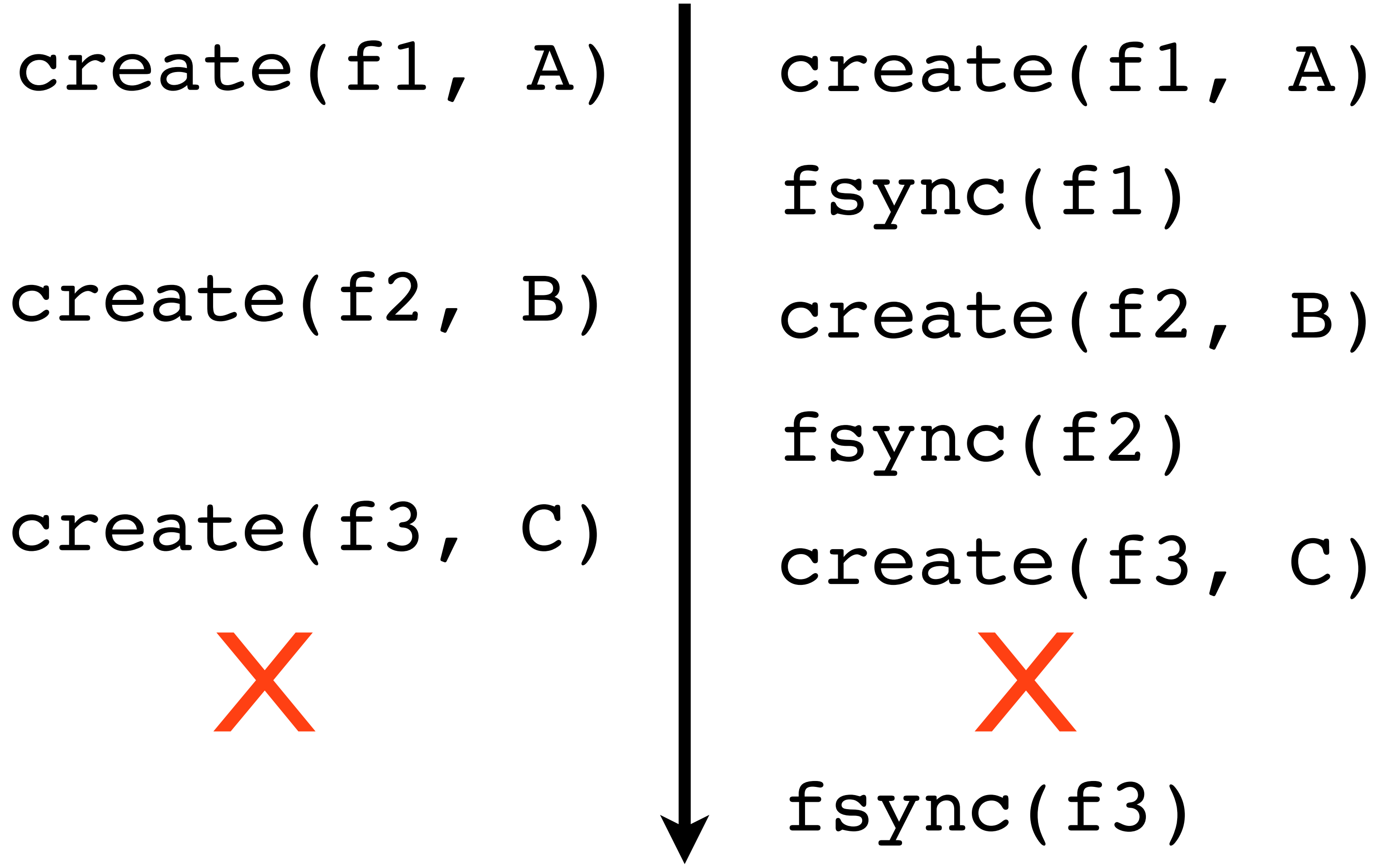

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`osync()` ensures ordering and eventual durability

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osync() use cases

File formats like doc embed a number of files inside them [Harter11]

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Asynchronous Durability Notifications

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Conventional writes
return from the disk cache

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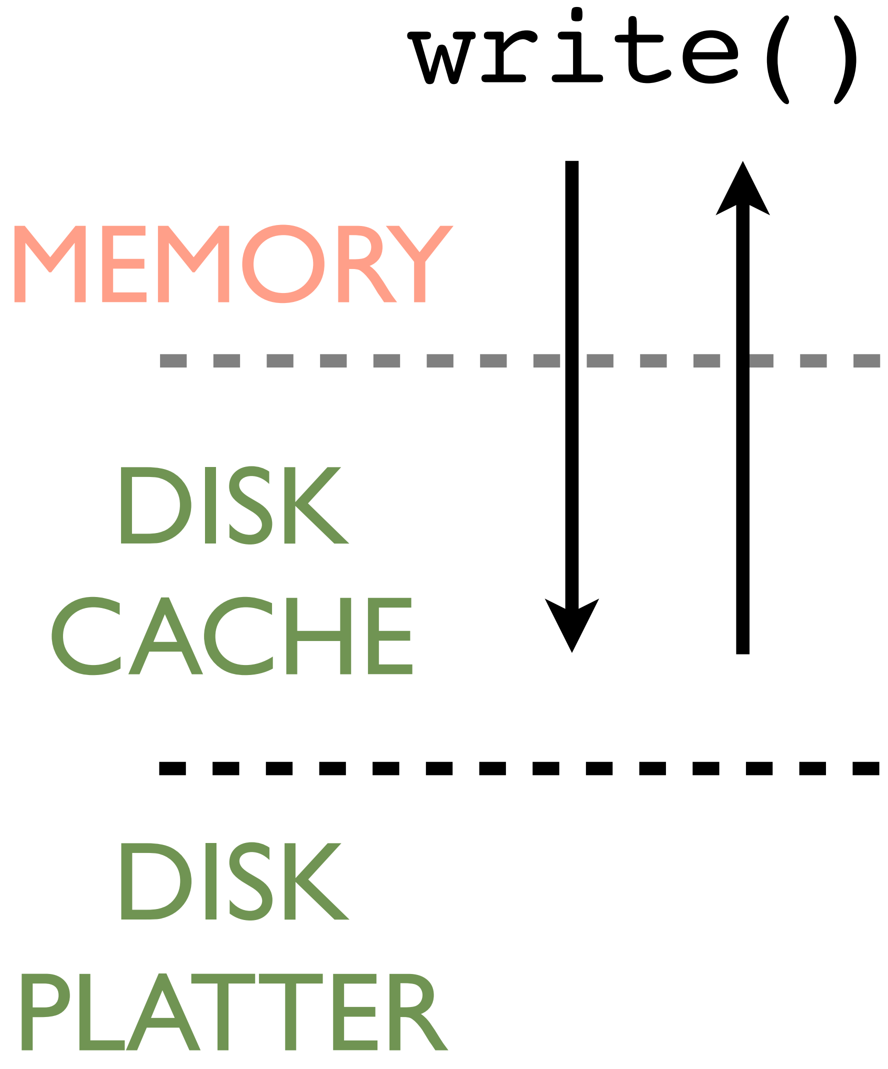
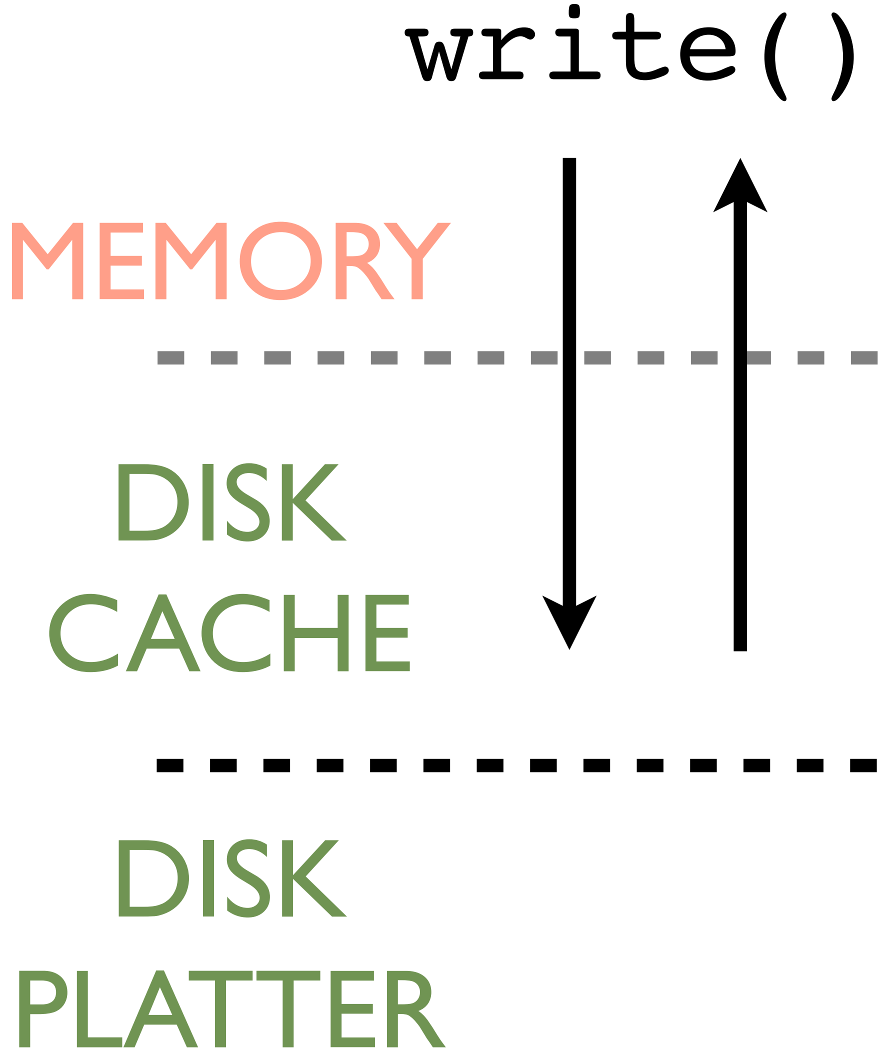


Asynchronous Durability Notifications

Conventional writes return from the disk cache

Flush command used to ensure durability

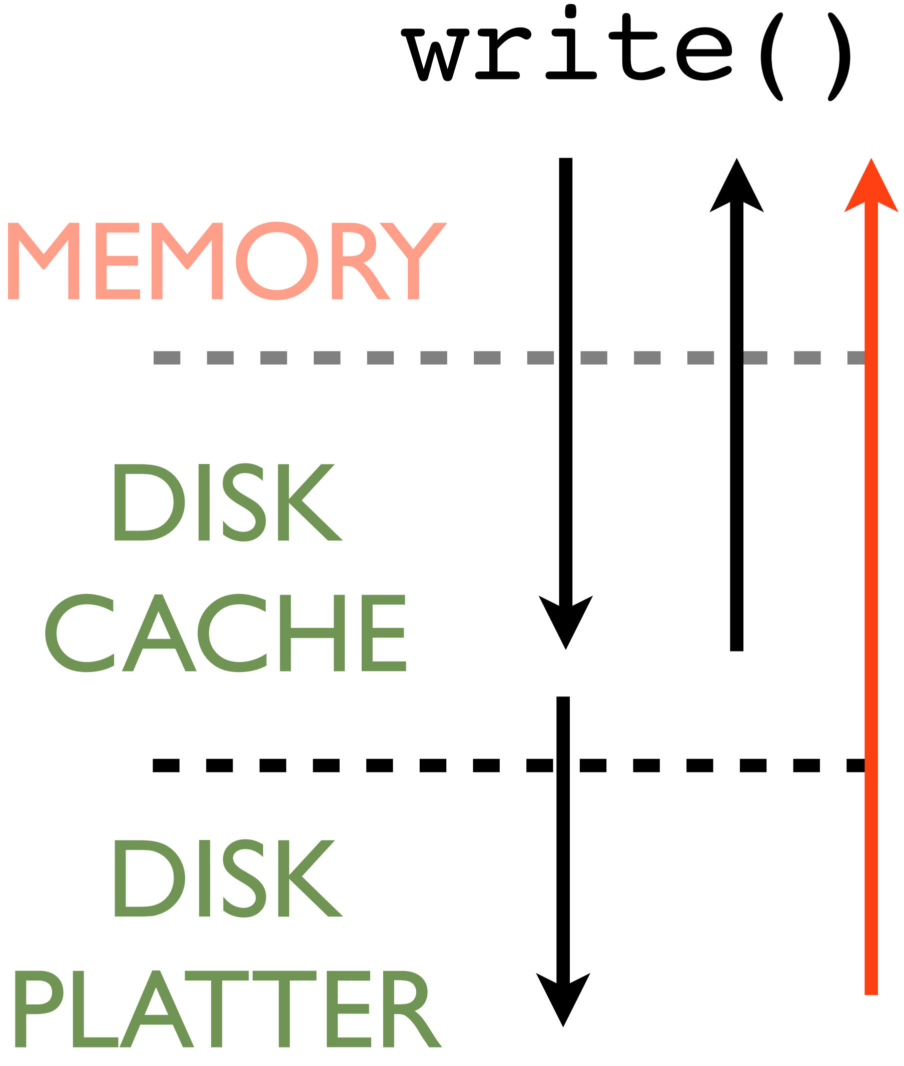


Asynchronous Durability Notifications

Conventional writes return from the disk cache

Flush command used to ensure durability

Asynchronous Durability notifications informs upper layer when blocks are durable



Optimistic Techniques

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Early Commit	D Jc JM M Jc D JM M

Optimistic Techniques

Early Commit	D	JC	JM	M
Checksums	JC	D	JM	M

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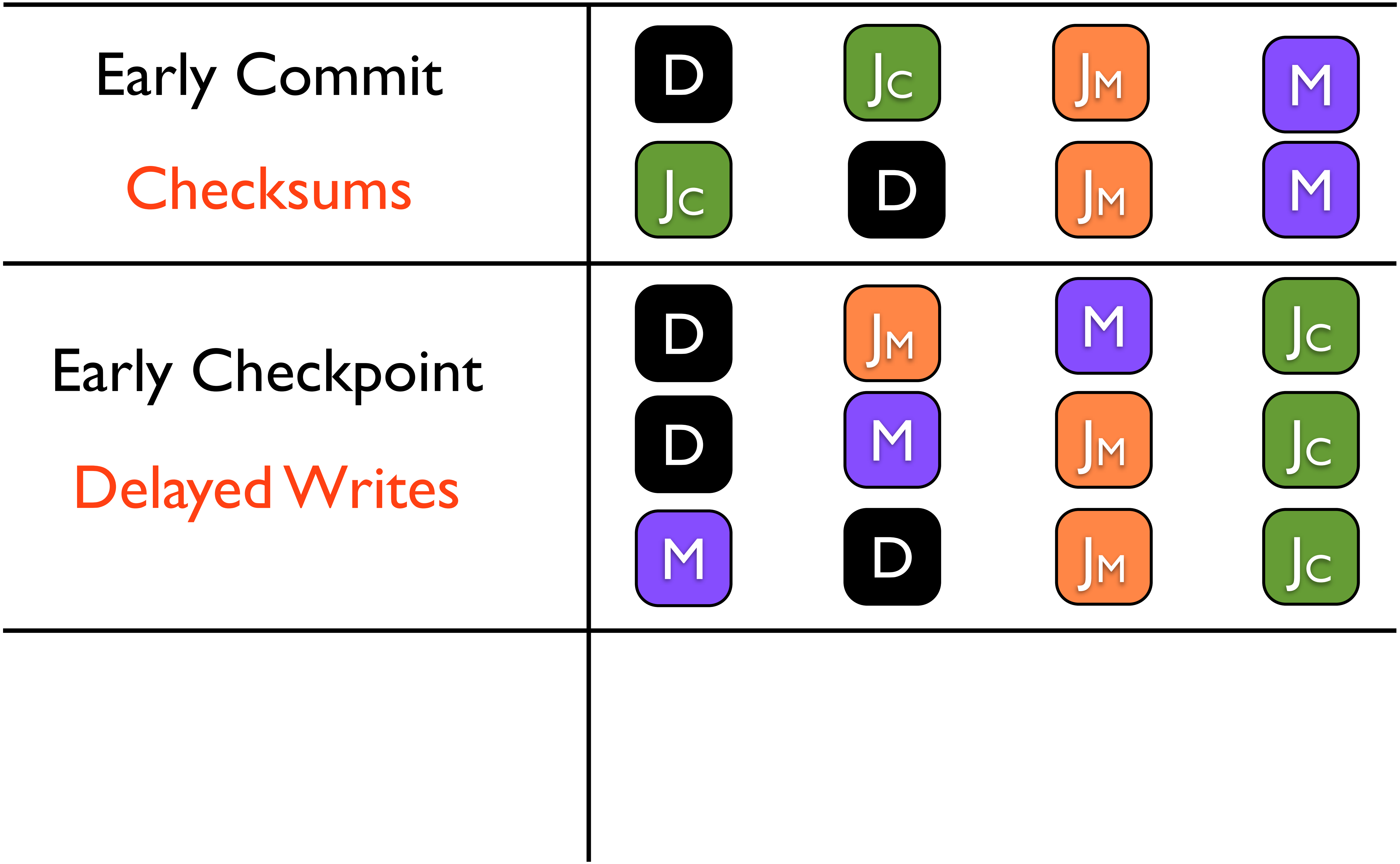
Early Commit	D	JC	JM	M
Checksums	JC	D	JM	M
Early Checkpoint	D	JM	M	JC
	D	M	JM	JC
	M	D	JM	JC

Optimistic Techniques



Early Commit

Checksums

Early Checkpoint

Delayed Writes

Optimistic Techniques

Early Commit

Checksums

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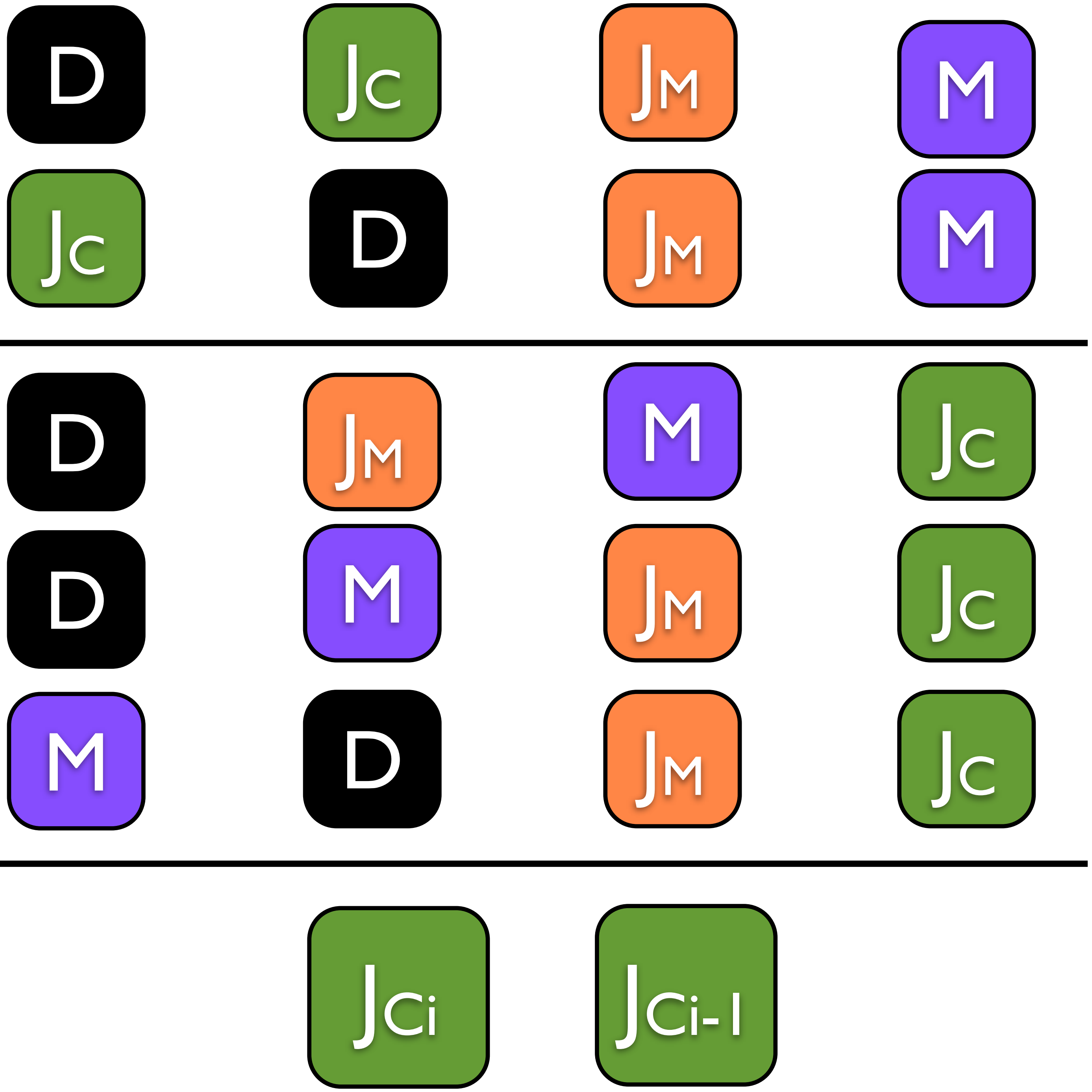
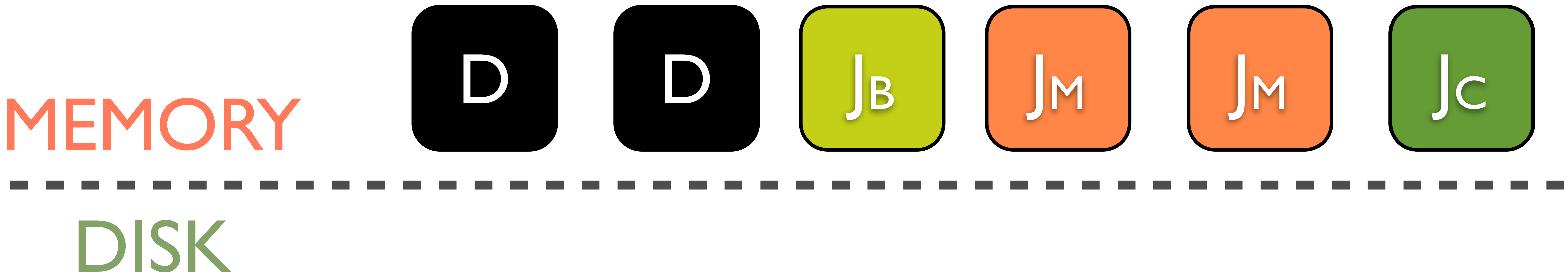
Transaction Misorder



Optimistic Techniques

Early Commit Checksums	D J_C J_M M J_C D J_M M
Early Checkpoint Delayed Writes	D J_M M J_C D M J_M J_C M D J_M J_C
Transaction Misorder In-order Journal Replay & Recovery	J_{C_i} $J_{C_{i-1}}$

Allowing re-ordering



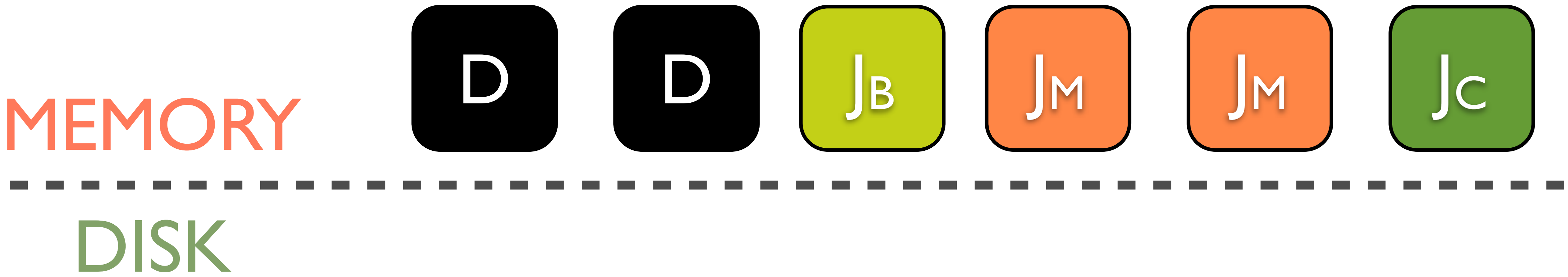
MEMORY

D D J_B J_M J_M J_C

DISK

Allowing re-ordering

We use two checksums to detect mis-ordering upon crash



Allowing re-ordering

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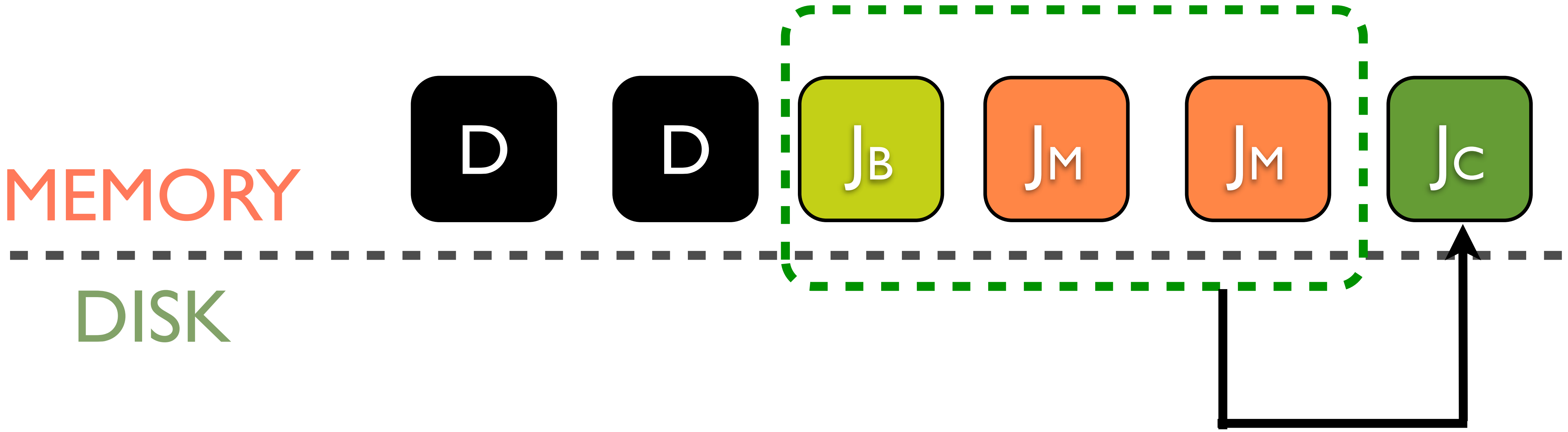
- Metadata transactional checksum [Prabhakaran05]



Allowing re-ordering

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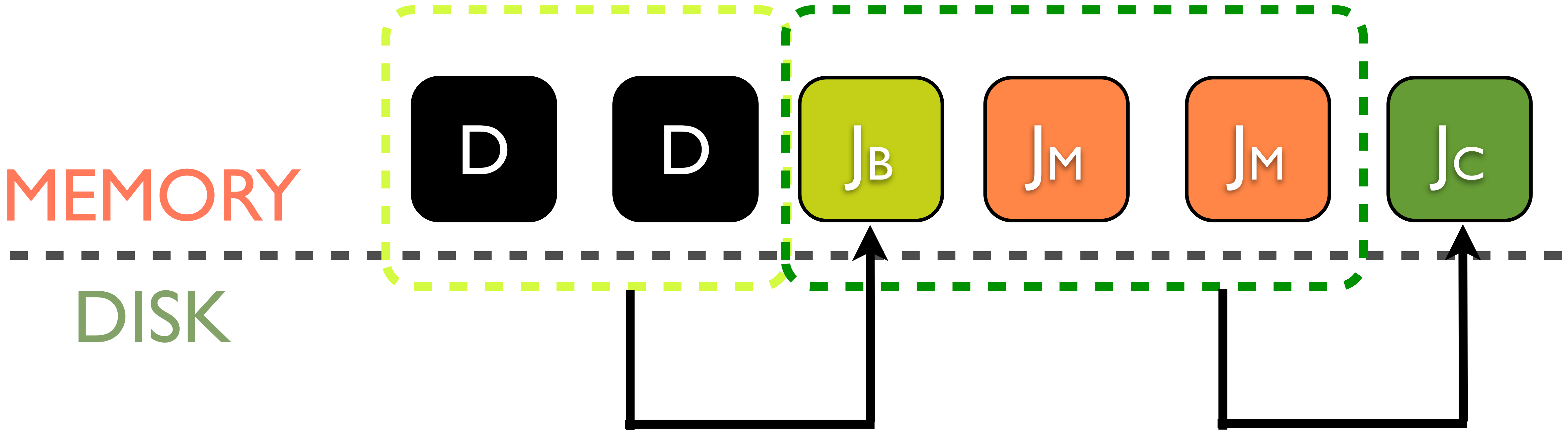
- Metadata transactional checksum [Prabhakaran05]
- Data transactional checksum



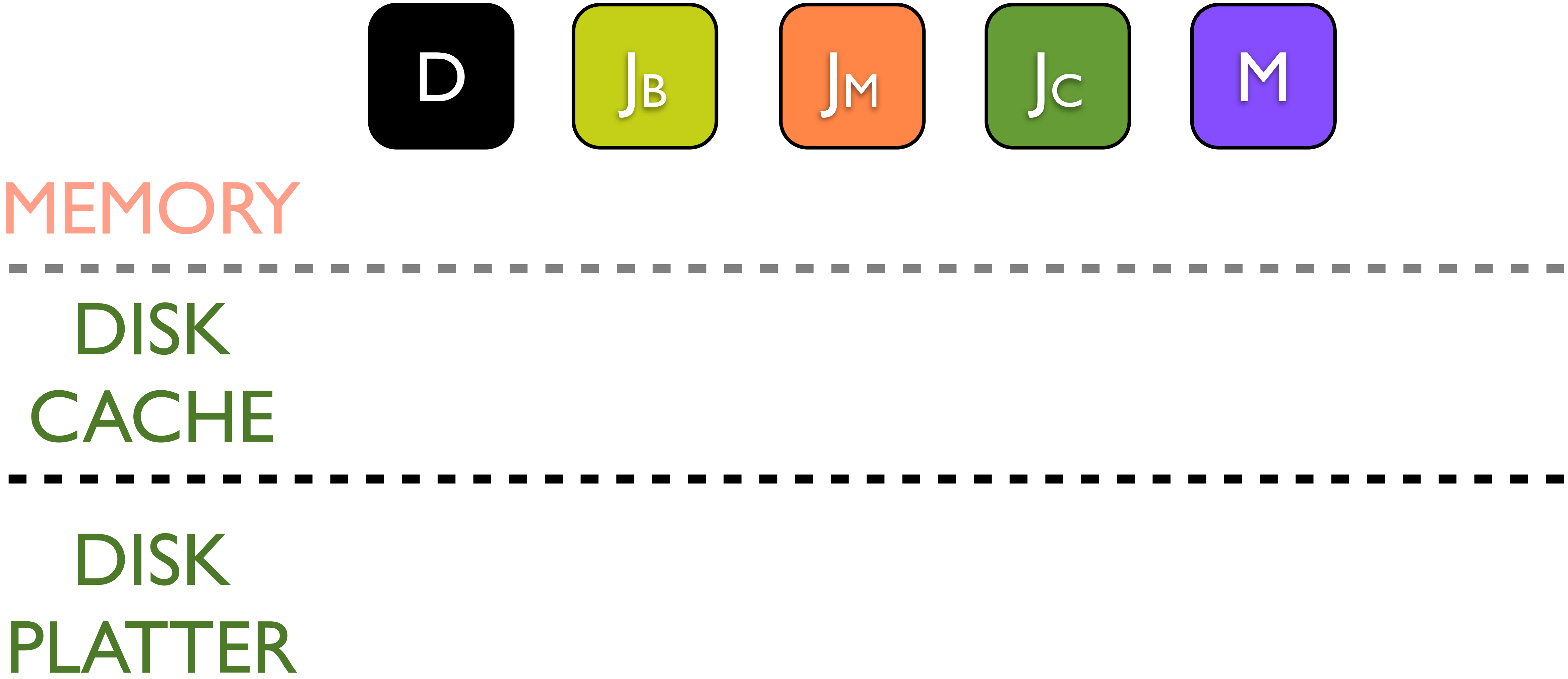
Avoiding re-ordering

We use durability notifications to know when writes leave the disk cache

We avoid having writes we don't want re-ordered in the disk cache at the same time

Avoiding re-ordering

Example: checkpoint writes



D

J_B

J_M

J_C

M

MEMORY

DISK CACHE

DISK PLATTER

Avoiding re-ordering

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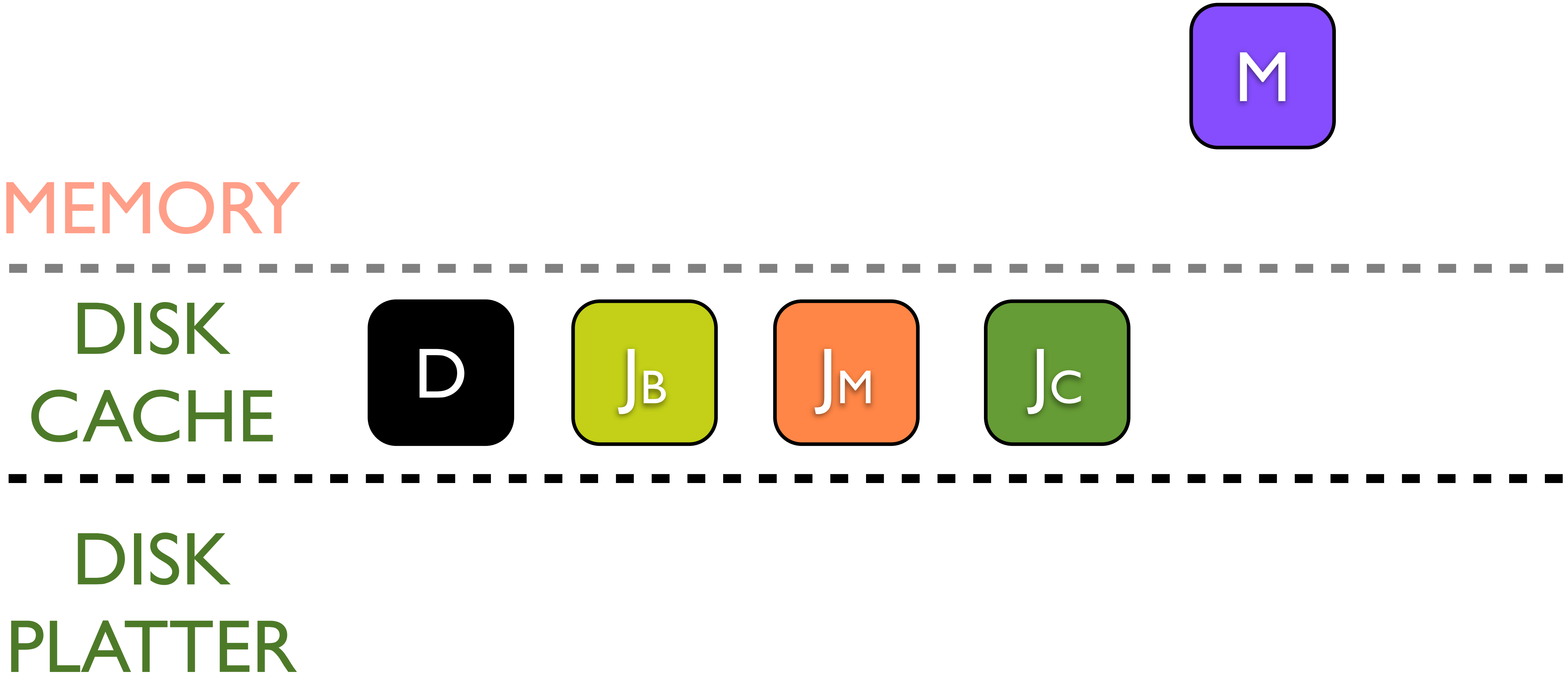

M

MEMORY

DISK CACHE

D

JB

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JC

DISK PLATTER

Avoiding re-ordering

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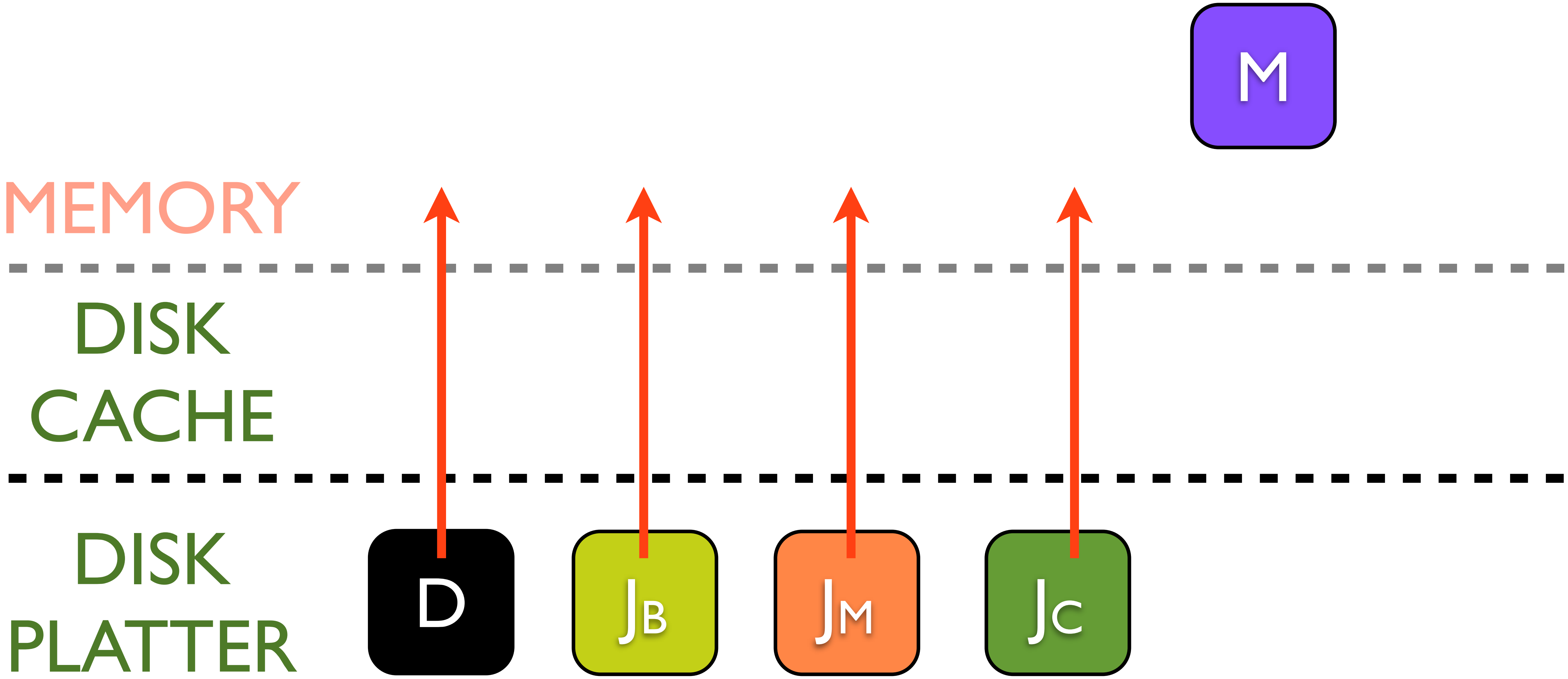

Avoiding re-ordering

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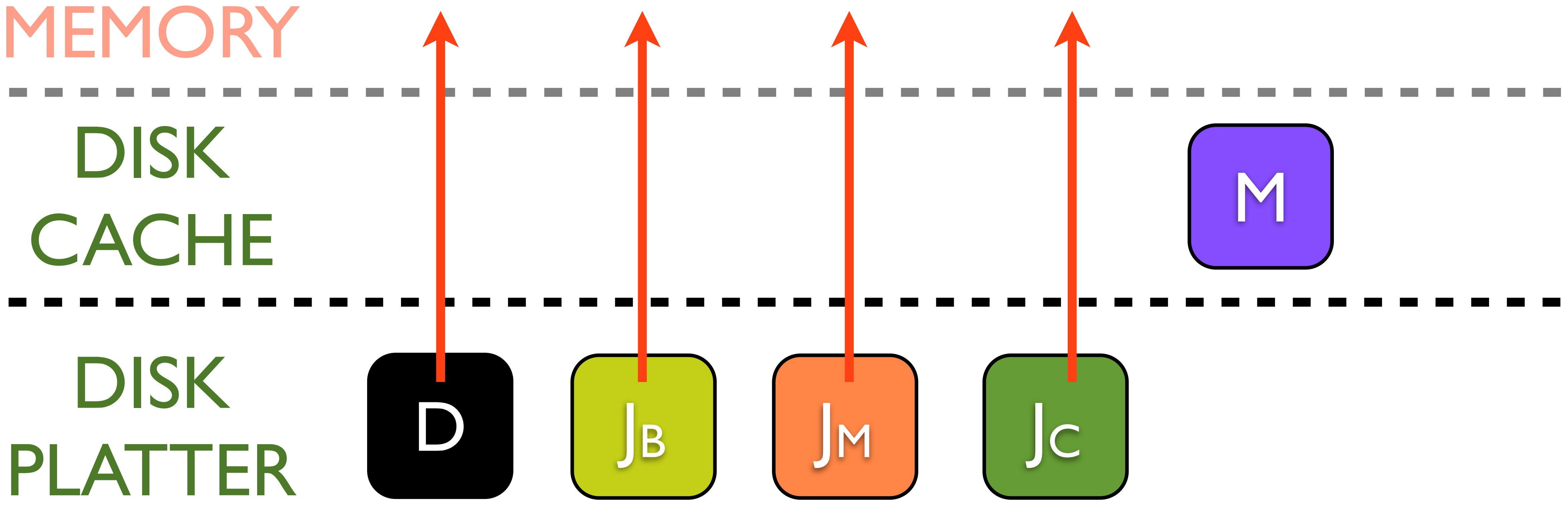

Avoiding re-ordering

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We delay checkpoint writes:

- Write checkpoint blocks only after the entire transaction is durable
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Avoiding re-ordering

We delay checkpoint writes:

- Write checkpoint blocks only after the entire transaction is durable
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We delay freeing journal blocks:

- Free journal blocks only after entire transaction has been durably checkpointed
- Free journal transaction blocks in order

In-order recovery

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After a crash, we recover journal transactions in order

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Eligible transactions are replayed

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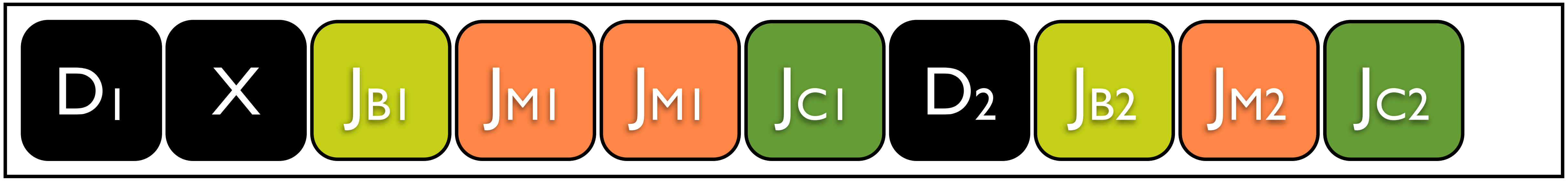
On-disk journal



D_1 X J_{B1} J_{M1} J_{M1} J_{C1} D_2 J_{B2} J_{M2} J_{C2}

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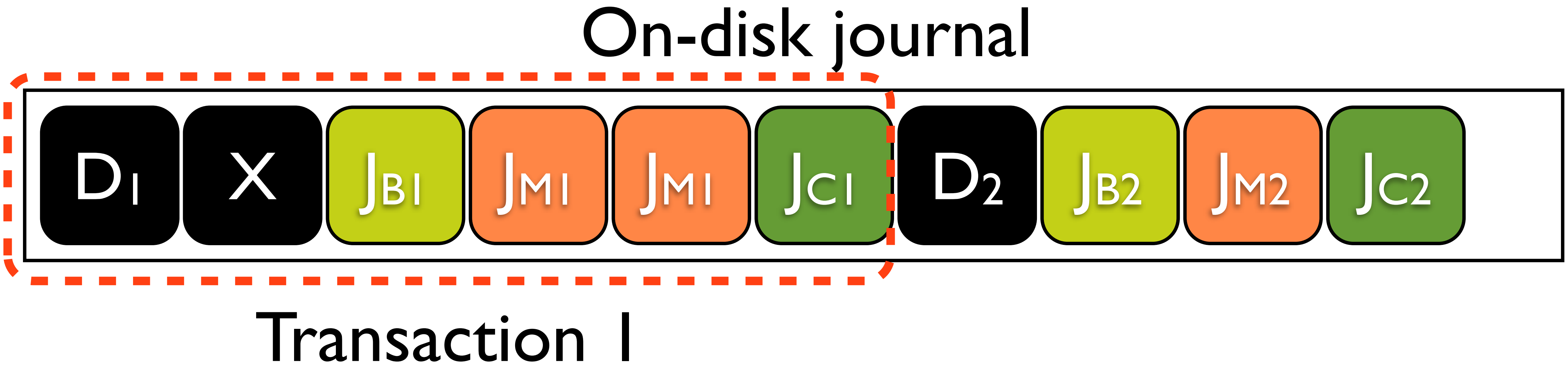

On-disk journal

Transaction 1

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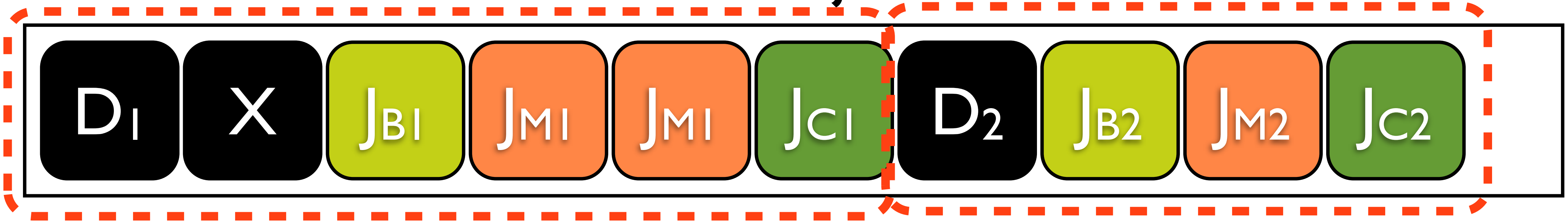
On-disk journal



Transaction 1

Transaction 2

Handling Data Overwrites

In ordered journaling mode, even if tx fails, data block cannot be rolled back

D JM JC M

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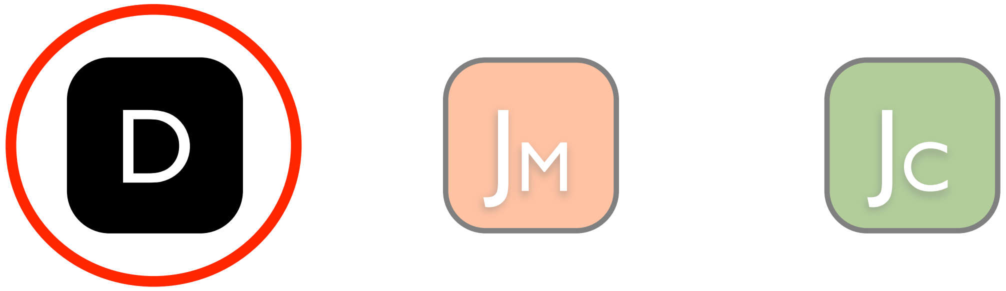

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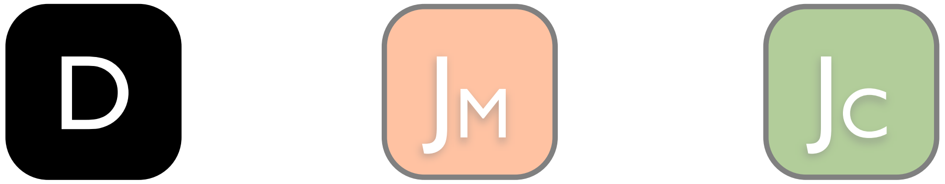

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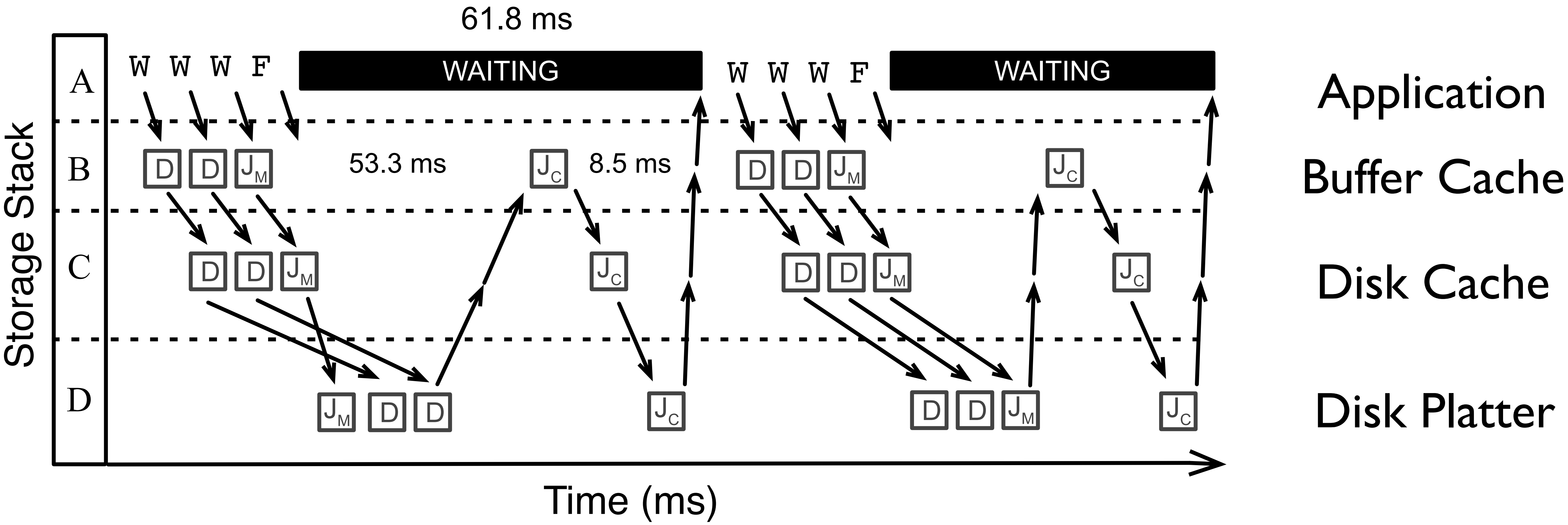
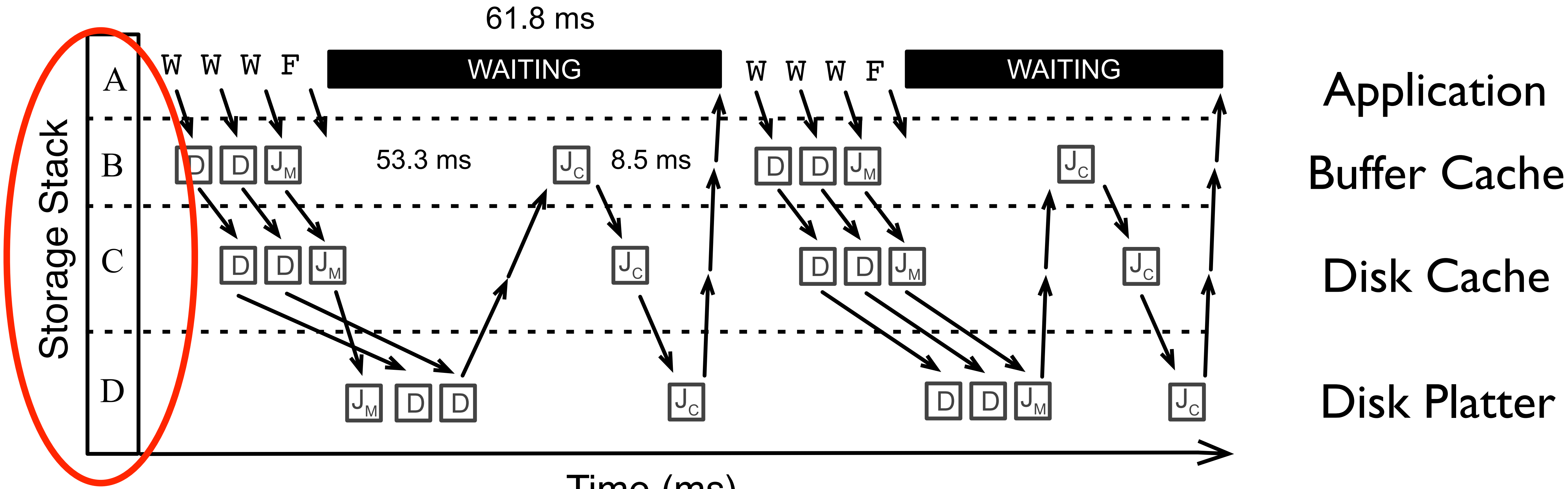
Using checksums, delayed writes and in-order recovery, the optimistic protocol ensures consistency without flushing



ext4 with barriers



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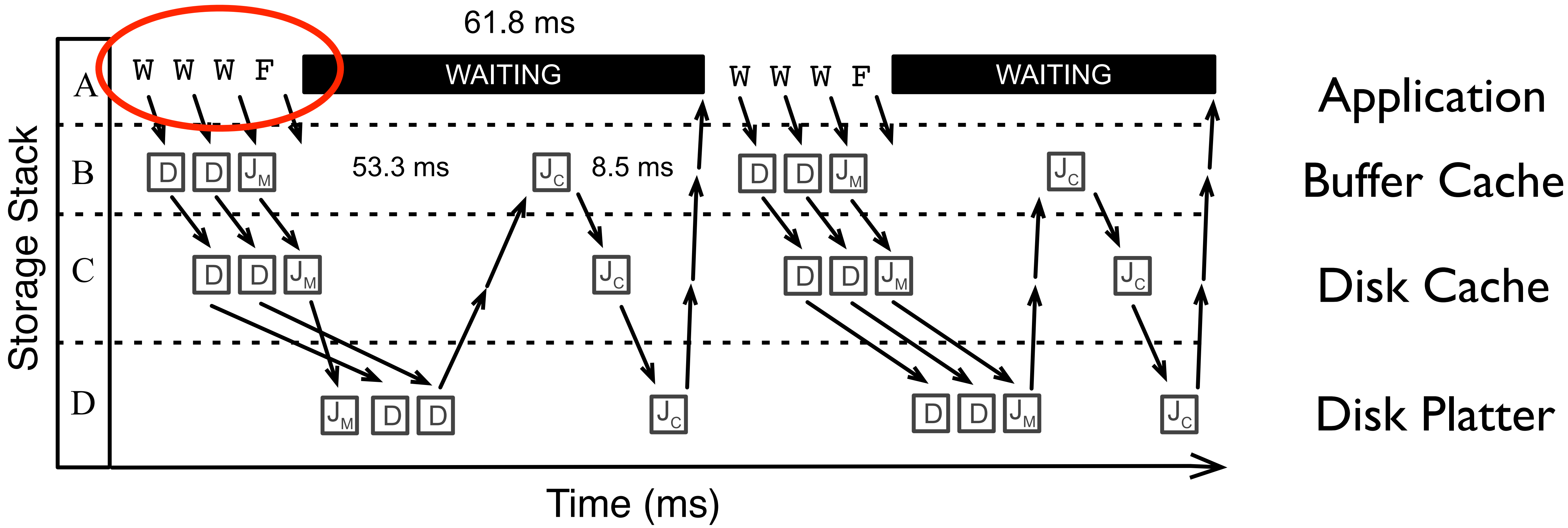

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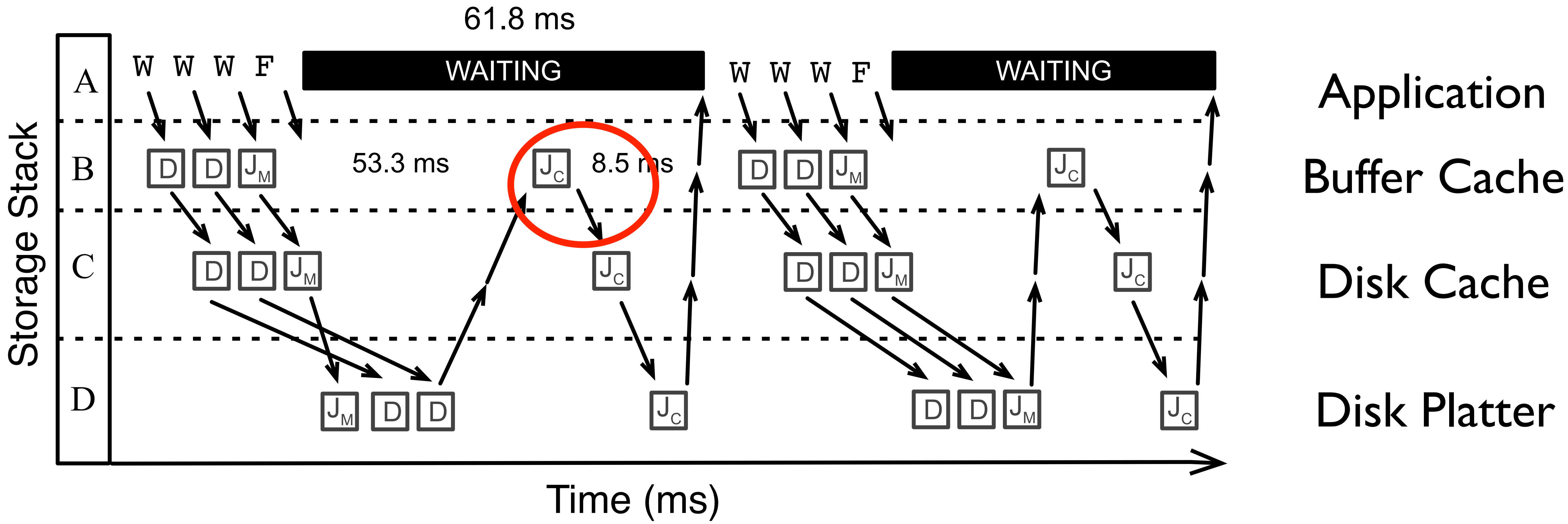

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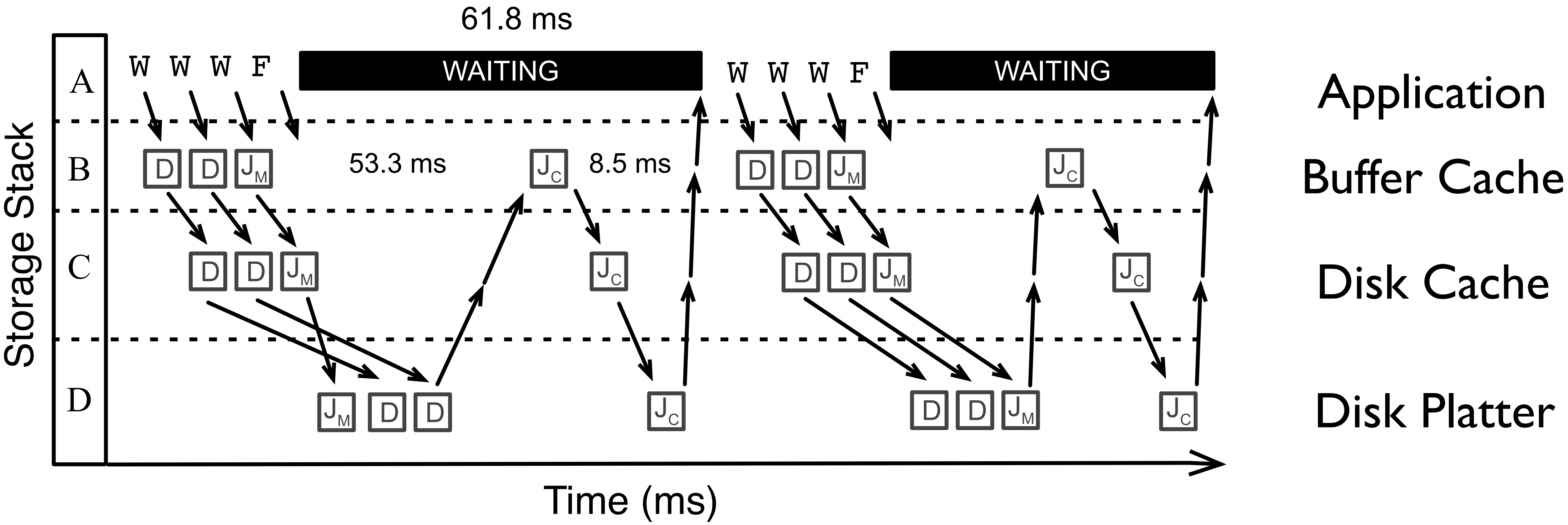

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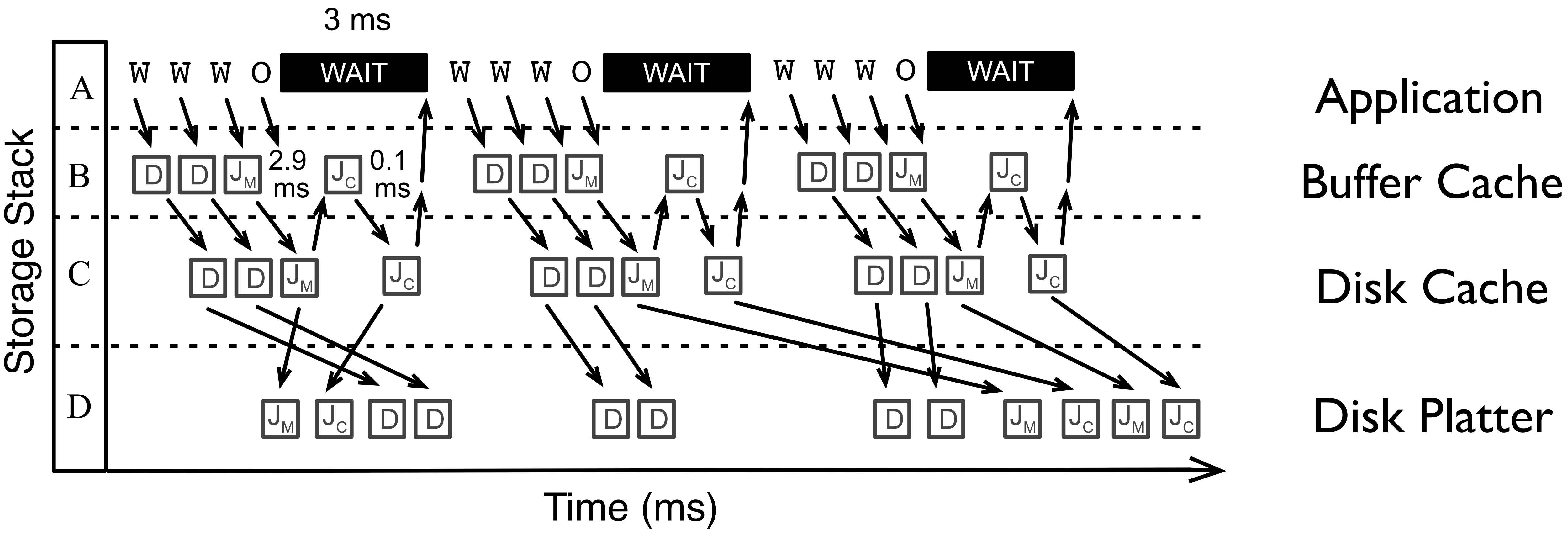
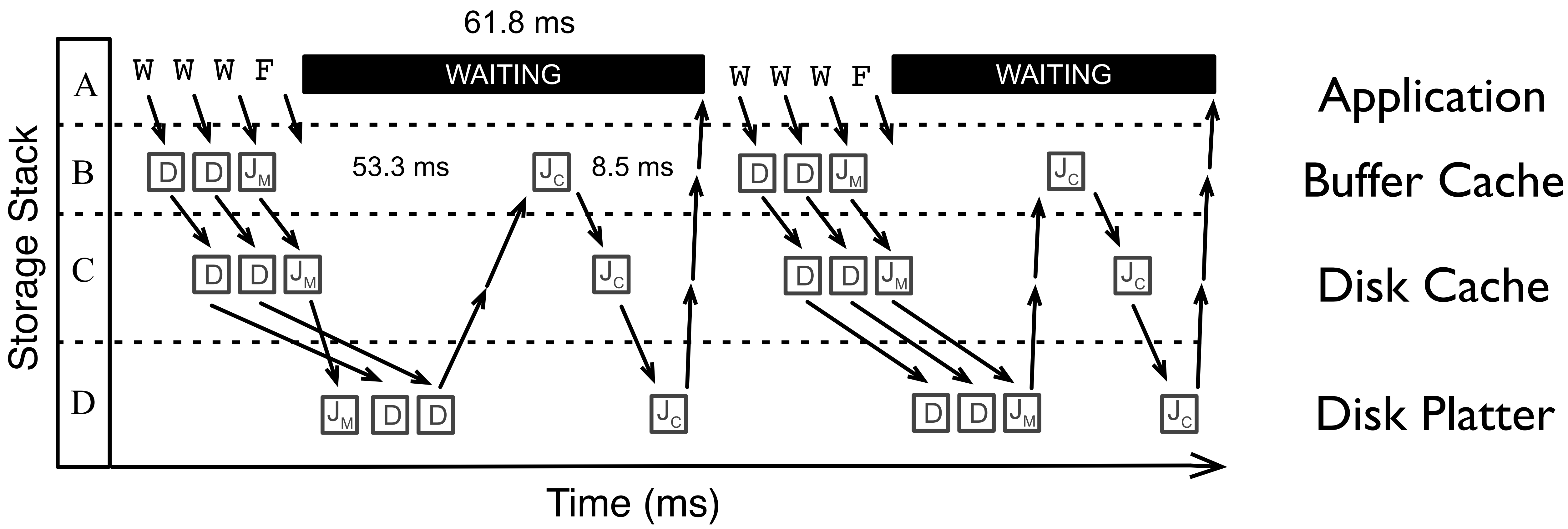


OptFS



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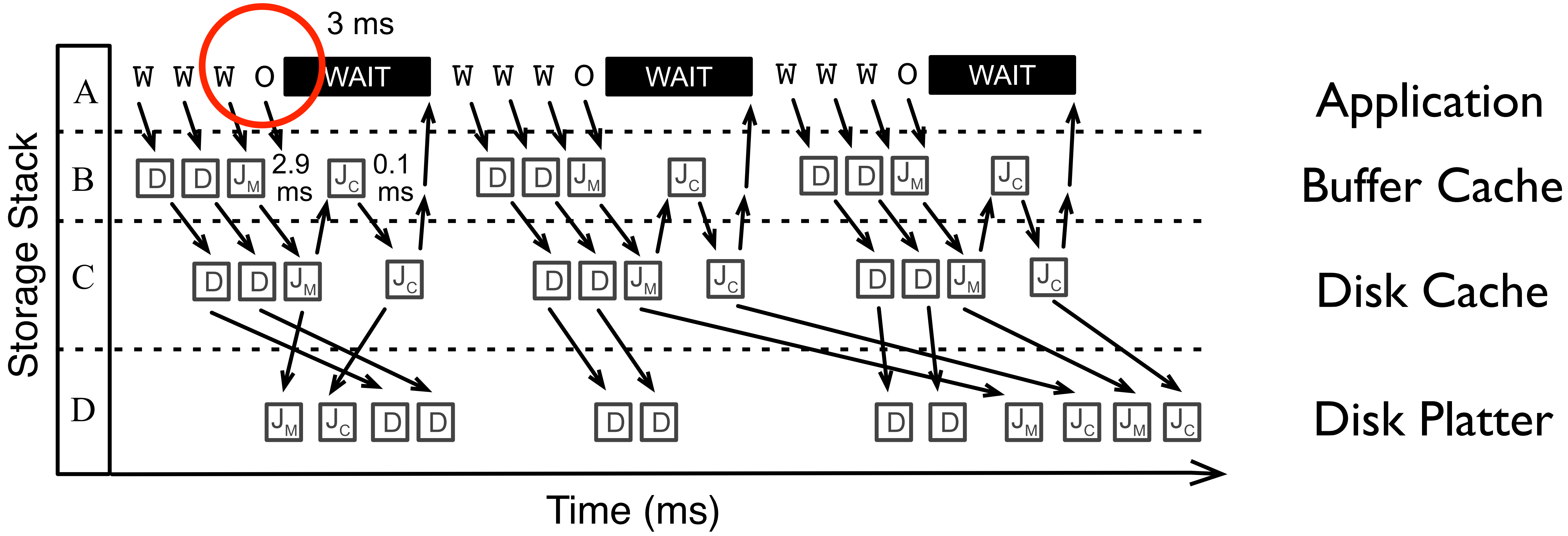

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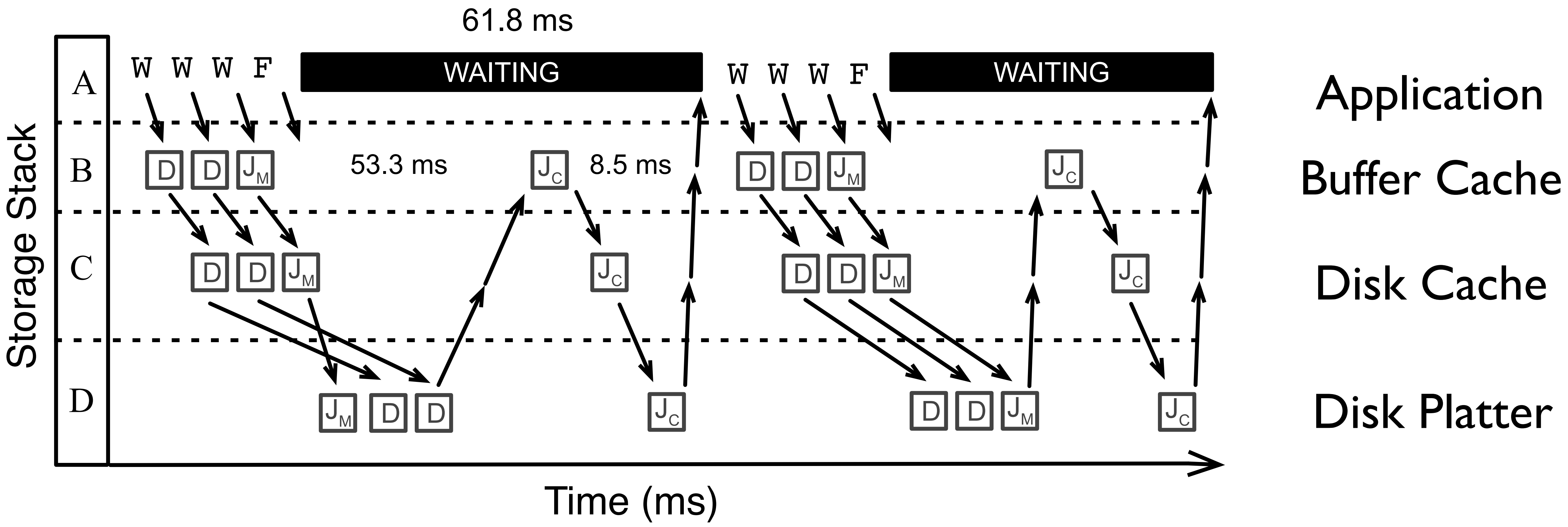
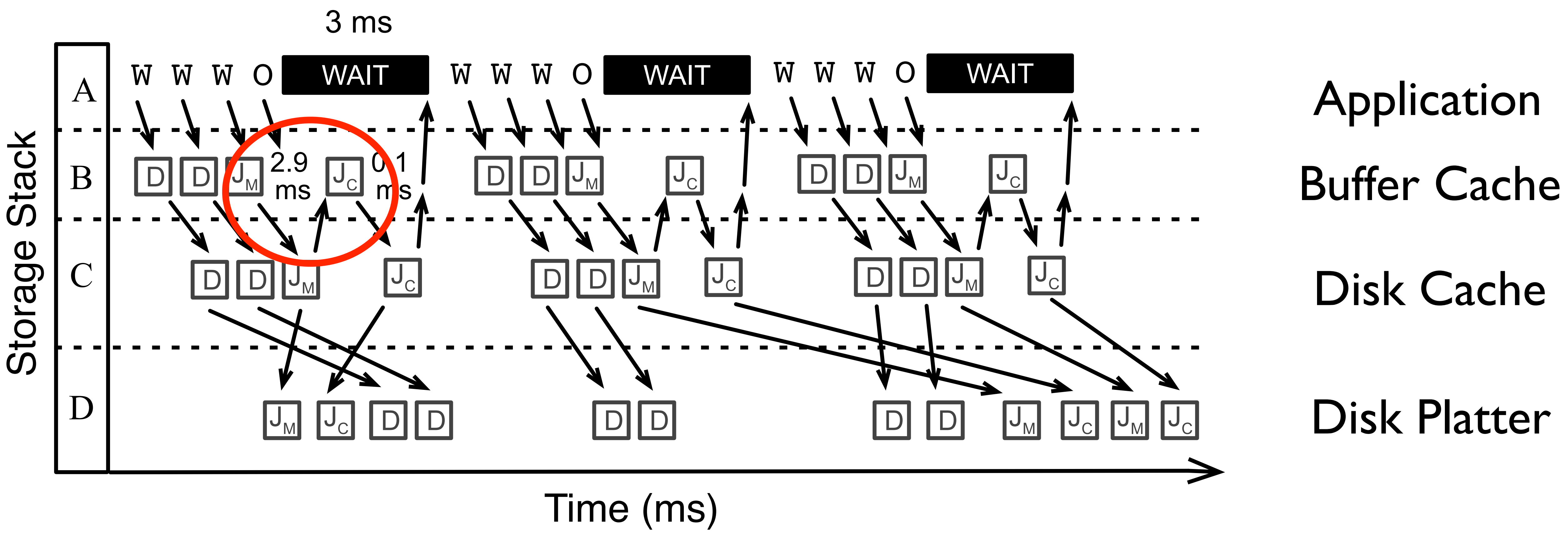
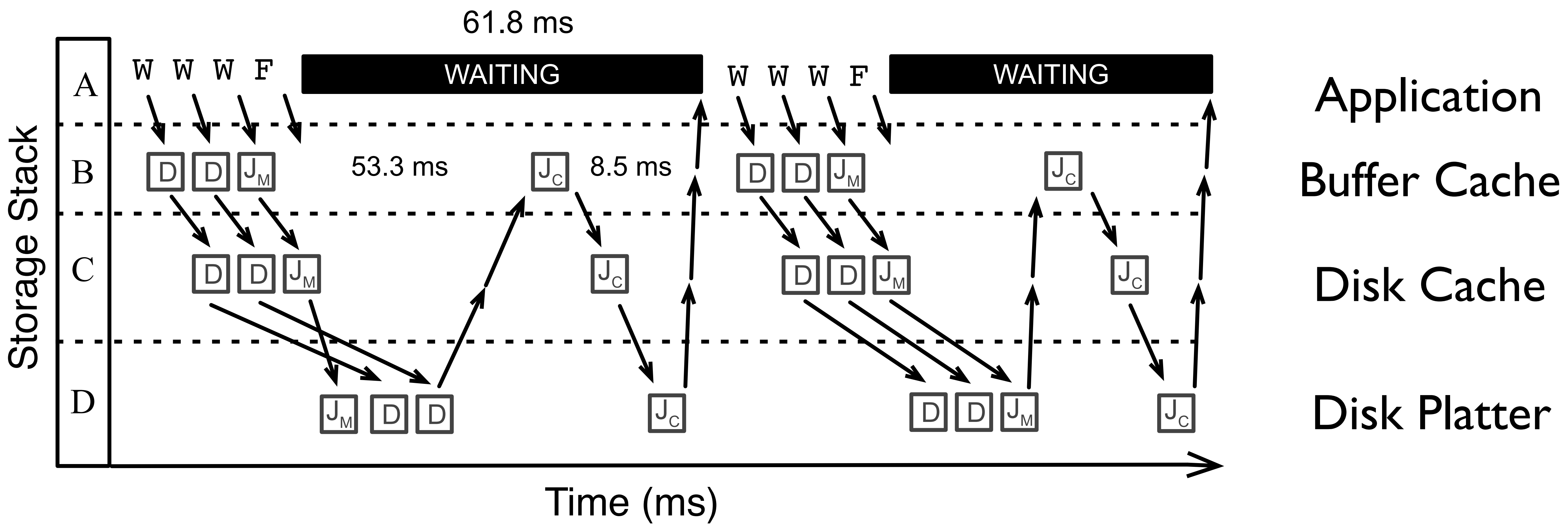


ext4 with barriers



OptFS



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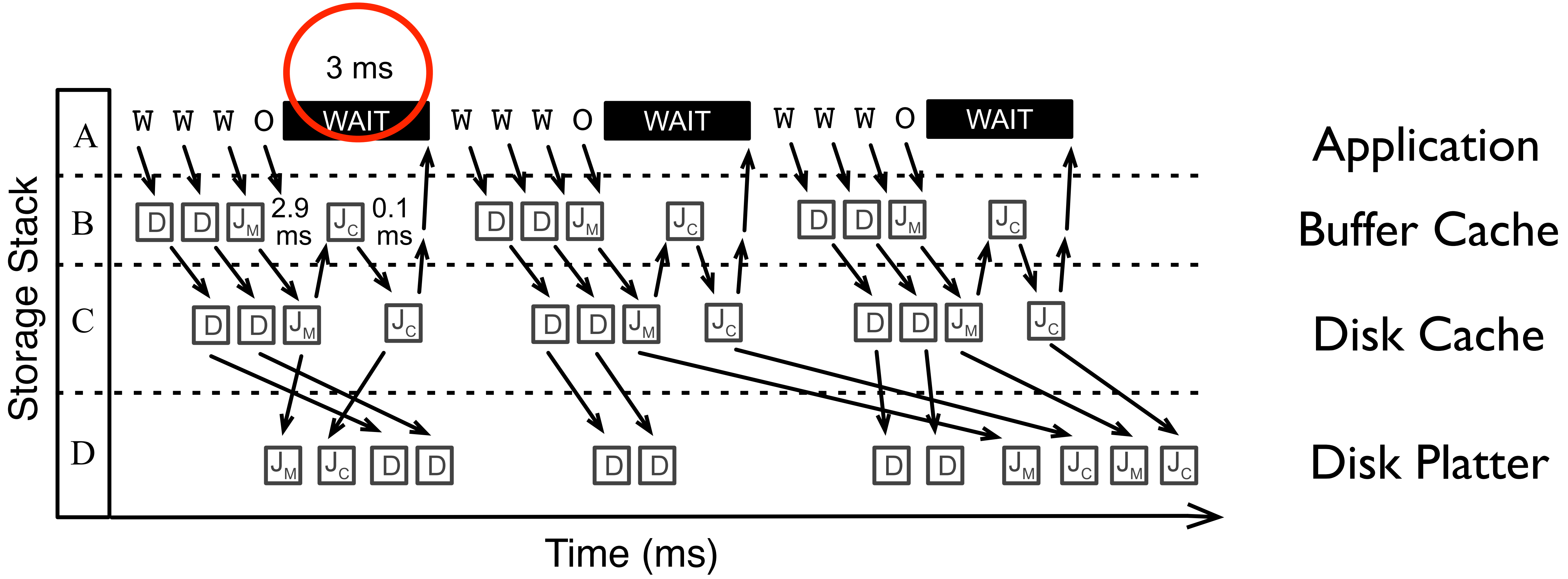

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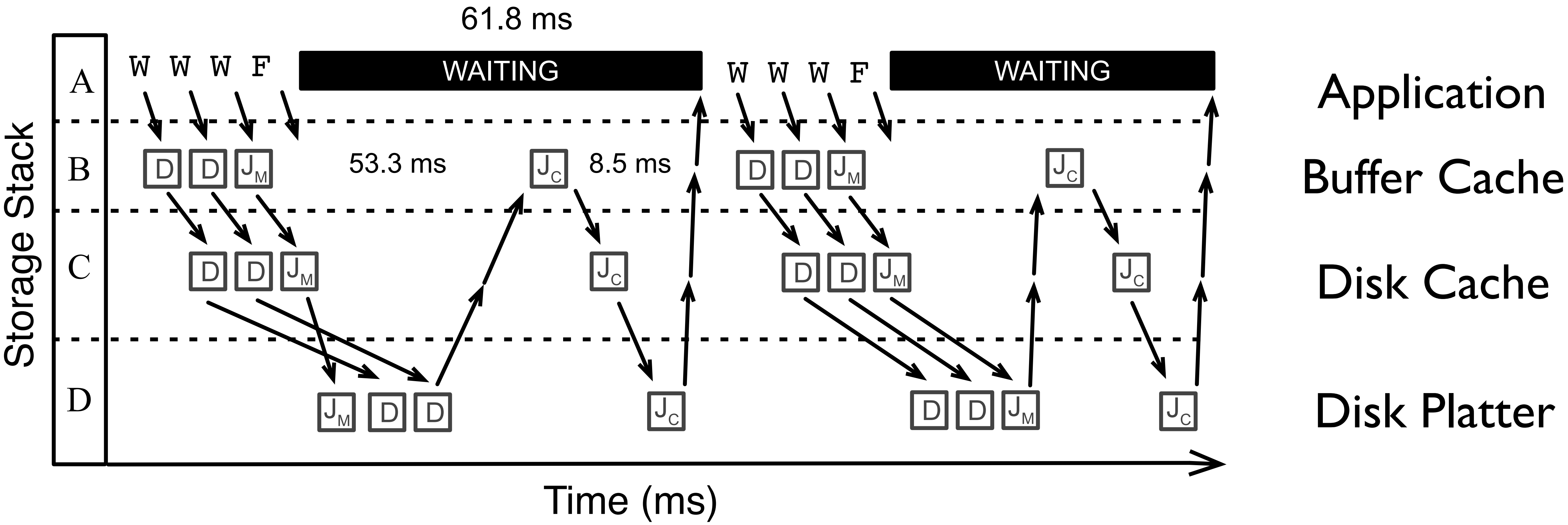

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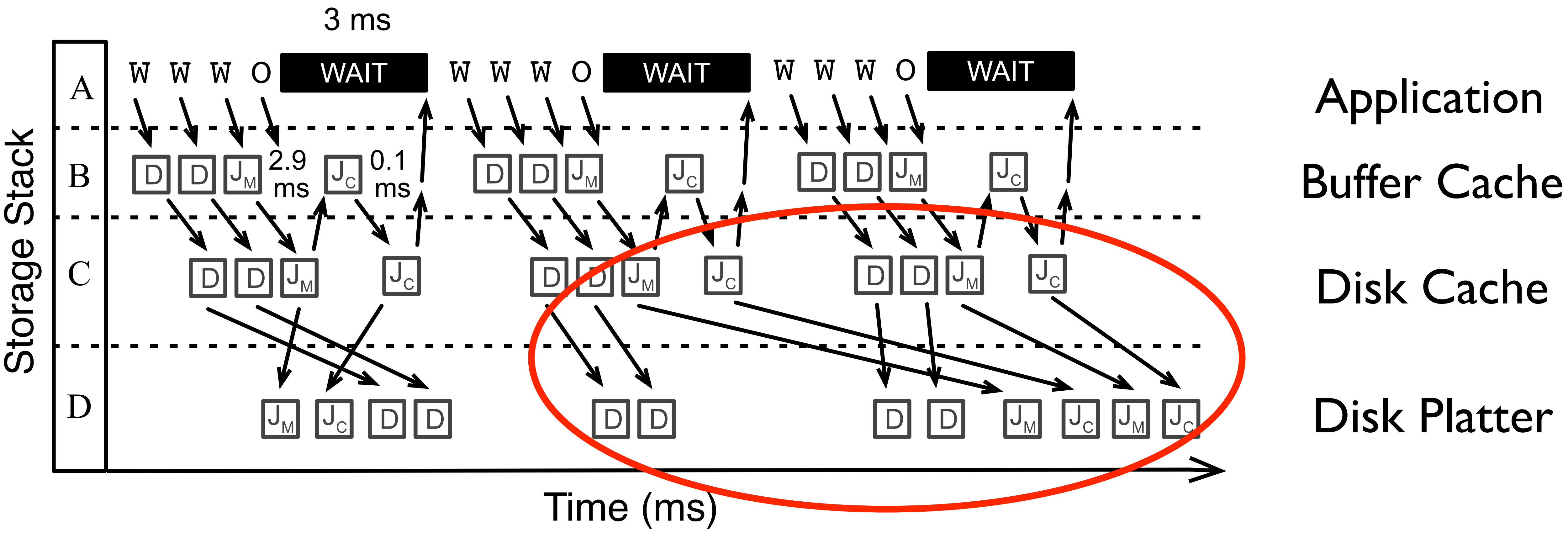

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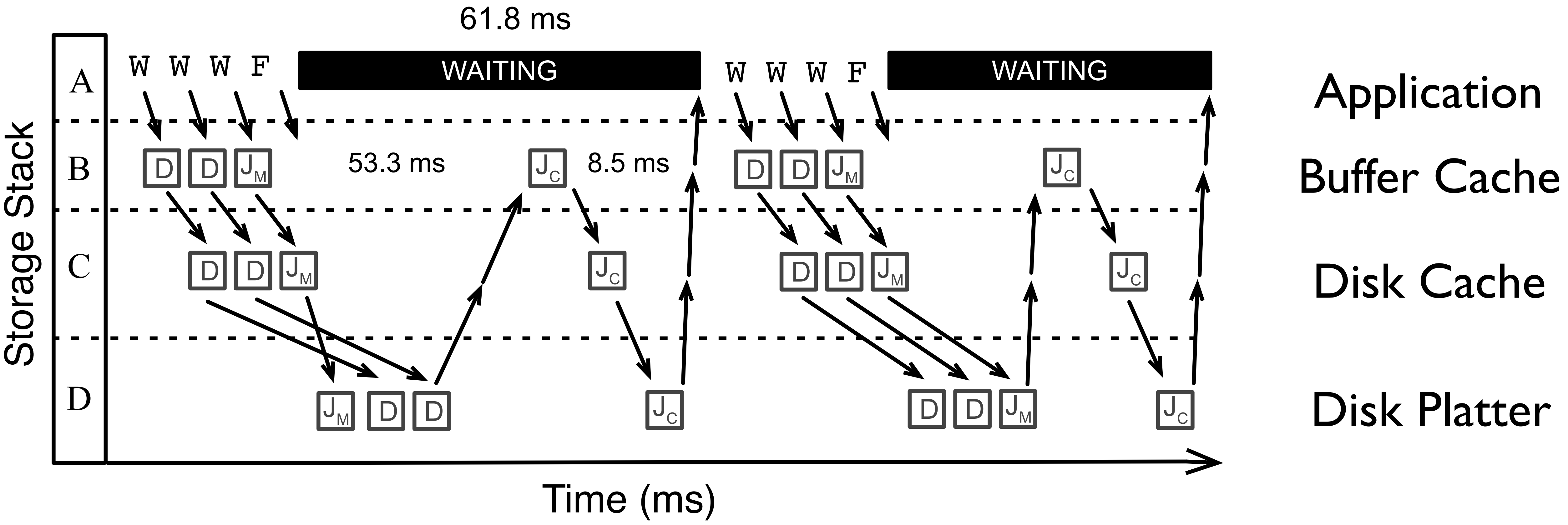

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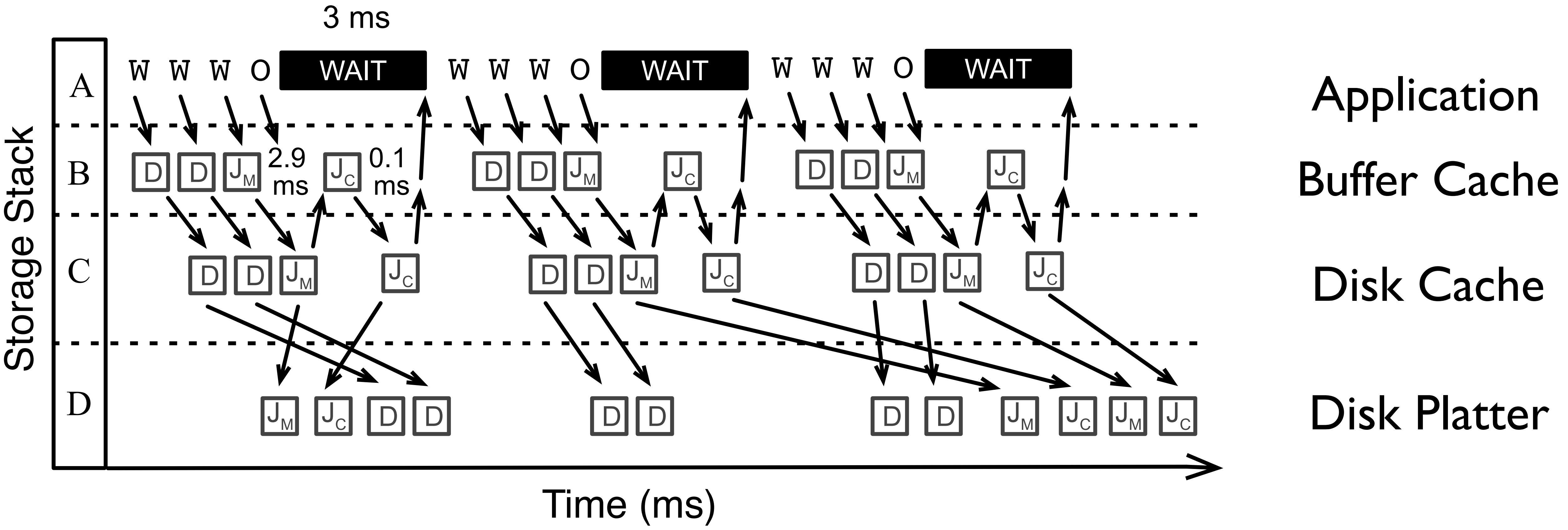

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Evaluation

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Is OptFS reliable to random crashes?

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What is the performance of OptFS?

- Evaluate on different workloads
- Overwrites in OptFS cause 2 writes: one to the journal and one to the file system

Reliability

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Built a crash-testing framework

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Workloads:

- Append to a file
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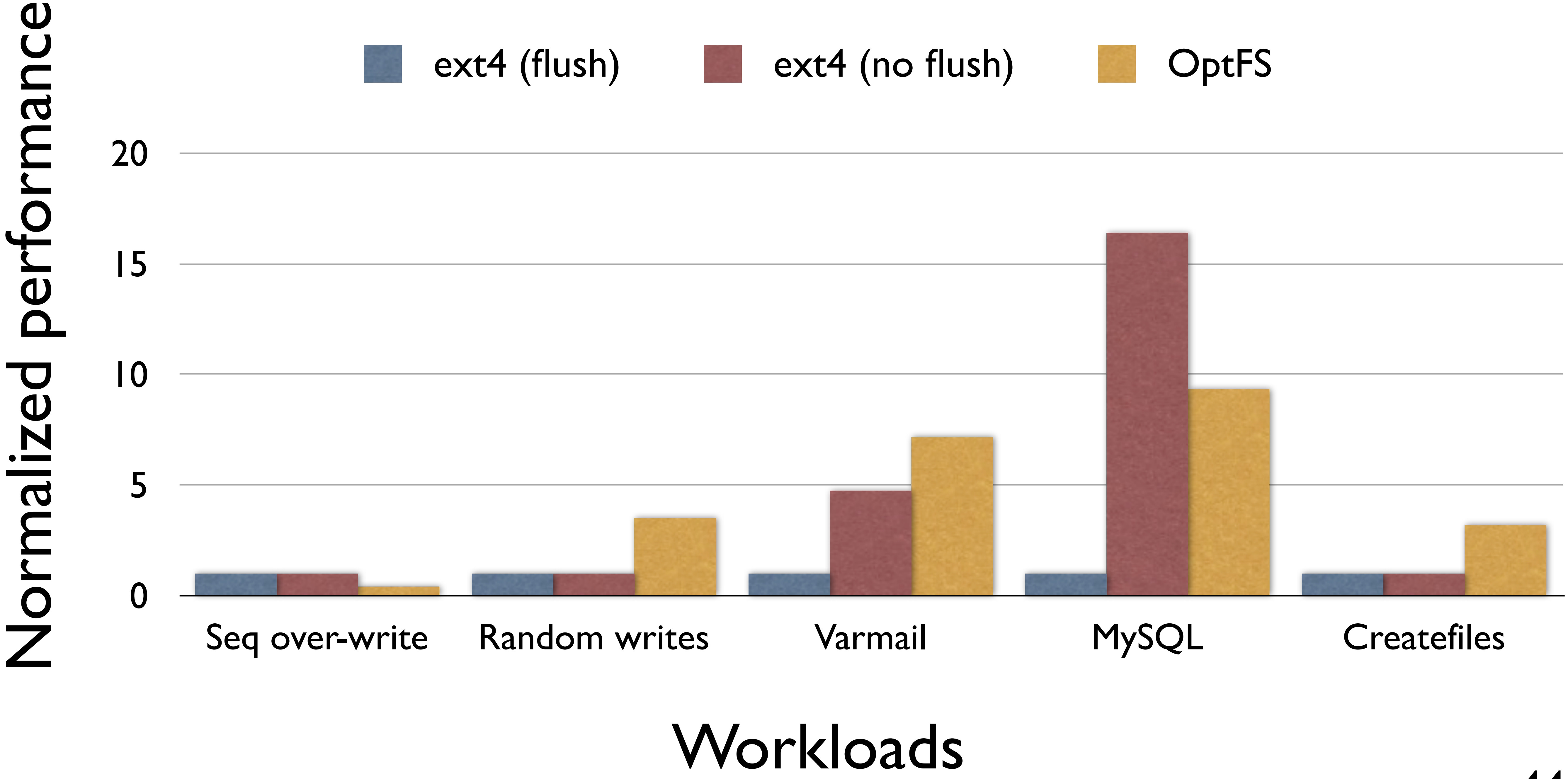

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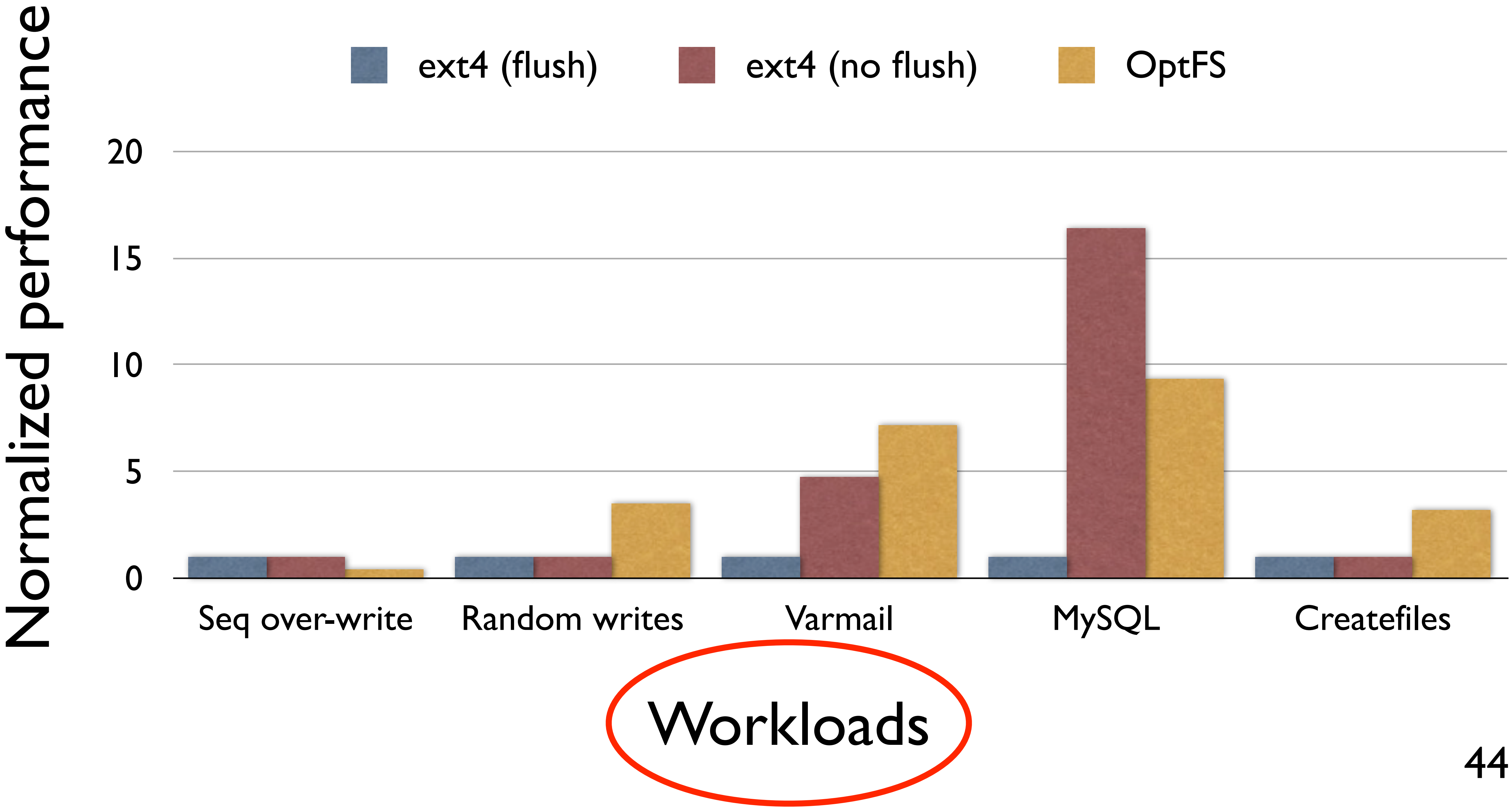

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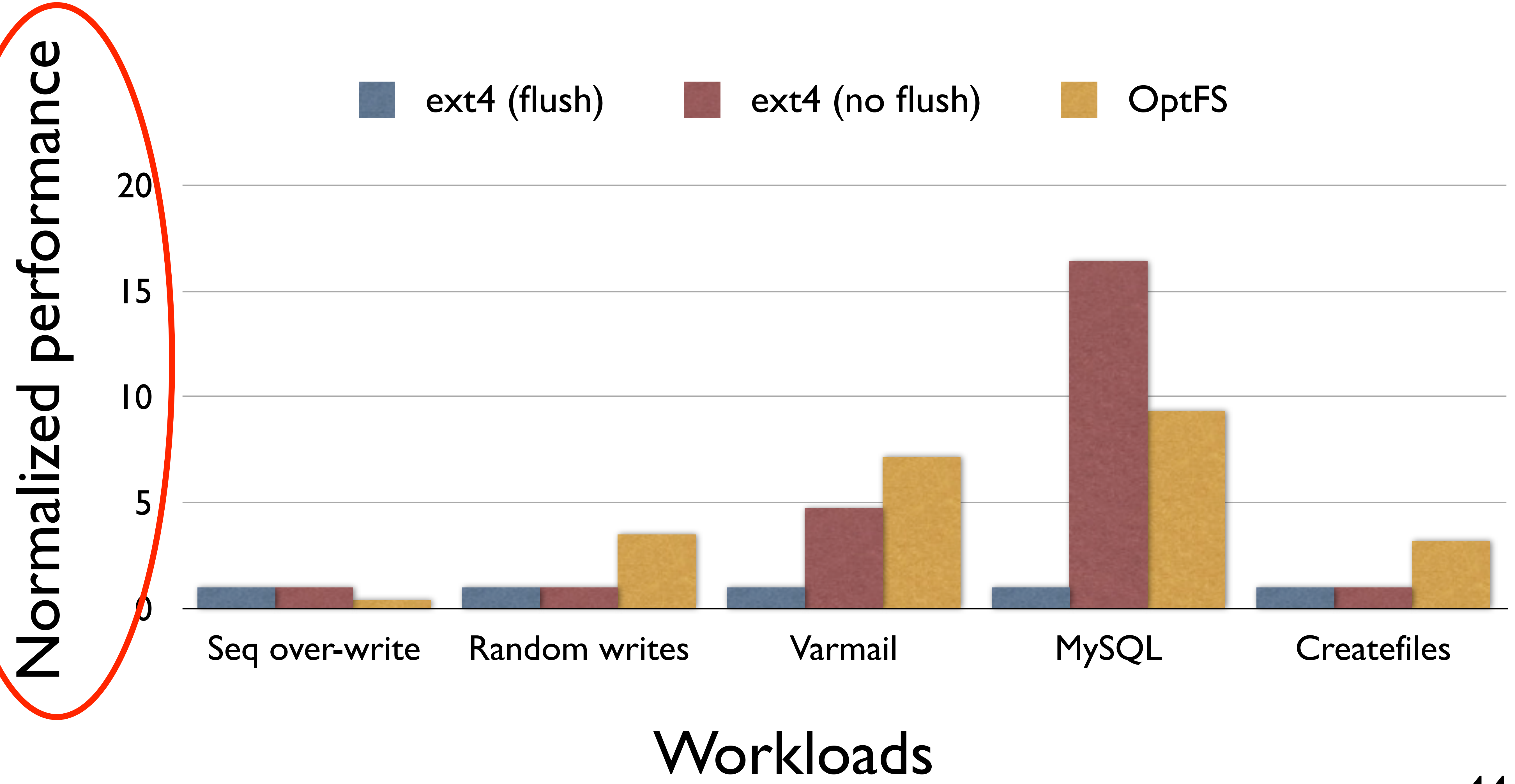

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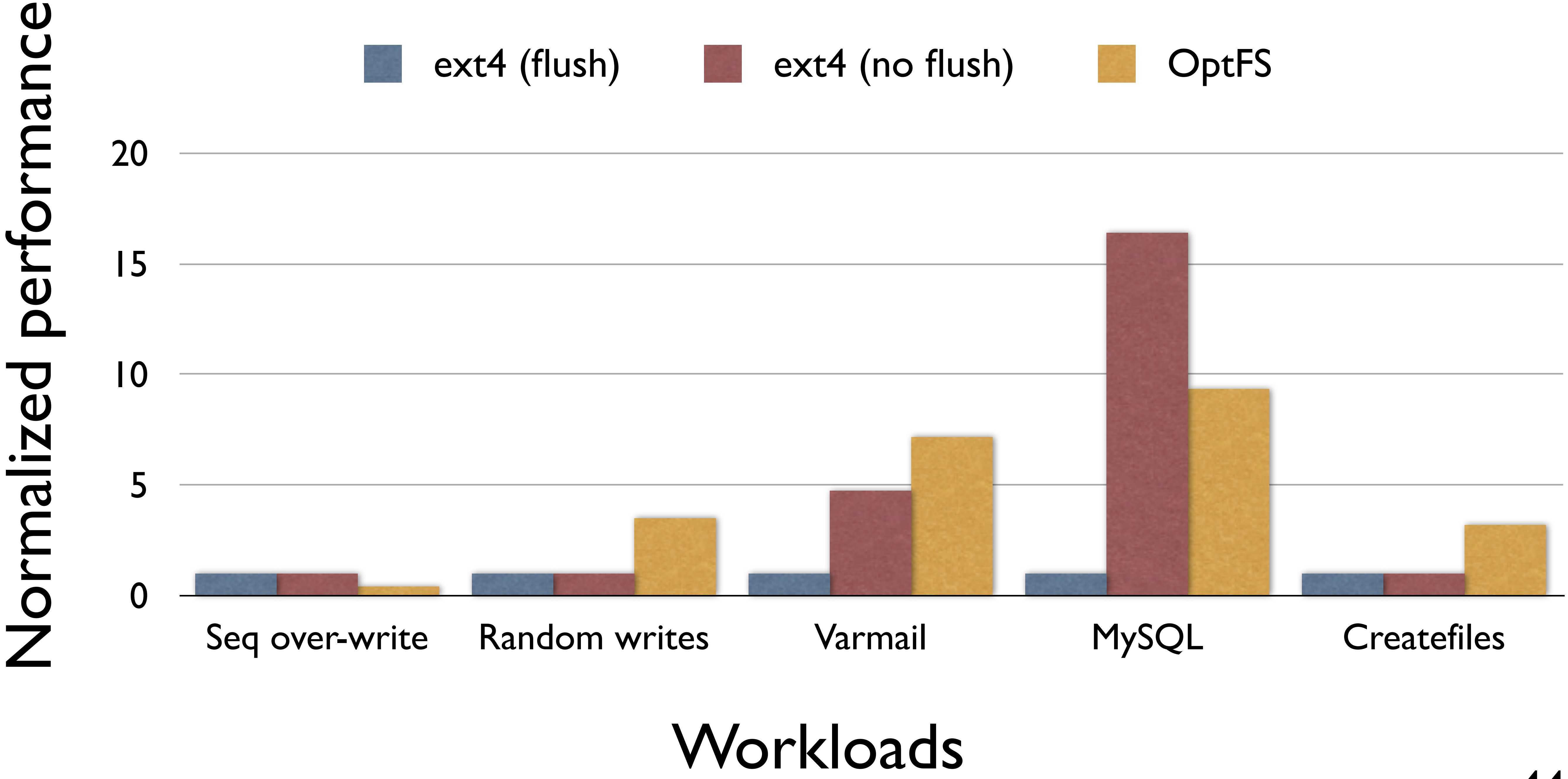

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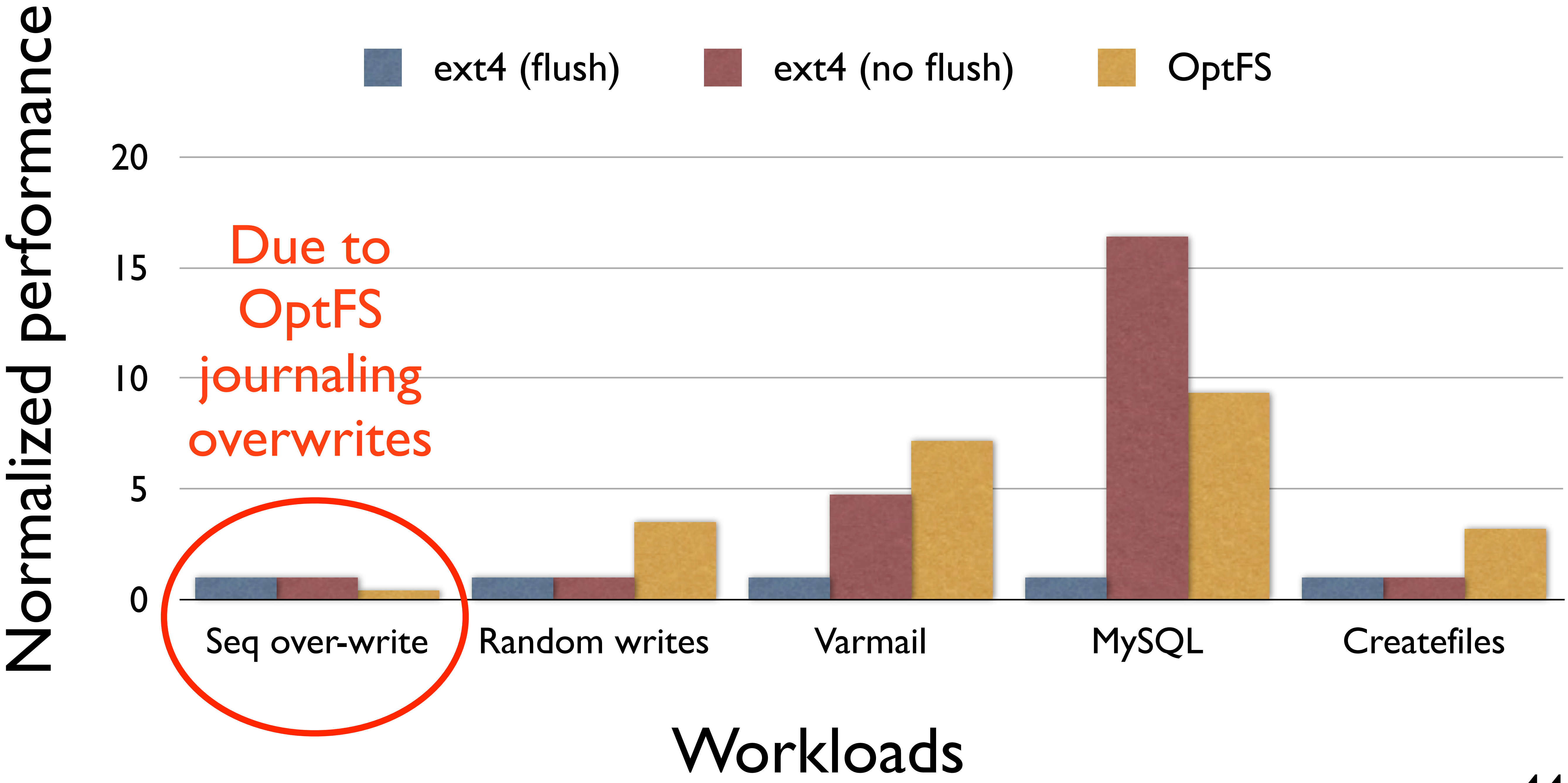

Due to OptFS journaling overwrites

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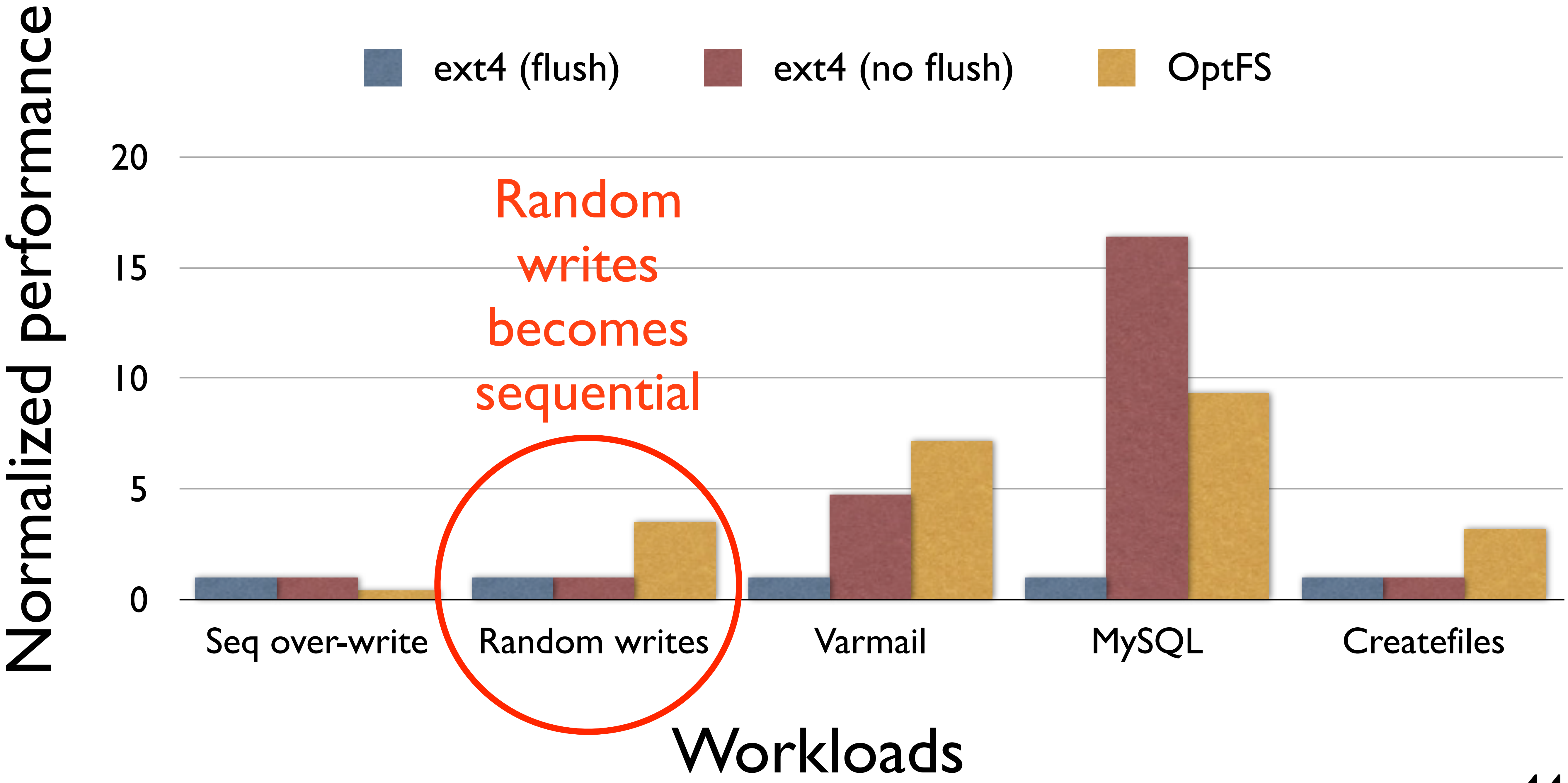
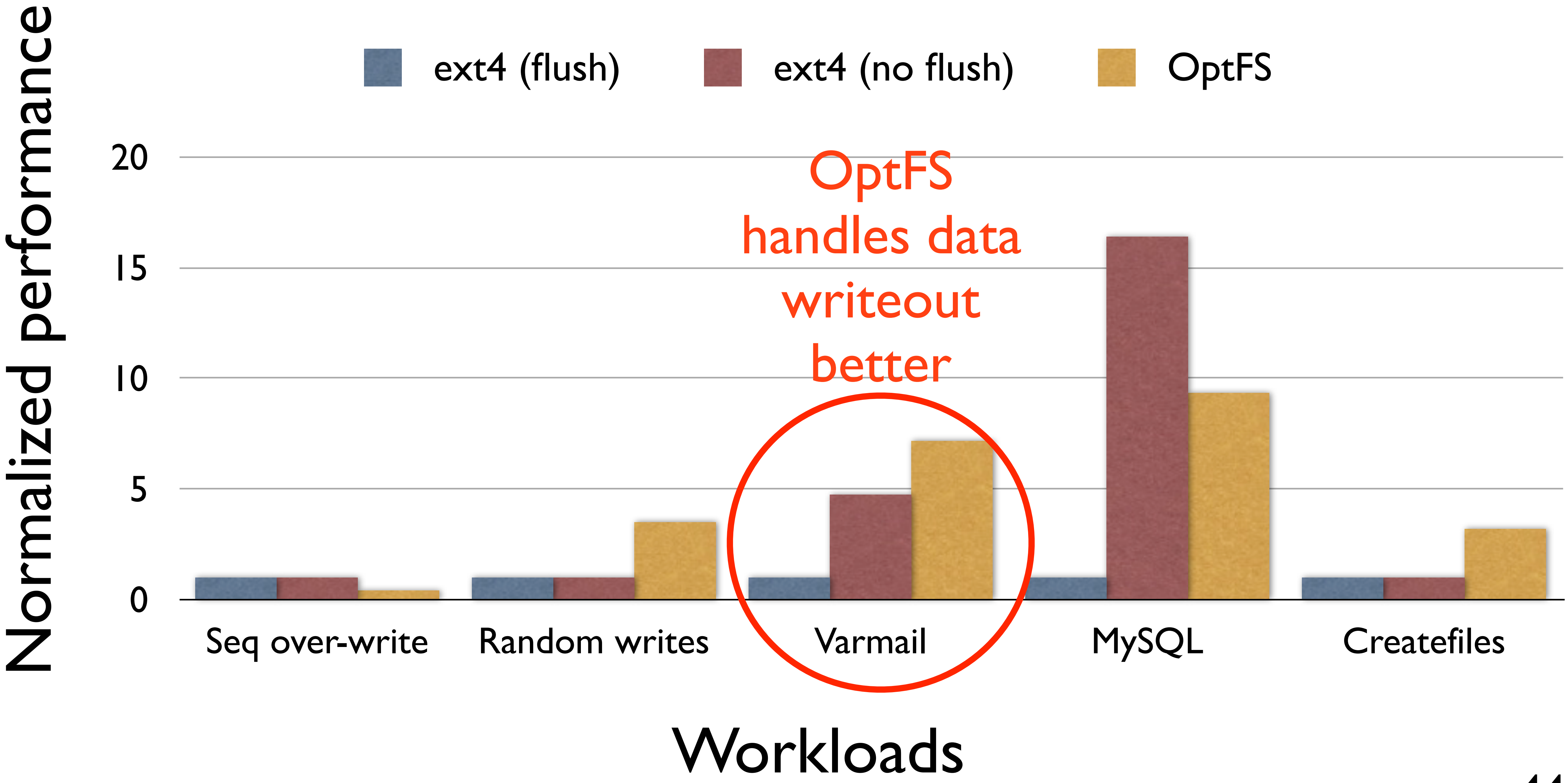


Random writes becomes sequential

Performance



OptFS handles data writeout better

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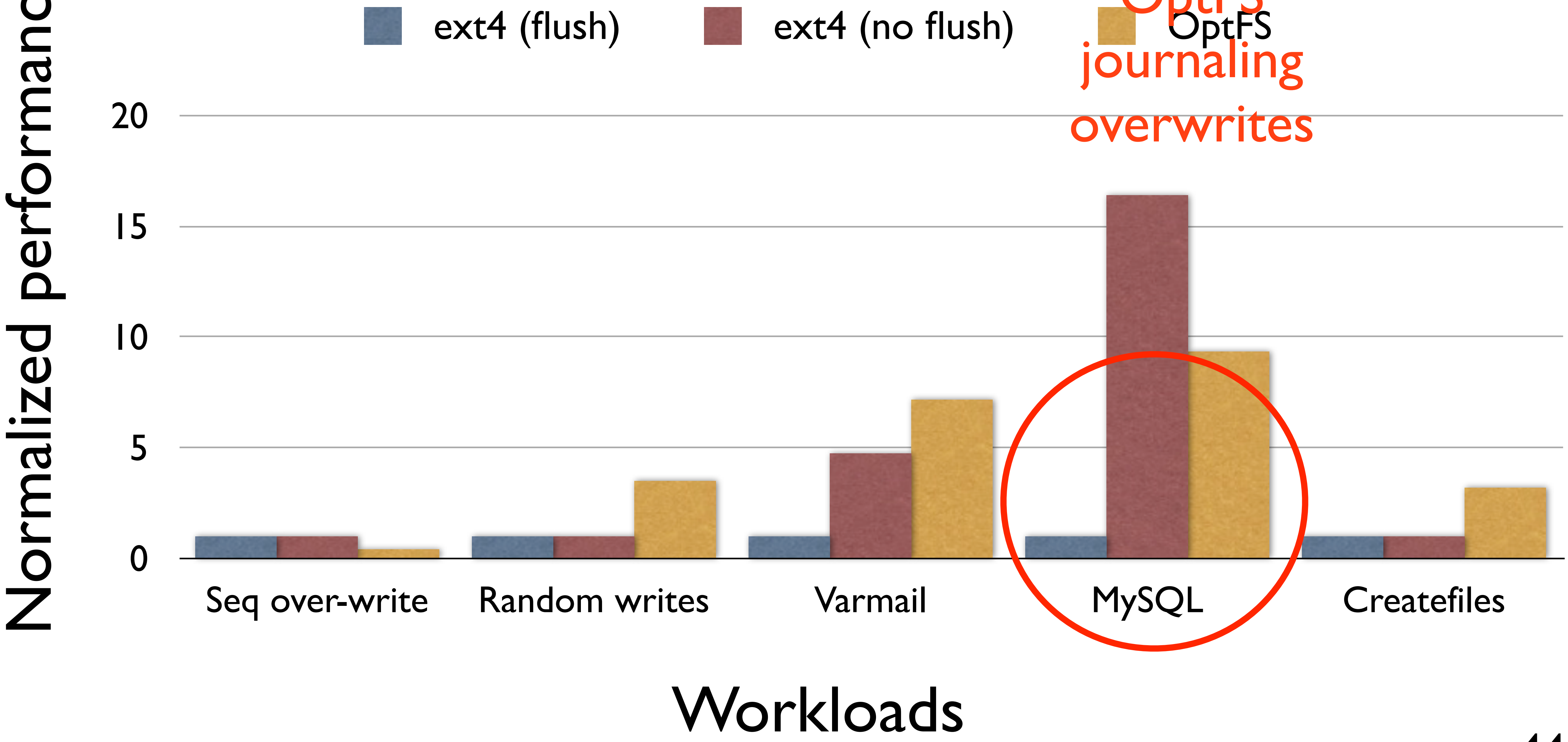

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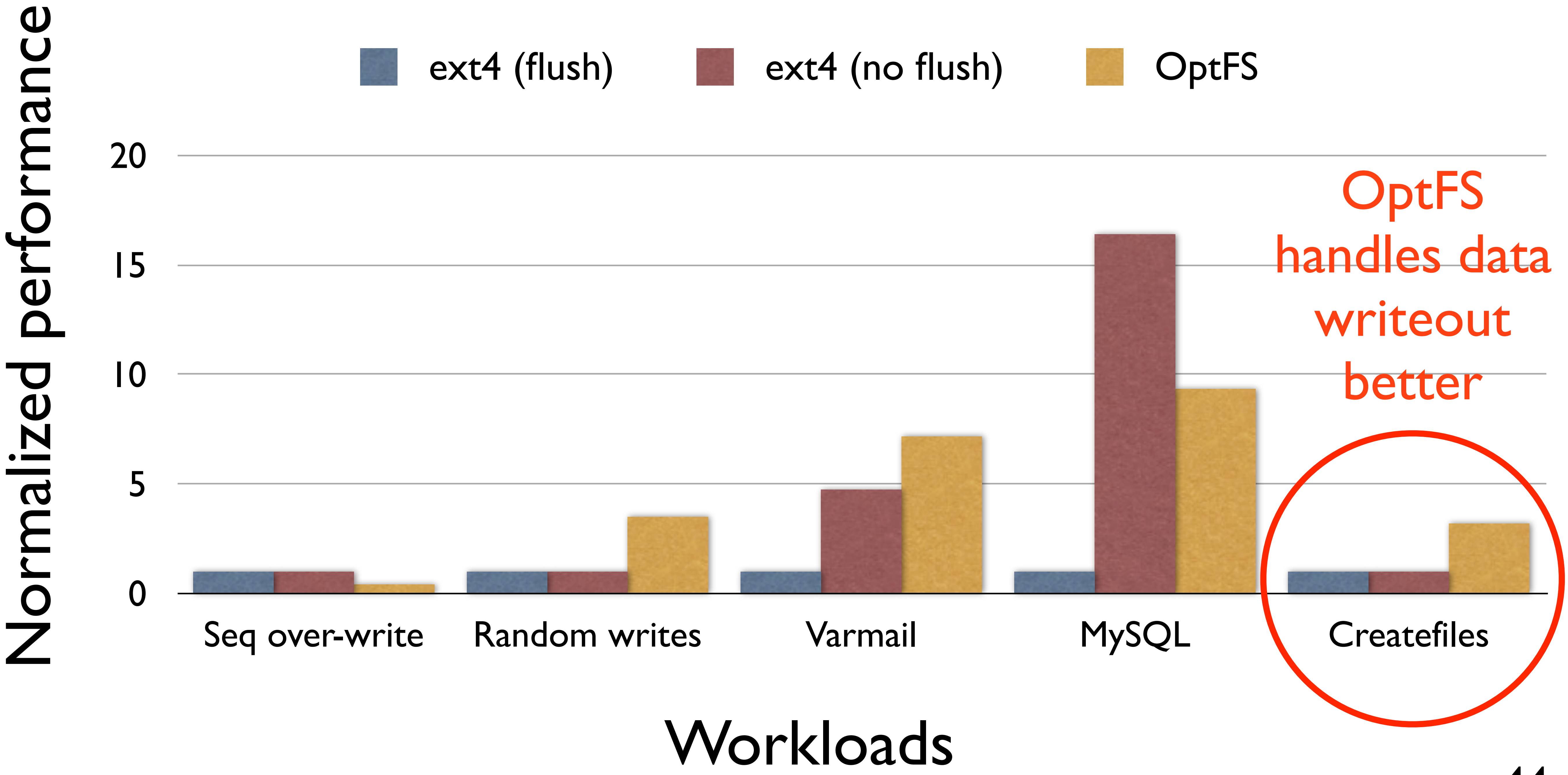

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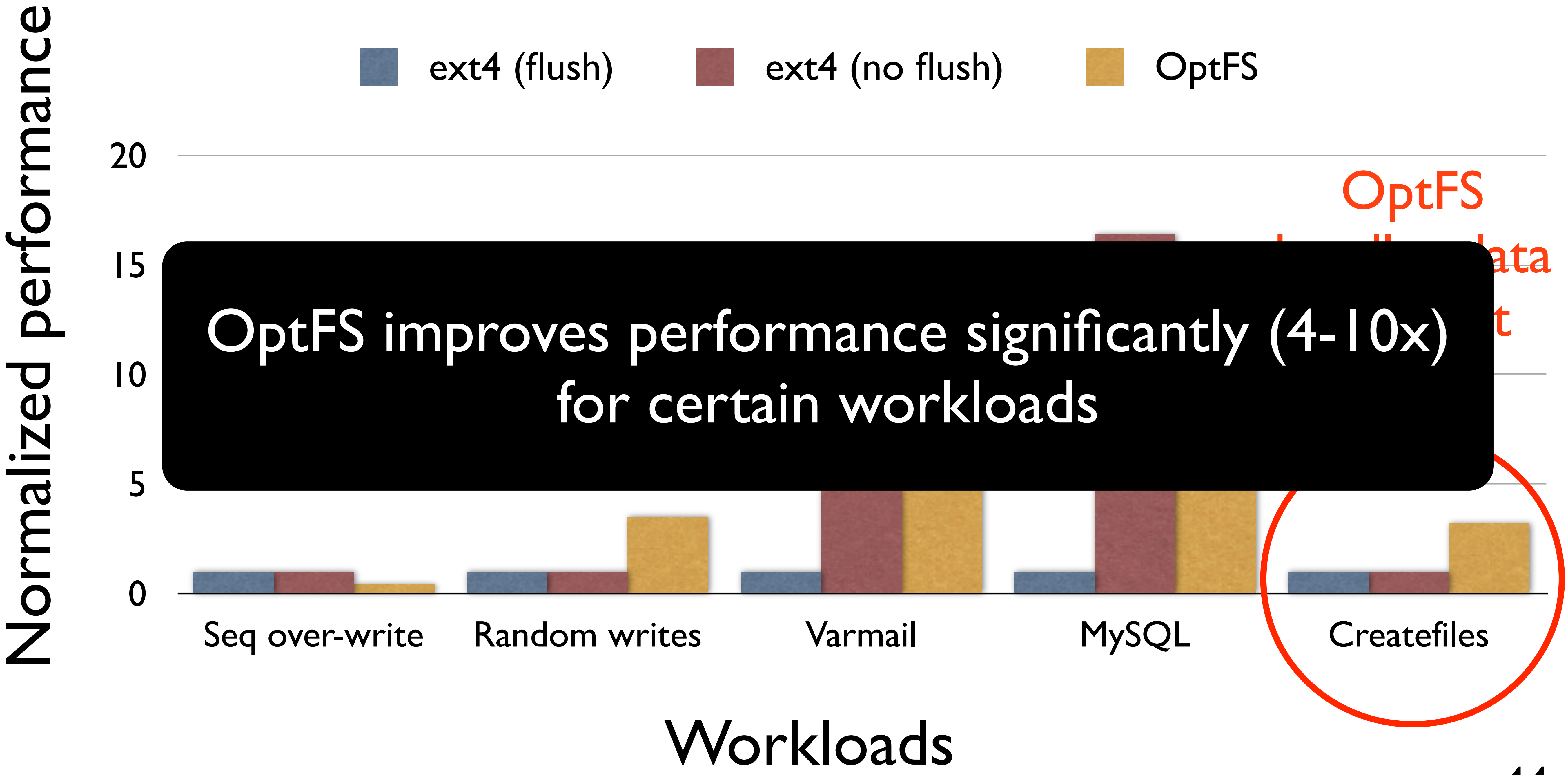

OptFS improves performance significantly (4-10x) for certain workloads

Application level consistency

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Studied behavior on recovery from random crashes:

- Gedit
- SQLite

Consistency in SQLite

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File-system consistency	*SQLite consistency*

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Crash SQLite in the middle of a transaction

Experimentally SQLite is consistent, but potentially stale

Case studies: Application level consistency

Application: SQLite

Total crashpoints: 100

	Ext4 w/o flush	Ext4 w/ flush	OptFS
Inconsistent	73	0	0
Old state	8	50	76
New state	19	50	24
Time per op (ms)	23.28	152	15.3

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SQLite is able to provide ACI semantics with osync(), at 10x performance

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Time per op (ms)	23.28	152	15.3

Conclusion

OptFS provides consistency without flushes

Asynchronous Durability Notifications allow the disk to perform optimally

Eventual Durability trades freshness for increased performance

osync() provides a cheap primitive to order application writes

Project Ideas

1. Delayed Durability
2. OptFS on Flash
3. Optimistic btrfs
4. p-inconsistency for RAID, Flash
5. Rewrite applications with osync()/dsync()
6. Forced Unit Access (FUA) study
7. Consistency testing framework

Project Ideas

If you are interested, come talk to me

vijayc@cs.wisc.edu

7366 CS

Thank you

Questions?

Backup Slides

Resource Consumption

FS	CPU	Memory (MB)
ext4 (flush)	3.39	487
ext4 (no flush)	14.86	516
OptFS	25.32	749

Why not just `fsync()` in the background?

Does not solve the problem for the whole system: flushes will still be caused

Any application using foreground fsync() will be affected

Many mobile applications have auto sync at the same time, causing problems [Agrawal12]

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