Protocol-Aware Recovery for Consensus-Based Storage

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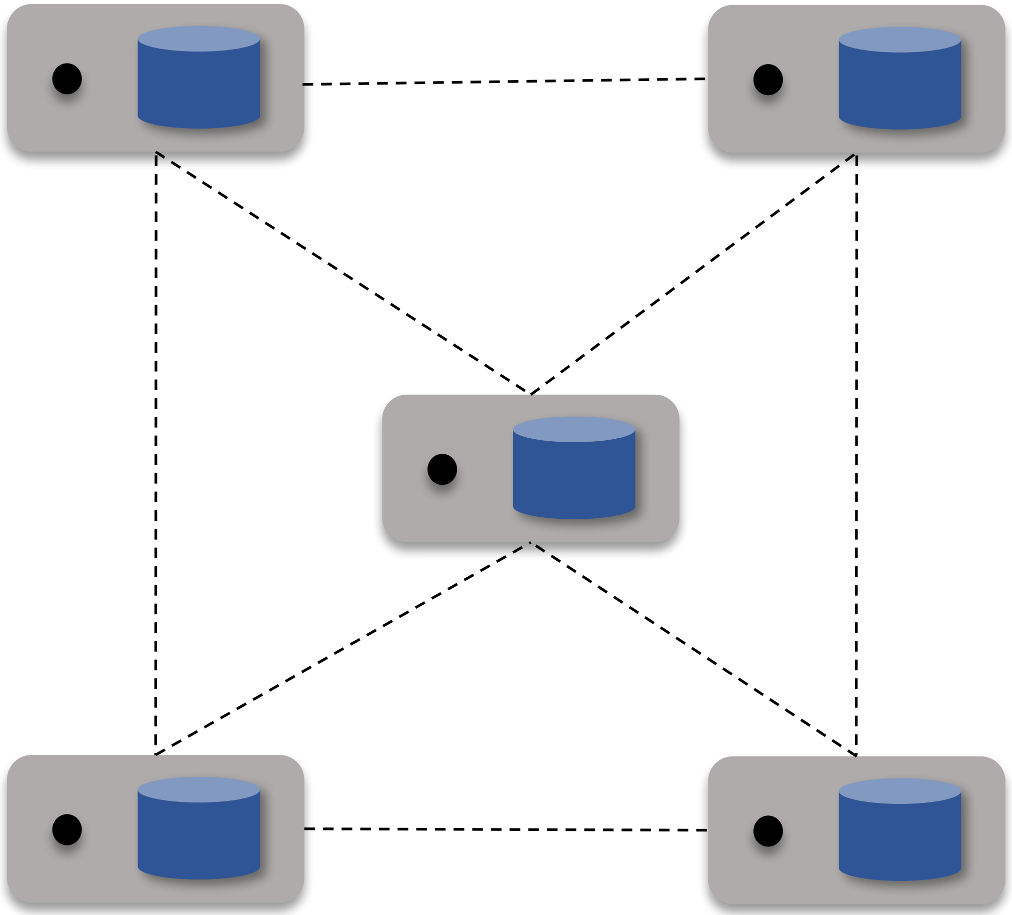
Andrea Arpaci-Dusseau, and Remzi Arpaci-Dusseau

University of Wisconsin – Madison
*University of Texas at Austin

Redundancy Enables Reliability

Redundancy helps distributed storage systems mask failures



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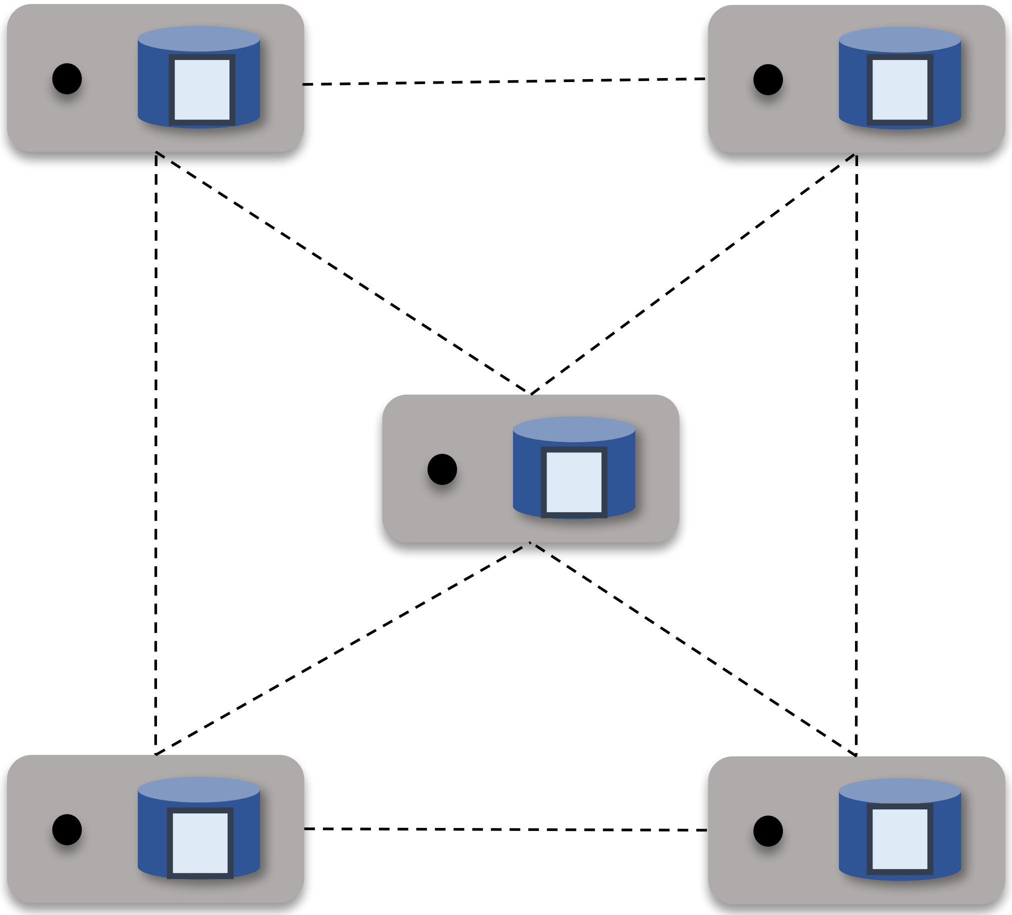

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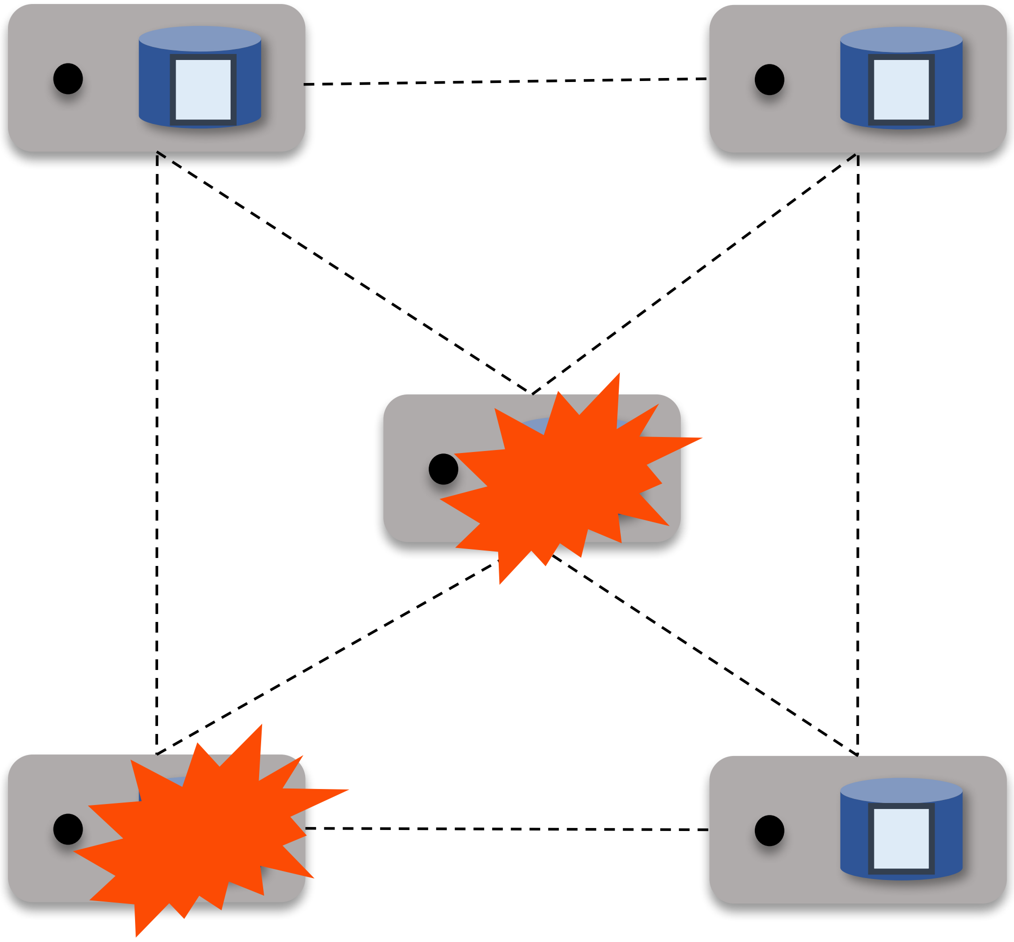

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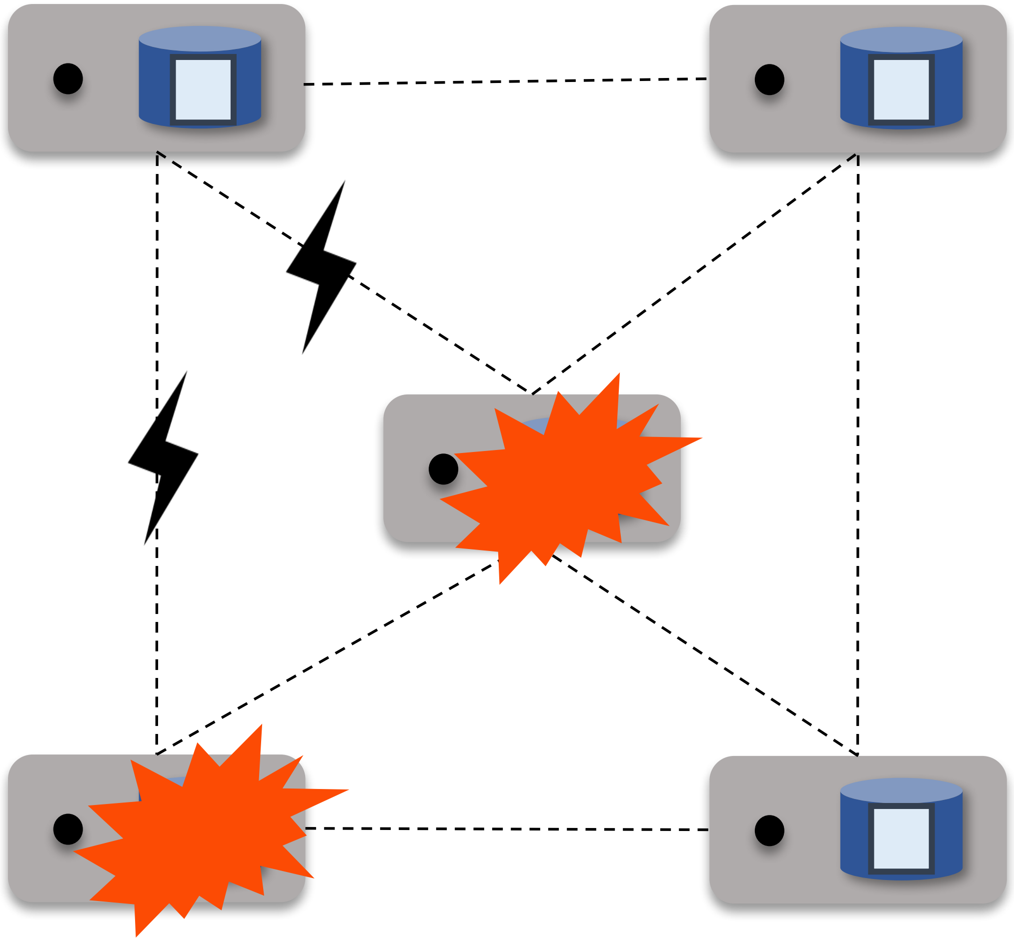

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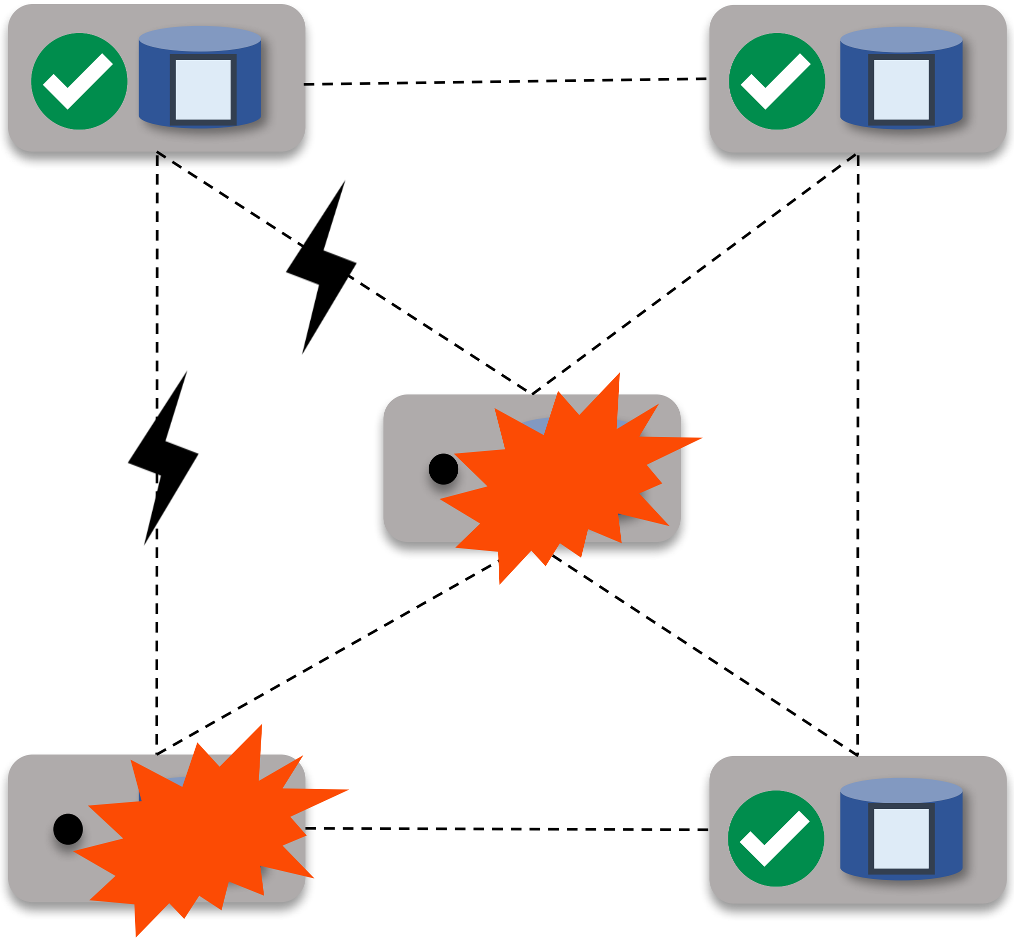
System as a whole unaffected

- ➡ data is available
- ➡ data is correct



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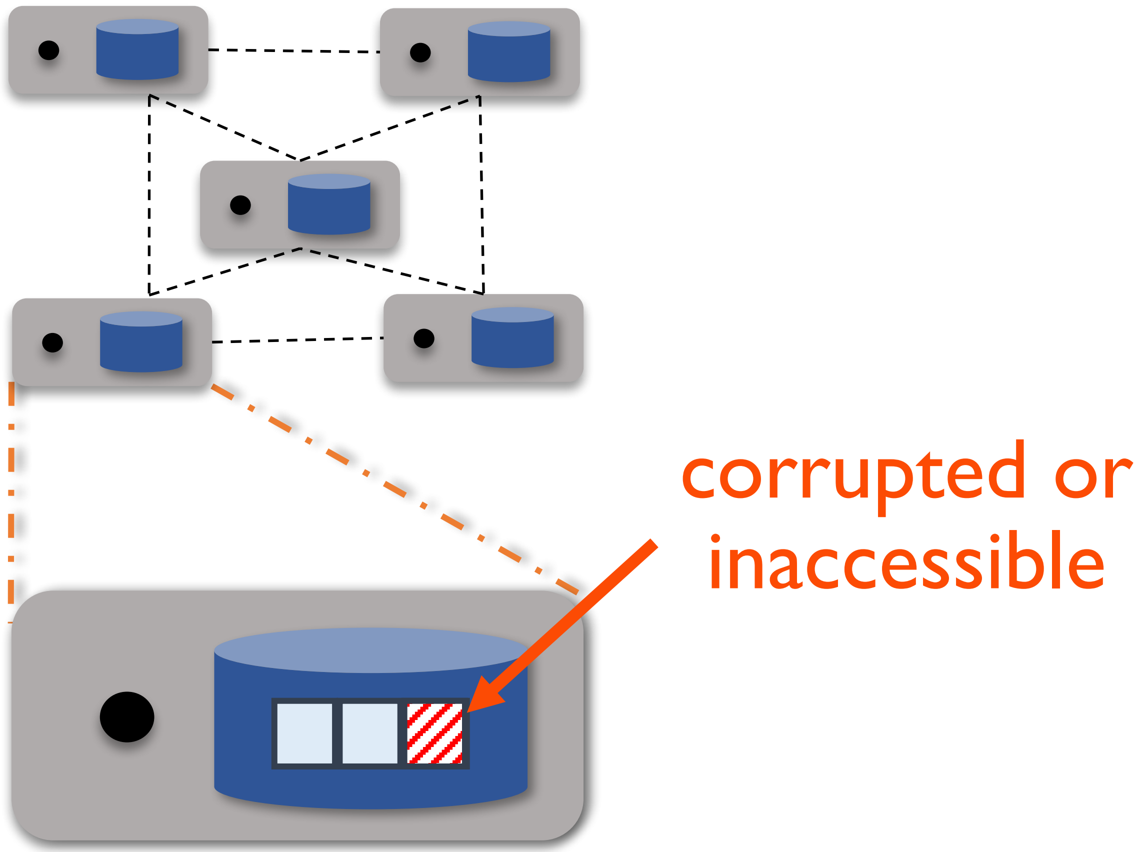

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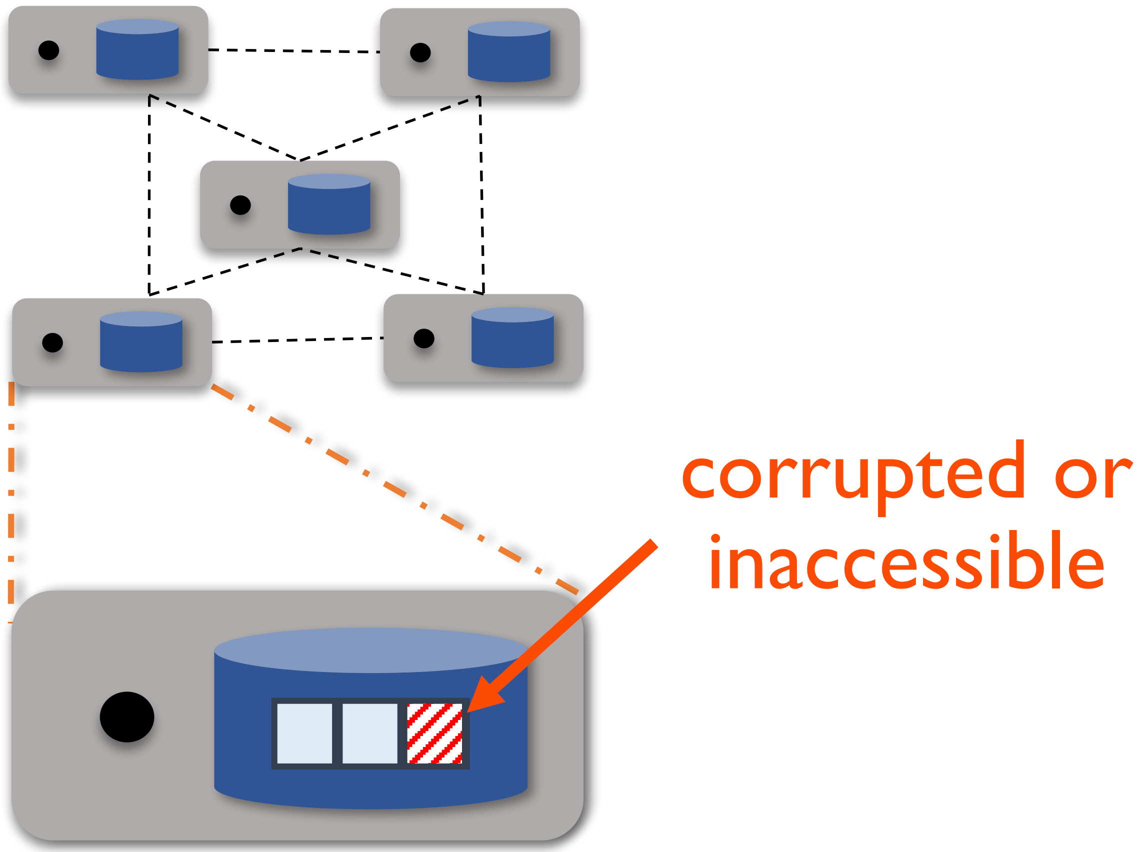
We call these storage faults



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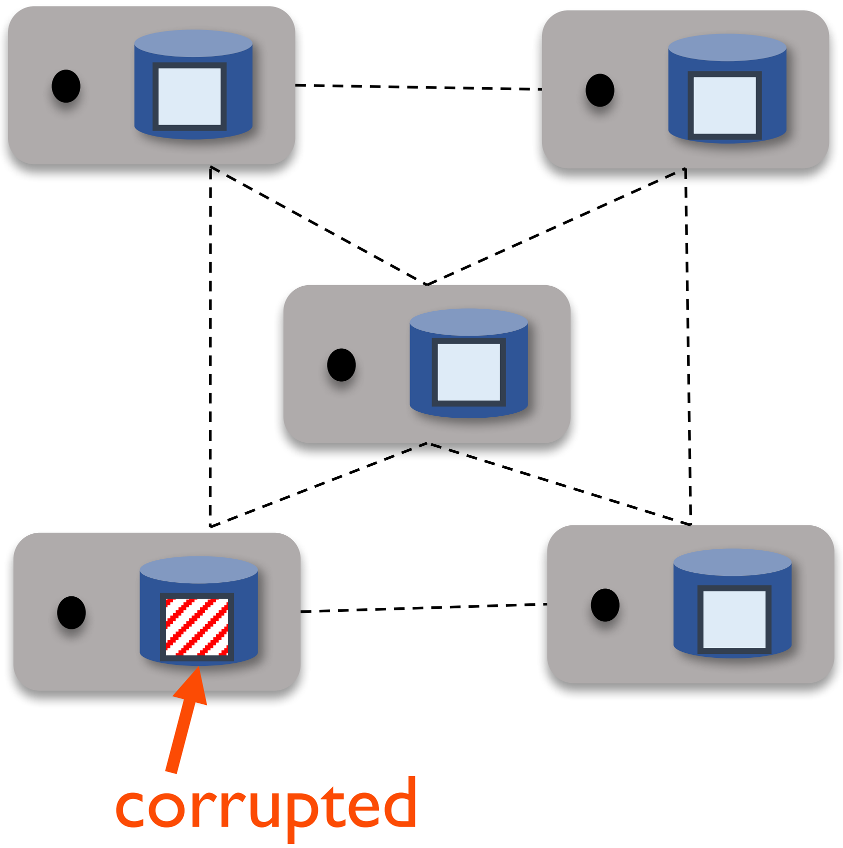

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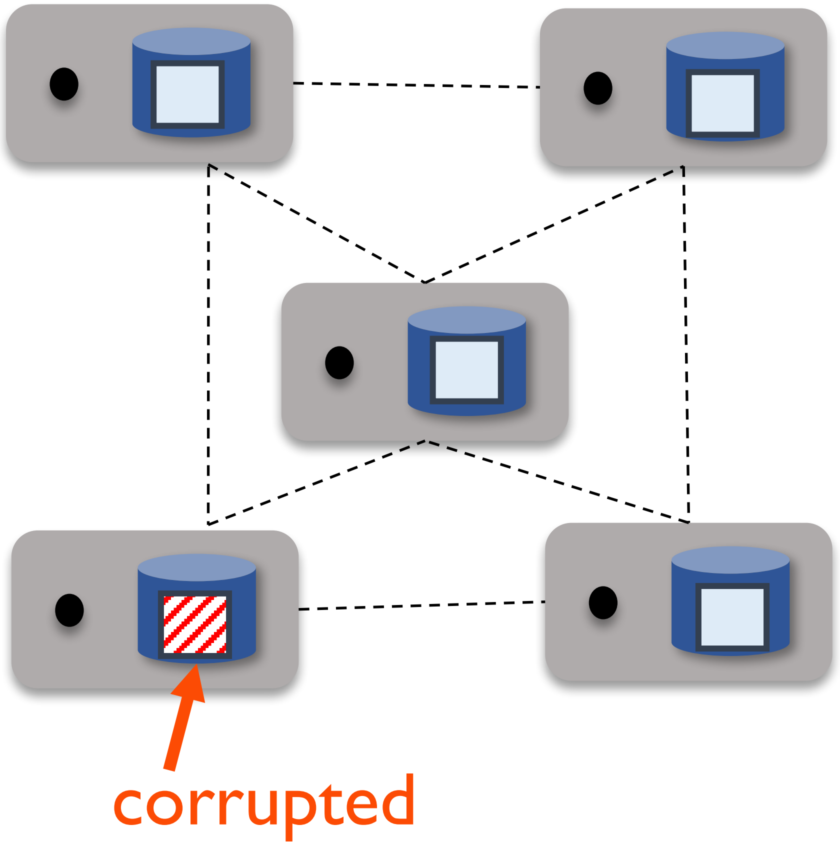

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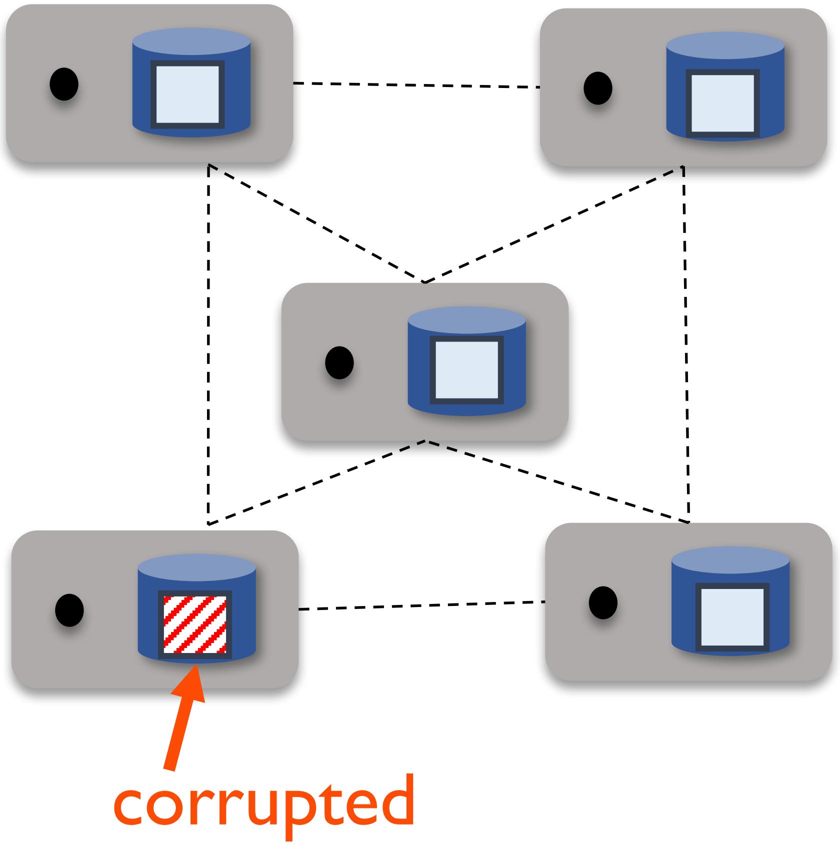

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> ZooKeeper fails to start? How can I fix?
> Try clearing all the state in Zookeeper: stop Zookeeper , wipe the Zookeeper data directory, restart it
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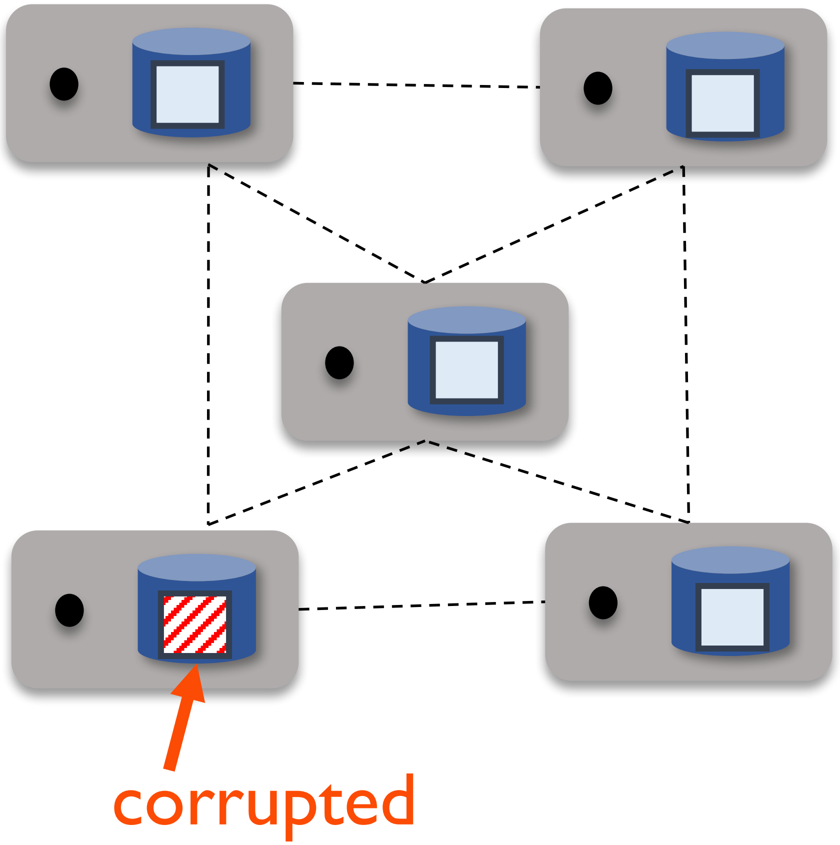

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– Recommendation from developers [2]

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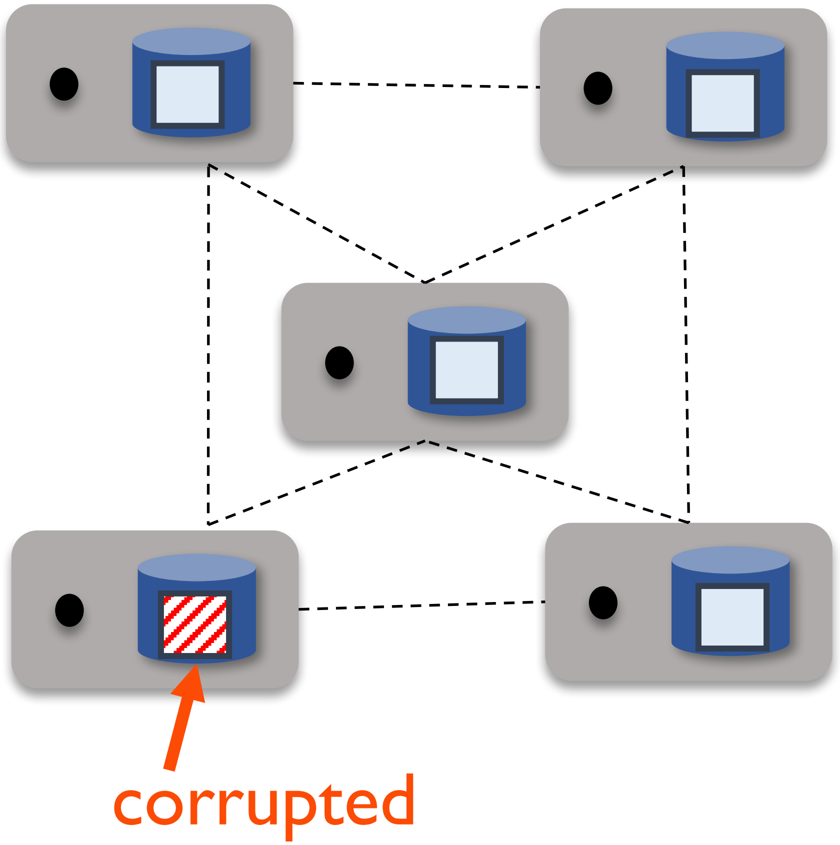

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Looks reasonable: redundancy will help

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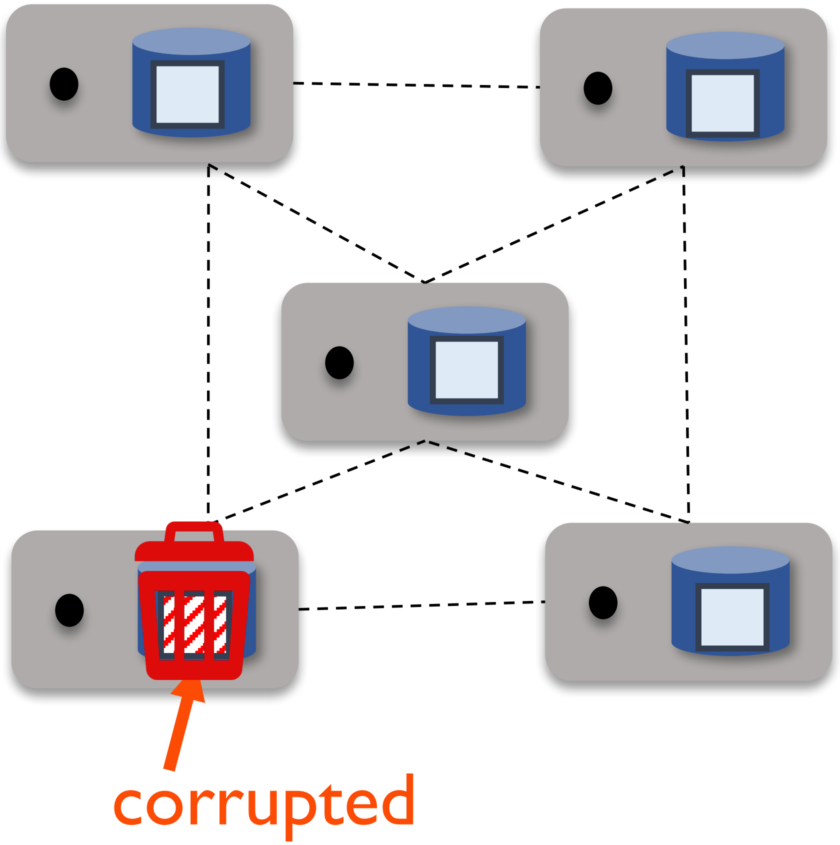

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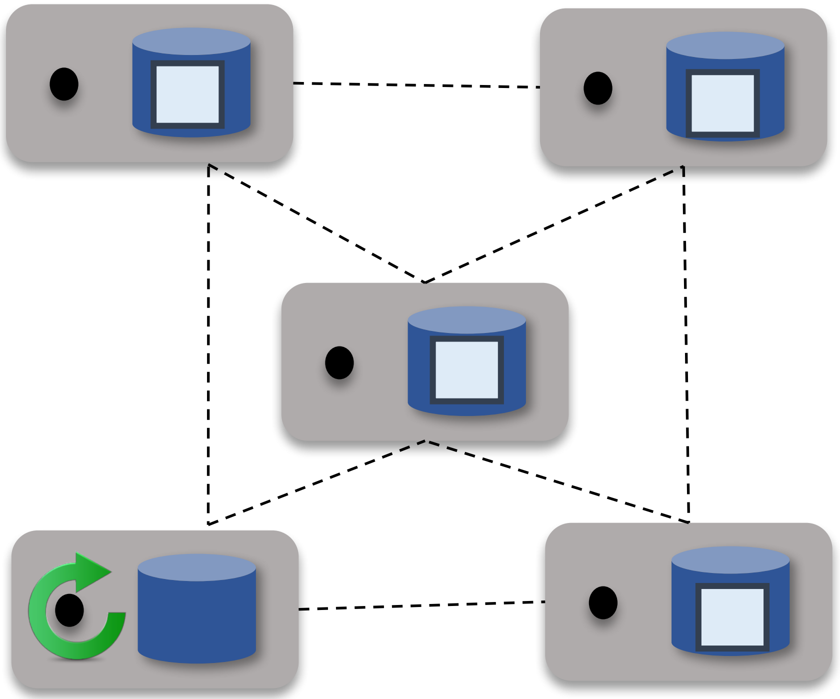

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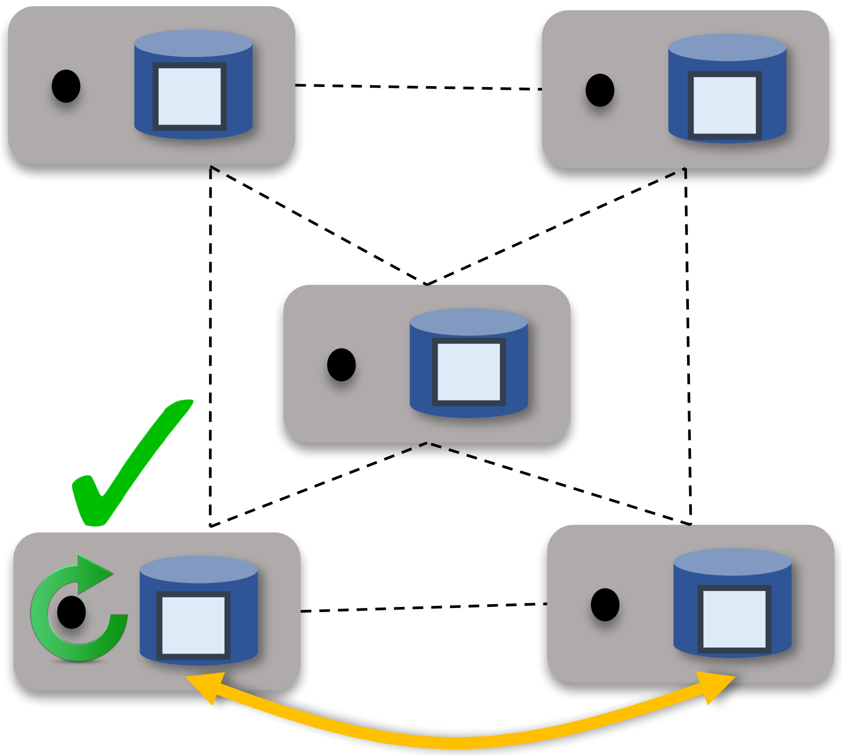

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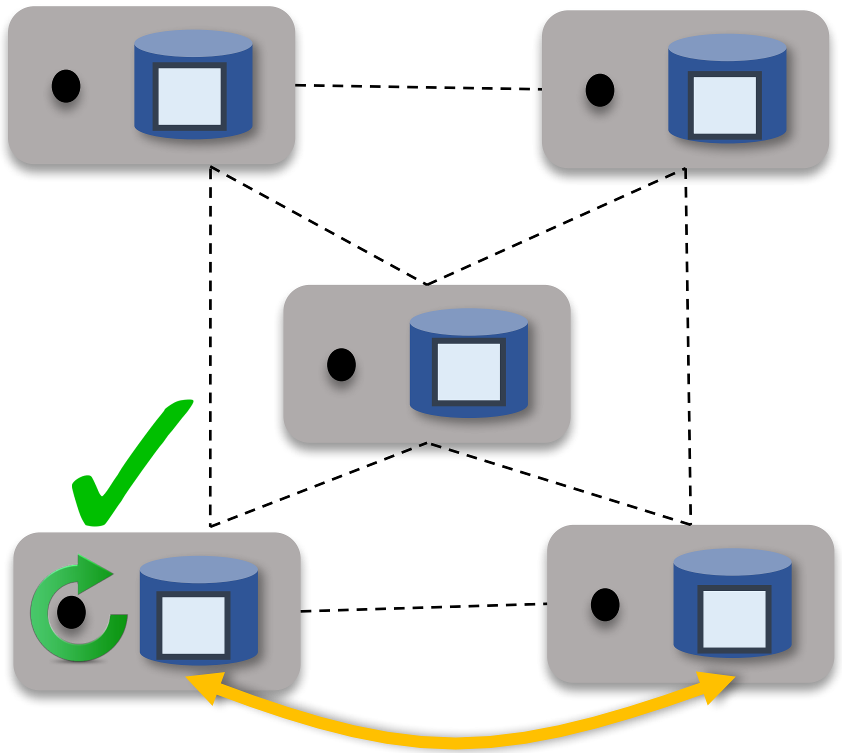

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The approach seems intuitive and works - all good, right?

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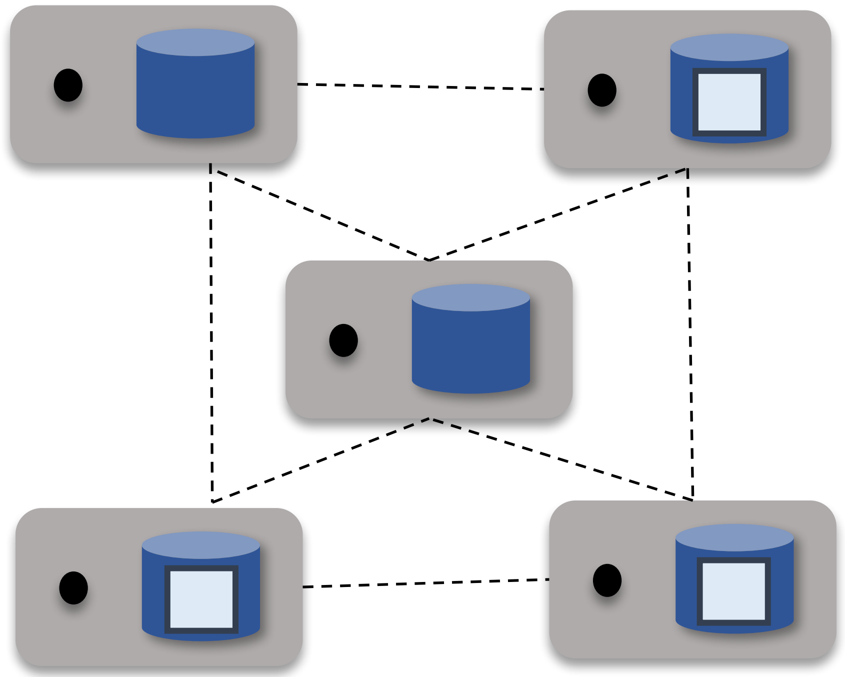

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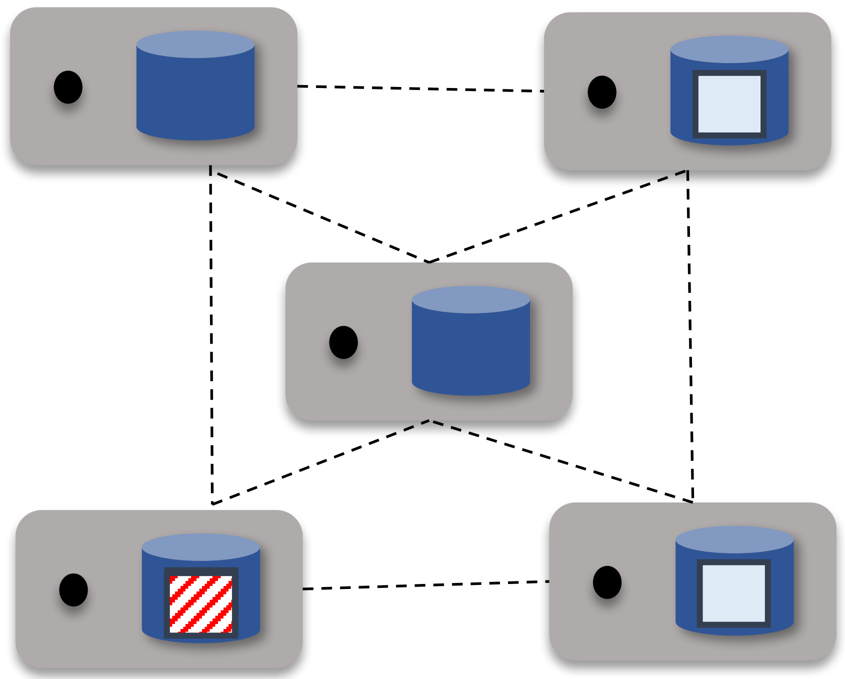

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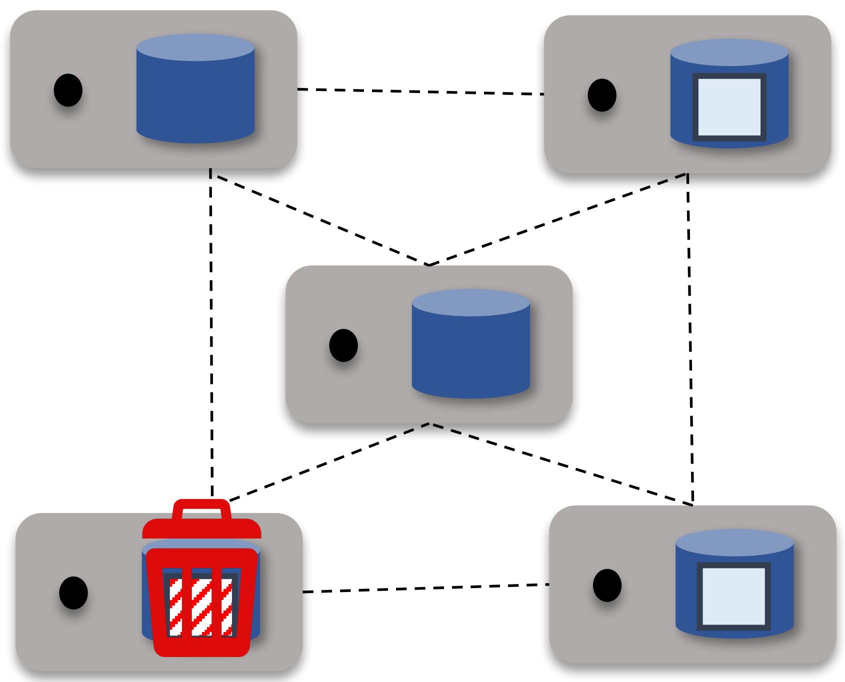

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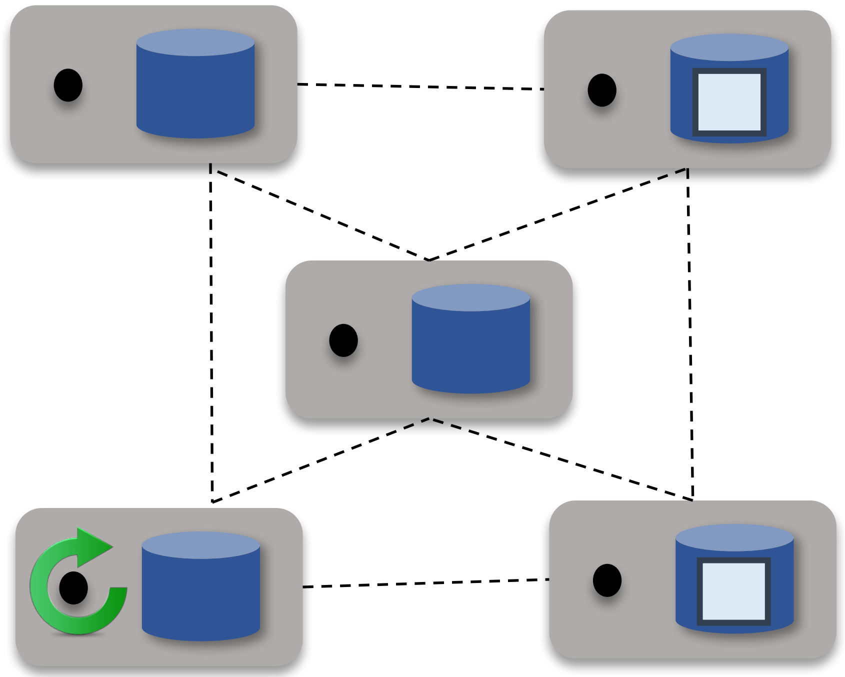

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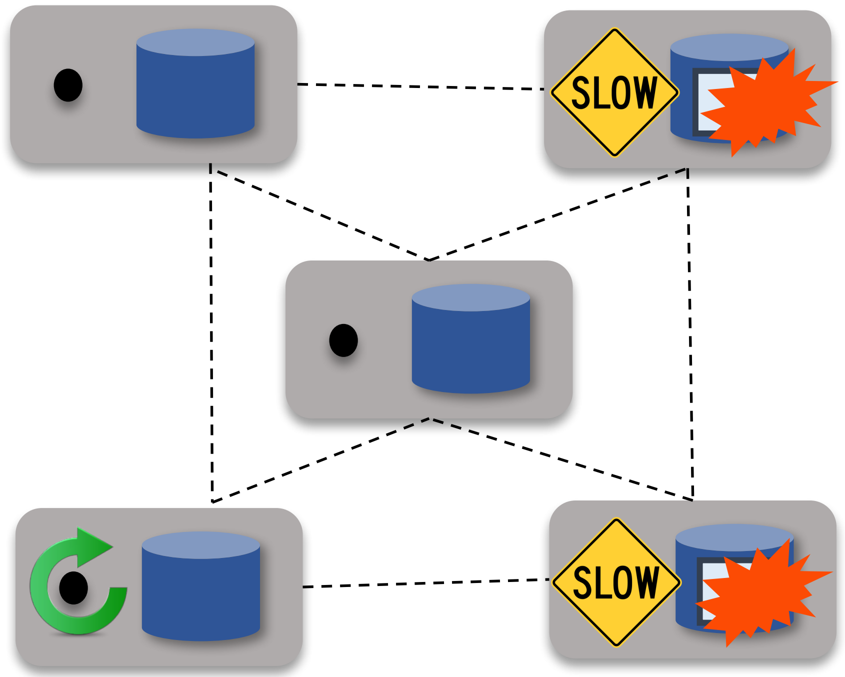

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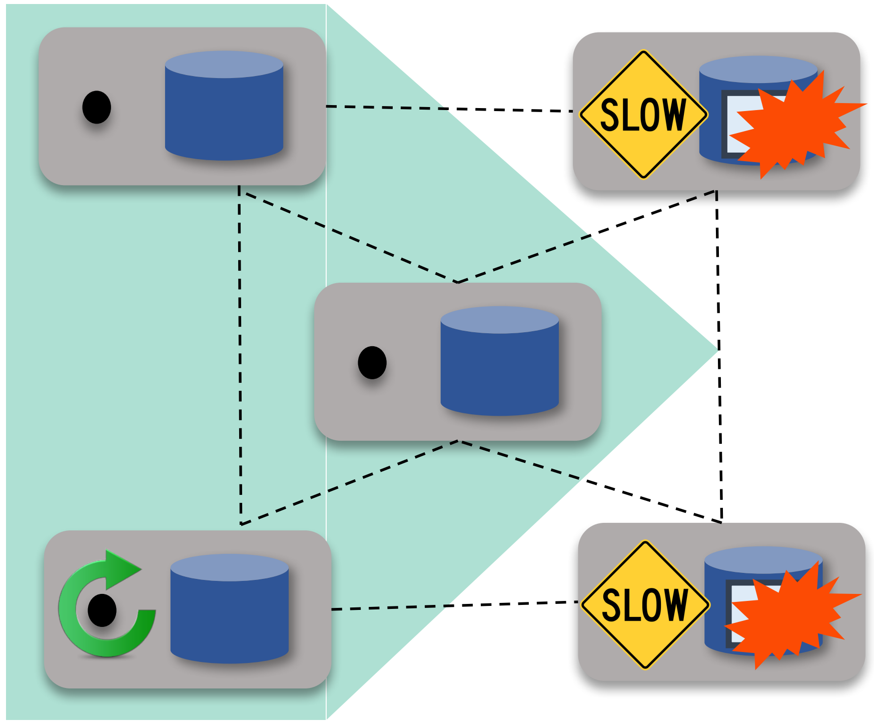

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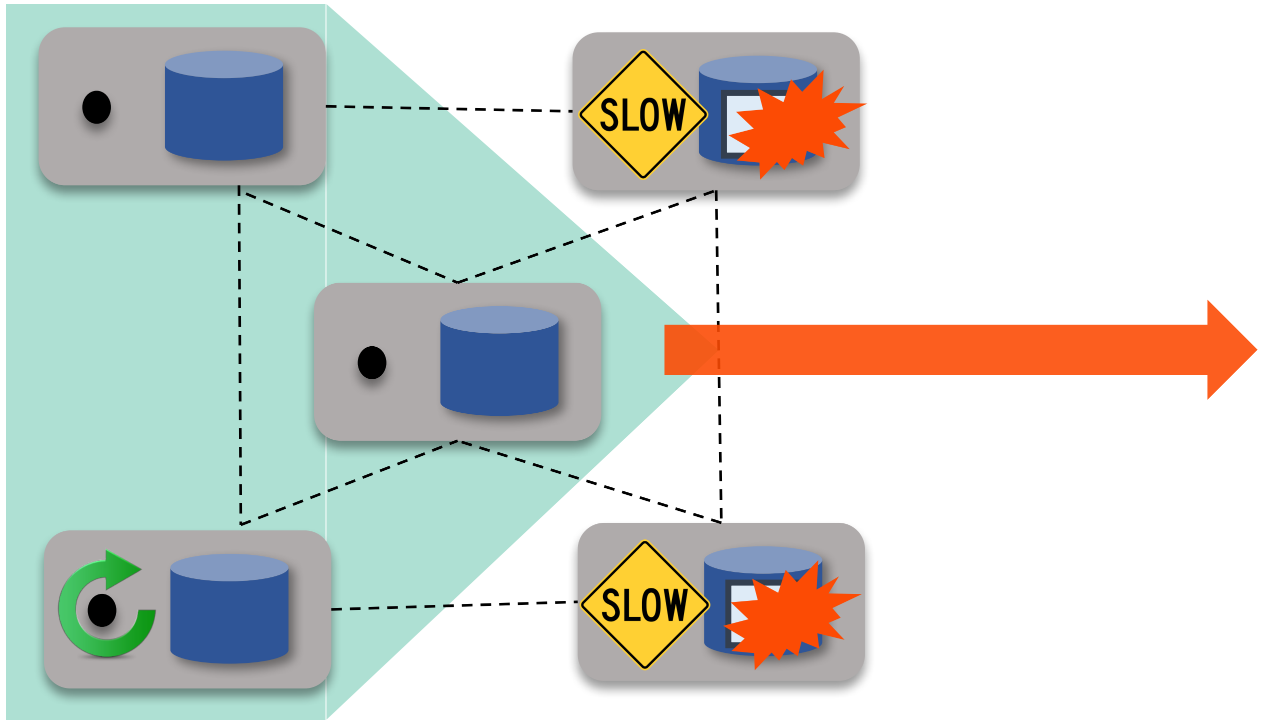

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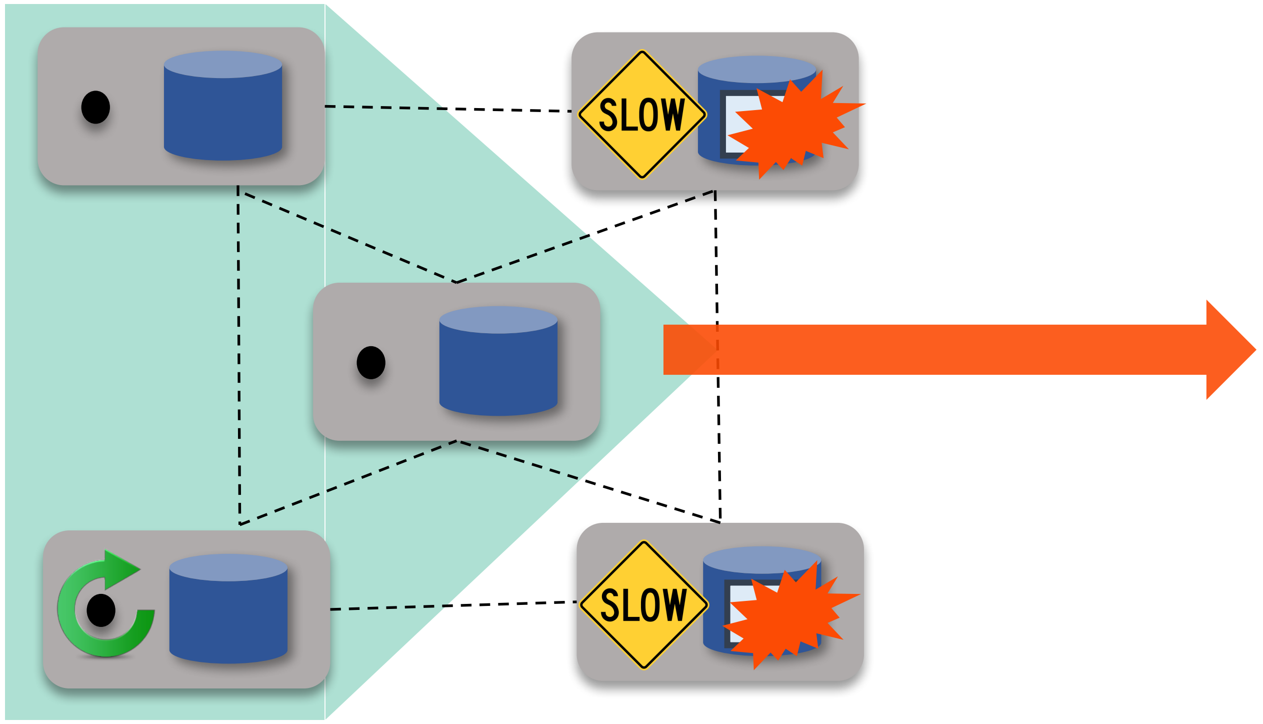

This majority has no idea about the committed data
Committed data is lost!

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e.g., the delete + rebuild approach was oblivious to the protocol used by the system to update the replicated data

Our Proposal: Protocol-Aware Recovery (PAR)

To safely recover, a recovery approach should be carefully designed based on properties of underlying protocols of the distributed system

e.g., is there a dedicated leader? constraints on leader election? how is the replicated state updated? what are the consistency guarantees?

We call such an approach protocol-aware

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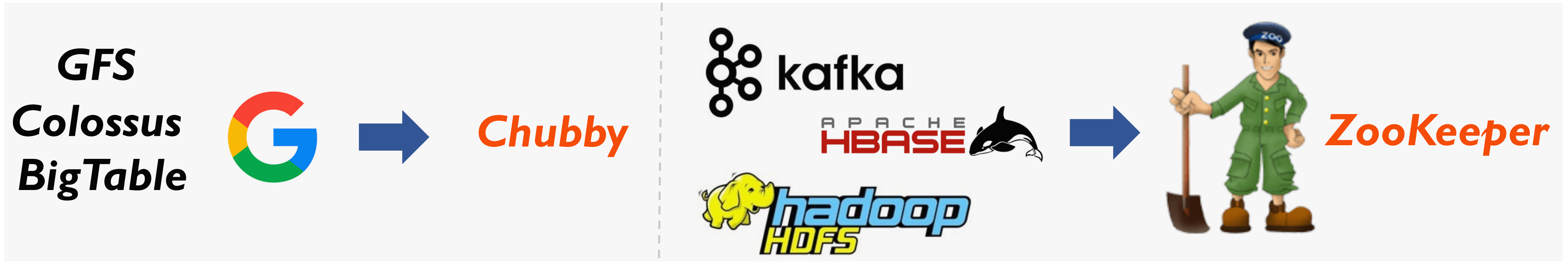

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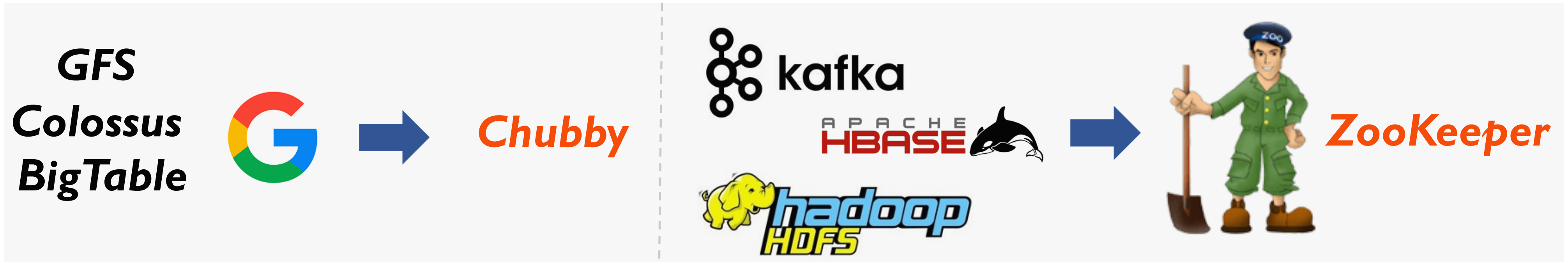

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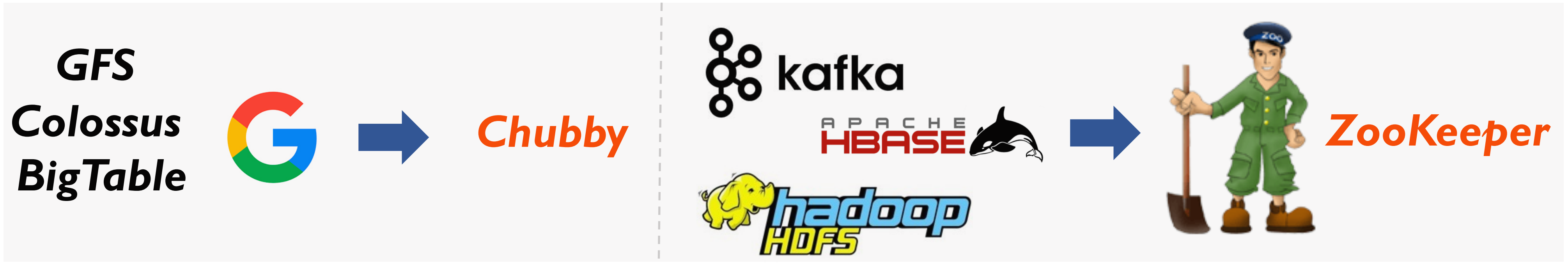

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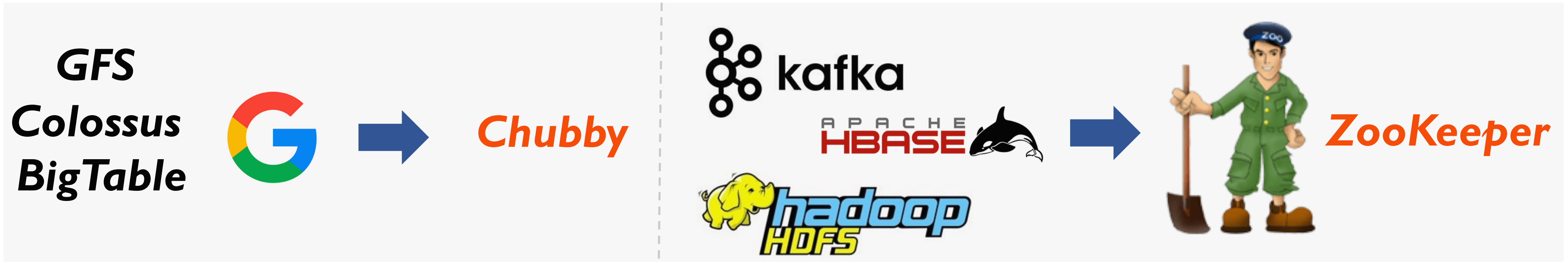

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A hard problem

- ➡ strong guarantees, even a small misstep can break guarantees

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- ➡ applied to LogCabin and ZooKeeper
- ➡ experimentally verified guarantees and little overheads (4%-8%)

Outline

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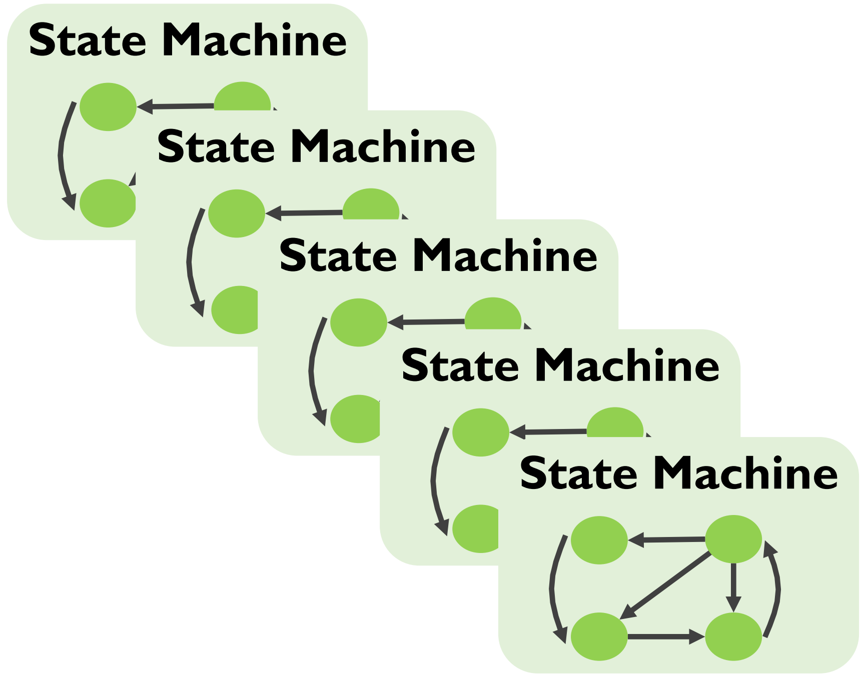

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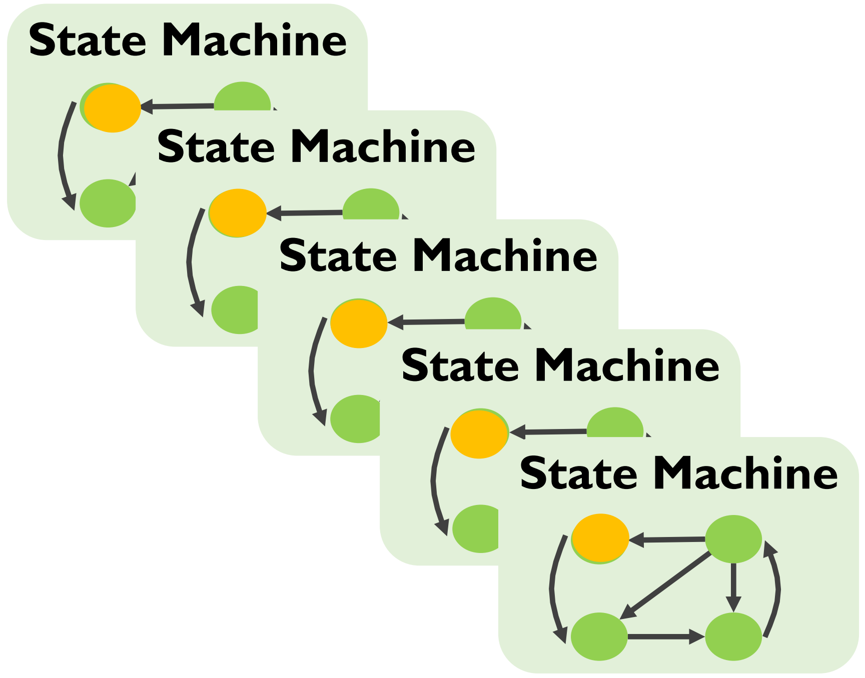

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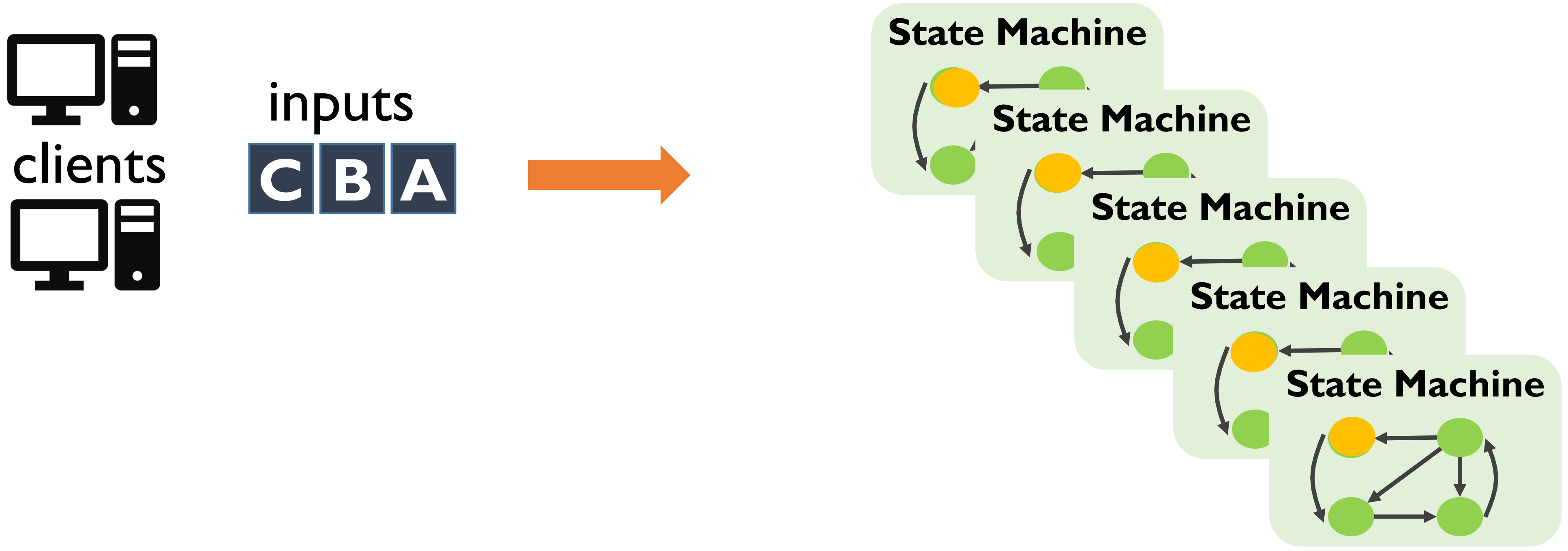

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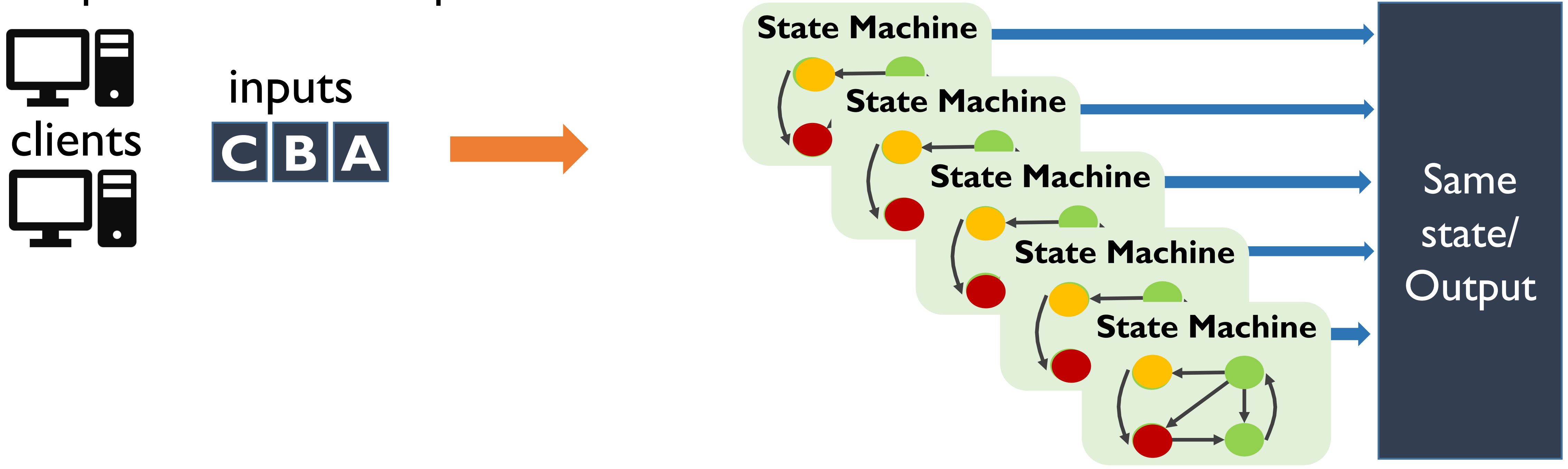

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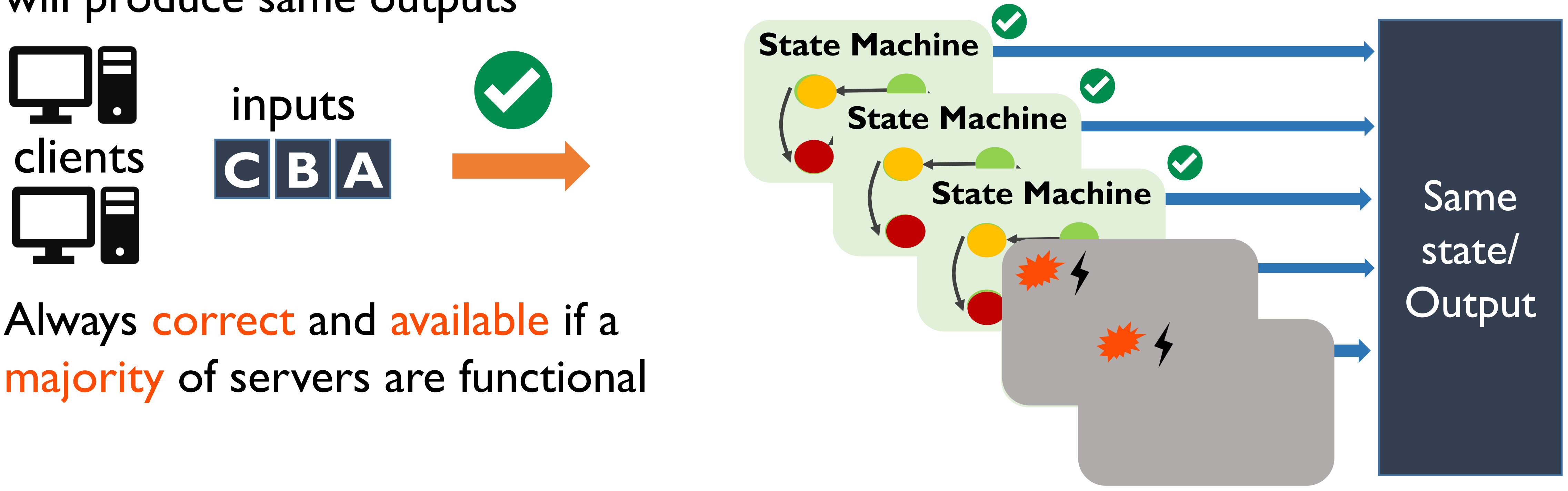

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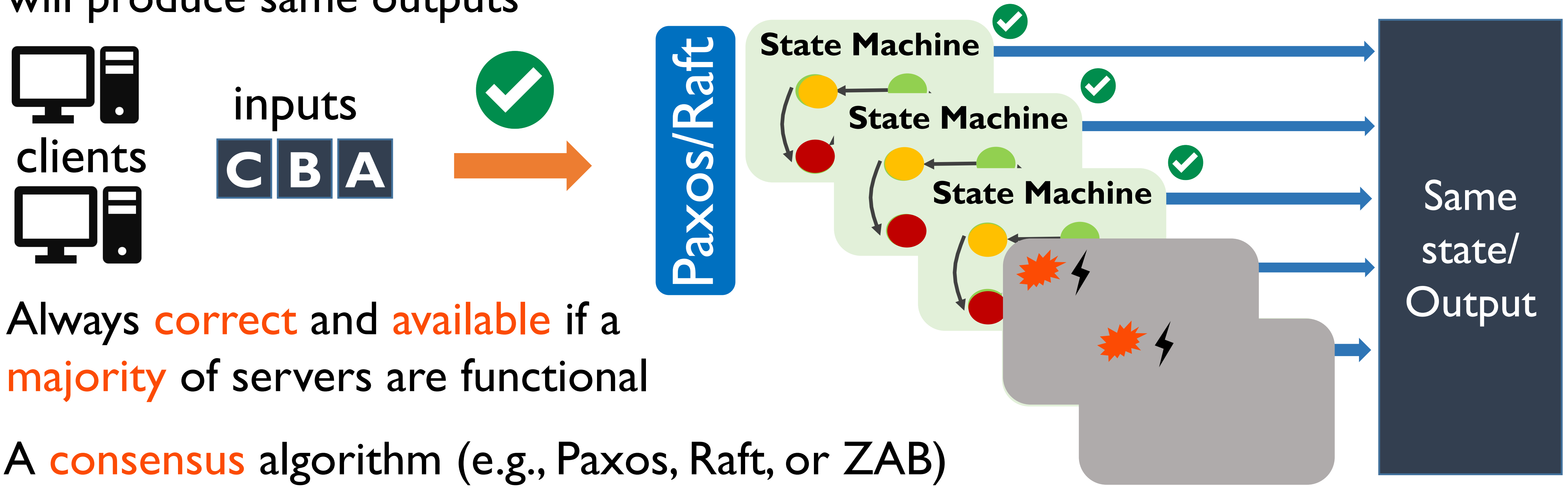

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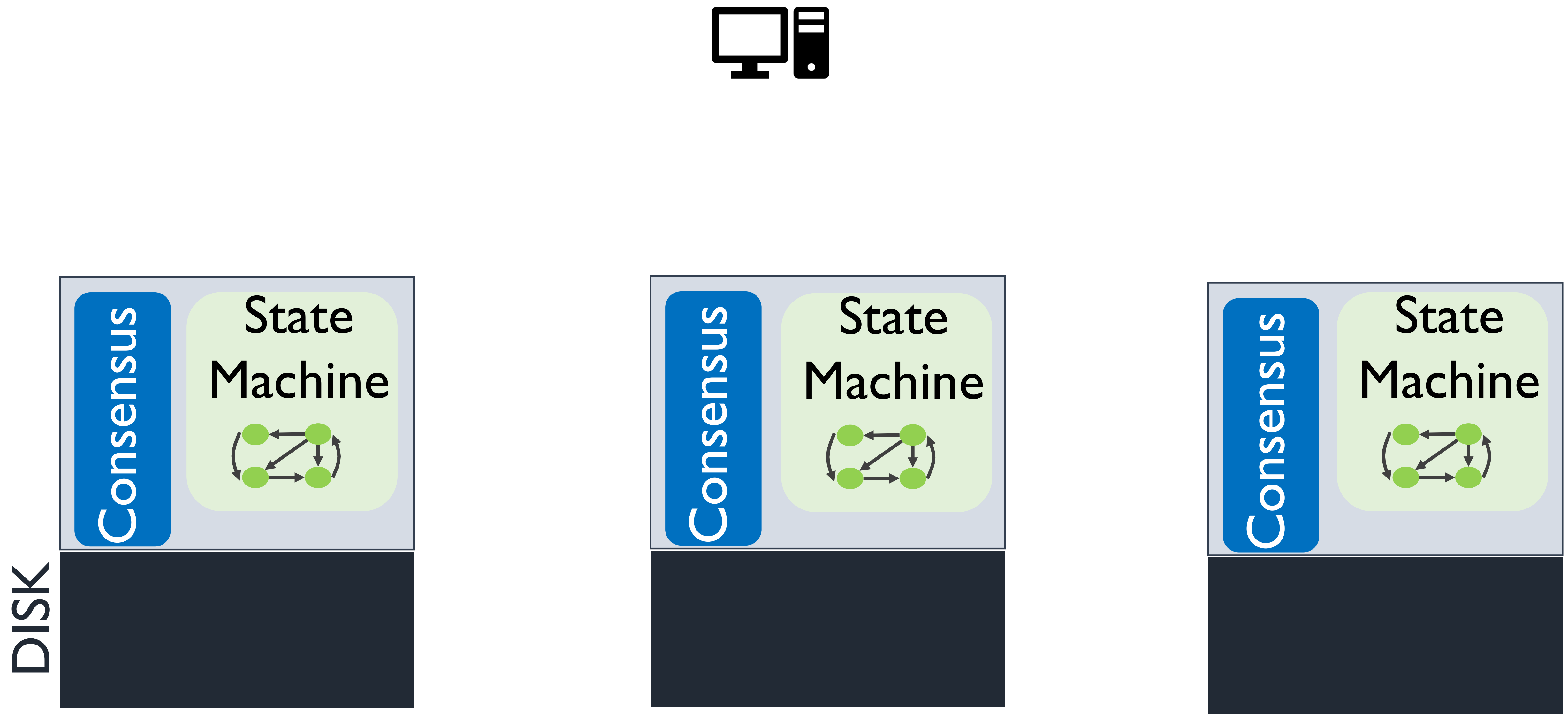
A consensus algorithm (e.g., Paxos, Raft, or ZAB) ensures SMs process commands in the same order

Replicated State Update



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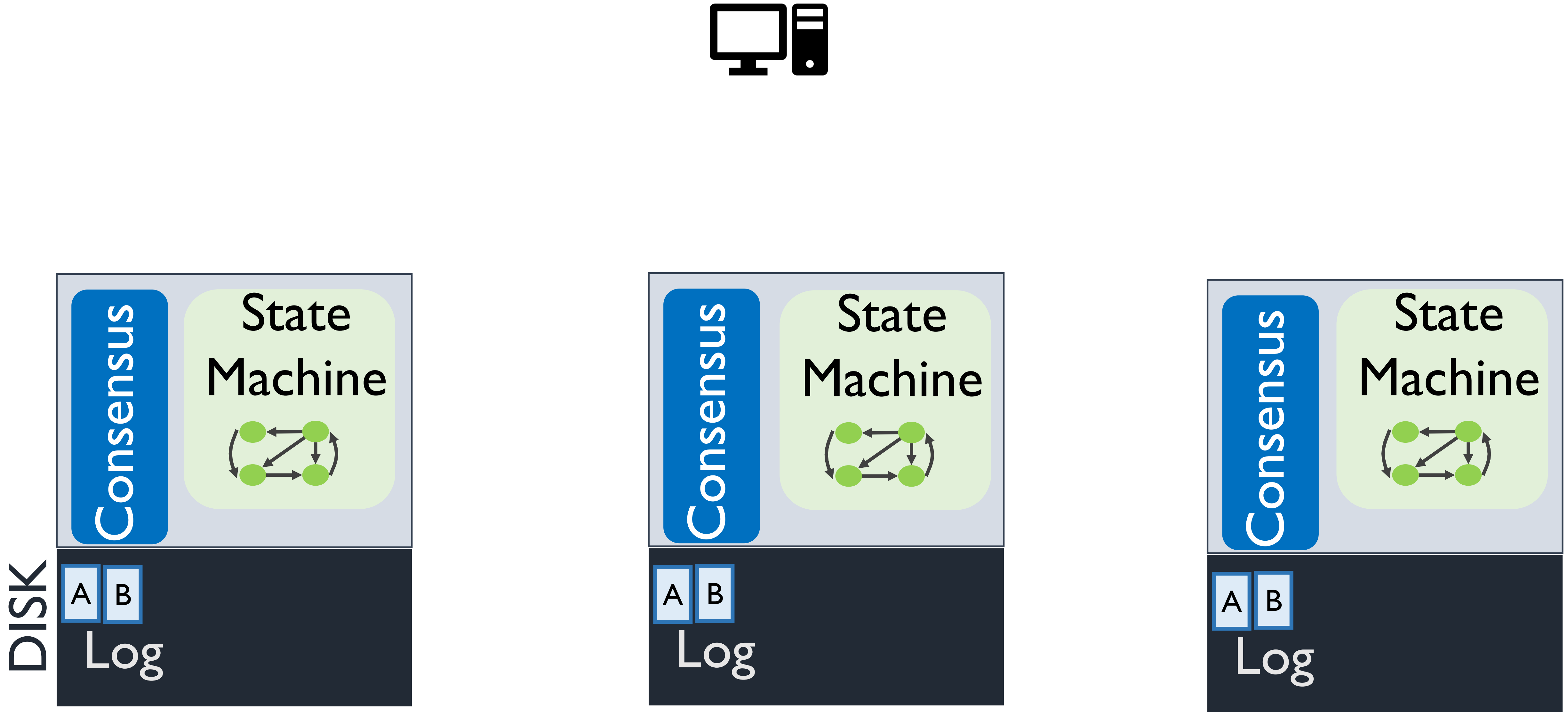

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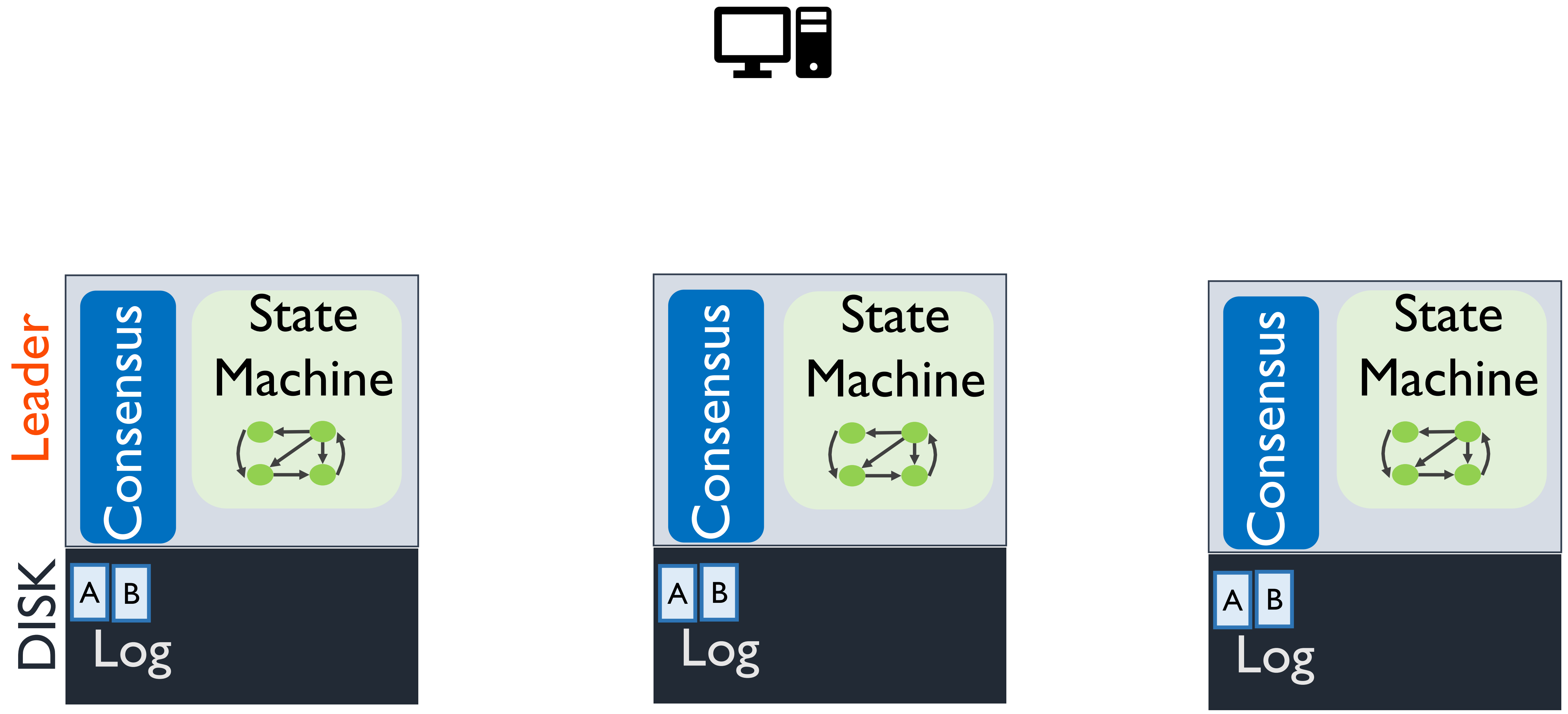

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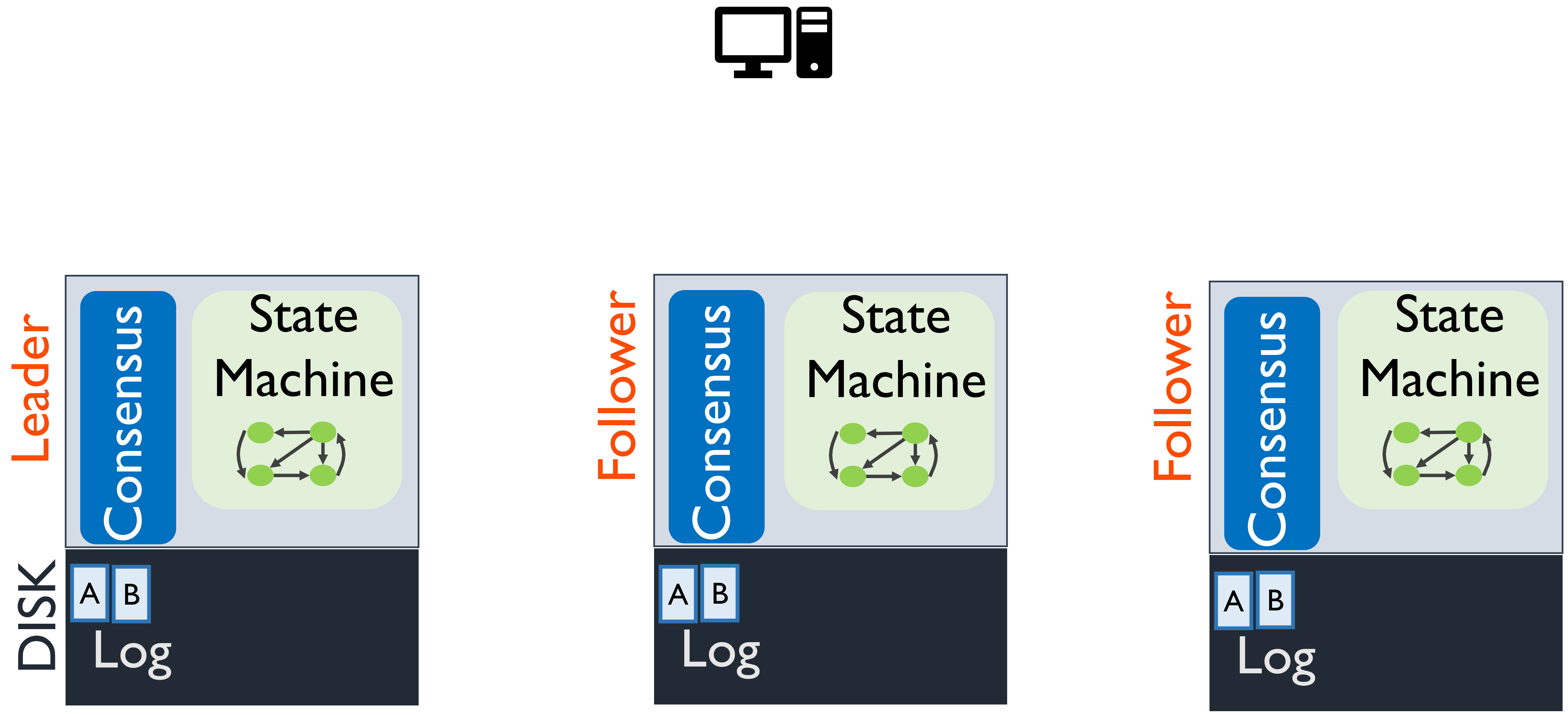

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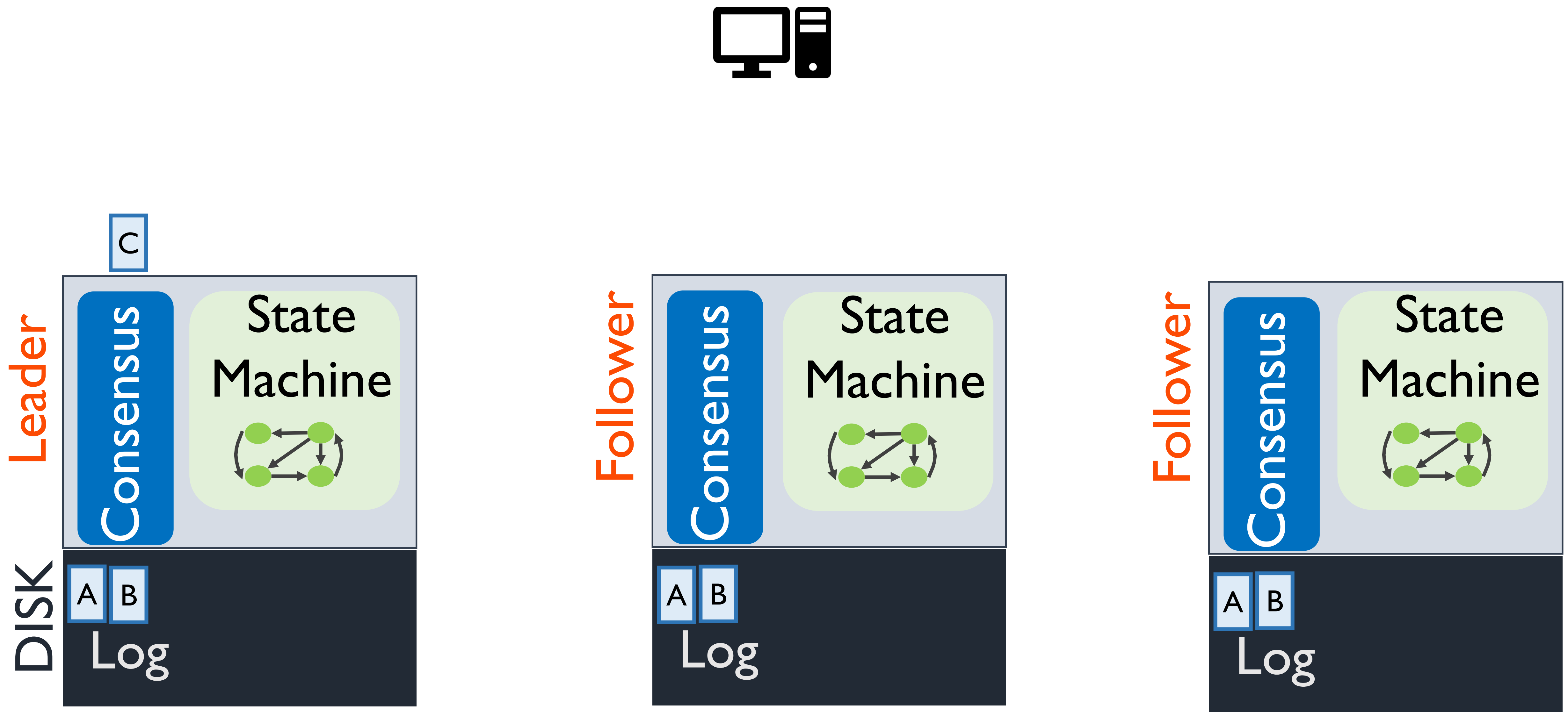

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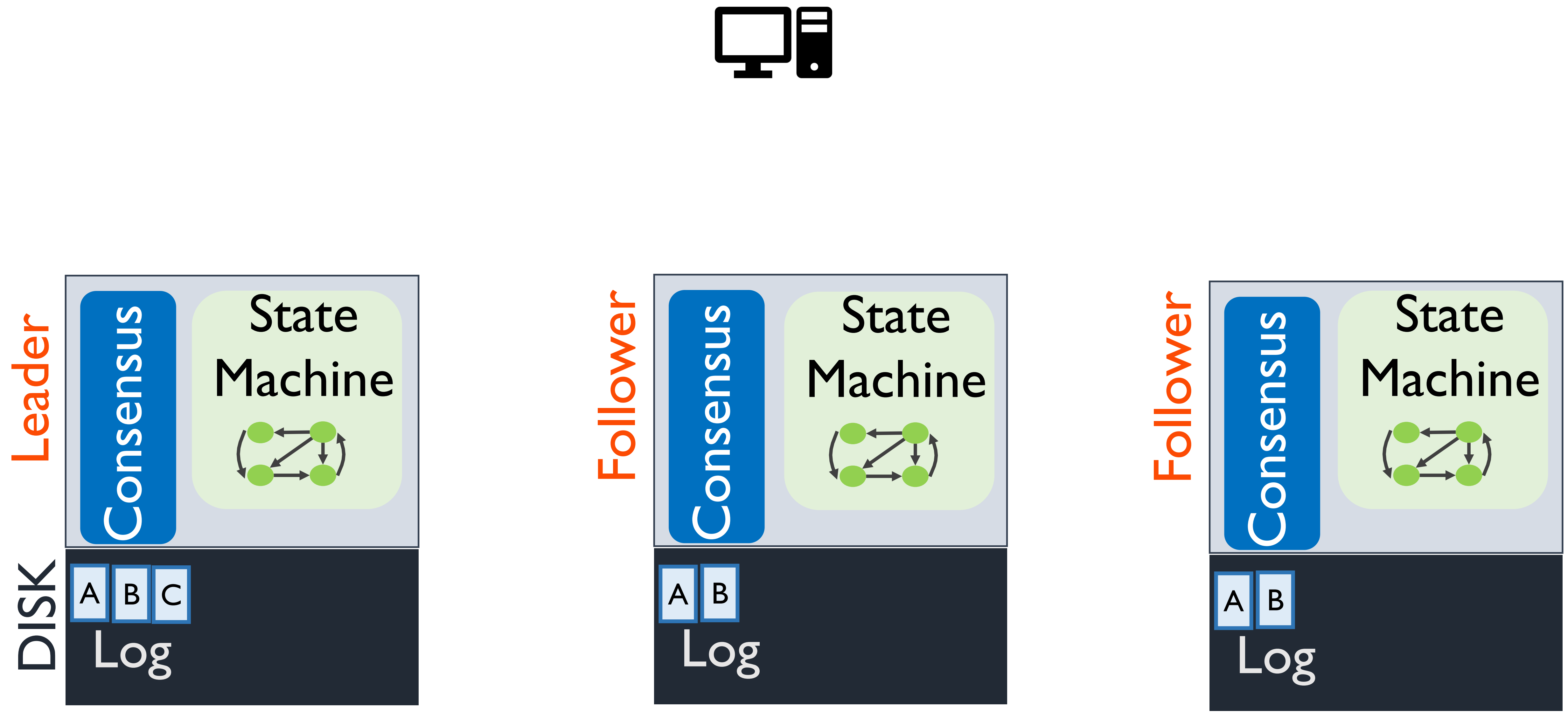

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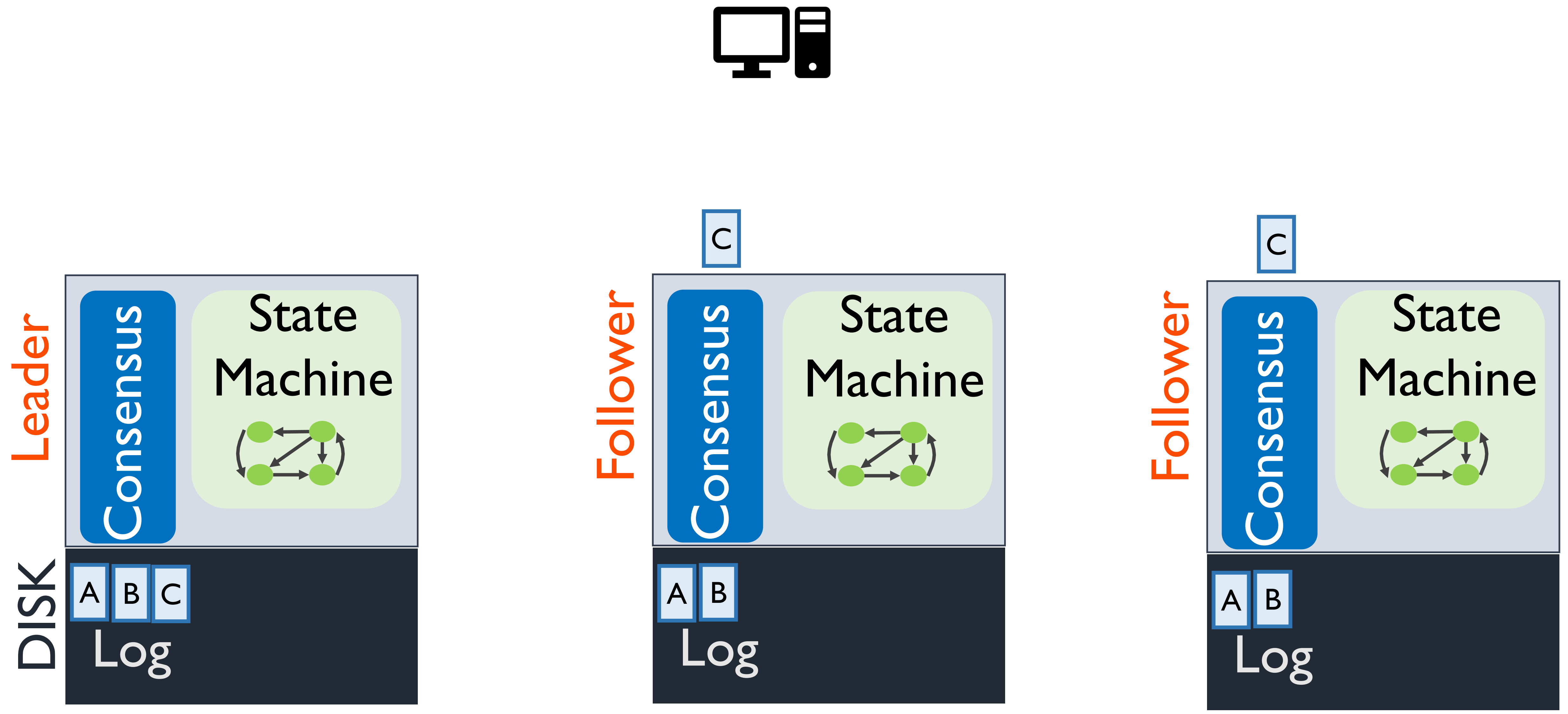

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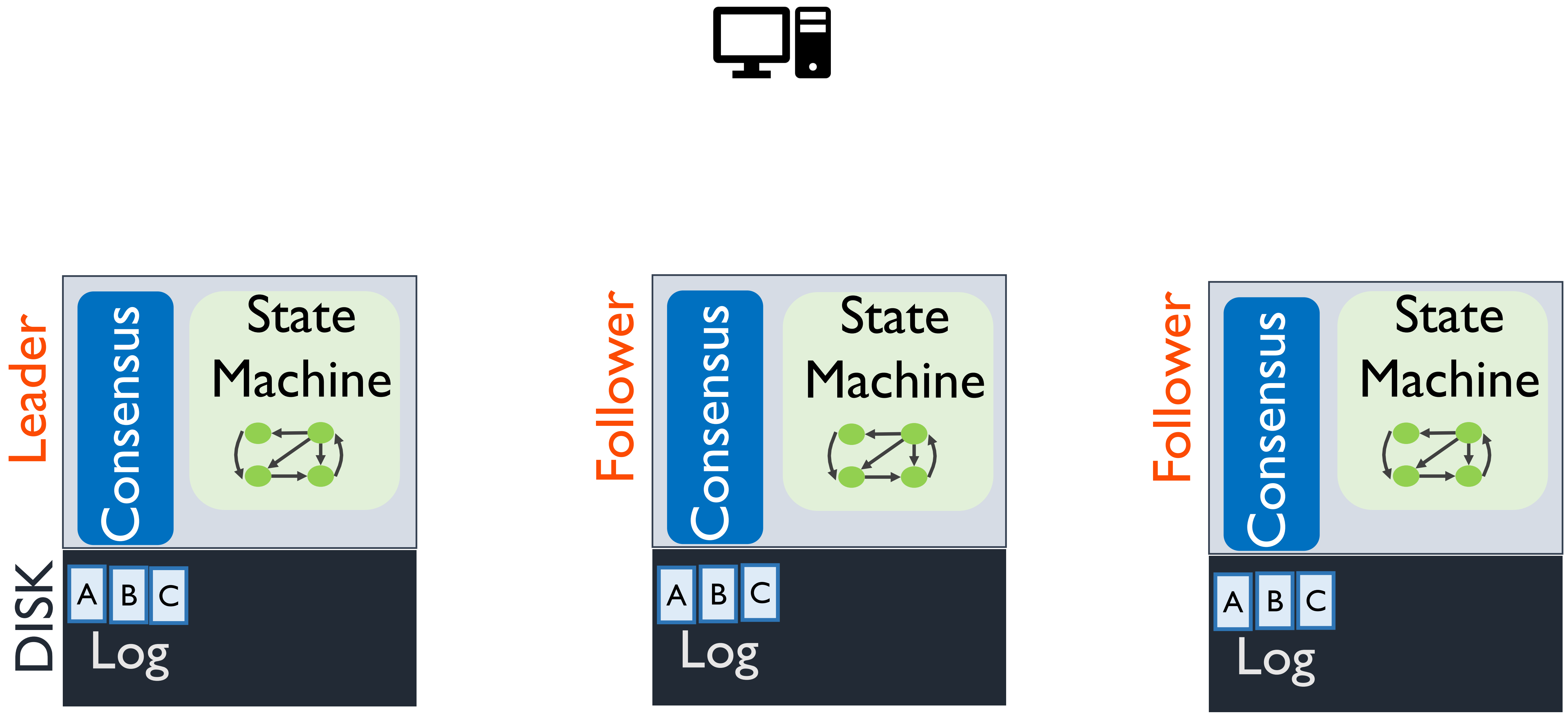

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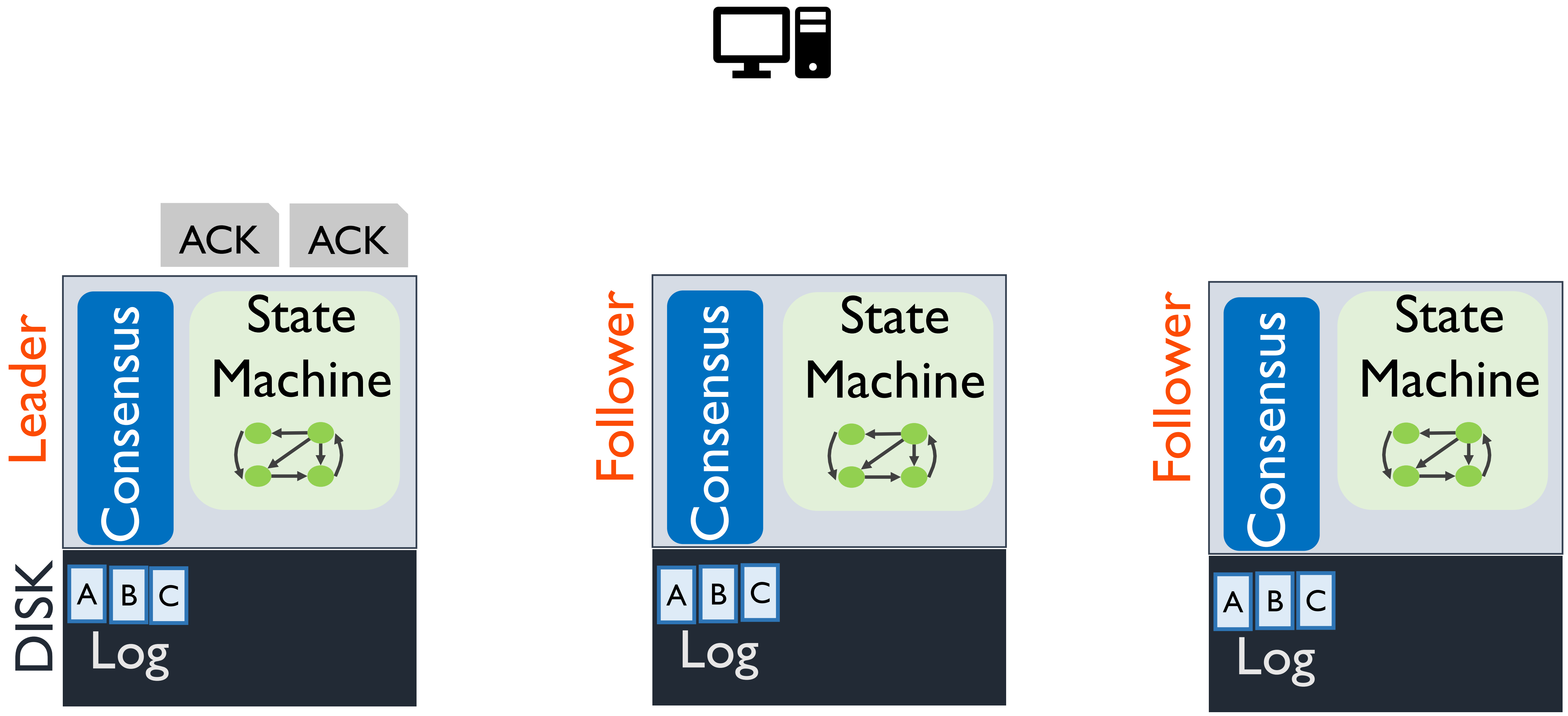

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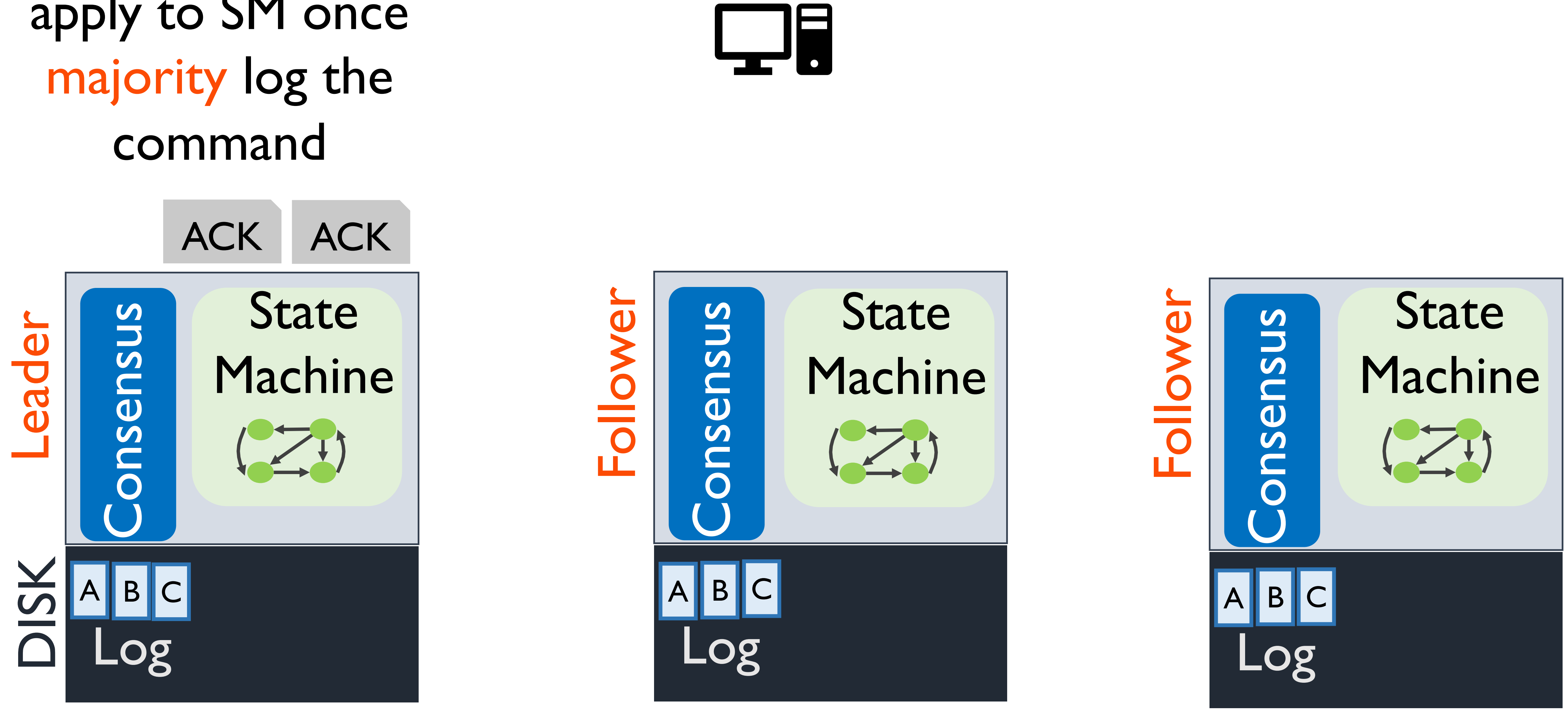
apply to SM once majority log the command



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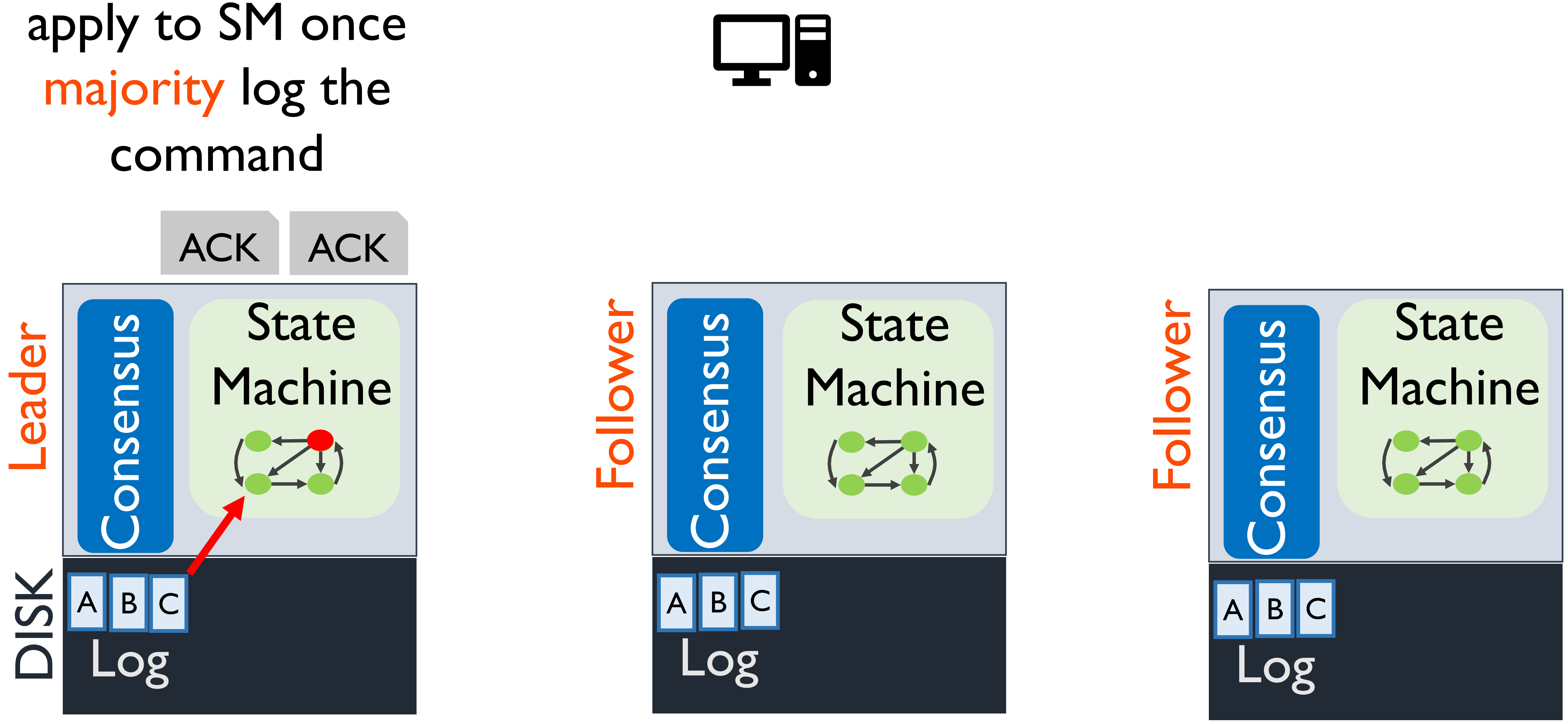

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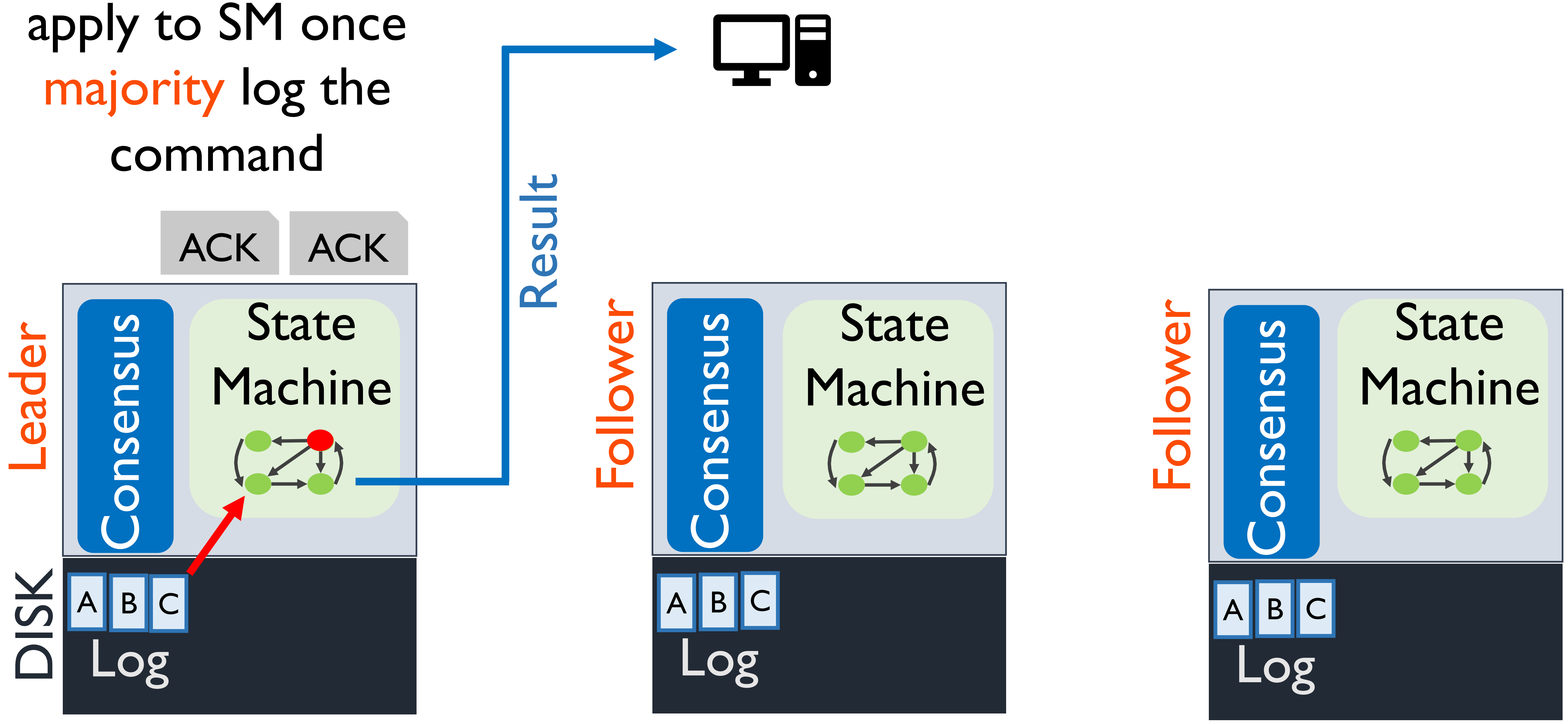

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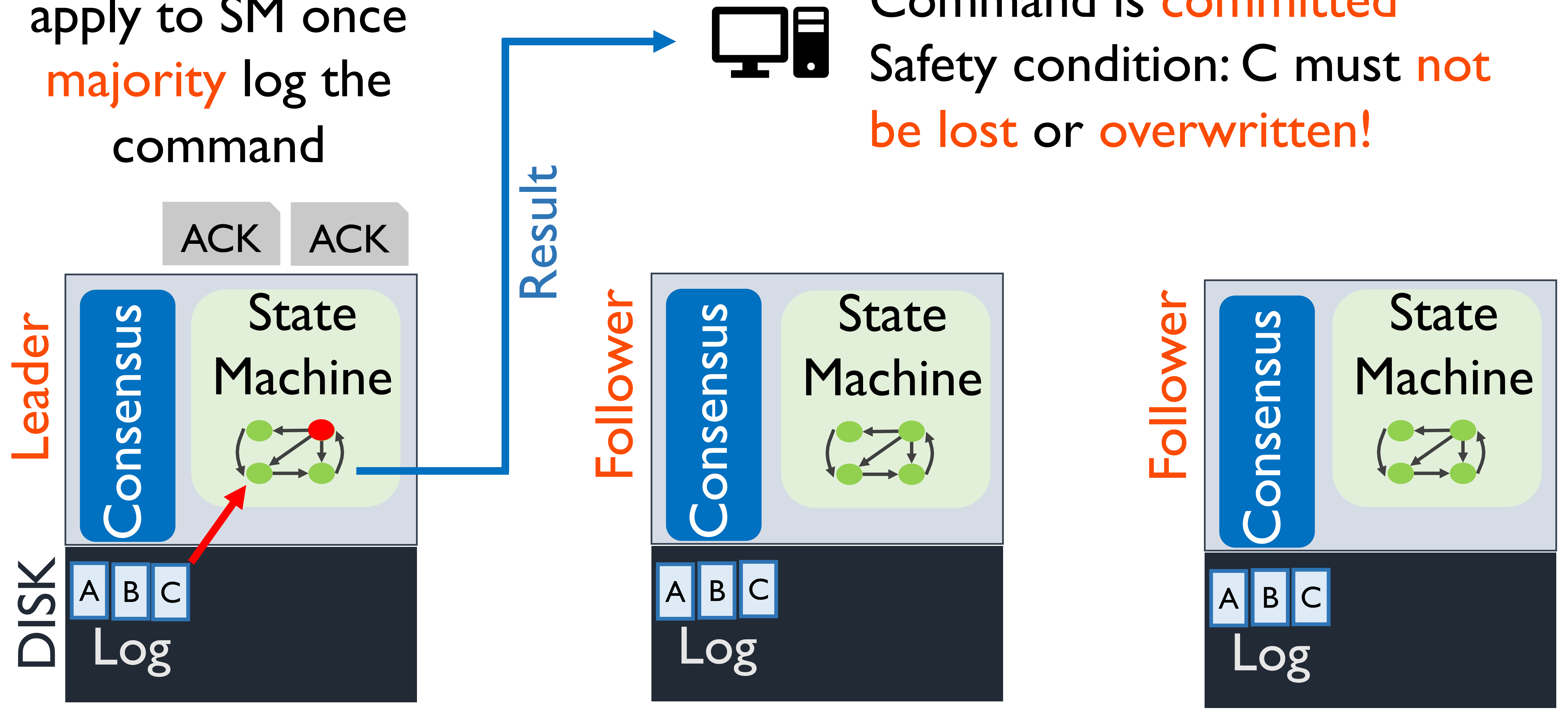
Command is committed
Safety condition: C must not be lost or overwritten!



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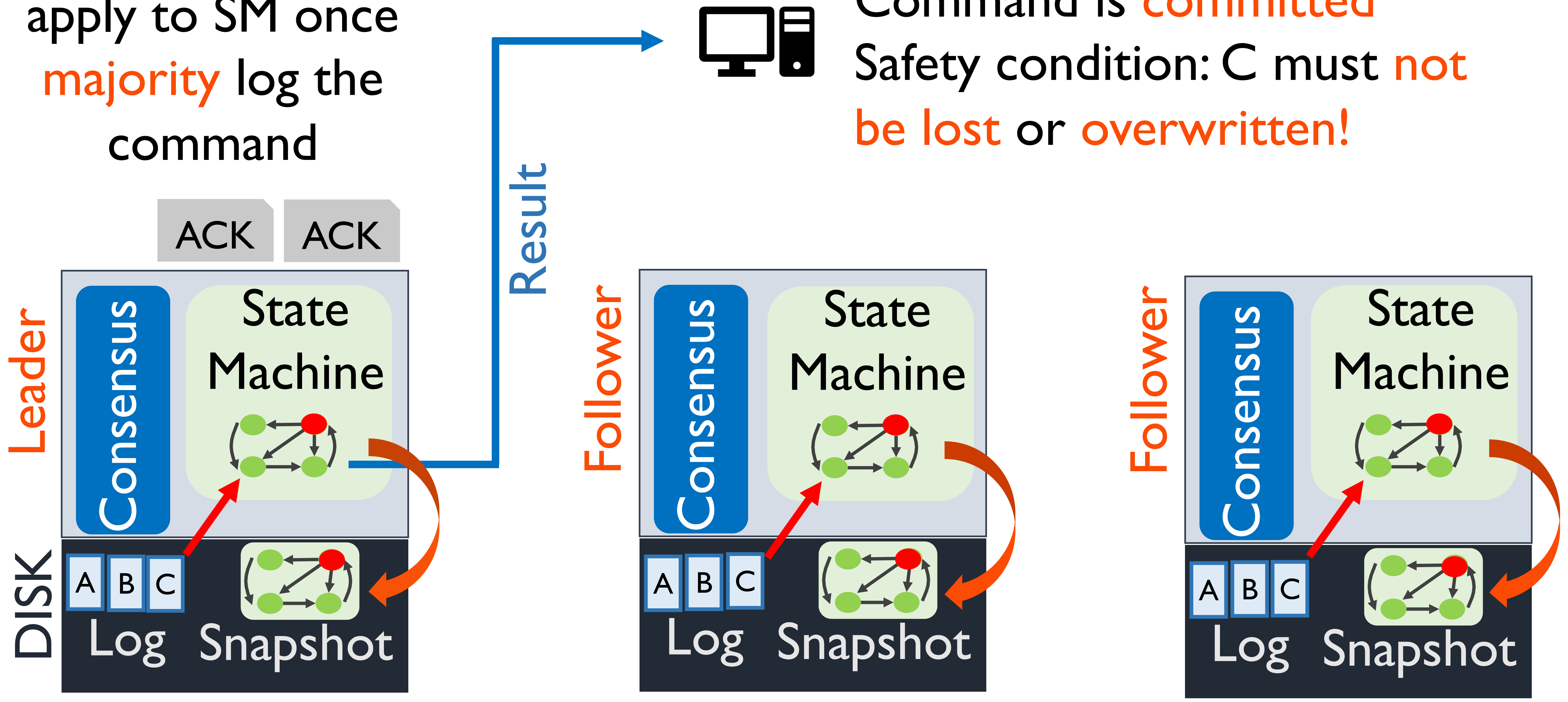

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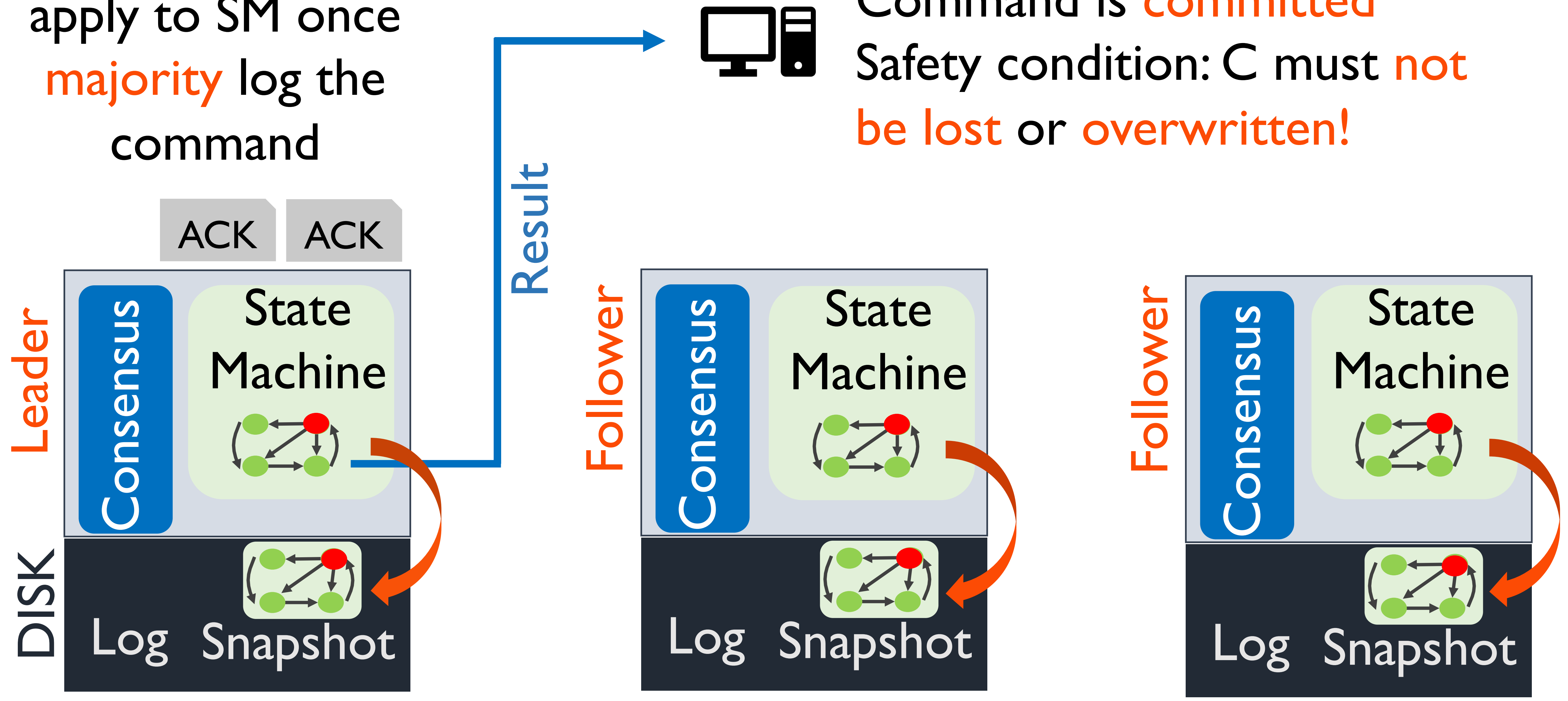
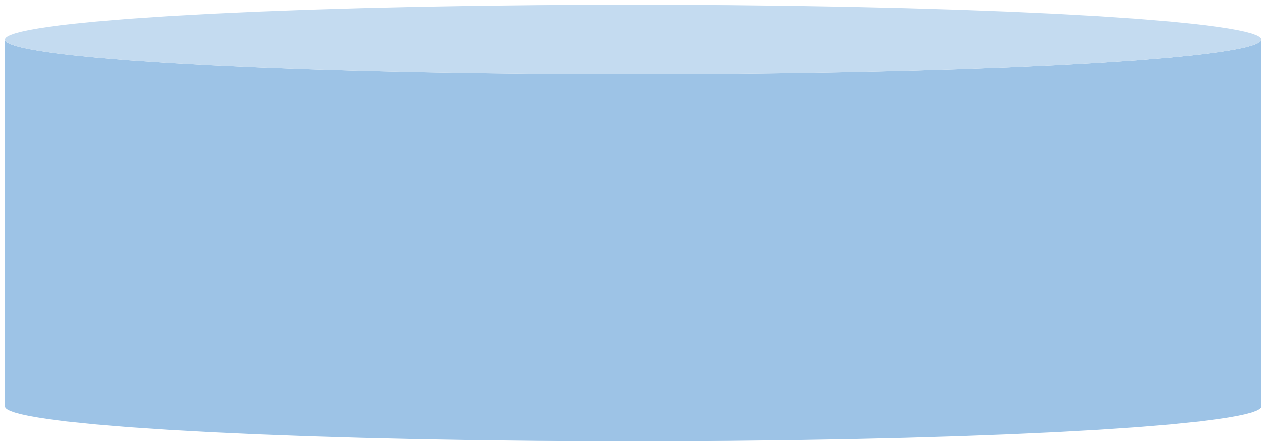


RSM Persistent Structures



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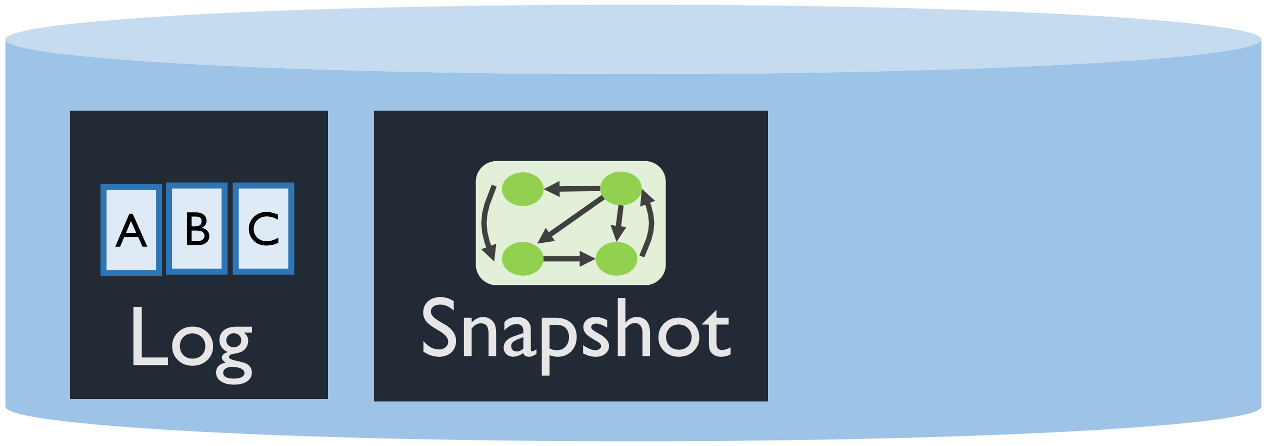

Log - commands are persistently stored

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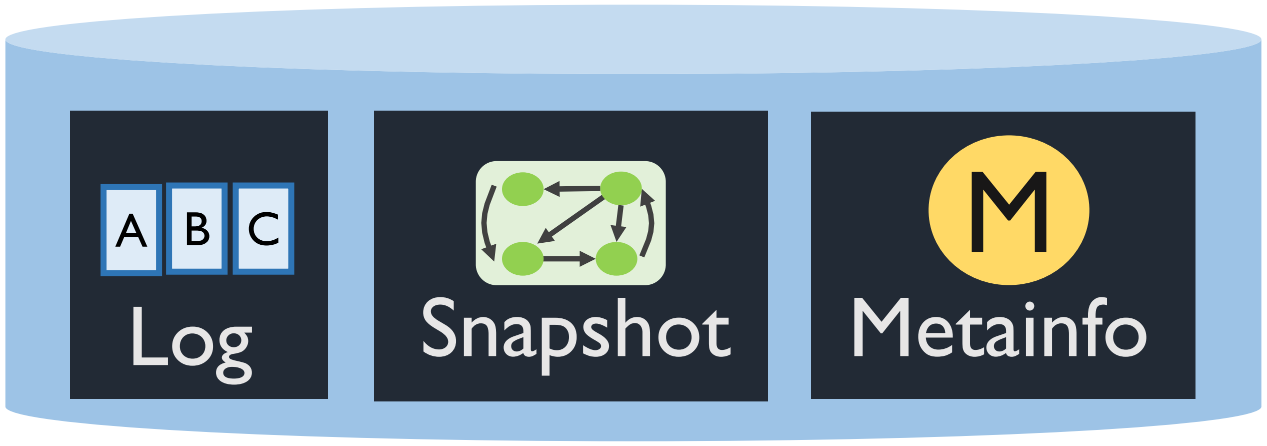

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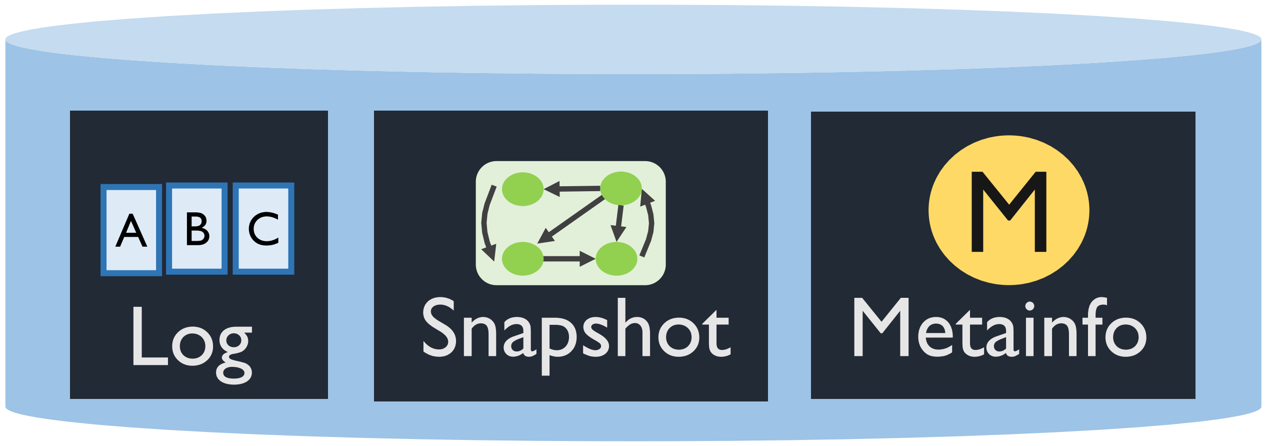

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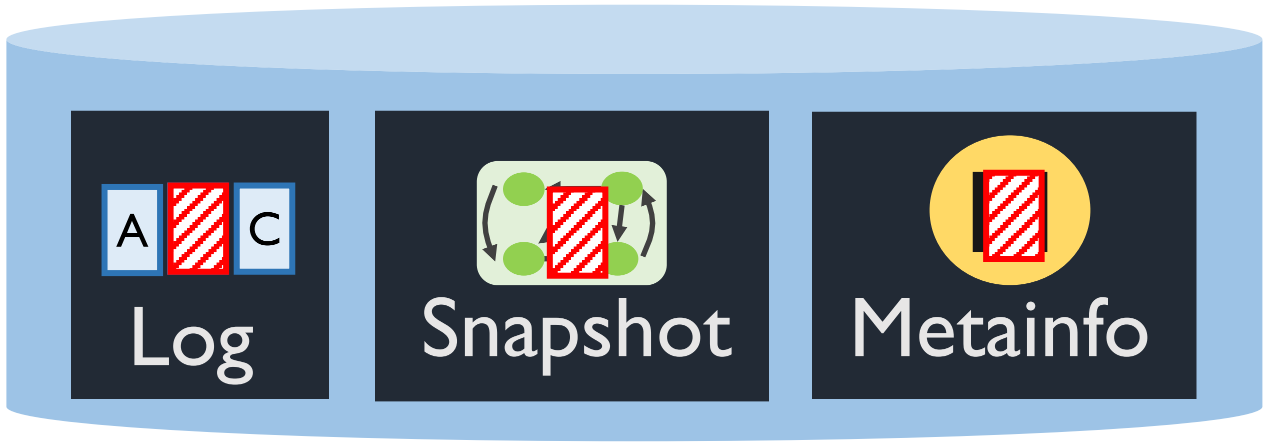

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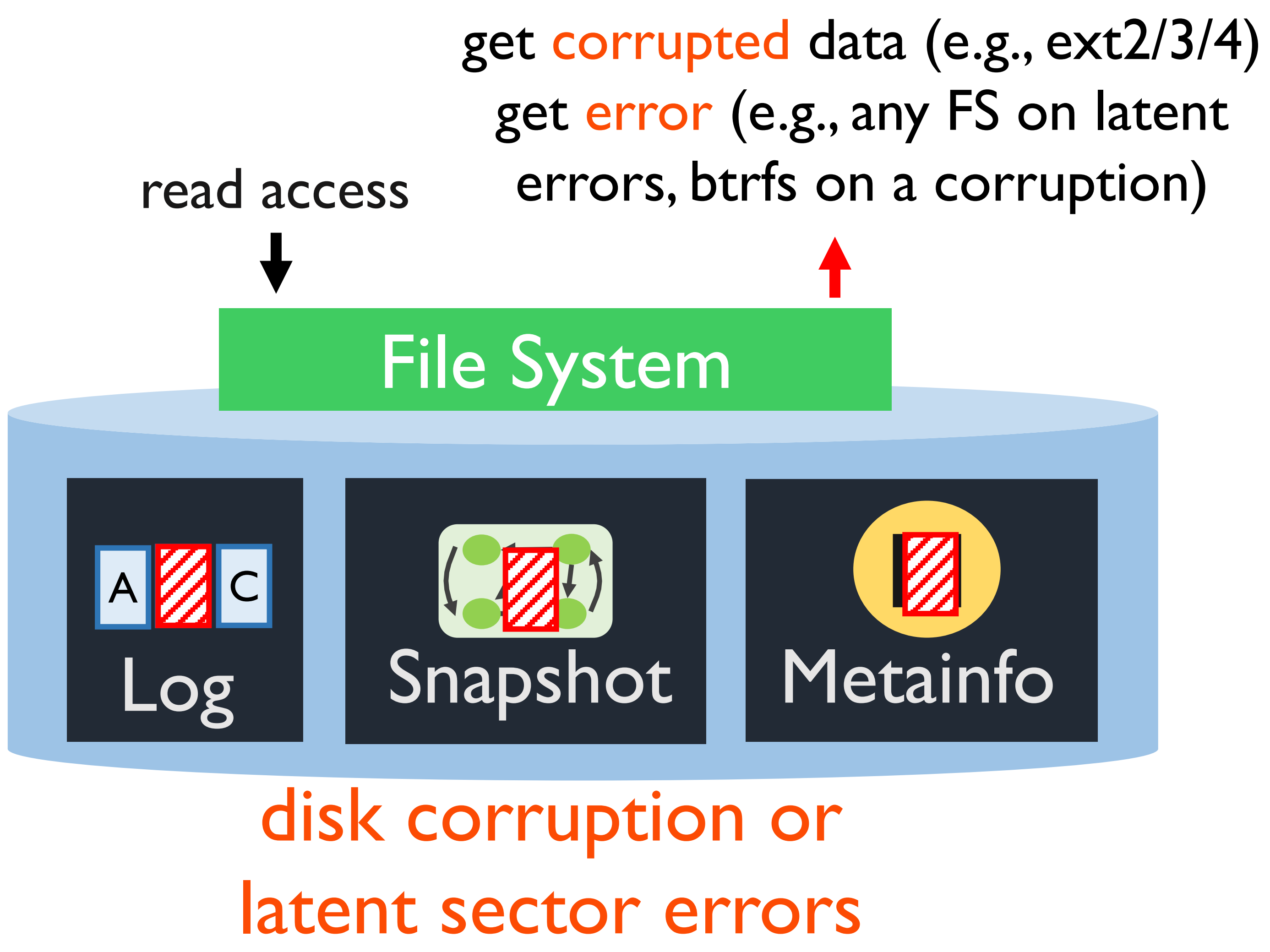
get corrupted data (e.g., ext2/3/4)
get error (e.g., any FS on latent errors, btrfs on a corruption)
read access
File System
A
C
Log
Snapshot
Metainfo
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Outline

Introduction

Replicated state machines

Current approaches to storage faults

CTRL: corruption-tolerant replication

Evaluation

Summary and conclusion

Current Approaches to Handling Storage Faults

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Methodology

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Protocol-oblivious

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Protocol-aware

- ➡ use some protocol knowledge but incorrectly or ineffectively

Protocol-Oblivious: Crash

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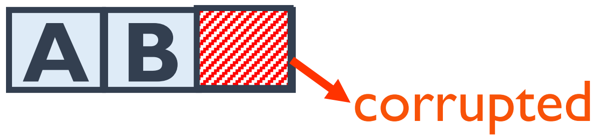

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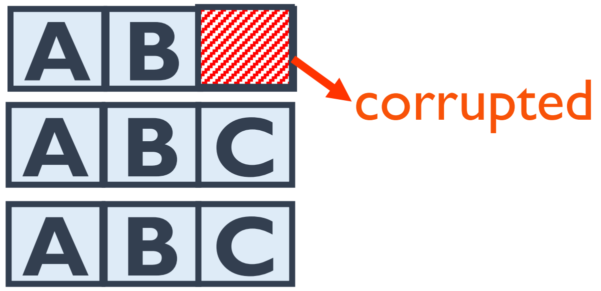

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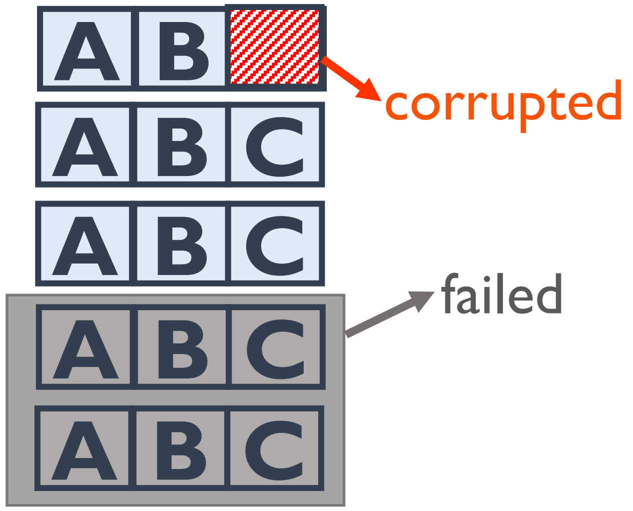

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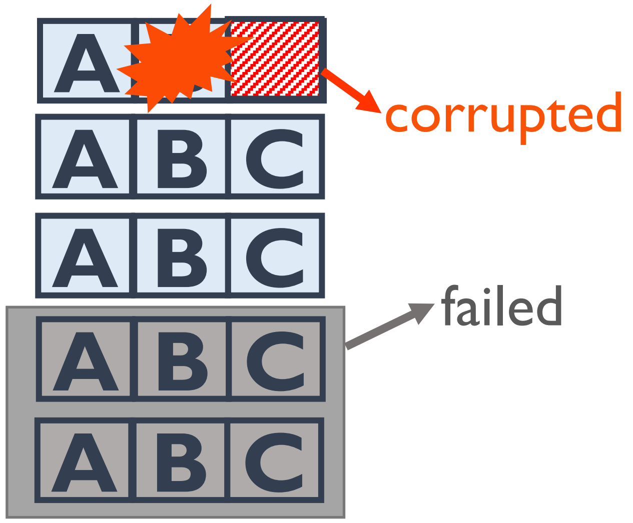

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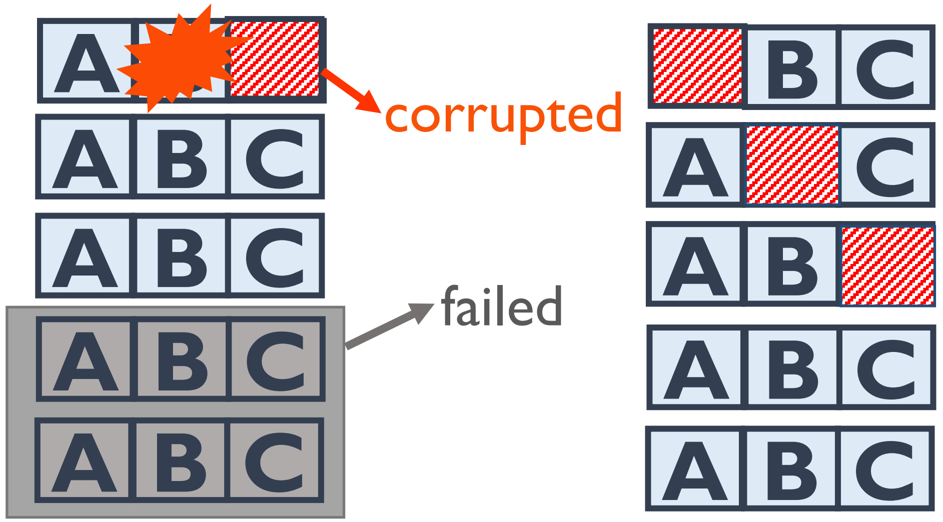

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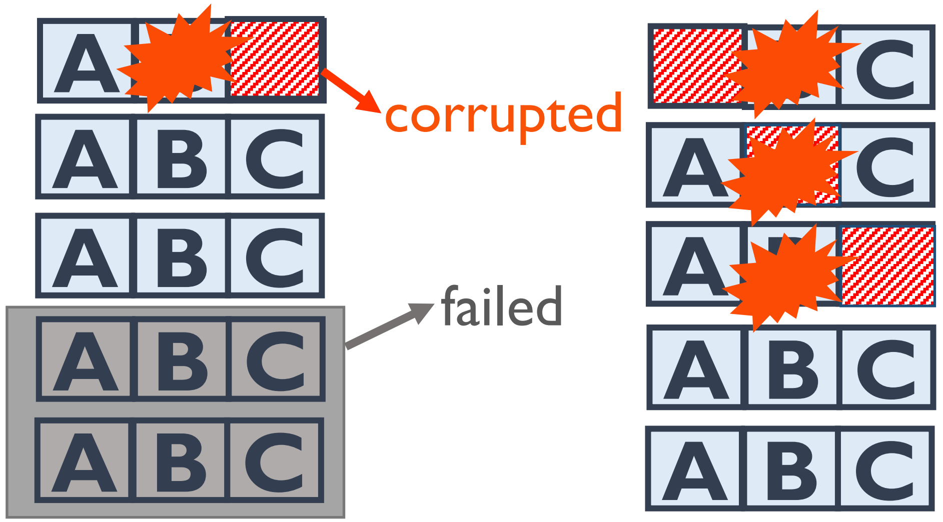

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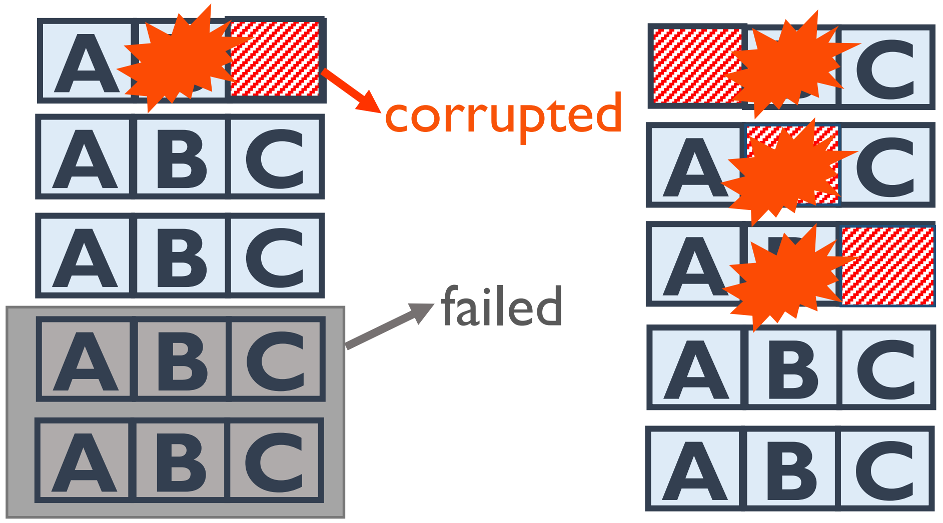

Restarting the node does not help

- ➡ persistent fault, so remain in crash-restart loop
- ➡ need error-prone manual intervention (can lead to safety violations)

Protocol-Oblivious: Truncate

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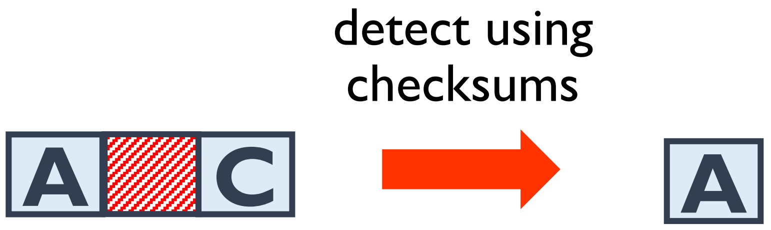

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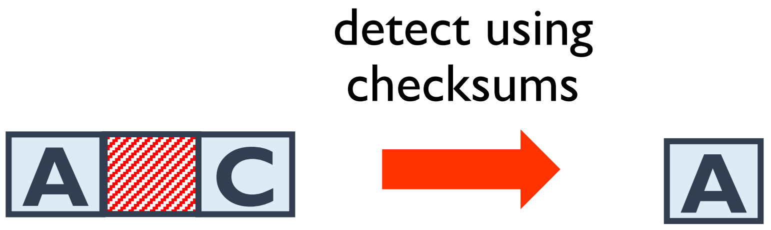

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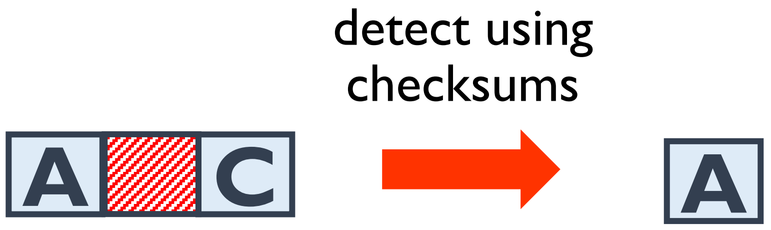

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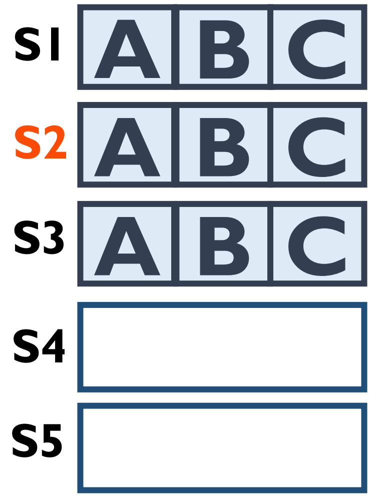

S2 - Leader

A,B,C

committed

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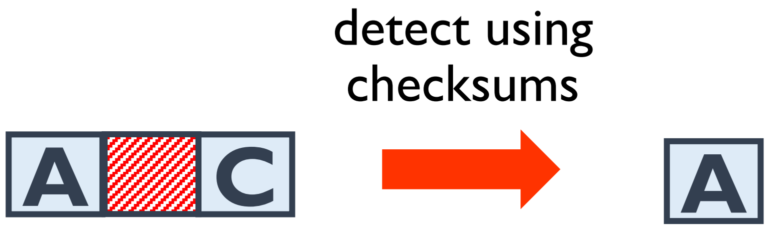

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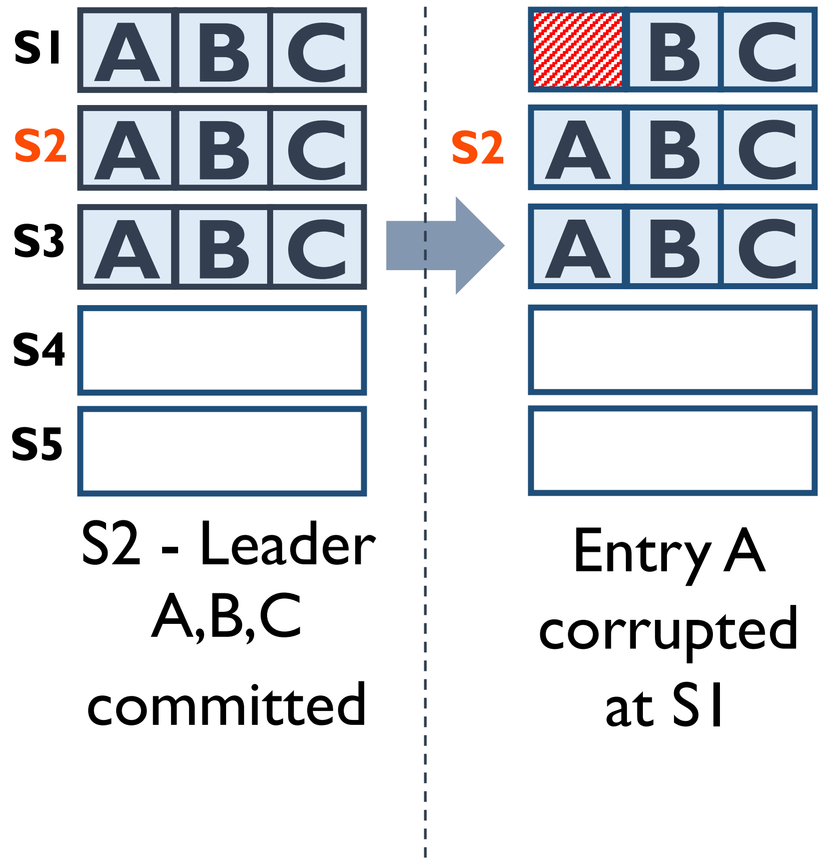

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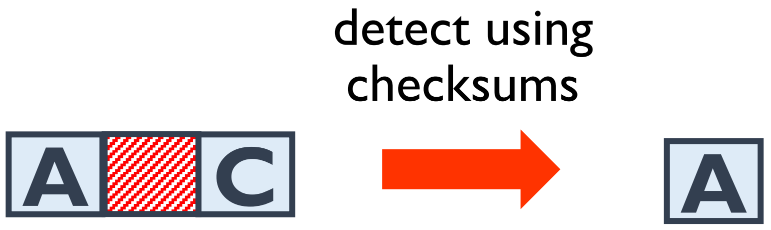

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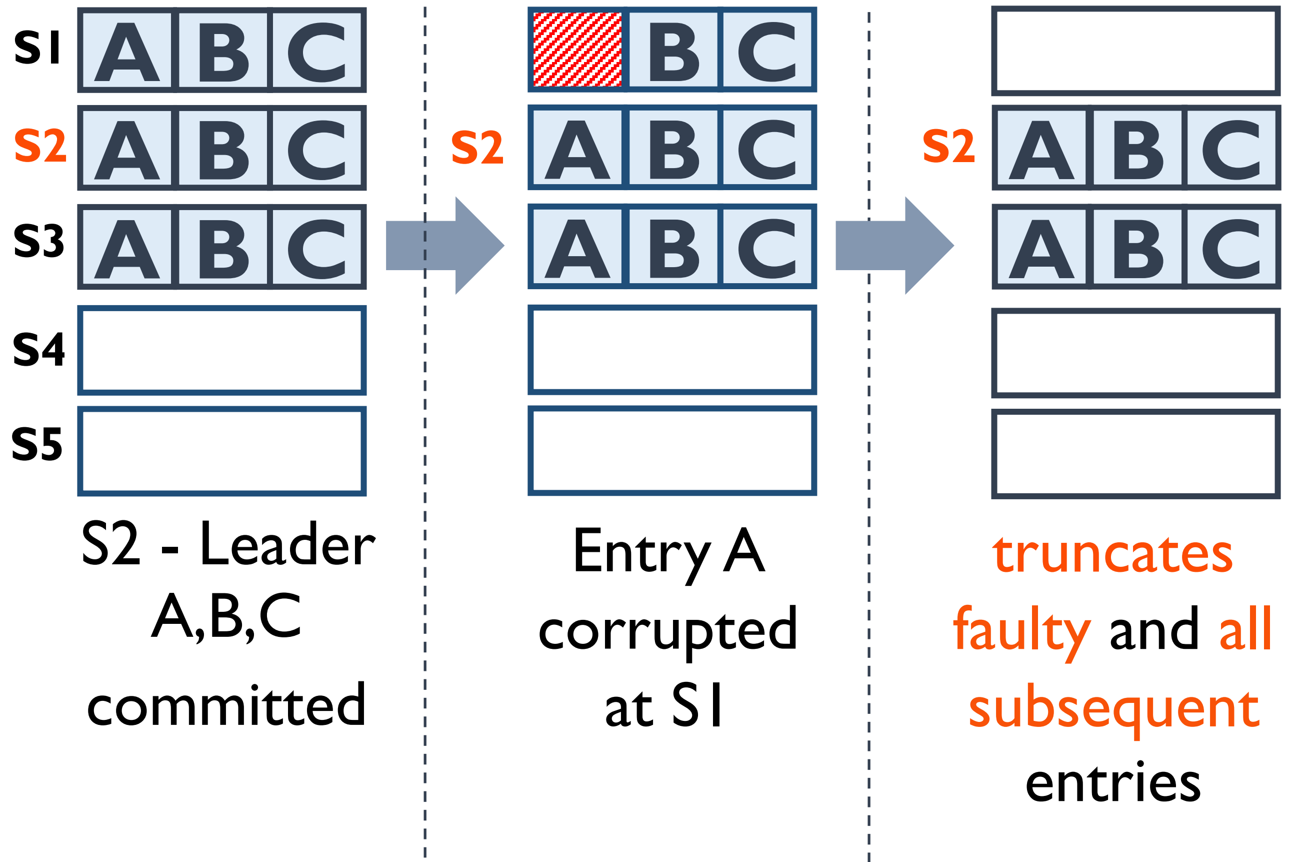

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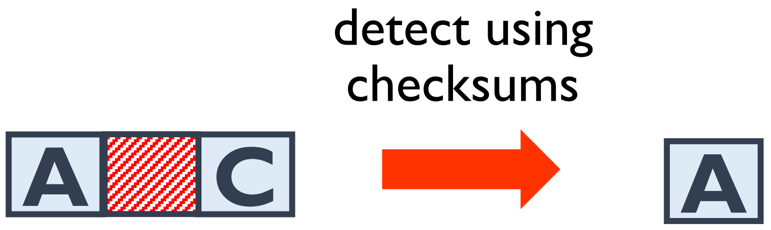

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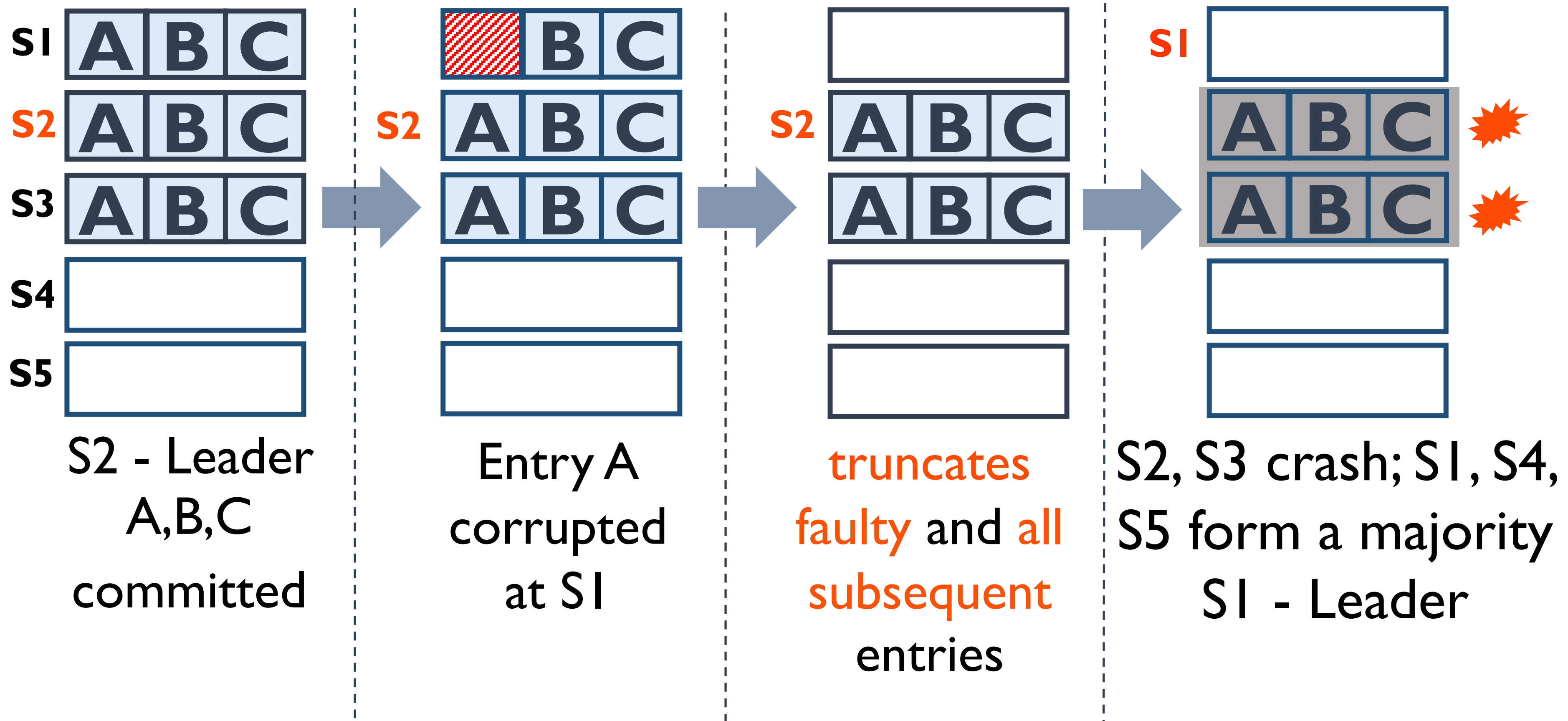

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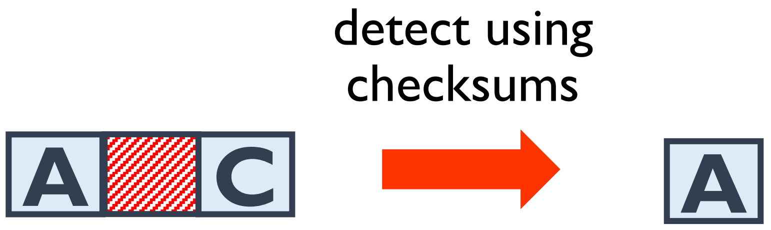

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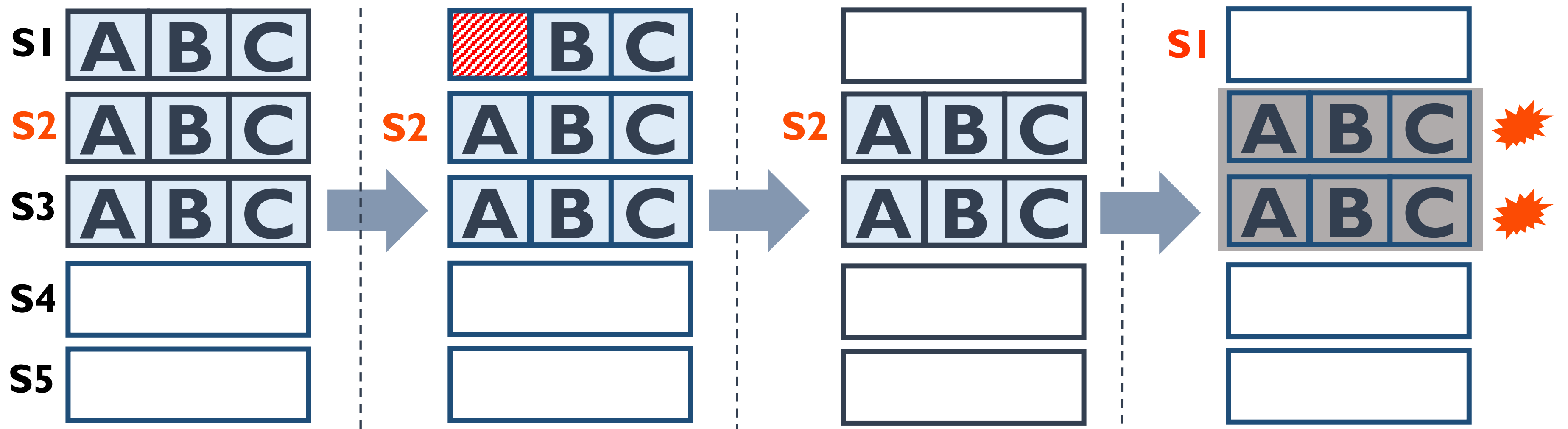

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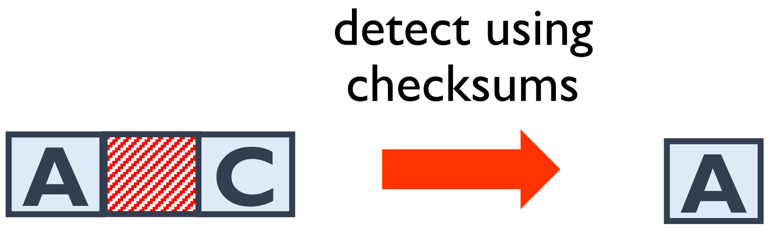

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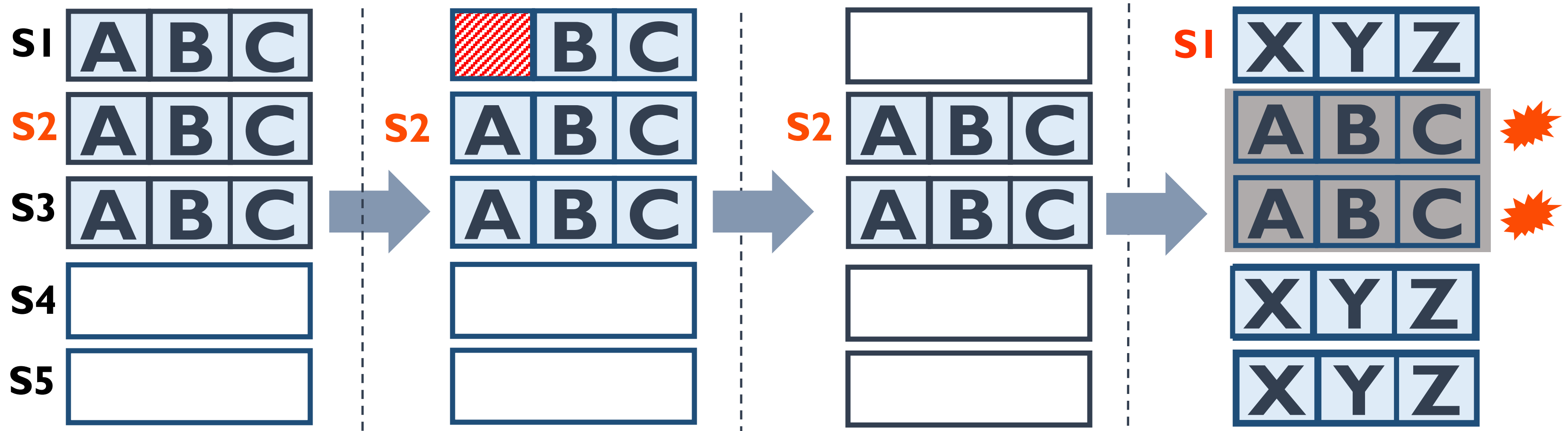

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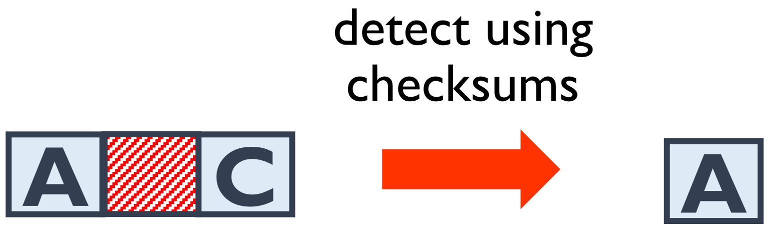

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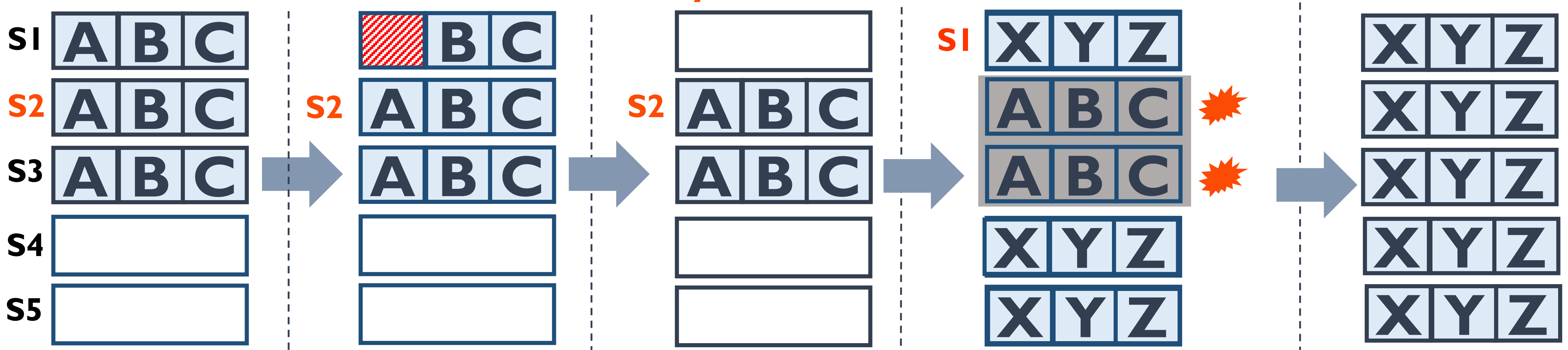

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S2, S3 follow leader's log, removing A,B,C

Recovery Approaches Summary

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Class
Protocol-oblivious
Protocol-aware

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Class	**Approach**
Protocol-oblivious	NoDetection
	Crash
	Truncate
	DeleteRebuild
Protocol-aware	MarkNonVote [1]
	Reconfigure [2]
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	CTRL	✓	✓	✓	✓	✓	✓	✓

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Outline

CTRL Overview

CTRL Overview

Two components

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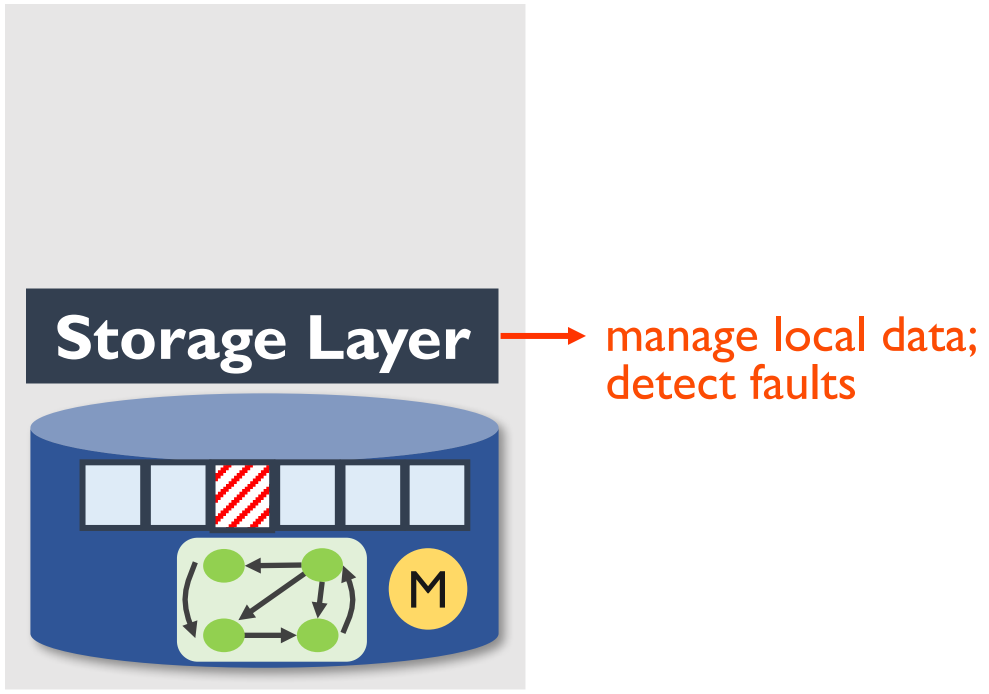
Local storage layer

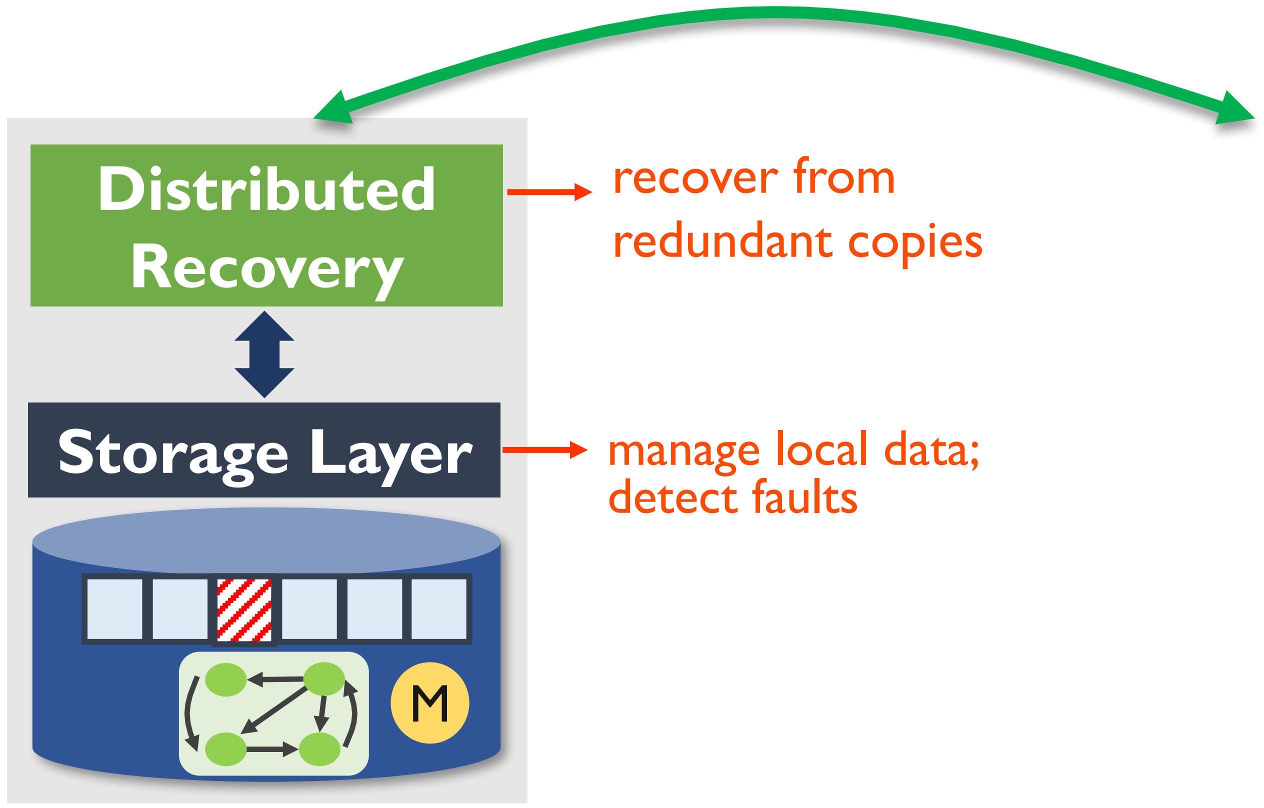


CTRL Overview

Two components

Local storage layer

Distributed recovery


Distributed Recovery
Storage Layer
M
recover from redundant copies
manage local data; detect faults

CTRL Overview

Two components

Local storage layer

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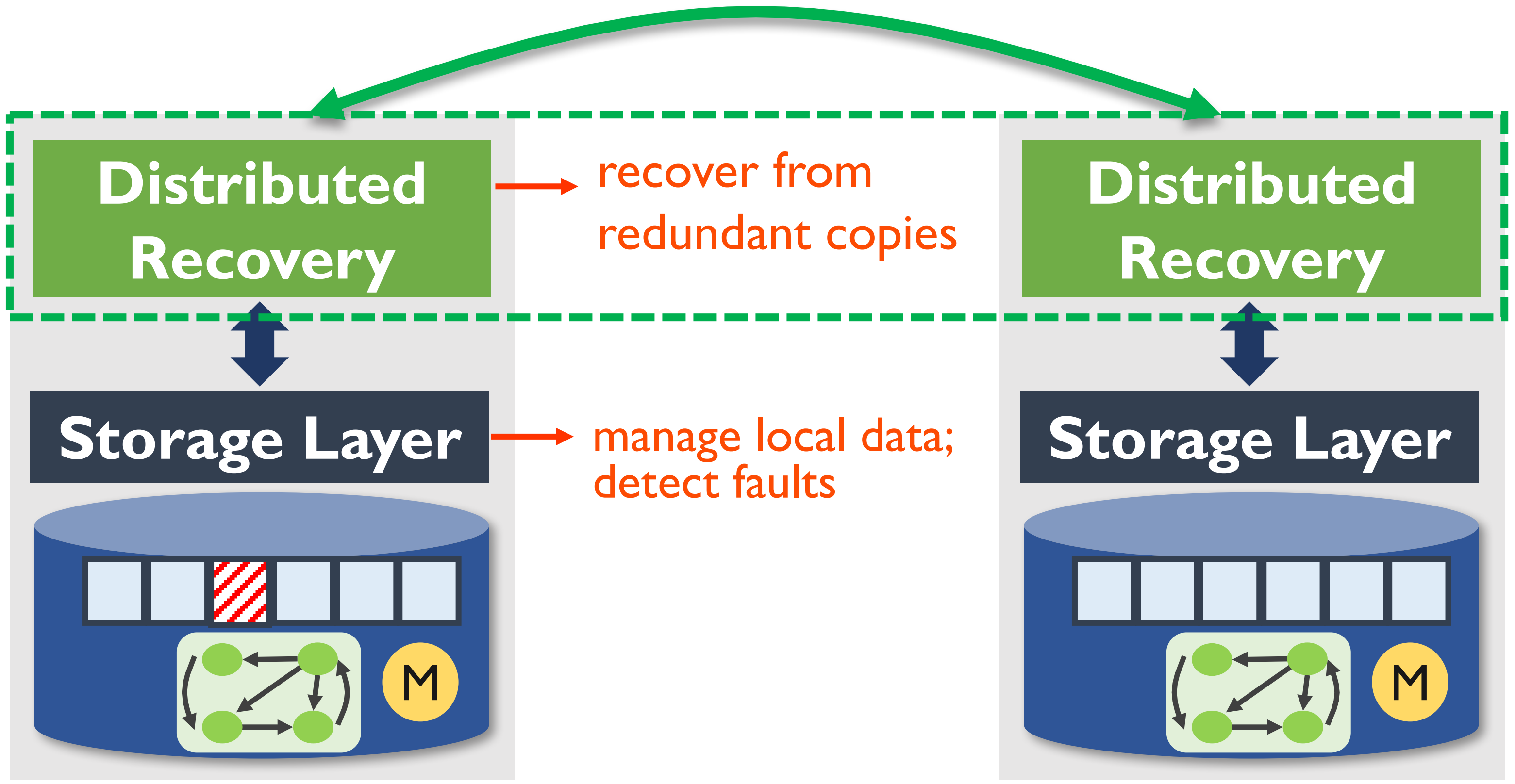

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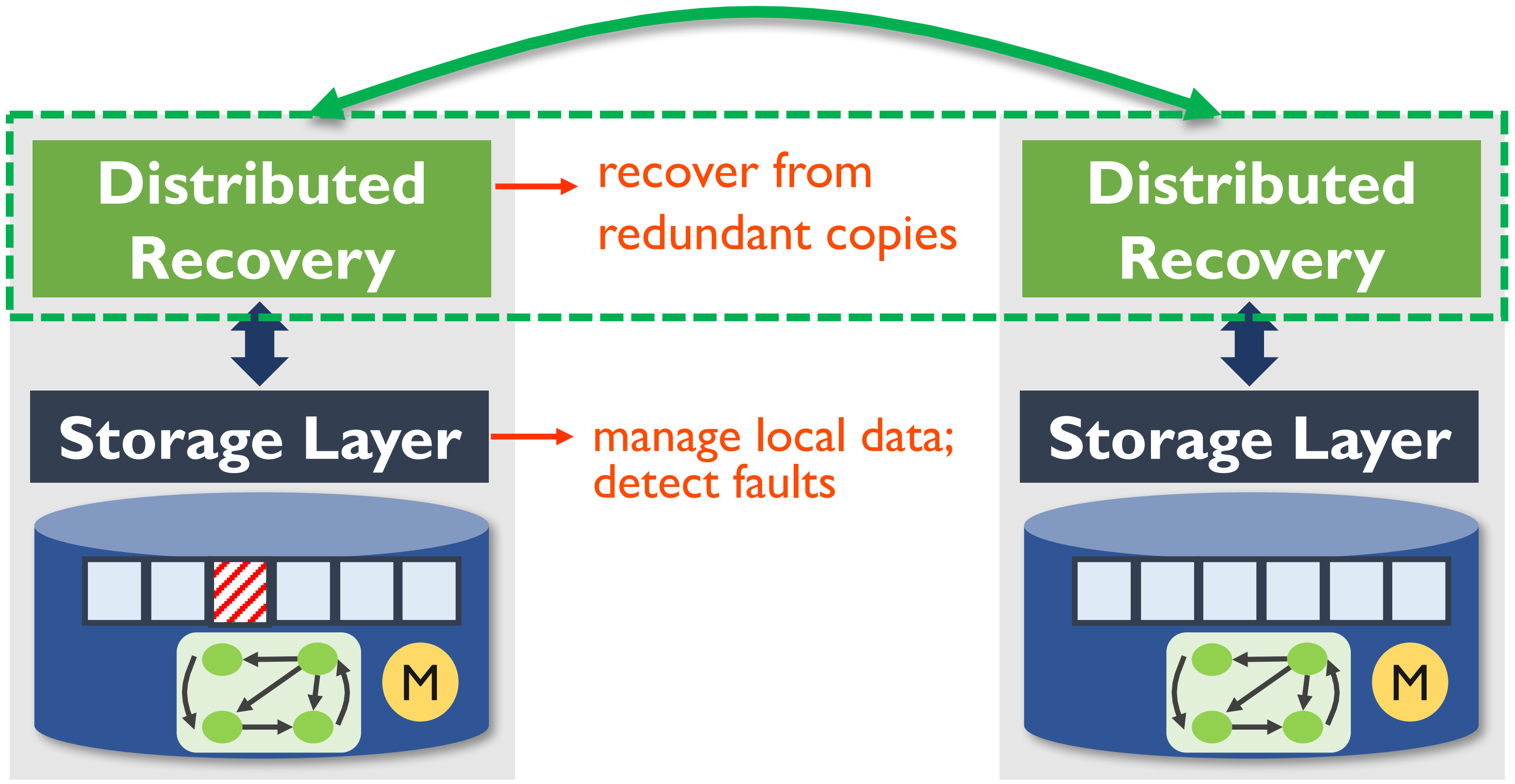

Exploit RSM knowledge to correctly and quickly recover faulty data

CTRL Fault Model

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Standard failure assumptions

- ➡ crashes
- ➡ network failures

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CTRL Fault Model

Standard failure assumptions

- crashes
- network failures

Augment with storage faults

- data blocks of log, snapshots, and metainfo can be faulty
  - depending on FS, return corrupted data or turn into errors
- FS metadata blocks could also be faulty
  - e.g., inode of a log file corrupted
  - e.g., files/directories implementing the log may go missing
  - e.g., files may appear with fewer or more bytes

CTRL Guarantees

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Committed data will never be lost

- ➡ as long as one intact copy of a data item exists
- ➡ correctly remain unavailable when all copies are faulty

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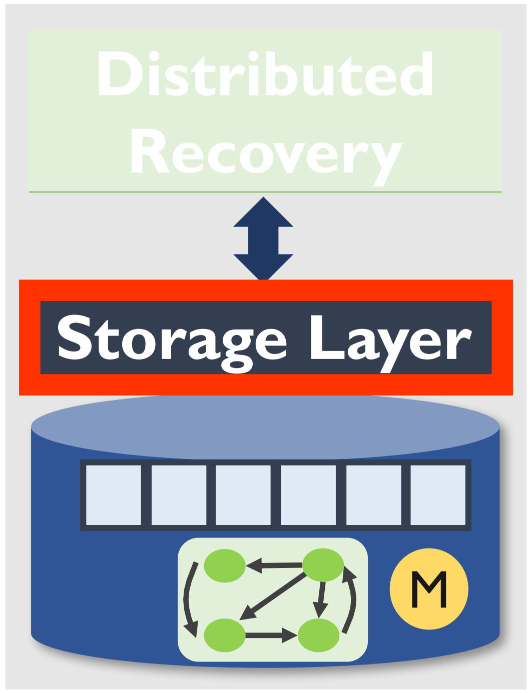
Provide the highest possible availability

CTRL Local Storage



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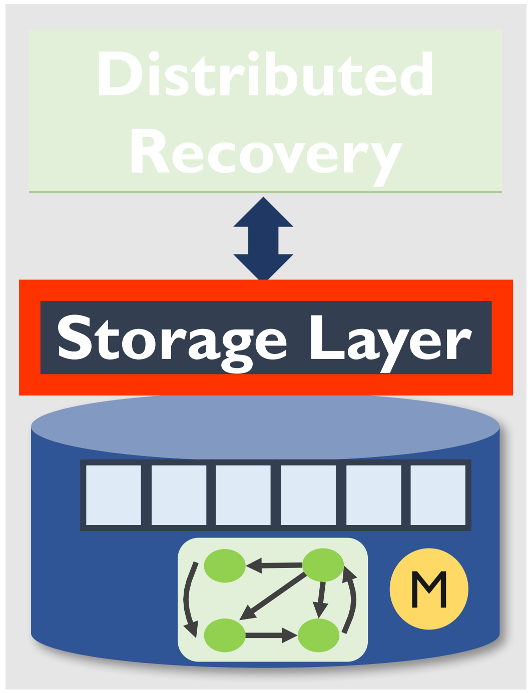
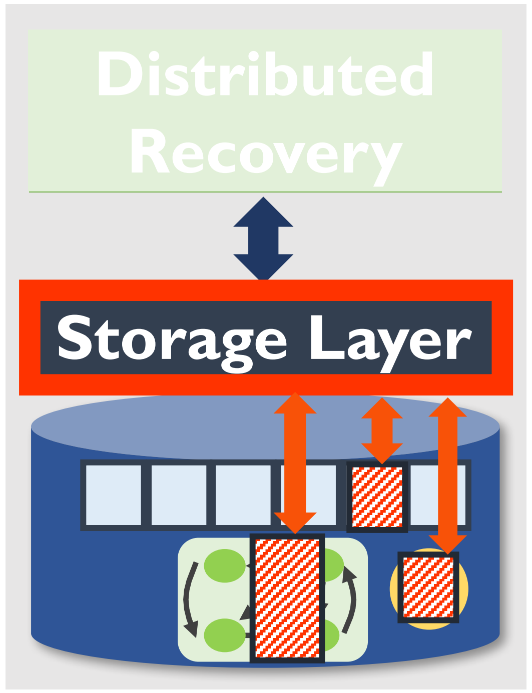


Main function: detect and identify

- ➡ whether log/snapshot/metainfo faulty or not?
- ➡ what is corrupted? (e.g., which log entry?)

CTRL Local Storage



Main function: detect and identify

- whether log/snapshot/metainfo faulty or not?
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- low performance overheads
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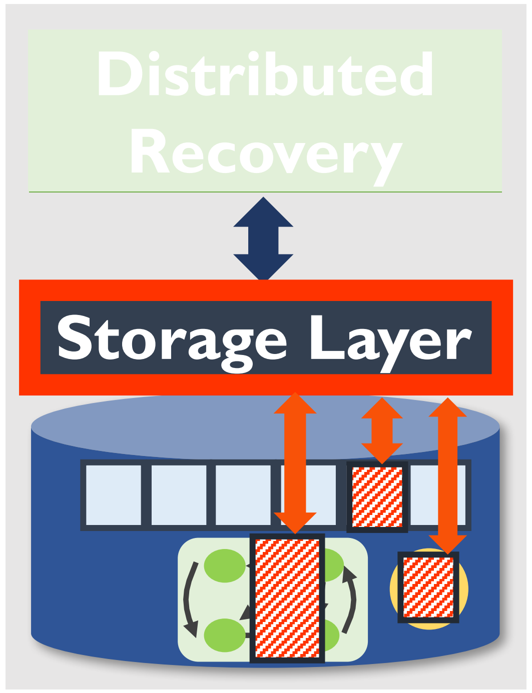

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An interesting problem: disentangling crashes and corruptions in log

- ➡ checksum mismatch due to crash or disk corruption?

Crash-Corruption Entanglement in the Log

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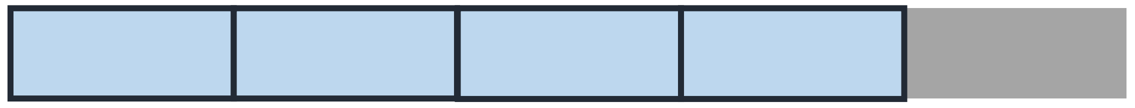

append()

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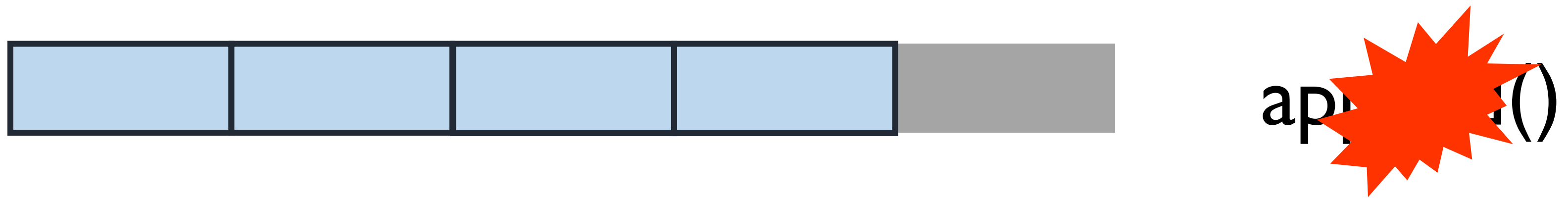

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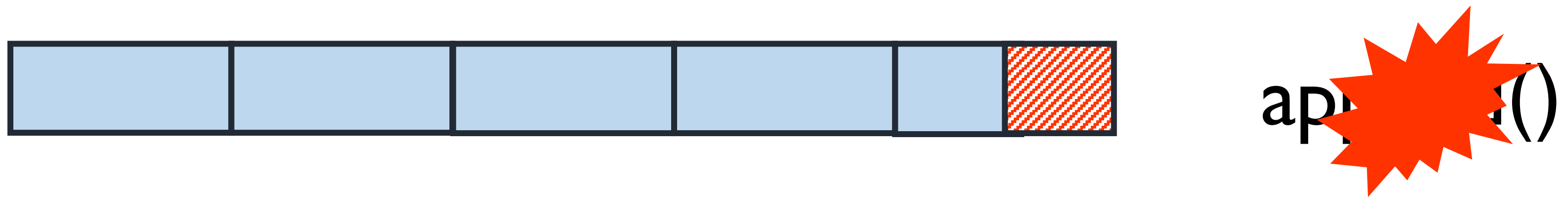

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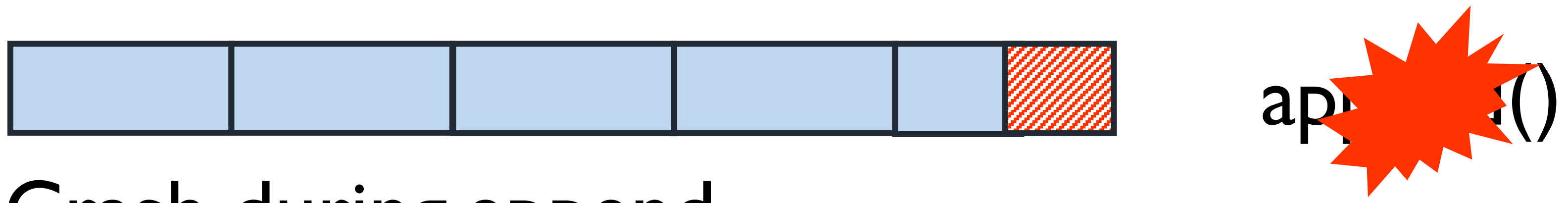

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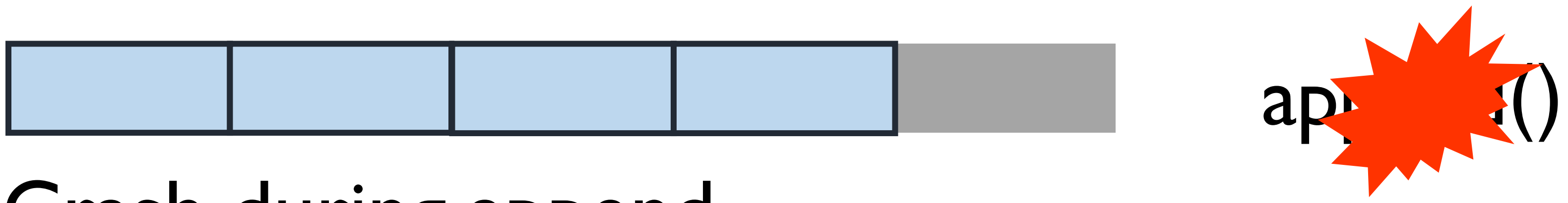

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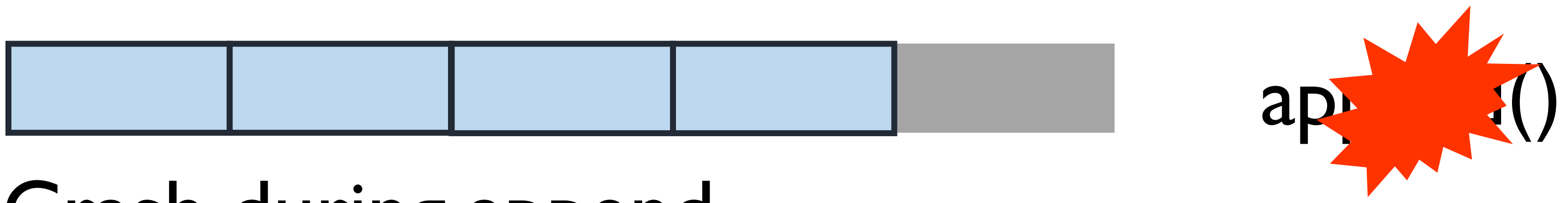

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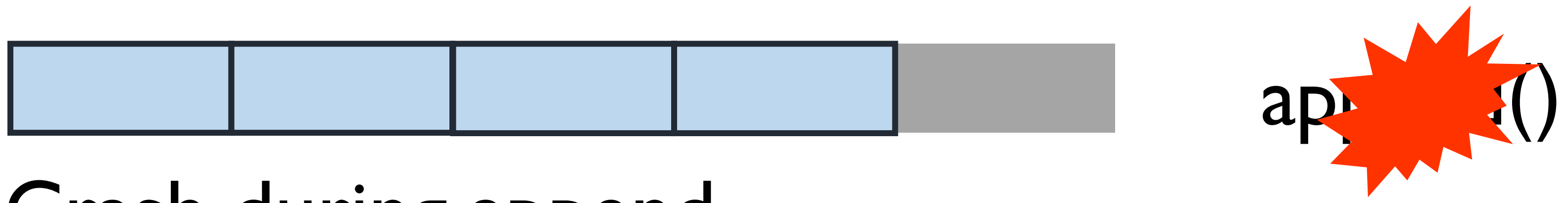

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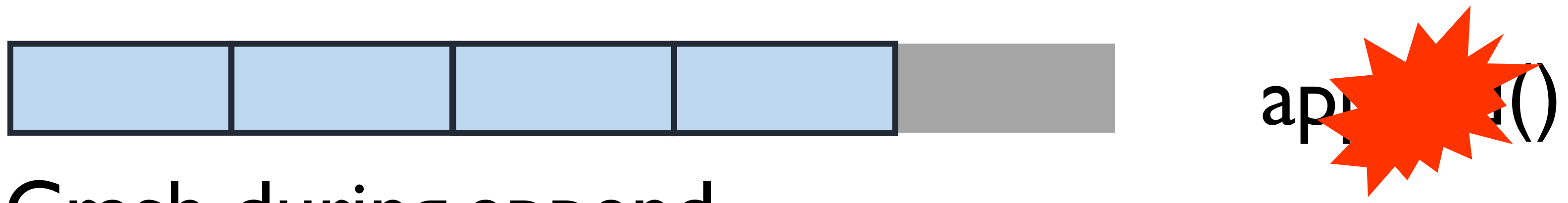

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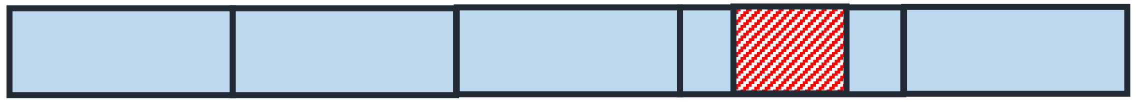

disk
corruption

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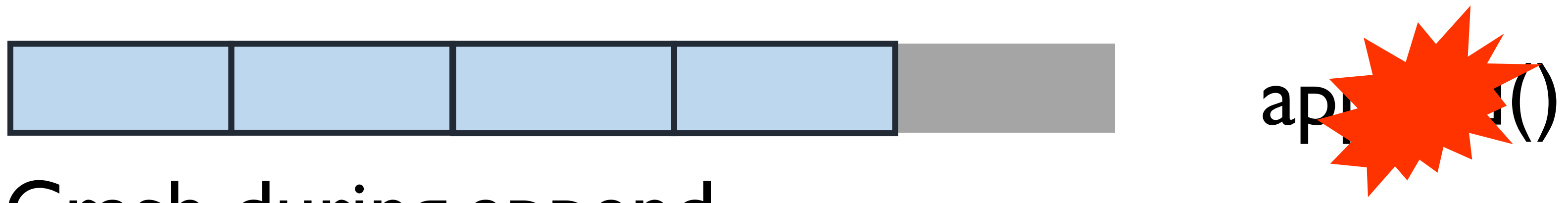

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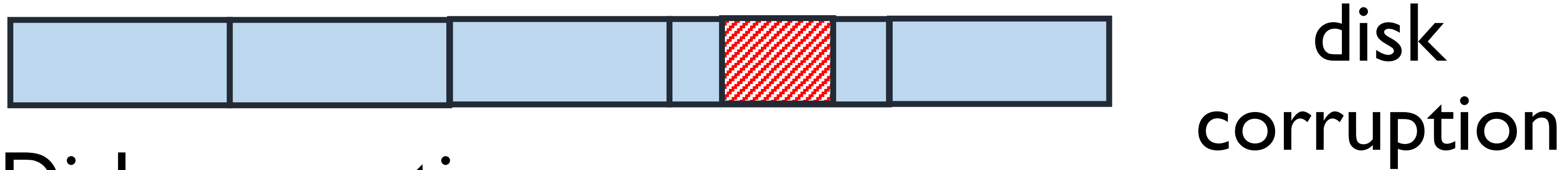

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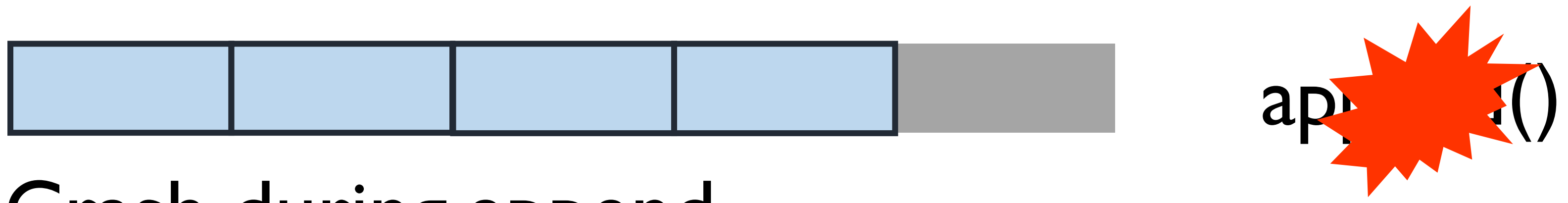

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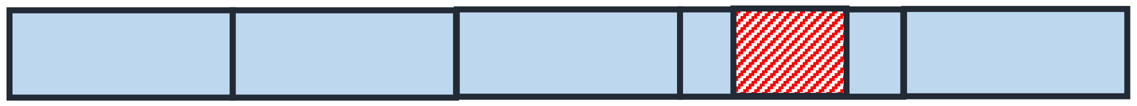

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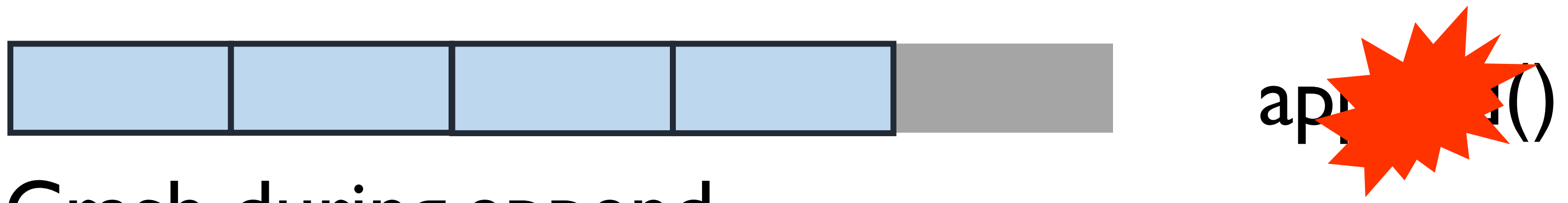

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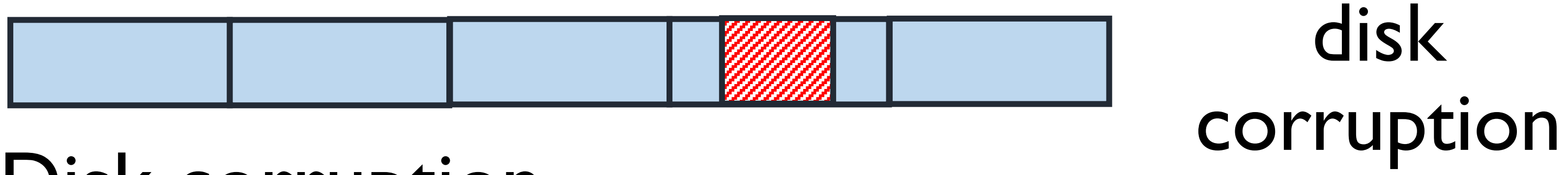

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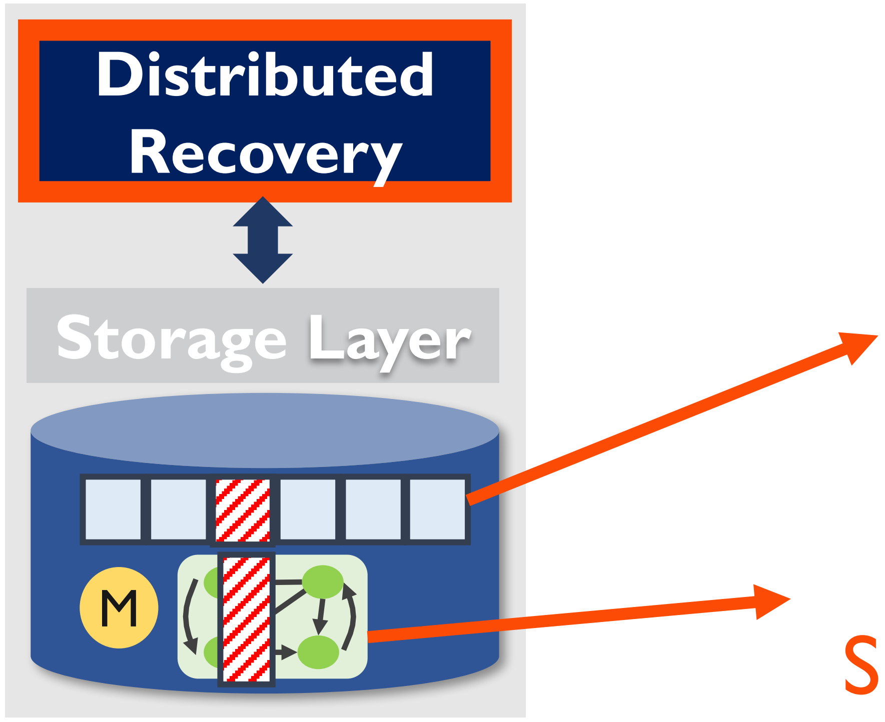
CTRL: modified local update – write additional information

➡ enables disentanglement, performant - more details in the paper…

CTRL Distributed Recovery



Distributed
Log Recovery

Distributed
Snapshot Recovery

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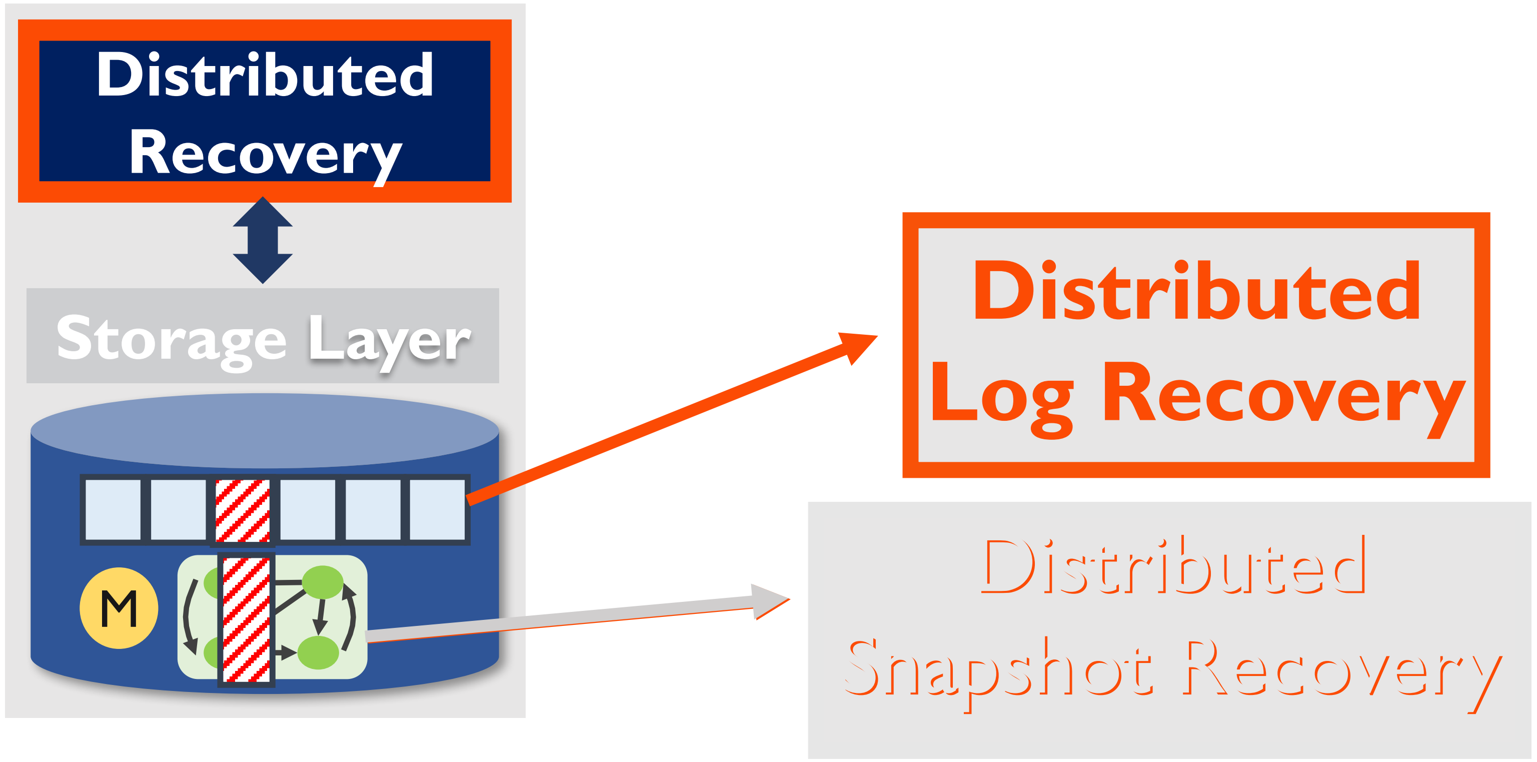

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CTRL exploits these properties to perform recovery

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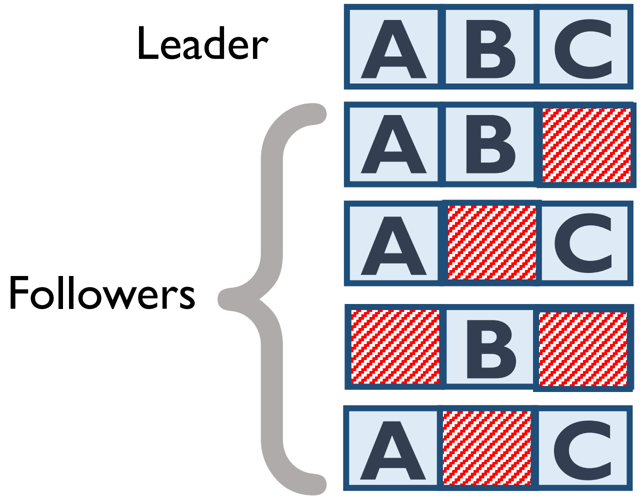

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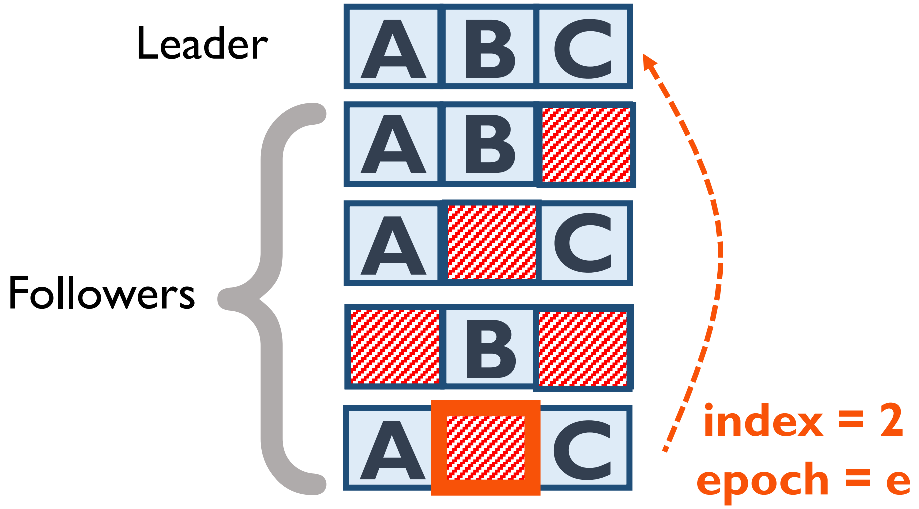

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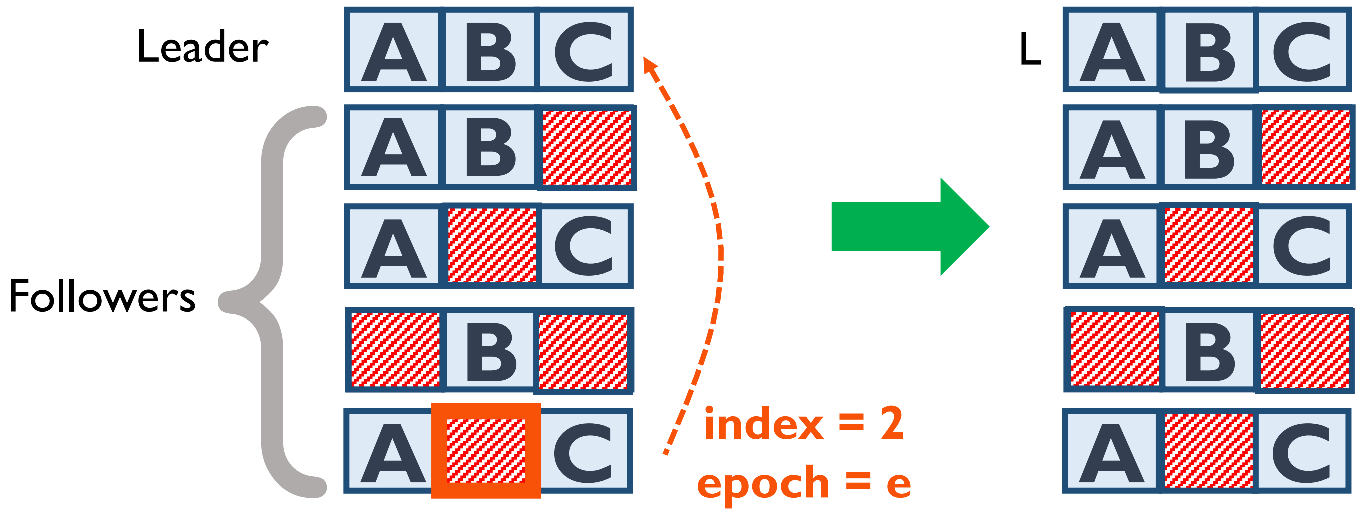

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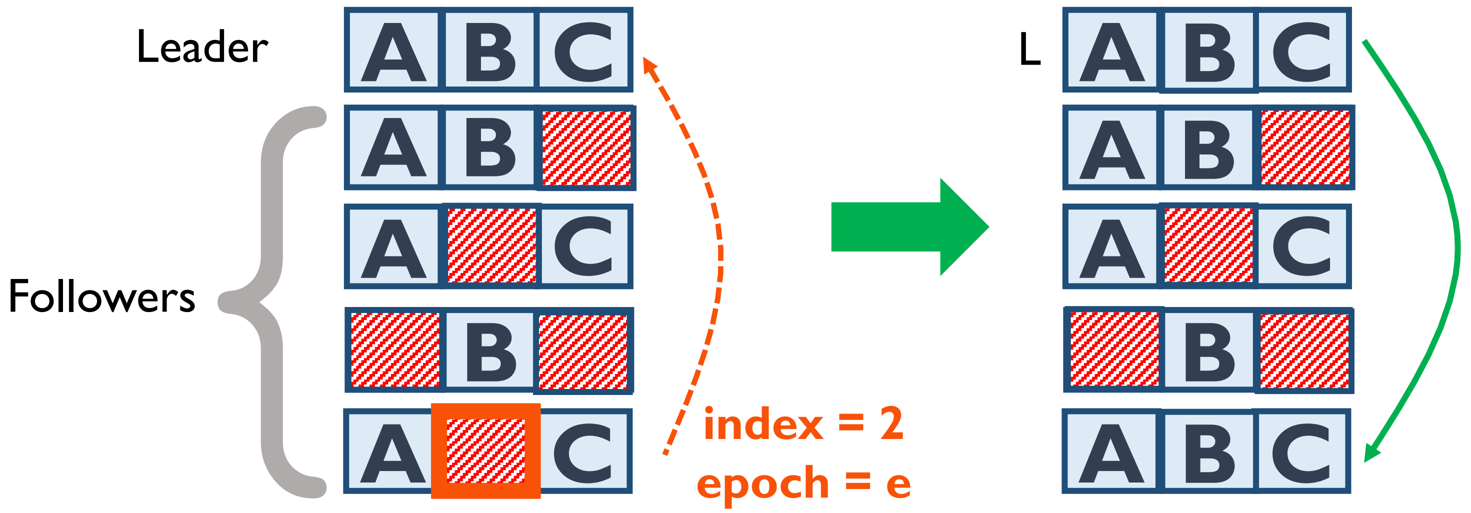

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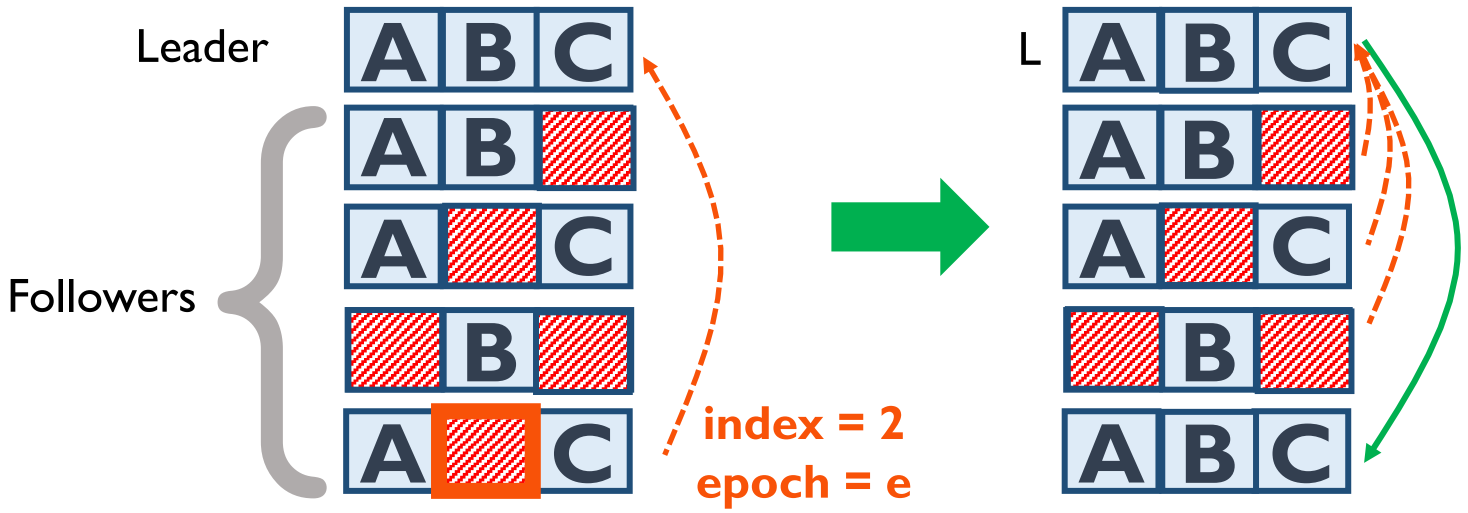

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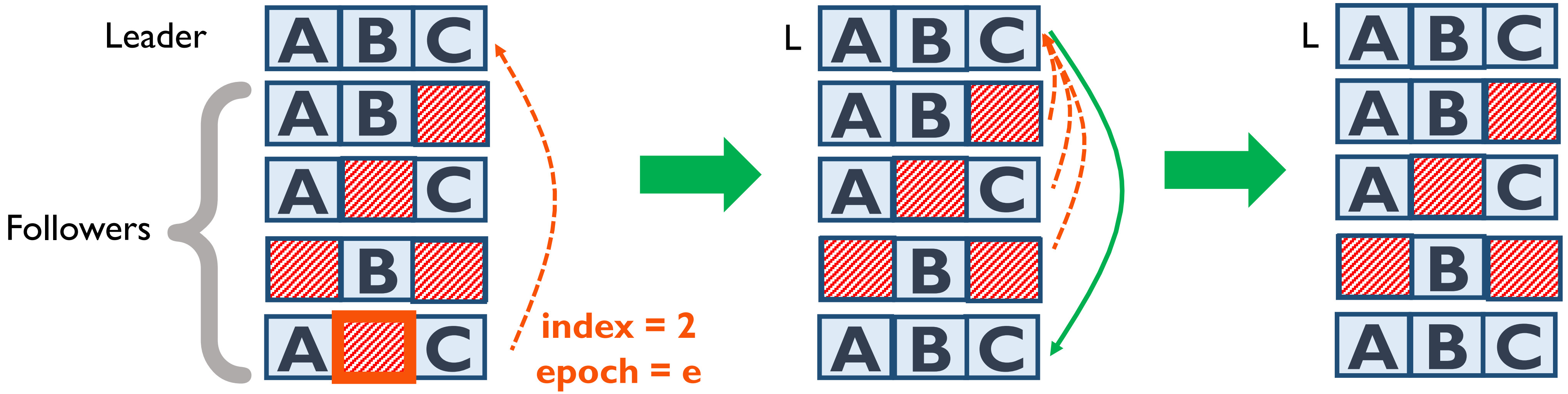

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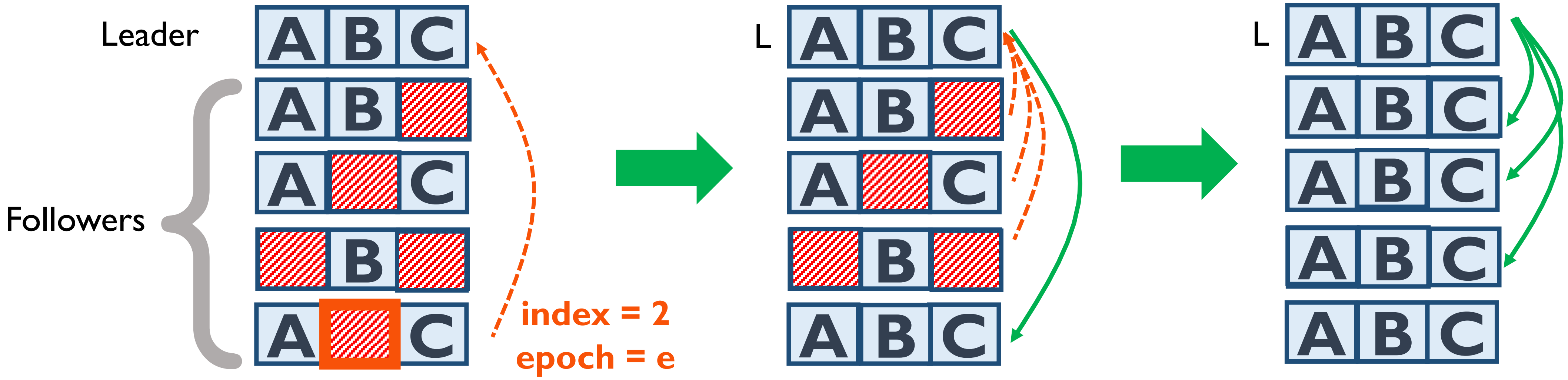

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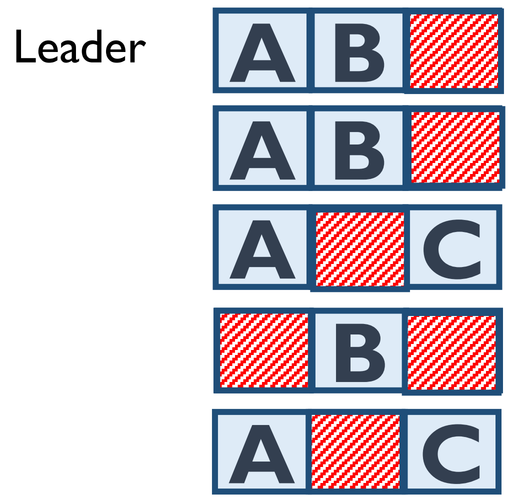

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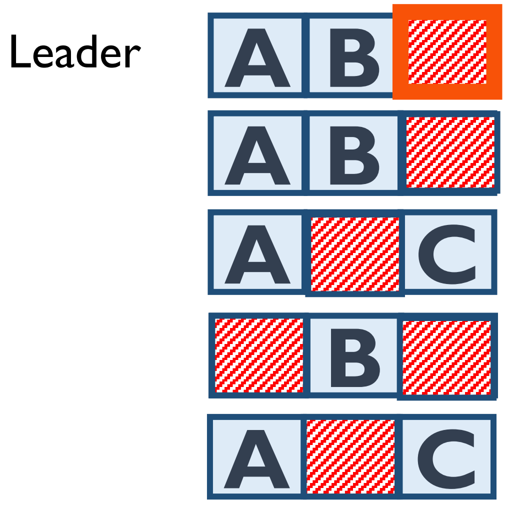

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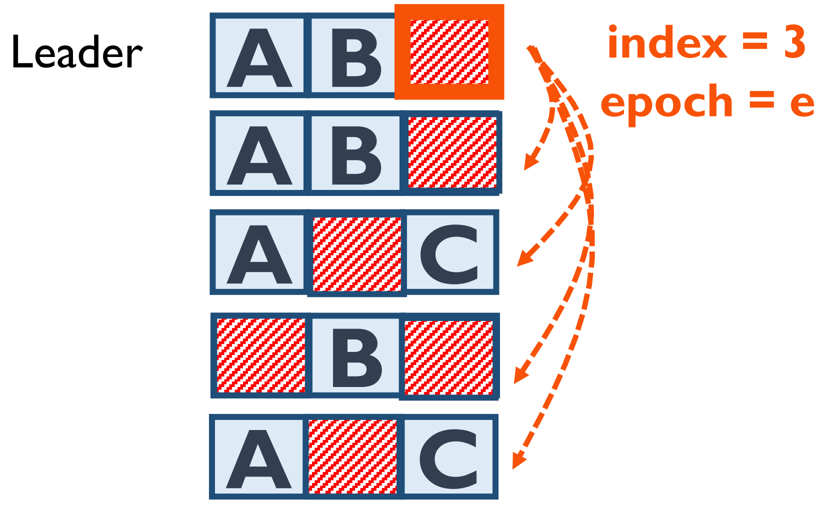

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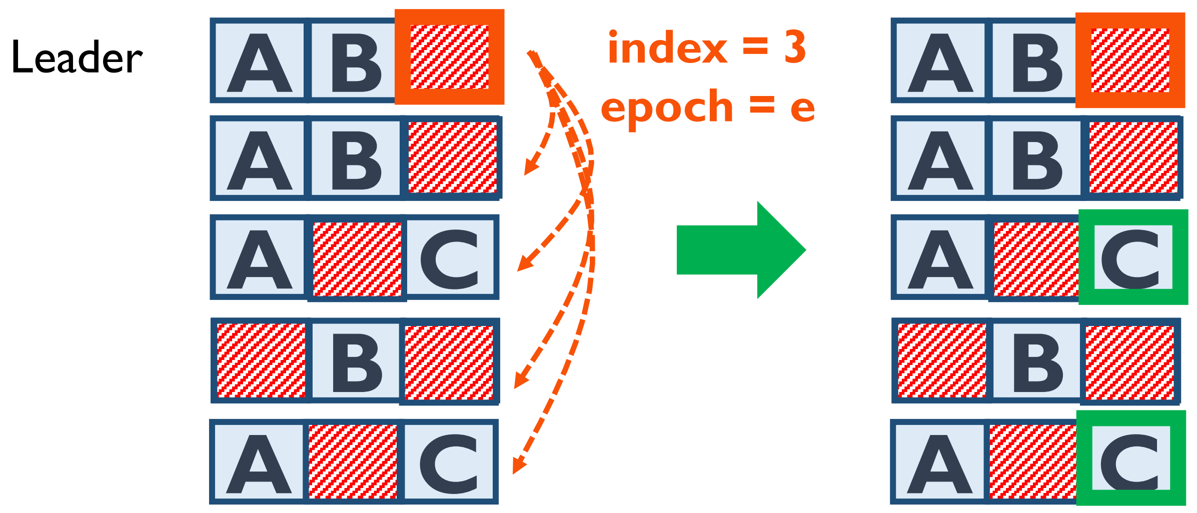

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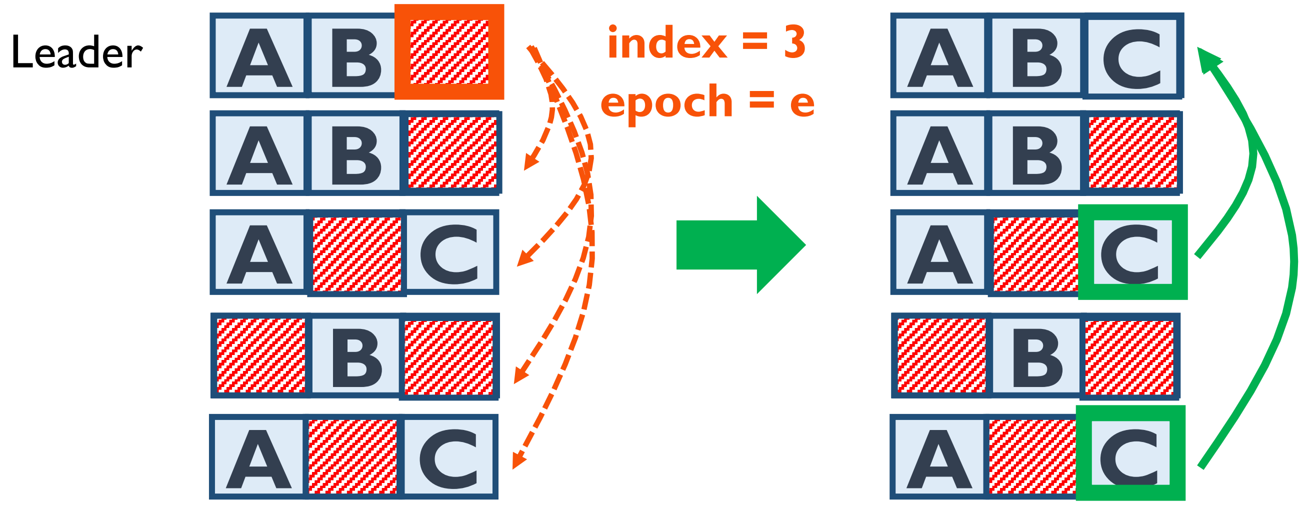

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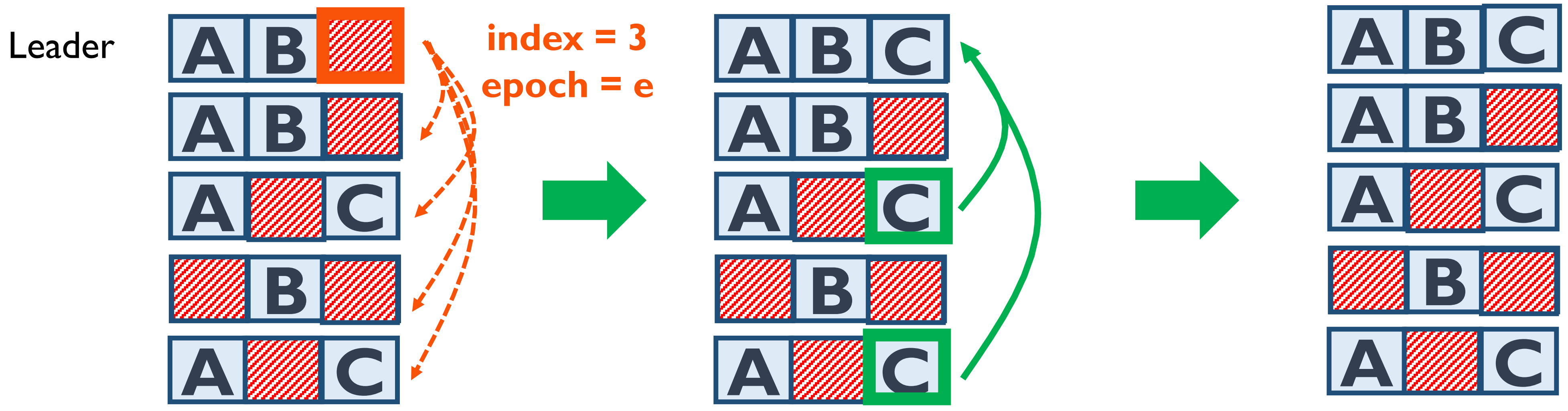

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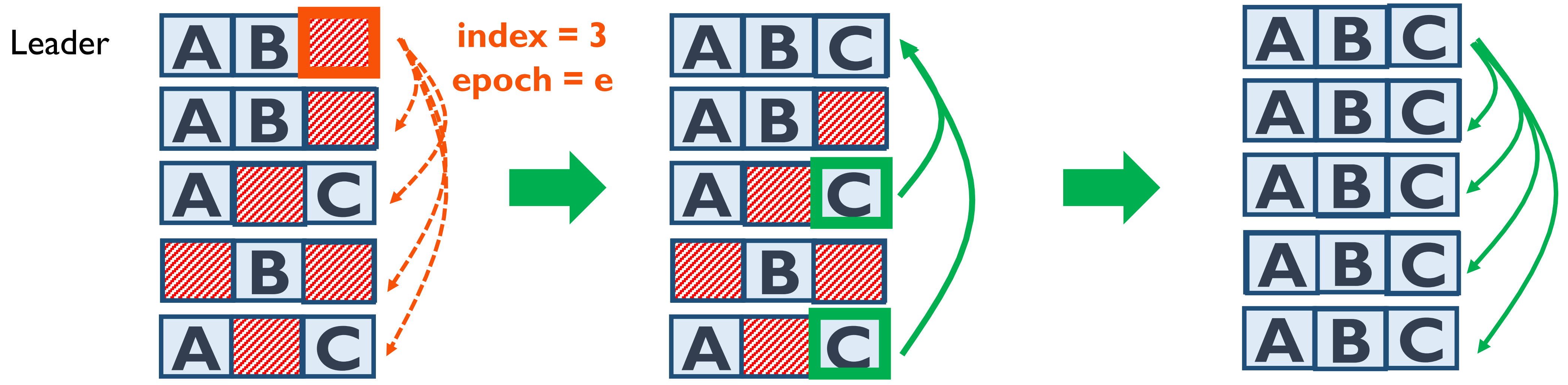

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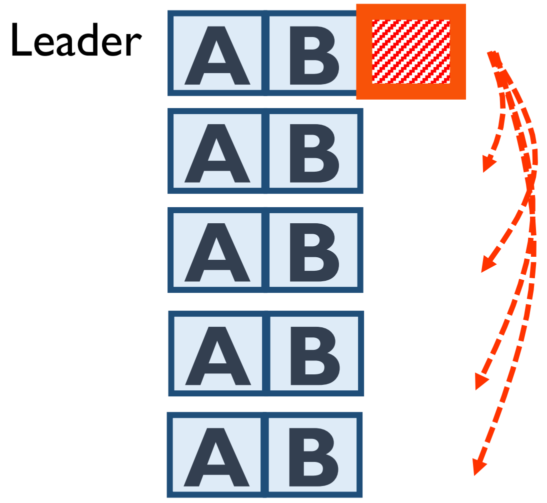

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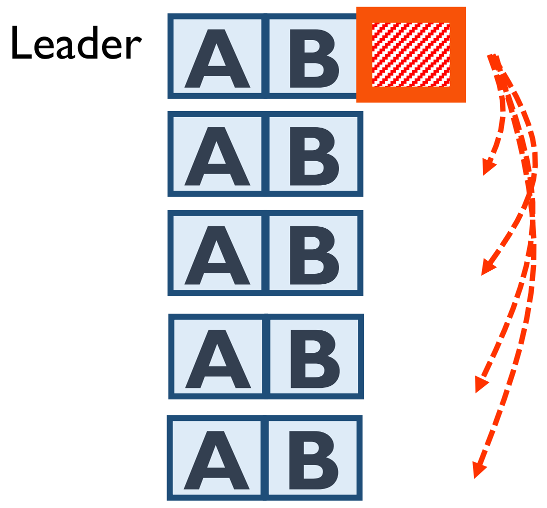

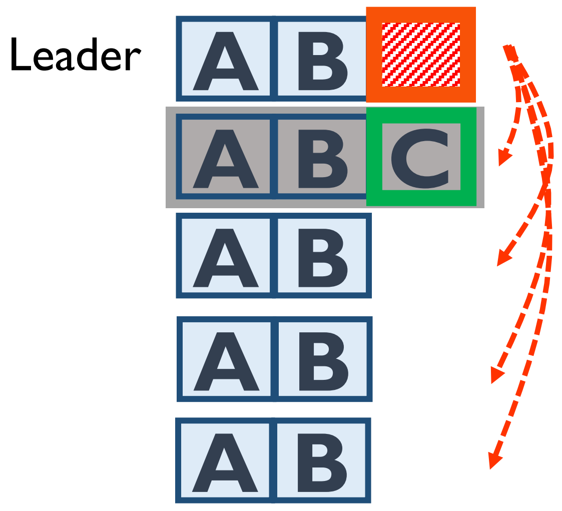

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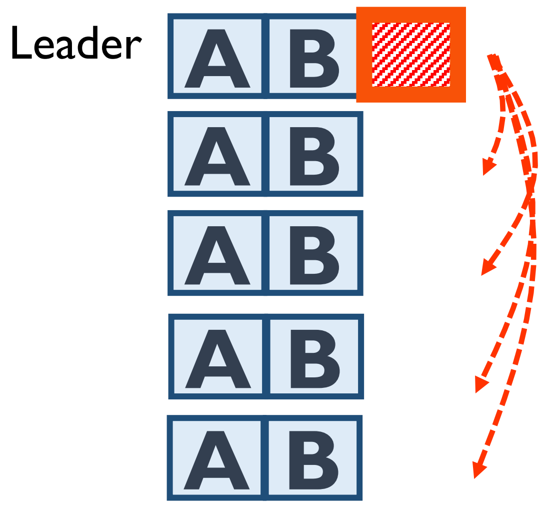

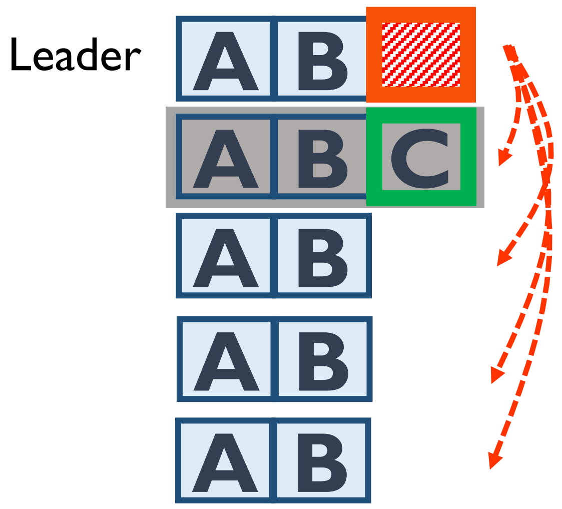

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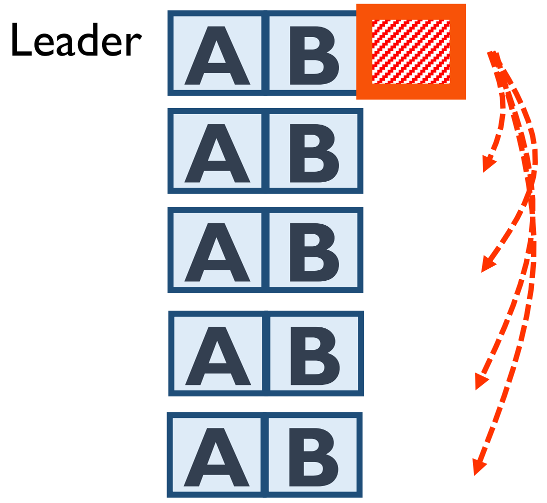

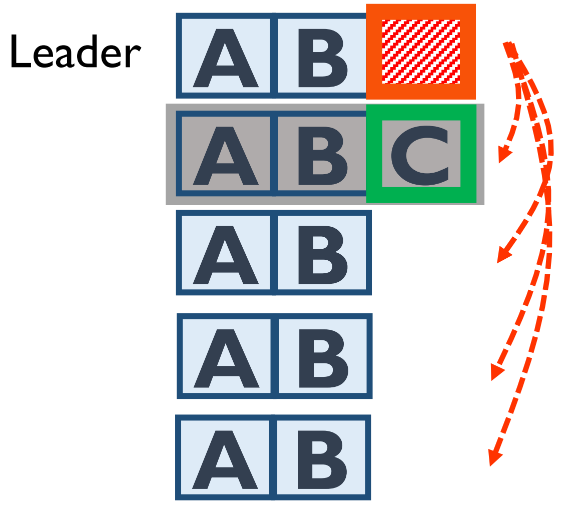

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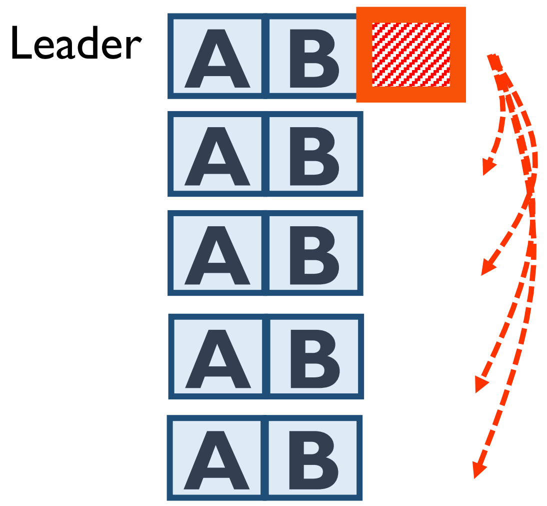

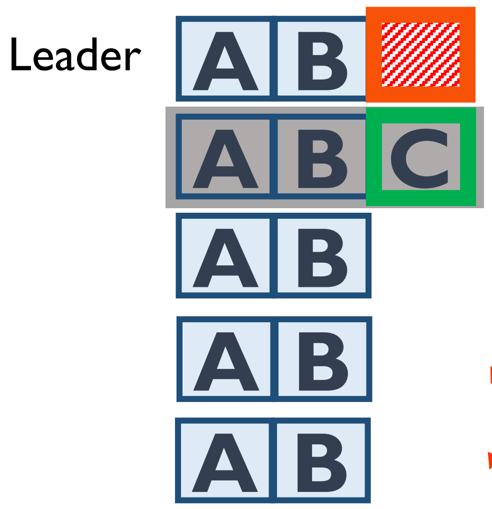

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- ➜ discard uncommitted as early as possible for improved availability

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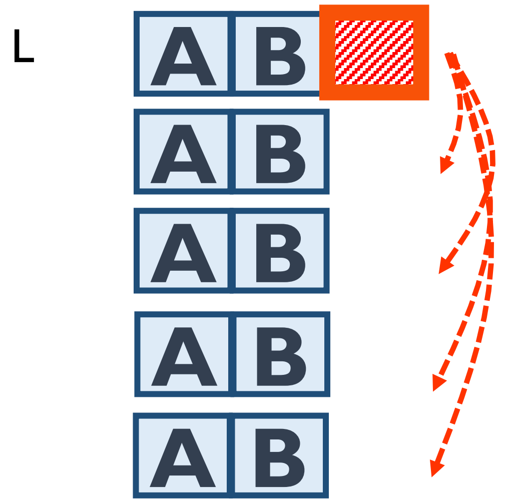

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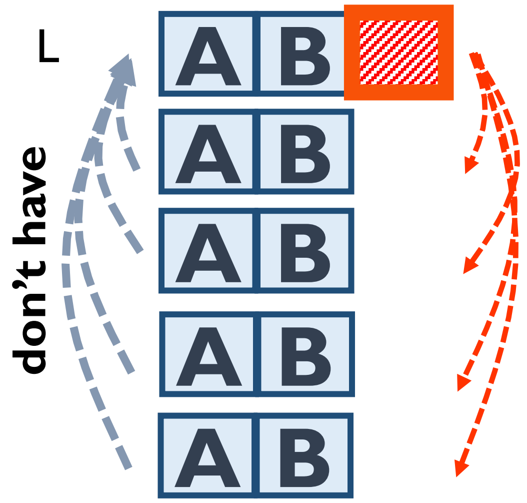

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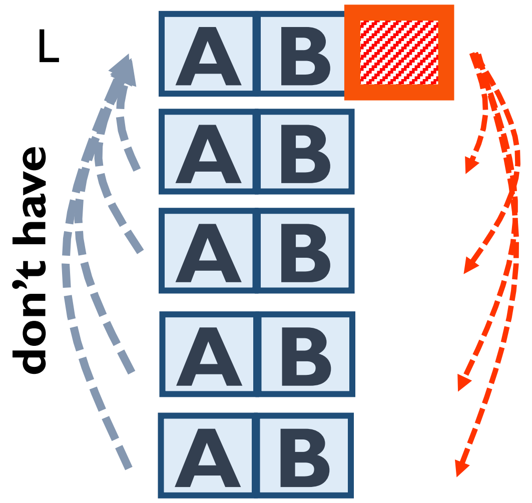

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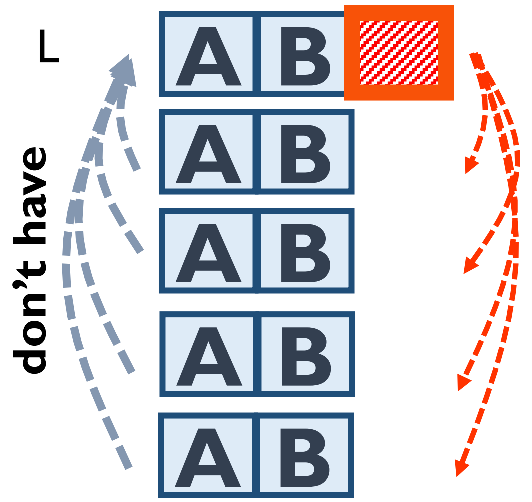

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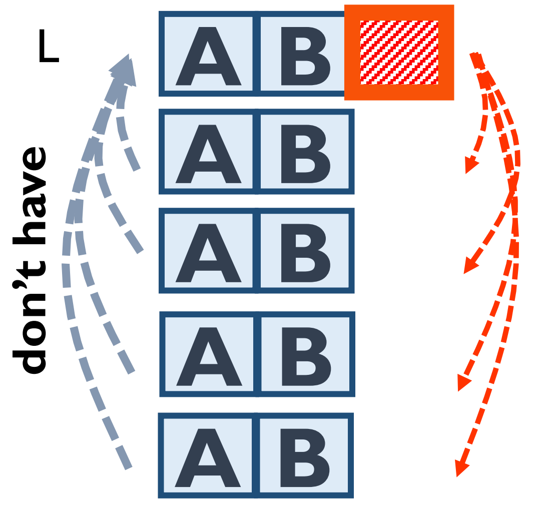

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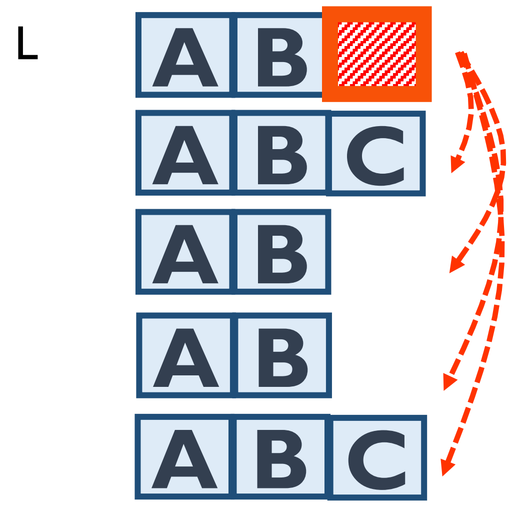

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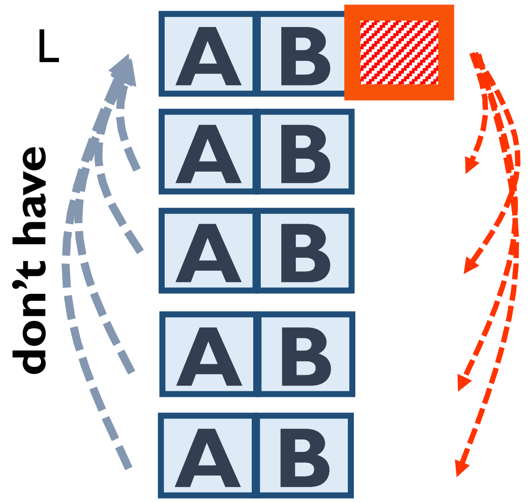

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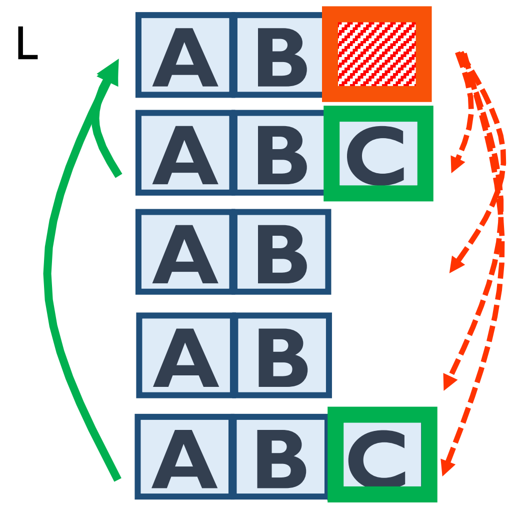

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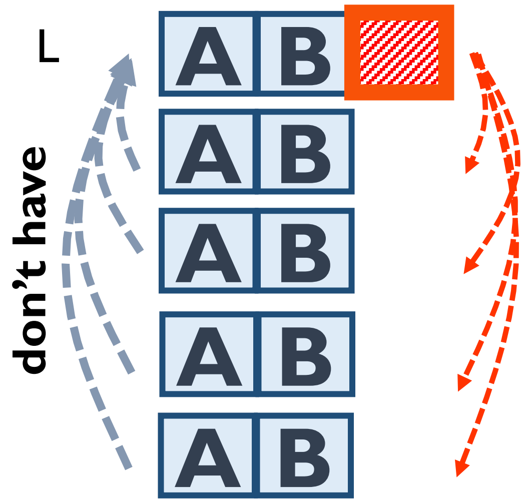

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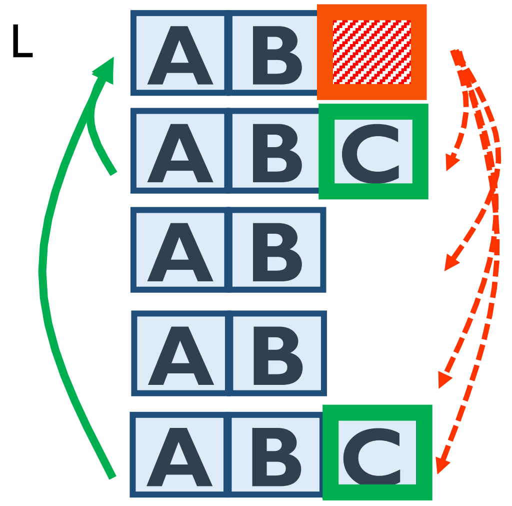

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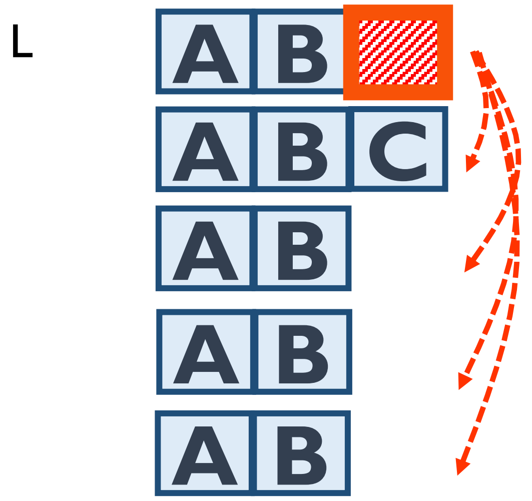

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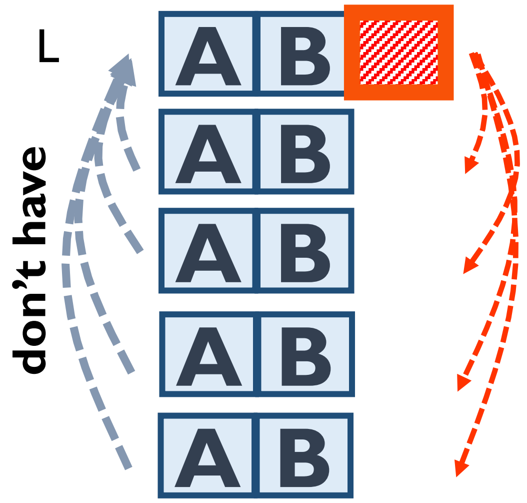
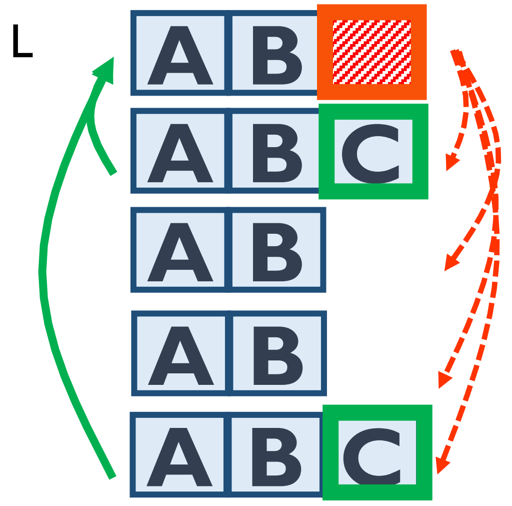


discard faulty, continue



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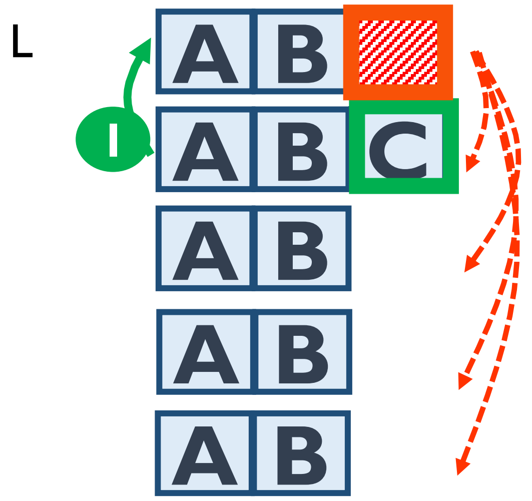

Leader Log Recovery: Determining Commitment

Leader queries for a faulty entry

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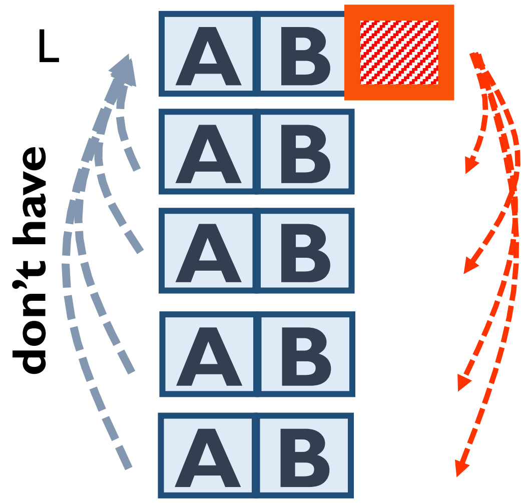

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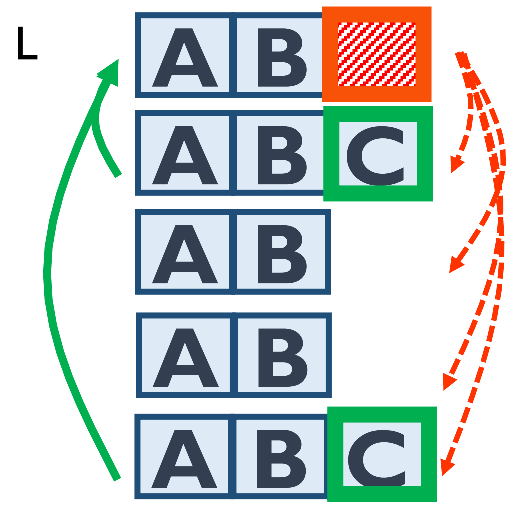

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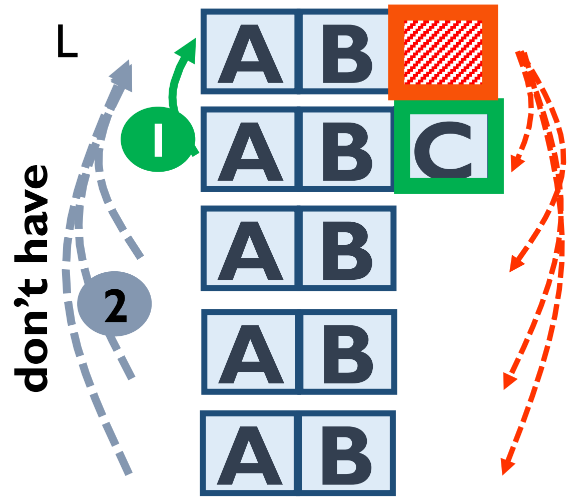

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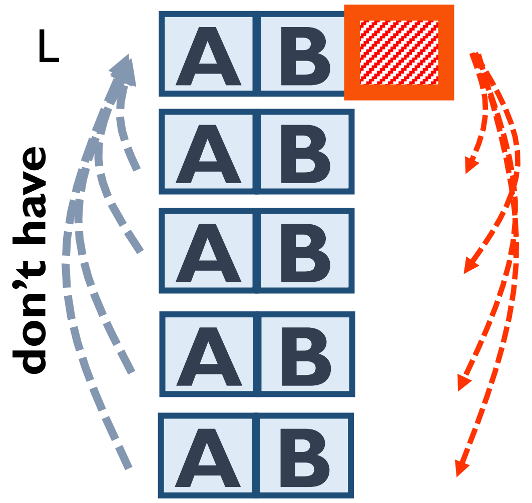

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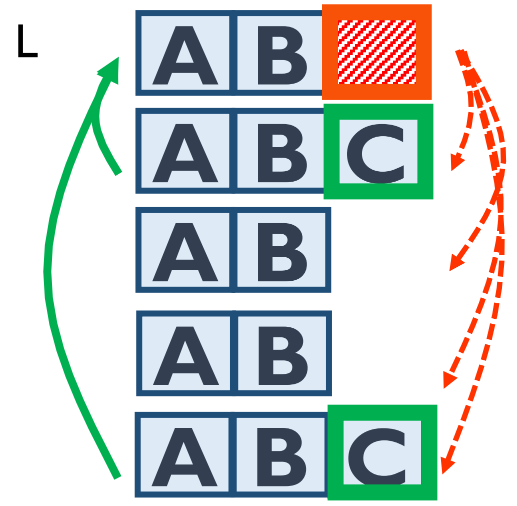

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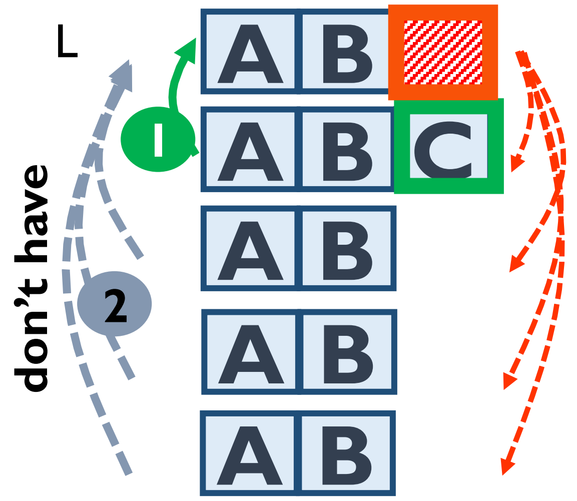

either fix log or discard, depending on order

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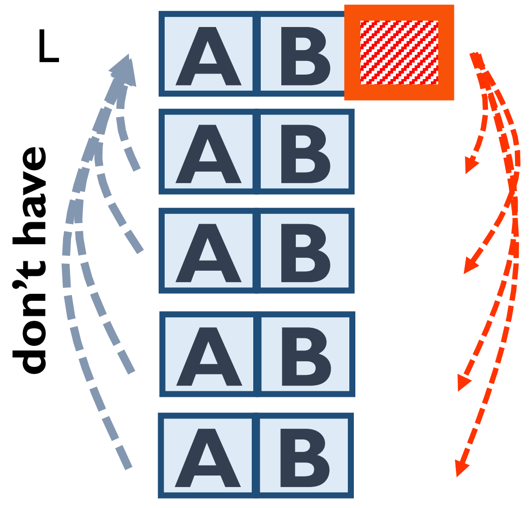

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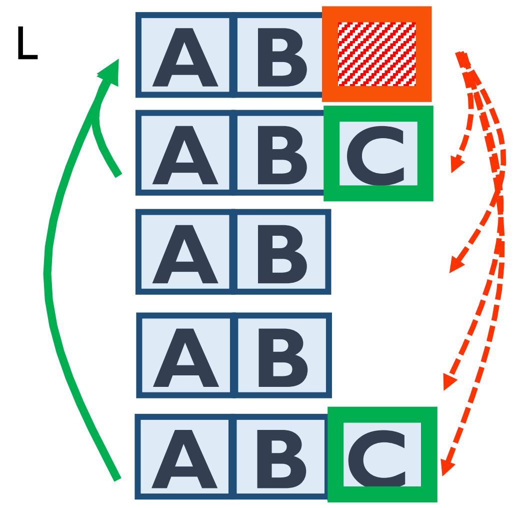

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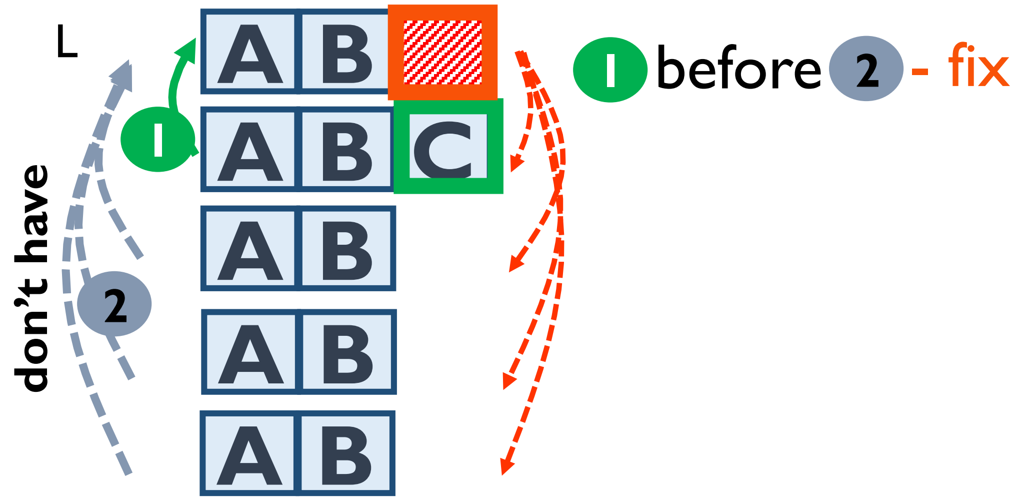

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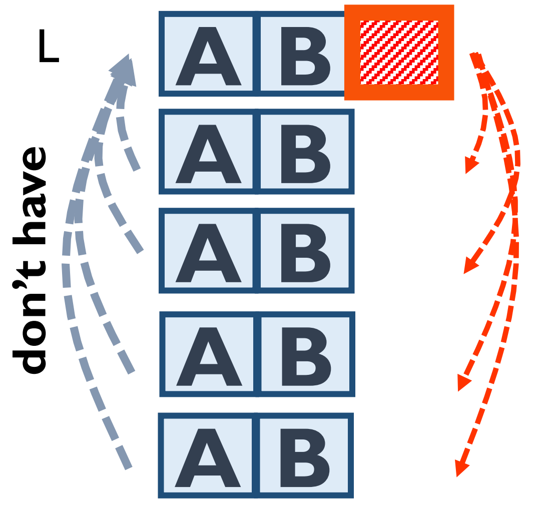

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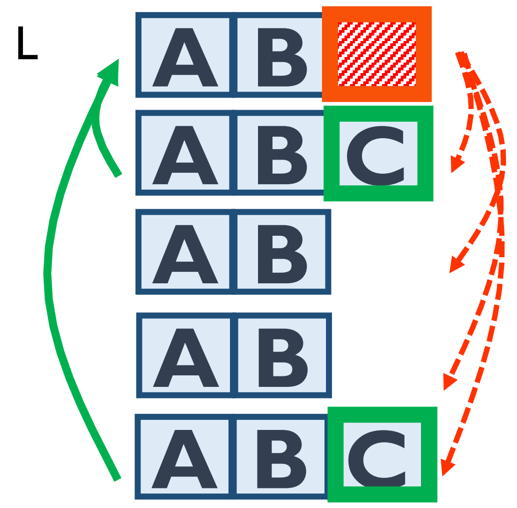

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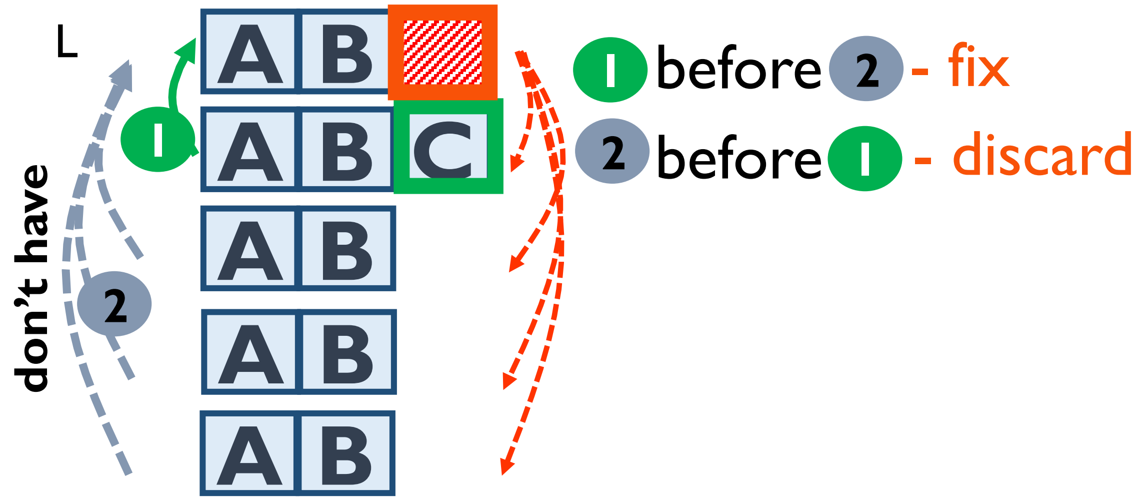

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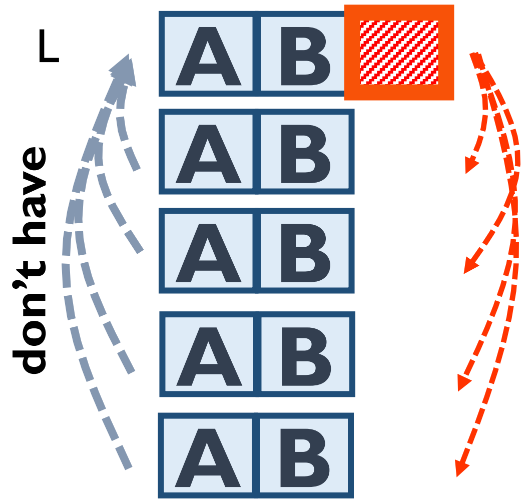

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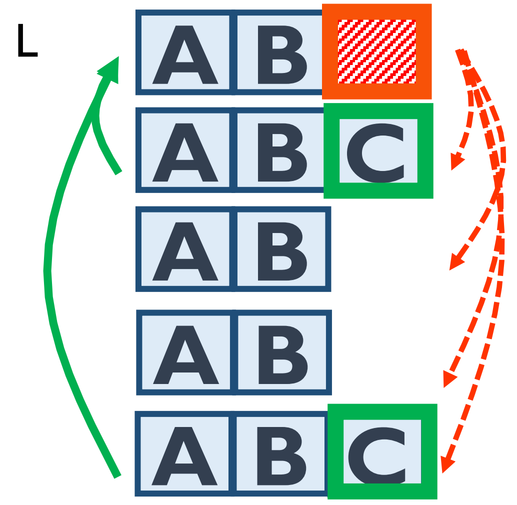

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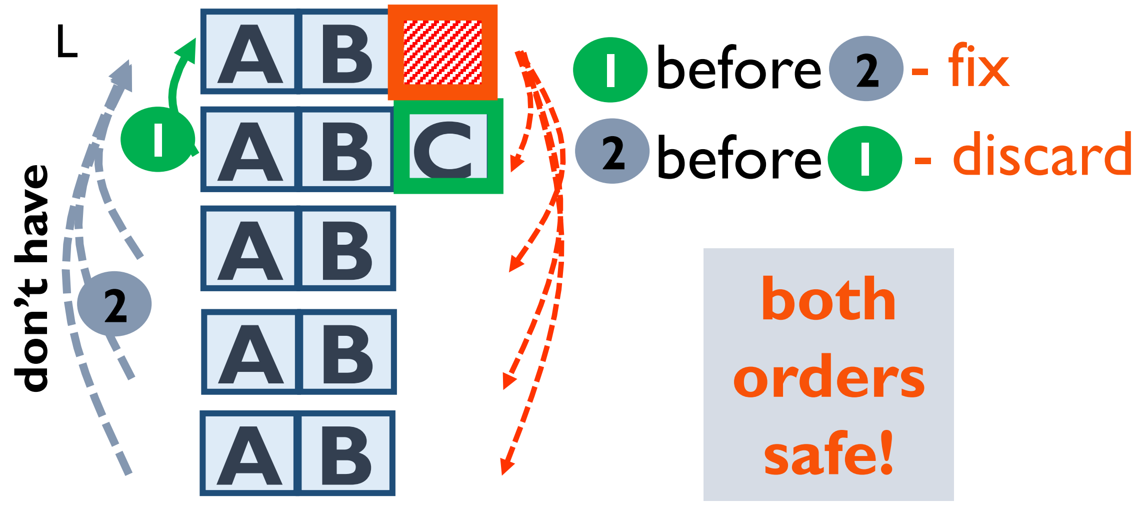


either fix log or discard, depending on order

More In The Paper…

More In The Paper…

Log recovery

- ➡ faulty entry on follower unknown to leader
- ➡ nodes could be down during recovery
- ➡ different entries at same log index

Snapshot recovery

Metainfo recovery

FS metadata fault handling

Outline

Evaluation

We apply CTRL in two systems

LogCabin

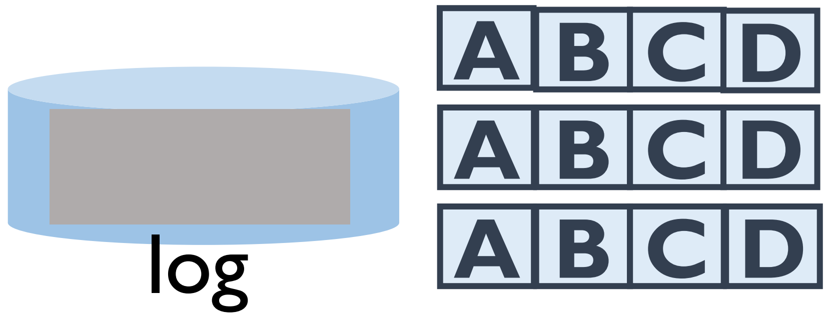
- ➡ based on Raft

ZooKeeper

- ➡ based on ZAB

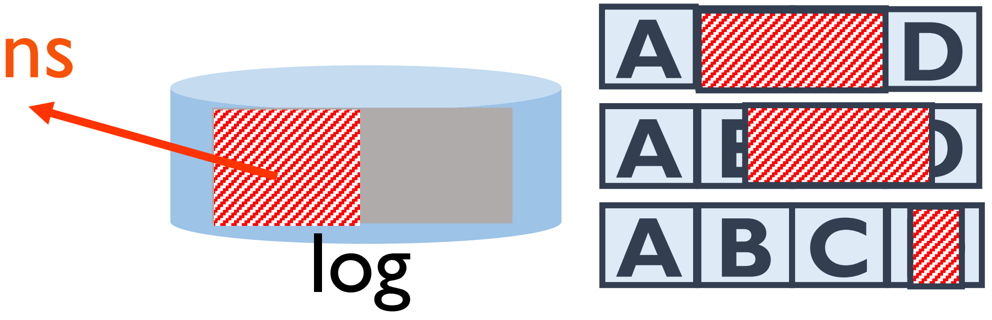
Reliability Experiments Example

Reliability Experiments Example

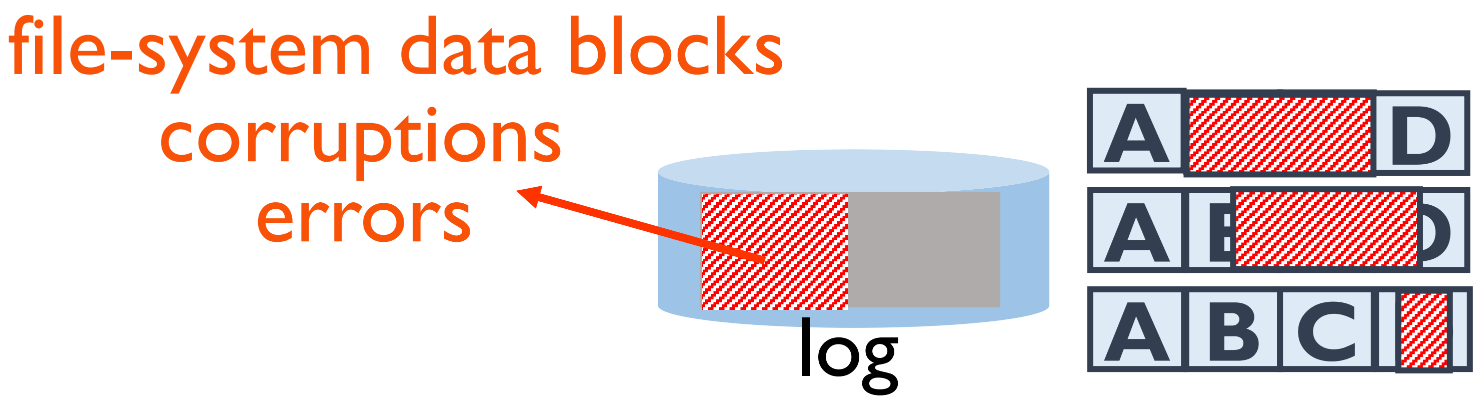


Reliability Experiments Example

file-system data blocks
corruptions
errors



Reliability Experiments Example



Original

- ➡ corruptions: 30% unsafe or unavailable
- ➡ errors: 50% unavailable

Reliability Experiments Example

file-system data blocks
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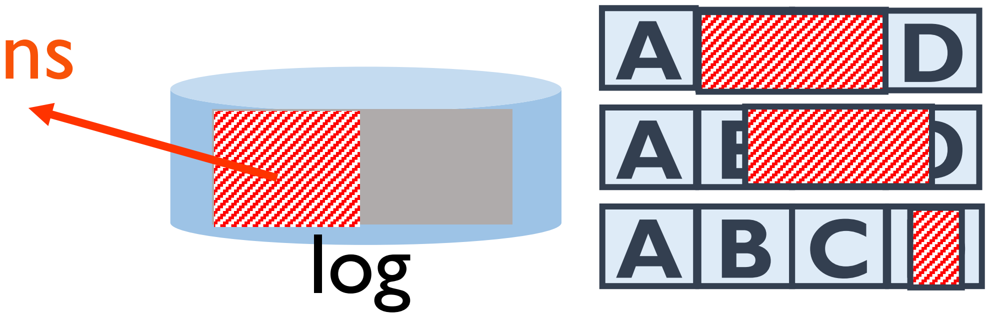


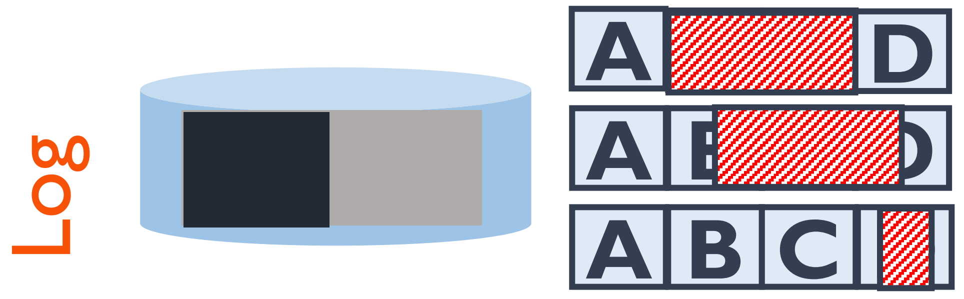
Original

- corruptions: 30% unsafe or unavailable
- errors: 50% unavailable

CTRL

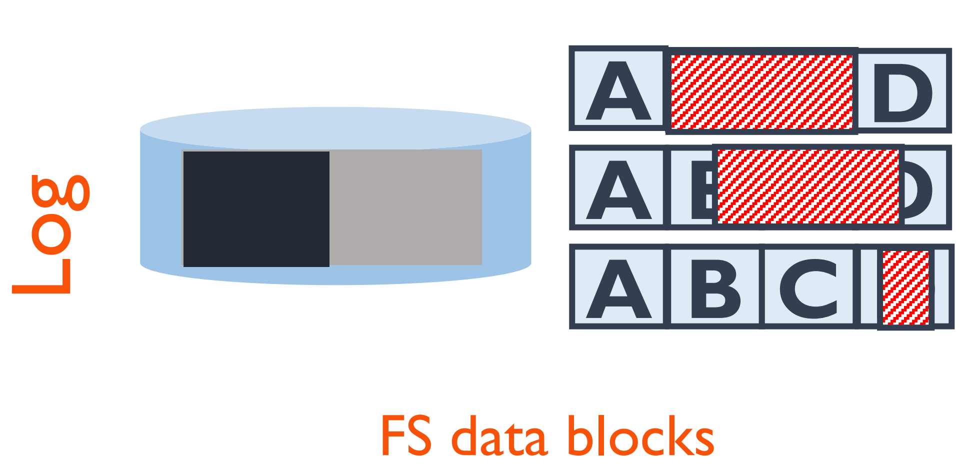
- corruptions and errors: always safe and available

Reliability Experiments Summary



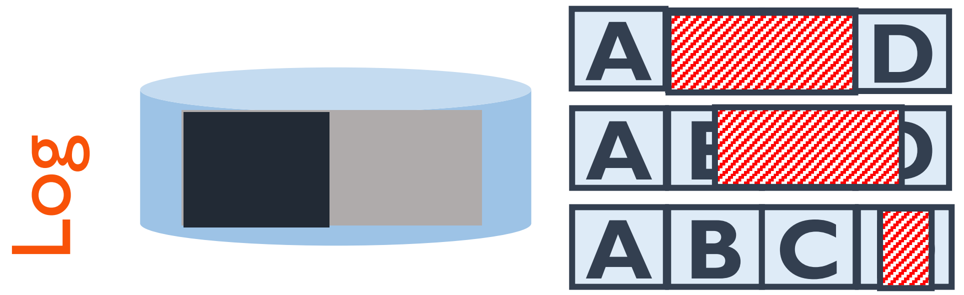
FS data blocks

Reliability Experiments Summary



A
B
C
A
B
C
A
B
C
Targeted entries

Reliability Experiments Summary



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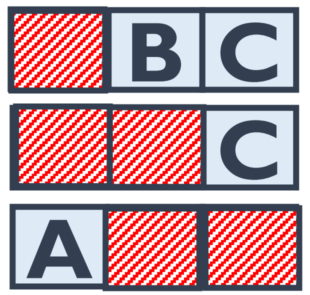

all possible combinations (for thoroughness)

Targeted entries

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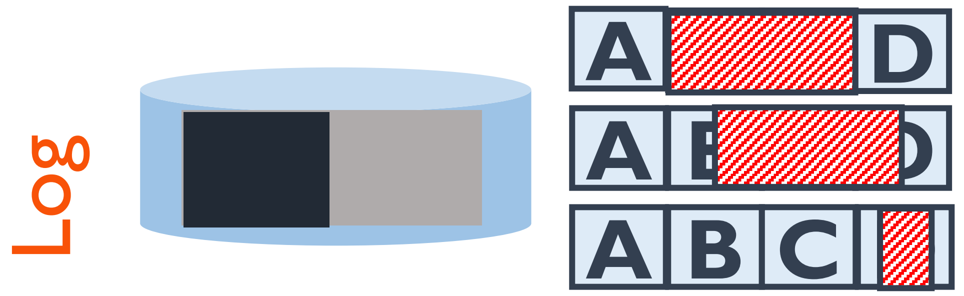

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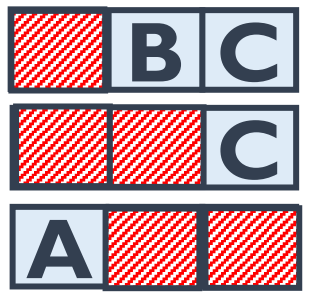

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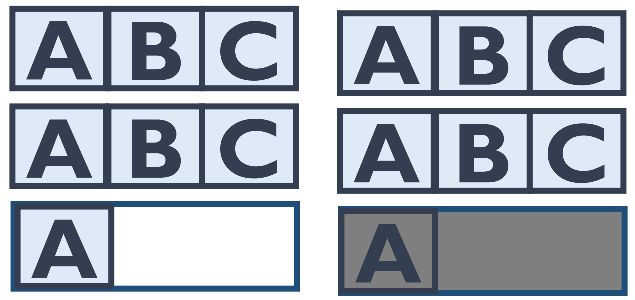
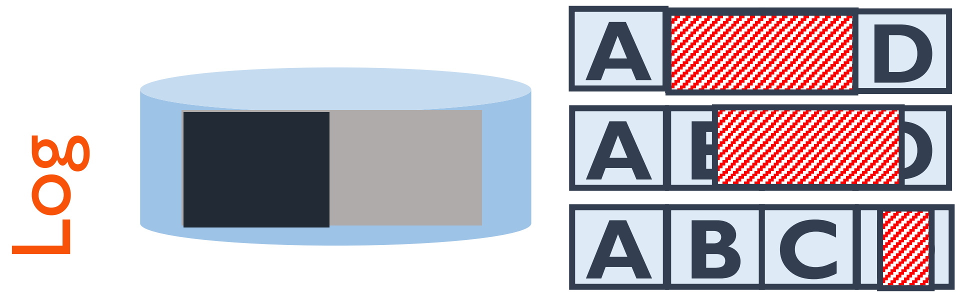


Lagging and crashed

Reliability Experiments Summary



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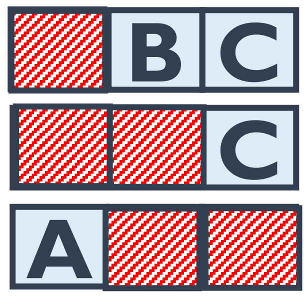

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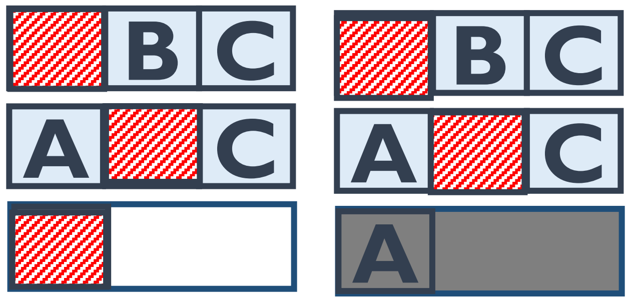
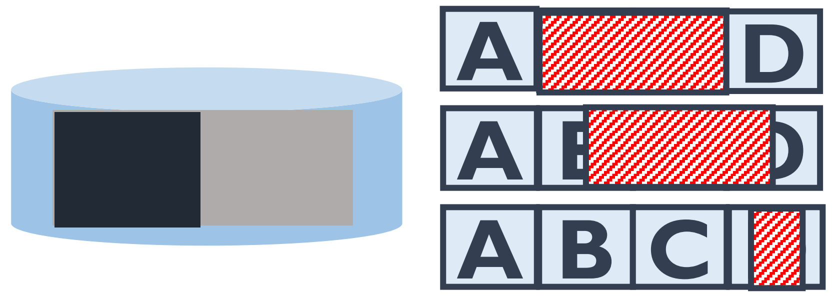


Lagging and crashed

Reliability Experiments Summary

Log



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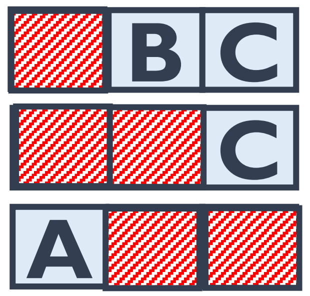

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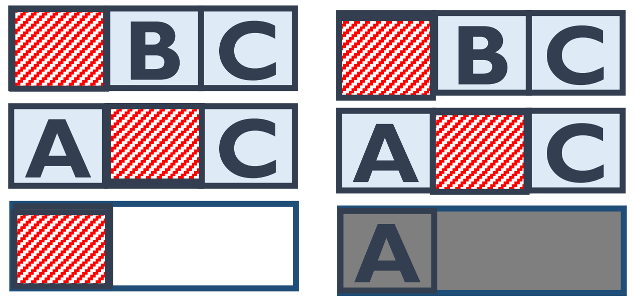
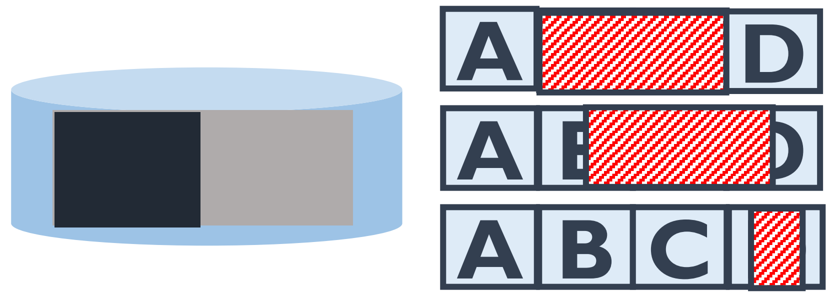


Lagging and crashed

Snapshots

Reliability Experiments Summary

Log



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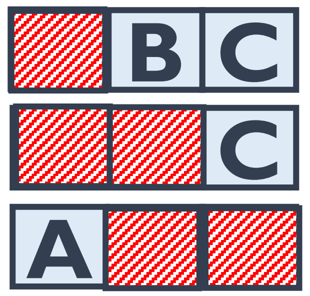

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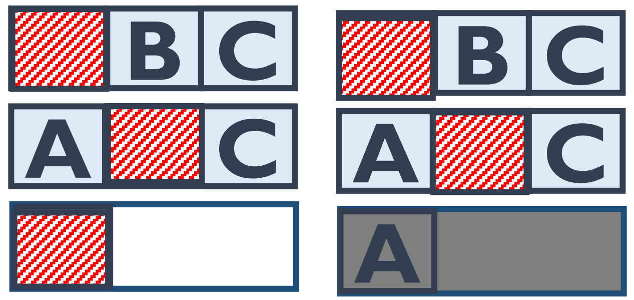

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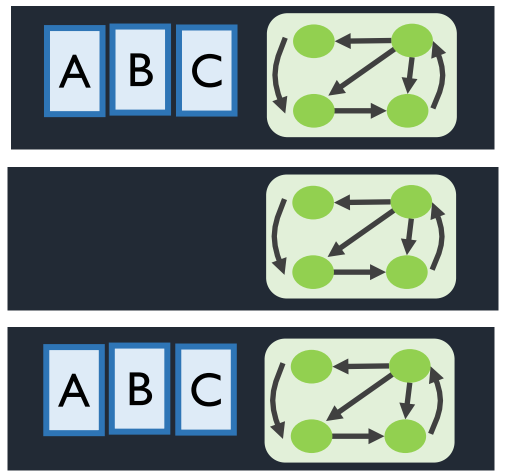

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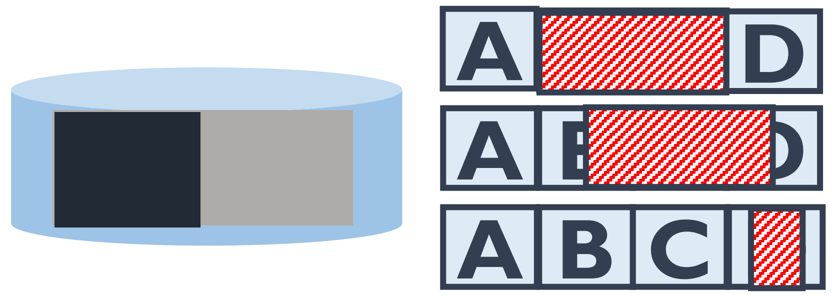

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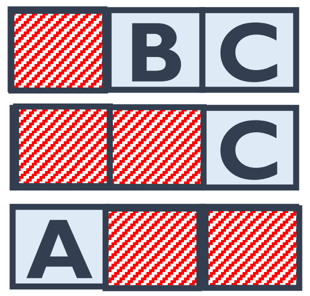

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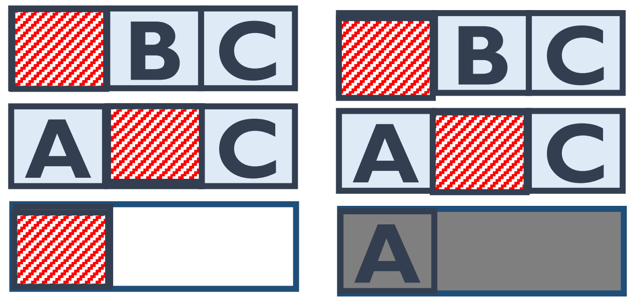

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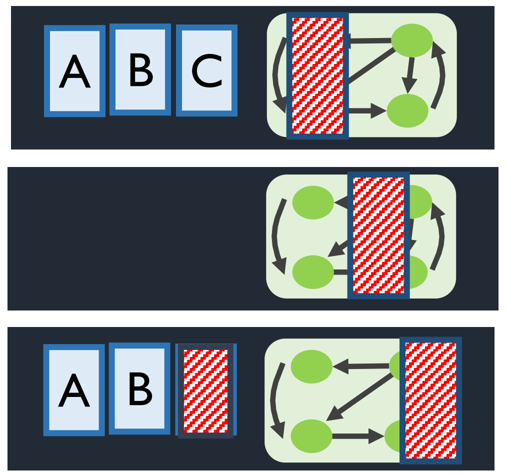

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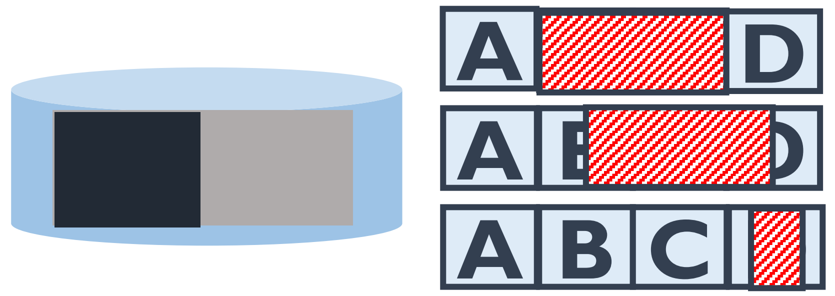

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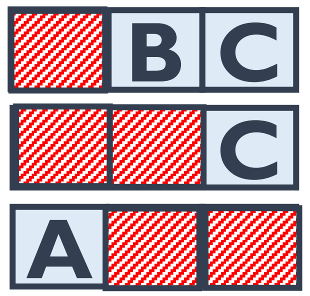

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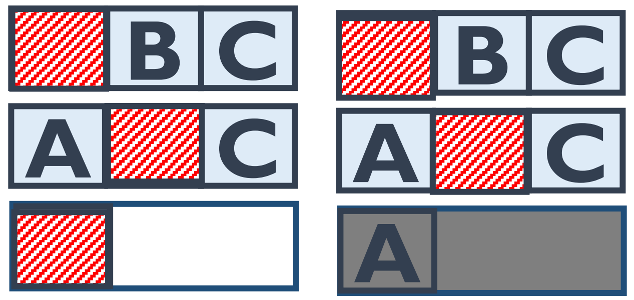

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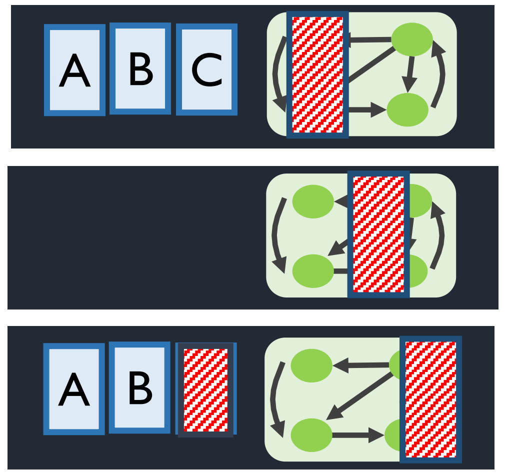
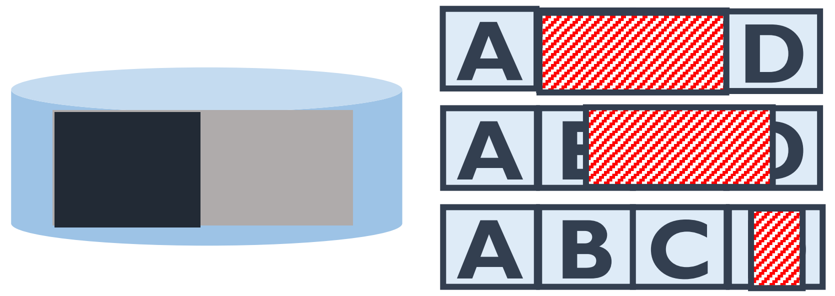


FS Metadata Faults

Reliability Experiments Summary

Log



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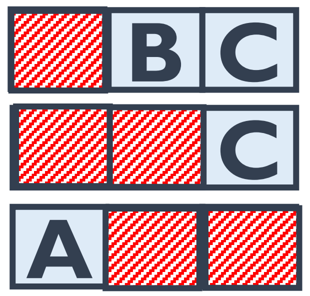

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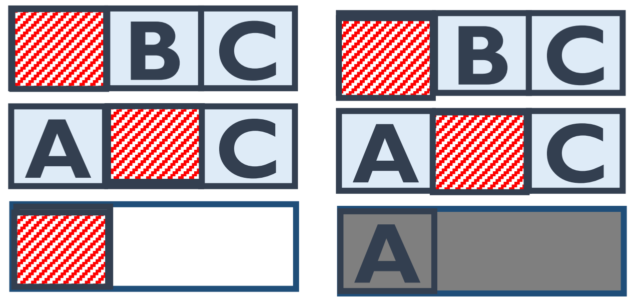

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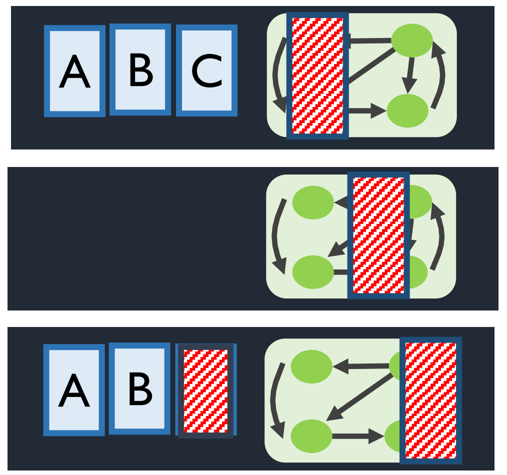
Snapshots



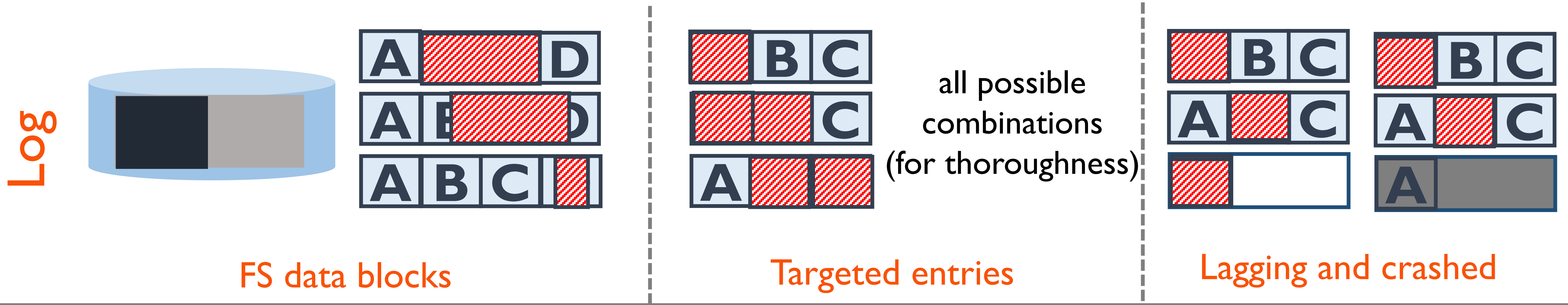
FS Metadata Faults

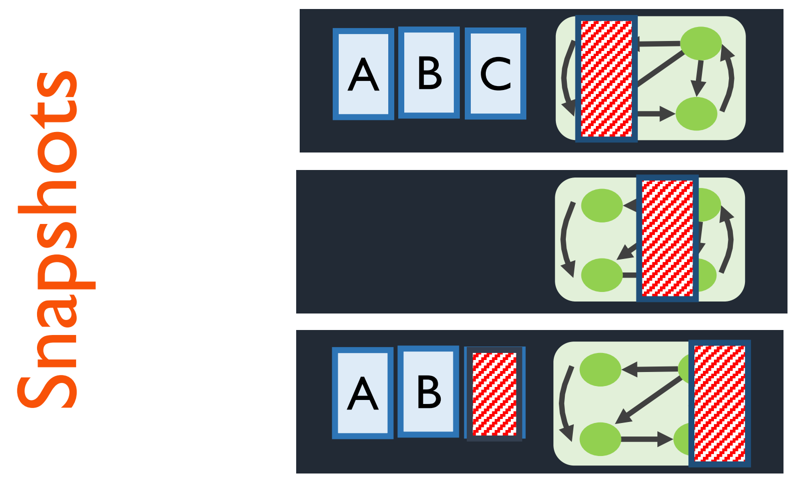
Un-openable files

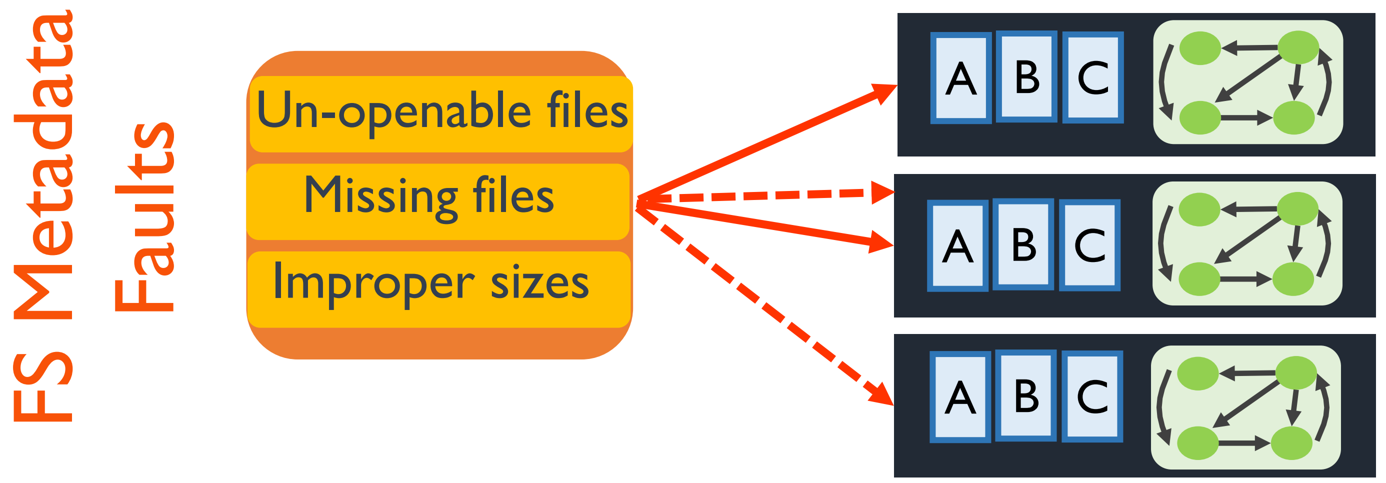
Missing files

Improper sizes

Reliability Experiments Summary







Reliability Results Summary

Reliability Results Summary

Original systems

Reliability Results Summary

Original systems

- ➡ unsafe or unavailable in many cases

Reliability Results Summary

Original systems

➡ unsafe or unavailable in many cases

CTRL versions

Reliability Results Summary

Original systems

➡ unsafe or unavailable in many cases

CTRL versions

➡ safe always and highly available

Reliability Results Summary

Original systems

- ➡ unsafe or unavailable in many cases

CTRL versions

- ➡ safe always and highly available
- ➡ correctly unavailable in some cases (when all copies are faulty)

Update Performance (SSD)

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Workload: insert entries (1K) repeatedly, background snapshots

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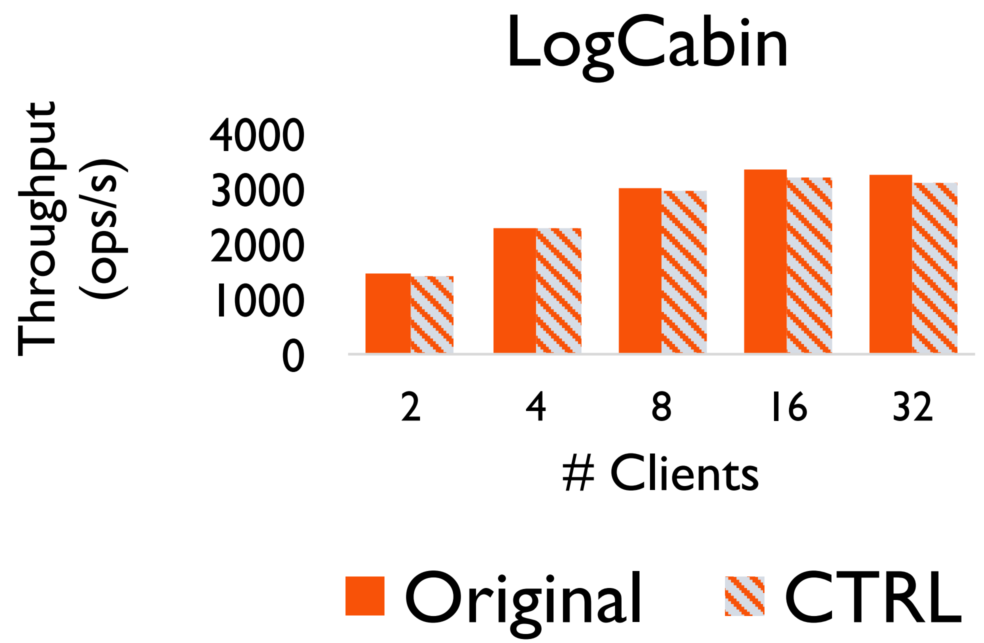

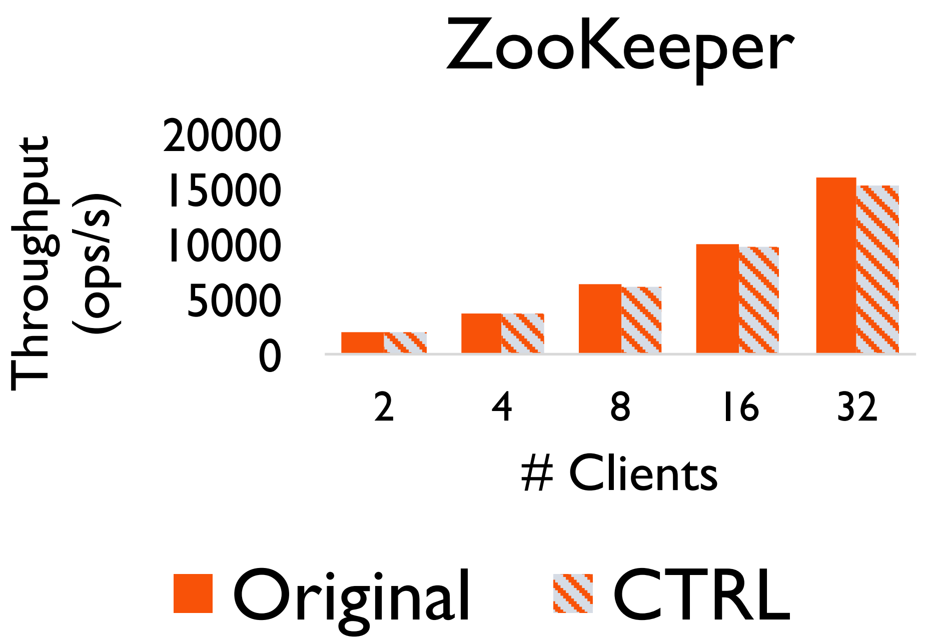

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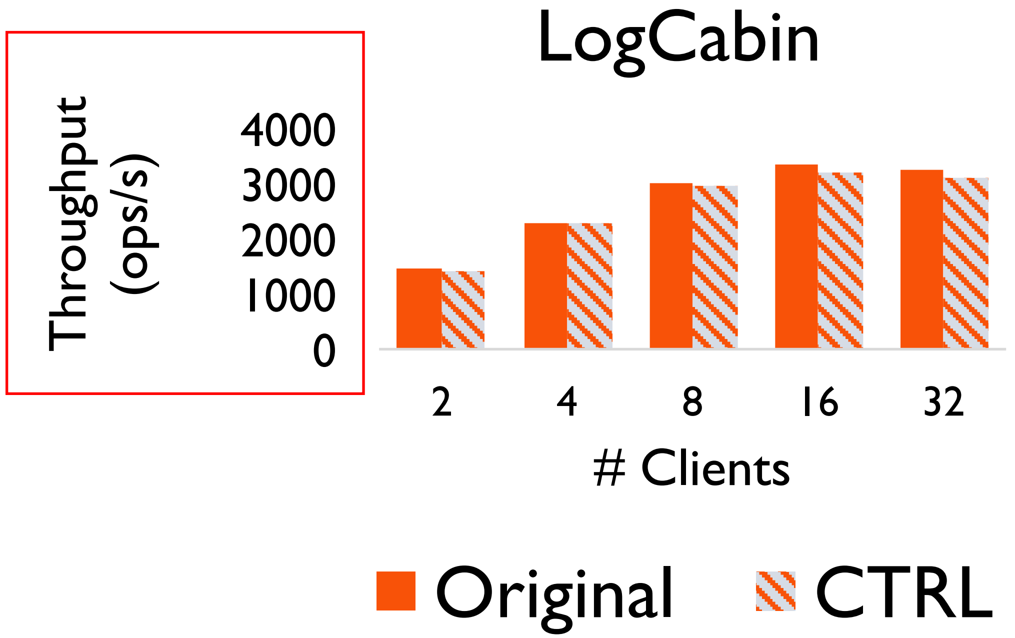

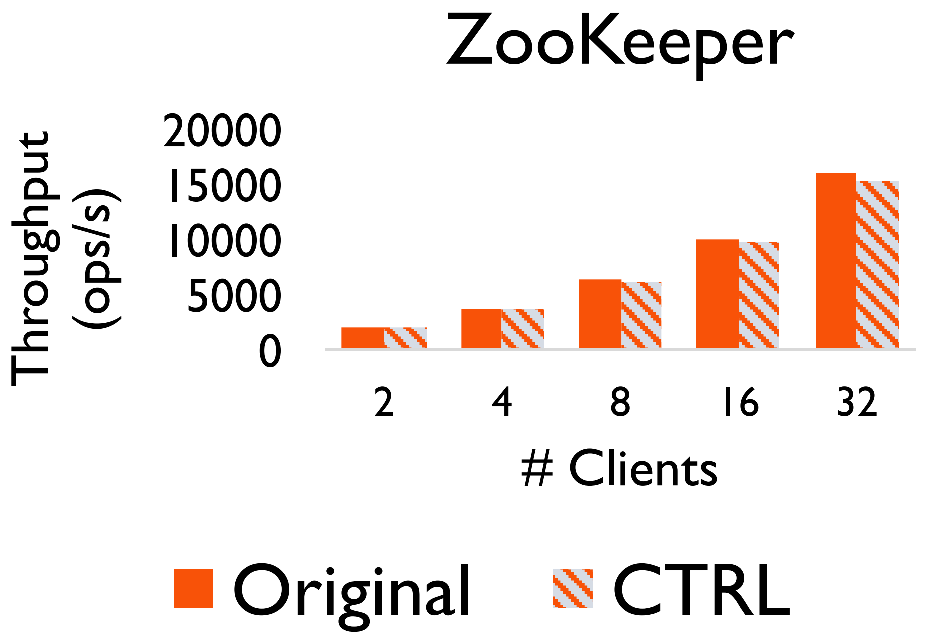

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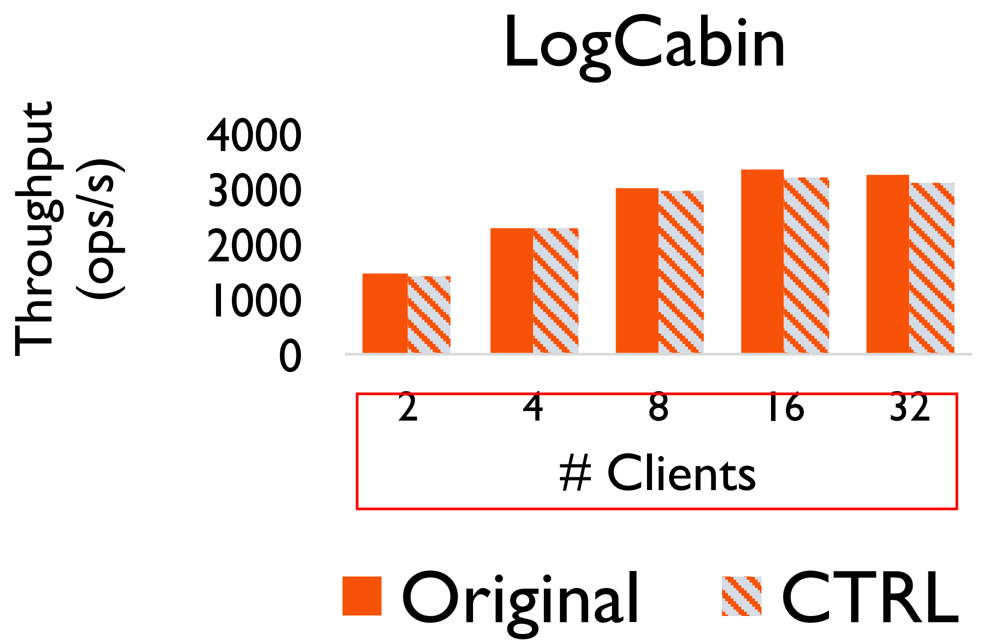
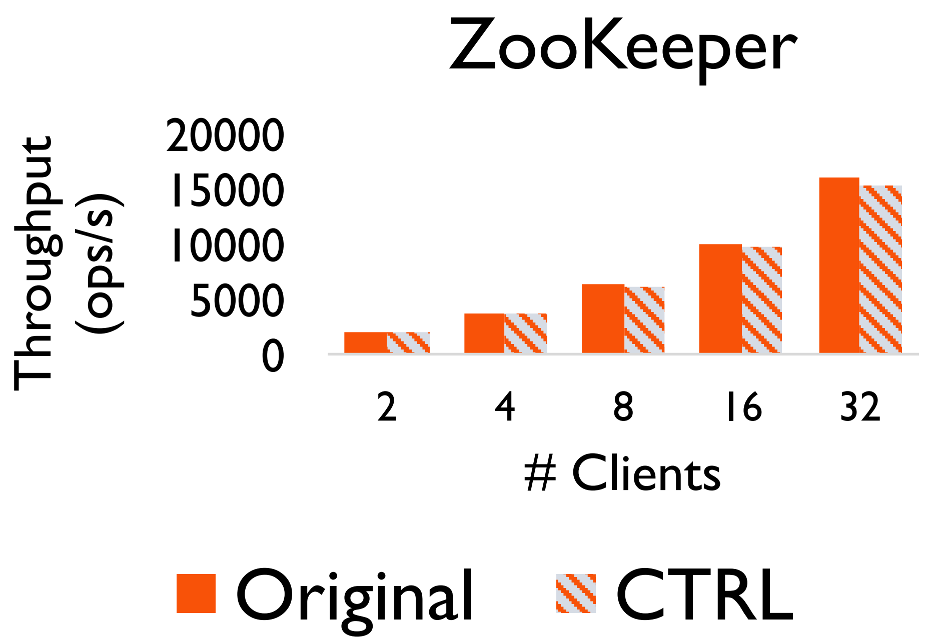
Workload: insert entries (1K) repeatedly, background snapshots





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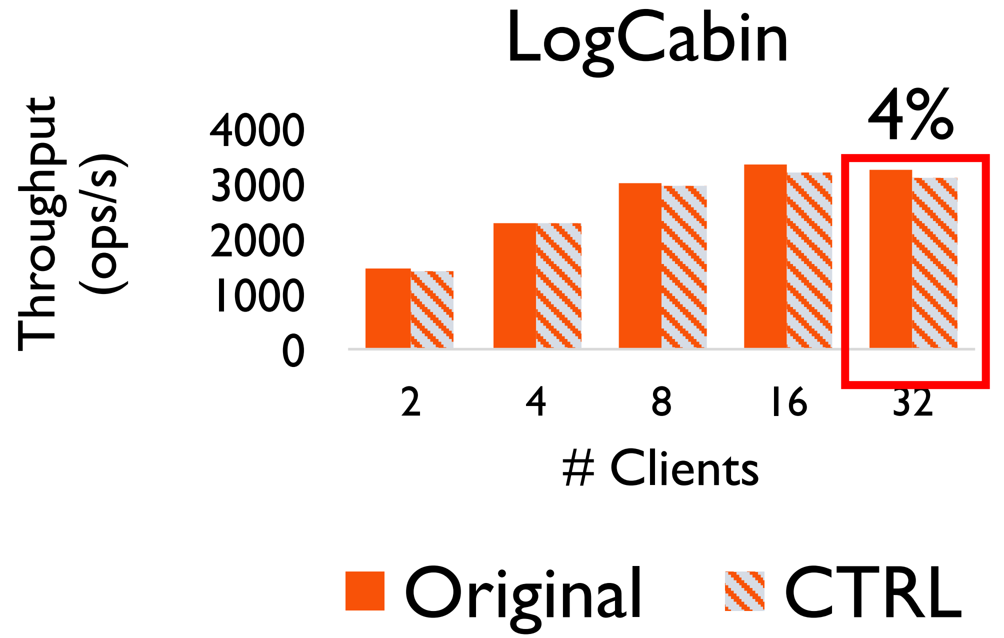
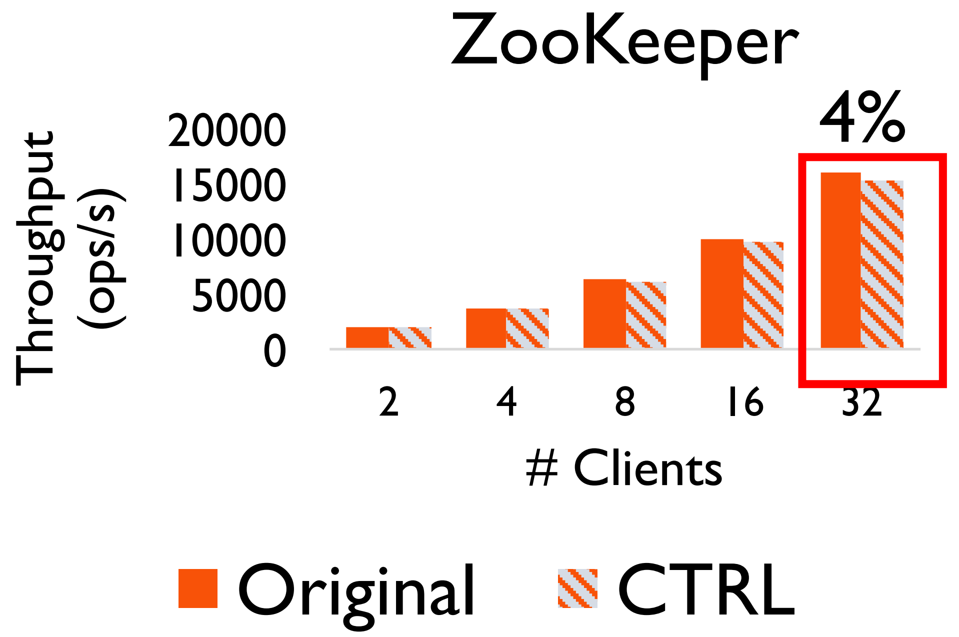
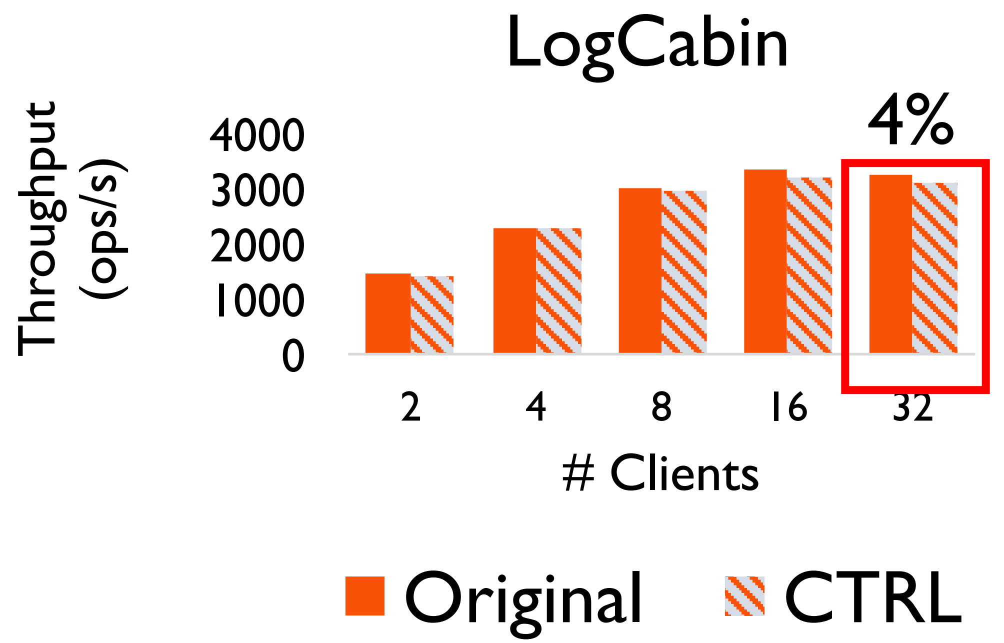


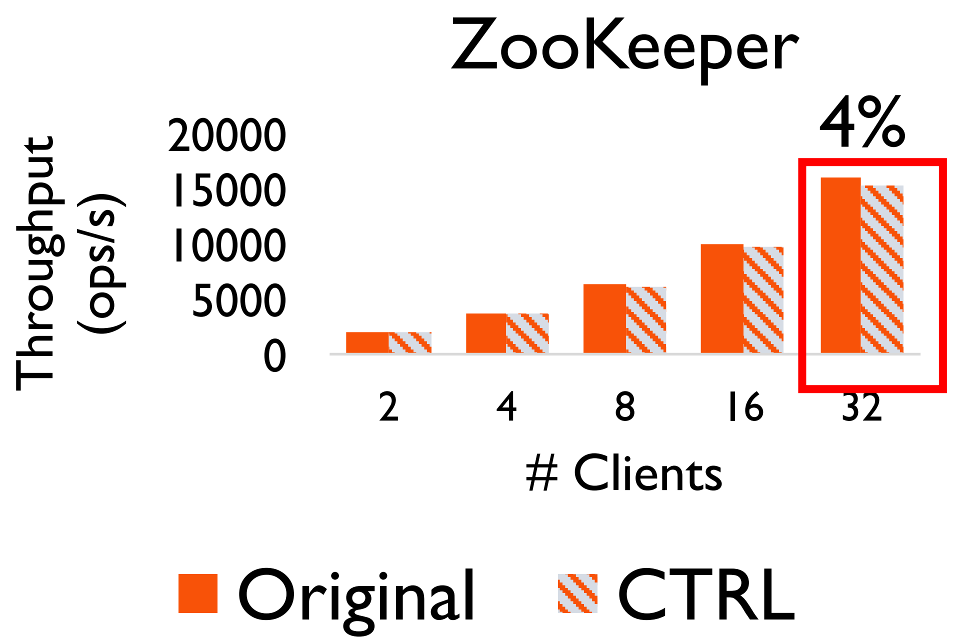


Overheads (because CTRL's storage layer writes additional information for each log entry) – however, little: SSDs 4% worst case, disks: 8% to 10%

Update Performance (SSD)

Workload: insert entries (1K) repeatedly, background snapshots





Overheads (because CTRL's storage layer writes additional information for each log entry) – however, little: SSDs 4% worst case, disks: 8% to 10%

Note: all writes, so worst-case overheads

Summary

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CTRL: a protocol-aware recovery approach for RSM

- ➡ guarantees safety and provides high availability, with little performance overhead

Conclusions

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- ➡ other classes of systems (e.g., quorum-based systems) remain vulnerable

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http://research.cs.wisc.edu/adsl/Publications/par/

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