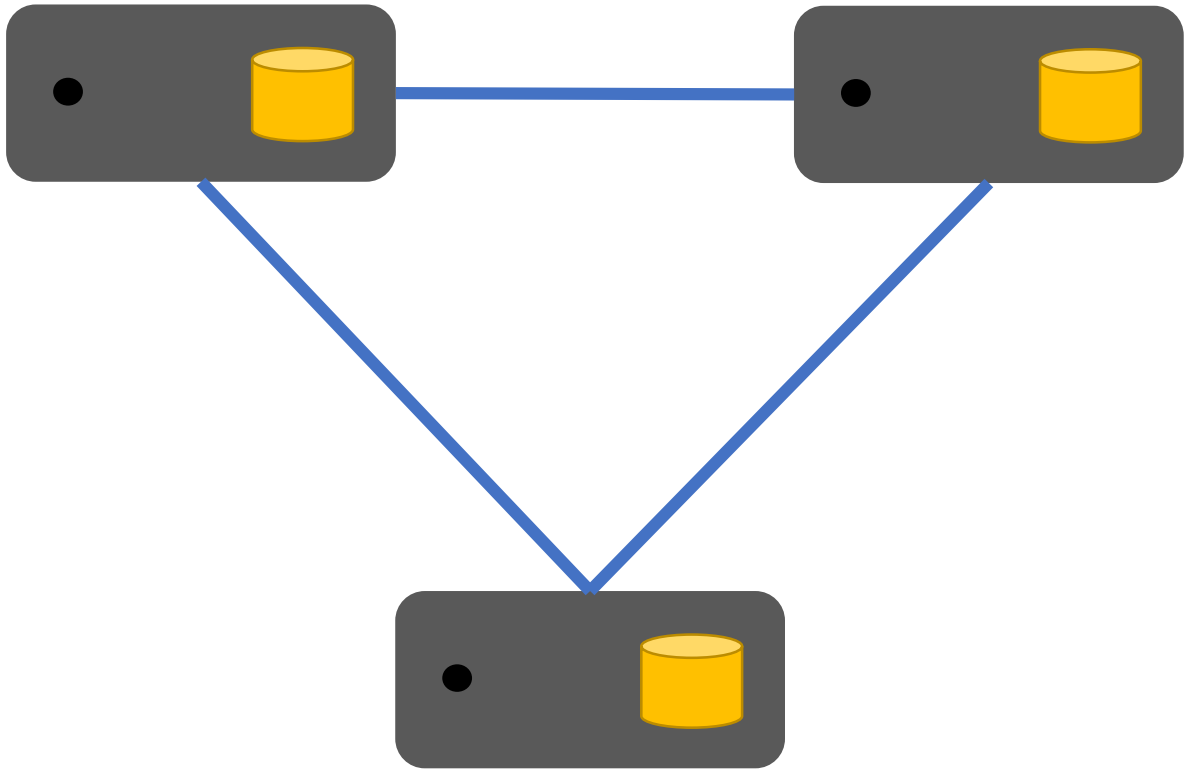
Redundancy Does Not Imply Fault Tolerance:

Analysis of Distributed Storage Reactions to Single Errors and Corruptions

Aishwarya Ganesan, Ramnatthan Alagappan,

Andrea Arpaci-Dusseau, Remzi Arpaci-Dusseau

Redundancy for Fault Tolerance



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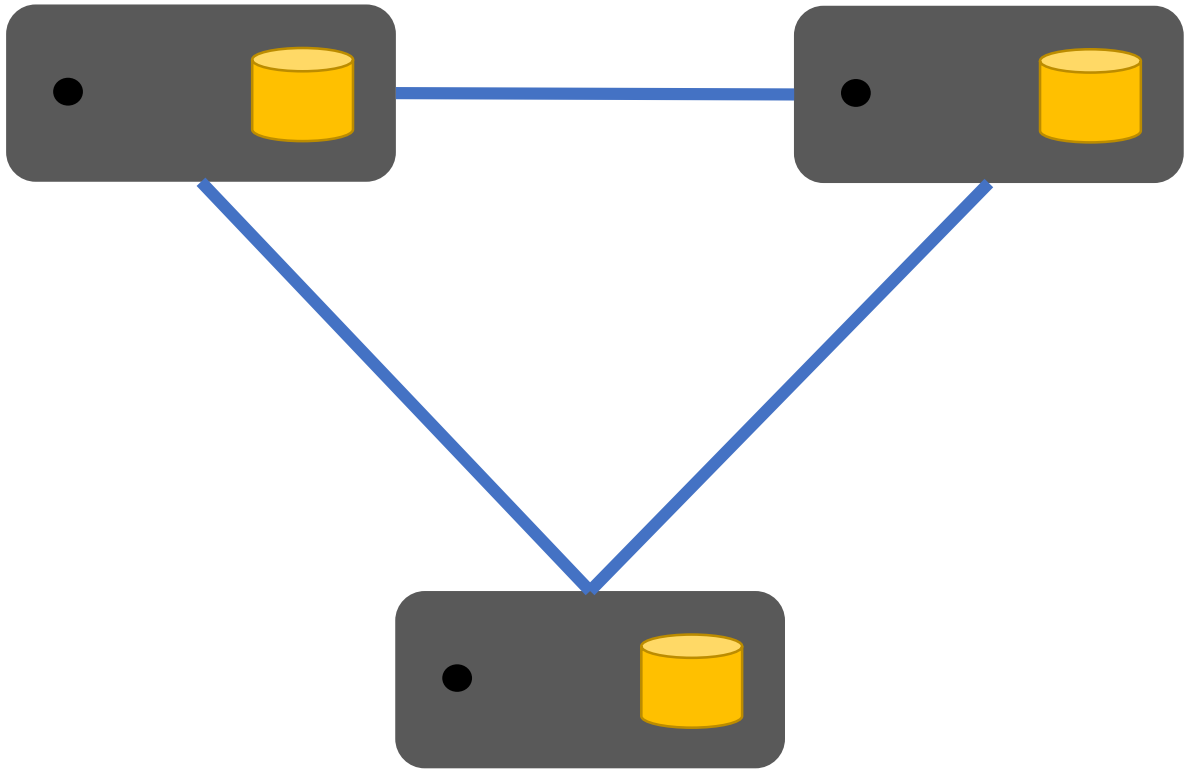

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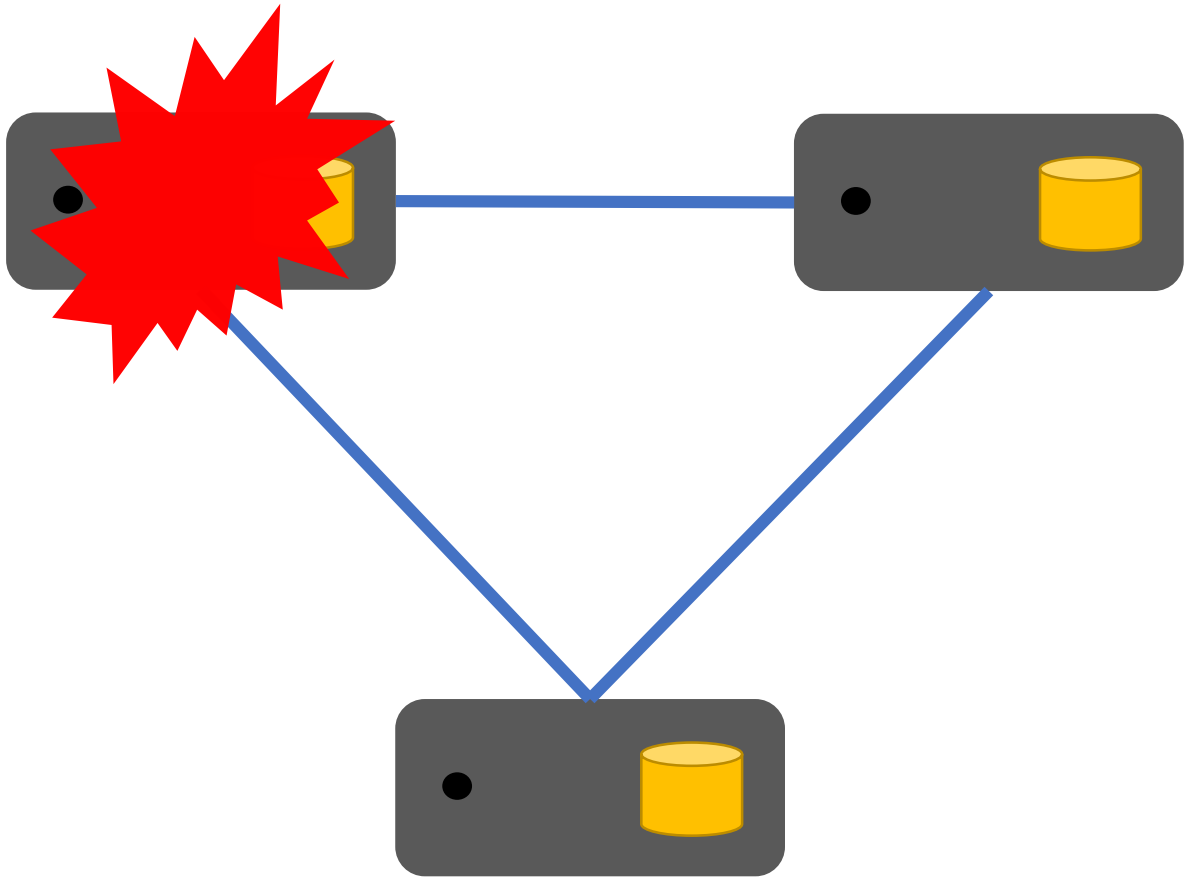

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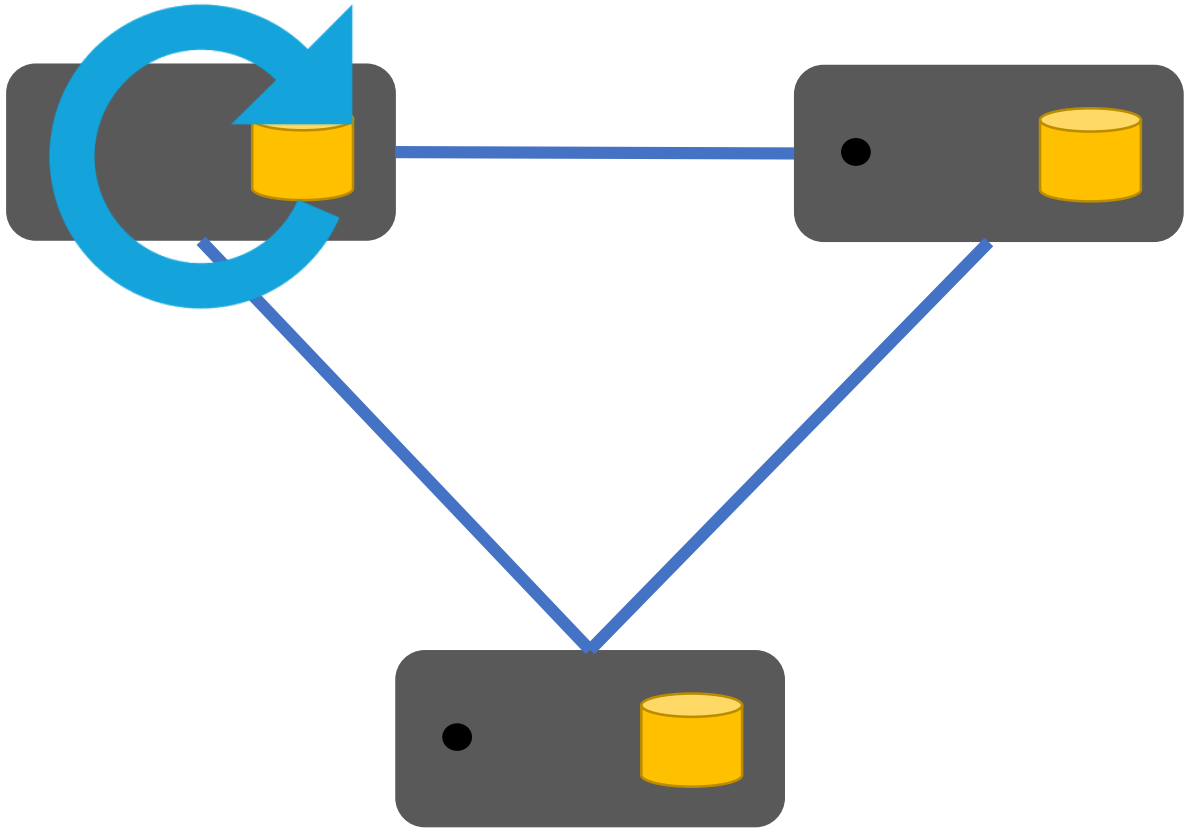

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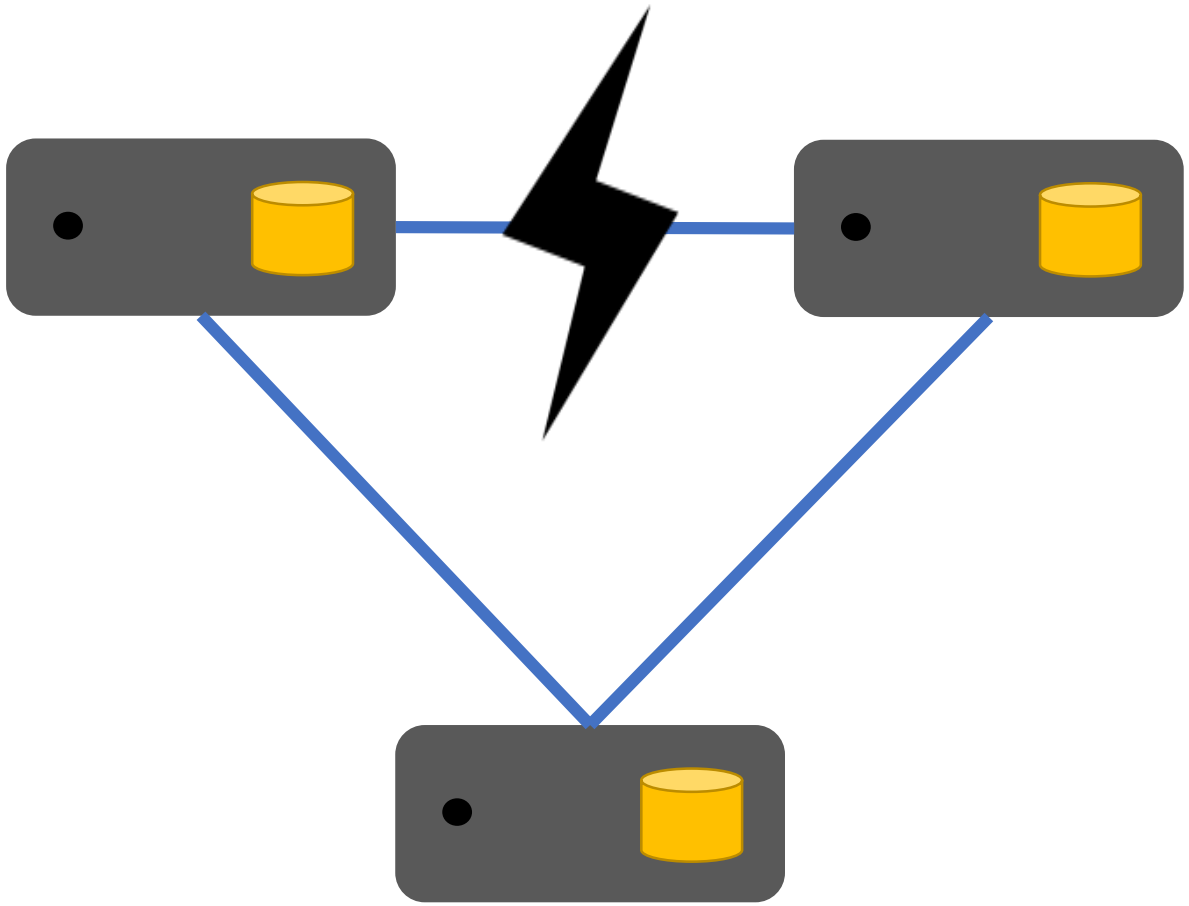

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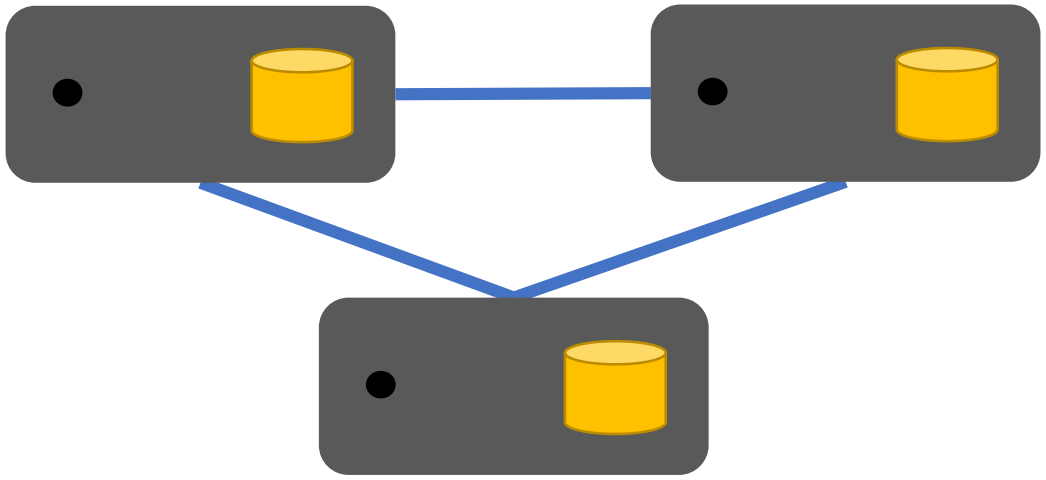
Redundancy in Distributed Storage



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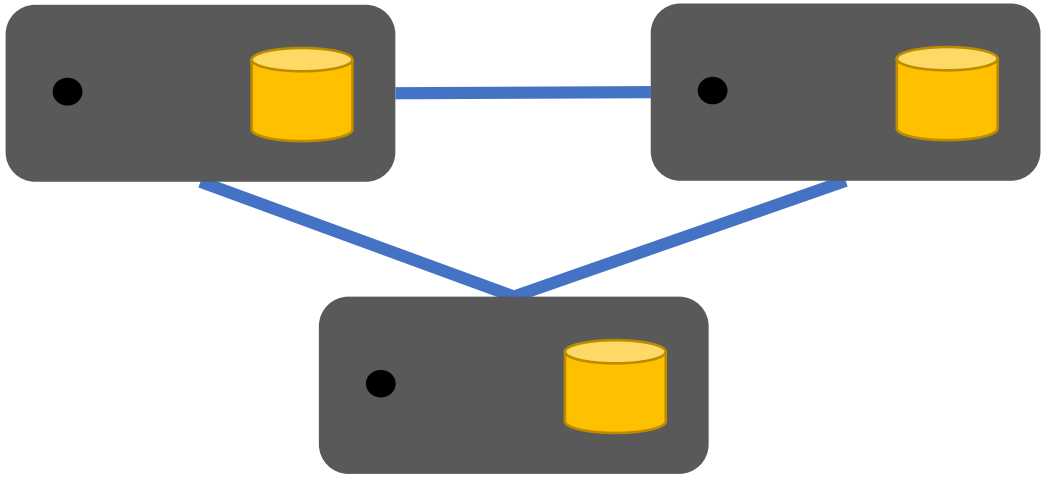
Depend on local file systems to store data



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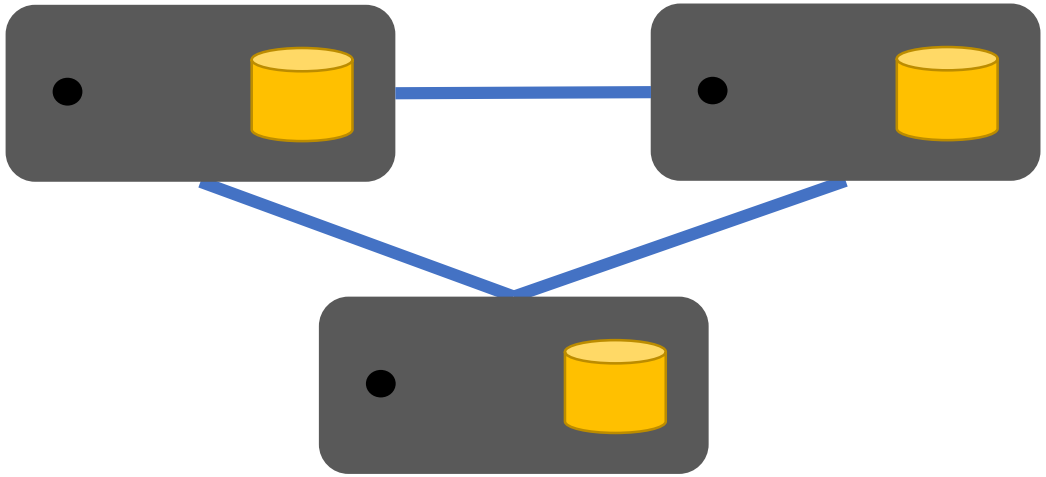

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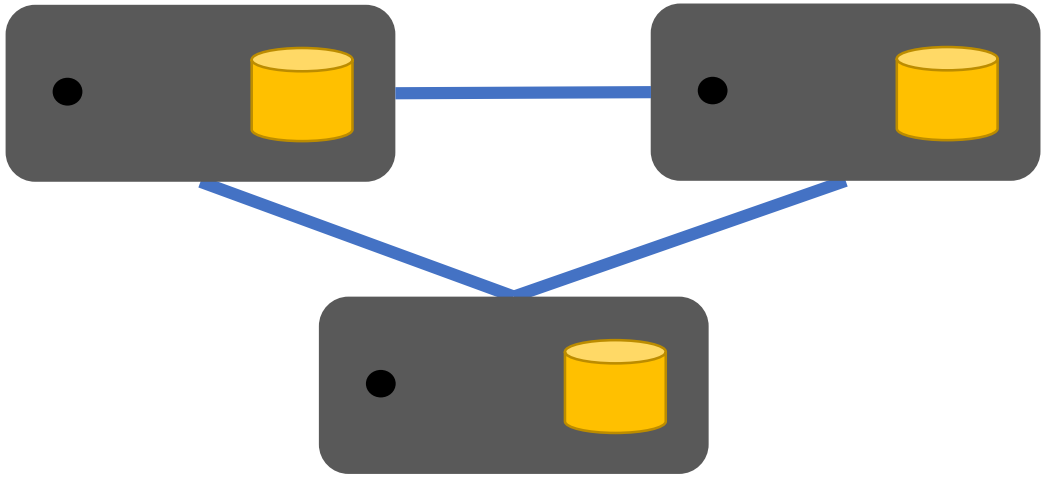

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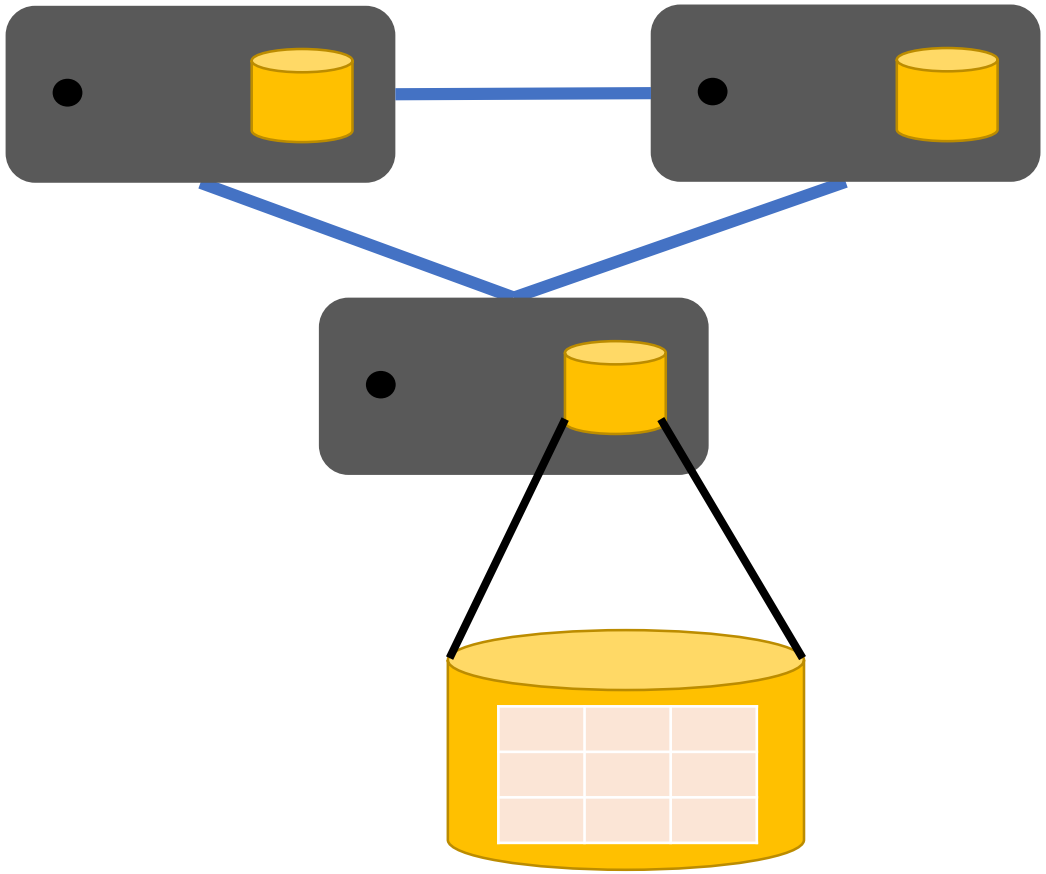

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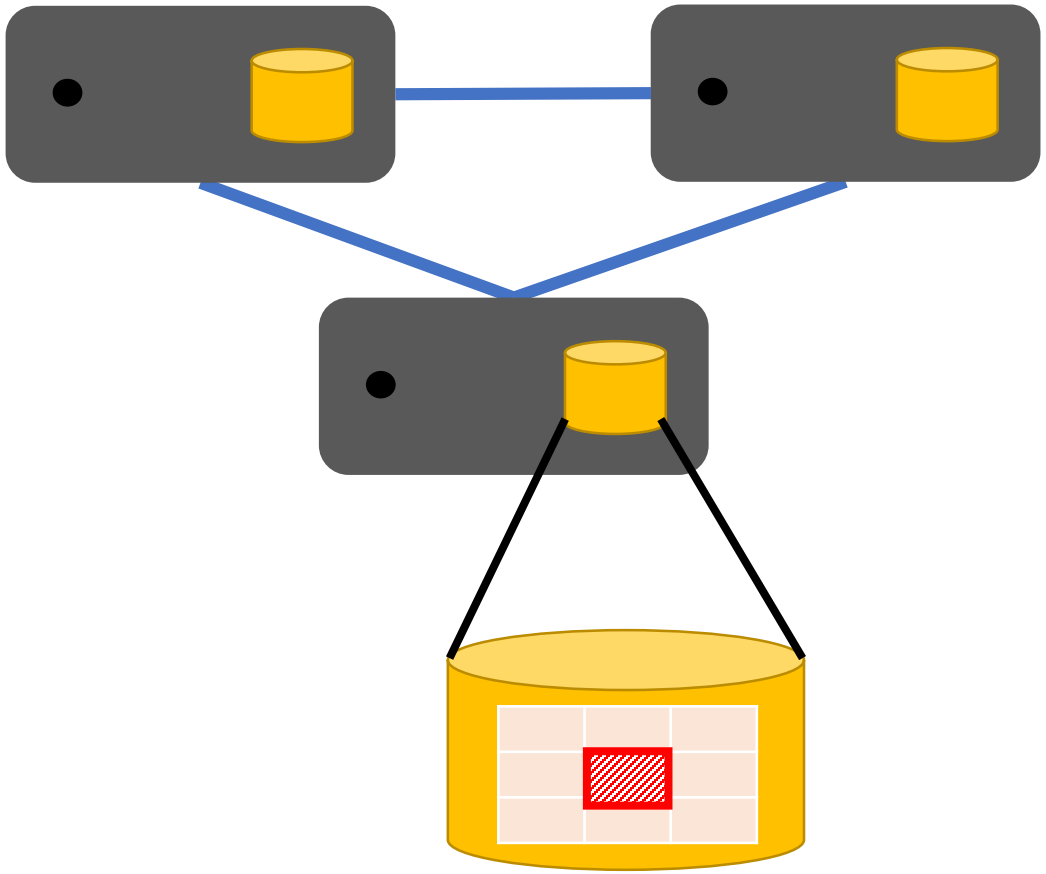

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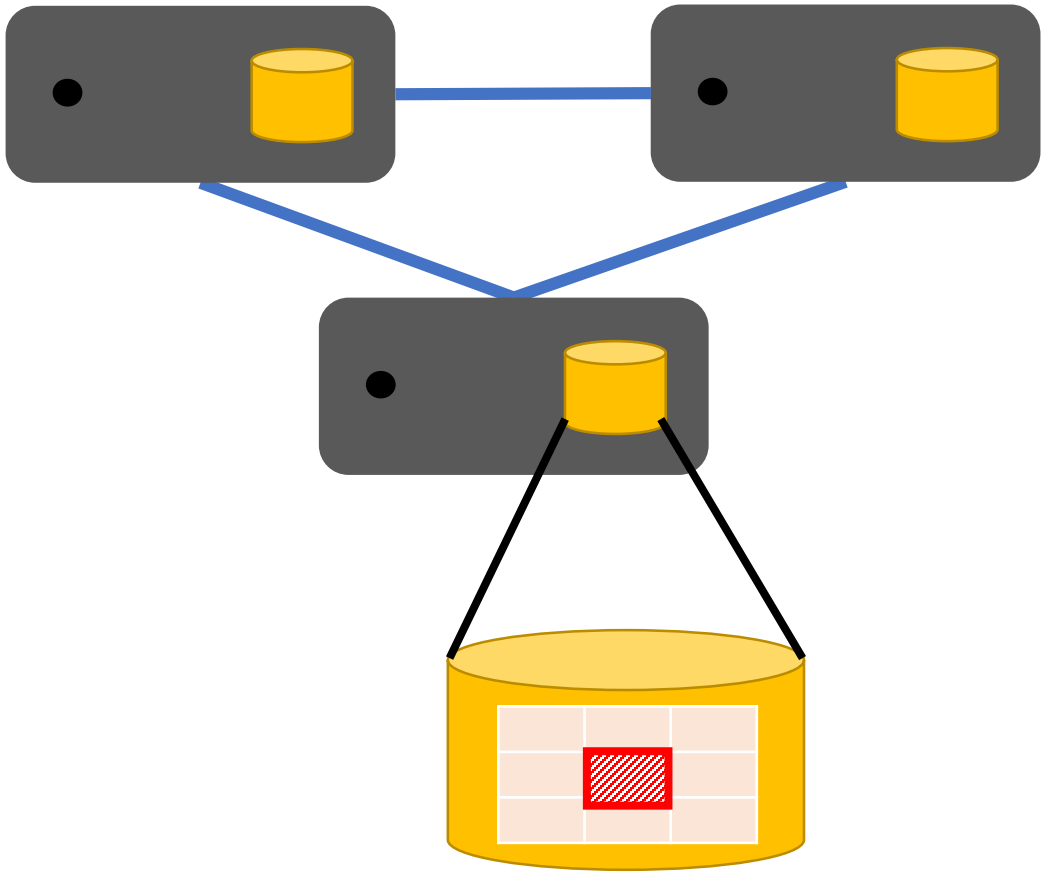

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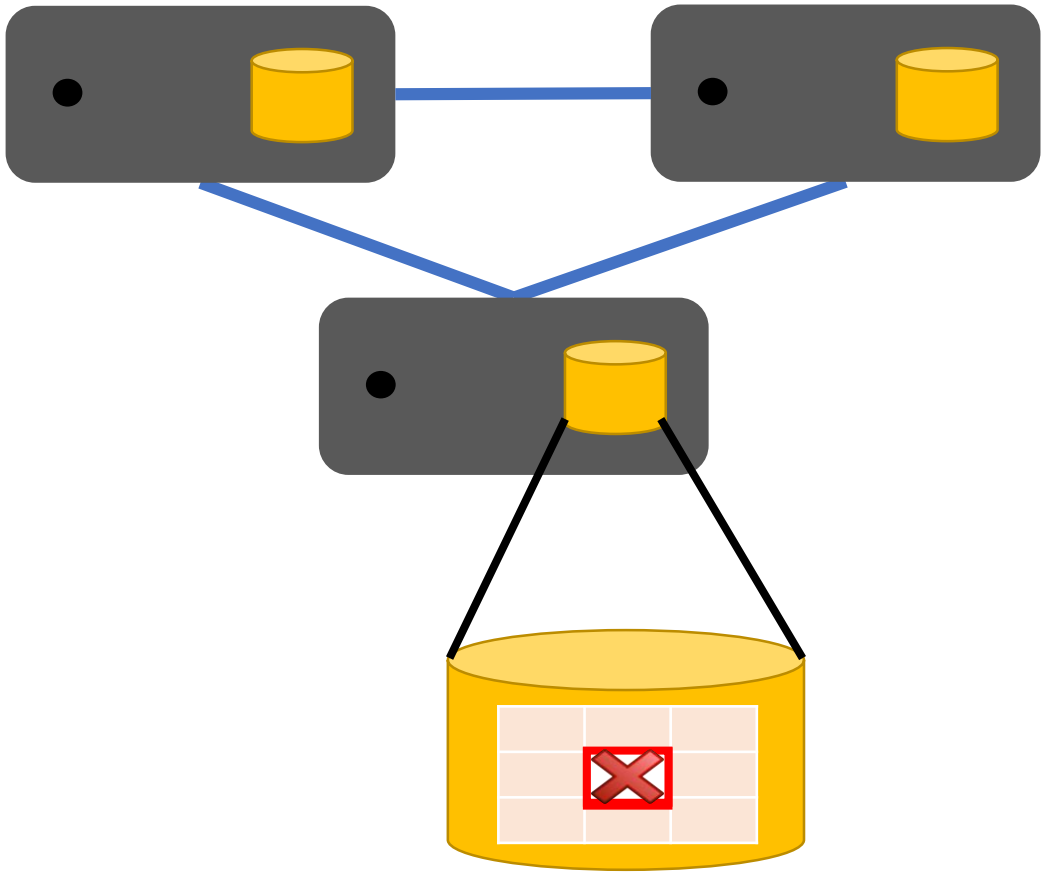

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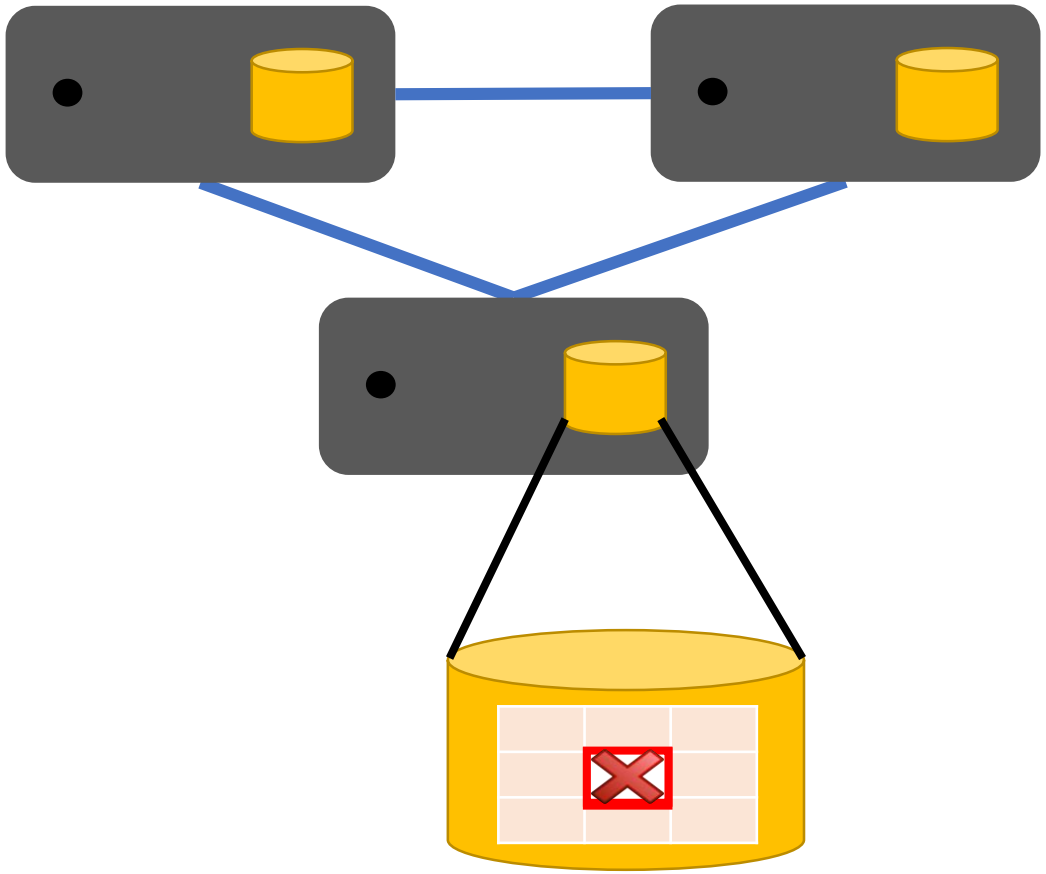

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We call these file-system faults

Redundancy in Distributed Storage

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File system may return corrupted data

Do distributed storage systems use *redundancy* to *recover* from local file-system faults?

read

- latent sector error

We call these file-system faults

Our Study

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Behavior of eight distributed systems in response to file-system faults

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Broad spectrum of replication and consensus protocols

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Dynamo-style quorum

- Cassandra (decentralized, no leader/follower)

Fault model

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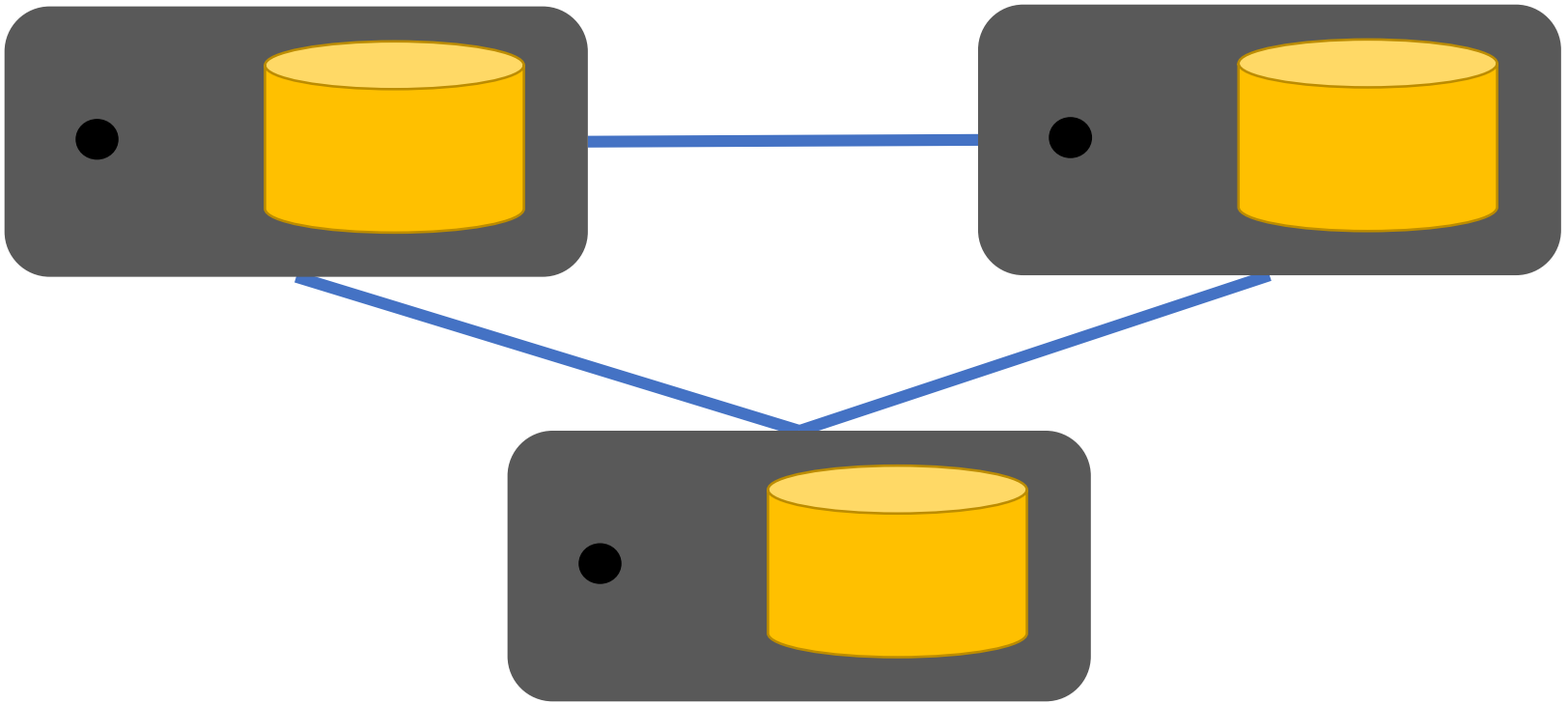
Type of faults:

- corruptions
- read errors
- write errors

Common Expectation



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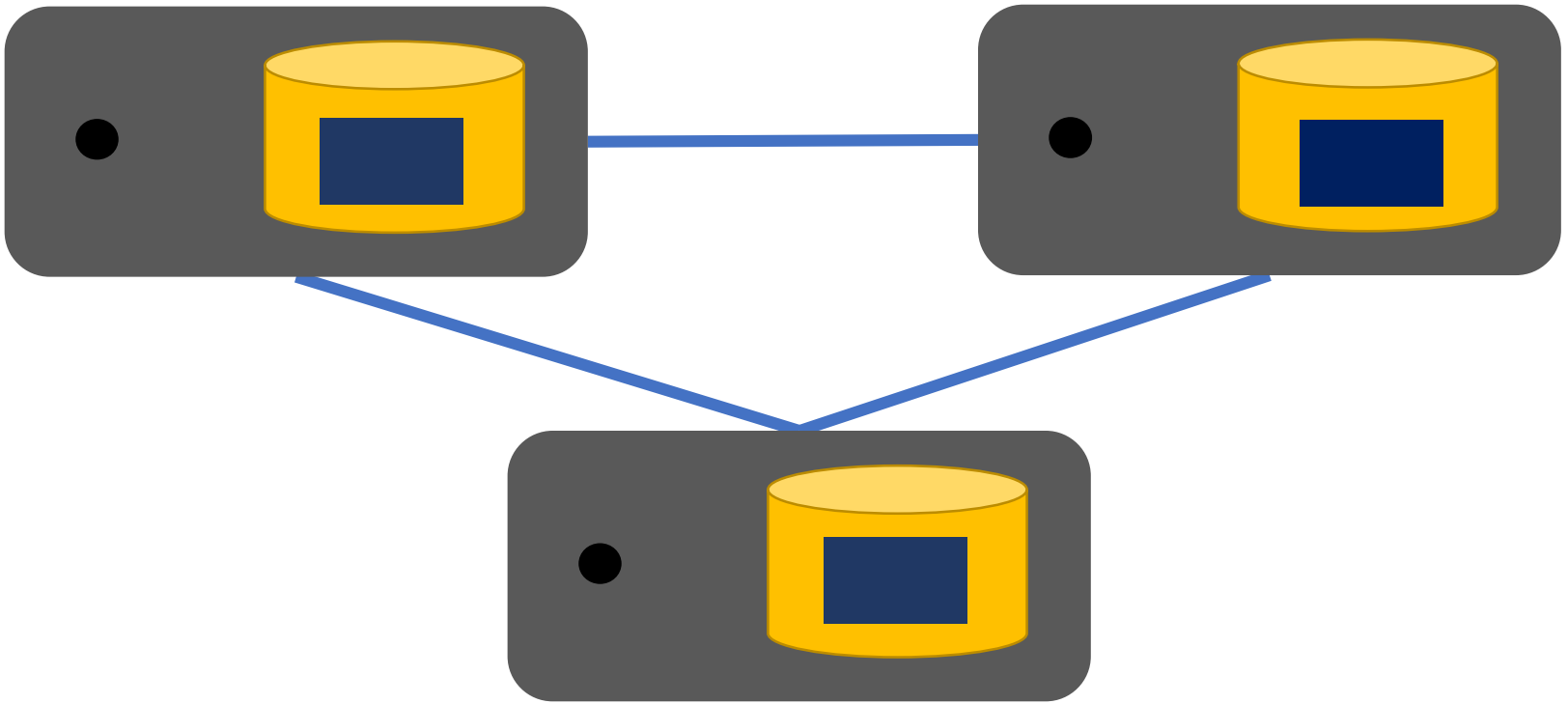

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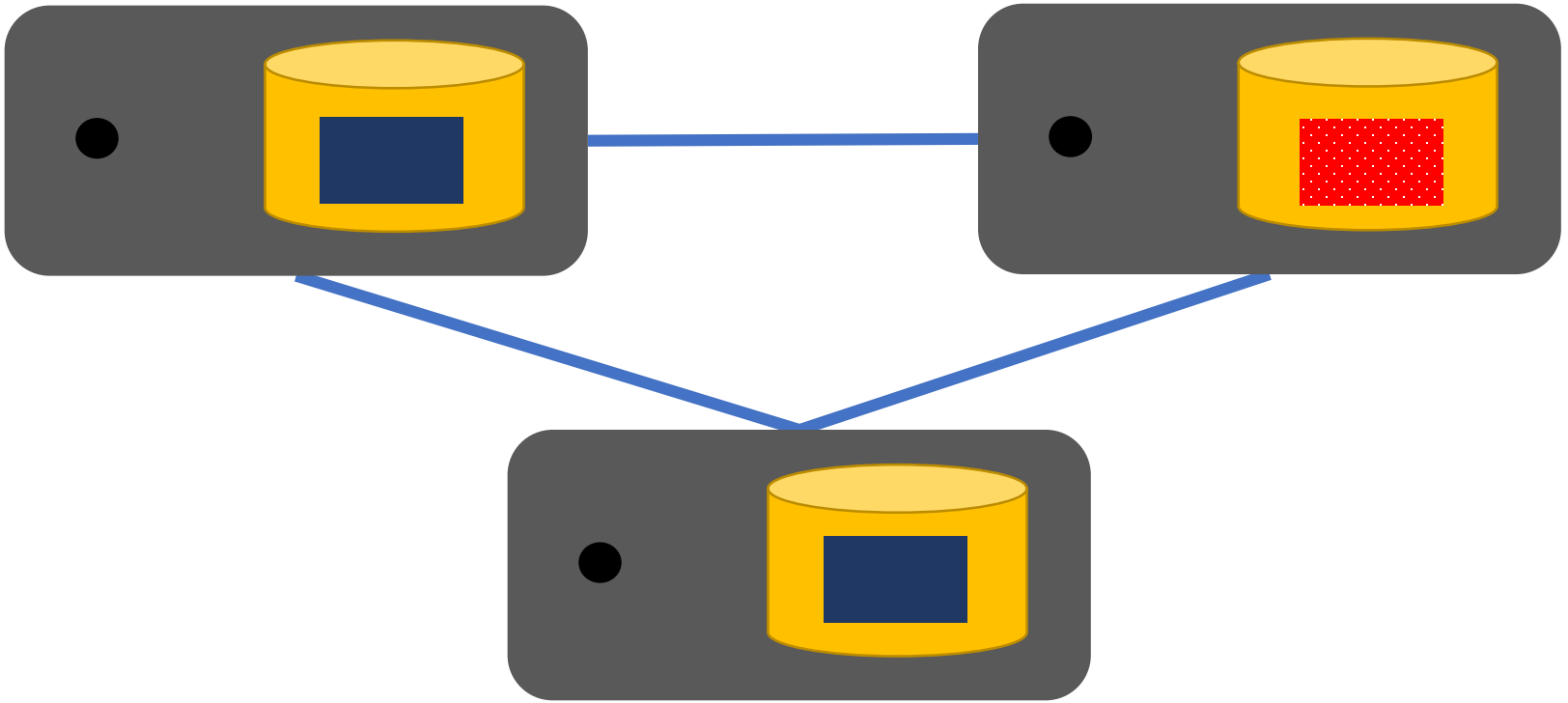

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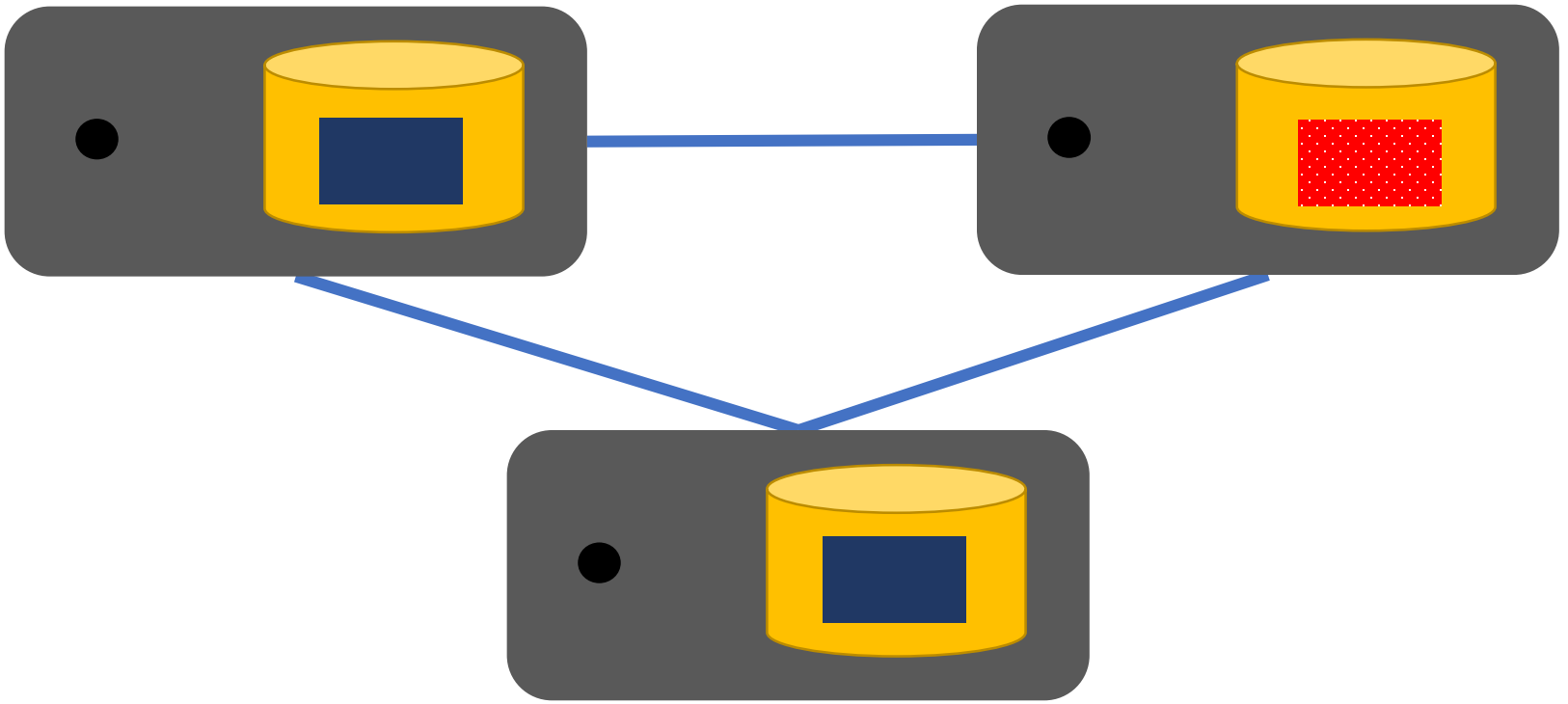

Redundancy would enable recovery from local file-system faults

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	Silent corruption	Unavailability	Data loss	Reduced redundancy	Query failures
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Unsafe interaction between local behavior and global distributed protocols can spread corruption or data loss

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Outline

Introduction

Fault Injection

System Behavior Analysis

Major Results

Observations Across Systems

Conclusion

Fault Model

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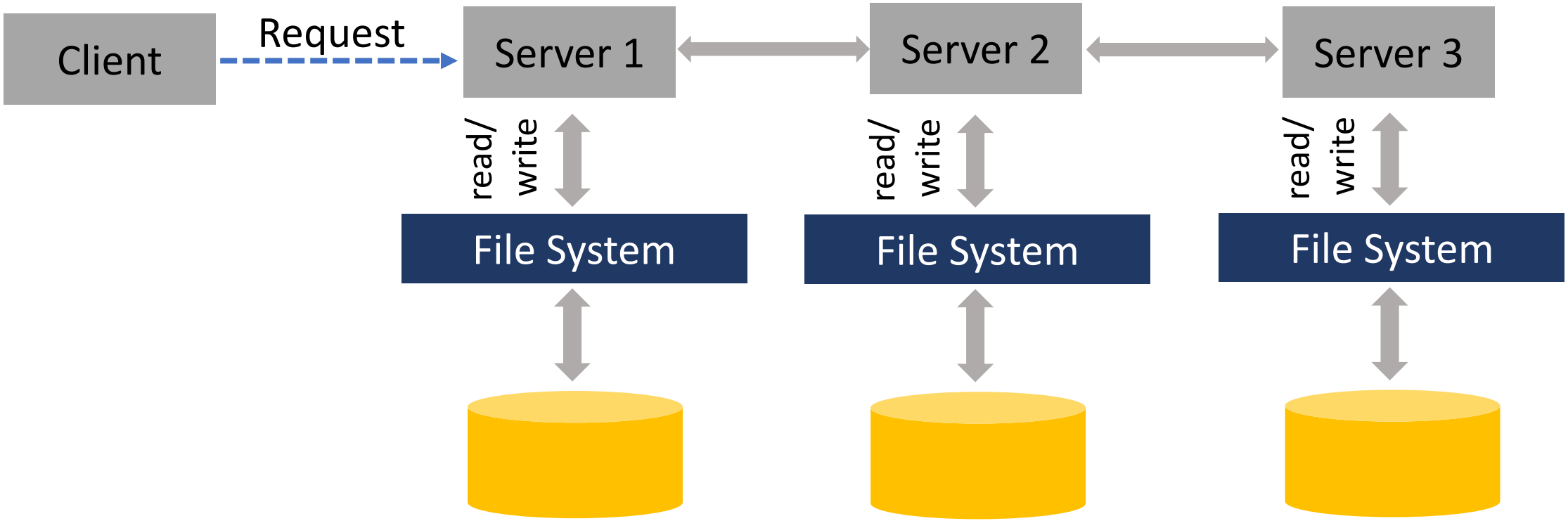
Client
Request
Server 1
Server 2
Server 3
read/
write
read/
write
read/
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File System
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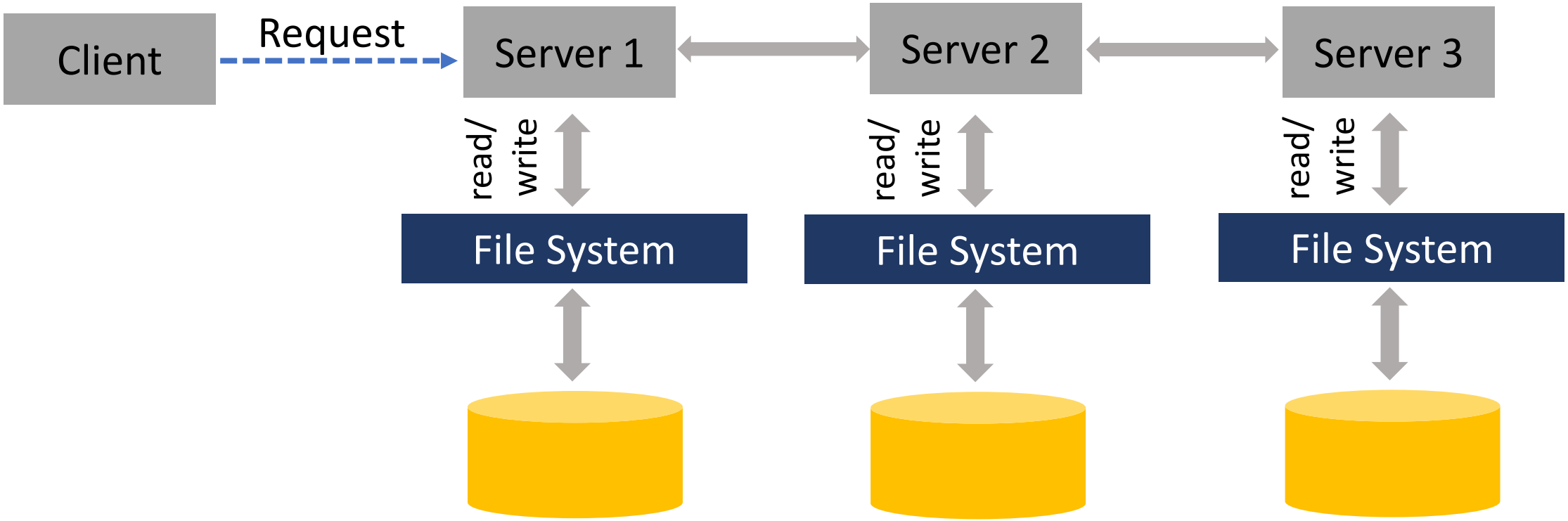

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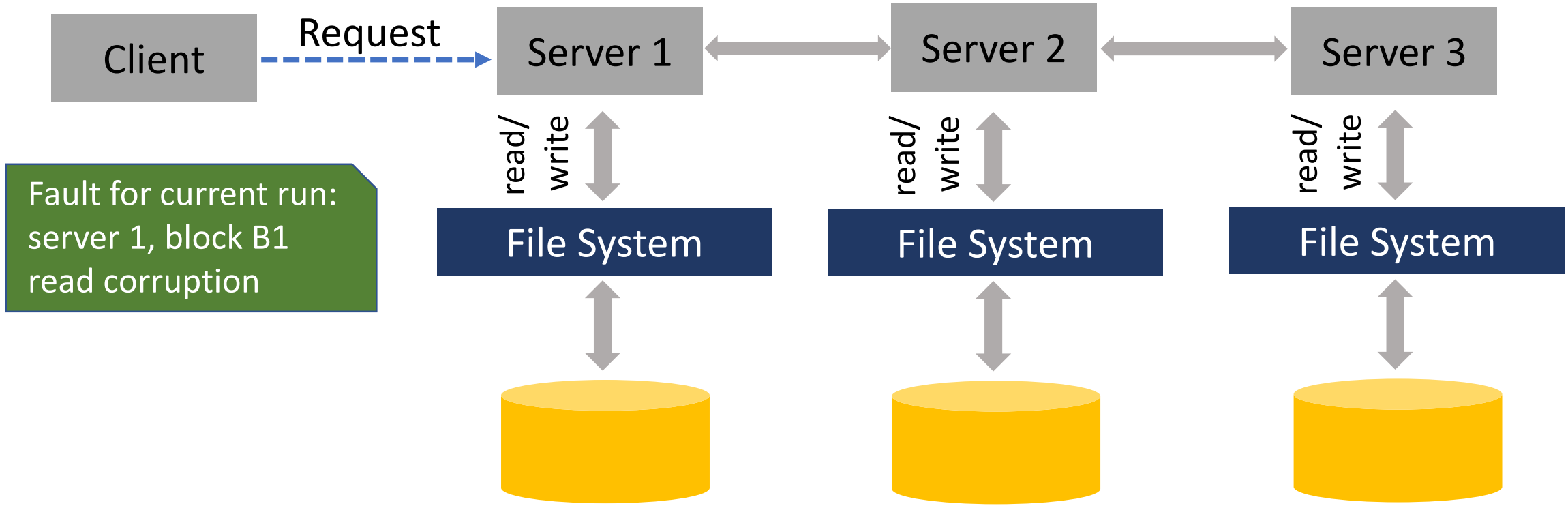

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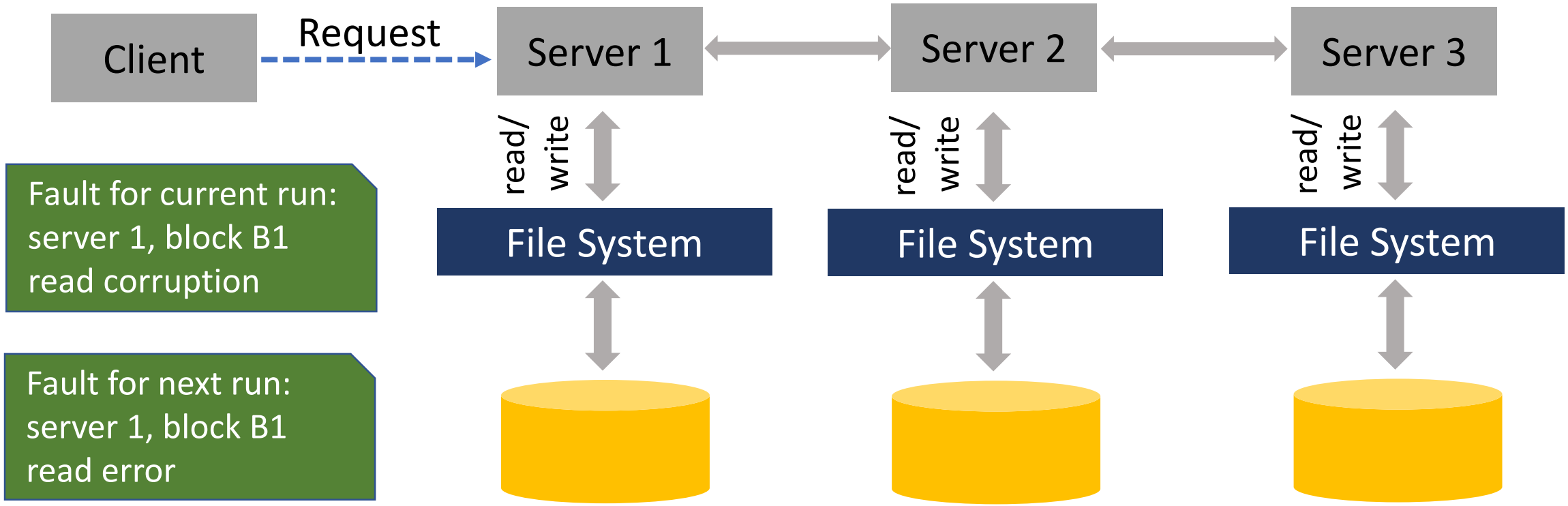

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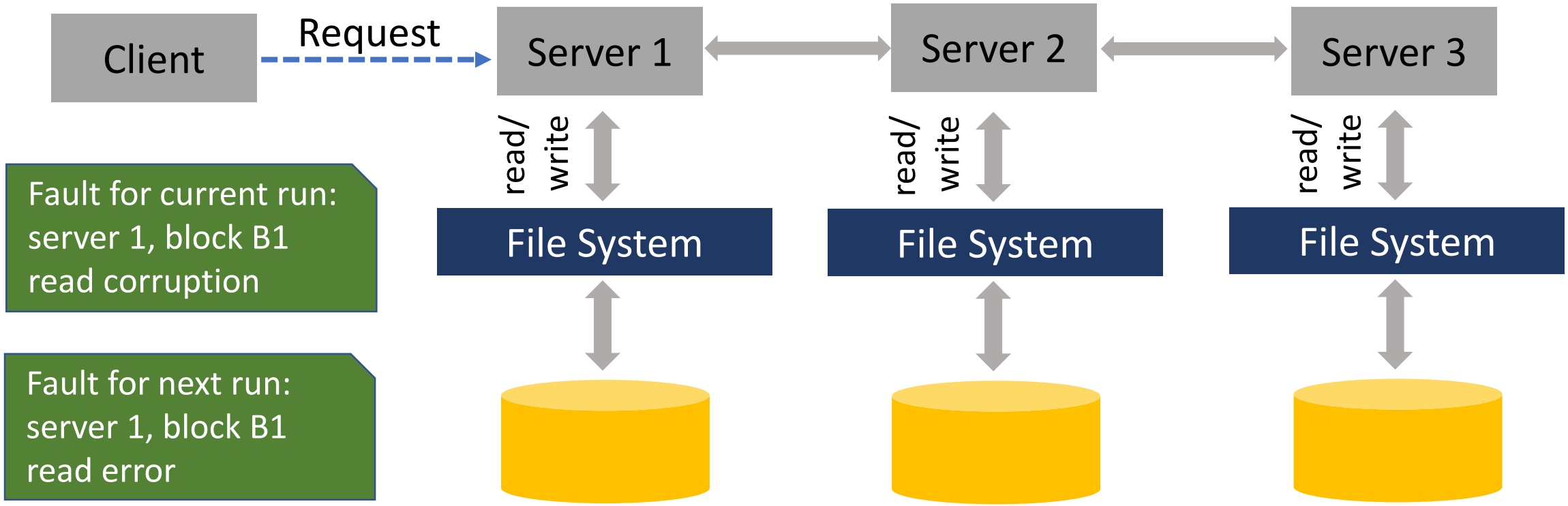

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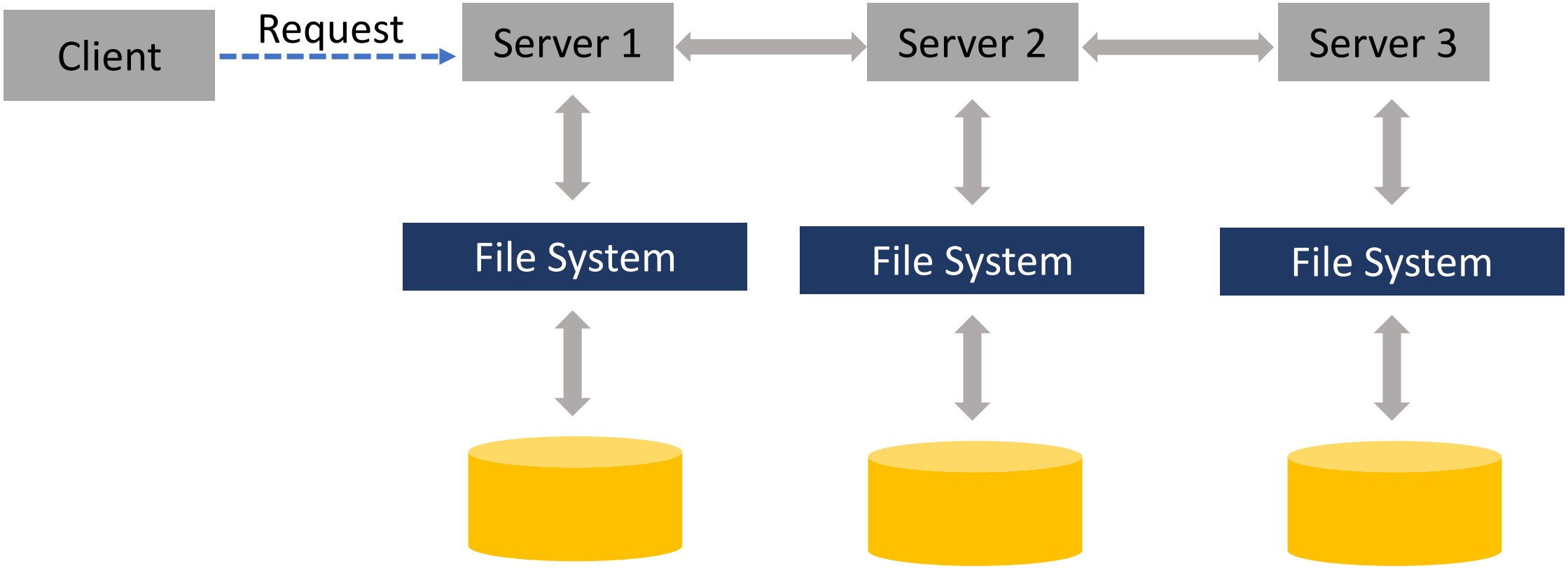
Faults injected only to user data not filesystem metadata

Fault Model: ext4 and btrfs



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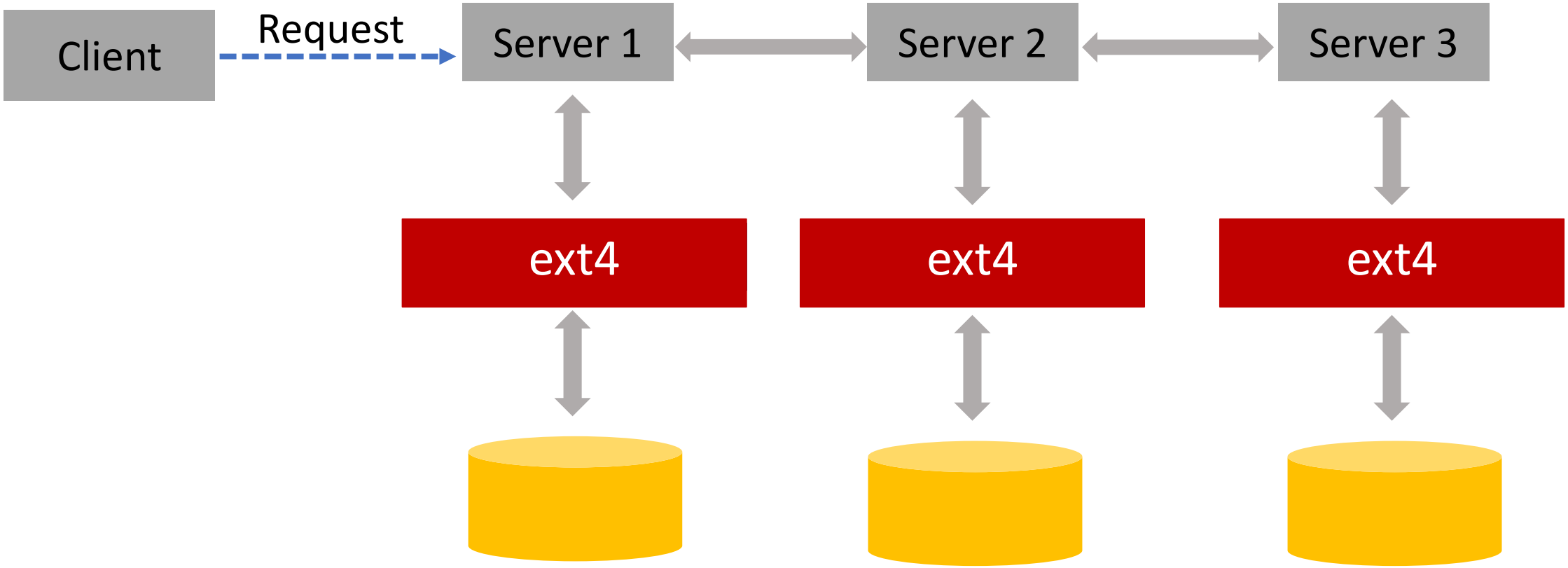

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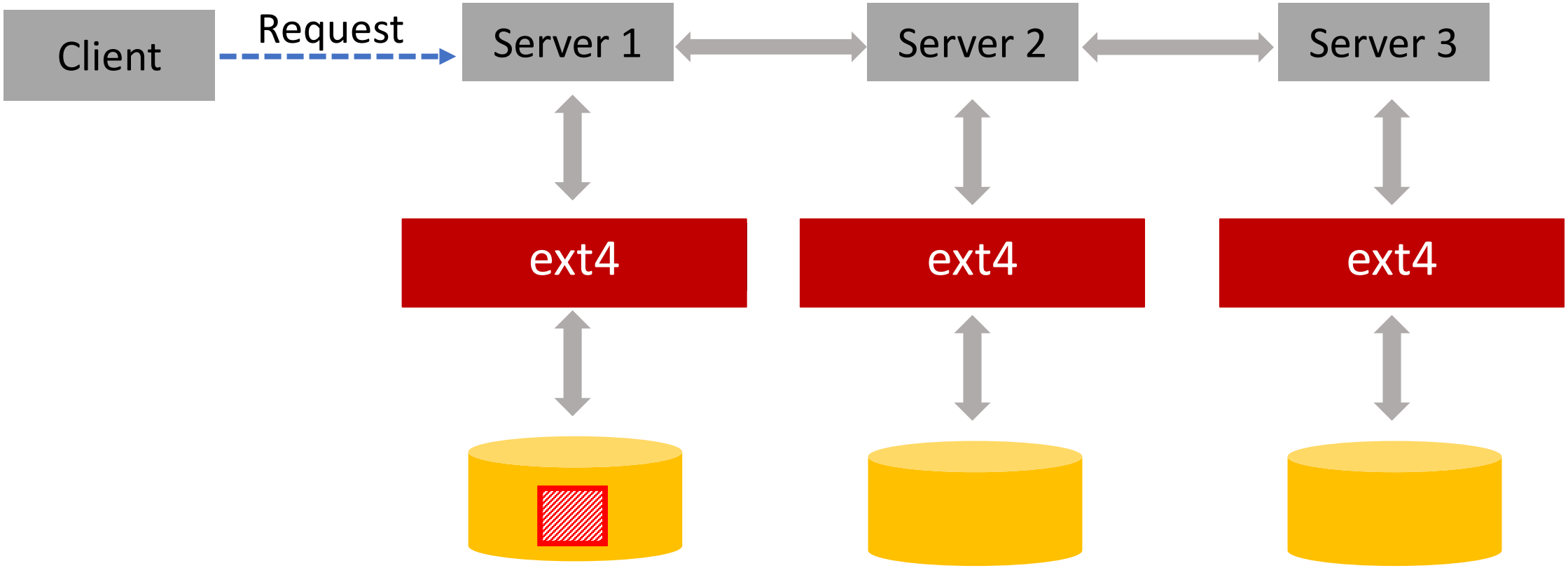

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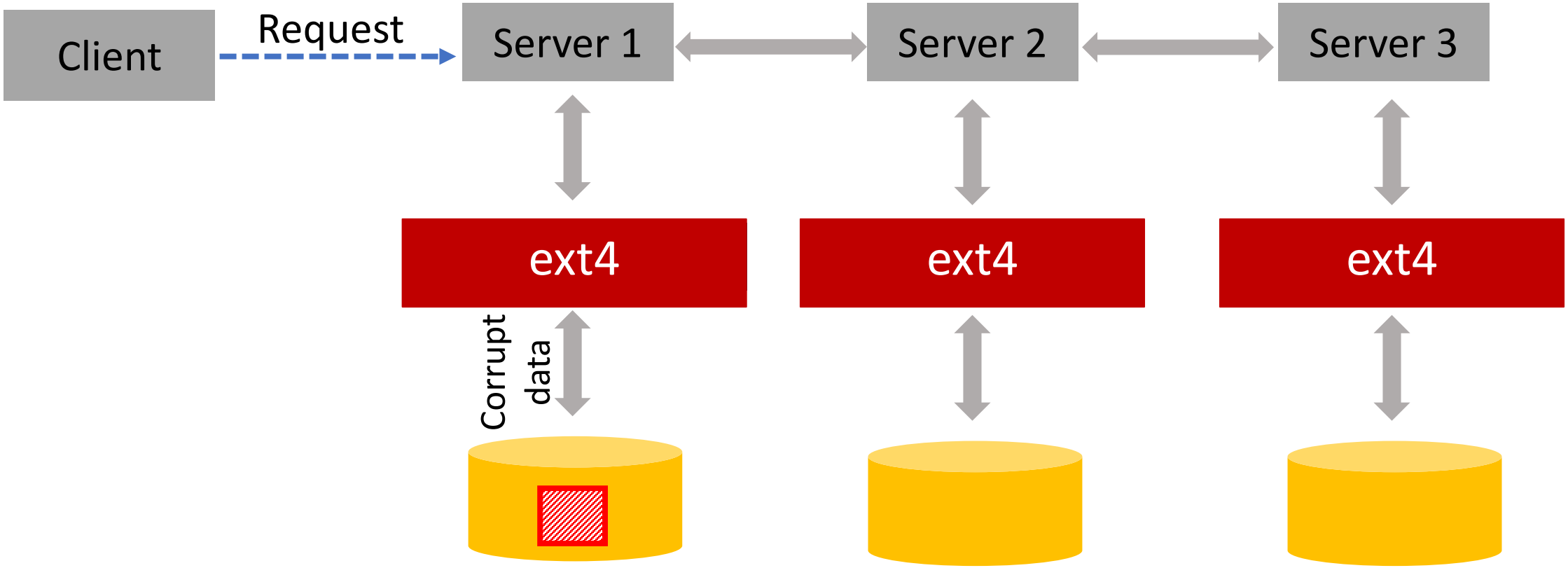

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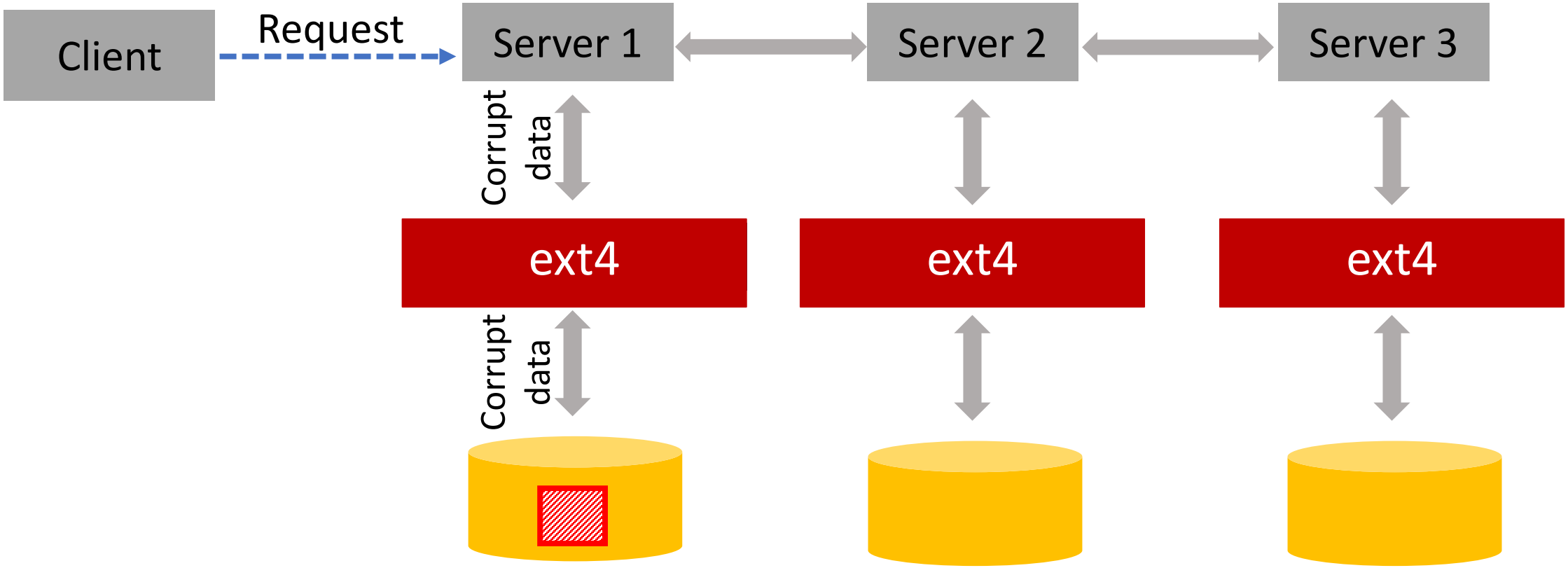

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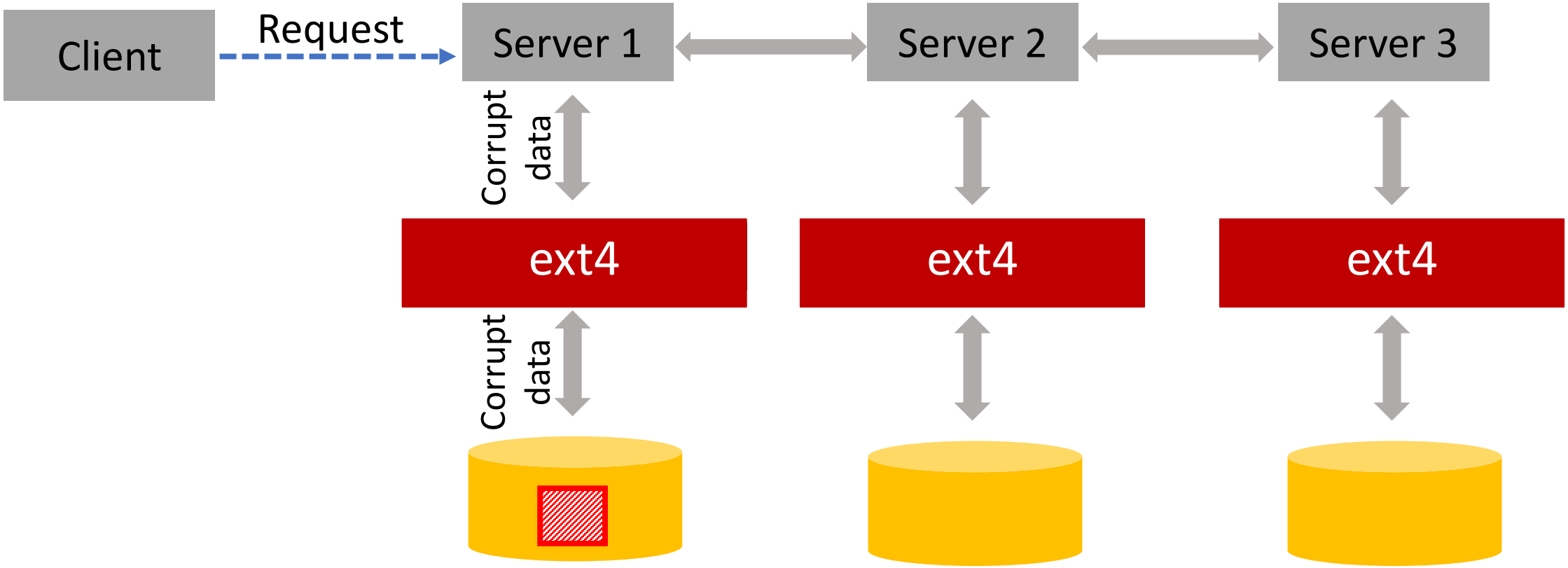

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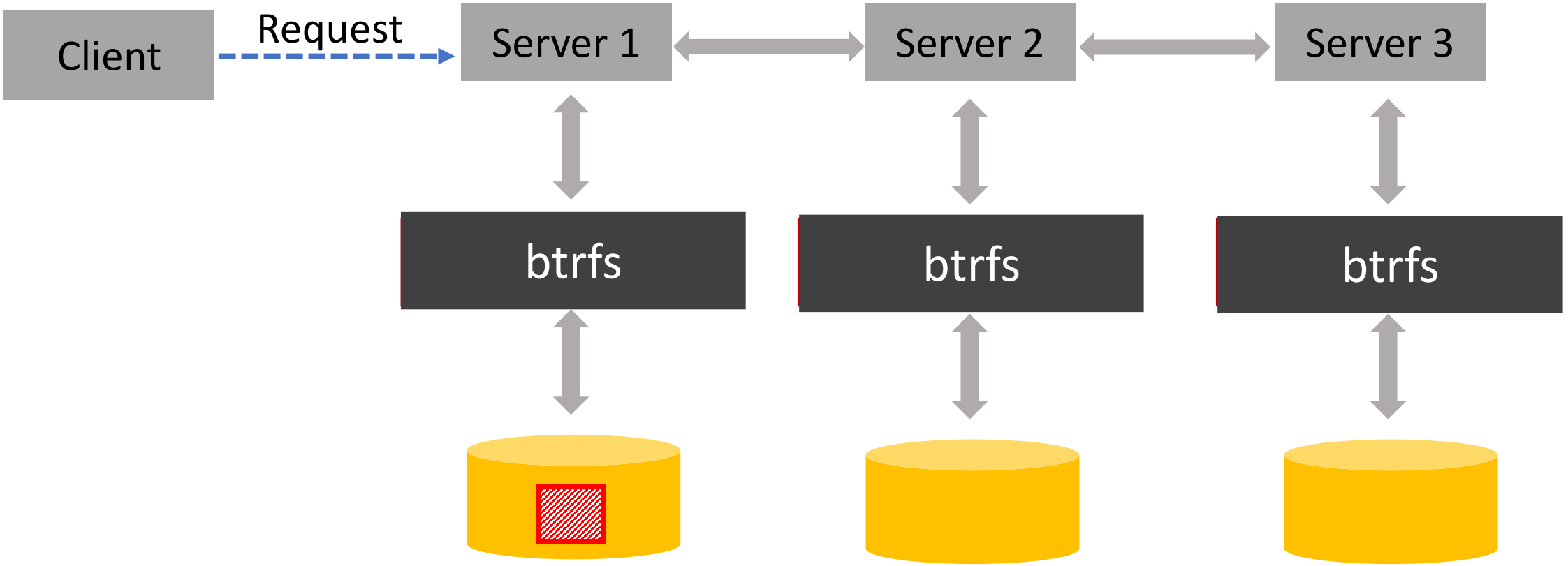

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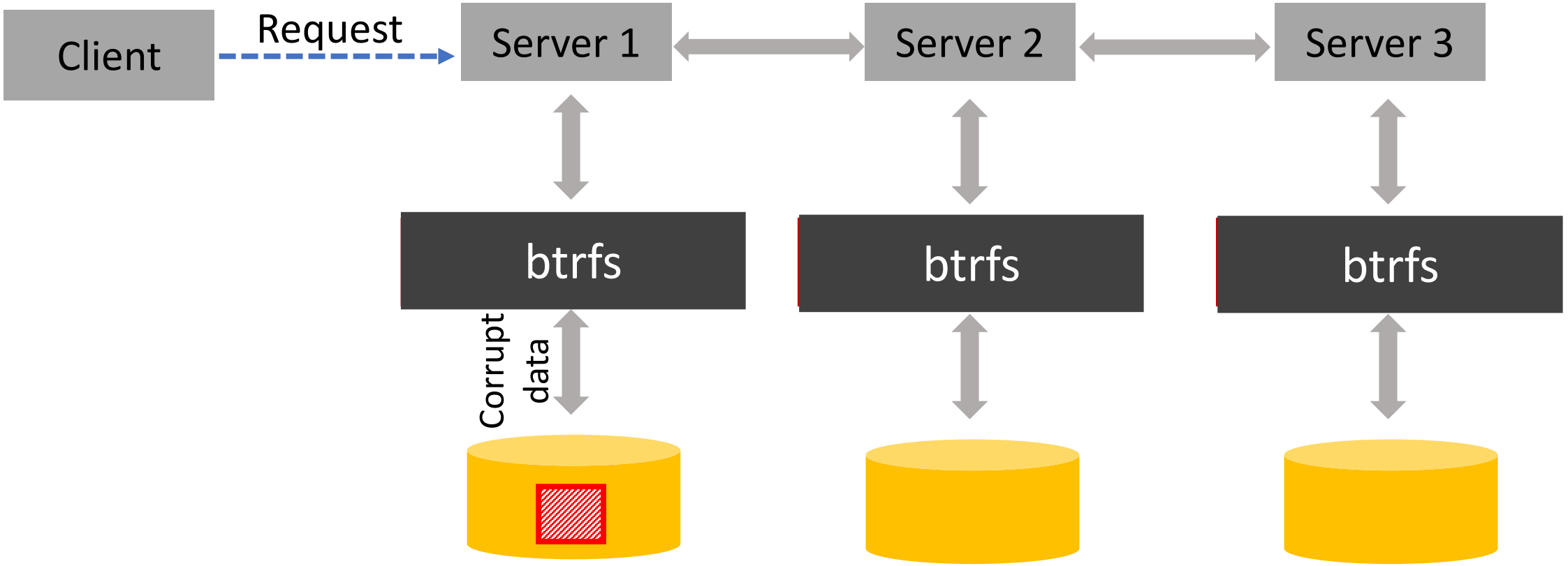

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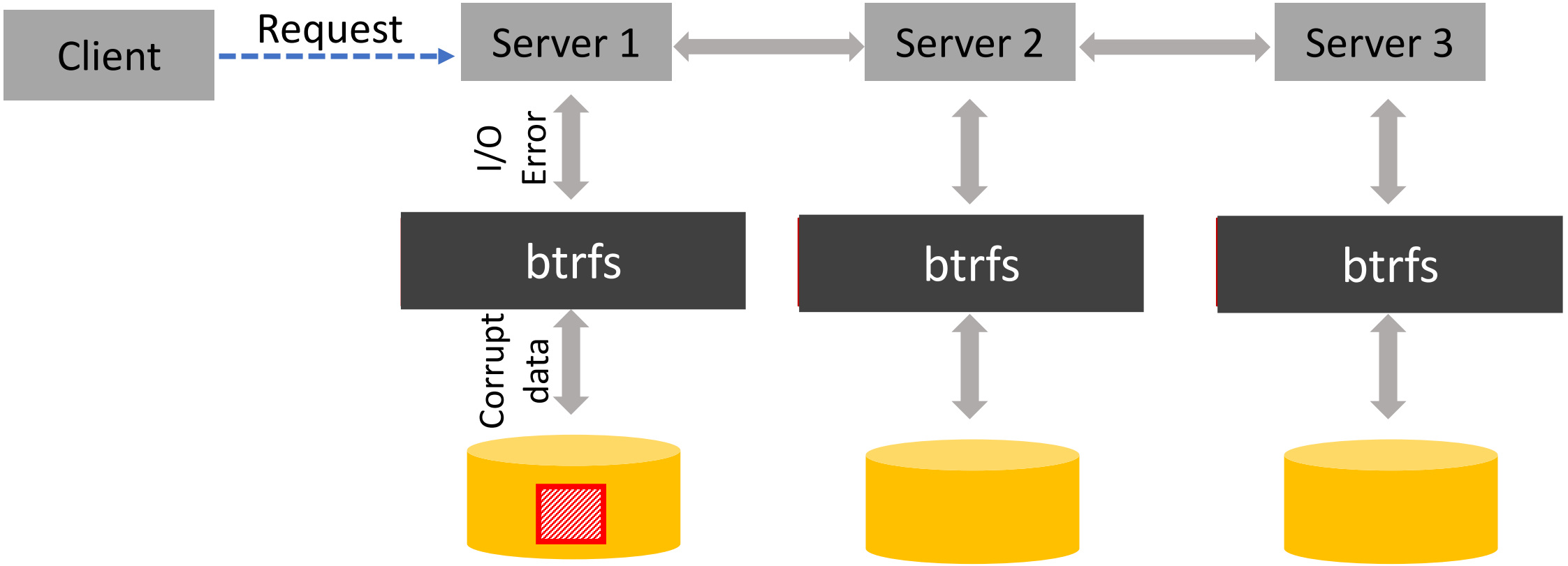

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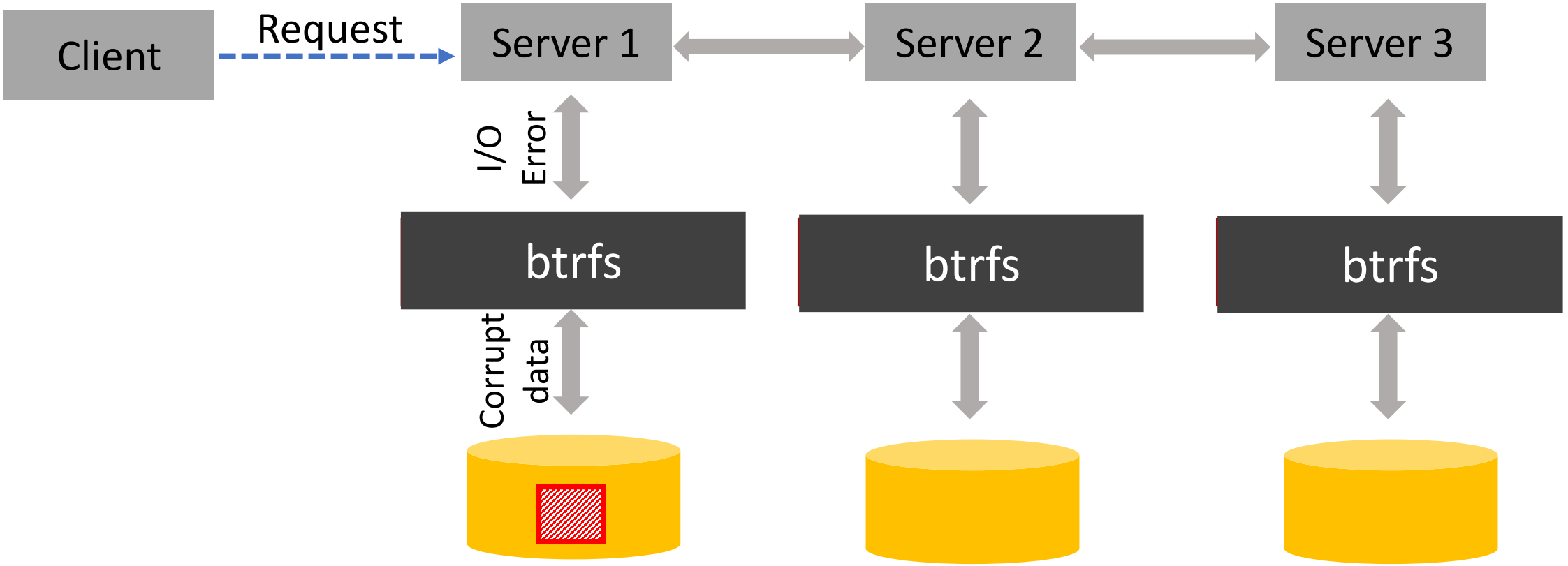

Ext4: disk corruption → corrupted data to applications

Btrfs: disk corruption → I/O error to applications

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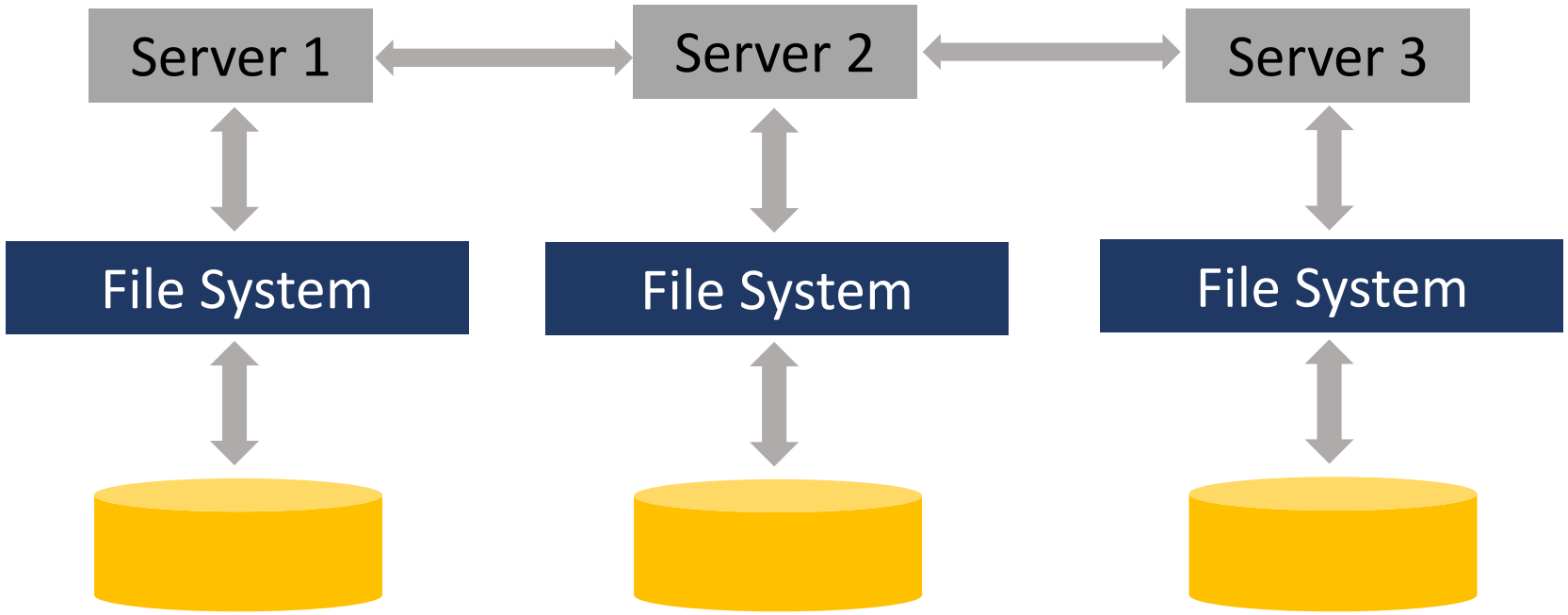

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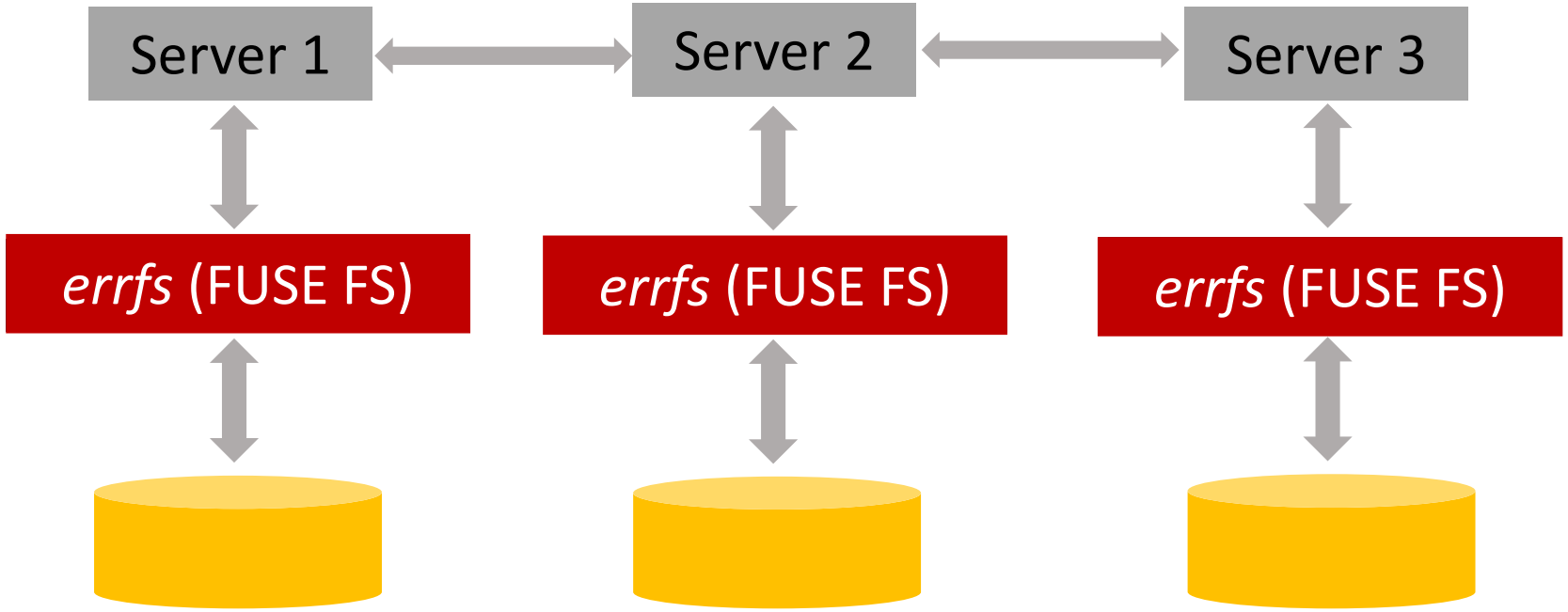

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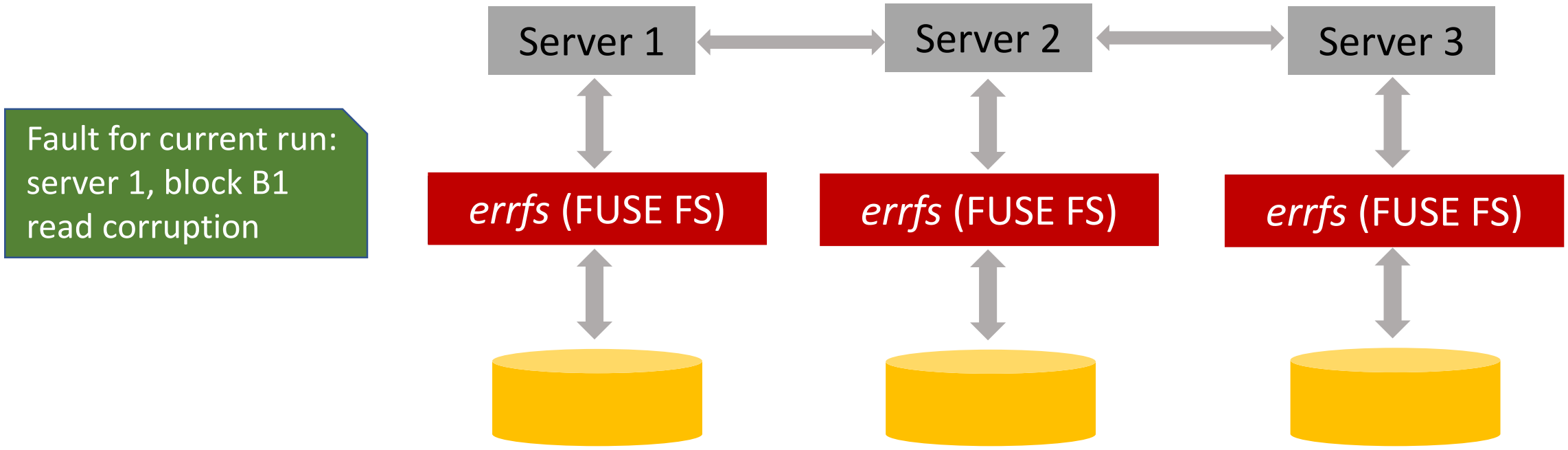

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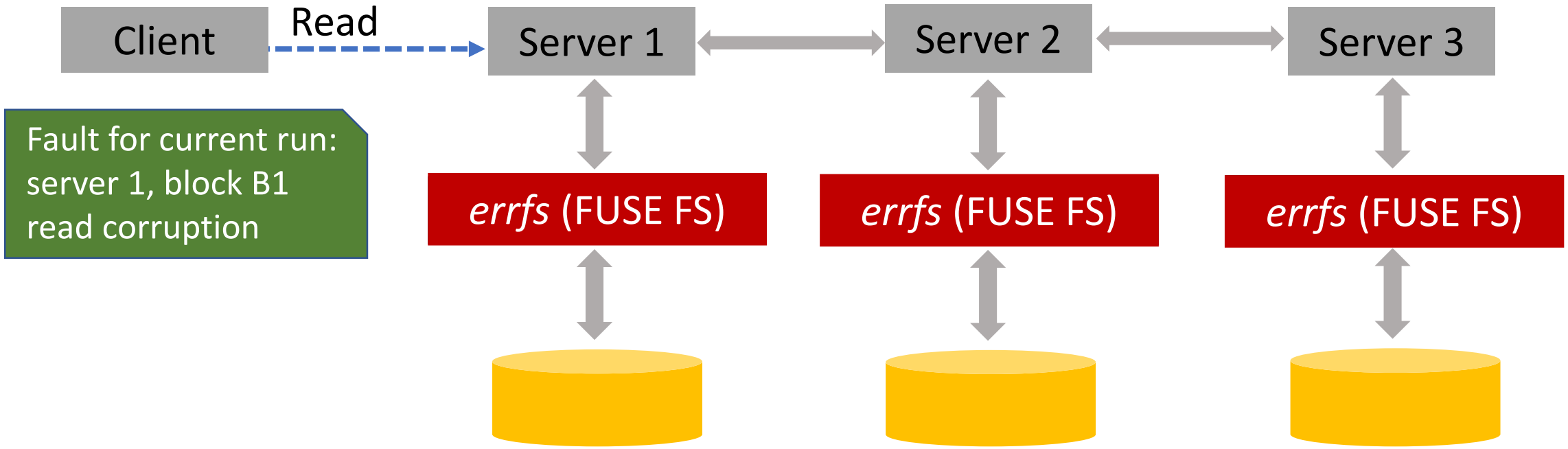

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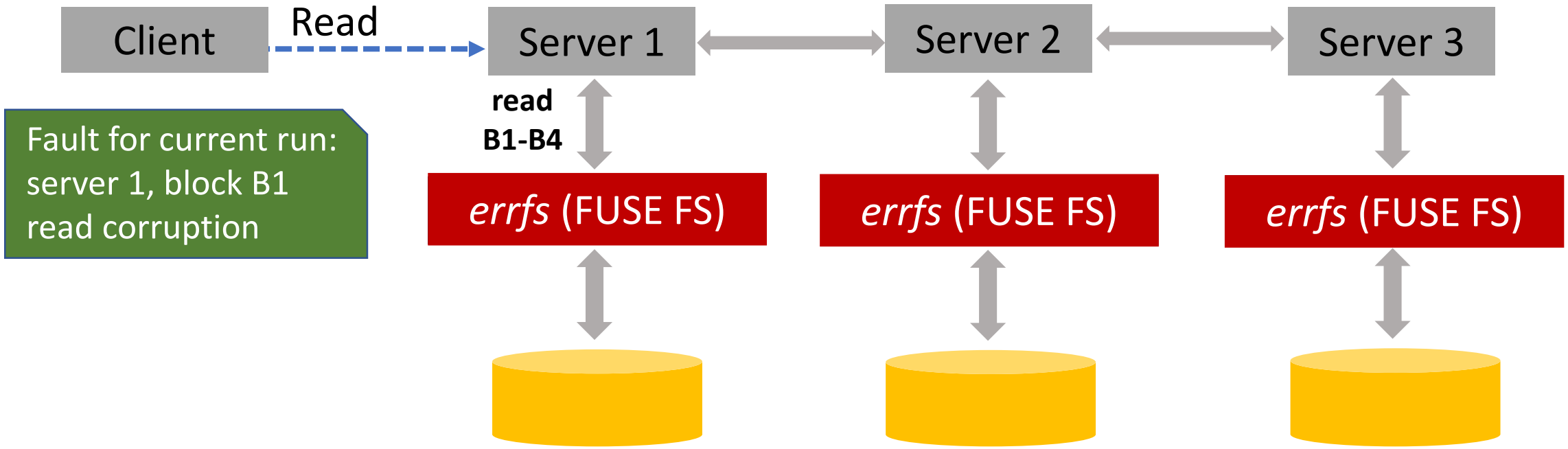

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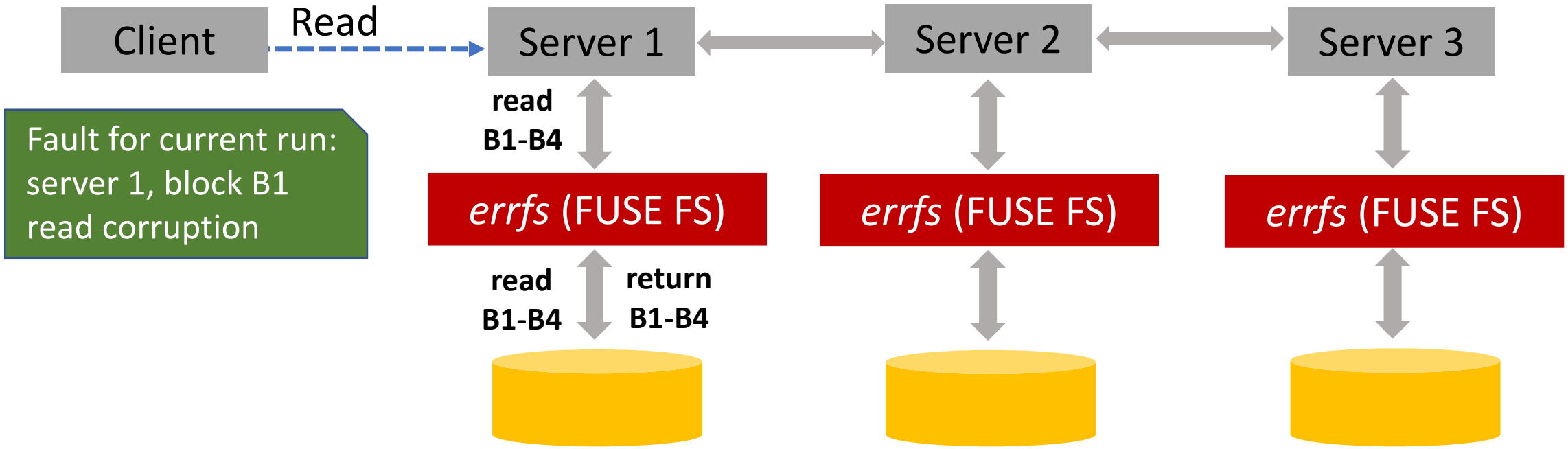

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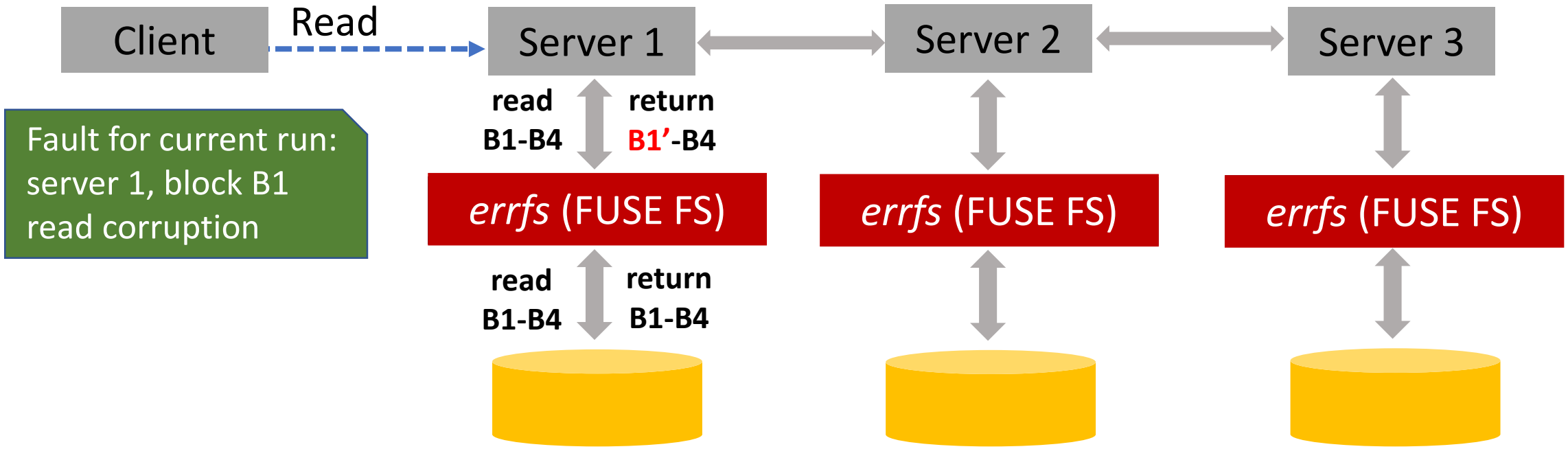

Fault Injection Methodology

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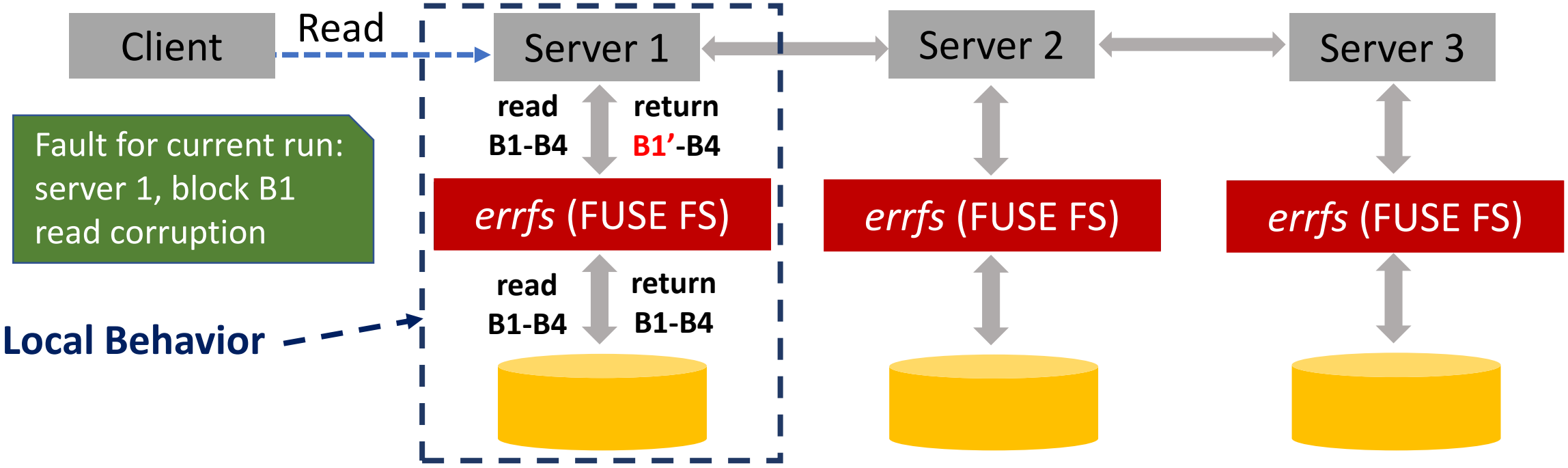

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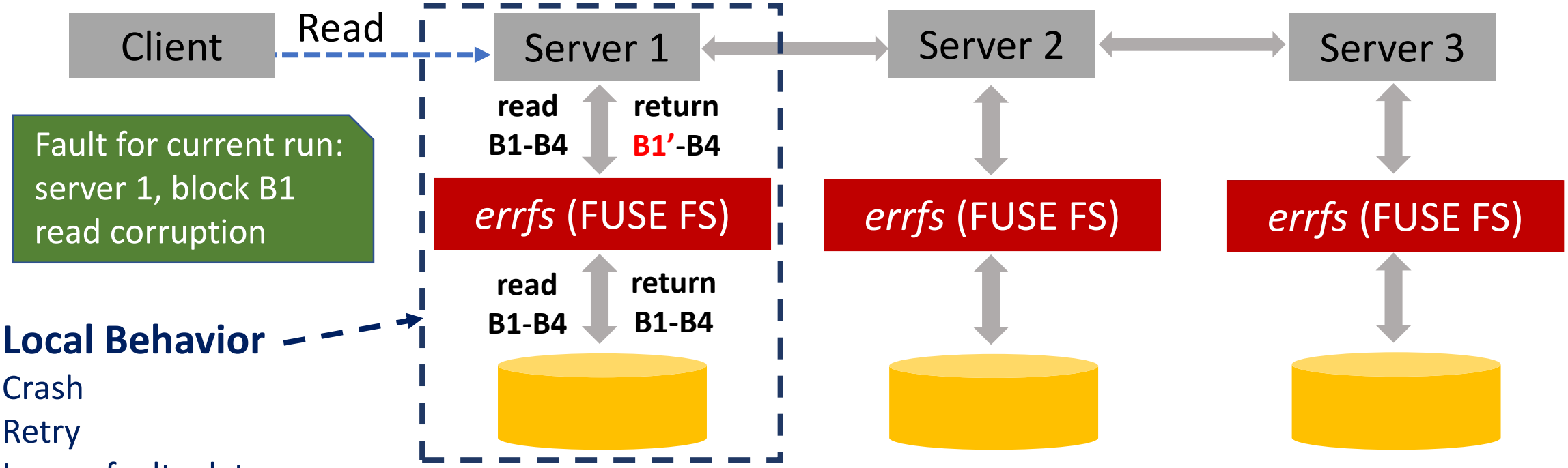

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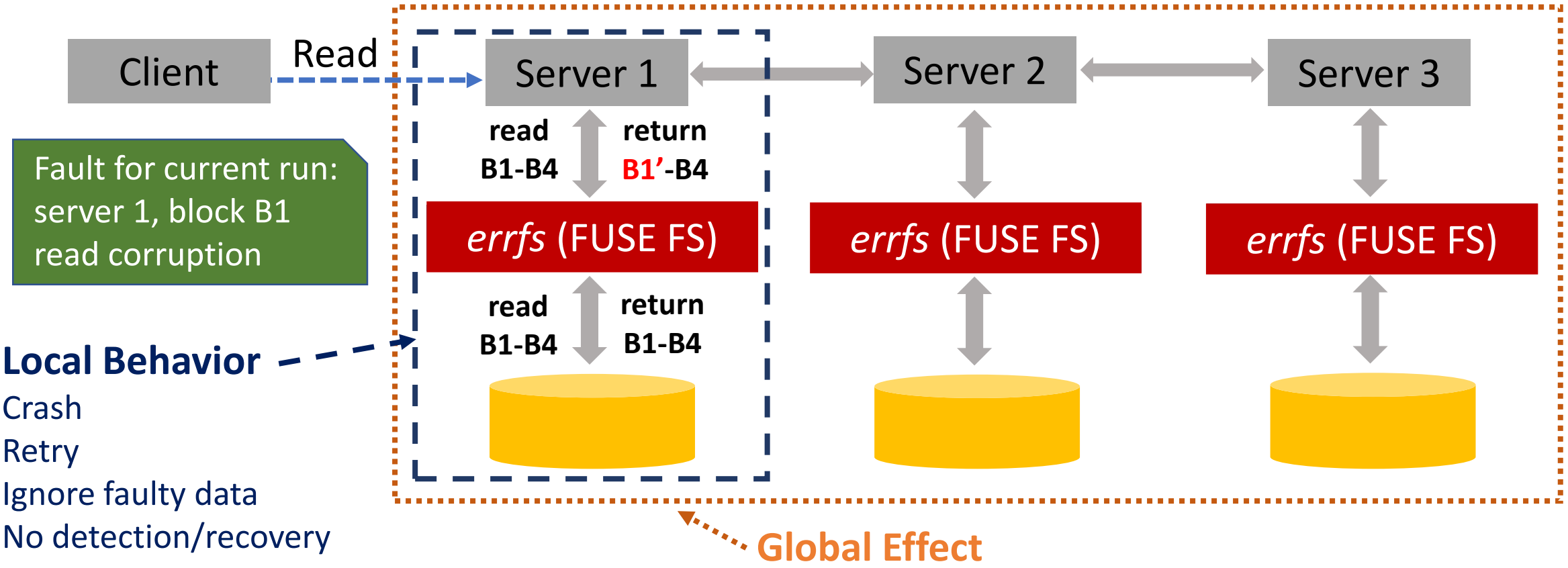

Fault Injection Methodology

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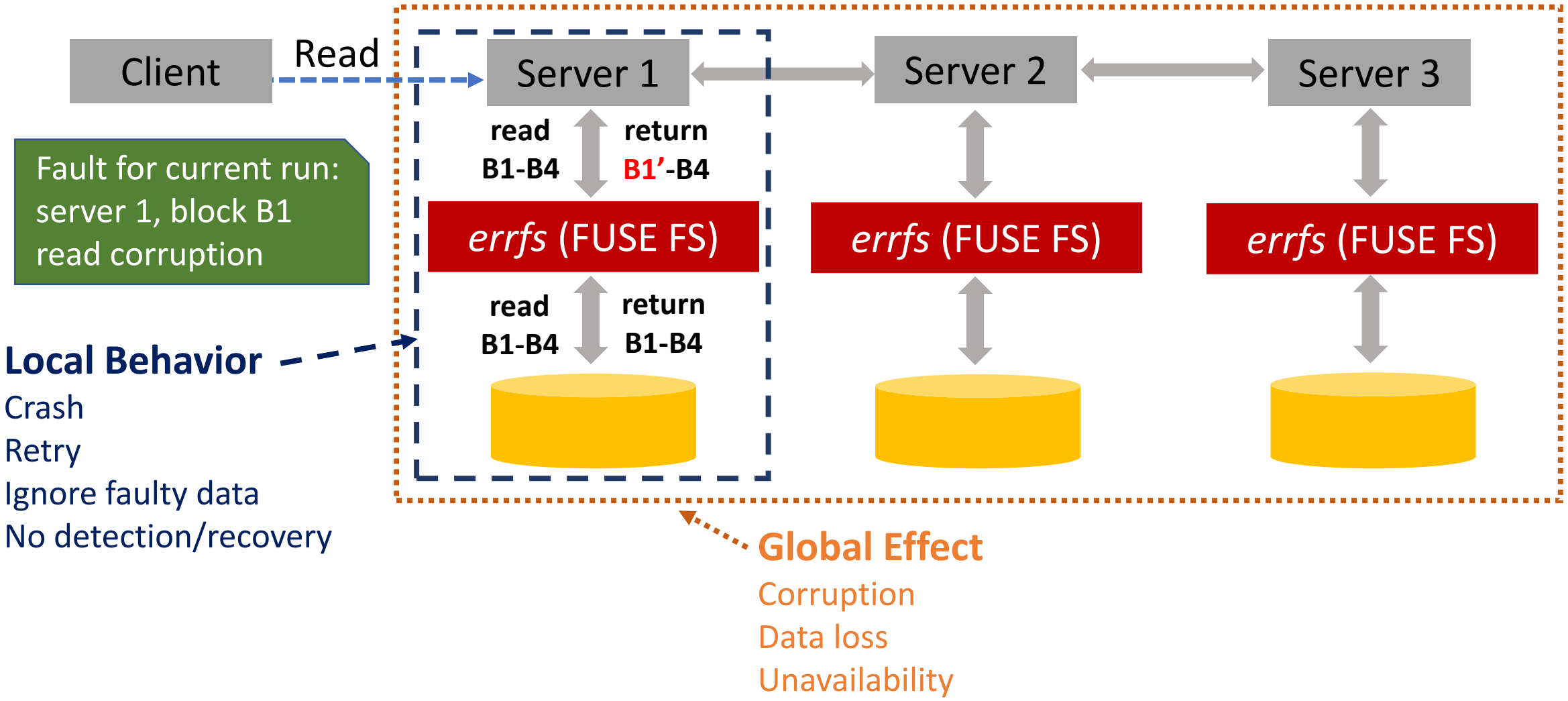

Outline

Introduction

Fault Injection

System Behavior Analysis

Major Results

Observations Across Systems

Conclusion

System Behavior Analysis

Behavior of eight distributed systems in response to file-system faults

Broad spectrum of replication and consensus protocols

Replicated state machines

- ZooKeeper (uses ZAB for consensus)
- LogCabin, CockroachDB, and RethinkDB (uses RAFT for consensus)

Primary backup replication

- MongoDB
- Redis
- Kafka (in-sync replicas for leader election)

Dynamo-style quorum

- Cassandra (decentralized, no leader/follower)

An Example: Redis

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Redis is a popular data structure store

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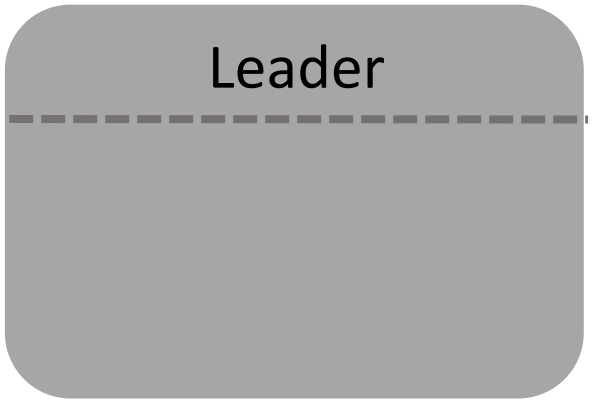

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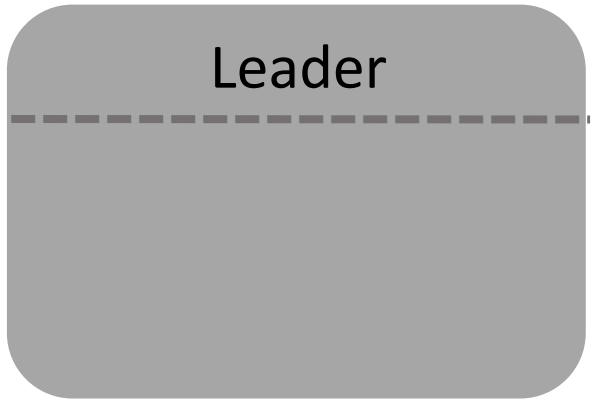

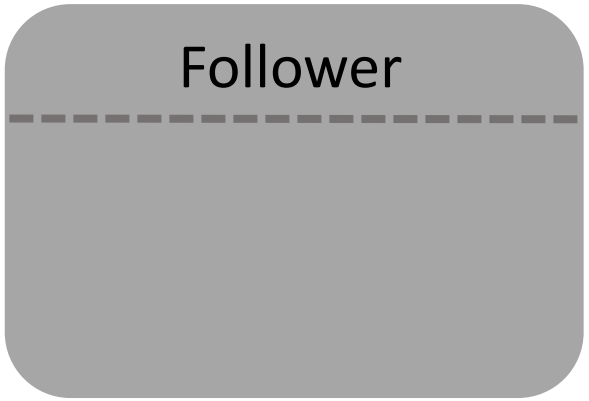

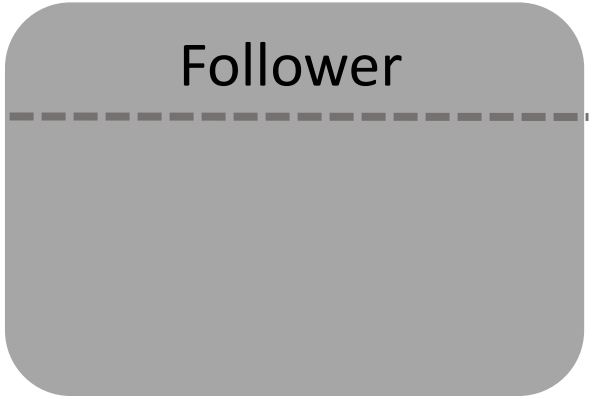

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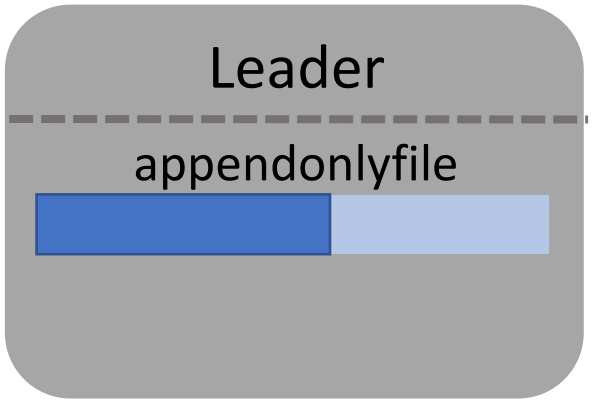

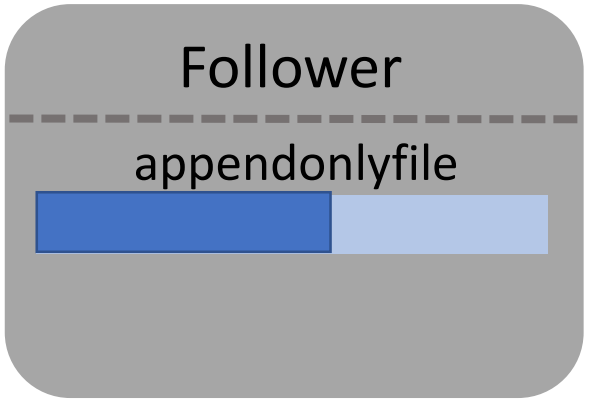

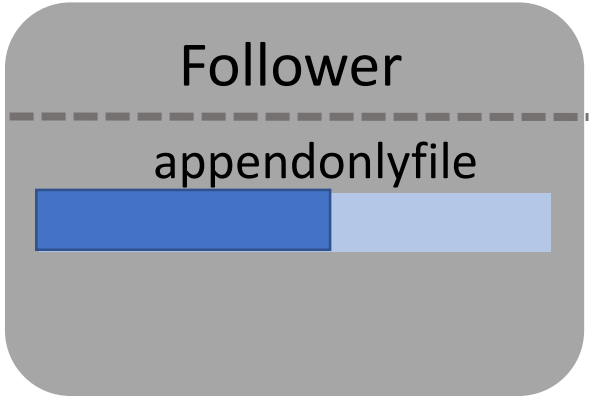

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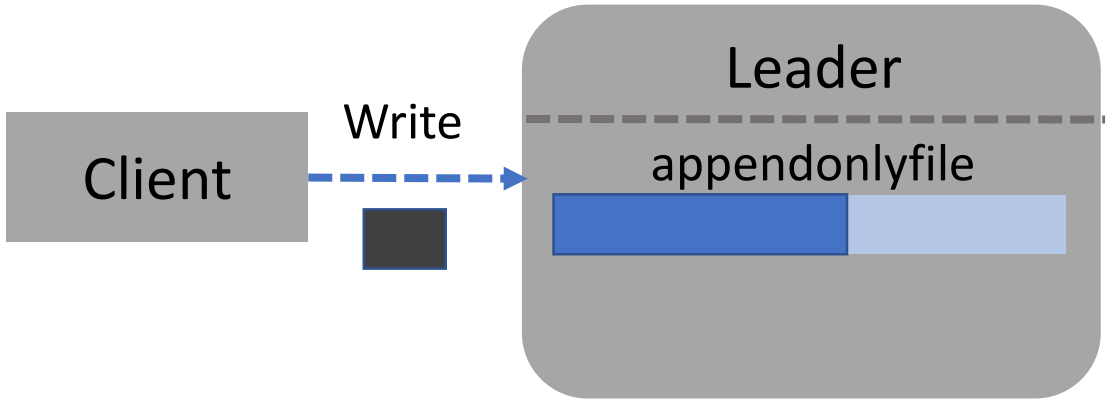

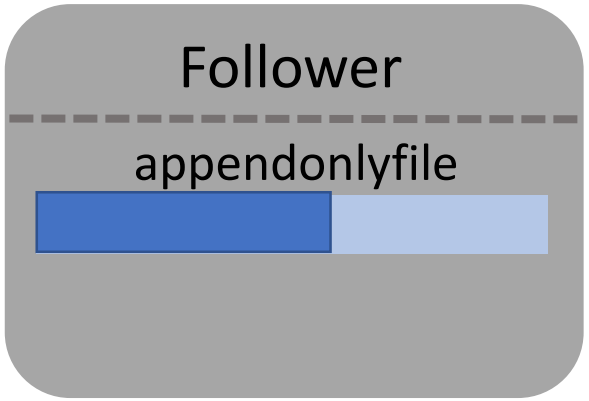

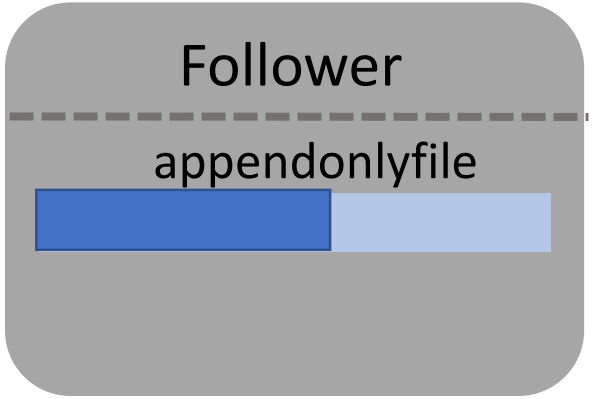

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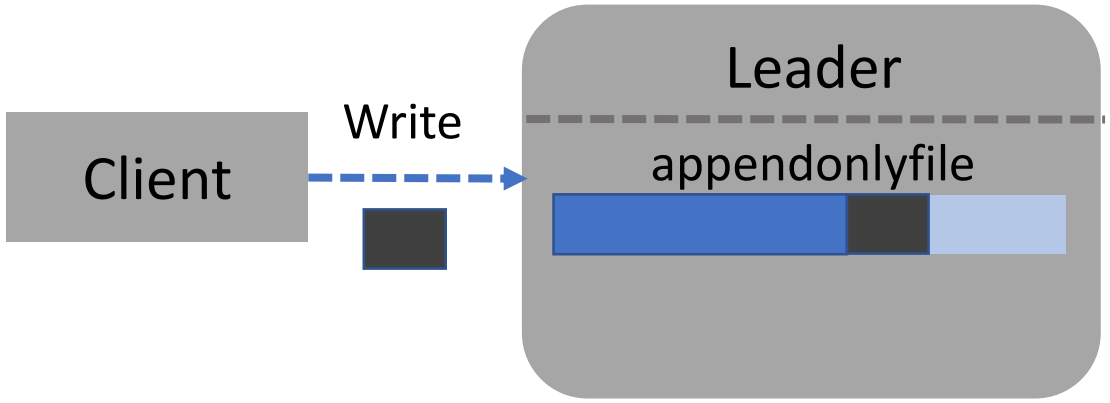

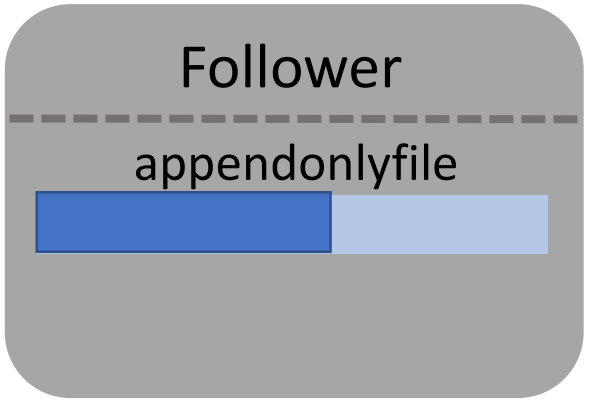

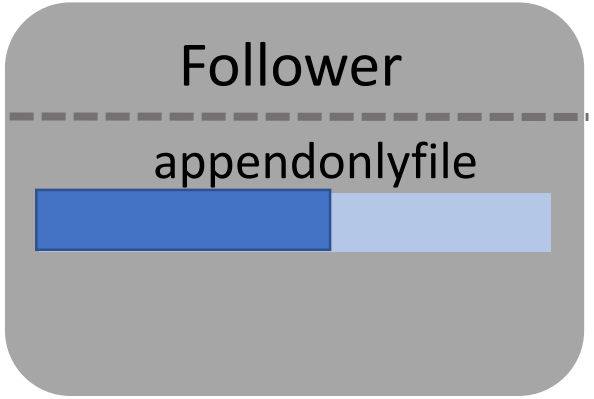

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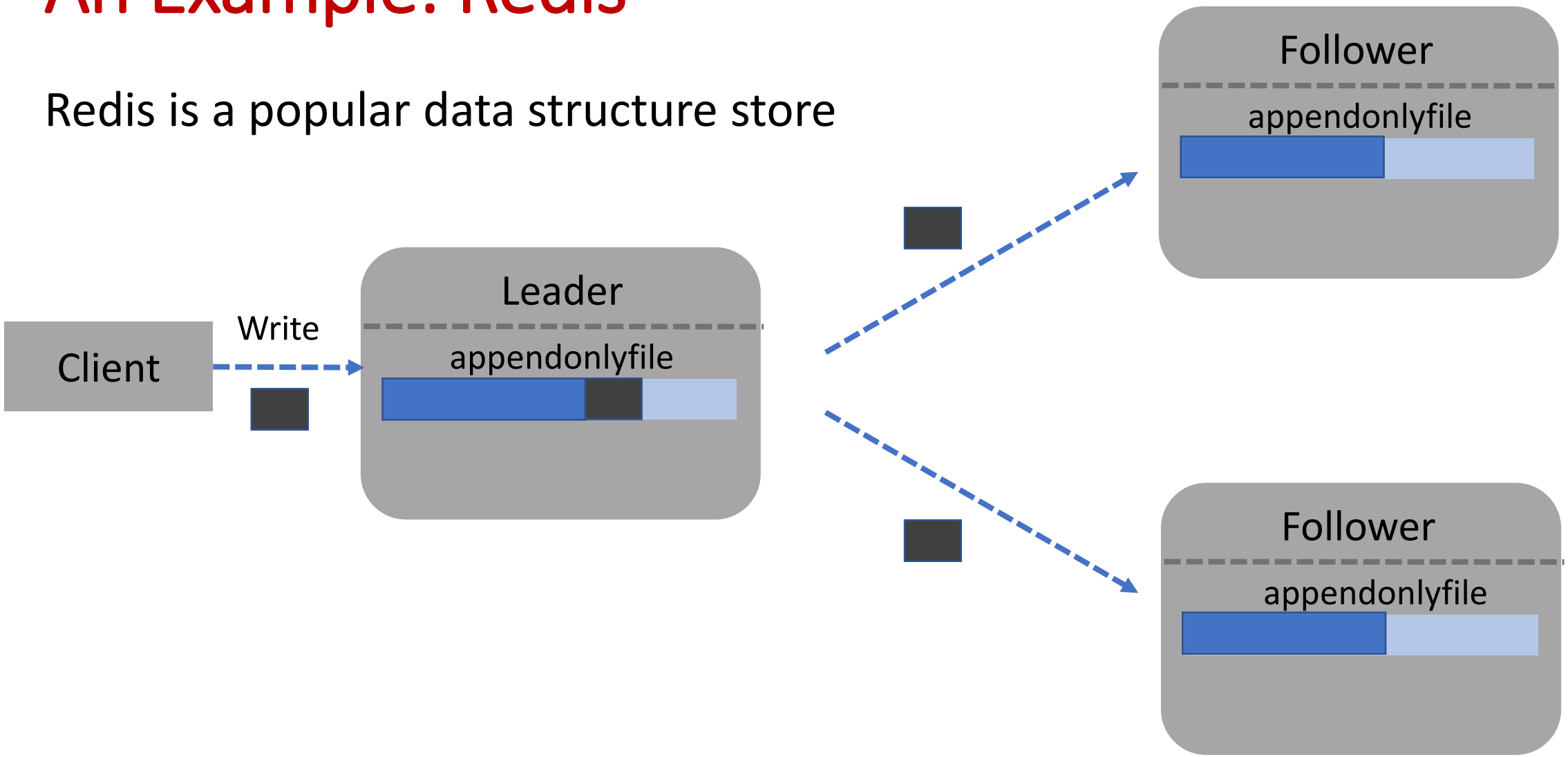

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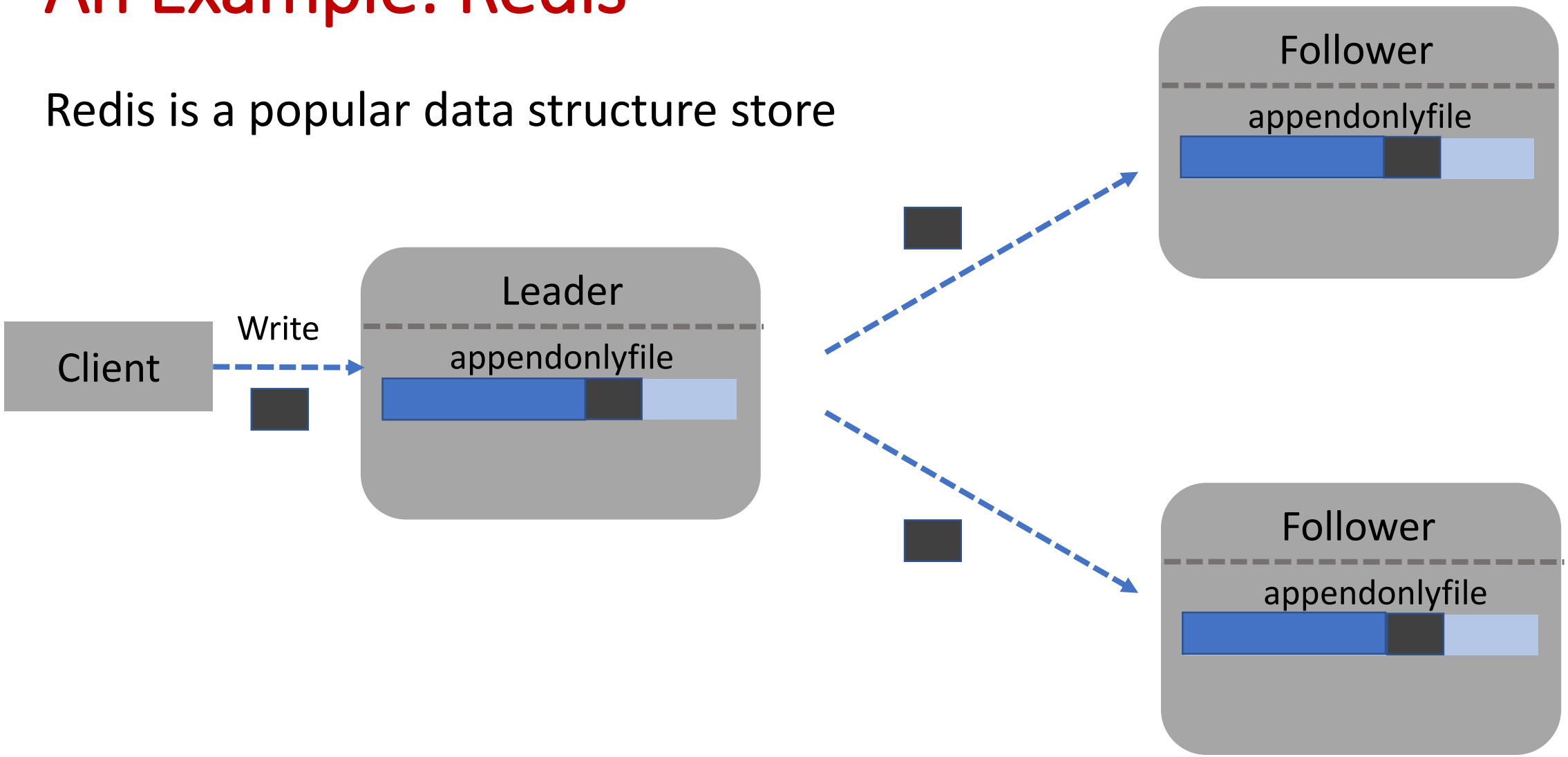

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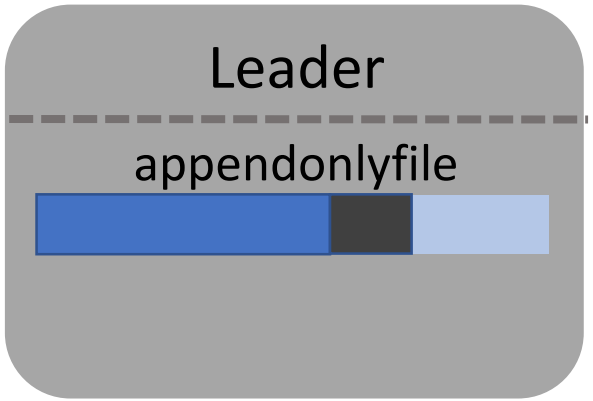

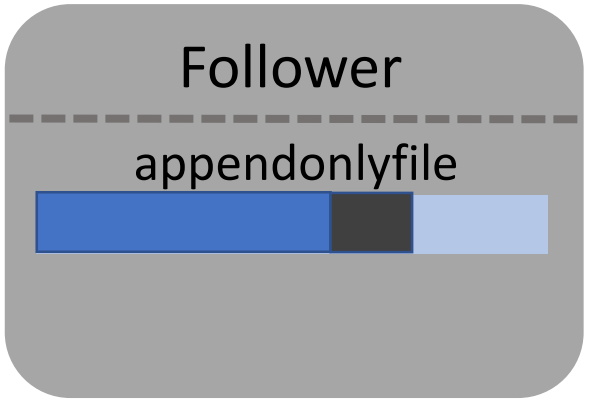

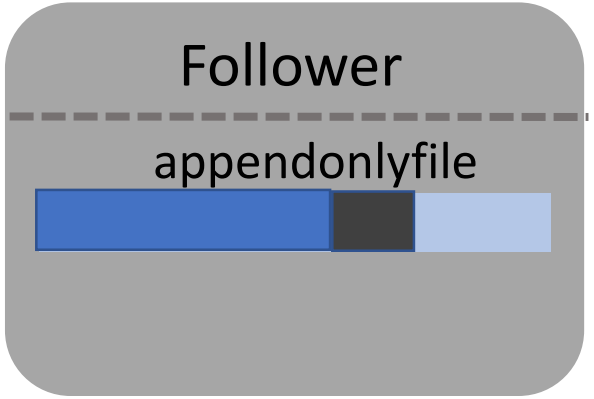

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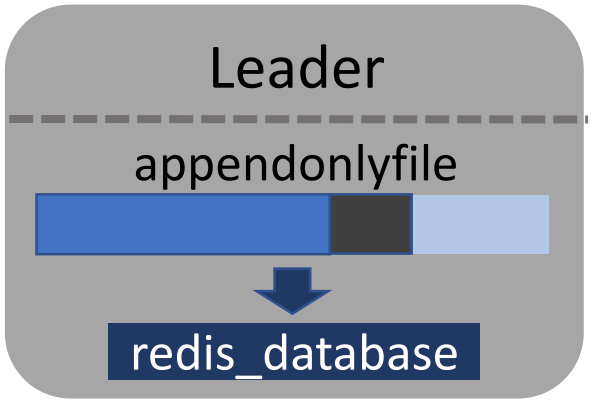

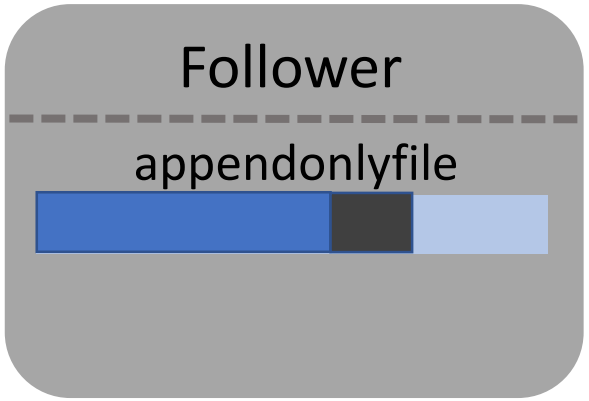

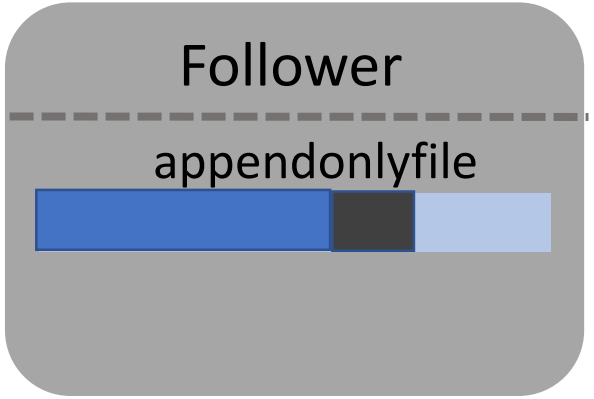

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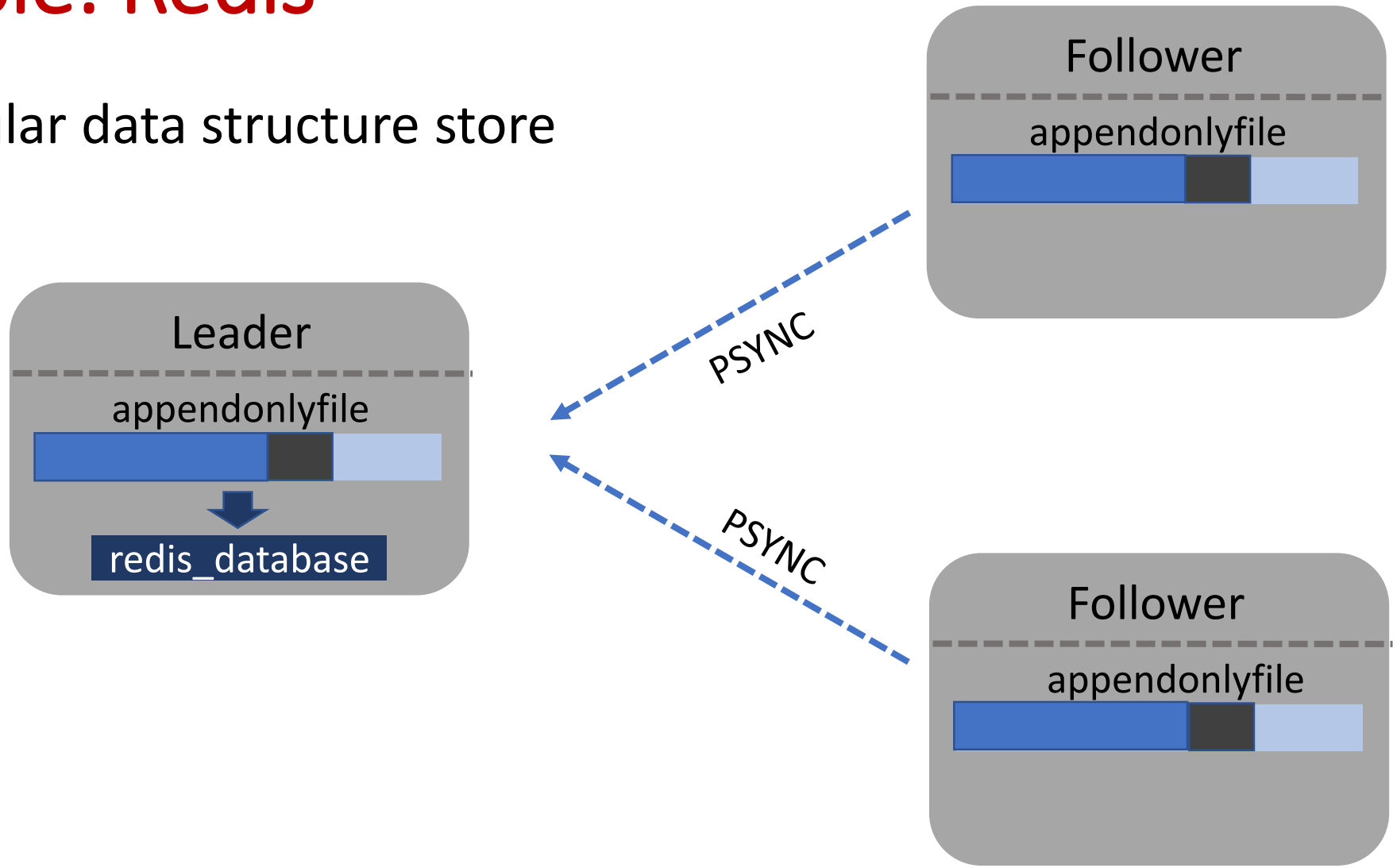

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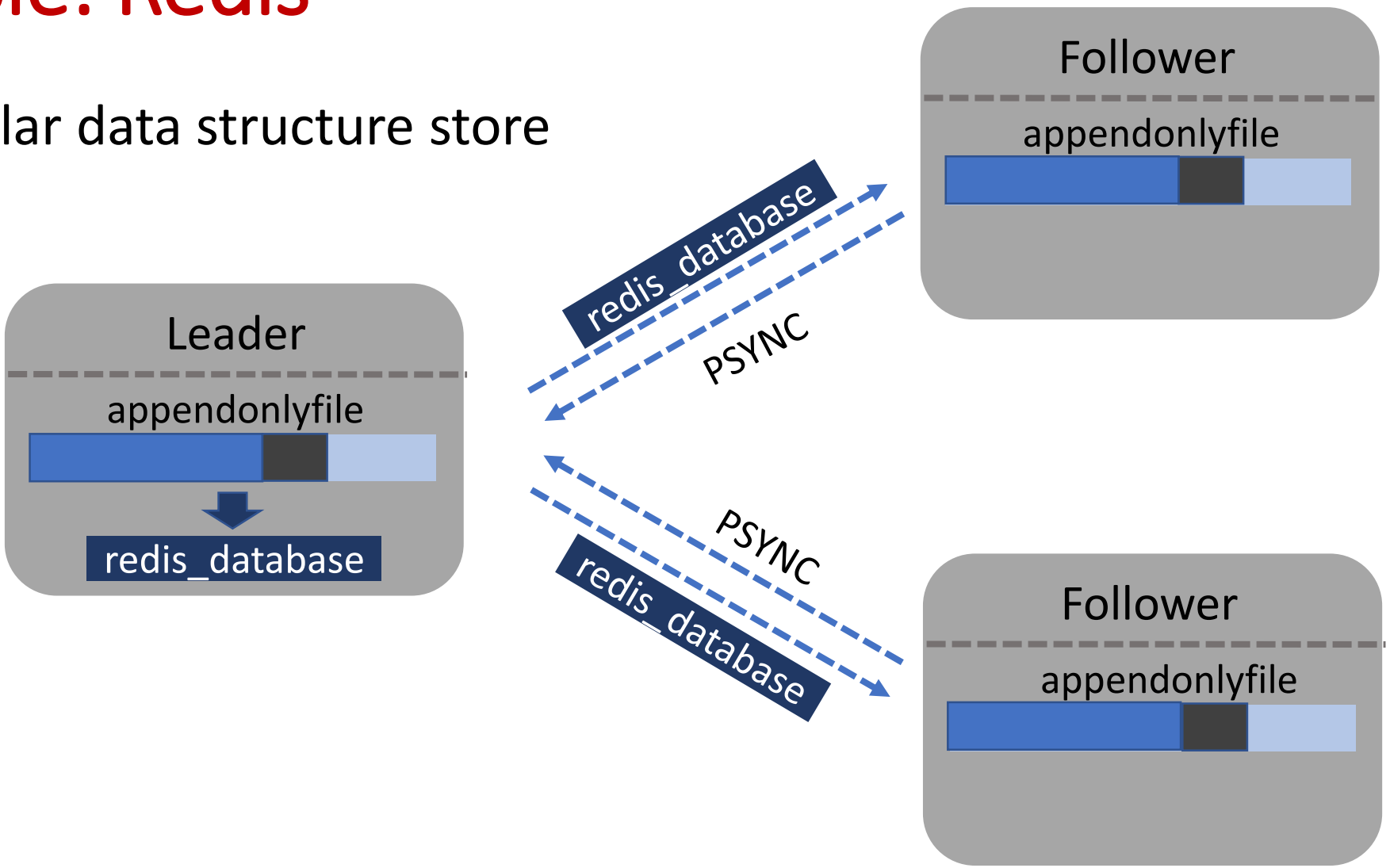

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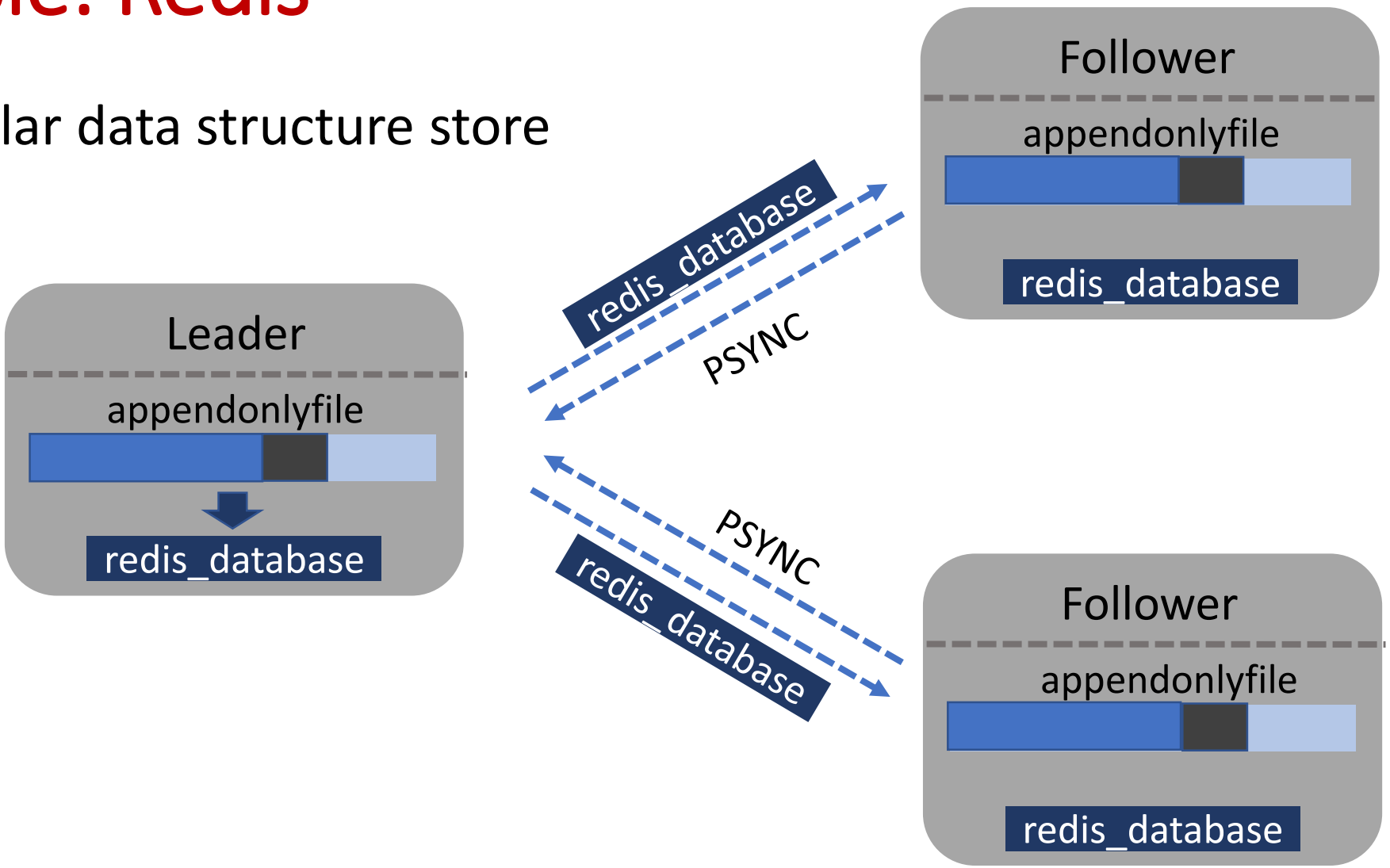

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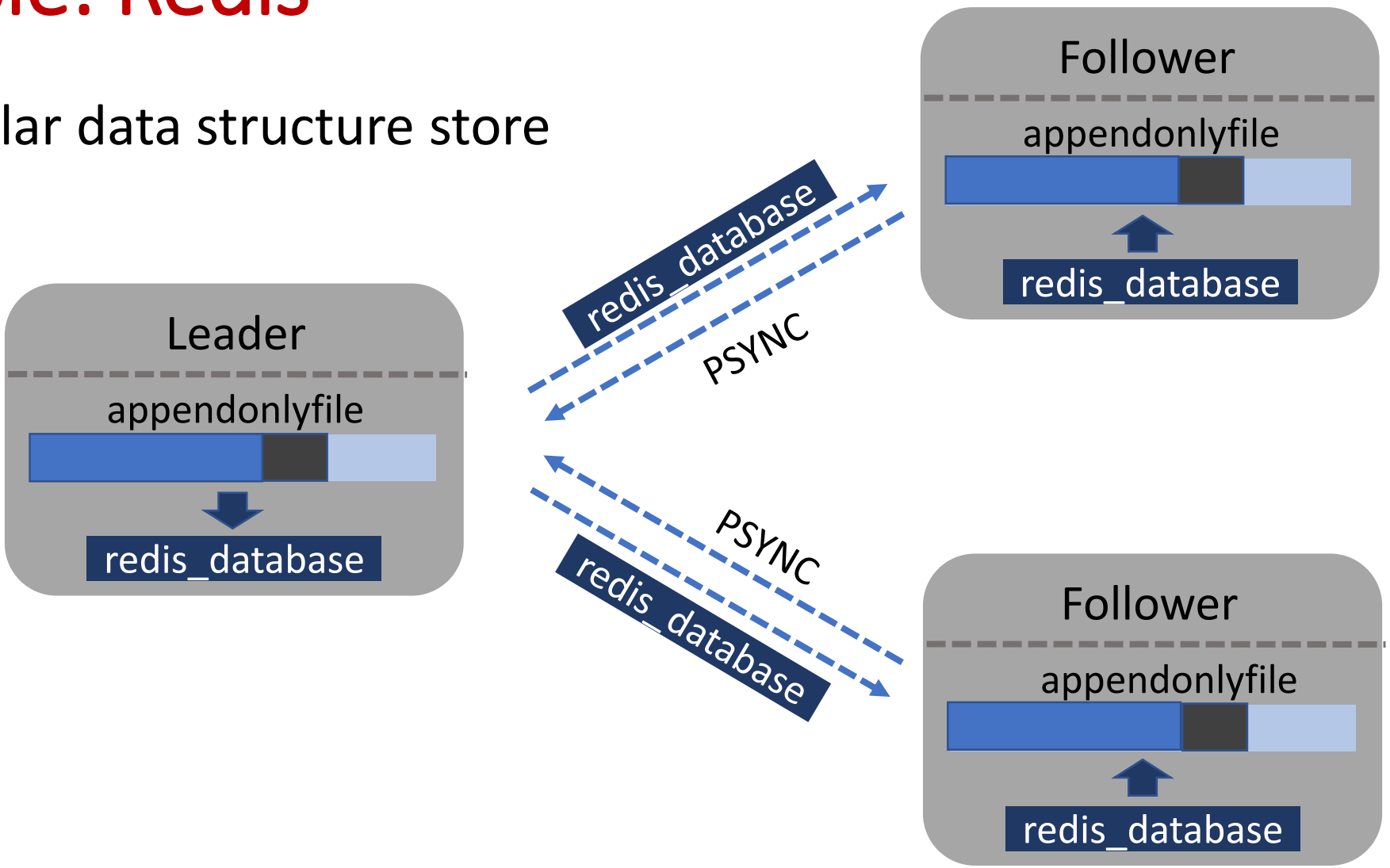

Redis: Behavior Analysis

Redis: Behavior Analysis

Read Workload

Redis: Behavior Analysis

Read Workload

Local Behavior

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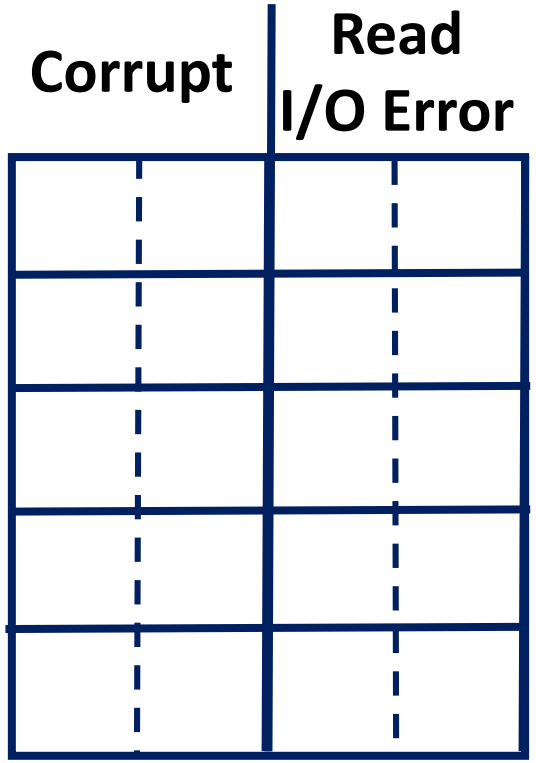

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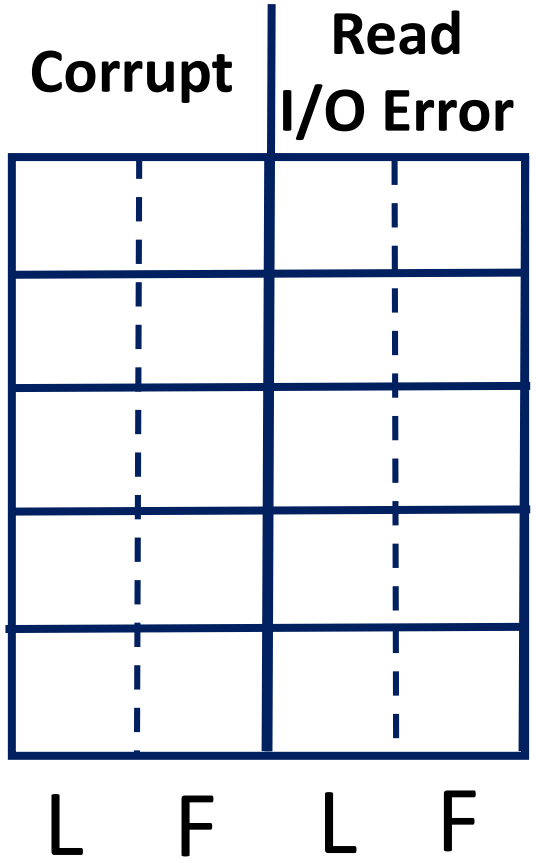

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L Leader

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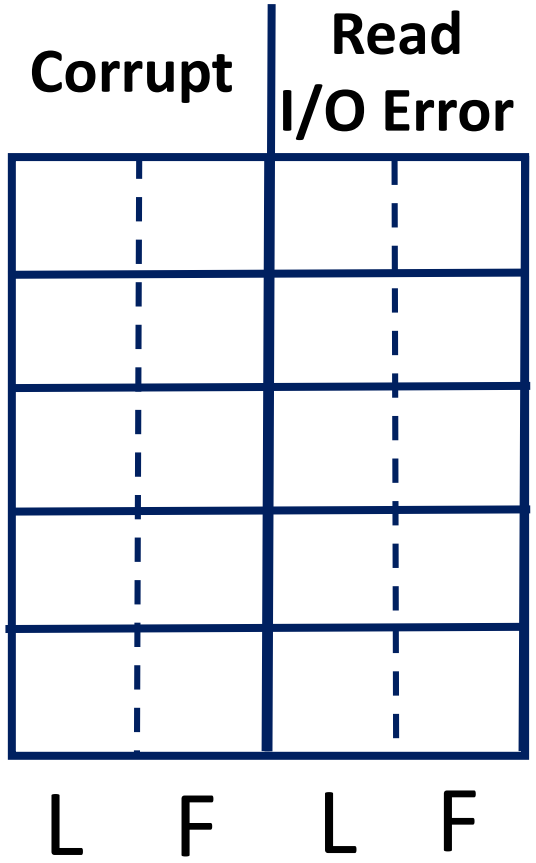

Redis: Behavior Analysis

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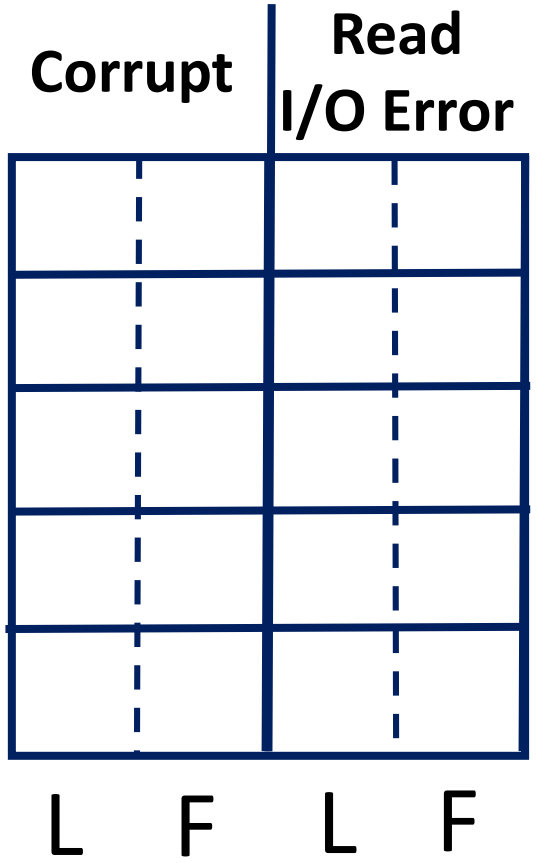

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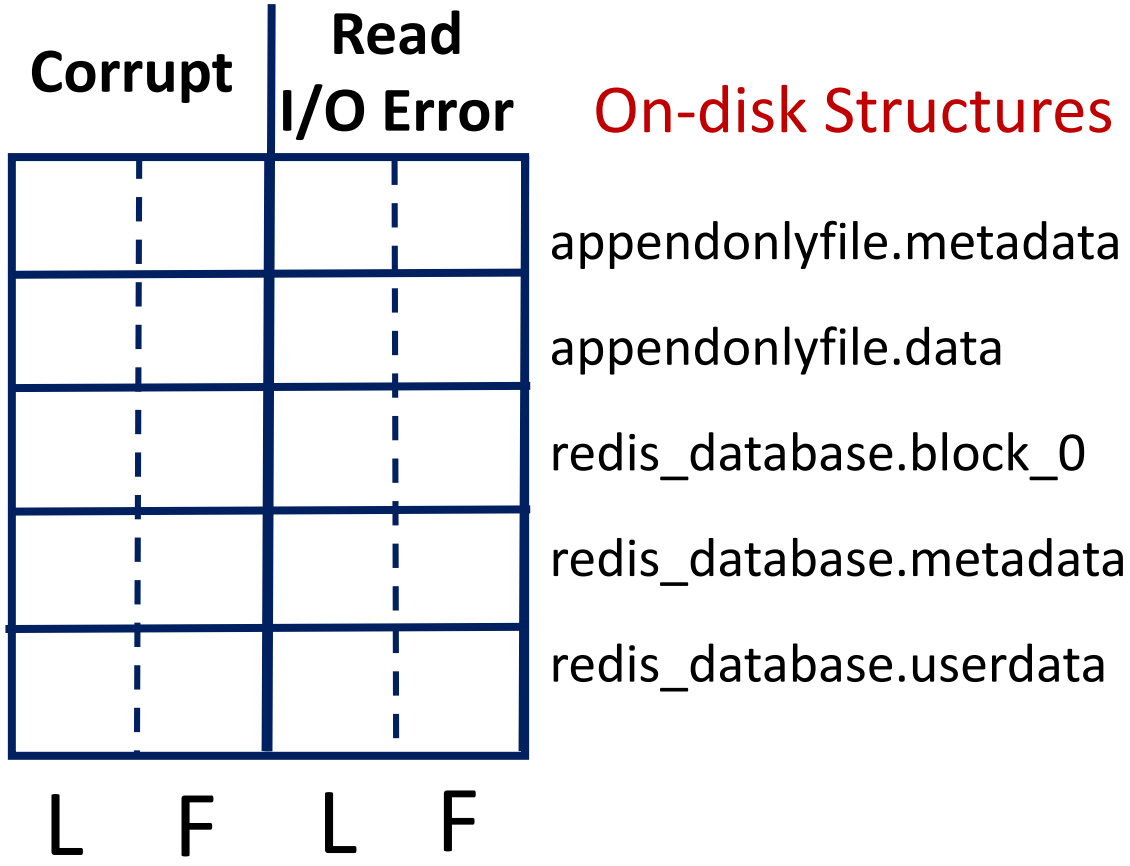

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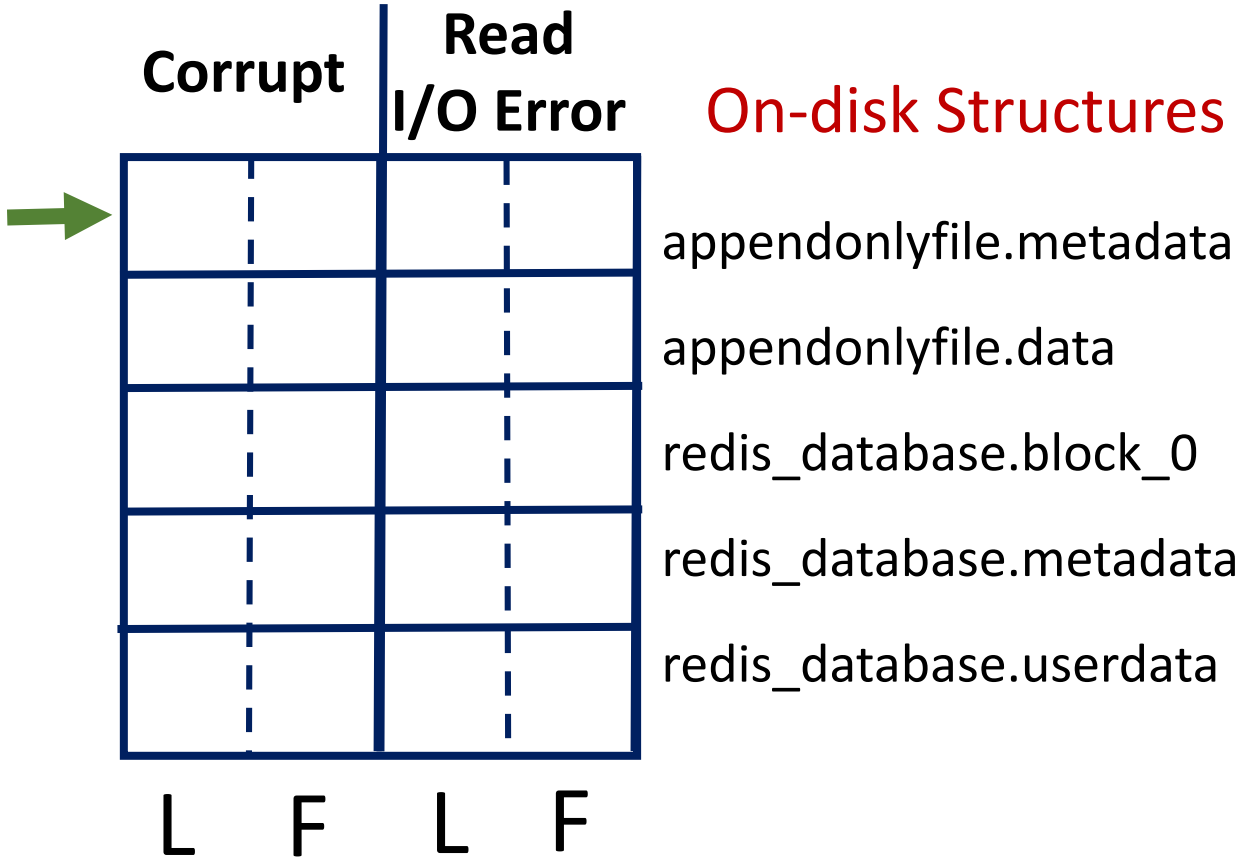

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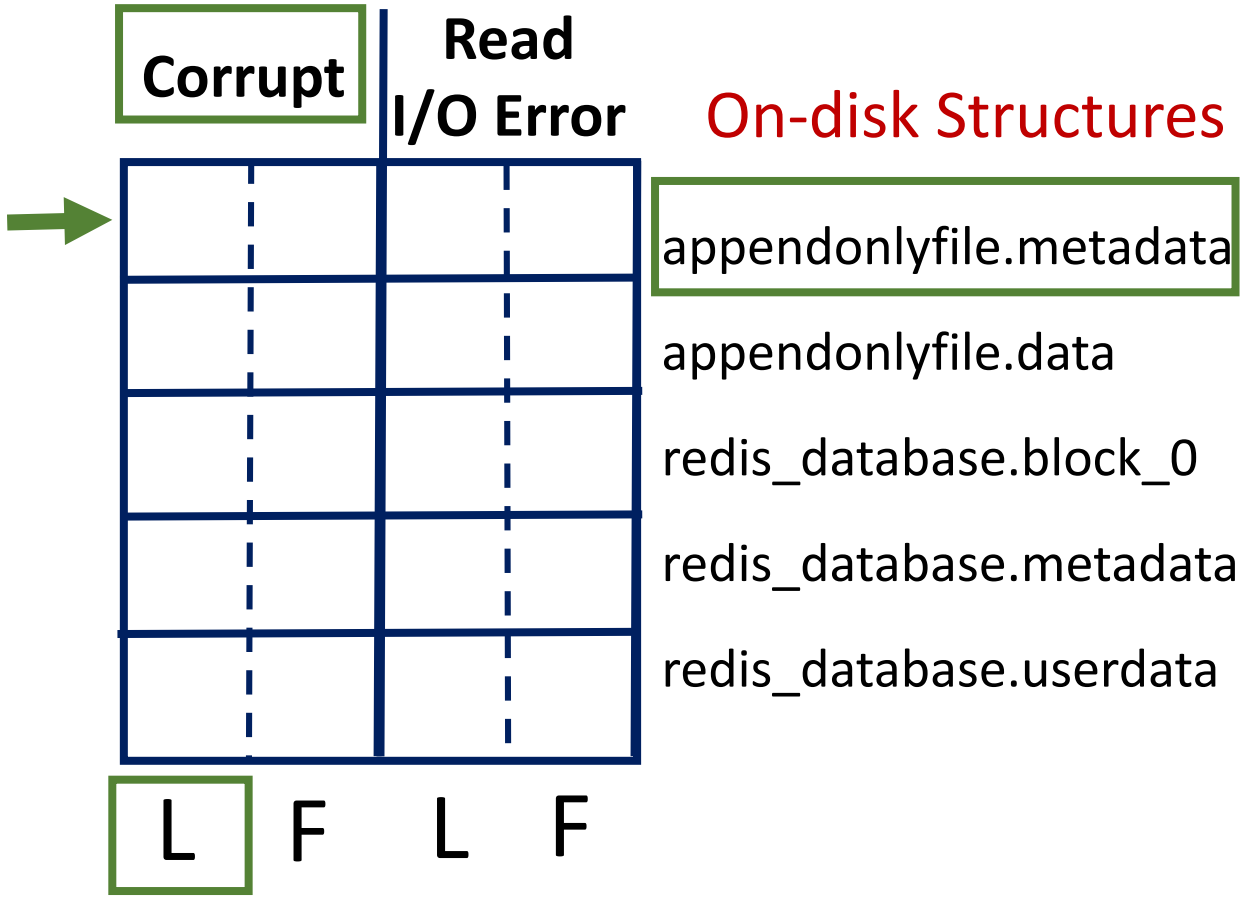

Redis: Behavior Analysis

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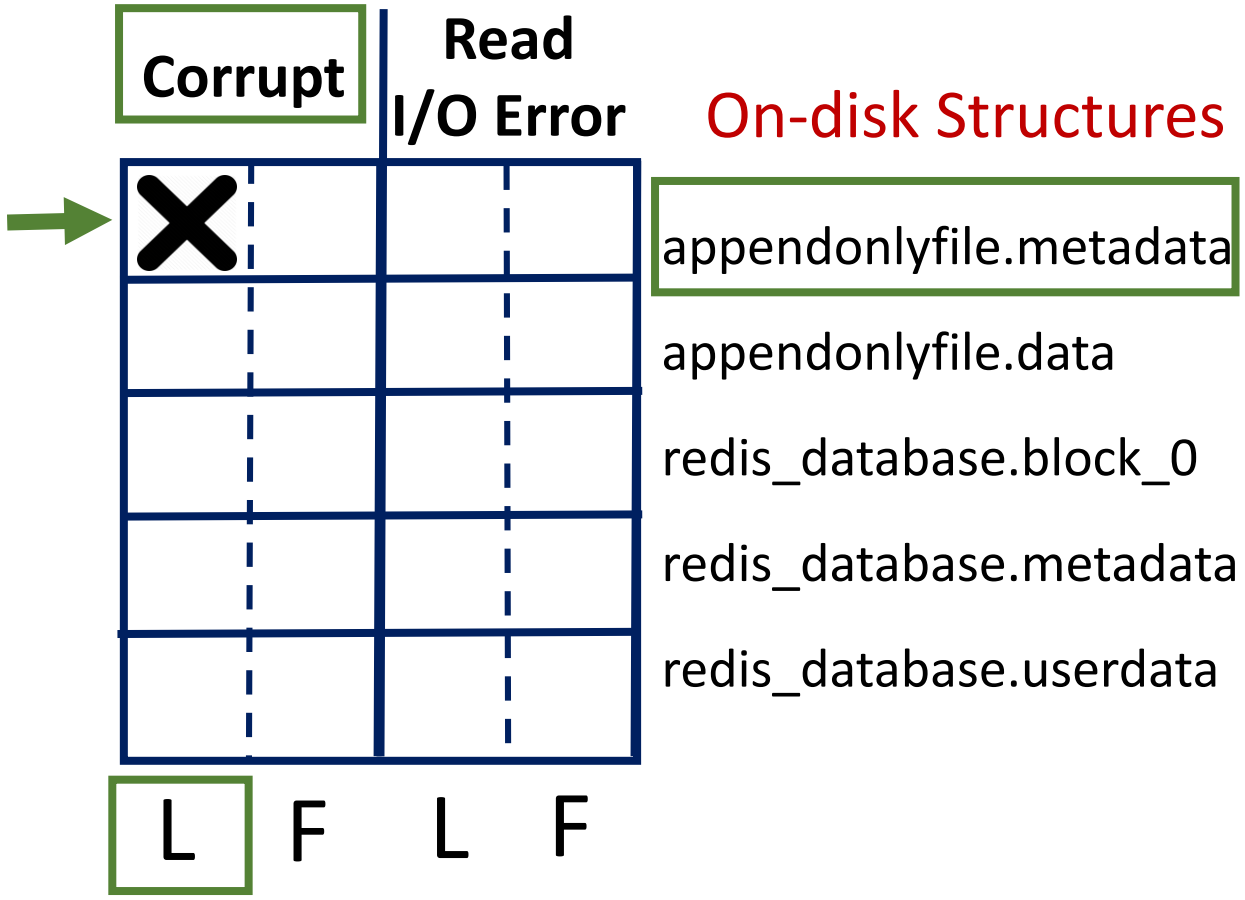
Local Behavior

Crash

Read Workload

Local Behavior



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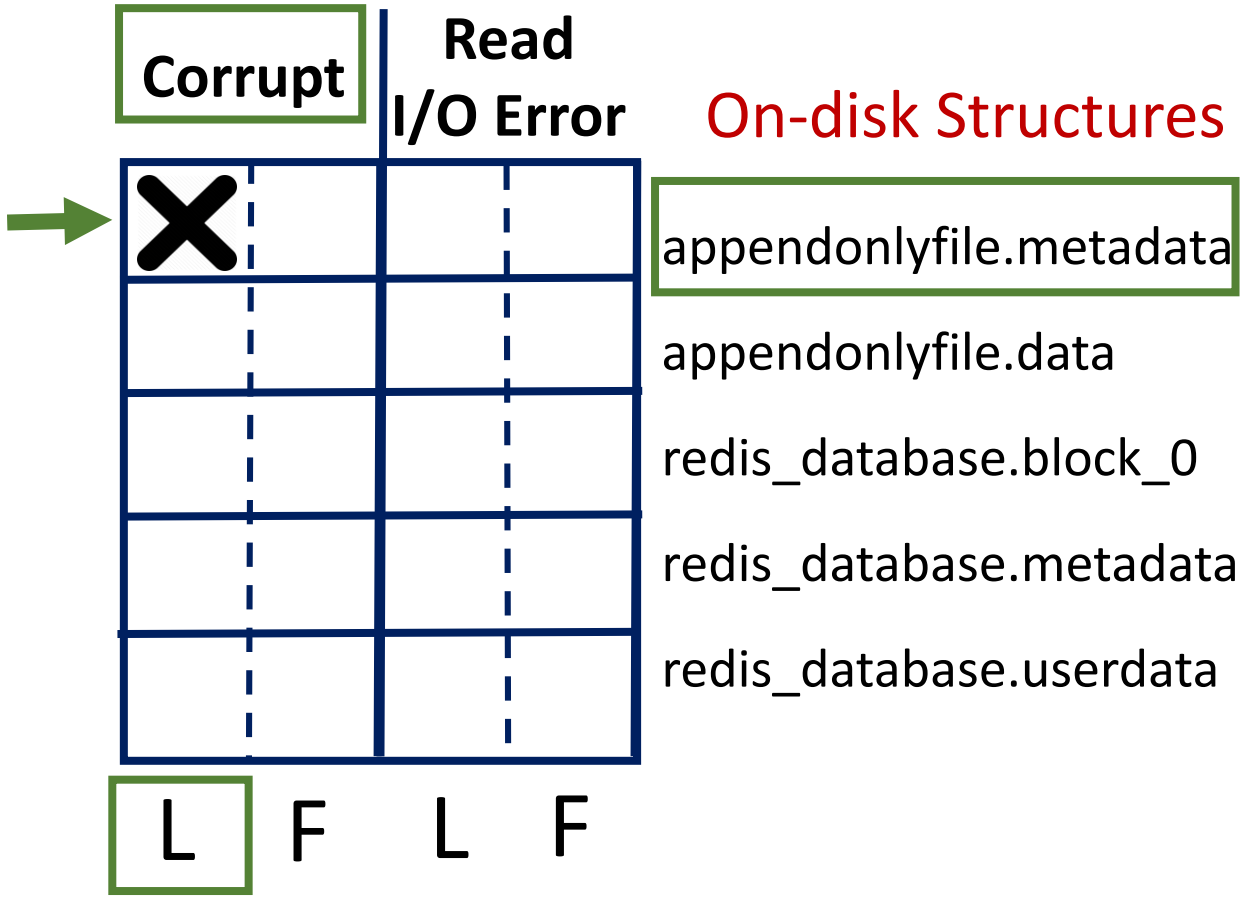
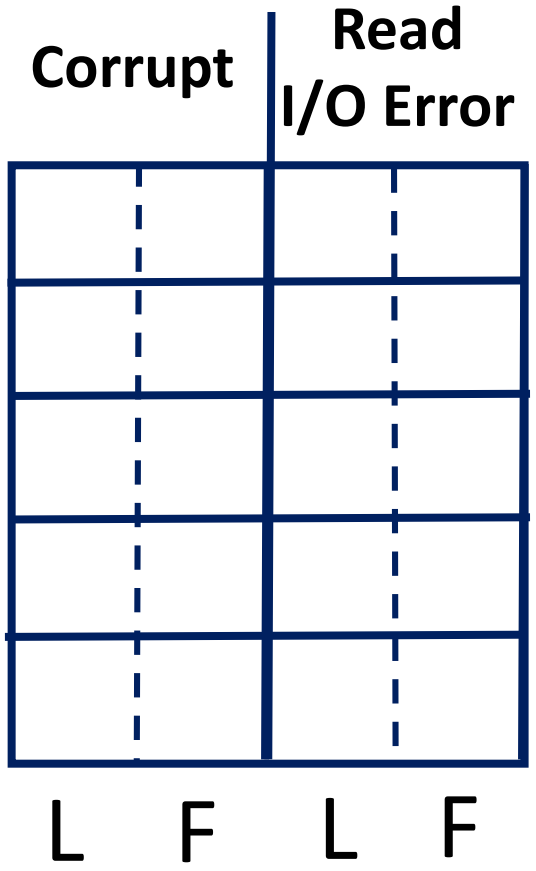


Global Effect



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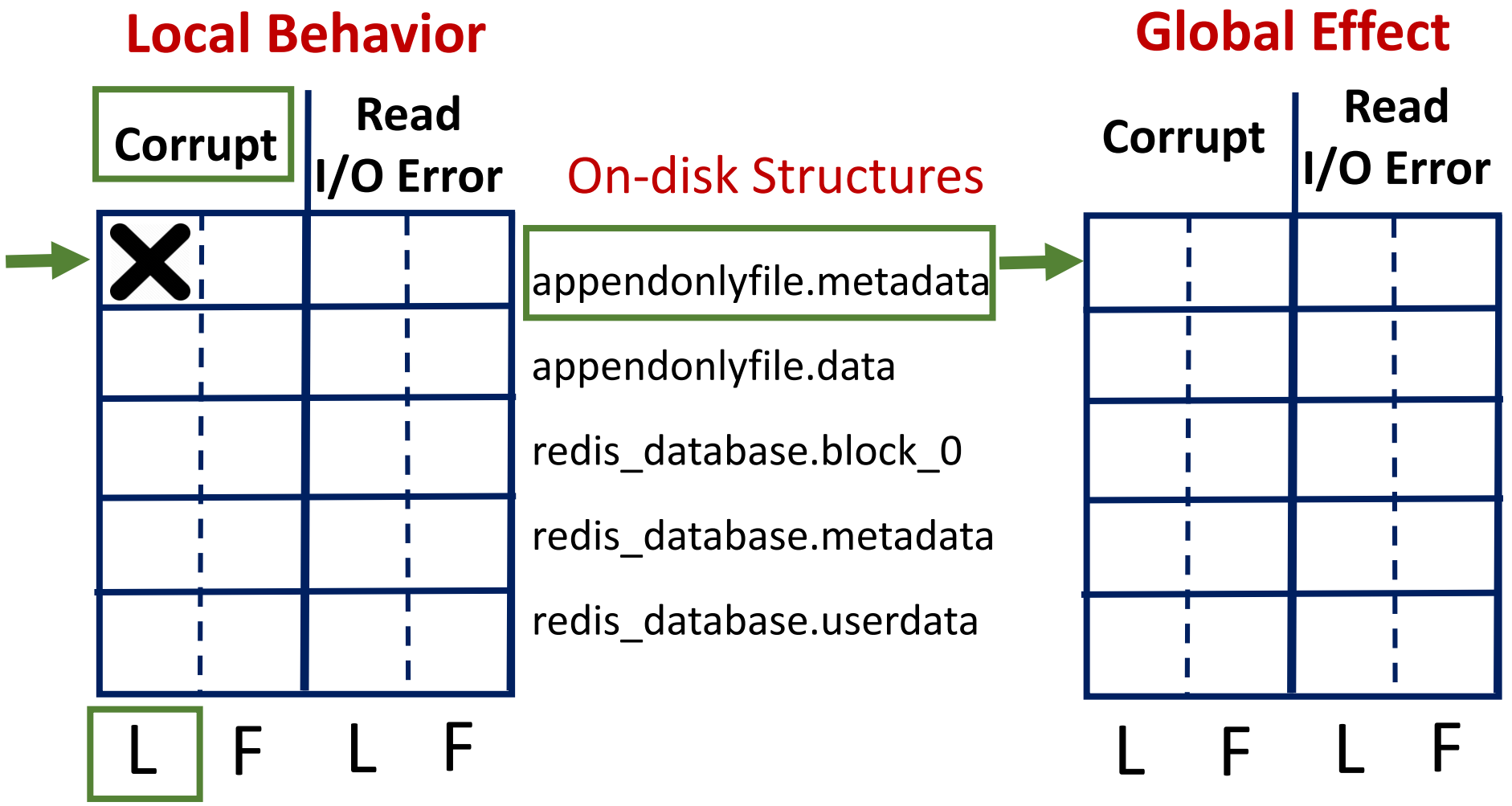

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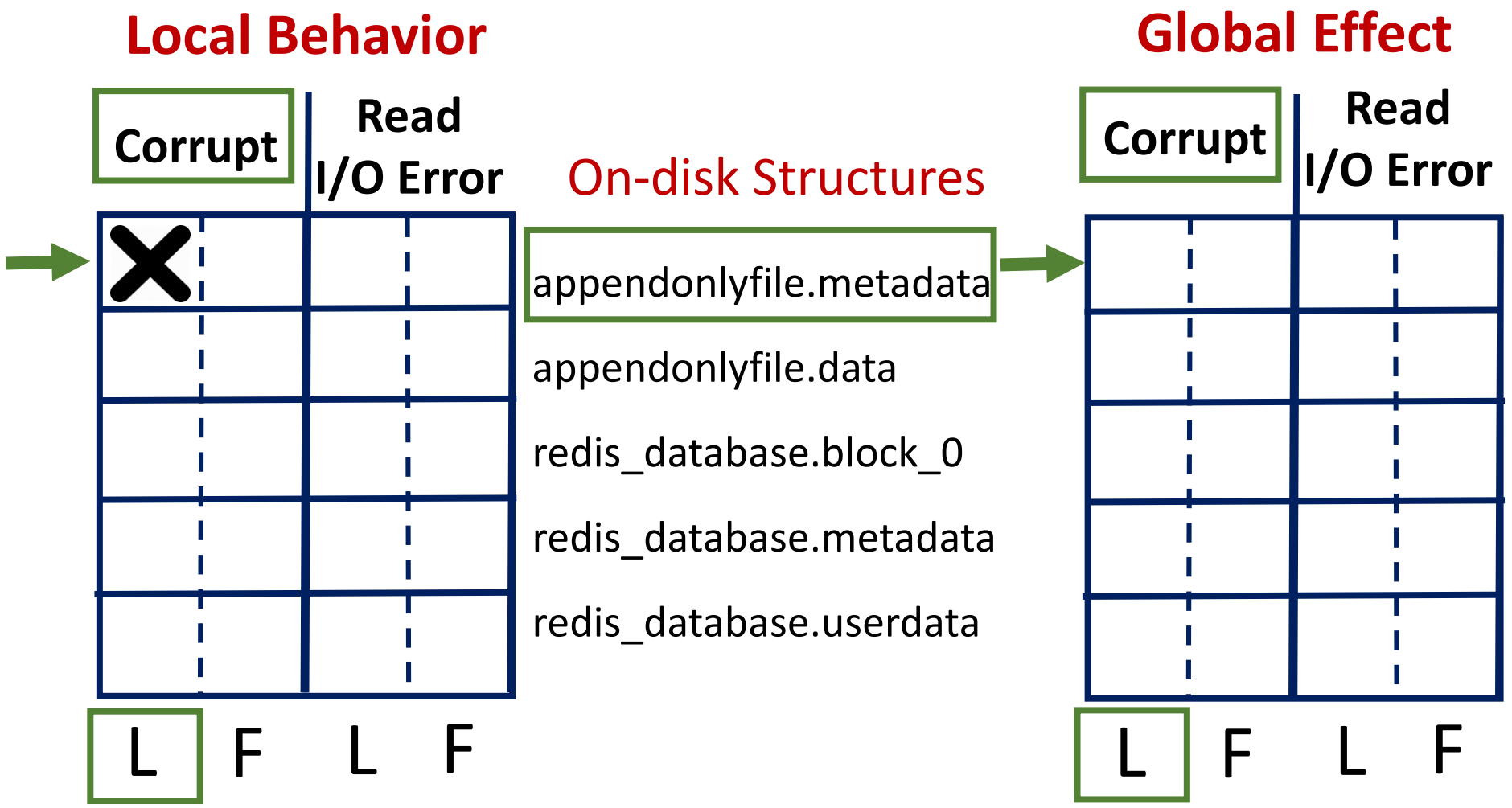

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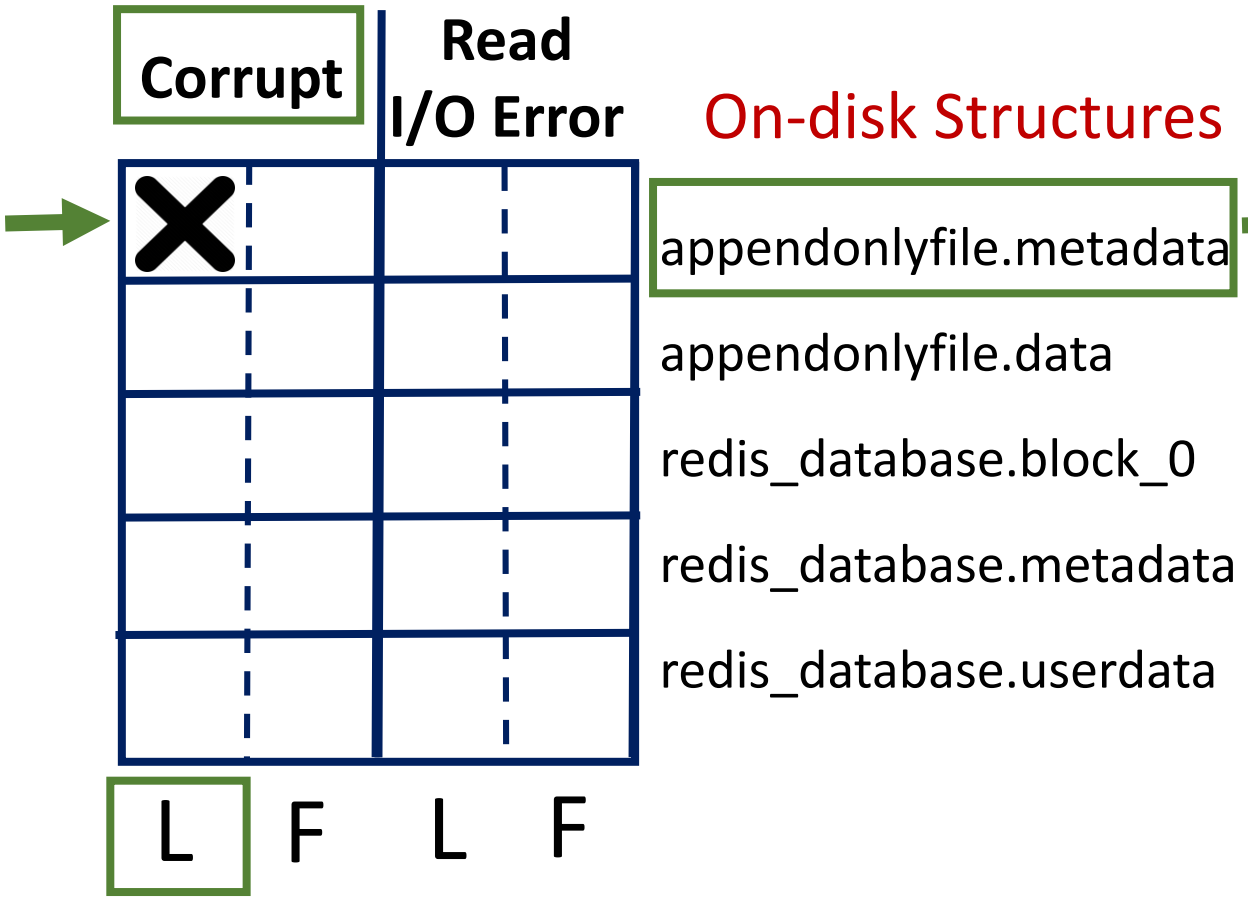

On-disk Structures

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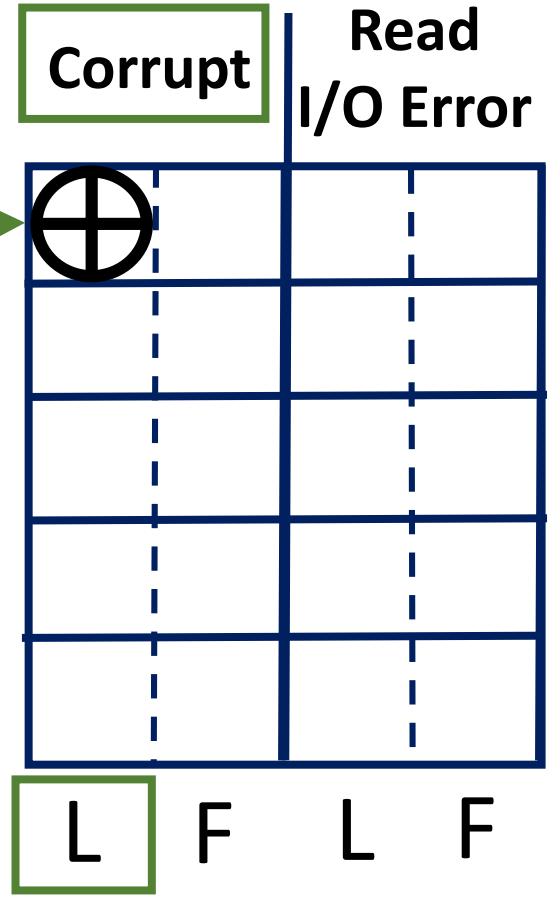
- appendonlyfile.data
- redis_database.block_0
- redis_database.metadata
- redis_database.userdata

Global Effect



Local Behavior

Crash

Global Effect

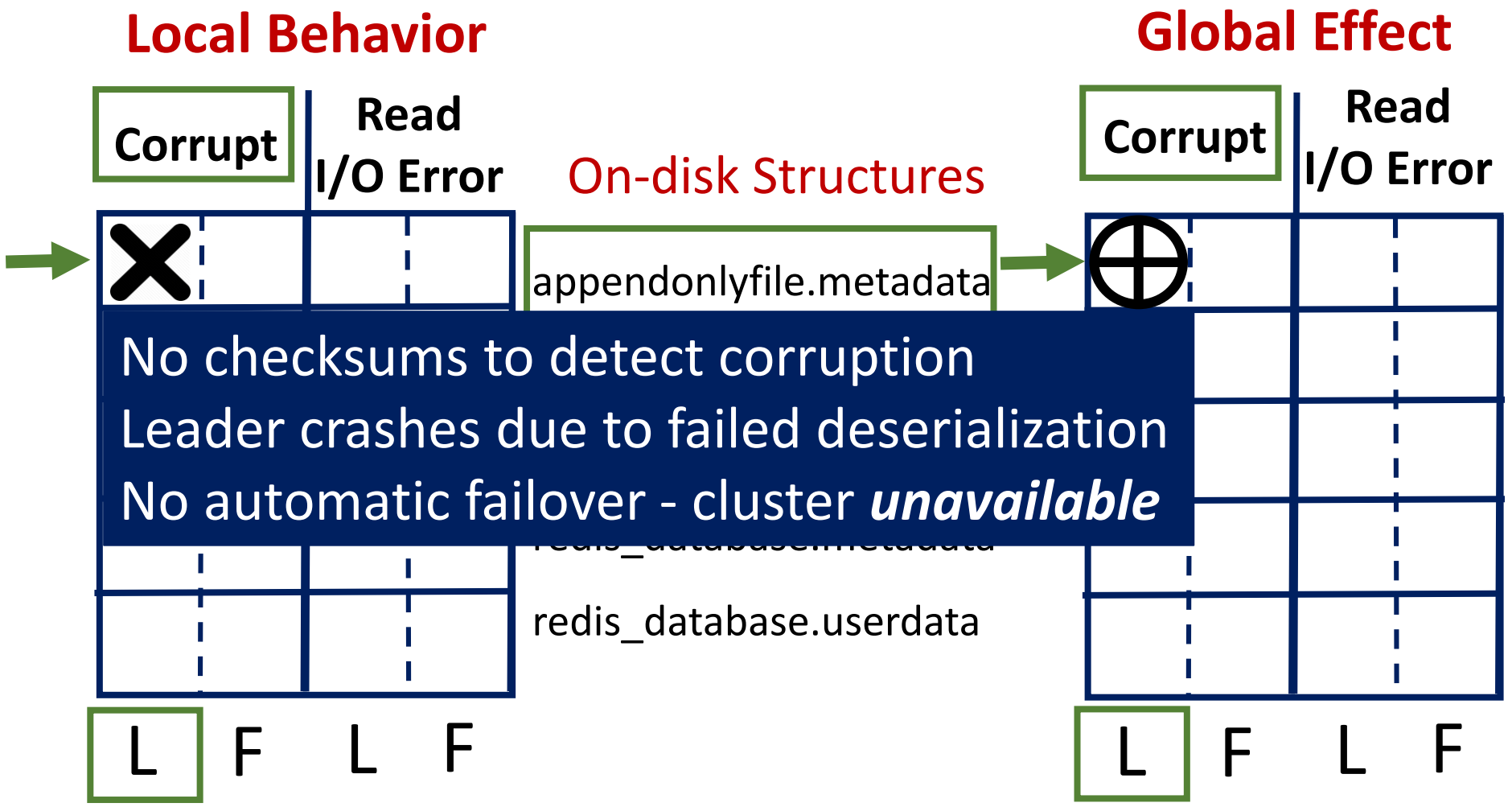
Unavailability

Redis: Behavior Analysis

Read Workload

L Leader

F Follower



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Read Workload

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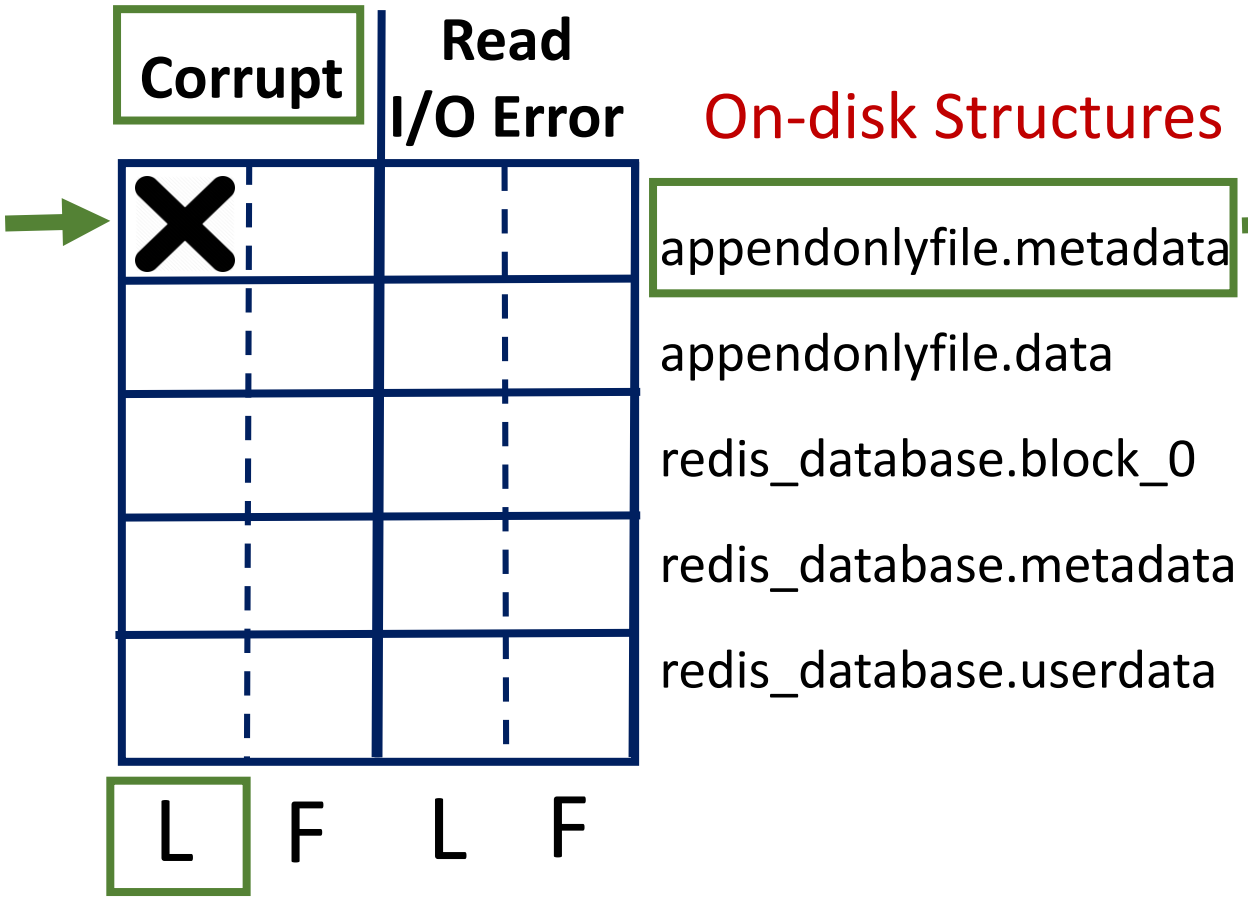

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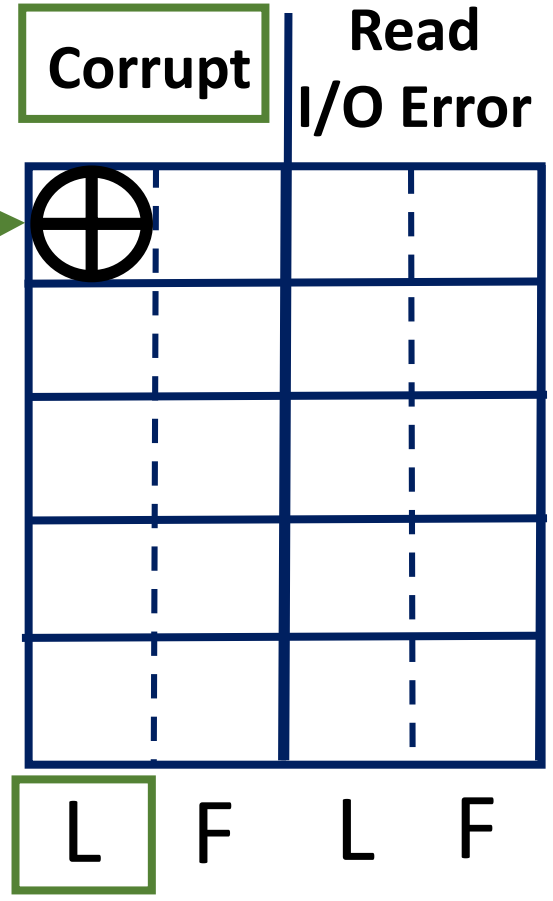

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Read Workload

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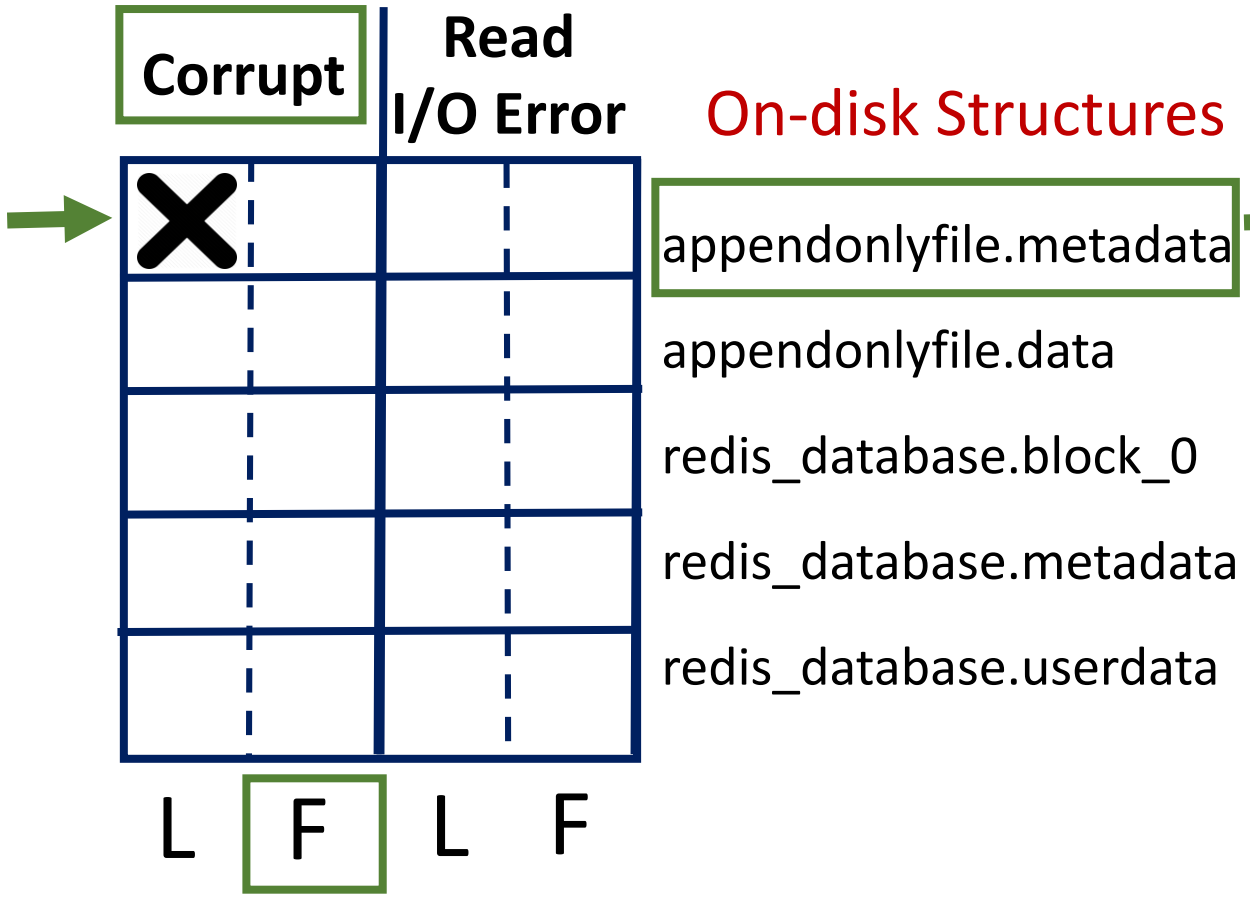

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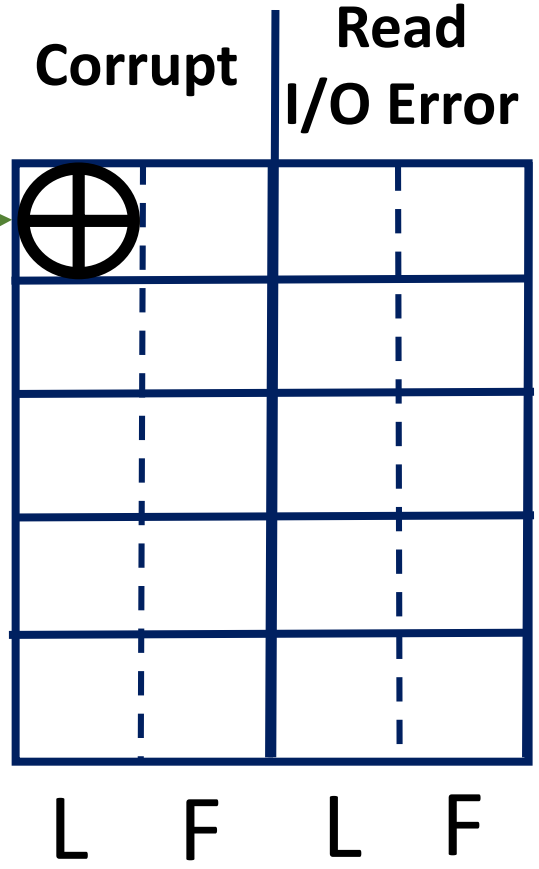

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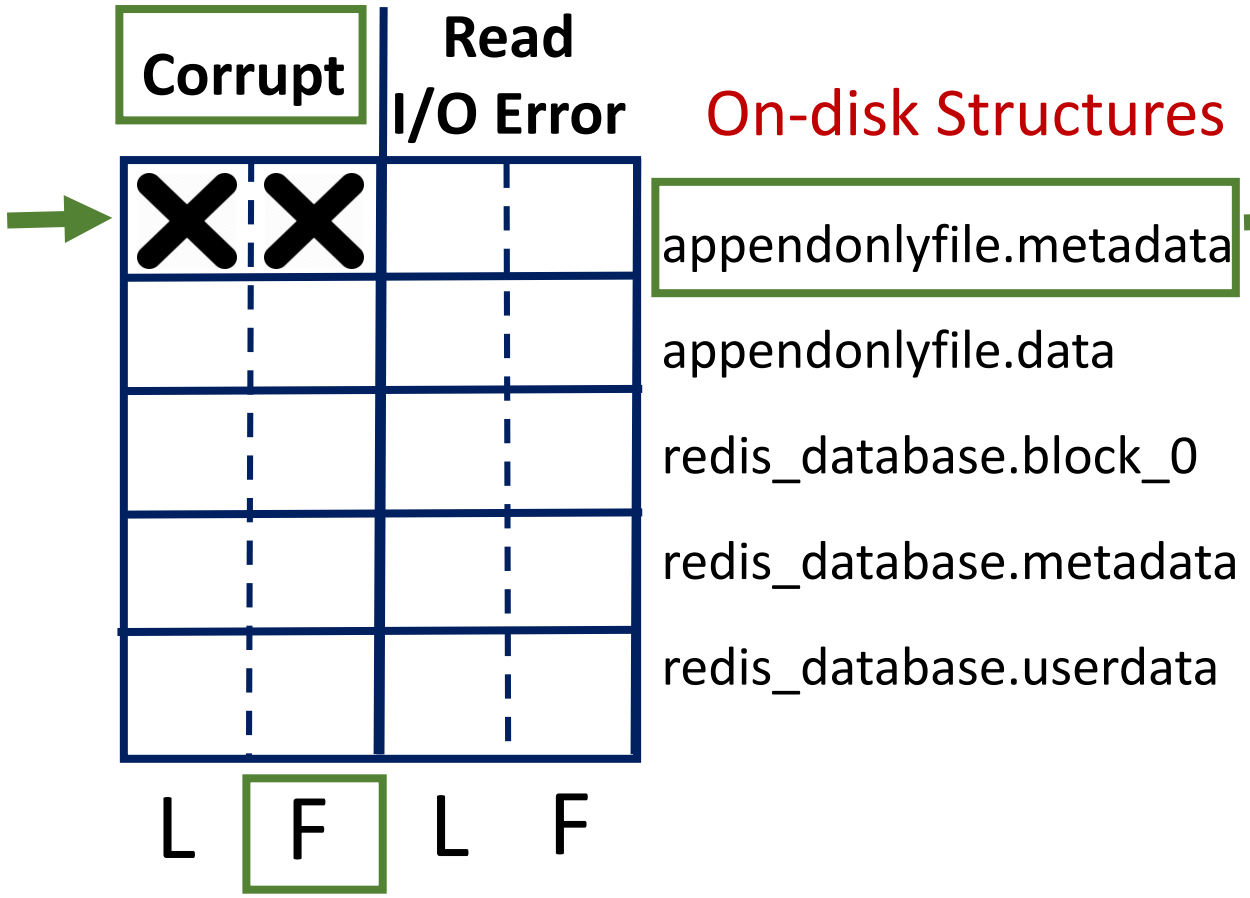

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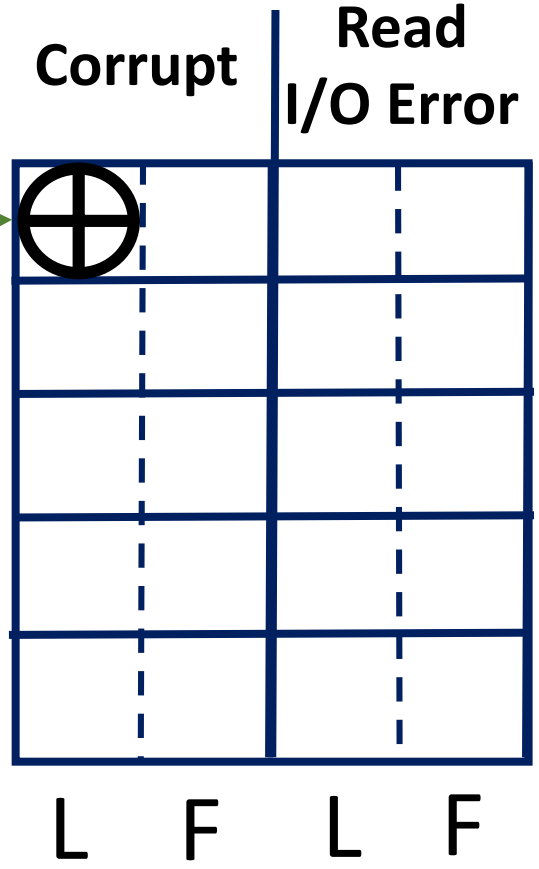

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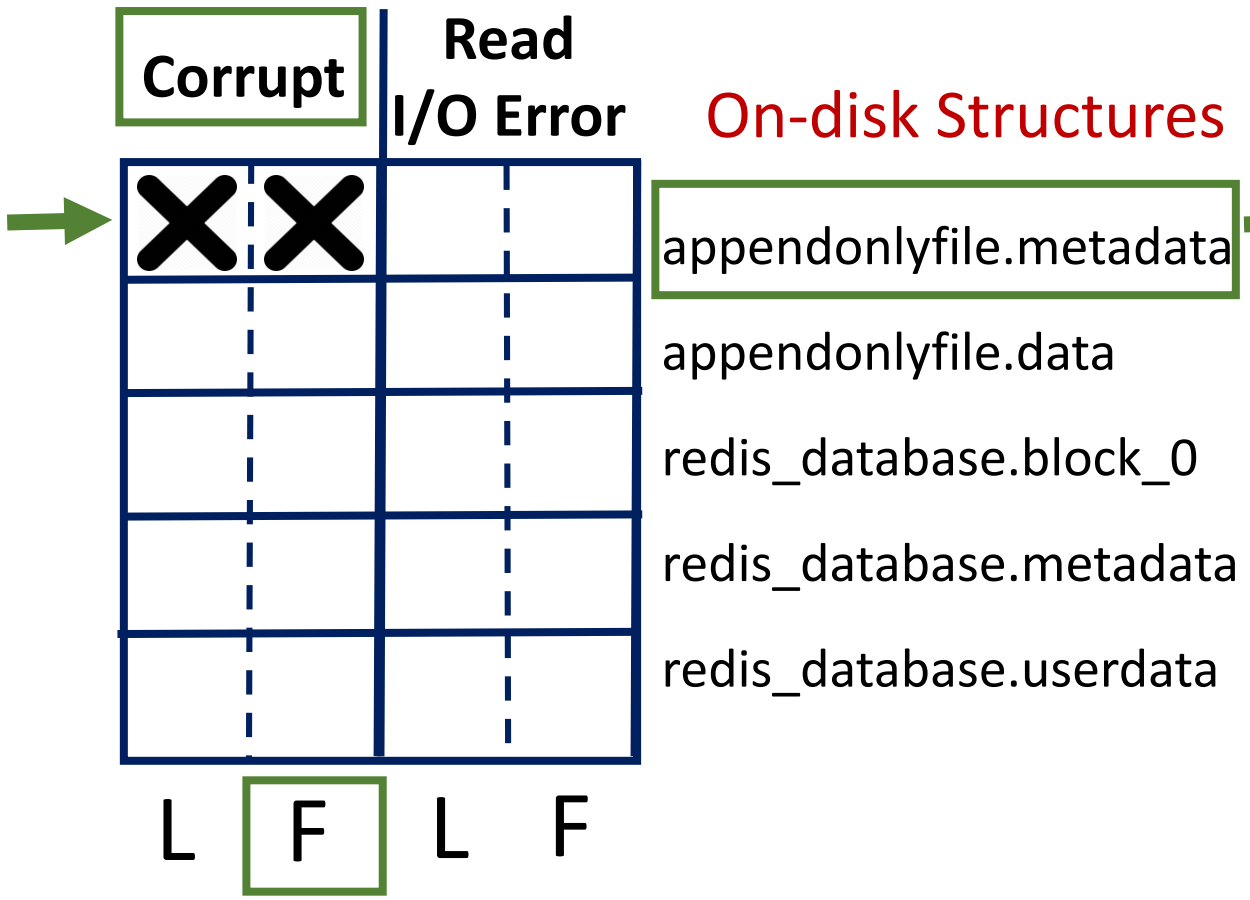

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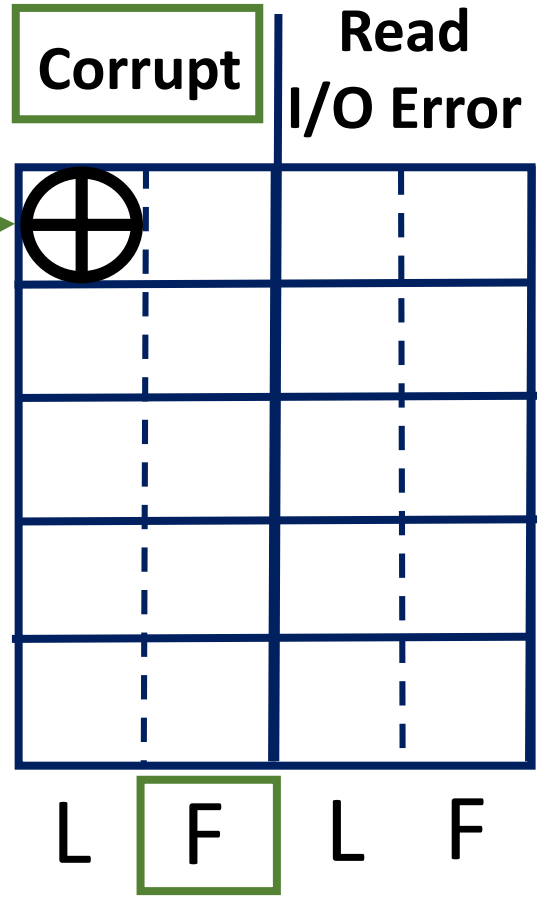

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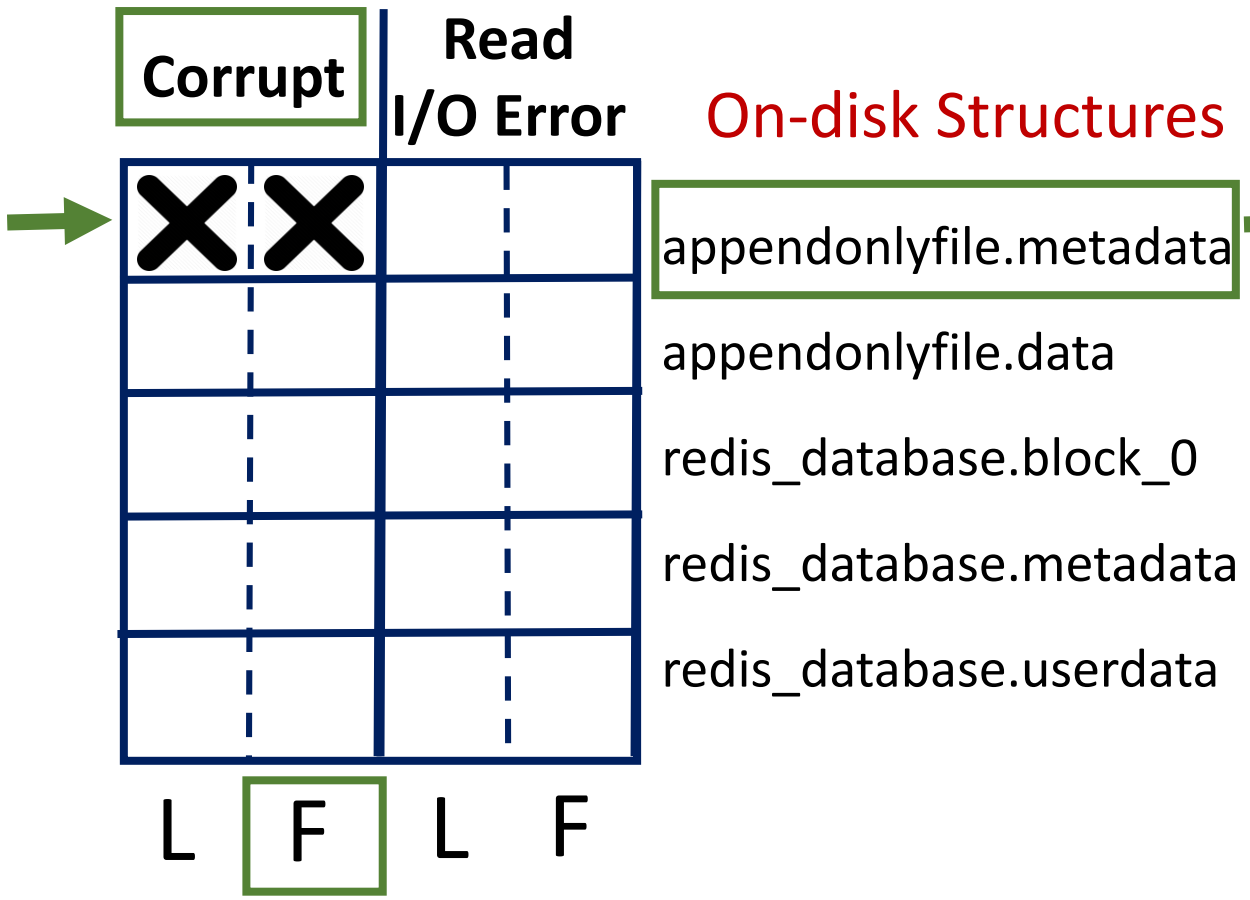
L Leader

F Follower

Read Workload

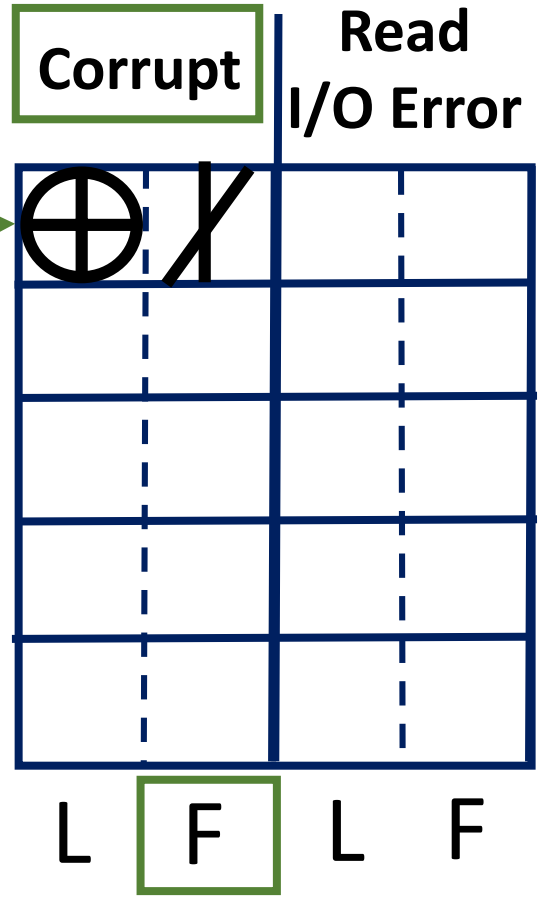
Local Behavior



On-disk Structures

- appendonlyfile.metadata
- appendonlyfile.data
- redis_database.block_0
- redis_database.metadata
- redis_database.userdata

Global Effect



Local Behavior

Crash

Global Effect

Unavailability

Reduced Redundancy

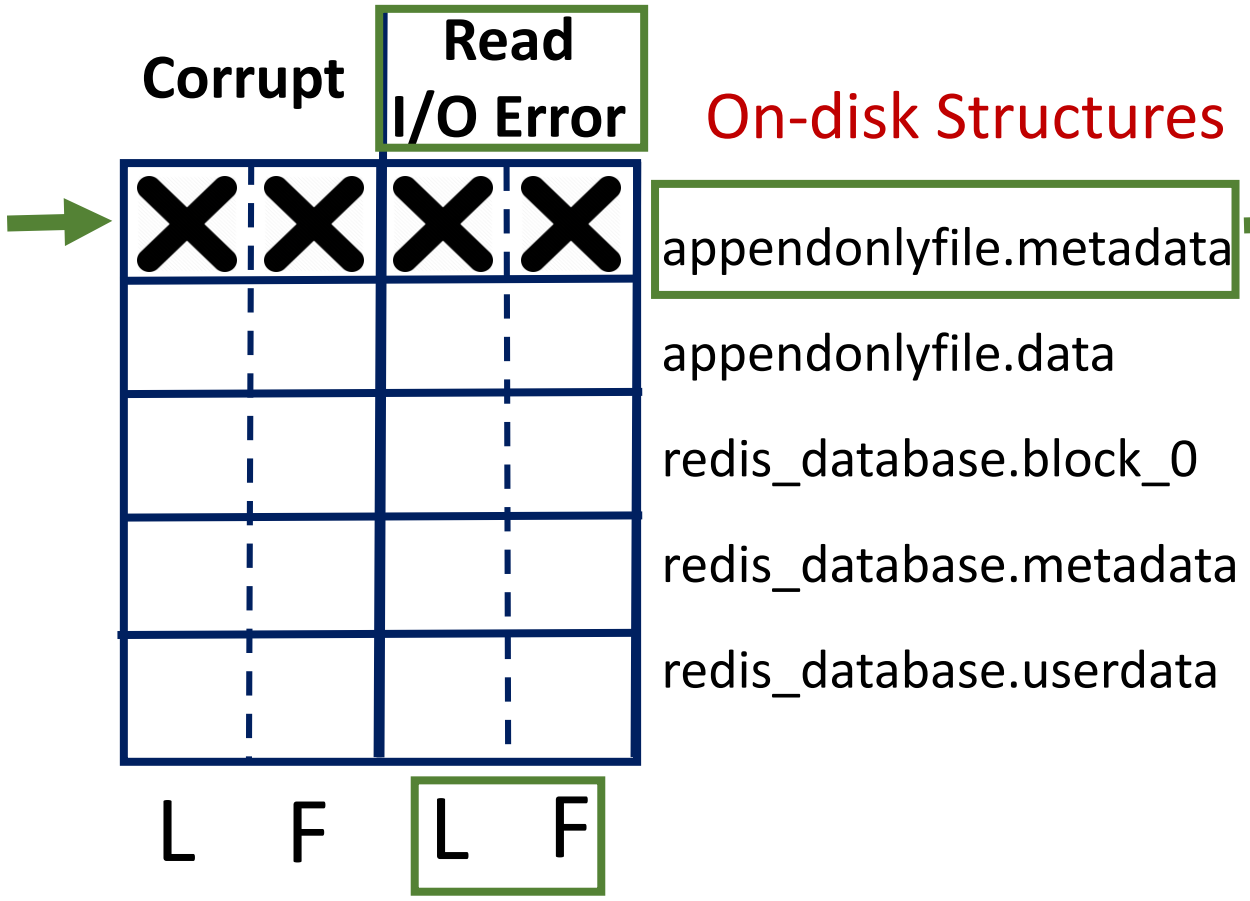
Redis: Behavior Analysis

Read Workload

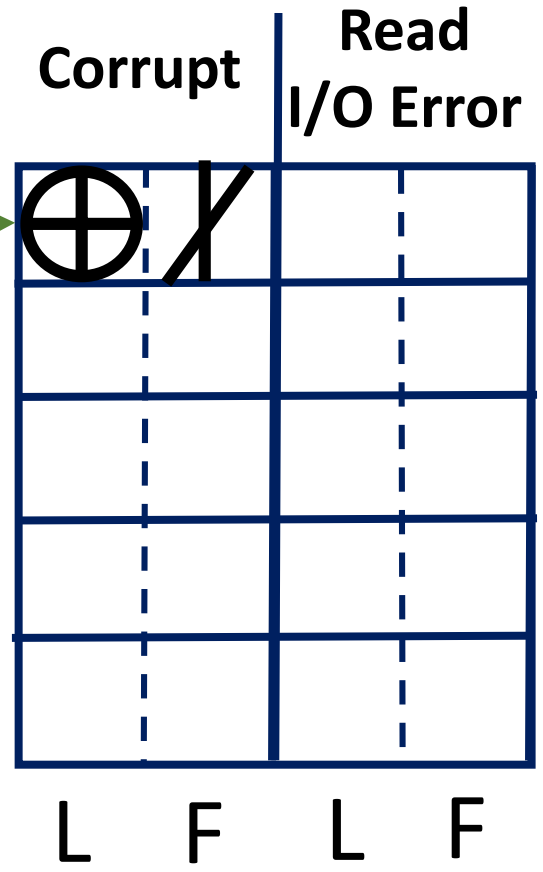
L Leader

F Follower

Local Behavior



Global Effect



Local Behavior

Crash

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Unavailability

Reduced Redundancy

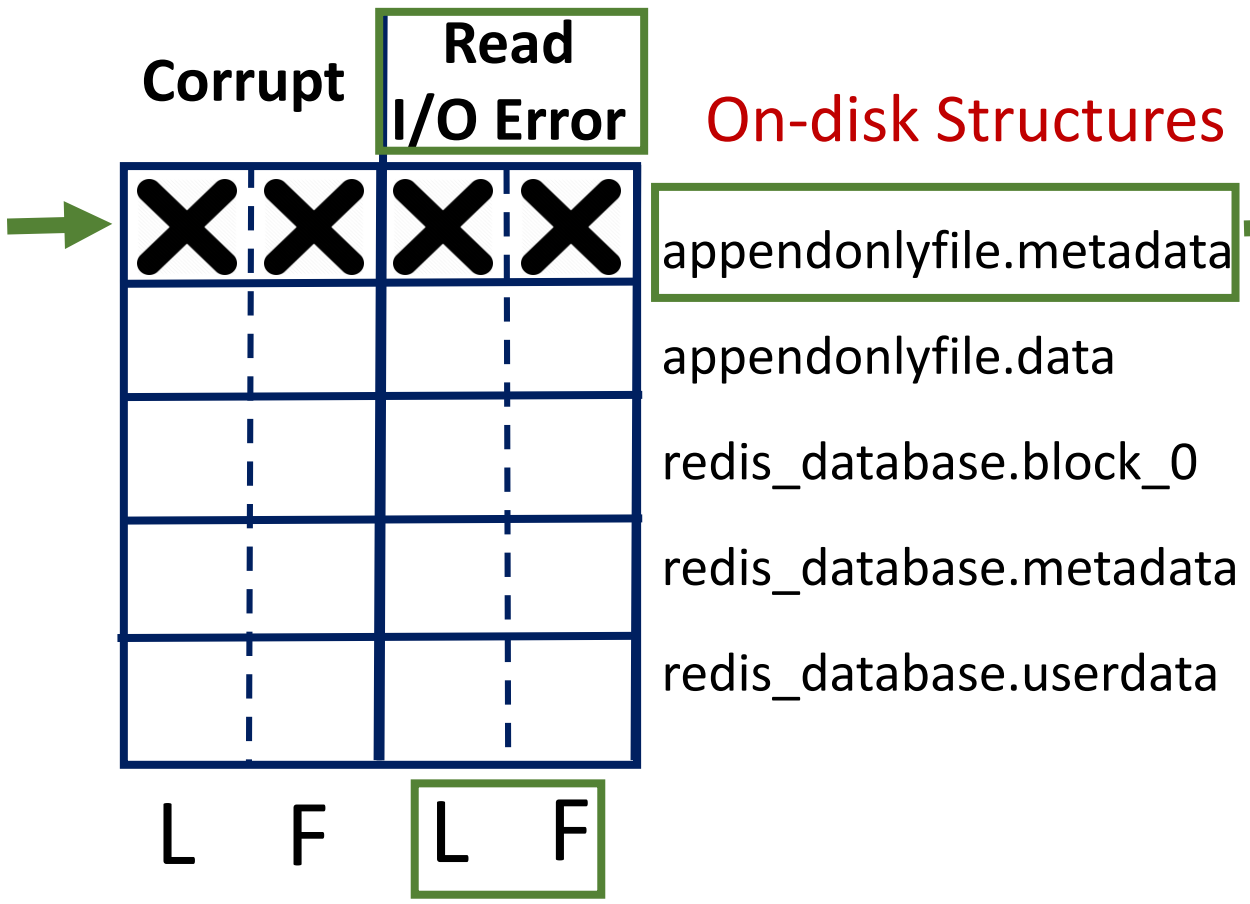
Redis: Behavior Analysis

Read Workload

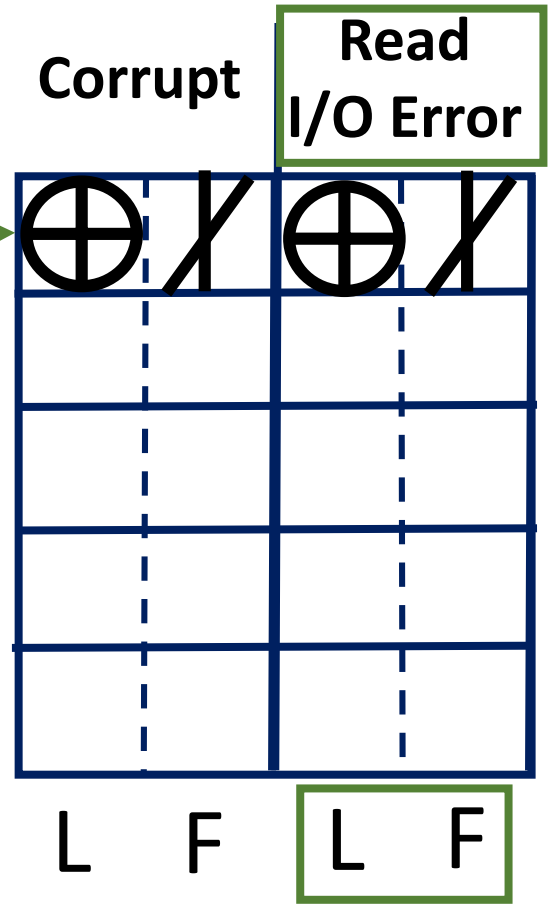
L Leader

F Follower

Local Behavior



Global Effect



Local Behavior

Crash

Global Effect

Unavailability

Reduced Redundancy

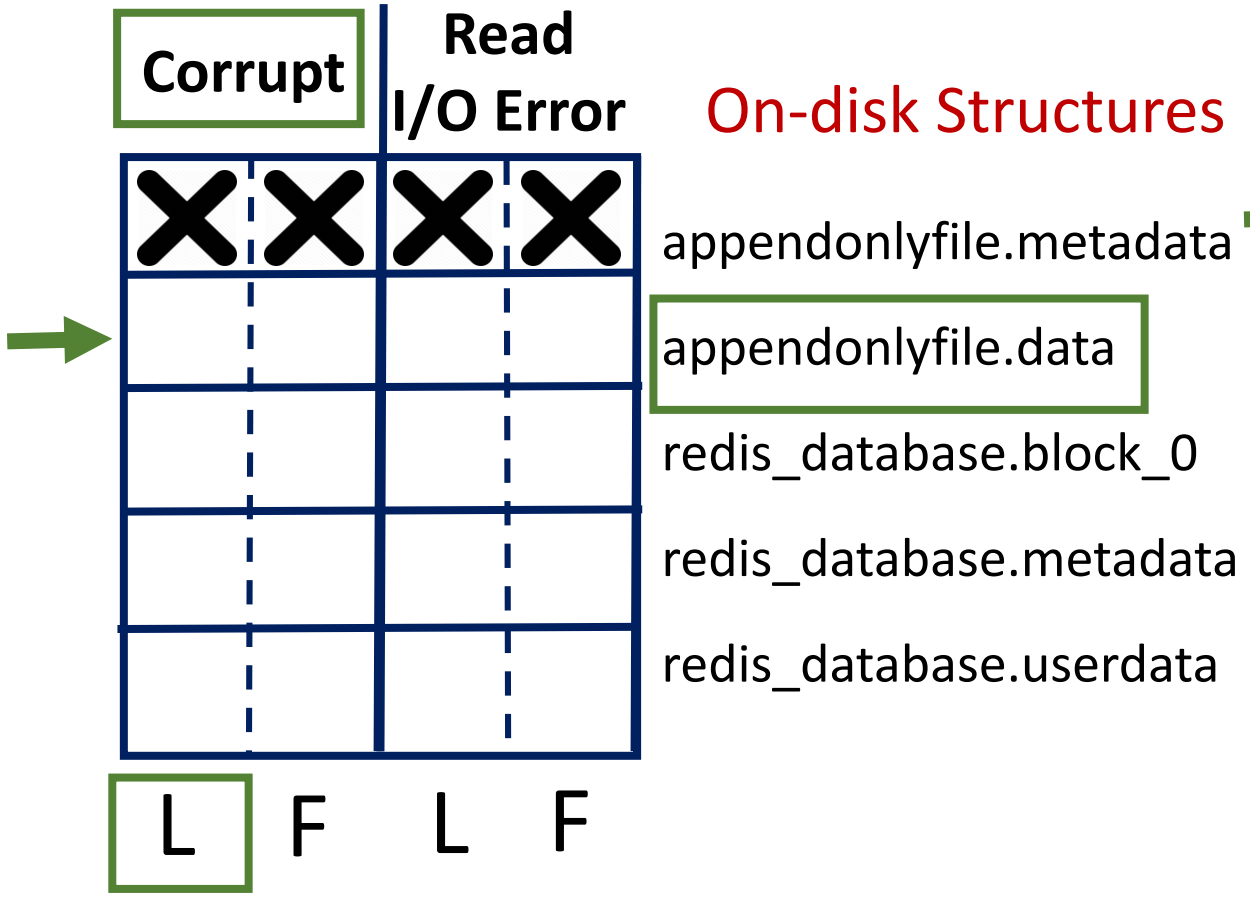
Redis: Behavior Analysis

L Leader

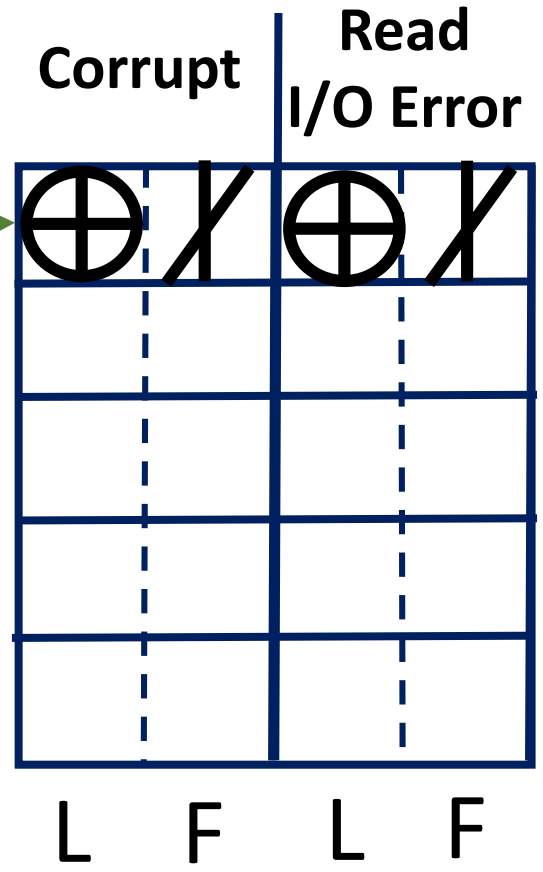
F Follower

Read Workload

Local Behavior



Global Effect



Local Behavior

Crash

Global Effect

Unavailability

Reduced Redundancy

Redis: Behavior Analysis

Read Workload

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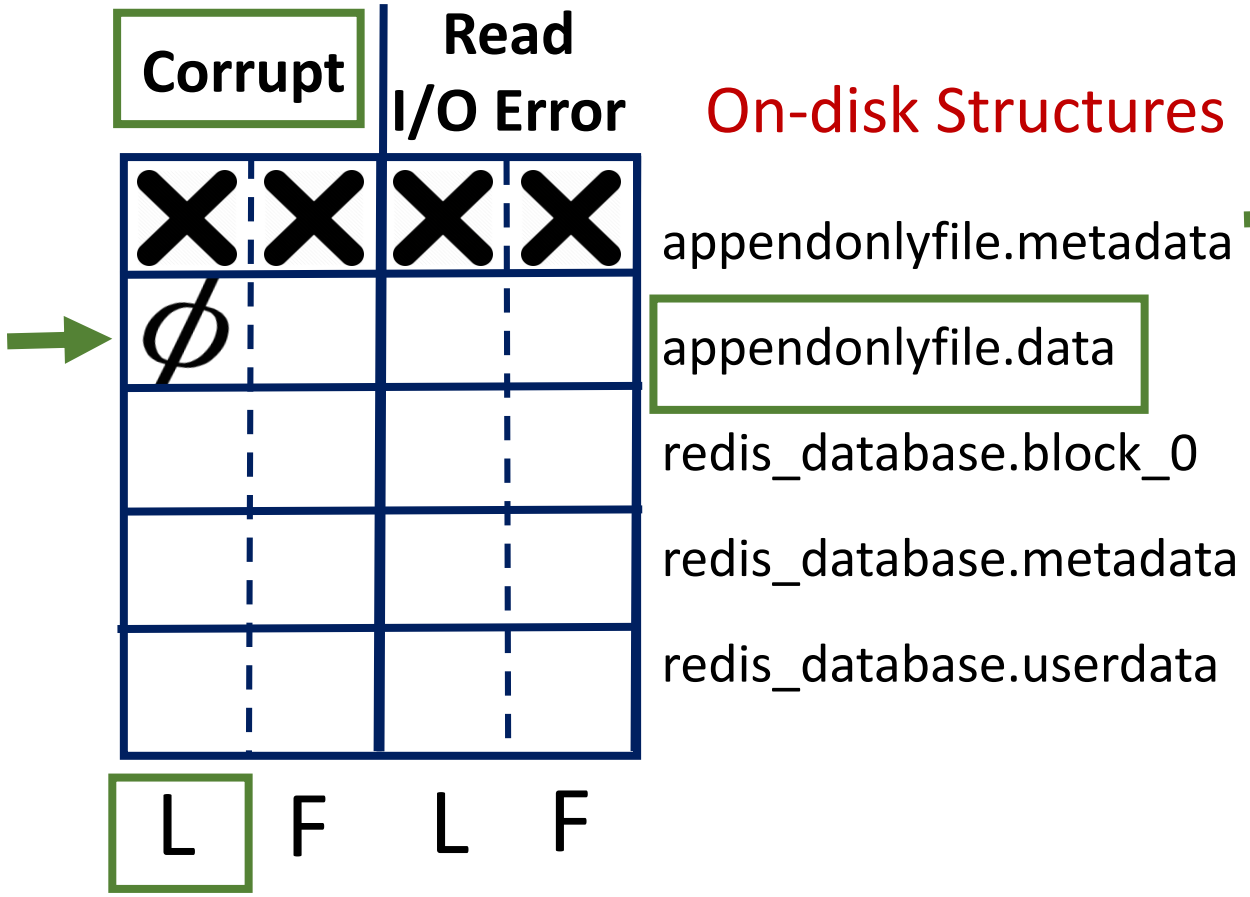
Local Behavior



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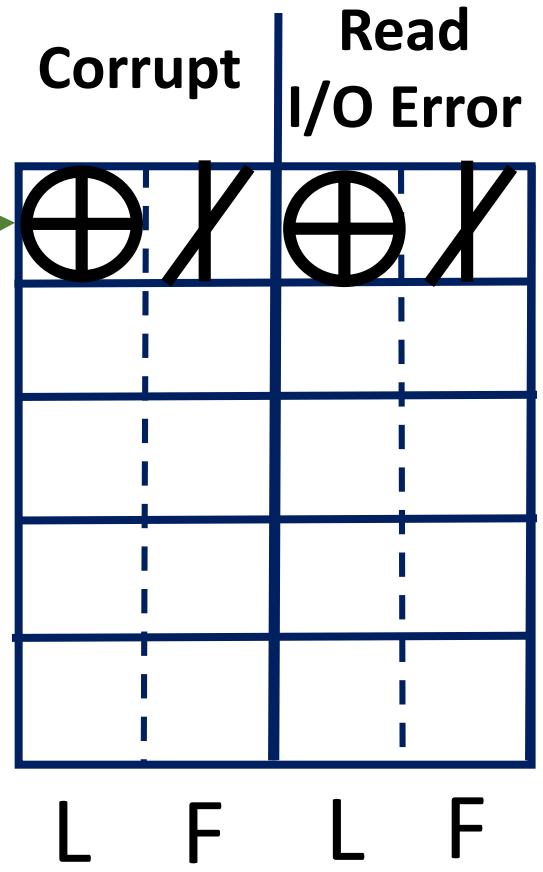
Global Effect



Local Behavior

- Crash
- No Detection/ No Recovery

Global Effect

- Unavailability
- Reduced Redundancy

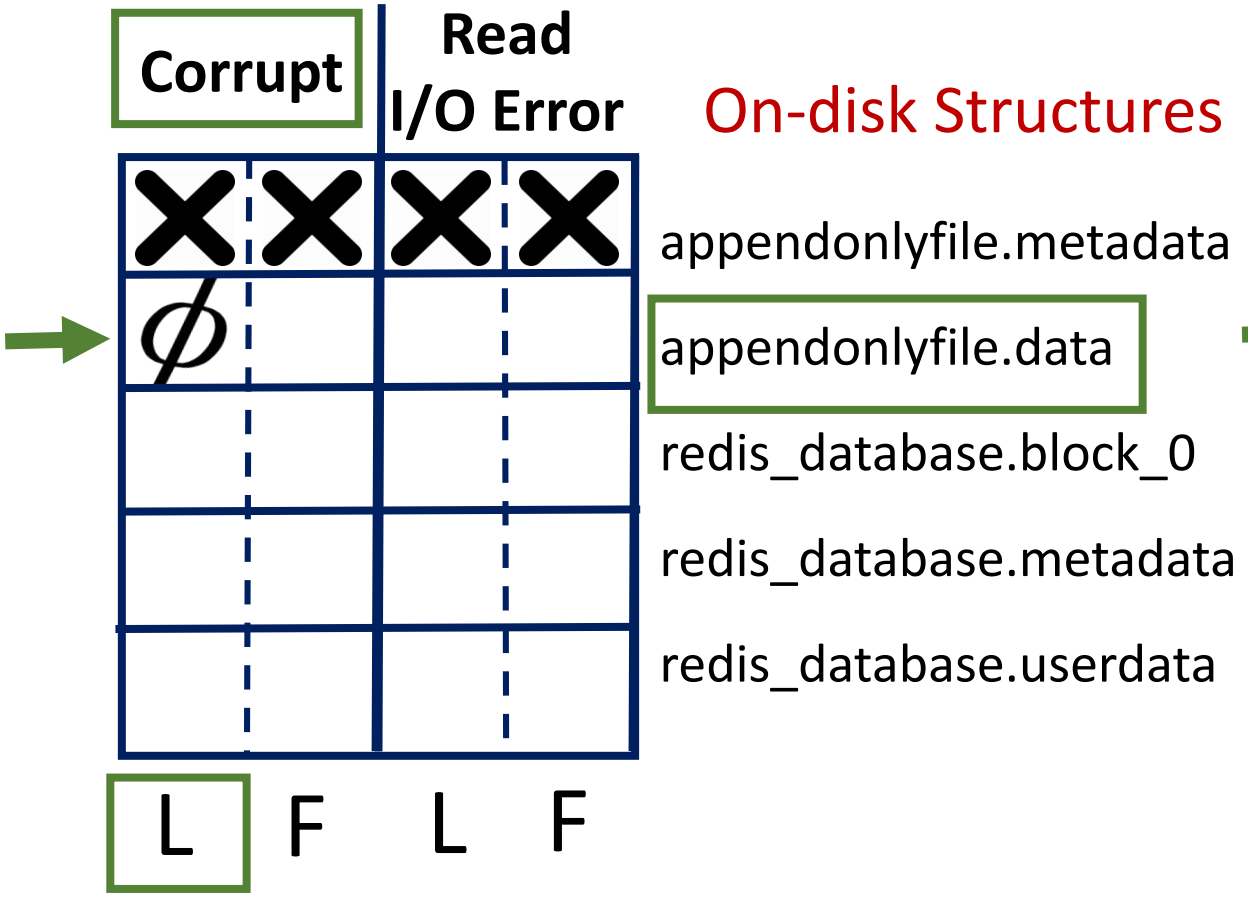
Redis: Behavior Analysis

Read Workload

L Leader

F Follower

Local Behavior



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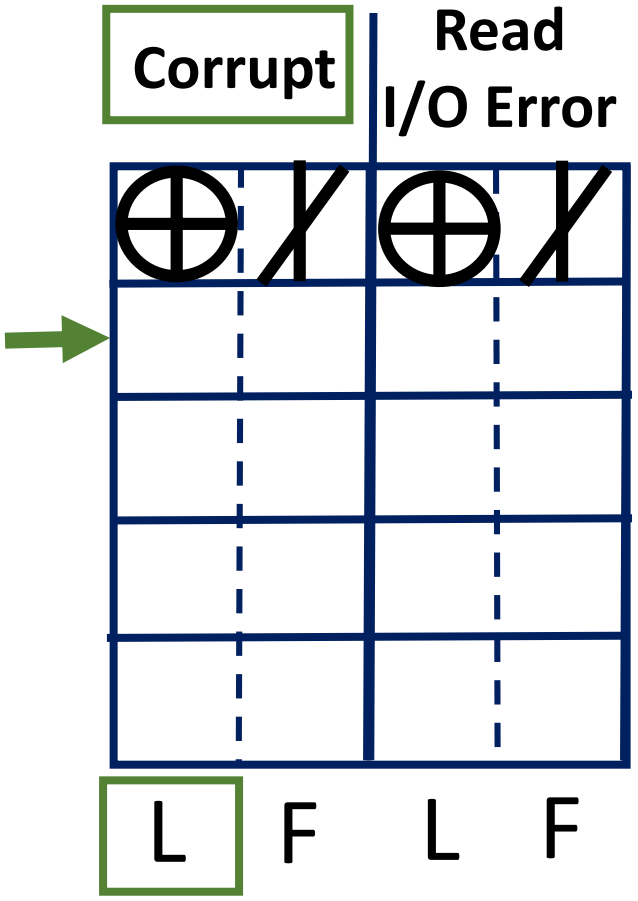

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Global Effect

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Redis: Behavior Analysis

Read Workload

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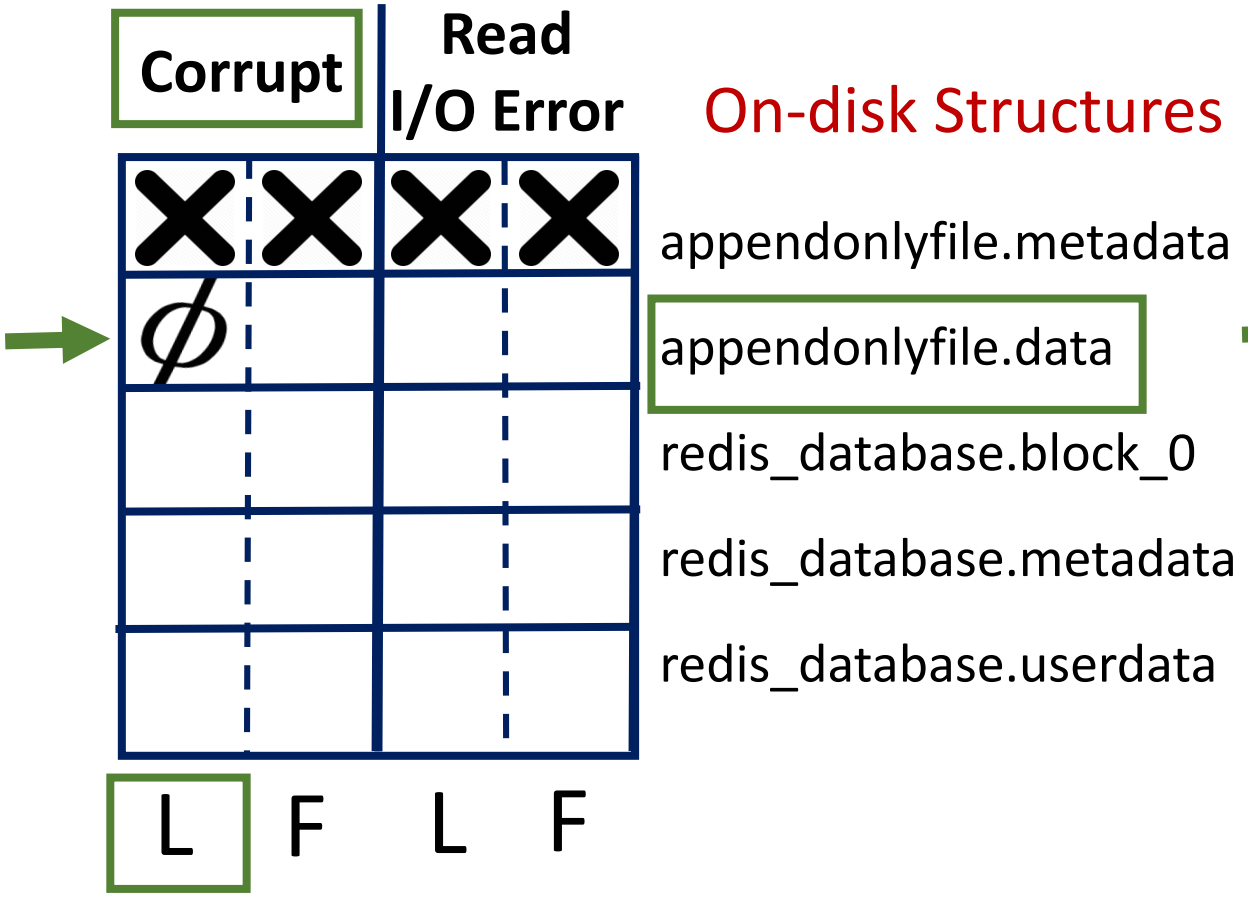

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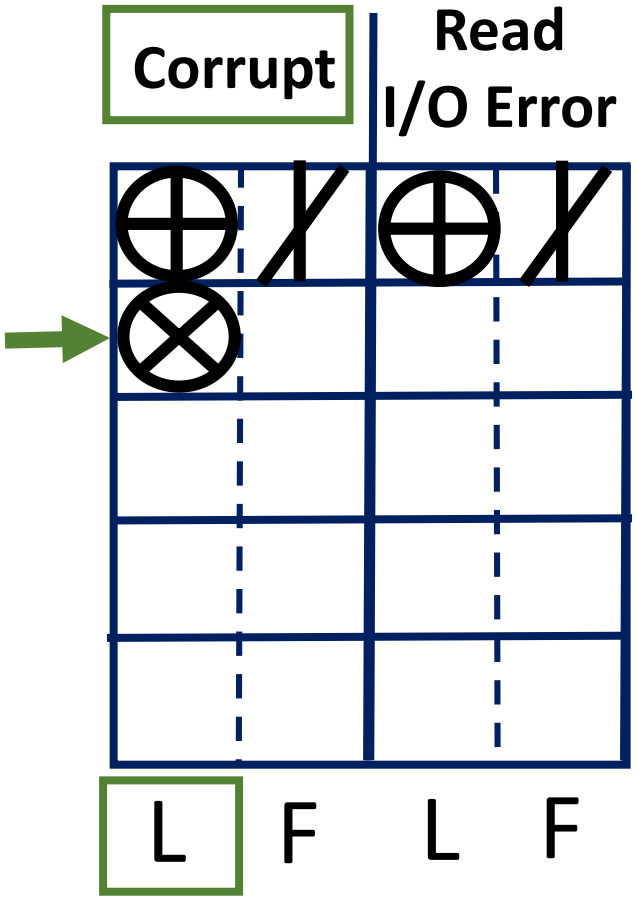


Local Behavior

- Crash
- No Detection/ No Recovery

Global Effect

- Unavailability
- Reduced Redundancy
- Corruption

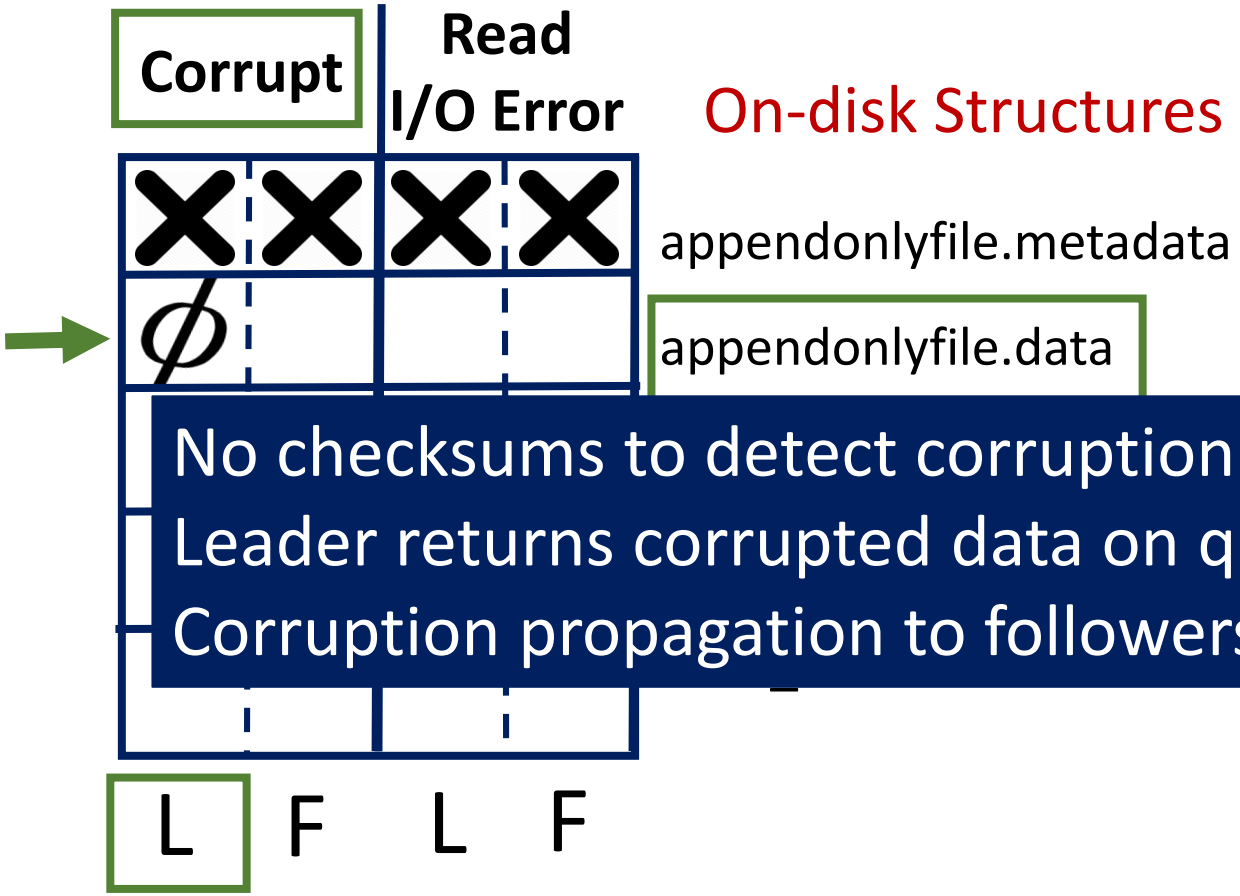
Redis: Behavior Analysis

L Leader

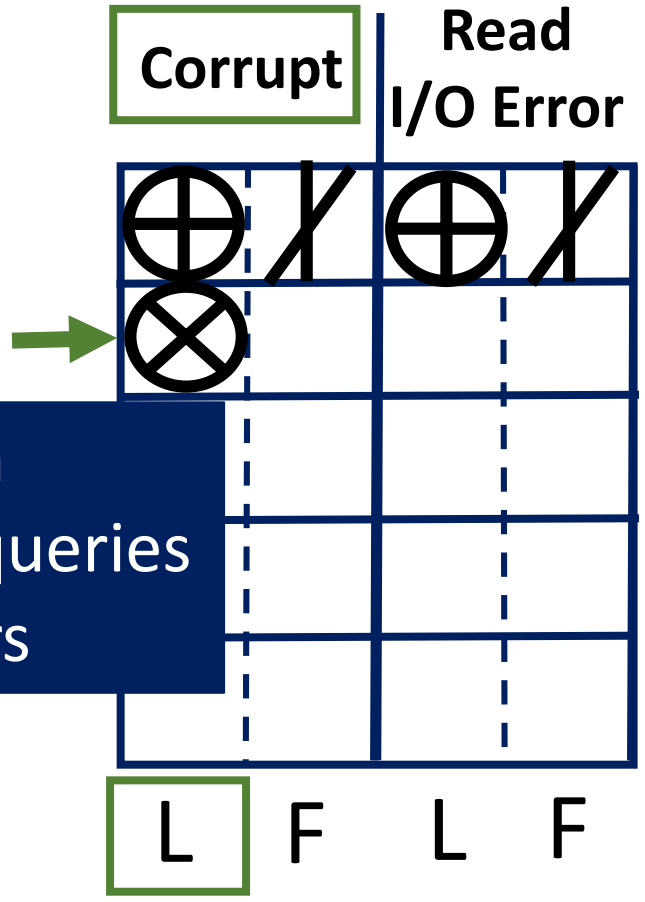
F Follower

Read Workload

Local Behavior



Global Effect



Local Behavior

Crash

No Detection/
No Recovery

Global Effect

Unavailability

Reduced
Redundancy

Corruption

Redis: Behavior Analysis

Read Workload

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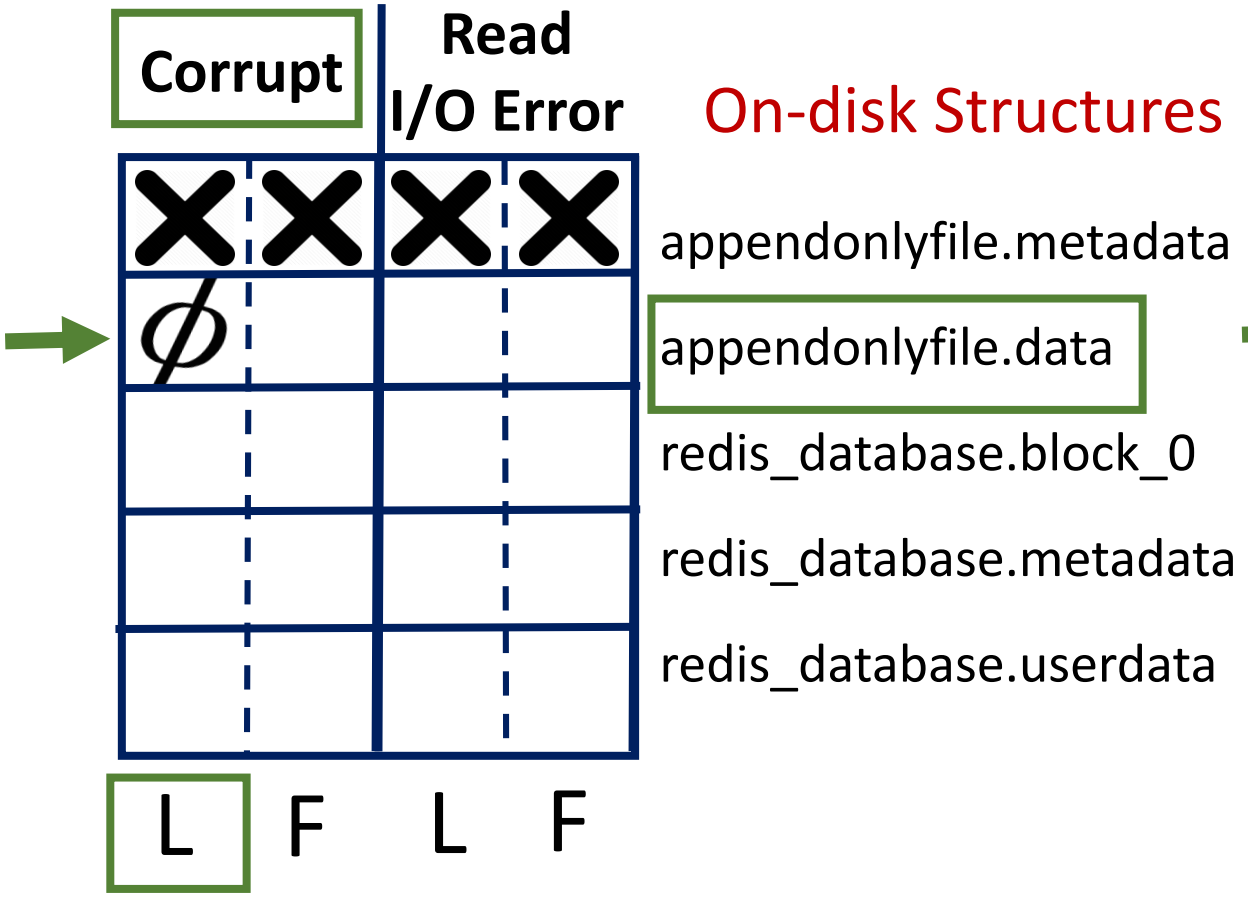
F Follower

Local Behavior



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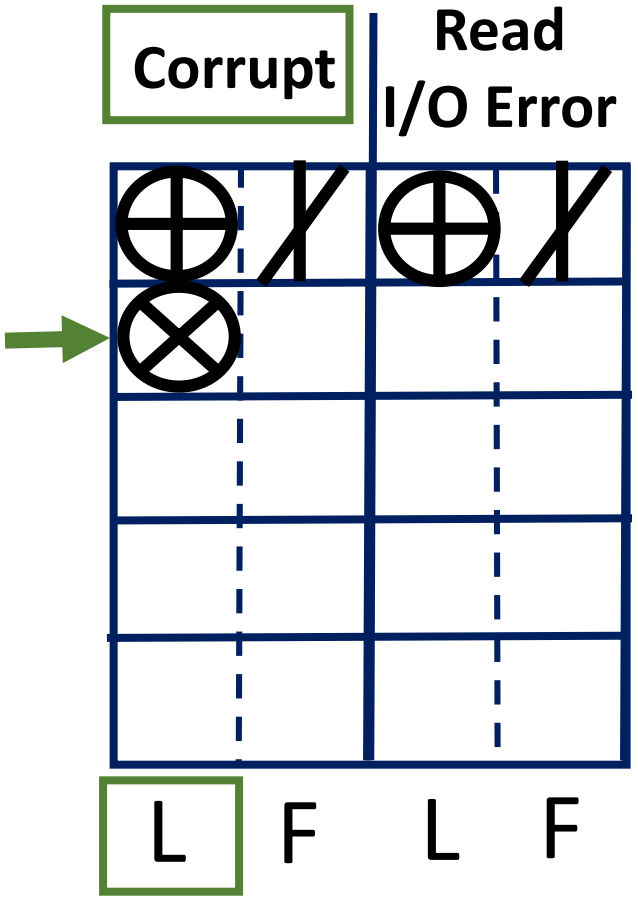

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- No Detection/ No Recovery

Global Effect

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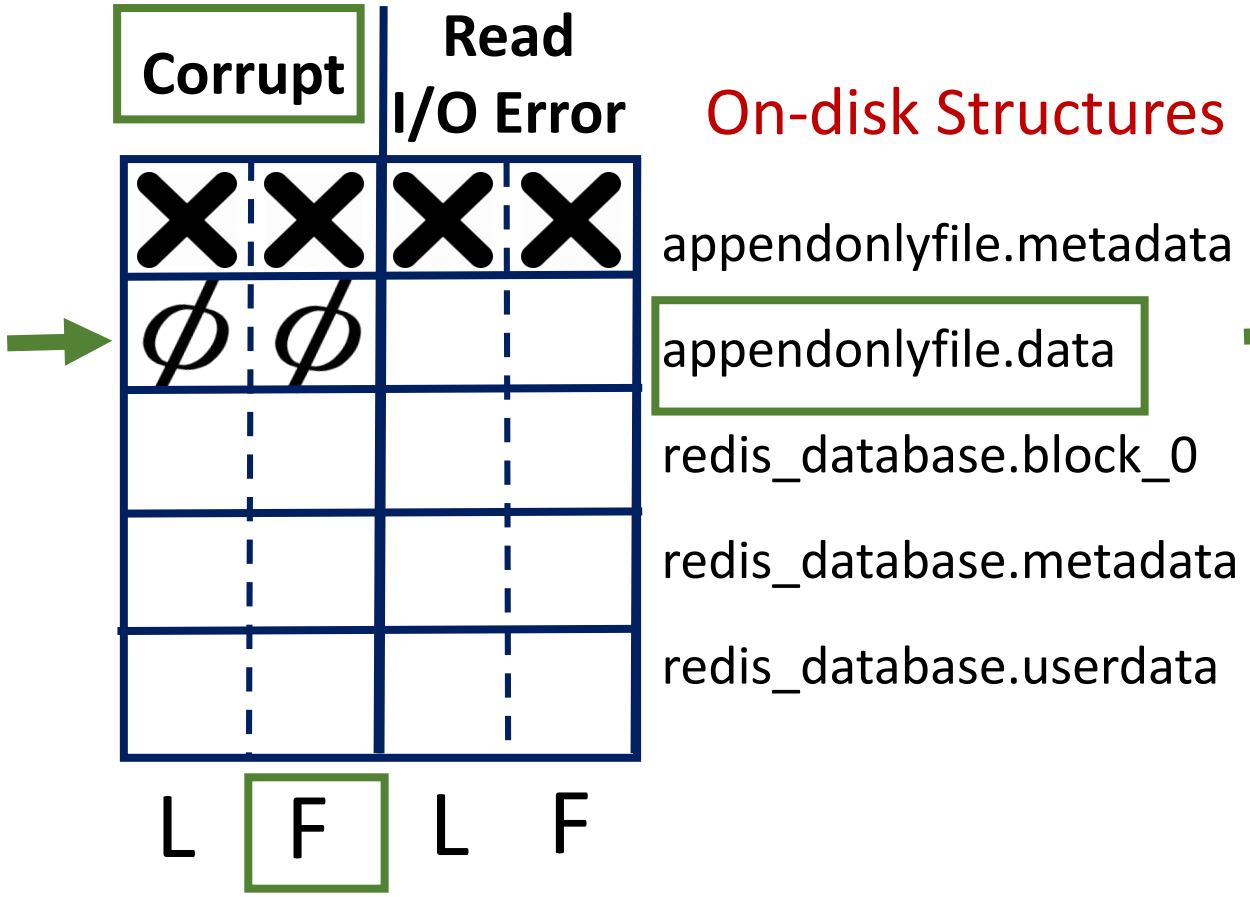
- Reduced Redundancy
- Corruption

Redis: Behavior Analysis

Read Workload

Local Behavior



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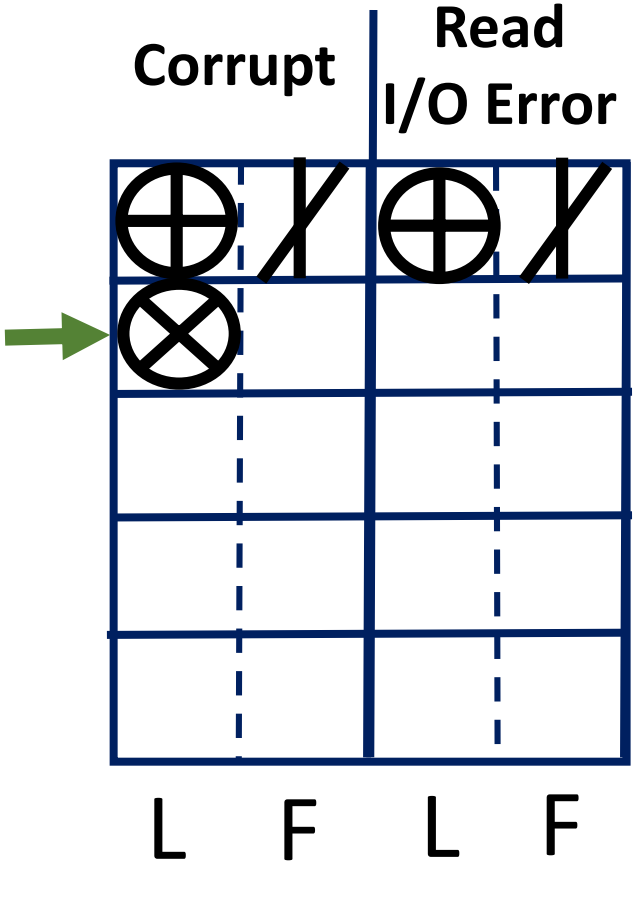
Global Effect



L Leader

F Follower

Local Behavior

- Crash
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Global Effect

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- Corruption

Redis: Behavior Analysis

Read Workload

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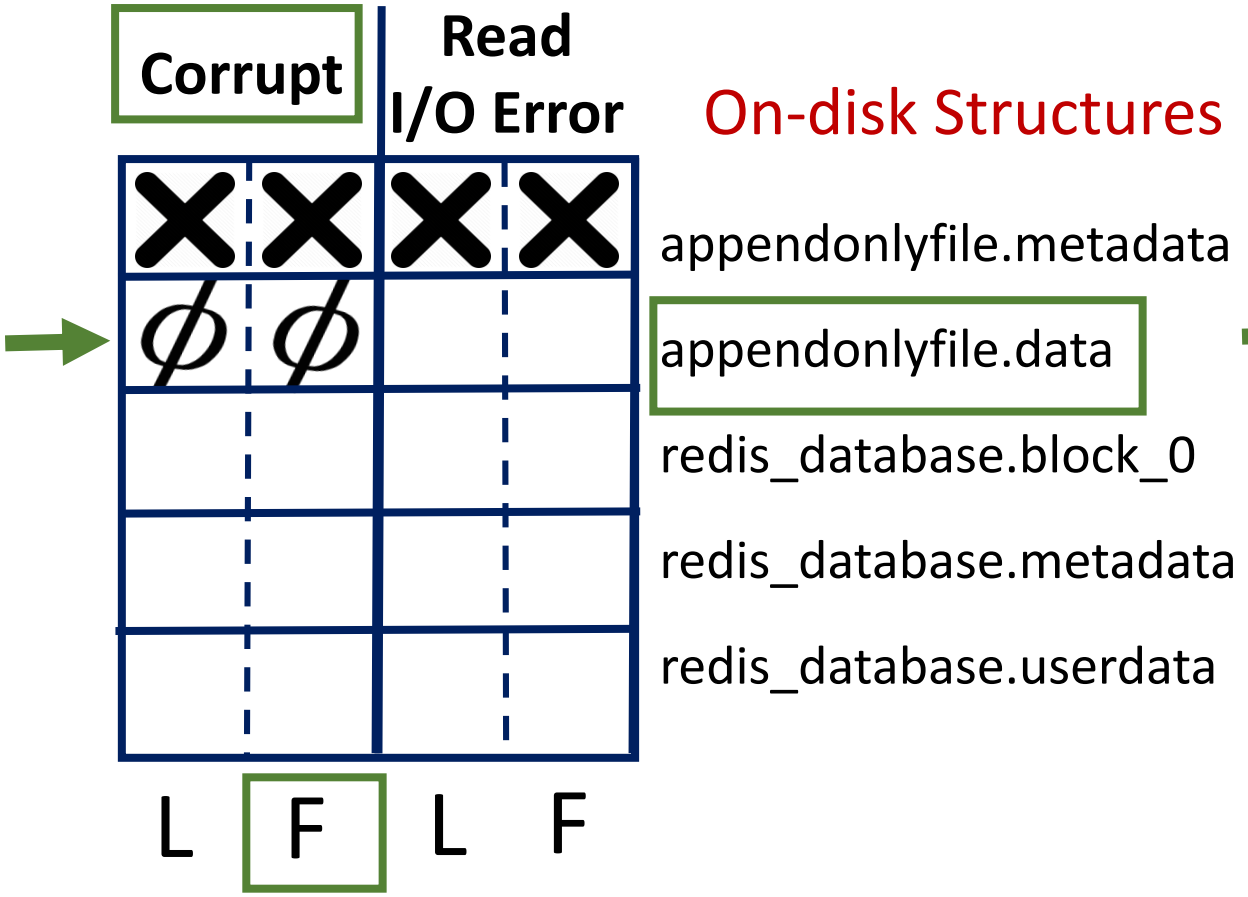
Local Behavior



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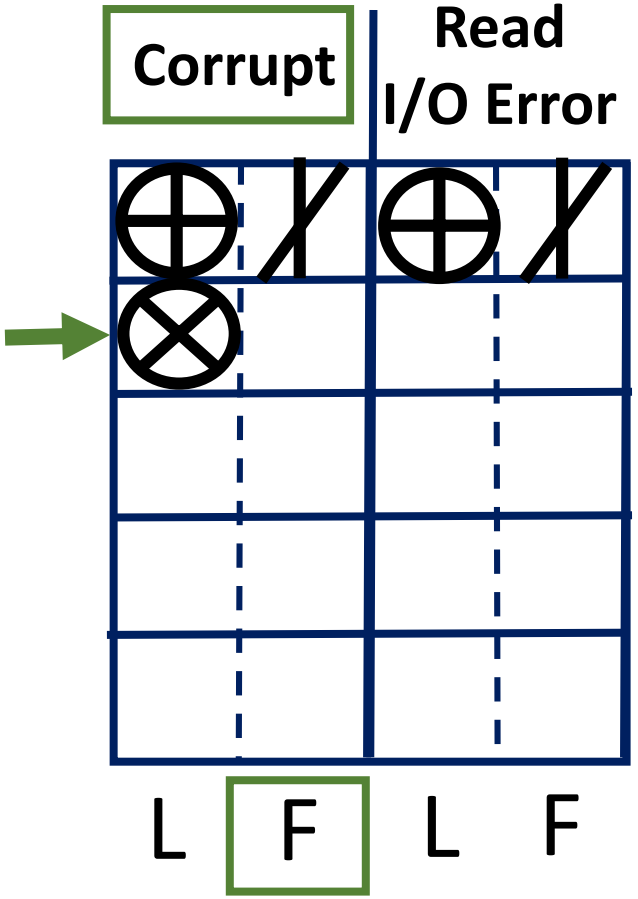


Local Behavior

- Crash
- No Detection/ No Recovery

Global Effect

- Unavailability
- Reduced Redundancy
- Corruption

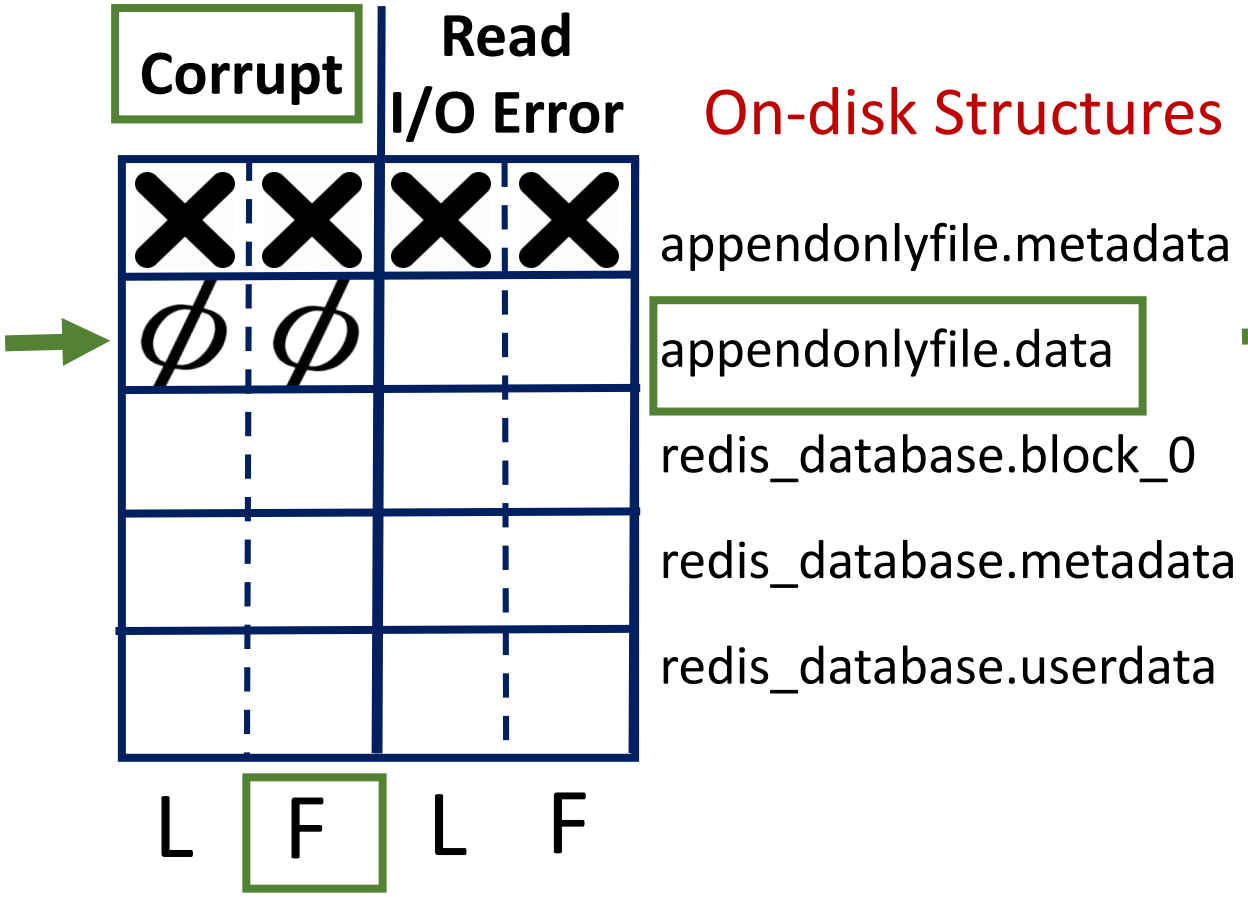
Redis: Behavior Analysis

Read Workload

L Leader

F Follower

Local Behavior



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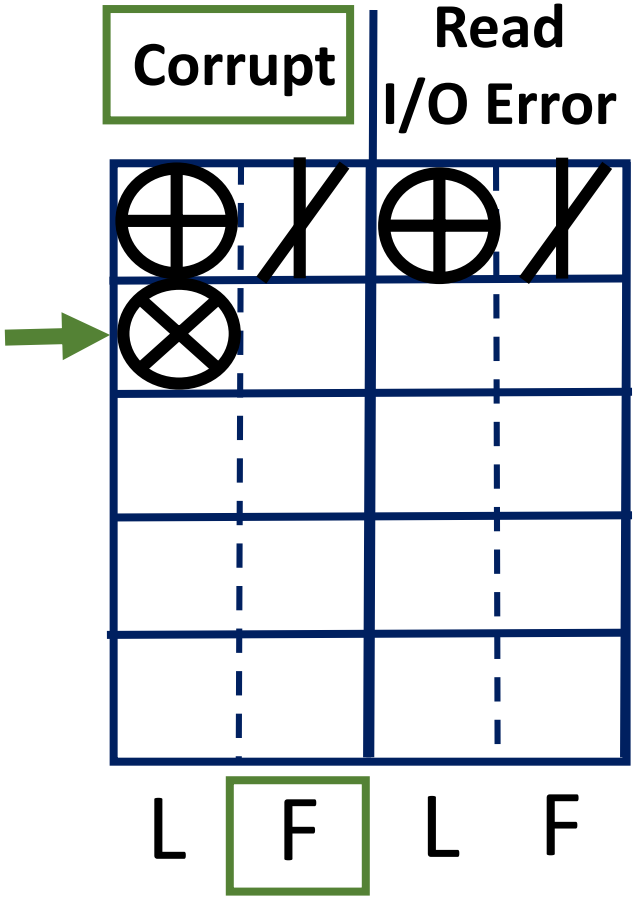


Local Behavior

- Crash
- No Detection/ No Recovery

Global Effect

- Unavailability
- Reduced Redundancy
- Corruption
- Correct

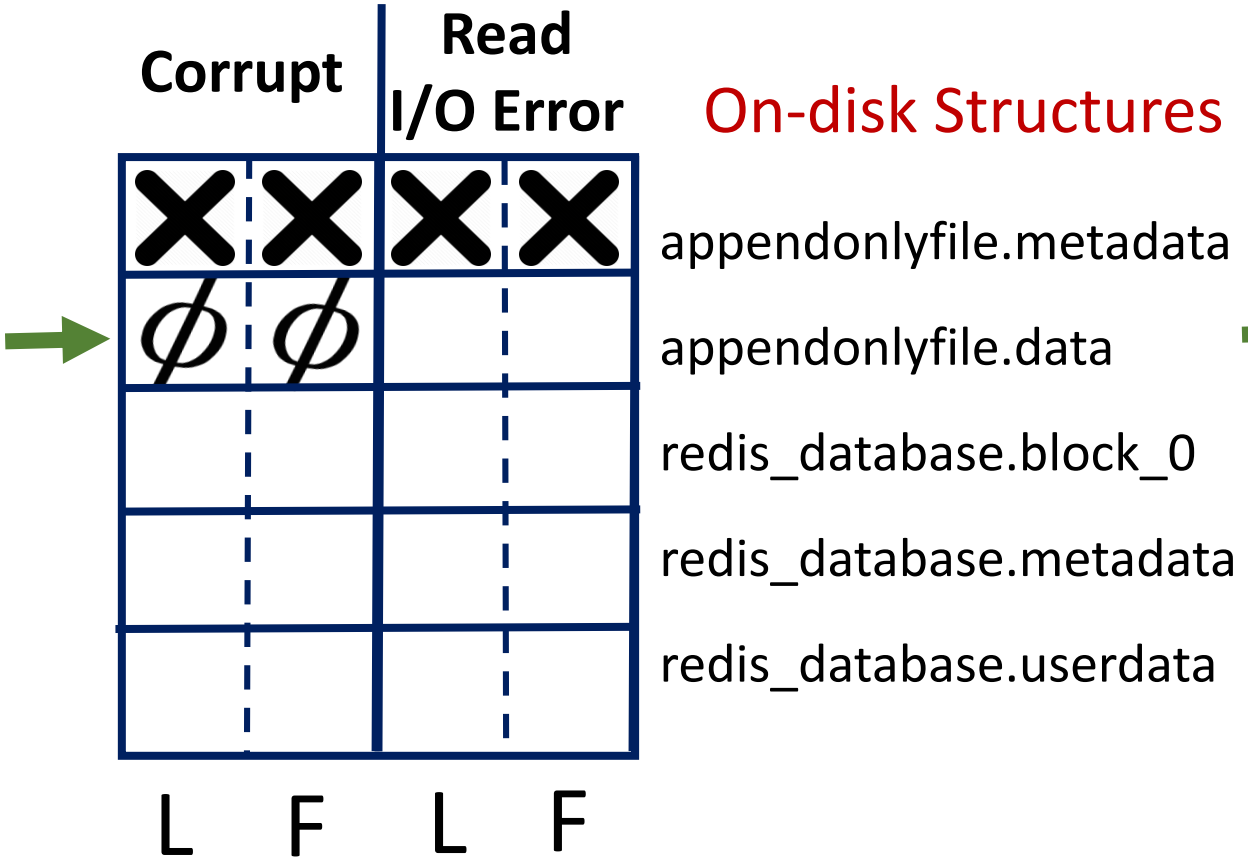
Redis: Behavior Analysis

Read Workload

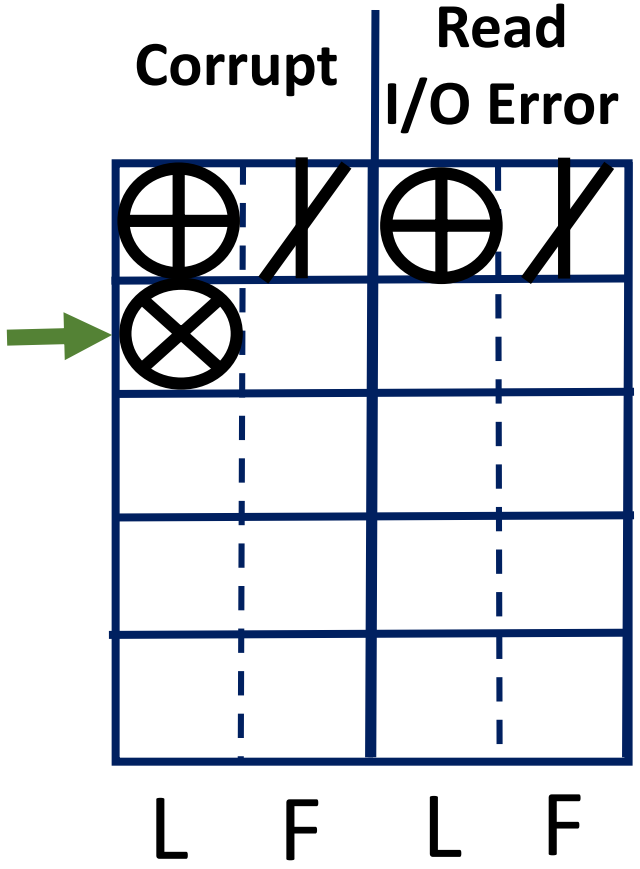
L Leader

F Follower

Local Behavior



Global Effect



Local Behavior

Crash

No Detection/ No Recovery

Global Effect

Unavailability

Reduced Redundancy

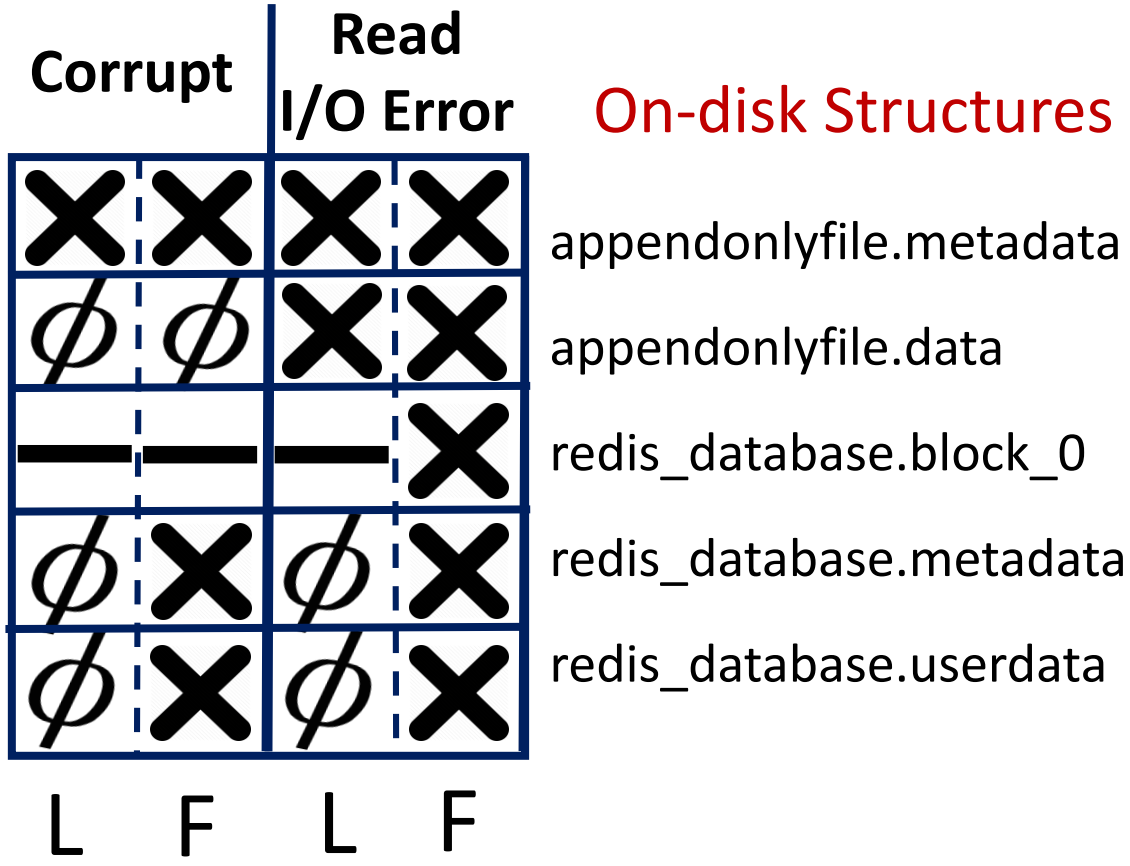
Corruption

Correct

Redis: Behavior Analysis

Read Workload

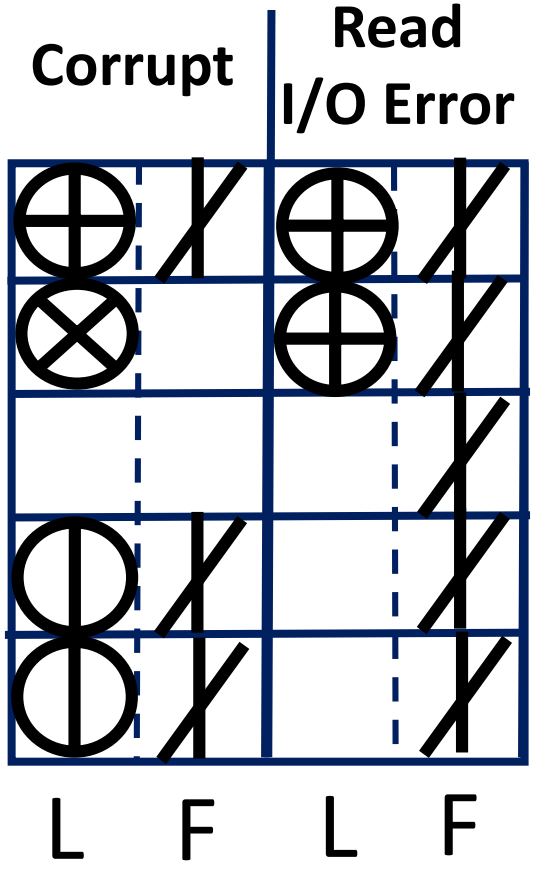
Local Behavior



L Leader

F Follower

Global Effect



Local Behavior

- Crash
- No Detection/ No Recovery
- Retry

Global Effect

- Unavailability
- Reduced Redundancy
- Corruption
- Correct
- Write Unavailability

Other Systems

Other Systems

Metadata stores: ZooKeeper, LogCabin

Wide column store: Cassandra

Document stores: MongoDB

Distributed databases: RethinkDB, CockroachDB

Message Queues: Kafka

Outline

Introduction

Fault Injection

System Behavior Analysis

Major Results

- Redundancy Does not Provide Fault Tolerance

Observations Across Systems

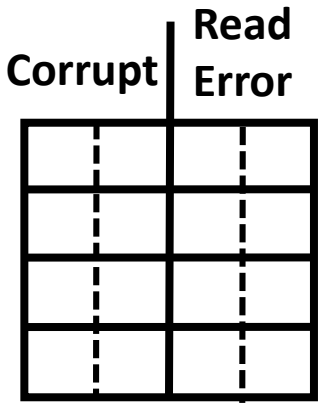
Conclusion

Redundancy Does not Provide Fault Tolerance

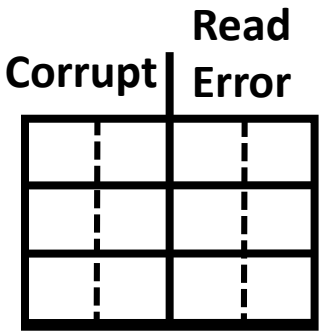
Redundancy Does not Provide Fault Tolerance

Redundancy Does not Provide Fault Tolerance

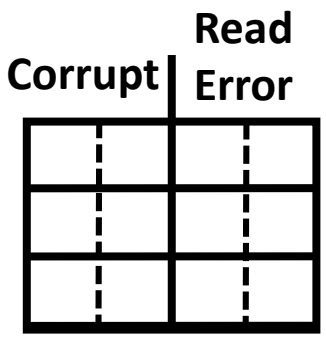
Redis Read



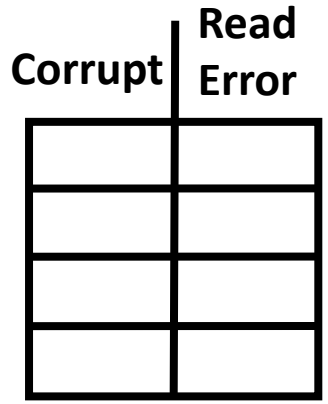
Kafka Read



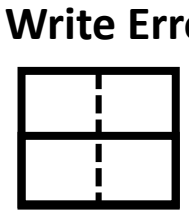
Kafka Write



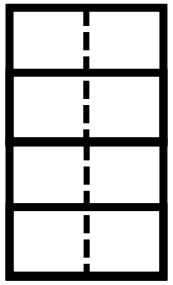
Cassandra Read



ZooKeeper Write

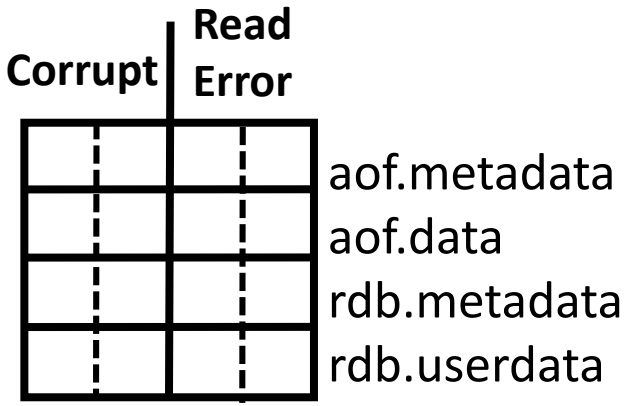


RethinkDB Read



Redundancy Does not Provide Fault Tolerance

Redis Read



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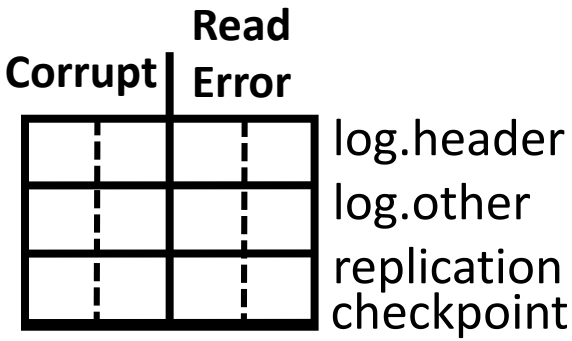

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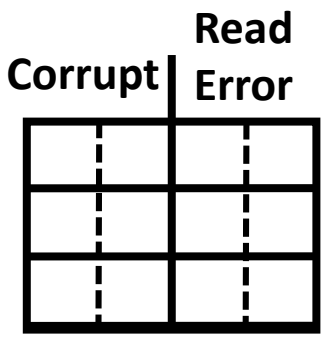

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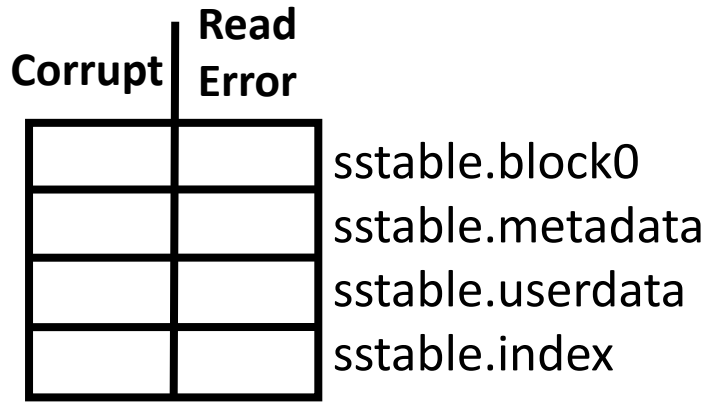
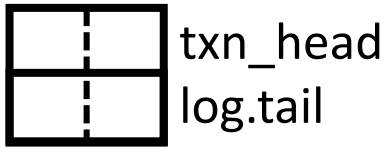


ZooKeeper Write



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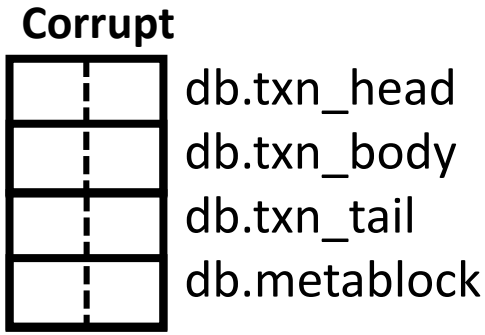
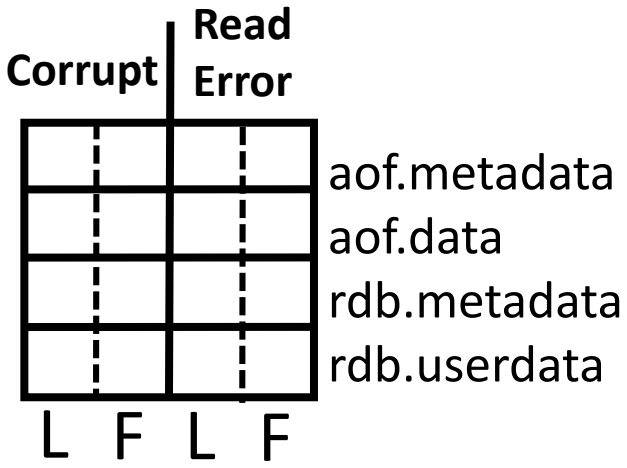
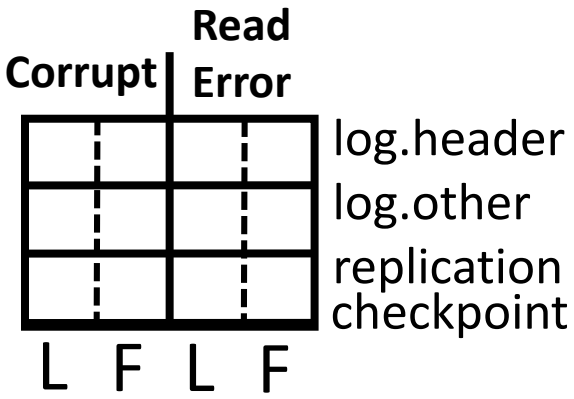


Redundancy Does not Provide Fault Tolerance

Redis Read



Kafka Read



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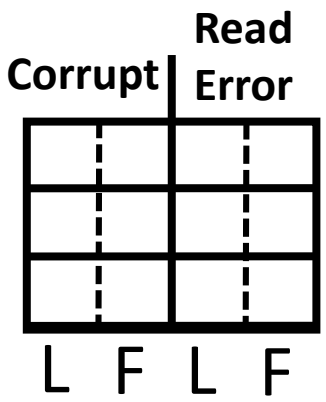
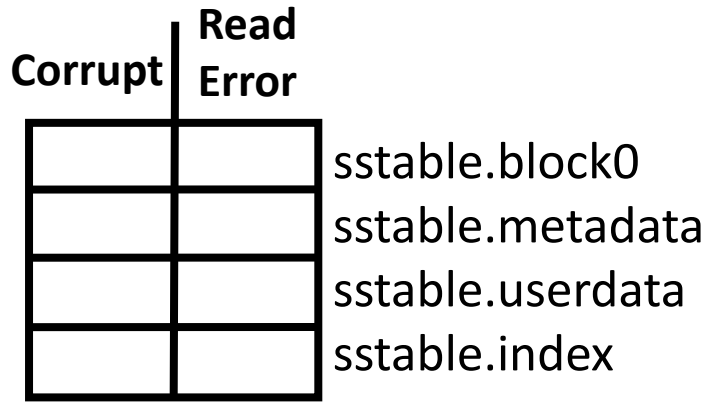
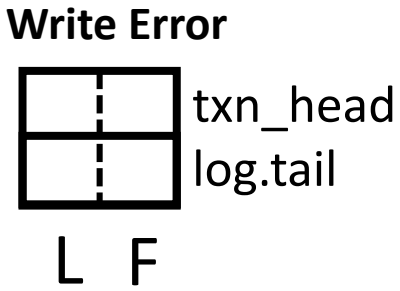


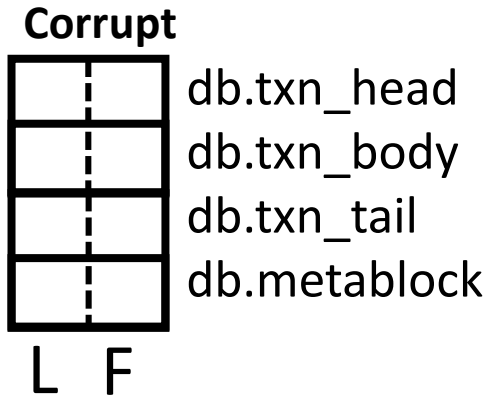
Cassandra Read



ZooKeeper Write

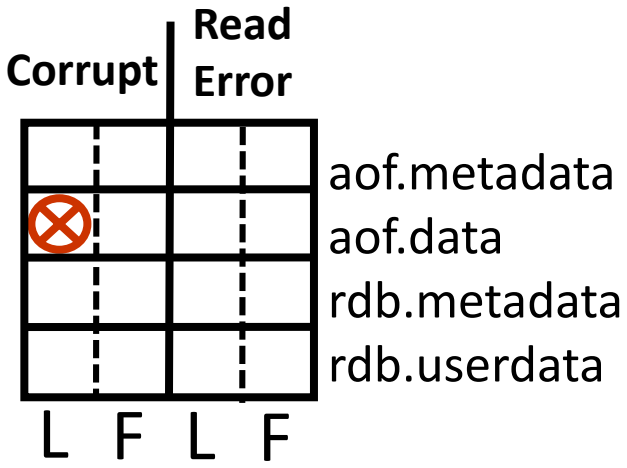


RethinkDB Read



Redundancy Does not Provide Fault Tolerance

Redis Read



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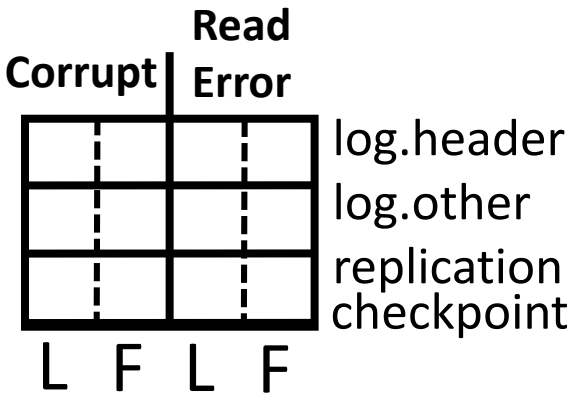

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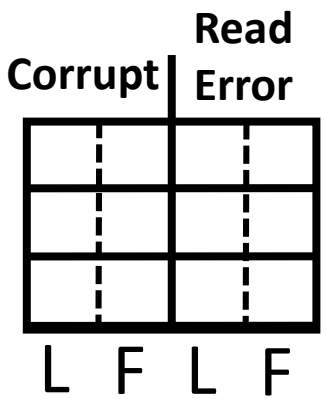

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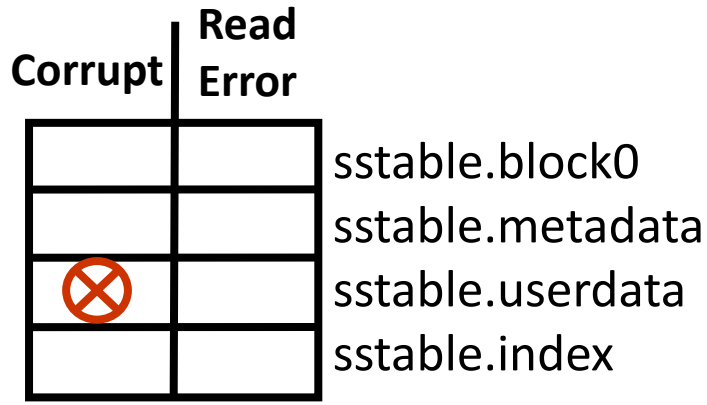
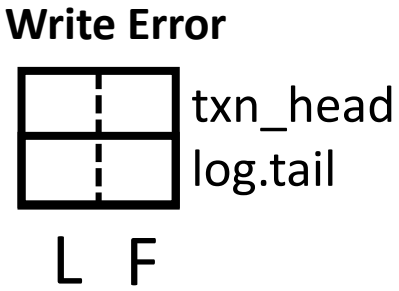
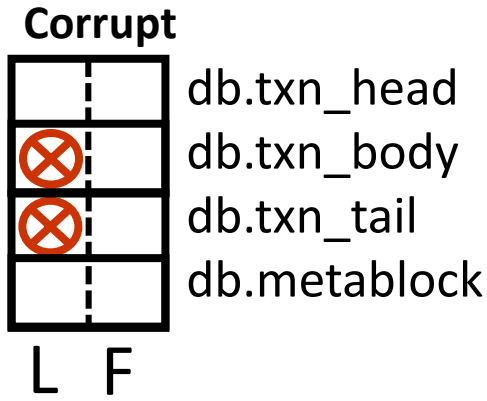


ZooKeeper Write



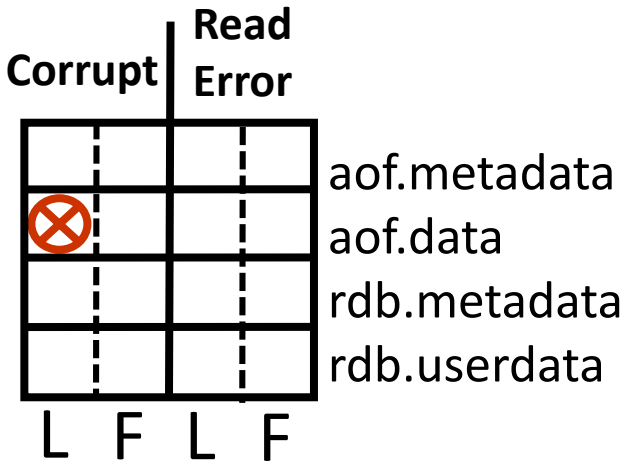
RethinkDB Read



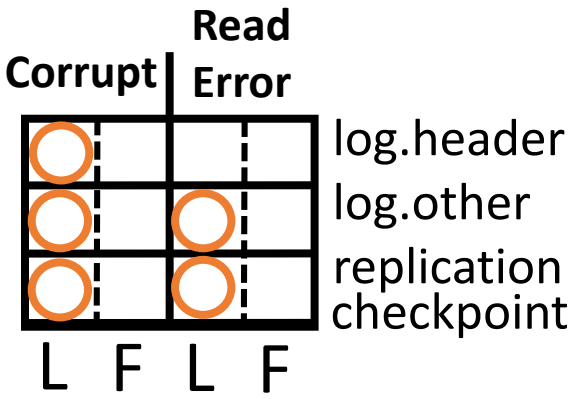
Corruption

Redundancy Does not Provide Fault Tolerance

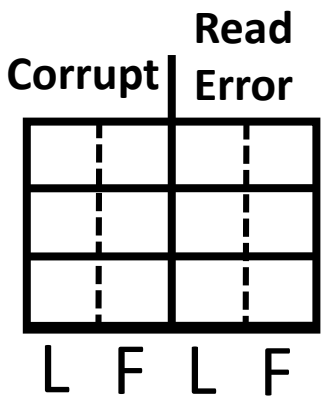
Redis Read



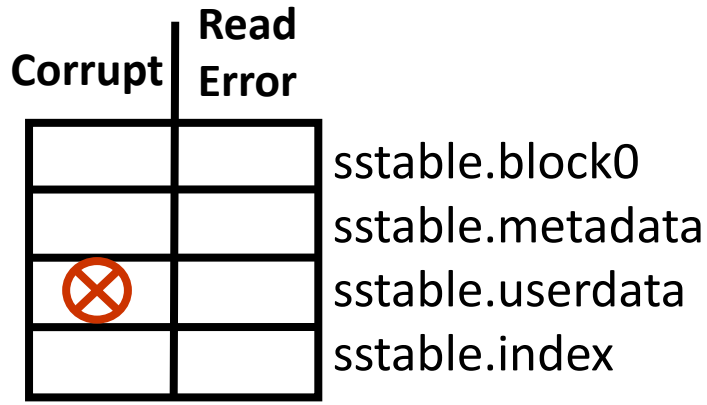
Kafka Read



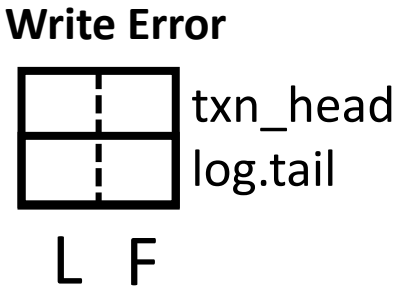
Kafka Write



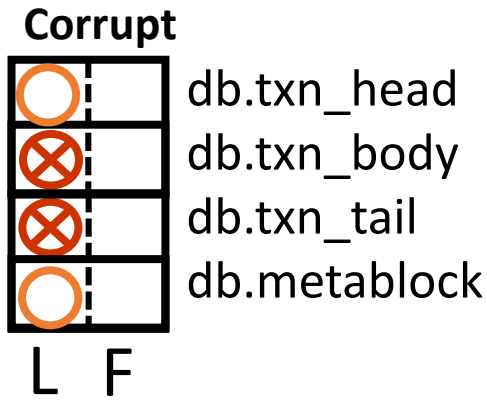
Cassandra Read



ZooKeeper Write



RethinkDB Read

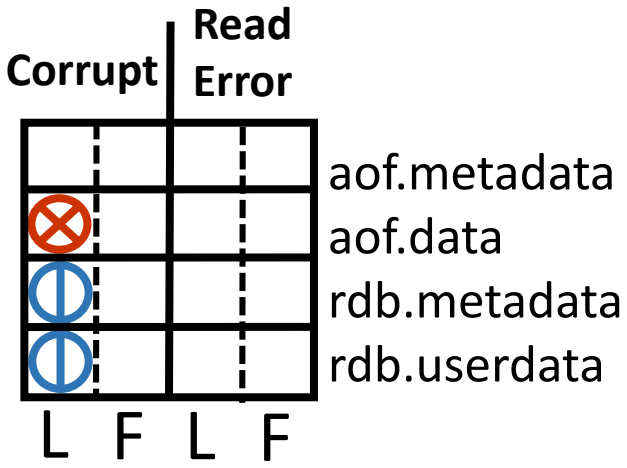


Corruption

Data Loss

Redundancy Does not Provide Fault Tolerance

Redis Read



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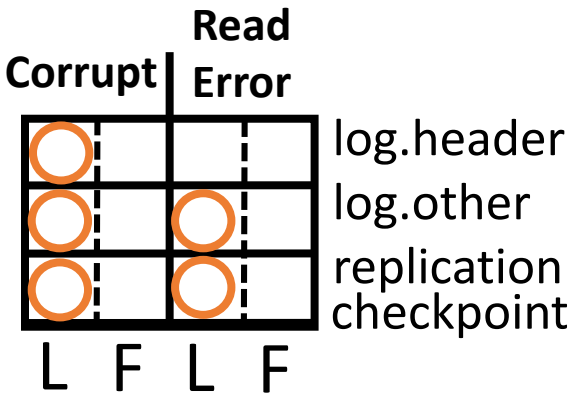
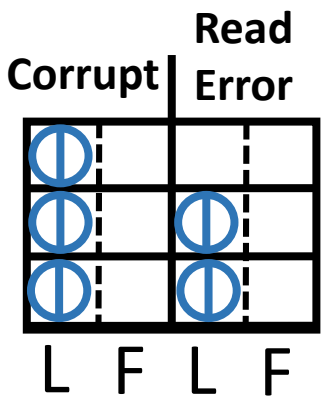
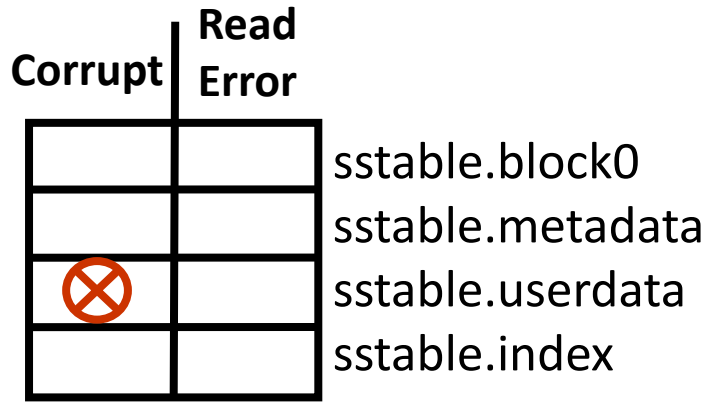


Kafka Write



Cassandra Read



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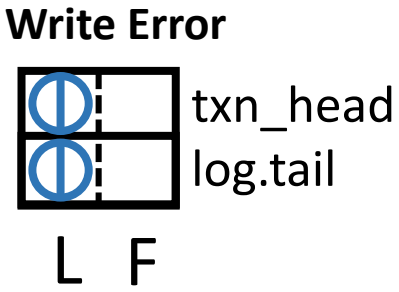
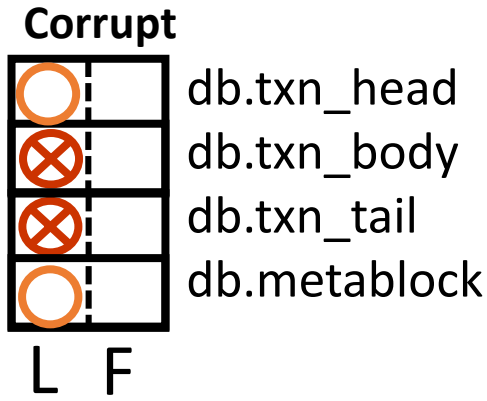
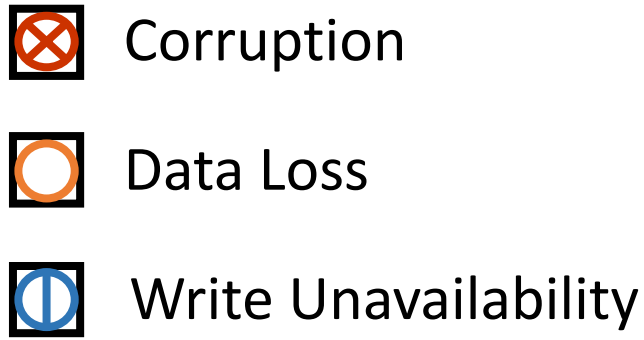


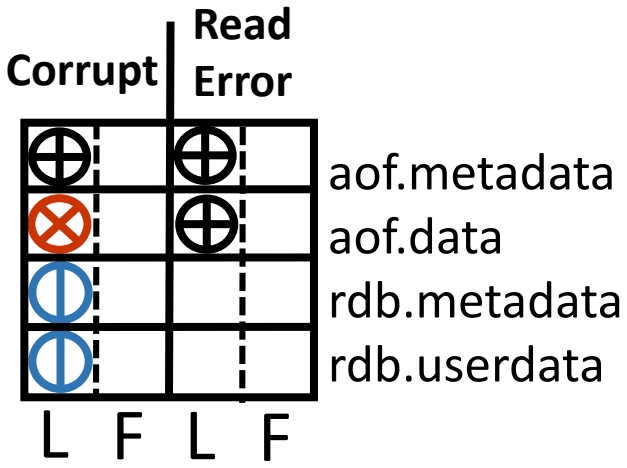
RethinkDB Read





Redundancy Does not Provide Fault Tolerance

Redis Read



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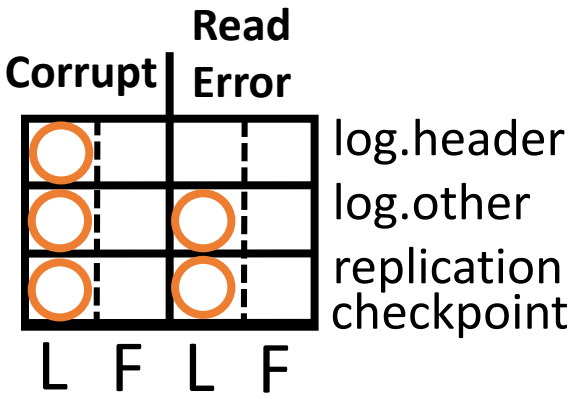

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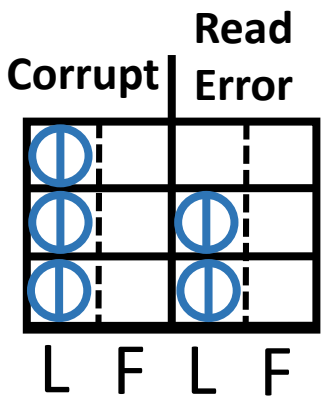
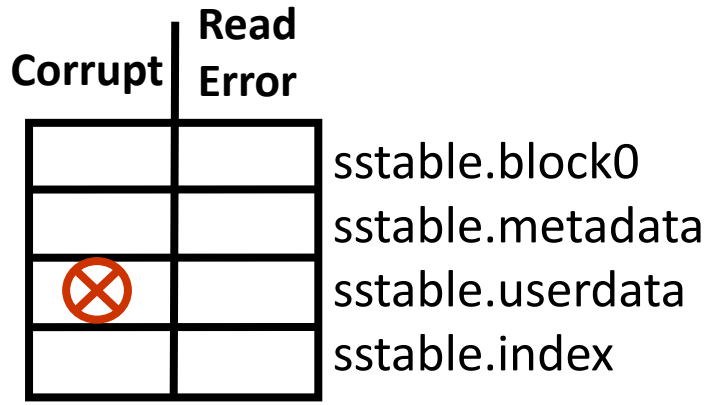
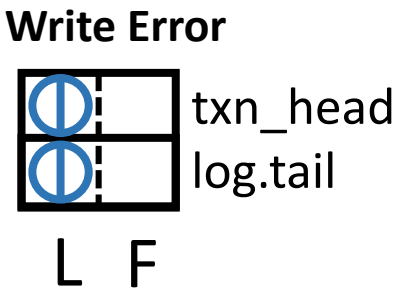


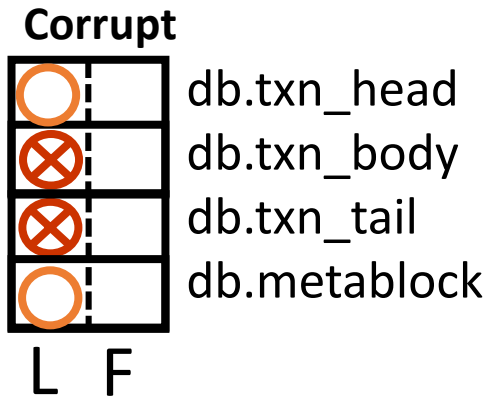
Cassandra Read



ZooKeeper Write



RethinkDB Read



Corruption

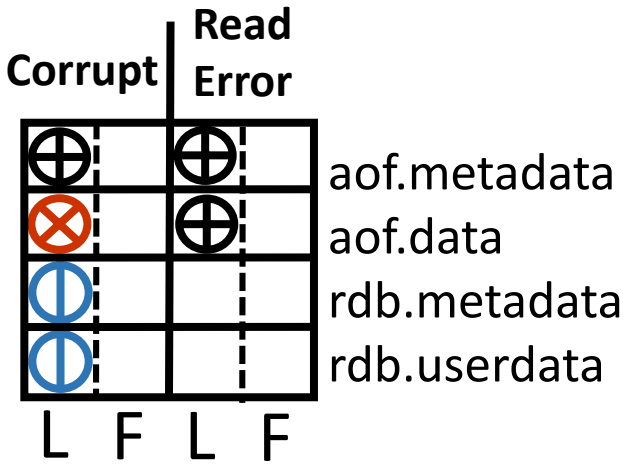
Unavailability

Data Loss

Write Unavailability

Redundancy Does not Provide Fault Tolerance

Redis Read



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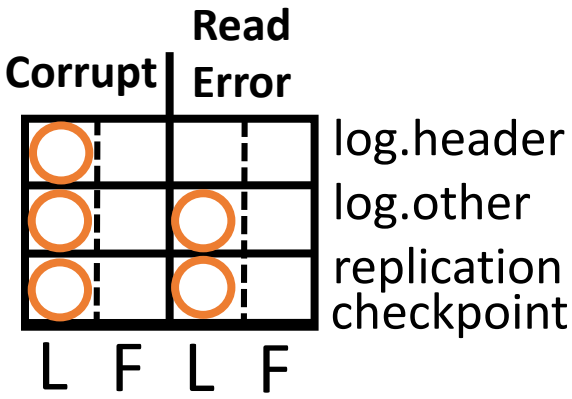

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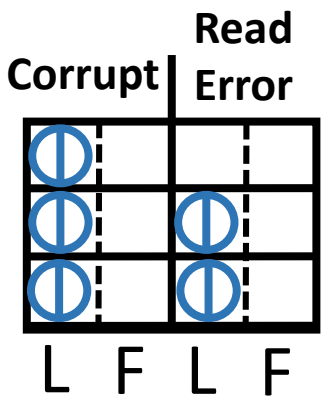

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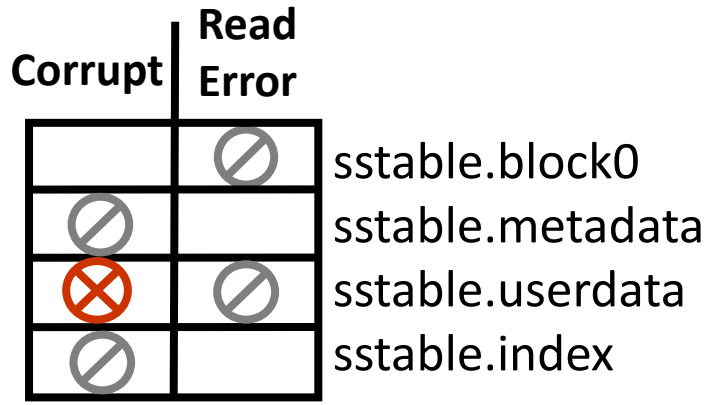

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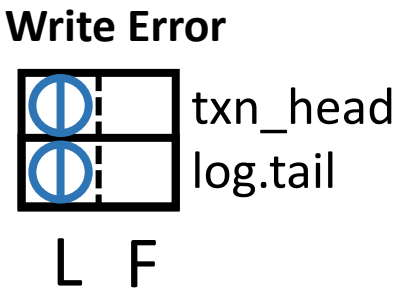
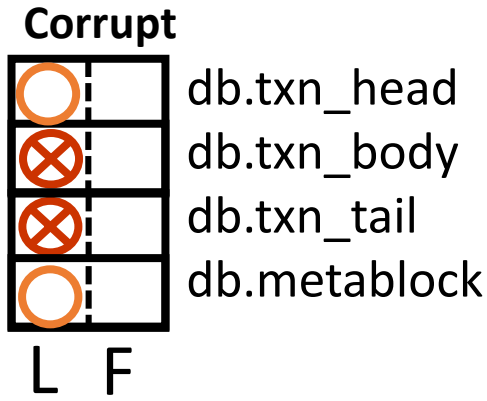
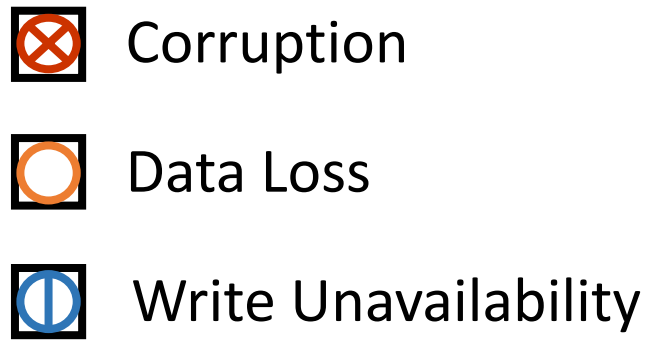
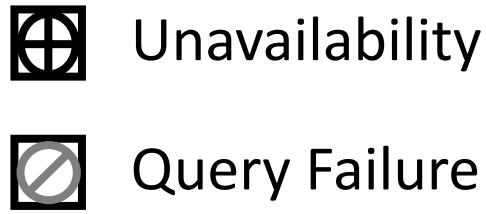


RethinkDB Read

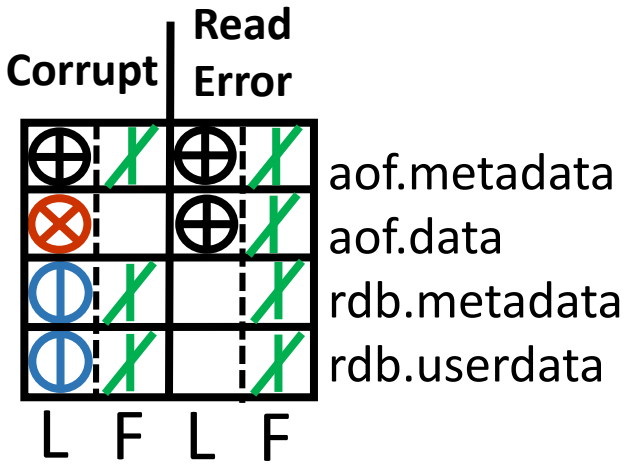






Redundancy Does not Provide Fault Tolerance

Redis Read



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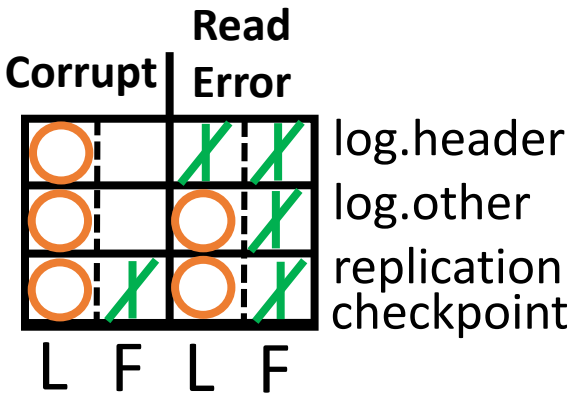

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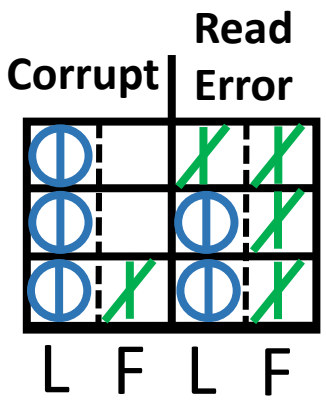
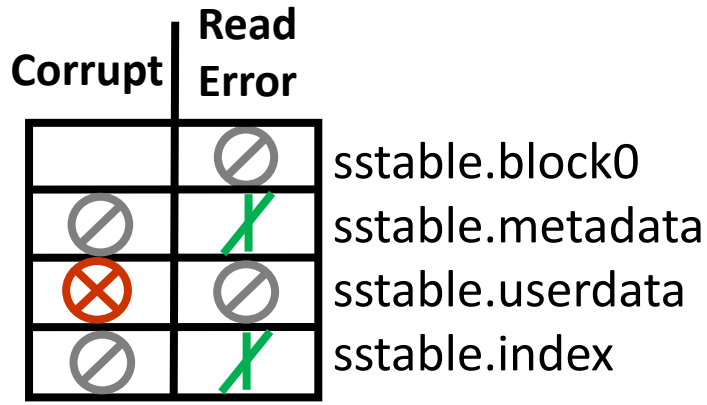
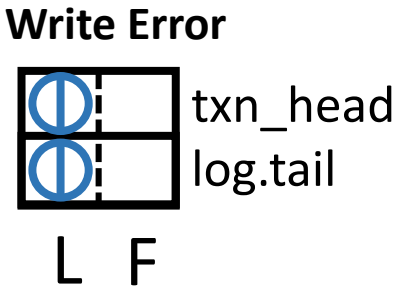


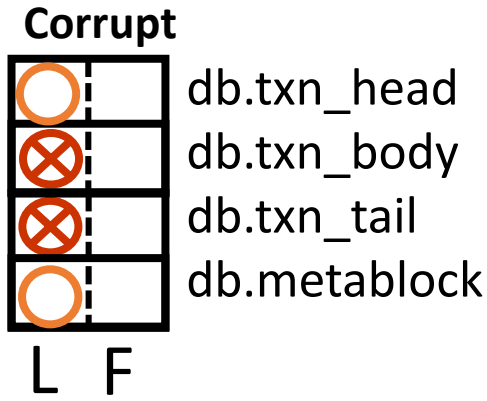
Cassandra Read

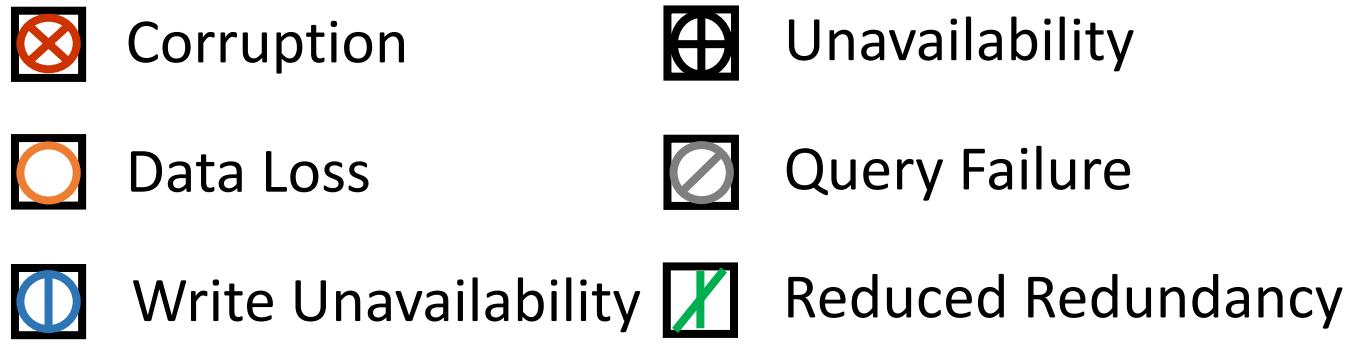


ZooKeeper Write



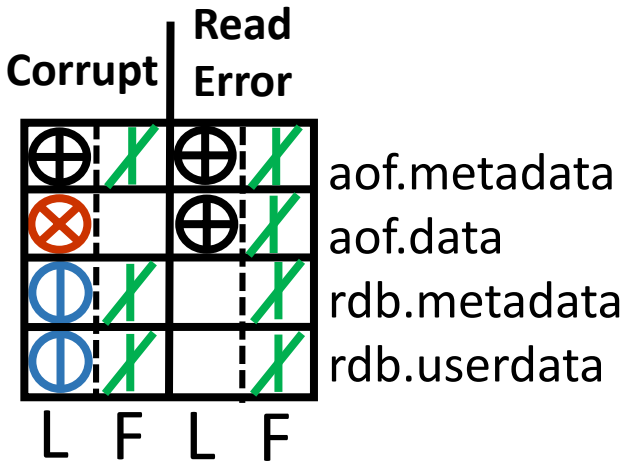
RethinkDB Read



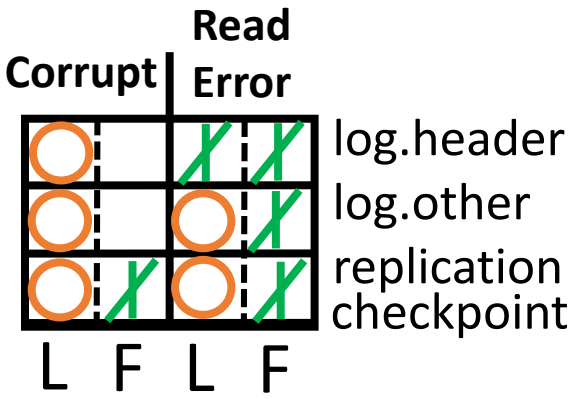


Redundancy Does not Provide Fault Tolerance

Redis Read



Kafka Read



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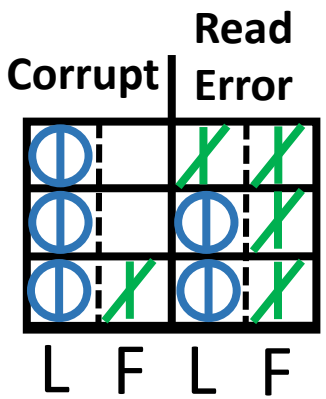
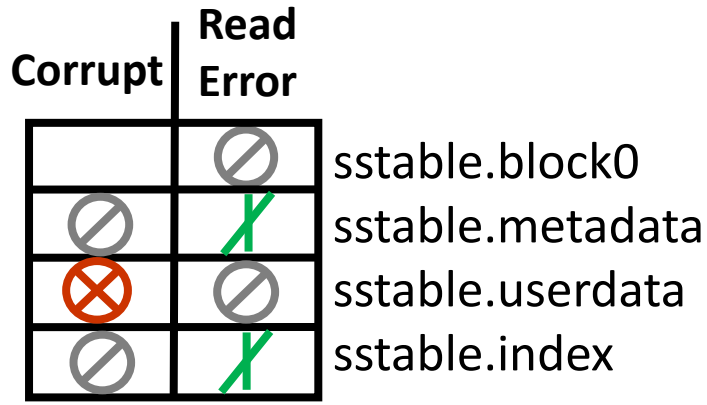
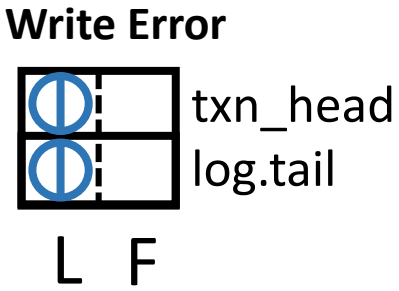


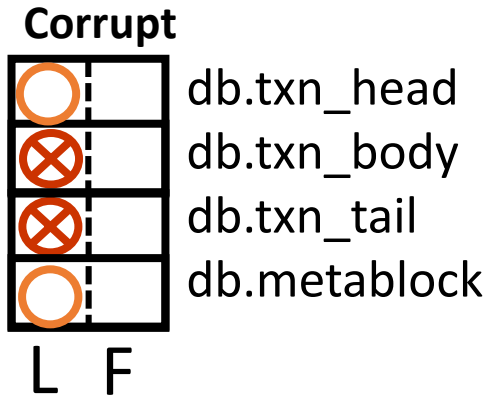
Cassandra Read

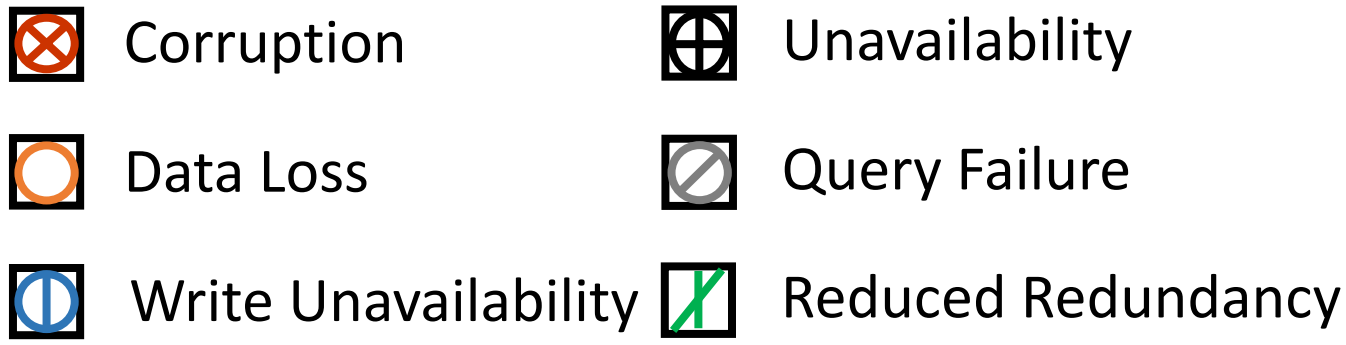


ZooKeeper Write



RethinkDB Read

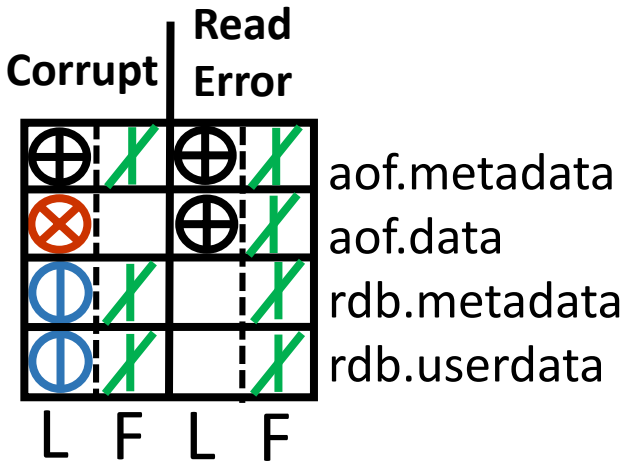




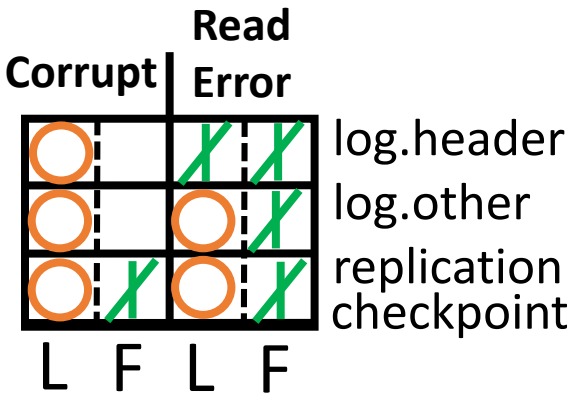
Harmful global effects despite redundancy

Redundancy Does not Provide Fault Tolerance

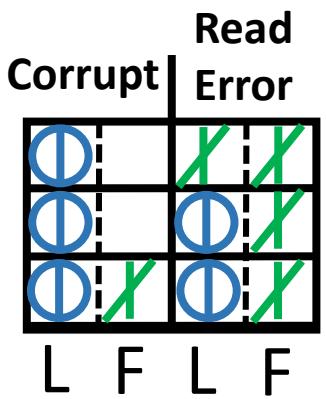
Redis Read



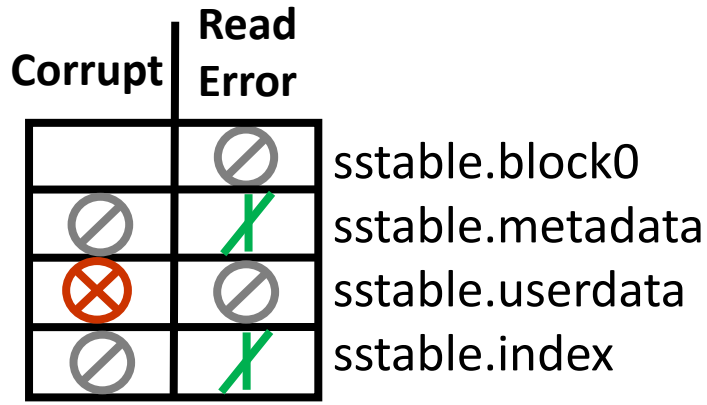
Kafka Read



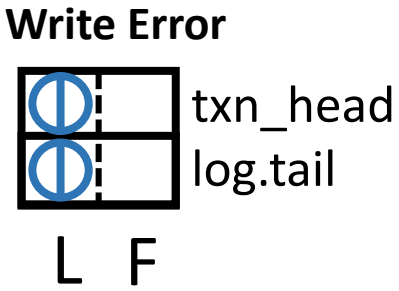
Kafka Write



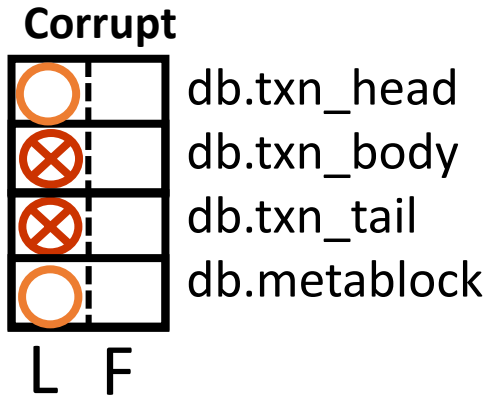
Cassandra Read

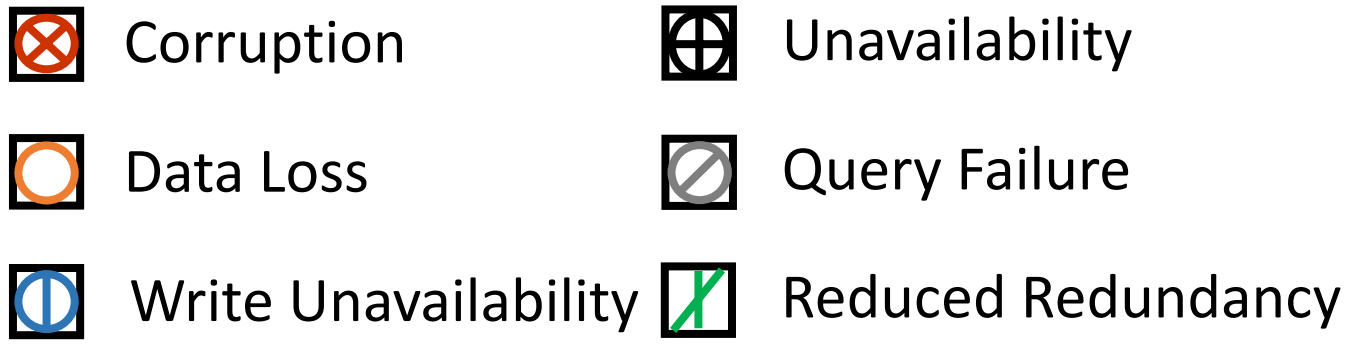


ZooKeeper Write



RethinkDB Read





Harmful global effects despite redundancy

Not simple implementation bugs - fundamental problems across multiple systems!

Outline

Introduction

Fault Injection

System Behavior Analysis

Major Results

Observations Across Systems

- Faults are Often Undetected Locally
- Crashing: Common Local Reaction
- Crash and Corruption Handling are Entangled
- Unsafe interaction between local and global protocols

Conclusion

Faults are Often Undetected Locally

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Undetected faults may lead to harmful global effect

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- Locally undetected corruption → global silent corruption

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Cassandra: Locally Undetected Fault

Faults are Often Undetected Locally

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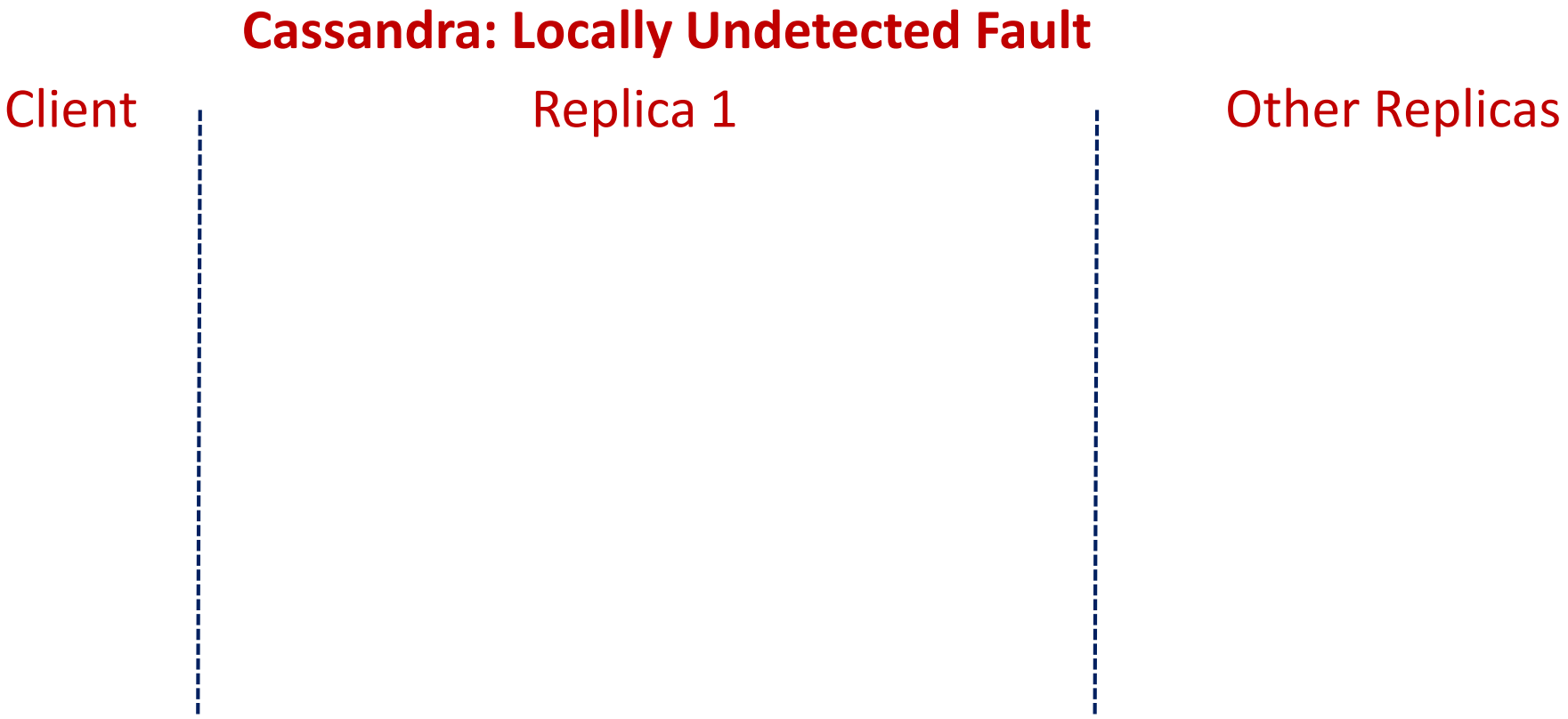

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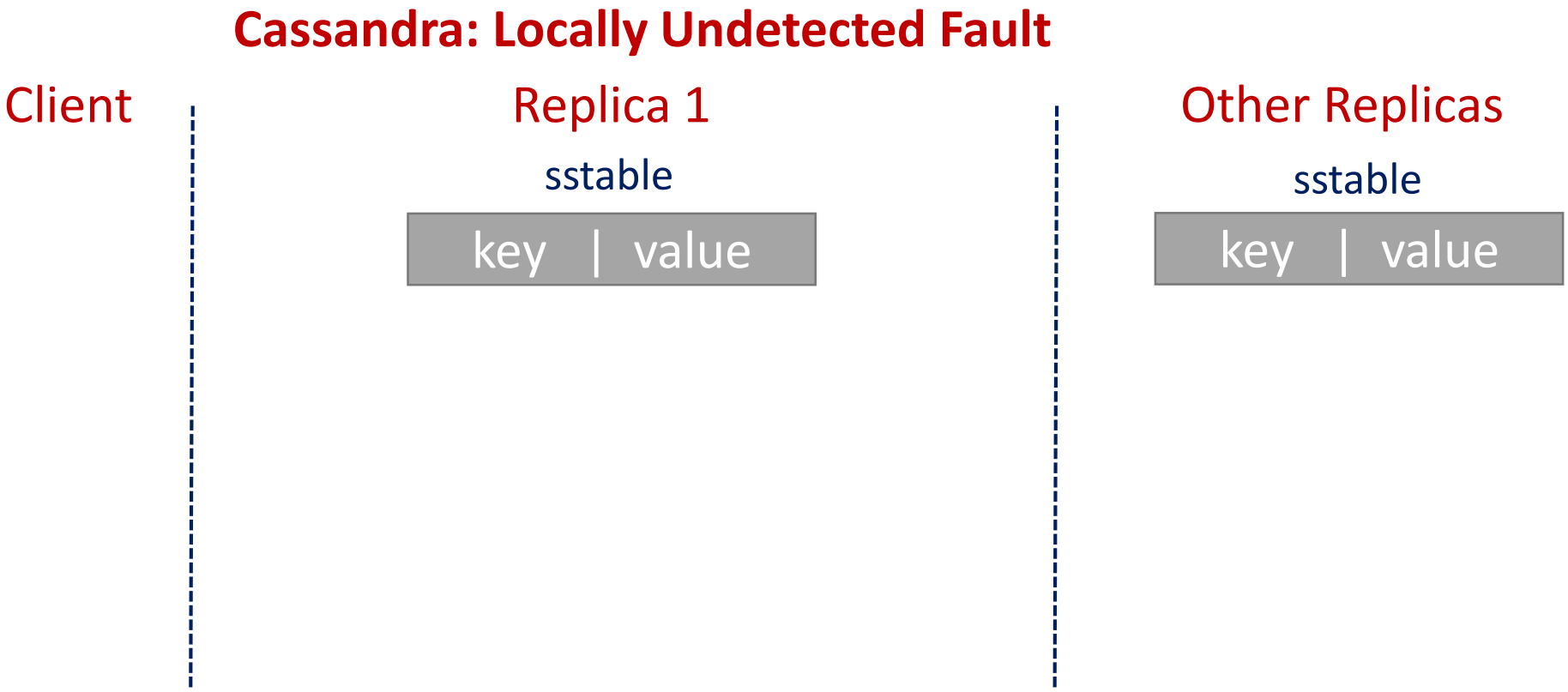

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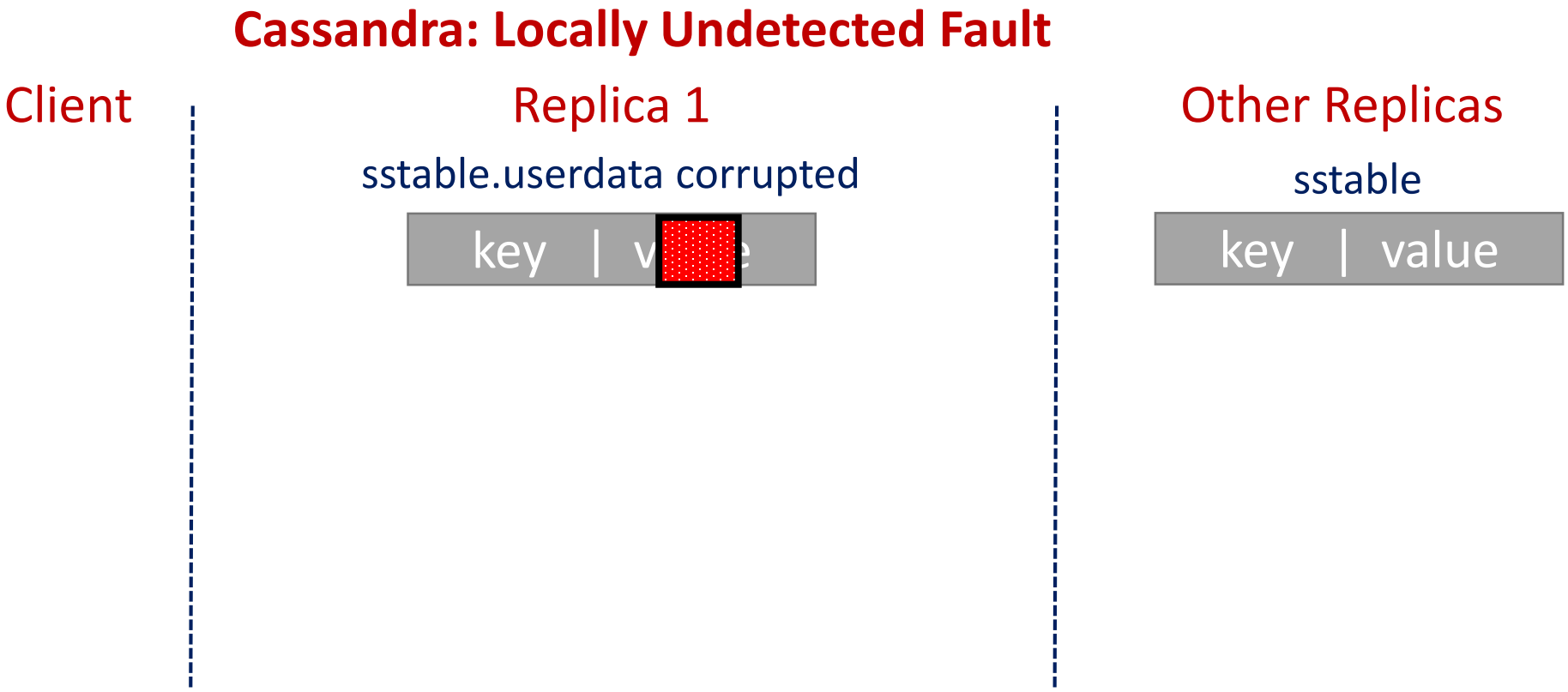

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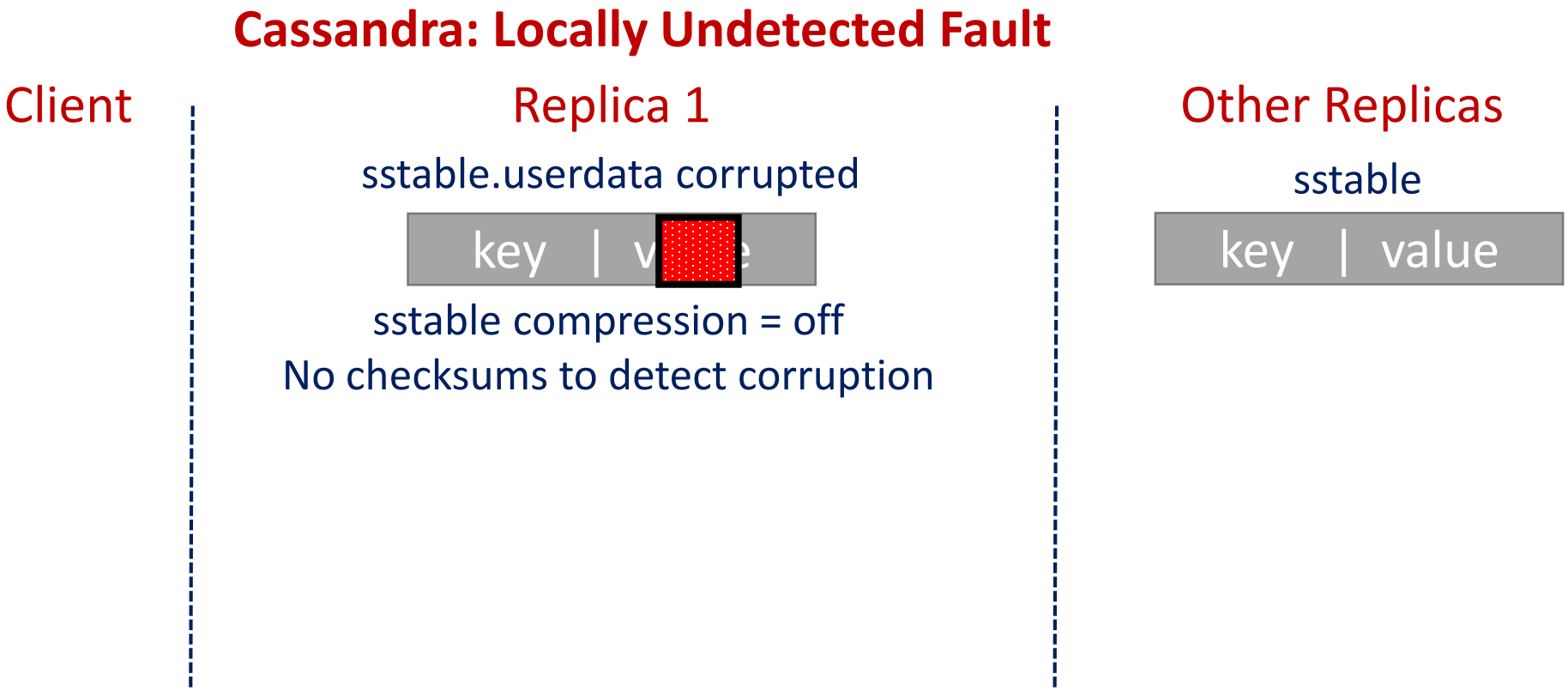

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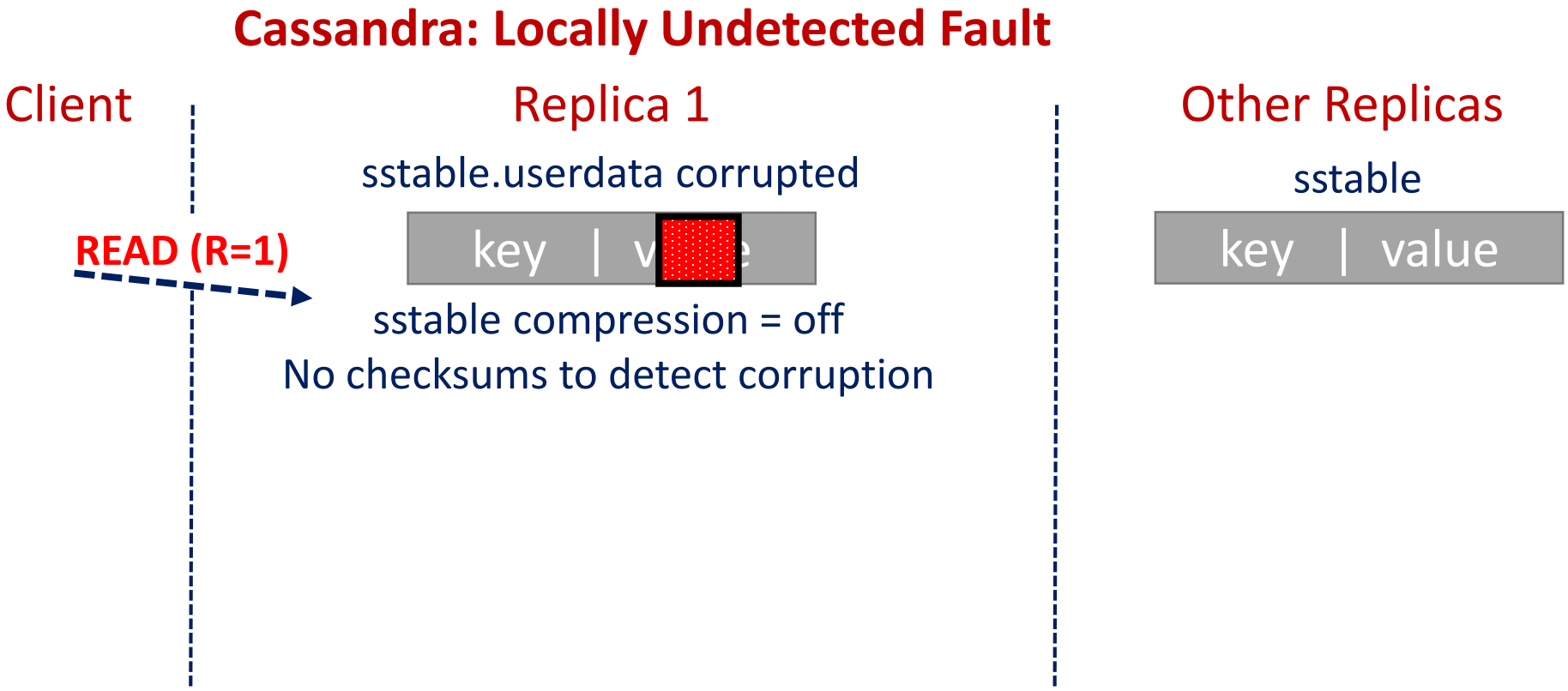

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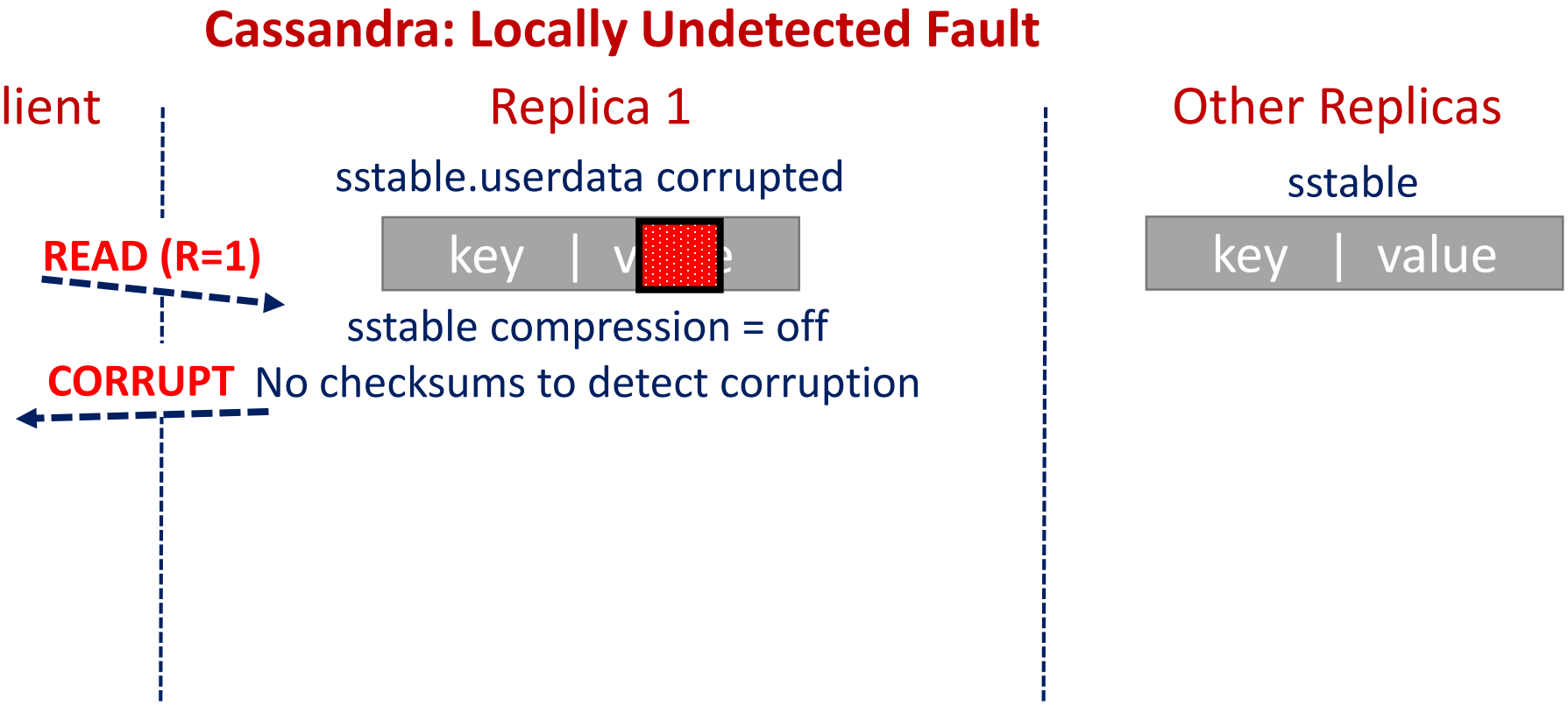

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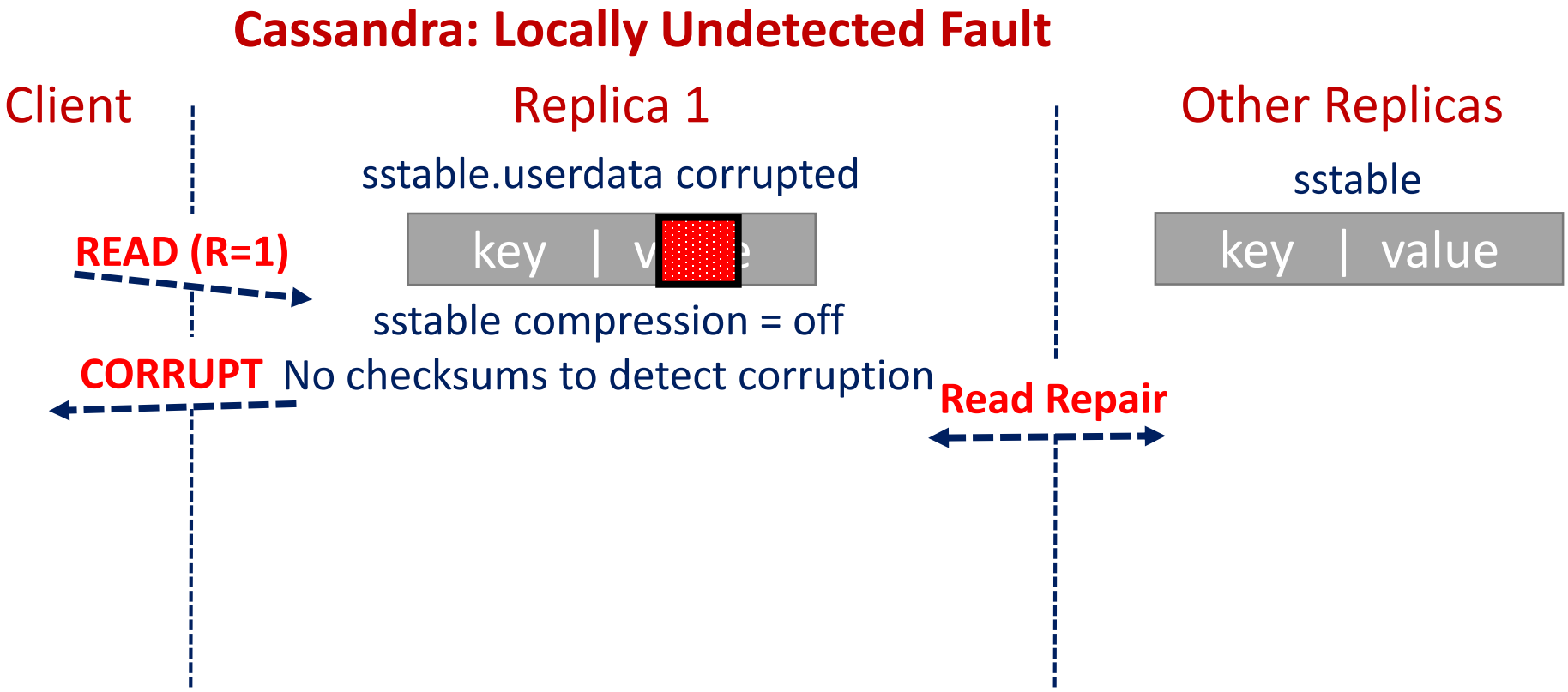

Faults are Often Undetected Locally

Undetected faults may lead to harmful global effect

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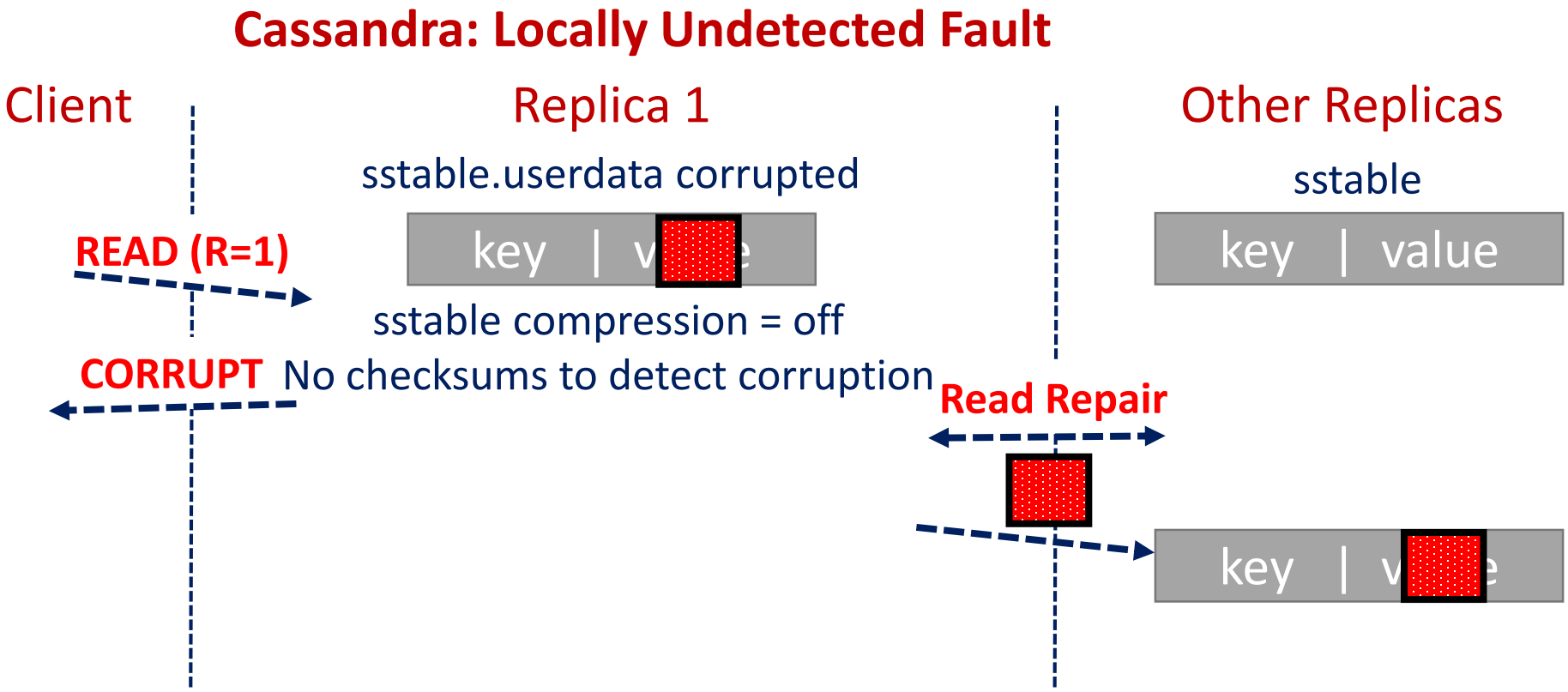

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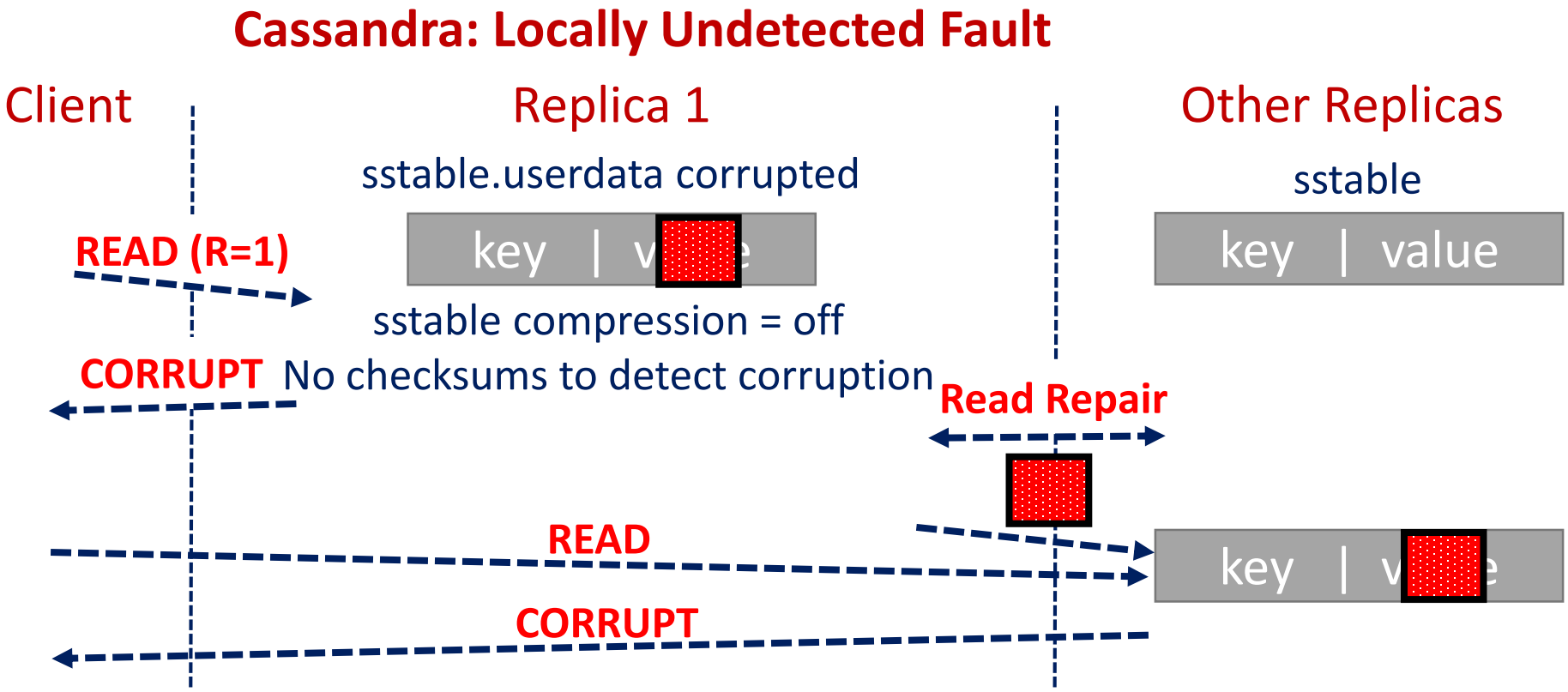

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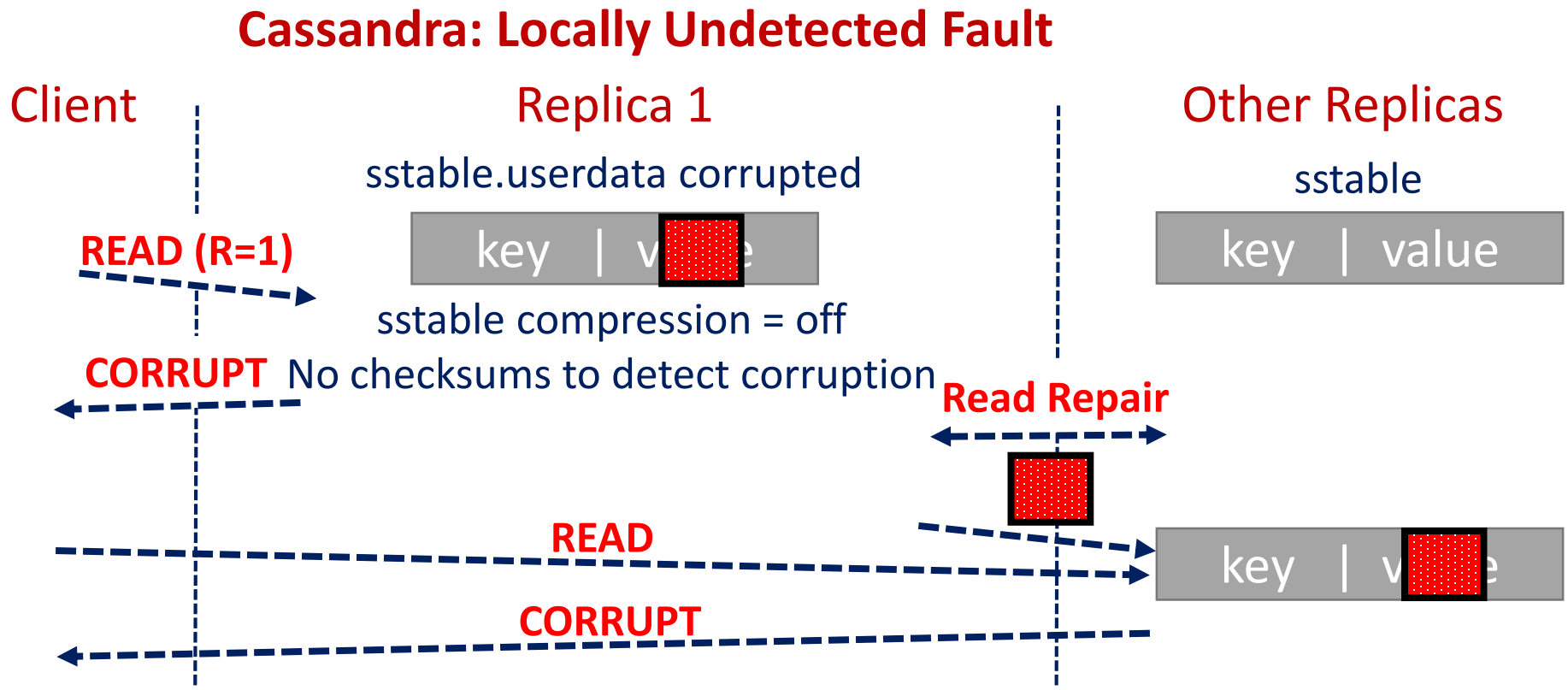

Need for end-to-end integrity and error handling

Crashing - Common Local Reaction

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Many systems that reliably detect fault simply crash on encountering faults

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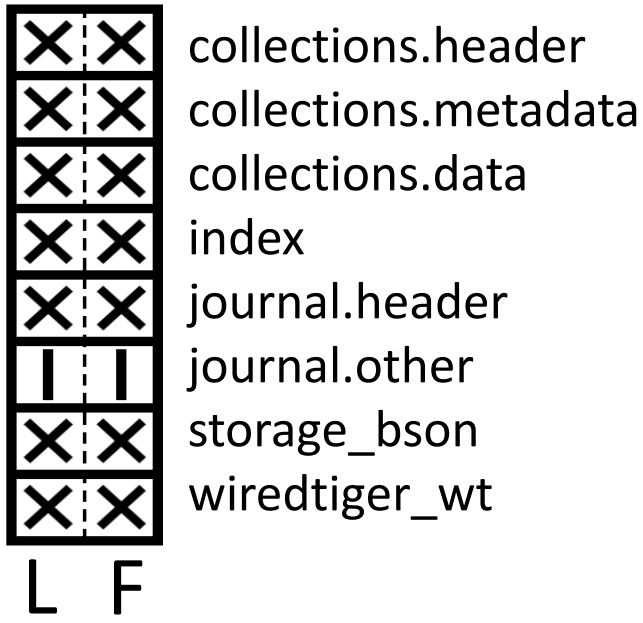
Block Corruption during Read Workloads

MongoDB



☒ Crash

L Leader

F Follower

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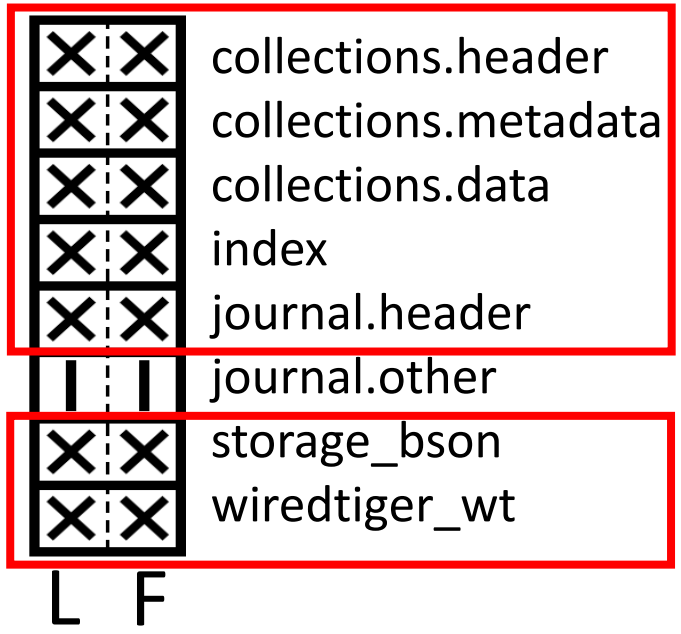

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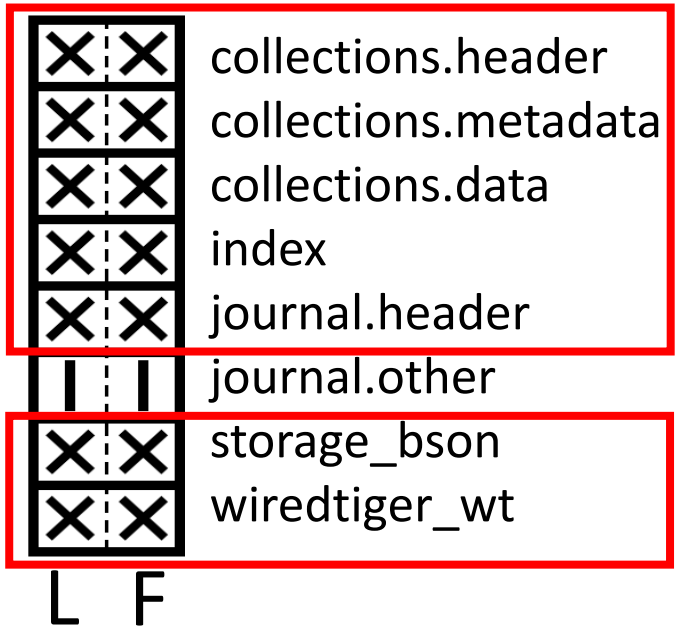
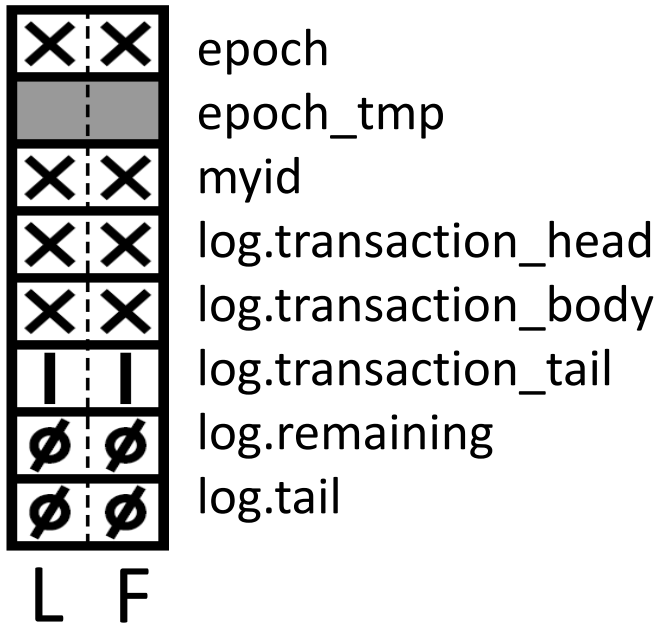


ZooKeeper



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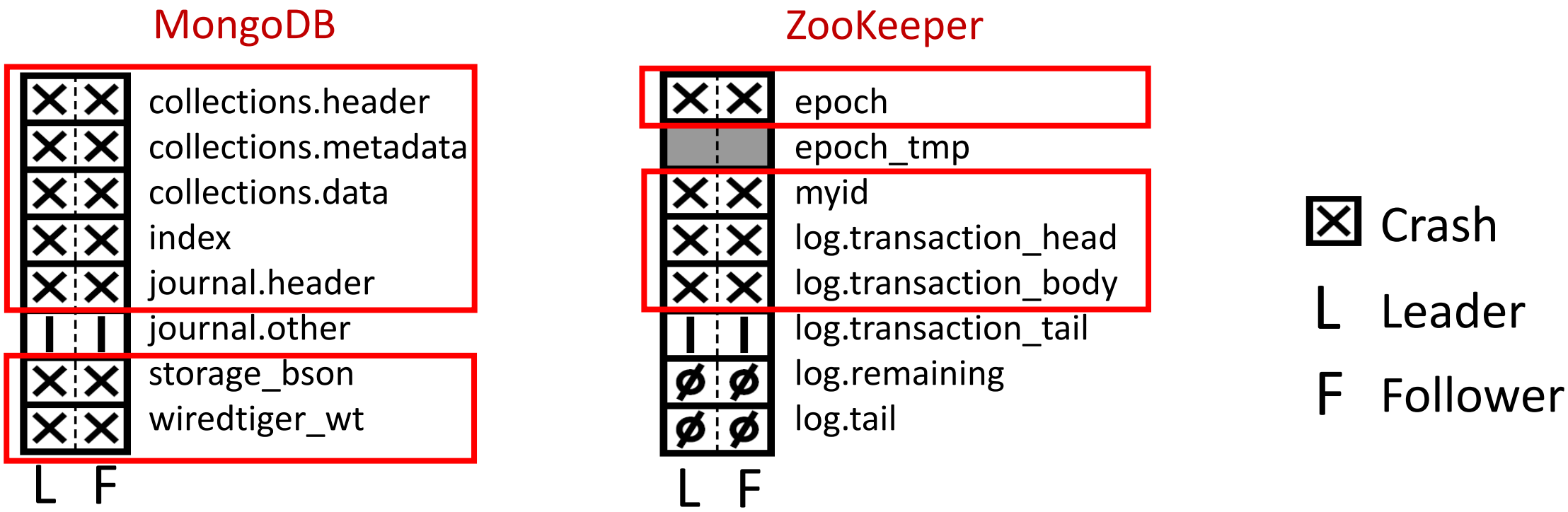

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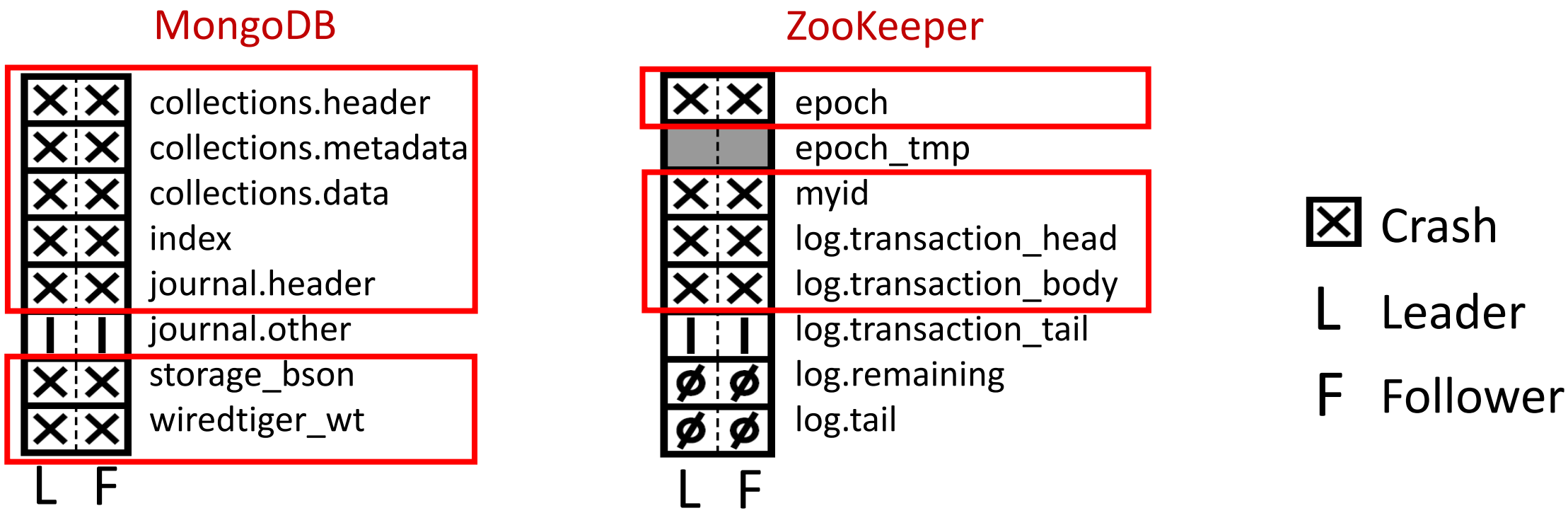

Crashing leads to reduced redundancy and imminent unavailability

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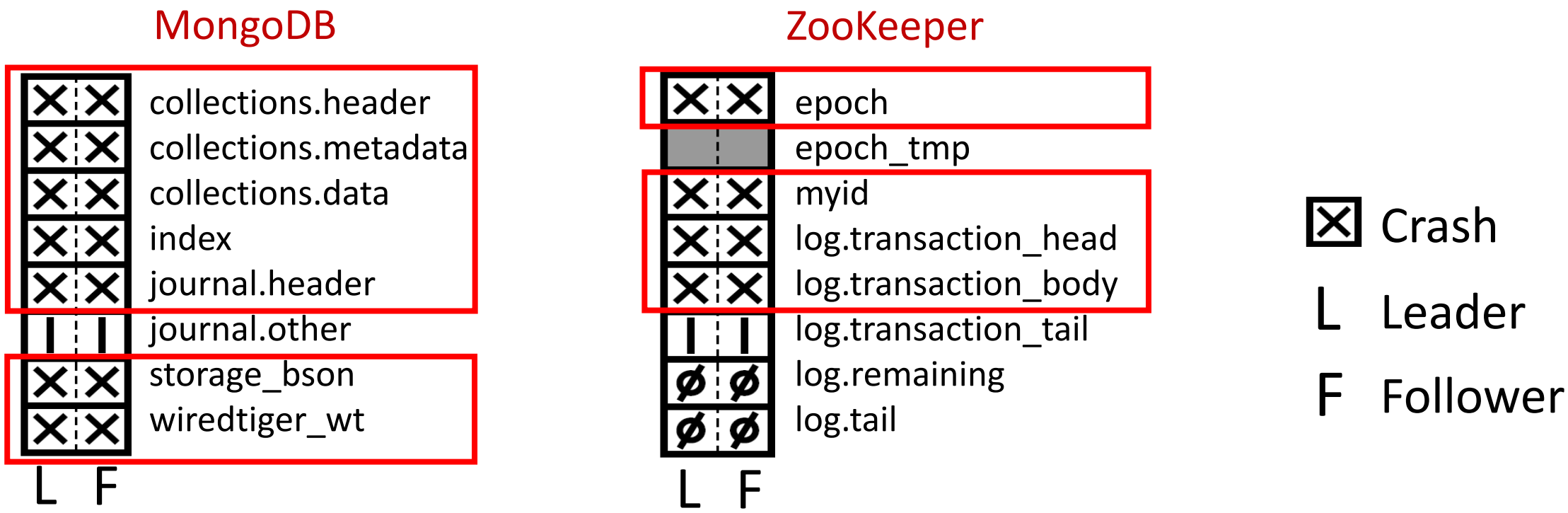

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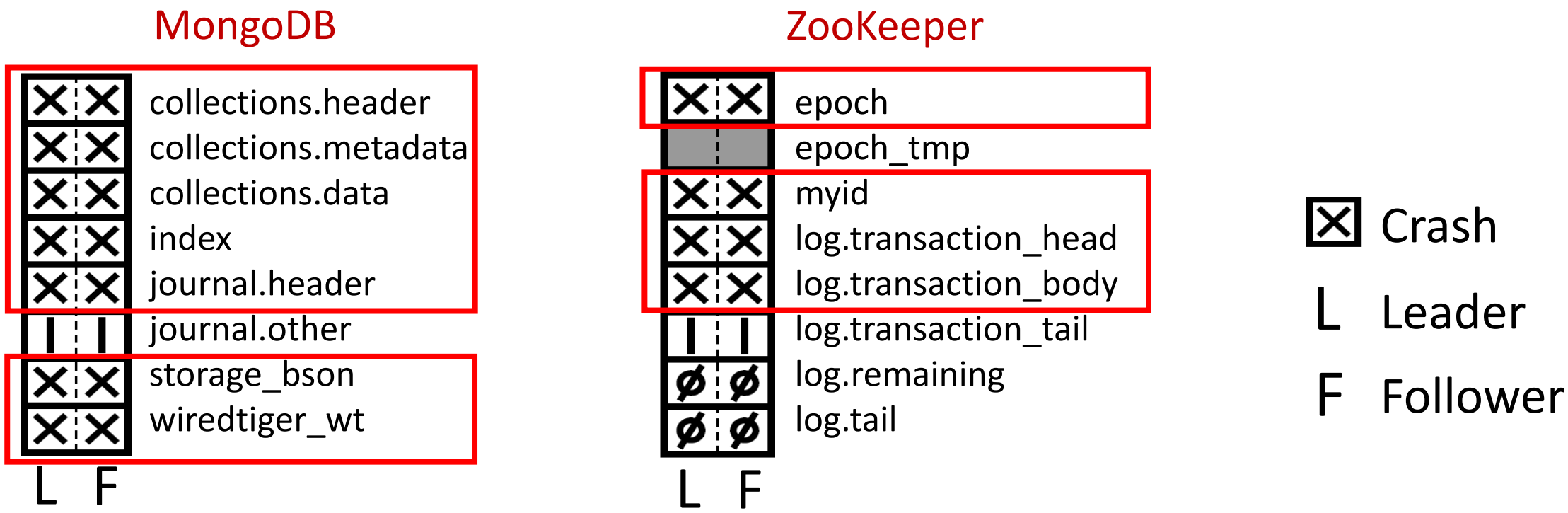

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Redundancy underutilized!

Crash and Corruption Handling are Entangled

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Kafka Message Log

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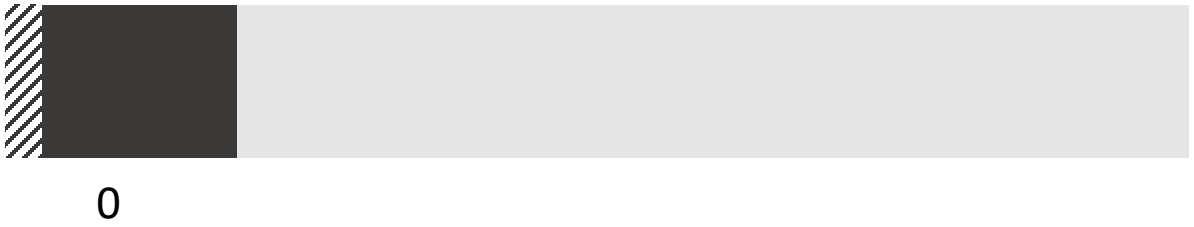
Kafka Message Log



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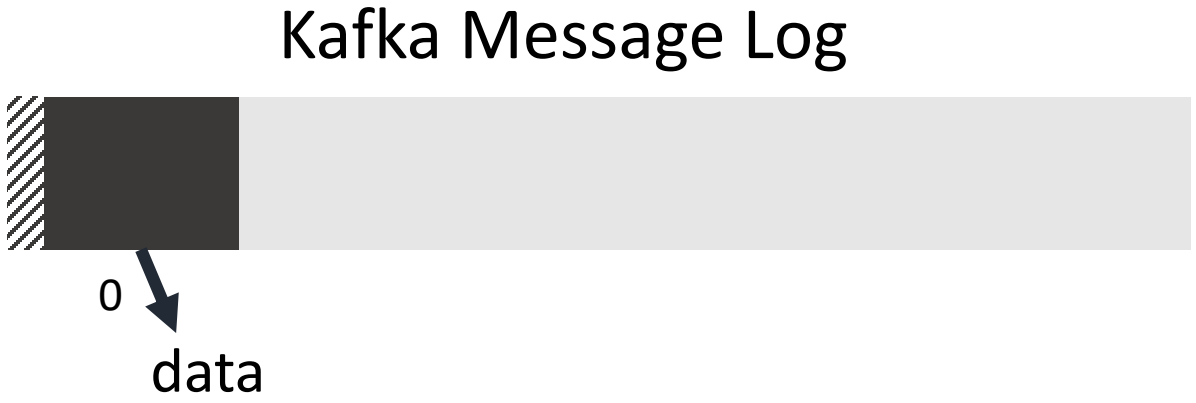

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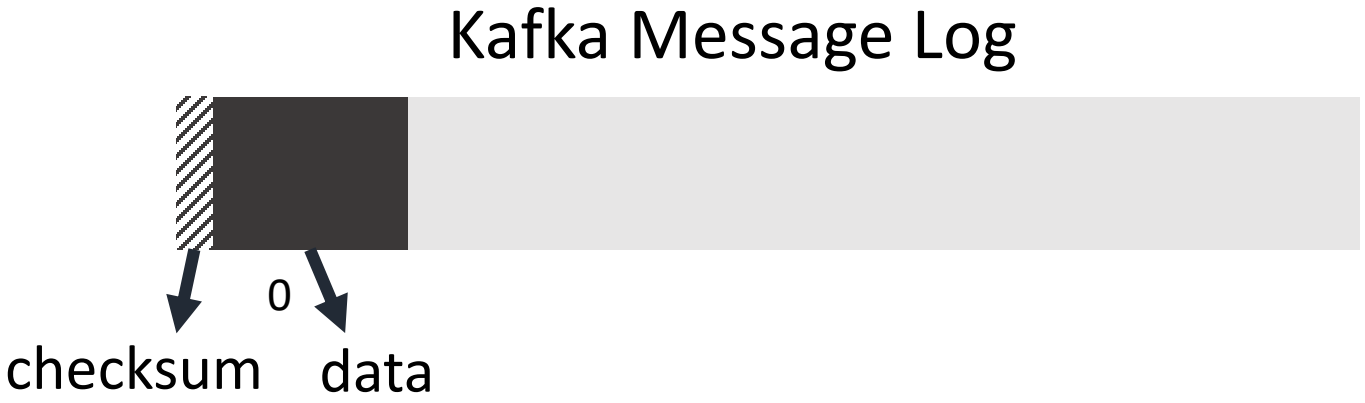

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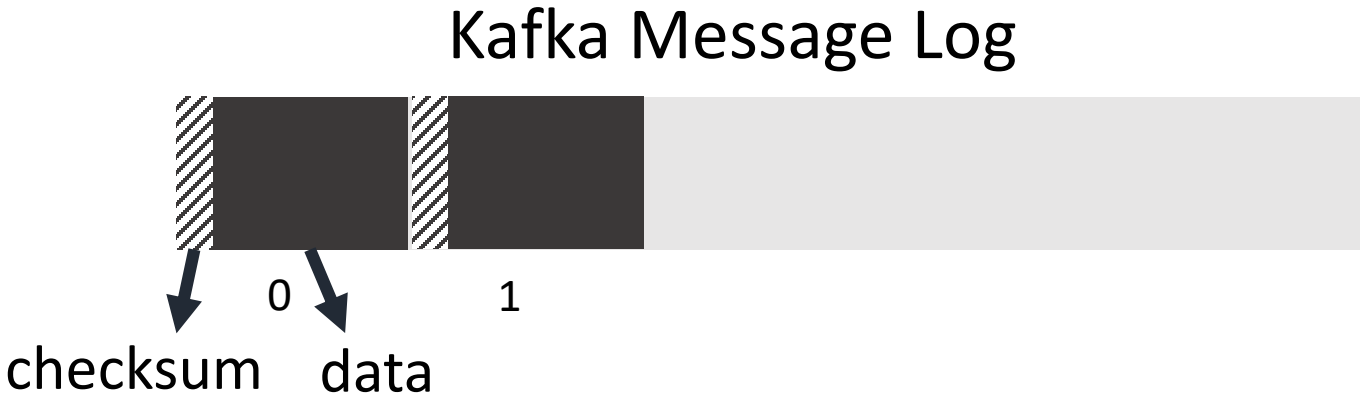

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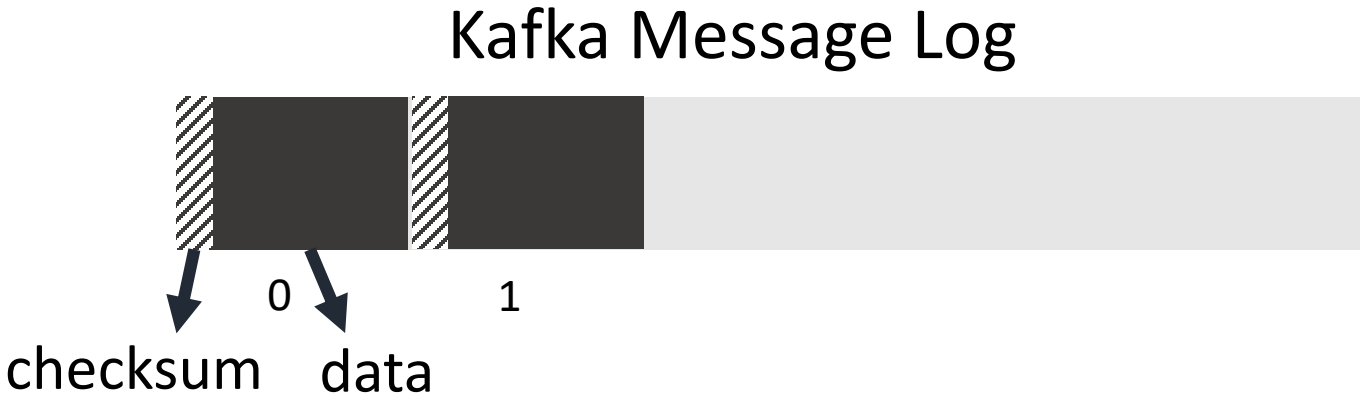
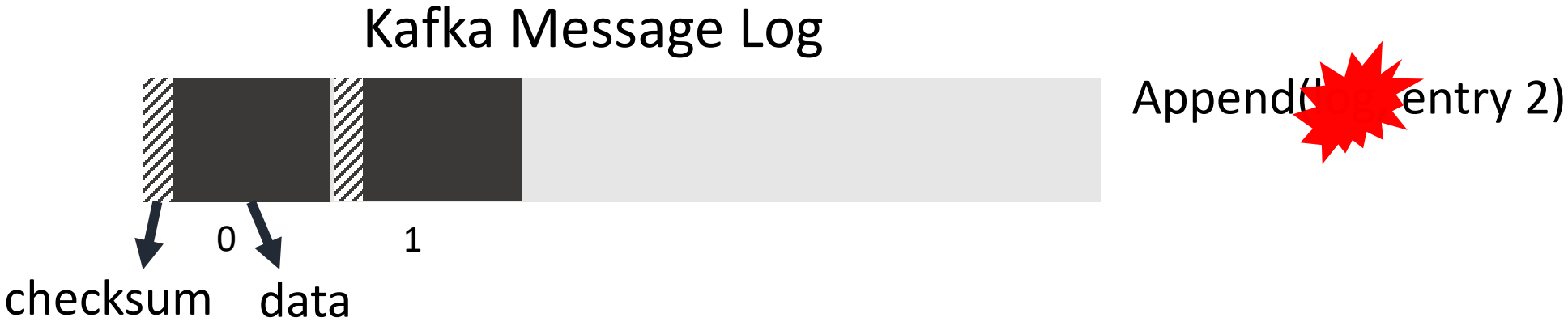


Append(log, entry 2)

Crash and Corruption Handling are Entangled



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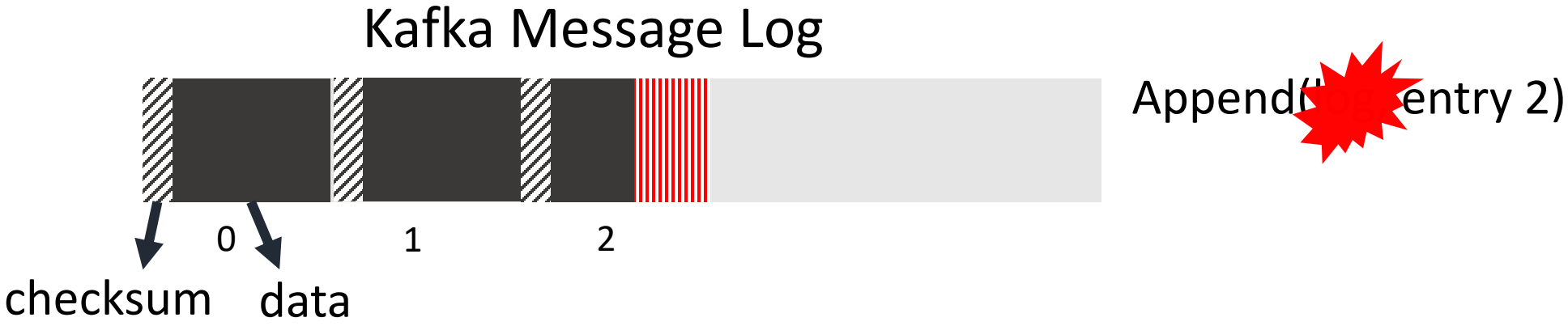

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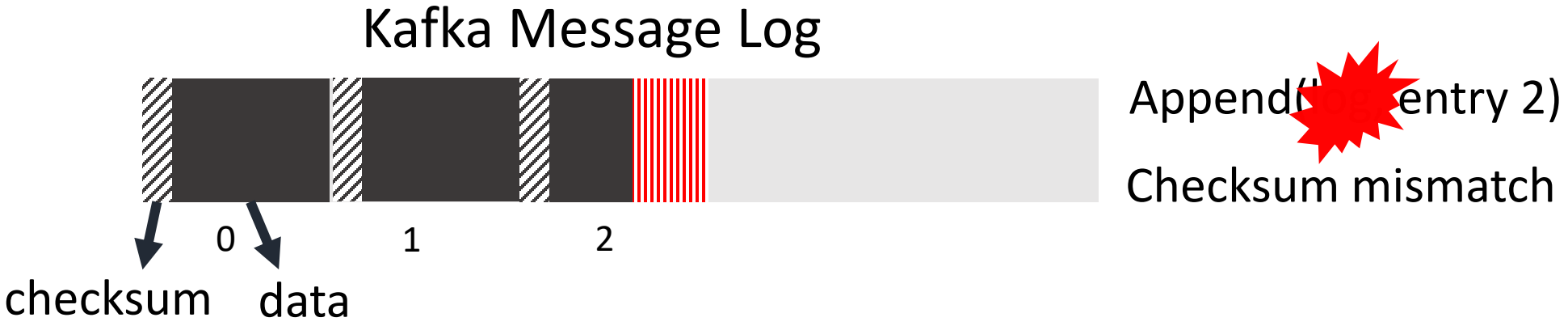

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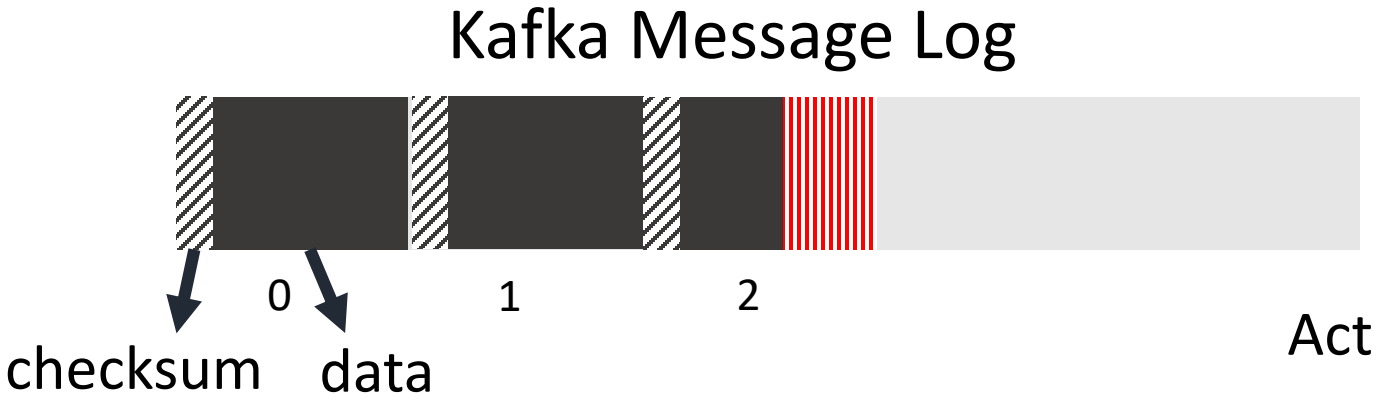

Append([illegible] entry 2)

Checksum mismatch

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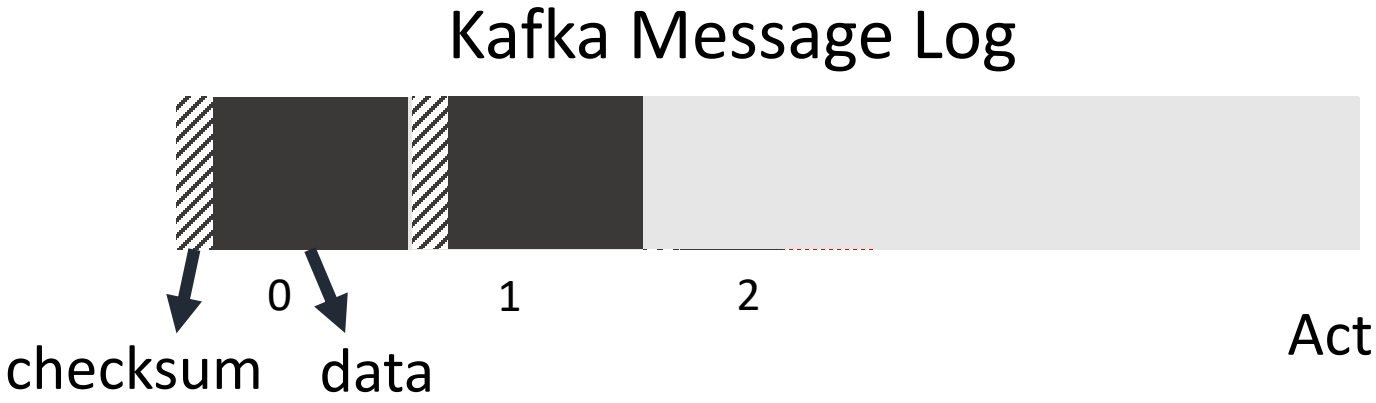

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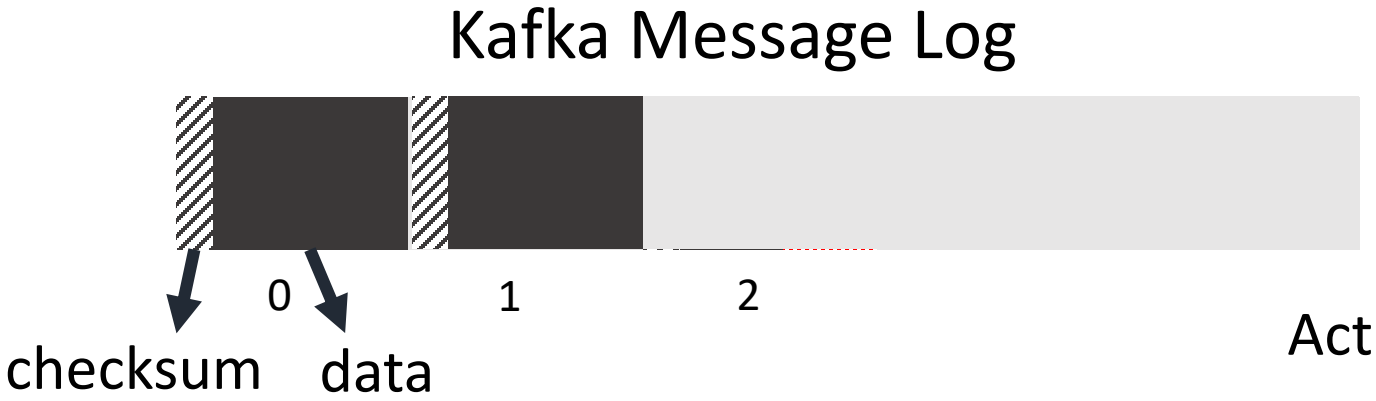

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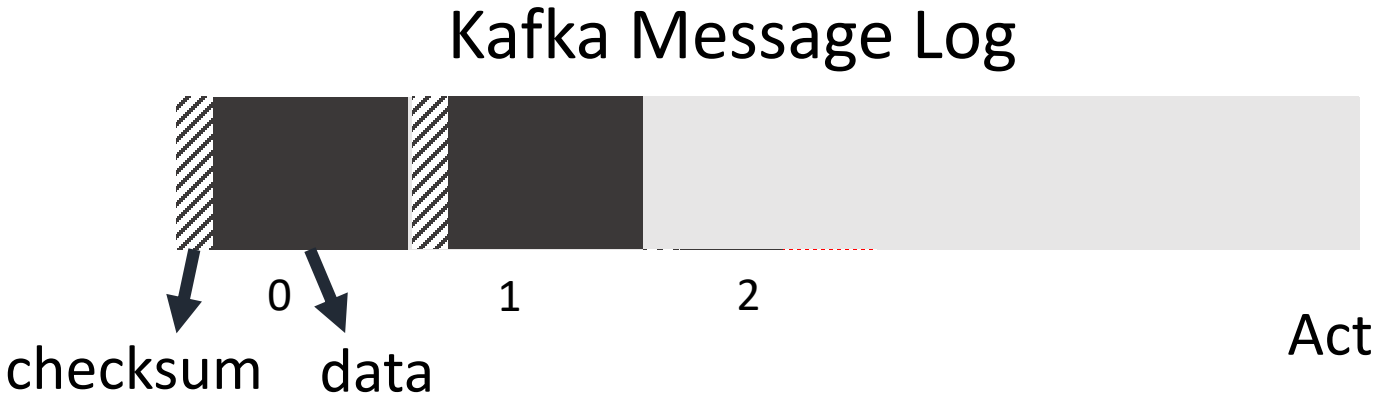

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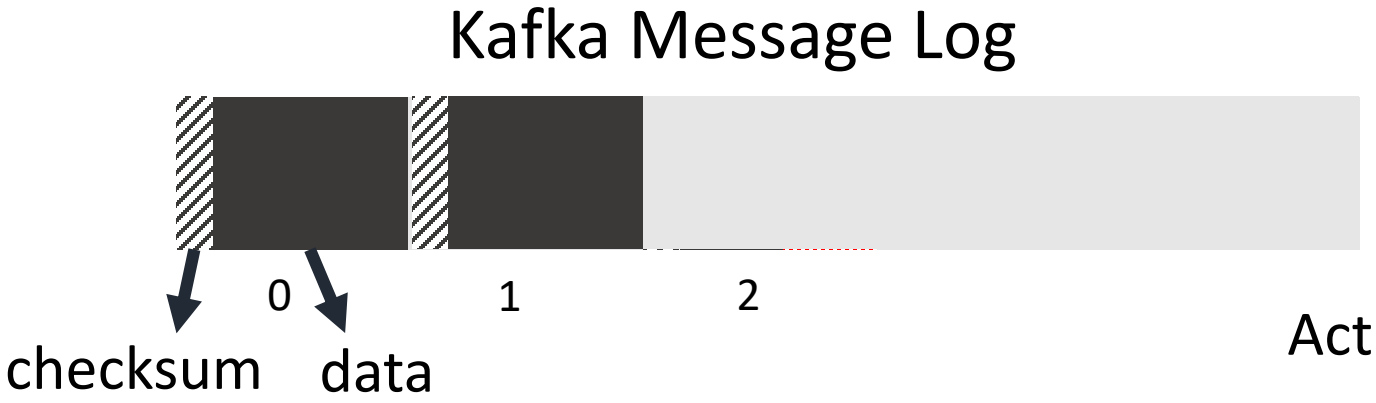

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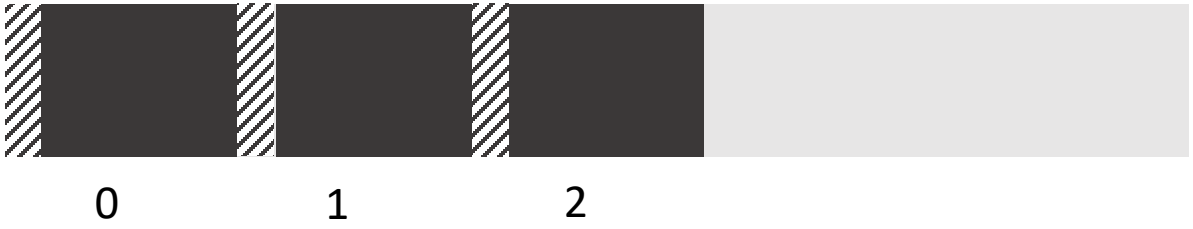

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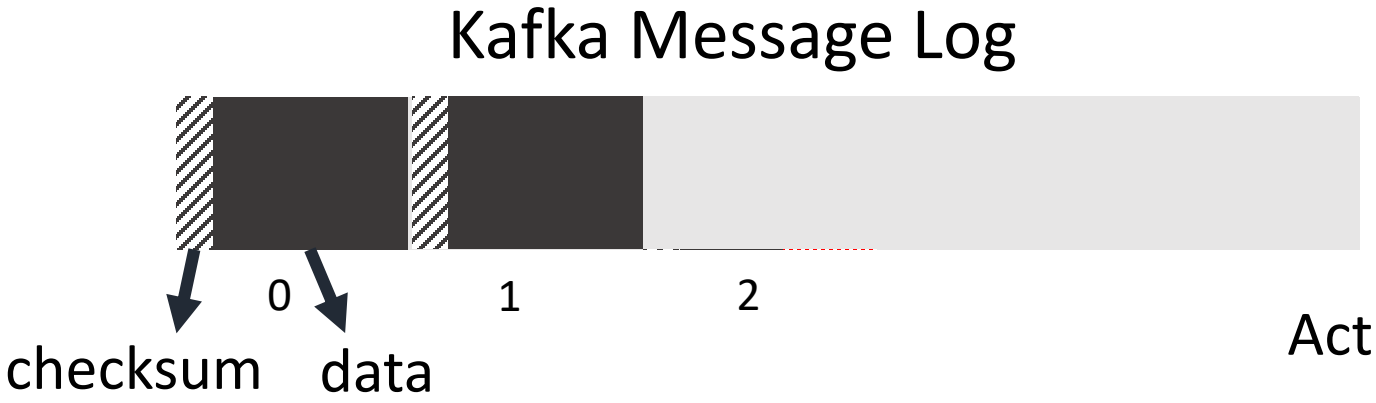

Append(bad entry 2)

Checksum mismatch

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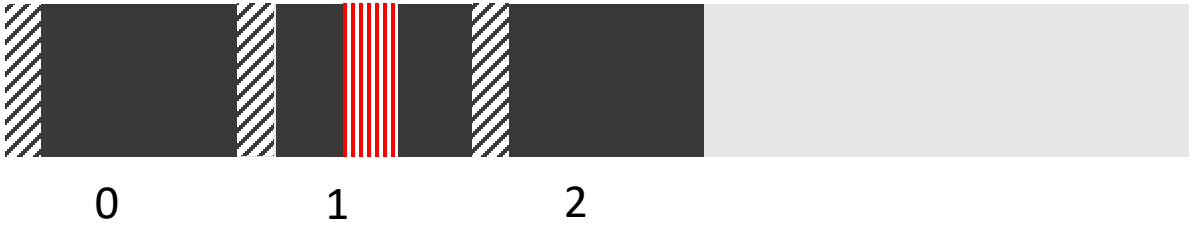
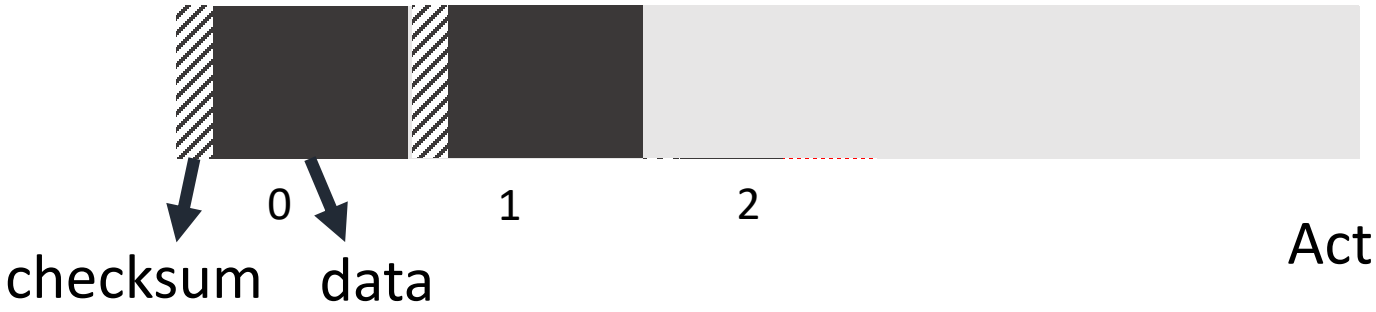


Crash and Corruption Handling are Entangled

Kafka Message Log



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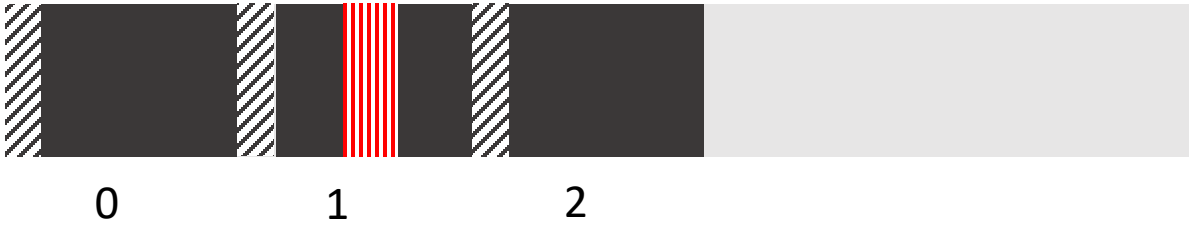
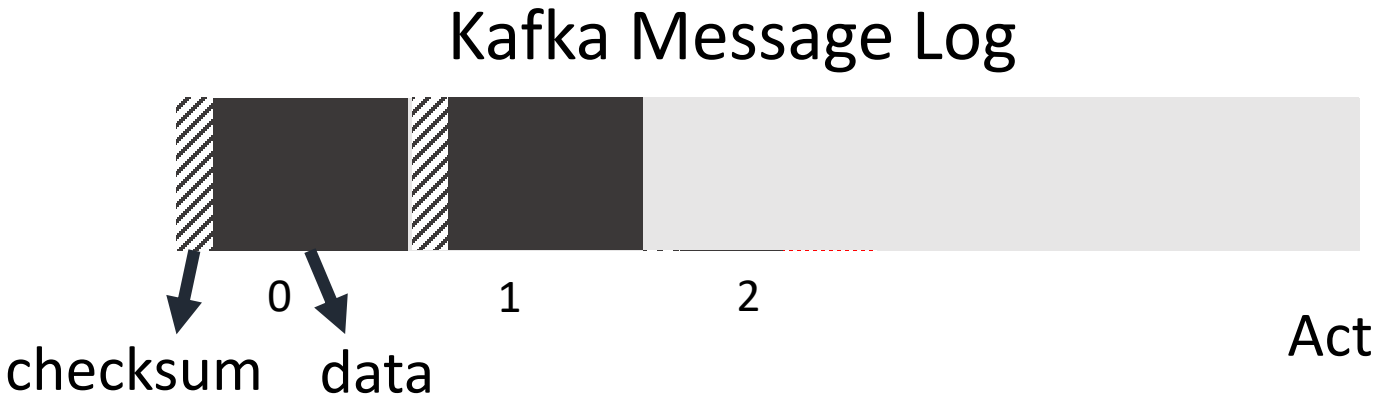


Disk corruption

Crash and Corruption Handling are Entangled



Append(log entry 2)

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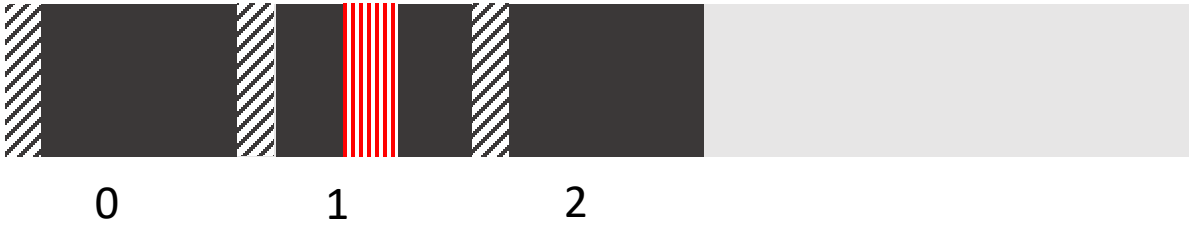

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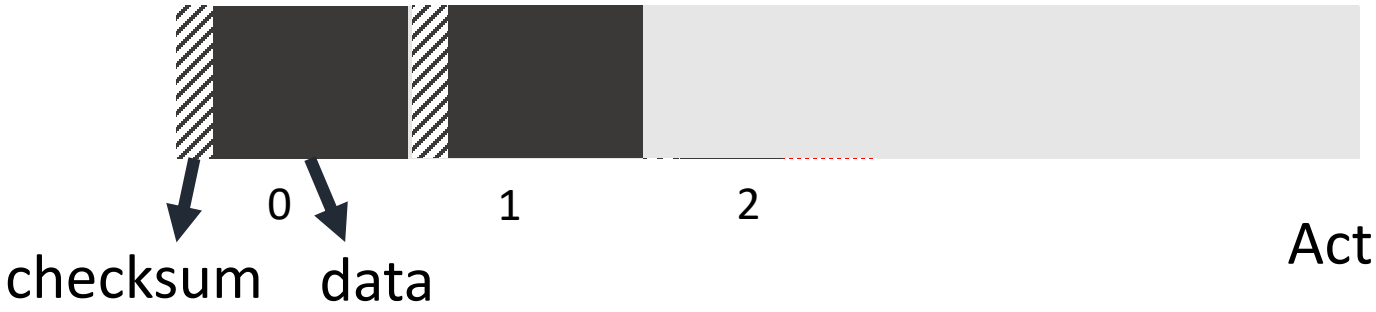

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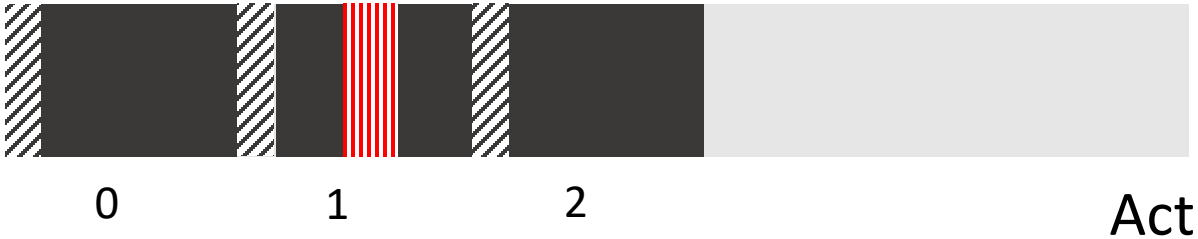
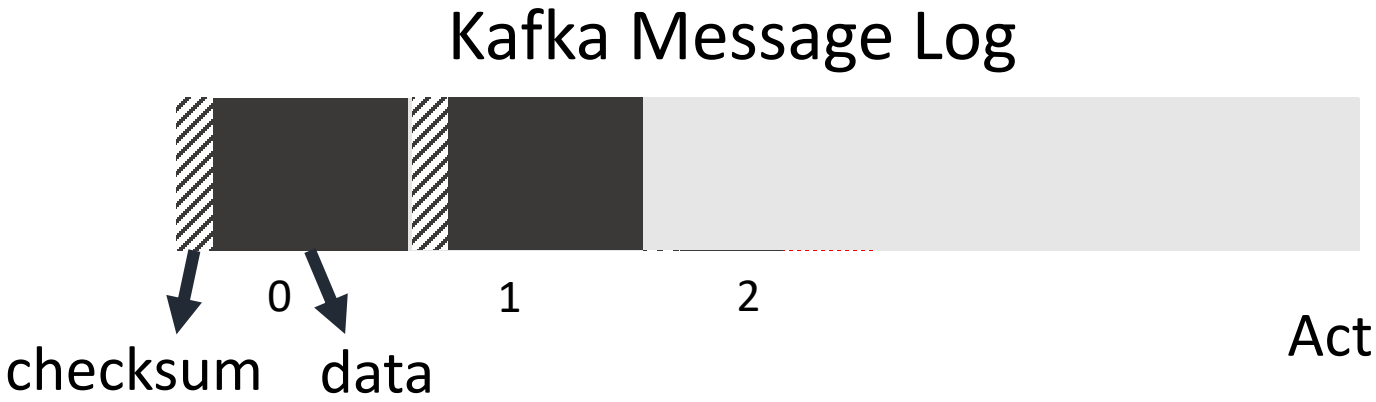


Disk corruption

Checksum mismatch

Action: Truncate log at 0

Crash and Corruption Handling are Entangled



Append(… entry 2)

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Disk corruption

Checksum mismatch

Action: Truncate log at 0

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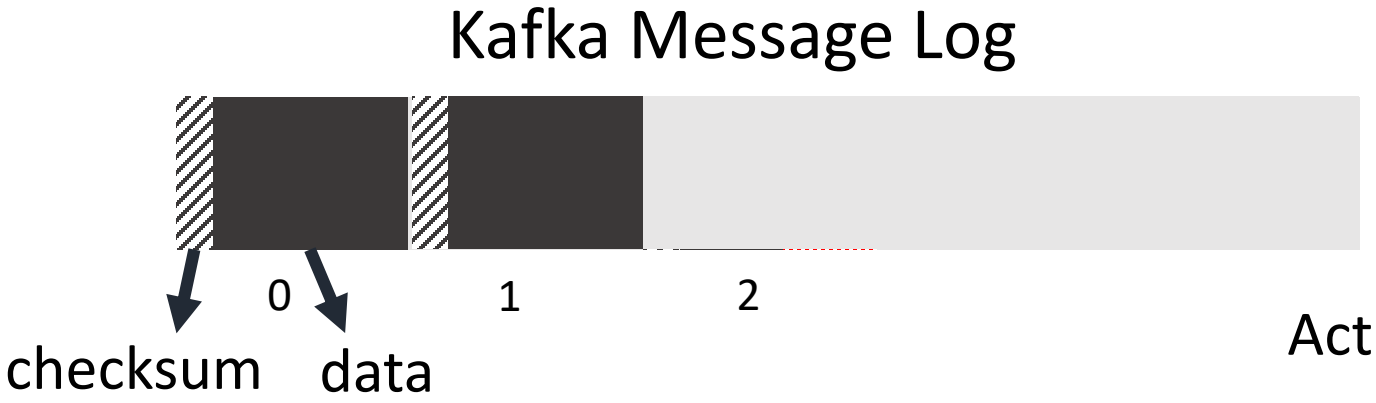

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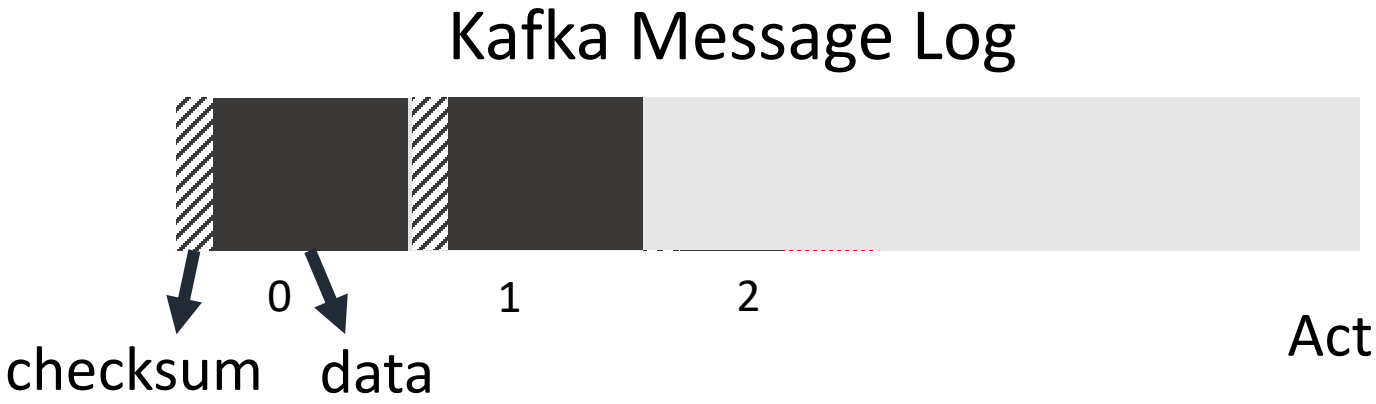
Disk corruption

Checksum mismatch

Action: Truncate log at 0

Lose committed data!

Crash and Corruption Handling are Entangled



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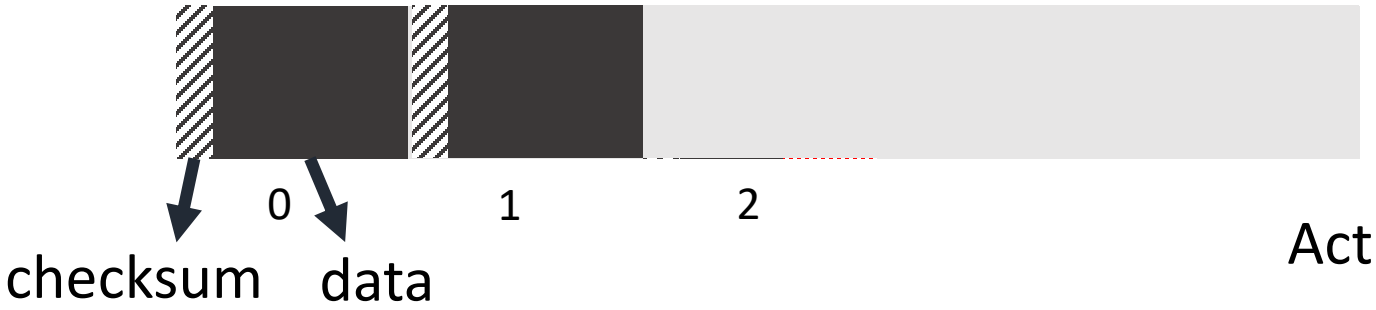
Developers of LogCabin and RethinkDB agree entanglement is the problem

Crash and Corruption Handling are Entangled

Kafka Message Log



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Need for discerning corruptions due to crashes from other type of corruptions

Unsafe Interaction between Local & Global Protocols

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Disk corruption
Checksum mismatch

Unsafe Interaction between Local & Global Protocols

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Unsafe Interaction between Local & Global Protocols

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Disk corruption

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Lose committed data!

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Local Behavior

Disk corruption

Checksum mismatch

Action: Truncate log at 0

Lose committed data!

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Local Behavior

Disk corruption

Checksum mismatch

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Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

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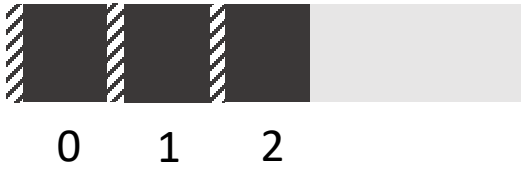
Lose committed data!

Node1

Other Nodes



Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Local Behavior

Disk corruption
Checksum mismatch
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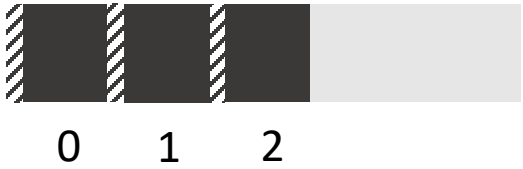
Lose committed data!

Set of in-sync replicas

Node1

Other Nodes



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Node1 with truncated log not removed from in-sync replicas

Node1

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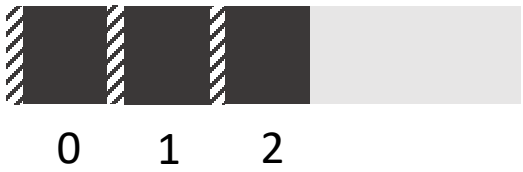

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Local Behavior

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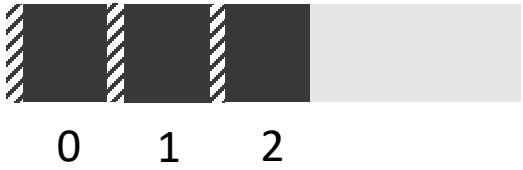
Node1 with truncated log not removed from in-sync replicas

Node 1 elected as leader

Leader

Followers



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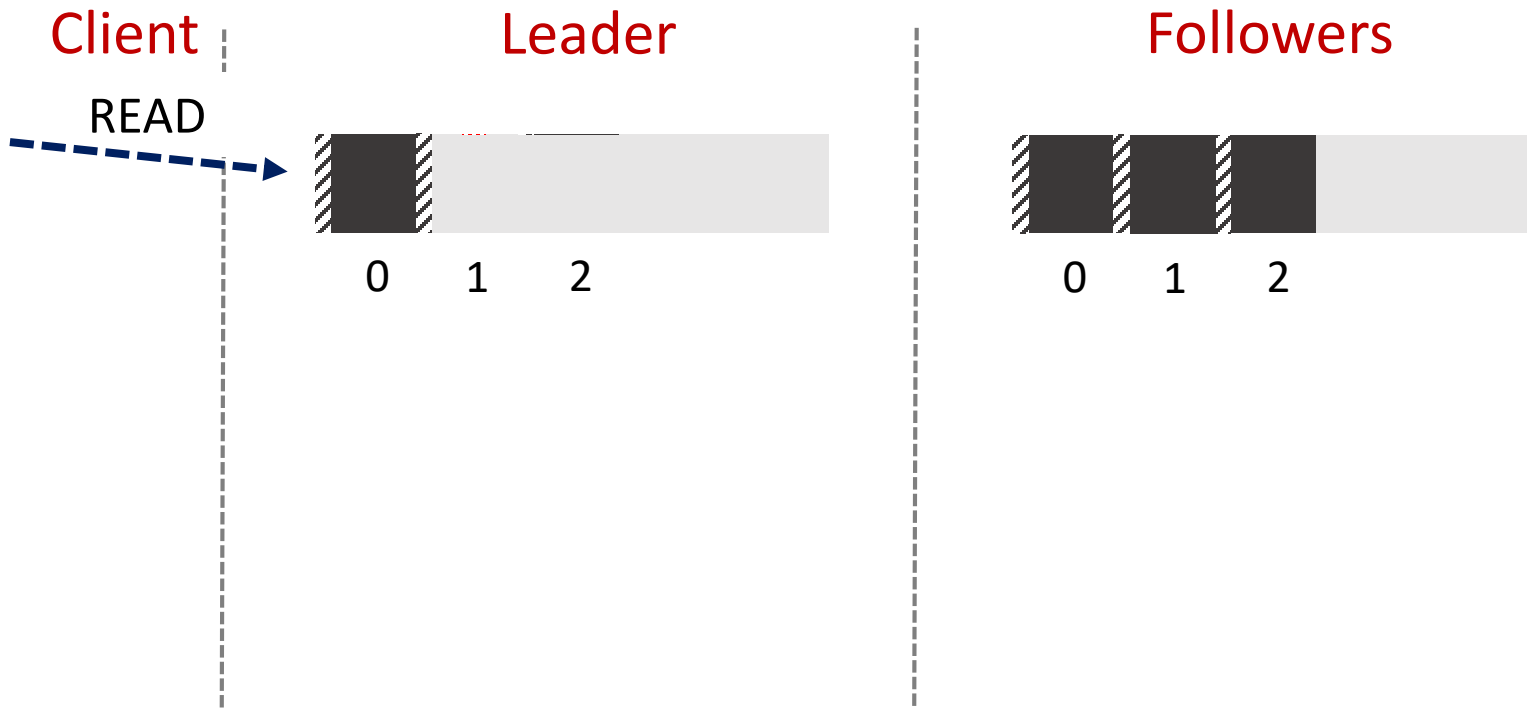

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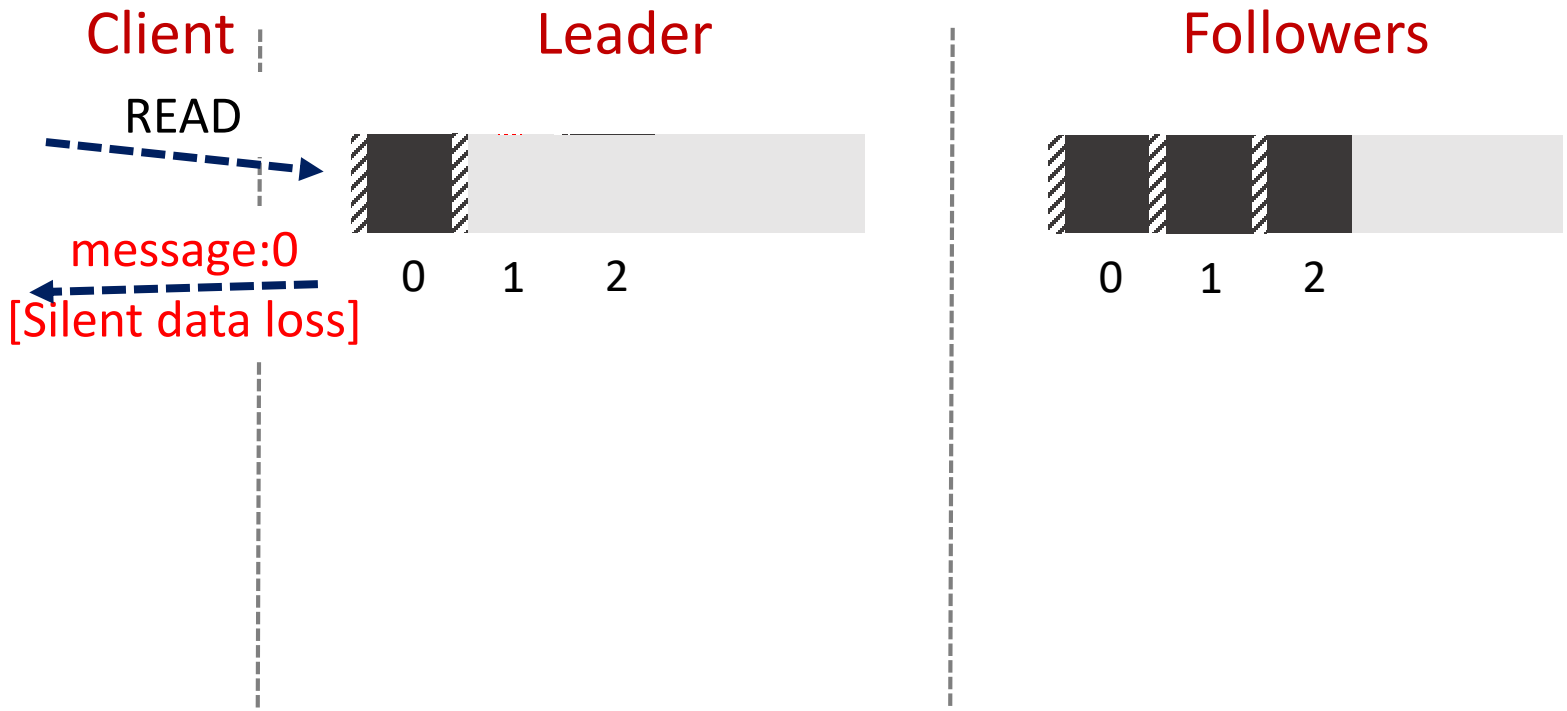

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

Local Behavior

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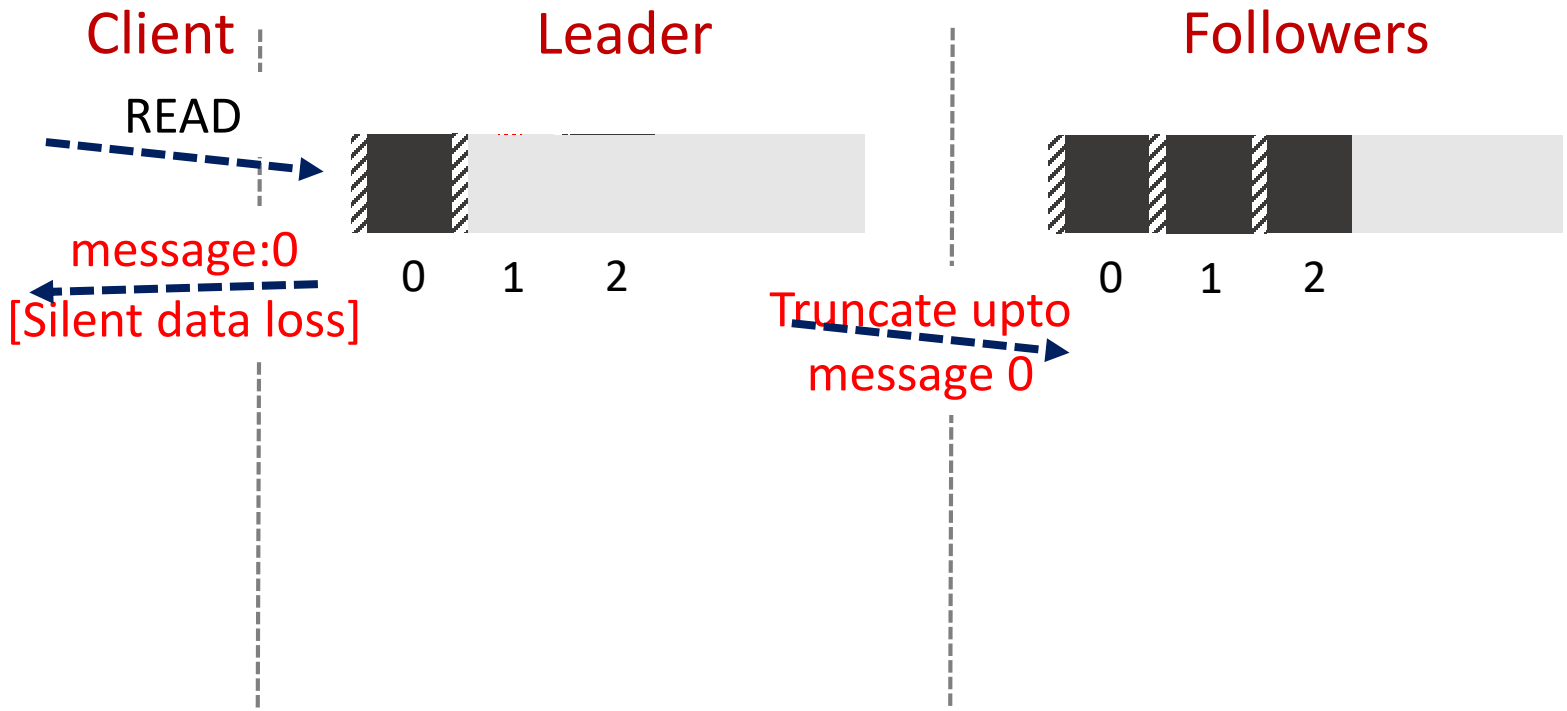

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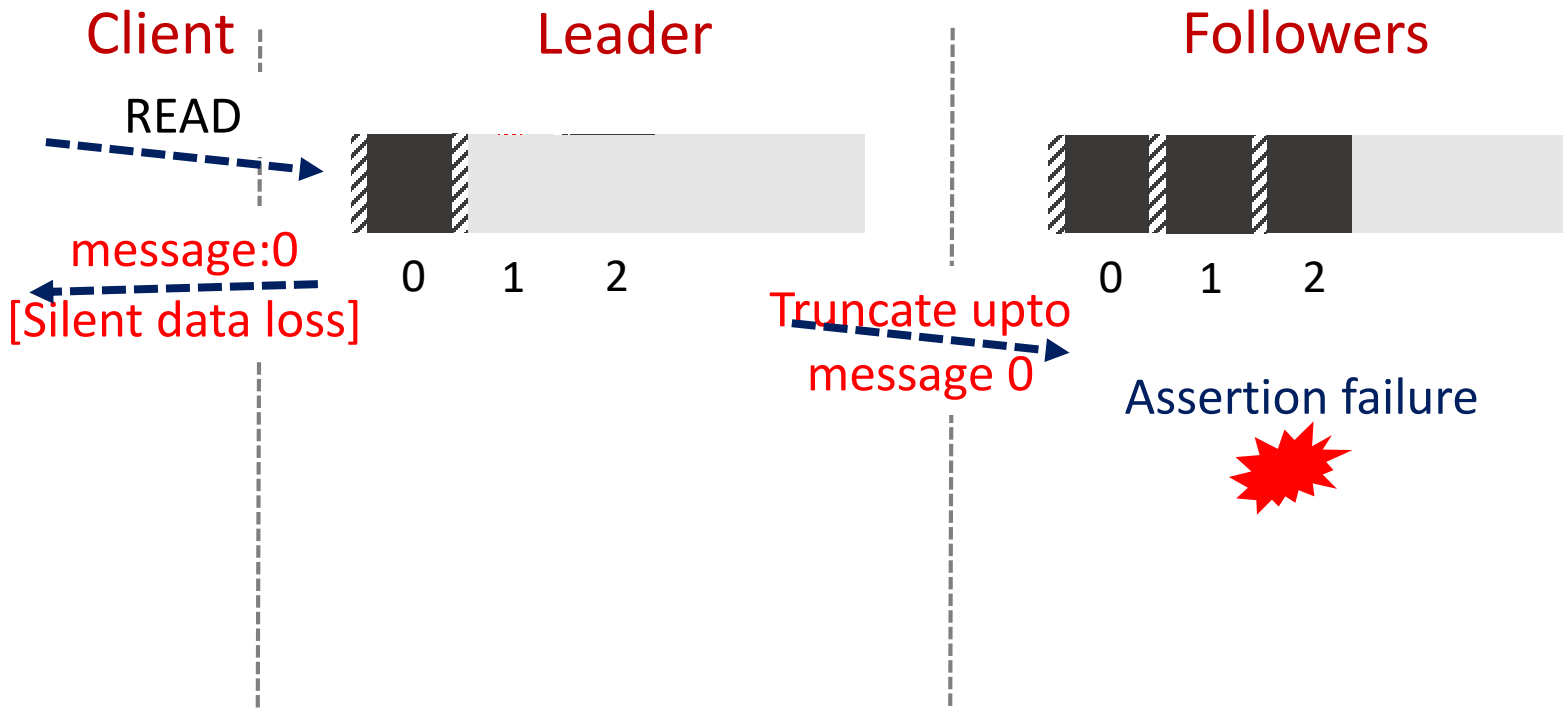

Unsafe Interaction between Local & Global Protocols

Kafka: Message log at Node 1

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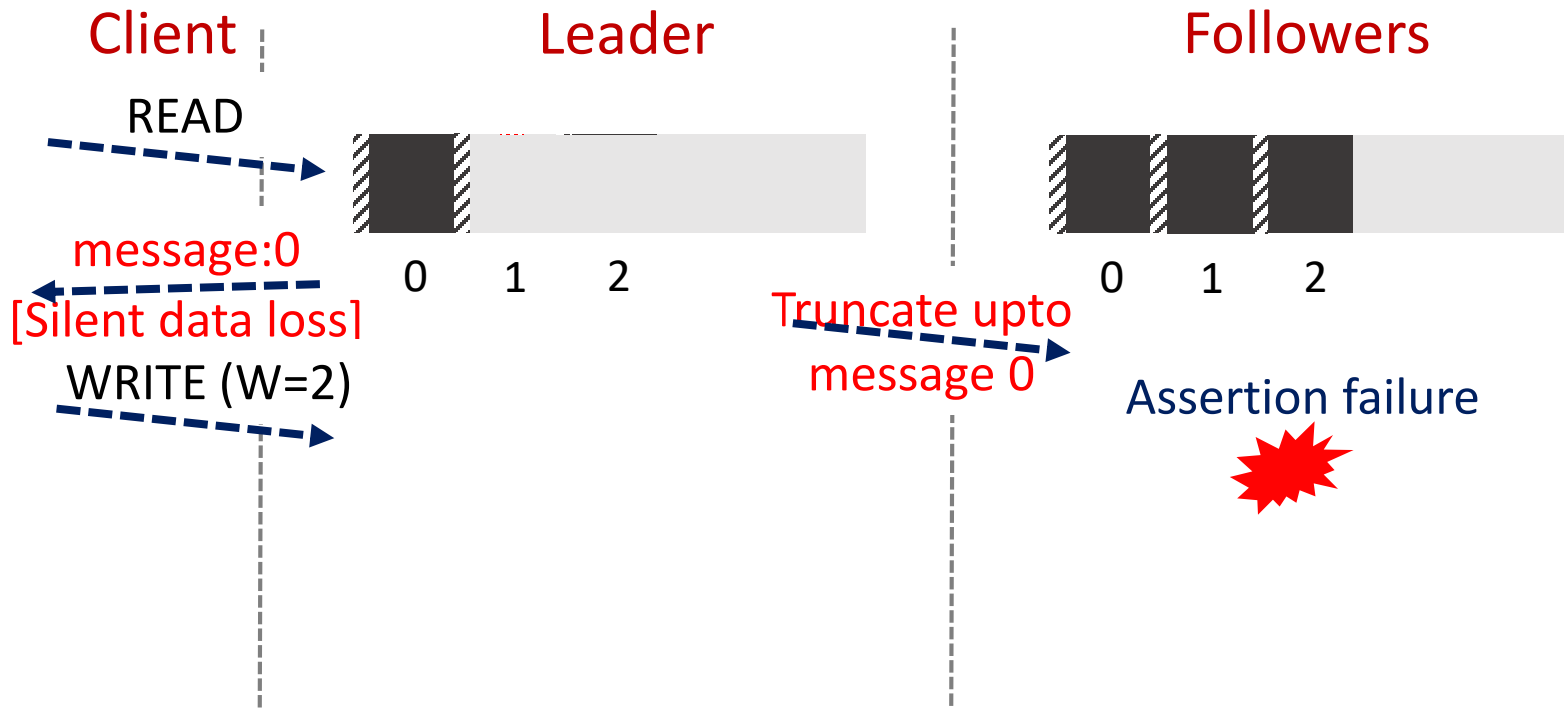

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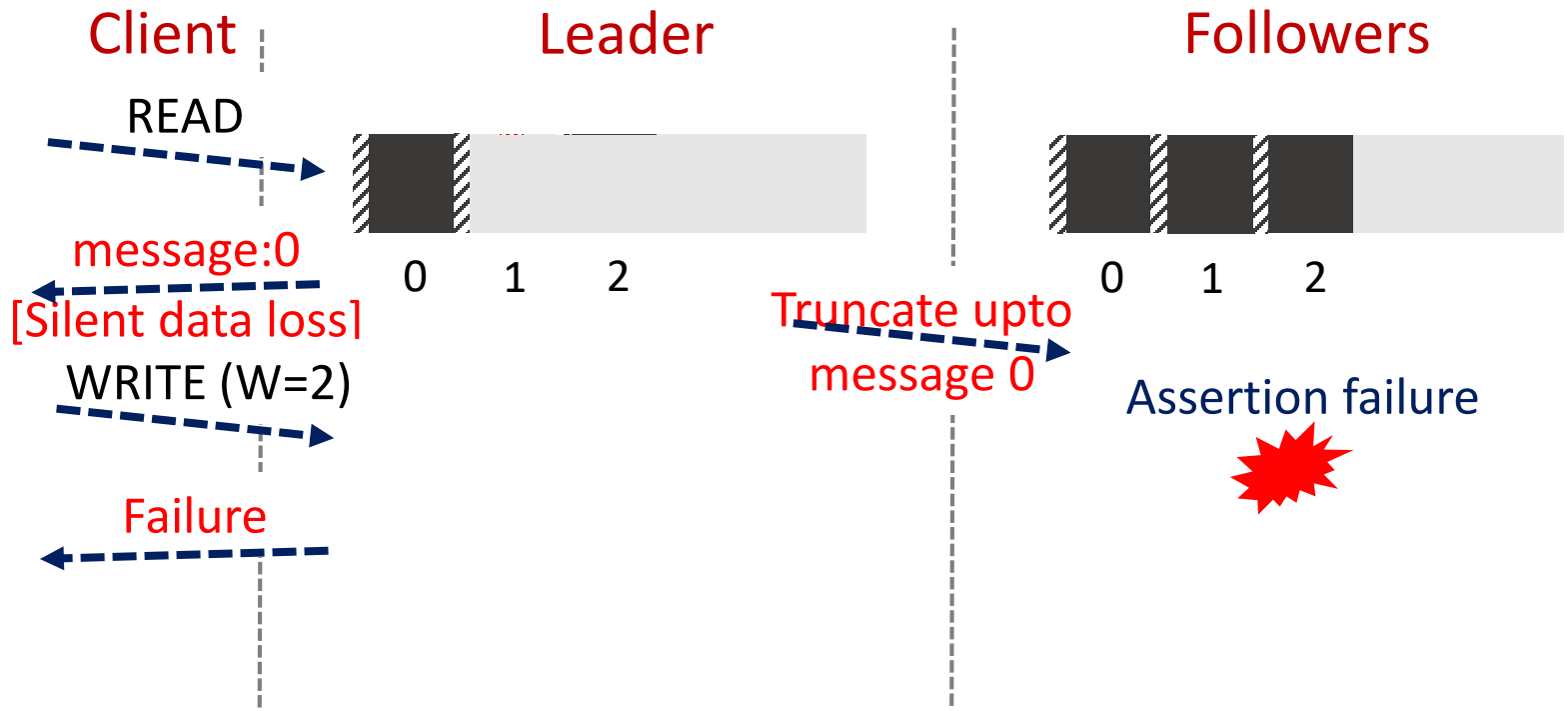

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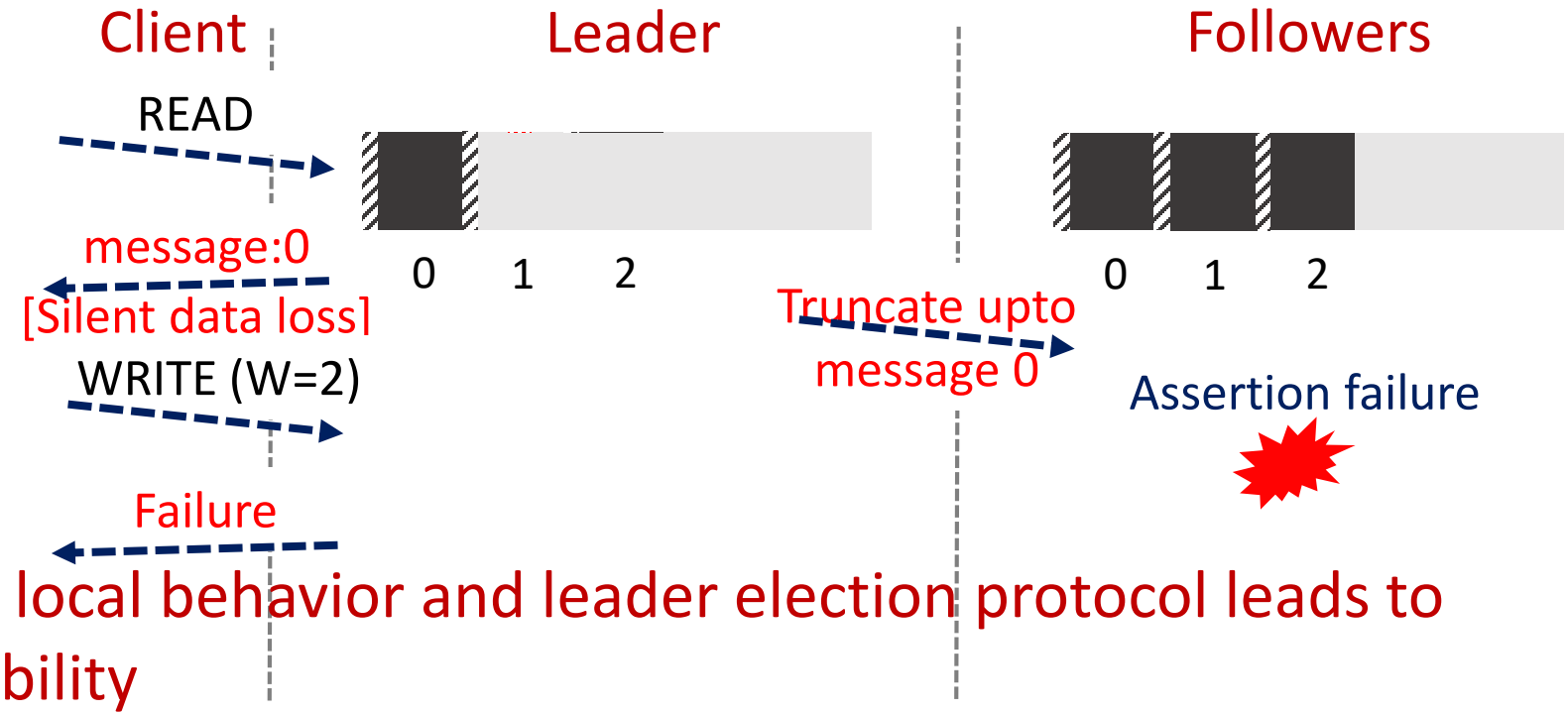

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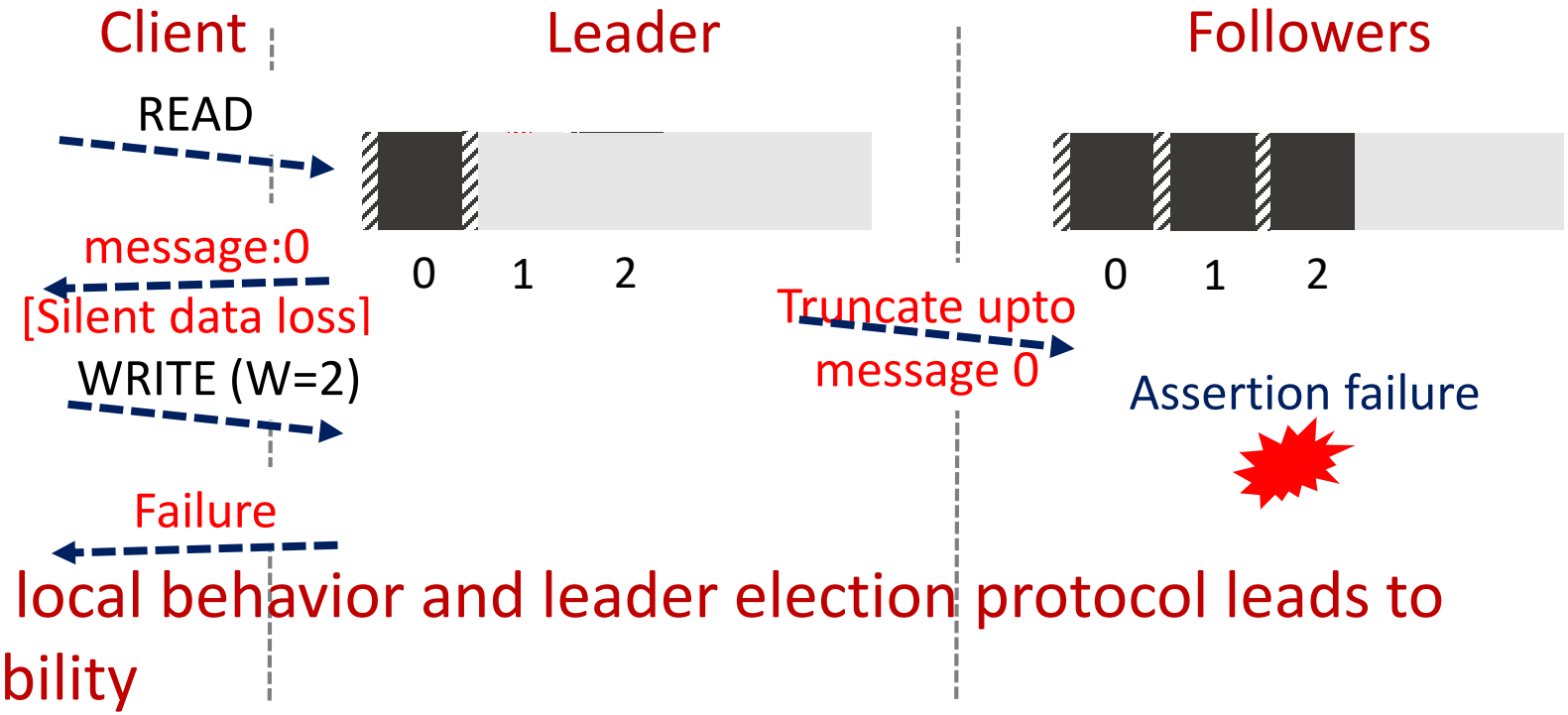

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Need for synergy between local behavior and global protocol

Redundancy Does not Provide Fault Tolerance

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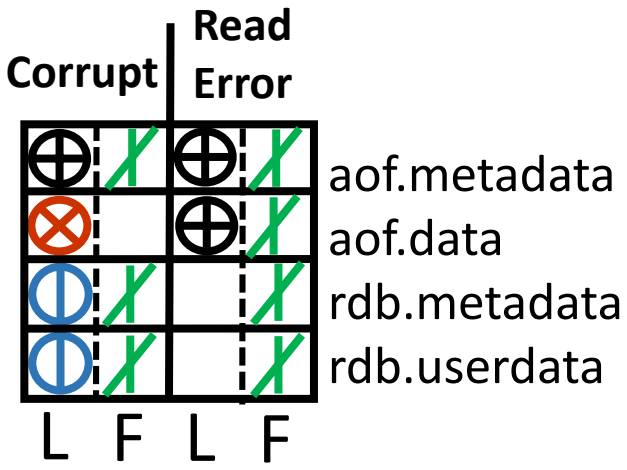
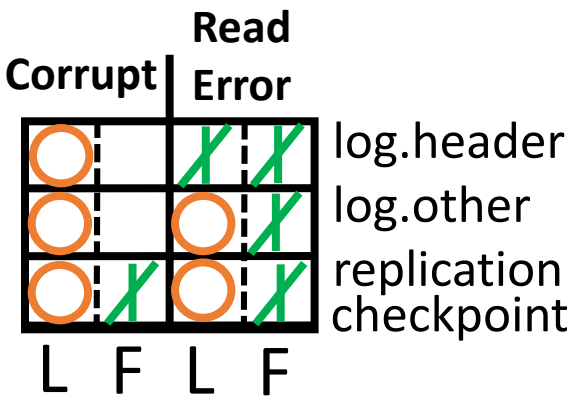


Kafka Read



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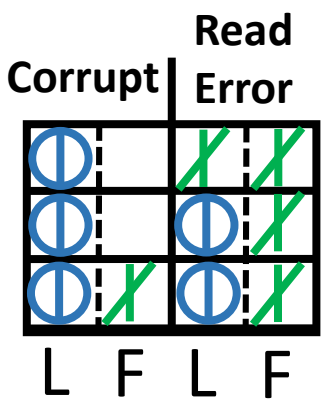
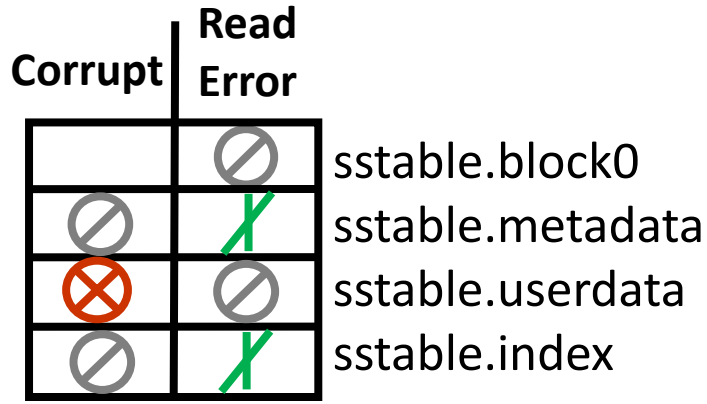
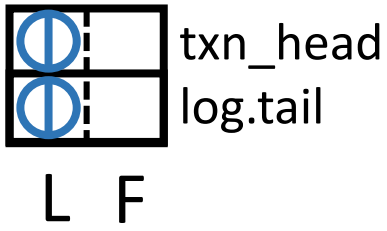


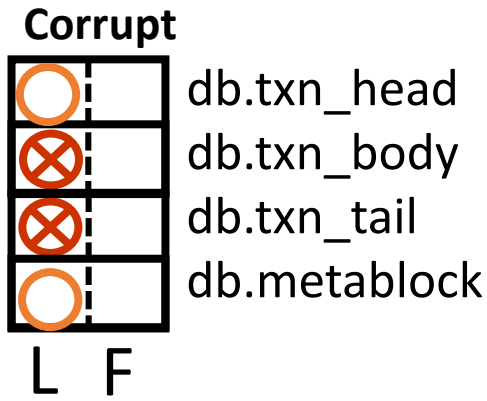
Cassandra Read

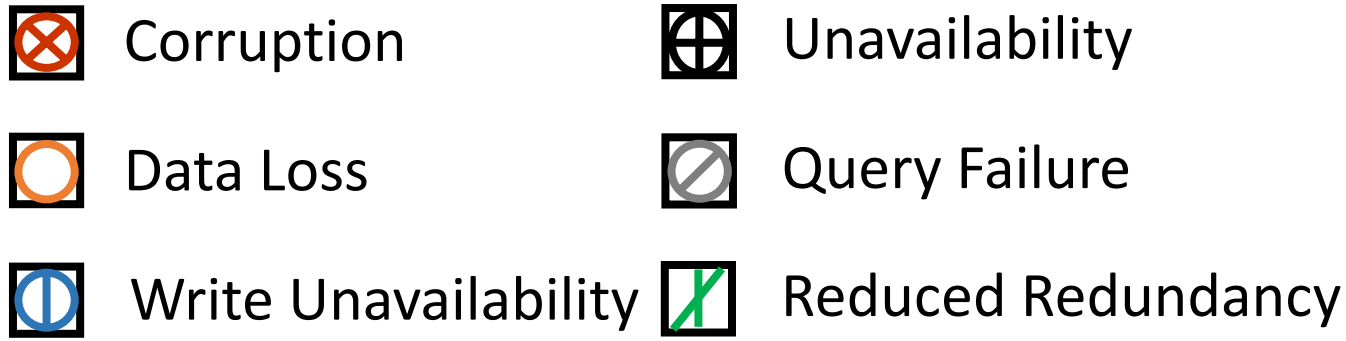


ZooKeeper Write



RethinkDB Read





Why does Redundancy Not Imply Fault Tolerance?

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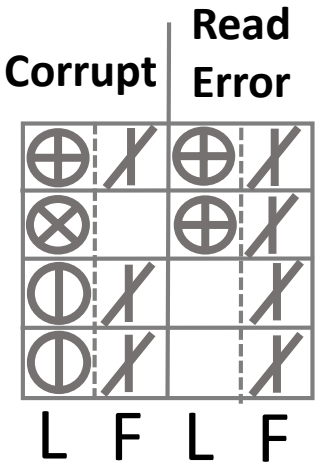

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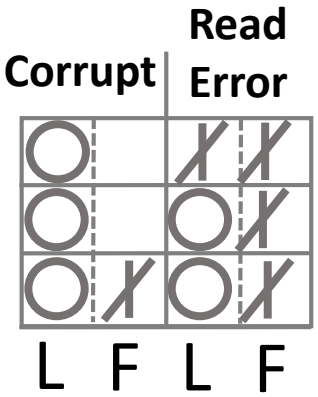

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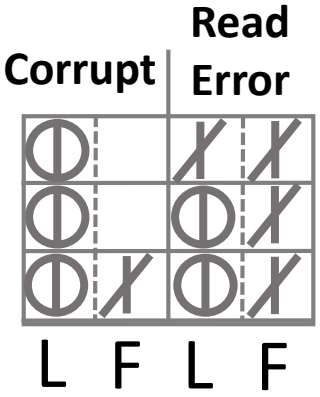

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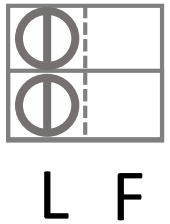

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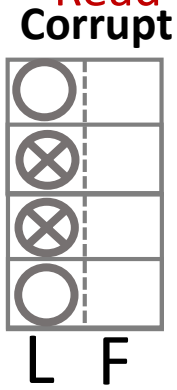
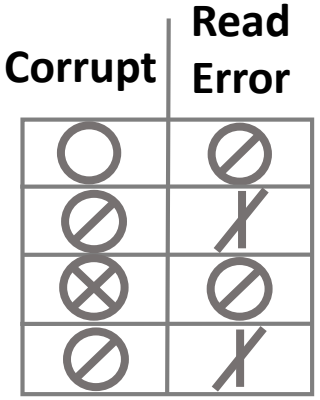


Cassandra Read



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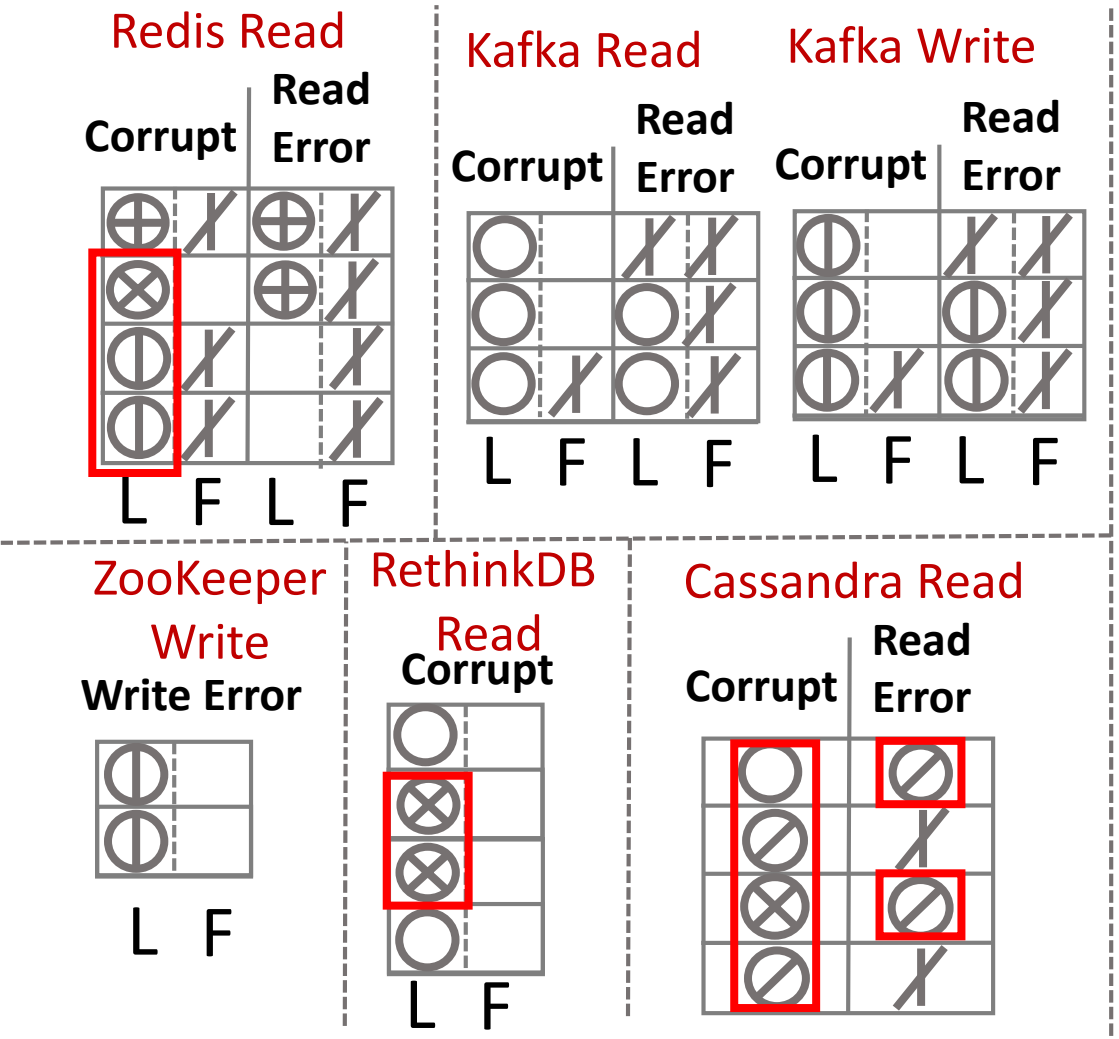

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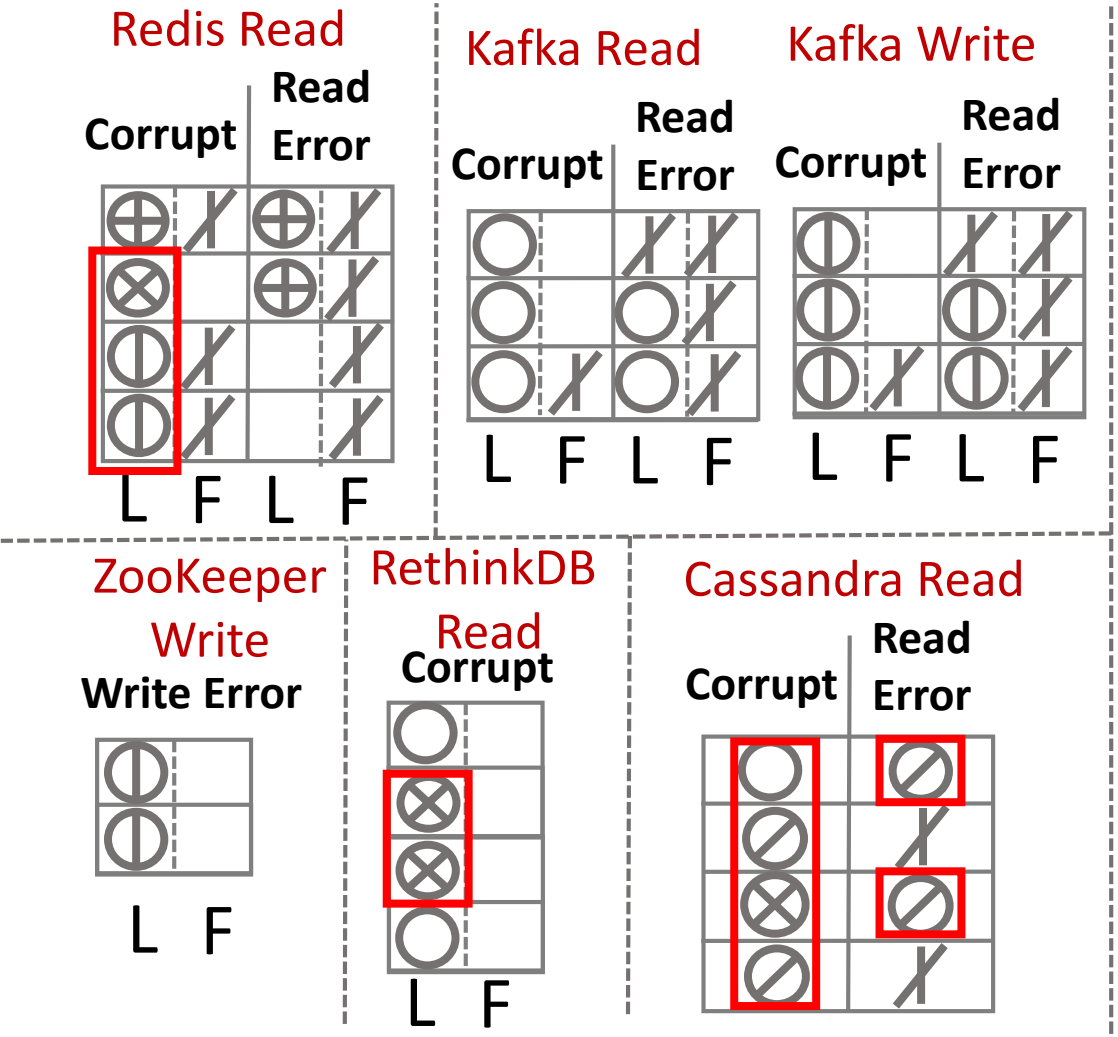

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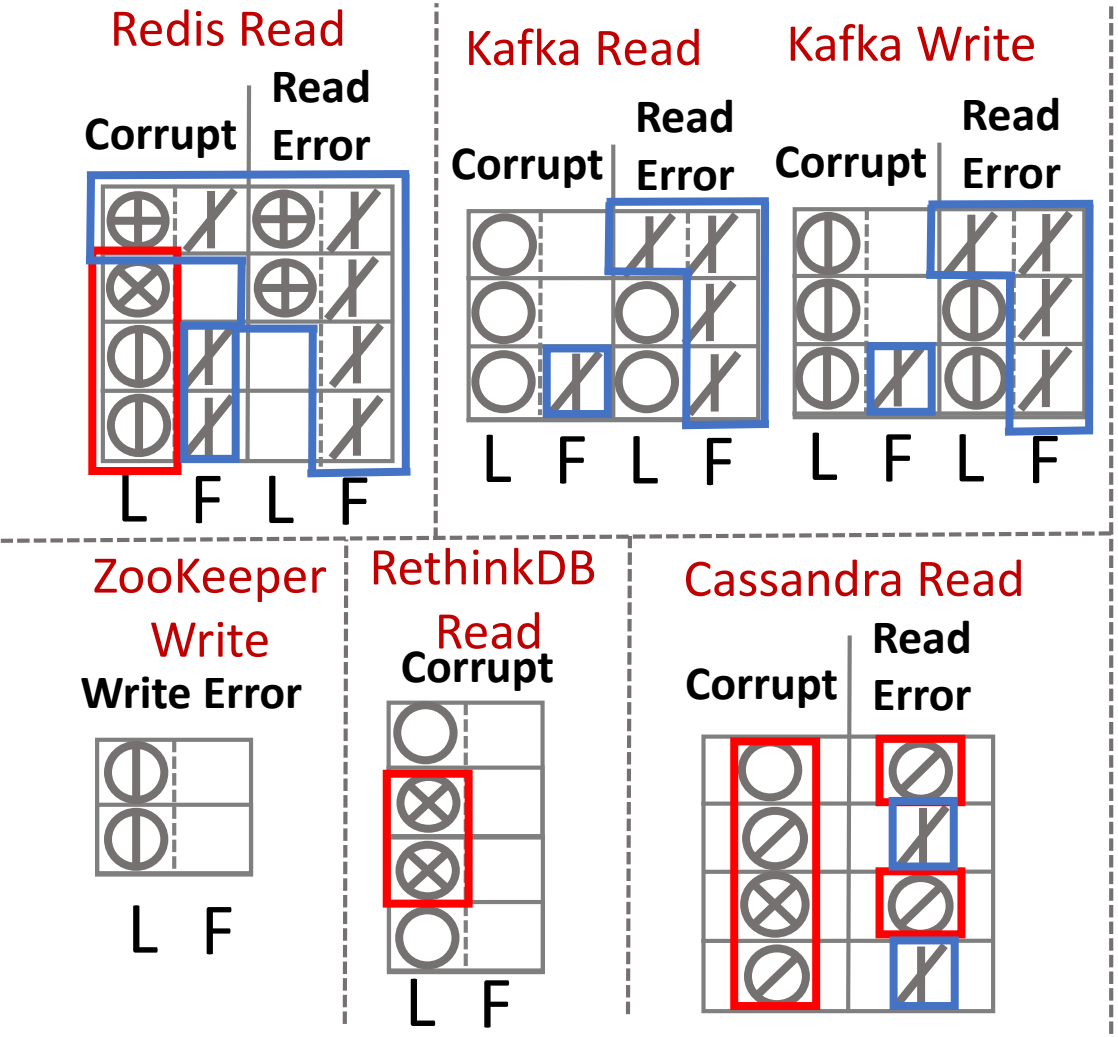

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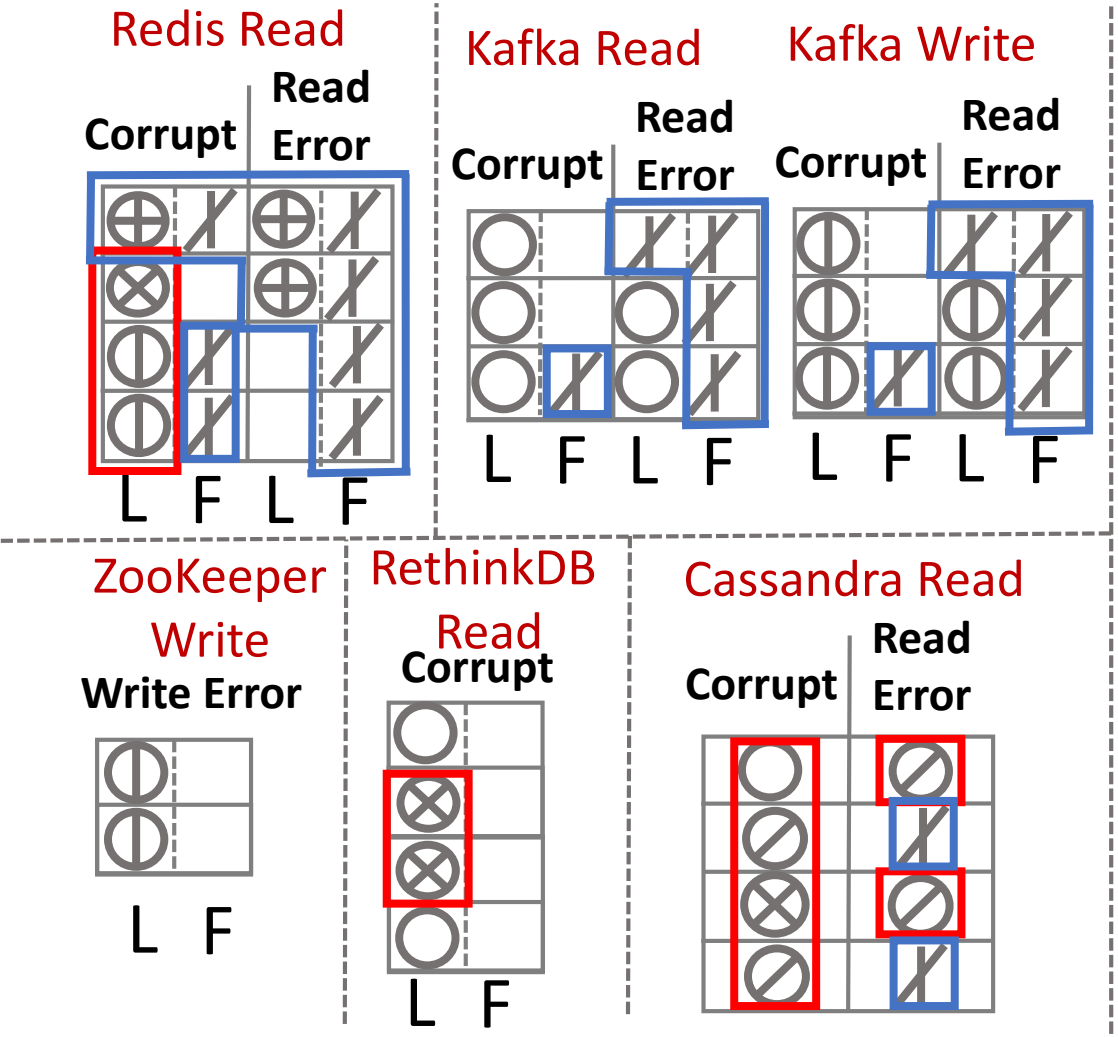

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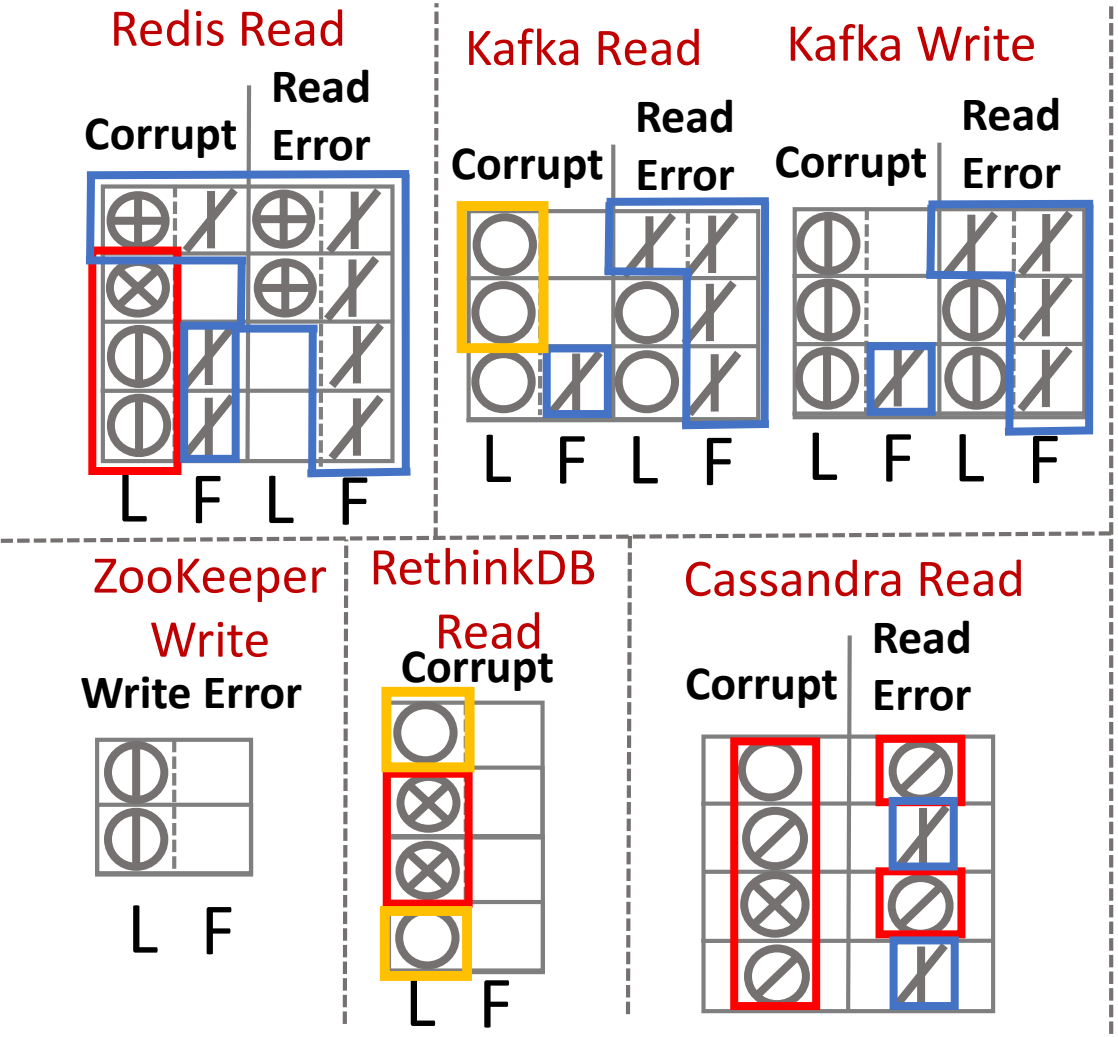

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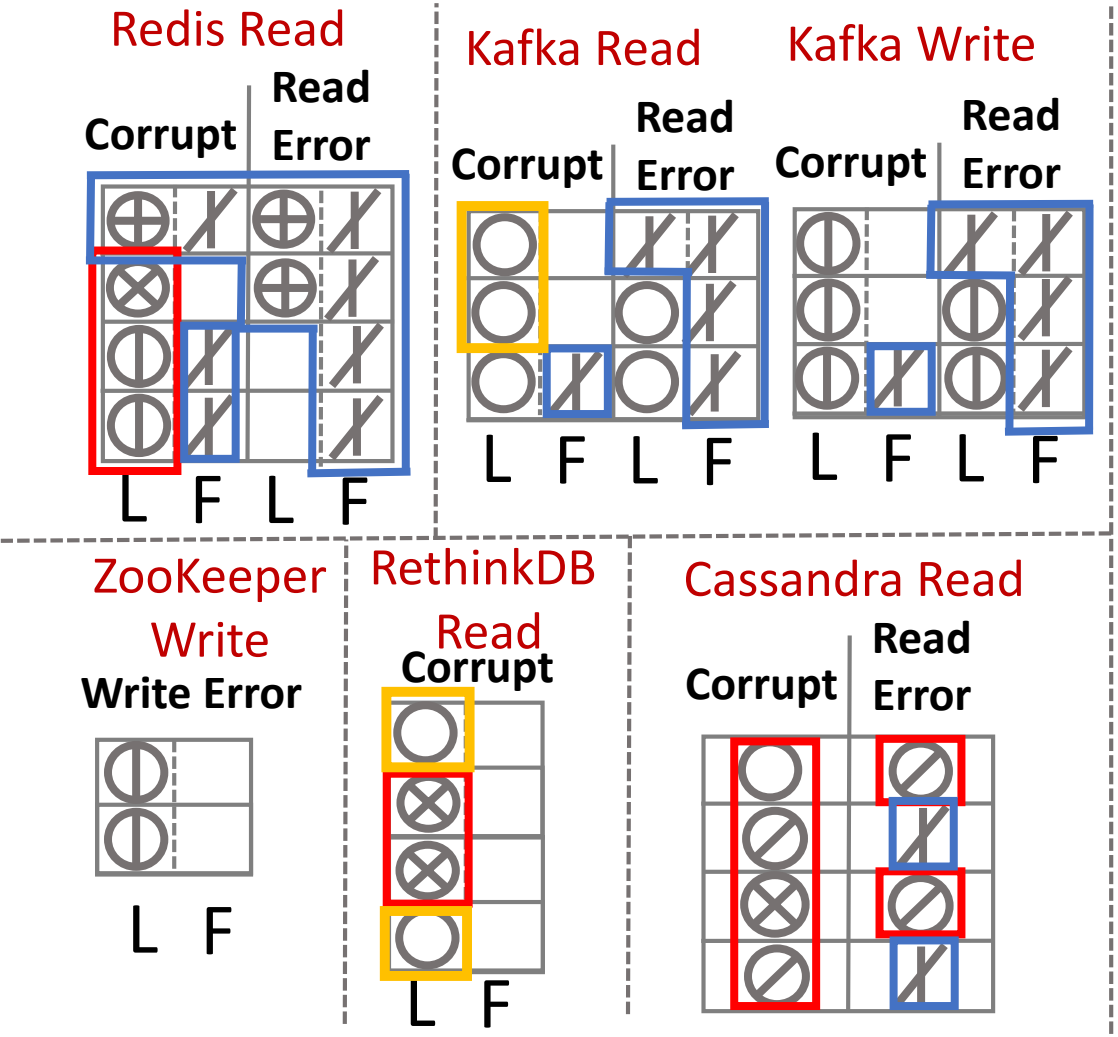

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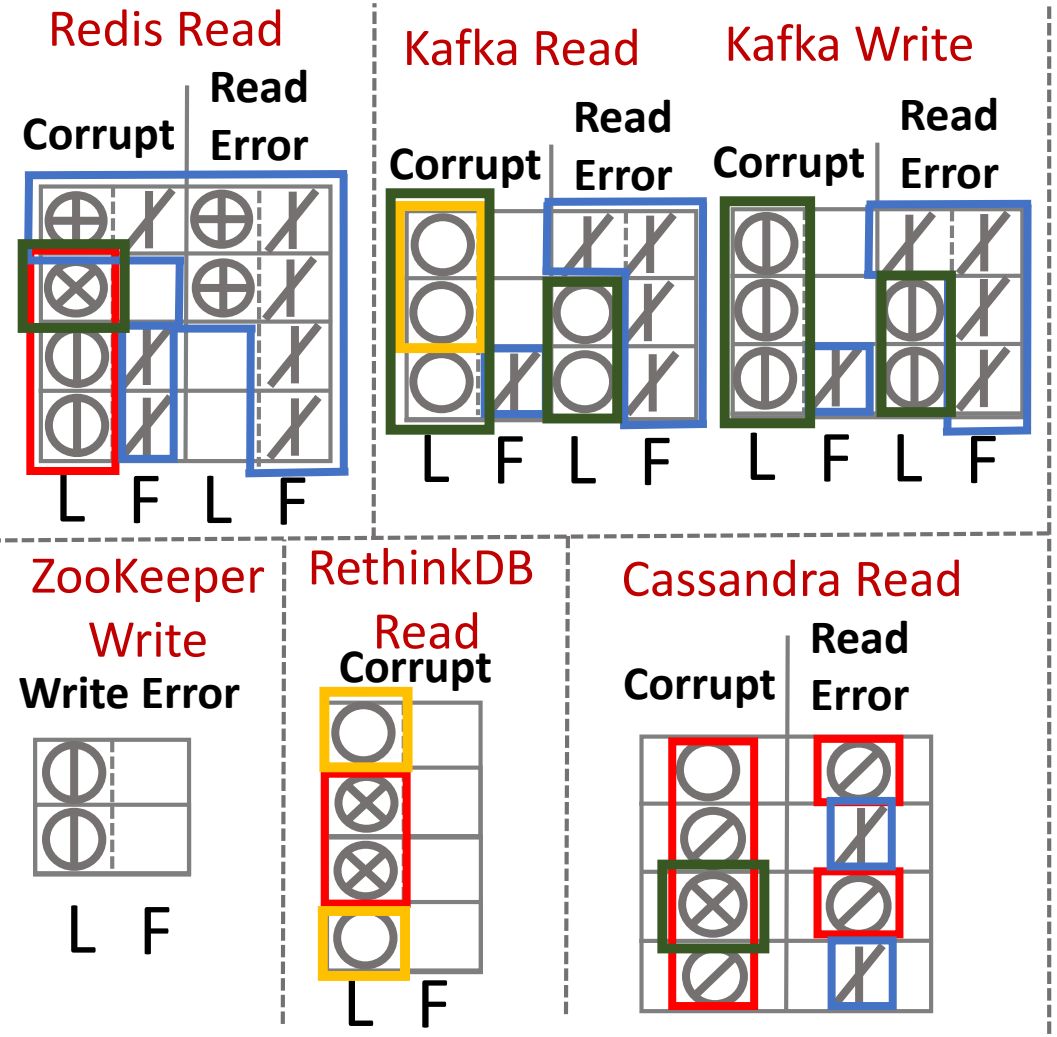

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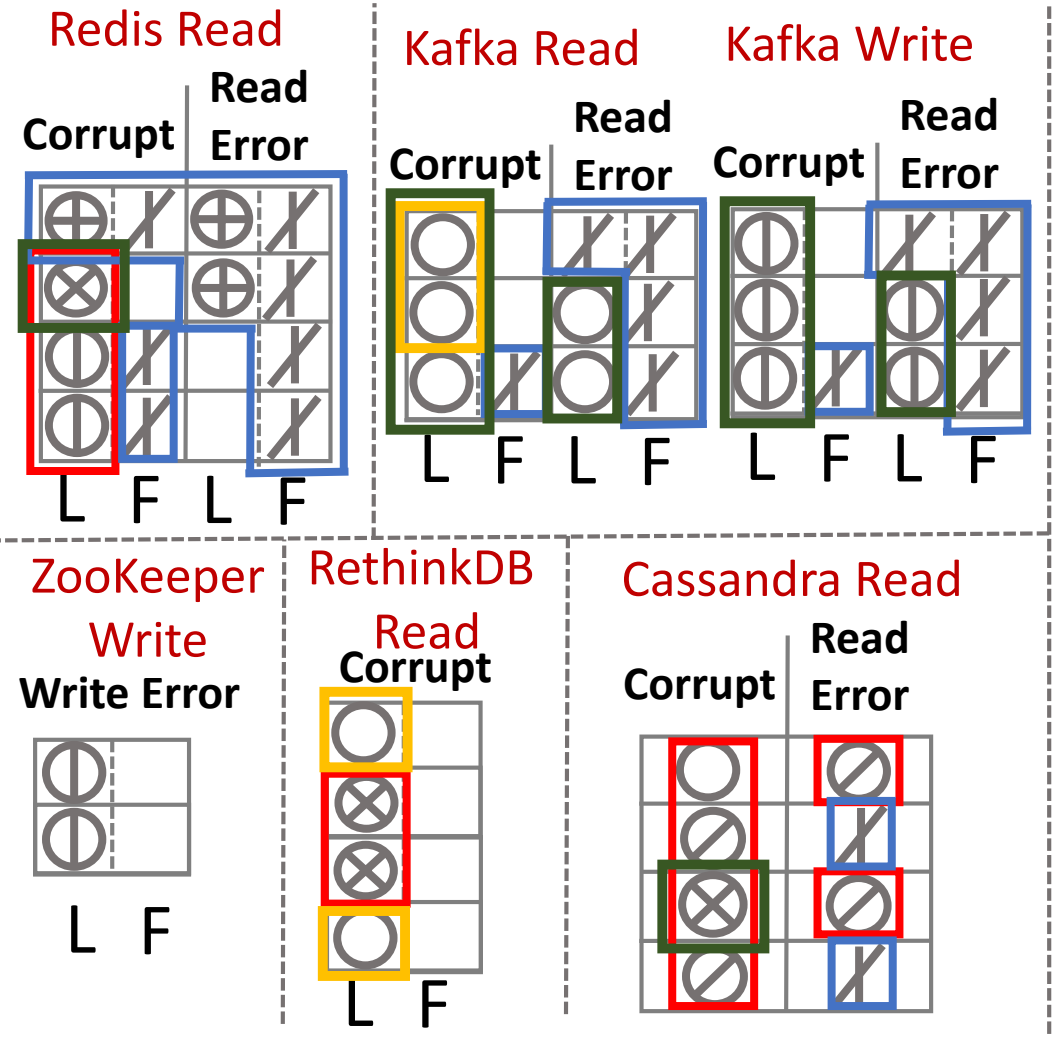

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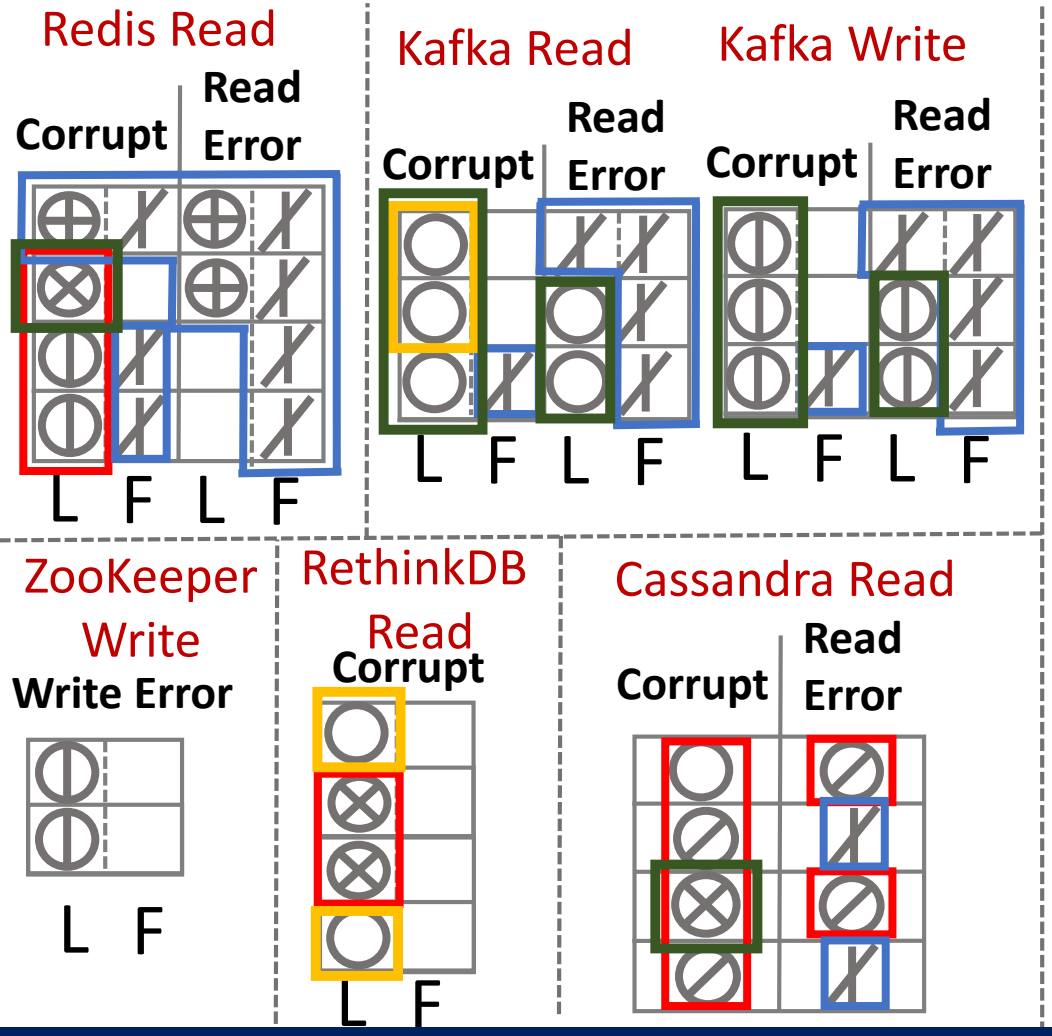

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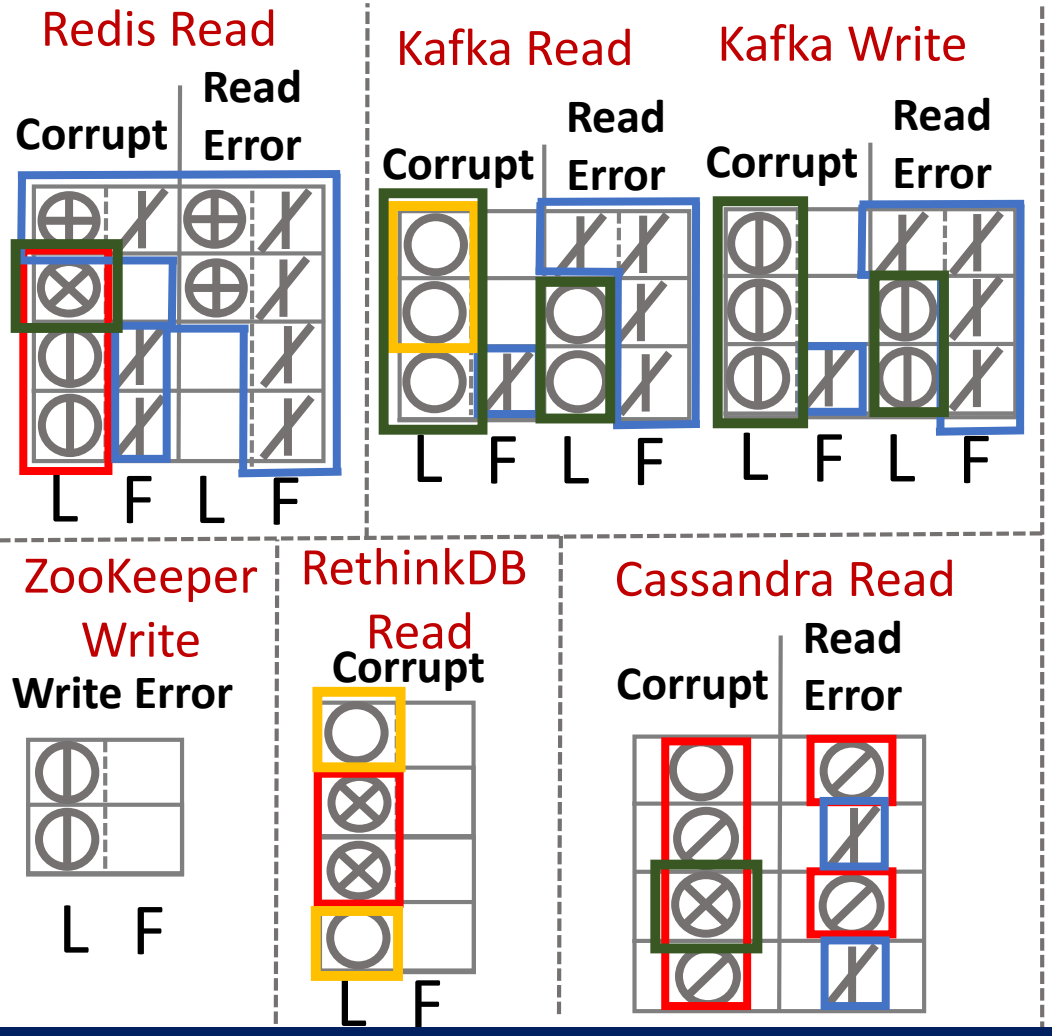

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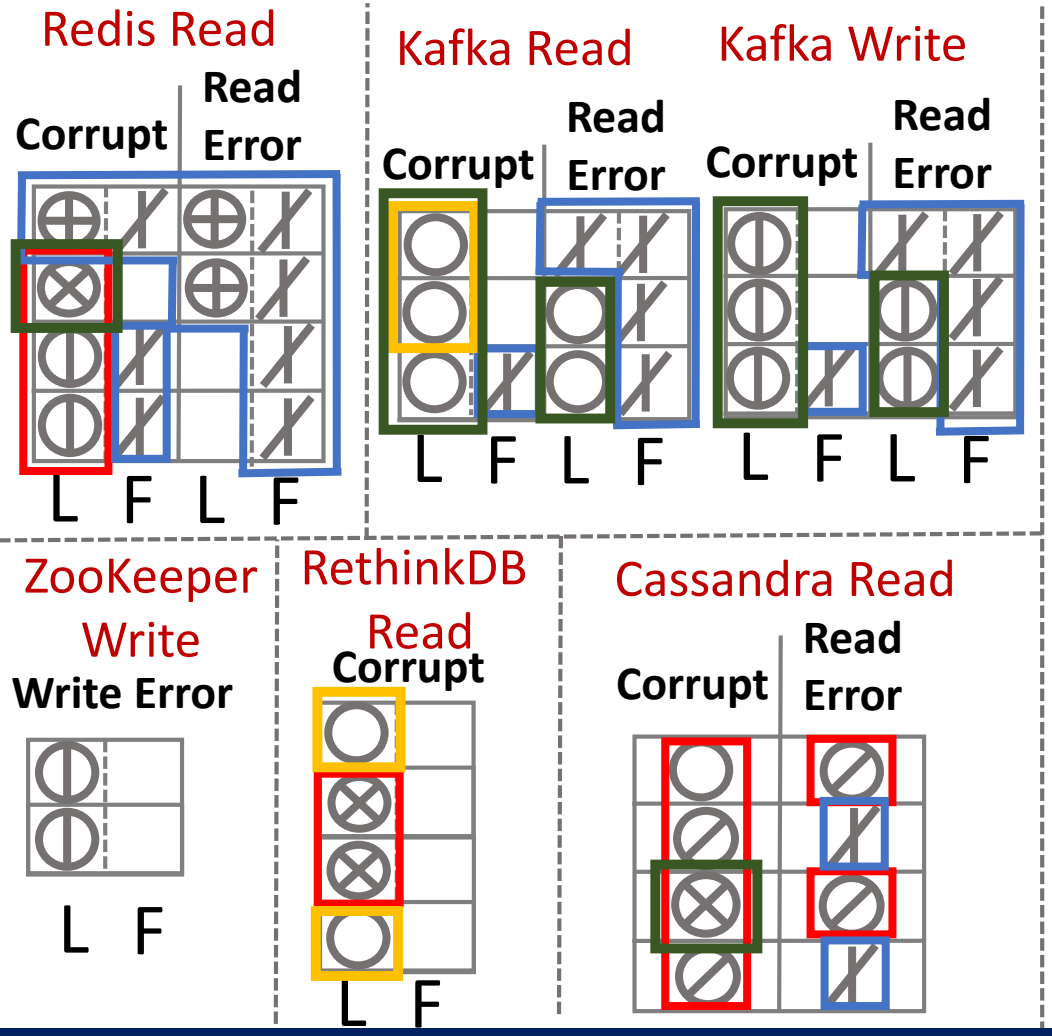

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More observations, results, and discussions in the paper …

Outline

Introduction

Fault Injection

System Behavior Analysis

Major Results

Observations Across Systems

- Faults are Often Undetected Locally
- Crashing: Common Local Reaction
- Crash and Corruption Handling are Entangled
- Unsafe interaction between local and global protocols

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Our fault injection framework available online:
http://research.cs.wisc.edu/adsl/Software/cords/

Thank you!