Correlated Crash Vulnerabilities

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Distributed Storage Systems

Central to building modern services

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Reliability by Replication

Reliability of user data is important

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Core mechanism: Replication

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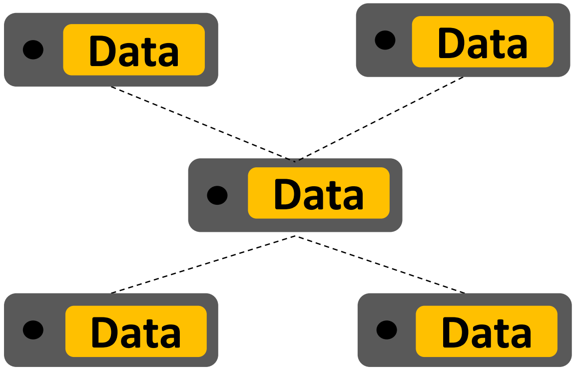

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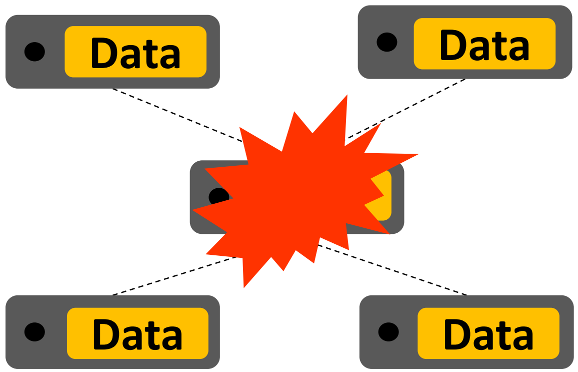

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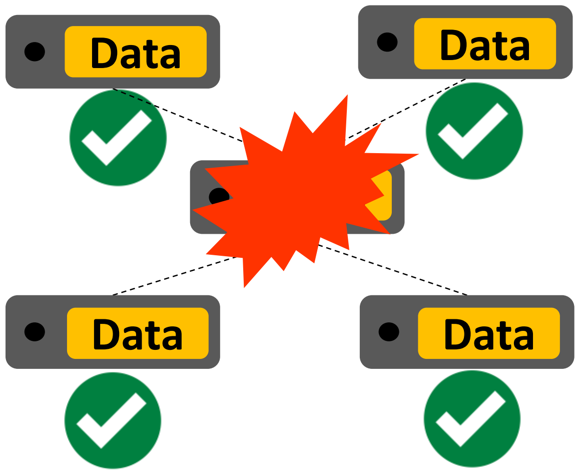

Distributed storage systems can endure single machine crashes

Our Focus: Correlated Crashes

All data replicas crash and recover together

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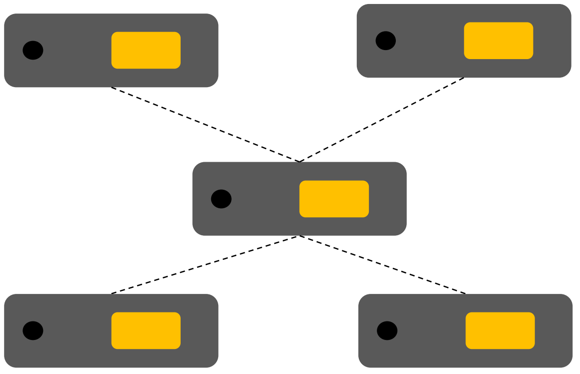

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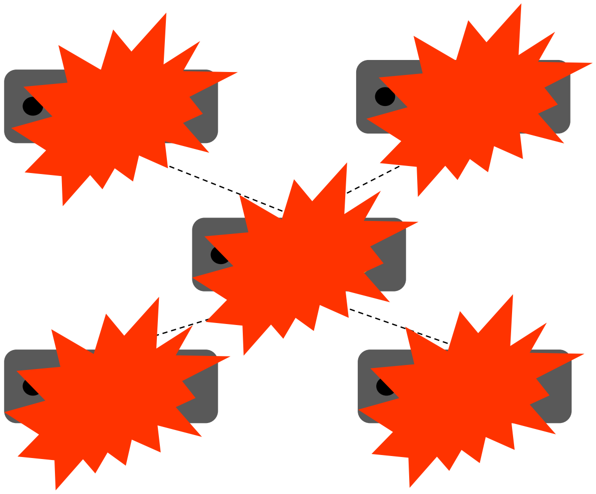

Obviously, unavailable during failure

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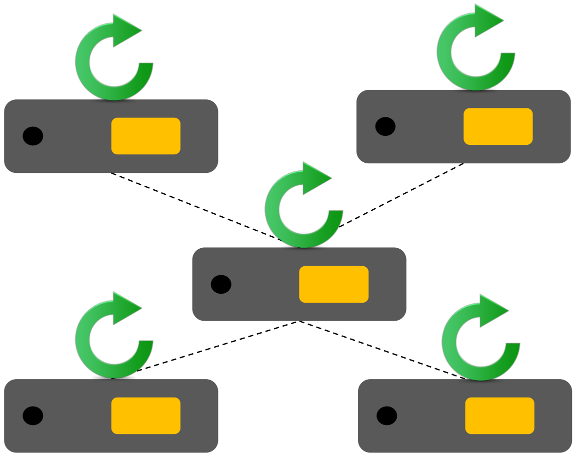

Obviously, unavailable during failure

However, correct data should be available after recovery

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How often do they happen?

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More often than we think!

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Correlated reboots (kernel bugs, power outage, upgrades) - Ford et al., OSDI’ 10

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Bank of Scotland and Halifax customers not able to access money

The Huffington Post, Gawker, Gizmodo, and Buzzfeed go down as data center flood …

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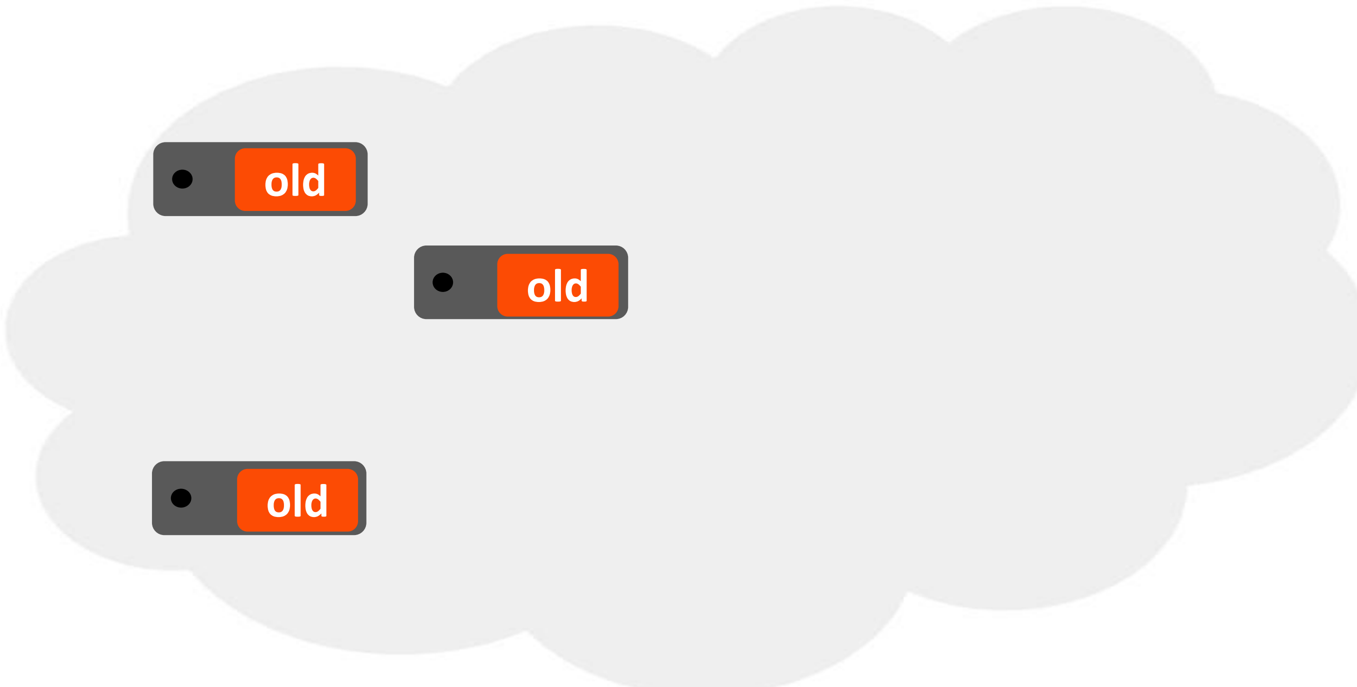

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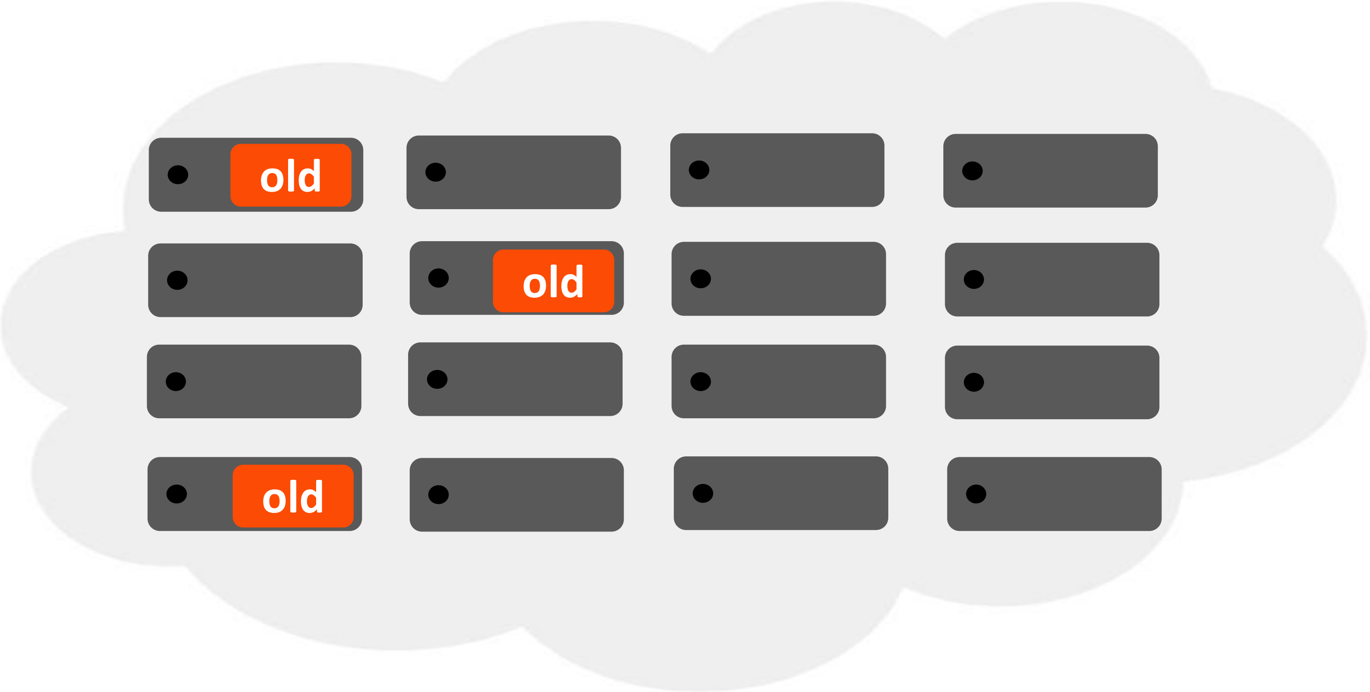

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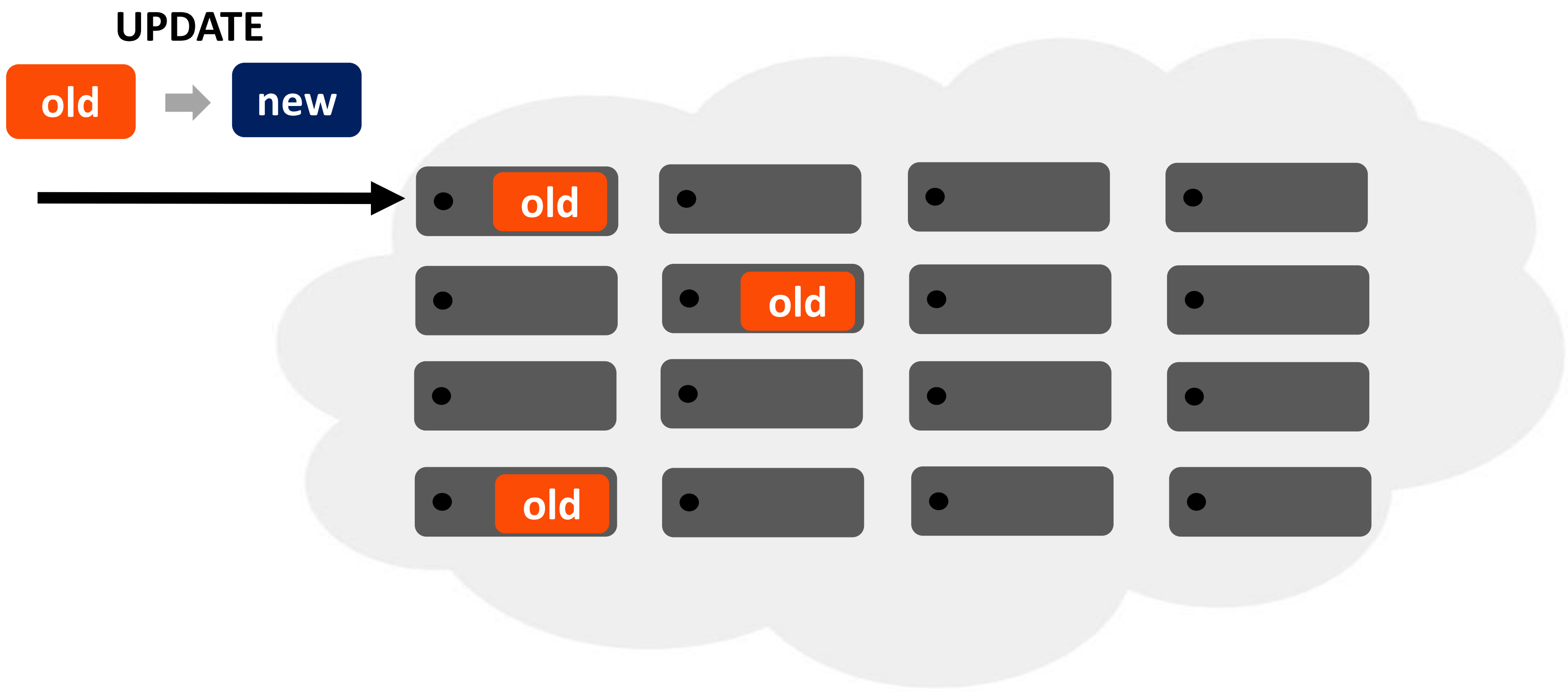

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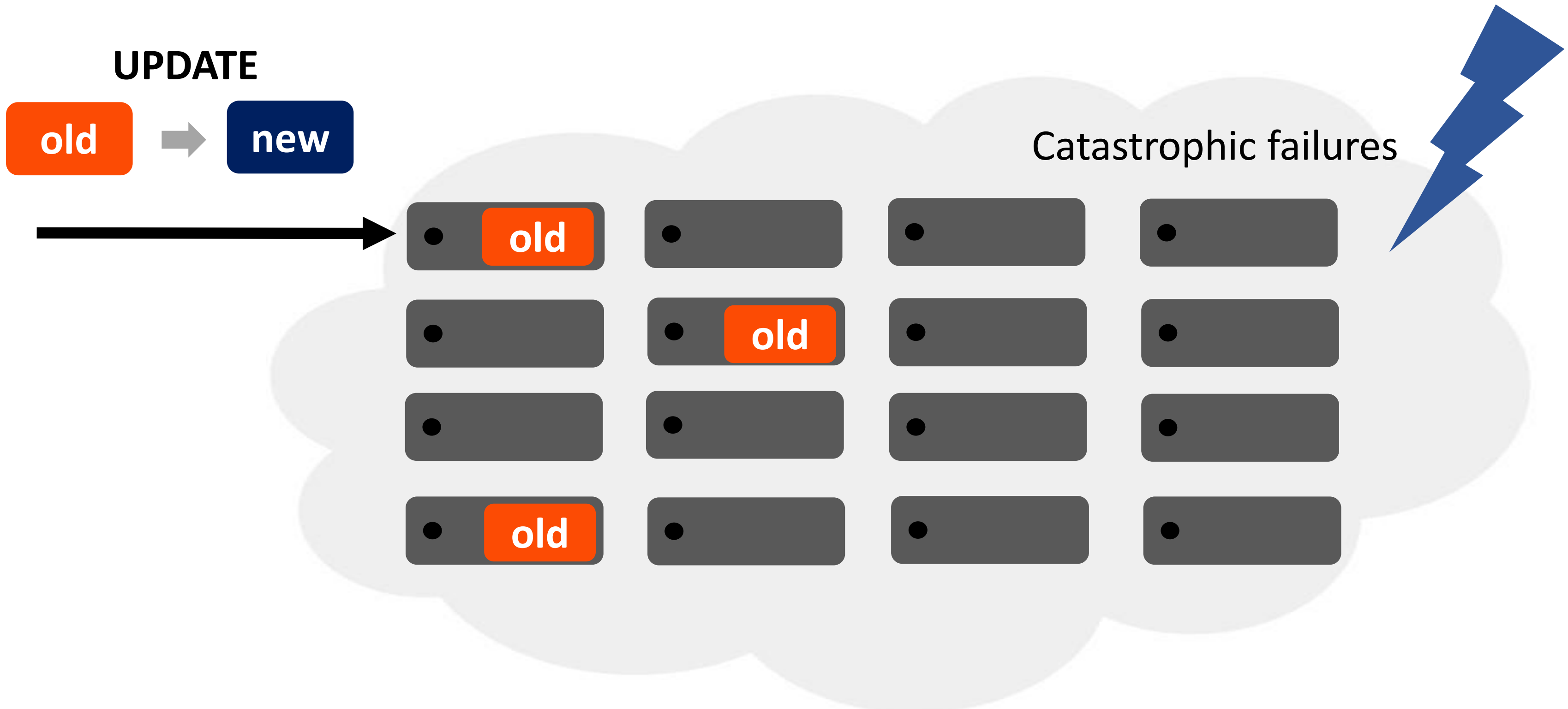

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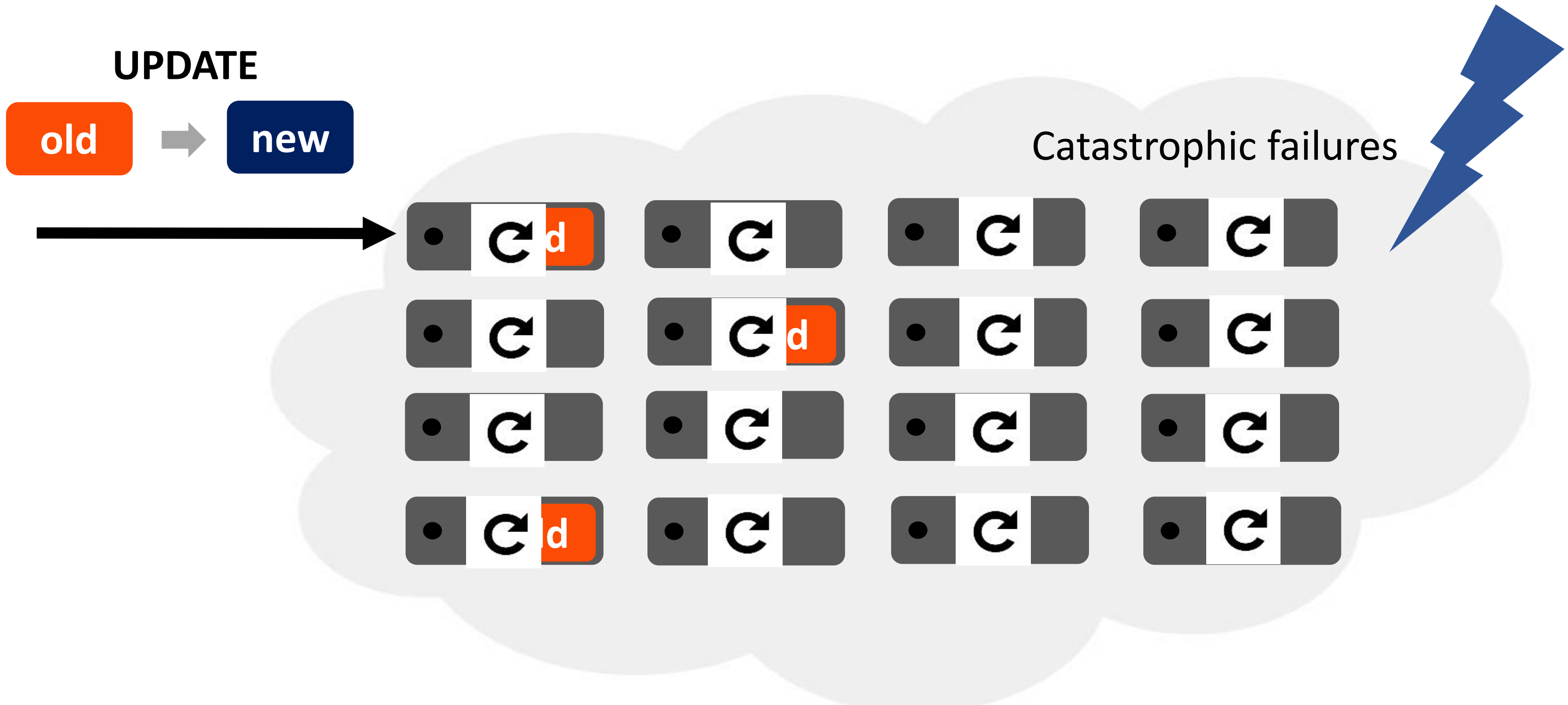

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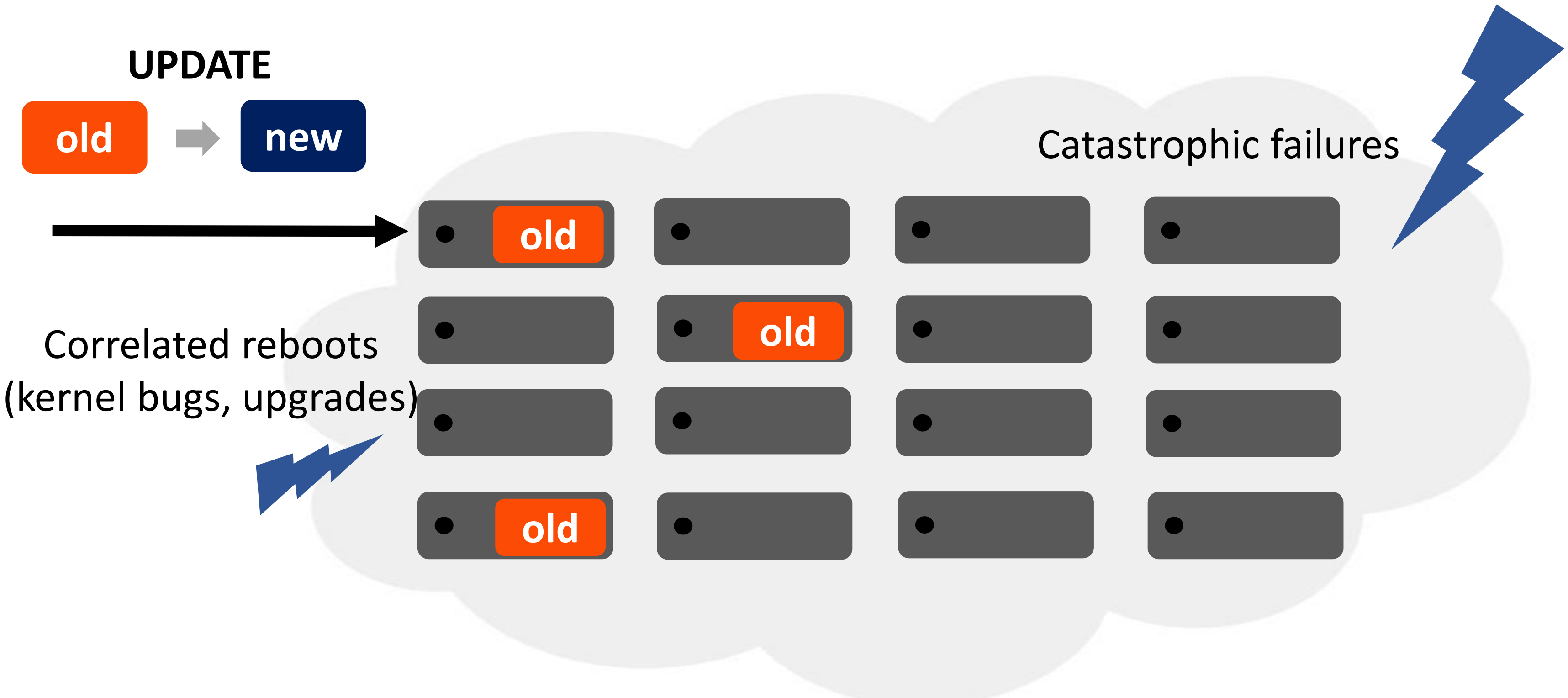

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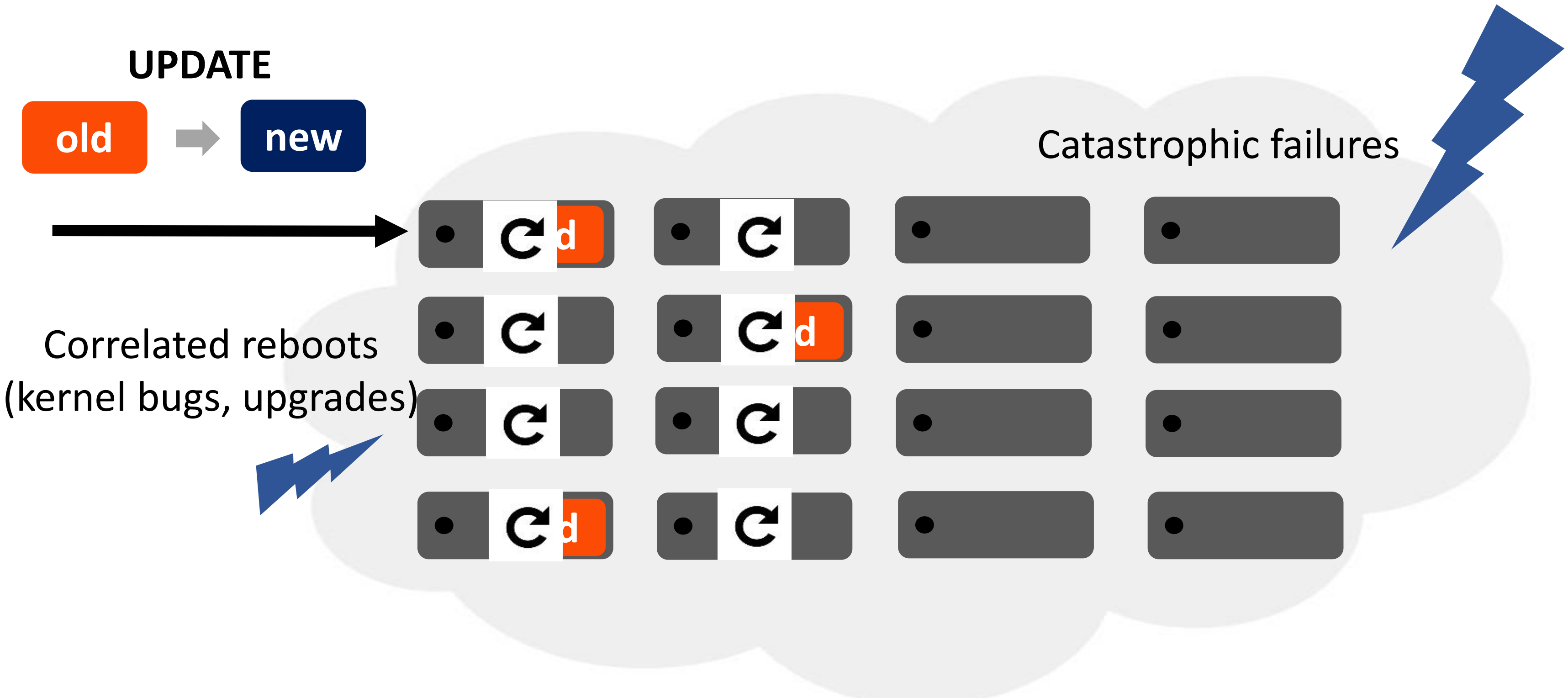

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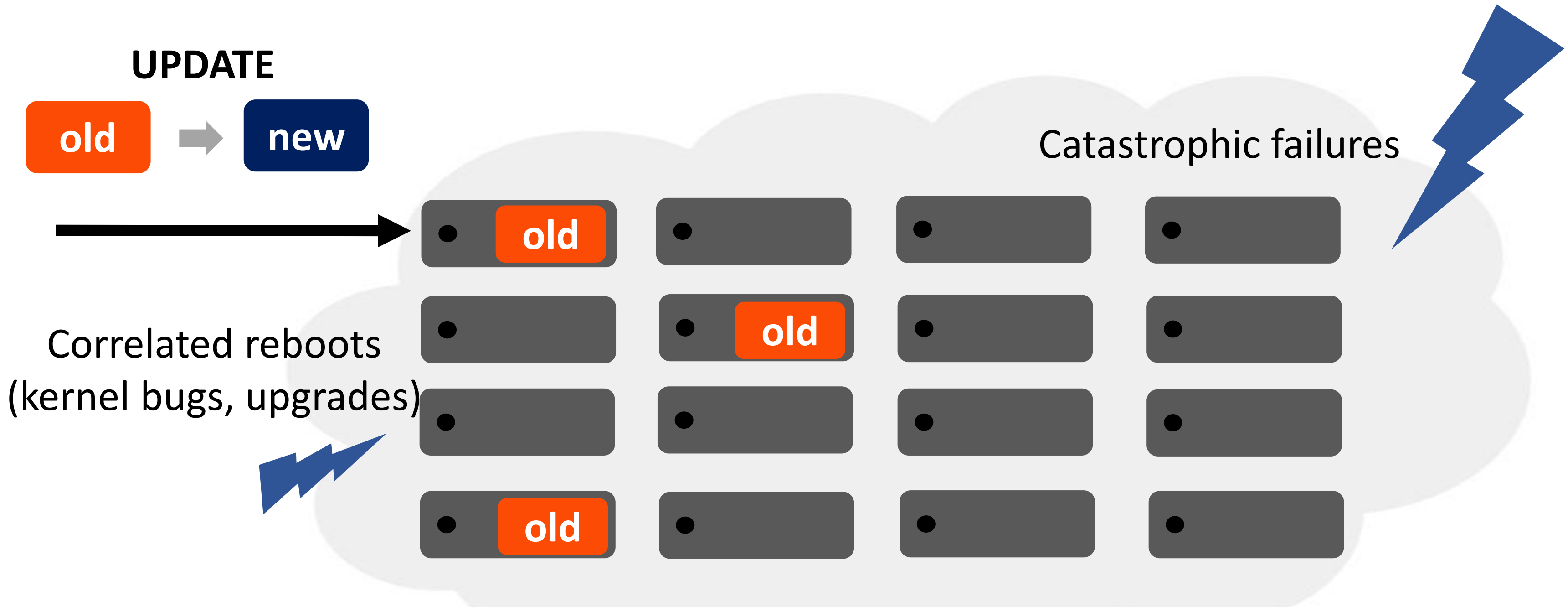

In such crash scenarios, nodes left only with persistent state

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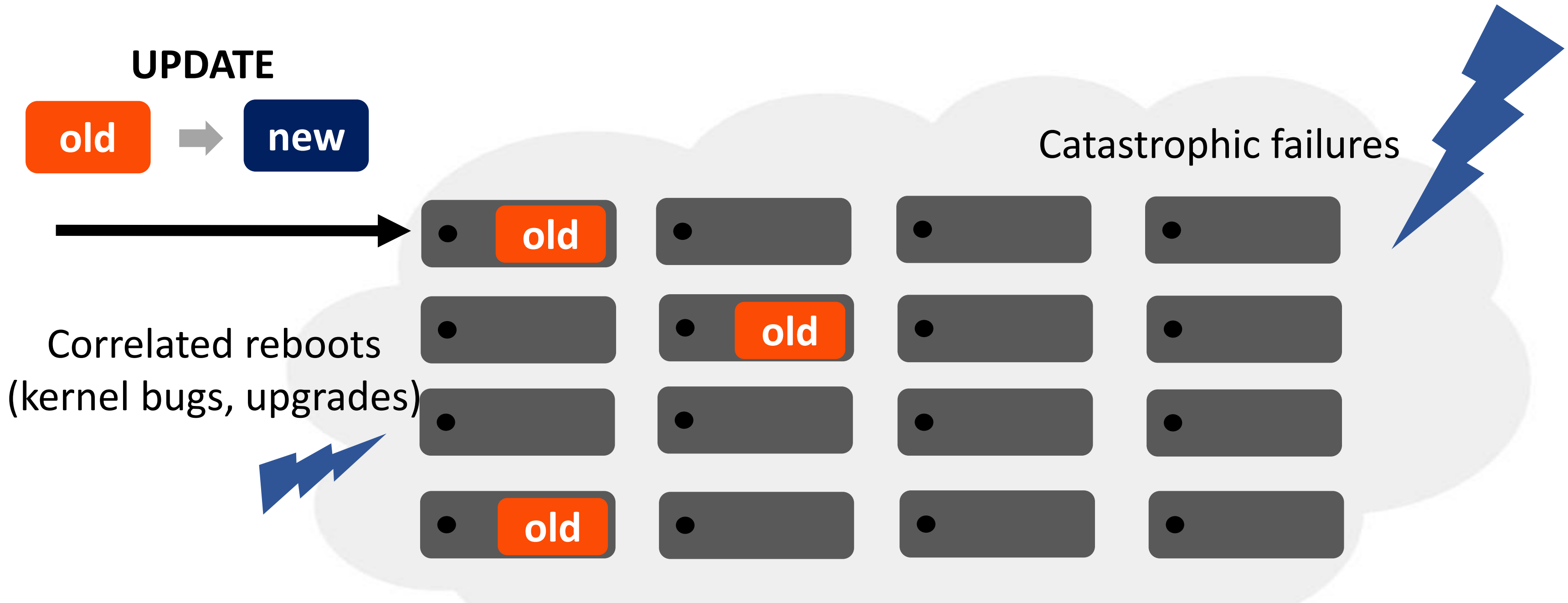

In such crash scenarios, nodes left only with persistent state

After recovery, users expect:

Either new (if acknowledged) or old

No corrupted data

Available after recovery

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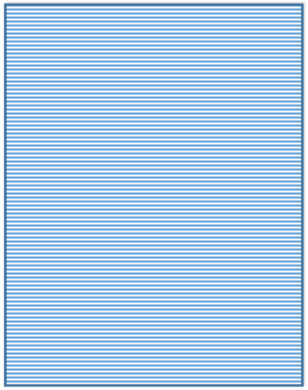

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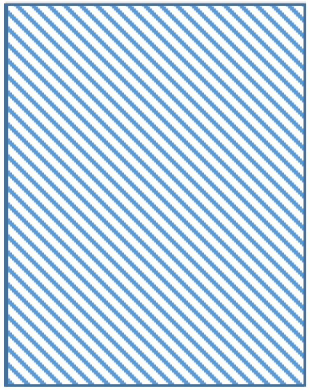

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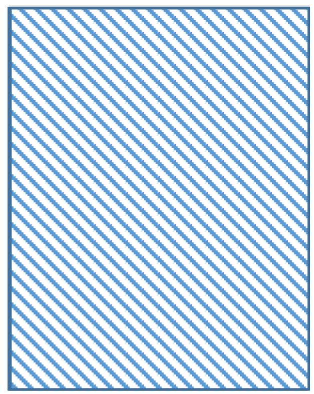
/foo

pwrite(“/foo”, buf, 4K, 0)



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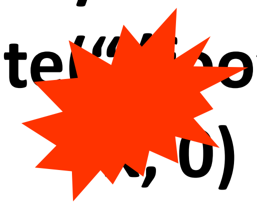

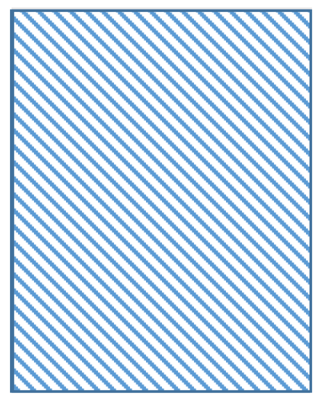

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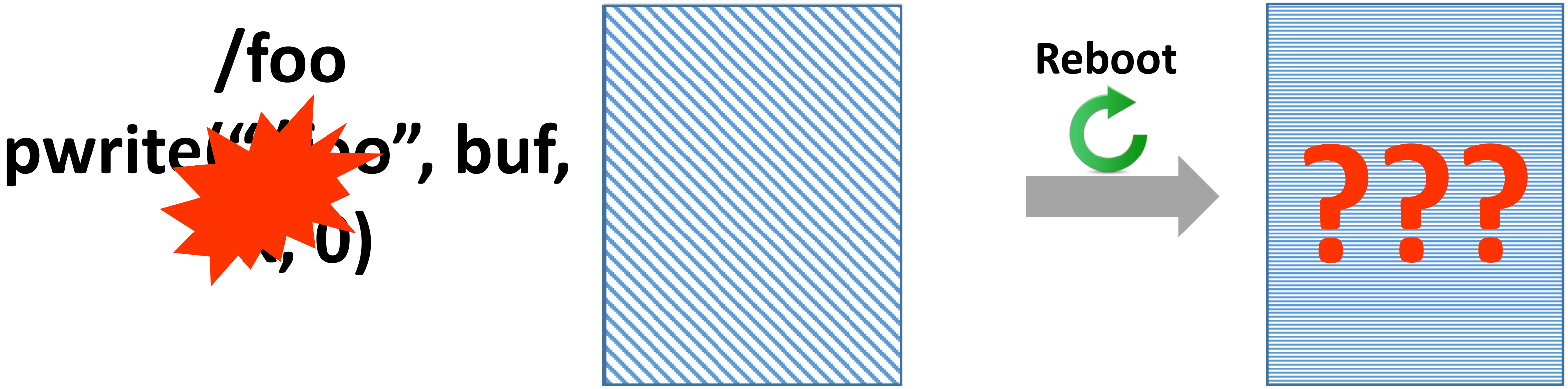

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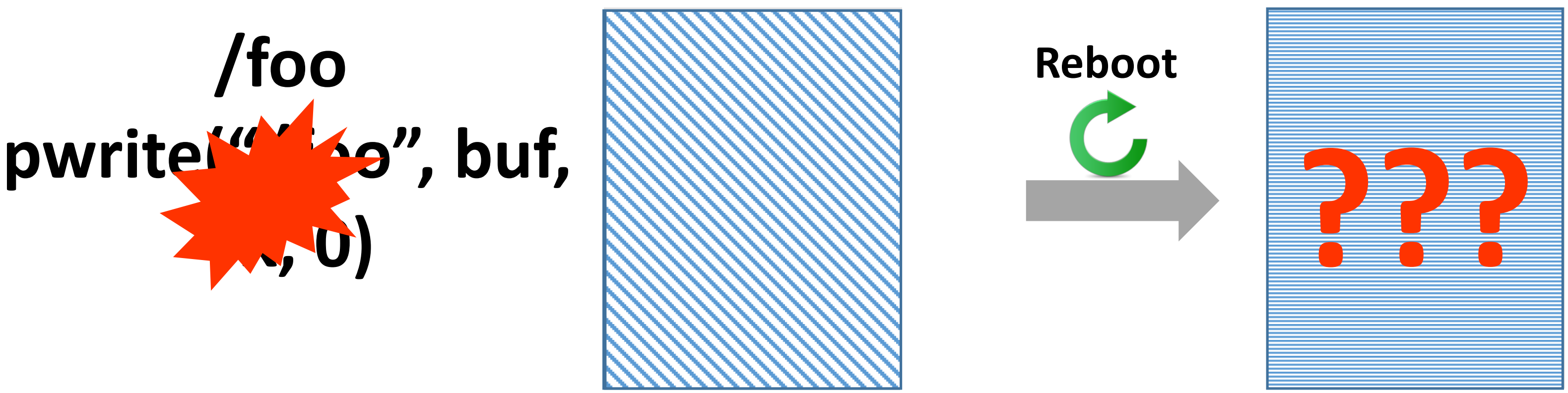

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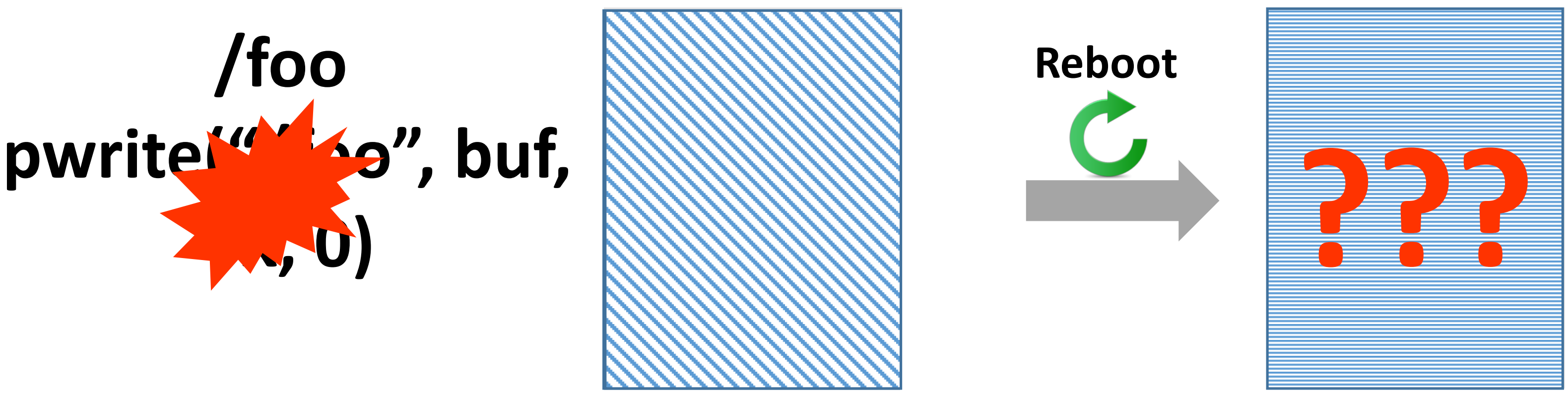

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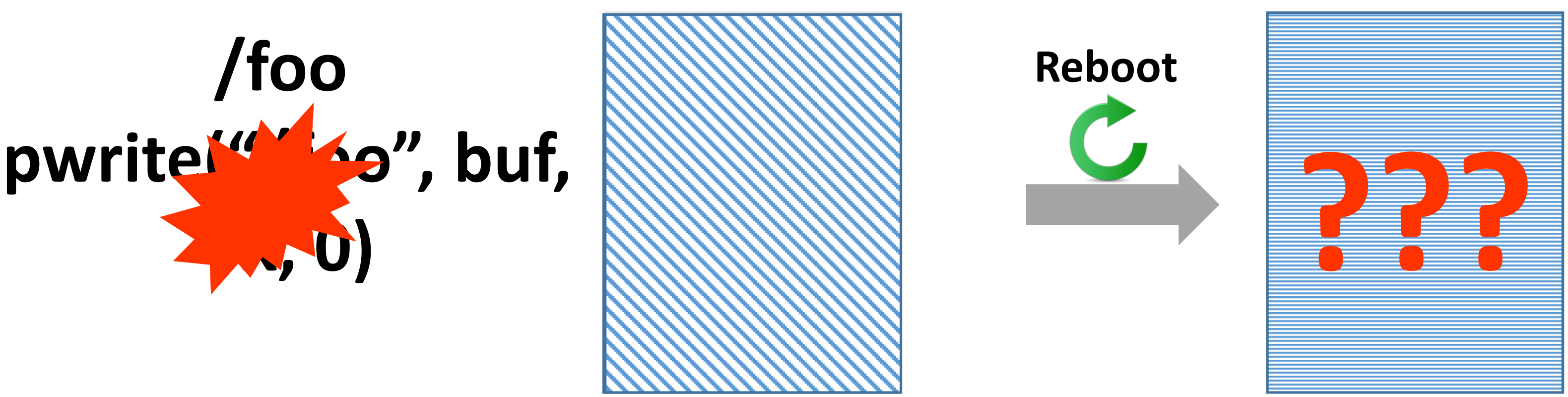

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- On ext3 and ext4 (default), XFS, ext2 ***NO!***

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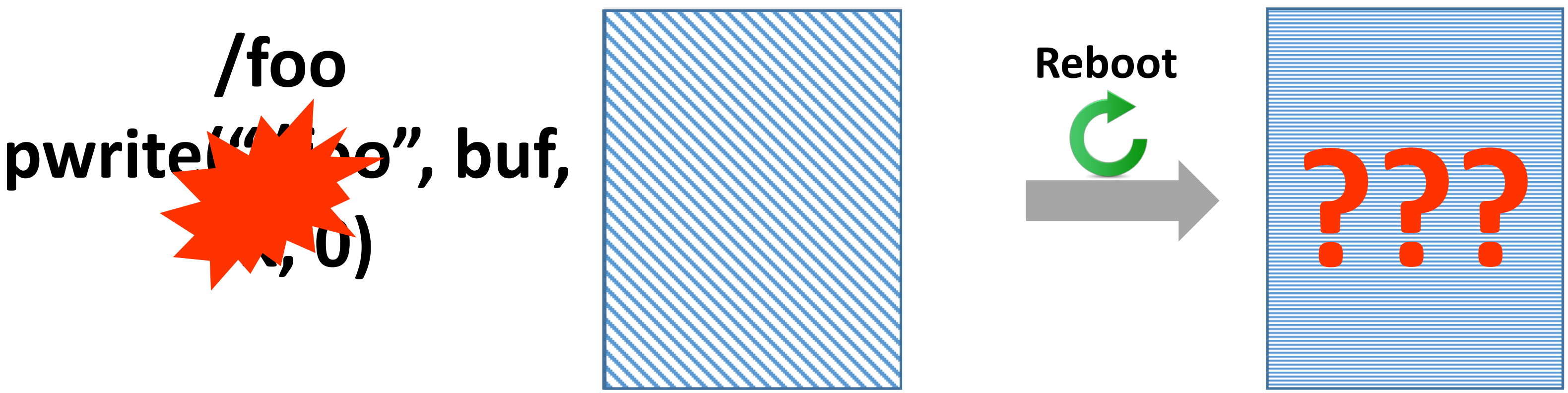

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Affects distributed storage systems

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Do distributed storage systems violate user-level expectations in the presence of correlated crashes?

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- How do distributed crash recovery protocols interact with file-system crash behaviors?

How to check for correlated crash vulnerabilities?

- PACE (Protocol-Aware Crash Explorer)
- Prunes state space using protocol knowledge

Results Summary

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Applied PACE to eight systems: Redis, MongoDB, Kafka, ZooKeeper, RethinkDB, LogCabin, etcd, and iNexus

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Found **26** unique vulnerabilities with severe consequences - data loss, corruption, unavailable clusters etc.,

- Many on commonly used file systems

Many confirmed by developers

- Many fixed
- Some fundamentally hard

Overarching lessons

1. File-system crash behaviors impact distributed storage systems

2. Problems in local storage protocols are not fixed by distributed recovery protocols (in many cases)
   - False sense of reliability

Outline

Introduction and Motivation

Correlated Crash States

- **General Approach: Reachable States**
- **States due to File System Behaviors**

Protocol-Aware Crash Explorer

Vulnerability Study

Conclusion

How to capture persistent states that can occur during a correlated crash?

Approach: Finding Reachable States

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Node P ***Node Q***

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 # State $P_{\emptyset}$ *# State $Q_{\emptyset}$*

Approach: Finding Reachable States

Node P

 # State $P_{\emptyset}$

send(Q, M1)

Node Q

 # State $Q_{\emptyset}$

recv(M1)

Approach: Finding Reachable States

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Approach: Finding Reachable States

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send(Q, M1)

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write(fd, “baz”,3)	
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write(fd, “foo”,3)	
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# State P_2	
send(Q, M2)	recv(M2)
# State P_2	*# State $Q_{\emptyset}$*

Approach: Finding Reachable States

Node P	***Node Q***
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send(Q, M1)	recv(M1)
# State $P_ø$	*# State $Q_ø$*
write(fd, “foo”,3)	
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	write(fd, “bar”, 3)

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Globally **reachable** persistent states

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Node P	***Node Q***		
# State $P_{\emptyset}$	*# State $Q_{\emptyset}$*	$<\mathbf{P_{\emptyset}}, \mathbf{Q_{\emptyset}}>$	Globally **reachable** persistent states
send(Q, M1)			
	recv(M1)		
# State $P_{\emptyset}$	*# State $Q_{\emptyset}$*		
write(fd, “foo”,3)			
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# State P_2			
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# State P_2	*# State $Q_{\emptyset}$*		
	write(fd, “bar”, 3)		
	# State Q_1		

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send(Q, M2)	recv(M2)		
# State P_2	*# State $Q_{\varnothing}$*		
	write(fd, “bar”, 3)		
	# State Q_1	$<\mathbf{P_2, Q_1}>$	

Approach: Finding Reachable States

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 # State $P_{\emptyset}$ *# State $Q_{\emptyset}$* <$P_{\emptyset}$, $Q_{\emptyset}$>

Globally **reachable** persistent states

send(Q, M1) → recv(M1)

 # State $P_{\emptyset}$ *# State $Q_{\emptyset}$*

write(fd, “foo”,3)

 # State P_1 <P_1, $Q_{\emptyset}$>

write(fd, “baz”,3)

 # State P_2

send(Q, M2) → recv(M2)

 # State P_2

 # State $Q_{\emptyset}$

write(fd, “bar”, 3)

 # State Q_1

<P_2, Q_1>

Approach: Finding Reachable States

Node P ***Node Q***

 # State $P_\emptyset$ *# State $Q_\emptyset$* $\langle \boldsymbol{P_\emptyset}, \boldsymbol{Q_\emptyset} \rangle$

Globally **reachable** persistent states

send(Q, M1) → recv(M1)

 # State $P_\emptyset$ *# State $Q_\emptyset$*

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 # State P_1 $\langle \boldsymbol{P_1}, \boldsymbol{Q_\emptyset} \rangle$

write(fd, “baz”,3)

 # State P_2 $\langle \boldsymbol{P_2}, \boldsymbol{Q_\emptyset} \rangle$

send(Q, M2) → recv(M2)

 # State P_2

 # State $Q_\emptyset$

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 # State Q_1

$\langle \boldsymbol{P_2}, \boldsymbol{Q_1} \rangle$

Approach: Finding Reachable States

Node P	***Node Q***	
# State $P_{\varnothing}$	*# State $Q_{\varnothing}$*	$\langle \mathbf{P_{\varnothing}, Q_{\varnothing}} \rangle$
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# State $P_{\varnothing}$	*# State $Q_{\varnothing}$*	
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	# State Q_1	
		$\langle \mathbf{P_2, Q_1} \rangle$

Globally **reachable** persistent states

Consistent Cuts

Reachable Persistent Prefixes

Approach: Finding Reachable States

Node P ***Node Q***

\# State $P_{\emptyset}$ \# State $Q_{\emptyset}$ $<P_{\emptyset}, Q_{\emptyset}>$

send(Q, M1)

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\# State $P_{\emptyset}$ \# State $Q_{\emptyset}$

write(fd, “foo”,3)

\# State P_1 $<P_1, Q_{\emptyset}>$

write(fd, “baz”,3)

\# State P_2 $<P_2, Q_{\emptyset}>$

send(Q, M2)

recv(M2)

\# State P_2

\# State $Q_{\emptyset}$

write(fd, “bar”, 3)

\# State Q_1

$<P_2, Q_1>$

Globally **reachable** persistent states

Consistent Cuts

Reachable Persistent Prefixes

Not Reachable

$<P_{\emptyset}, Q_1>$ $<P_1, Q_1>$

File-System Behaviors: Reordering

Node P	***Node Q***
# State $P_\emptyset$	*# State $Q_\emptyset$*
send(Q, M1)	
	recv(M1)
# State $P_\emptyset$	*# State $Q_\emptyset$*
1 write(fd, “foo”,3)	
# State P_1	
2 write(fd, “baz”,3)	
# State P_2	<P_2, $Q_\emptyset$>
send(Q, M2)	
	recv(M2)
# State P_2	
	# State $Q_\emptyset$
	write(fd, “bar”, 3)
	# State Q_1

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Node P	***Node Q***
# State $P_\varnothing$	*# State $Q_\varnothing$*
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# State P_2	**<P_2, $Q_\varnothing$>**
send(Q, M2)	
	recv(M2)
# State P_2	*# State $Q_\varnothing$*
	write(fd, “bar”, 3)
	# State Q_1

File systems may **reorder** updates to disk

1 write(fd, “foo”,3)

2 write(fd, “baz”,3)

File-System Behaviors: Reordering

Node P	***Node Q***
# State $P_ø$	*# State $Q_ø$*
send(Q, M1)	recv(M1)
# State $P_ø$	*# State $Q_ø$*
1 write(fd, “foo”,3)	
# State P_1	
2 write(fd, “baz”,3)	
# State P_2	<P_2, $Q_ø$>
send(Q, M2)	recv(M2)
# State P_2	*# State $Q_ø$*
	write(fd, “bar”, 3)
	# State Q_1

File systems may **reorder** updates to disk

1 write(fd, “foo”,3)

2 write(fd, “baz”,3)

File-System Behaviors: Reordering

Node P	***Node Q***
# State $P_\emptyset$	*# State $Q_\emptyset$*
send(Q, M1)	recv(M1)
# State $P_\emptyset$	*# State $Q_\emptyset$*
1 write(fd, "foo",3)	
# State P_1	
2 write(fd, "baz",3)	
# State P_2	$\langle \boldsymbol{P_2}, \boldsymbol{Q_\emptyset} \rangle$
send(Q, M2)	recv(M2)
# State P_2	*# State $Q_\emptyset$*
	write(fd, "bar", 3)
	# State Q_1

File systems may **reorder** updates to disk

1. write(fd, "foo",3)
2. write(fd, "baz",3)

File-System Behaviors: Reordering

Node P	***Node Q***
# State $P_{\emptyset}$	*# State $Q_{\emptyset}$*
send(Q, M1)	recv(M1)
# State $P_{\emptyset}$	*# State $Q_{\emptyset}$*
1 write(fd, "foo",3)	
# State P_1	
2 write(fd, "baz",3)	
# State P_2	<P_2, $Q_{\emptyset}$>
send(Q, M2)	recv(M2)
# State P_2	*# State $Q_{\emptyset}$*
	write(fd, "bar", 3)
	# State Q_1

File systems may **reorder** updates to disk

1 write(fd, "foo",3)

2 write(fd, "baz",3)

Reboot

File-System Behaviors: Reordering

Node P	***Node Q***
# State $P_\varnothing$	*# State $Q_\varnothing$*
send(Q, M1)	recv(M1)
# State $P_\varnothing$	*# State $Q_\varnothing$*
1 write(fd, “foo”,3)	
# State P_1	
2 write(fd, “baz”,3)	
# State P_2	<**P_2, $Q_\varnothing$**>
send(Q, M2)	recv(M2)
# State P_2	*# State $Q_\varnothing$*
	write(fd, “bar”, 3)
	# State Q_1

File systems may **reorder** updates to disk

1 write(fd, “foo”,3)

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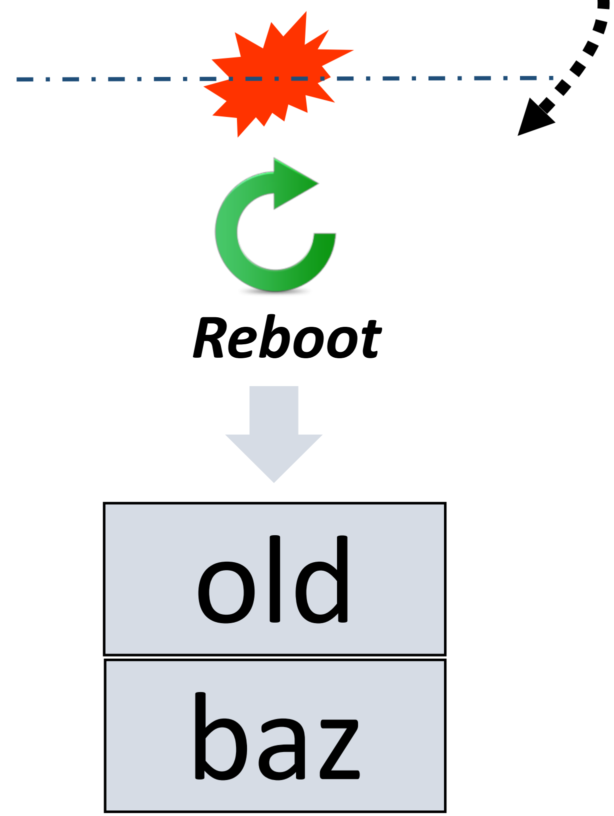


File-System Behaviors: Atomicity

Node P	***Node Q***
# State $P_{\varnothing}$	*# State $Q_{\varnothing}$*
send(Q, M1)	
	recv(M1)
# State $P_{\varnothing}$	*# State $Q_{\varnothing}$*
write(fd, “foo”,3)	
# State P_1	
write(fd, “baz”,3)	
# State P_2	
send(Q, M2)	
	recv(M2)
# State P_2	*# State $Q_{\varnothing}$*
	write(fd, “bar”, 3)
	# State Q_1

File-System Behaviors: Atomicity

Node P

 # State $P_{\emptyset}$

send(Q, M1)

 # State $P_{\emptyset}$

write(fd, “foo”,3)

 # State P_1

2 write(fd, “baz”,3)

 # State P_2

send(Q, M2)

 # State P_2

Node Q

 # State $Q_{\emptyset}$

recv(M1)

 # State $Q_{\emptyset}$

recv(M2)

 # State $Q_{\emptyset}$

write(fd, “bar”, 3)

 # State Q_1

File systems may **partially persist operations**

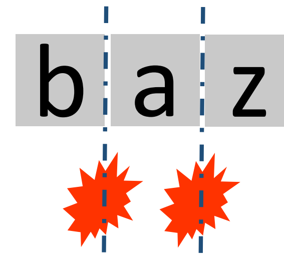
2 write(fd, “baz”,3)

File-System Behaviors: Atomicity

Node P	***Node Q***
# State $P_{\varnothing}$	# State $Q_{\varnothing}$
send(Q, M1)	recv(M1)
# State $P_{\varnothing}$	# State $Q_{\varnothing}$
write(fd, "foo",3)	
# State P_1	
2 write(fd, "baz",3)	
# State P_2	
send(Q, M2)	recv(M2)
# State P_2	# State $Q_{\varnothing}$
	write(fd, "bar", 3)
	# State Q_1

File systems may **partially persist operations**

2 write(fd, "baz",3)



File-System Behaviors: Atomicity

Node P	***Node Q***
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	recv(M1)
# State $P_{\varnothing}$	*# State $Q_{\varnothing}$*
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# State P_1	
2 write(fd, "baz",3)	
# State P_2	
send(Q, M2)	
	recv(M2)
# State P_2	*# State $Q_{\varnothing}$*
	write(fd, "bar", 3)
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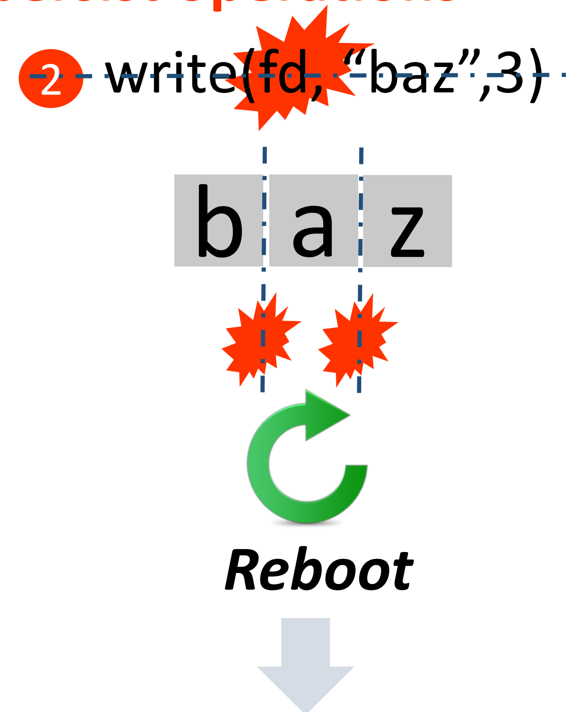
File systems may **partially persist operations**



File-System Behaviors: Atomicity

Node P

 # State $P_\varnothing$

send(Q, M1)

 # State $P_\varnothing$

write(fd, "foo",3)

 # State P_1

2 write(fd, "baz",3)

 # State P_2

send(Q, M2)

 # State P_2

Node Q

 # State $Q_\varnothing$

recv(M1)

 # State $Q_\varnothing$

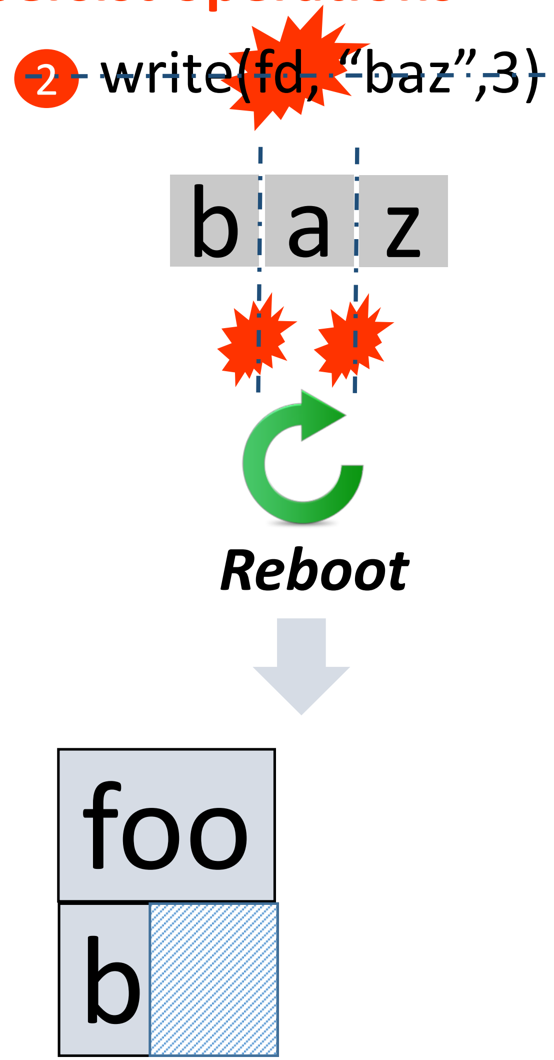
recv(M2)

 # State $Q_\varnothing$

write(fd, "bar", 3)

 # State Q_1

File systems may **partially persist operations**



File-System Behaviors: Atomicity

Node P	***Node Q***
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send(Q, M2)	recv(M2)
# State P_2	*# State $Q_\emptyset$*
	write(fd, “bar”, 3)
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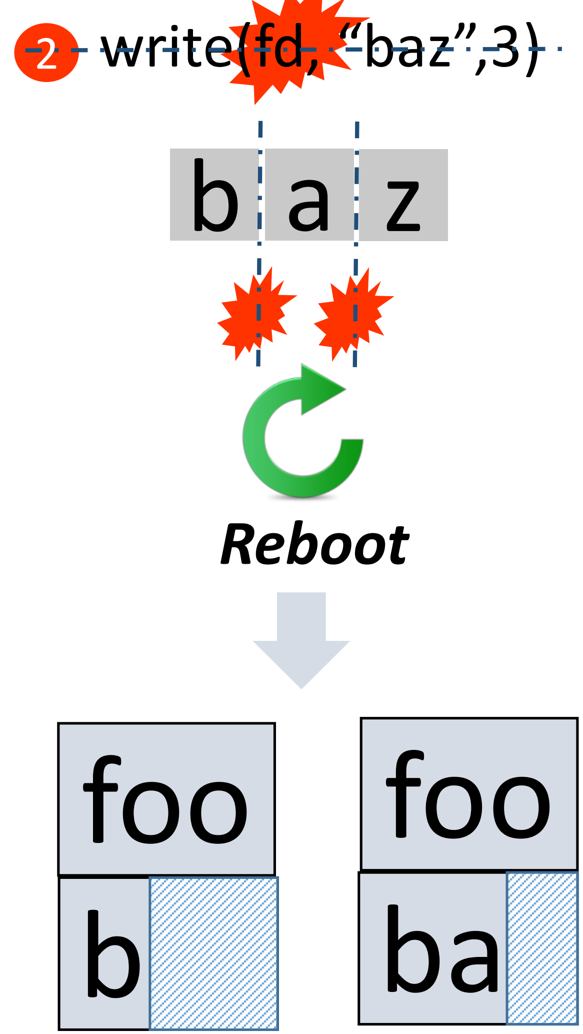

Modeling File-System Behaviors

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Reordering and partially persisting on crashes

– Relaxations

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Reordering and partially persisting on crashes

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Relaxations vary across file systems

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Reordering and partially persisting on crashes

– Relaxations

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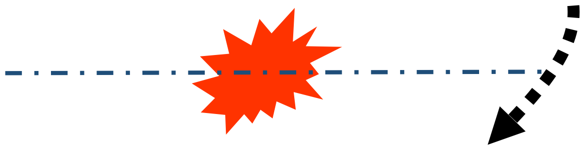

Modeling File-System Behaviors

Reordering and partially persisting on crashes

– Relaxations

Relaxations vary across file systems

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2 write(fd, “baz”,3)

Can happen on: ext3 and ext4 (writeback, ordered), ext2, XFS

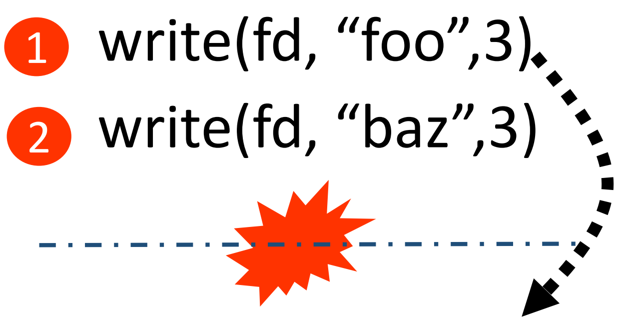
Not on: ext3 and ext4(data), btrfs

Modeling File-System Behaviors

Reordering and partially persisting on crashes

– Relaxations

Relaxations vary across file systems



Can happen on: ext3 and ext4 (writeback, ordered), ext2, XFS

Not on: ext3 and ext4(data), btrfs

Abstract Persistence Model (APM) [Pillai et., OSDI’14] defines relaxations allowed on a particular file system

Outline

Introduction

Correlated Crashes

PACE (Protocol-Aware Crash Explorer)

- **State Space and PACE Rules**
- **Methodology**

Vulnerability Study

Conclusion

Protocol-Aware Crash Explorer

Protocol-Aware Crash Explorer

Relaxations on one node results in many states for that node

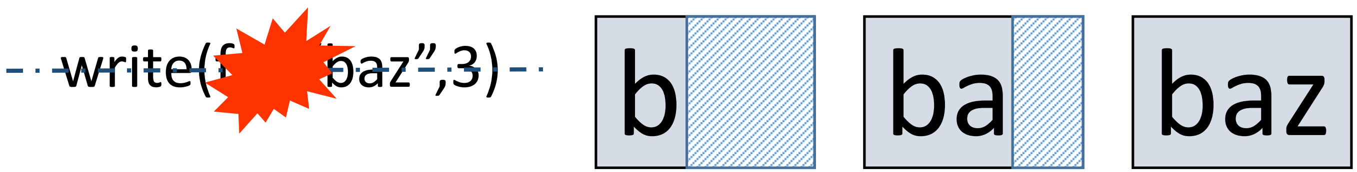
Protocol-Aware Crash Explorer

Relaxations on one node results in many states for that node

write(fd, “baz”,3)

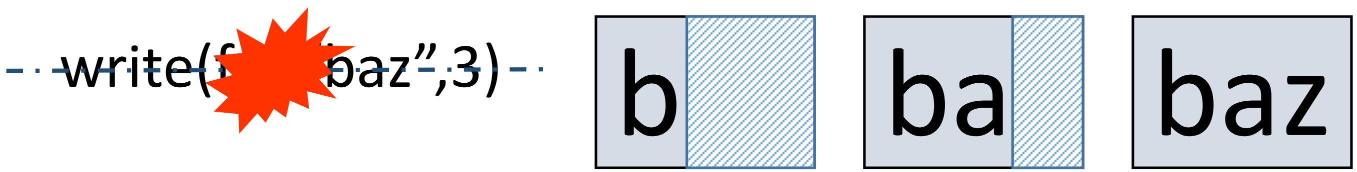
Protocol-Aware Crash Explorer

Relaxations on one node results in many states for that node



Protocol-Aware Crash Explorer

Relaxations on one node results in many states for that node



PACE needs to consider relaxations in different combinations of nodes on all reachable prefixes

Protocol-Aware Crash Explorer

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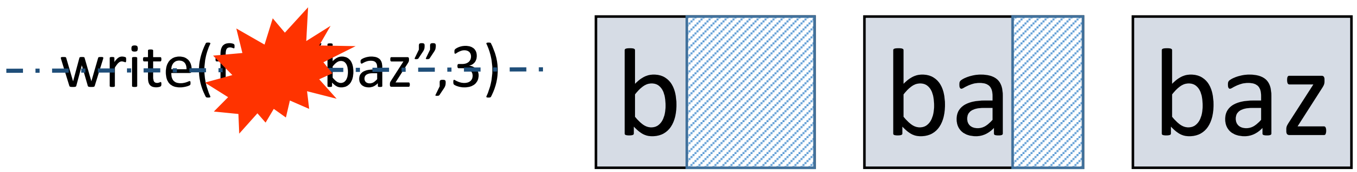

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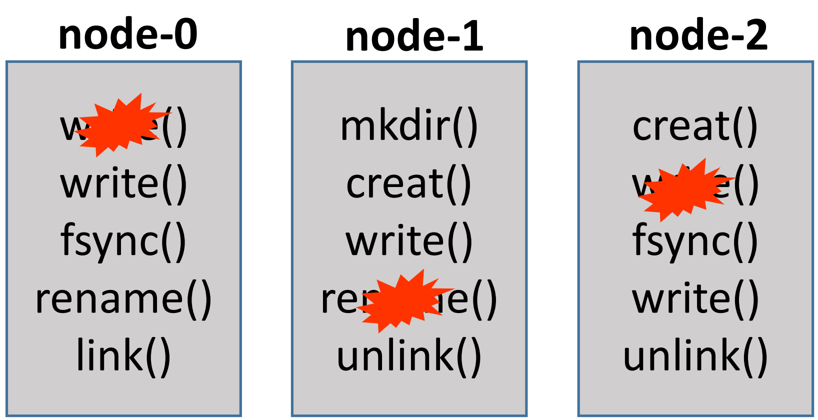
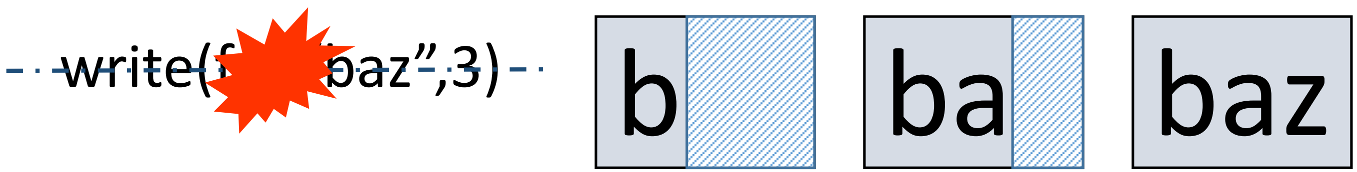


Protocol-Aware Crash Explorer

Relaxations on one node results in many states for that node



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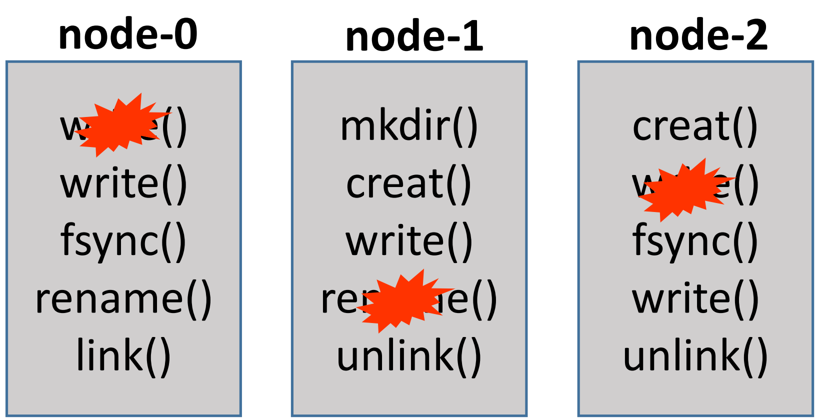

Relax on {0} {1} {2} {0,1} {0,2} {1,2} {0,1,2} ⇒ huge state space

Protocol-Aware Crash Explorer

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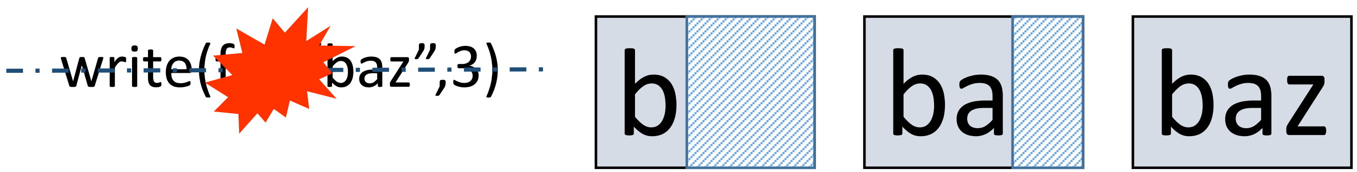

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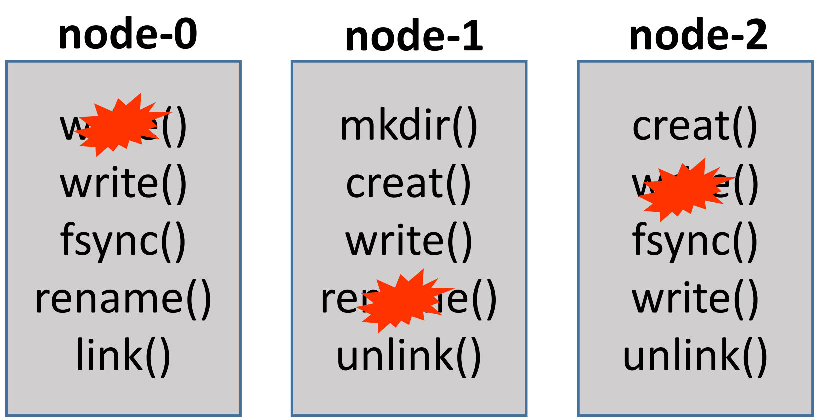

Relax on {0} {1} {2} {0,1} {0,2} {1,2} {0,1,2} ⇒ huge state space

PACE prunes this space using generic rules

PACE Pruning Rules

Replicated State Machine (RSM) approaches

Other (non-RSM) approaches

Details in the paper …

PACE: Effectiveness of Pruning

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LogCabin (RSM)

- brute-force explored ~1M states (over a week) to find 2 vulnerabilities
- PACE explored only ~28K states (in under 8 hours) and found the same vulnerabilities

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- brute-force explored ~1M states (over a week) to find 2 vulnerabilities
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Redis (non-RSM)

- PACE explored 11x fewer states than the brute – force search finding the same 3 vulnerabilities

PACE: Methodology

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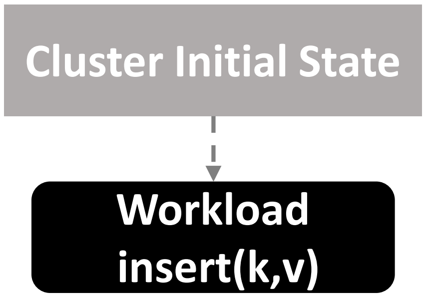
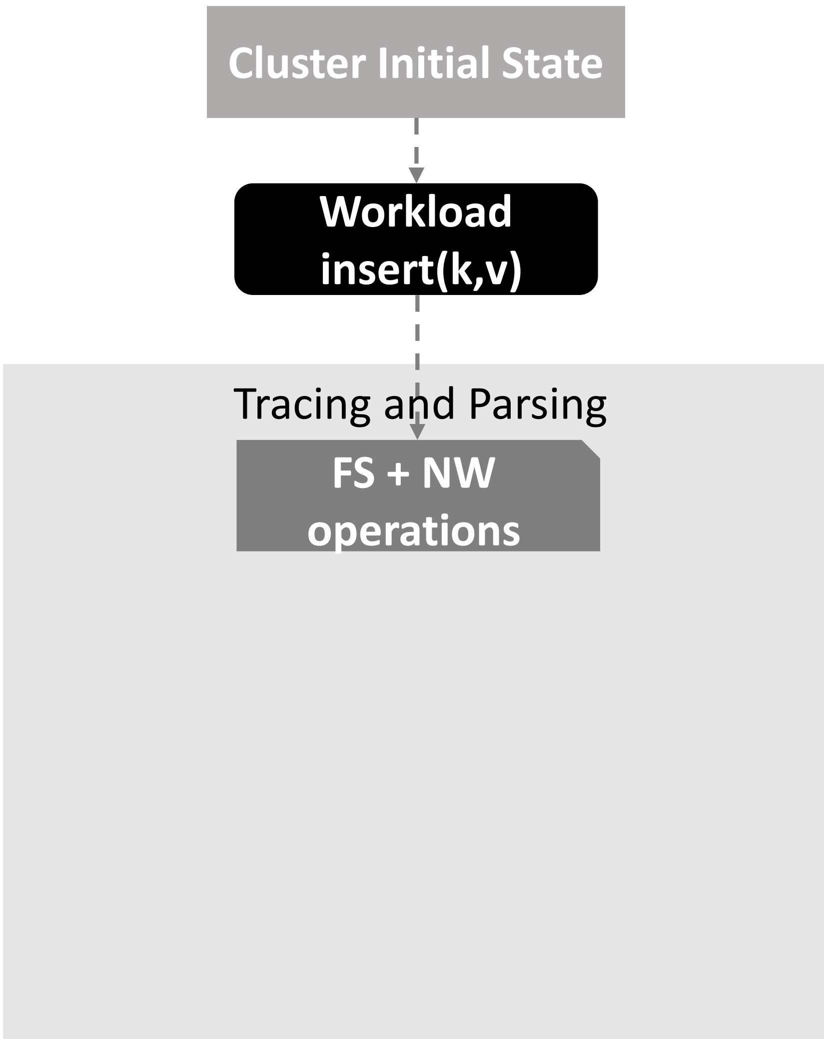


PACE: Methodology



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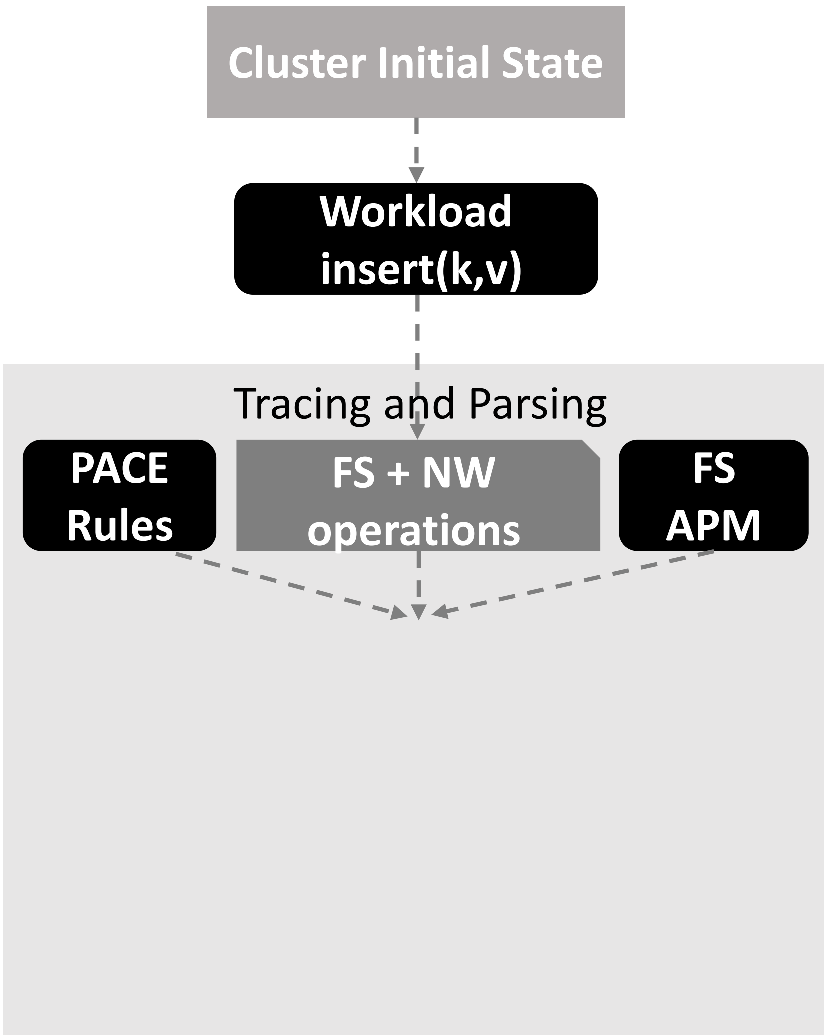

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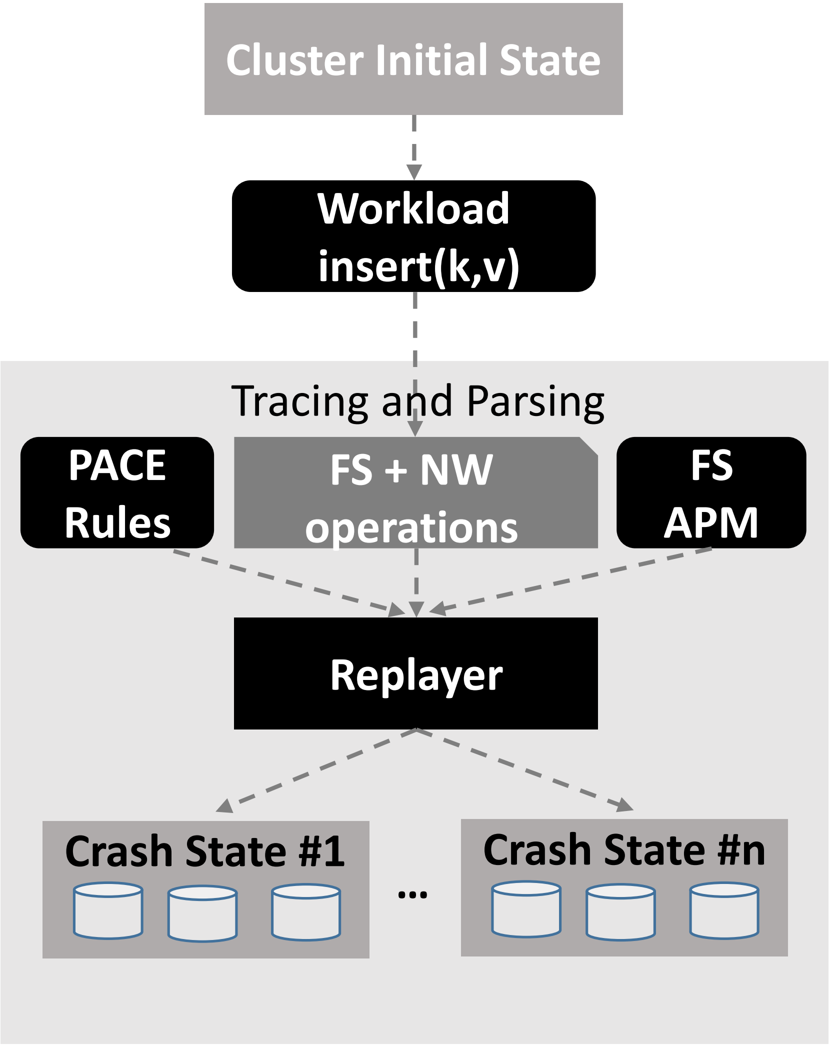

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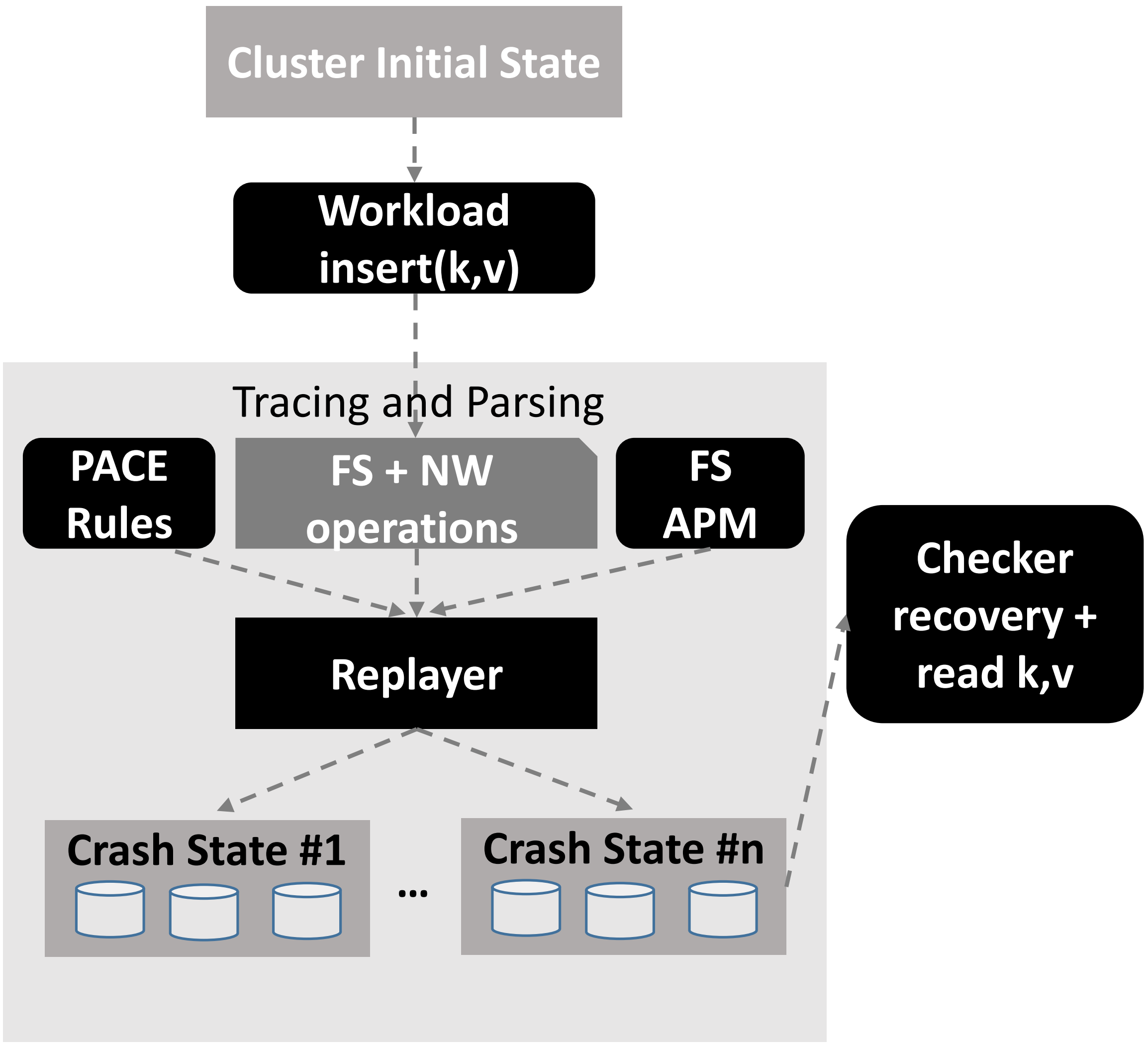
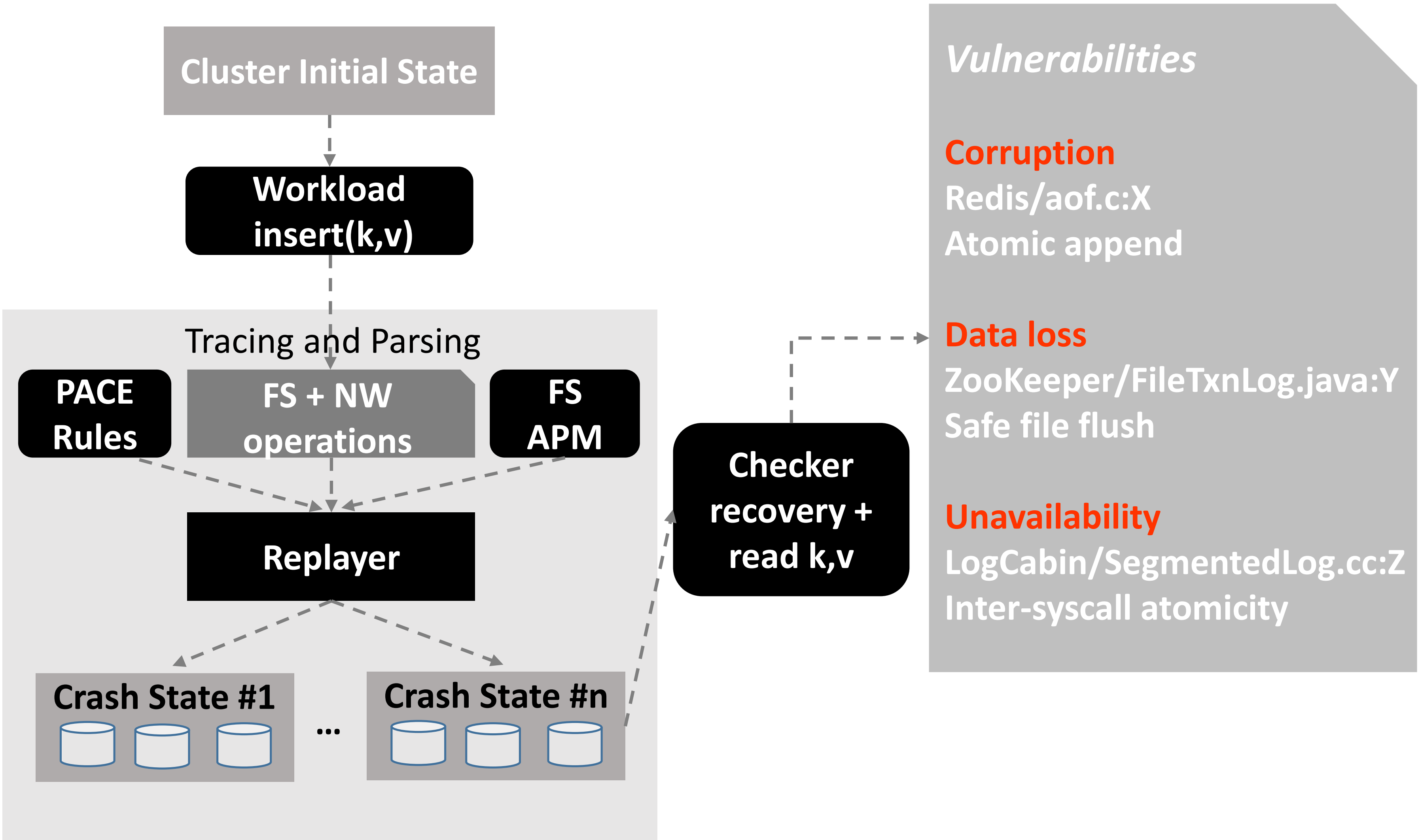


PACE: Methodology



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Vulnerability Study

Concluding Remarks

Vulnerability Study: Systems

Database caches: Redis

Metadata stores: ZooKeeper, LogCabin, etcd

Real-time DB: RethinkDB

Document stores: MongoDB

Message Queues: Kafka

Key-value stores: iNexus

Safest configurations: synchronous replication, synchronous disk writes, checksums etc.,

Example: Redis

Example: Redis

Follower1 **Master** **Follower2**

Example: Redis

Follower1	Master	Follower2
creat(tmp) append(tmp) rename(tmp, tmp-bg) rename(tmp-bg, aof) fdatasync(aof)		creat(tmp) append(tmp) rename(tmp, tmp-bg) rename(tmp-bg, aof) fdatasync(aof)

Example: Redis

Update request

Follower1

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

Master

Follower2

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

Example: Redis

Update request

Follower1

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

Master

append(aof)

Follower2

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

Example: Redis

Update request

Follower1	**Master**	**Follower2**
creat(tmp) append(tmp) rename(tmp, tmp-bg) rename(tmp-bg, aof) fdatasync(aof)	append(aof) fdatasync(aof)	creat(tmp) append(tmp) rename(tmp, tmp-bg) rename(tmp-bg, aof) fdatasync(aof)

Example: Redis

Update request

Follower1

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

Master

append(aof)
fdatasync(aof)
send(data)
send(data)

Follower2

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

Example: Redis

Update request

Follower1

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

recv(data)
append(aof)
fdatasync(aof)
send(ack)

Master

append(aof)
fdatasync(aof)
send(data)
send(data)

Follower2

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

recv(data)
append(aof)
fdatasync(aof)
send(ack)

Example: Redis

Update request

Follower1

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

recv(data)
append(aof)
fdatasync(aof)
send(ack)

Master

append(aof)
fdatasync(aof)
send(data)
send(data)

recv(ack)
recv(ack)
send(client, ack)

Follower2

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

recv(data)
append(aof)
fdatasync(aof)
send(ack)

Acknowledgment

Example: Redis

Update request

Follower1

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

recv(data)
append(aof)
fdatasync(aof)
send(ack)

Master

append(aof)
fdatasync(aof)
send(data)
send(data)

recv(ack)
recv(ack)
send(client, ack)

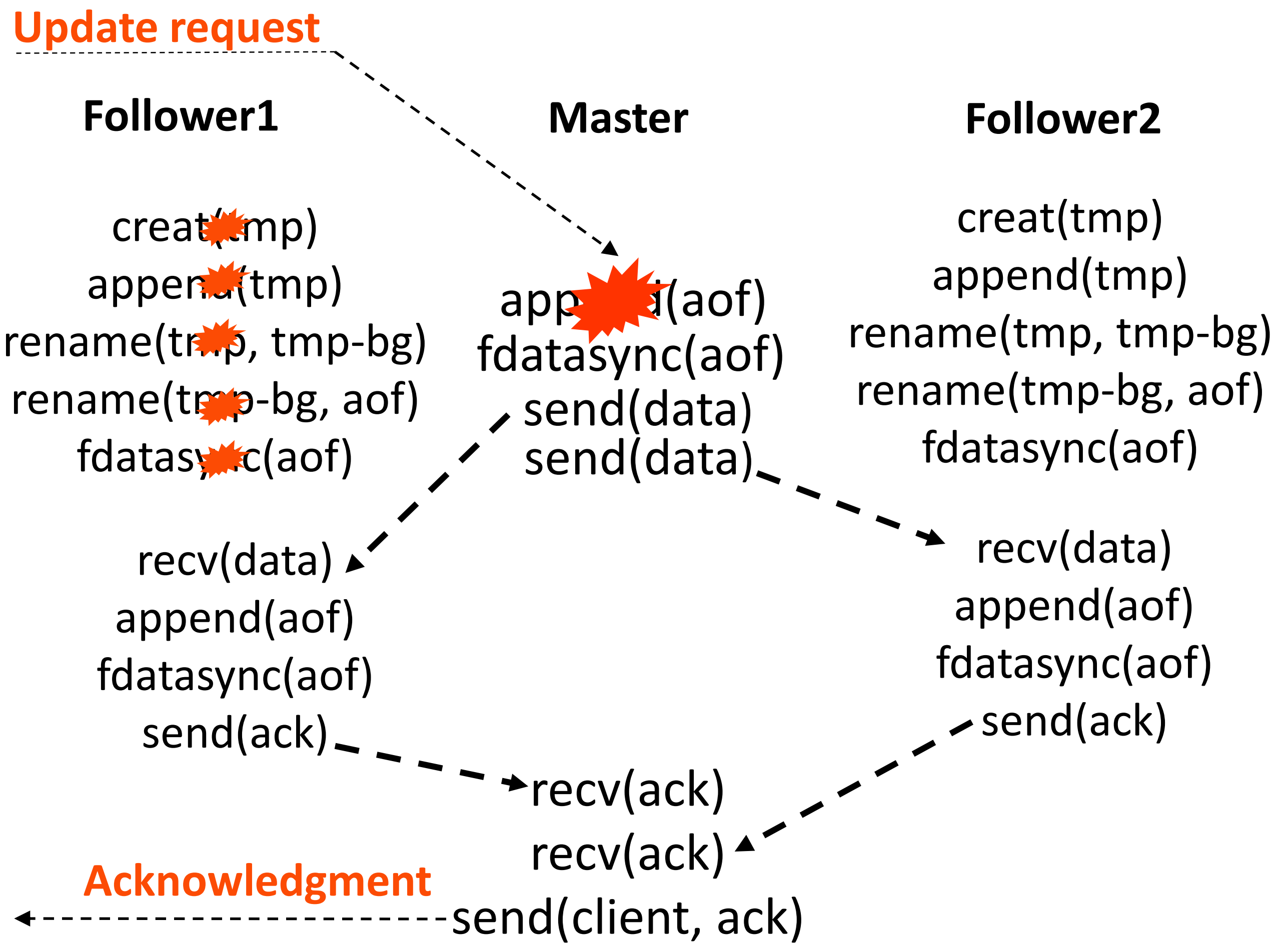
Follower2

creat(tmp)
append(tmp)
rename(tmp, tmp-bg)
rename(tmp-bg, aof)
fdatasync(aof)

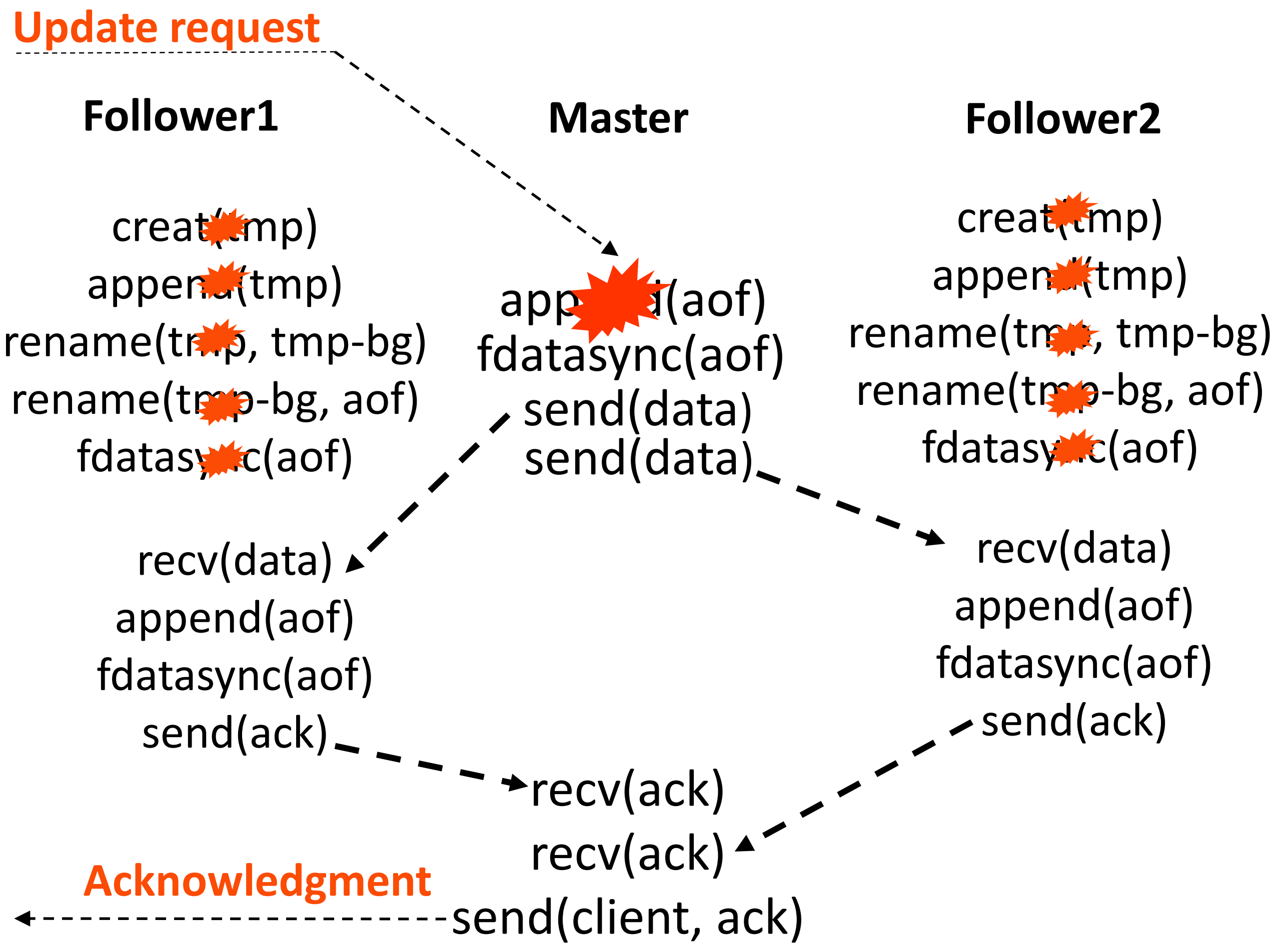
recv(data)
append(aof)
fdatasync(aof)
send(ack)

Acknowledgment

Example: Redis



Example: Redis



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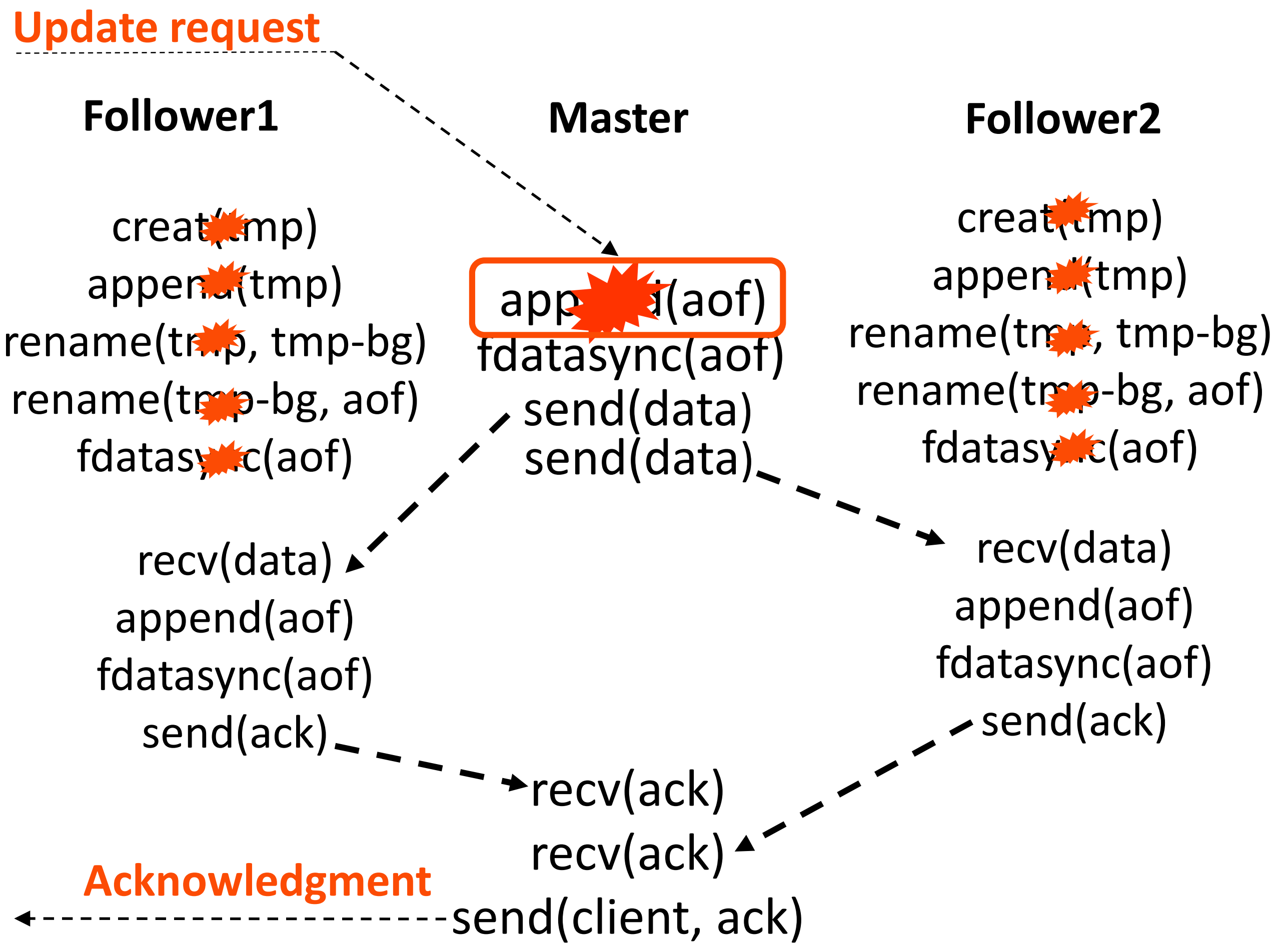

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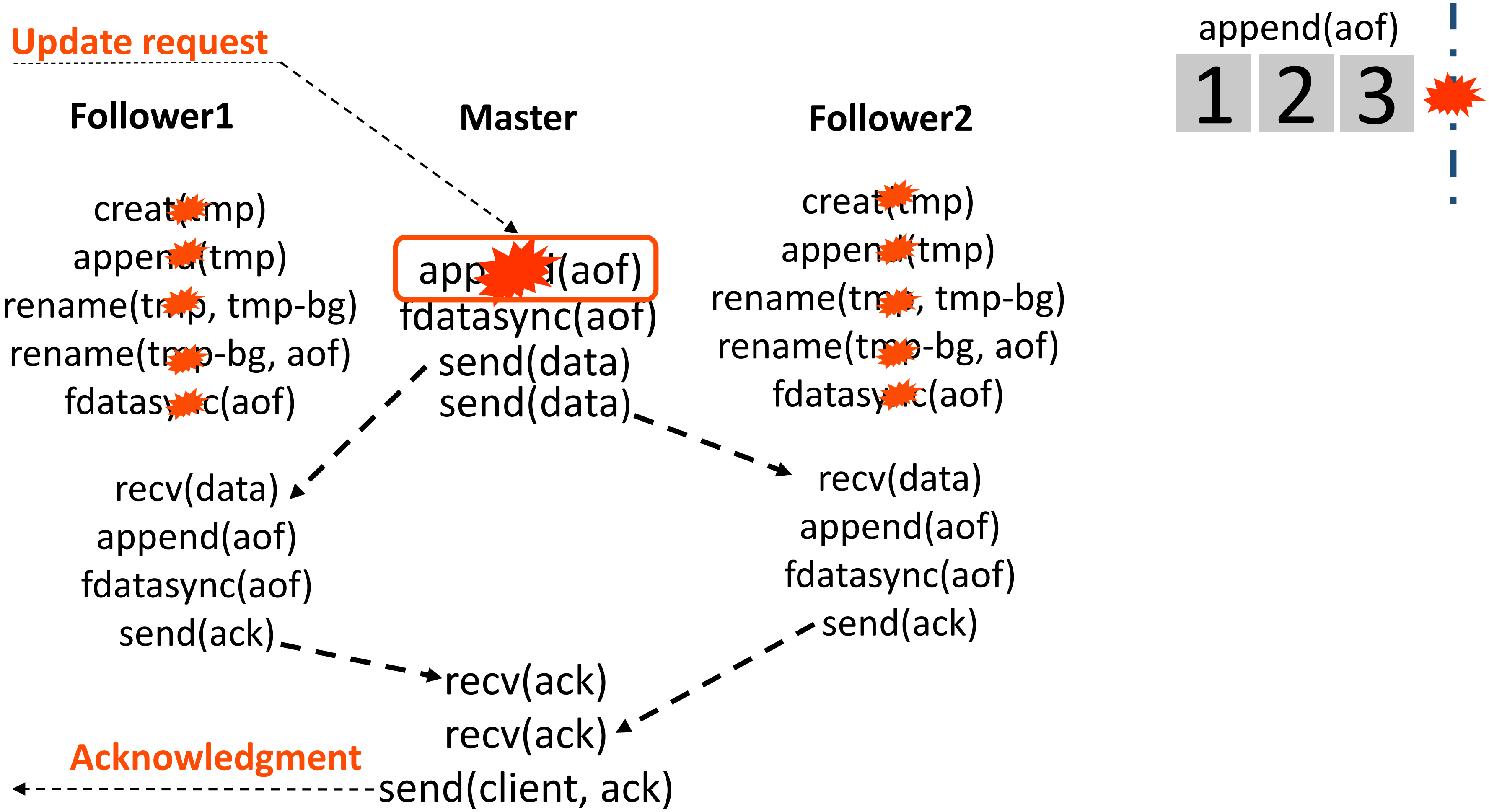

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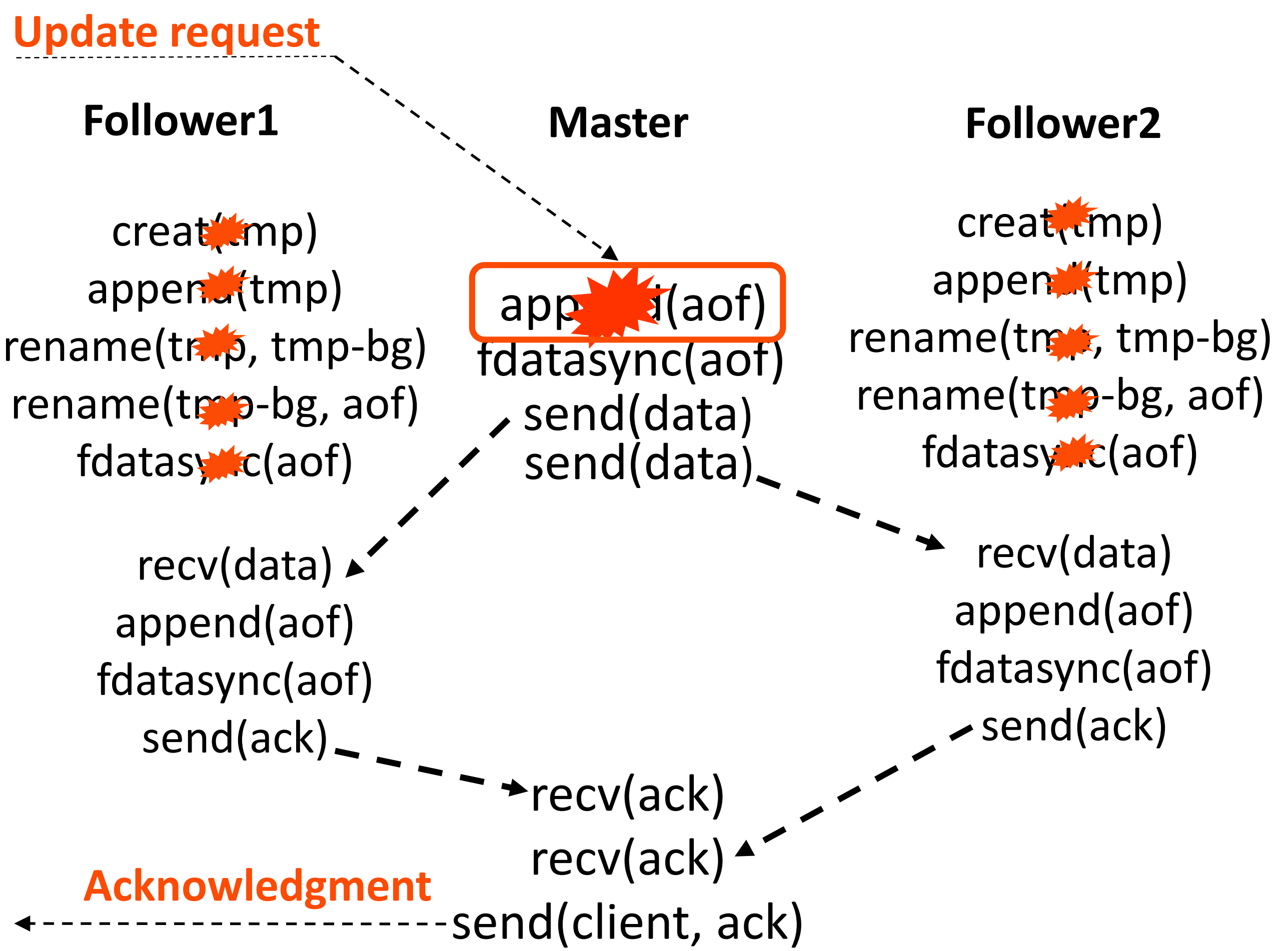

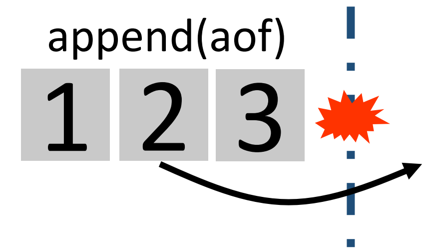

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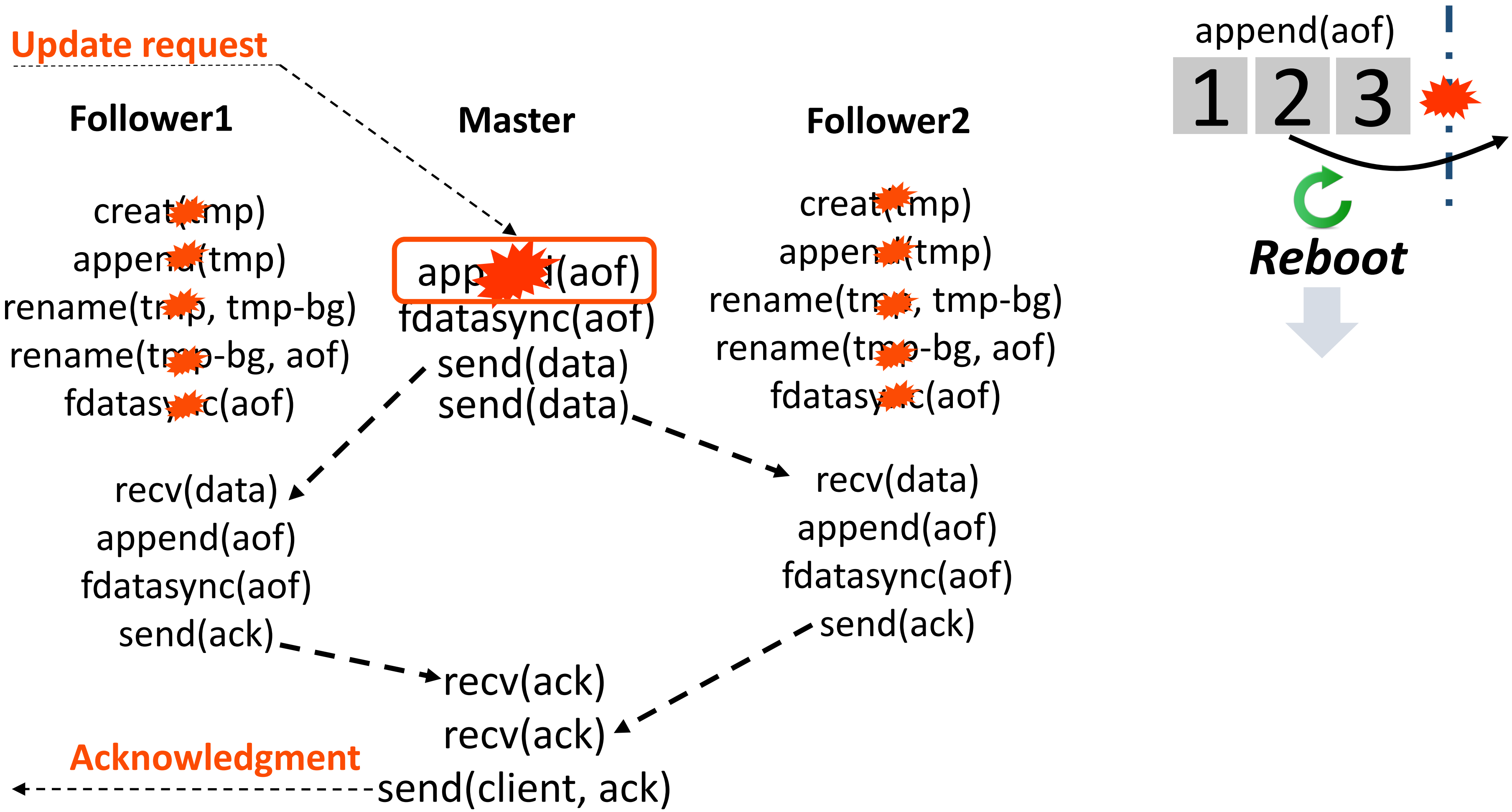

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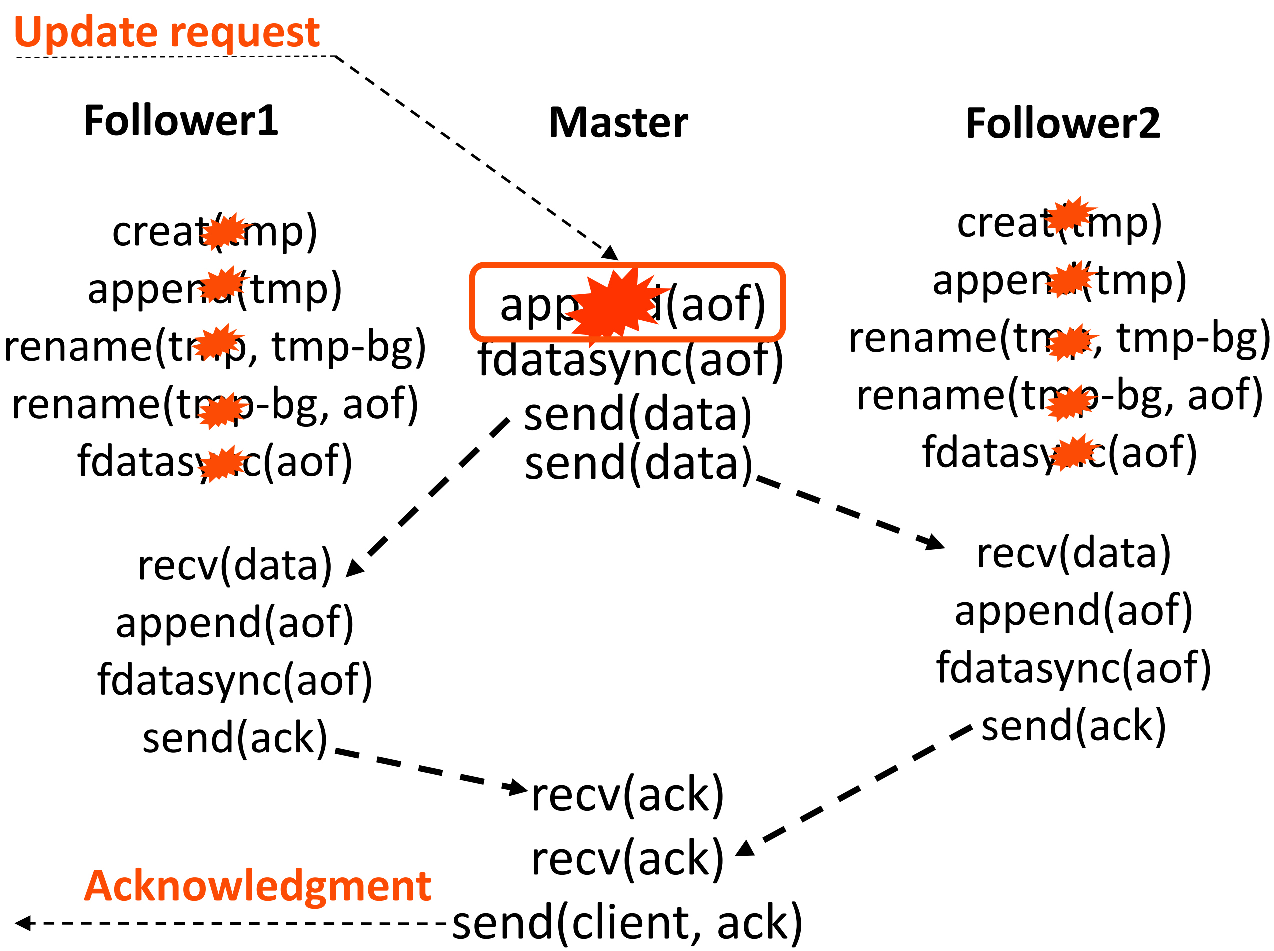

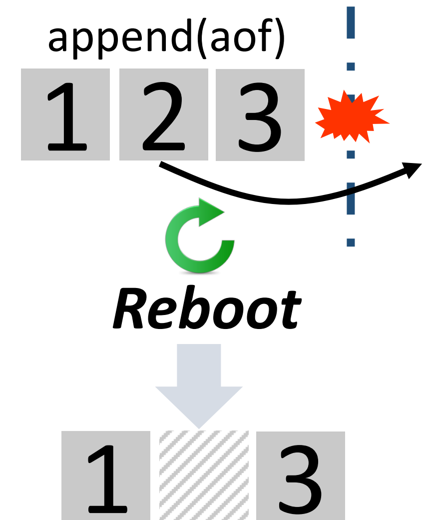

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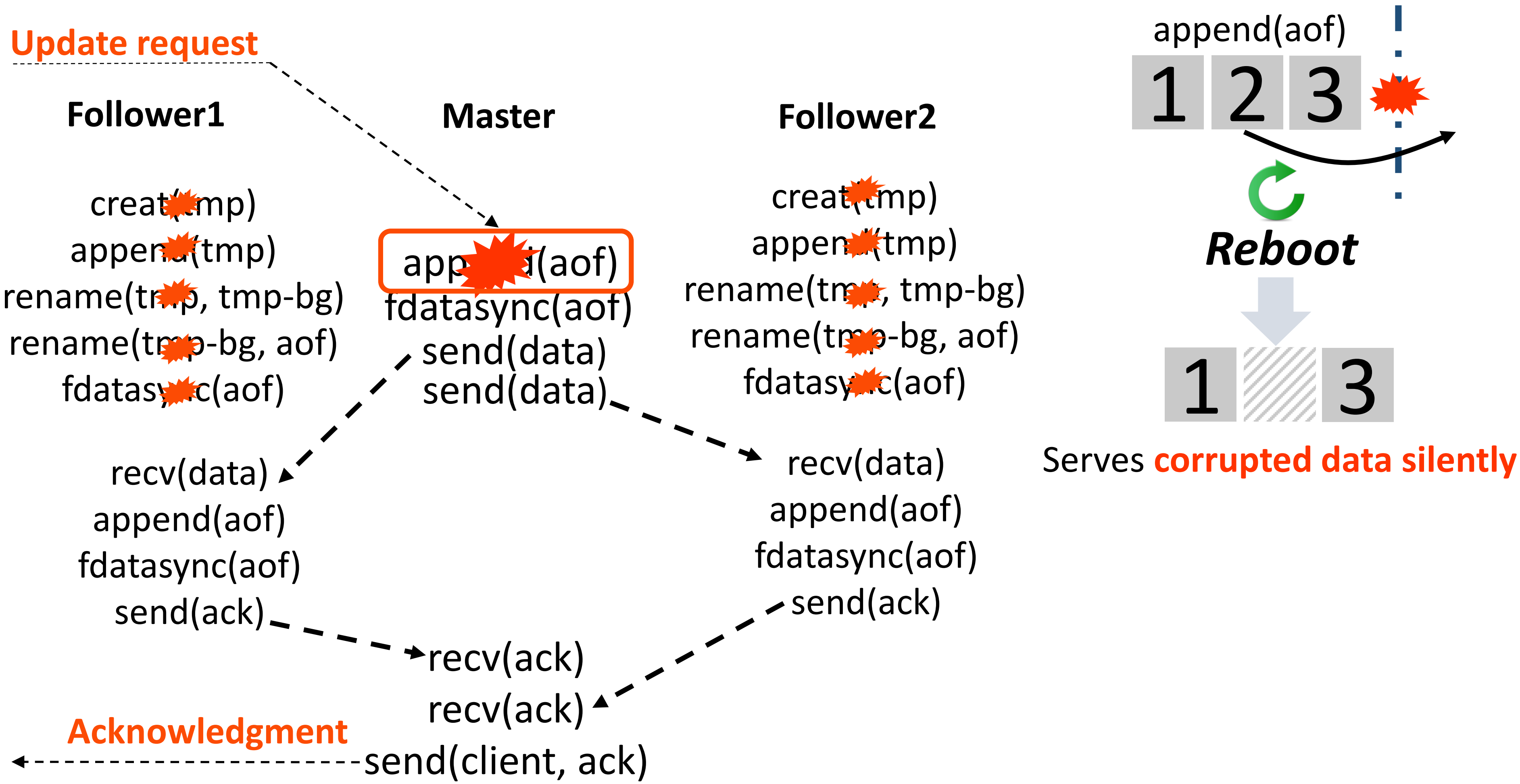

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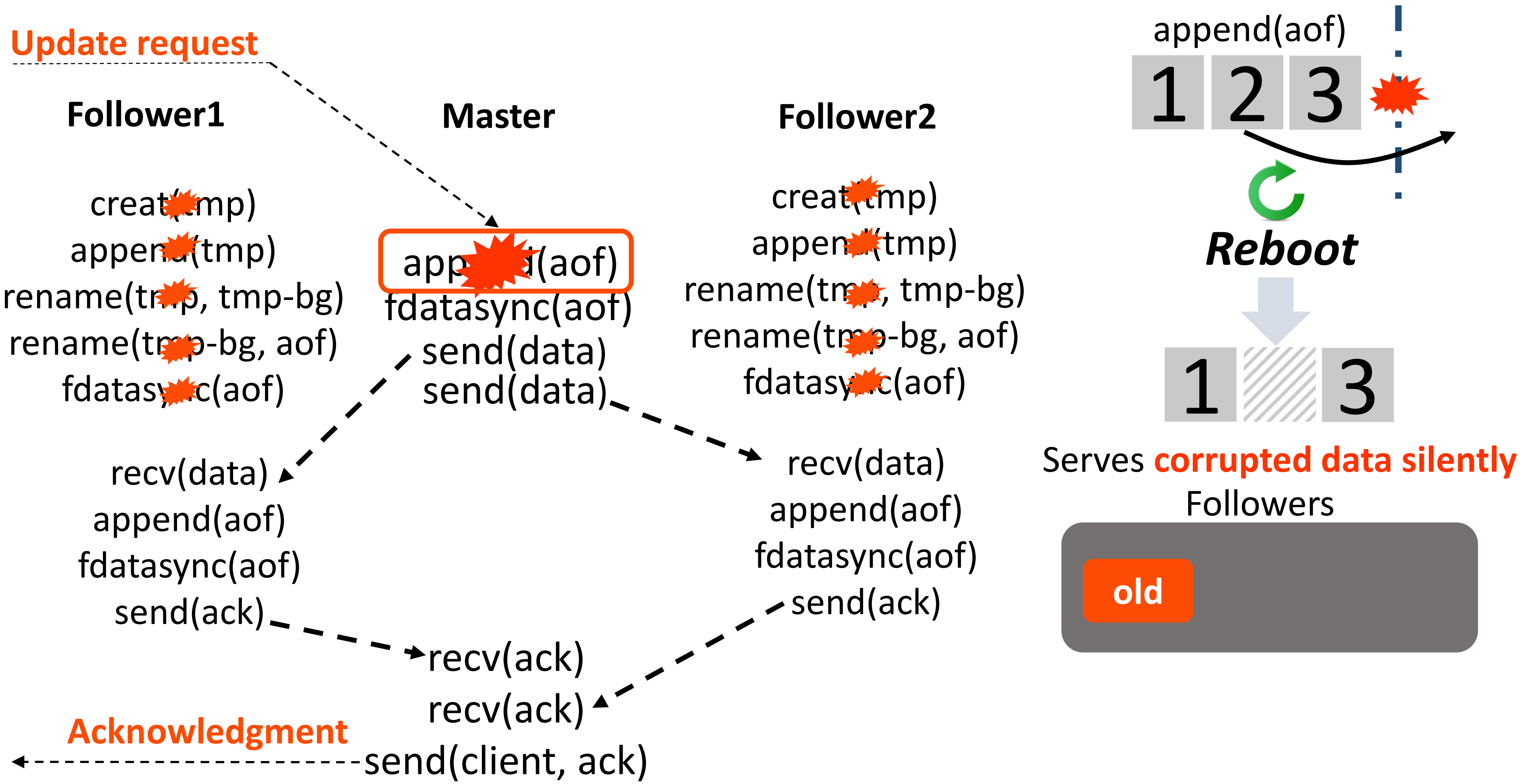

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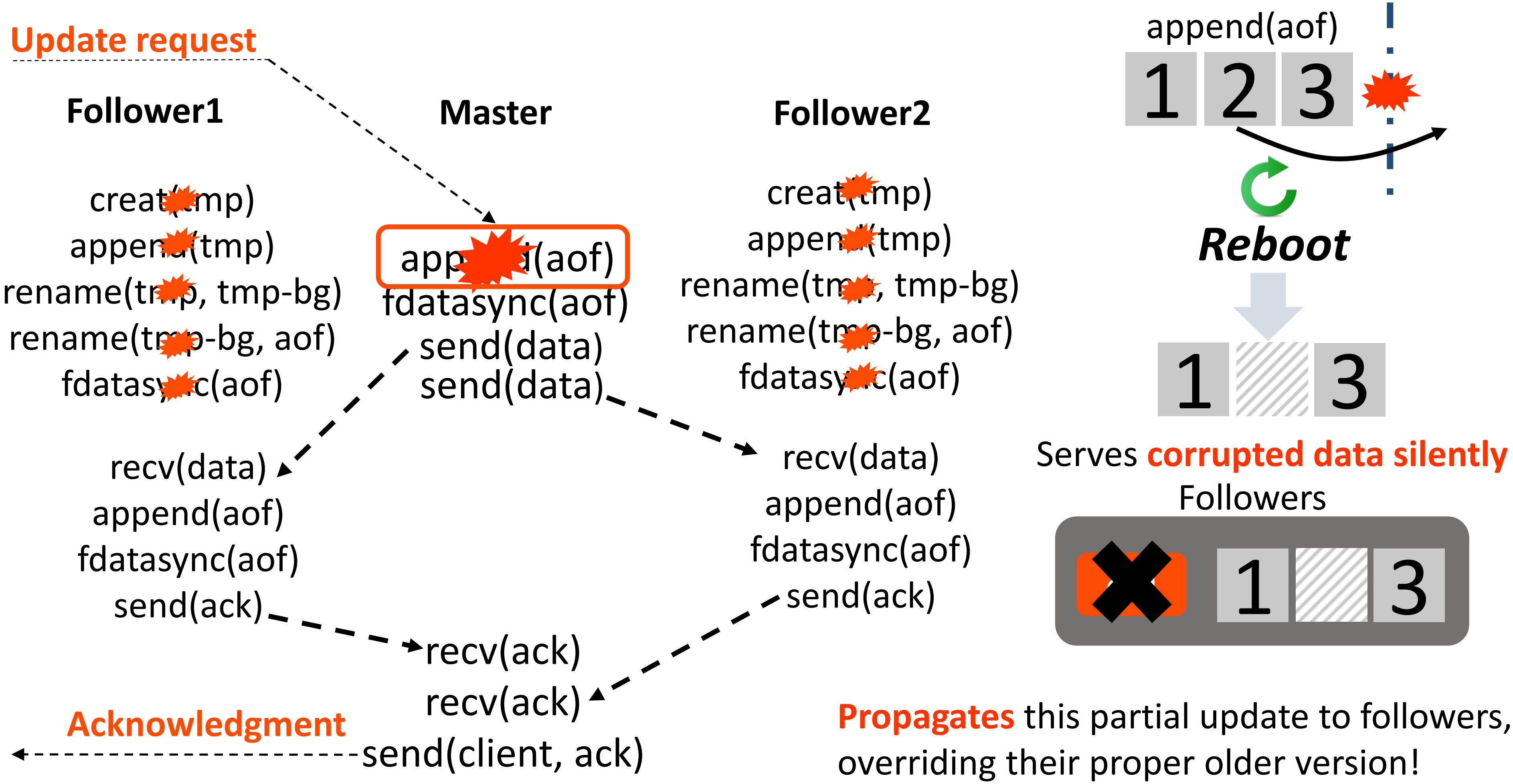
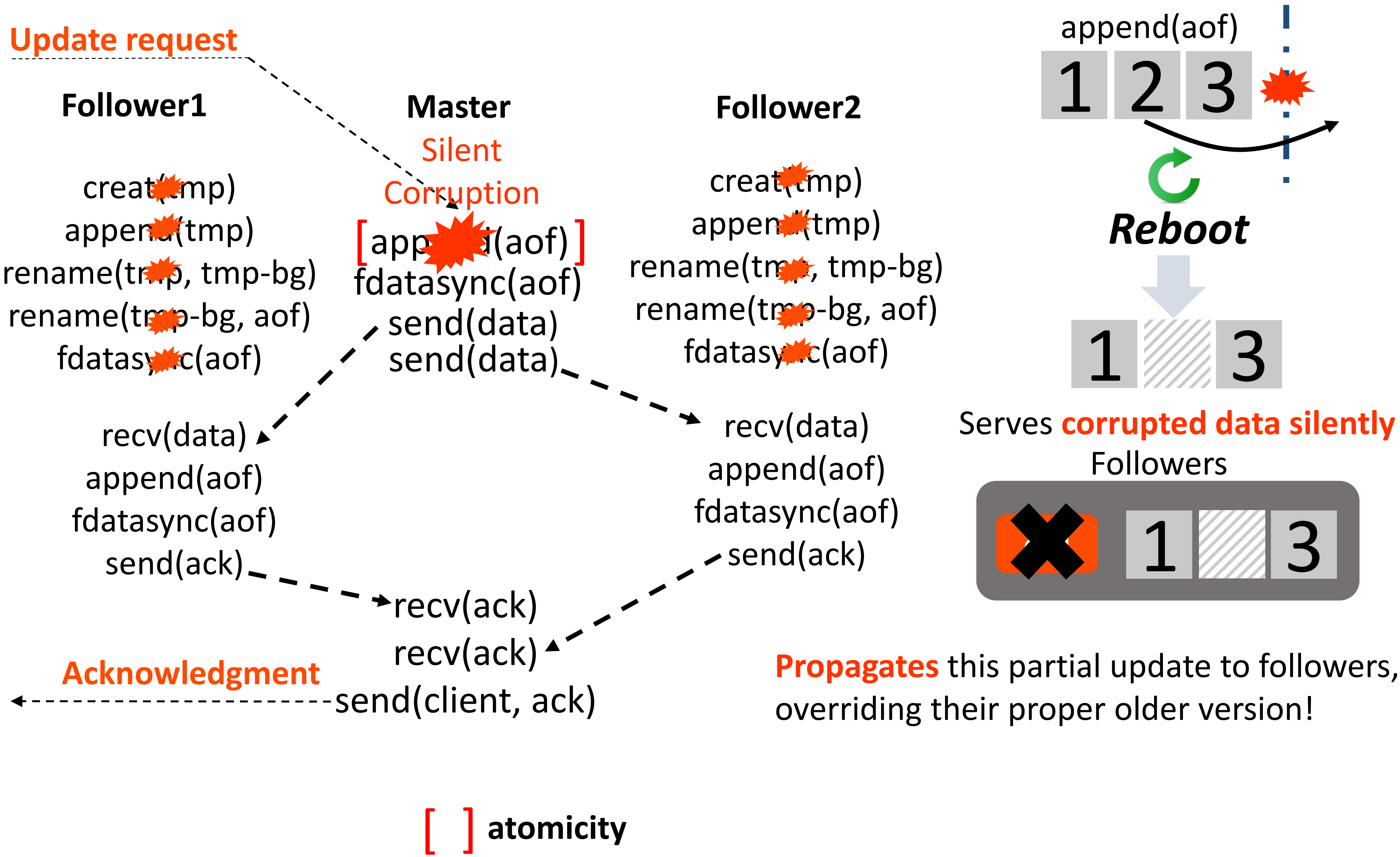


Propagates this partial update to followers, overriding their proper older version!

Example: Redis



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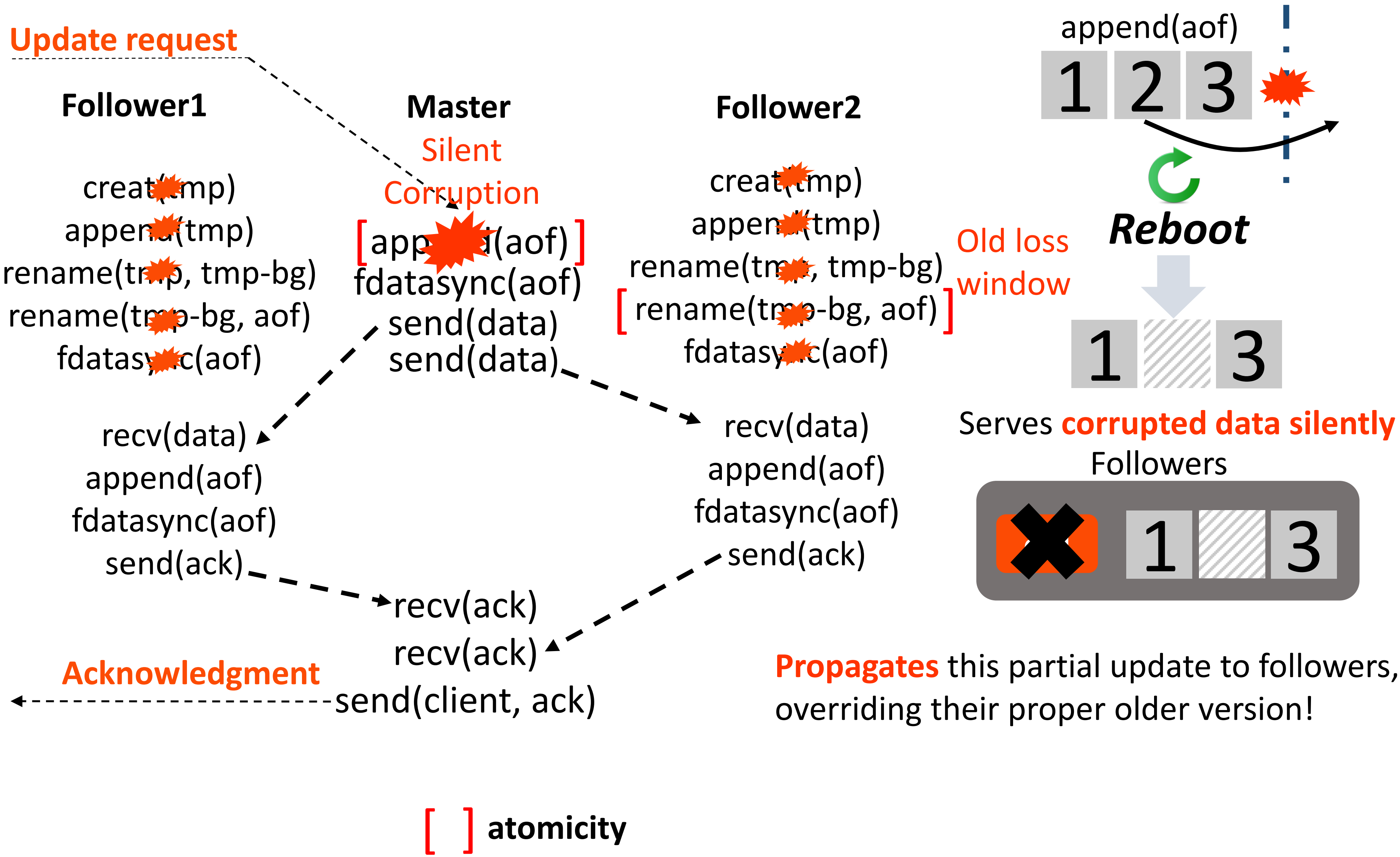
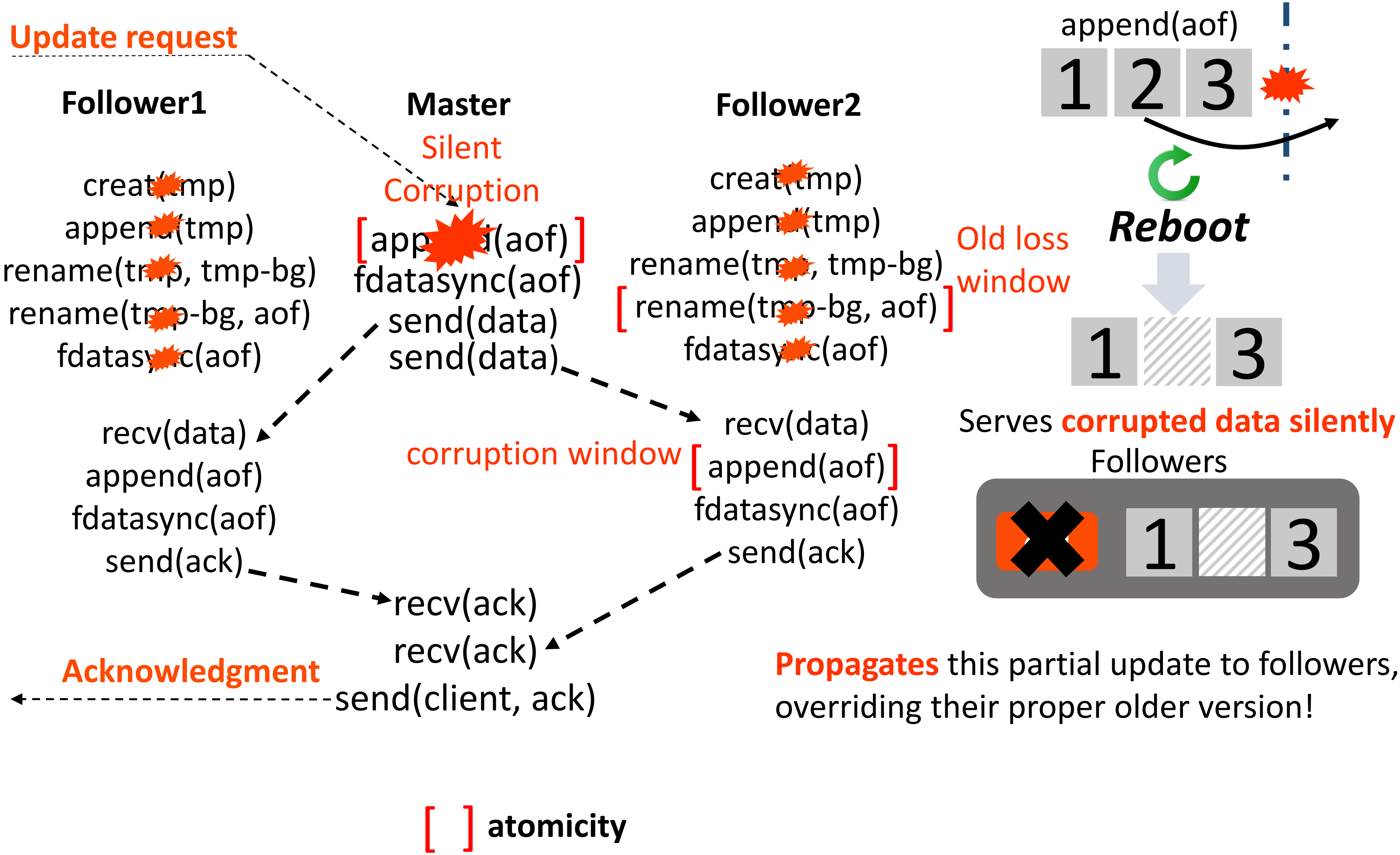


Example: Redis



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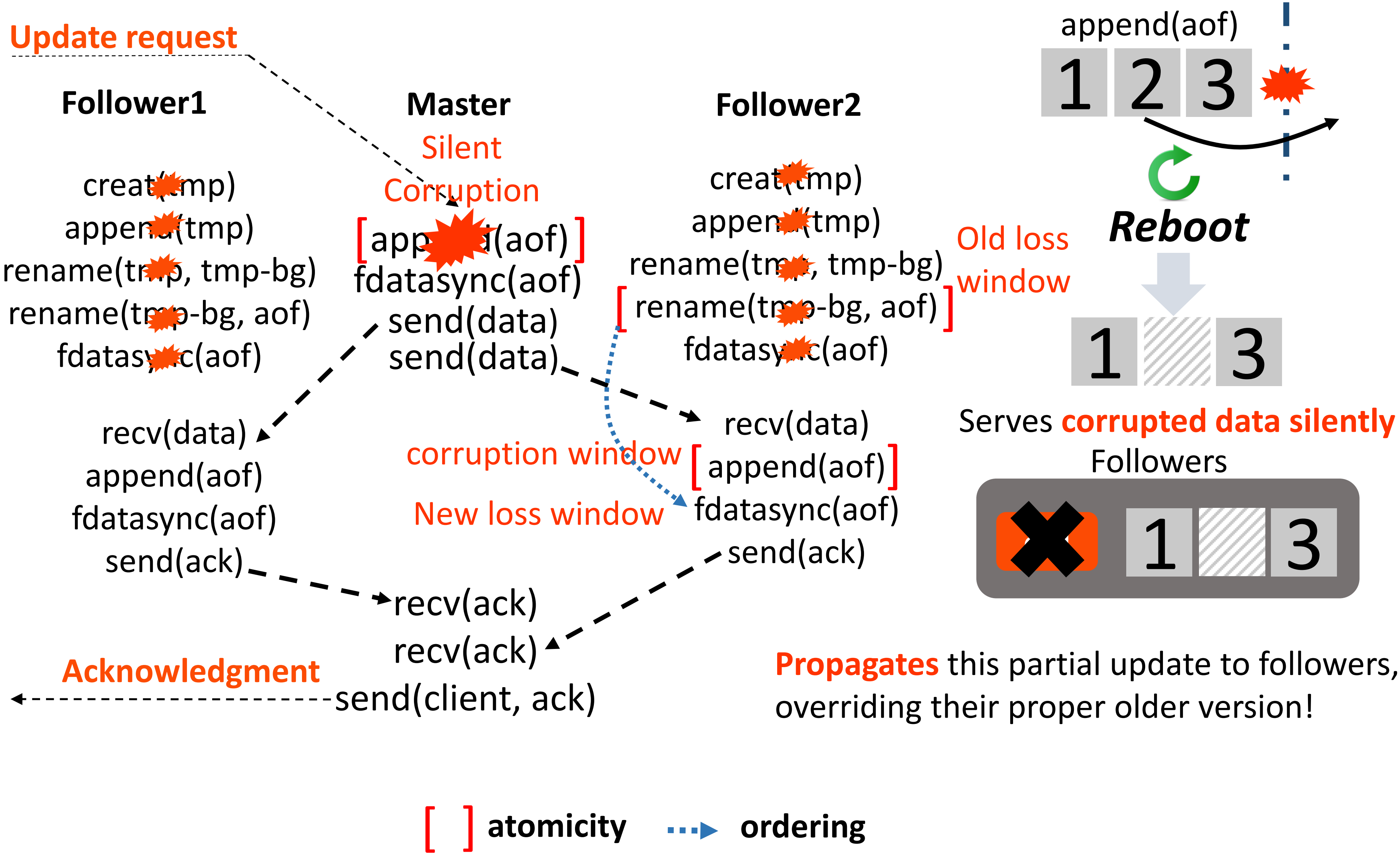

Example: Redis

Update request

Follower1

Master

Follower2

append(aof)

1 2 3

1. File-system crash behaviors impact distributed storage systems

2. Problems in local storage protocols are not fixed by distributed recovery protocols

send(client, ack)

overriding their proper older version!

[ ] **atomicity** ordering

Vulnerability Consequences

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On ext2 – weak crash guarantees

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Silent Corruption	Data Loss		Cluster Unavailability		Window		Total
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ZooKeeper			1	4	1			6
LogCabin		1		1			1	2
etcd			1	1	2			3
MongoDB-WT				1				1
MongoDB-Rocks			3	3				5
Kafka			3					3
iNexus		1	1	2				3

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Vulnerabilities on Real File Systems

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ZooKeeper	6	3	1	1	1	3
LogCabin	2	1	1	1	1	1
etcd	3	2				
MongoDB-WT	1					
MongoDB-R	5	2	2	2		3
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Less vulnerabilities on ordered file systems

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Popular, well-tested systems are vulnerable

Local file system crash behaviors directly affect distributed storage systems

In many cases, distributed recovery protocols do not fix problems in local storage protocols

Conclusion

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Reliability is crucial in distributed storage systems – primary choice for storing large amounts of data

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Complex ways to fail and subtle interactions between components

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Thank you!