Monarch: A Fuzzing Framework for Distributed File Systems

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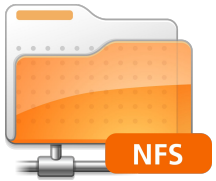
DFSes are critical infrastructure

High Performance Computing

Serverless[1]

Machine Learning Model Training[2]



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1. How Amazon EFS works 2. Building Meta's GenAI Infrastructure

But DFSes are not reliable

- Memory-unsafe languages
- State-sharing across clients
- High concurrency
- Fault tolerance

Finding and fixing bugs in DFSes become important

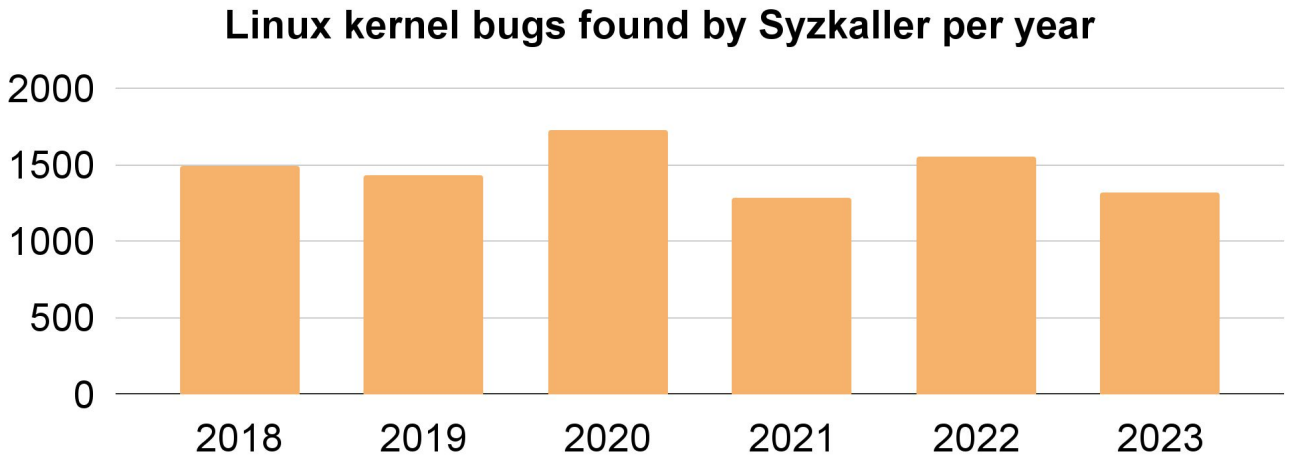
Existing approaches to finding DFSes bugs

Regression Testing	**Model Checking**	**Formal Verification**
Test suit	Modist SAMC	Verdi Ironfleet
Manual expert effort **Limited test cases**	**State explosion**	**Manual expert effort** **Mostly verify critical parts**

Any automatic and scalable bug-finding techniques?

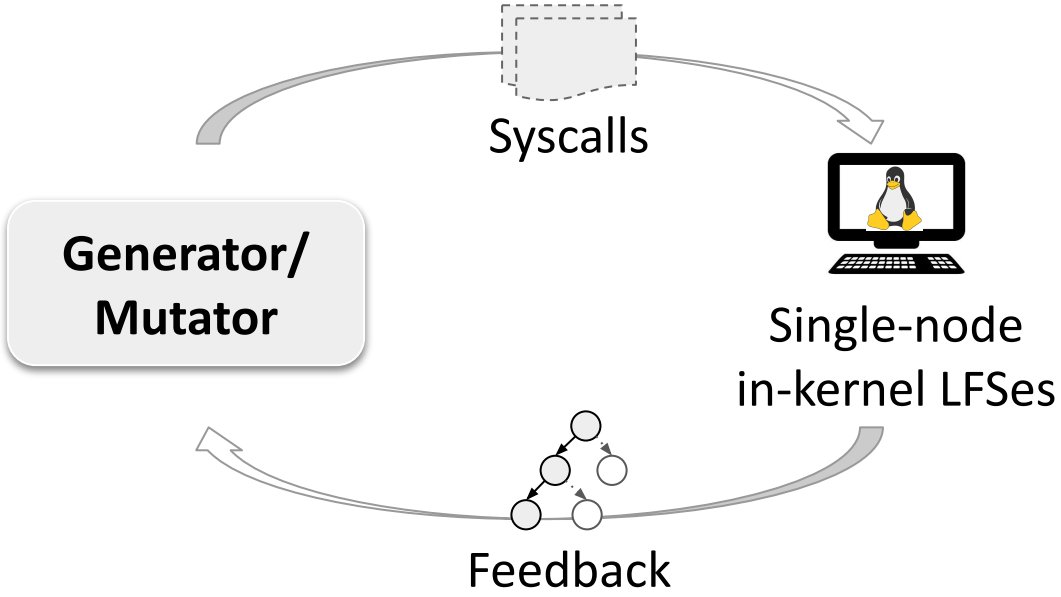
Fuzzing: A practical and impactful approach

- Linux kernel fuzzer, **syzkaller**, detects over **1K bugs every year**[1]
- Specifically, more than **800 bugs in local file systems** over the years



1. Syzbot/Syzkaller https://syzkaller.appspot.com/upstream/graph/found-bugs

How does fuzzing work?



Crash consistency and
memory bug checker

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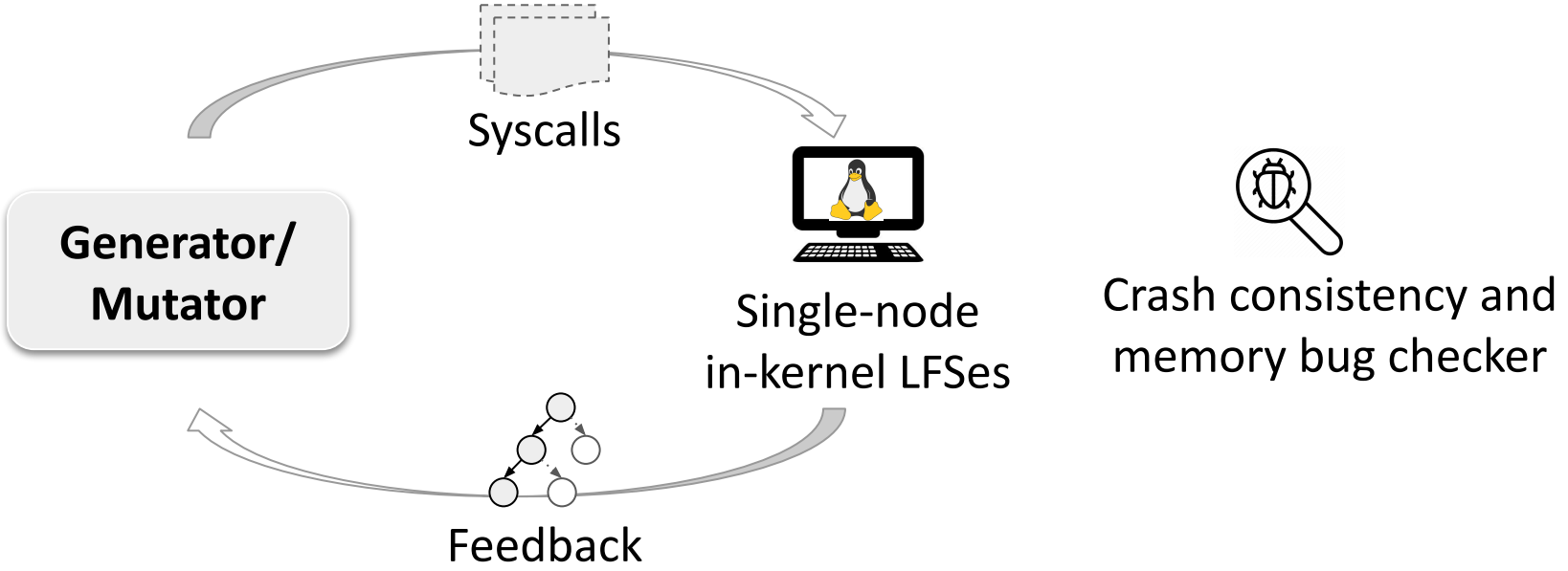
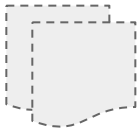


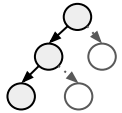
Current LFS fuzzers are not applicable for DFSes

Missing pieces for fuzzing DFSes

Single-node and in-kernel file system



Syscalls



Representation of single-kernel exe state

Crash consistency + memory checker

Multi-node cross-kernel/userspace fuzzing architecture

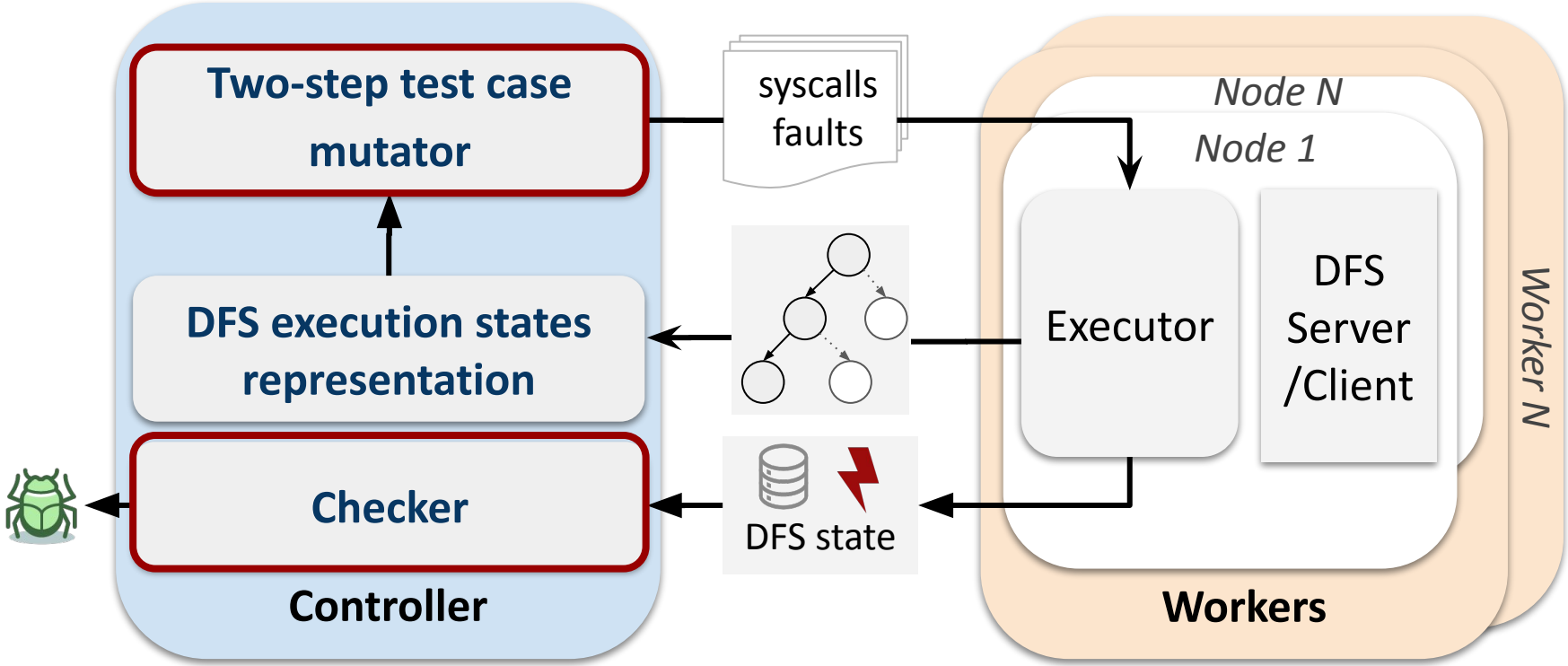
Distributed faults as a testing input space

Representation of cross-node and cross-kernel/userspace execution states

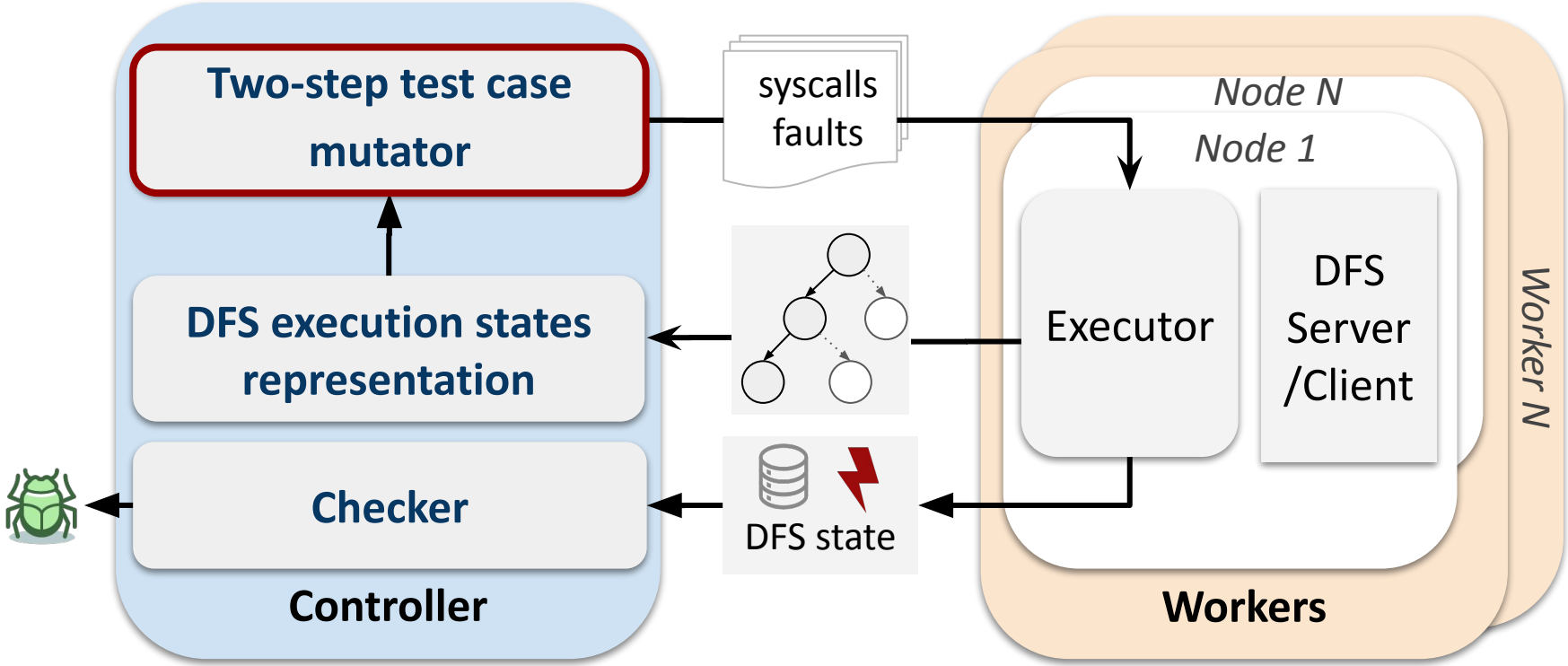
A systematic DFS semantic checker

MONARCH
A distributed file system fuzzer

Monarch architecture



Monarch architecture



Two-step test case mutator

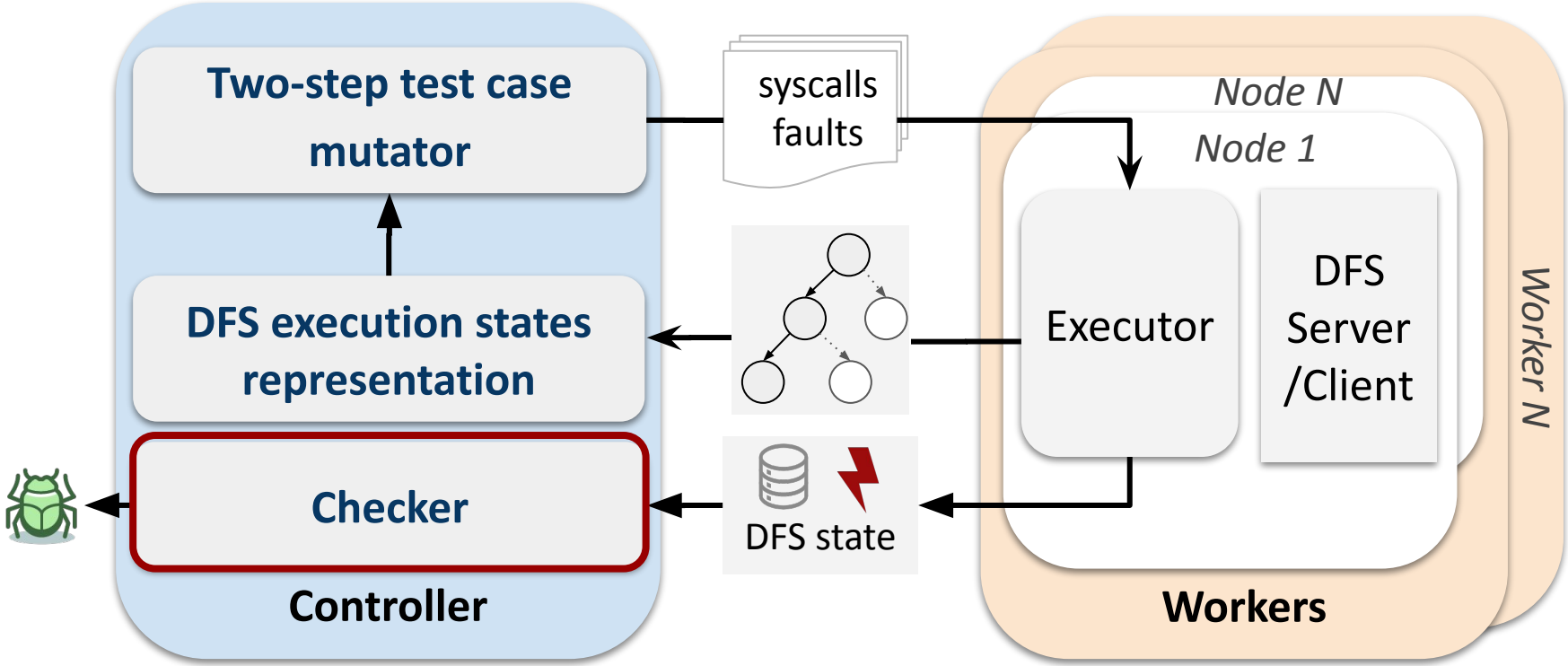
Non-fault mode: Testing with file system syscalls only (e.g., open, read)

- Syscall templates and mutation rules

Fault mode: Testing with syscalls + injected faults

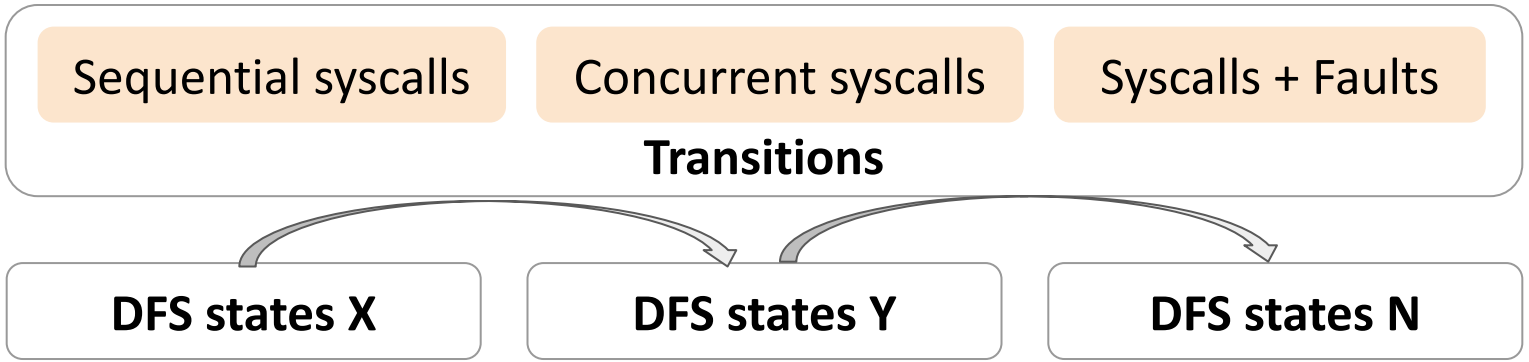
- **Distributed faults** → Network partitions, node crashes
- **How to deterministically inject faults?** → Synchronization primitives
- **At which granularity to inject faults?** → Syscall granularity
- **When to inject faults?** → After a test case triggers new execution state

Monarch architecture



What are the semantic bugs in DFS?

- **Semantic**: DFS state transitions specified in the spec
  - Syscalls: sequential and concurrent
  - Syscalls + faults



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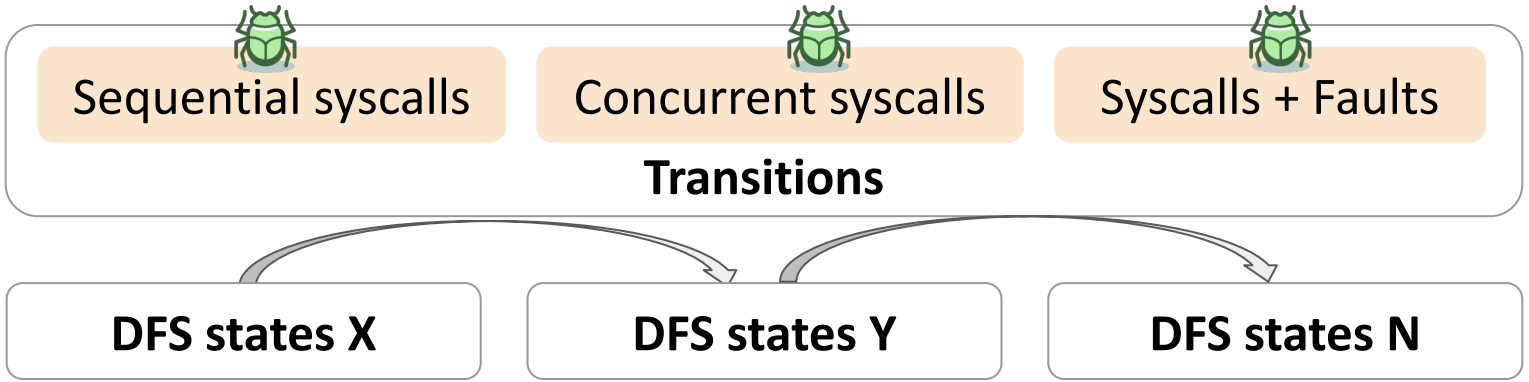

Which semantic bug types are missing?

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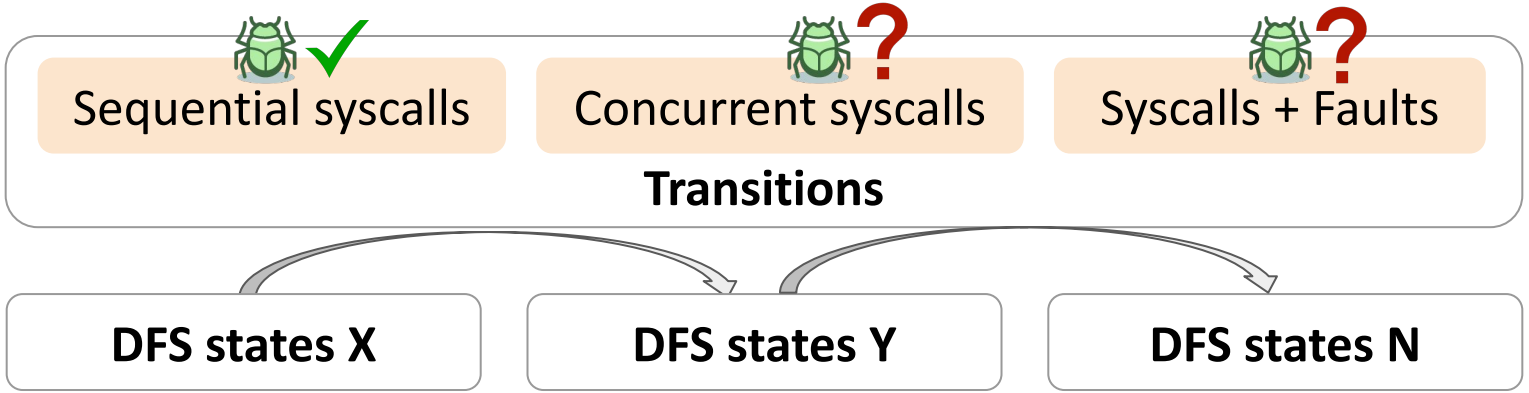
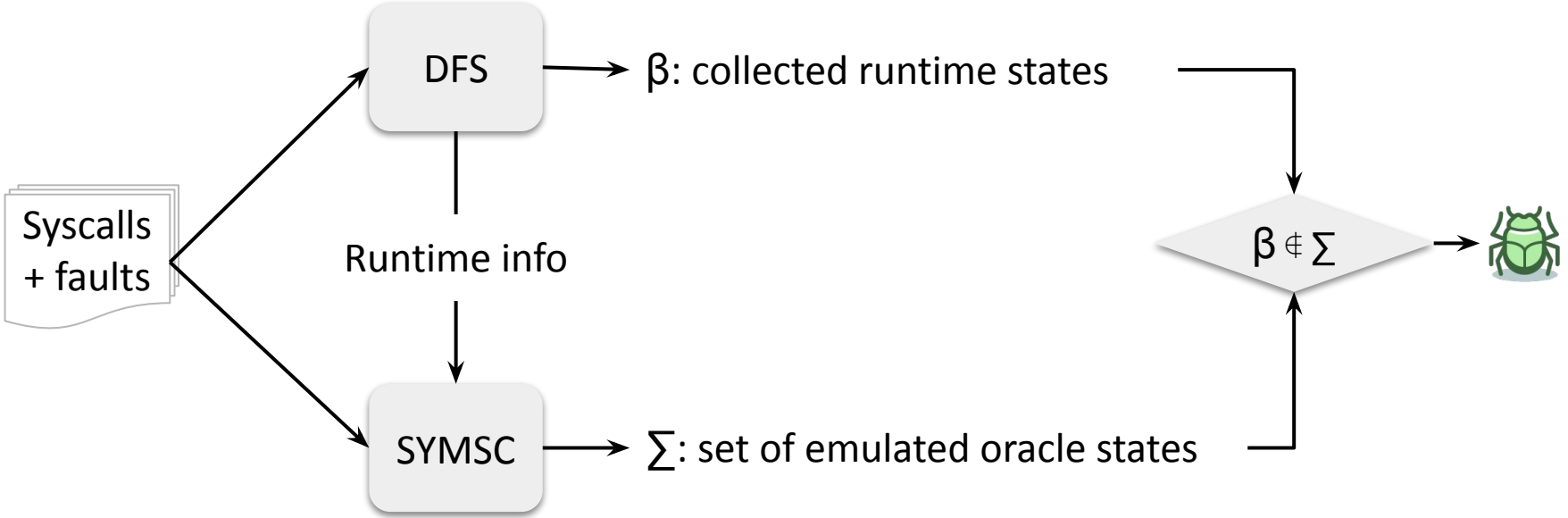


DFS semantic checker: SYMSC



Emulate sequential syscall executions

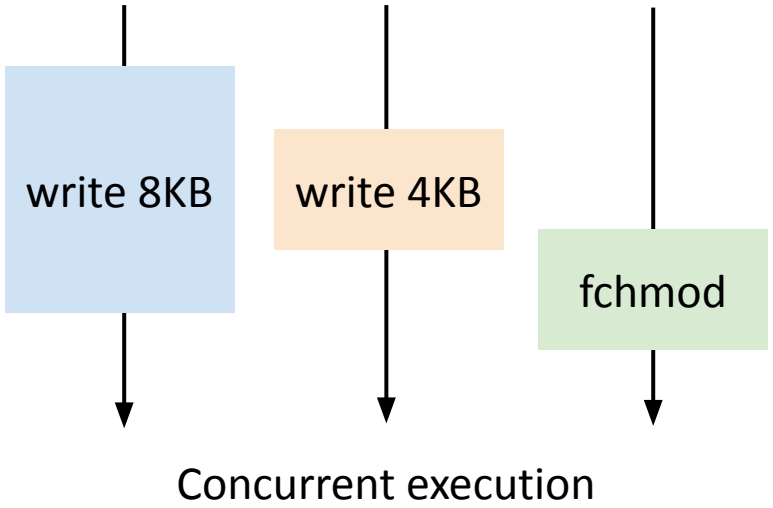
- Emulate syscalls one by one according to the specification

Sequential syscalls	Emulated states
mkdir A	Inode0.dents = [., A] Inode1.dents = []
setxattr A user.key:val	Inode1.xattr = [user.key:val] …

But the spec does not specify semantics under concurrency and faults

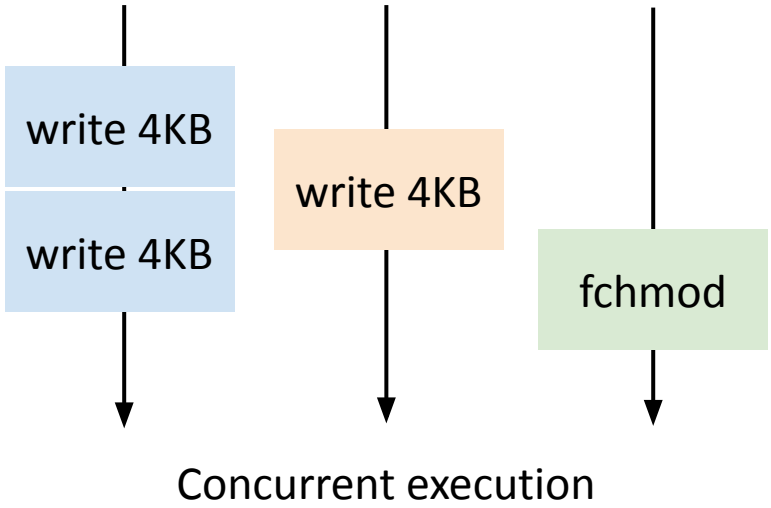
How to emulate semantic under concurrency?

- Concurrency relation built from syscall's start and end timestamp



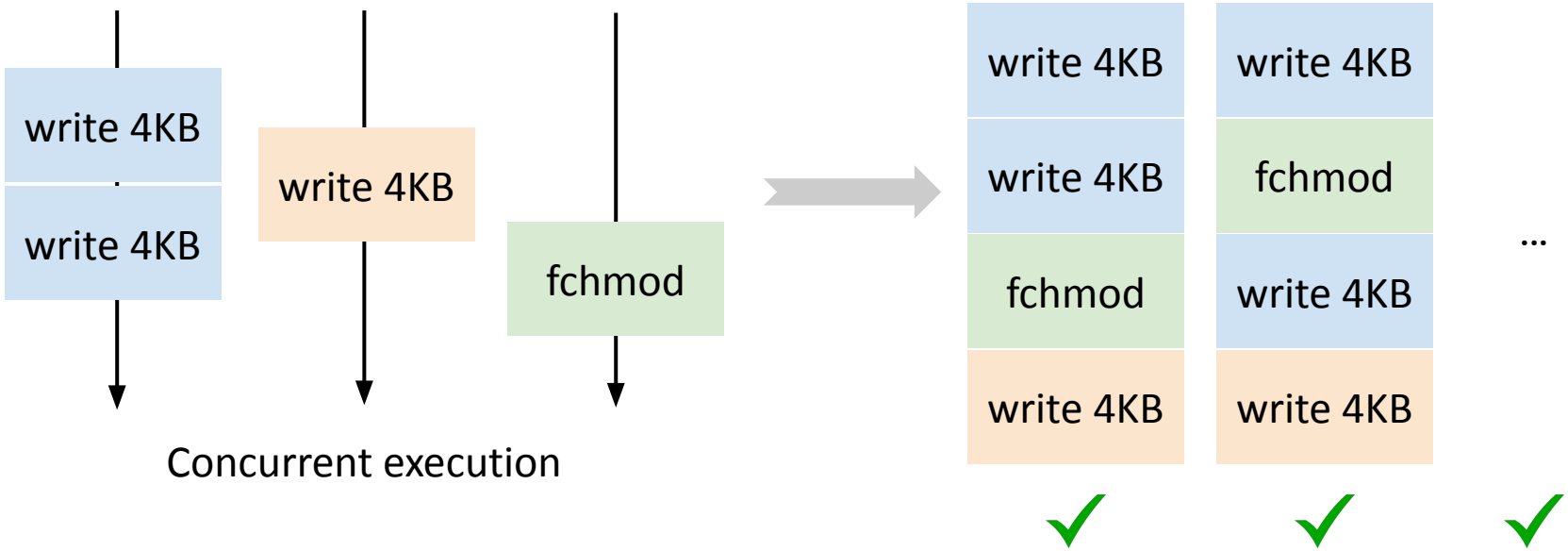
Syscalls to atomic operations

- Syscalls are splitted into one or more atomic operations

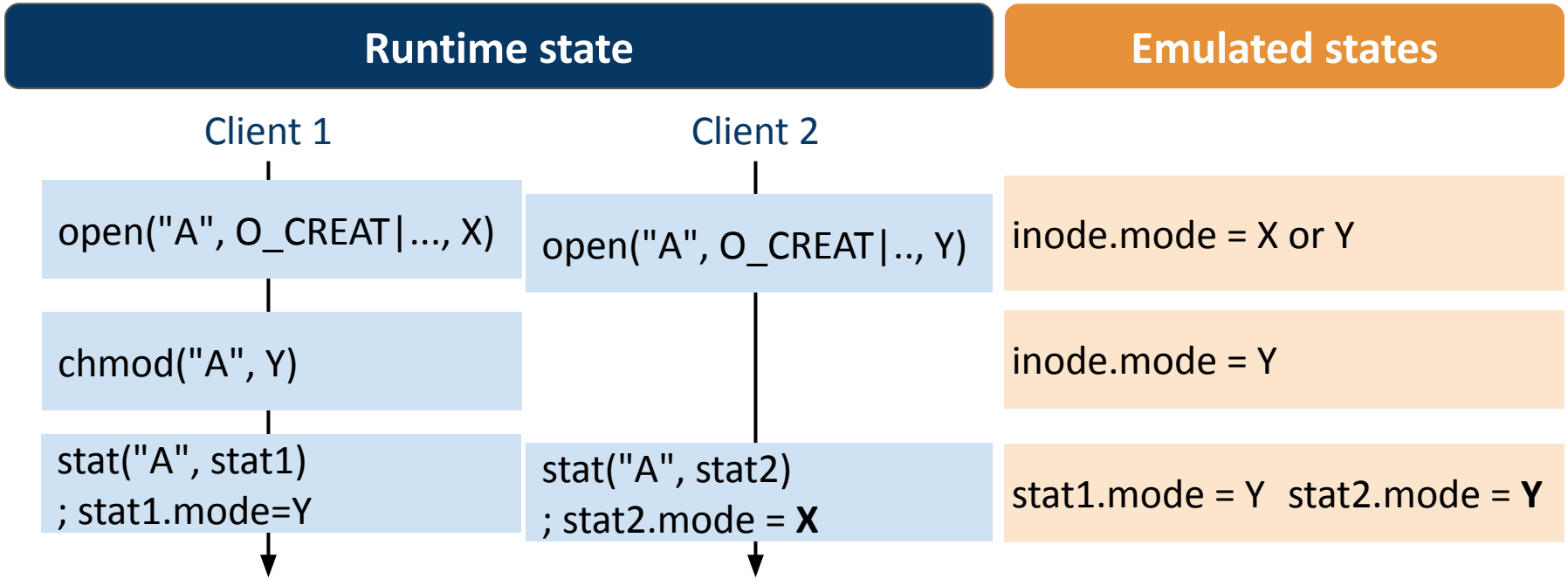


Serialize concurrent atomic operations

- Syscalls are splitted into one or more atomic operations
- **Oracle states**: emulate all interleavings among concurrent atomic operations



Case study of a CephFS bug



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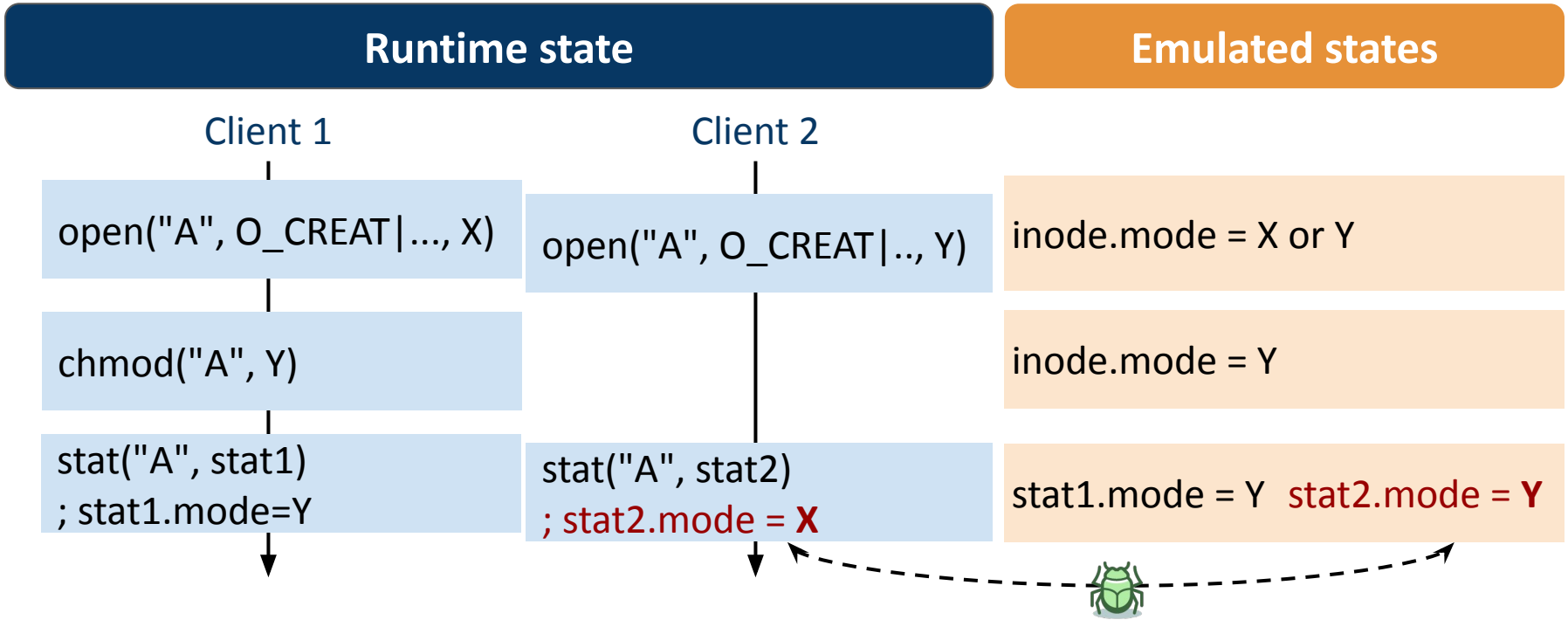
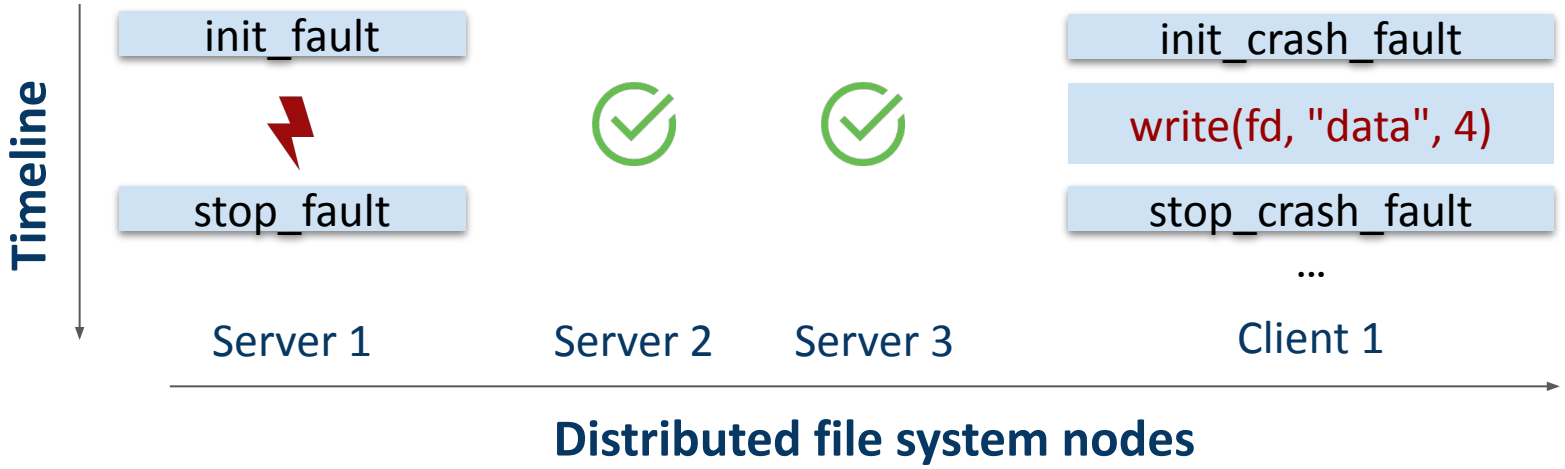


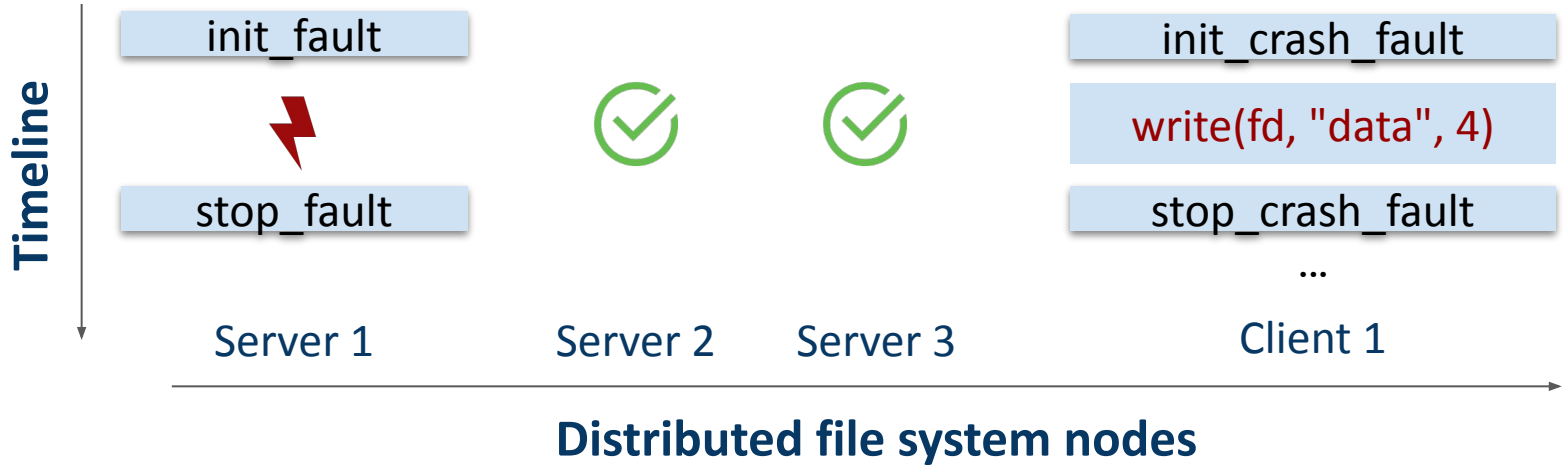
What is the semantic under faults?

What's the semantic of a write under faults?



What is the semantic under faults?

- Apply the original semantic if the DFS is available to this syscall
- Return errors otherwise



Implementation and evaluation setup

- Two 64-core machines
- Ran intermittently for two months on six targeted DFSes

How effective is Monarch in finding bugs?

- Monarch found bugs in all DFSes and categories, with a total of 48 bugs

DFS	Memory bugs	Semantic bugs
Lustre	8	0
GlusterFS	17	5
OrangeFS	3	0
BeeGFS	0	2
CephFS	4	1
NFS	8	0
Total	**40**	**8**

What are the characteristics of DFS bugs?

Faults play a critical role in exposing these bugs

→ 14/40 memory bugs and 3/8 semantic bugs are exposed under faults

Vulnerable code is scattered in both servers and clients

→ 17 bugs (servers) vs 31 bugs (clients)

→ The root causes of semantics bugs are mostly in DFS servers

Bug exposure might depend on specific DFS configurations

Conclusion

- **Problem:** Automatic and scalable bug-finding tool for DFSes
- **Our solution Monarch**: The first DFS fuzzing framework
  - Multi-node and cross-context fuzzing architecture
  - A two-step mutator to test DFSes with syscalls and faults
  - DFS semantic checker
- **Takeway**: Fuzzing is effective on distributed systems as well
- **Artifact**: https://github.com/rs3lab/Monarch

Thank you!