Finding File System Crash-Consistency Bugs using Chameleon

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vmware

TEXAS
The University of Texas at Austin

Crashes

Image source : https://www.fotolia.com

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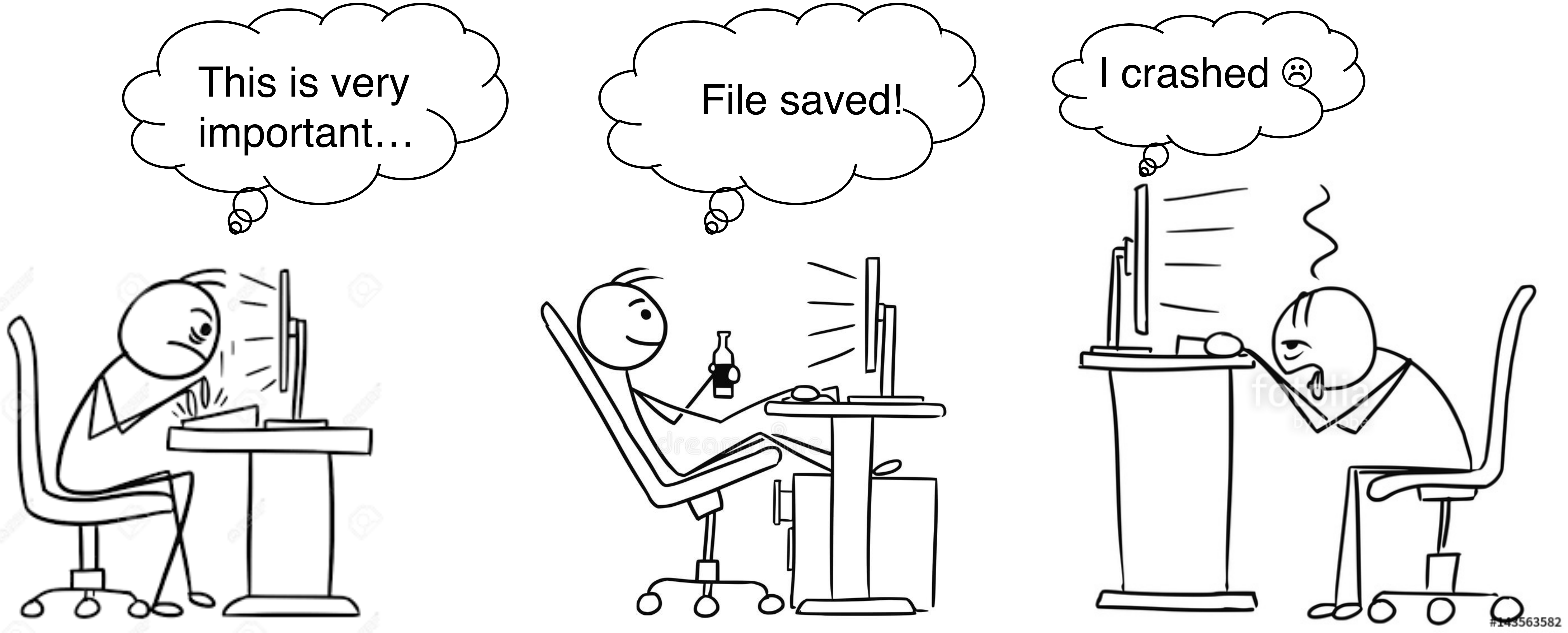
Crashes



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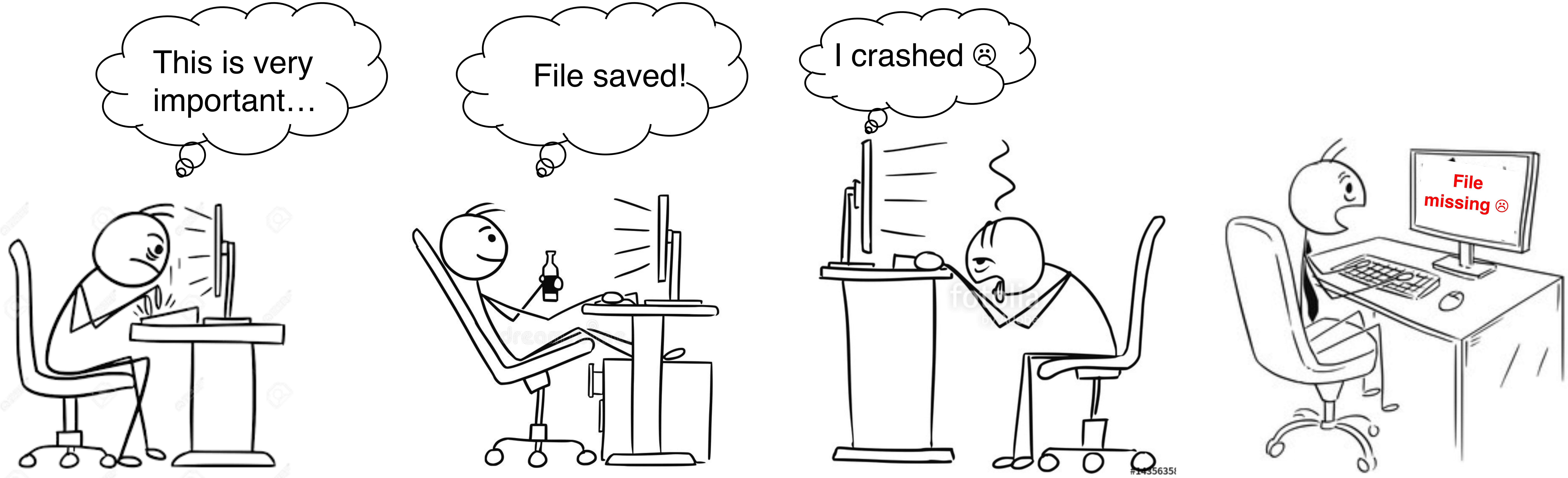

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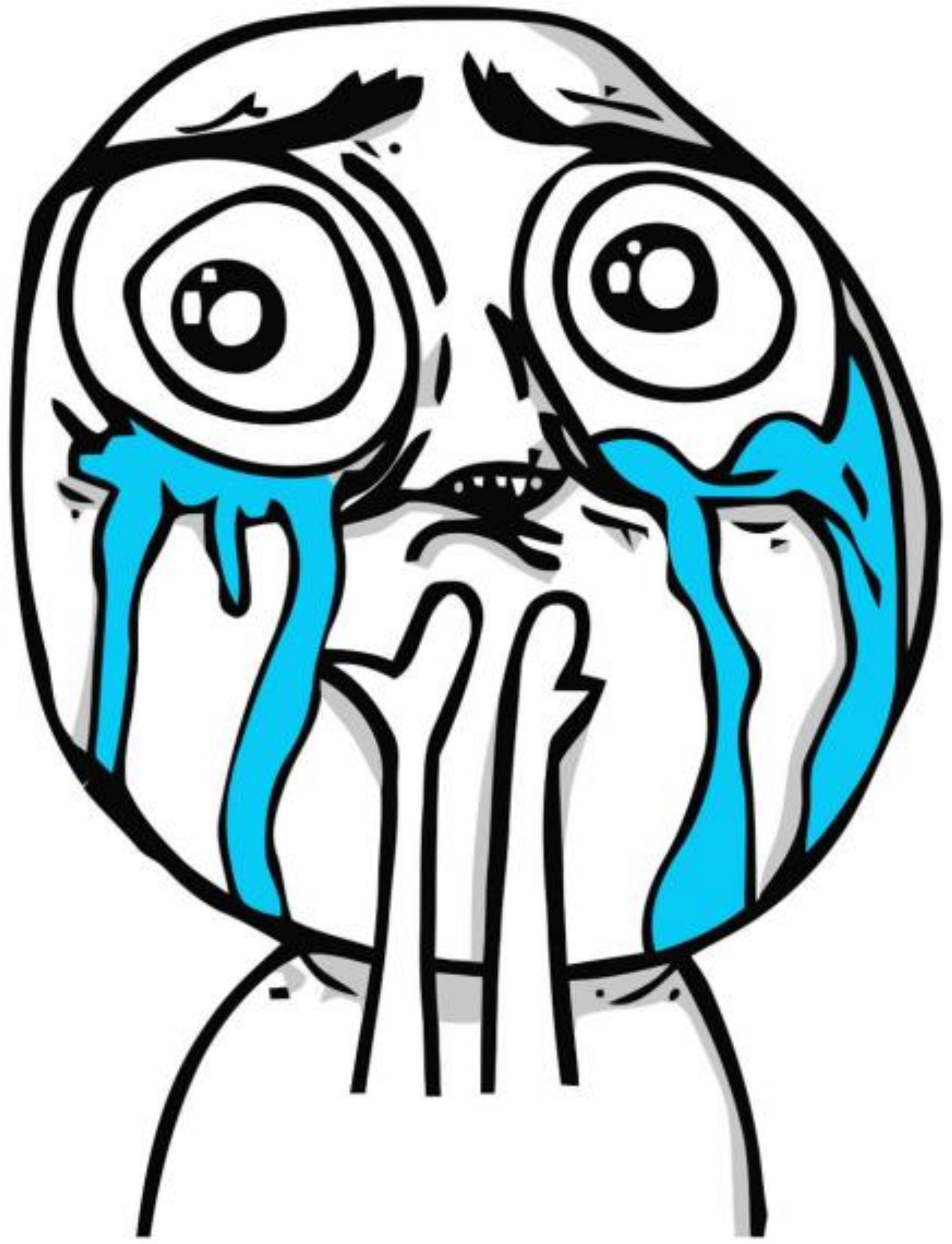
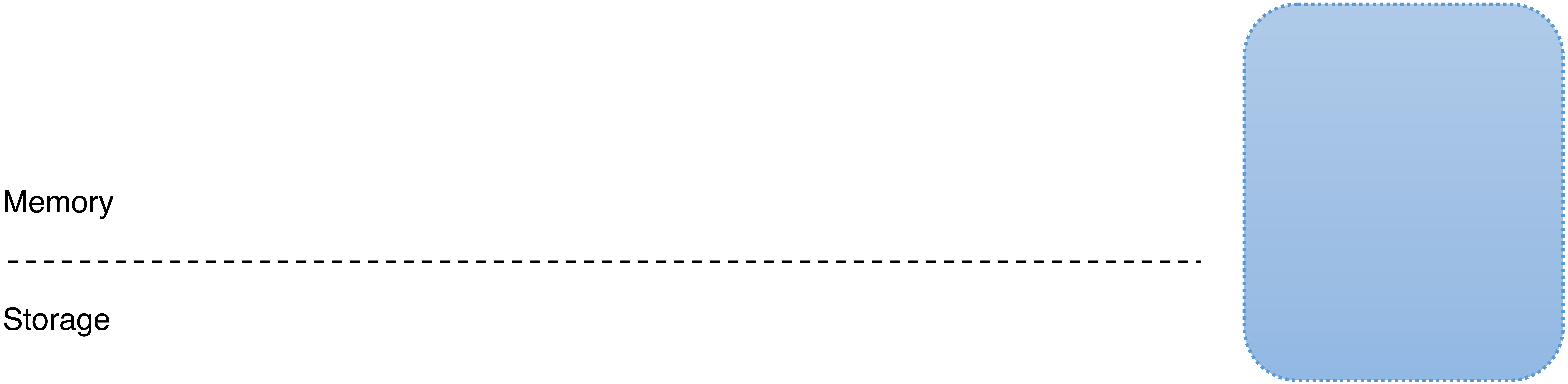
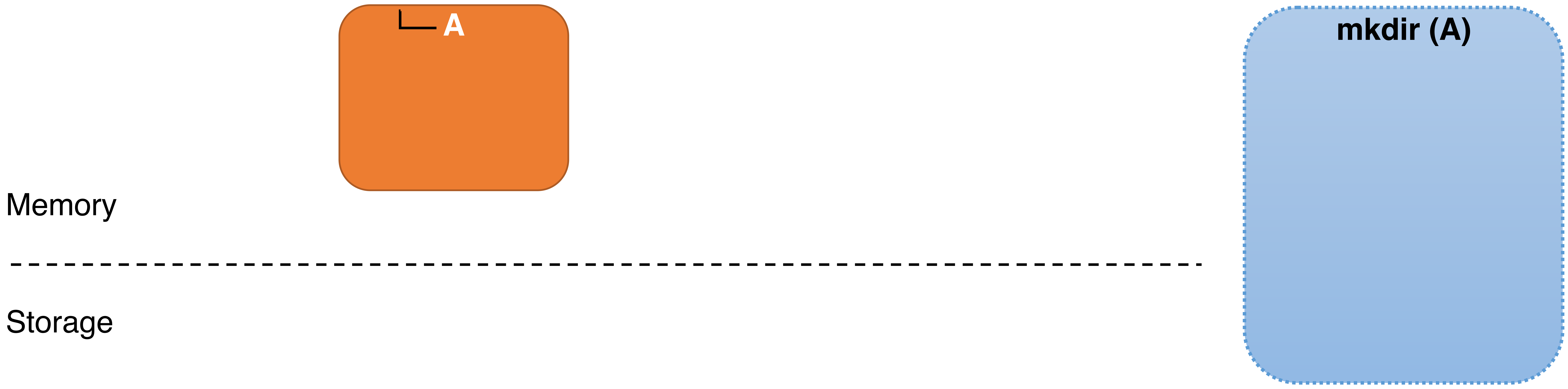
I wish filesystems were crash-consistent!



Rename atomicity bug



Rename atomicity bug in btrfs



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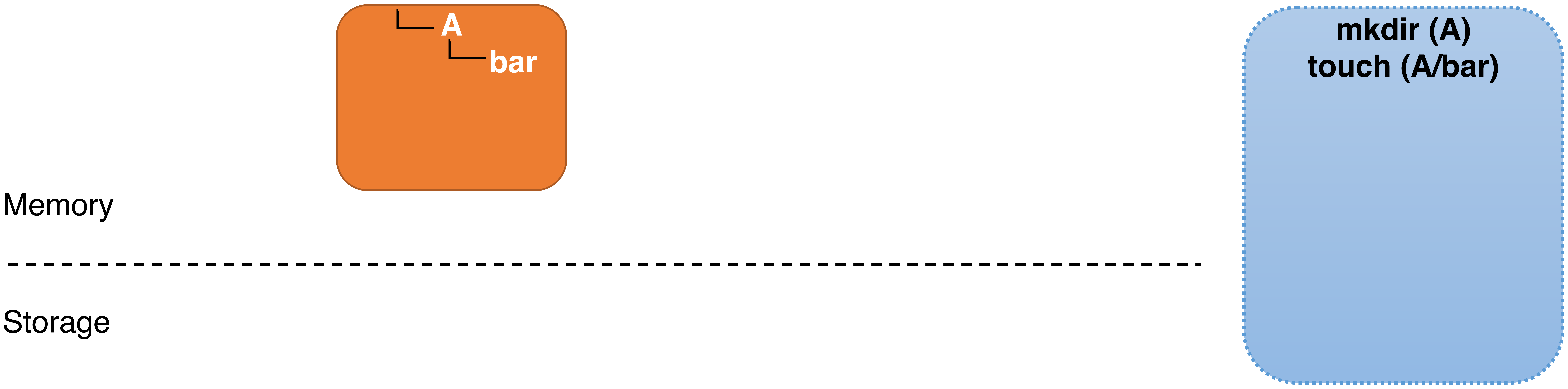

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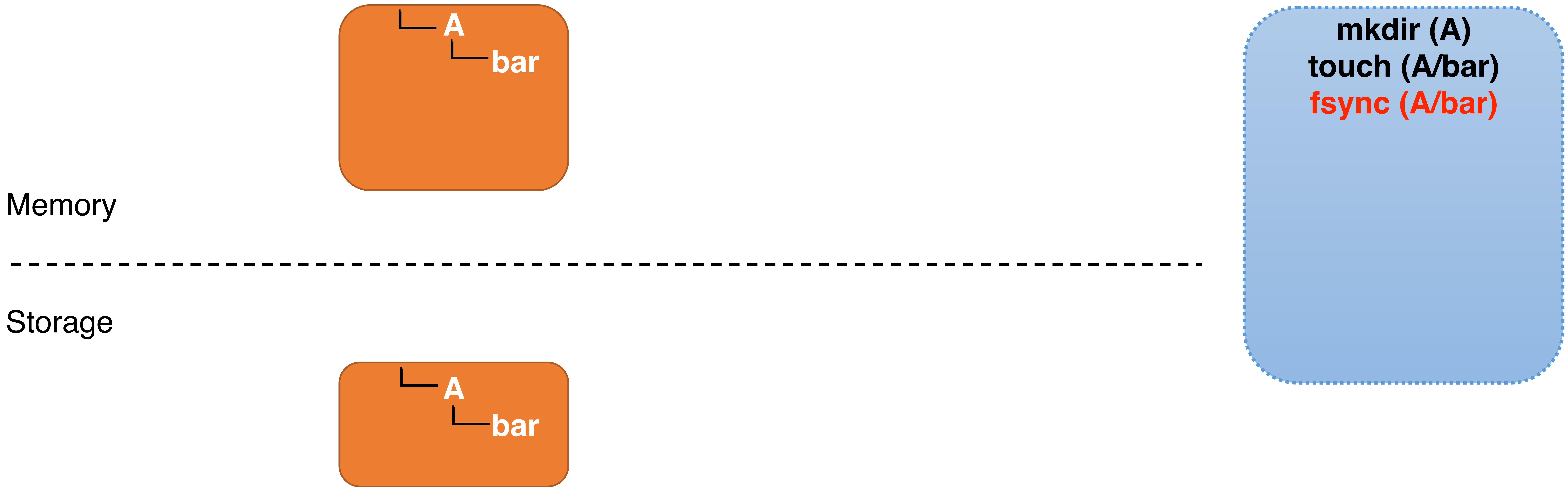

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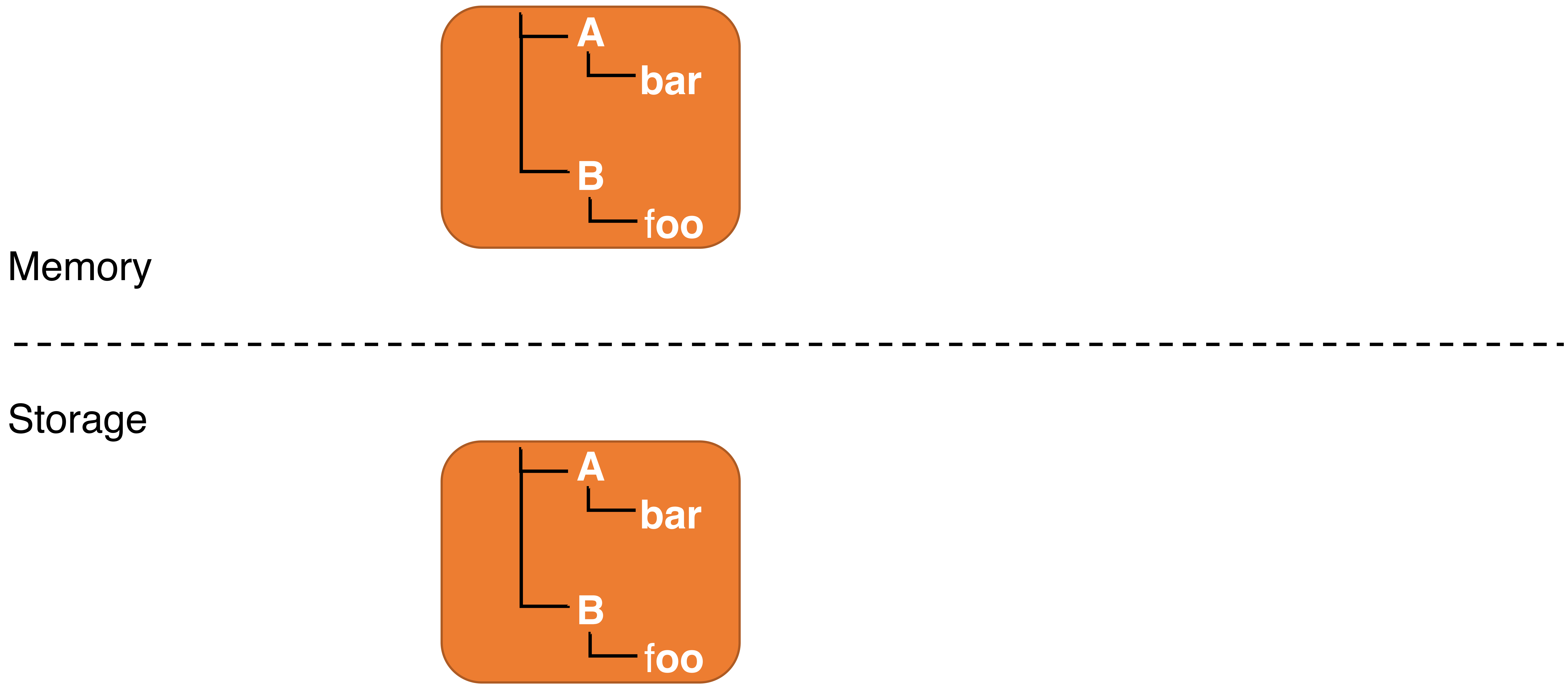

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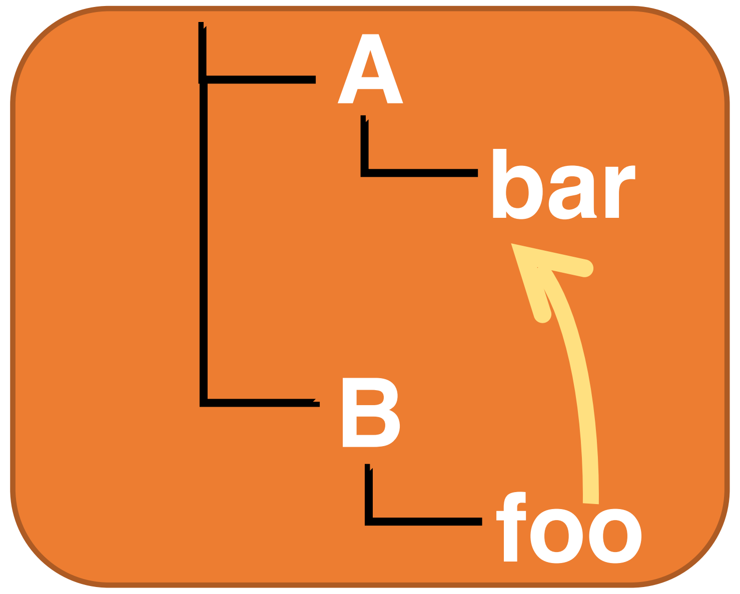
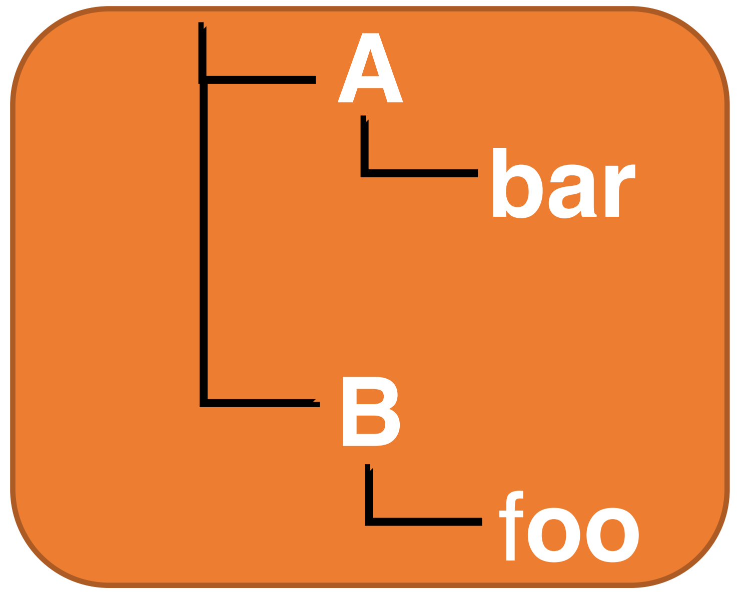


Memory

Storage



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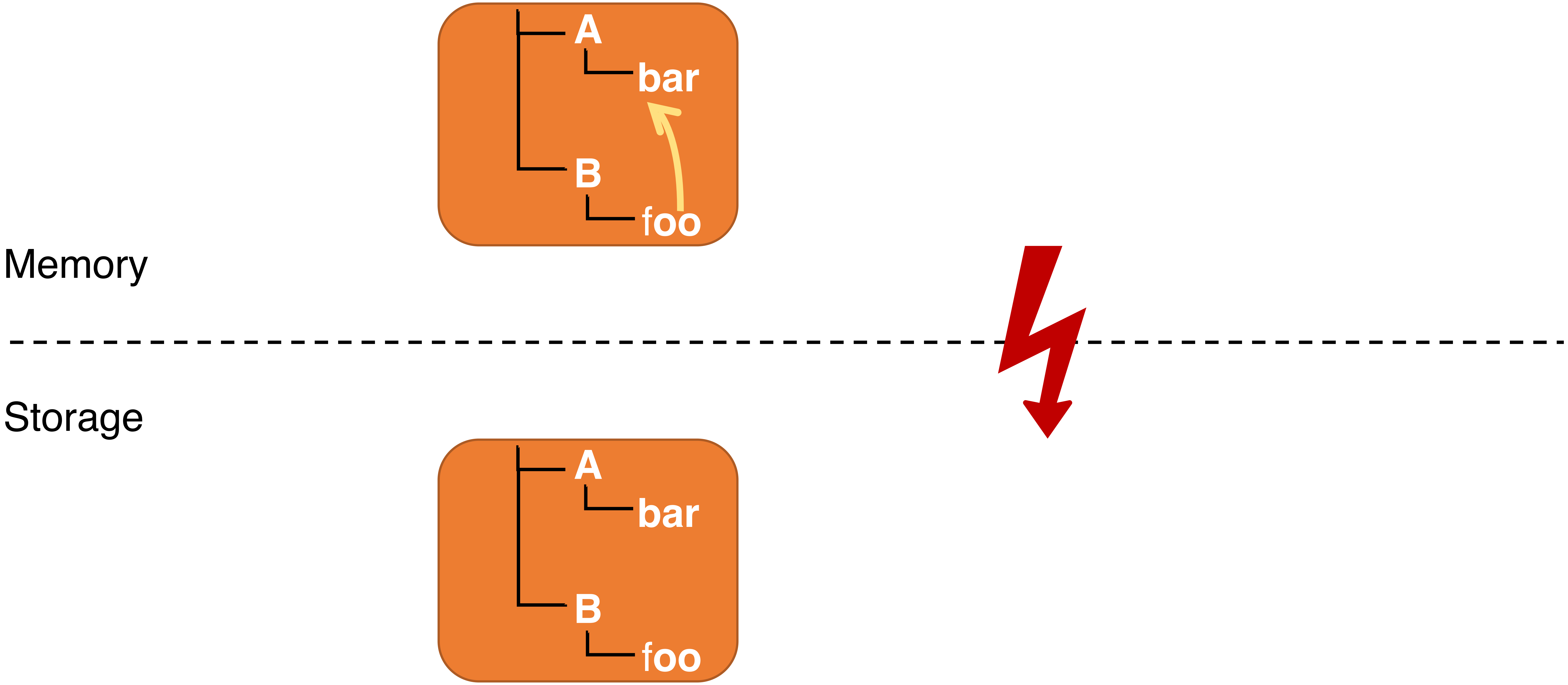

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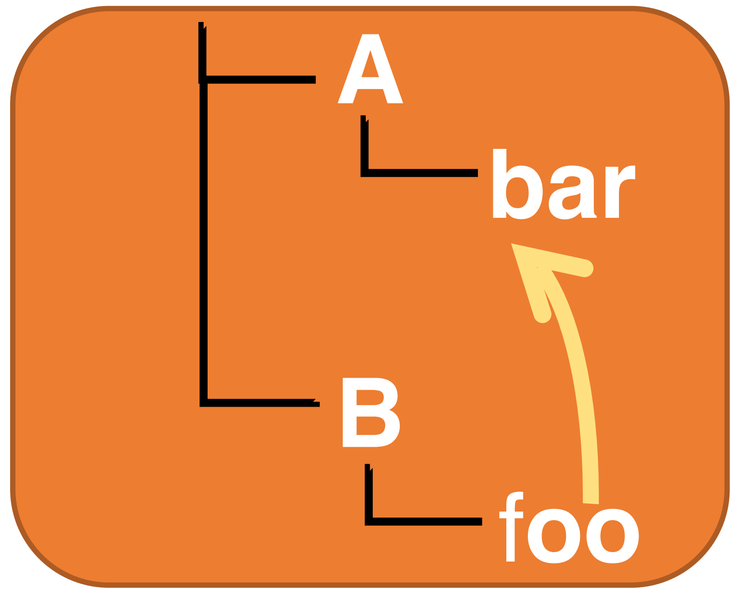

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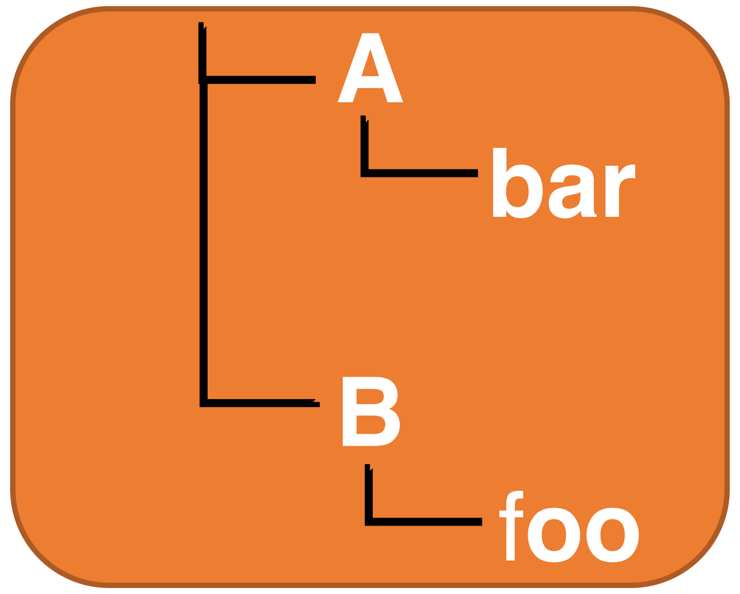

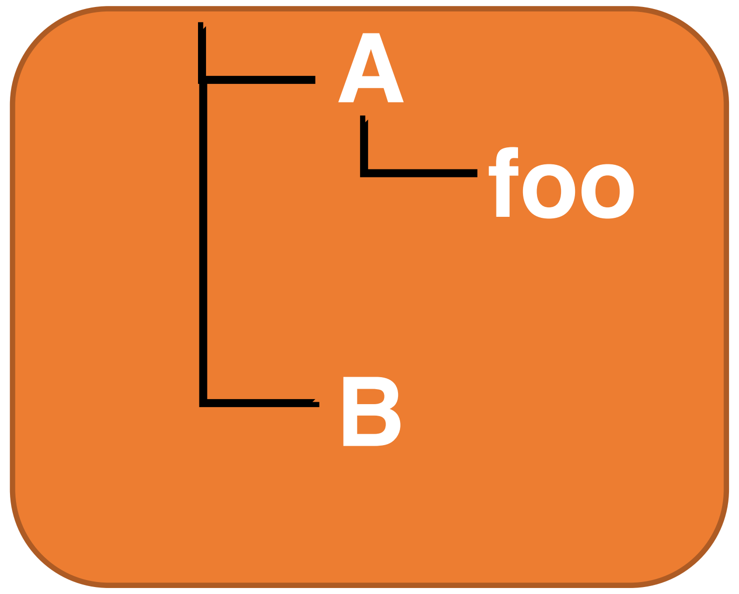

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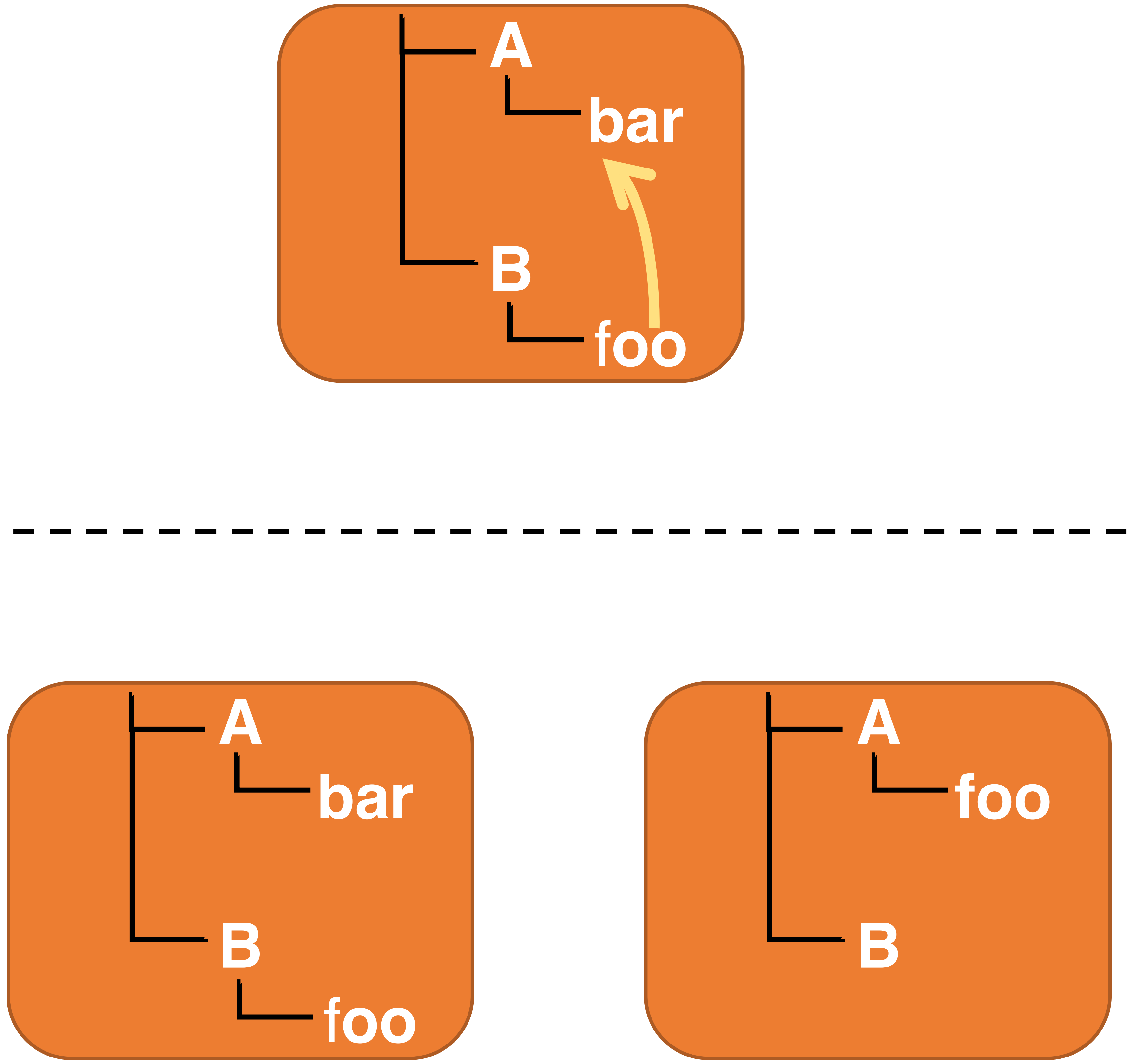

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Storage

Expected

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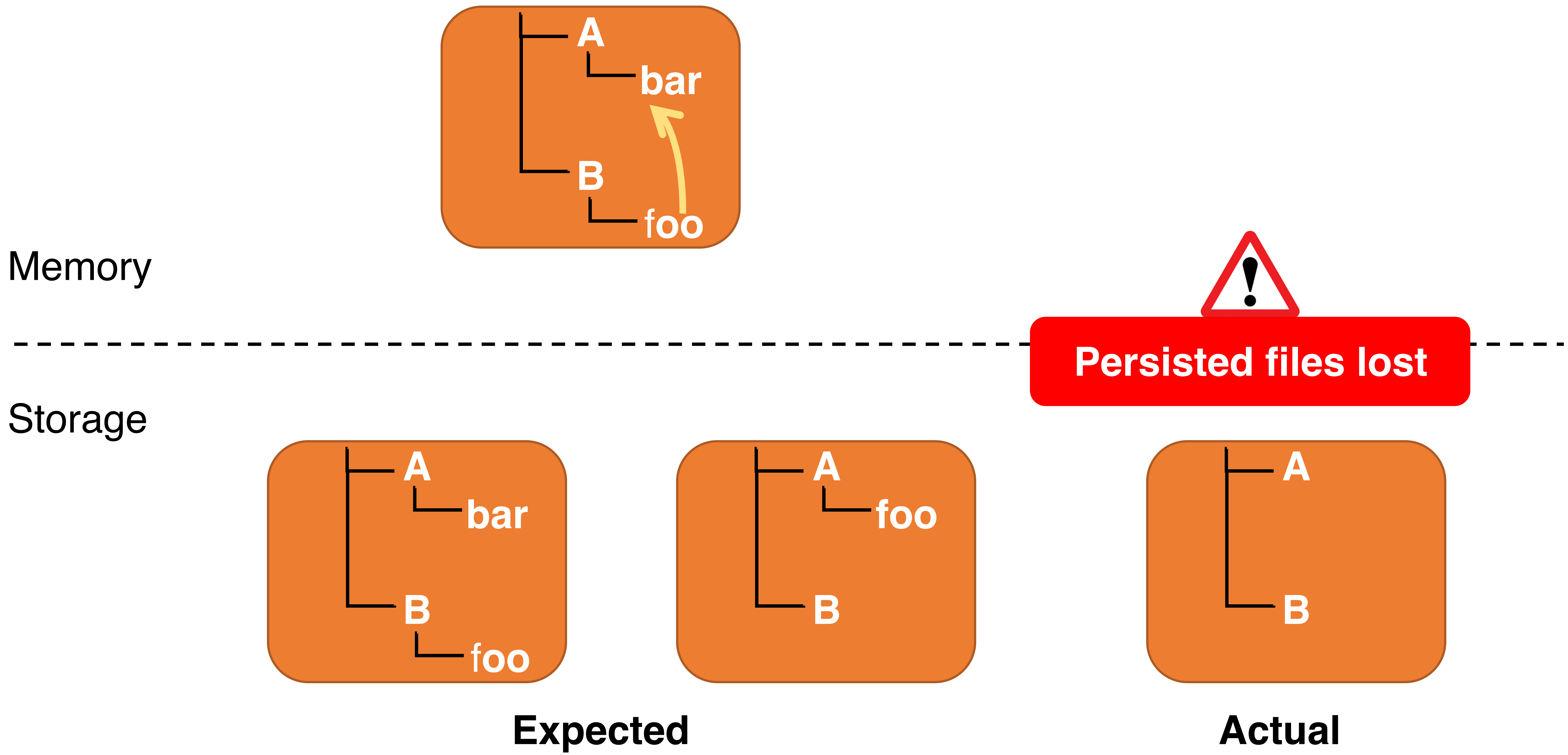

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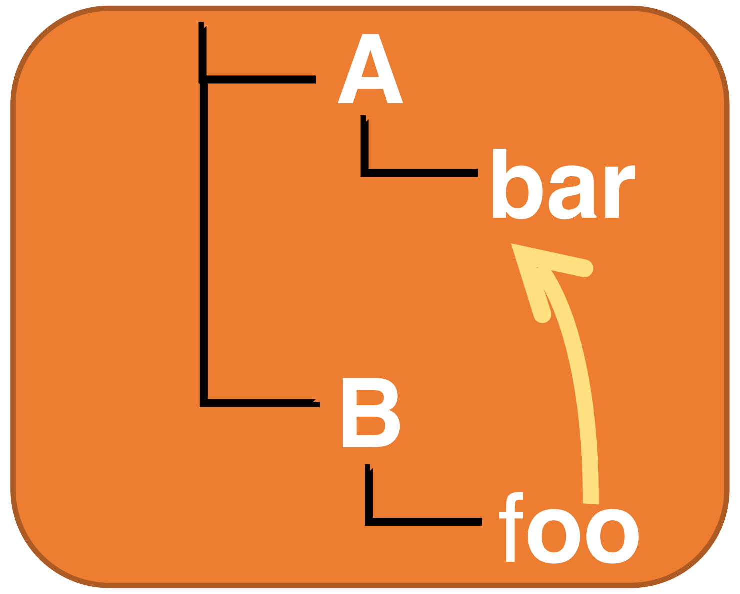

Memory

Storage

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Persisted files lost

Variant of this bug exists in the kernel since 2014!
Found by ACE and CrashMonkey

Expected

Actual

Challenges in crash consistency testing

Lack of automated infrastructure

Challenges

Infinite workload space

Challenges in crash consistency testing

Lack of automated infrastructure

Challenges

Infinite workload space

Our work addresses both these issues, to provide a systematic testing framework

Bounded Black-Box Crash Testing (B^3)

New approach to testing file-system crash consistency

www.github.com/utsaslab/crashmonkey

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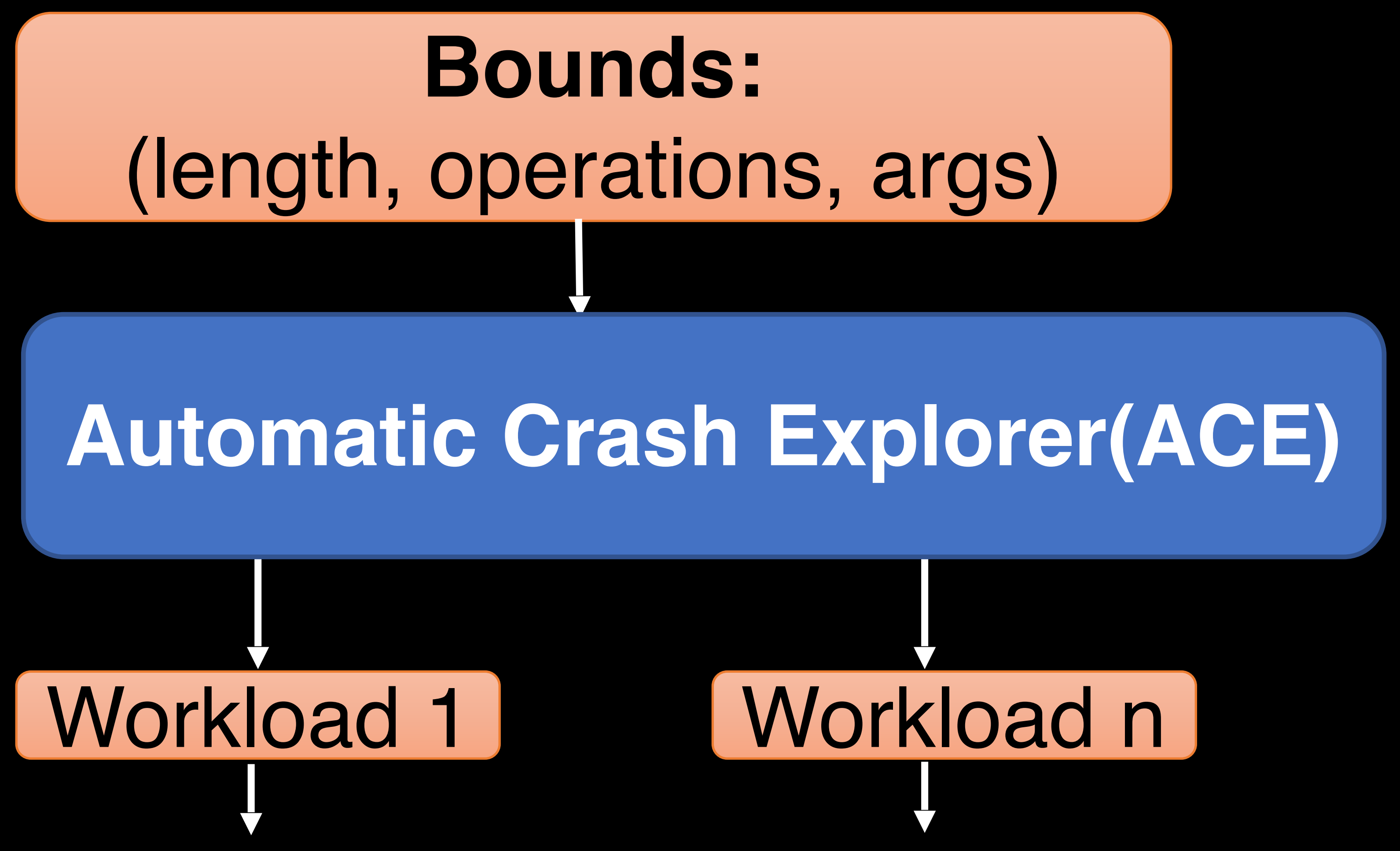

- ➡ Focus on reproducible bugs resulting in metadata corruption, data loss.
- ➡ Found 10 new bugs across btrfs and F2FS;
- ➡ Found 1 bug in FSCQ (verified file system)
- ➡ Filesystem agnostic – works with any POSIX file system

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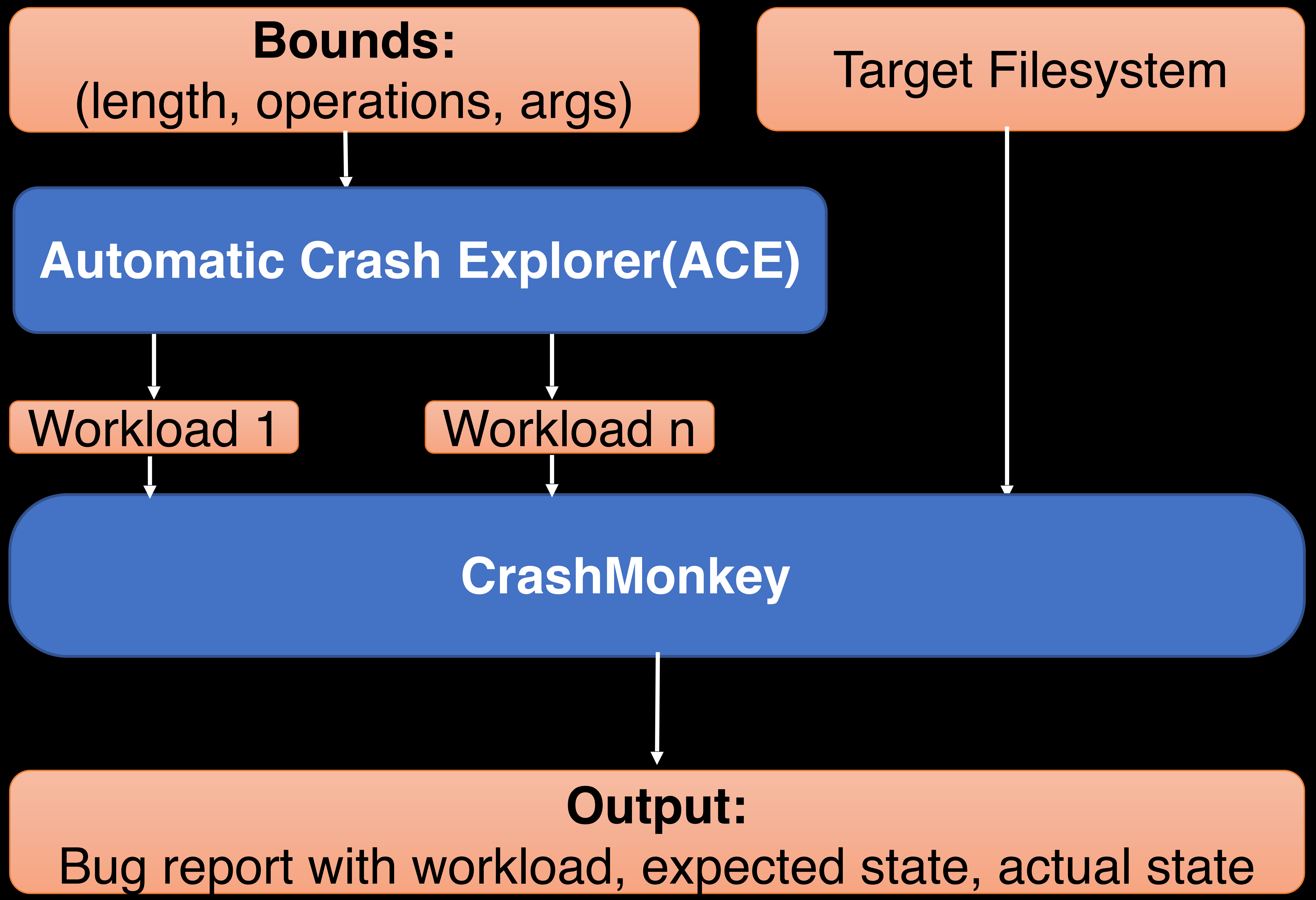

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CrashMonkey and Ace : Features

Fully automated

Completely black-box

File system agnostic

Finds real bugs

CrashMonkey and Ace : Features

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No manual checkers and workloads

File system agnostic

Finds real bugs

CrashMonkey and Ace : Features

Fully automated

Completely black-box

No annotations
Doesn't need to look at file system code

File system agnostic

Finds real bugs

CrashMonkey and Ace : Features

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Works on any POSIX file system, including verified FS

File system agnostic

Finds real bugs

CrashMonkey and Ace : Features

Fully automated

Completely black-box

Acknowledged and patched by kernel developers

File system agnostic

Finds real bugs

Outline

- CrashMonkey
- Bounded Black Box Crash Testing
- Automatic Crash Explorer (ACE)
- Deployment and Testing on Chameleon

Challenges with systematic testing

Lack of automated infrastructure

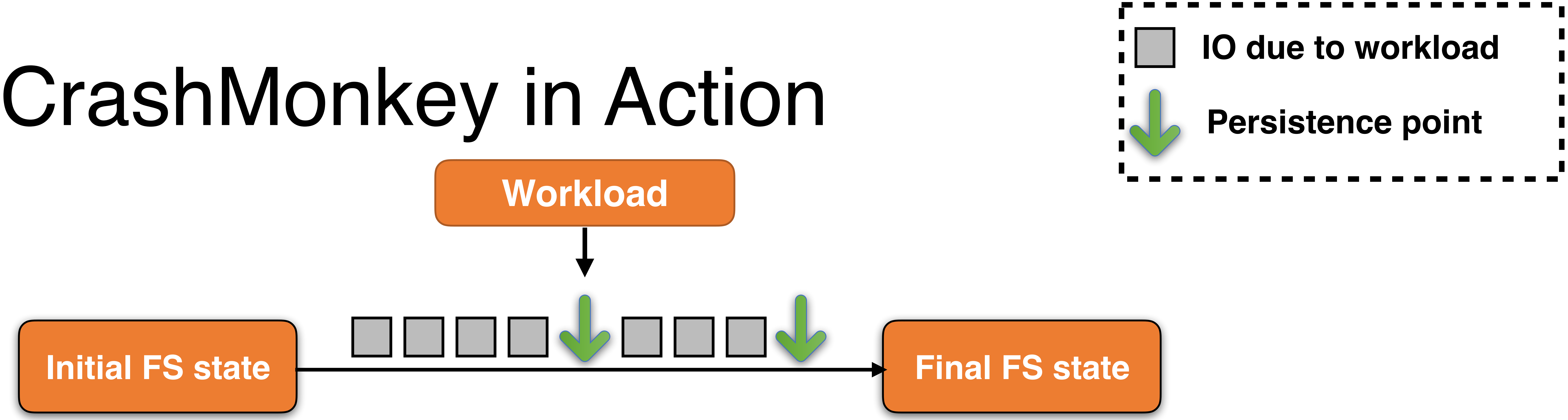
Challenges

Infinite workload space

CrashMonkey

- Efficient infrastructure to record and replay block level IO requests
- Simulate crash at different points in the workload
- Automatically test for consistency after crash.
- Copy-on-write RAM block device

CrashMonkey in Action



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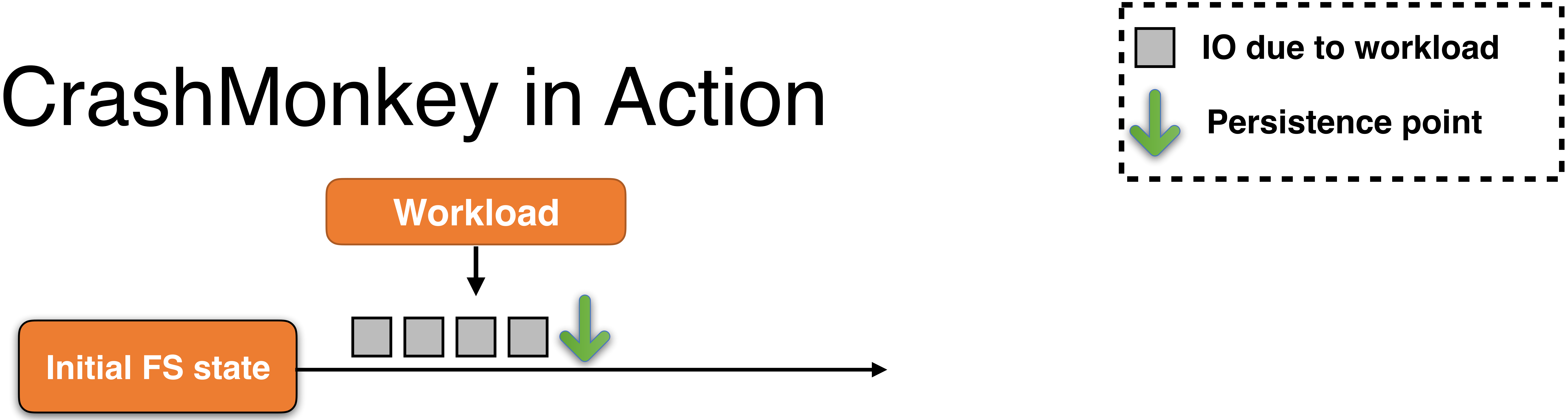
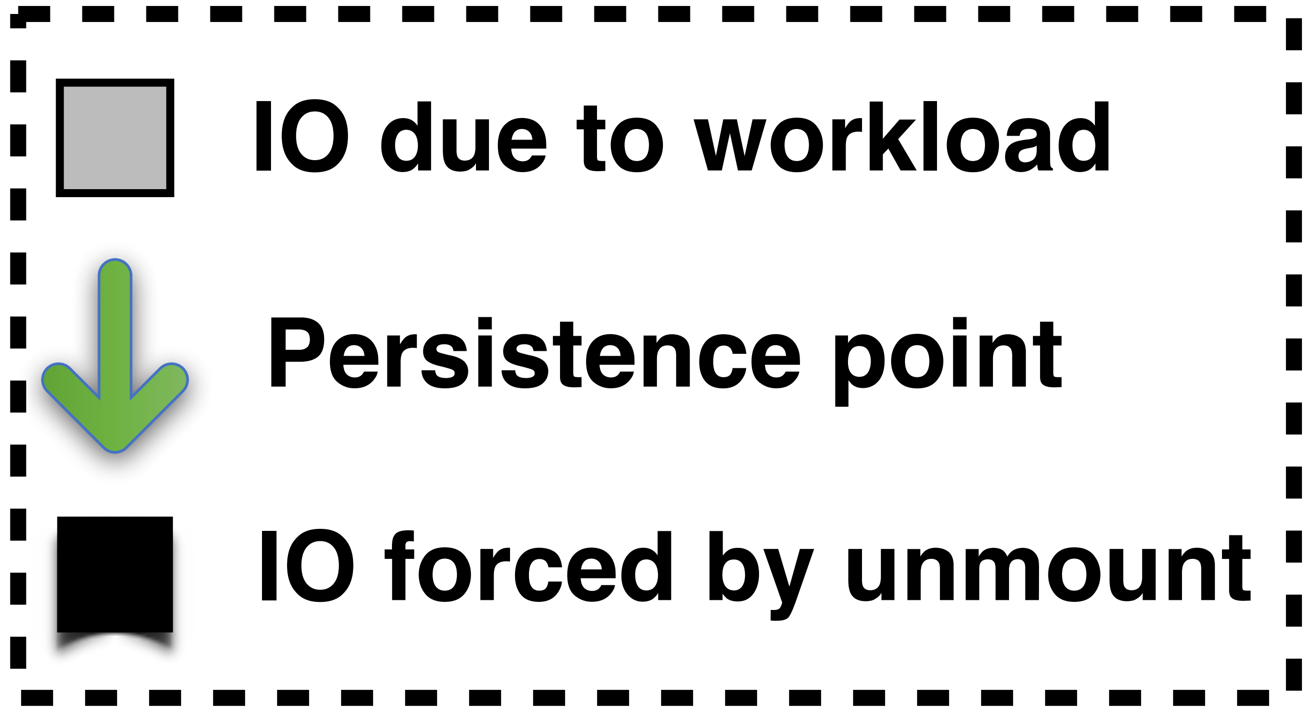
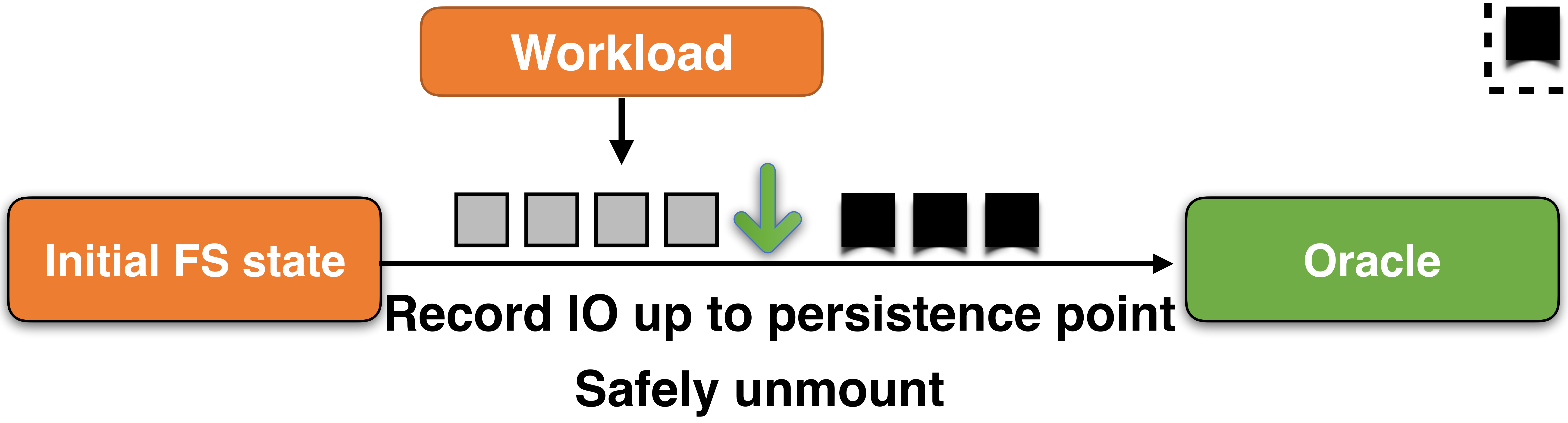
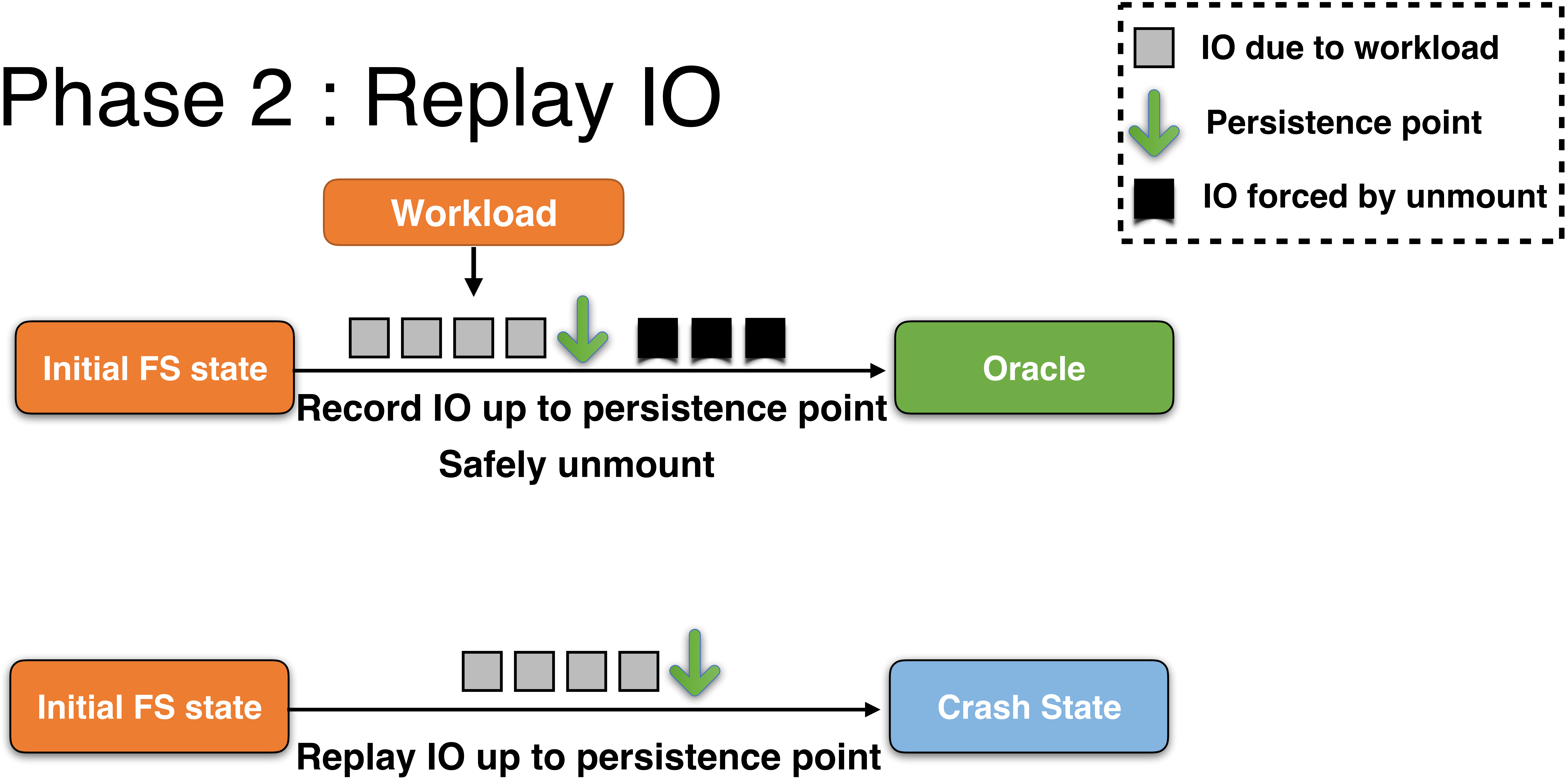


Phase 1 : Record IO





Phase 2 : Replay IO



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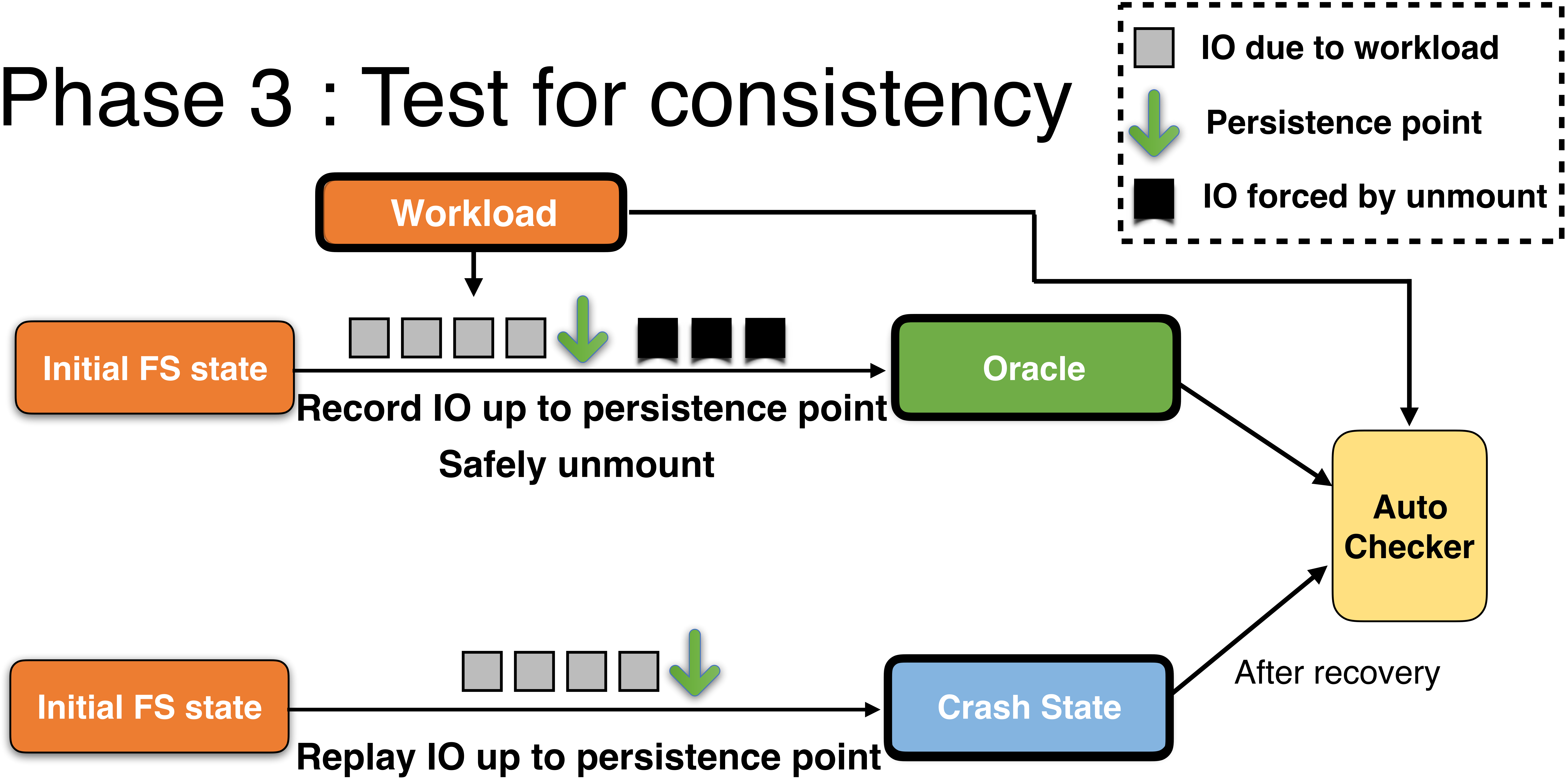

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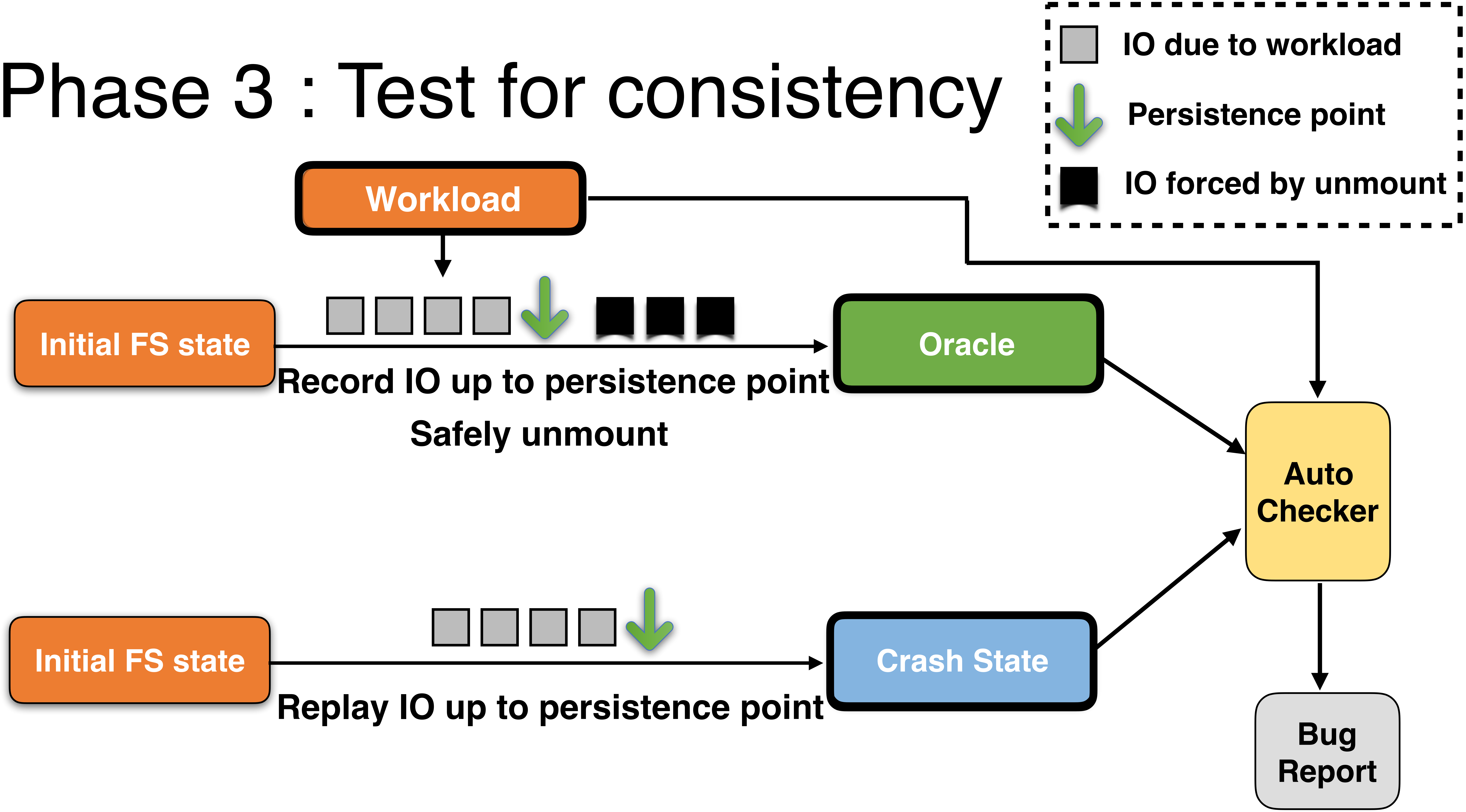
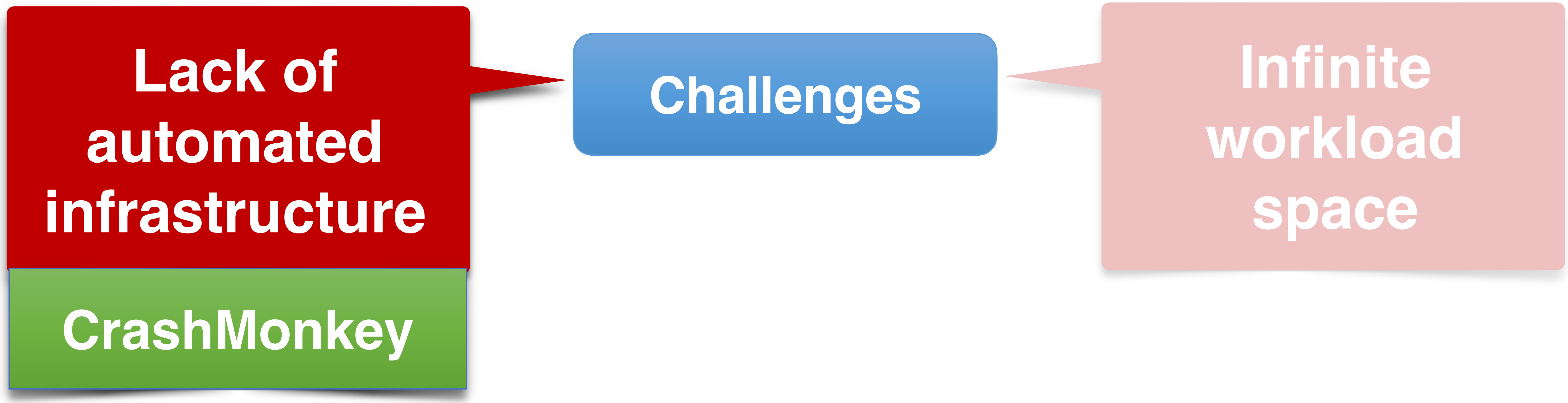


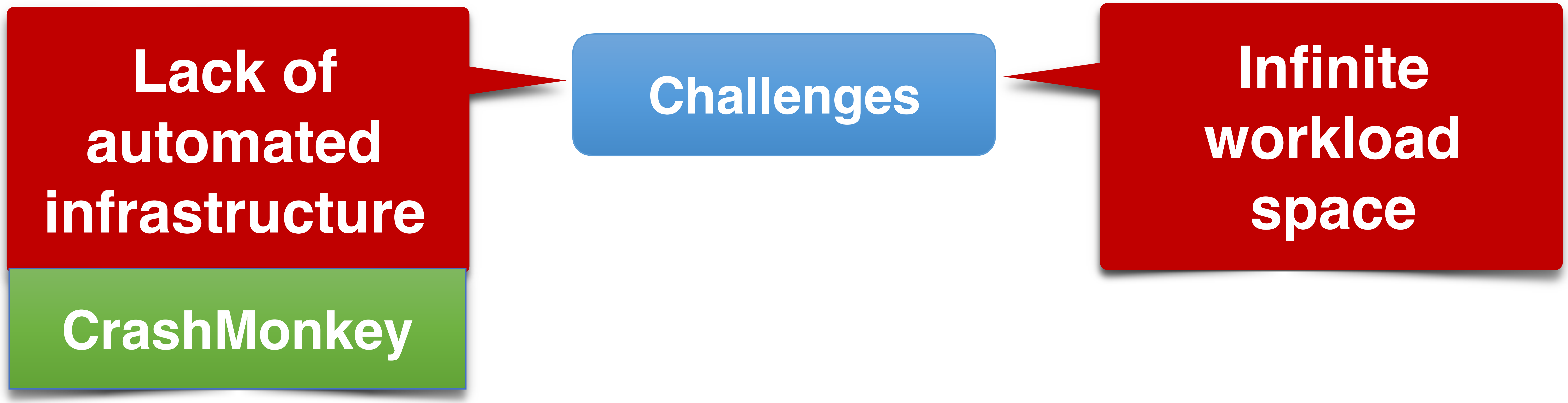
Challenges with Systematic Testing



So Far…

- Given a workload compliant to POSIX API, we saw how CrashMonkey generates crash states and automatically tests for consistency

Challenges with Systematic Testing



So Far…

- Given a workload compliant to POSIX API, we saw how CrashMonkey generates crash states and automatically tests for consistency

- Next question : How to automatically generate workloads in an the infinite workload space?

Exploring the infinite workload space

Challenges:

- Infinite length of workloads
- Large set of filesystem operations
- Infinite parameter options (file/directory names, depth)
- Infinite options for initial filesystem state
- When in the workload to simulate a crash?

Outline

- CrashMonkey
- **Bounded Black Box Crash Testing**
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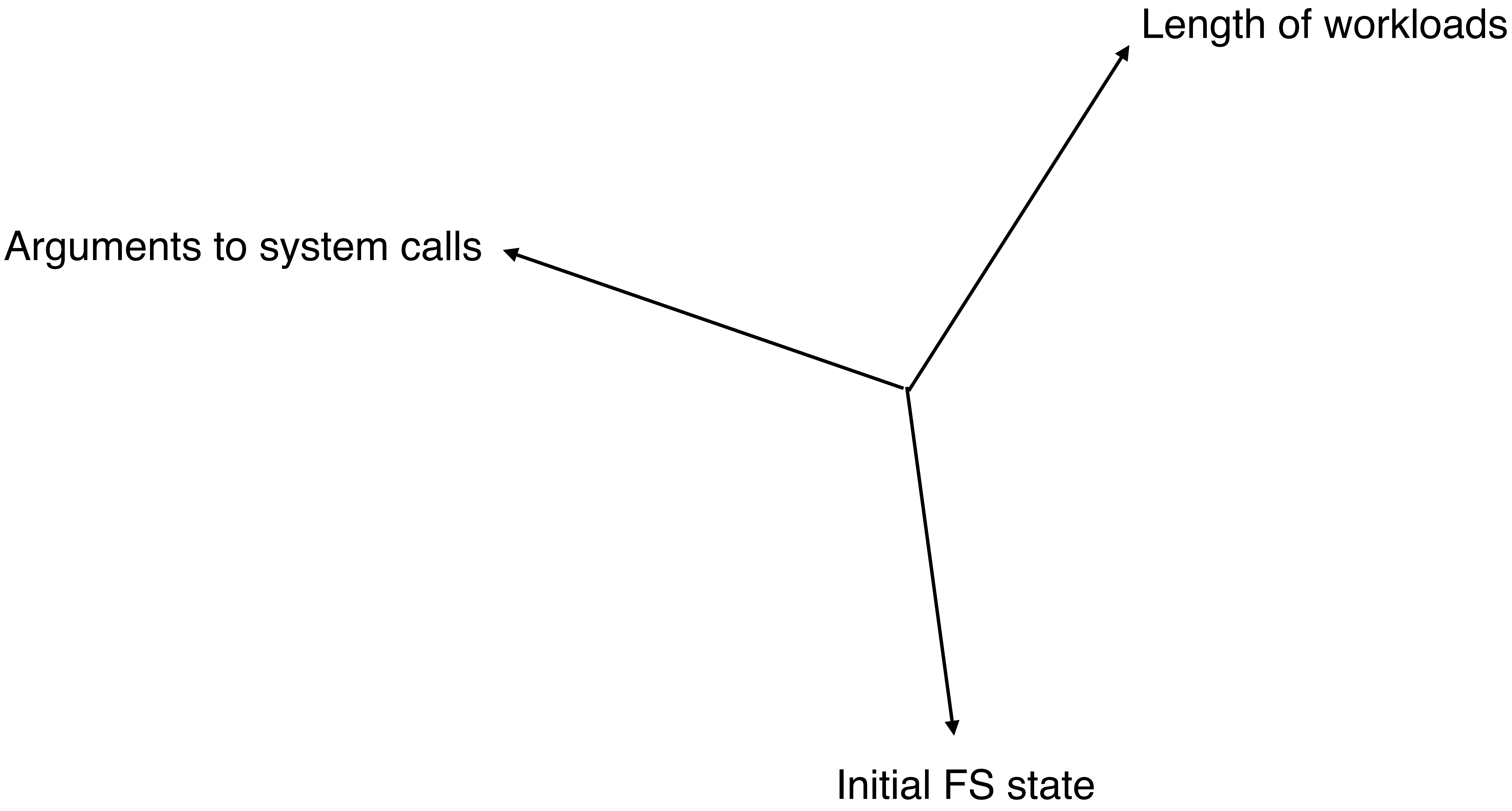
B^3 : Bounded Black Box Crash Testing



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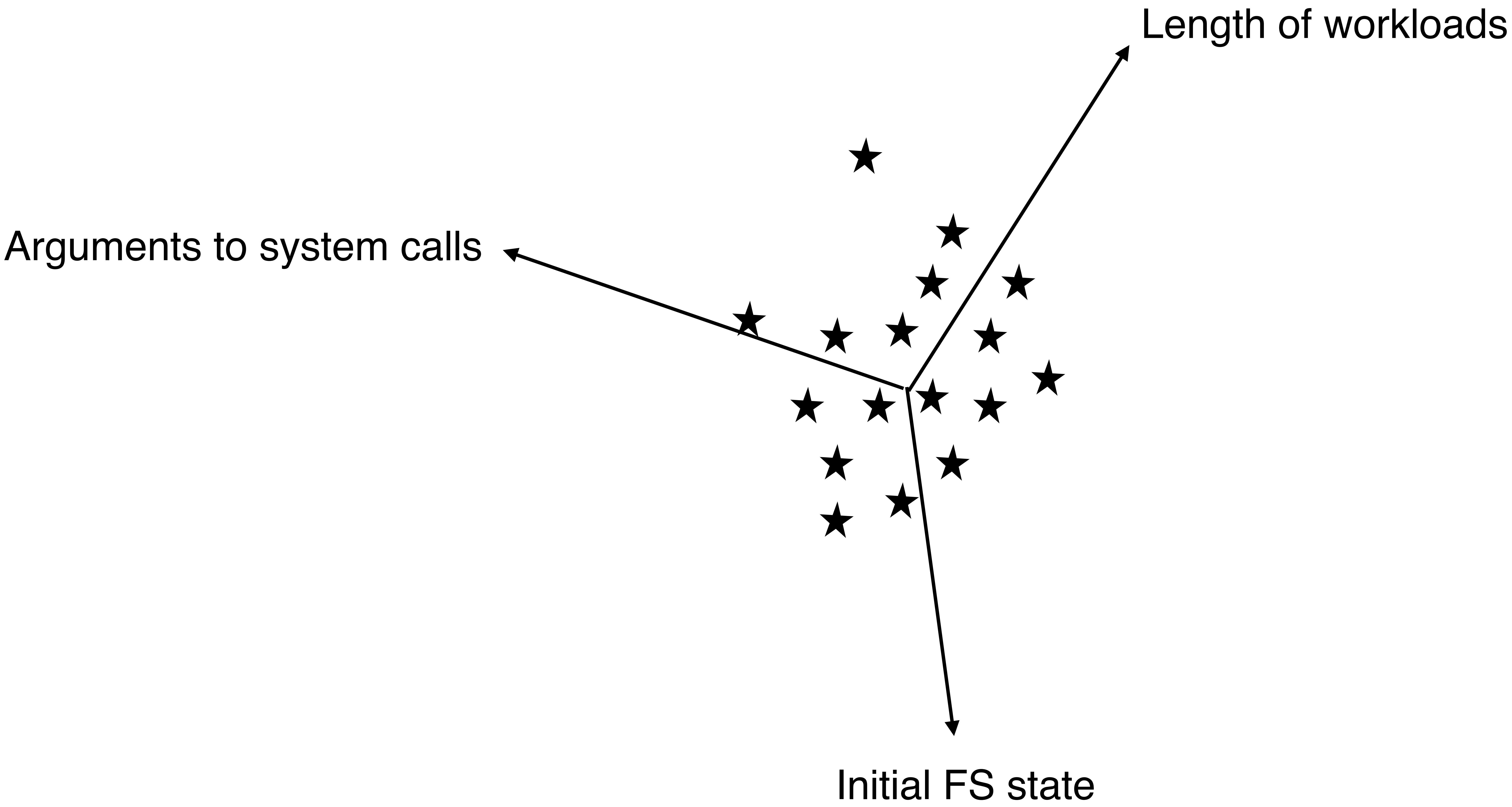

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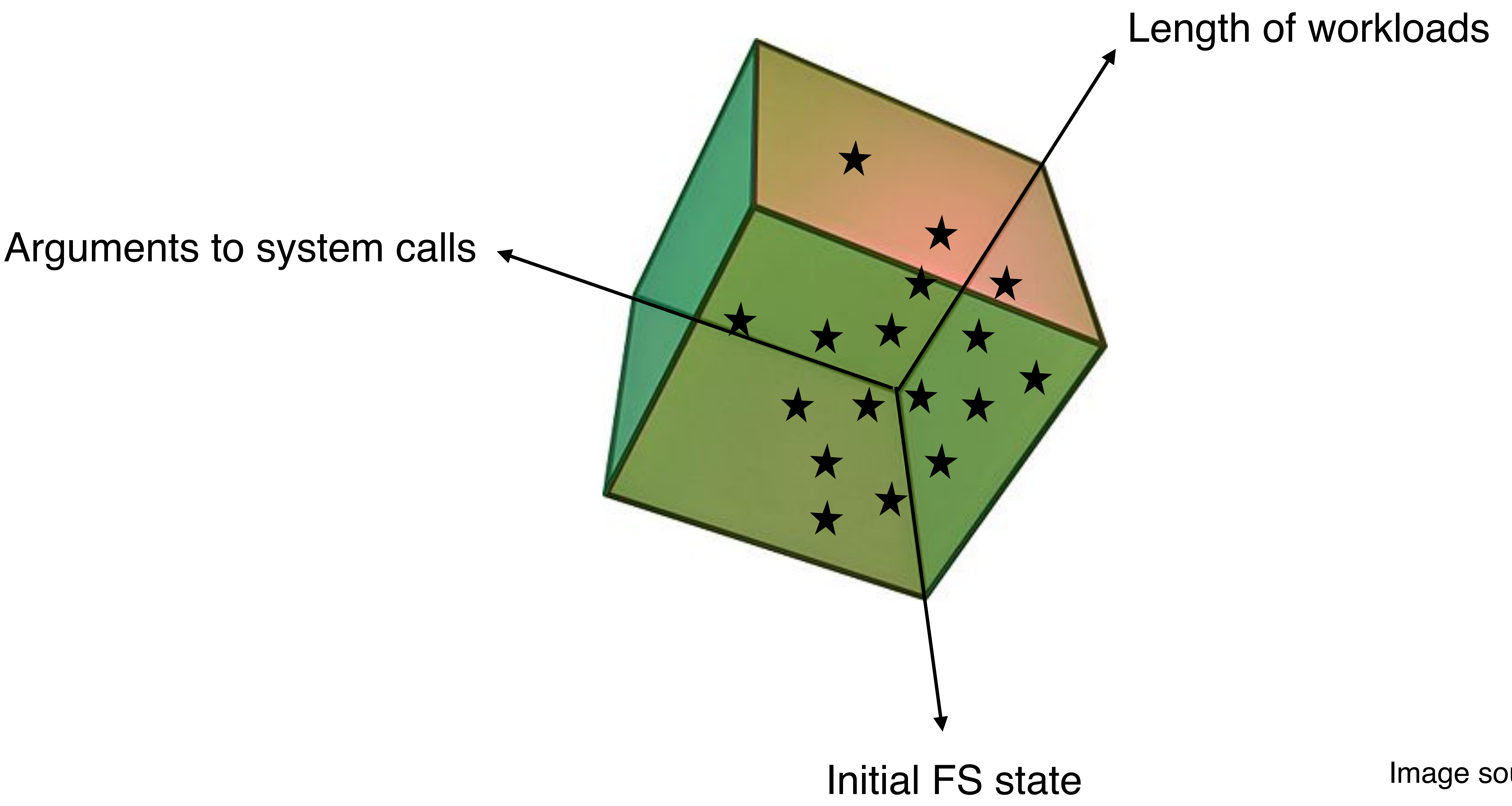
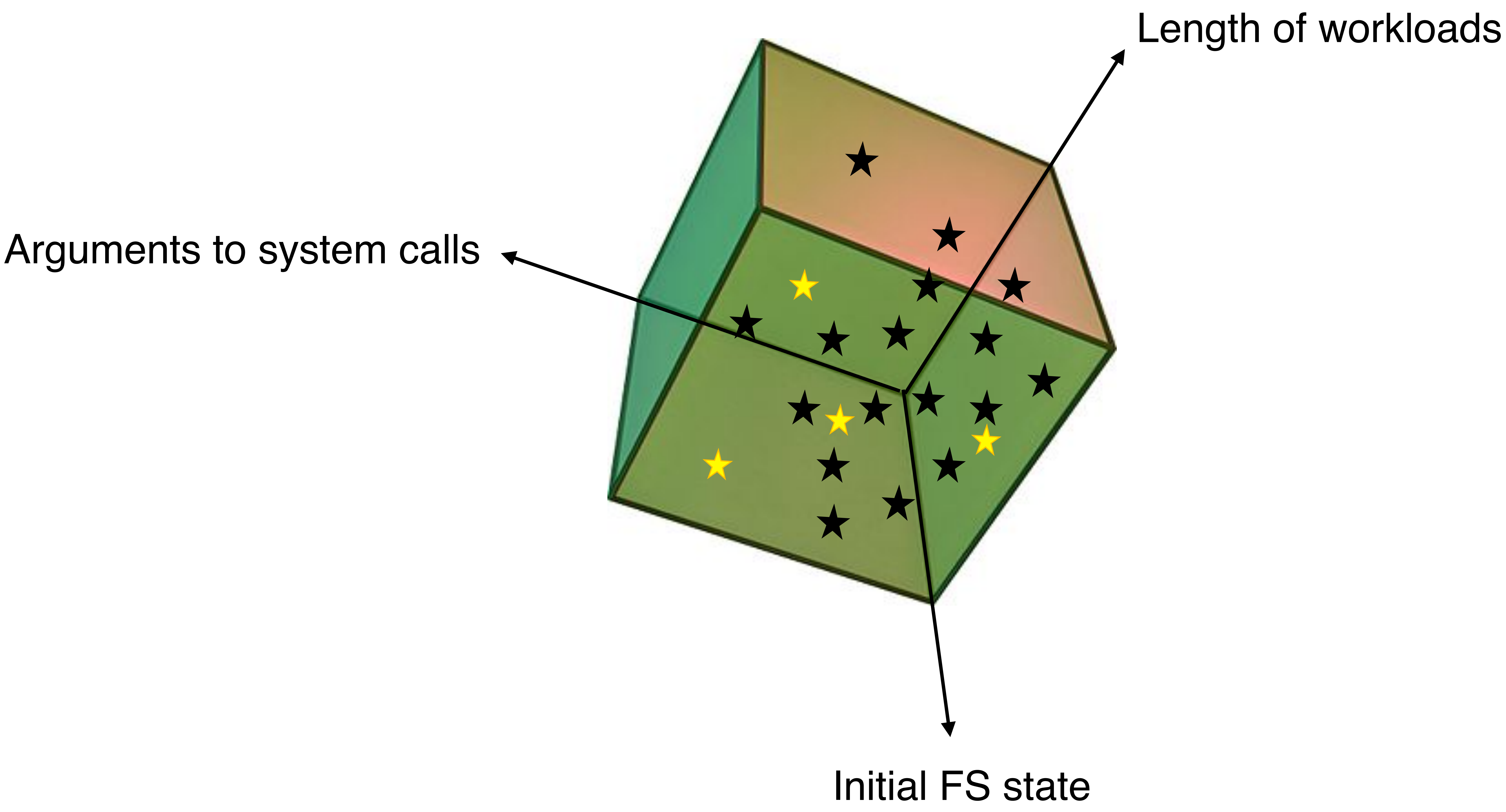


Image source: https://en.wikipedia.org/wiki/Cube

B³ : Bounded Black Box Crash Testing



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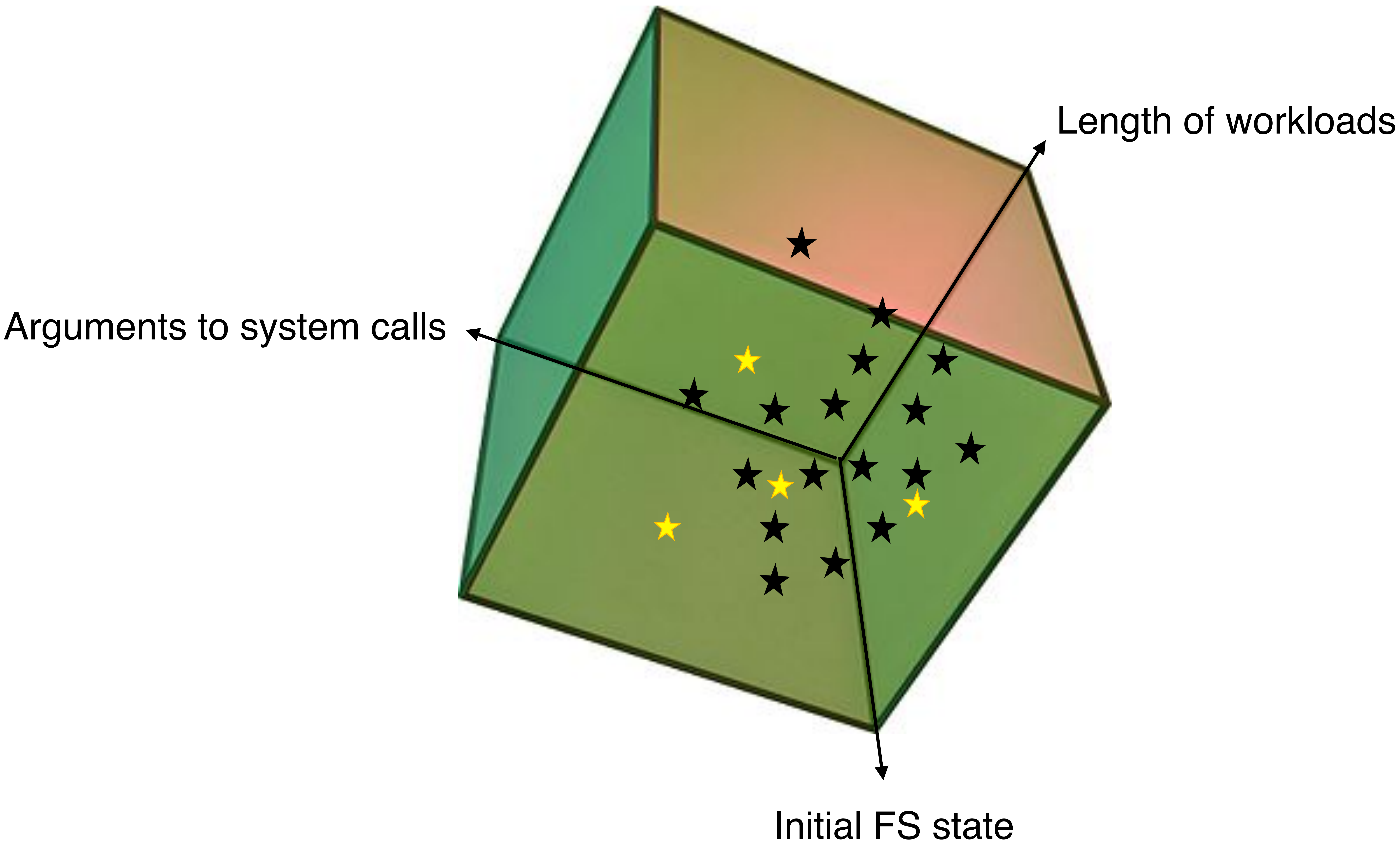

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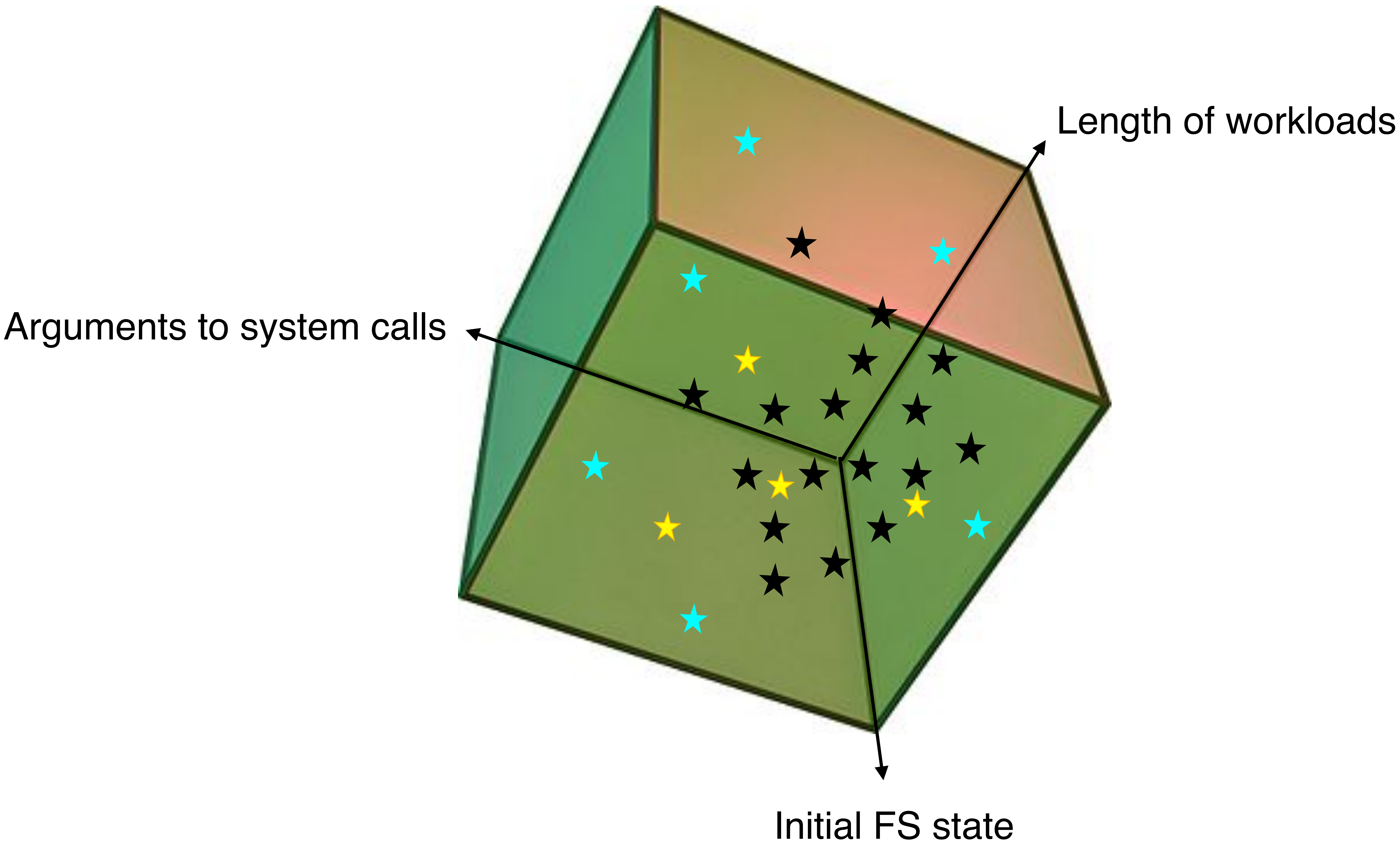

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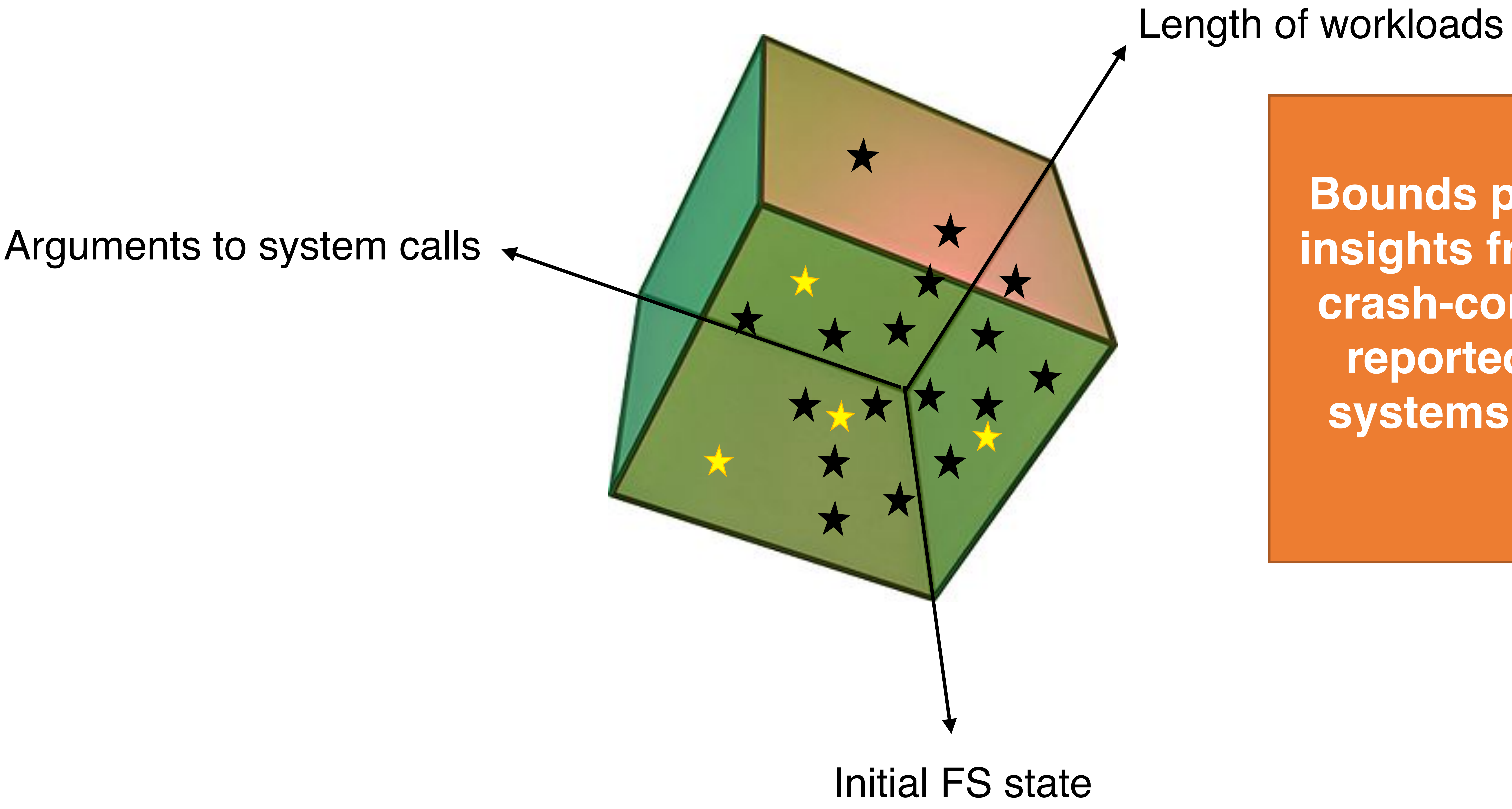
- Bounded Black Box Crash Testing
- **Automatic Crash Explorer (ACE)**
- Deployment and Testing on Chameleon

Bounds chosen by ACE



Bounds picked based on insights from the study of crash-consistency bugs reported on Linux file systems over the last 5 years

Bounds chosen by ACE

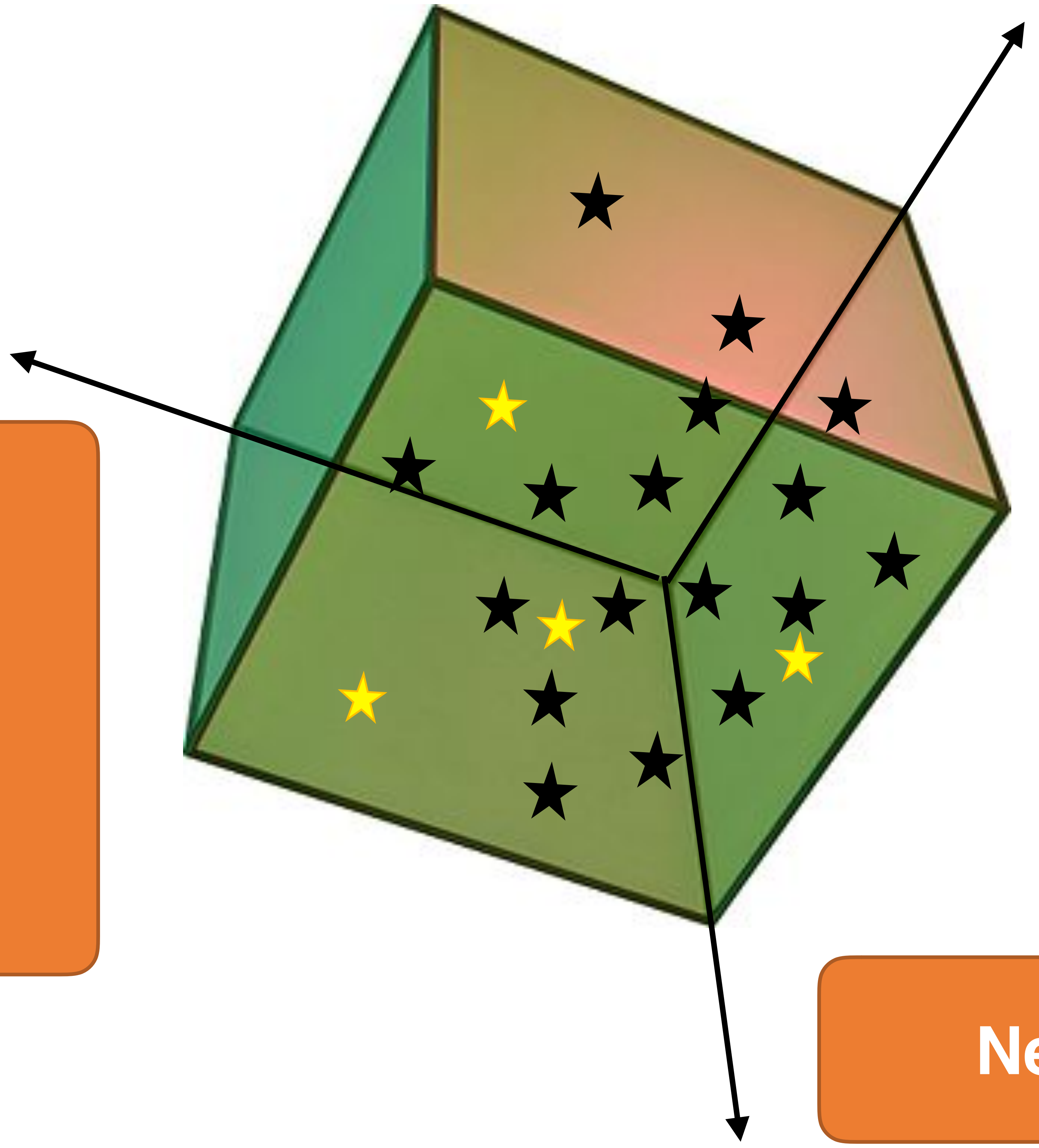
Length of workloads

Maximum # core ops is 3

Arguments to system calls

Root → A → (foo, bar)
Root → B → (foo, bar)

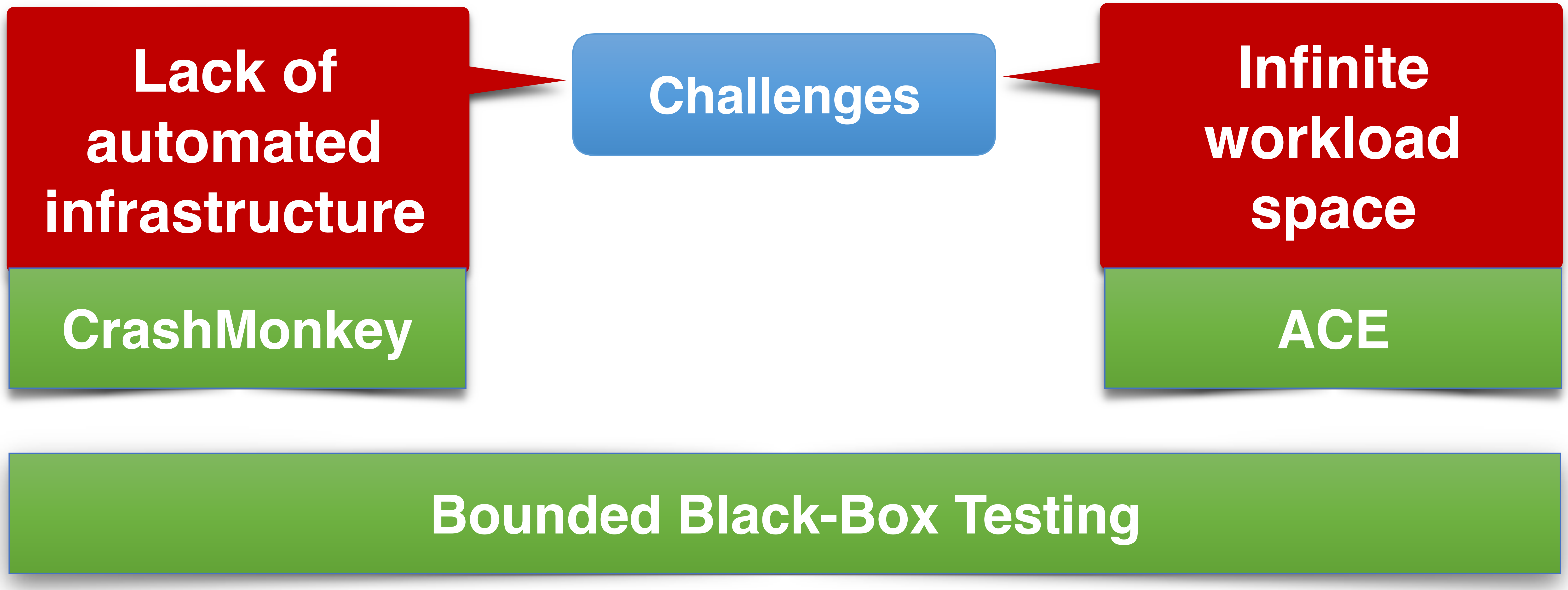
Overwrites to start, middle, end and append



New, 100MB FS

Initial FS state

Challenges with Systematic Testing



Outline

- CrashMonkey
- Bounded Black Box Crash Testing
- Automatic Crash Explorer (ACE)
- **Deployment and Testing on Chameleon**

Testing

- Need to test a large number of workloads
  - Seq 2 : 254K workloads
  - Seq 3 : Over 3 million
- Conservative estimate of 20 seconds per workload (including cleanup overhead)
- 58 days to run Seq-2 workloads sequentially
- Needs high parallelism

Testing on the Chameleon Cloud

- Academic cloud computing testbed
- Created 65 bare metal instances (compute_haswell nodes)
- Only one instance of CrashMonkey can run per node
- Seq-2 workloads still takes 1 day to complete per FS
- Still very slow, cannot move to higher sequences

Sequential	Chameleon 65 nodes
58 days	1 day

Parallelize even more!

- Each instance is beefy
  - 128GB RAM, 24 cores, 250GB HDD
- 12 VMs per instance, each with 2GB RAM, 10GB disk
- New parallelism = 65*12 = 780!

Sequential	Chameleon 65 nodes	Chameleon 780 VMs
58 days	1 day	2 hours

Testing workloads on Chameleon Cloud

Challenges

- **Instances could fail or become unreachable**
  - Need to handle faults at software level
  - Retry instance creation until all succeed
  - Re-run workloads selectively on instances that failed

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- **Instances could fail or become unreachable**
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- **VMs unresponsive/read-only**
  - Due to the load on underlying storage, VMs become unresponsive
  - Needs a restart to fix the VM

Challenges

- **Inflexible leases**
  - Can extend leases only a couple of days before they expire
  - In most cases, cannot extend lease on the same set of nodes
  - Requires re configuration of all set-up in the new instances

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- **Setting up 12 VMs per machine can be tedious**
  - Export a VM per instance, and clone others
  - Automate VM set-up and configuration

Chameleon features required

- **Flexible leases**
  - Must be able to extend leases irrespective of whether all the nodes in the previous lease are available
  - Seamless transition of data to new lease

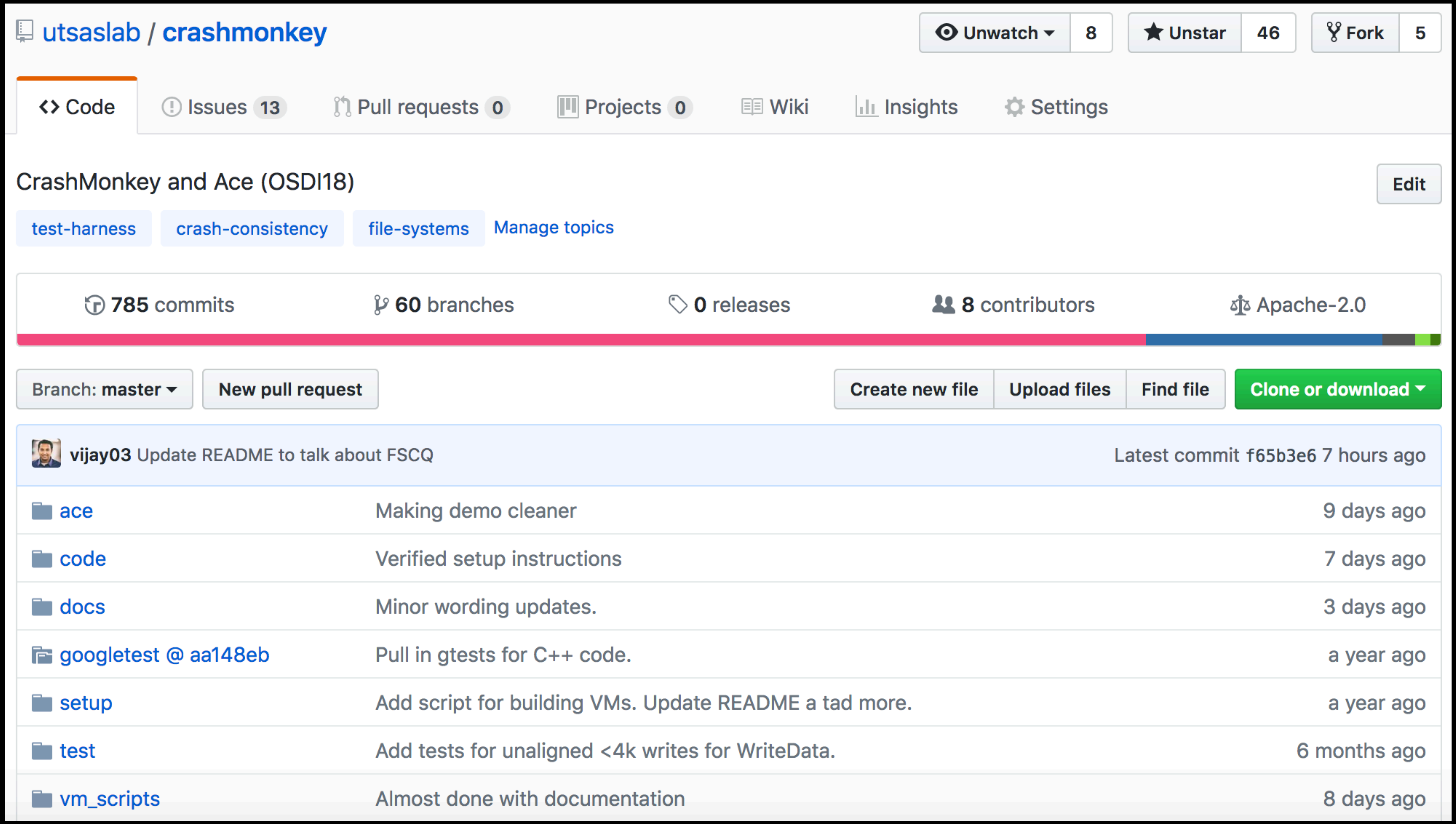
- **Automatic snapshot**
  - Automatically snapshot the instance and set-up the new instances so that execution can resume in the new lease

Results

- Reproduced 24/26 known bugs across ext4, btrfs and F2FS
- Found 10 new bugs across btrfs and F2FS
- Found 1 bug in a verified file system, FSCQ
- Contributed workloads to Linux xfstests

Bounded Black-Box Crash Testing

- B^3 makes exhaustive testing feasible using informed bound selection
- Easily generalizable to test larger workloads if more compute is available
- Found 10 new bugs across btrfs and F2FS, most of which existed since 2014
- Found 1 bug in FSCQ



Thanks!

Try our tools : https://github.com/utsaslab/crashmonkey

Backup slides

Testing Crash Consistency Today

- Build FS from scratch

Verified Filesystems

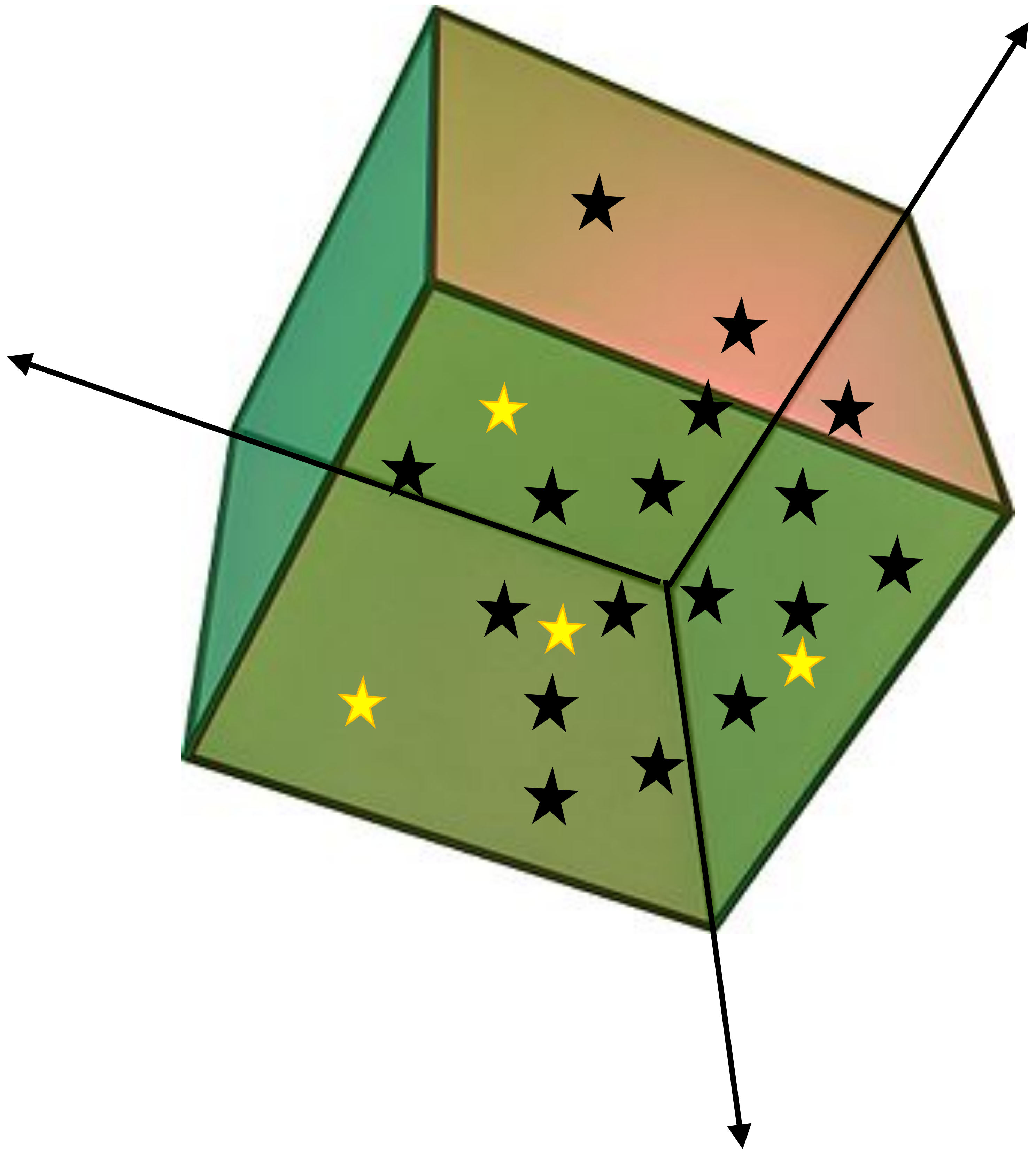
Model Checking

- Annotate filesystems
- Hard to do for existing FS

- State of the Art : xfstest suite
  - Collection of 482 regression tests

Only 5% of tests in xfstest check for file system crash consistency

Bounds chosen by ACE



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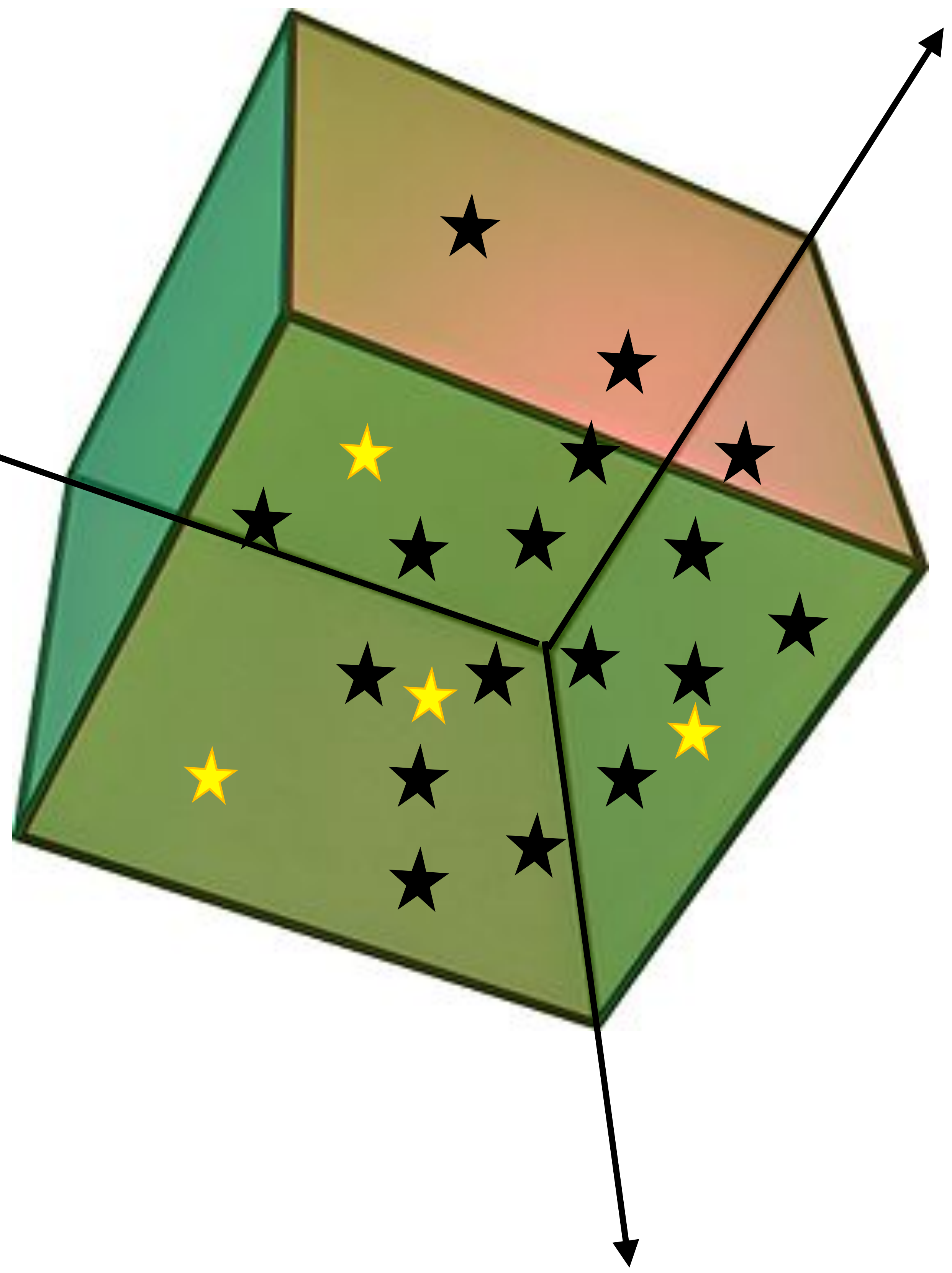


Maximum # core ops is 3

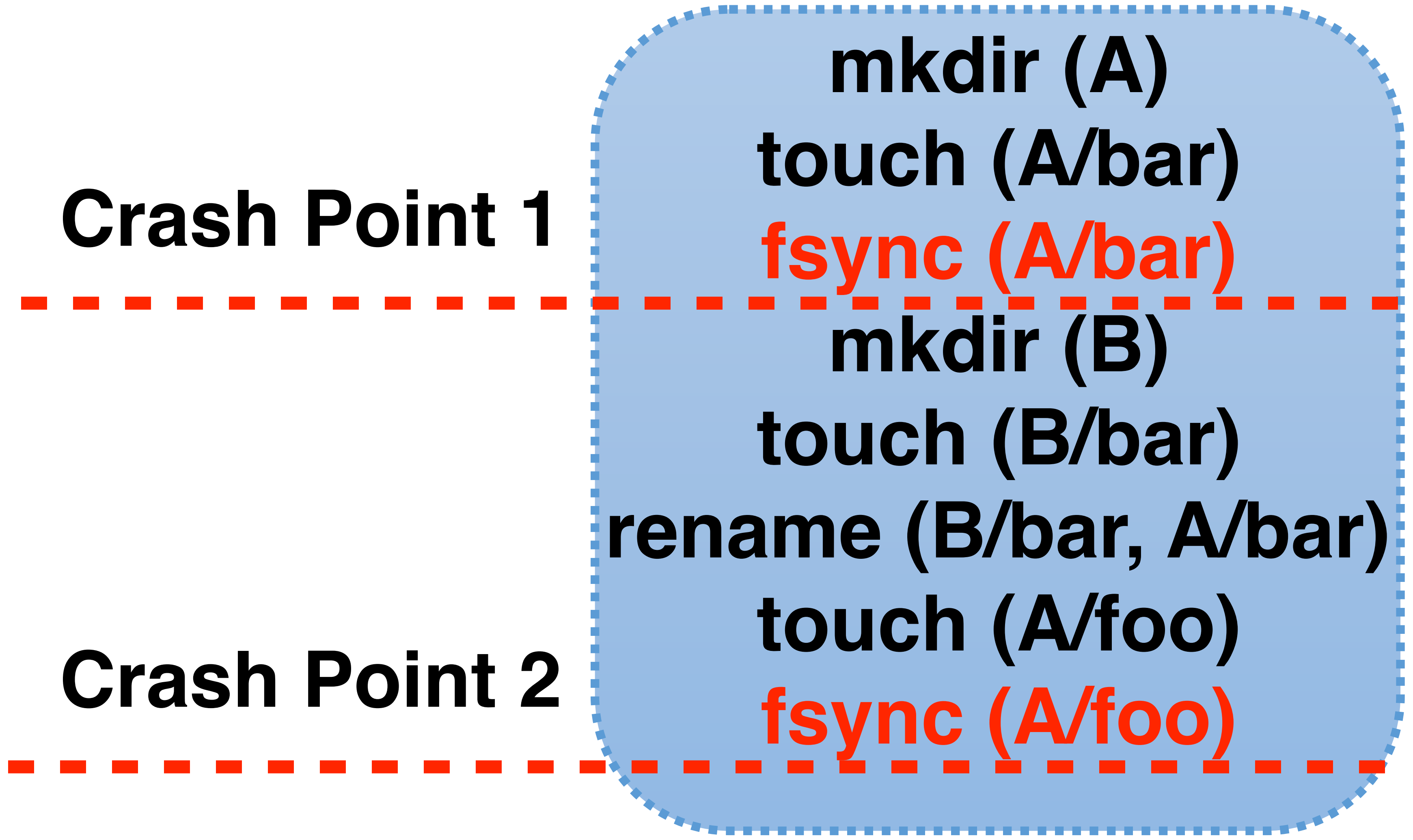
Root → A → (foo, bar)
Root → B → (foo, bar)

Overwrites to start, middle, end of a file and append

B^3 : Bounded Black Box Crash Testing

Choice of crash point

- Only after fsync(), fdatasync() or sync()
- Not in the middle of system call



- Developers are motivated to patch bugs that break semantics of persistence operations
- Crashing in the middle of system calls leads to exponentially large crash-states.

Limitations of B^3

- No guarantee of finding **all** crash-consistency bugs in a filesystem
- Assumes the correct working of crash-consistency mechanism like journaling or CoW
  - Does not crash in the middle of system calls
- Can only reveal if a bug has occurred, not the reason or origin of bug.
- Needs larger compute to test higher sequence lengths

Phases of ACE

Operation Set

creat()
link()
rename()
write()

Generating skeletons of sequence-2. : 4*4 = 16

creat()
creat()

creat()
rename()

creat()
link()

creat()
write()

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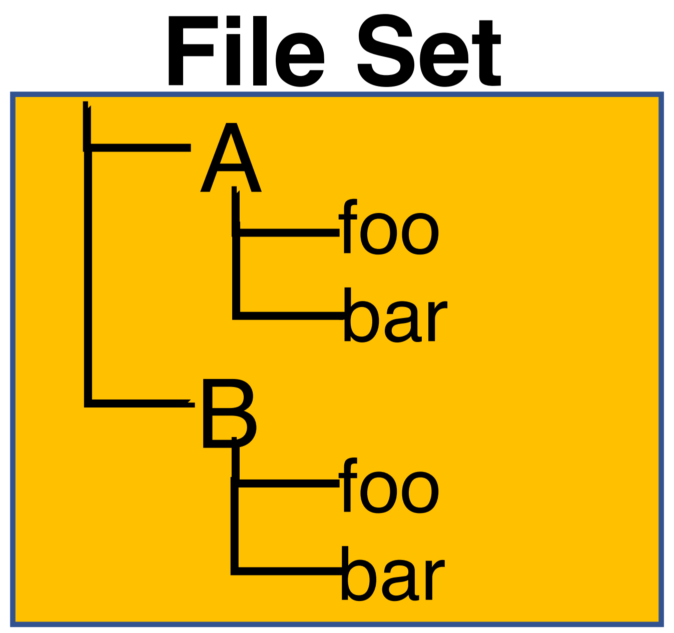
Generating skeletons of sequence-2. : 4*4 = 16

creat() creat()	creat() rename()	creat() link()	creat() write()	link() link()	link() creat()	link() rename()	link() write()
rename() rename()	rename() creat()	rename() link()	rename() write()	write() write()	write() creat()	write() link()	write() rename()



Phases of ACE

1. Select Operations

1. **creat()**
2. **rename()**

File Set

```
├─A
│ ├─foo
│ └─bar
└─B
  ├─foo
  └─bar
```

Phases of ACE

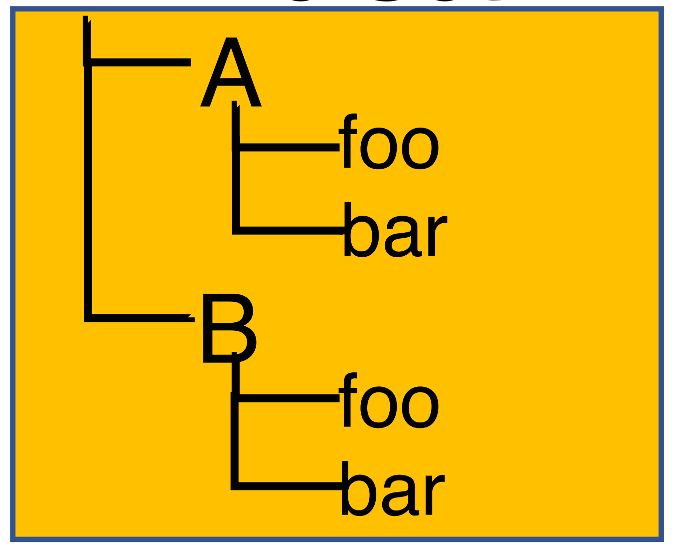
1. Select Operations

1. **creat()**
2. **rename()**

- If metadata operations, pick file or directory names
- If data operations, pick a range of offset and length

2. Select Parameters

File Set



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1. **creat()**
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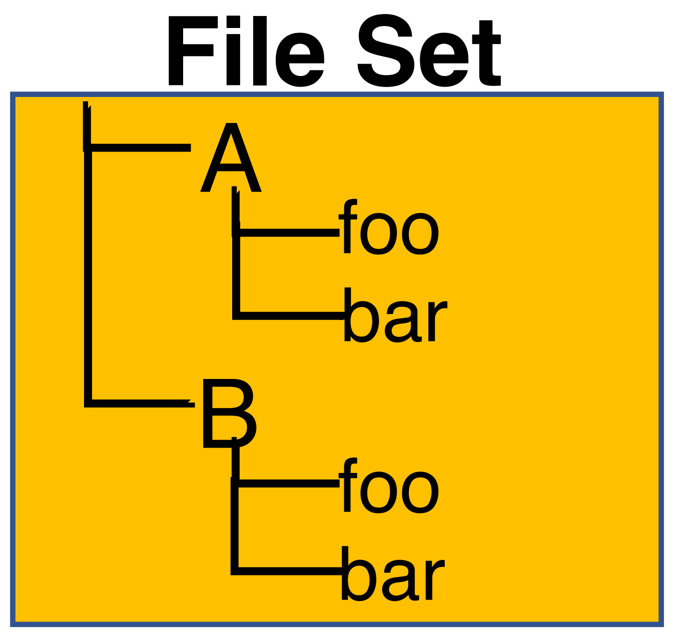
- If metadata operations, pick file or directory names
- If data operations, pick a range of offset and length

2. Select Parameters

1. **creat(A/bar)**
2. **rename(B/bar, A/bar)**



Phases of ACE

1. Select Operations

1. **creat()**
2. **rename()**

2. Select Parameters

1. **creat(A/bar)**
2. **rename(B/bar, A/bar)**

3. Add Persistence

- Between each core operation, add a persistence operation
- Consistency will be checked at these points
- Parameter to the persistence function is again chosen from the file/ directory pool

File Set

- A
  - foo
  - bar
- B
  - foo
  - bar

Phases of ACE

1. Select Operations

1. **creat()**
2. **rename()**

2. Select Parameters

1. **creat(A/bar)**
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- Between each core operation, add a persistence operation
- Consistency will be checked at these points
- Parameter to the persistence function is again chosen from the file/directory pool

3. Add Persistence

1. **creat(A/bar)**
   fsync(A/bar)
2. **rename(B/bar, A/bar)**
   fsync(A/foo)

Phases of ACE

File Set

- A
  - foo
  - bar
- B
  - foo
  - bar

1. Select Operations

1. **creat()**
2. **rename()**

2. Select Parameters

1. **creat(A/bar)**
2. **rename(B/bar, A/bar)**

3. Add Persistence

1. **creat(A/bar)**
   fsync(A/bar)
2. **rename(B/bar, A/bar)**
   fsync(A/foo)

4. Add Dependencies

- Add file create/open/close to ensure the workload executes on any POSIX compliant filesystem.

Phases of ACE

File Set

```
├─A
│ ├─foo
│ └─bar
└─B
  ├─foo
  └─bar
```

1. Select Operations

1. **creat()**
2. **rename()**

2. Select Parameters

1. **creat(A/bar)**
2. **rename(B/bar, A/bar)**

3. Add Persistence

1. **creat(A/bar)**
   fsync(A/bar)
2. **rename(B/bar, A/bar)**
   fsync(A/foo)

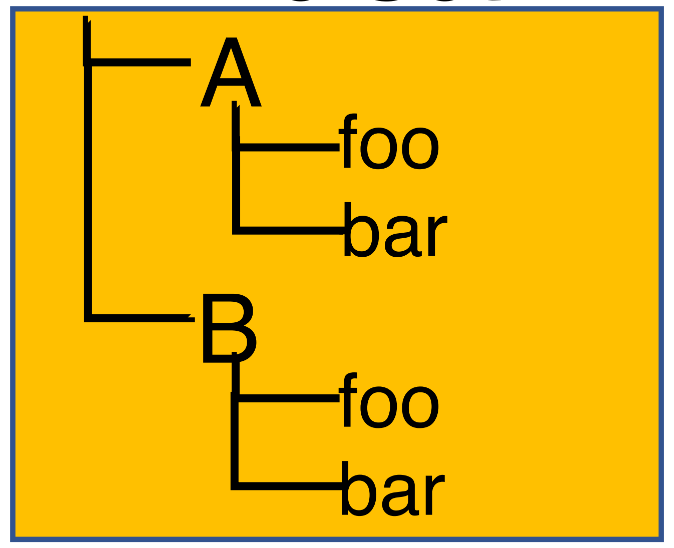
4. Add Dependencies

mkdir(A)
1. **creat(A/bar)**
   fsync(A/bar)
   mkdir(B)
   creat(B/bar)
2. **rename(B/bar, A/bar)**
   creat(A/foo)
   fsync(A/foo)
   close(A/foo)

- Add file create/open/close to ensure the workload executes on any POSIX compliant filesystem.

Phases of ACE

File Set



1. Select Operations

1. **creat()**
2. **rename()**

2. Select Parameters

1. **creat(A/bar)**
2. **rename(B/bar, A/bar)**

3. Add Persistence

1. **creat(A/bar)**
   fsync(A/bar)
2. **rename(B/bar, A/bar)**
   fsync(A/foo)

4. Add Dependencies

mkdir(A)
1. **creat(A/bar)**
   fsync(A/bar)
   mkdir(B)
   creat(B/bar)
2. **rename(B/bar, A/bar)**
   creat(A/foo)
   fsync(A/foo)
   close(A/foo)

This workload with 2 core operations is the same workload required to trigger rename atomicity bug!

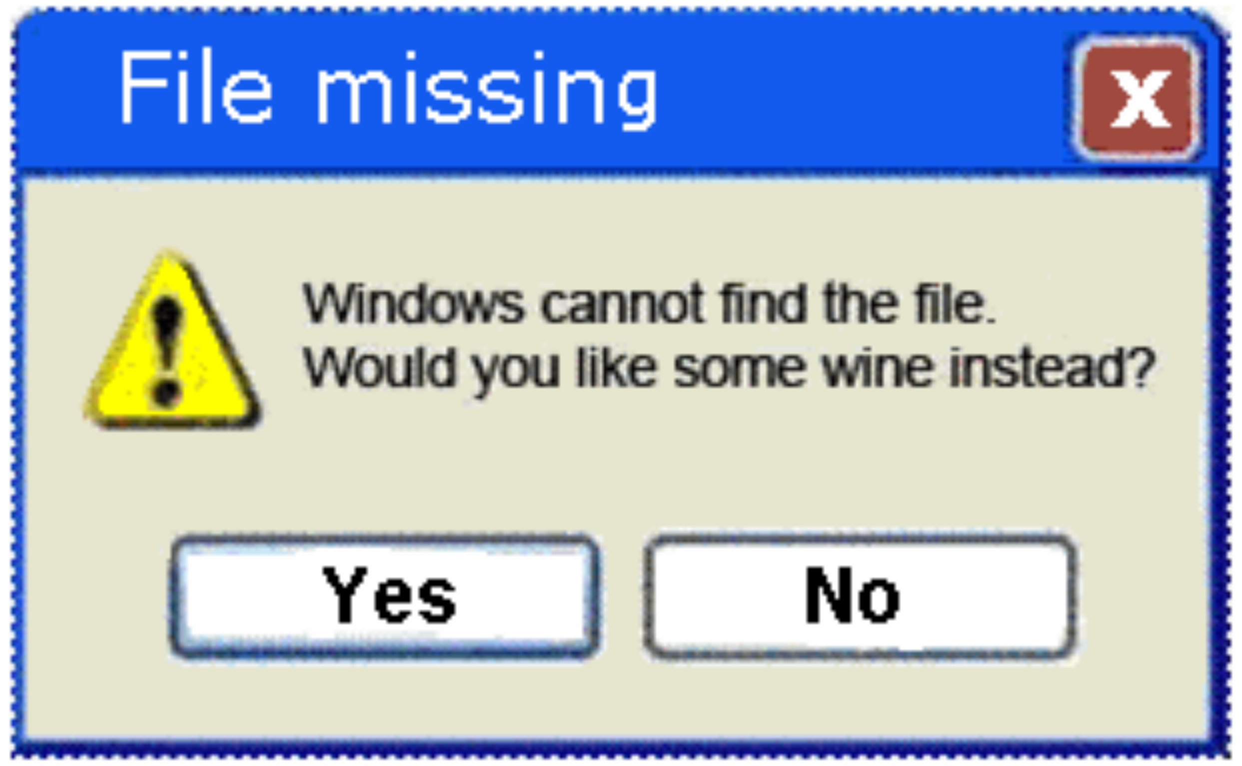
yashree-VirtualBox: /home/jayashree/crashmonkey/demo/crashmonkey

4:14 PM

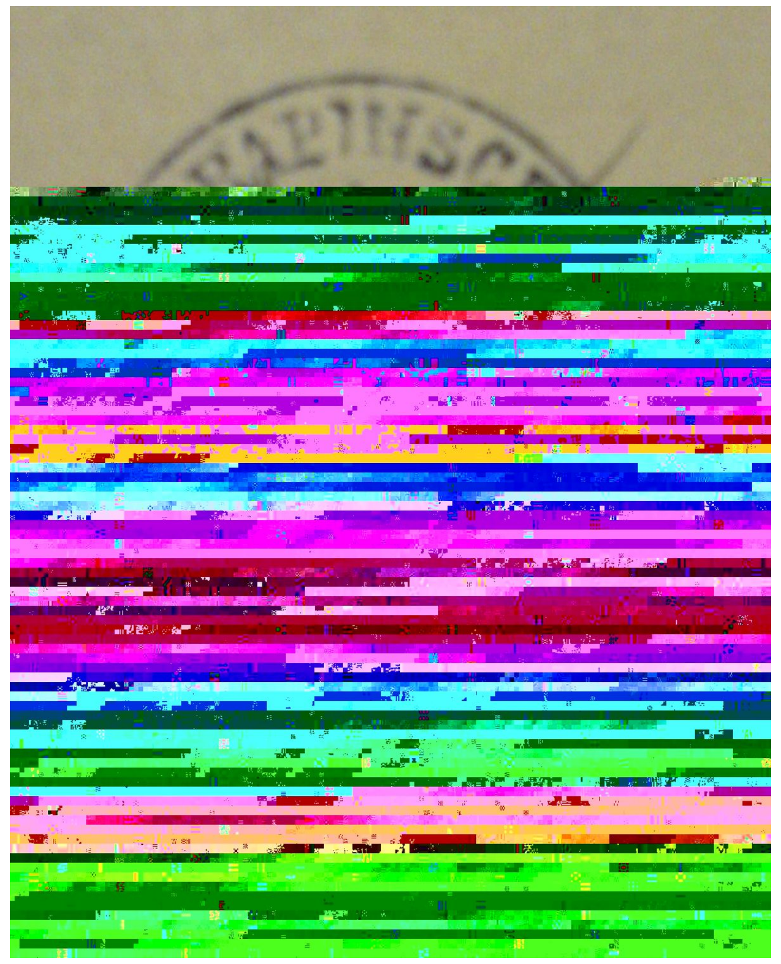
```
root@jayashree-VirtualBox:/home/jayashree/crashmonkey/demo/crashmonkey# ./demo.sh btrfs btrfs_out
```

Crash Consistency

- Filesystem operations change multiple blocks on storage that needs to be ordered
  - Inode, bitmaps, data blocks, superblock
  - Data and metadata must be consistent on a crash



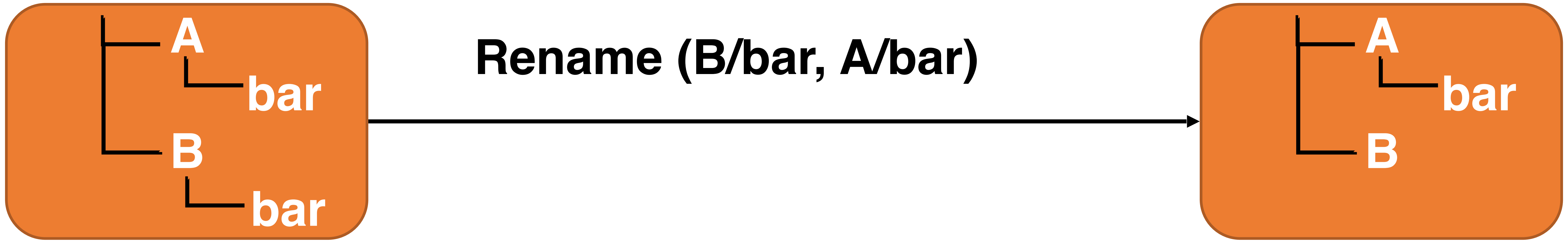
Metadata Corruption



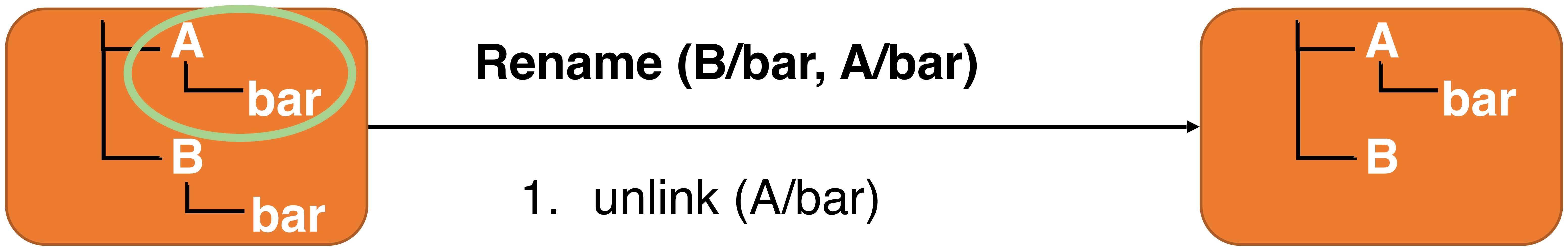
Data Corruption

Unmountable FS

What just happened?

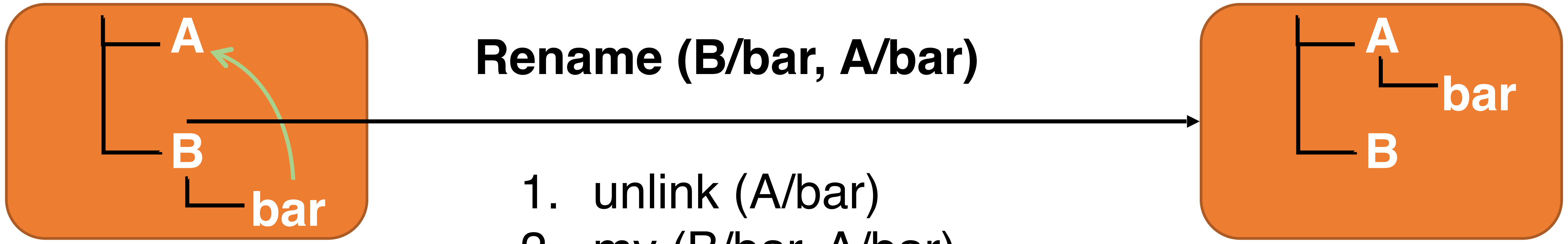


What just happened?



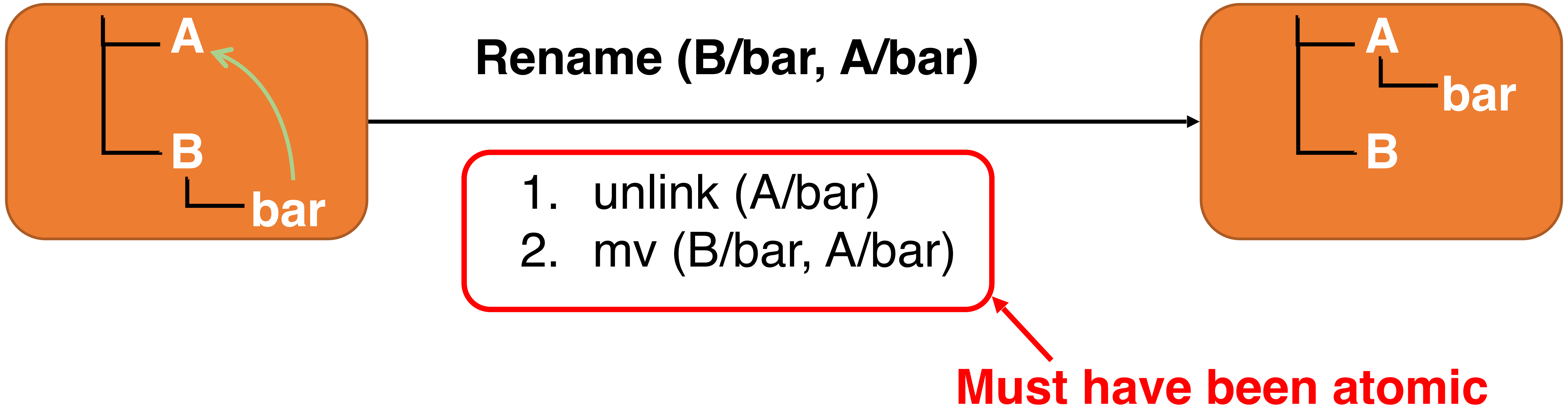
1. unlink (A/bar)

What just happened?



1. unlink (A/bar)
2. mv (B/bar, A/bar)

What just happened?



mkdir (A)
touch (A/bar)
fsync (A/bar)
mkdir (B)
touch (B/bar)
rename (B/bar, A/bar)
touch (A/foo)
fsync (A/foo)
CRASH!

- fsync(A/foo) commits tx that unlinks A/bar
- Which means step 1 above is persisted, but rename is not persisted
- **End up losing file A/bar**
- Exists in the kernel since 2014

Study of crash consistency bugs in the wild

- Study the workload pattern and impacts of crash consistency bugs reported in the **past 5 years**
  - Kernel mailing lists
  - Crash consistency tests submitted to xfstests

- **26 unique bugs** across ext4, F2FS, and btrfs

Study of crash consistency bugs in the wild

Consequence	# bugs
Corruption	17
Data inconsistency	6
Unmountable FS	3
Total	**26**

Filesystem	# bugs
Ext4	2
F2FS	2
btrfs	24
Total	**28**

# ops	# bugs
1	3
2	14
3	9
Total	**26**

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1. Crash consistency bugs are hard to find

- Bugs have been around in the kernel for up to 7 years before being identified and patched
- Usually involve reuse of files/ directories

Study of crash consistency bugs in the wild

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2	14
3	9
Total	**26**

1. Crash consistency bugs are hard to find
2. **Small workloads are sufficient to reveal bugs**
    - 2-3 core operations on a new, empty file-system

Study of crash consistency bugs in the wild

Consequence	# bugs
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Data inconsistency	6
Unmountable FS	3
Total	**26**

Filesystem	# bugs
Ext4	2
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Total	**28**

# ops	# bugs
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2	14
3	9
Total	**26**

1. Crash consistency bugs are hard to find
2. Small workloads are sufficient to reveal bugs
3. **Crash after persistence points**
   - Sufficient to crash after a call to fsync(), fdatasync(), or sync()

Study of crash consistency bugs in the wild

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Data inconsistency	6
Unmountable FS	3
Total	**26**

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1. Crash consistency bugs are hard to find
2. Small workloads are sufficient to reveal bugs
3. Crash after persistence points
4. **Systematic testing is required**

Study of crash consistency bugs in the wild

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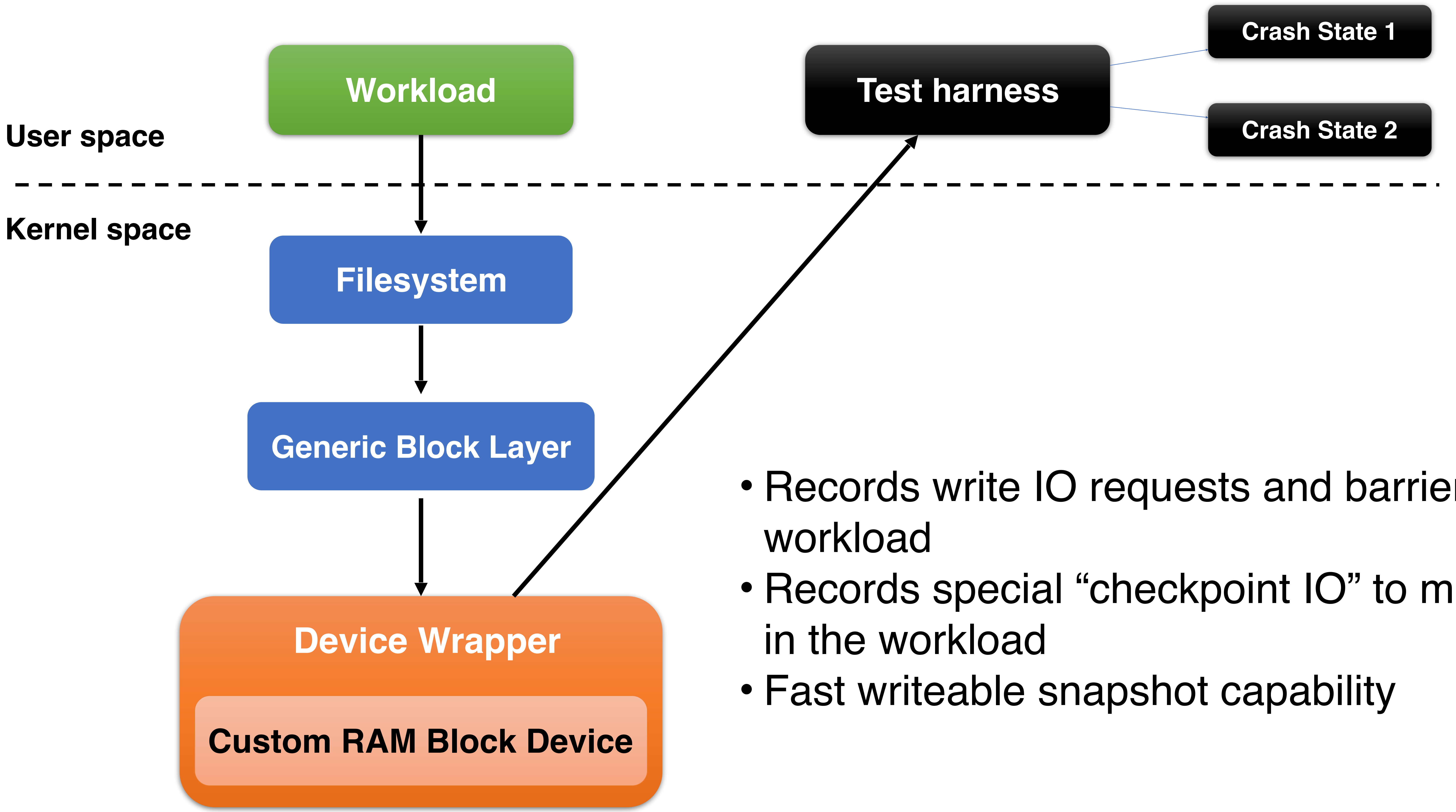
1. Crash consistency bugs are hard to find
2. Small workloads are sufficient to reveal bugs
3. Crash after persistence points
4. **Systematic testing is required**

Fallocate : punch_hole : 2015

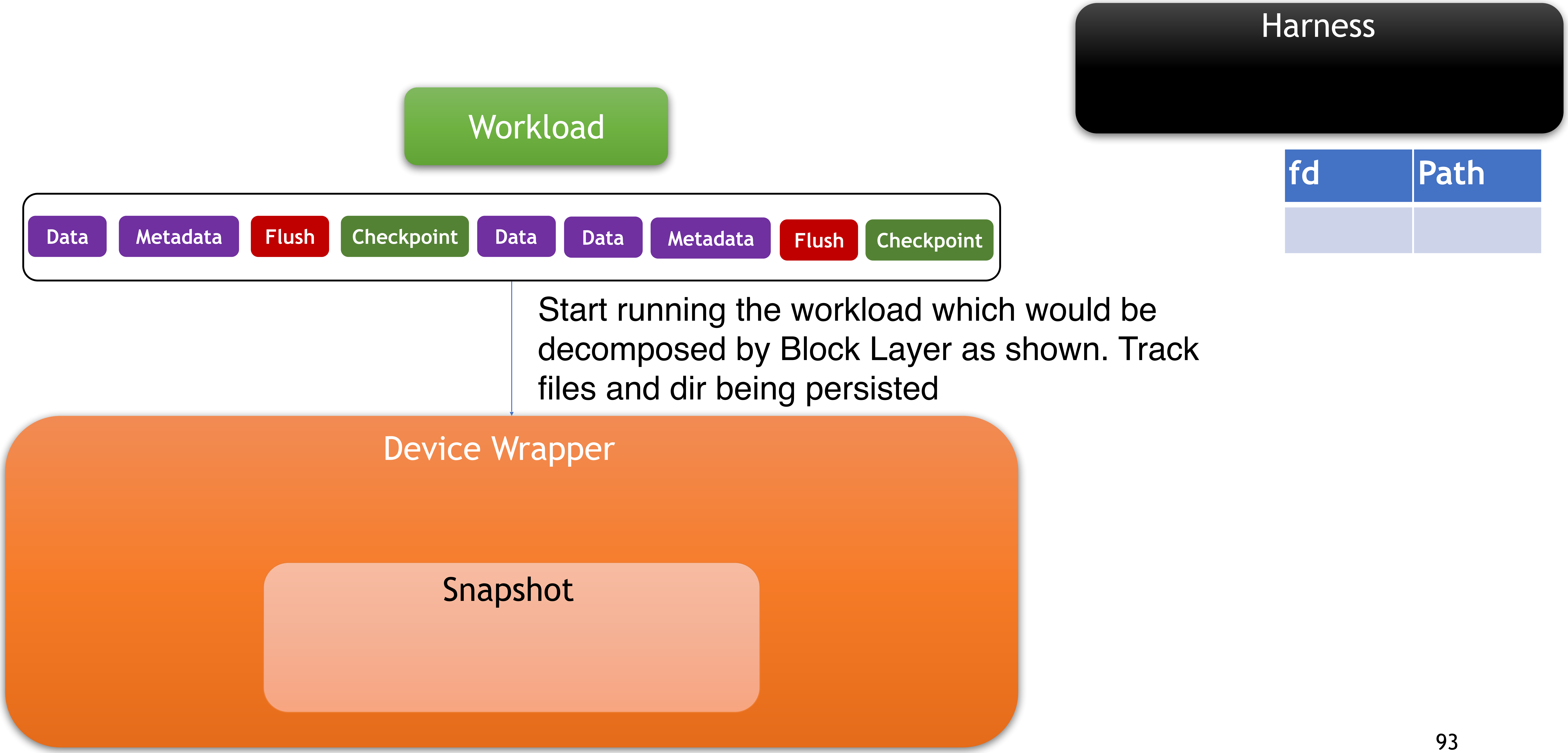
Fallocate : zero_range : 2018

CrashMonkey Internals



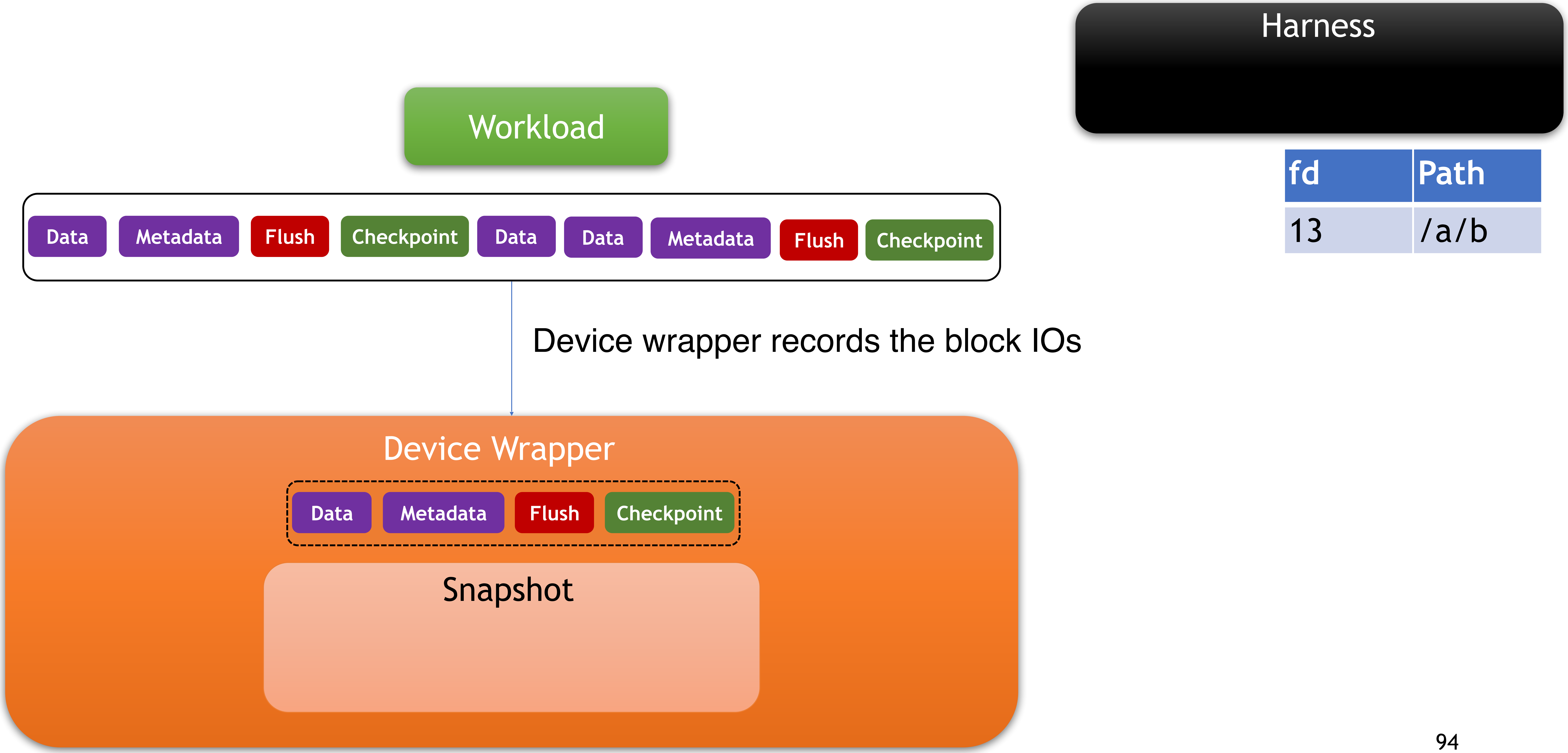
- Records write IO requests and barriers (flush/FUA) in the workload
- Records special “checkpoint IO” to mark persistence points in the workload
- Fast writeable snapshot capability

CrashMonkey in Action



Start running the workload which would be decomposed by Block Layer as shown. Track files and dir being persisted

CrashMonkey in Action : Profiling

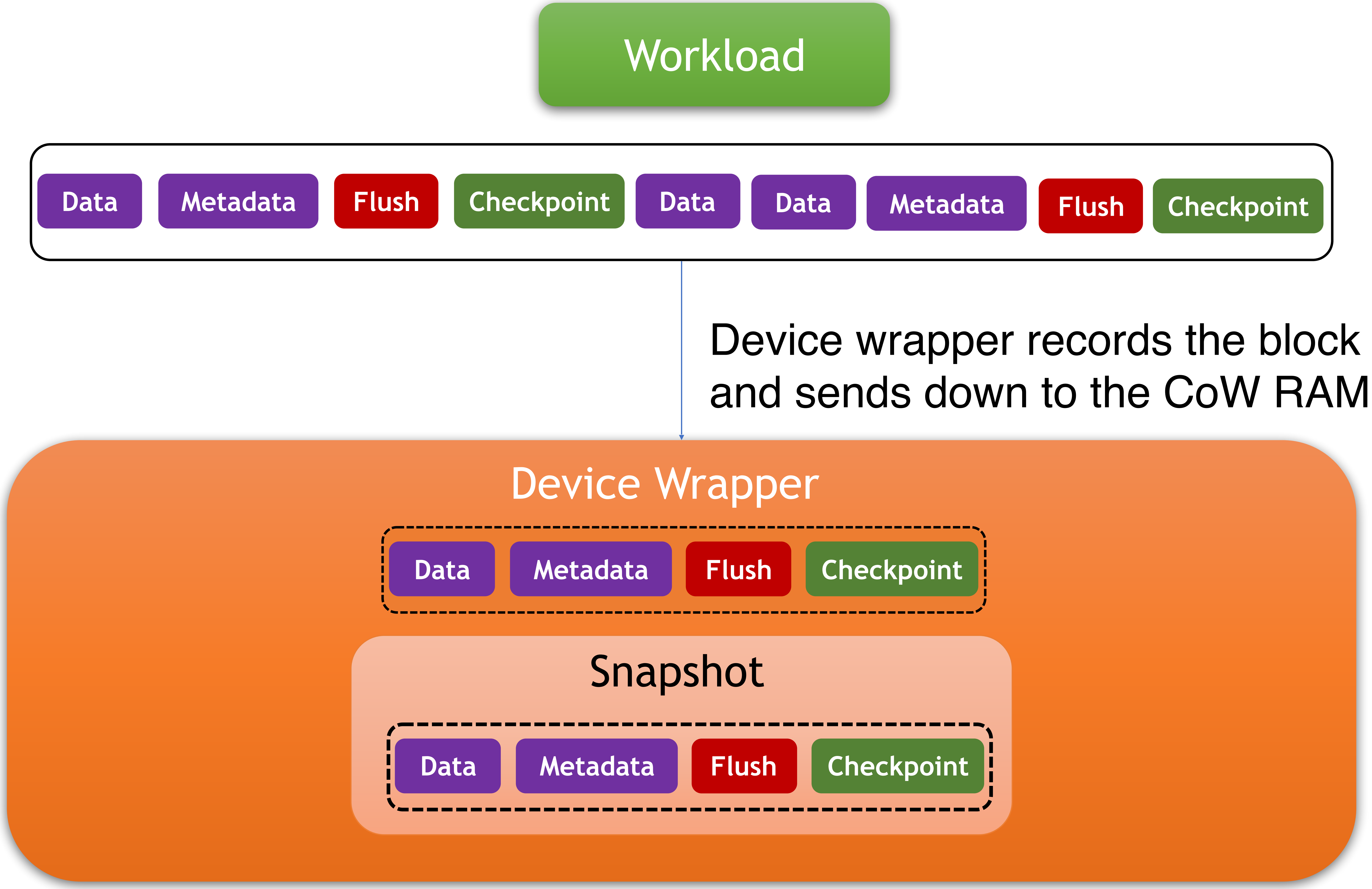


fd	Path
13	/a/b

CrashMonkey in Action : Profiling

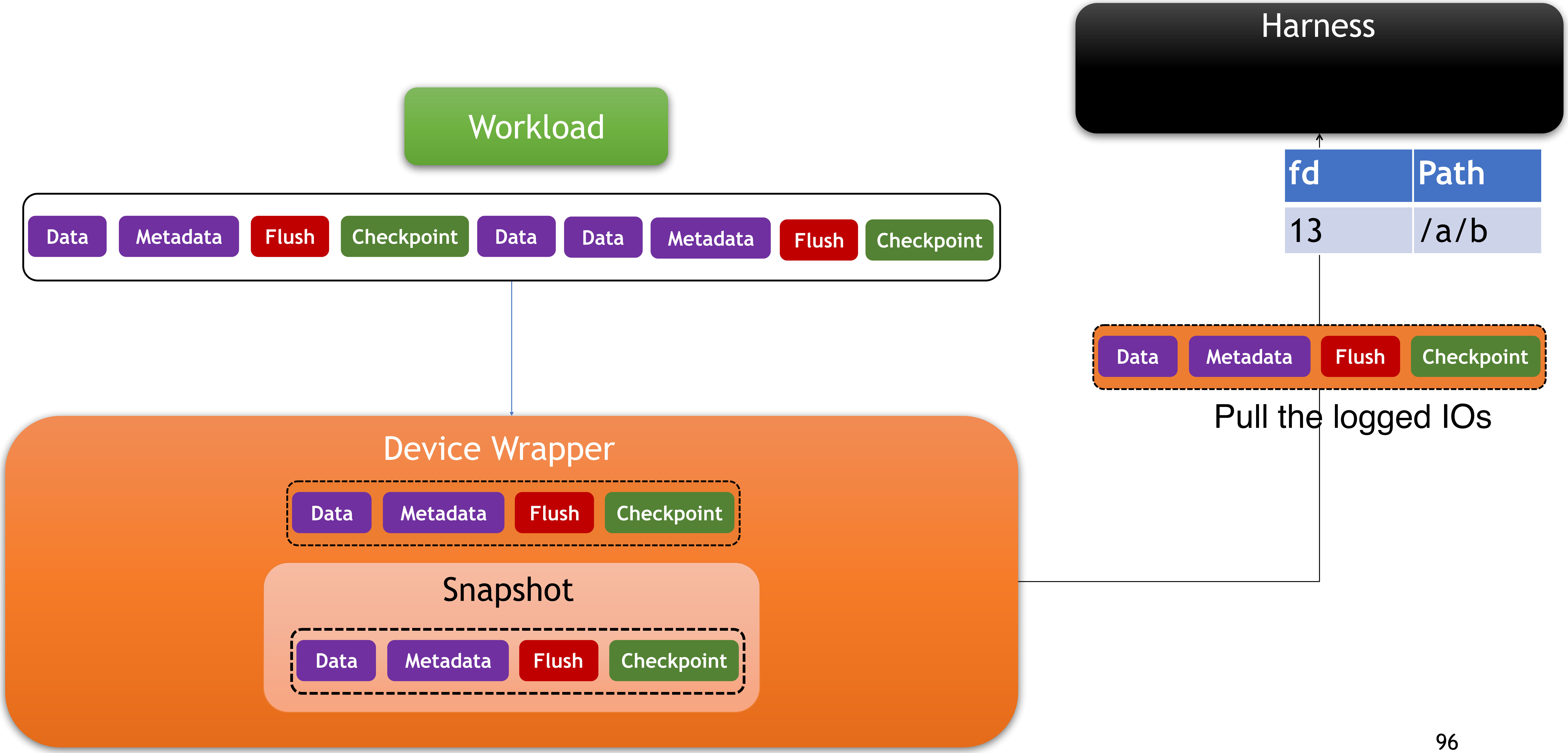
Harness

fd	Path
13	/a/b

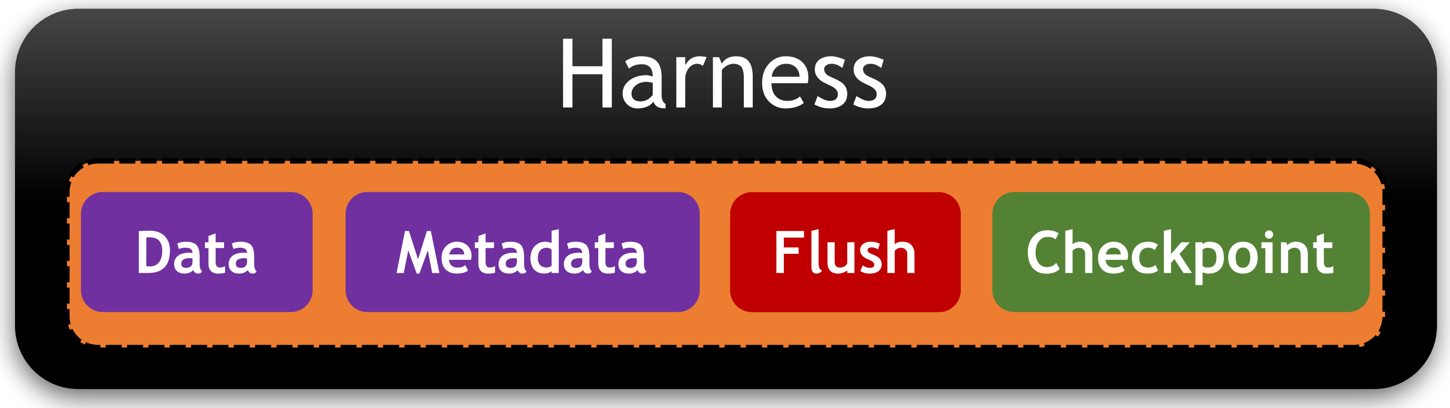


Device wrapper records the block IOs and sends down to the CoW RAM device

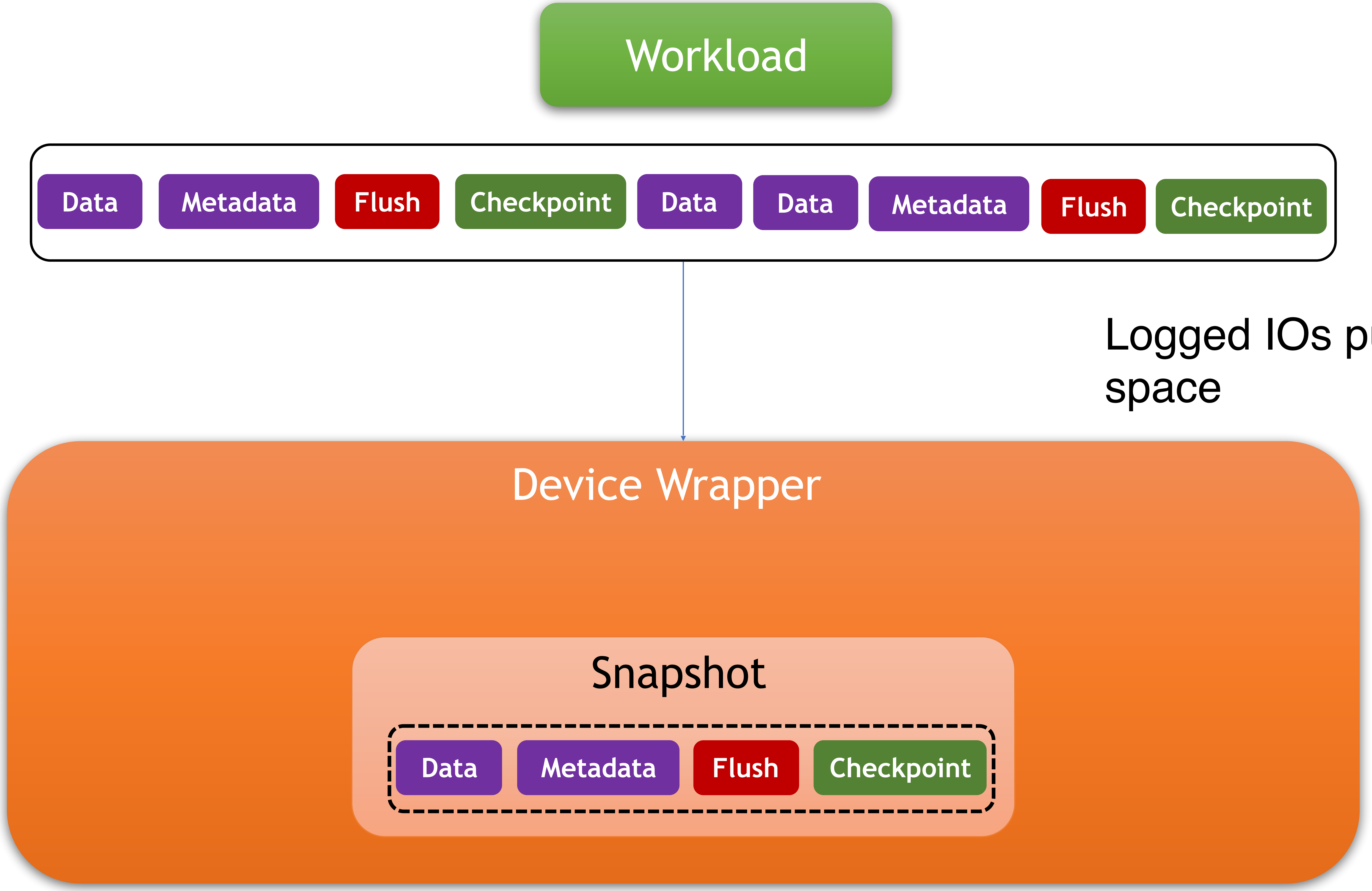
CrashMonkey in Action : Profiling



CrashMonkey in Action : Profiling

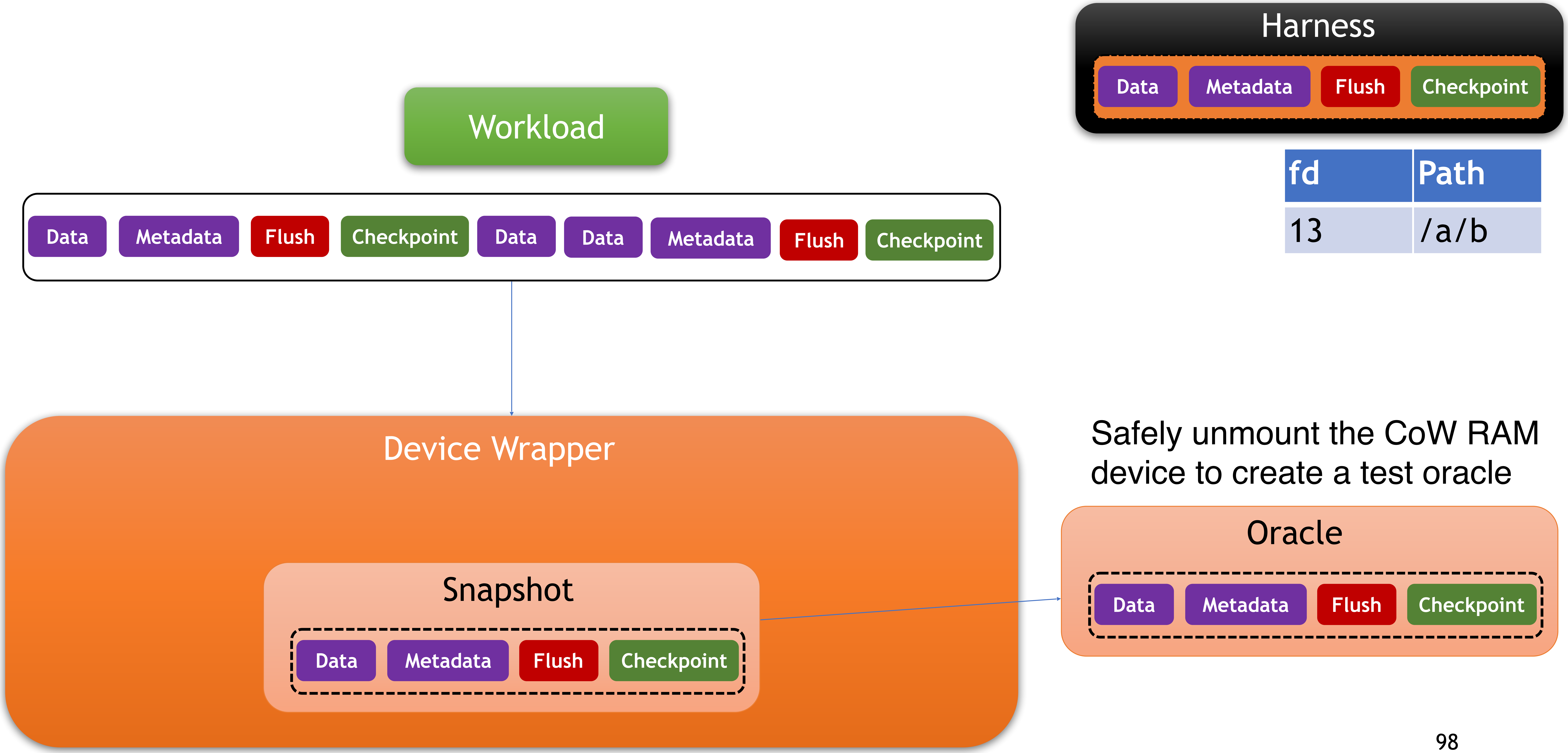


fd	Path
13	/a/b

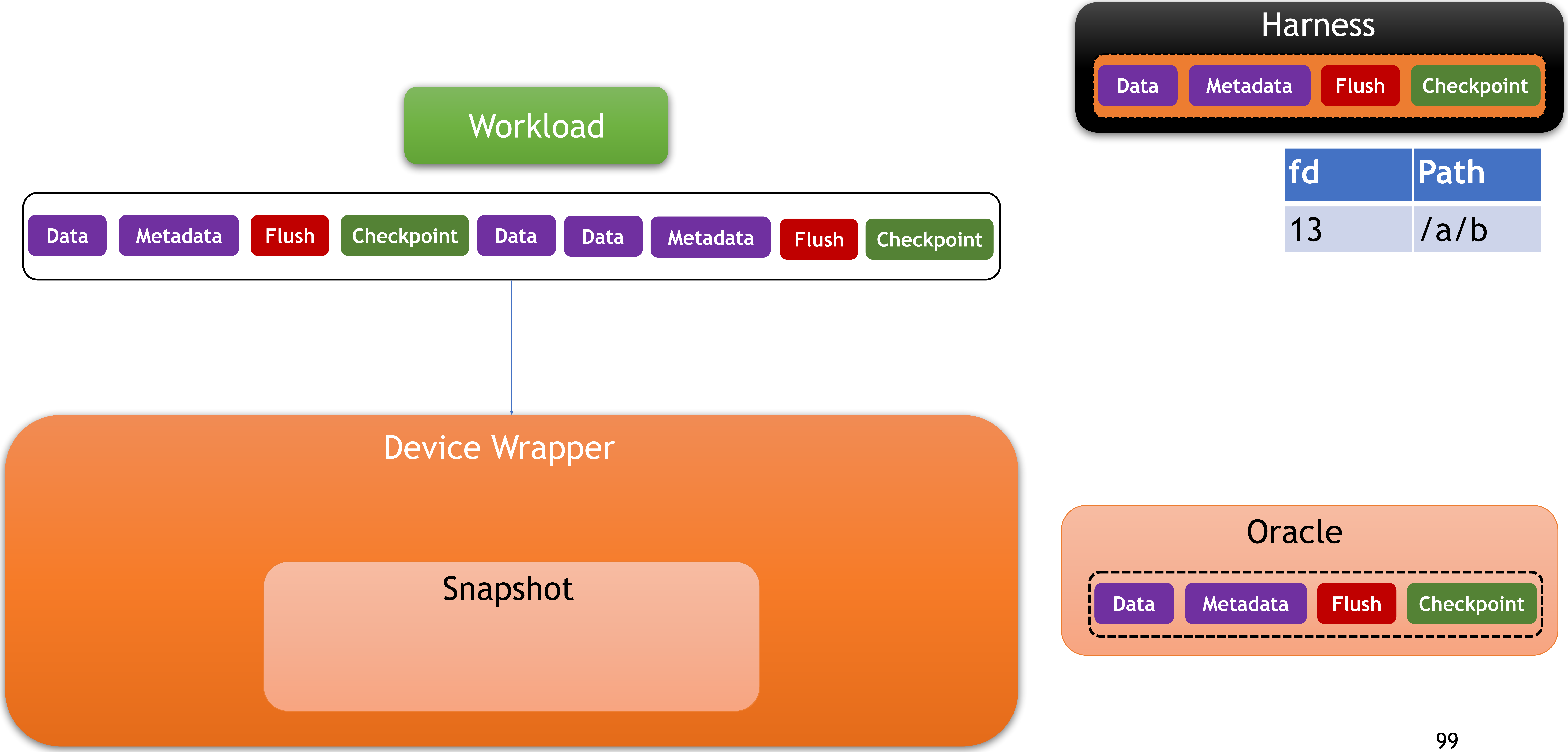


Logged IOs pulled to the user space

CrashMonkey in Action : Profiling

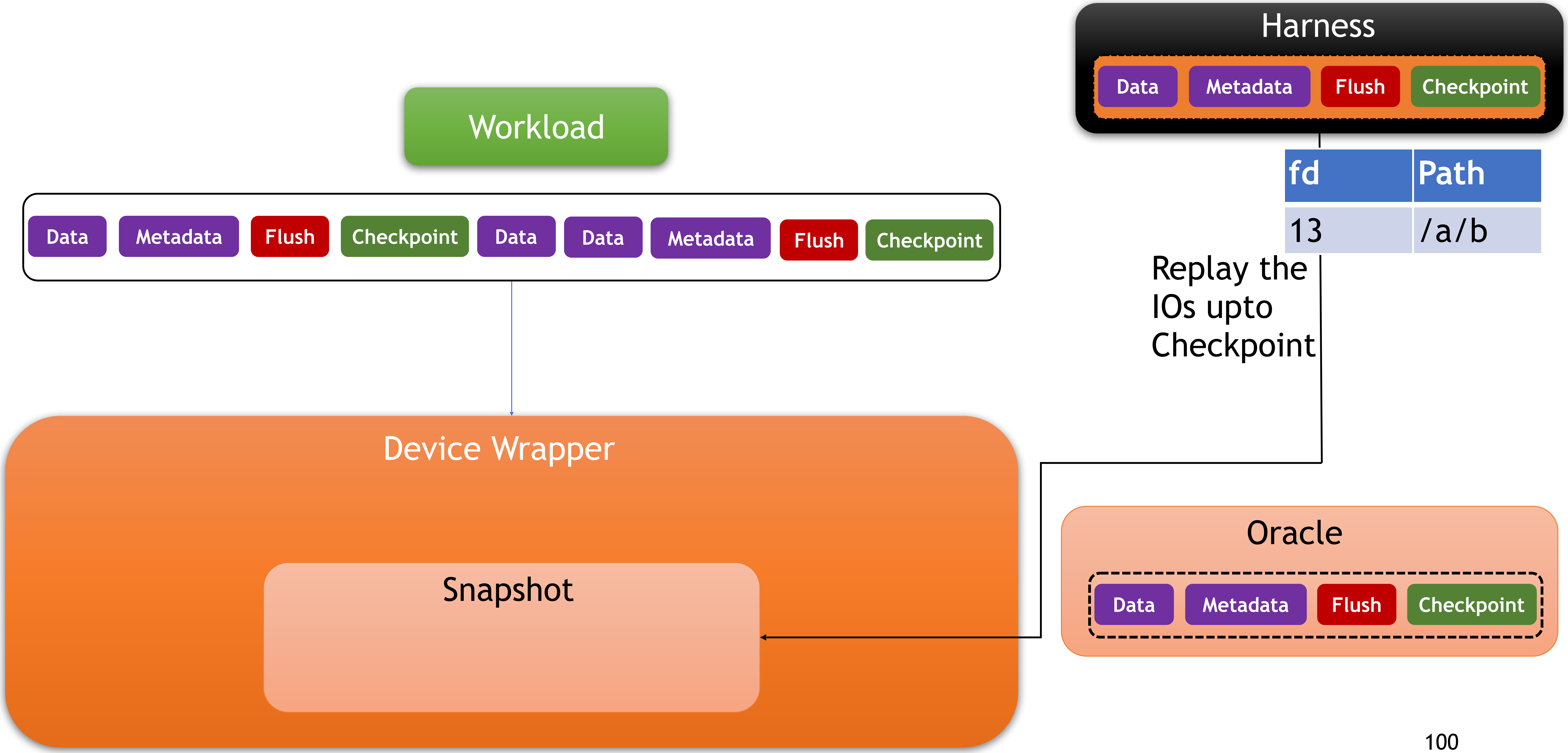


CrashMonkey in Action : Profiling

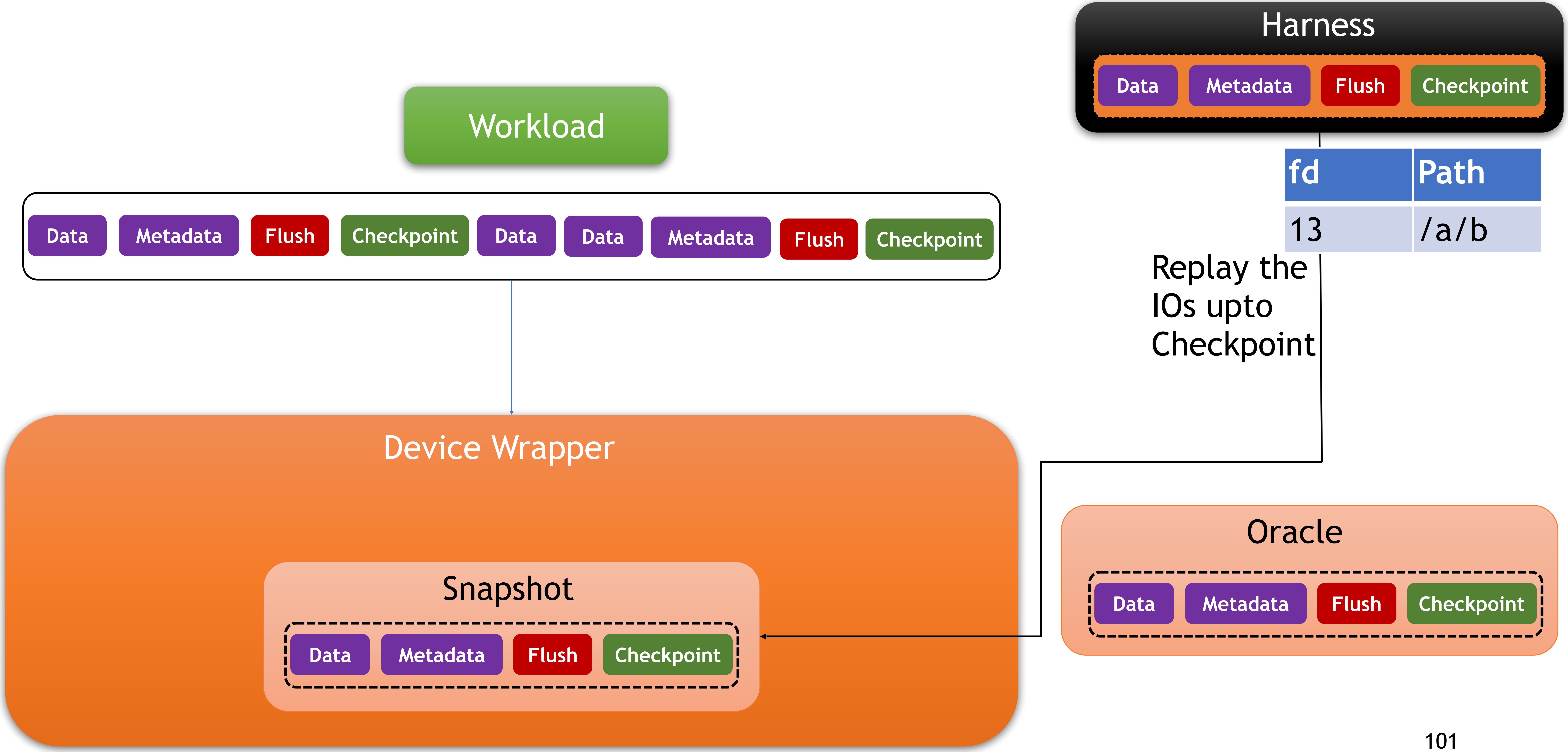


fd	Path
13	/a/b

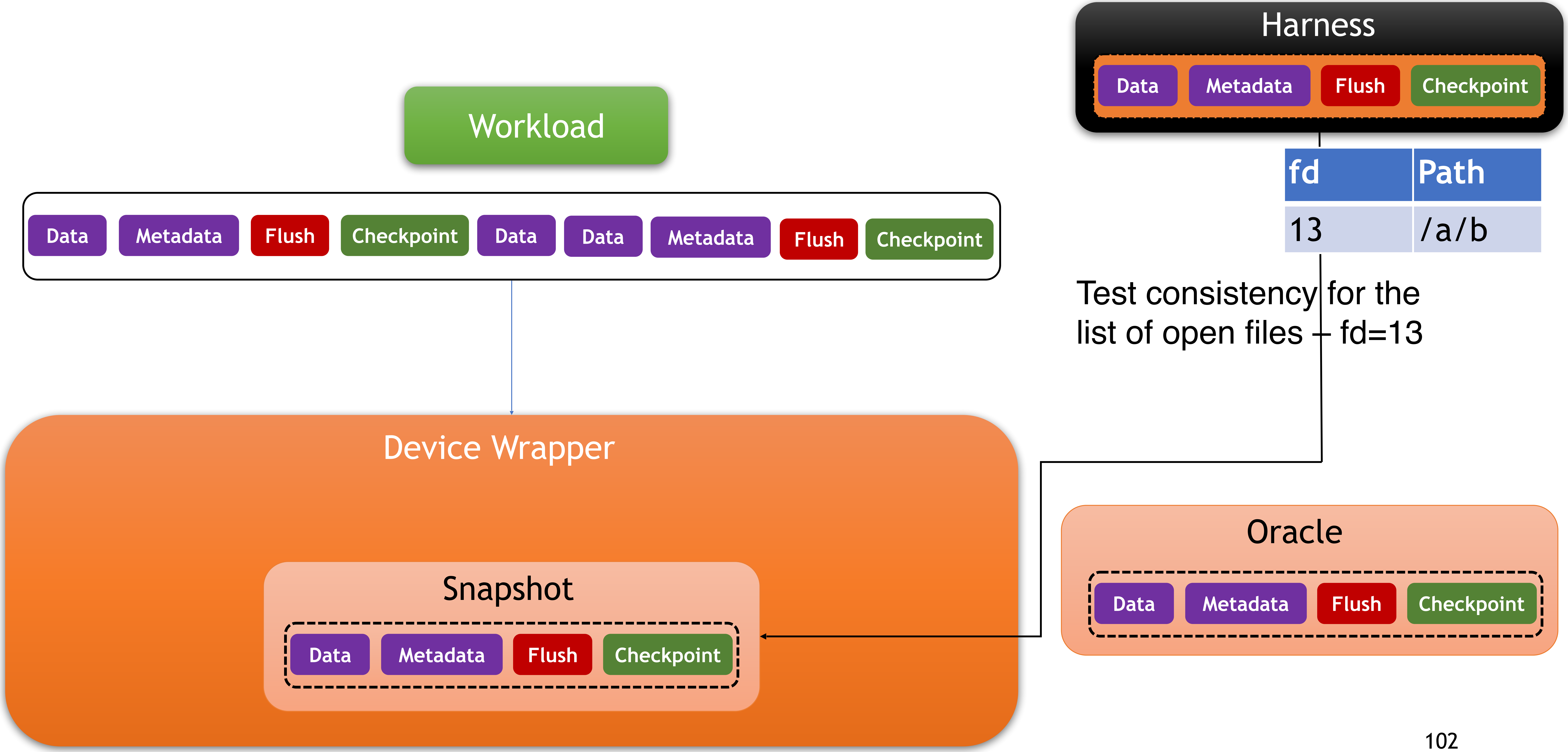
CrashMonkey in Action : Replay



CrashMonkey in Action : Replay



CrashMonkey in Action : Testing



Test consistency for the list of open files – fd=13

Testing Strategy to find new bugs

- We test seq-1, seq-2 workloads on all filesystems : ext4, xfs, f2fs, btrfs
- We run all other workloads on btrfs and F2FS first.
  - For every workload that generated a bug, we run it on all other FS

- To run all workloads upto seq-3, you need to dedicate 2 days of compute per filesystem with (testing in parallel on 780 VM)

Results at a glance

Sequence Length	# workloads	# Bugs Reproduced	# Bugs found
Seq-1			
Seq-2			
Seq-3 metadata			
Seq-3 data			
Seq-3 nested			
Total			

- 25 million workloads
- Needs 15 days of testing on 780 VMs in parallel!

Results at a glance

Sequence Length	# workloads	# Bugs Reproduced	# Bugs found
Seq-1	300	3	3
Seq-2	254K	14	3
Seq-3 metadata	120K	5	2
Seq-3 data	1.5M	2	0
Seq-3 nested	1.5M	2	2
Total	3.37M	26	10