# Chipmunk: Investigating Crash-Consistency in Persistent-Memory File Systems

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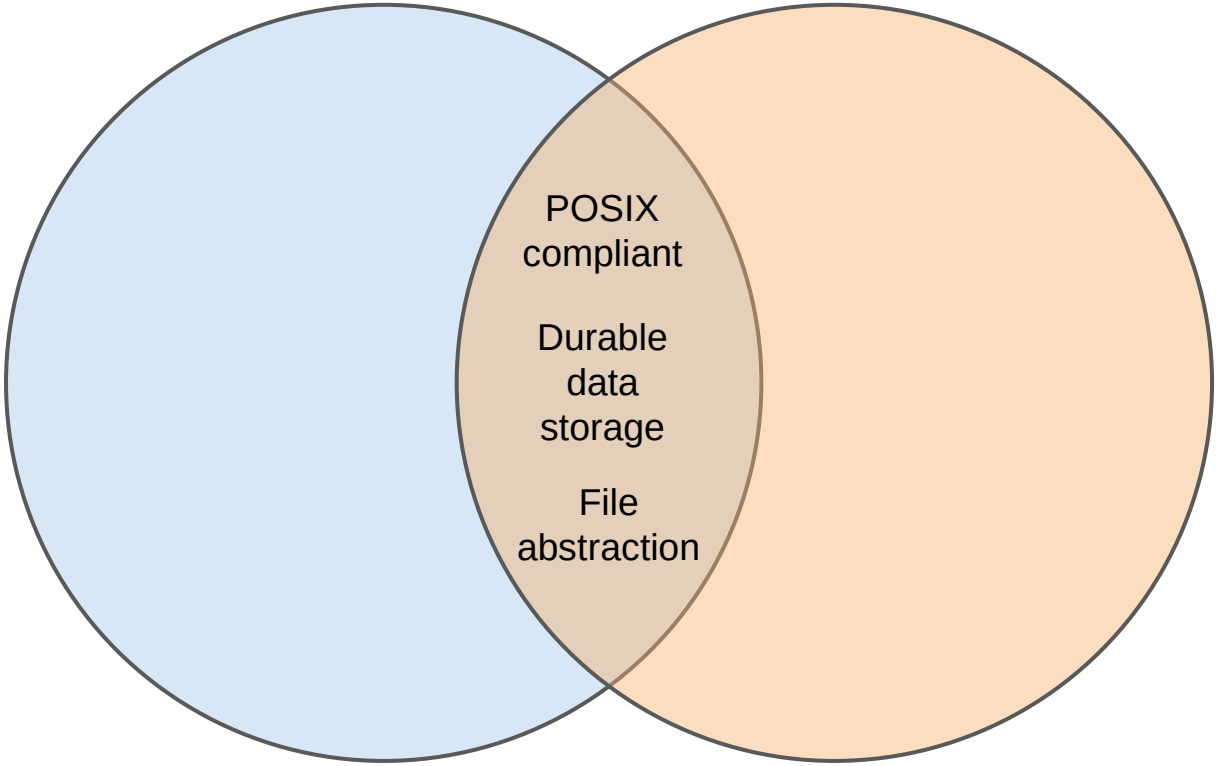
TEXAS
The University of Texas at Austin

vmware®

# File systems




Traditional FSes (HDD, SSD)

Persistent memory (PM) FSes

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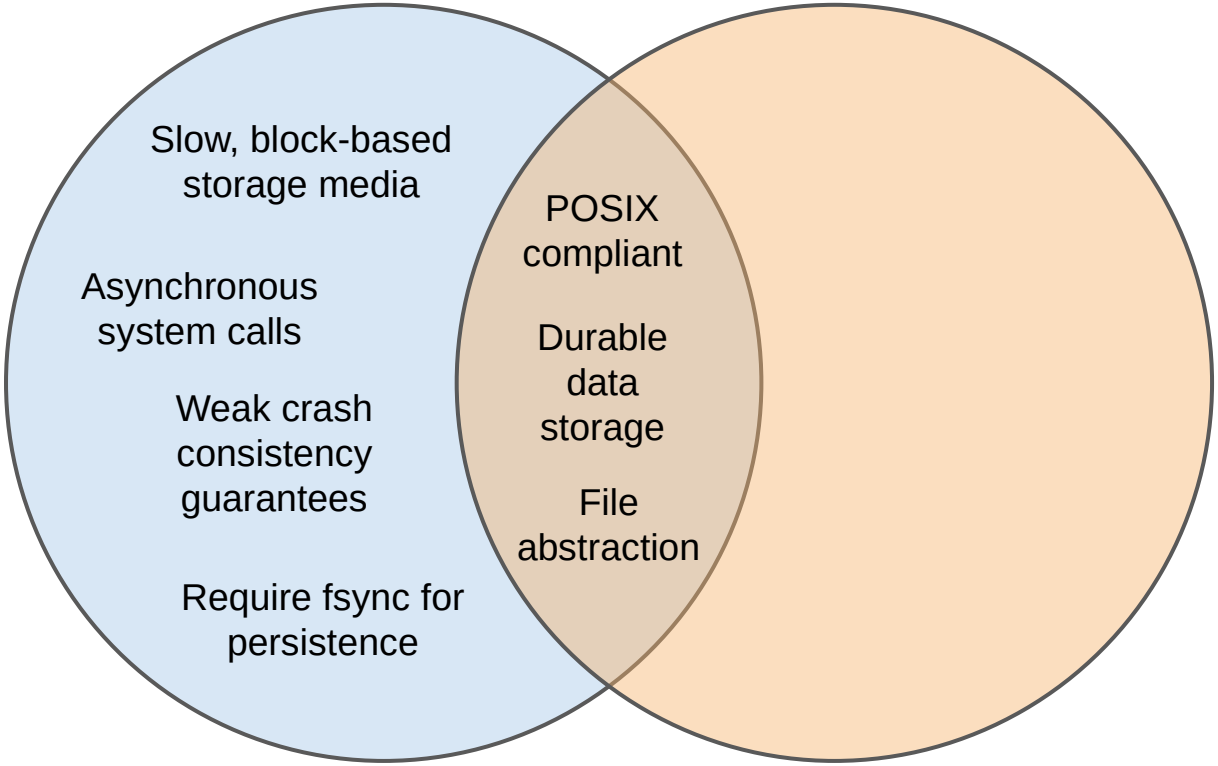


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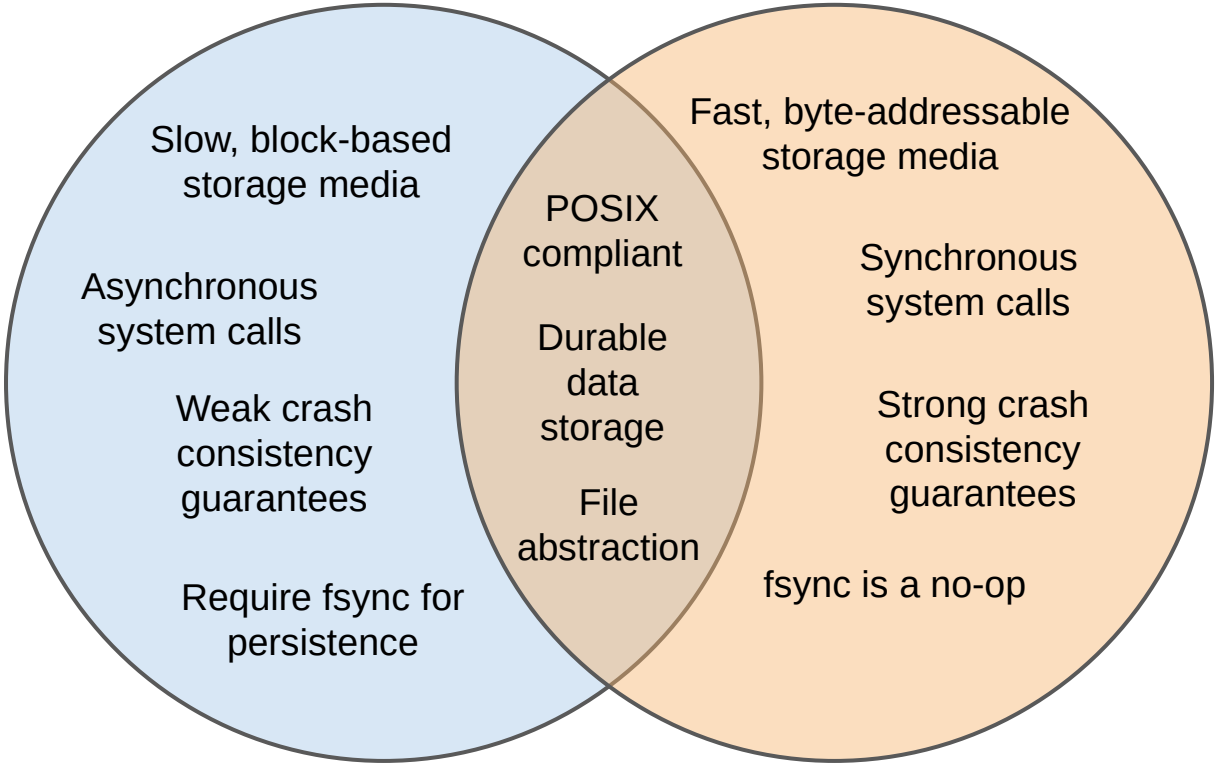


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**How do we test these new designs for crash consistency?**

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# Outline

1. Introduction
2. **Chipmunk overview**
3. Experiments and bugs
4. Observations and insights

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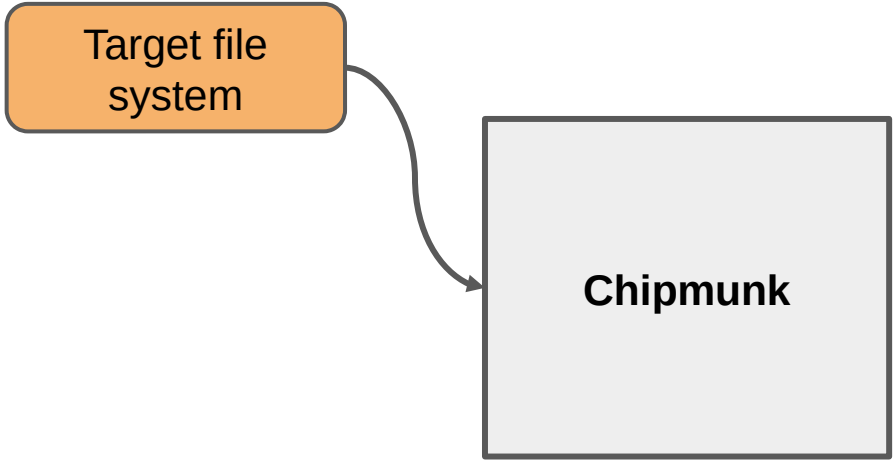

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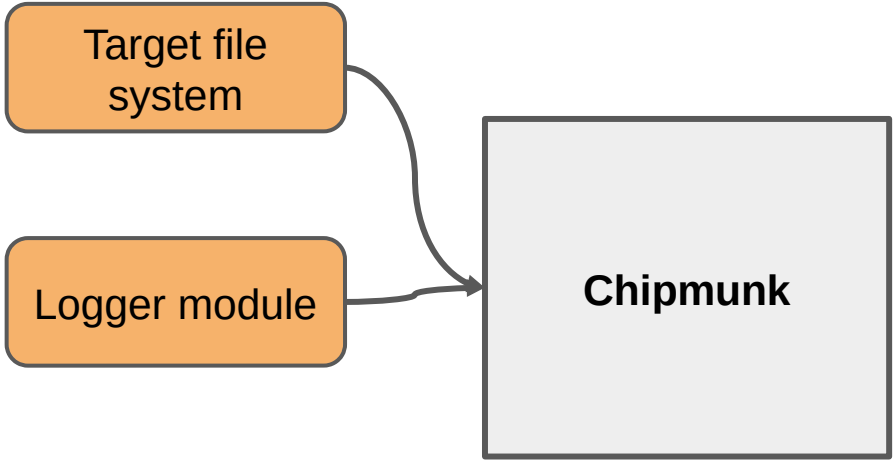

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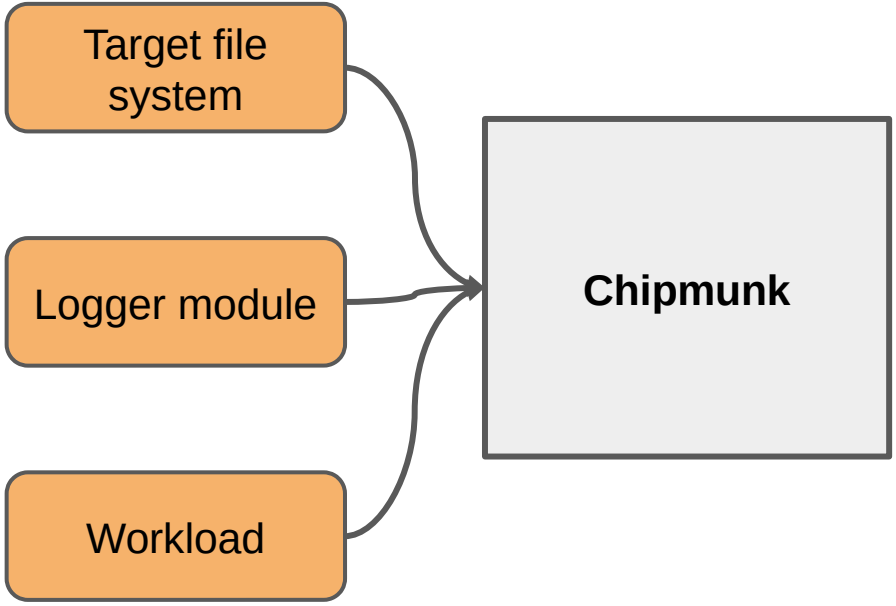

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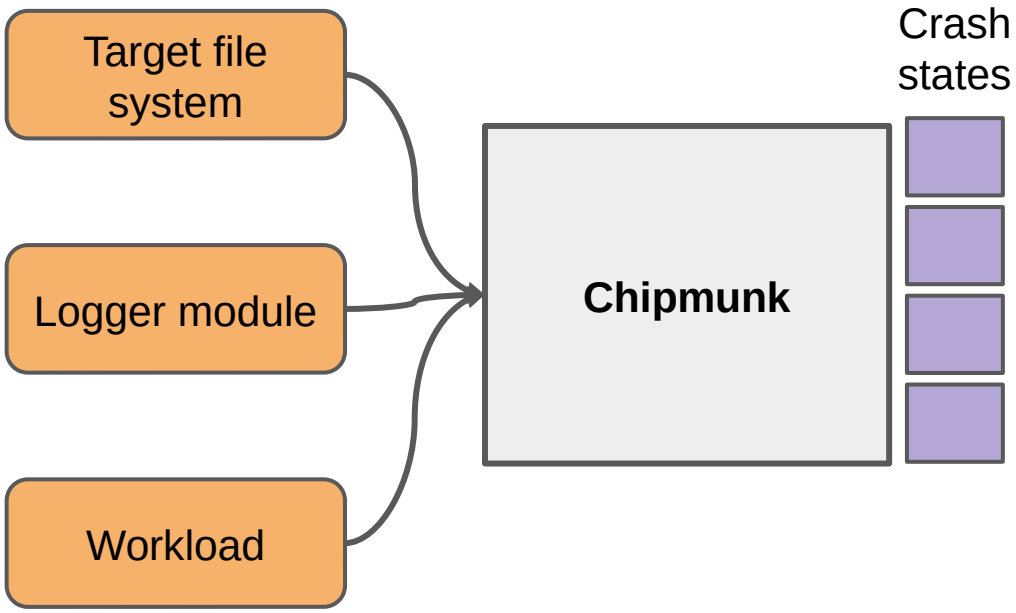

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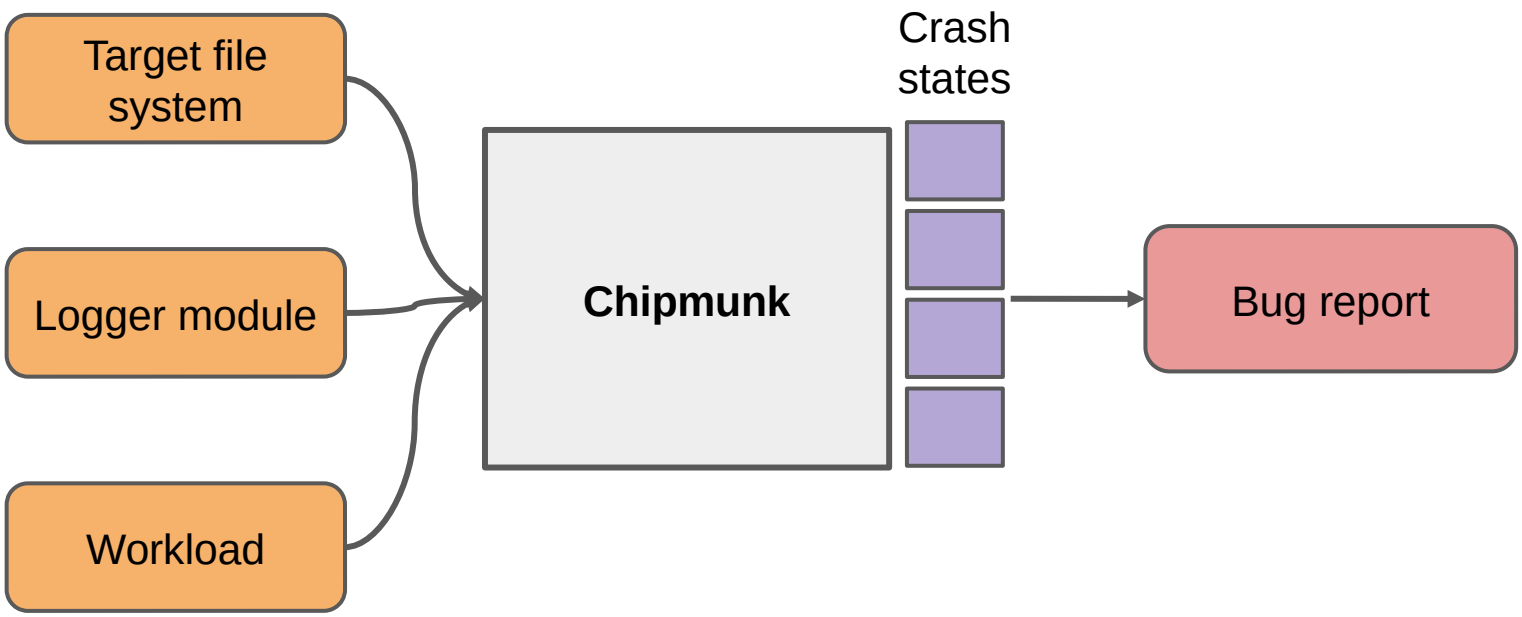

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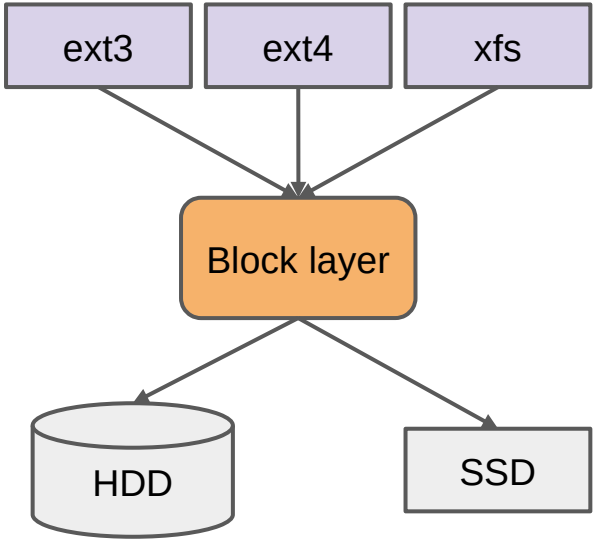

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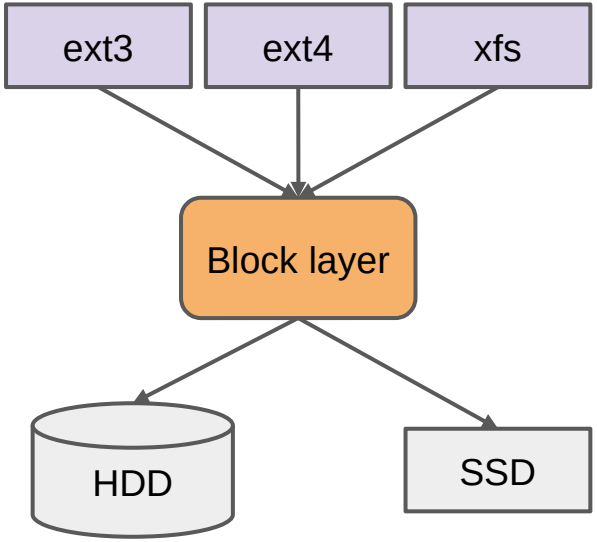


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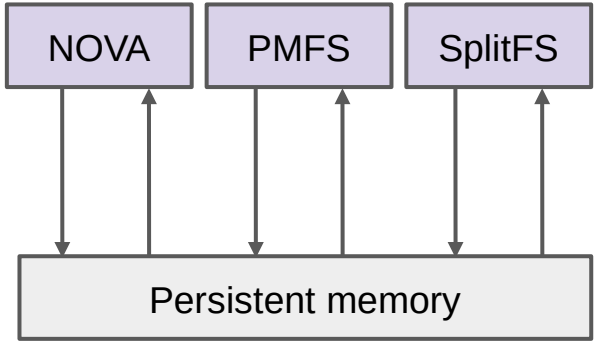

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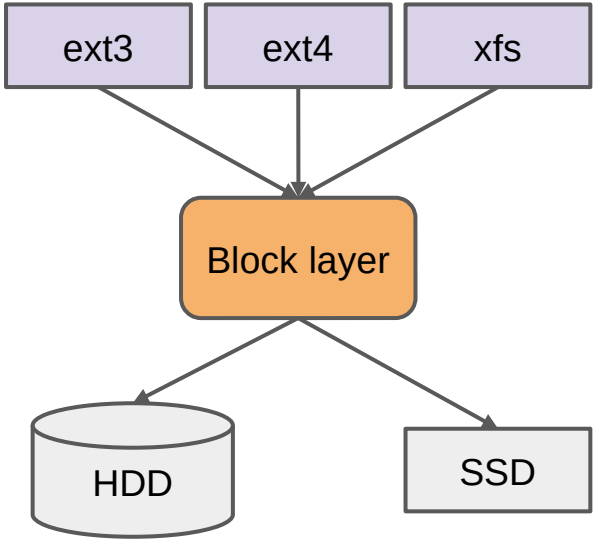


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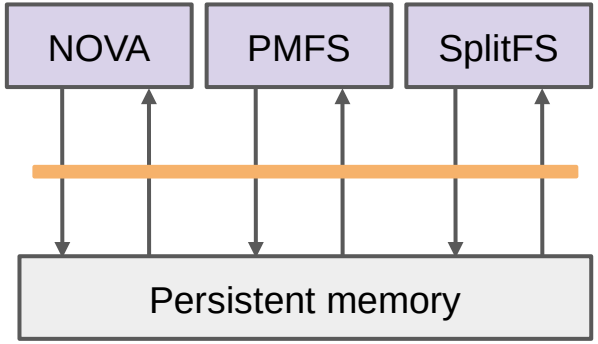

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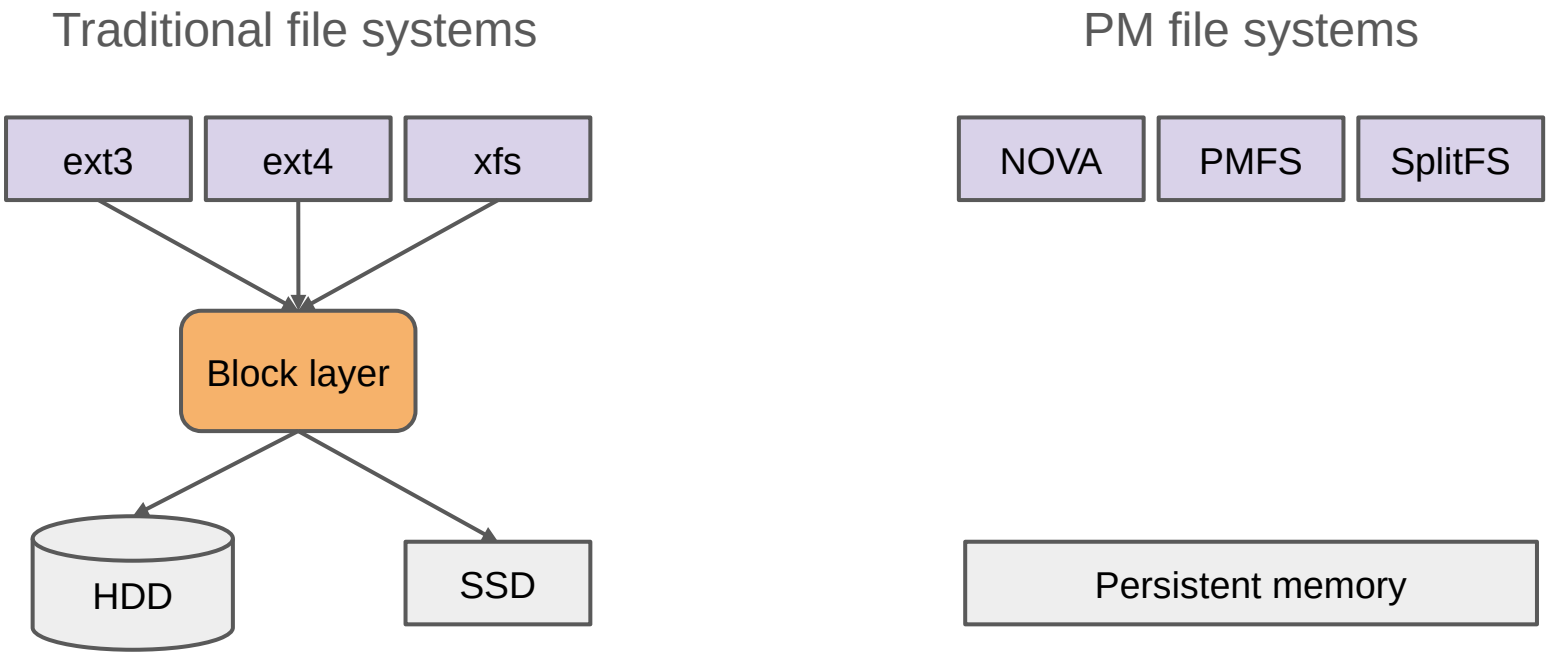

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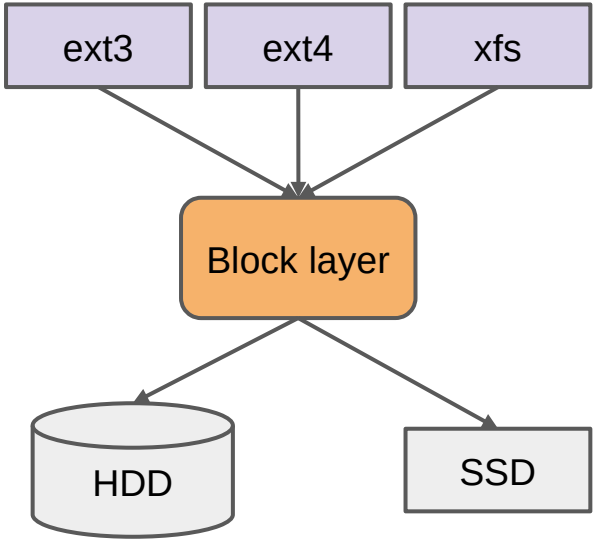
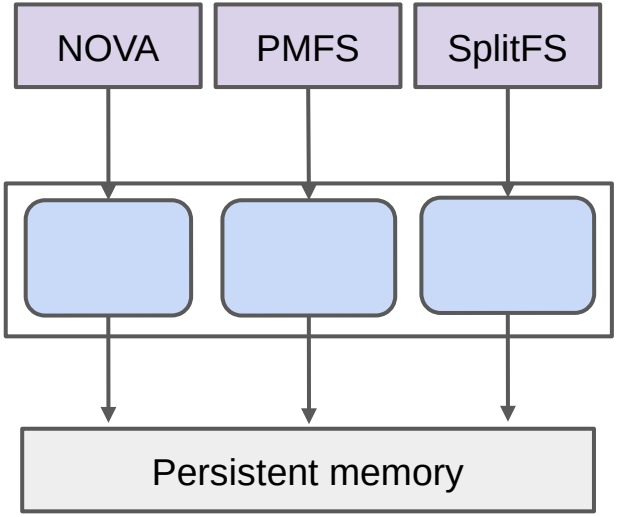



PM file systems

Centralized persistence functions



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- Tested **NOVA** (FAST ‘16), **NOVA-Fortis** (SOSP ‘17), **PMFS** (EuroSys ‘14), **SplitFS** (SOSP ‘19), **WineFS** (SOSP ‘21), ext4-DAX, xfs-DAX

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- Two workload generation techniques

1. **ACE**: systematic bounded test generator for file systems
2. **Syzkaller**: coverage-guided kernel fuzzer

# Bugs found by Chipmunk

**23 unique bugs found across 5 file systems**

- Make file system unmountable (3 bugs)
- Violate atomicity guarantees (5 bugs)
- Lose file data (6 bugs)
- Violate synchrony guarantees (3 bugs)
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**What can we learn from these bugs?**

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**Implication**: PM file system crash-consistency testing tools must check high-level consistency properties that cannot be validated at the level of individual writes

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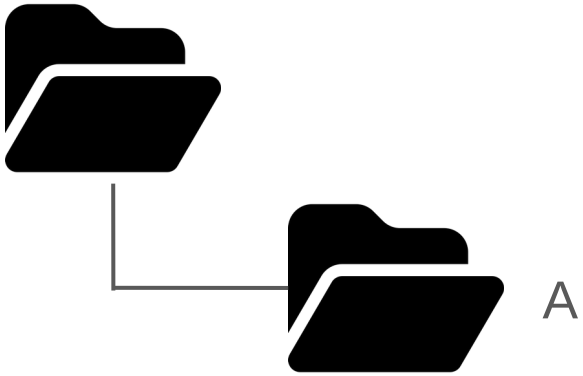

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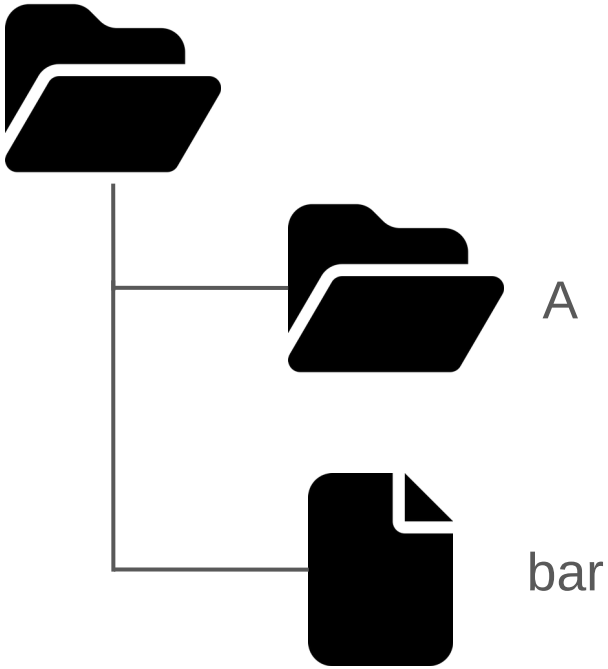

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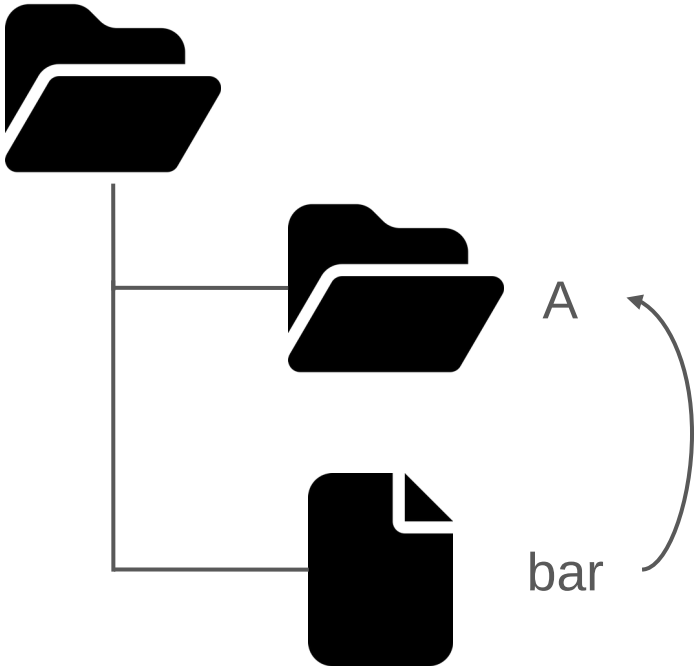

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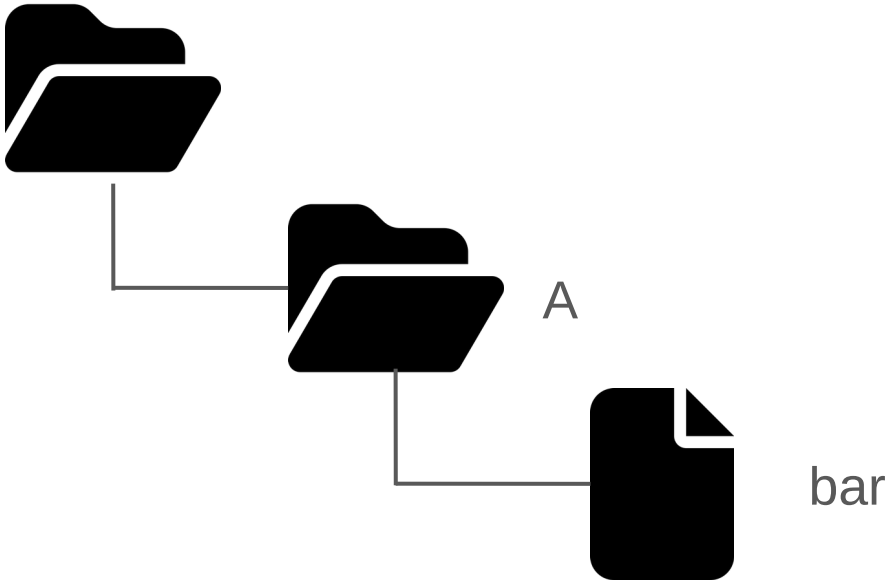

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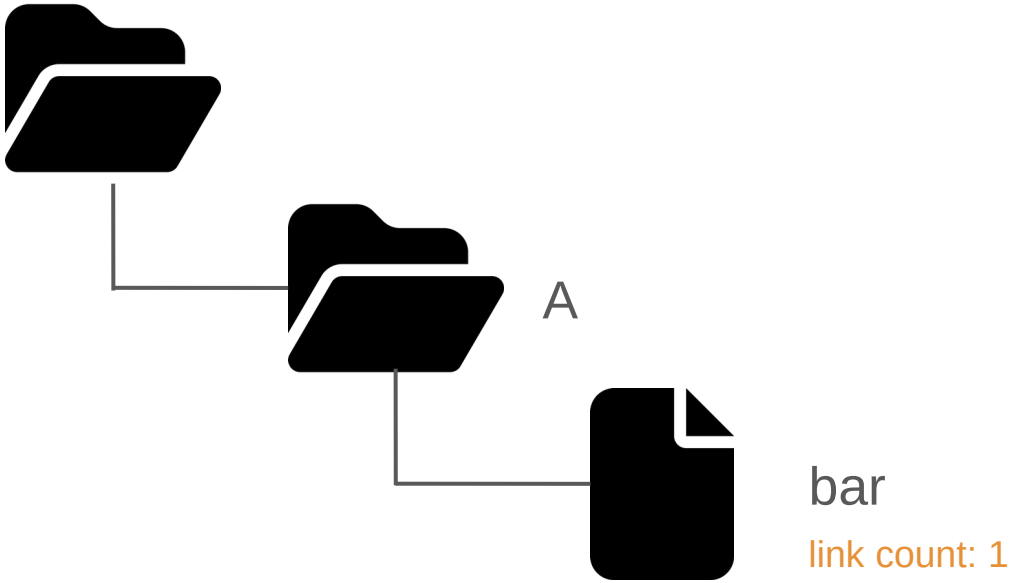

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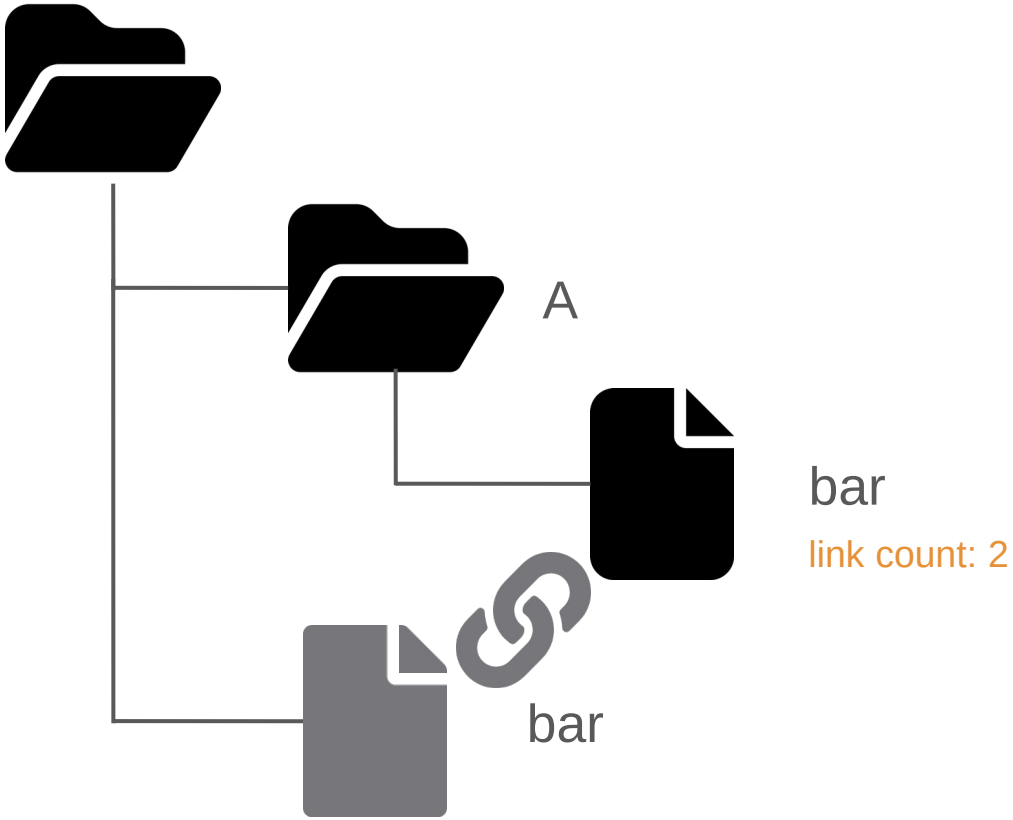

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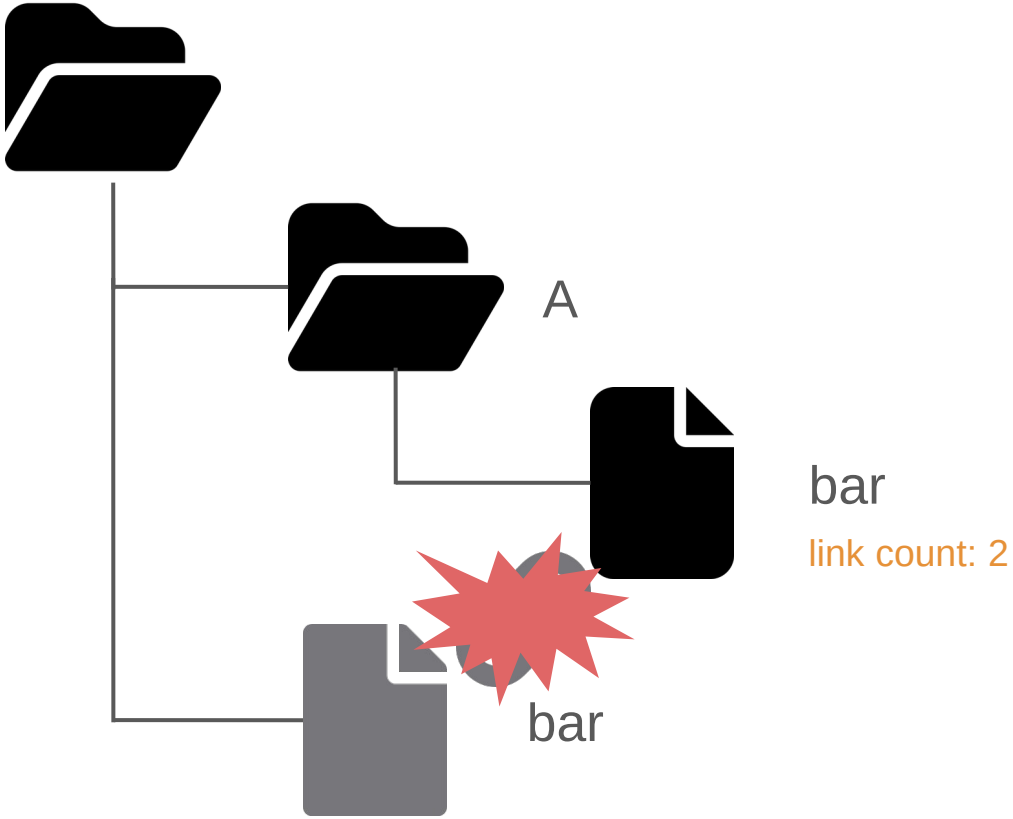

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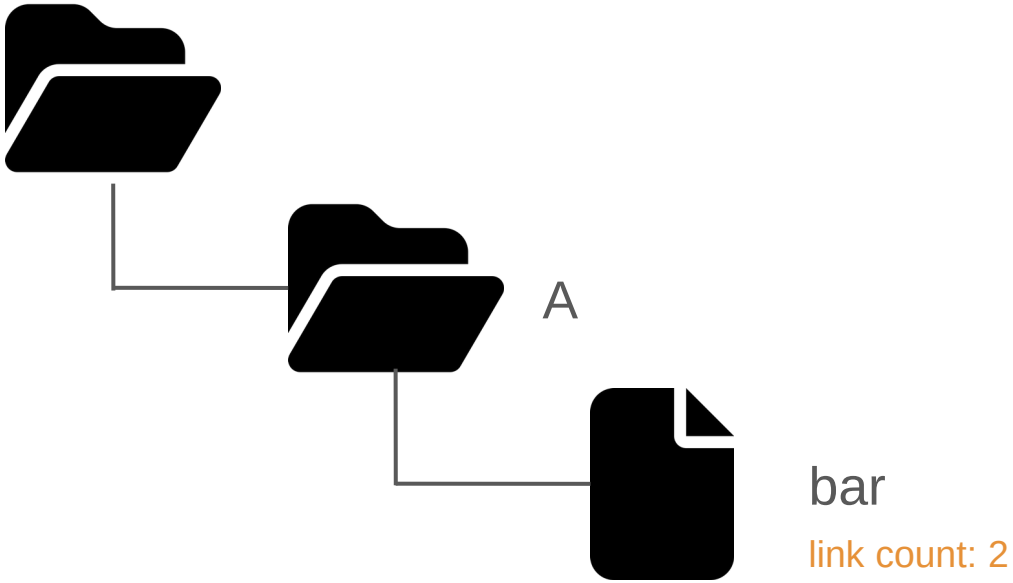

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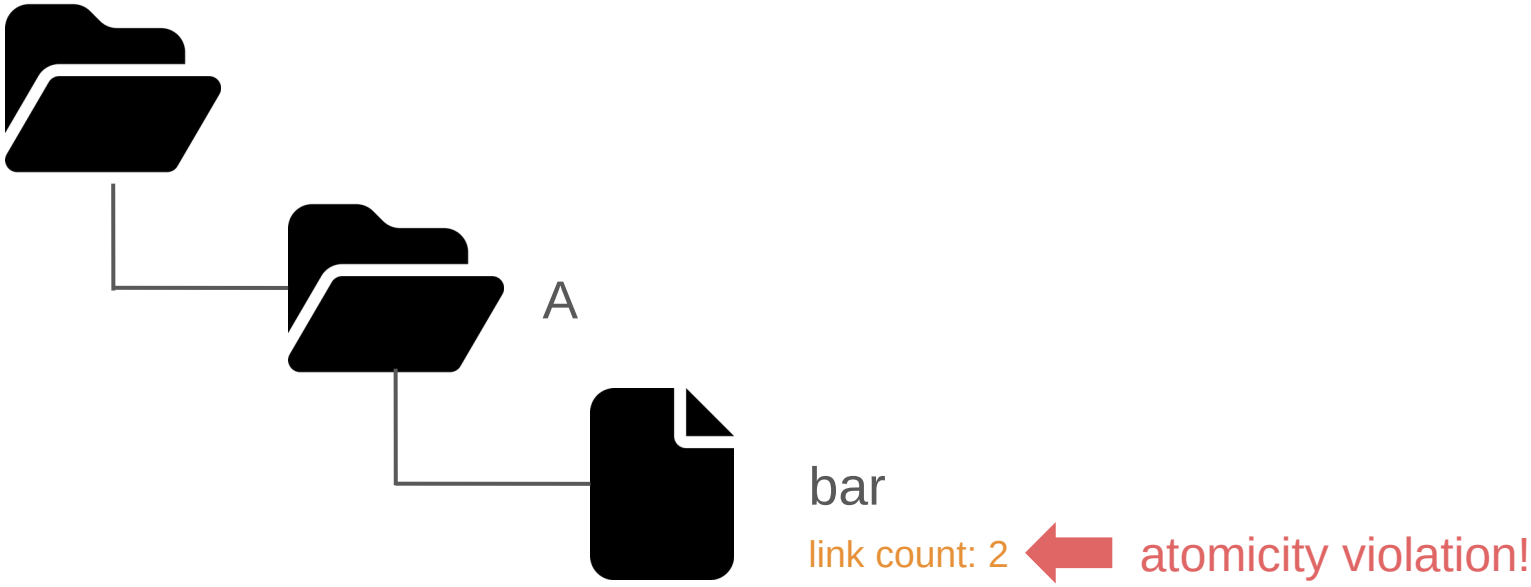

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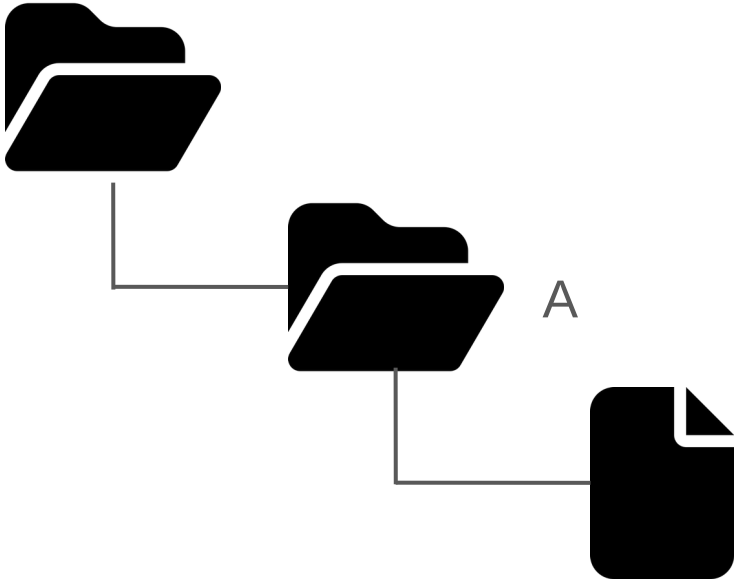


atomicity violation!

**Root cause: in-place update optimization to avoid journaling**

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**Implication**: In order to find all bugs, testing must cover a large number of intermediate crash states that are not checked by existing file system testing tools.

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**PM presents a deceptively simple interface for file system development and requires new tools to help build correct and performant systems**

# Conclusion

Chipmunk found **23 new bugs** across 5 PM file systems, many of which have severe consequences

Compatible with POSIX-compliant PM file systems in both user- and kernel-space

New insights into how to test PM file systems

Try Chipmunk: https://github.com/utsaslab/chipmunk

# Extra slides

# Related work: traditional file system testing

CrashMonkey (OSDI ‘18): black-box record-and-replay crash consistency testing framework

Hydra (SOSP ‘19): file system fuzzer focusing on crash consistency and POSIX violations

eXplode (OSDI ‘06): file system model checker focusing on crash consistency

# Related work: PM file system testing

Yat (ATC ‘14): hypervisor-based tester designed for PMFS

PMTest (ASPLOS ‘19): checks durability and ordering using developer-provided annotations

Vinter (ATC ‘22): hypervisor-based tester used to test NOVA and NOVA-Fortis

# Related work: PM application testing

Pmemcheck: Valgrind-based tool developed by Intel for use with their PMDK library

XFDetector (ASPLOS ‘20): focuses on finding “cross-failure bugs” involving regular and recovery code

Agamotto (OSDI ‘20): symbolic execution tool focusing on crash consistency

PMFuzz (ASPLOS ‘21): PM program fuzzer used with Pmemcheck and XFDetector

# Related work: PM application testing

Witcher (SOSP ‘21): PM key-value store tester for PM programming errors and “persistence atomicity violations”

PmDebugger (ASPLOS ‘21): tool for collecting and analyzing PM access traces

Durinn (OSDI ‘22): durable linearizability checker

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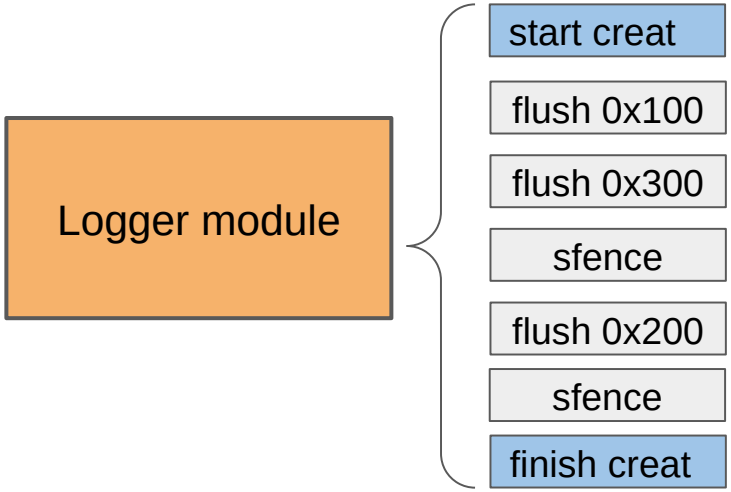


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recorded via Kprobes/Uprobes trigger on FS function

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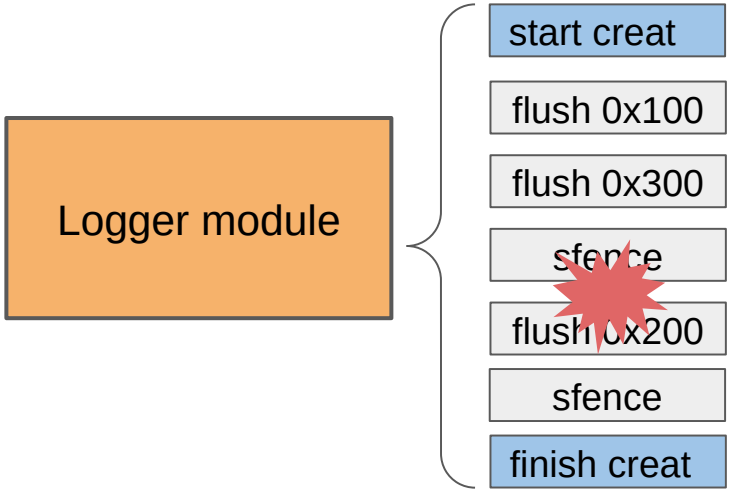


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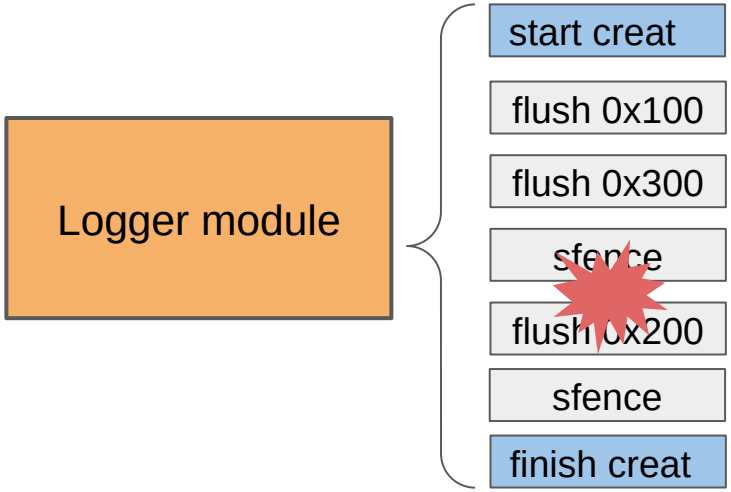


**Crash states**

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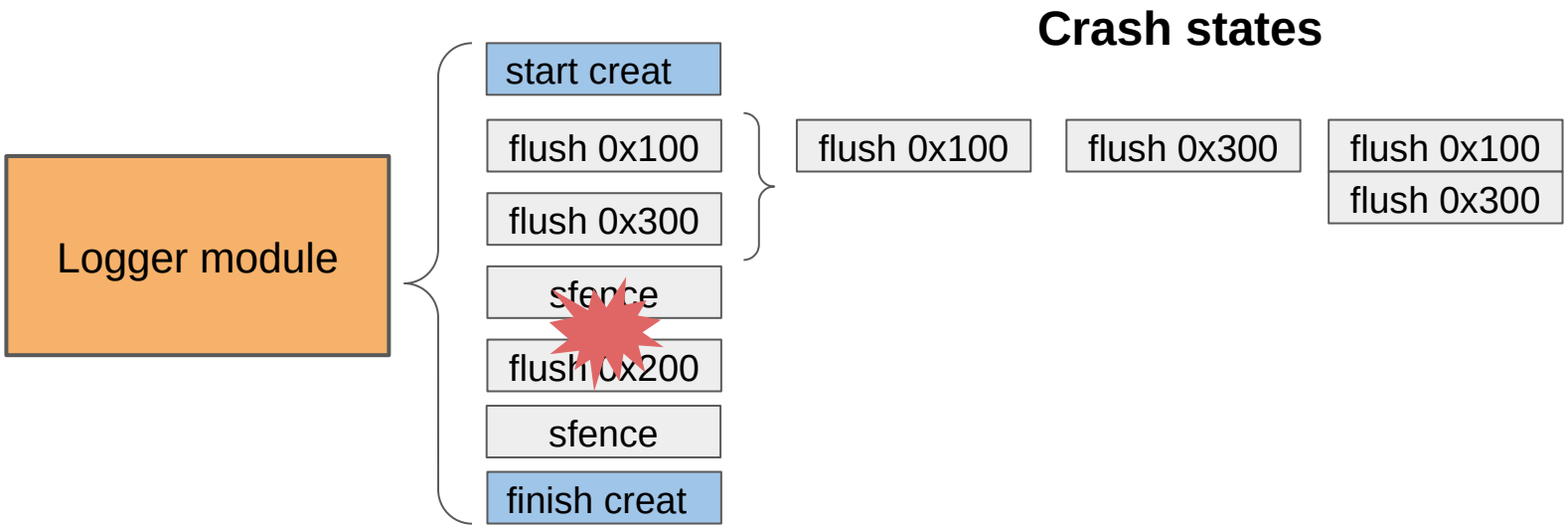


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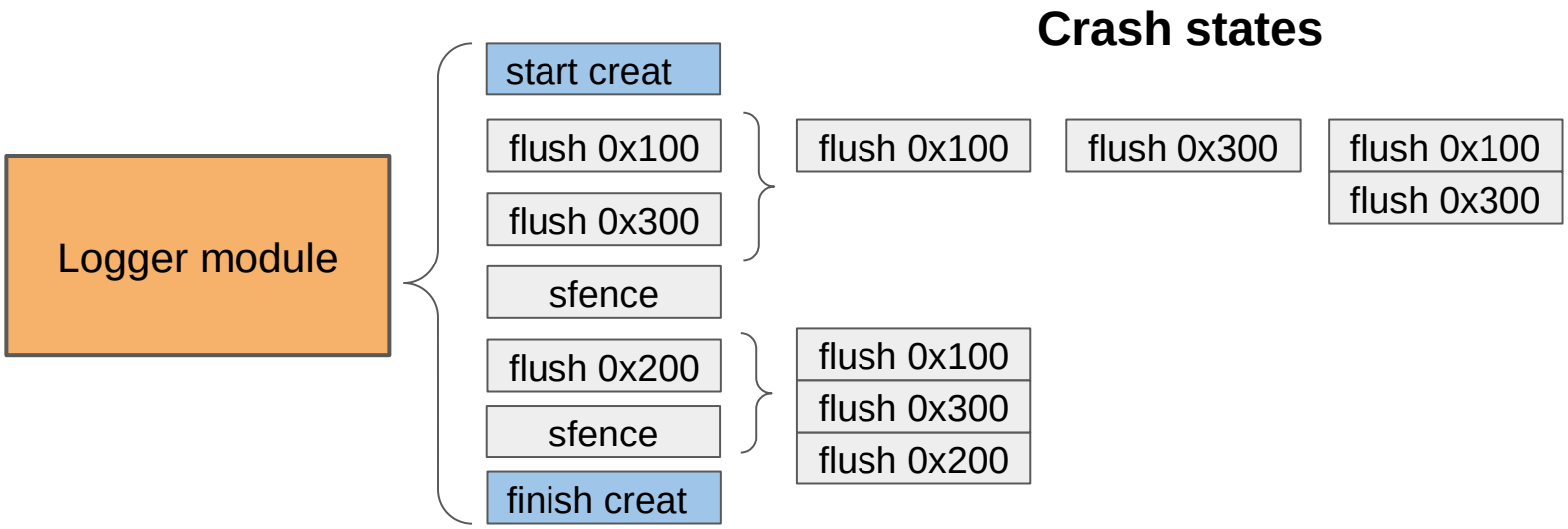


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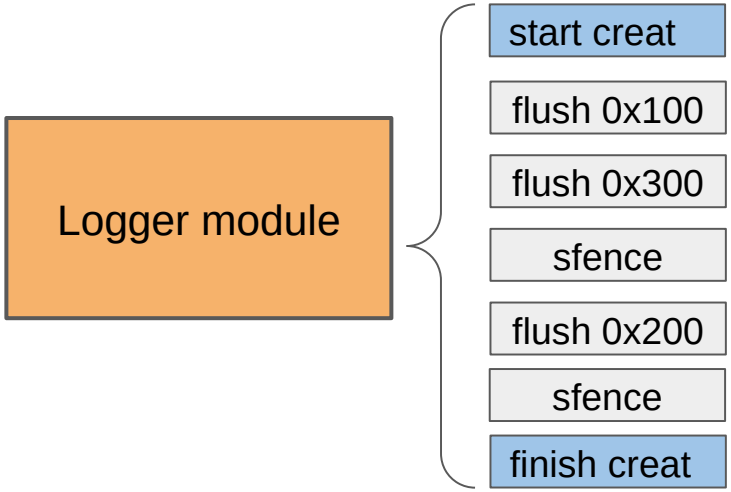


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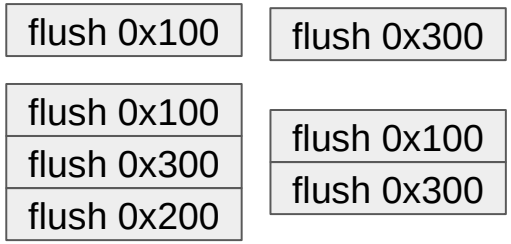


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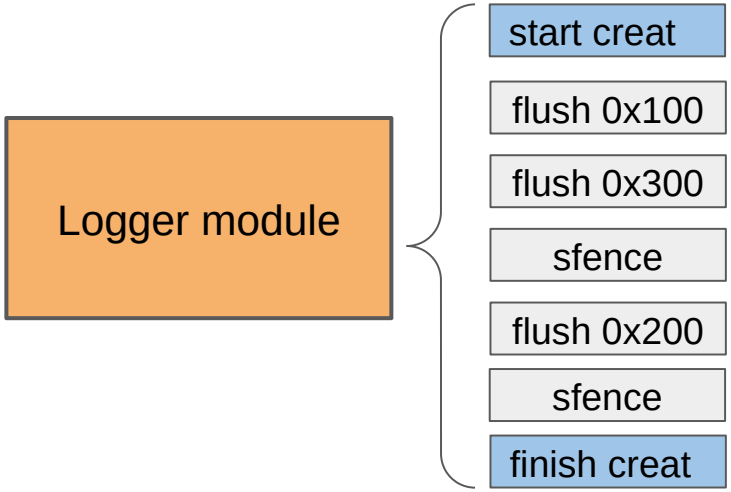


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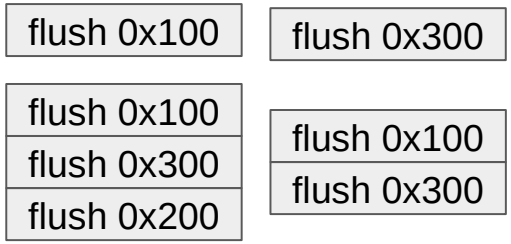


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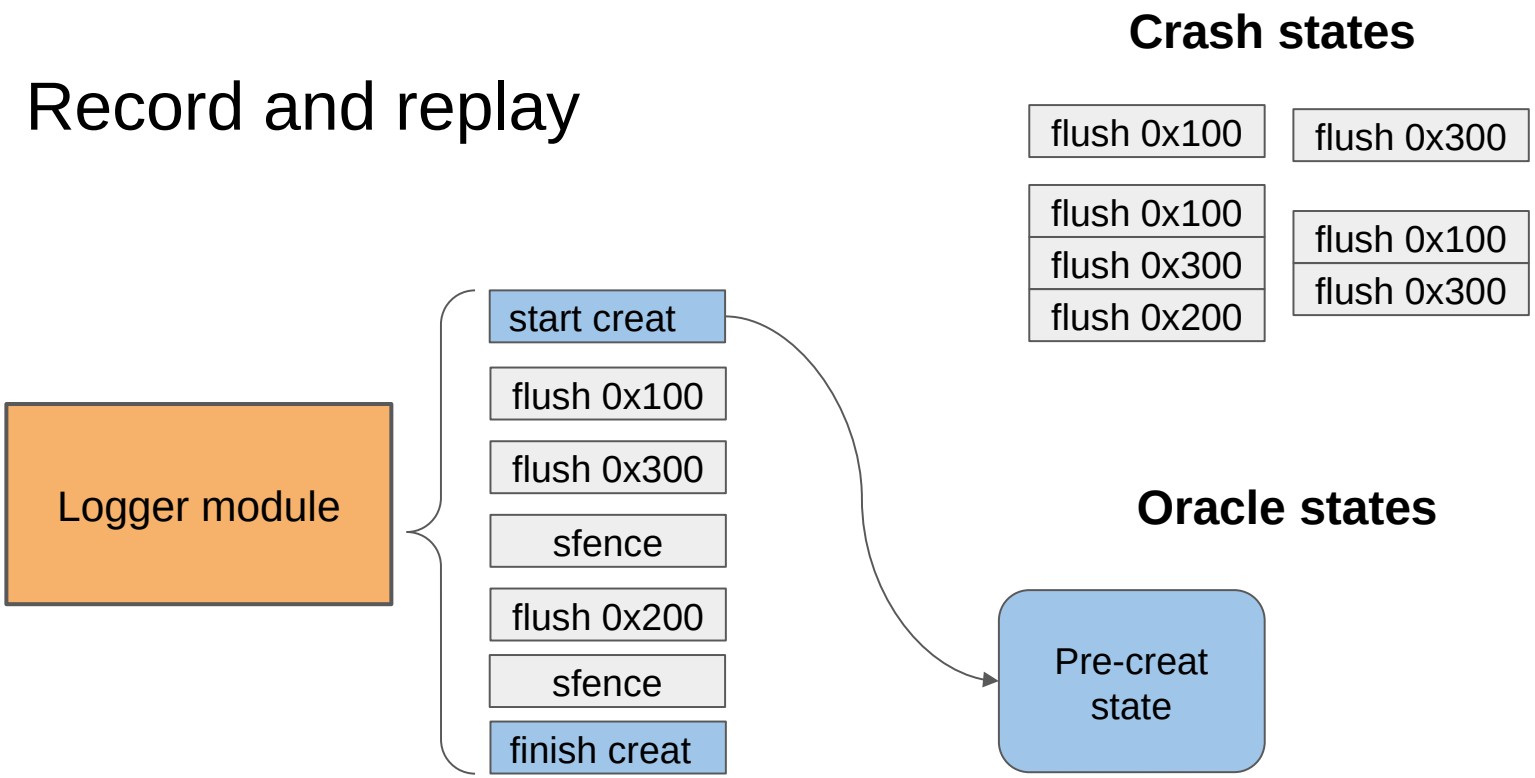


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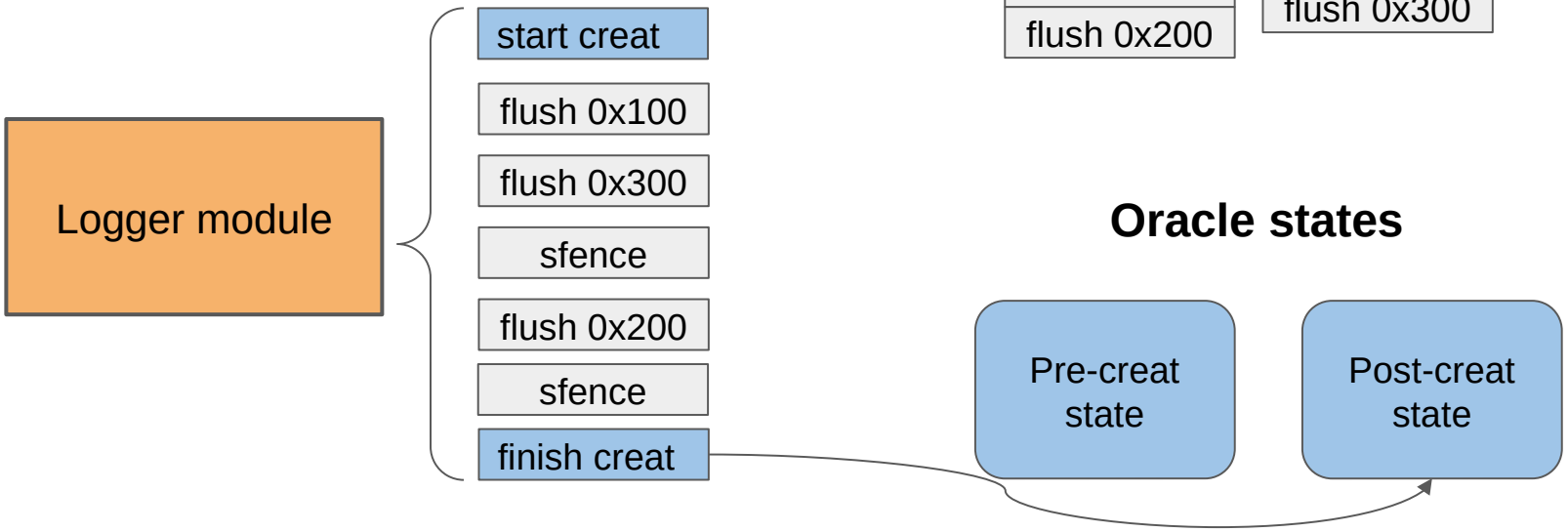


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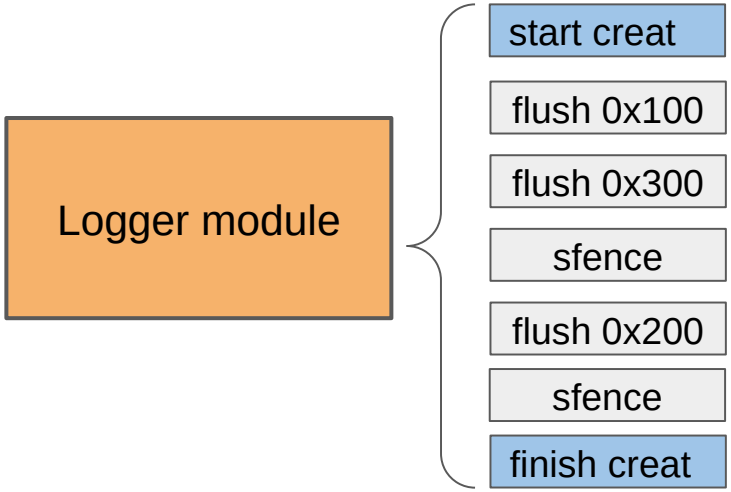
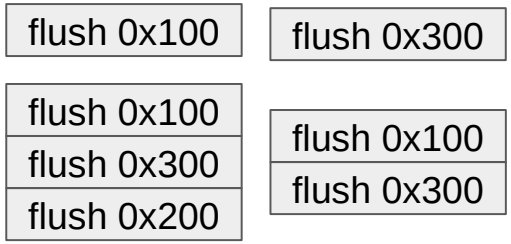
recorded via Kprobes/Uprobes trigger on FS function

# Record and replay

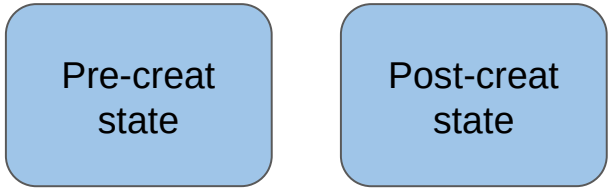



## Crash states




**vs**

## Oracle states



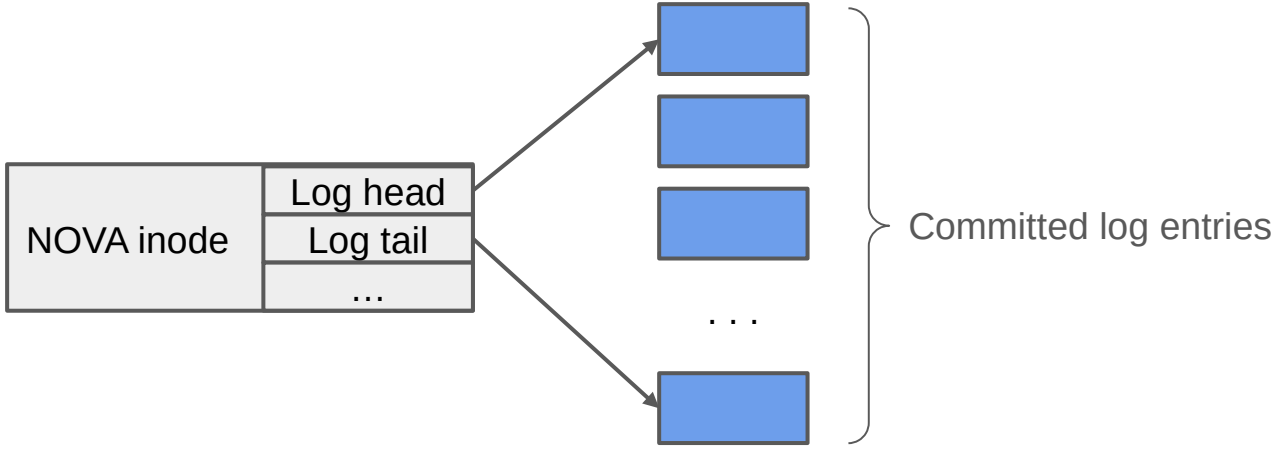

recorded via IOCTL issued by Chipmunk

recorded via Kprobes/Uprobes trigger on FS function

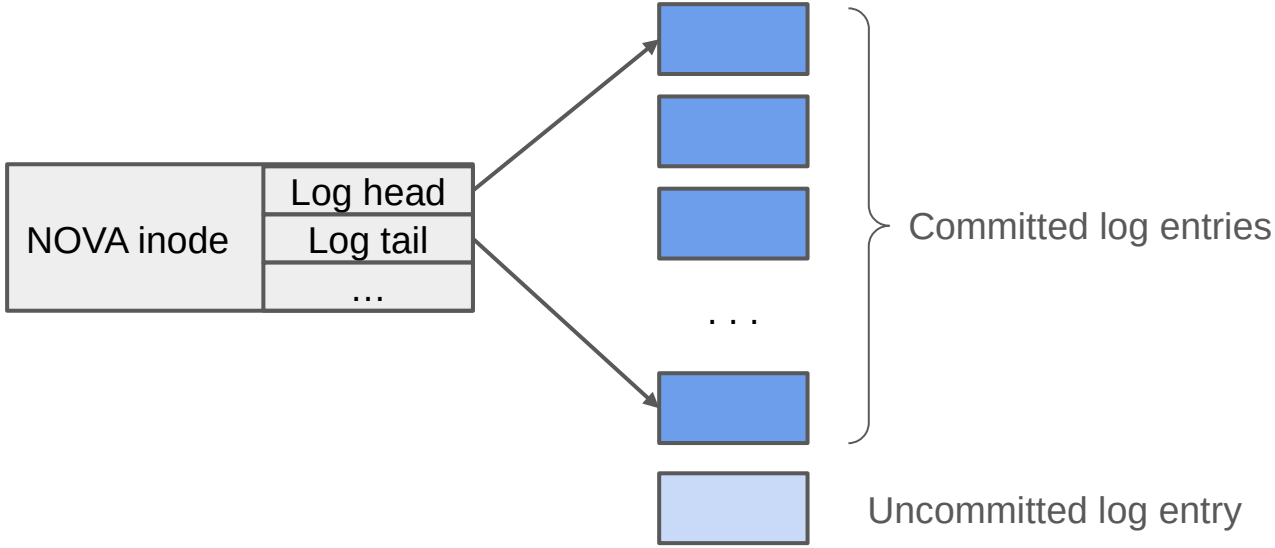
# Link atomicity bug in NOVA

| | |
|---|---|
| NOVA inode | Log head |
| | Log tail |
| | … |

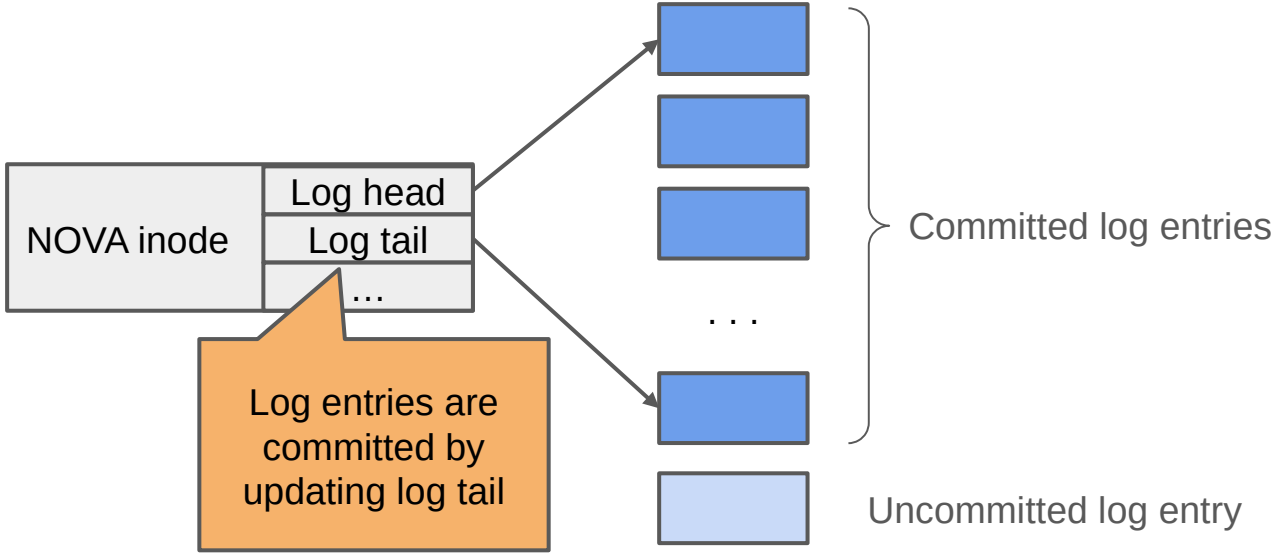
# Link atomicity bug in NOVA



# Link atomicity bug in NOVA



# Link atomicity bug in NOVA



# Link atomicity bug in NOVA

```
mkdir(“A”);
creat(“bar”);
rename(“bar”, “A/bar”);
link(“A/bar”, “bar”);
```

# Link atomicity bug in NOVA

```
mkdir("A");
creat("bar");
rename("bar", "A/bar");
link("A/bar", "bar");
```

**CRASH!!**

# Link atomicity bug in NOVA

```
mkdir(“A”);
creat(“bar”);
rename(“bar”, “A/bar”);
link(“A/bar”, “bar”);
```

**CRASH!!**

Result:

```
$ ls -l . A | awk ‘{print $2,$9}’;
2    A/bar
```

# Link atomicity bug in NOVA

```
mkdir("A");
creat("bar");
rename("bar", "A/bar");
link("A/bar", "bar");
```

**CRASH!!**

Result:

```
$ ls -l . A | awk '{print $2,$9}';
2    A/bar
```

Link count is 2, but link path bar does not exist!

# Link atomicity bug in NOVA

```
mkdir("A");
creat("bar");
rename("bar", "A/bar");
link("A/bar", "bar");
```

**CRASH!!**

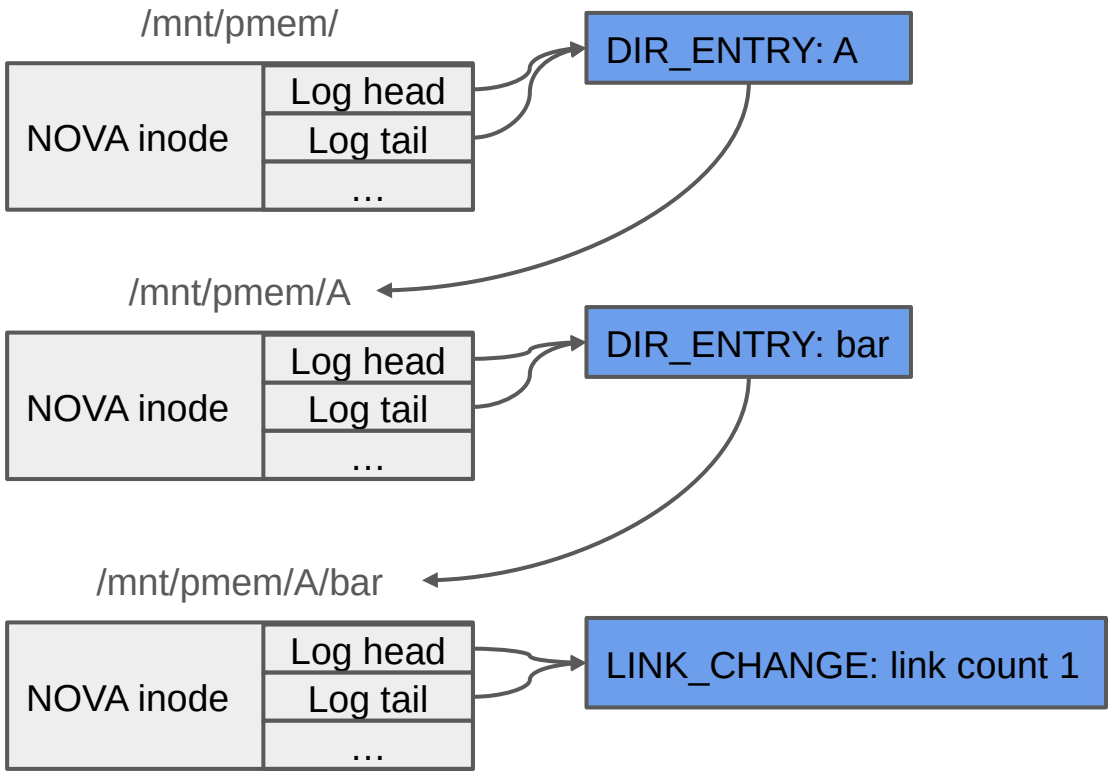
**Root cause: in-place update optimization to avoid journaling**

Result:

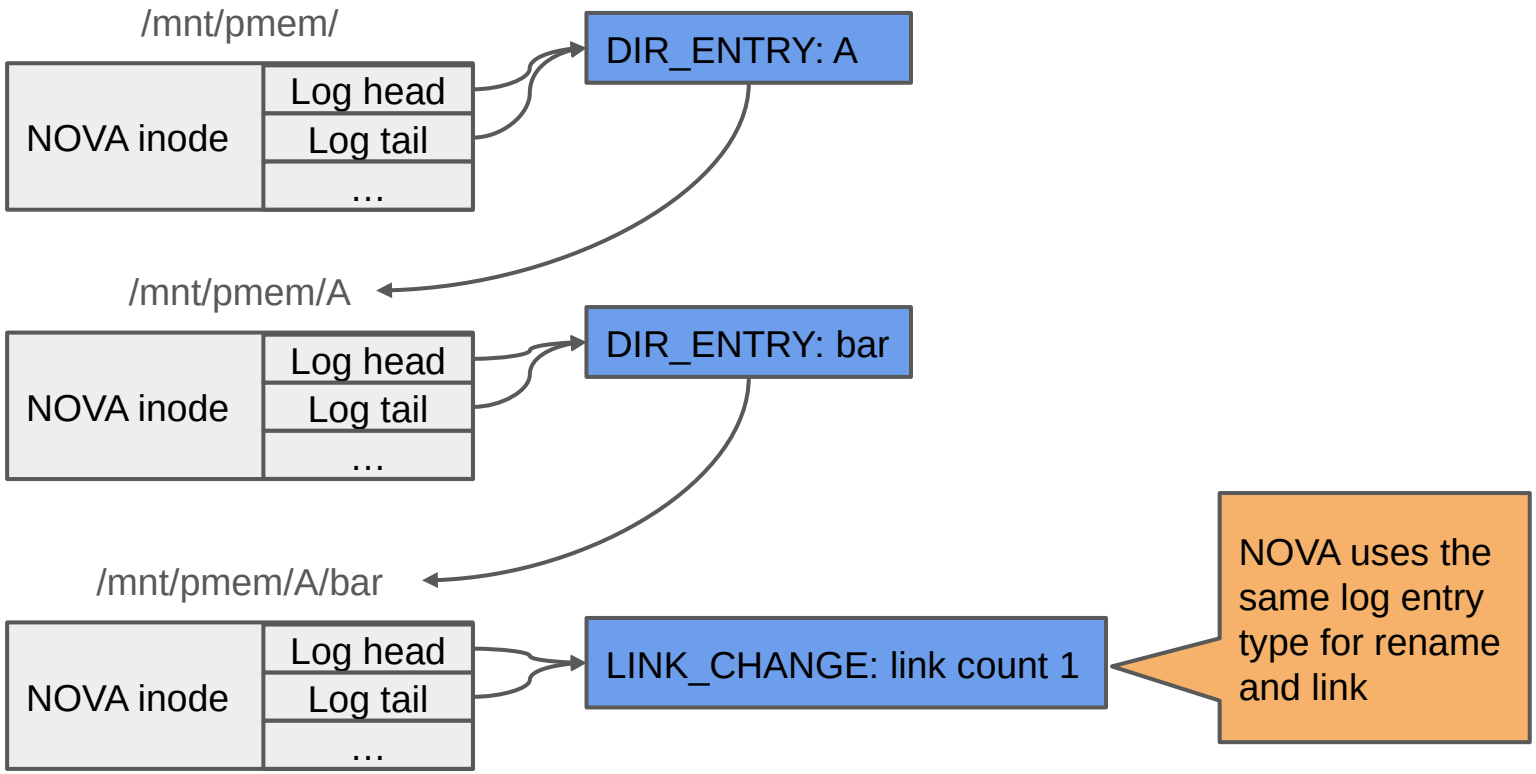
```
$ ls -l . A | awk '{print $2,$9}';
2    A/bar
```

Link count is 2, but link path bar does not exist!

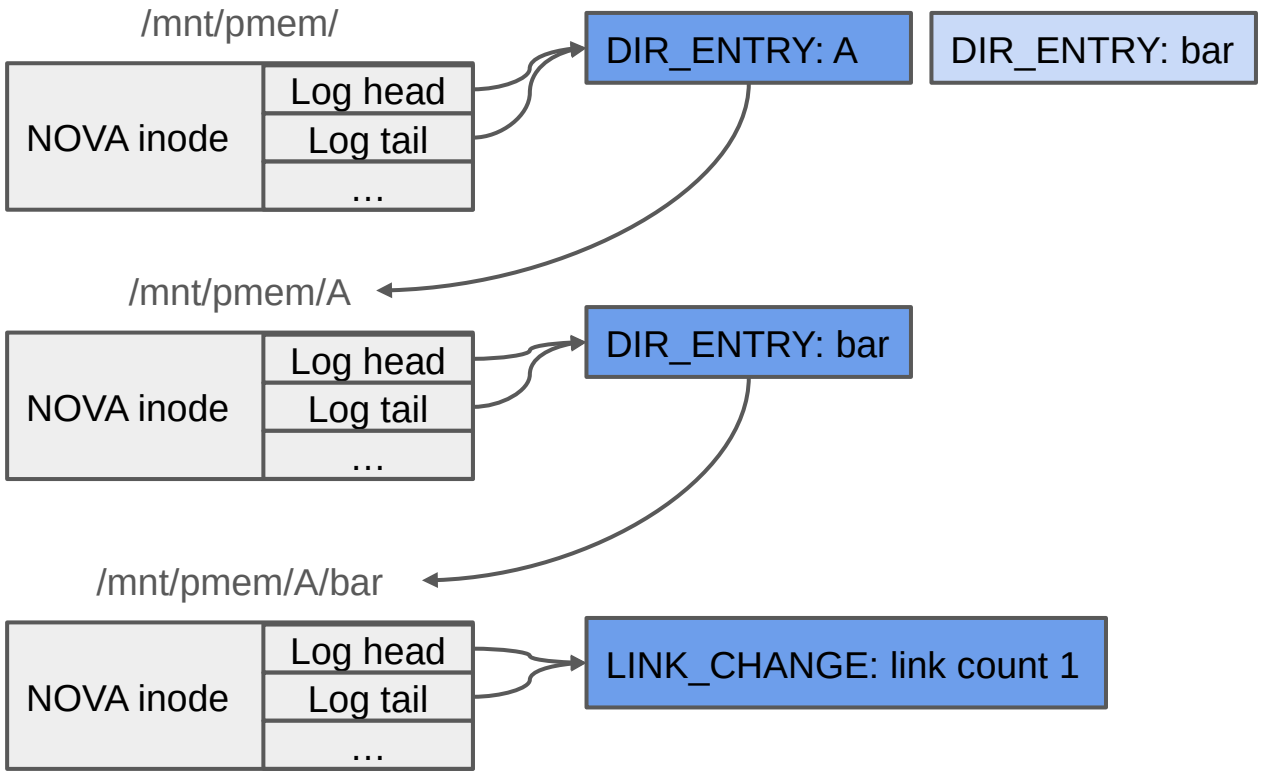
# Link atomicity bug in NOVA



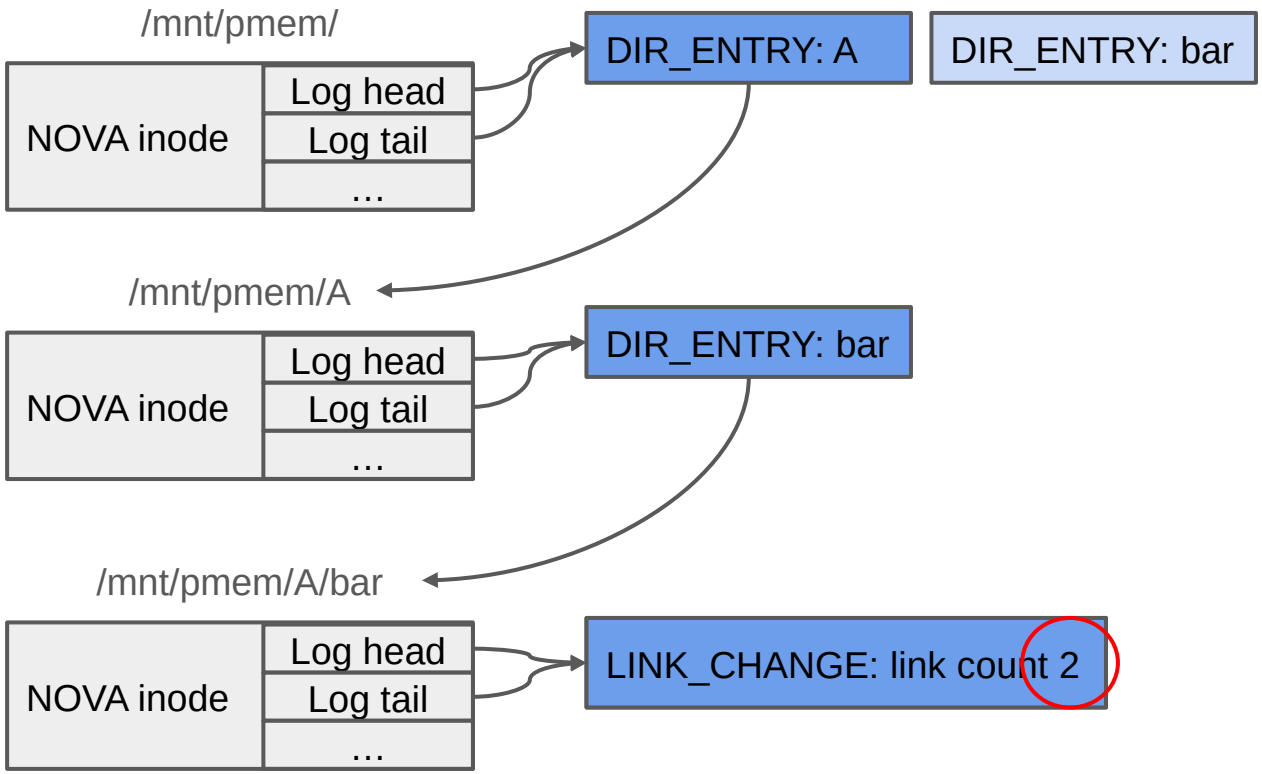
# Link atomicity bug in NOVA



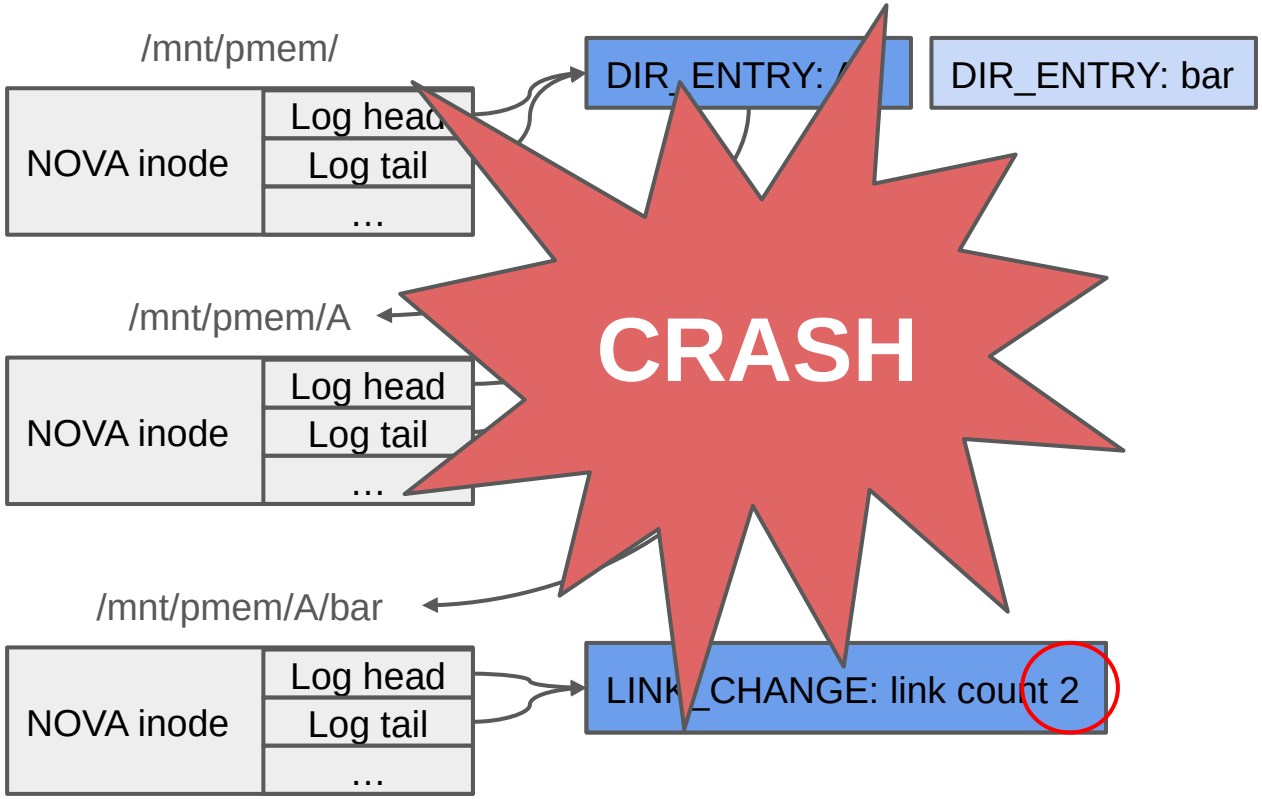
# Link atomicity bug in NOVA



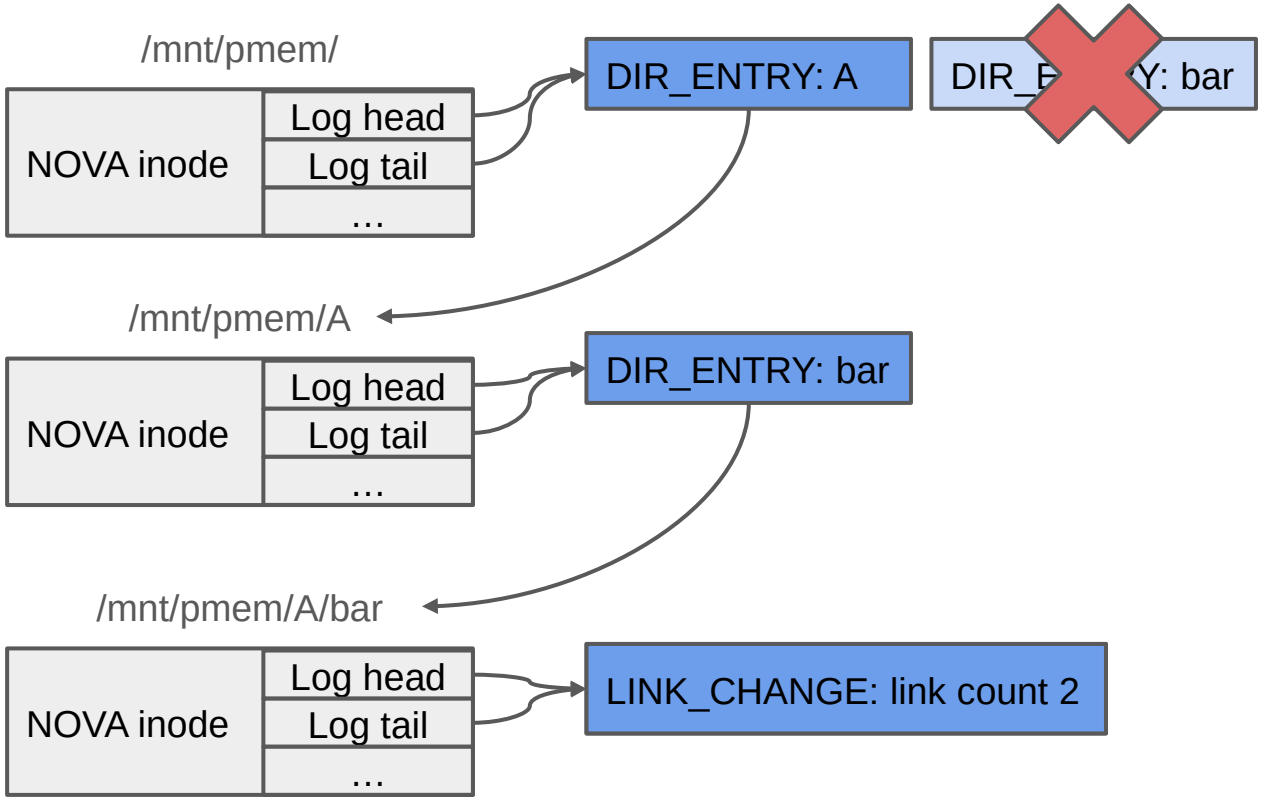
# Link atomicity bug in NOVA



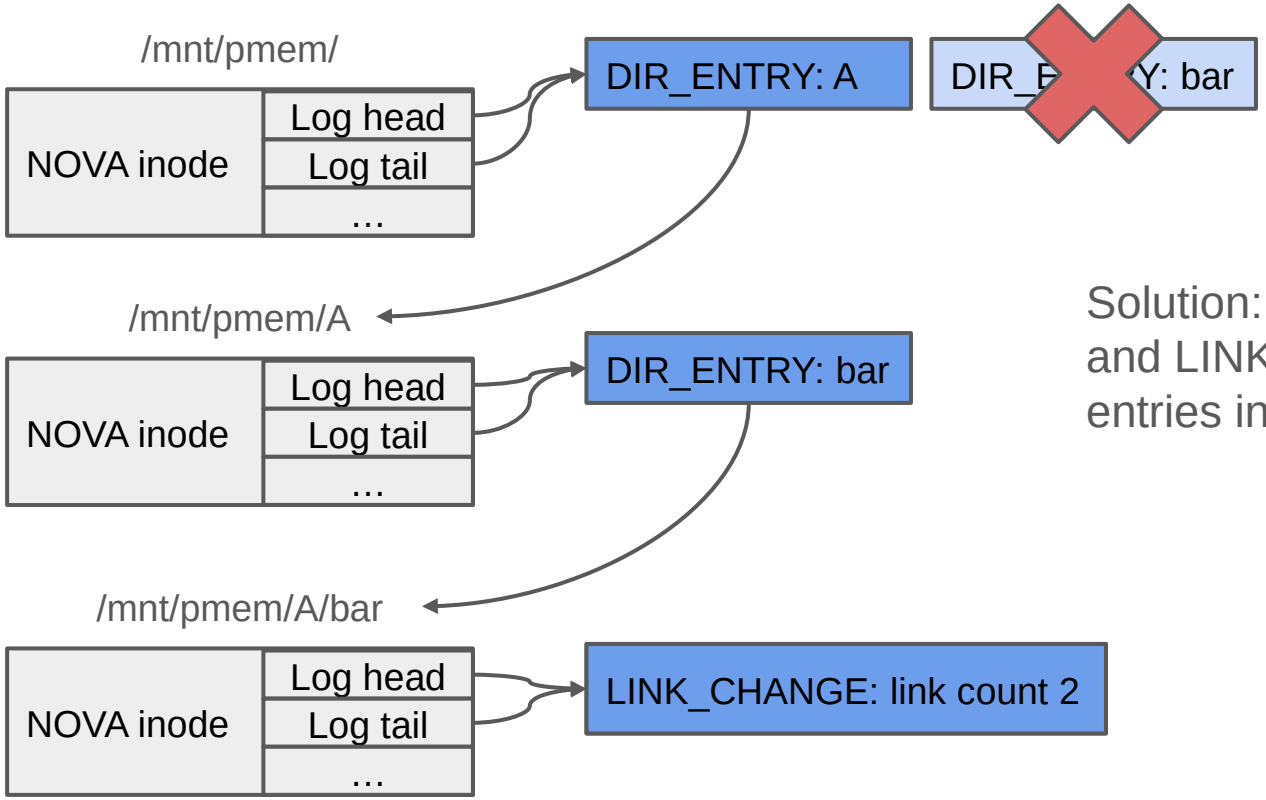
# Link atomicity bug in NOVA



# Link atomicity bug in NOVA



# Link atomicity bug in NOVA




Solution: add DIR_ENTRY and LINK_CHANGE log entries in a transaction