SquirrelFS: using the Rust compiler to check file-system crash consistency

Hayley LeBlanc, Nathan Taylor,
James Bornholt, Vijay Chidambaram

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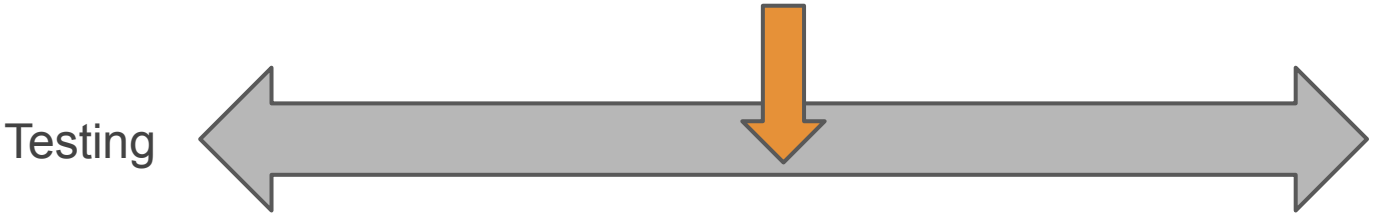

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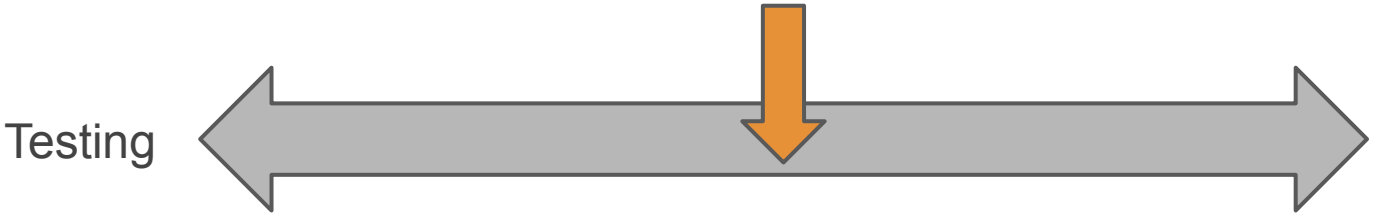

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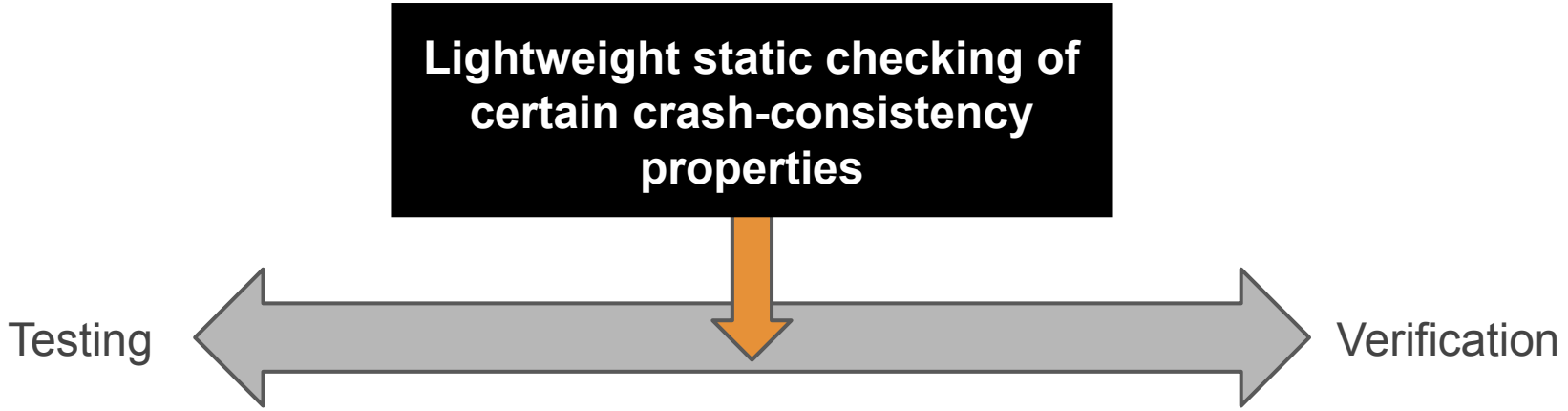

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Atomicity of system calls

SquirrelFS

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Achieves similar or better performance to other PM file systems

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https://github.com/utsaslab/squirrelfs

Roadmap

1. Introduction
2. Ordering for crash consistency
3. Typestate pattern
4. SquirrelFS implementation
5. Evaluation

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Simple example: creating a new file

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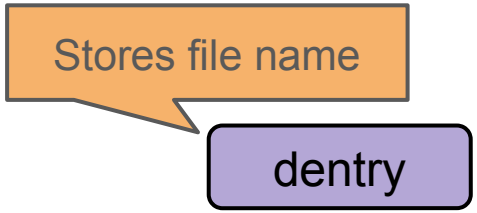

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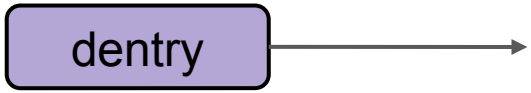

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Statically enforcing durable update ordering can prevent many crash-consistency bugs

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Track dependencies between durable in-place updates to enforce crash-consistent ordering (Ganger & Patt OSDI ‘94)

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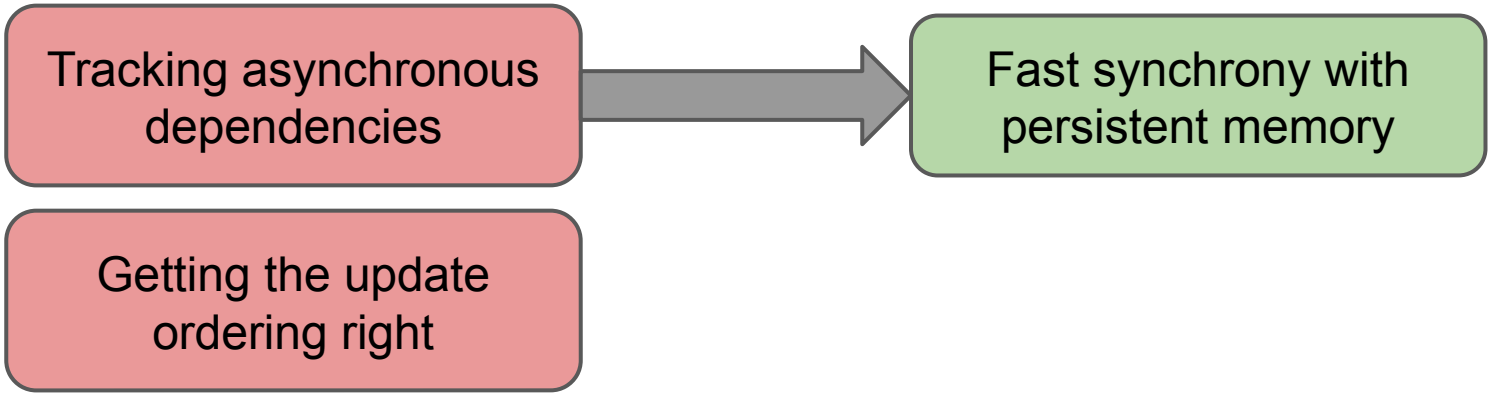

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Low-latency durable storage devices with DRAM-like interface

- Intel Optane DC PM
- Battery-backed DRAM
- Future CXL-attached mem

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Fast synchrony with persistent memory

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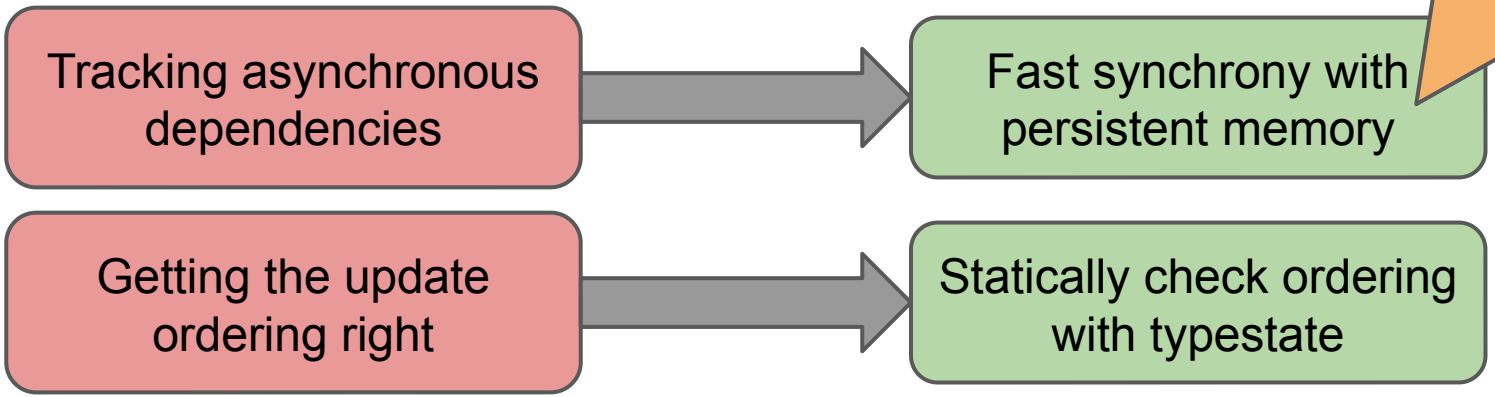

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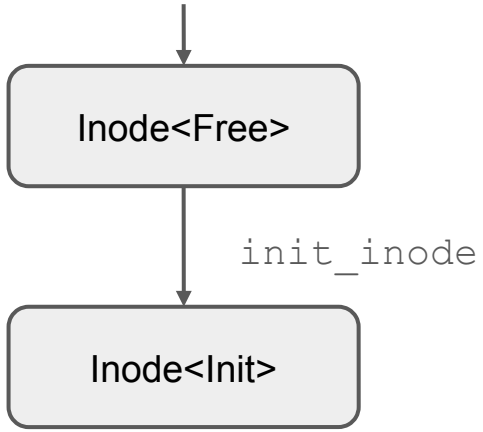

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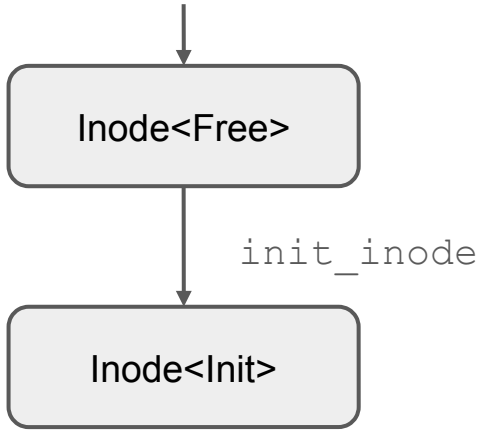

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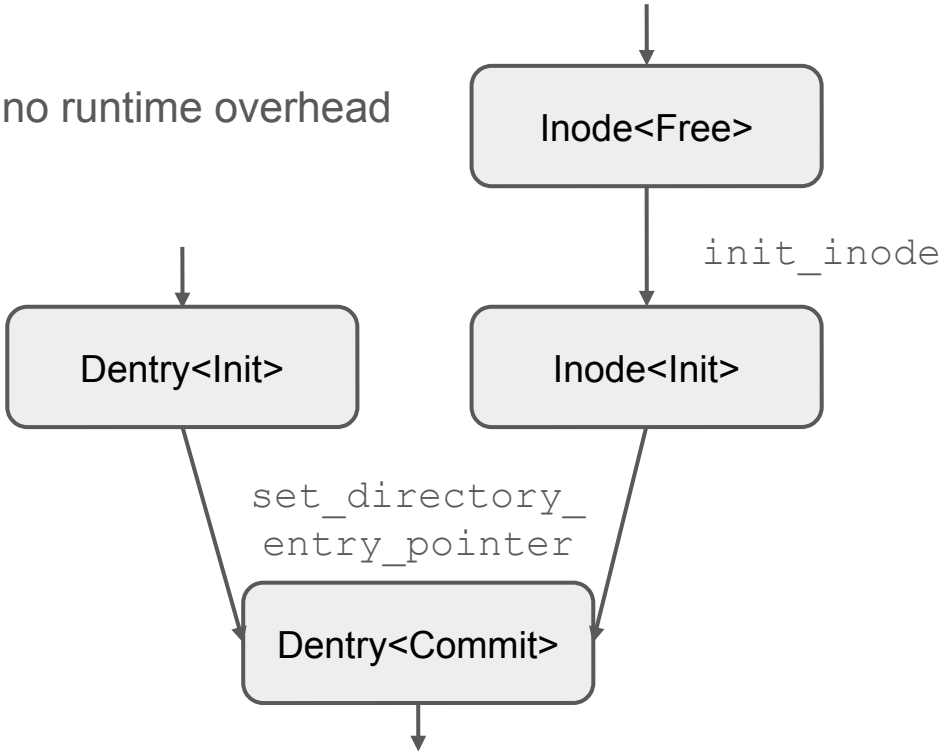

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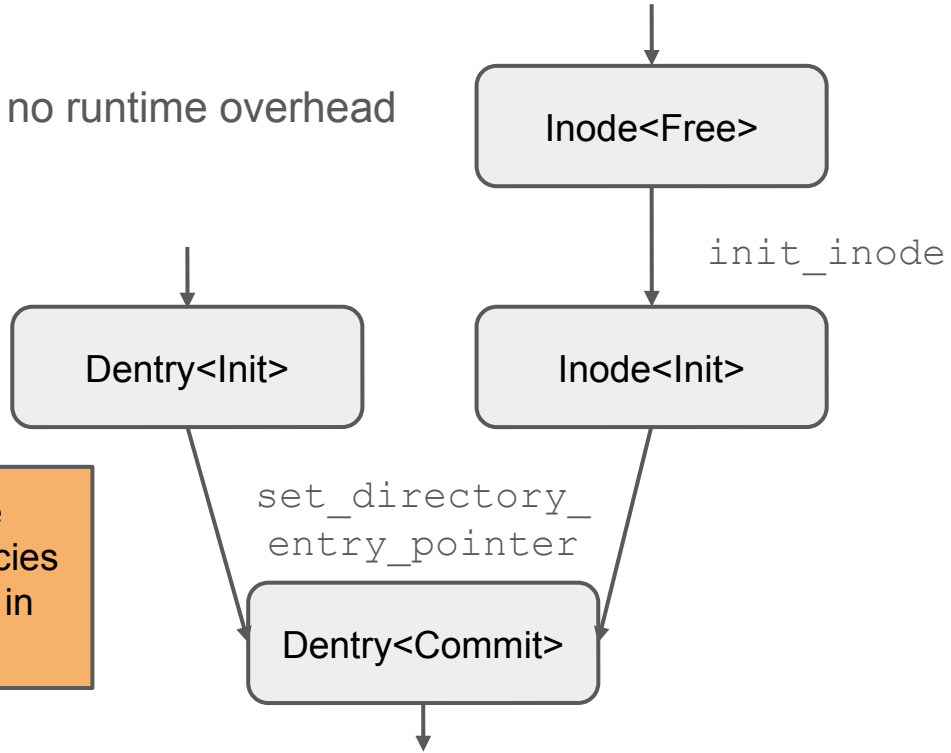

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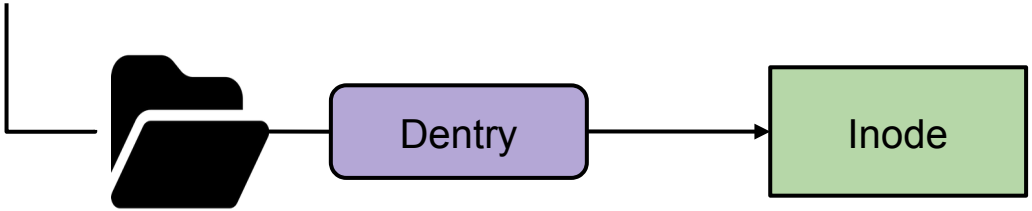


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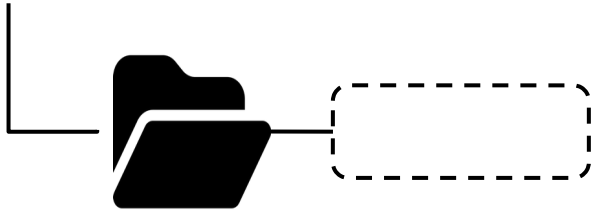

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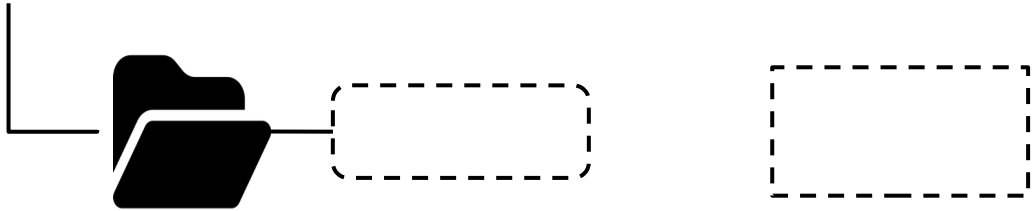

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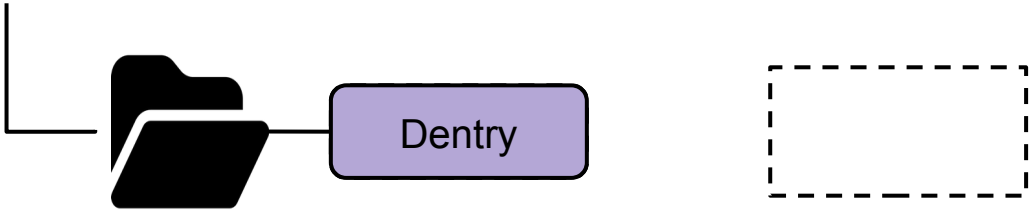


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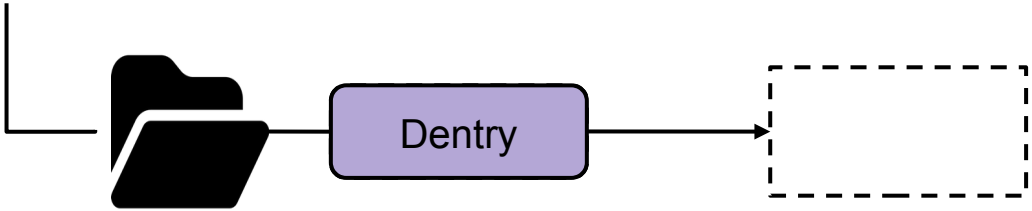


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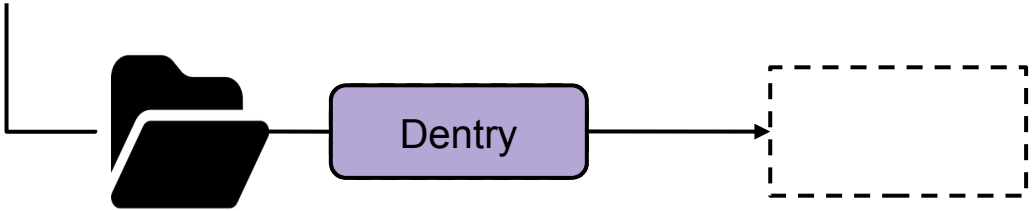


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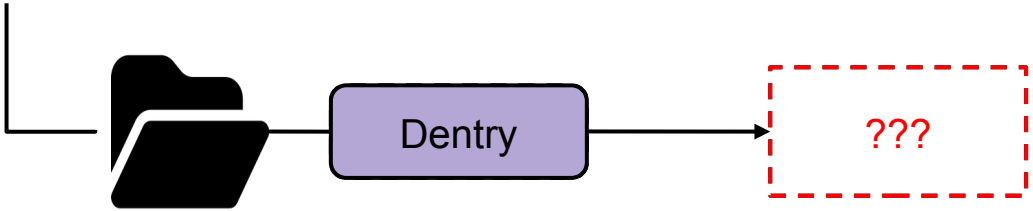


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```
error[E0308]: mismatched types
  --> src/main.rs:46:39
   |
46 |     let d = d.set_directory_entry_ptr(i);
   |               ---------------------- ^ expected `Inode<Init>`, found `Inode<Free>`
   |               |
   |               arguments to this method are incorrect
   |
   = note: expected struct `Inode<Init>`
              found struct `Inode<Free>`
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Roadmap

1. Introduction
2. Ordering for crash consistency
3. Typestate pattern
4. **SquirrelFS implementation**
5. Evaluation

SquirrelFS implementation

Typestate-checked Synchronous Soft Updates for crash consistency

7500 LOC of Rust

Simple durable layout with volatile indexes and allocators

Atomic metadata-related system calls (including `rename`)

Modeled as a transition system and model checked in Alloy

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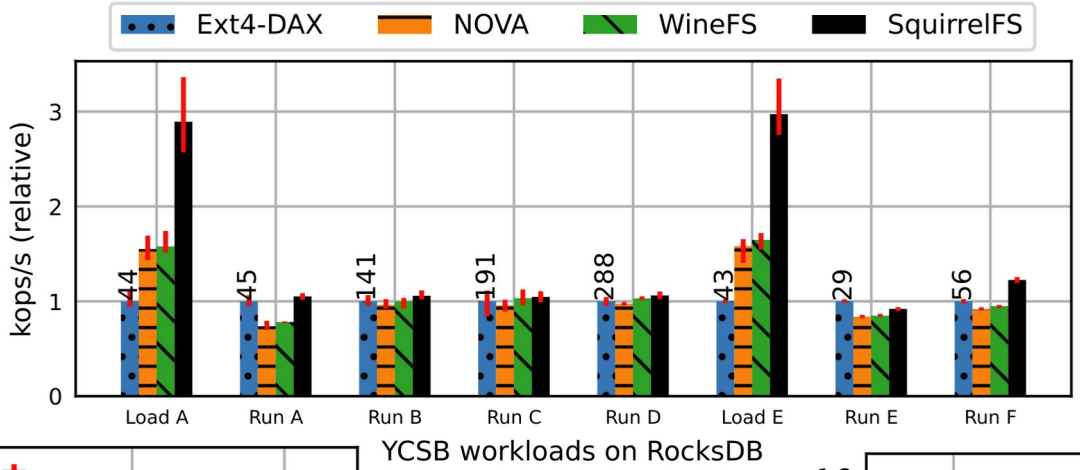
Evaluation

Evaluated on 128GB Intel Optane DC Persistent Memory Module

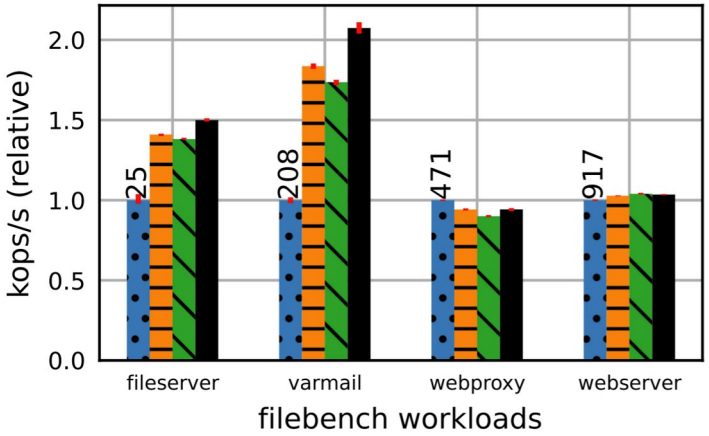
Compared against **Ext4-DAX**, **NOVA**, and **WineFS**

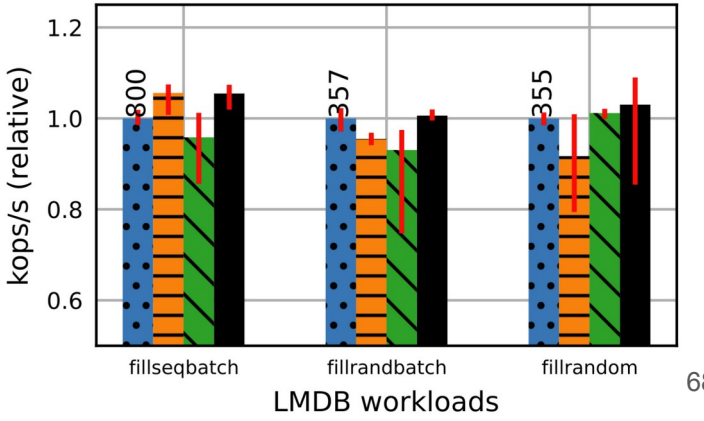
1. How does SquirrelFS compare to other PM file systems?
2. How long does it take to statically check SquirrelFS's crash-consistency properties?

SquirrelFS performance



higher is better





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NOVA	16K	20
WineFS	9K	13

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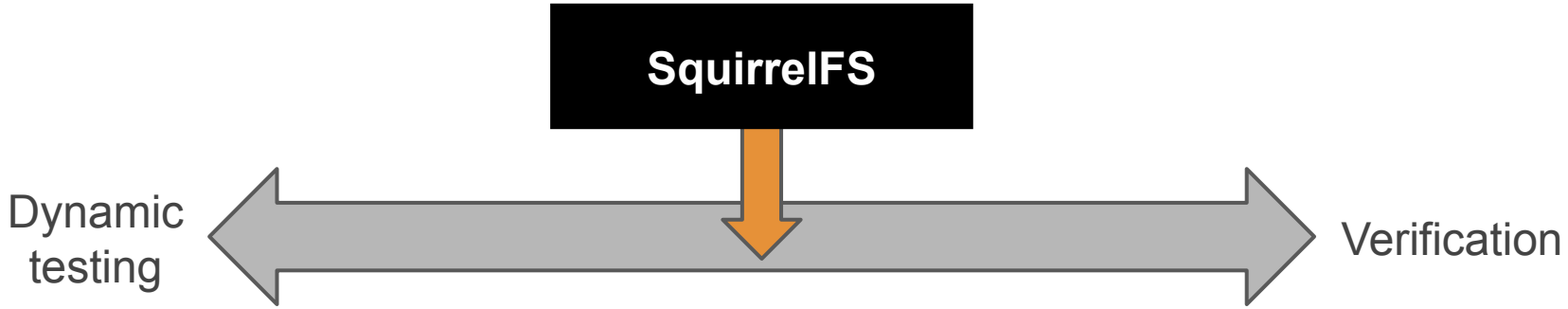
System (typestate-checked)	Lines of code	Compile+check time (s)
SquirrelFS	**7.5K**	**10**

Conclusion



Typestate pattern statically checks ordering for crash consistency

Synchronous Soft Updates crash-consistency mechanism

Comparable performance to existing PM file systems

https://github.com/utsaslab/squirrelfs

Extra slides

Background: persistent memory

Low latency on the order of DRAM

Byte-addressable via memory loads and stores

Cache-line flushes and memory fences for durability and ordering

Examples:

- Intel Optane DC Persistent Memory Module
- Battery-backed DRAM
- Future devices: Micron, startups, CXL.mem, …

Background: soft updates

Crash-consistency mechanism based on ordering in-place updates

Rules:

1. Never point to a structure before it is initialized
2. Never reuse a resource before nullifying existing references to it
3. Never reset the old pointer to a resource before setting the new one

Enforced by tracking update dependencies and ordering durable updates

Reduces write amplification, but increases complexity

Soft updates cyclic dependencies example

Soft updates cyclic dependencies example

1. unlink foo

Soft updates cyclic dependencies example

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Soft updates cyclic dependencies example

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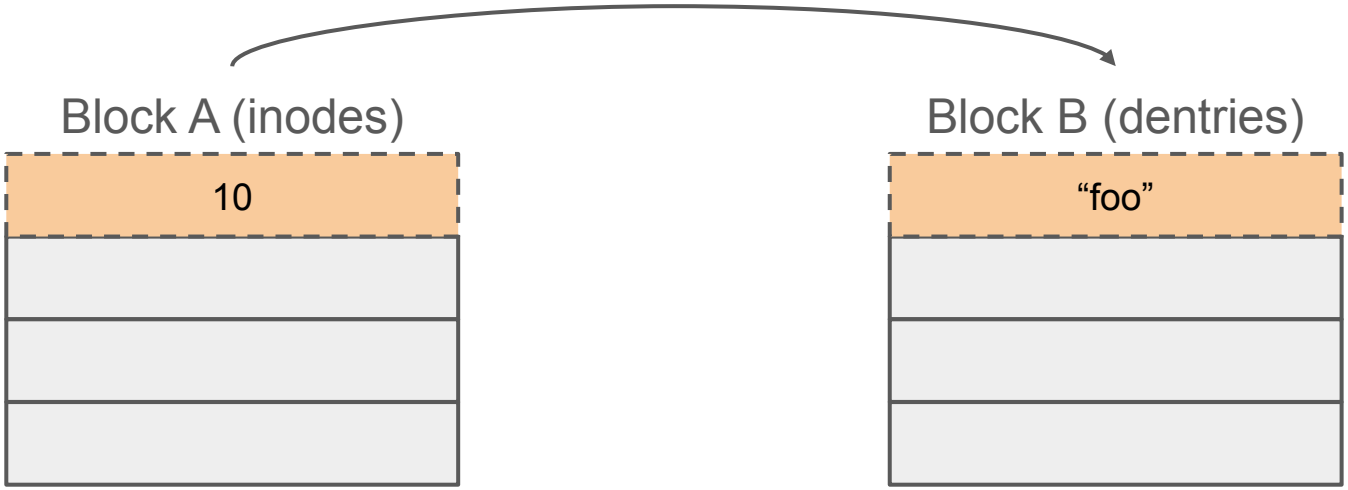
Soft updates cyclic dependencies example

1. unlink foo

Soft updates cyclic dependencies example



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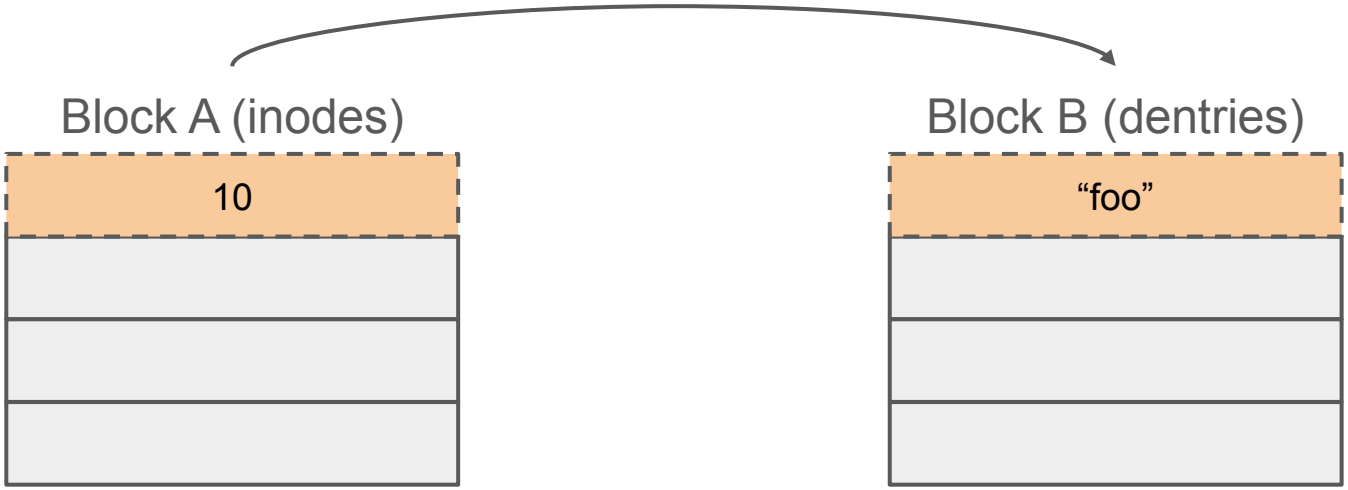
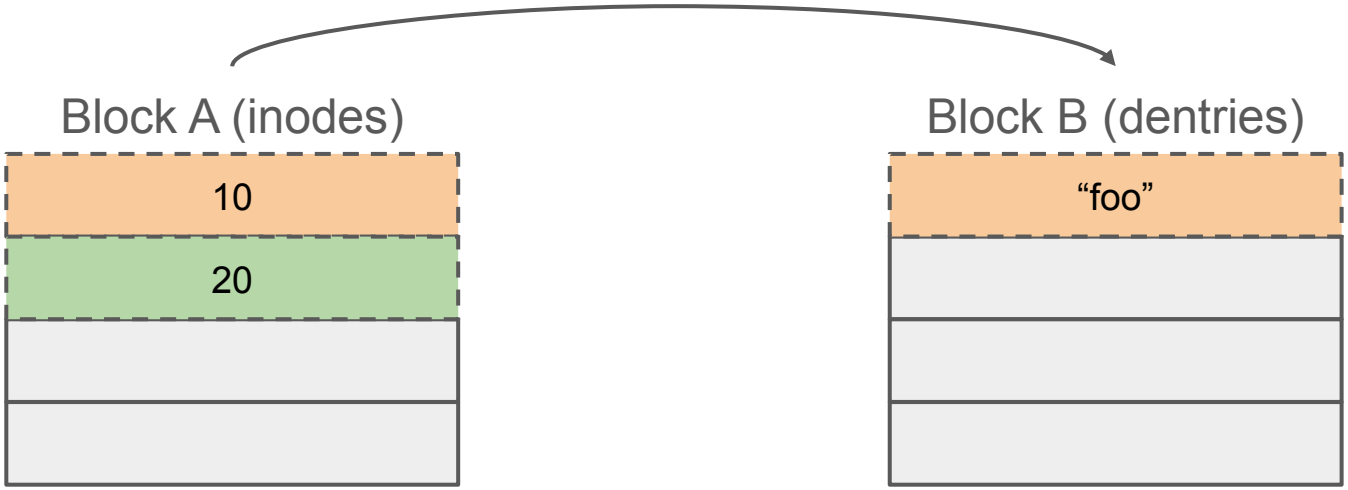
Soft updates cyclic dependencies example



1. unlink foo
2. create bar

Soft updates cyclic dependencies example



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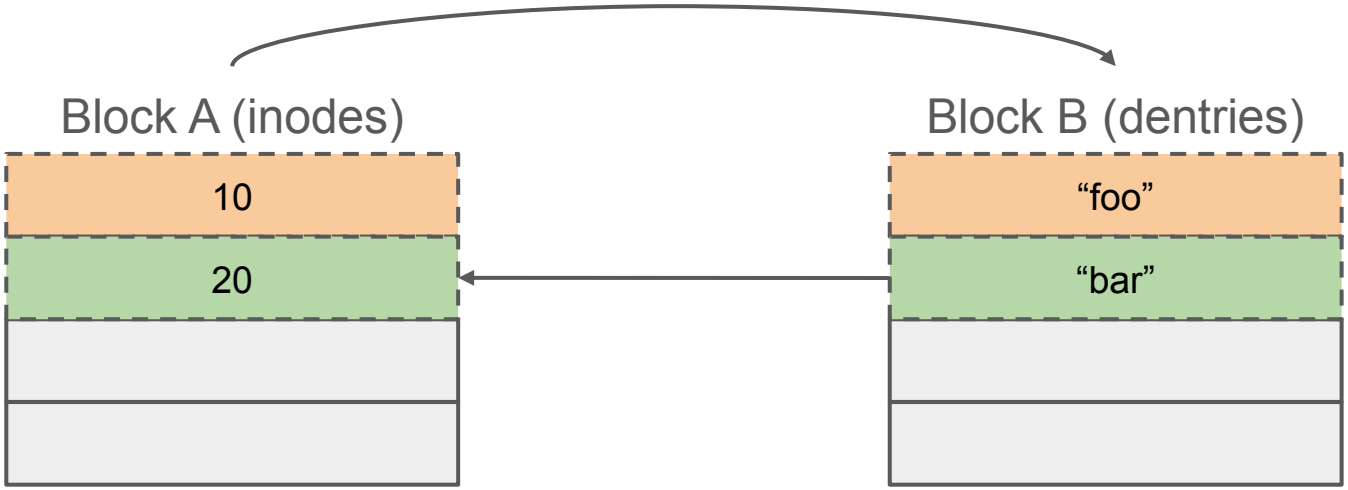

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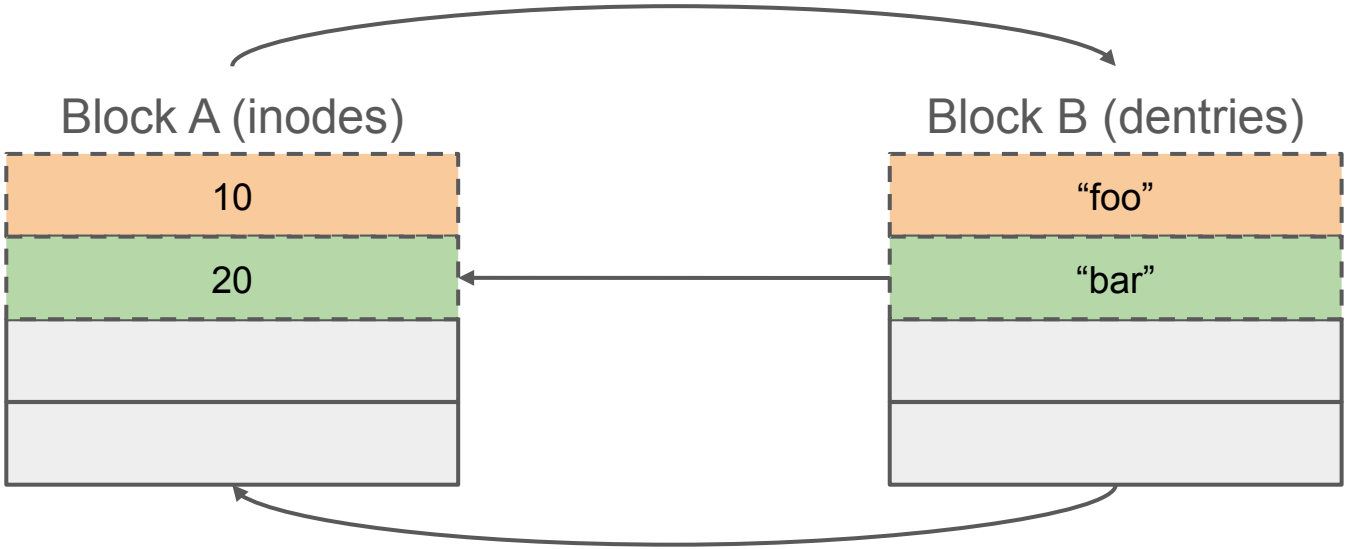


1. unlink foo
2. create bar

Background: verification

Mathematical proof that a program is correct

Prove that the complex implementation matches a simpler specification of correctness

Developer writes a proof, computer checks it

Uses verification-aware programming languages or interactive theorem provers

E.g.: Verus verification framework for Rust

Typestate in Rust: update operations

```
impl Inode<Clean,Free> {
    fn init(self,...) -> Inode<Dirty,Init> {...}
}
impl Dentry<Clean,Free> {
    fn set_name(self, name: String) -> Dentry<Dirty,Init> {...}
}
impl Dentry<Clean,Init> {
    fn set_ino(self, ino: Inode<Clean,Init>) -> Dentry<Dirty,Committed> {...}
}
```

Typestate: ensuring persistence

```
impl<S> Inode<Dirty,S> {

     fn flush(self) -> Inode<InFlight,S> {...}

}

impl<S> Inode<InFlight,S> {

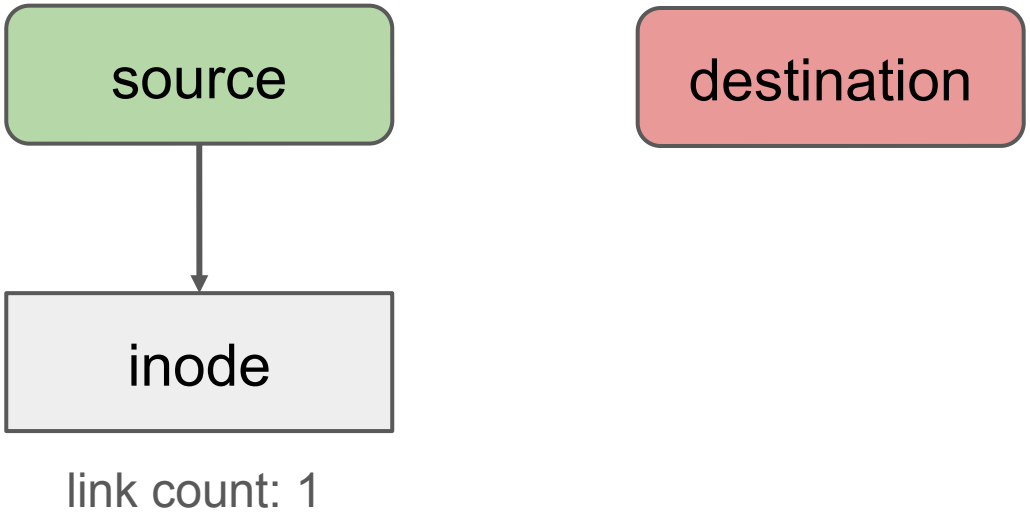
     fn fence(self) -> Inode<Clean,S> {...}

}
```

Directory entry validity rules

1. If a dentry's inode number is 0, the dentry is invalid.
2. If dst's rename pointer points to src, then:
    a. If dst.inode != src.inode, both dentries are valid
    b. If dst.inode == src.inode, src is invalid

Traditional soft updates rename



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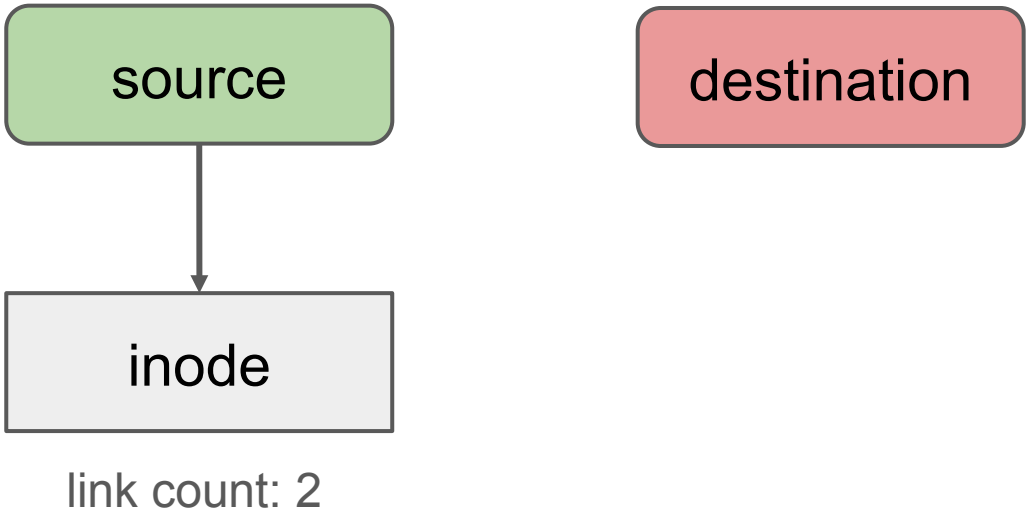

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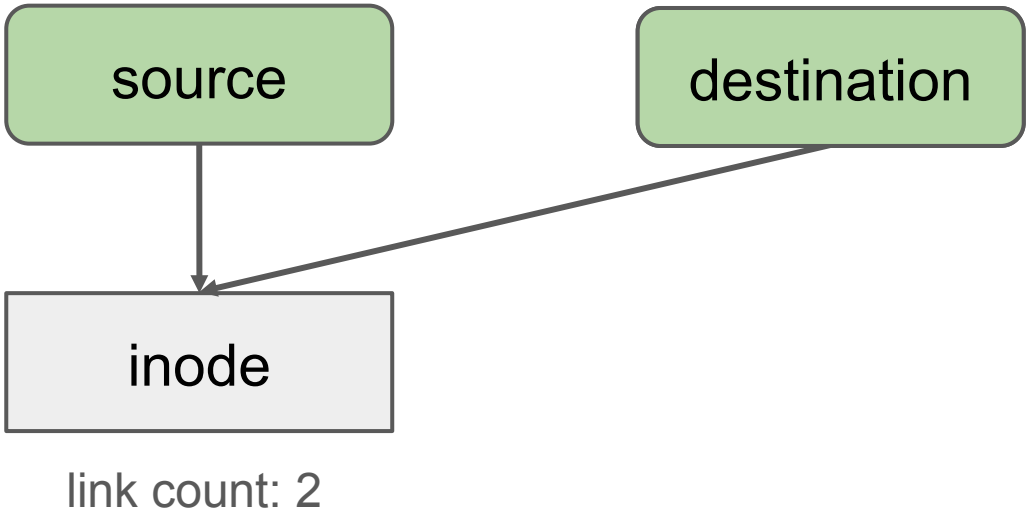

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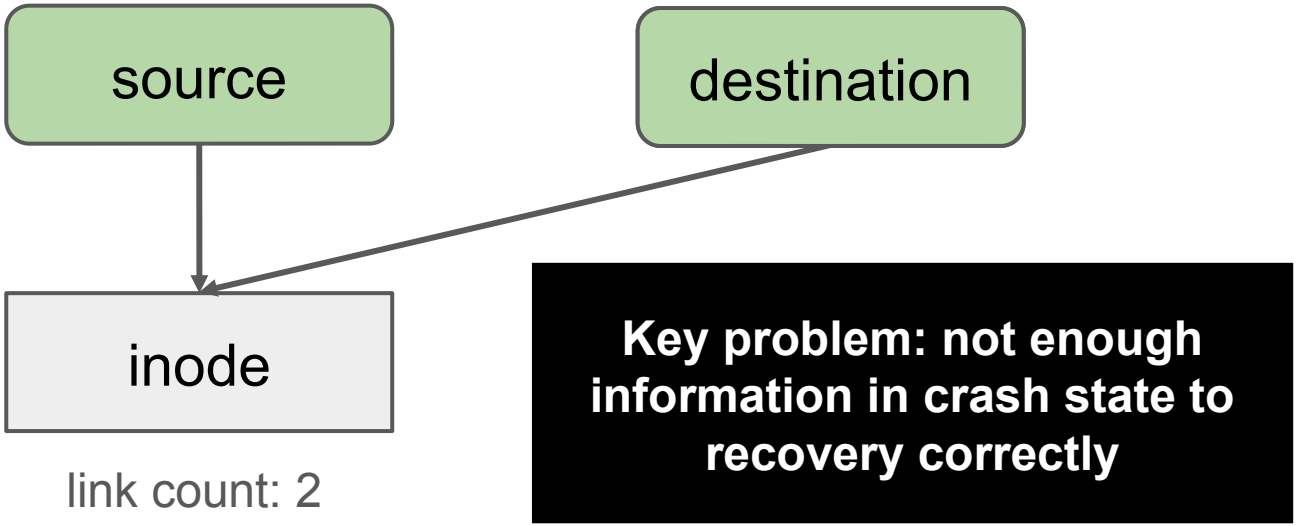

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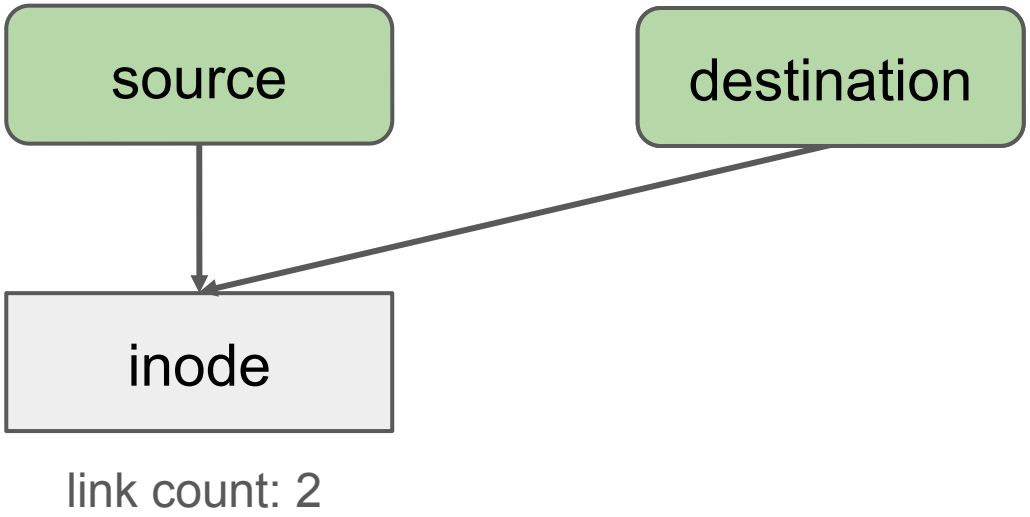

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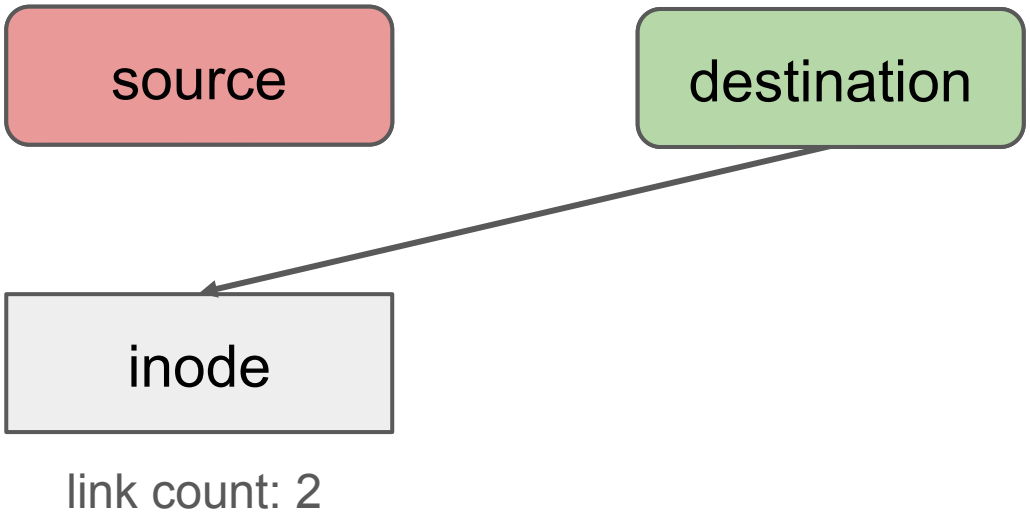

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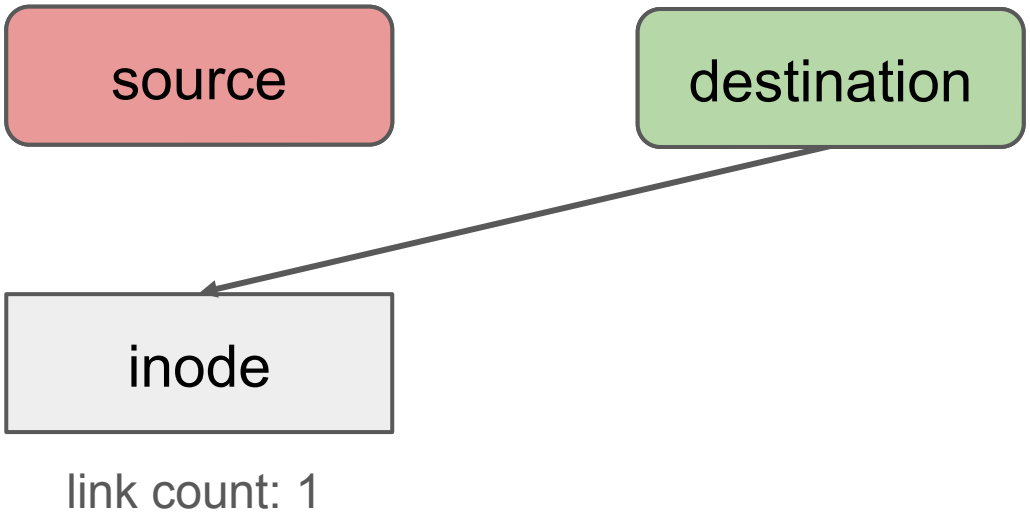

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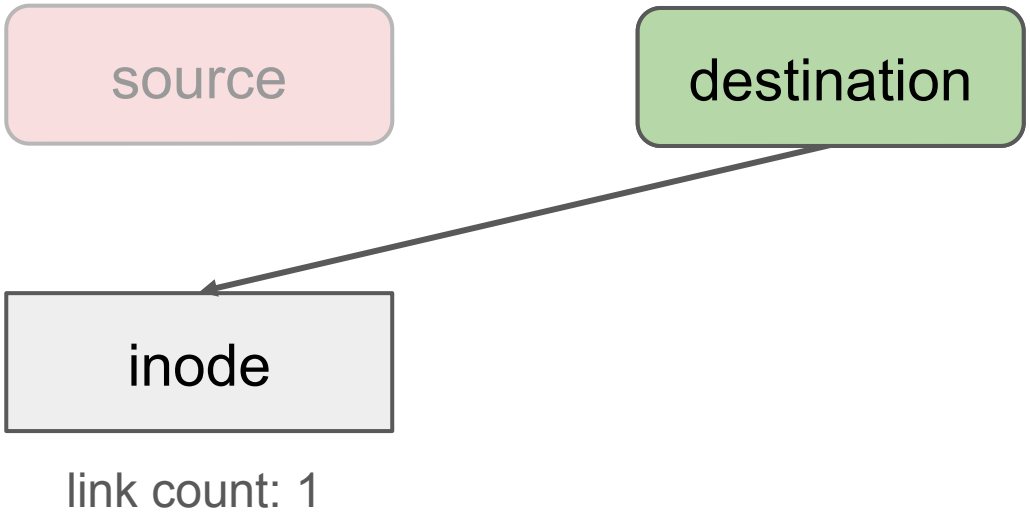
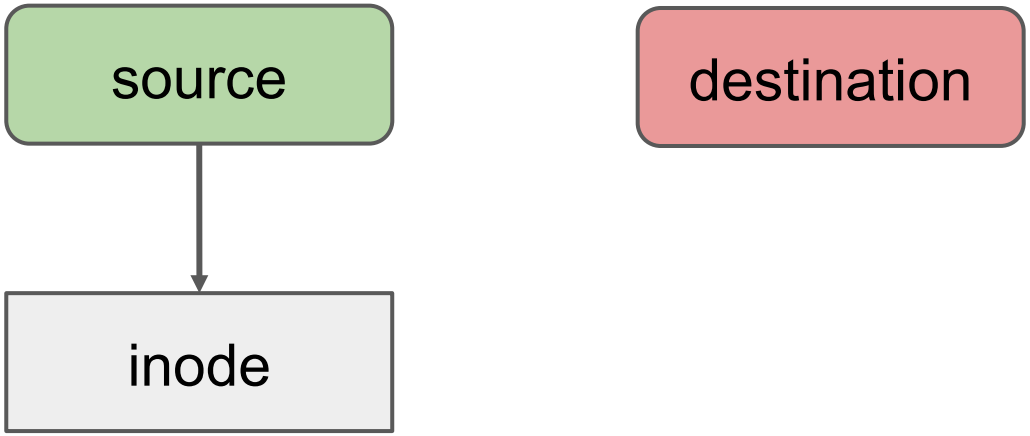
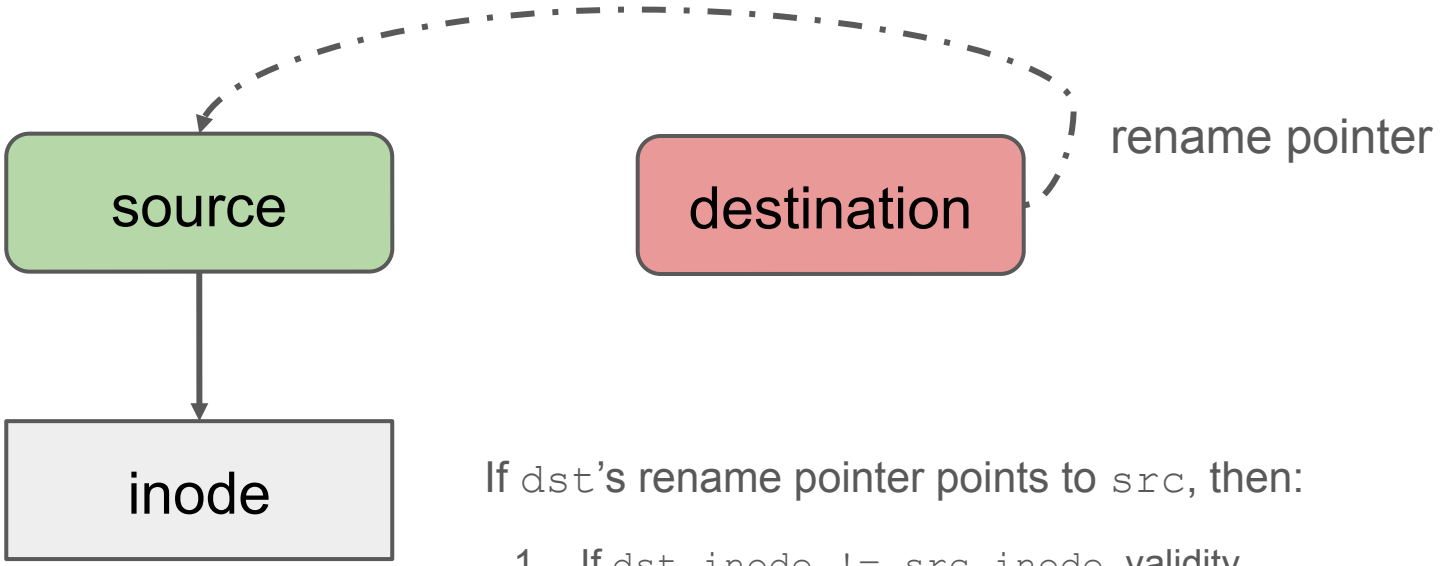


Atomic rename with SSU



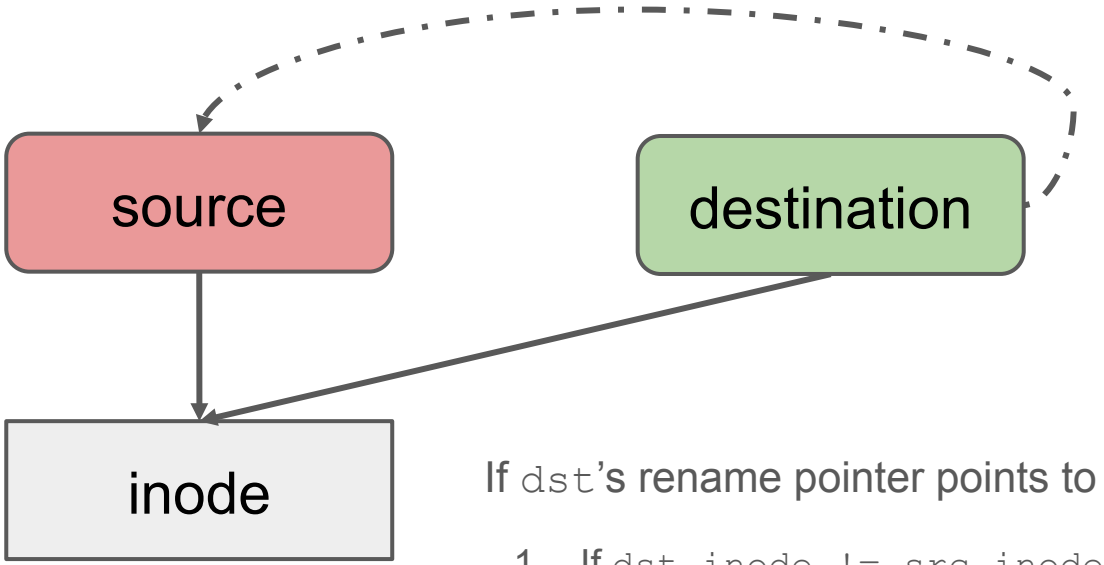
Atomic rename with SSU



If `dst`'s rename pointer points to `src`, then:

1. If `dst.inode != src.inode`, validity determined by inode number
2. If `dst.inode == src.inode`, src is invalid

Atomic rename with SSU



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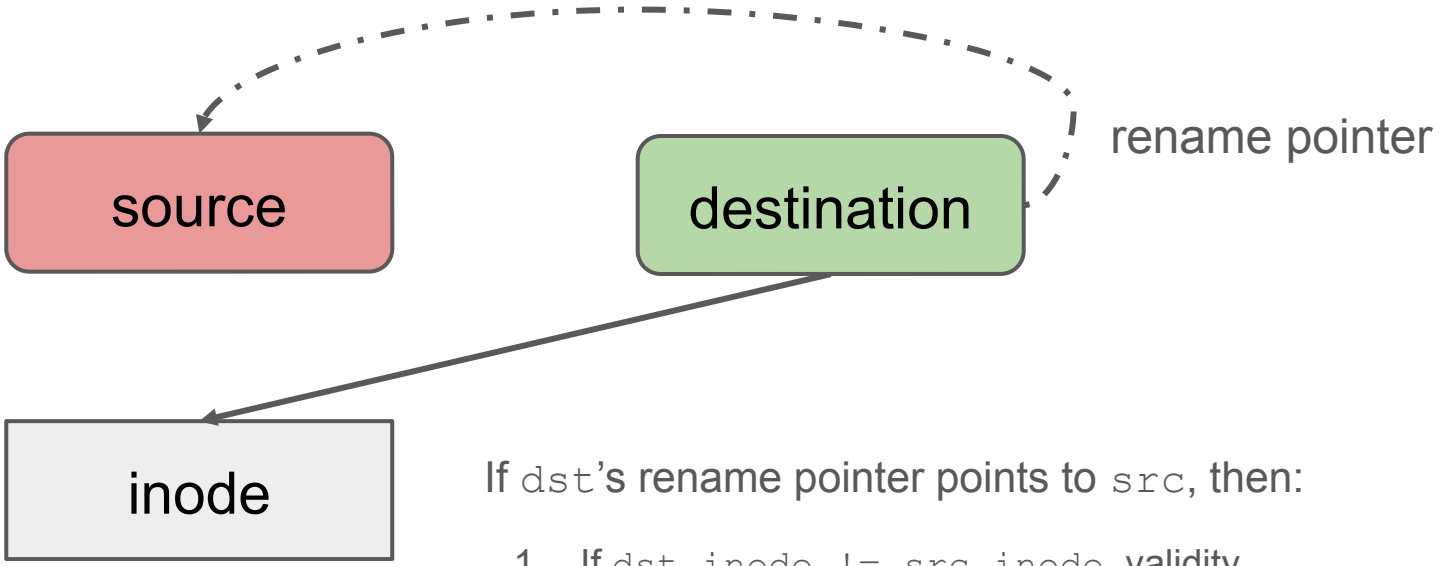

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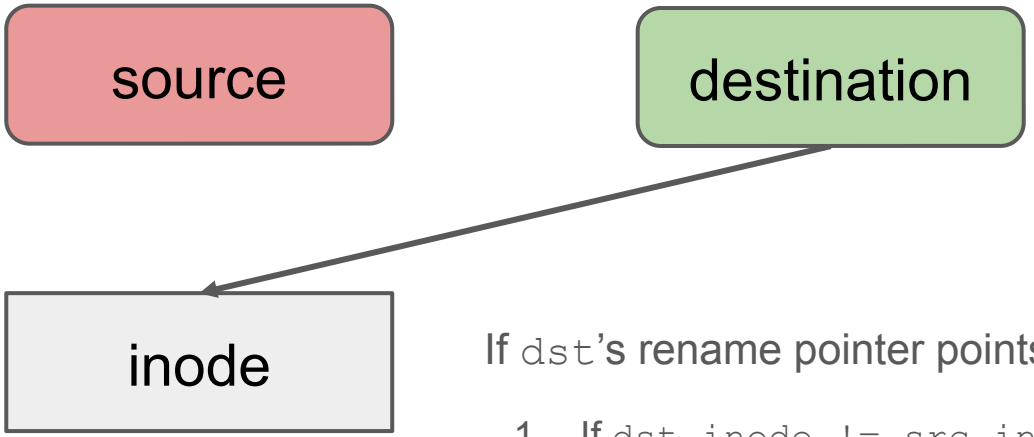

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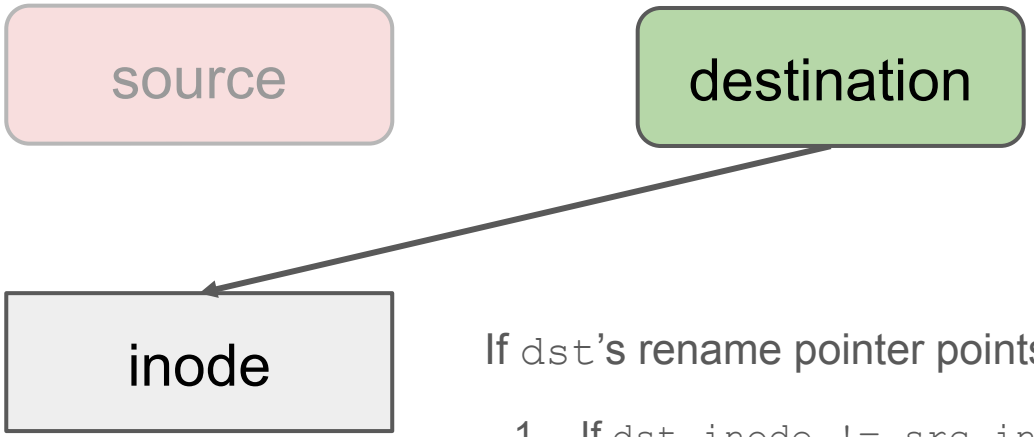

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Typestate in SquirrelFS

Operational typestate

- What operations have been performed on this object?
- Is it free? Initialized? Allocated but not initialized?

Persistence typestate

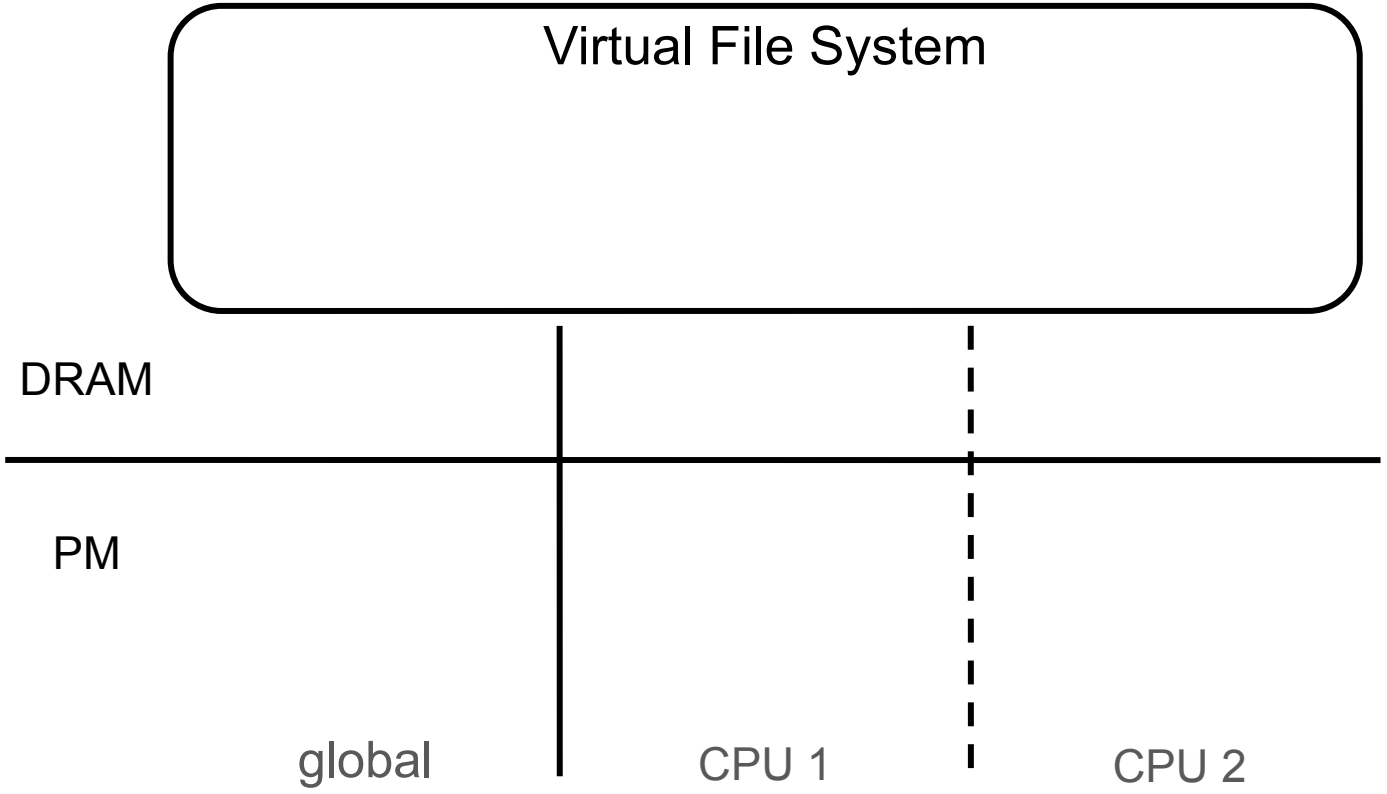
- Have the most recent updates been made durable?

Typestate transition functions make persistent updates and return the new typestate

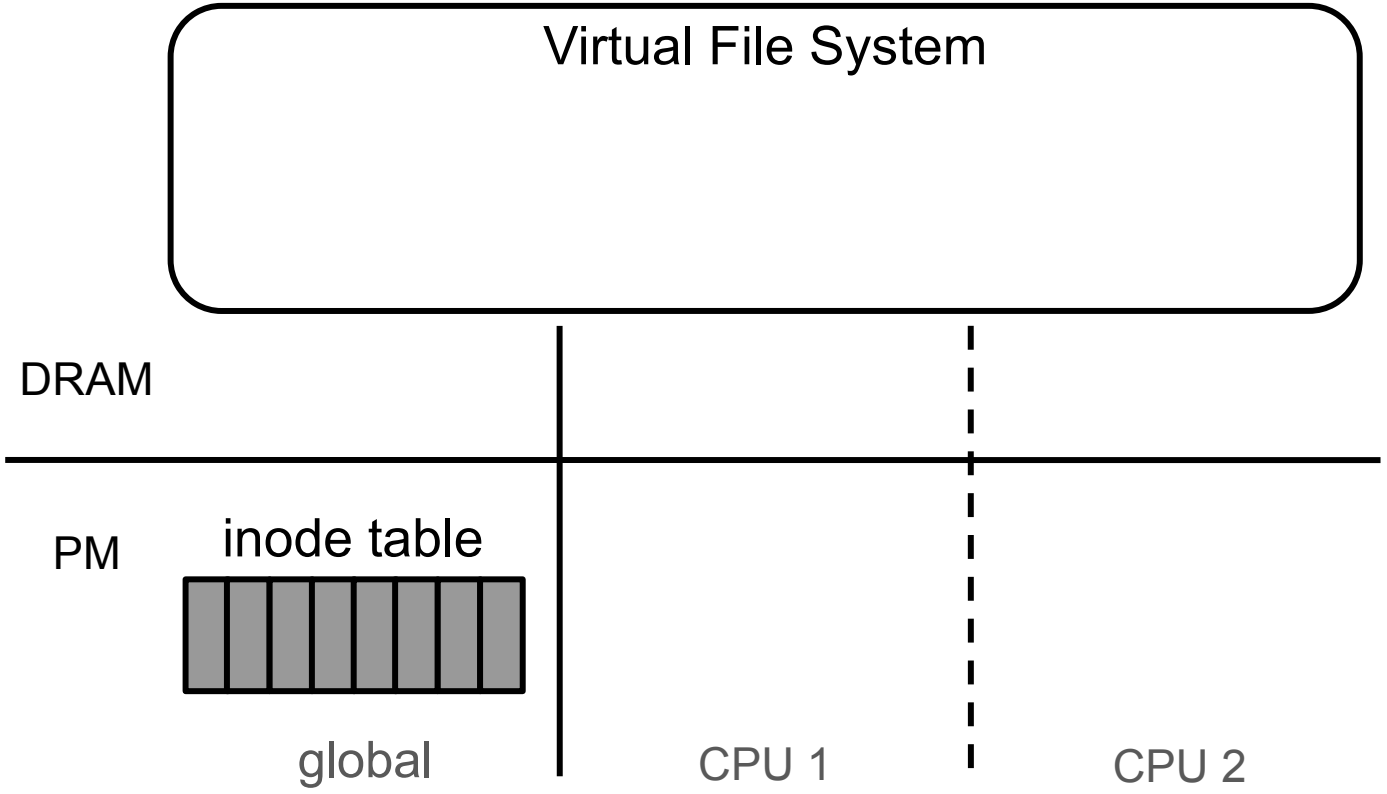
SquirrelFS crash consistency bugs

1. A cache line flush persistence function was passed a reference to a page pointer, rather than the page pointer itself (typestate transition body)
2. Missing case to free orphaned dir pages (recovery code)
3. Allocated but orphaned directory entries towards parent link count (recovery code)
4. Used persistent inode number, rather than inode table index, in inode table scan (recovery code)

SquirrelFS architecture



SquirrelFS architecture



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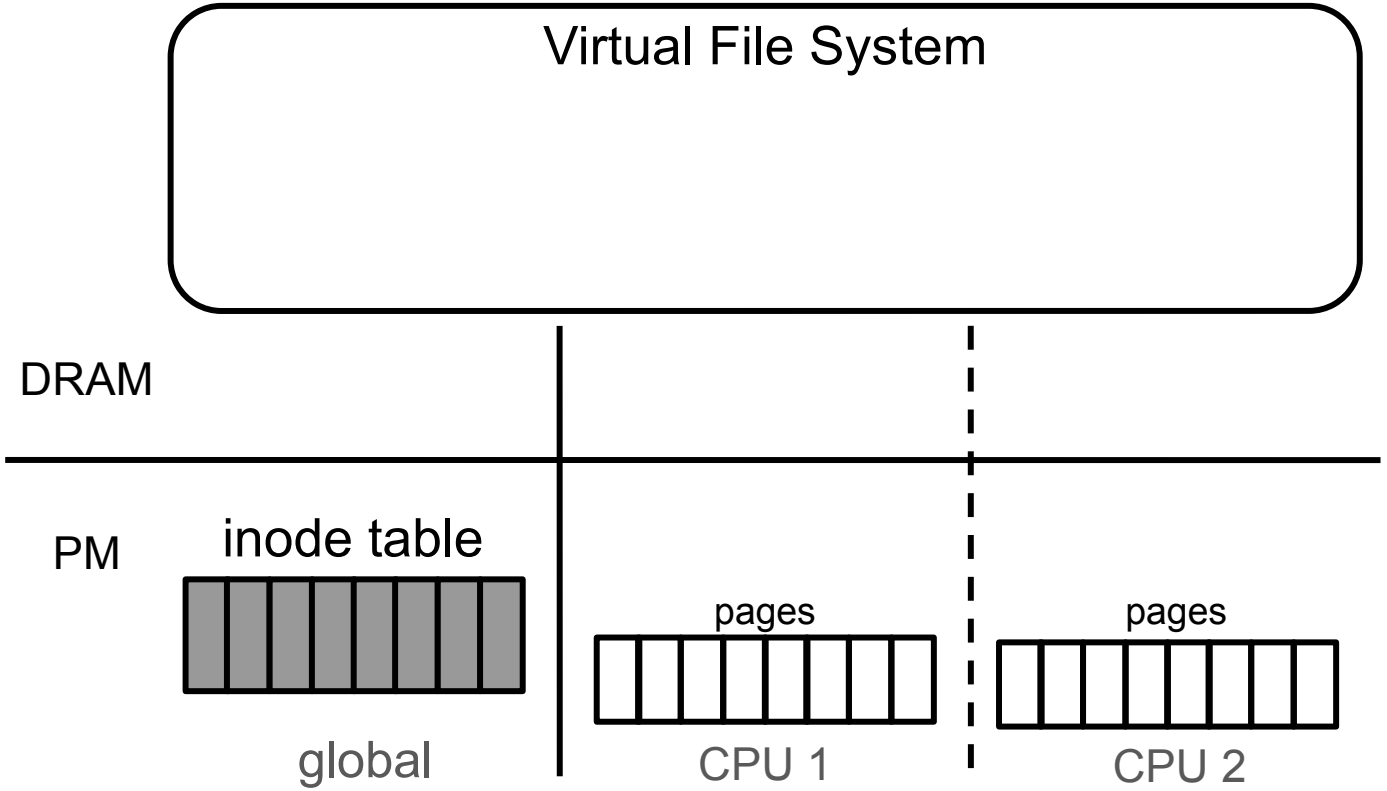

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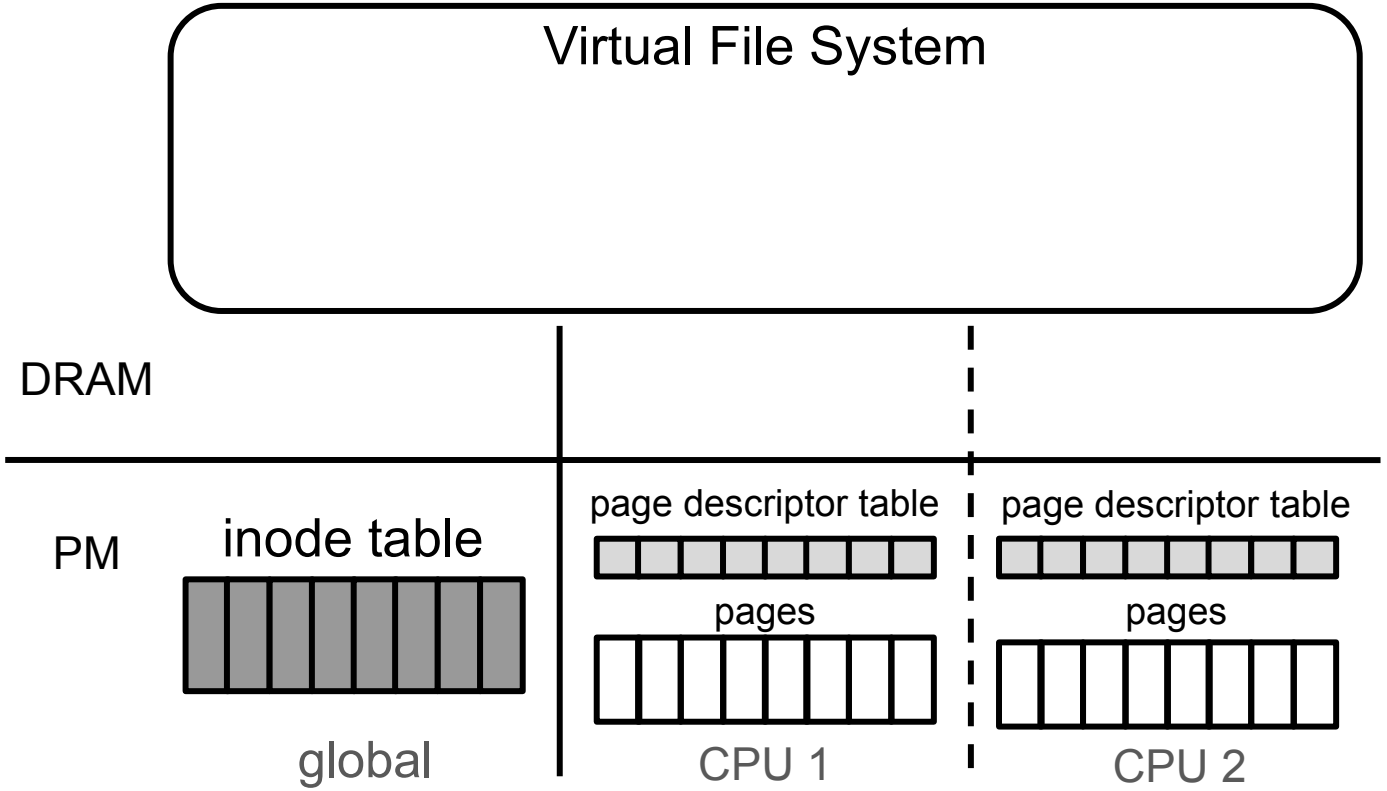

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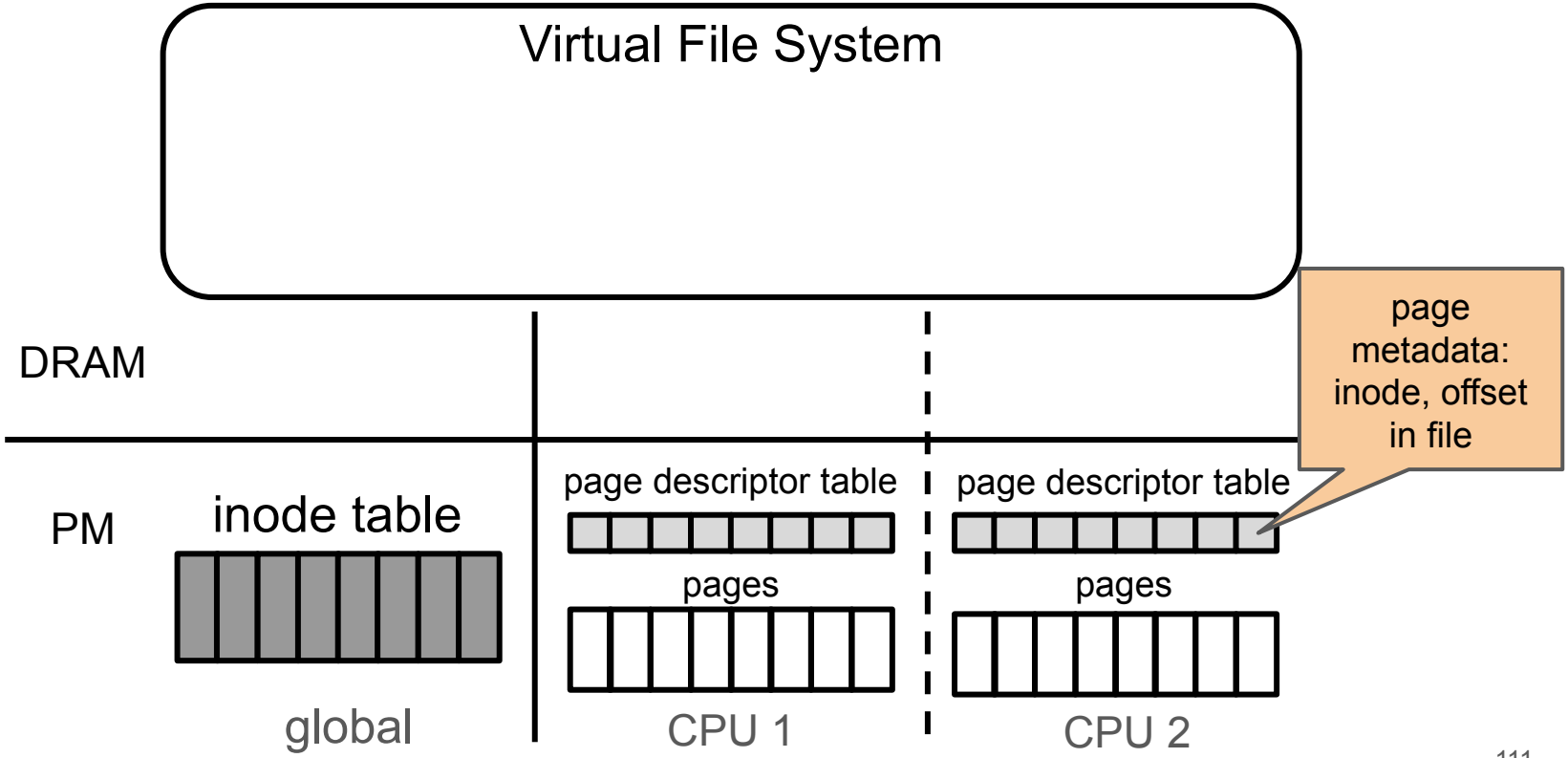

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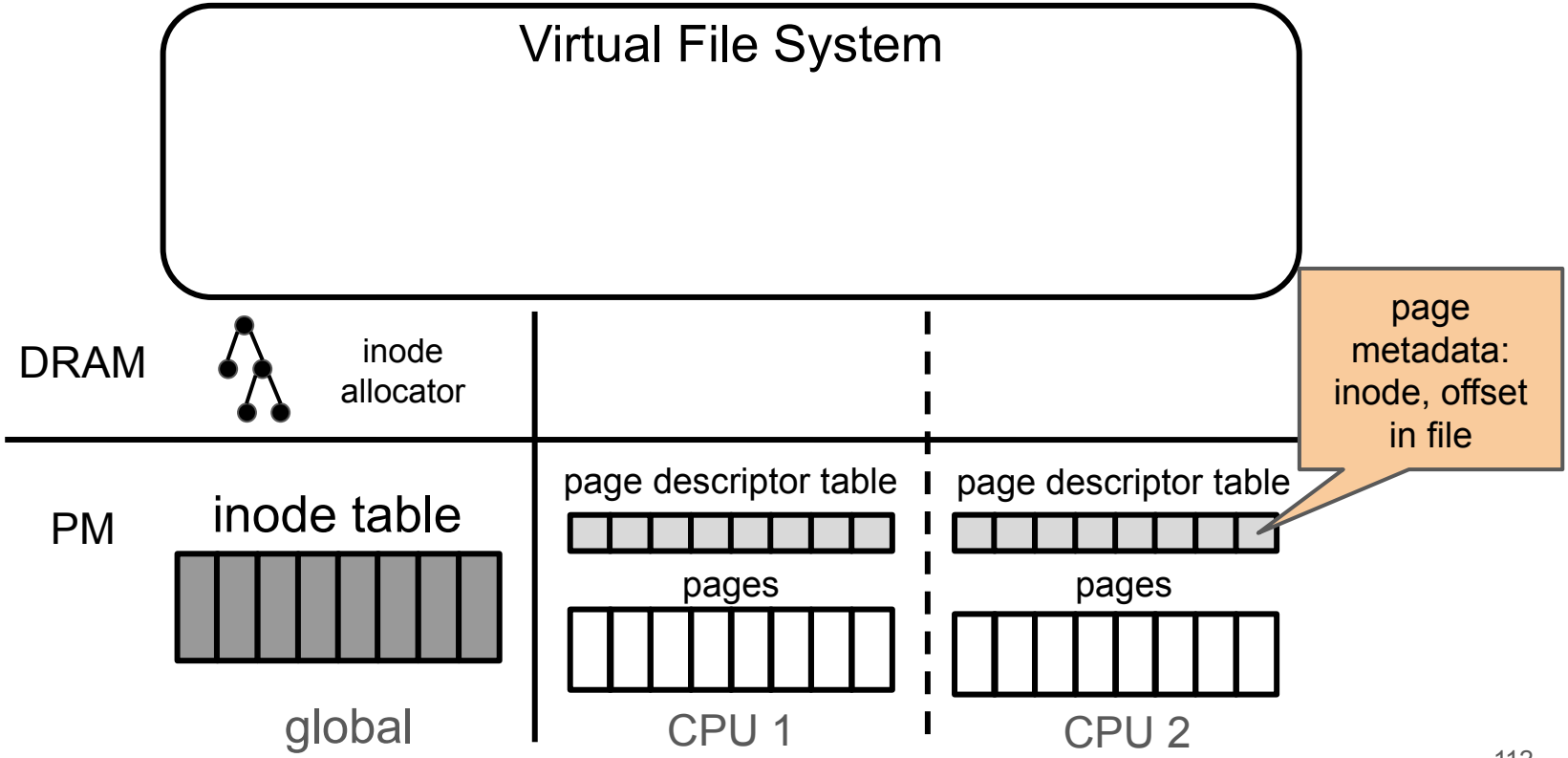

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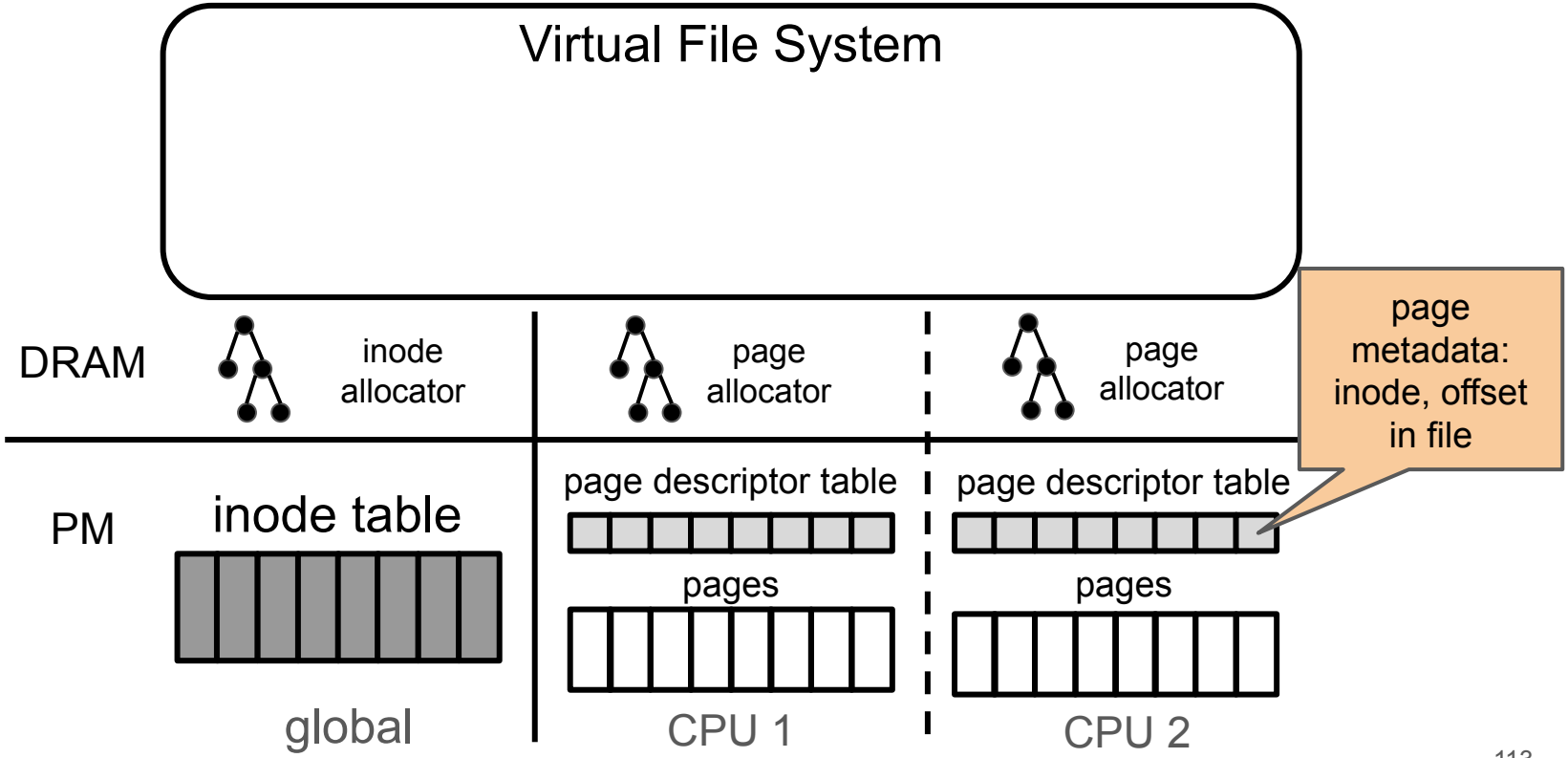

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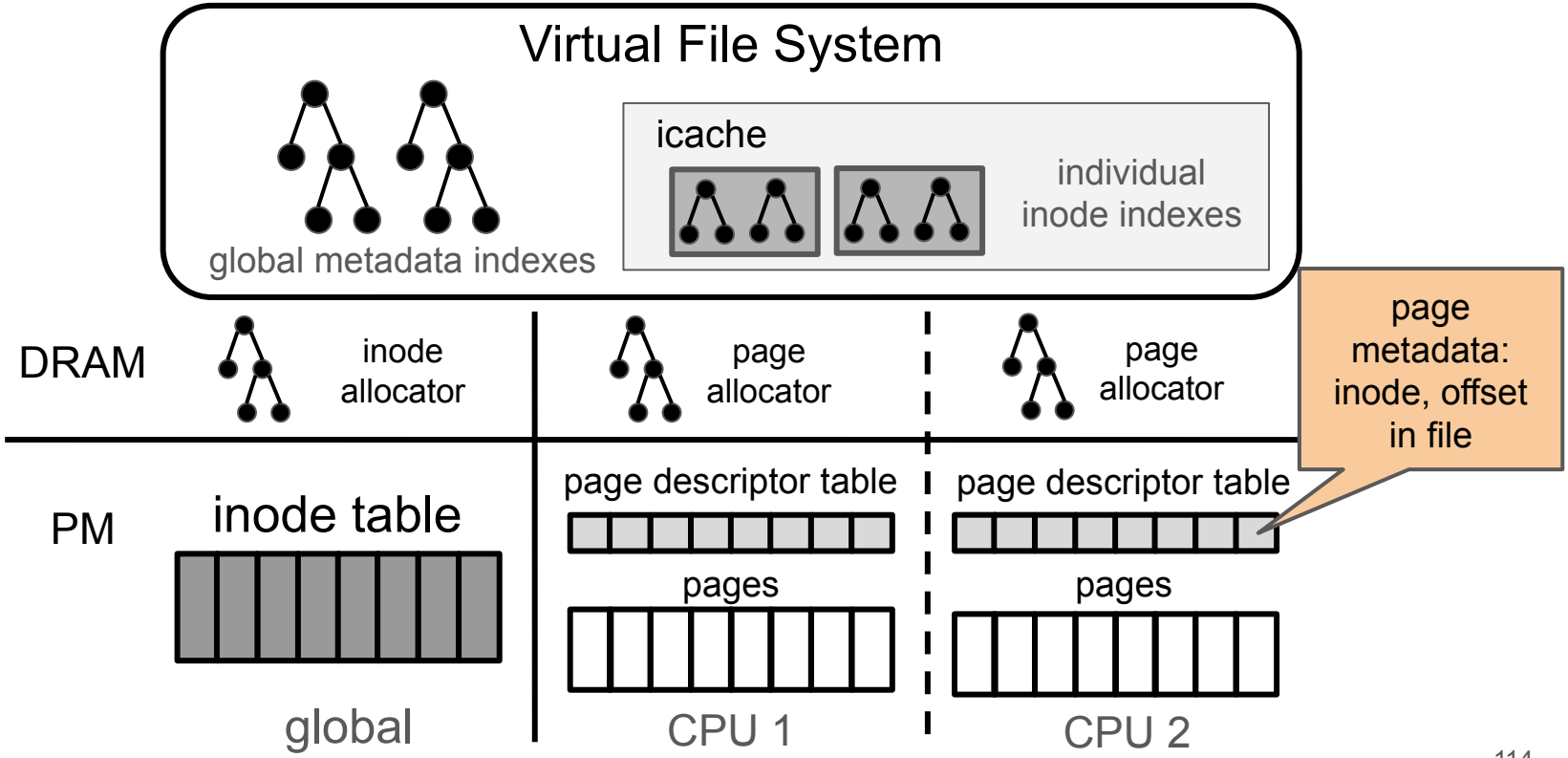


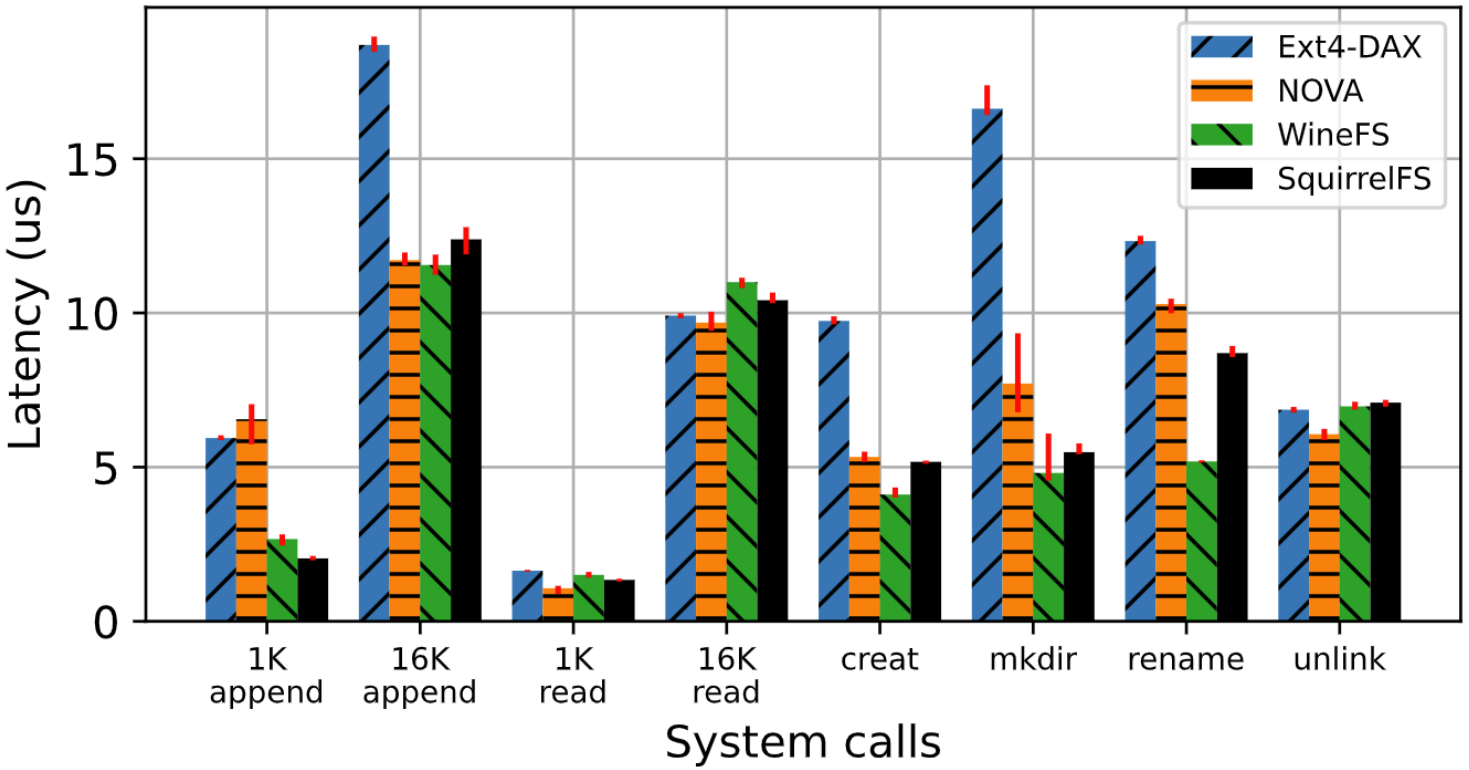
Bugs found with typestate

- Missing persistence primitives
  - E.g.: initial implementation of write was missing flush/fence calls after setting new page backpointer
- Incorrect ordering
  - E.g.: initial rename implementation incorrectly updated link count before clearing a directory entry, which could result in a dangling link later on

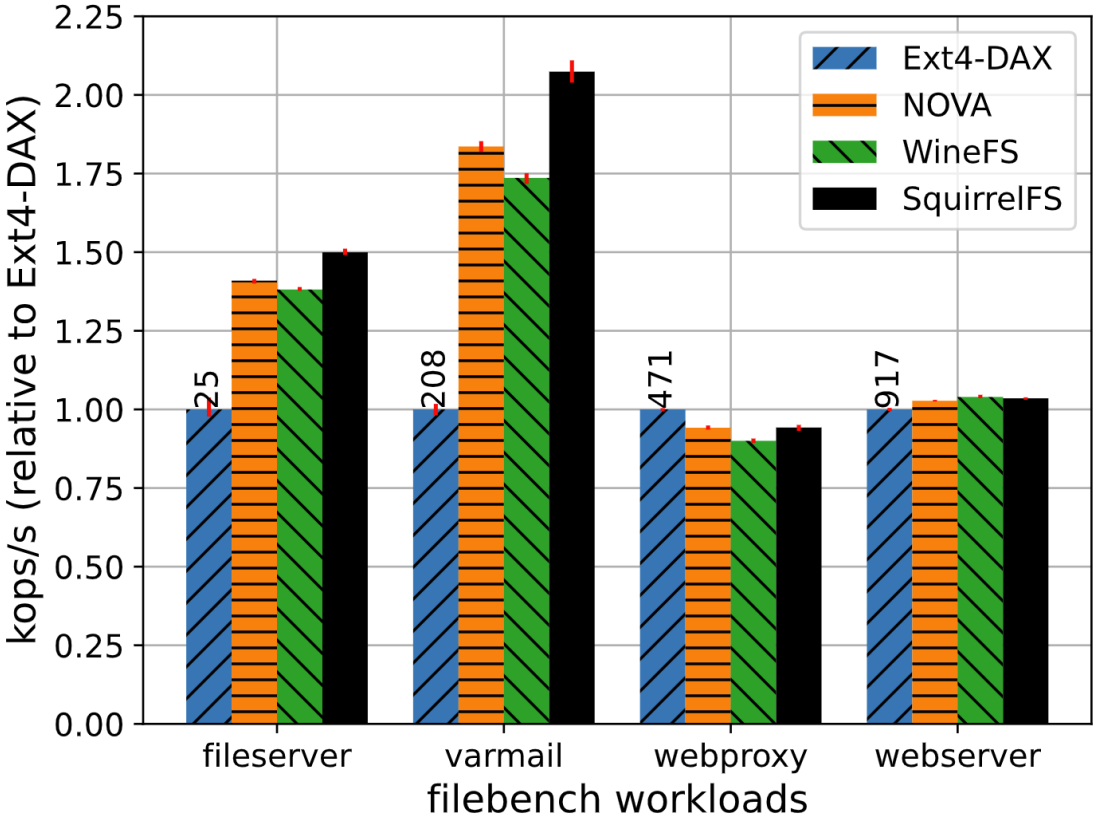
Bugs found with Alloy model

- Recovering from renames
  - Initial model did not include any crash recovery logic; we believed it was not necessary
  - Model found a counterexample where invalid directory entries could reappear after a crash during rename
  - Fixed by adding mandatory post-crash cleanup of rename pointers
- Handling . and .. dentries
  - Originally stored durably and included in update ordering rules
  - Alloy model repeatedly found issues with these rules, particularly during rename
  - Now stored only in volatile memory

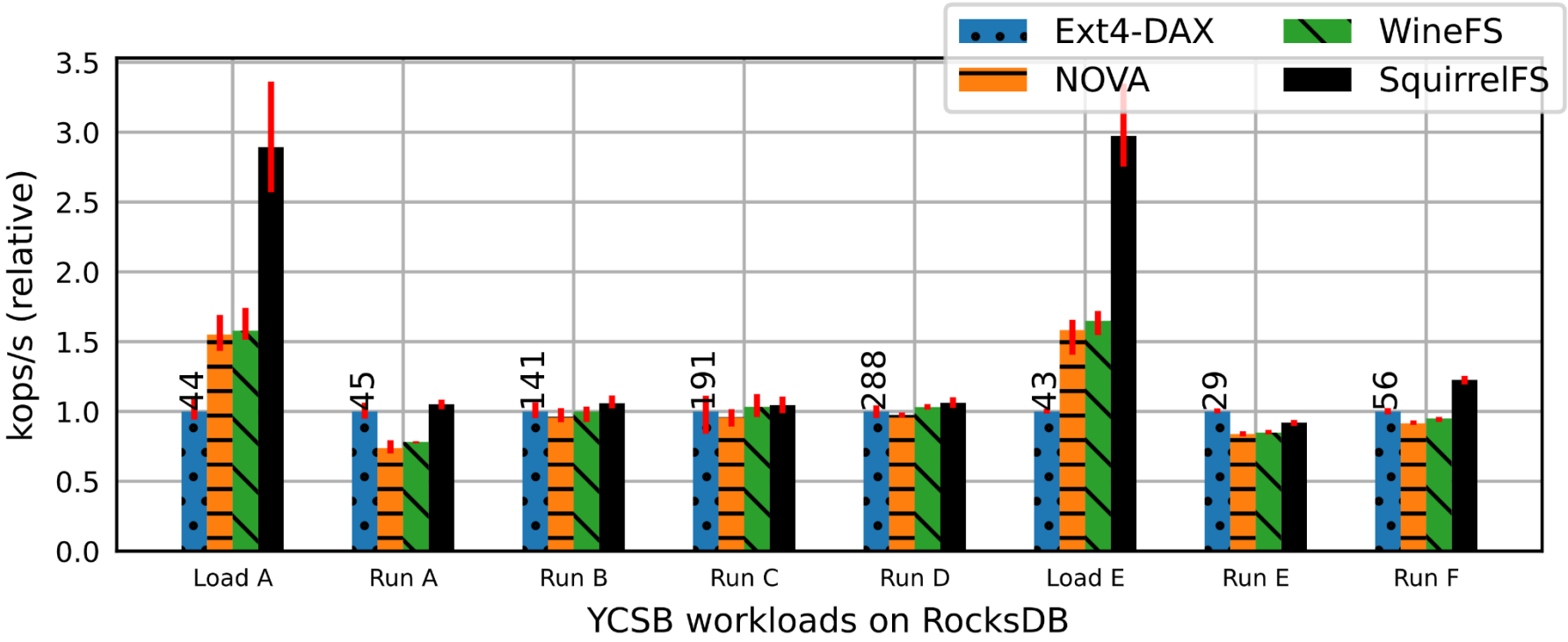
Microbenchmark: system call latency



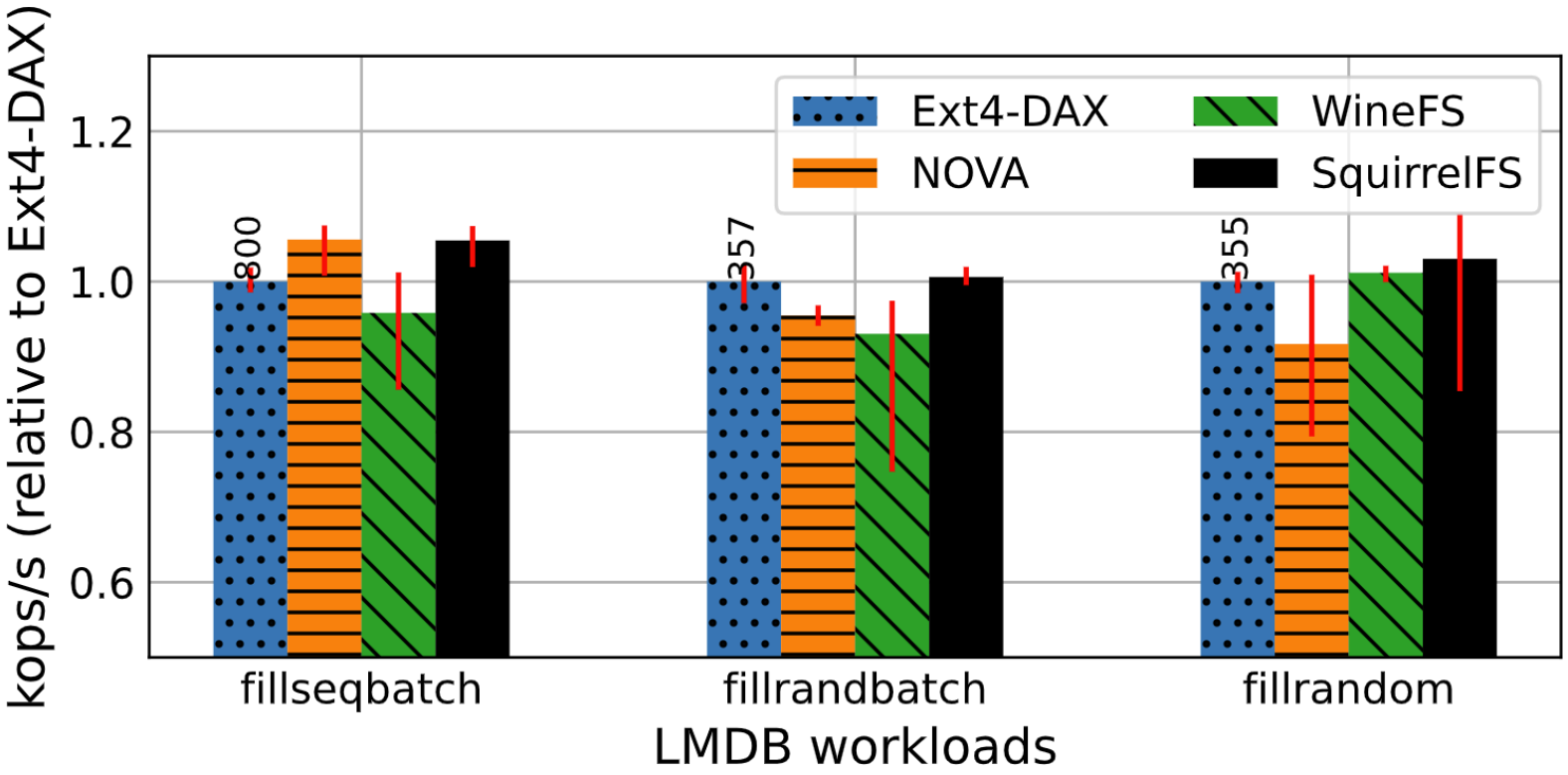
Macrobenchmark: filebench



Application benchmark: RocksDB



Application benchmark: LMDB



SquirrelFS mount times

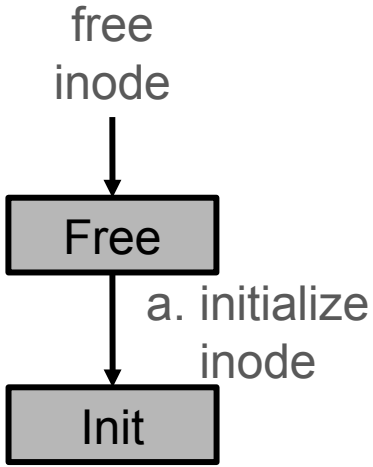
	System state	Mount time (s)
Normal mount	mkfs	5.80
	Empty	5.51
	Full	30.50
Recovery mount	Empty	5.76
	Full	55.50

Synchronous soft updates (SSU)

Soft updates: crash consistency from ordered in-place durable updates

Synchronous soft updates (SSU)

Soft updates: crash consistency from ordered in-place durable updates



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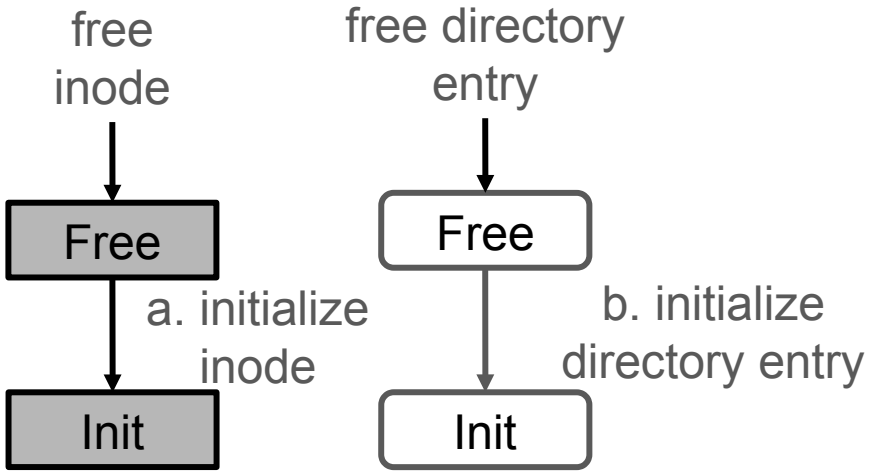

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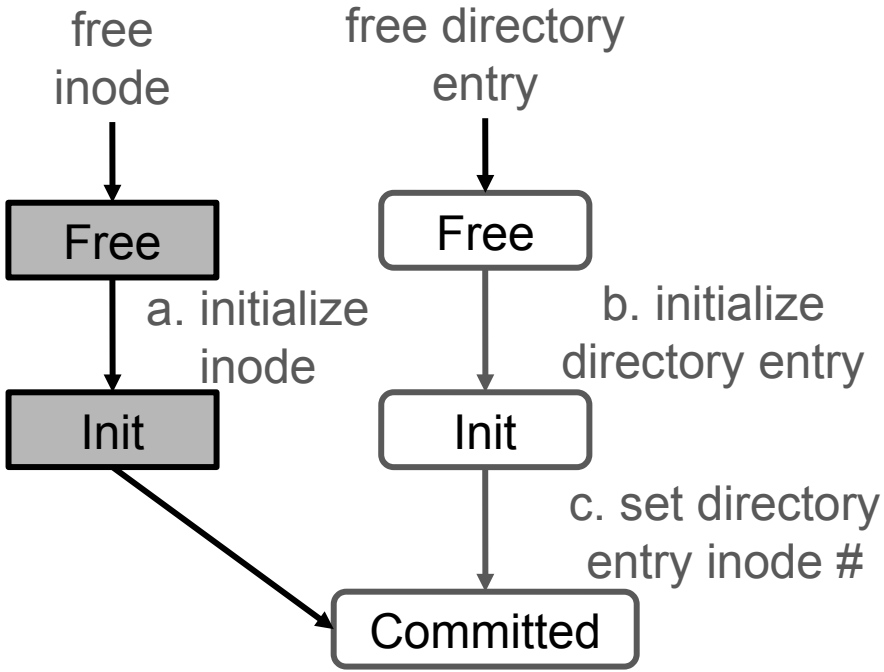

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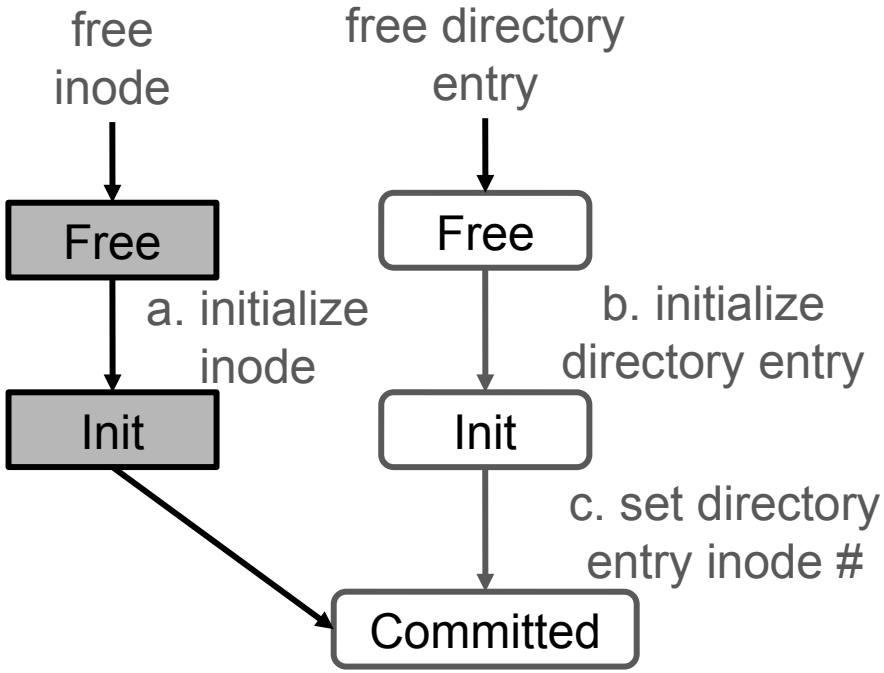
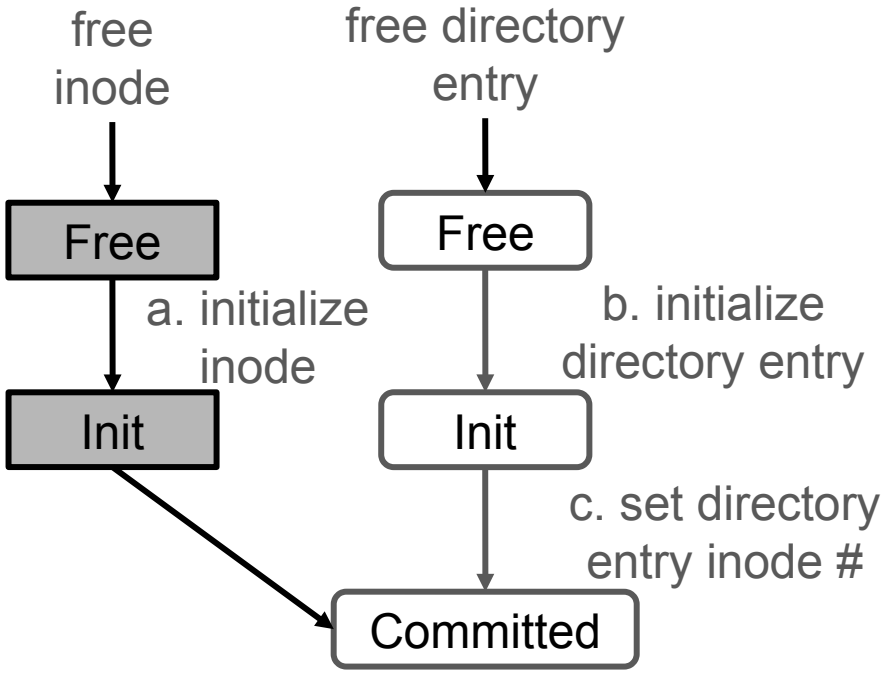


Managing update dependencies in **asynchronous** soft updates is notoriously difficult

Synchronous soft updates (SSU)

Soft updates: crash consistency from ordered in-place durable updates

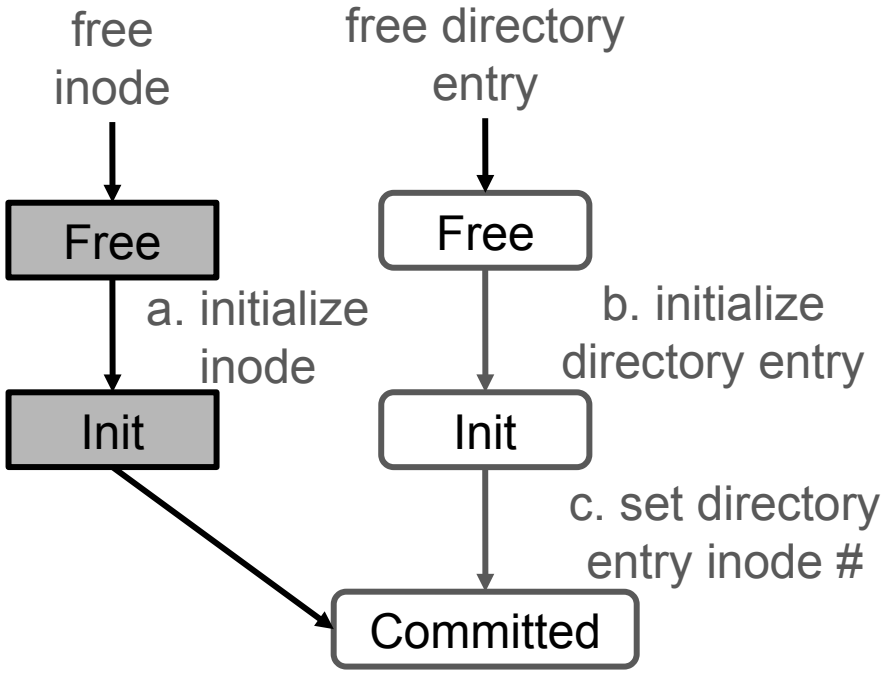


Managing update dependencies in **asynchronous** soft updates is notoriously difficult

Synchronous soft updates eliminates most complexity!

Synchronous soft updates (SSU)

Soft updates: crash consistency from ordered in-place durable updates

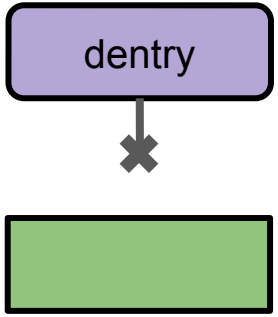


Managing update dependencies in **asynchronous** soft updates is notoriously difficult

Synchronous soft updates eliminates most complexity!

Fast **persistent memory** storage enables performant synchrony

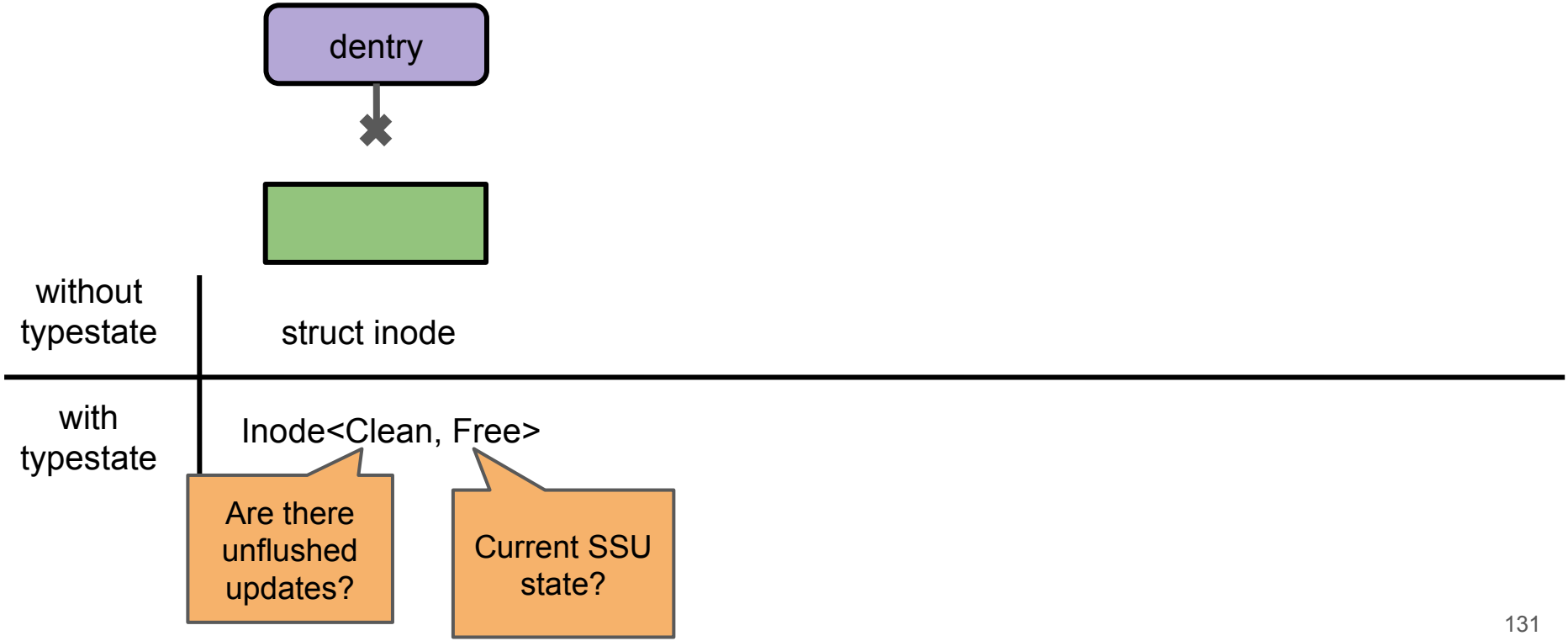
The typestate pattern



without typestate	struct inode
with typestate	Inode<Clean, Free>

The typestate pattern

The typestate pattern



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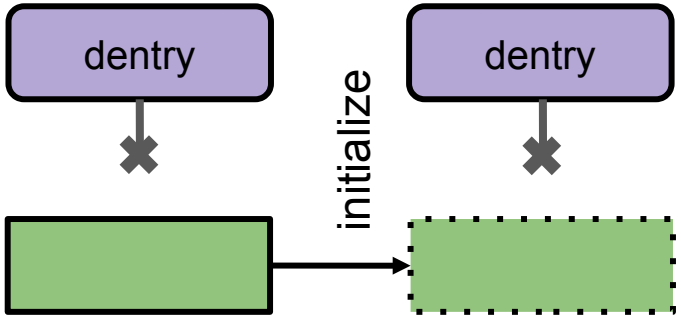


without typestate

struct inode

struct inode

with typestate

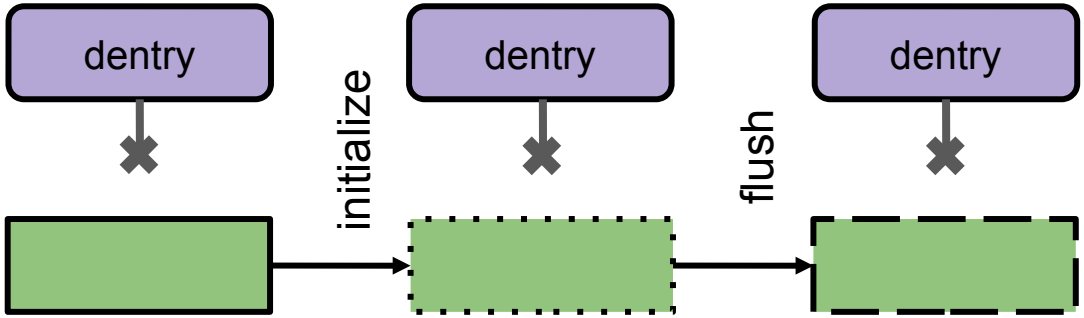
Inode<Clean, Free>

Inode<Dirty, Init>

Are there unflushed updates?

Current SSU state?

The typestate pattern



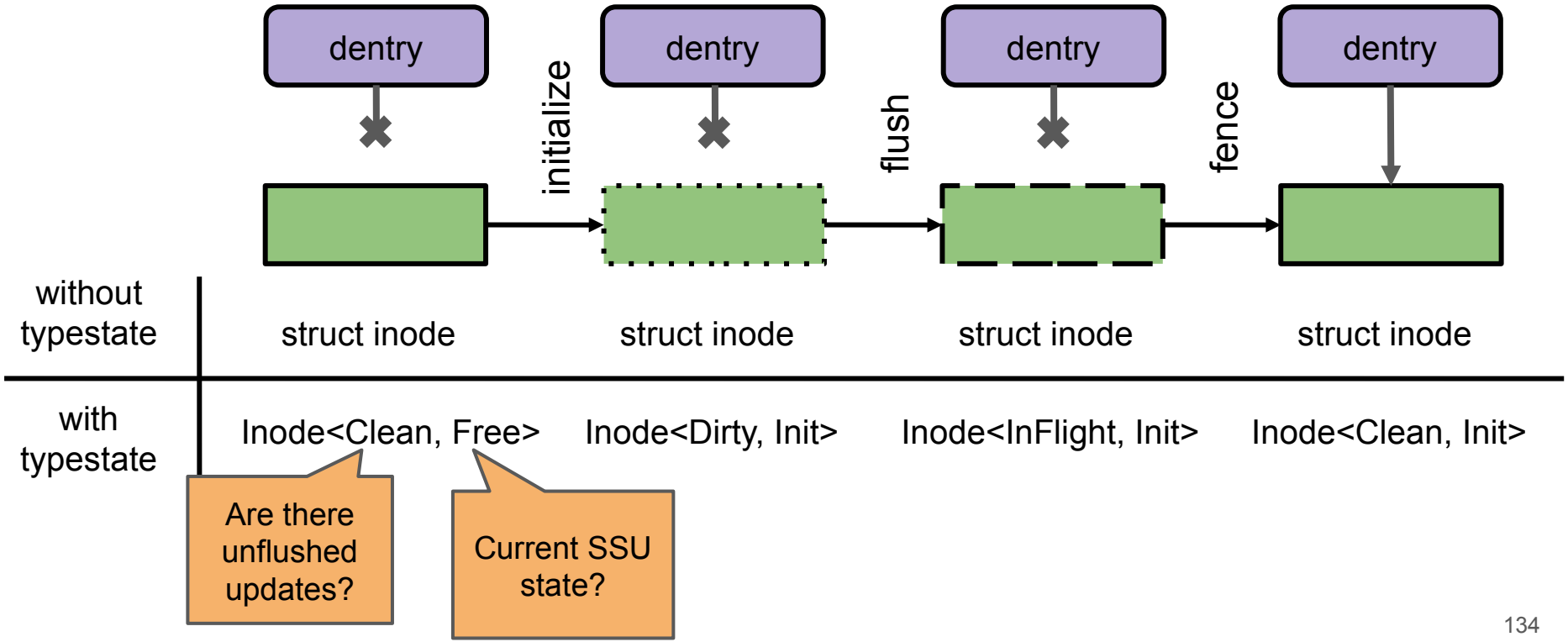
without typestate: struct inode | struct inode | struct inode

with typestate: Inode<Clean, Free> | Inode<Dirty, Init> | Inode<InFlight, Init>

Are there unflushed updates?

Current SSU state?

The typestate pattern



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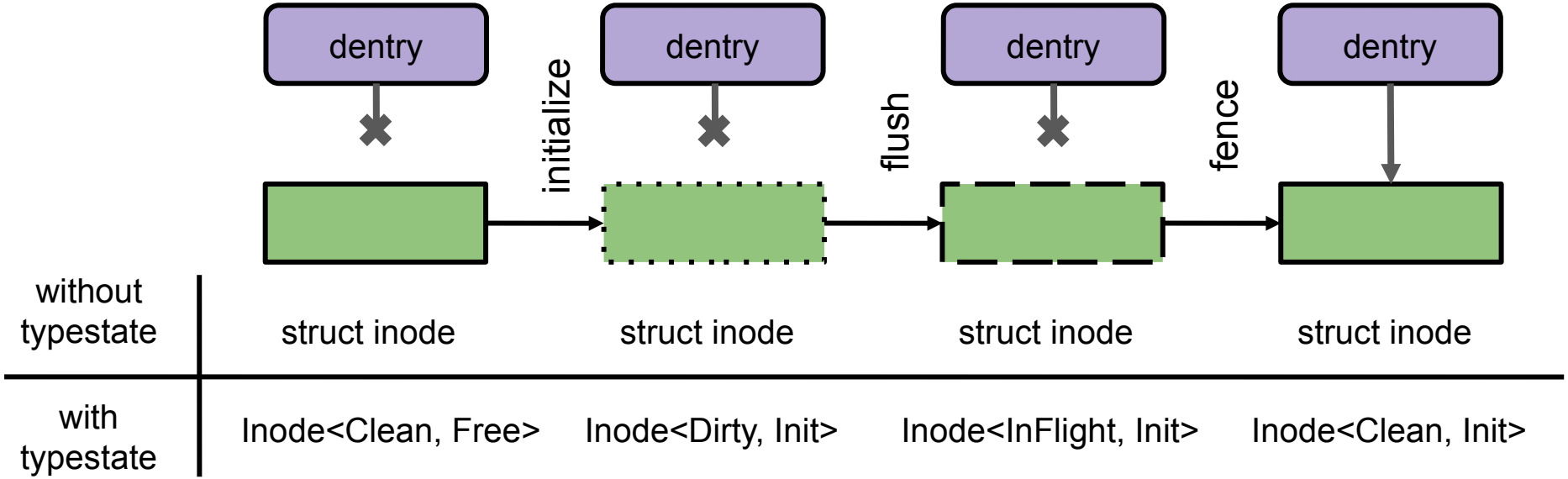

Ordering encoded in function signatures:

```
impl Inode<Clean,Free> {fn init(self) -> Inode<Dirty, Init> {...}}
```