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

Hayley LeBlanc, Nathan Taylor,
James Bornholt, Vijay Chidambaram

TEXAS
The University of Texas at Austin

Current approaches to ensuring crash consistency

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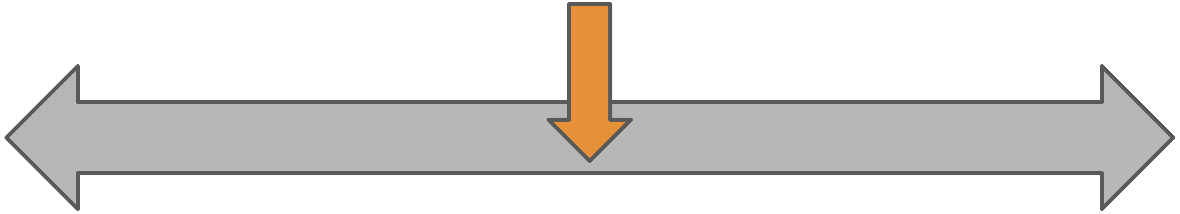

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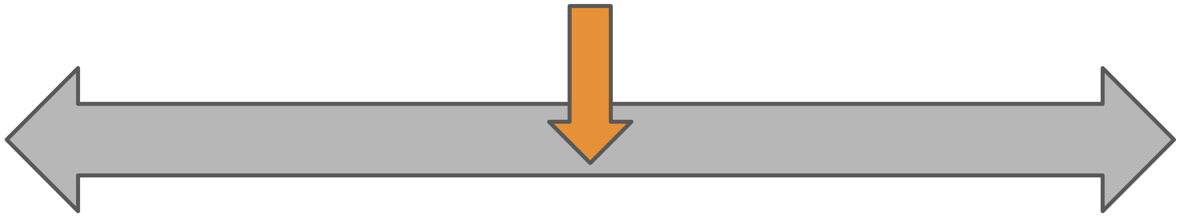

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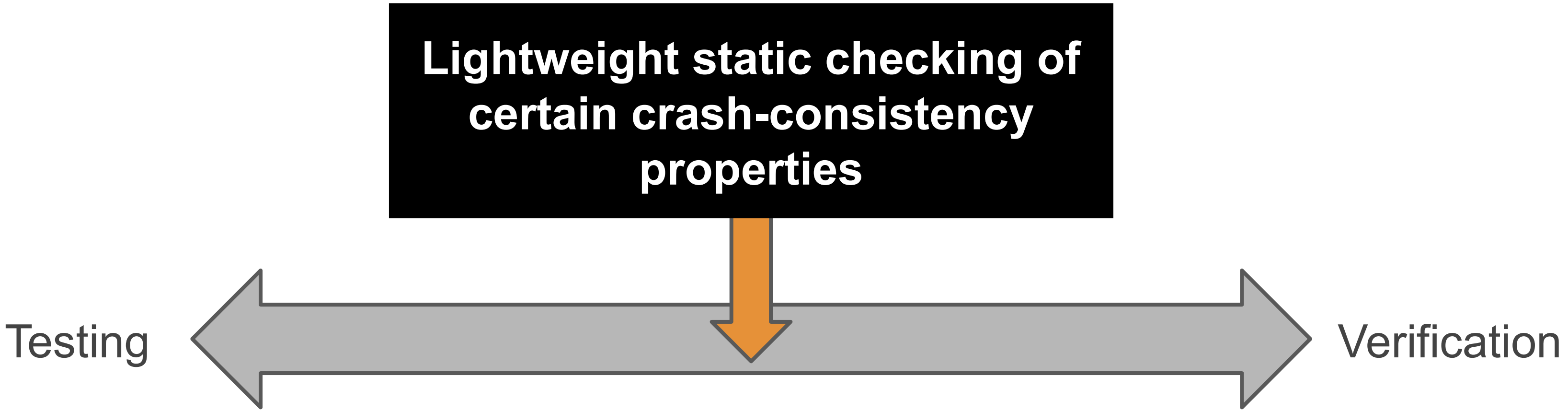
Lightweight static checking of certain crash-consistency properties
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High-performance, low-level systems programming language

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Atomicity of system calls

SquirrelFS

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Persistent memory file system with **statically-checked ordering-related crash-consistency properties**

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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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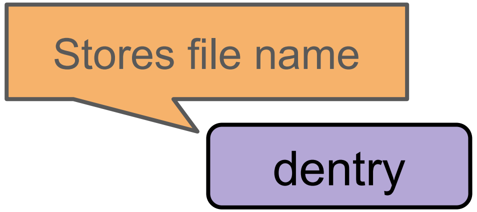

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Stores file name
dentry
Stores file metadata
inode

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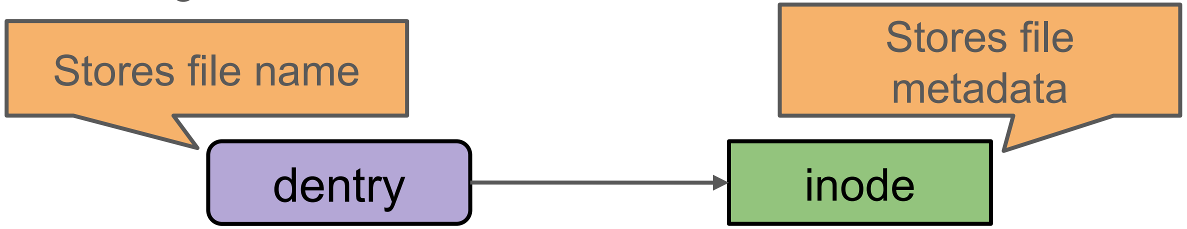

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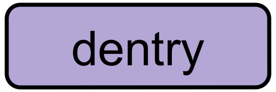

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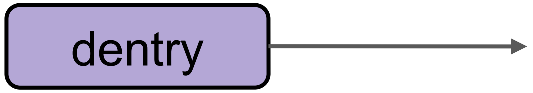

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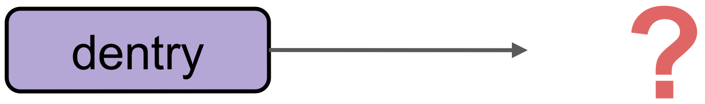

Setting dentry pointer depends on inode initialization

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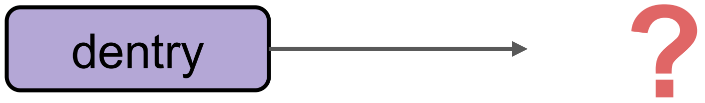

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Statically enforcing durable update ordering can prevent many crash-consistency bugs

Soft updates

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

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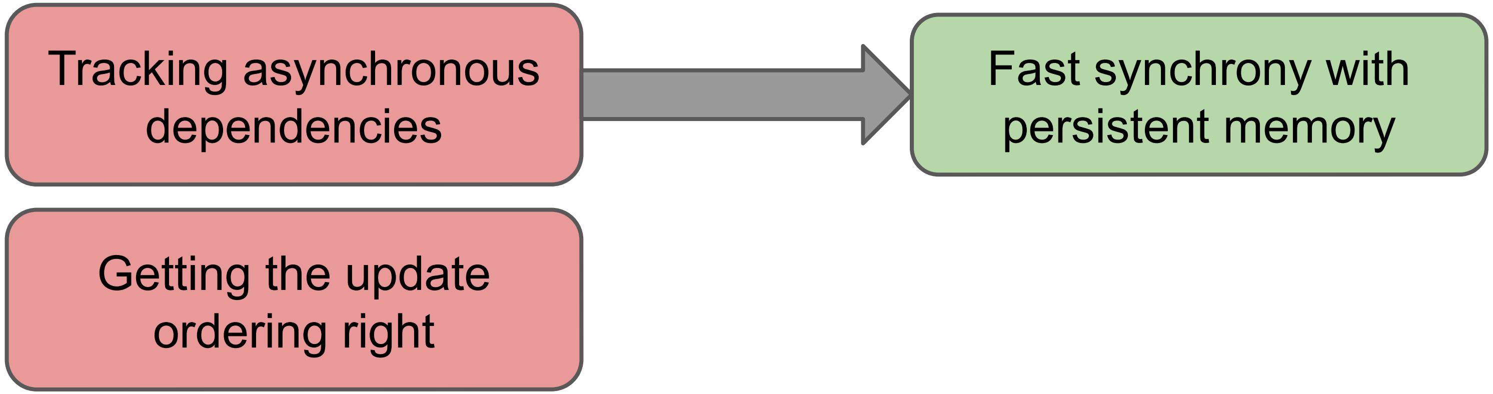
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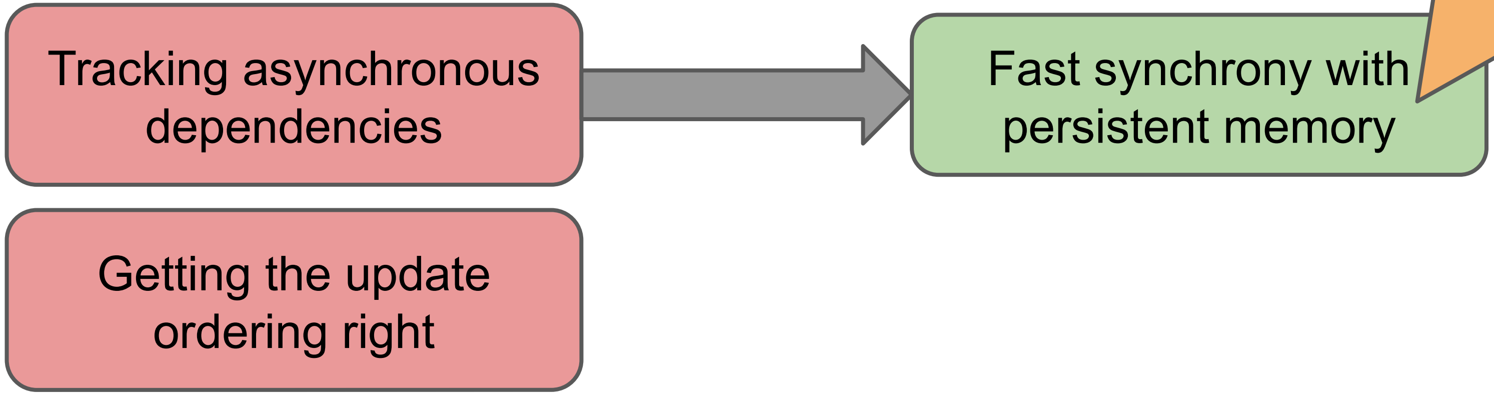
Low-latency durable storage devices with DRAM-like interface

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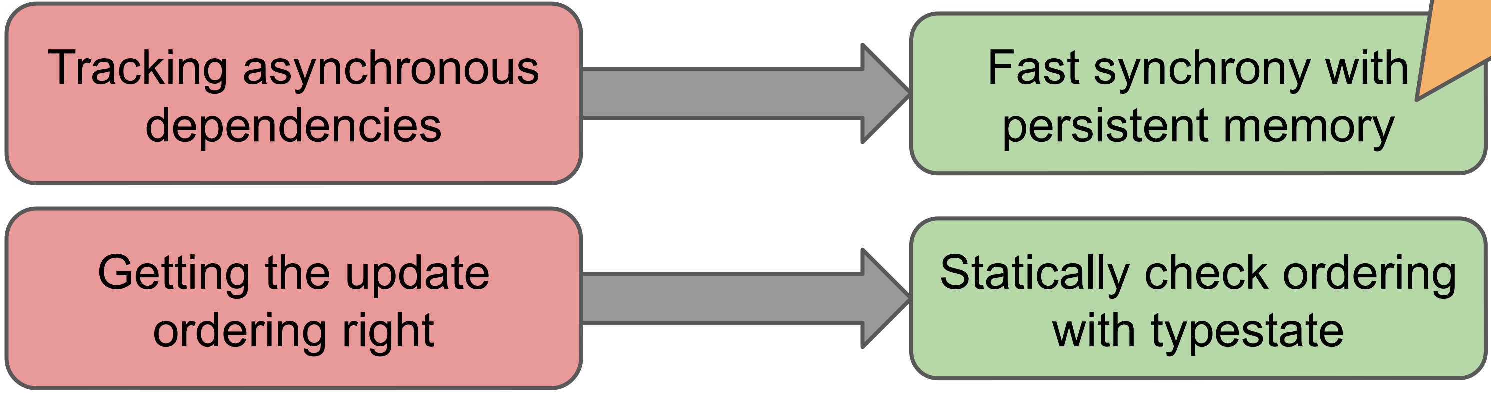
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Roadmap

The typestate pattern

Encode runtime state in an object’s type with no runtime overhead

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```
fn init_inode(i: &mut Inode)
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fn init_inode(i: Inode<Free>)
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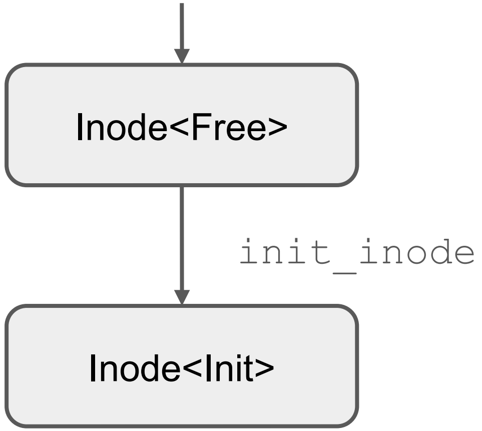

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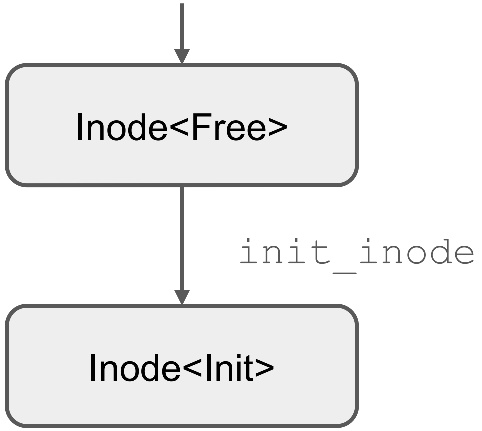

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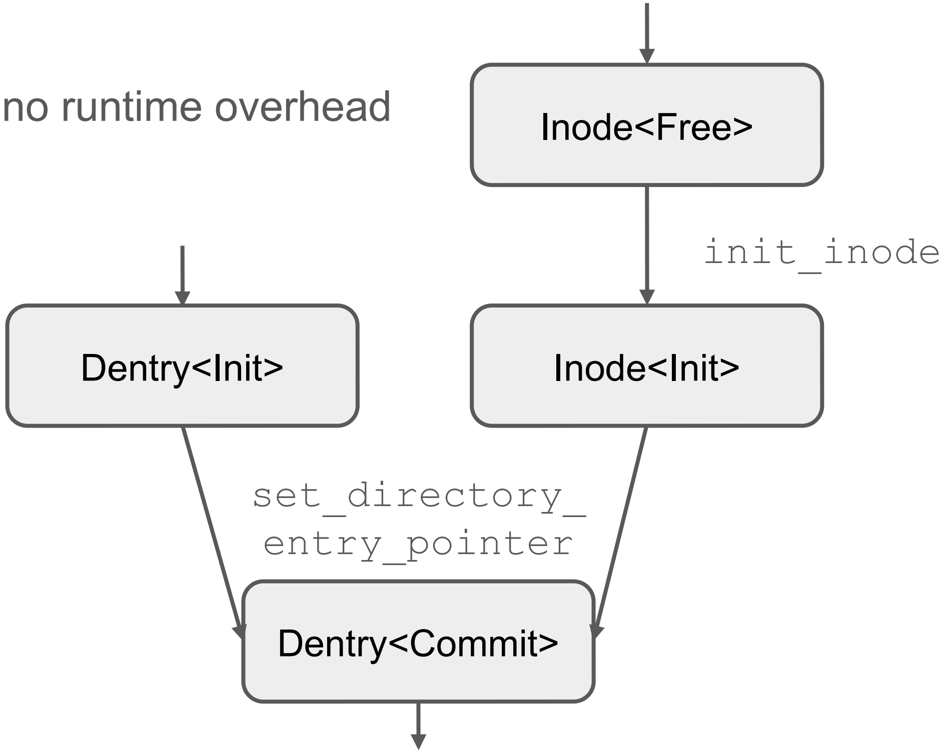

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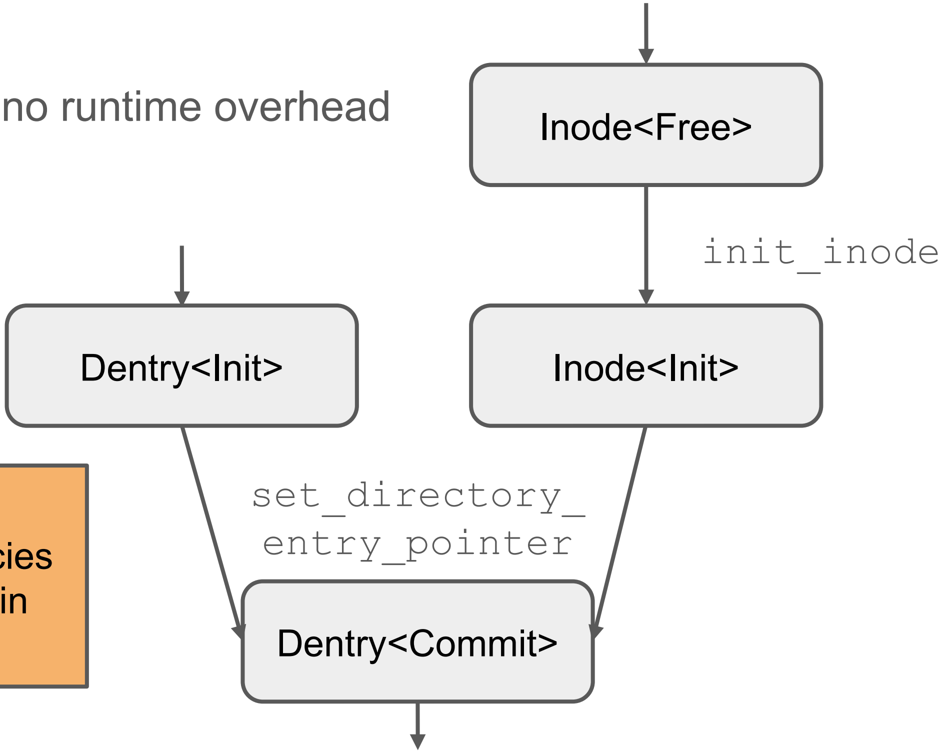
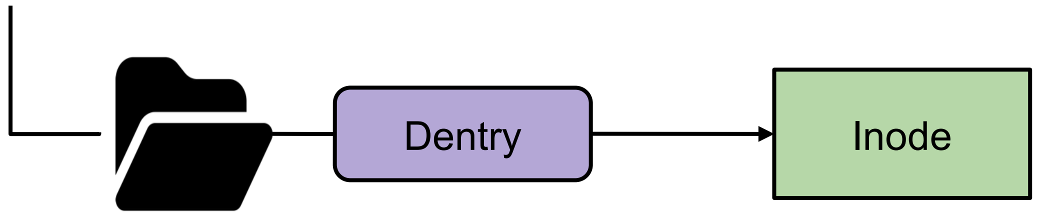


Typestate for crash consistency



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    let d = Dentry::get_free_dentry(); // obtain Dentry<Free>
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    let d = d.set_name(name); // Dentry<Free> -> Dentry<Init>
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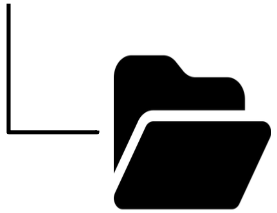

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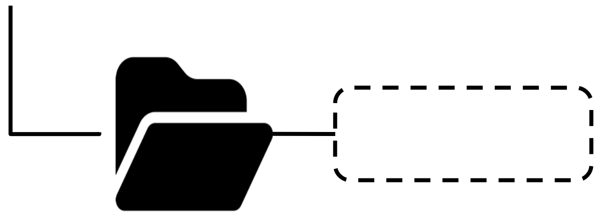

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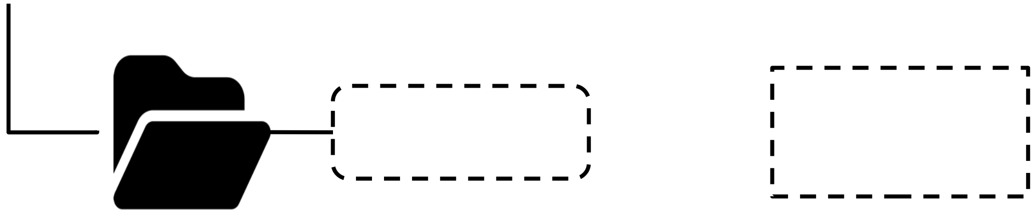

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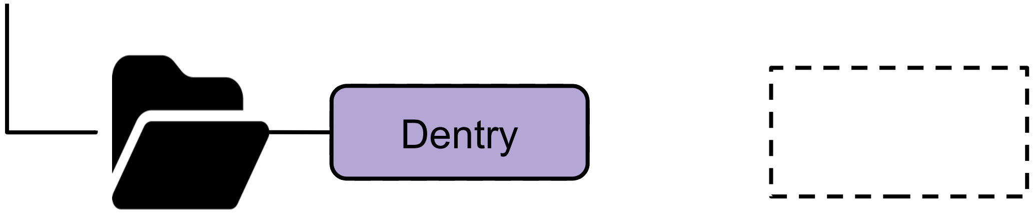

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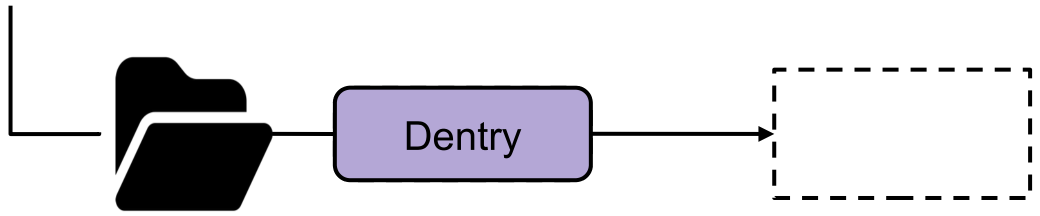

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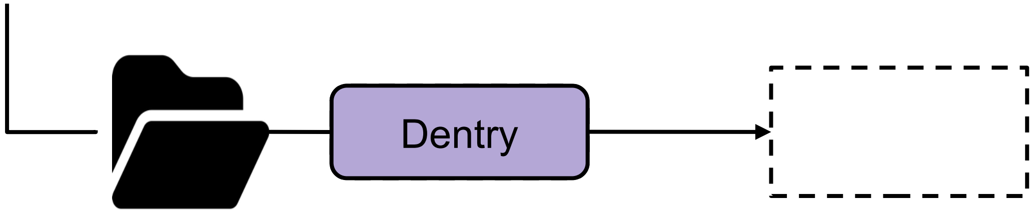

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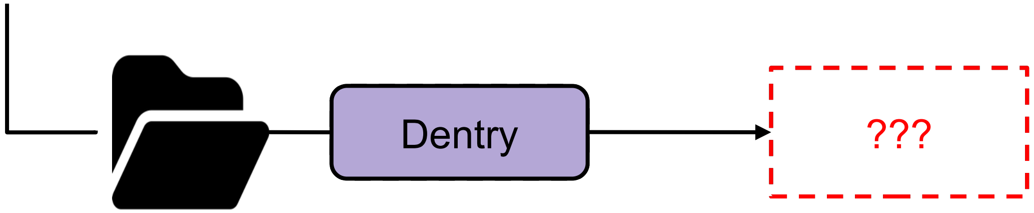

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```

```
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>`
```

Roadmap

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

Roadmap

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5. **Evaluation**

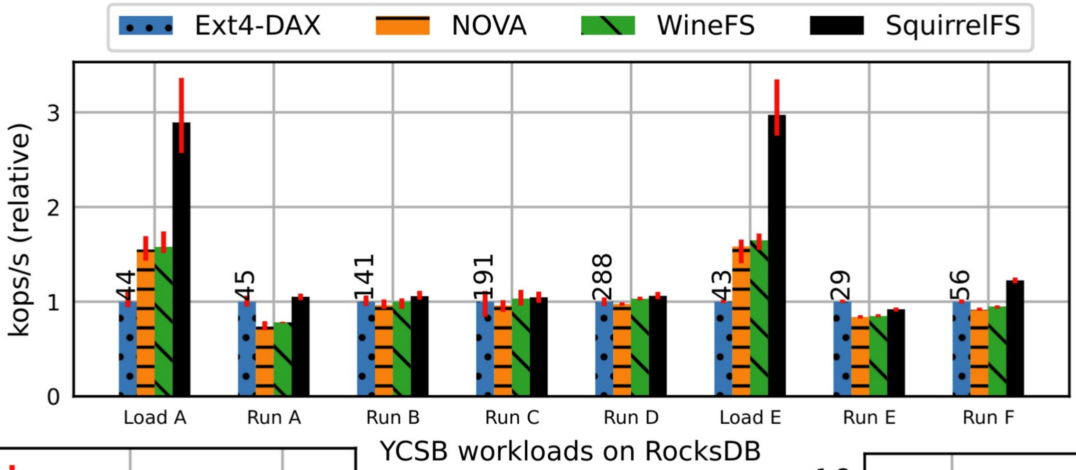
Evaluation

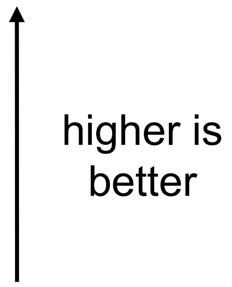
Evaluated on 128GB Intel Optane DC Persistent Memory Module

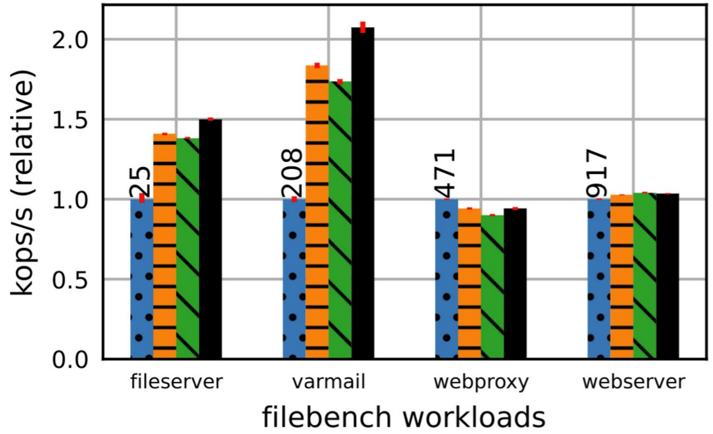
Compared against **Ext4-DAX**, **NOVA**, and **WineFS**

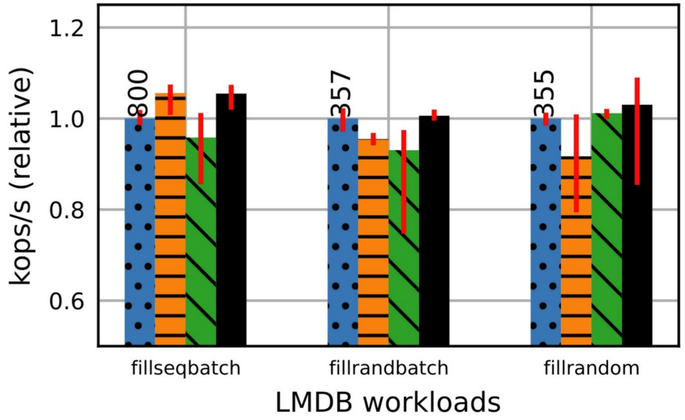
1. How does SquirrelFS compare to other PM file systems?
2. How long does it take to statically check SquirrelFS's crash-consistency properties?

SquirrelFS performance









Compilation and verification times

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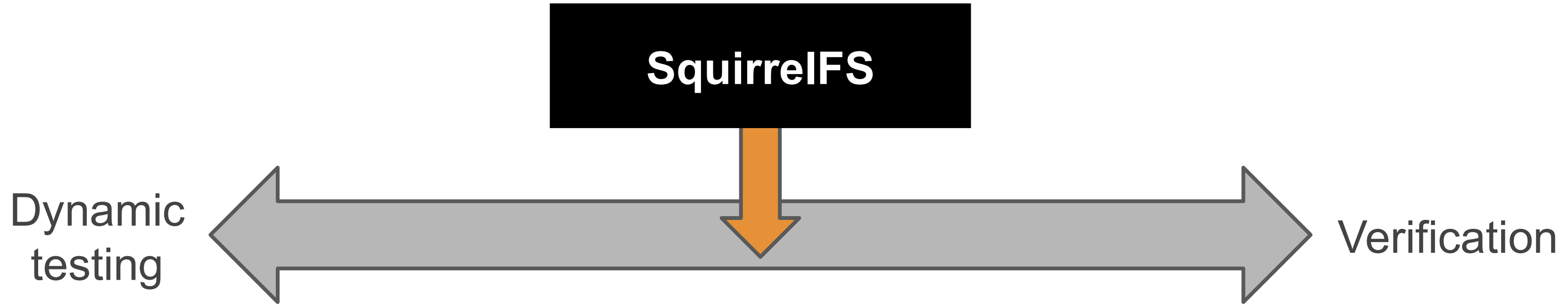
System (typestate-checked)	Lines of code	Compile+check time (s)
SquirrelFS	**7.5K**	**10**

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

ARTIFACT EVALUATED usenix ASSOCIATION AVAILABLE

ARTIFACT EVALUATED usenix ASSOCIATION FUNCTIONAL

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

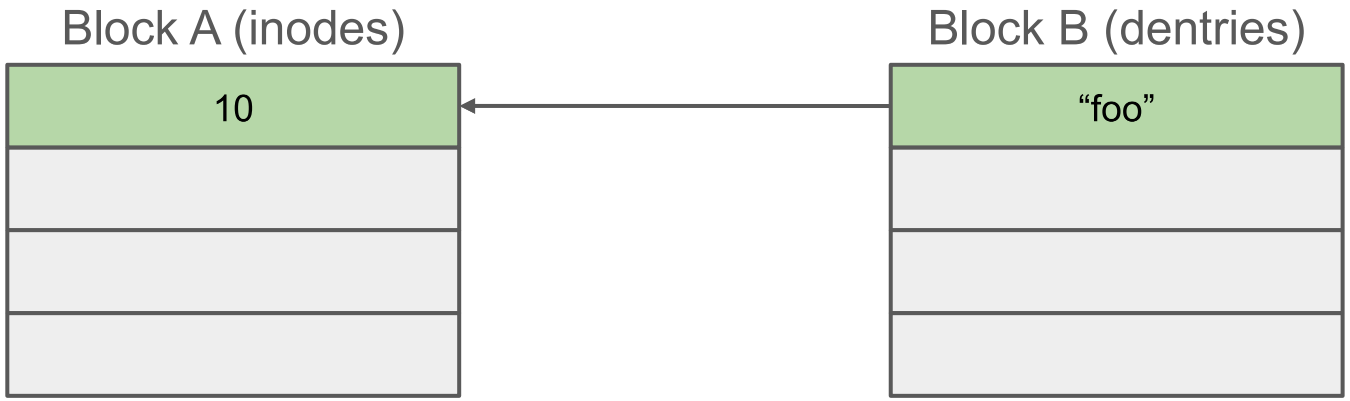
Rules:

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



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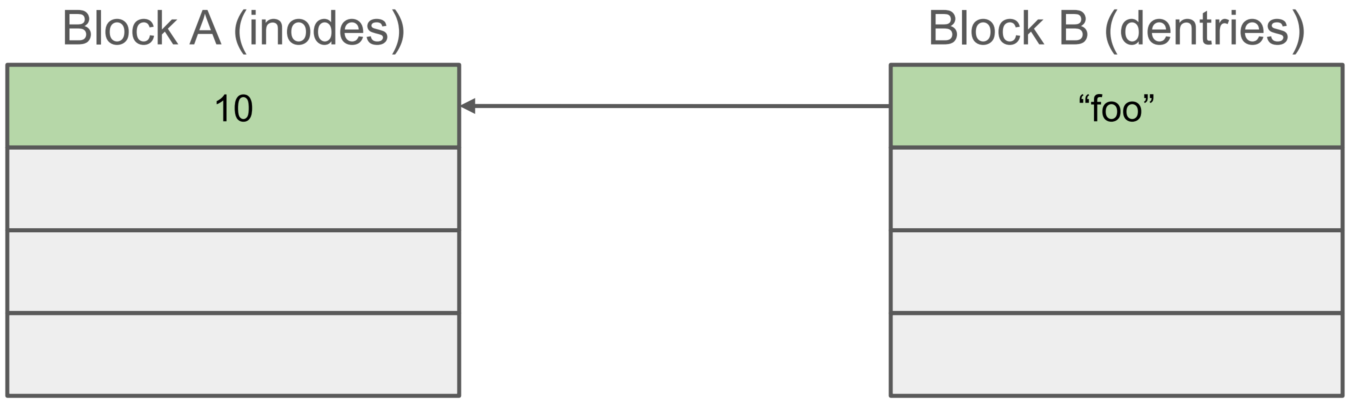

1. unlink foo

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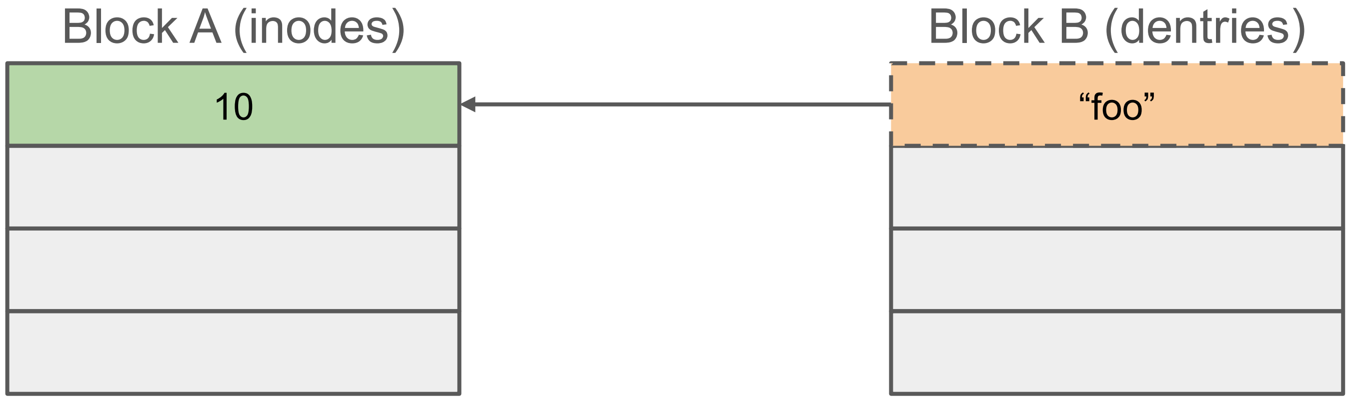

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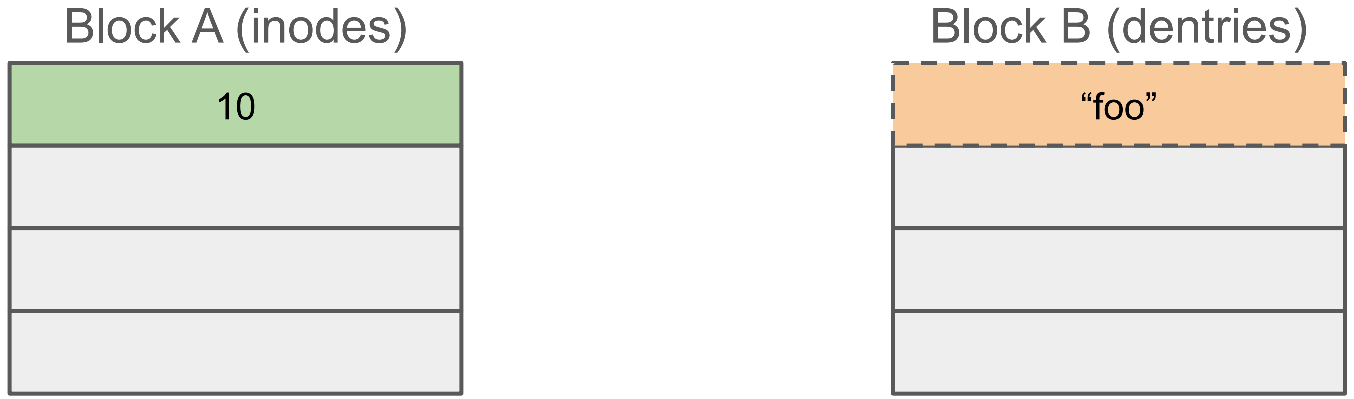

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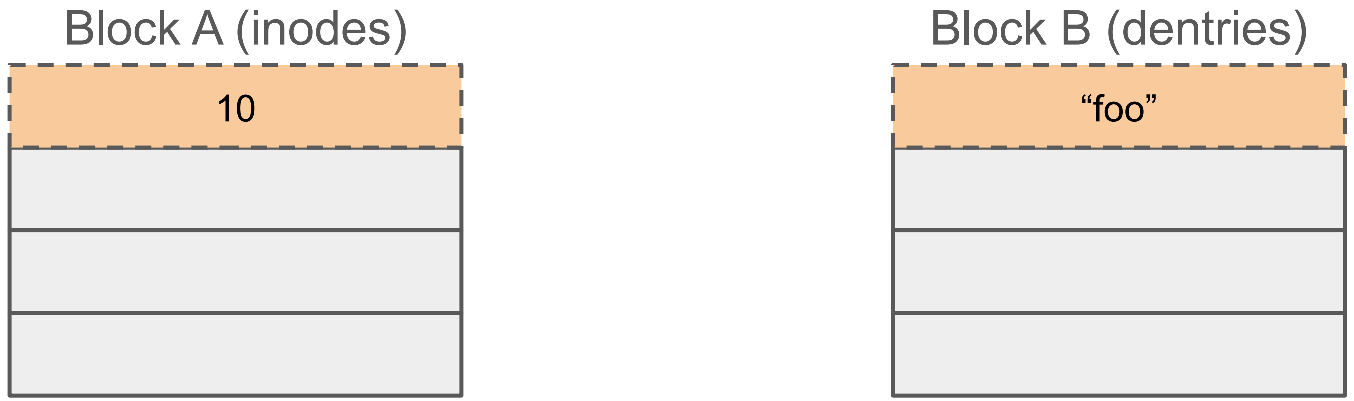

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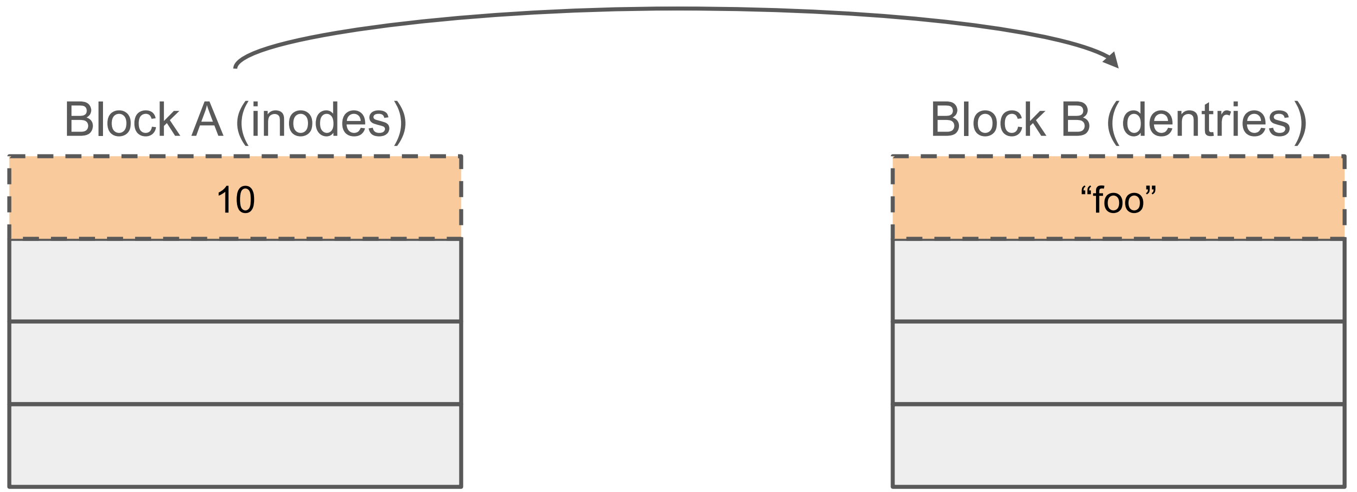

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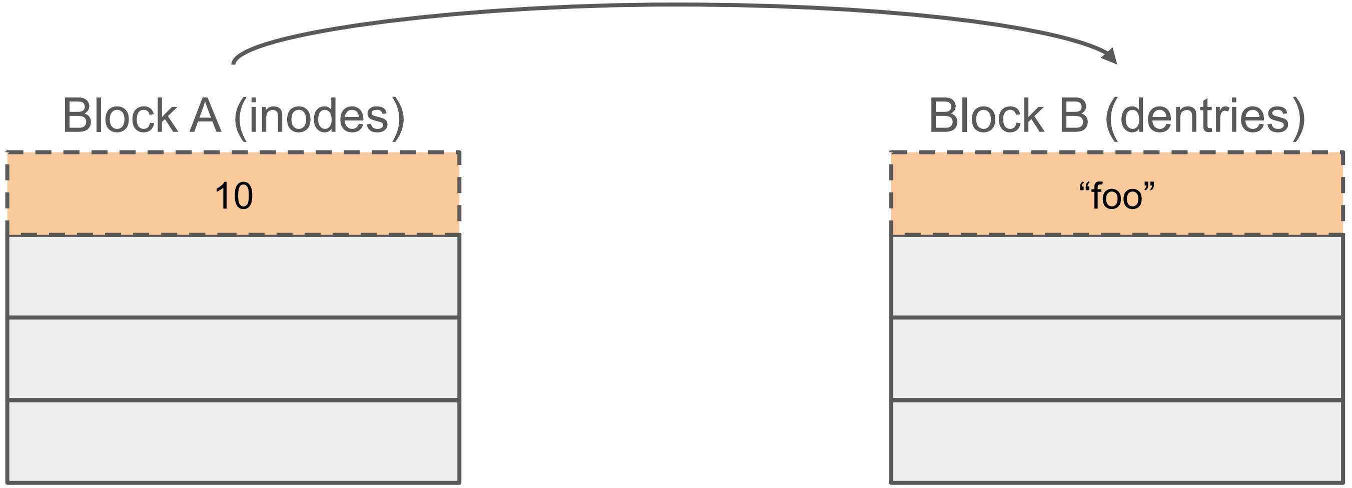

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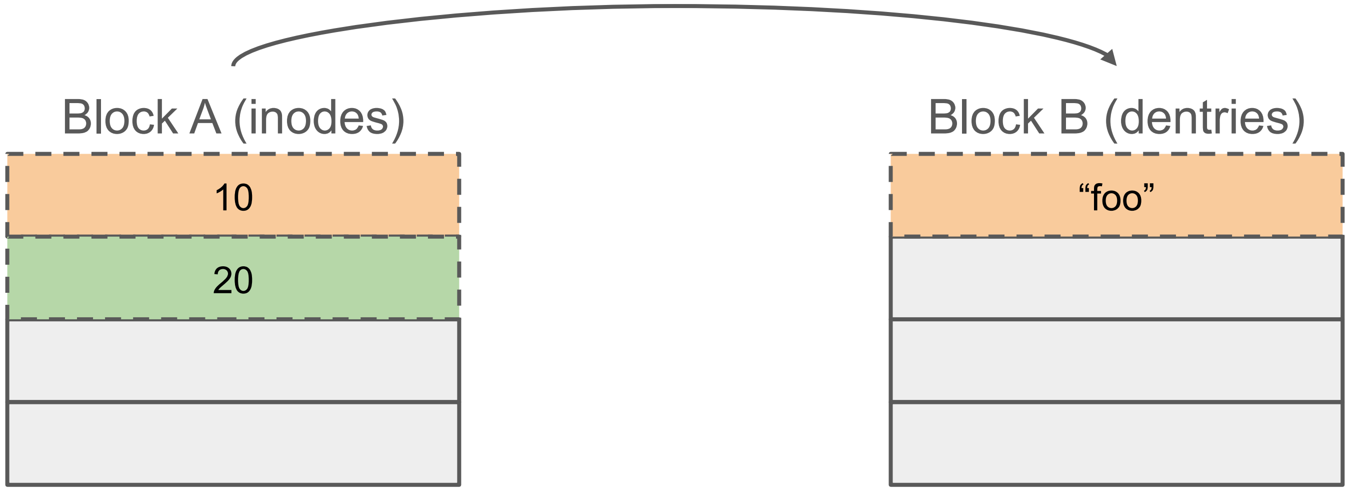

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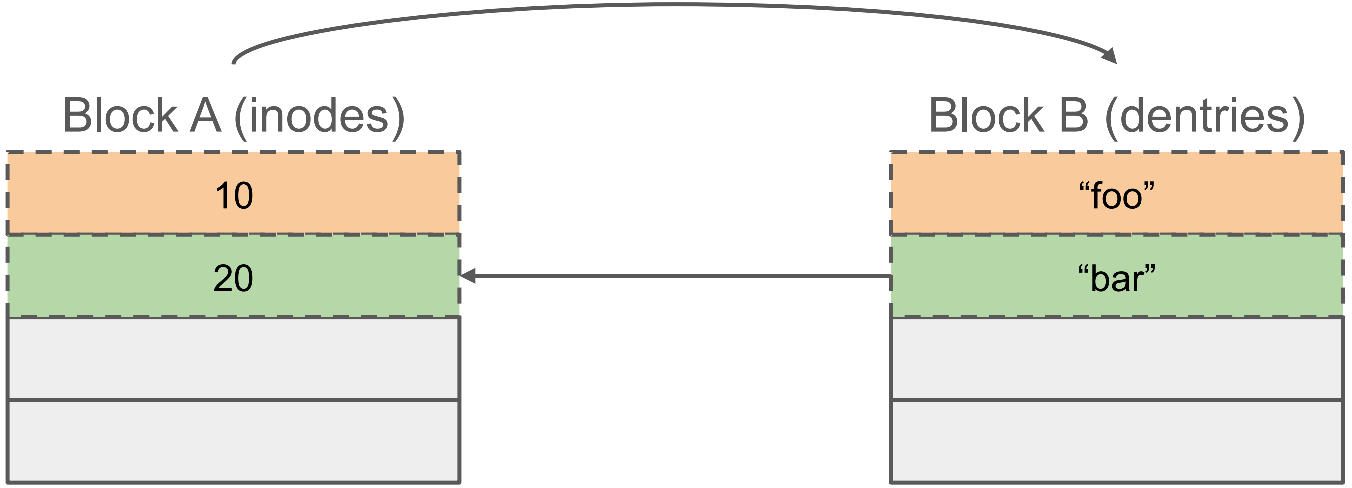

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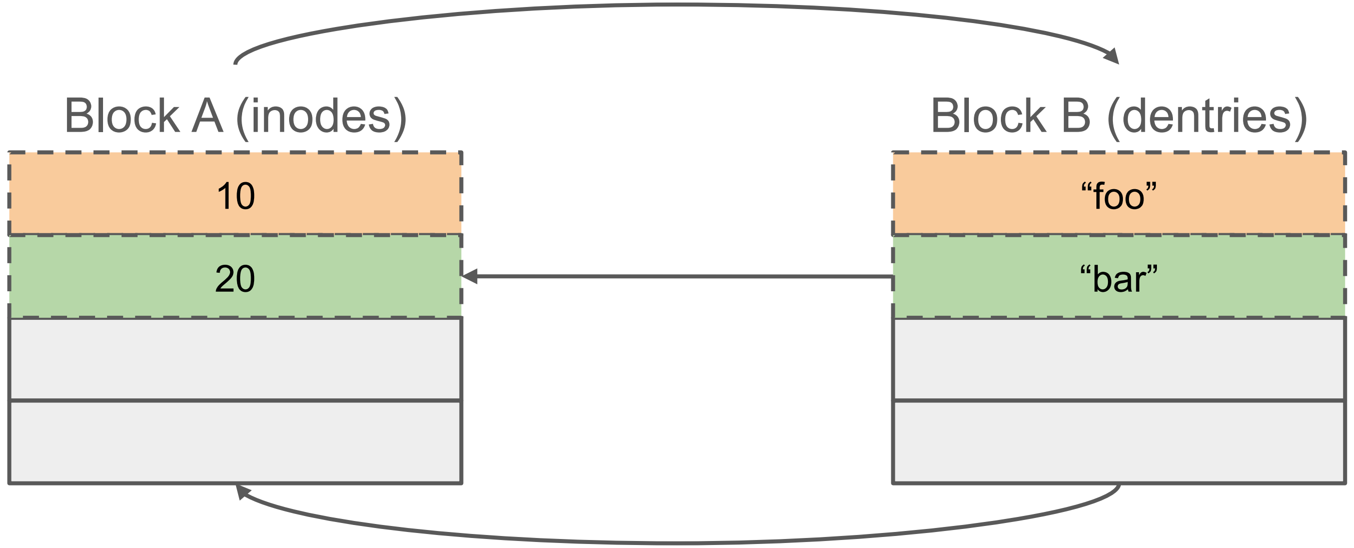

1. unlink foo
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Background: verification

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> {...}
}
```

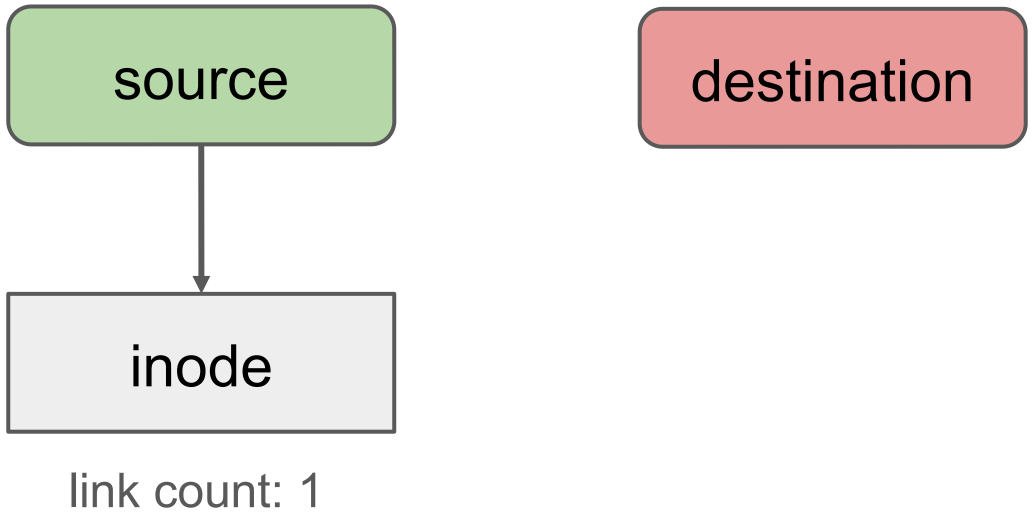
Typestate: ensuring persistence

```
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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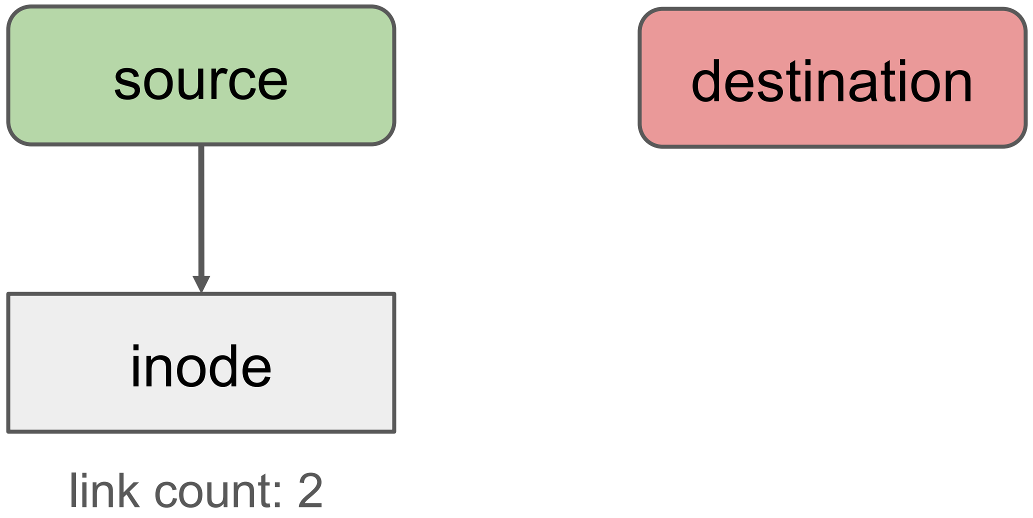

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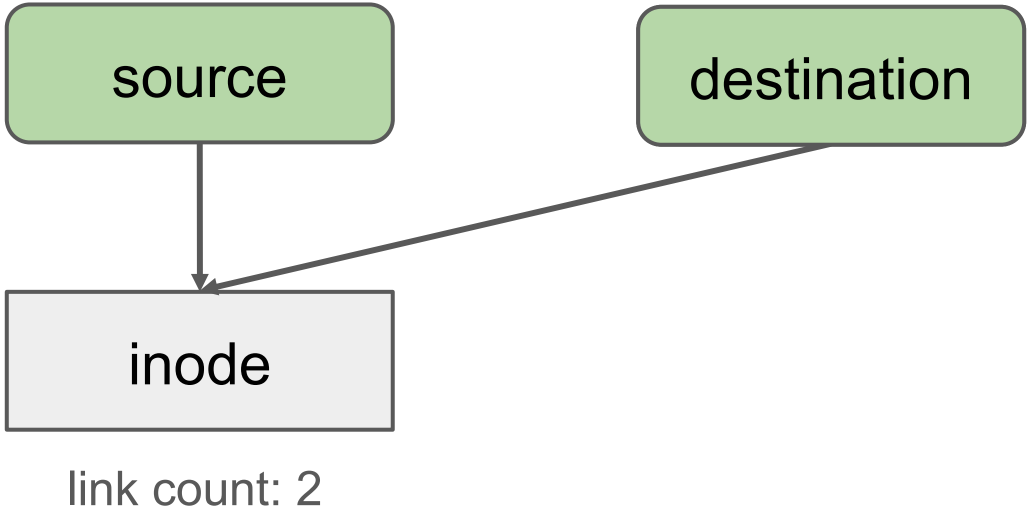

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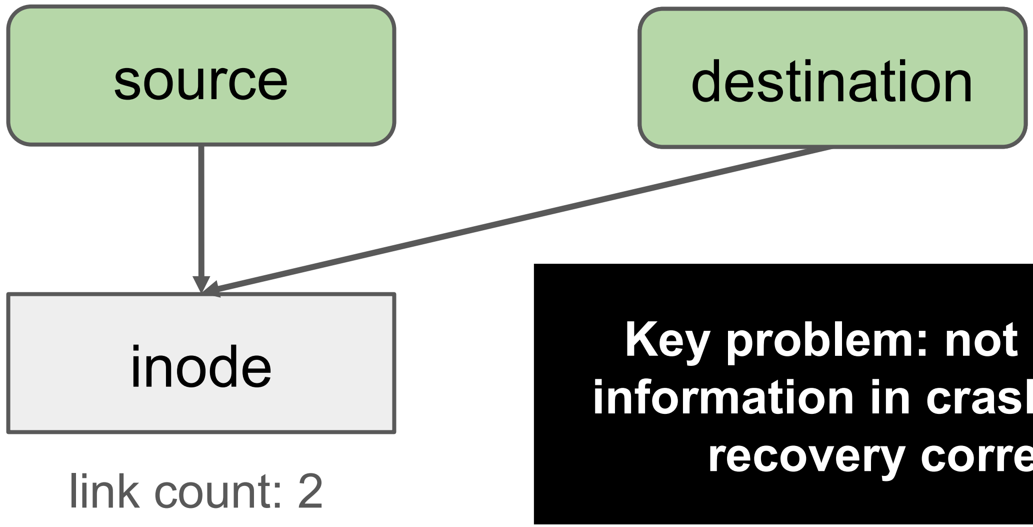
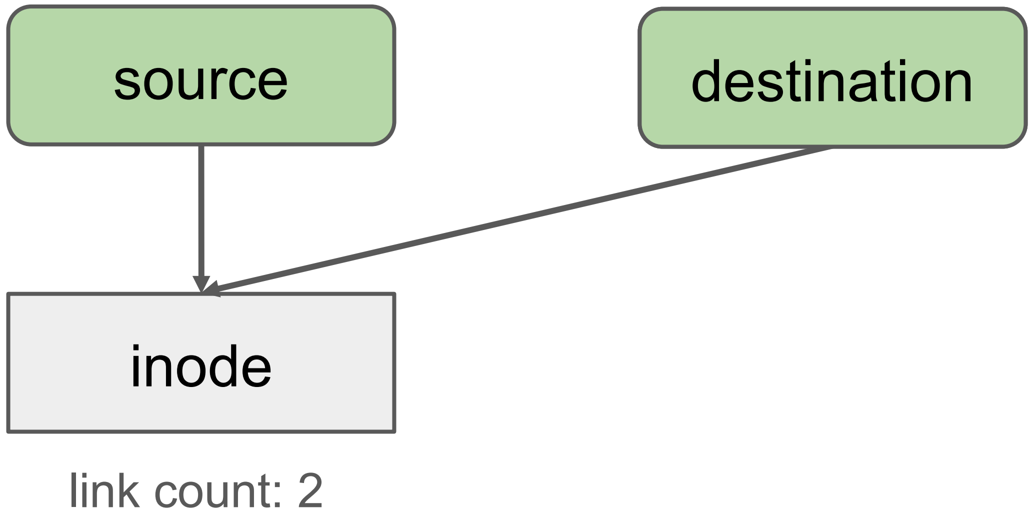


Key problem: not enough information in crash state to recovery correctly

Traditional soft updates rename



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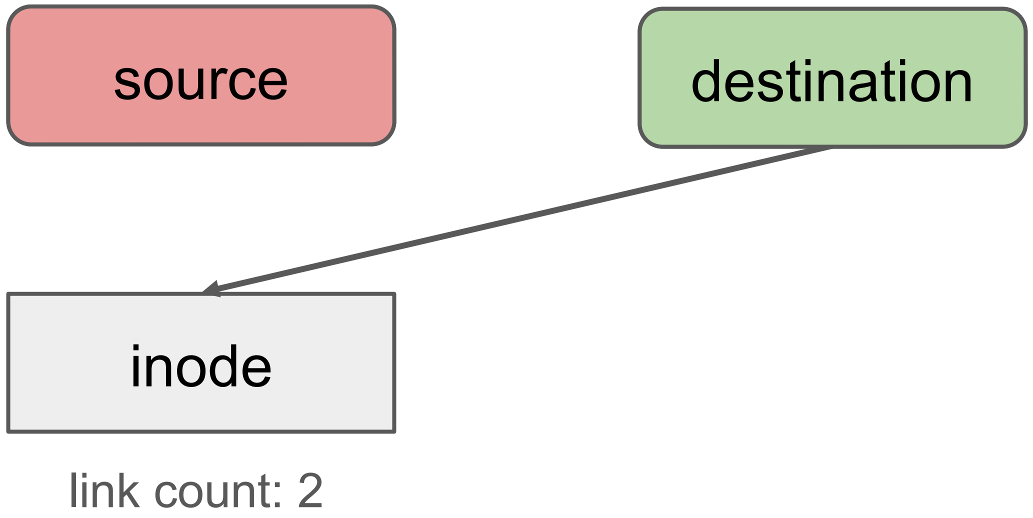

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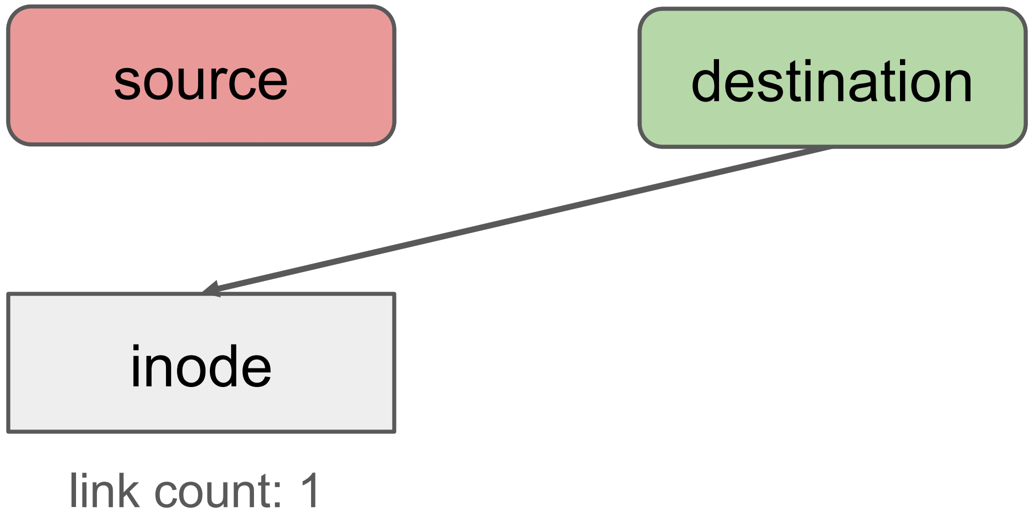

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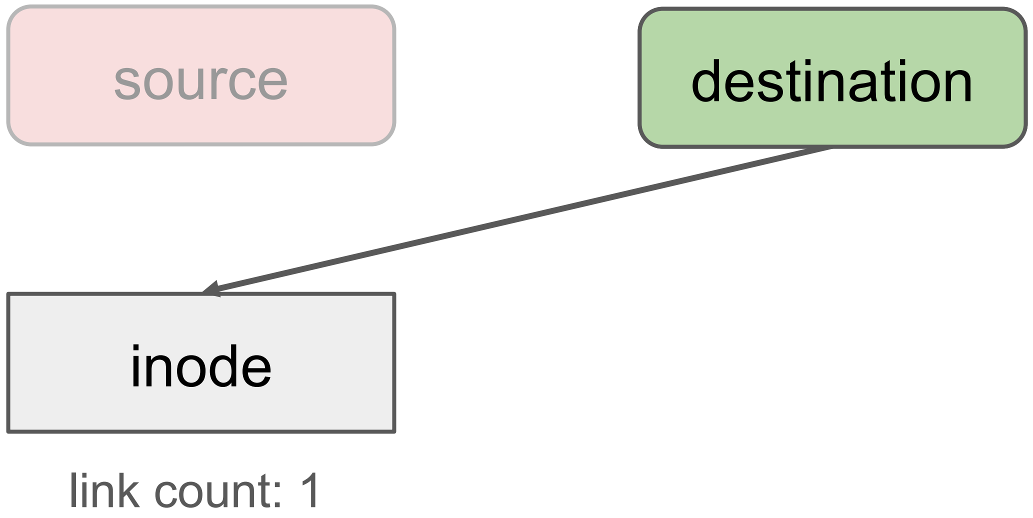
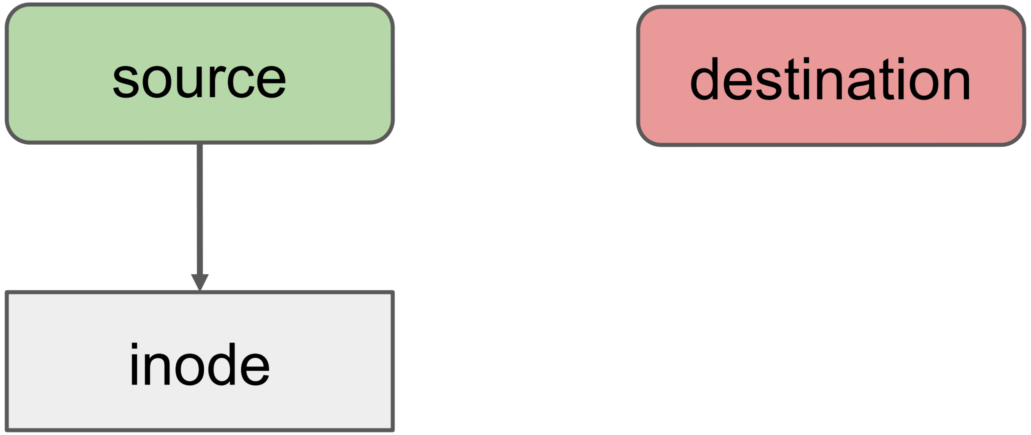


Atomic rename with SSU



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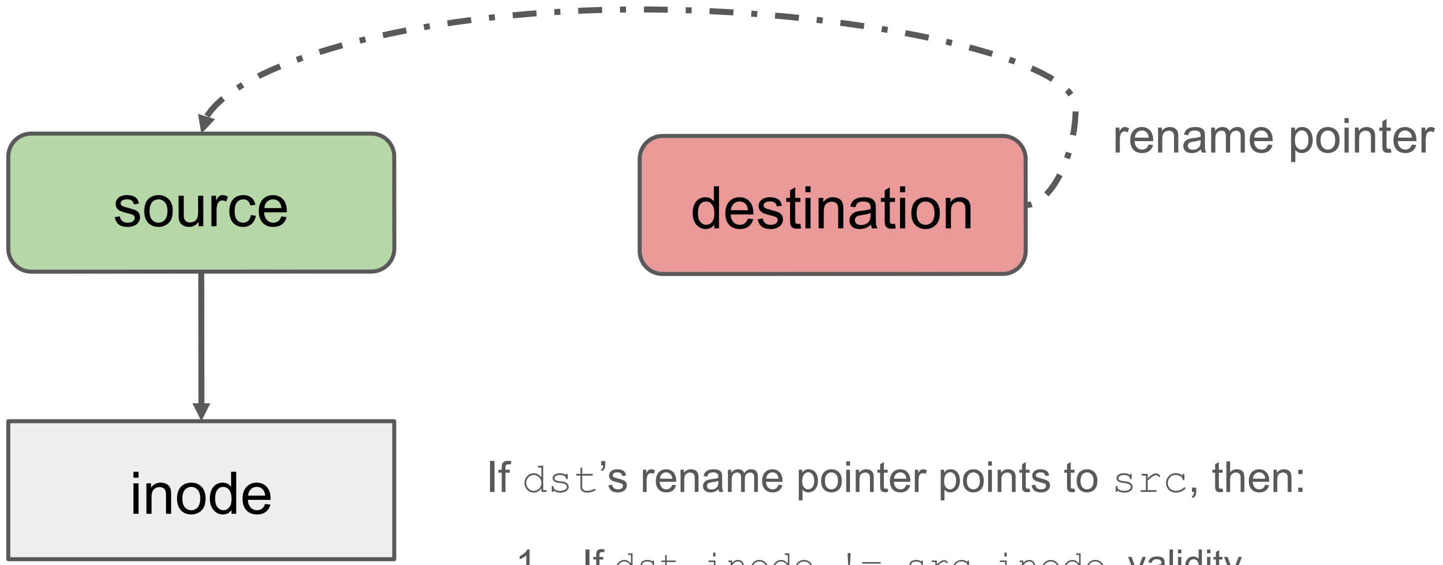

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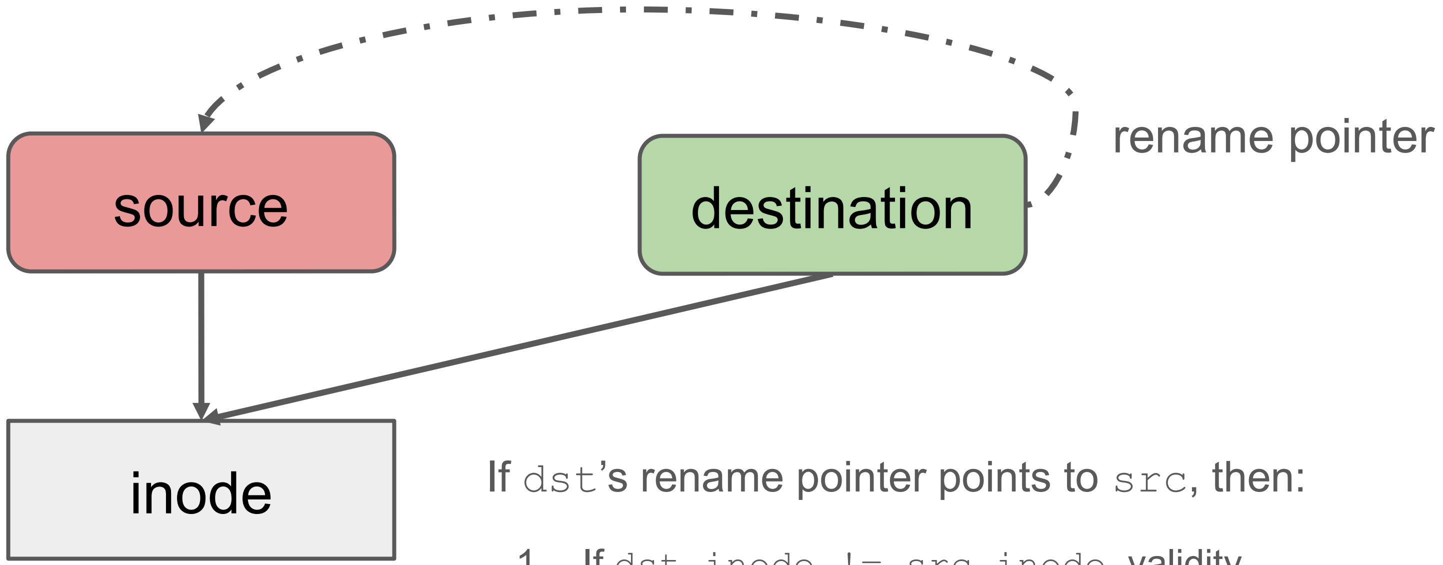

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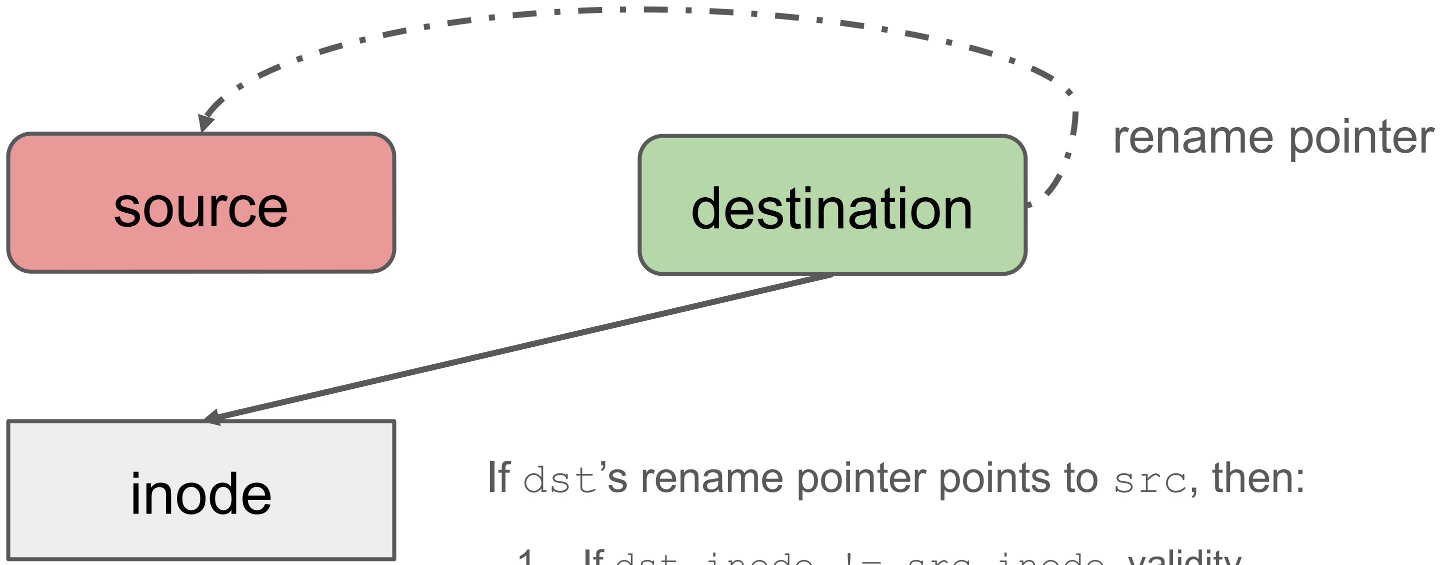

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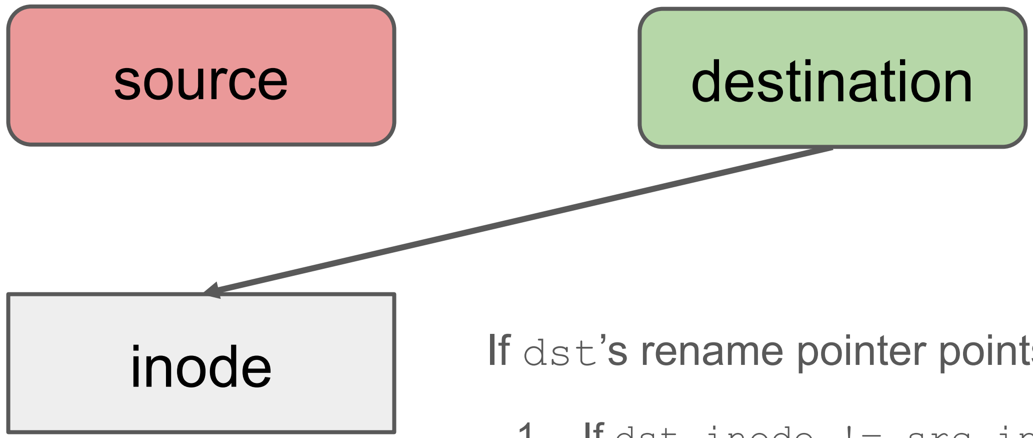

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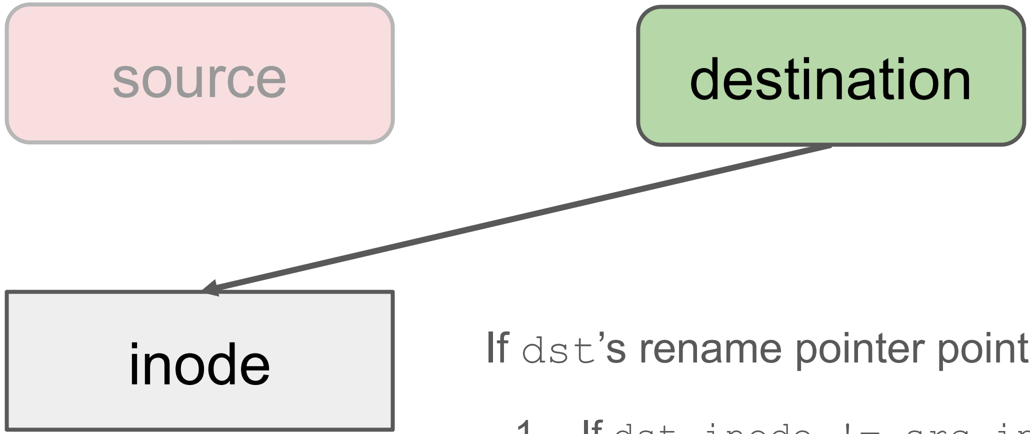

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Typestate in SquirrelFS

Operational typestate

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

Persistence typestate

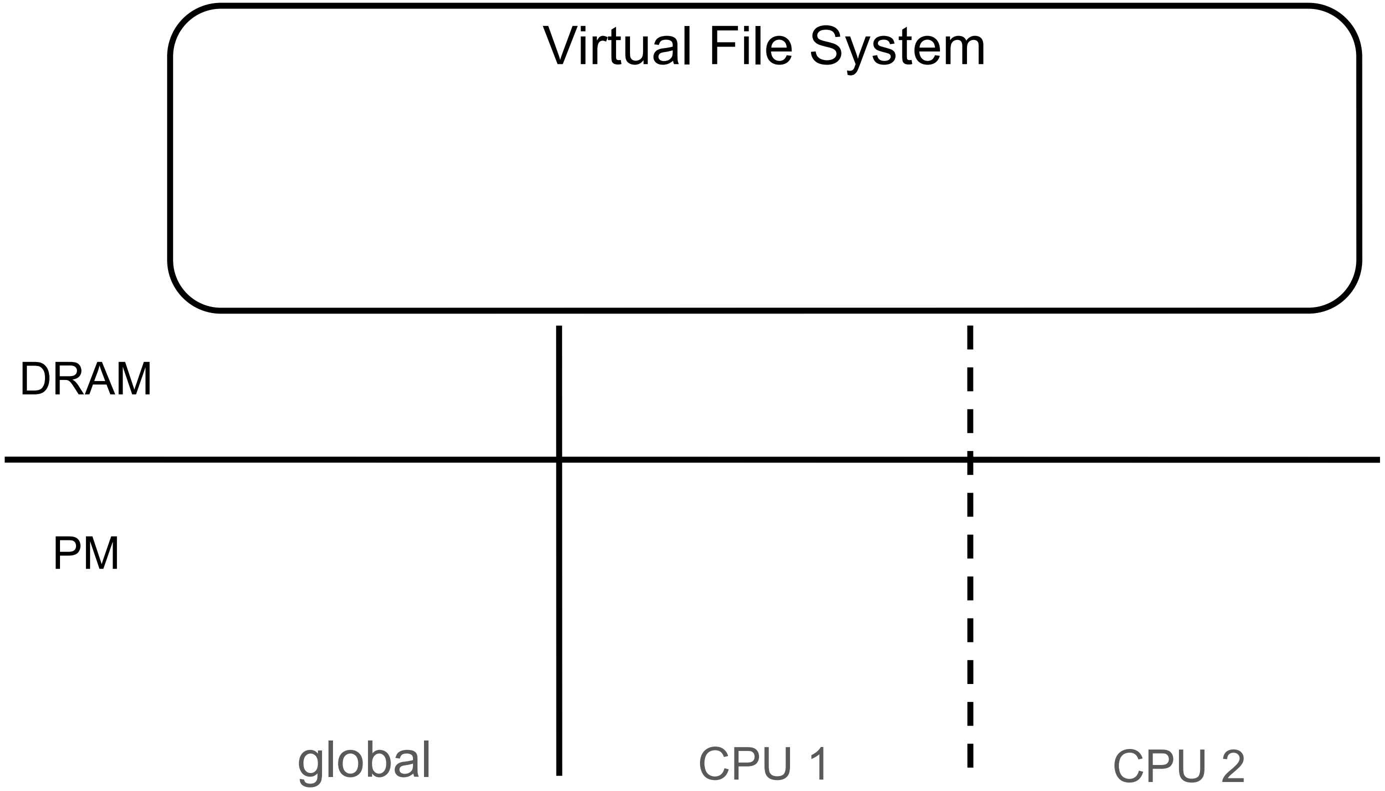
- Have the most recent updates been made durable?

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



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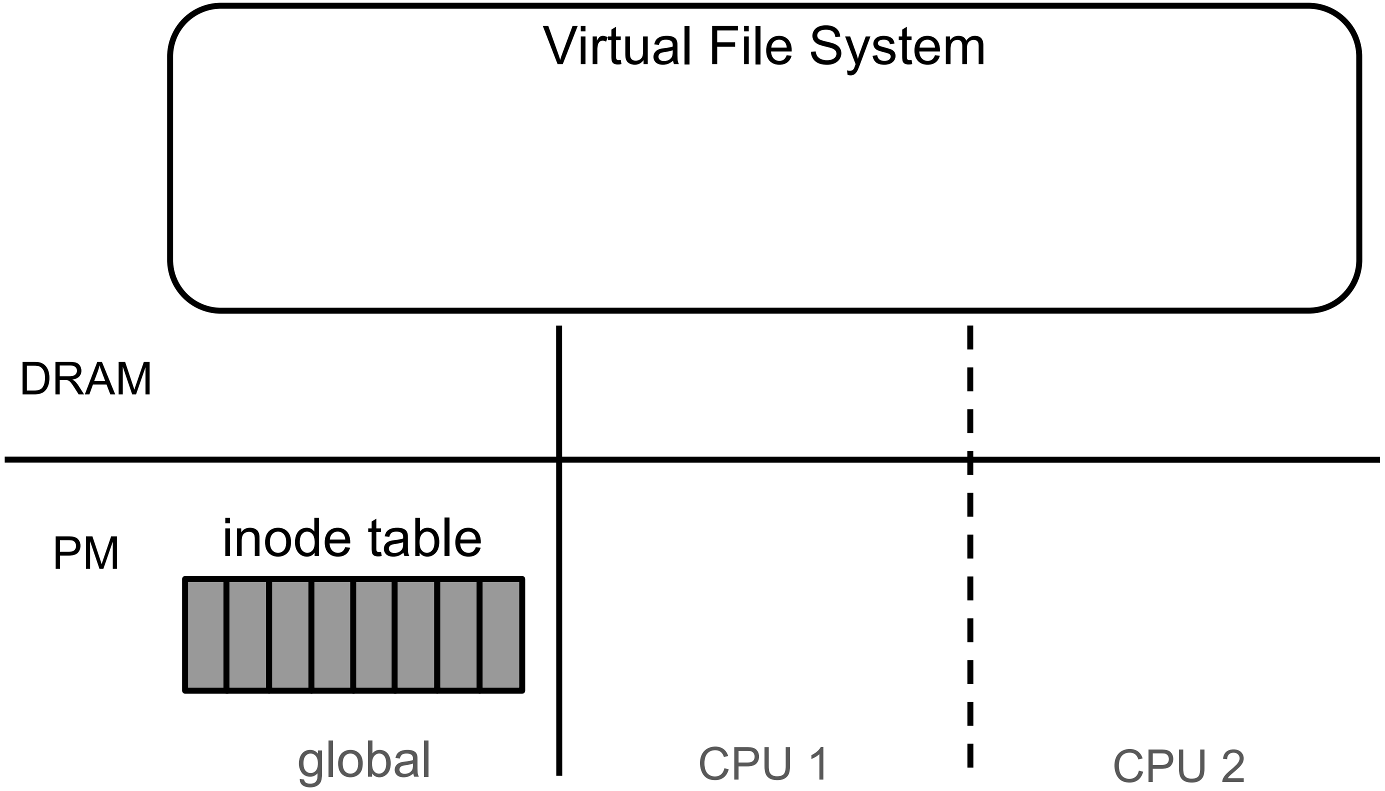

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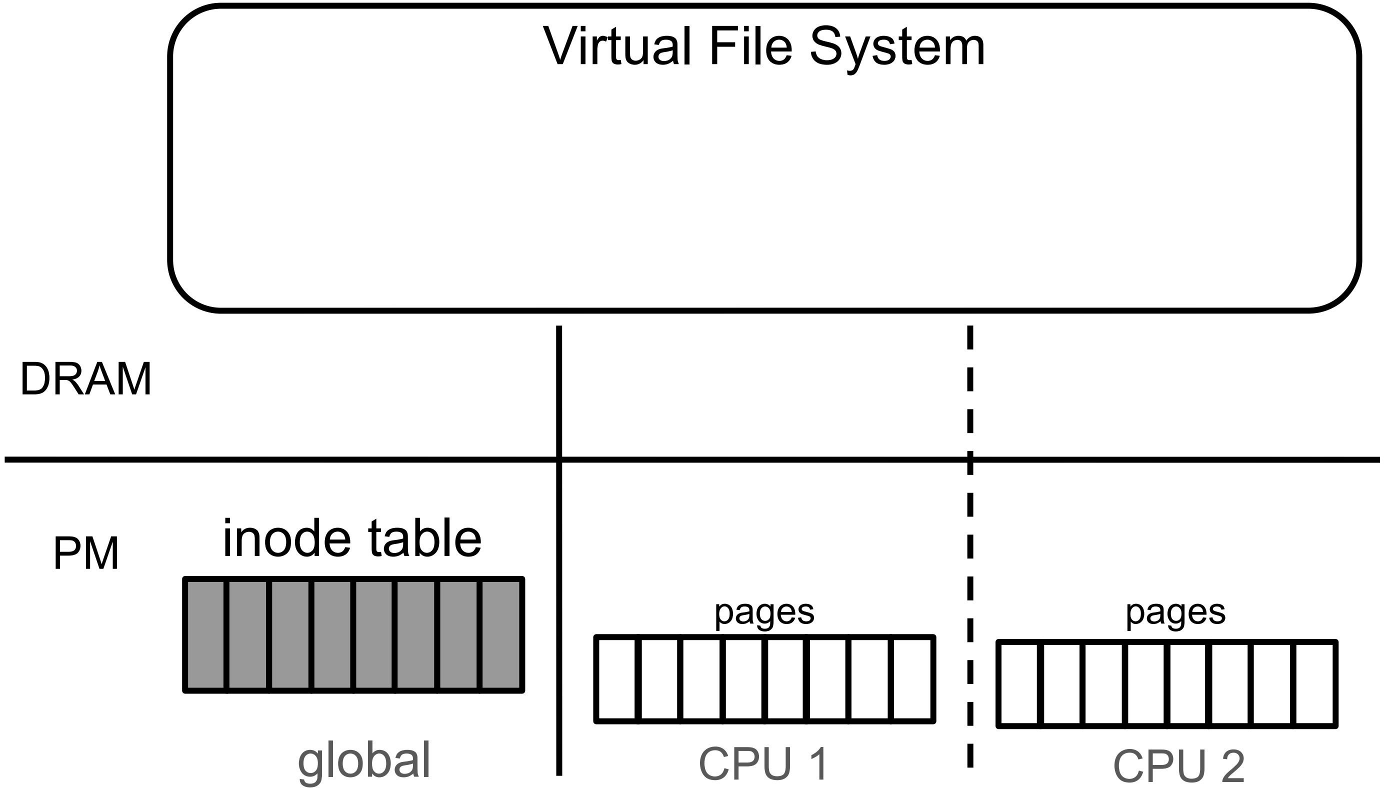

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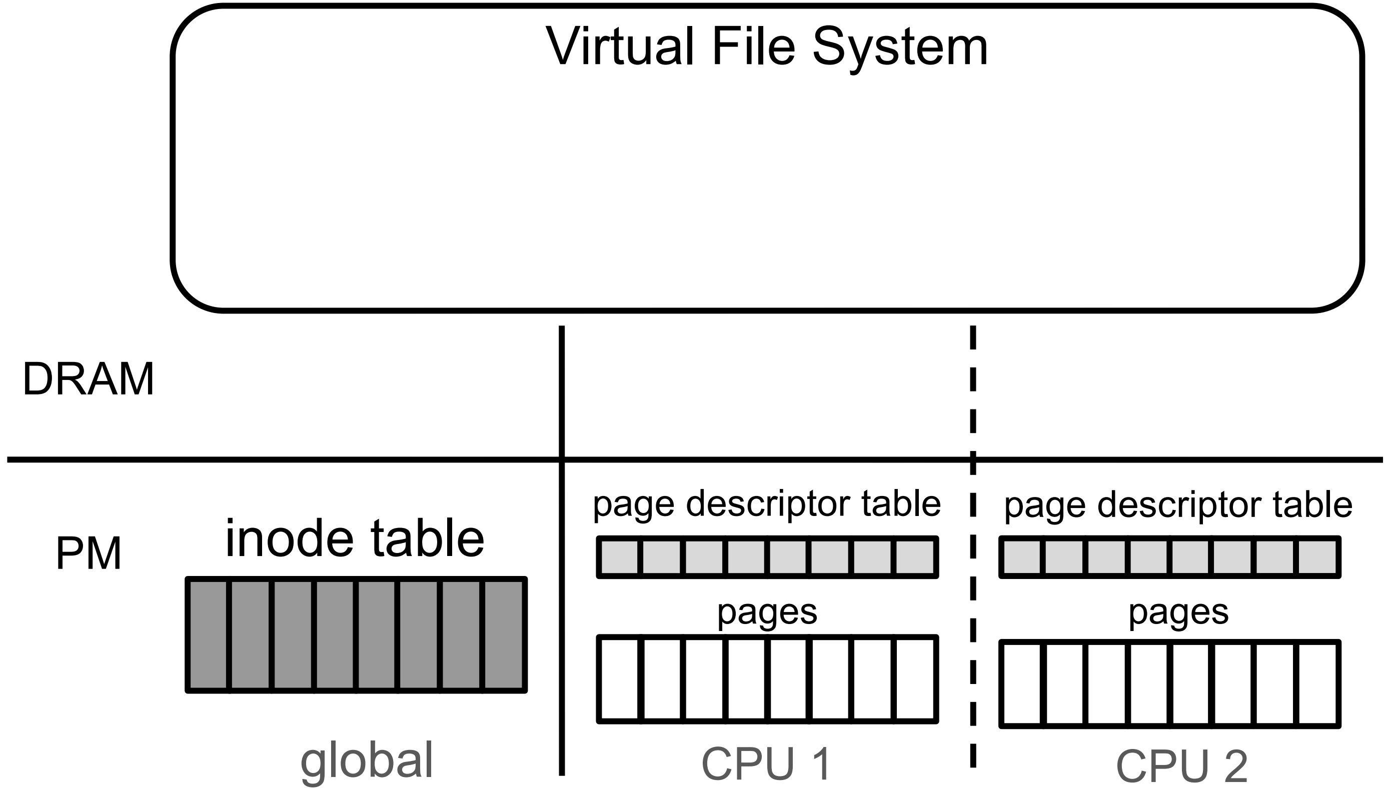

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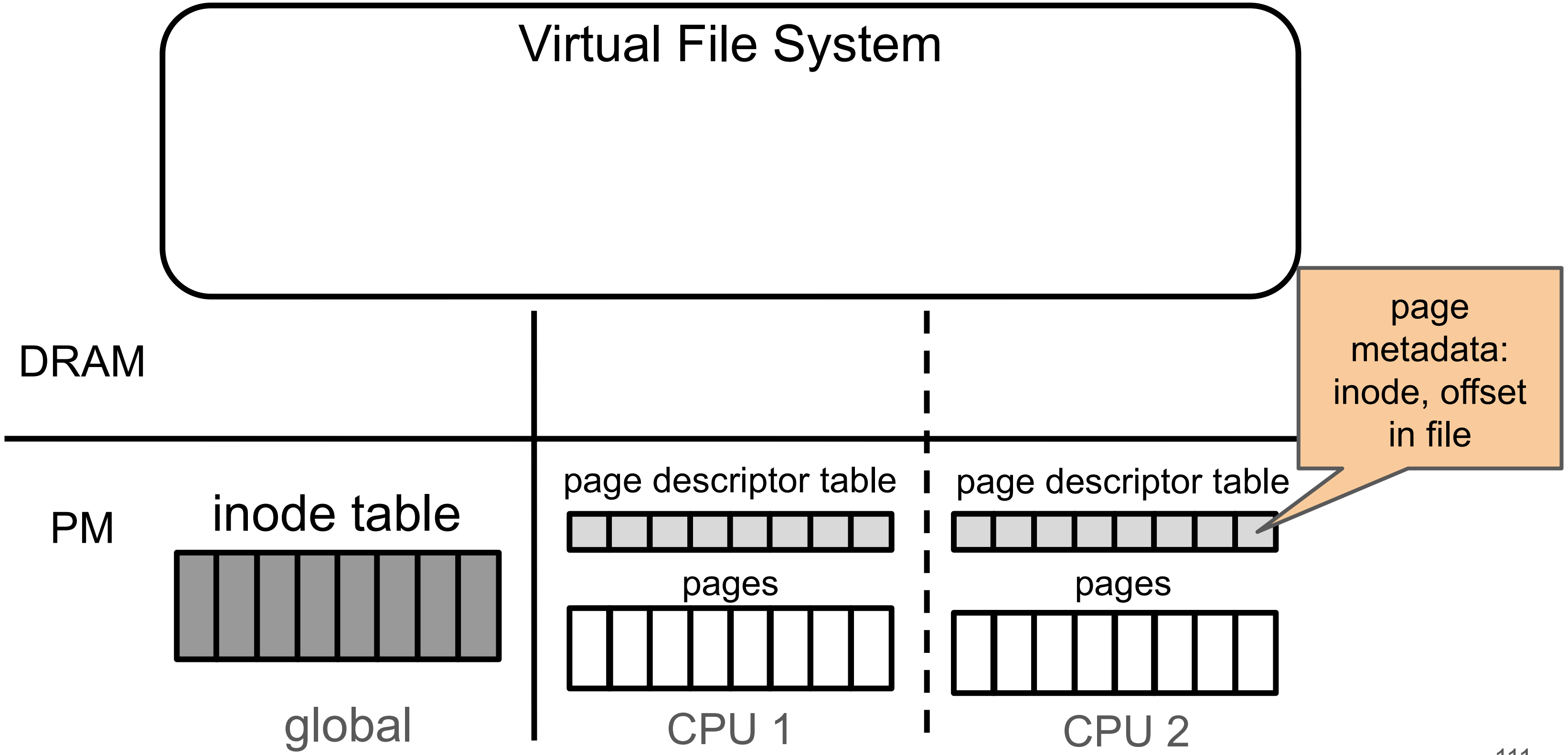

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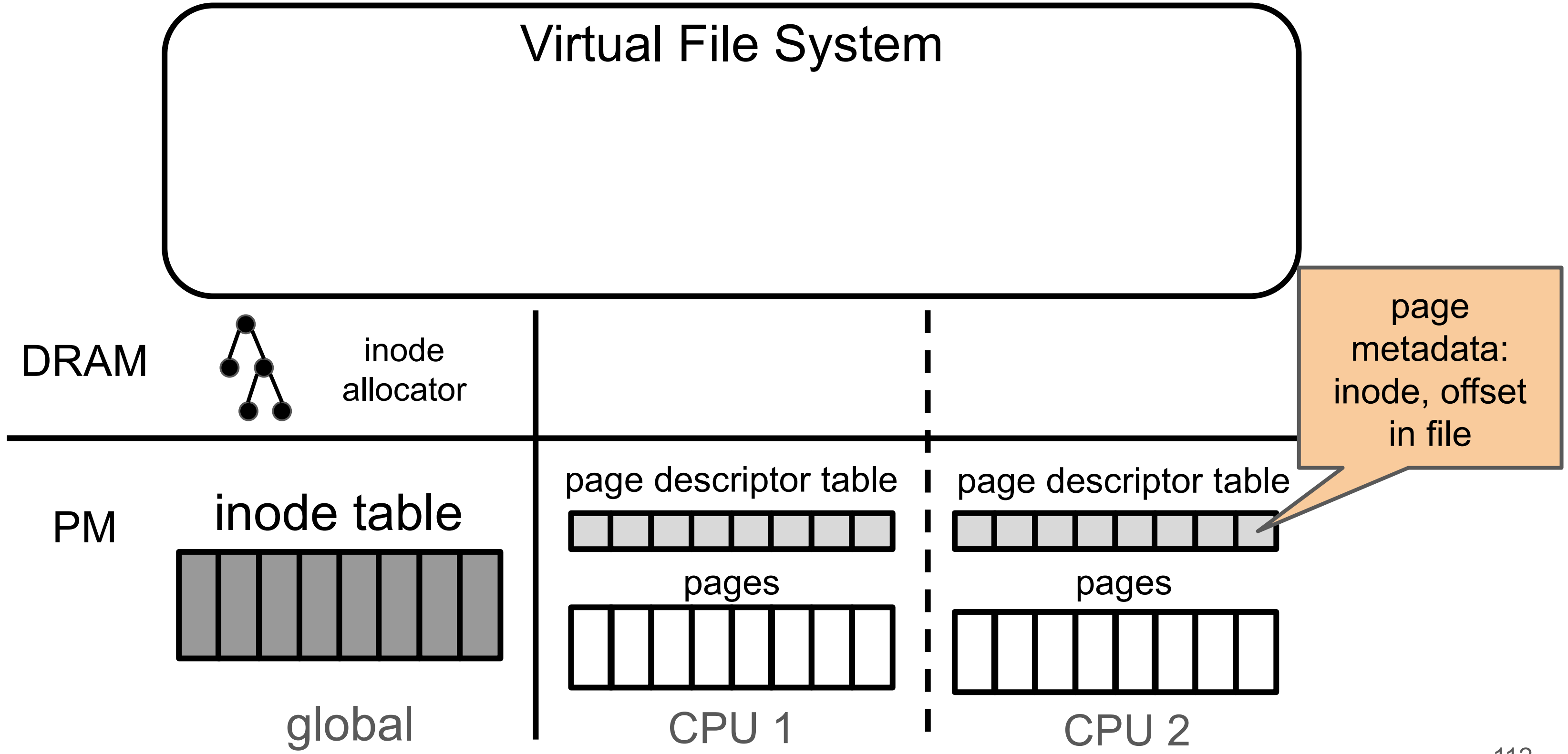

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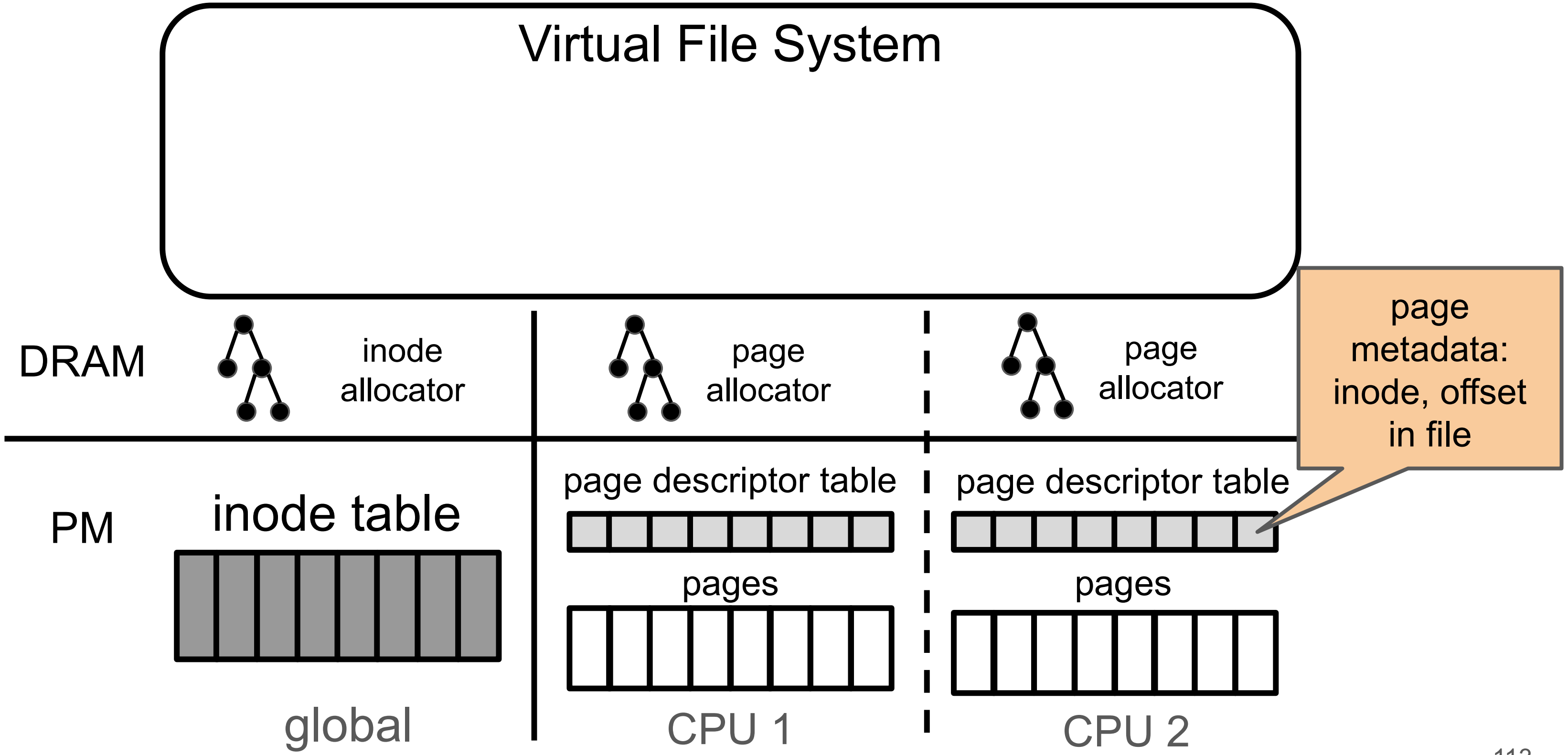

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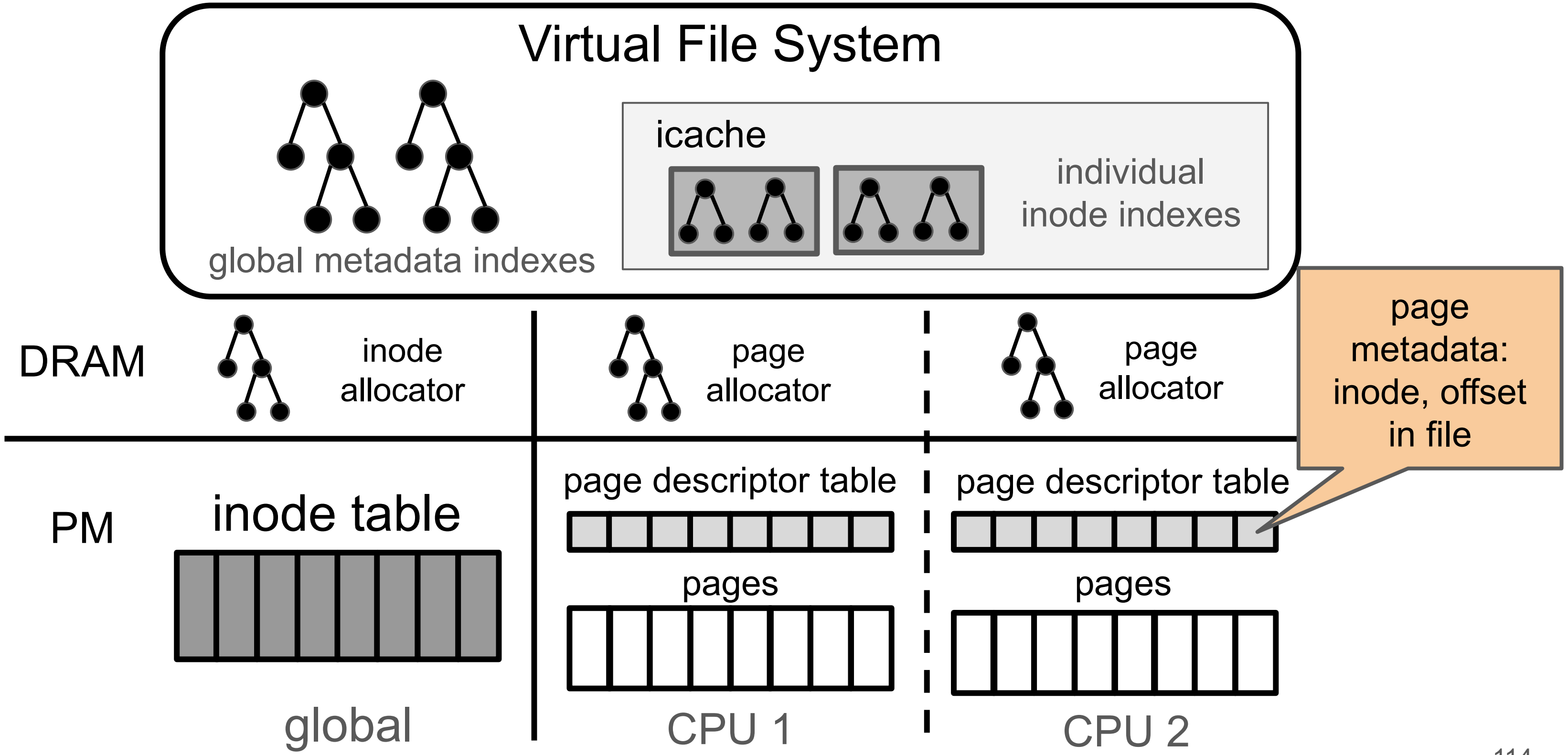


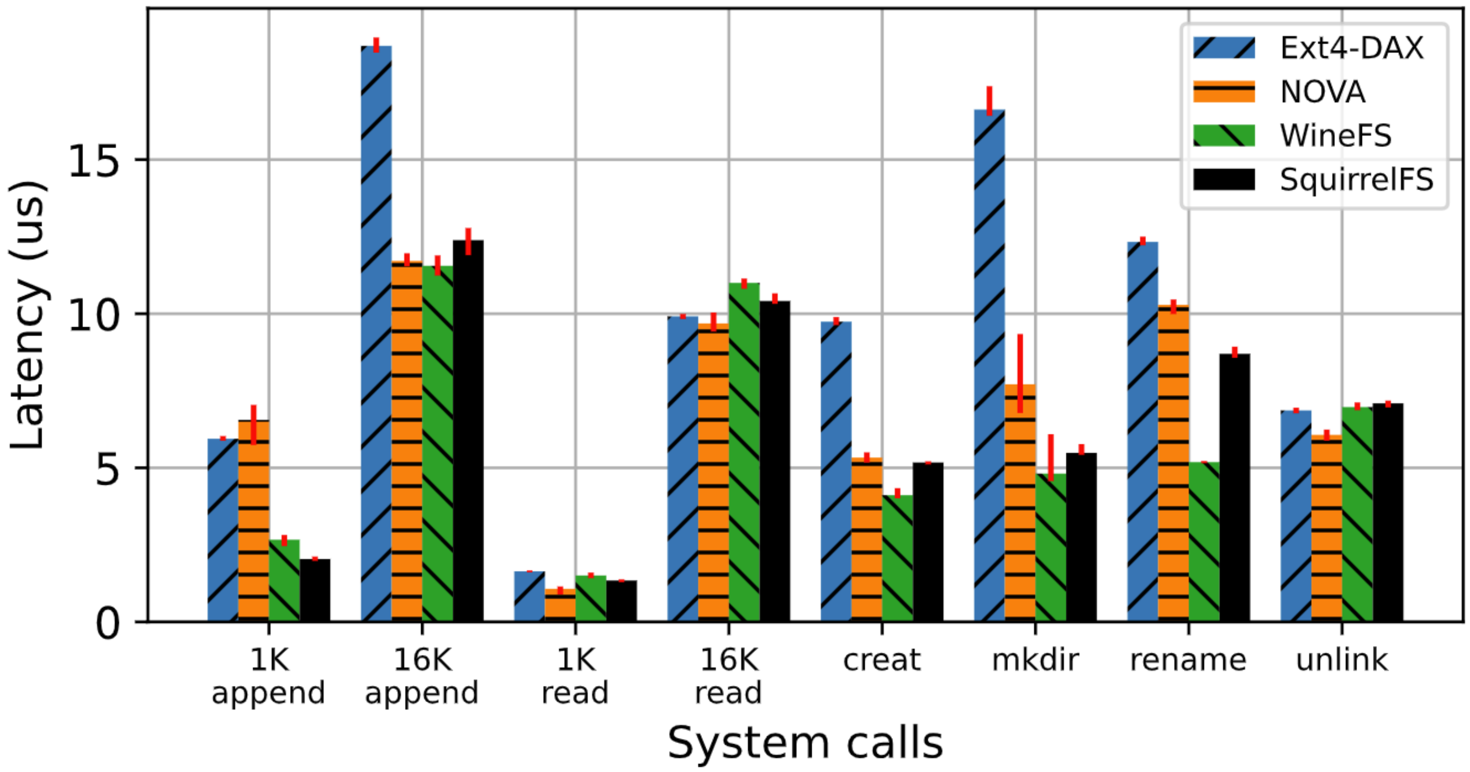
Bugs found with typestate

- 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

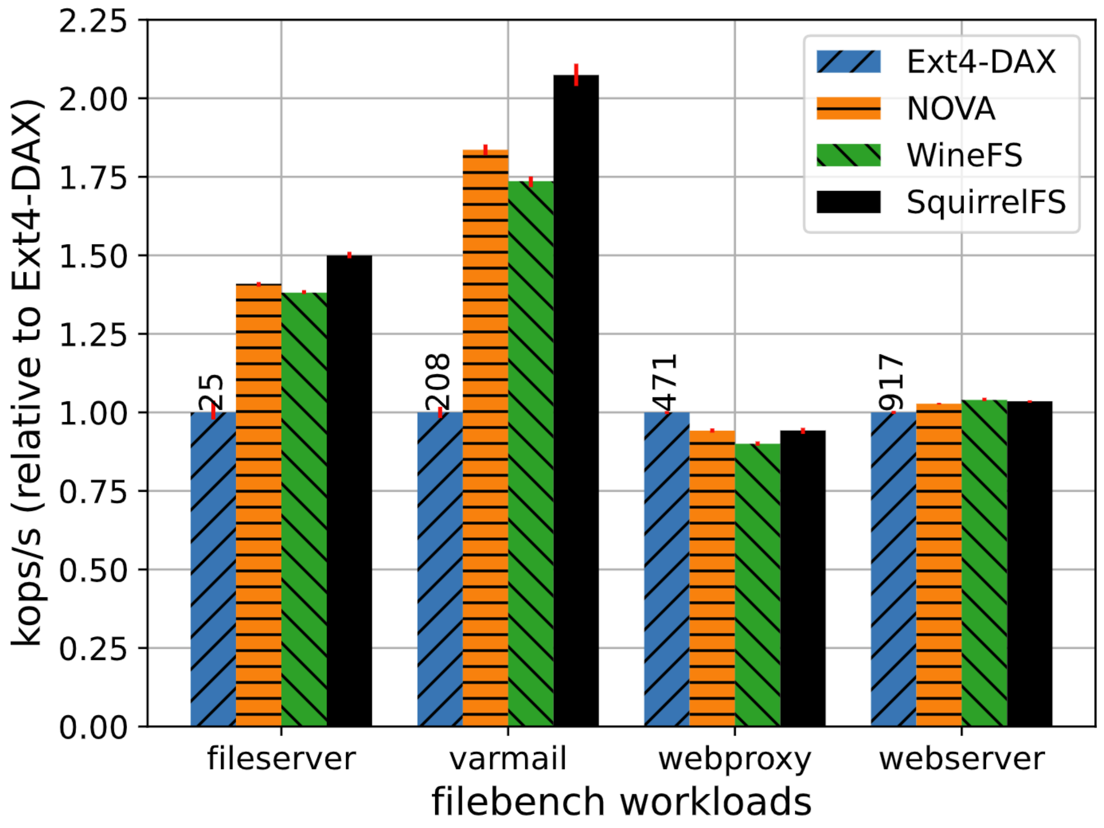
Bugs found with Alloy model

- 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

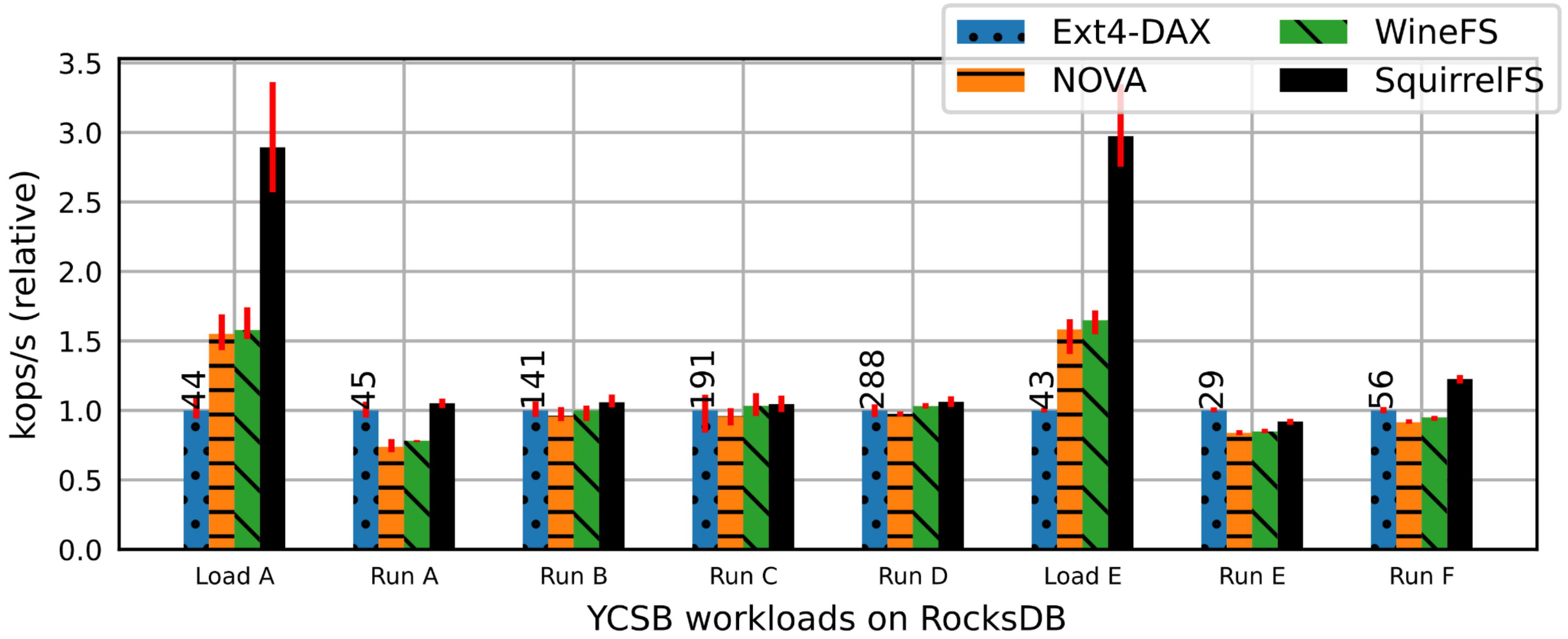
Microbenchmark: system call latency



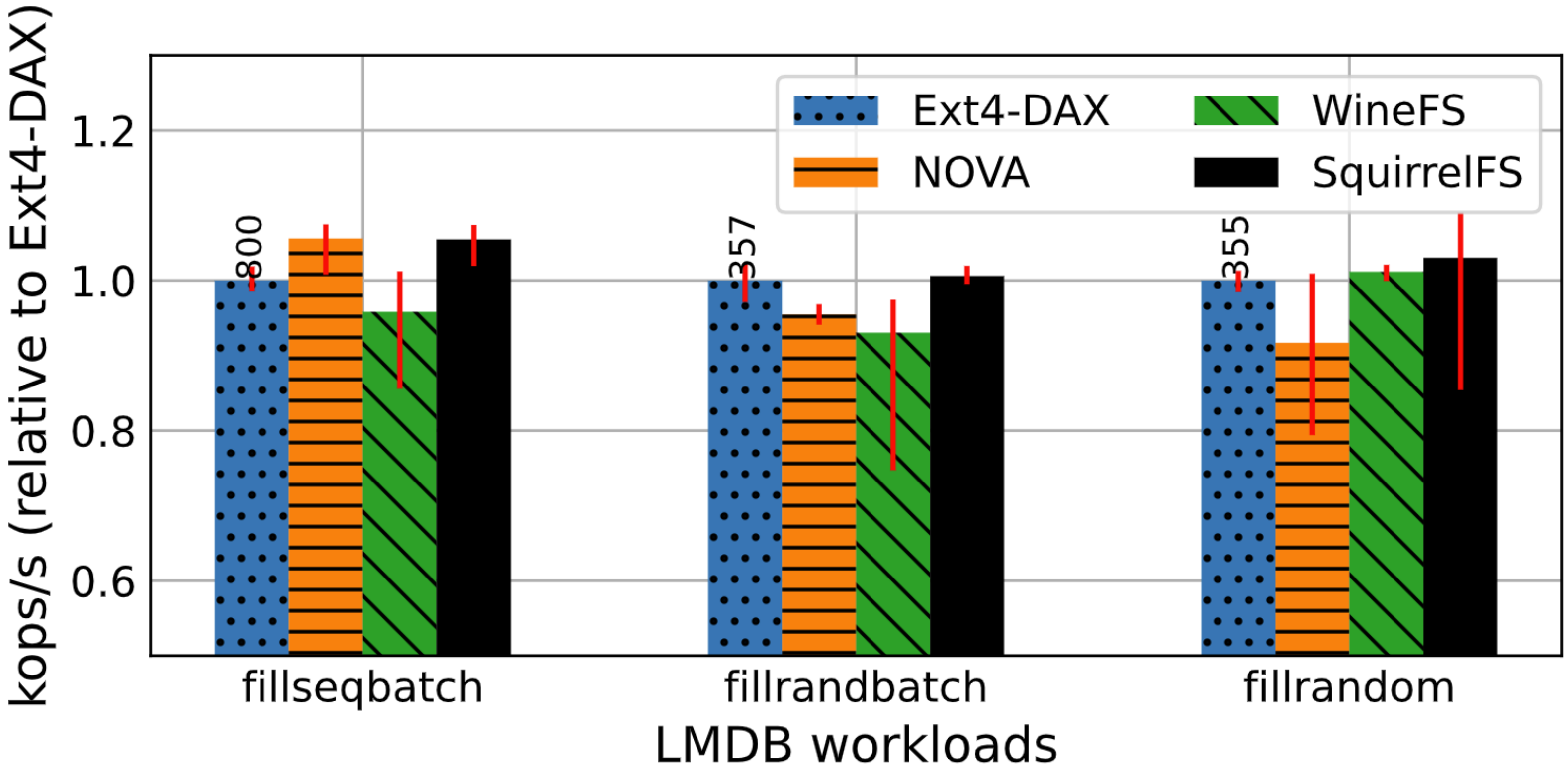
Macrobenchmark: filebench



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

Ordering for crash consistency

Running example: creating a new file

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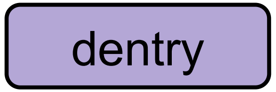

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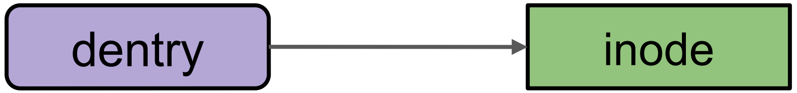

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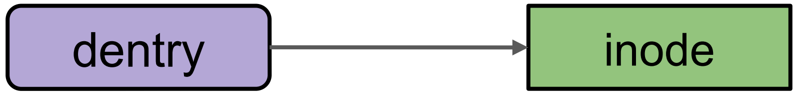

Invariant: a directory entry never points to an uninitialized inode

Ordering for crash consistency

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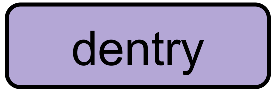

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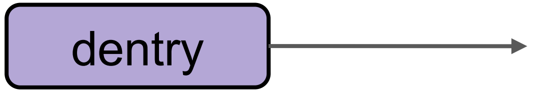

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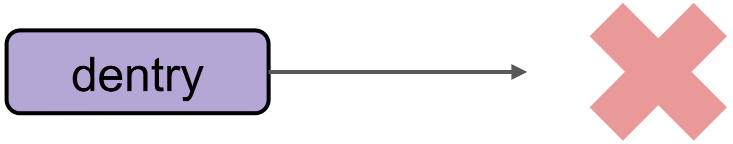

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Ordering for crash consistency

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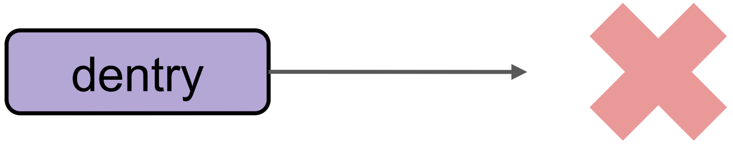
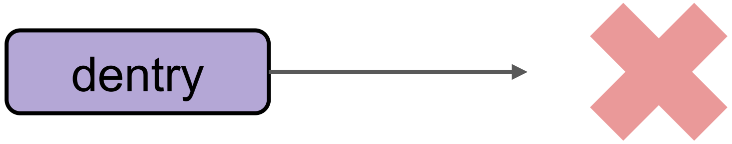


Invariant: a directory entry never points to an uninitialized inode

Ordering rule: inode must be initialized at the same time or before directory entry pointer is set

Ordering for crash consistency

Running example: creating a new file



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Statically enforcing durable update ordering can prevent crash-consistency bugs

Synchronous soft updates (SSU)

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

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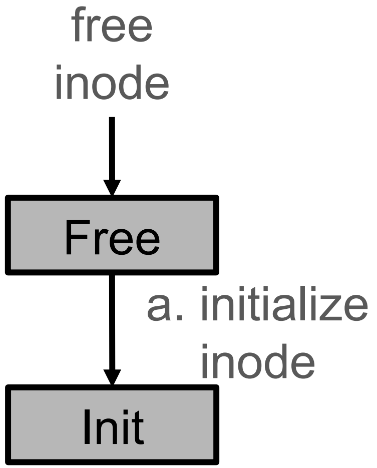
Soft updates: crash consistency from ordered in-place durable updates



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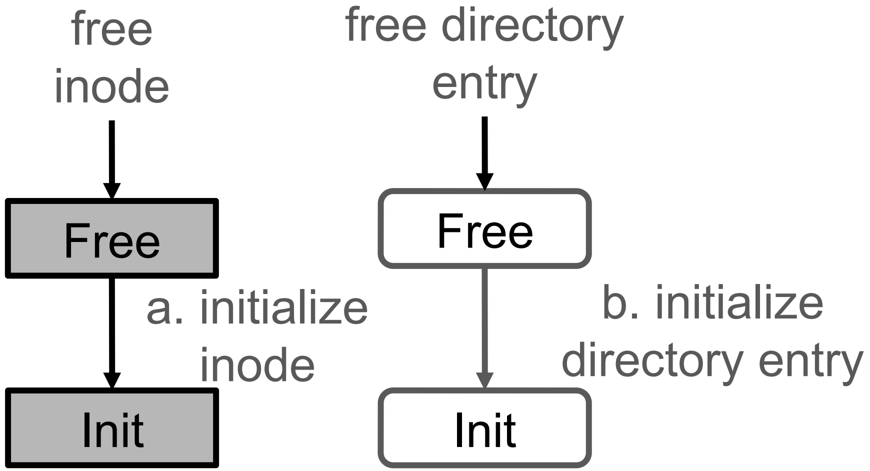

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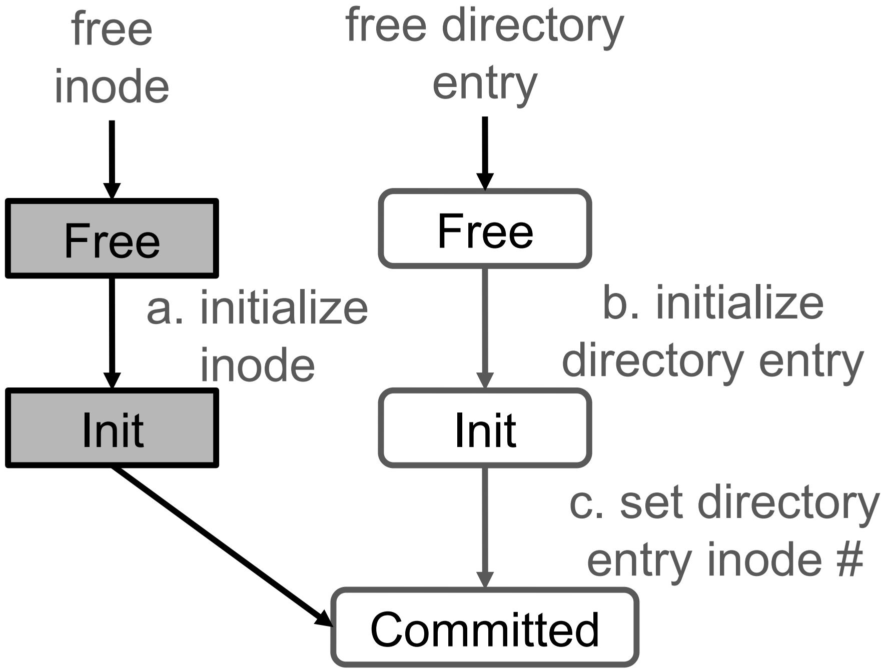

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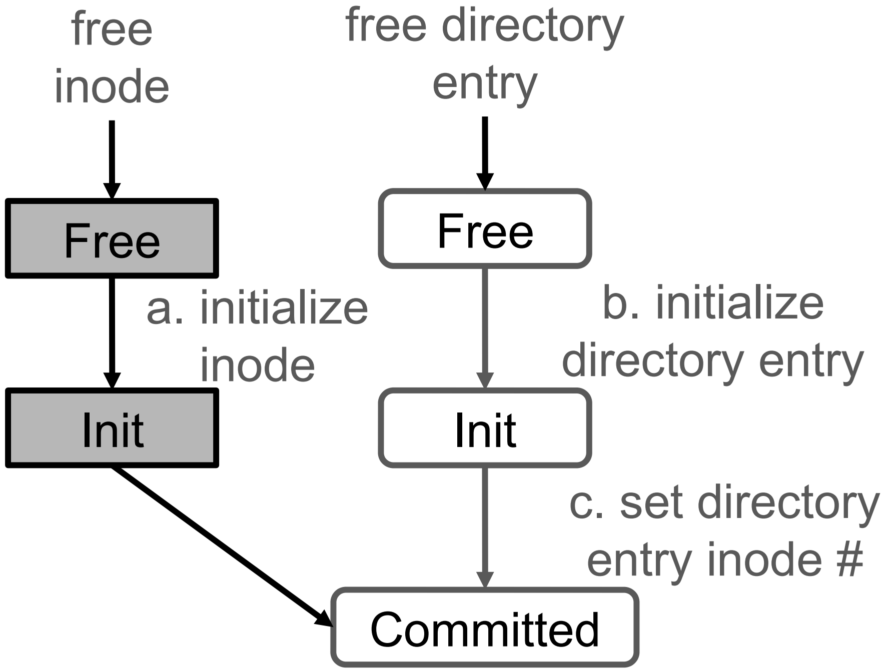

Managing update dependencies in **asynchronous** soft updates is notoriously difficult

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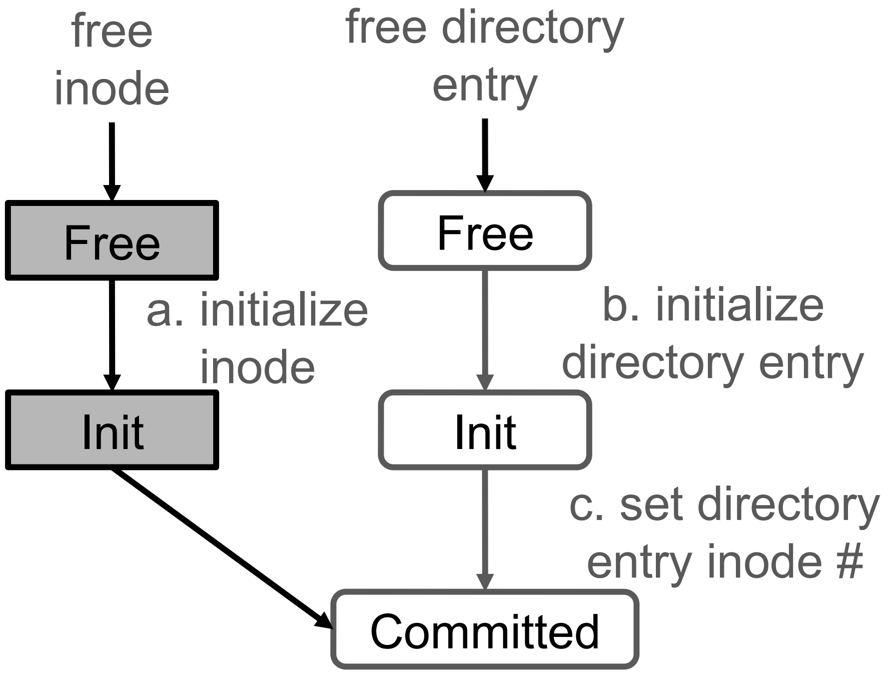
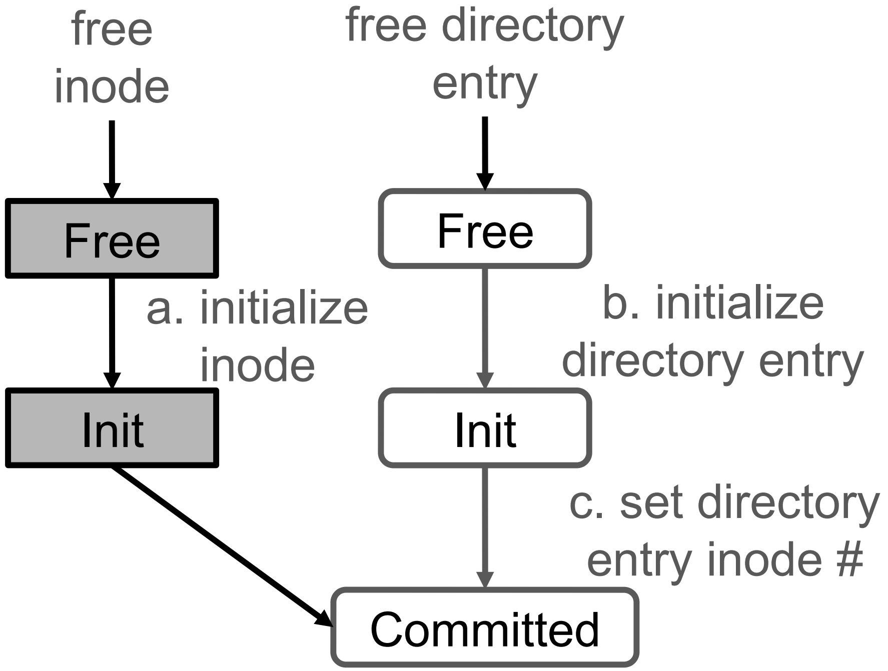


Managing update dependencies in **asynchronous** soft updates is notoriously difficult

Synchronous soft updates eliminates most complexity!

Synchronous soft updates (SSU)

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

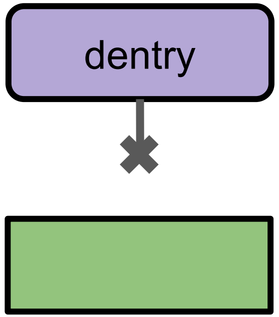


Managing update dependencies in **asynchronous** soft updates is notoriously difficult

Synchronous soft updates eliminates most complexity!

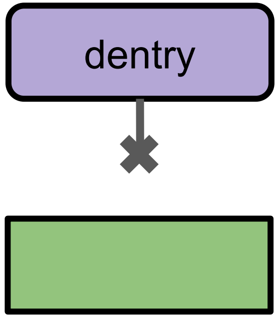
Fast **persistent memory** storage enables performant synchrony

The typestate pattern



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

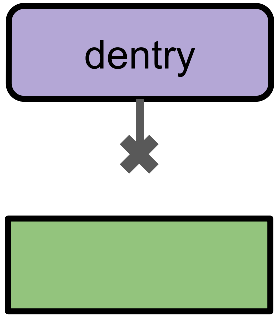
The typestate pattern



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

Are there unflushed updates?

The typestate pattern

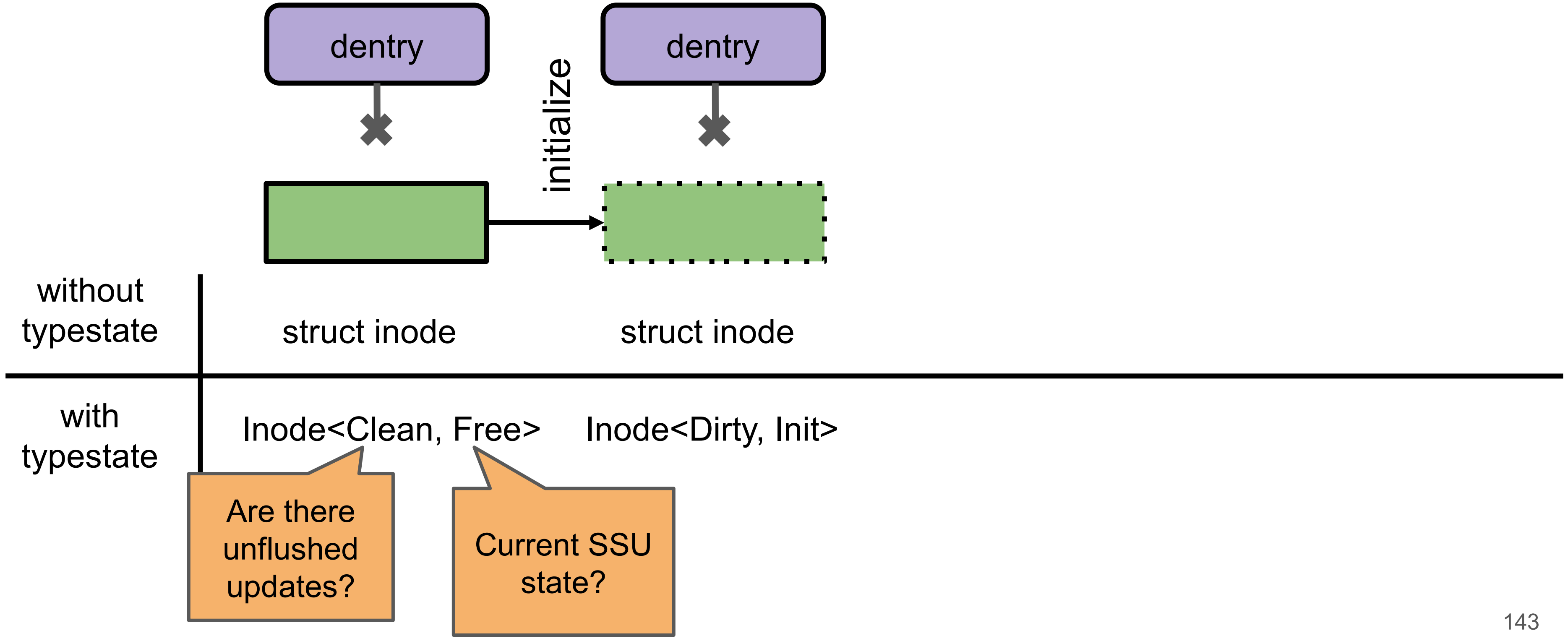


without typestate	struct inode
with typestate	Inode<Clean, Free>

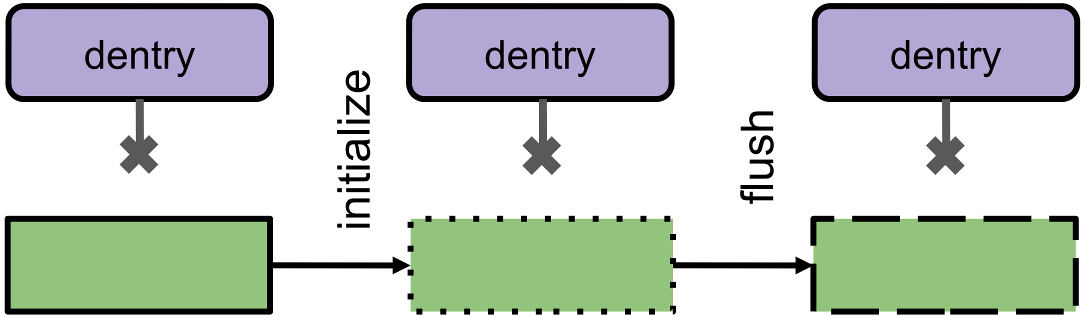
Are there unflushed updates?

Current SSU state?

The typestate pattern



The typestate pattern

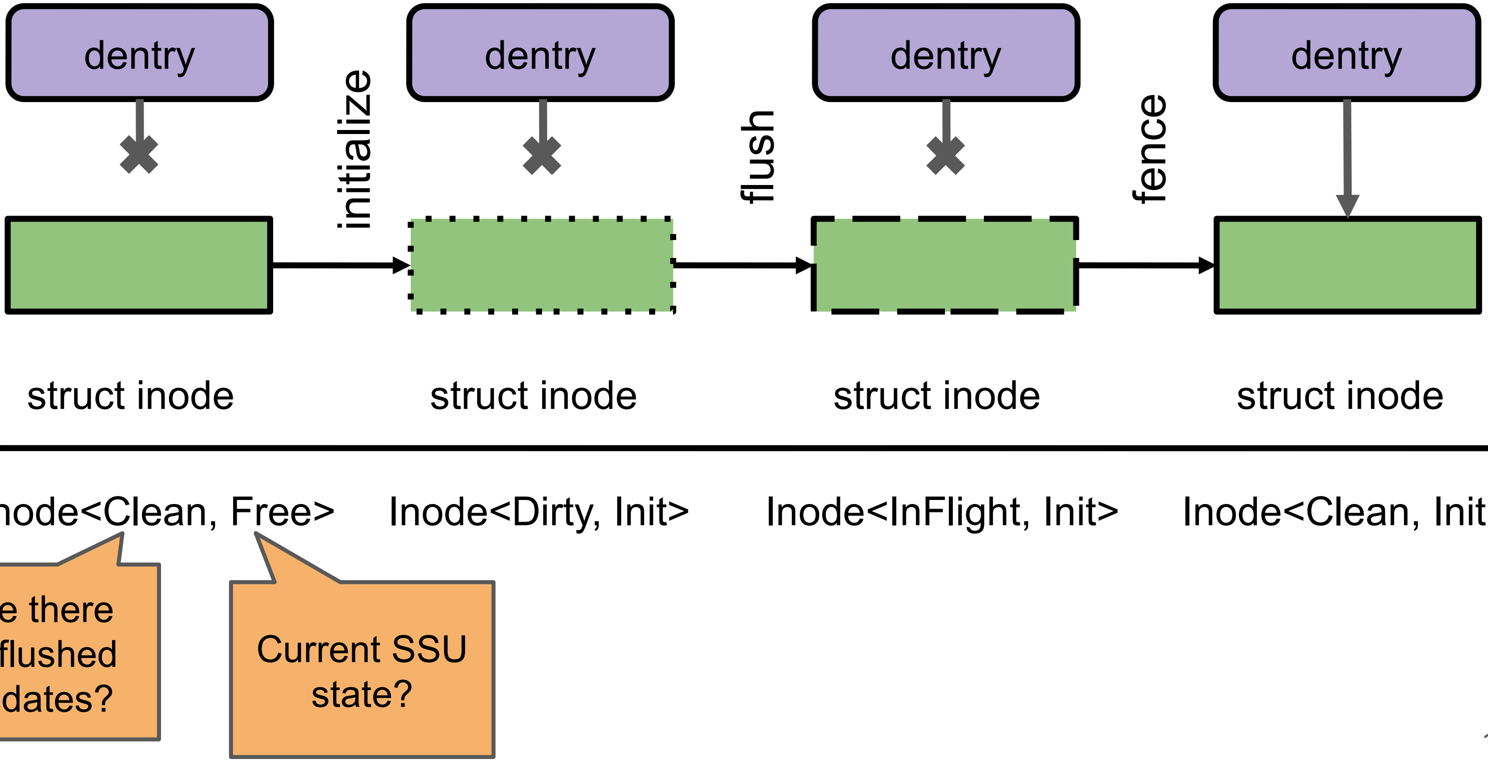


without typestate	struct inode	struct inode	struct inode
with typestate	Inode<Clean, Free>	Inode<Dirty, Init>	Inode<InFlight, Init>

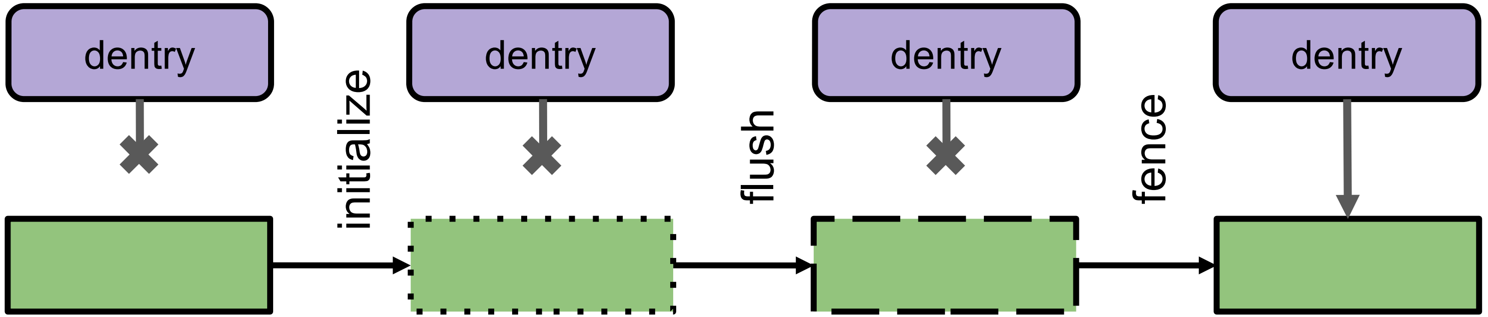
Are there unflushed updates?

Current SSU state?

The typestate pattern



The typestate pattern



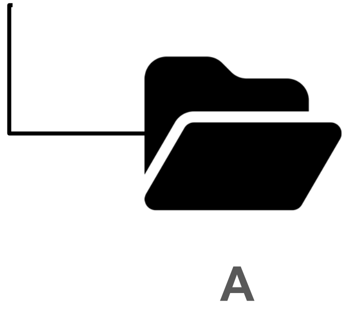
without typestate	struct inode	struct inode	struct inode	struct inode
with typestate	Inode<Clean, Free>	Inode<Dirty, Init>	Inode<InFlight, Init>	Inode<Clean, Init>

Ordering encoded in function signatures:

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

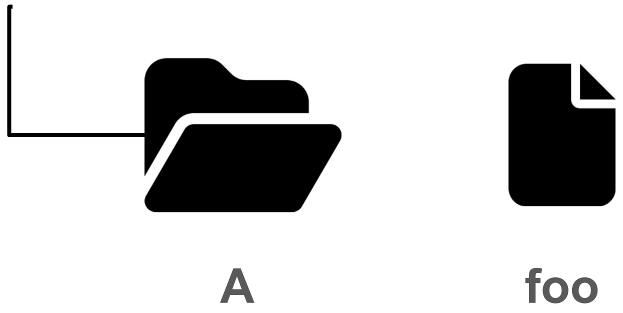
Ordering for crash consistency

Running example: creating a file



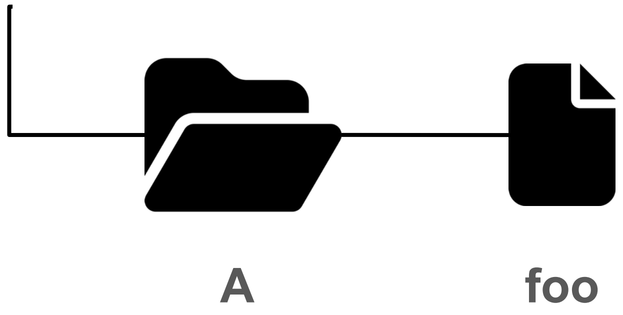
Ordering for crash consistency

Running example: creating a file



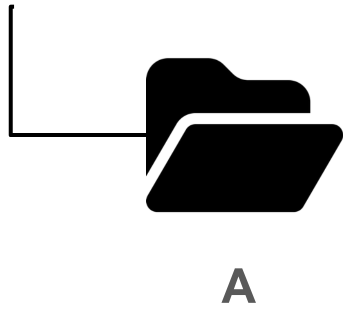
Ordering for crash consistency

Running example: creating a file



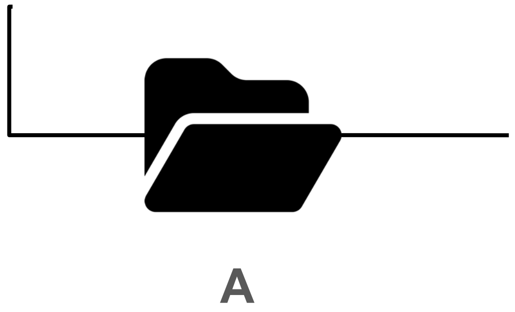
Ordering for crash consistency

Running example: creating a file



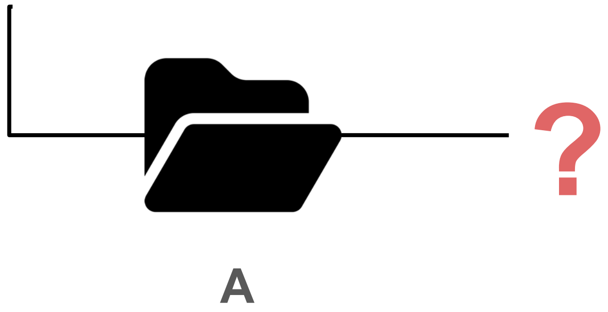
Ordering for crash consistency

Running example: creating a file



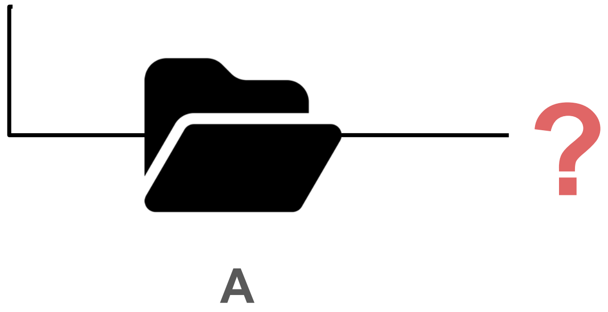
Ordering for crash consistency

Running example: creating a file



Ordering for crash consistency

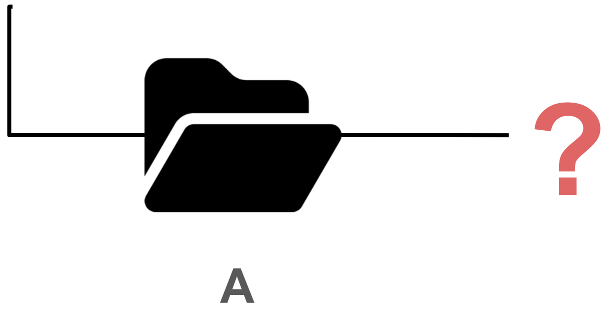
Running example: creating a file



Creating link from A → foo is dependent on initialization of foo

Ordering for crash consistency

Running example: creating a file

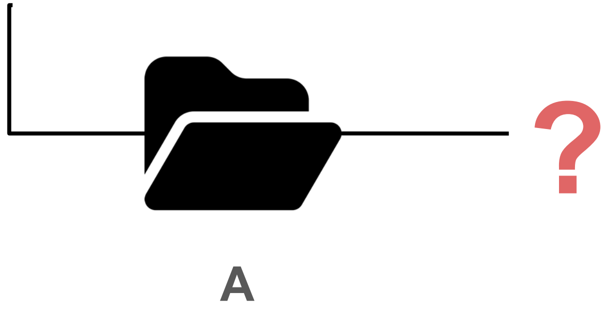


Creating link from A → foo is dependent on initialization of foo

Just two swapped operations can cause serious bugs!

Ordering for crash consistency

Running example: creating a file



Creating link from A → foo is dependent on initialization of foo

Just two swapped operations can cause serious bugs!

Statically enforcing durable update ordering can prevent crash-consistency bugs

Compilation times

System (unverified)	Lines of code	Compilation time (s)
Ext4	45K	38
NOVA	16K	20
WineFS	9K	13
SquirrelFS	**7.5K**	**10**

System (verified)	Lines of code	Verification time (**hours**)
FSCQ	31K	11
VeriBetrKV	45K	1.8