Verifying concurrent, crash-safe systems with **Perennial**

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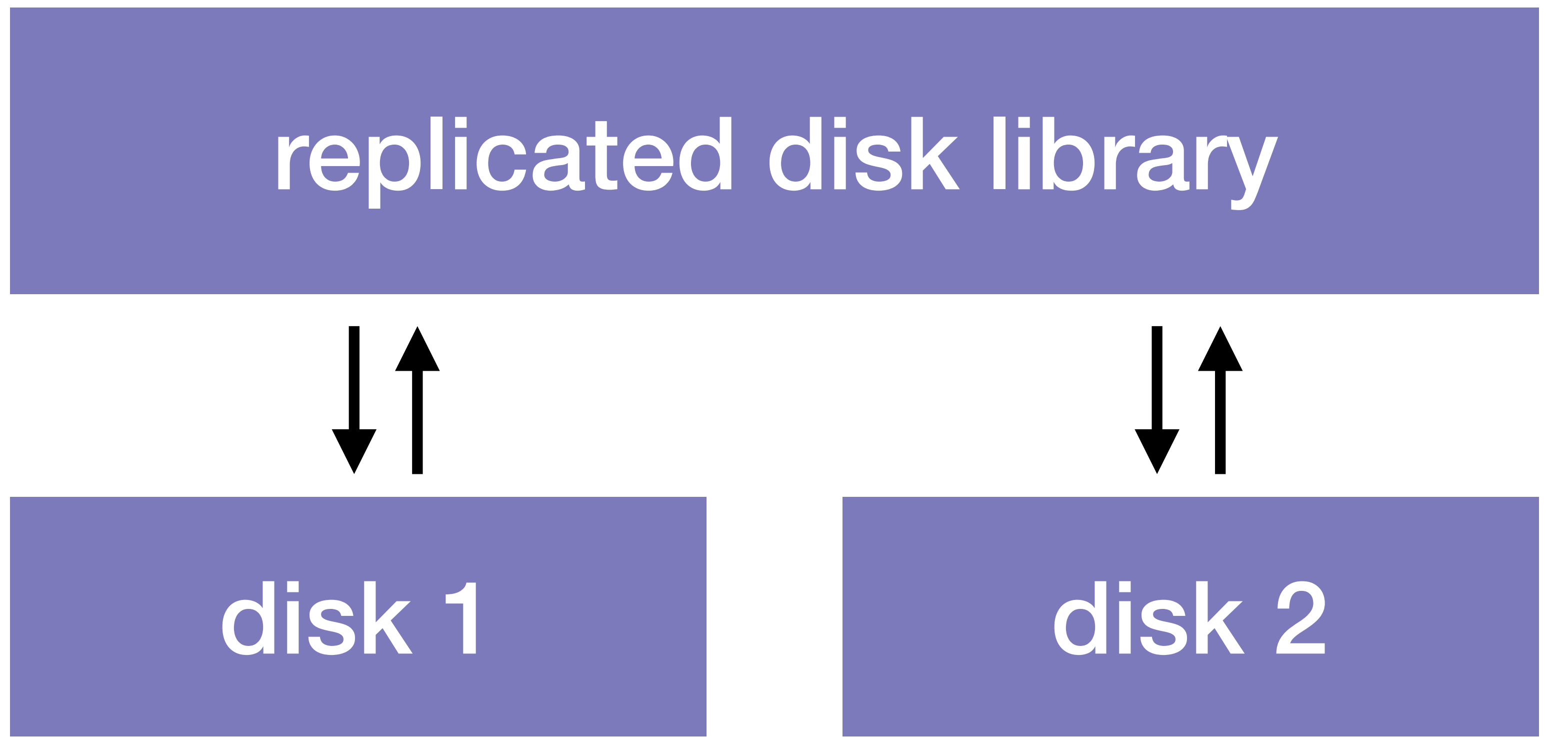
Many systems need concurrency and crash safety

Examples: file systems, databases, and key-value stores

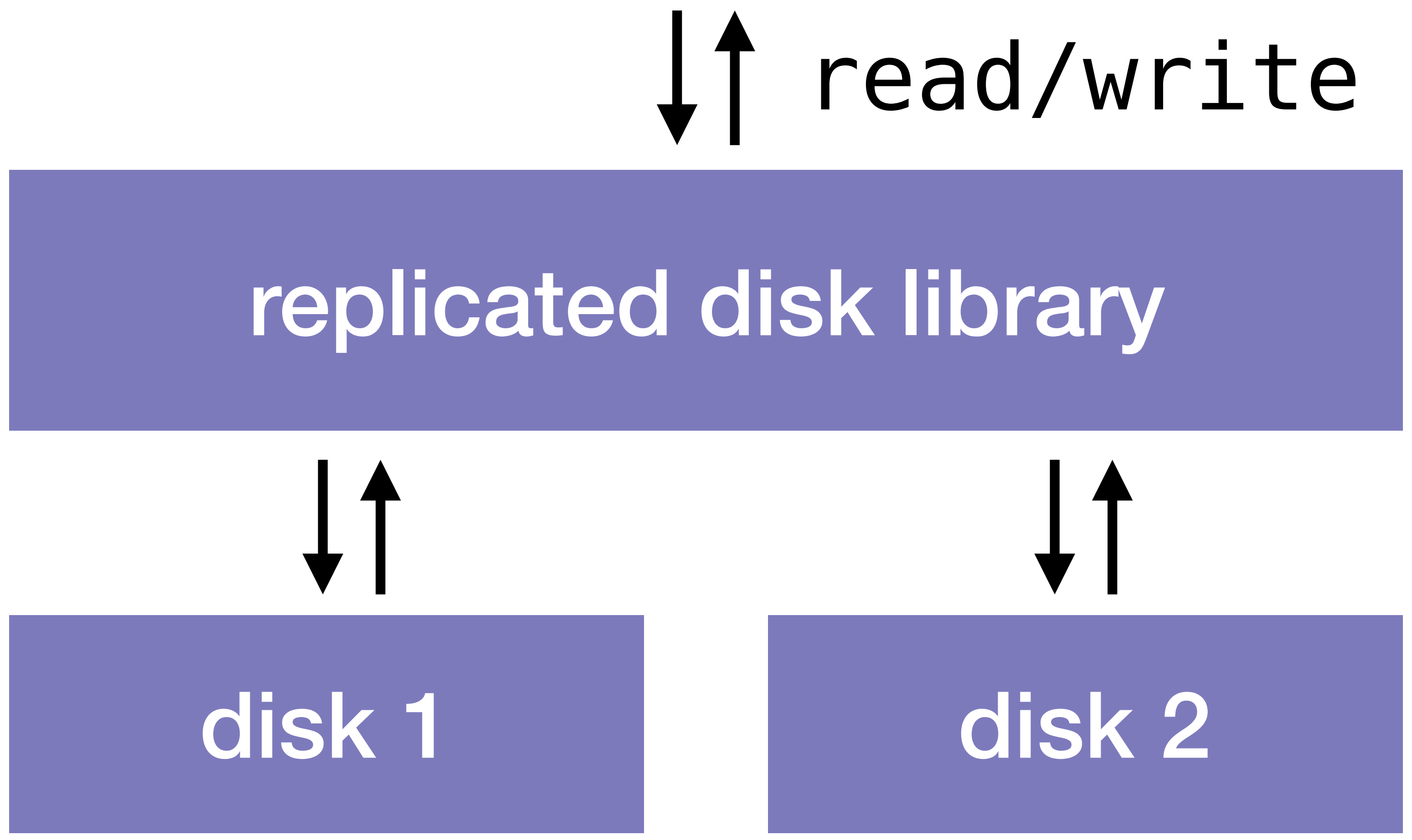
Make strong guarantees about keeping your data safe

Achieve high performance with concurrency

Simple example: replicated disk



Simple example: replicated disk



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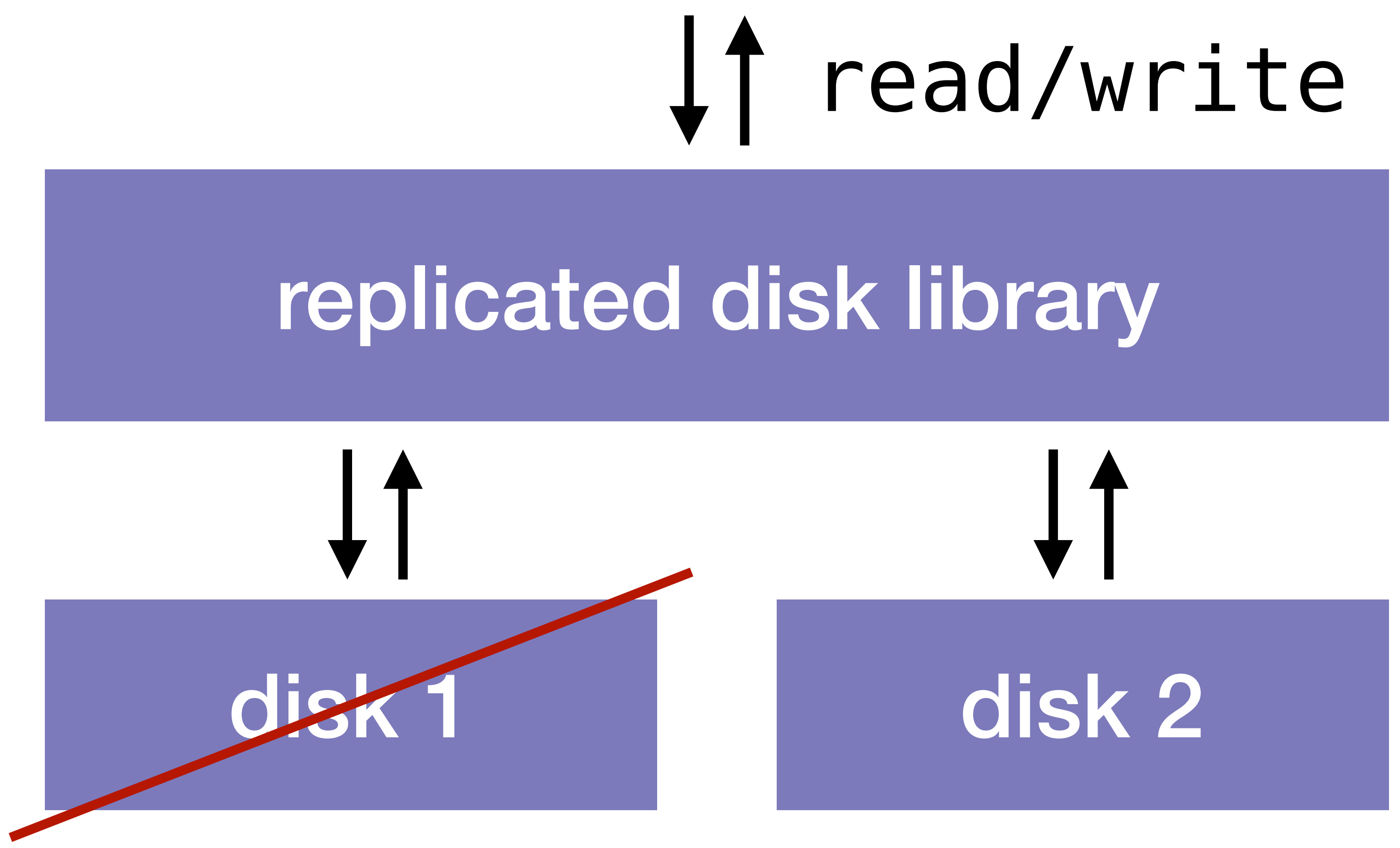

Replicated disk is subtle

```
func write(a: addr, v: block) {
  lock_address(a)
  d1.write(a, v)
  d2.write(a, v)
  unlock_address(a)
}
```

Replicated disk is subtle

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func write(a: addr, v: block) {
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what if system crashes here?

what if disk 1 fails?

Replicated disk is subtle

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what if system crashes here?
what if disk 1 fails?

```
// runs on reboot
func recover() {
  for a in … {
    // copy from d1 to d2
  }
}
```

Replicated disk is subtle

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what if system crashes here?
what if disk 1 fails?

```
// runs on reboot
func recover() {
  for a in … {
    // copy from d1 to d2
  }
}
```

```
func read(a: addr): block {
  lock_address(a)
  v, ok := d1.read(a)
  if !ok {
    v, _ = d2.read(a)
  }
  unlock_address(a)
  return v
}
```

Goal: systematically reason about all executions with formal verification

Existing verification frameworks do not support concurrency and crash safety

verified crash safety	verified concurrency
FSCQ [SOSP ’15]	CertiKOS [OSDI ’16]
Yggdrasil [OSDI ’16]	CSPEC [OSDI ’18]
DFSCQ [SOSP ’17]	AtomFS [SOSP ’19]
…	…

no system can do both

Combining verified crash safety and concurrency is challenging

Crash and recovery can interrupt a critical section

Crash wipes in-memory state

Recovery logically completes crashed threads’ operations

Perennial's techniques address challenges integrating crash safety into concurrency reasoning

Crash and recovery can interrupt a critical section

➡ **leases**

Crash wipes in-memory state

➡ **memory versioning**

Recovery logically completes crashed threads' operations

➡ **recovery helping**

Perennial’s techniques address challenges integrating crash safety into concurrency reasoning

see paper

Crash and recovery can interrupt a critical section

➡ **leases**

Crash wipes in-memory state

➡ **memory versioning**

this talk

Recovery logically completes crashed threads’ operations

➡ **recovery helping**

Contributions

Perennial: framework for reasoning about crashes and concurrency

see paper Goose: reasoning about Go implementations

Evaluation: verified mail server written in Go with Perennial

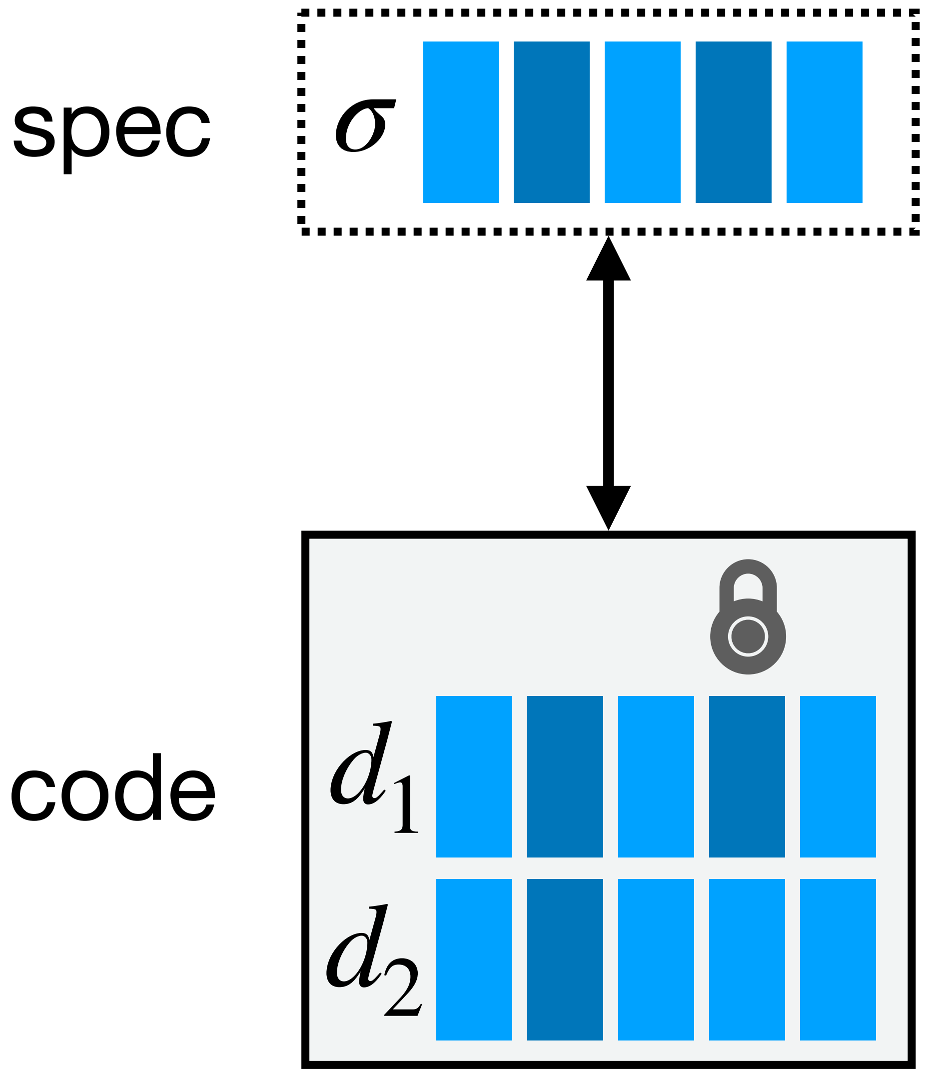
Specifying correctness: concurrent recovery refinement

All operations are **correct** and **atomic wrt concurrency and crashes**

Recovery repairs system after reboot

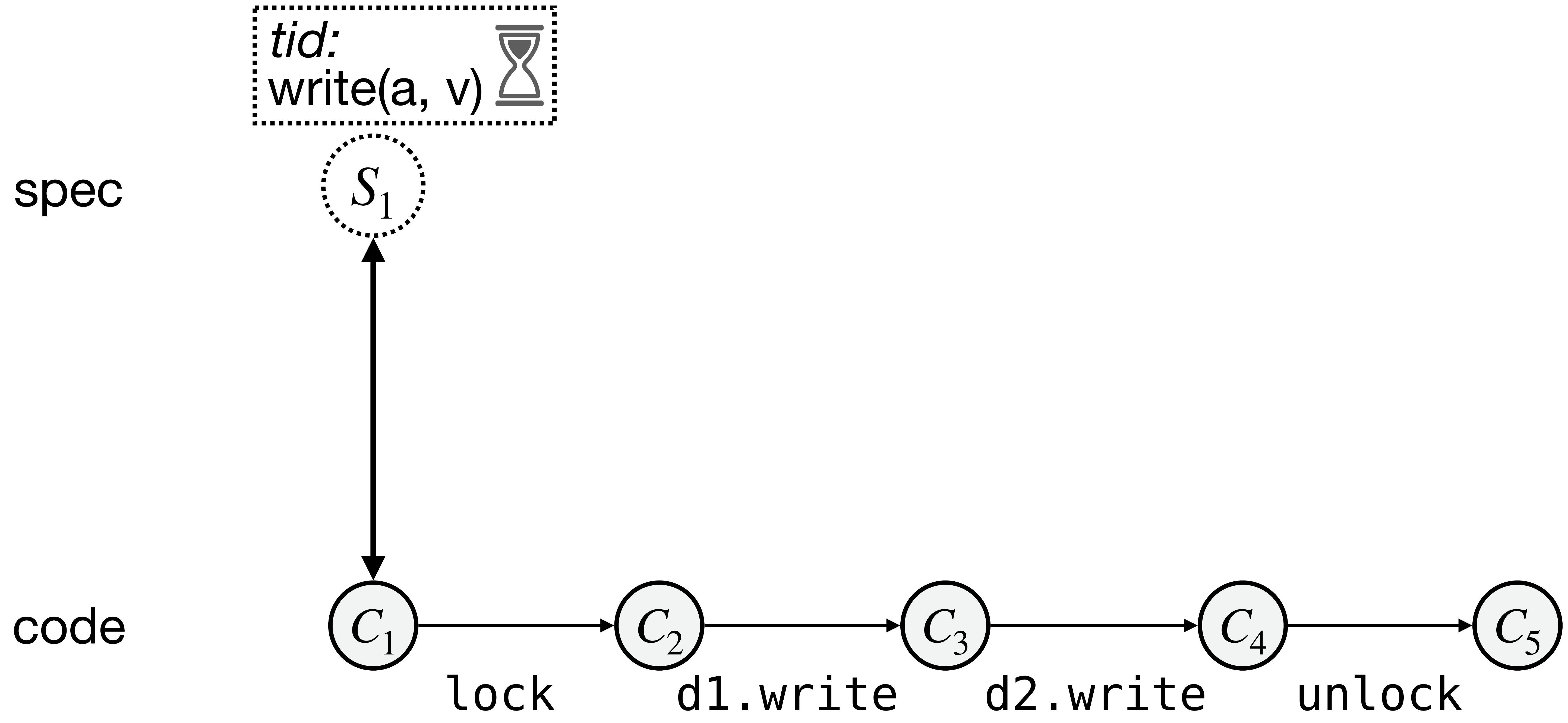
Proving the replicated disk correct

Proving refinement with forward simulation: relate code and spec states



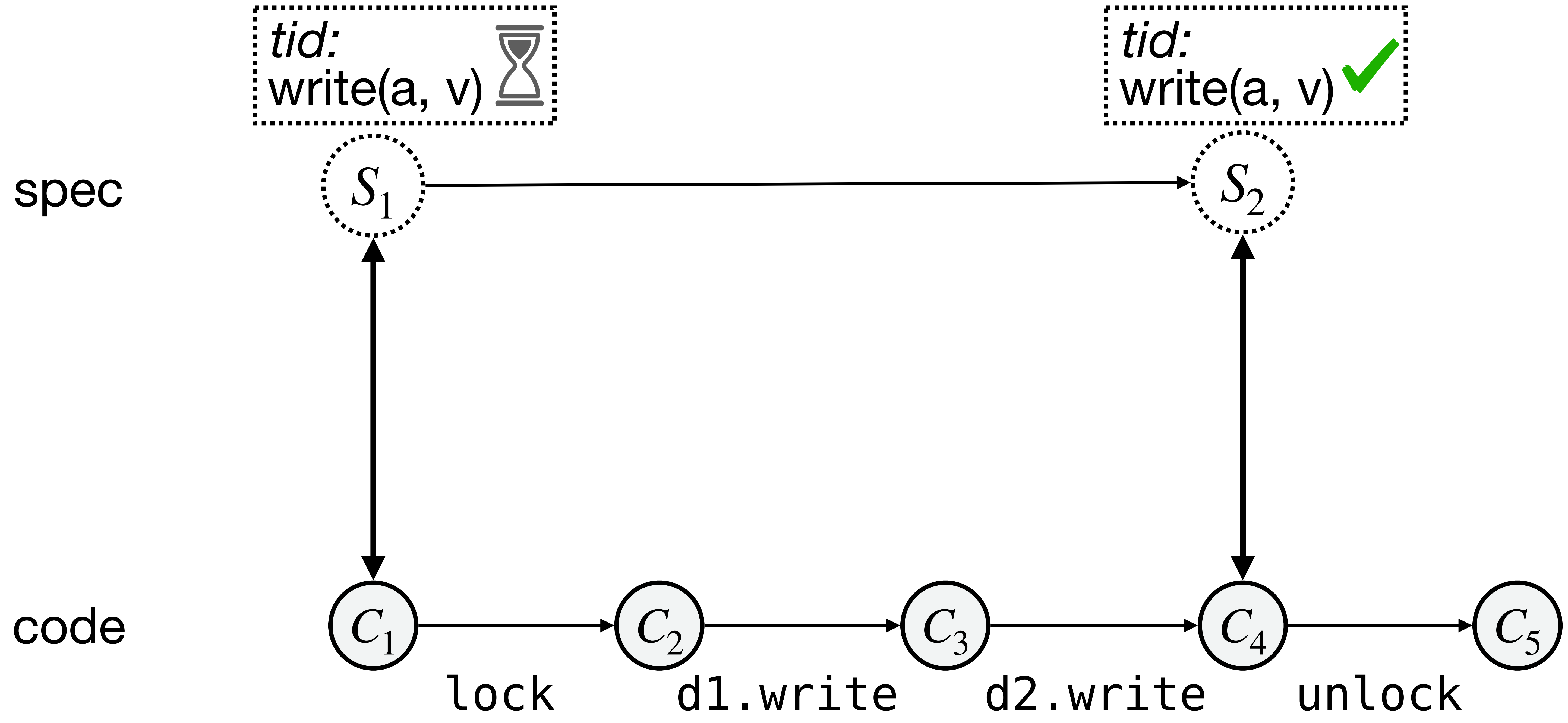
Proving refinement with forward simulation: prove every operation has a commit point

Background



1. Write down abstraction relation between code and spec states

Proving refinement with forward simulation: prove every operation has a commit point



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2. Prove every operation commits

Proving refinement with forward simulation: prove every operation has a commit point

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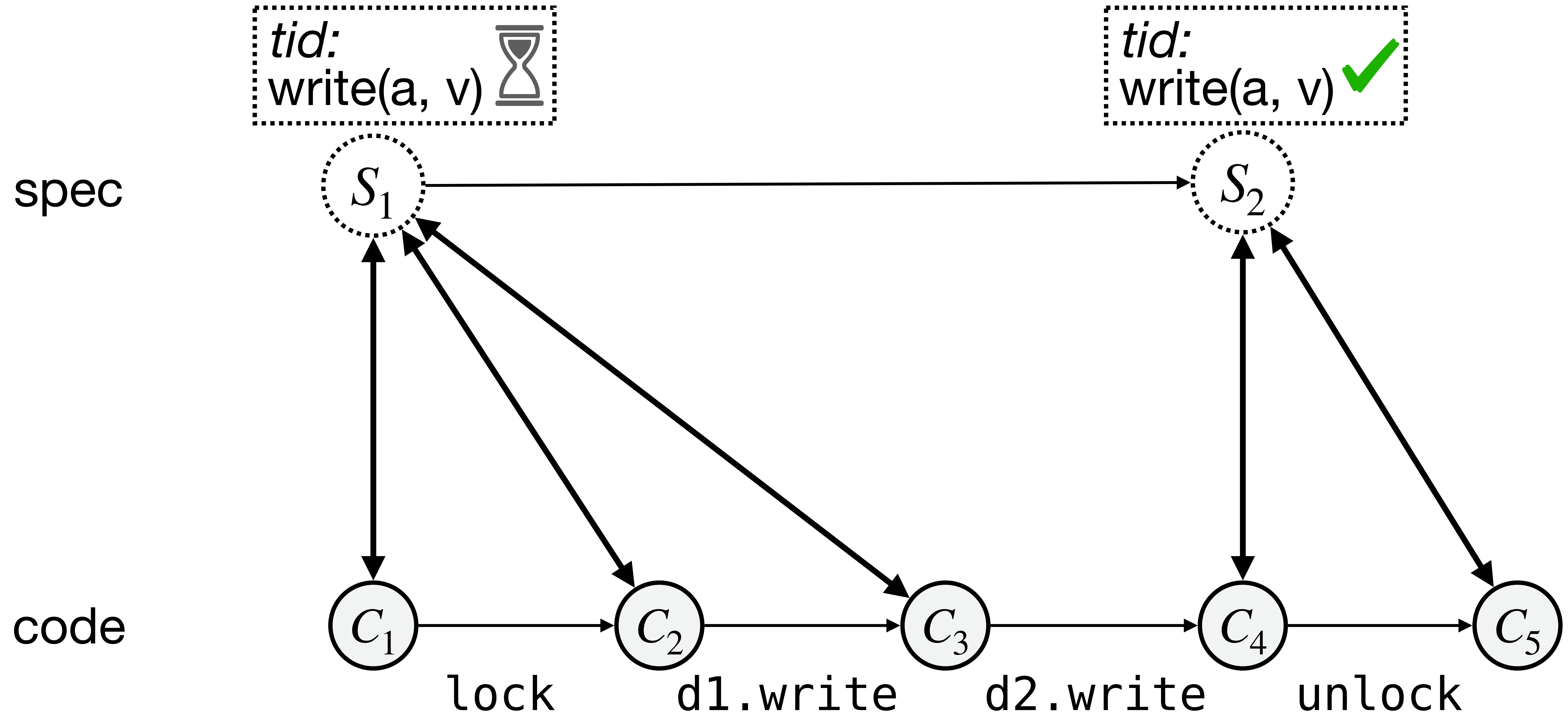
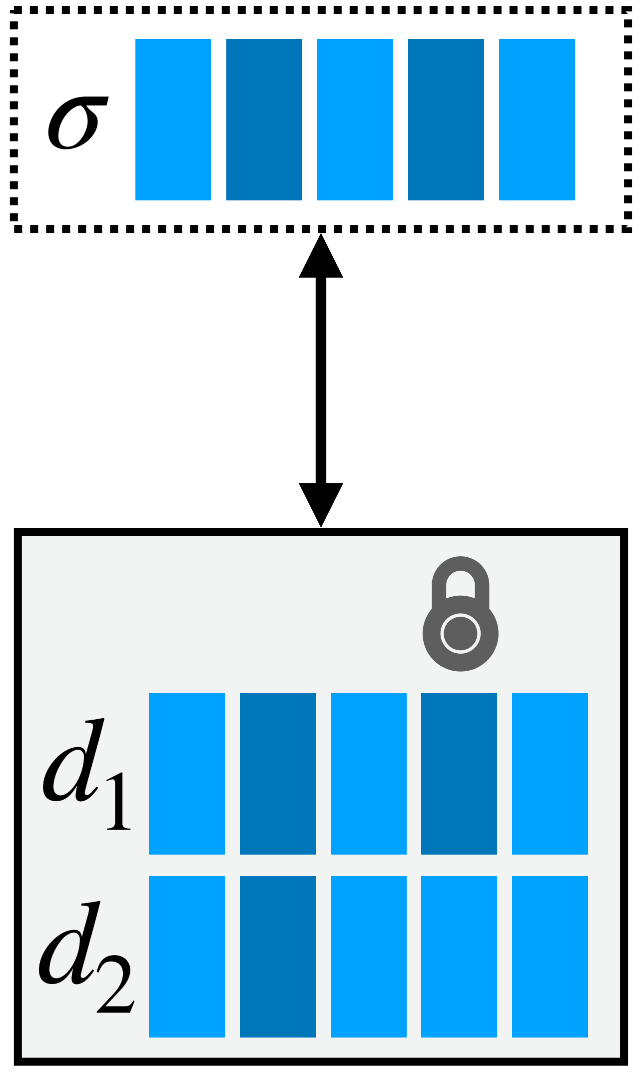


1. Write down abstraction relation between code and spec states
2. Prove every operation commits
3. Prove abstraction relation is preserved

Abstraction relation for the replicated disk



abstraction relation:

$$!\textbf{locked}(a) \implies \begin{array}{r} \sigma[a] = d_1[a] \\ \wedge\ \sigma[a] = d_2[a] \end{array}$$

(if the disk has not failed)

Crashing breaks the abstraction relation

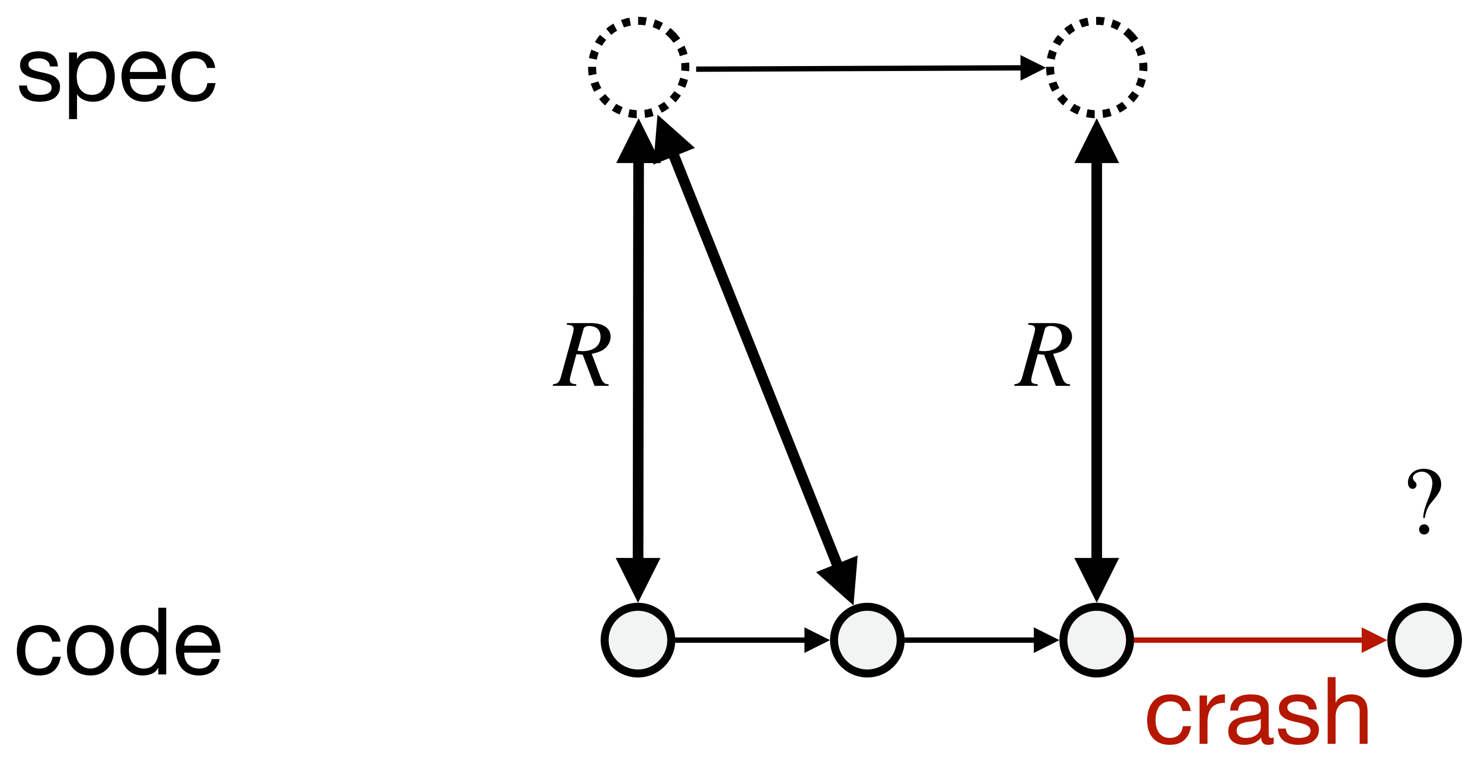
```
func write(a: addr,
           v: block) {

  lock_address(a)
  d1.write(a, v)
```

lock reverts to being free,
but disks are not in-sync

abstraction relation:

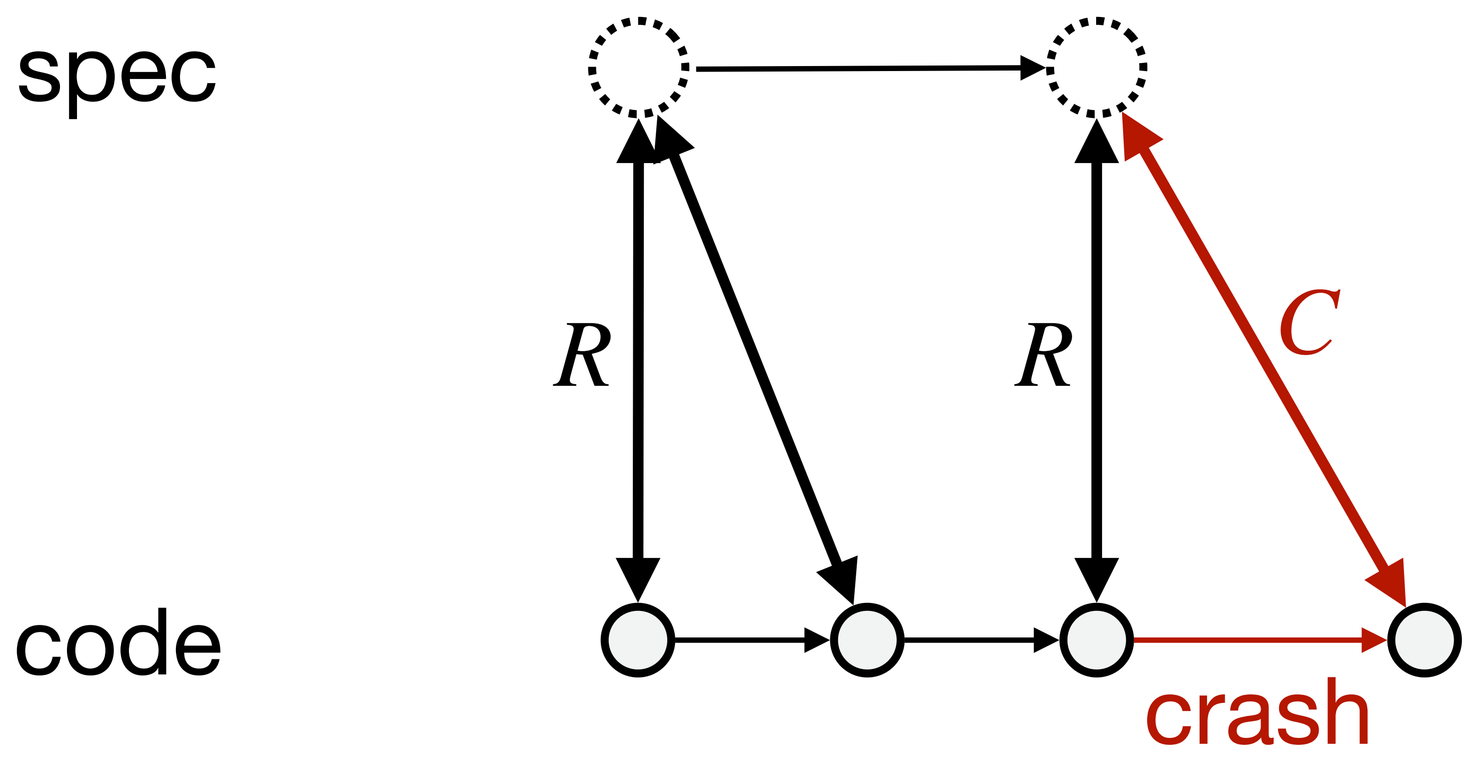
$$!\textbf{locked}(a) \implies \begin{array}{r} \sigma[a] = d_1[a] \\ \wedge\ \sigma[a] = d_2[a] \end{array}$$

So far: abstraction relation always holds



R abstraction relation

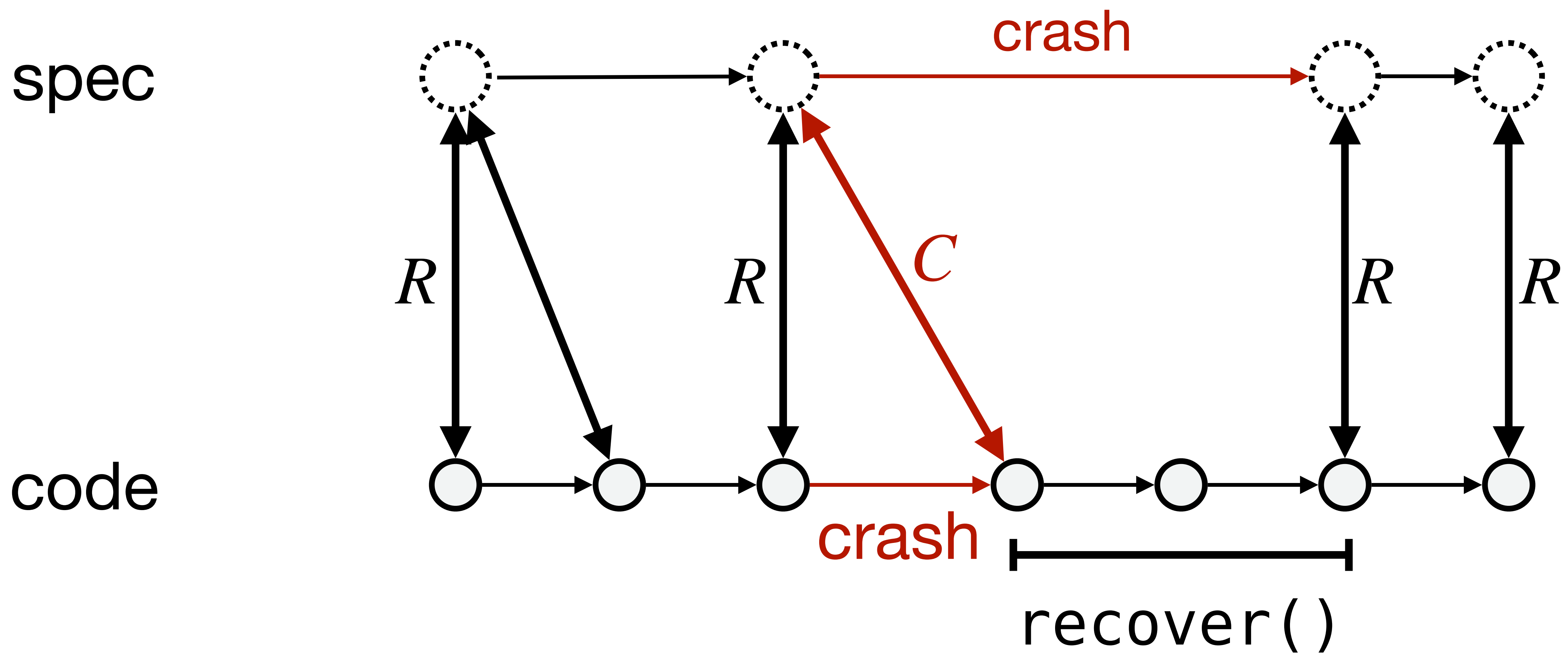
Separate a crash invariant from the abstraction relation



R abstraction relation

C crash invariant

Recovery proof uses the crash invariant to restore the abstraction relation



R abstraction relation

C crash invariant

Proving recovery correct: makes writes atomic

```
func write(a: addr,
           v: block) {

  lock_address(a)
  d1.write(a, v)
```

```
func recover() {
  for a in … {
    v, ok := d1.read(a)
    if !ok { … }
    d2.write(a, v)
  }

}
```

User sees an atomic write due to recovery

pending
spec operation

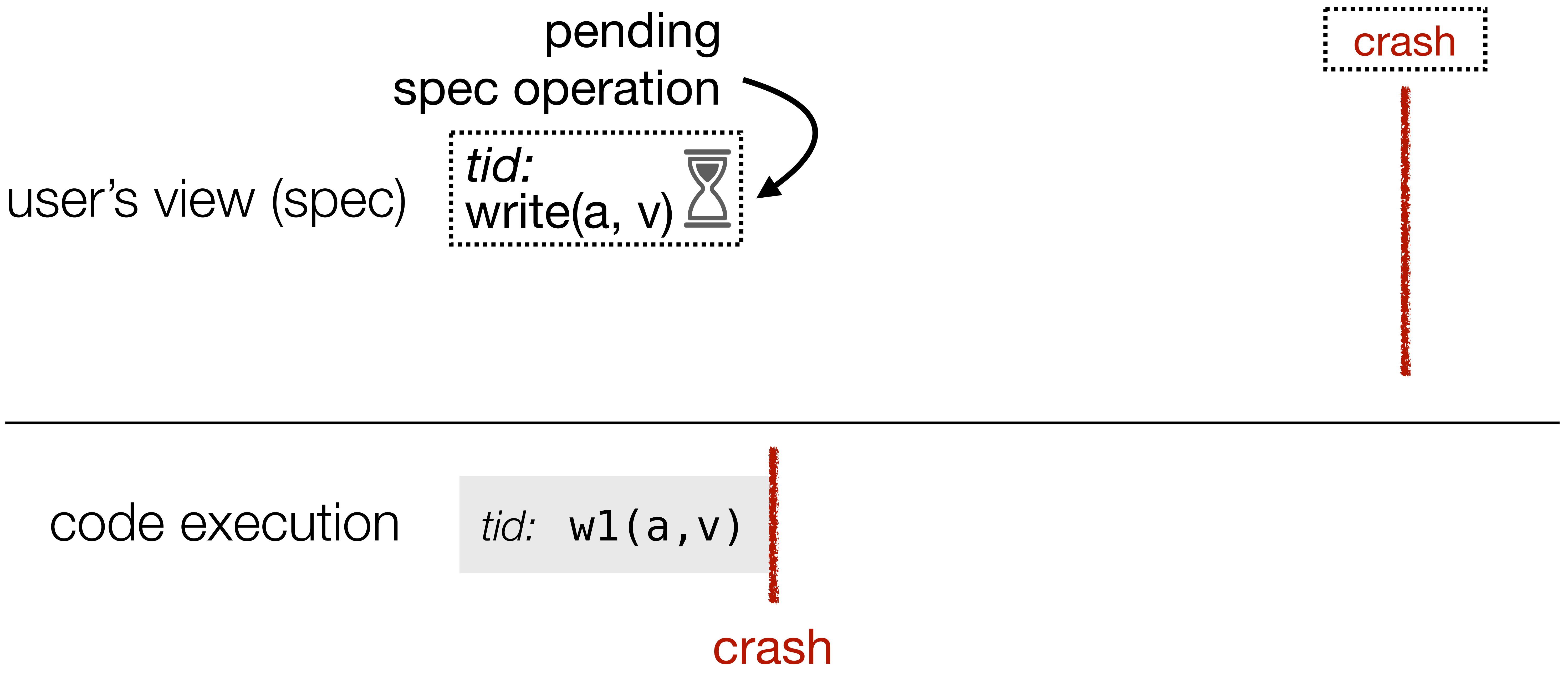
user's view (spec)

tid:
write(a, v)

crash

code execution

User sees an atomic write due to recovery



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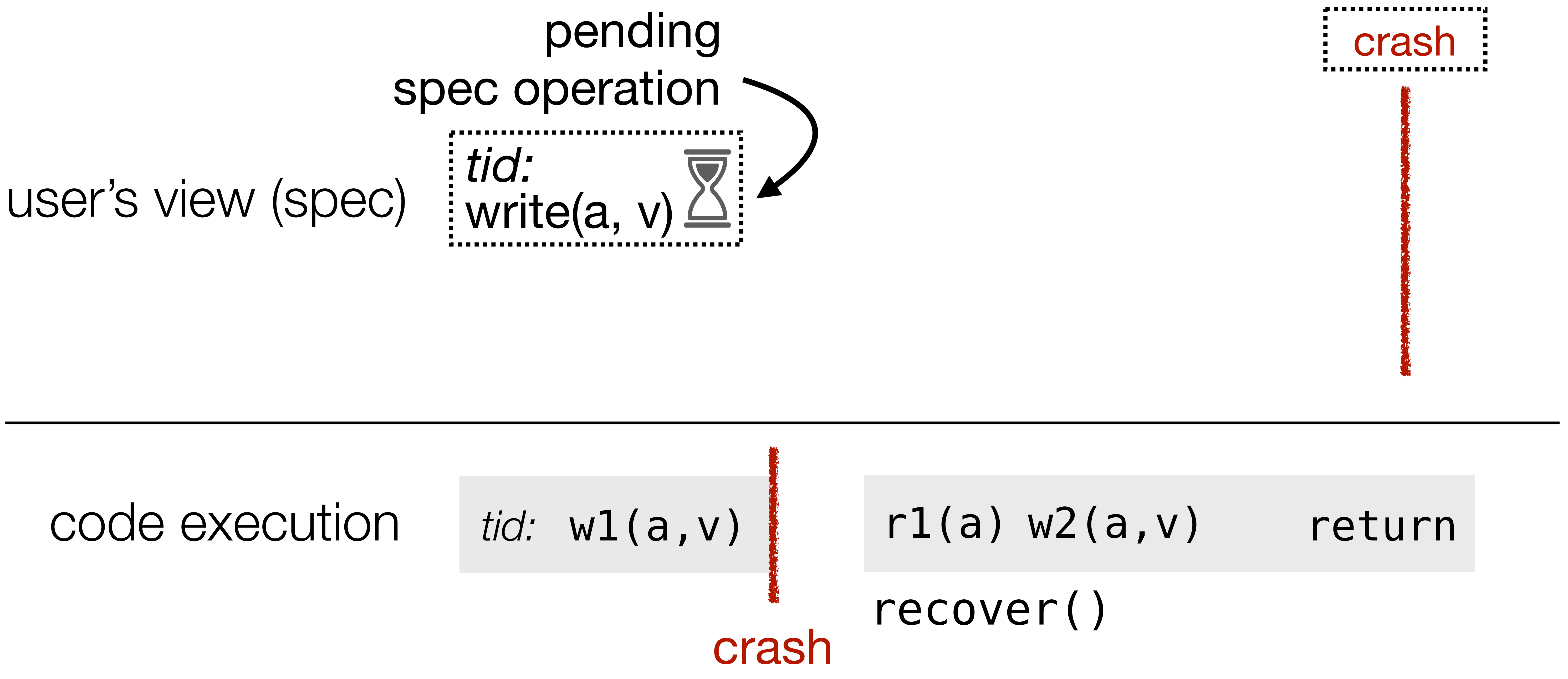

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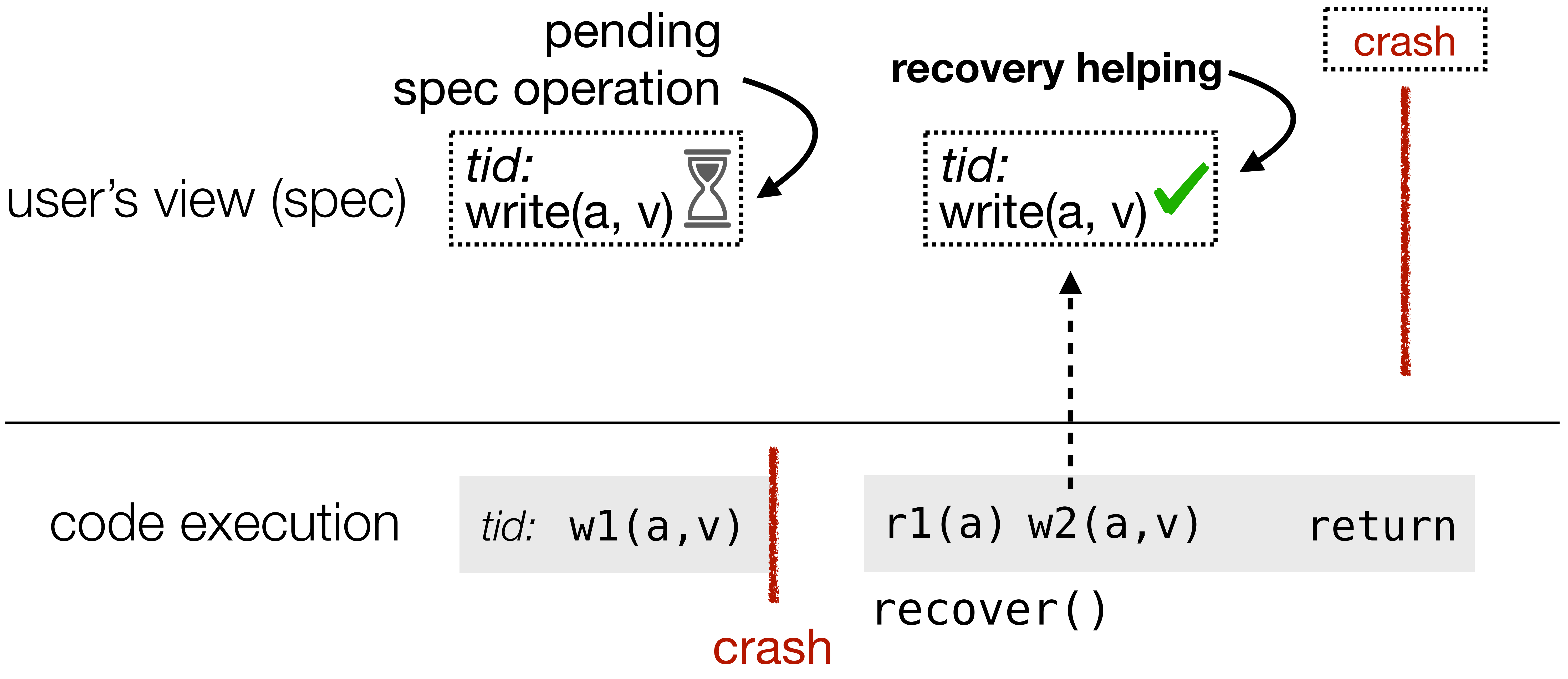

Recovery helping: recovery can commit writes from before the crash

```
func write(a: addr,
           v: block) {

  lock_address(a)
  d1.write(a, v)
```

tid:
write(a, v)

```
func recover() {
  for a in … {
    v, ok := d1.read(a)
    if !ok { … }
    d2.write(a, v)
  }

}
```

tid:
write(a, v)

Crash invariant says "if disks disagree, some thread was writing the value on the first disk"

```
func write(a: addr,
           v: block) {

  lock_address(a)
  d1.write(a, v)
```

tid:
write(a, v)

```
func recover() {
  for a in … {
    v, ok := d1.read(a)
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  }

}
```

tid:
write(a, v) ✓

crash invariant:

$d_1[a] \neq d_2[a] \implies$
$\exists \text{tid.}$ *tid:* write(a, $d_1[a]$)

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}
```

tid:
write(a, v)

crash invariant:

$d_1[a] \neq d_2[a] \implies$
$\exists \text{tid}.$ *tid:* write(a, $d_1[a]$)

Key idea: crash invariant can refer to interrupted spec operations

```
func write(a: addr,
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  d1.write(a, v)
```

tid:
write(a, v)

```
func recover() {
  for a in … {
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    d2.write(a, v)
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}
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tid:
write(a, v)

crash invariant:

$d_1[a] \neq d_2[a] \implies$
$\exists$tid. *tid:* write(a, $d_1[a]$)

Recovery proof shows code restores the abstraction relation by completing all interrupted writes

```
func write(a: addr,
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  lock_address(a)
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```

tid:
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```
func recover() {
  for a in … {
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}
```

tid:
write(a, v)

crash

abstraction relation:

$$\textbf{!locked}(a) \implies \begin{array}{l} \sigma[a] = d_1[a] \\ \wedge\ \sigma[a] = d_2[a] \end{array}$$

Proving concurrent recovery refinement

Recovery proof uses **crash invariant** to restore abstraction relation

Proof can refer to interrupted operations, enabling **recovery helping** reasoning

Users get **correct behavior** and **atomicity**

Implementation

Perennial (9k lines of Coq)
- leases
- memory versioning
- recovery helping

Iris concurrency framework

Coq

developer-written

this paper

prior work

Implementation

Go source

`go build`

`exe`

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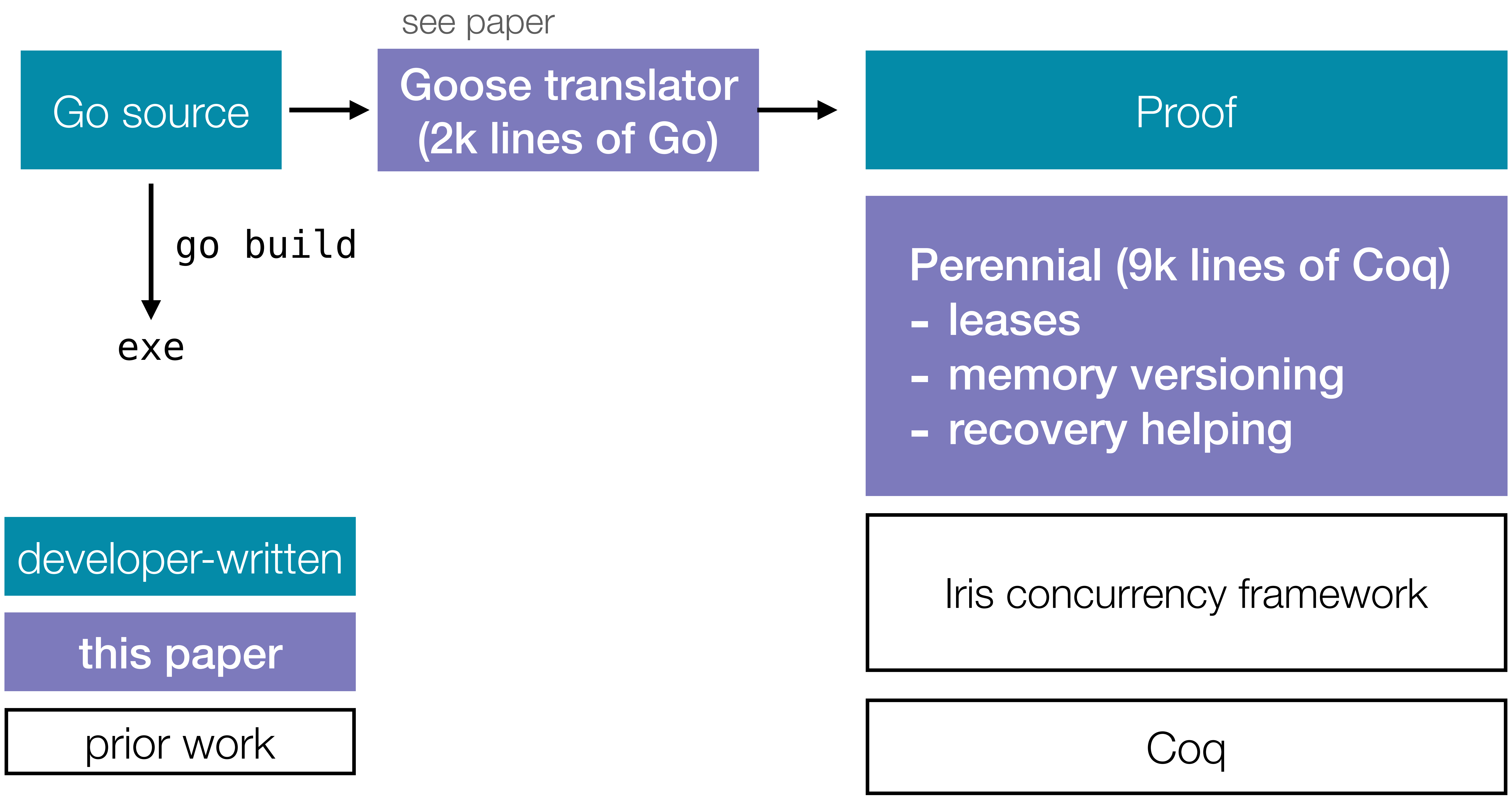

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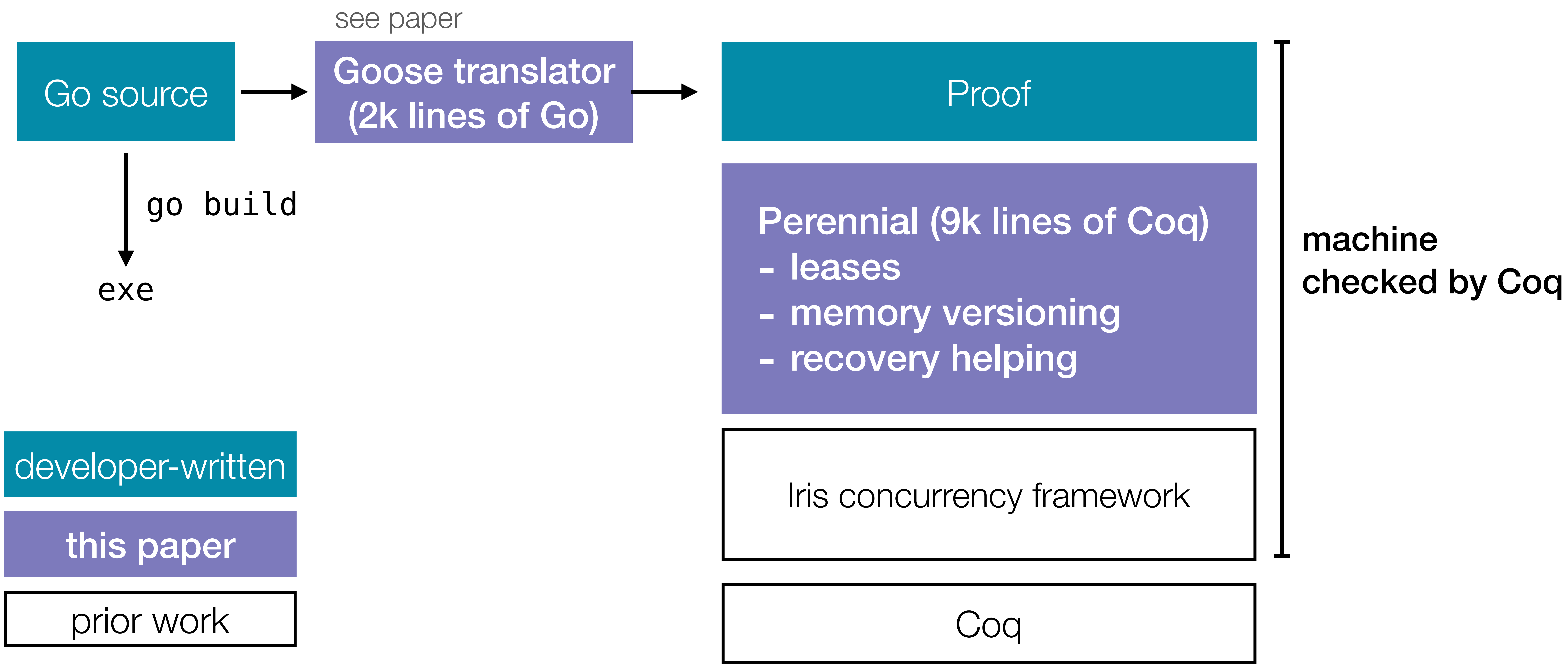


Evaluation

This talk:

- proof-effort comparison

See paper:

- verified examples
- TCB
- bug discussion

Methodology:
Verify the same mail server as previous work, CSPEC [OSDI ’18]

Users can read, deliver, and delete mail

Implemented on top of a file system

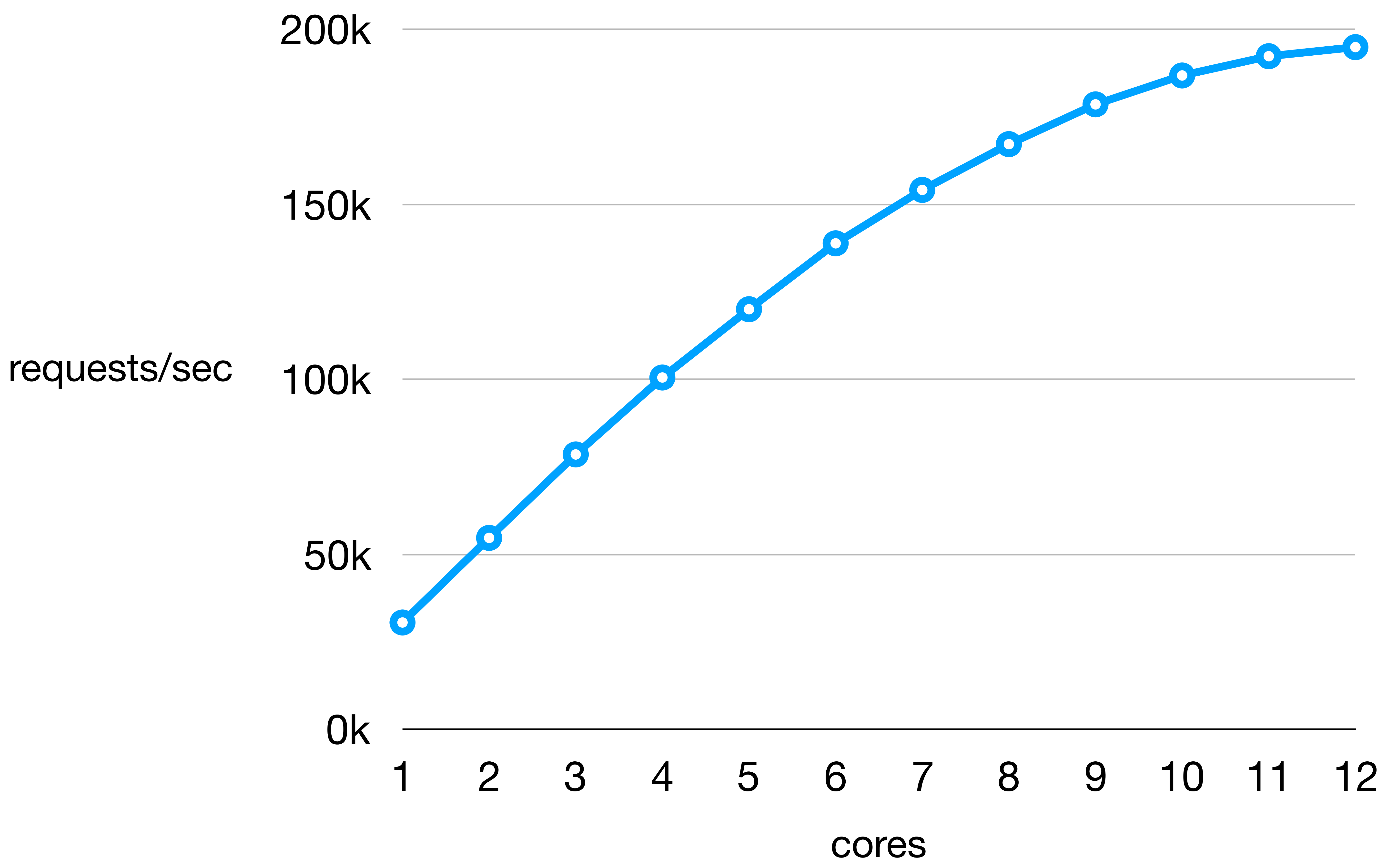
Operations are **atomic** (and **crash safe** in Perennial)

Perennial mail server was easier to verify and proves crash safety

	Perennial	**CSPEC** [OSDI ’18]
mail server proof	3,200	4,000
time	2 weeks (**after** framework)	6 months (**with** framework)
code	159 (Go)	215 (Coq)

Perennial mail server really is concurrent

(see the paper for details)



Conclusion

Perennial introduces **crash-safety techniques** that extend concurrent verification in Iris

Goose lets us reason about **Go implementations**

Verified a Go mail server with **less effort** than previous work and proved crash safety

chajed.io/perennial