GoJournal: a verified, concurrent, crash-safe journaling system

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Suppose we want to write a correct file system

Correct: file-system operations atomically follow specification, even on crash

Performant: take advantage of concurrent operations to efficiently use CPU and I/O

GoJournal gives a storage system efficient, atomic writes

atomic writes of multiple objects

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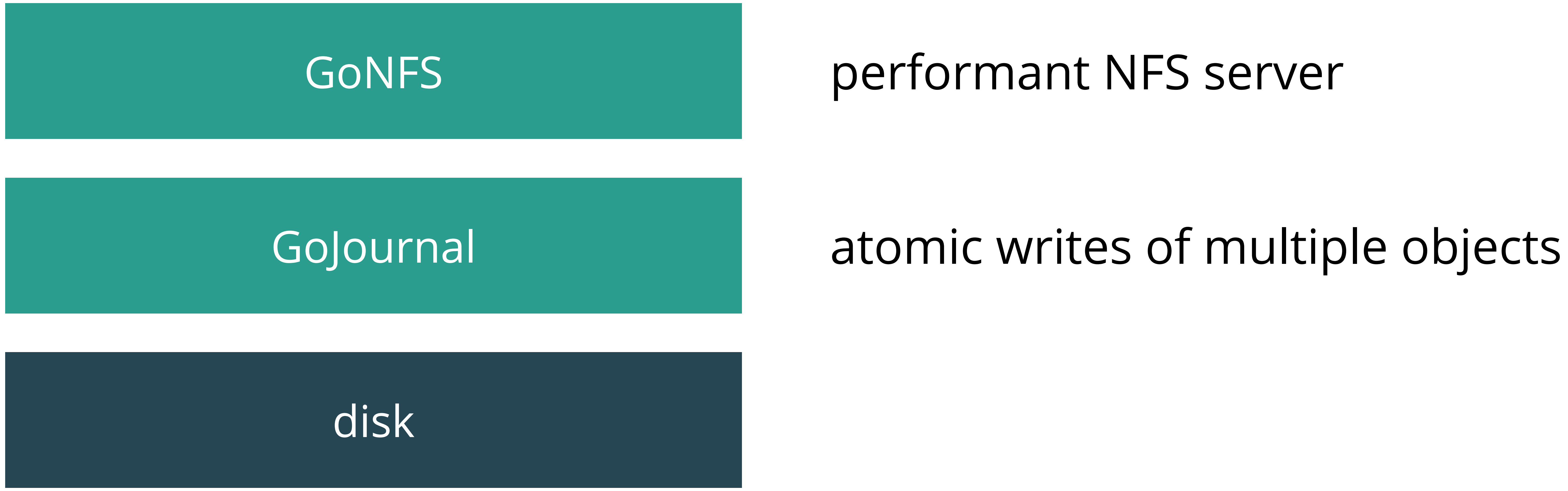

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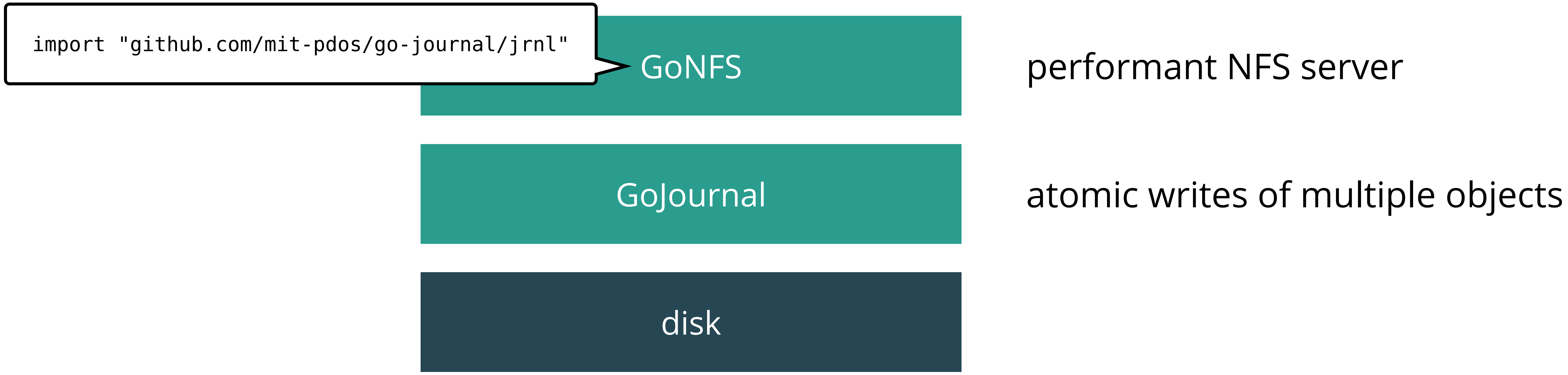
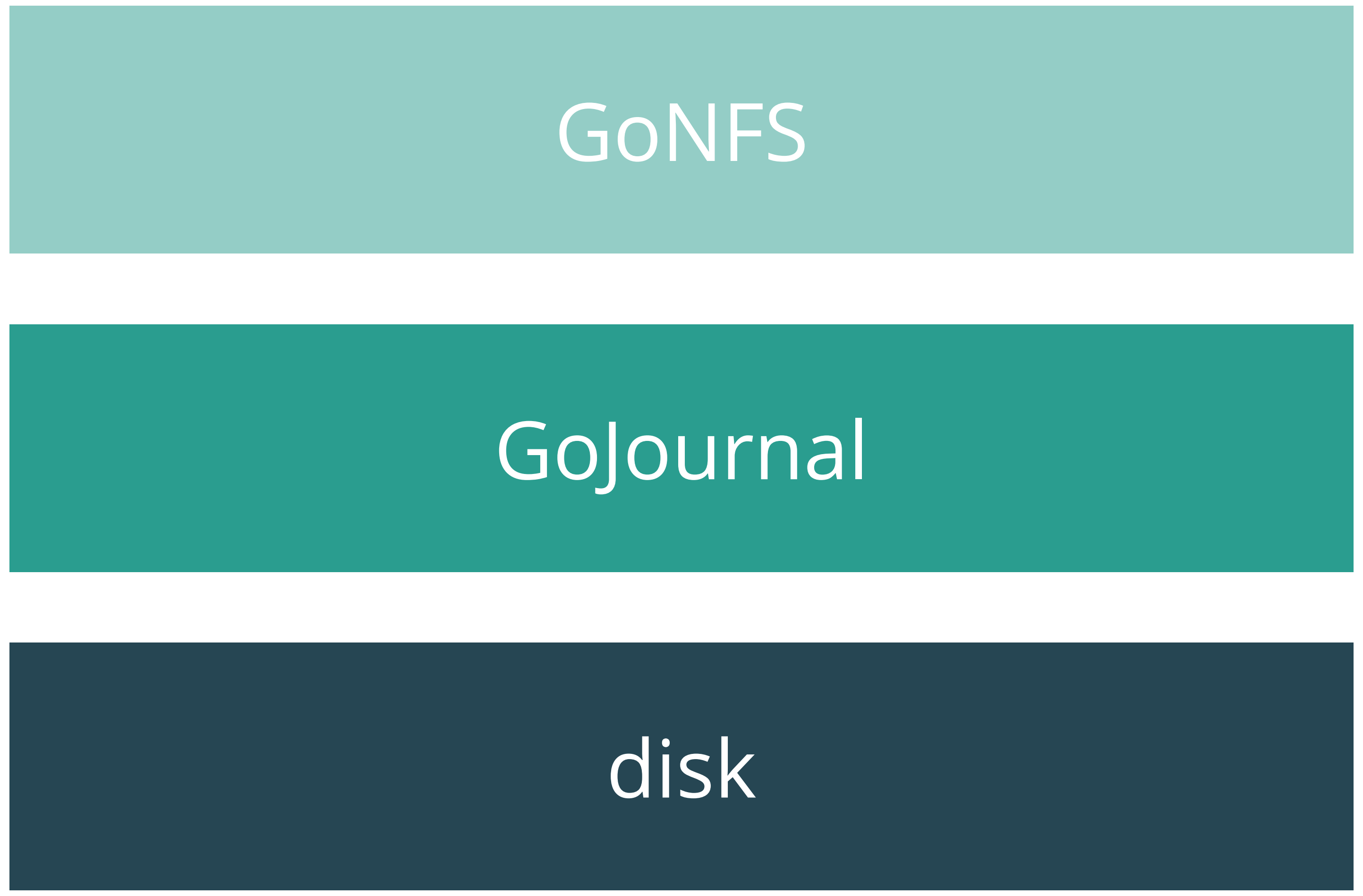


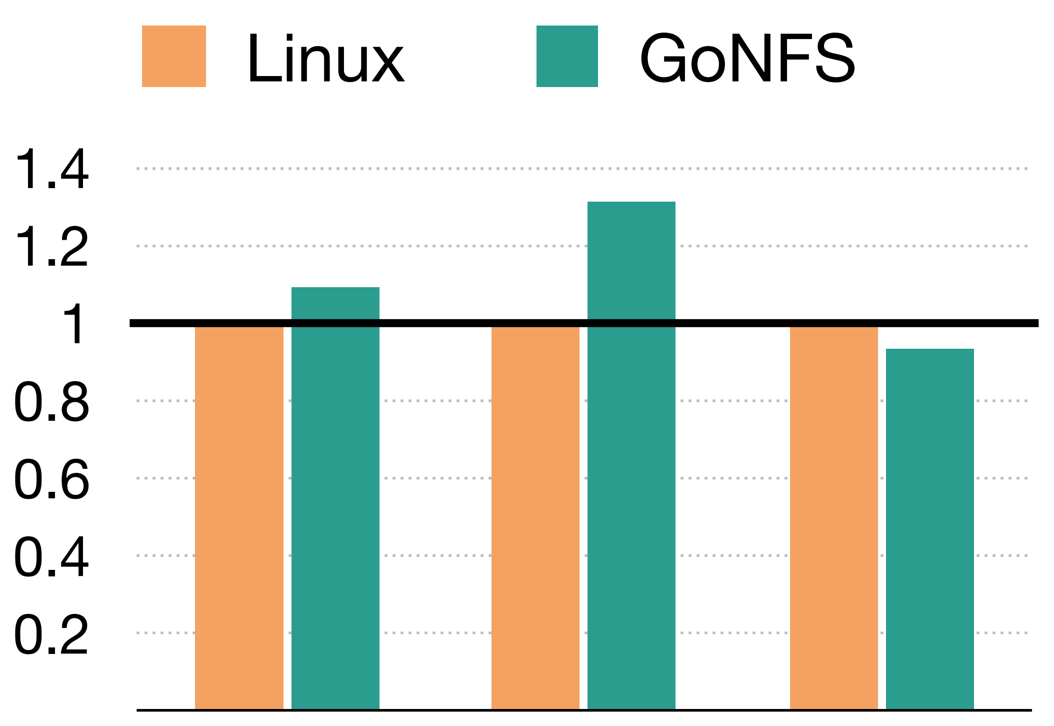
GoJournal is a verified journaling system



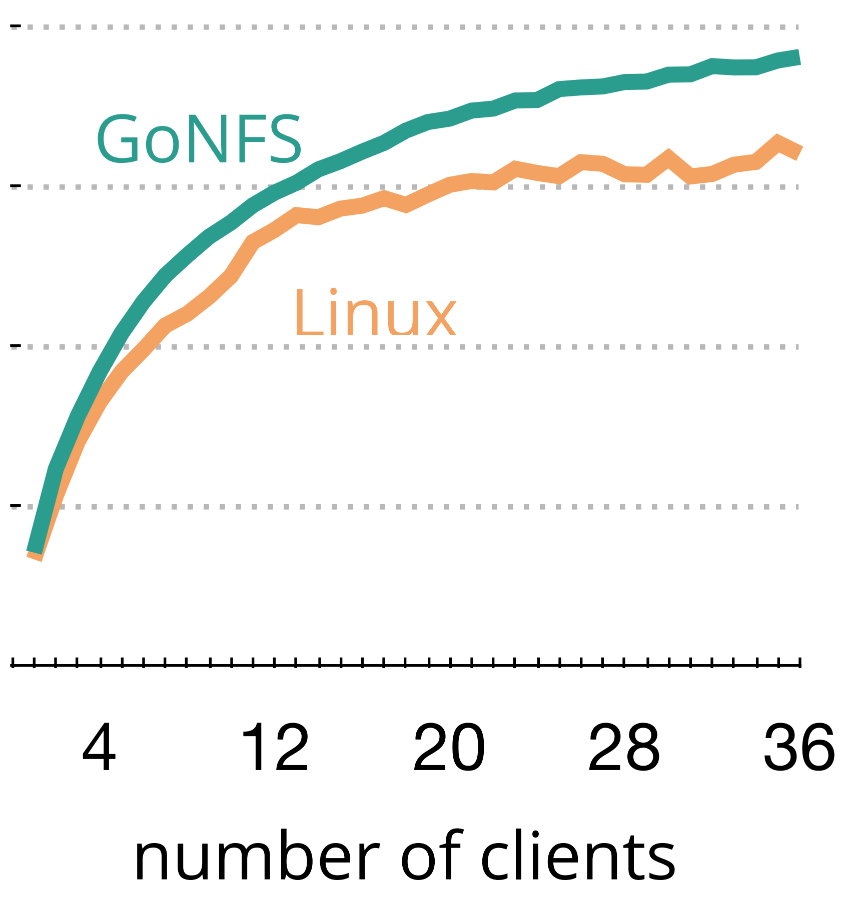
performant NFS server

atomic writes of multiple objects
comes with a machine-checked **proof**

GoJournal has a practical implementation



>95% throughput of Linux with a single client



Throughput scales with number of concurrent clients

Current approaches cannot handle a system of this complexity

Crash-safe but sequential file systems

FSCQ, Yggdrasil, VeriBetrFS

Concurrent systems

CertiKOS, AtomFS, ...

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Crash safety and concurrency
Perennial 1.0

Contributions

GoJournal, the first verified concurrent journal

Perennial 2.0, a new verification framework

SimpleNFS to evaluate specification

Evaluation showing GoJournal achieves good performance

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// one-time init
var d Disk
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// copy block at 0 to 1 and 2
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op.OverWrite(1, buf.Data)
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concurrent operations are atomic

caller is responsible for locking

Operations can concurrently manipulate objects within a block

File system has 128-byte inodes

Sub-block access improves concurrency since caller only locks the required objects

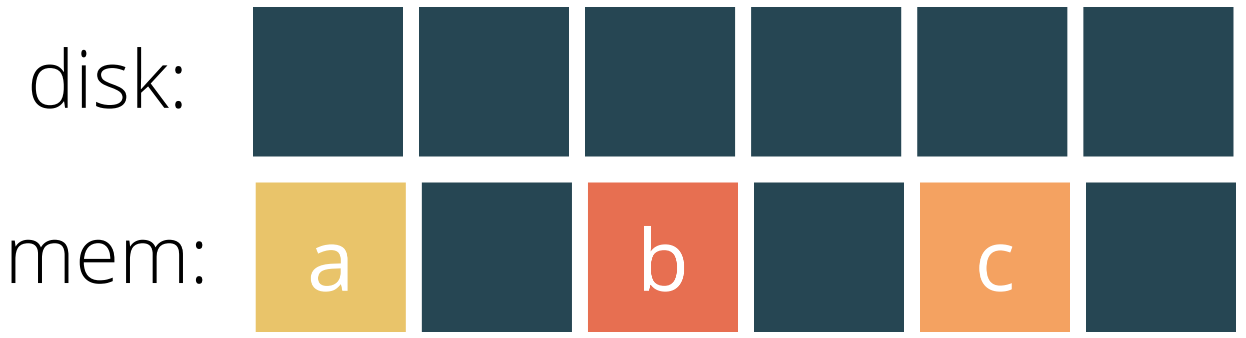
Specification challenge: what do concurrently committed operations do?

```
op := jrnl.Begin()
buf := op.ReadBuf(0, blockSz)
op.OverWrite(1, buf.Data)
op.OverWrite(2, buf.Data)
op.Commit()
```

||

```
op := jrnl.Begin()
op.OverWrite(7, data)
op.Commit()
```

Sequential journaling only maintains old and next state



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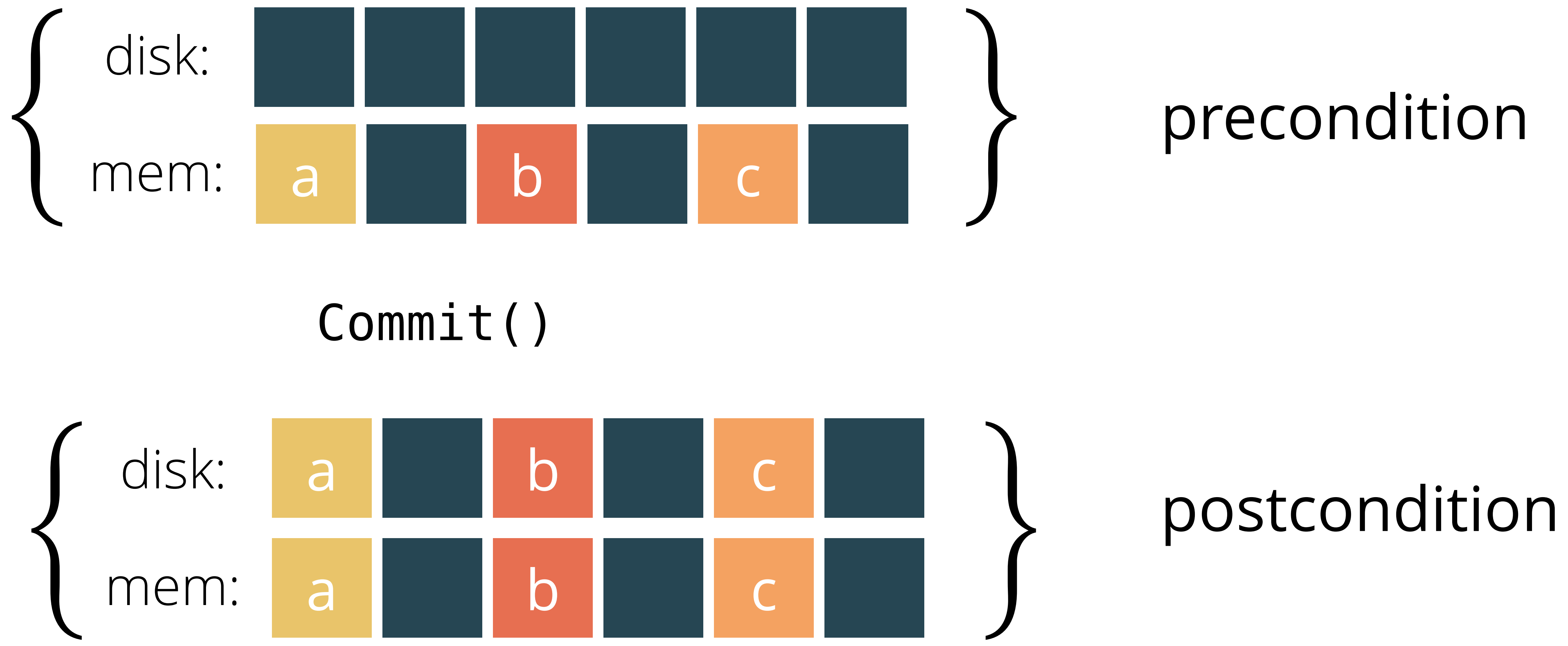

An operation's specification only refers to its disk footprint

says block at `0` has value b_0

`0` $\mapsto b_0$

disk

An operation's specification only refers to its disk footprint

$0 \mapsto b_0$ disk	$1 \mapsto -$ disk	$2 \mapsto -$ disk

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$$\left\{\ \boxed{0 \mapsto b_0 \ \ \text{disk}}\quad \boxed{1 \mapsto - \ \ \text{disk}}\quad \boxed{2 \mapsto - \ \ \text{disk}}\ \right\}$$

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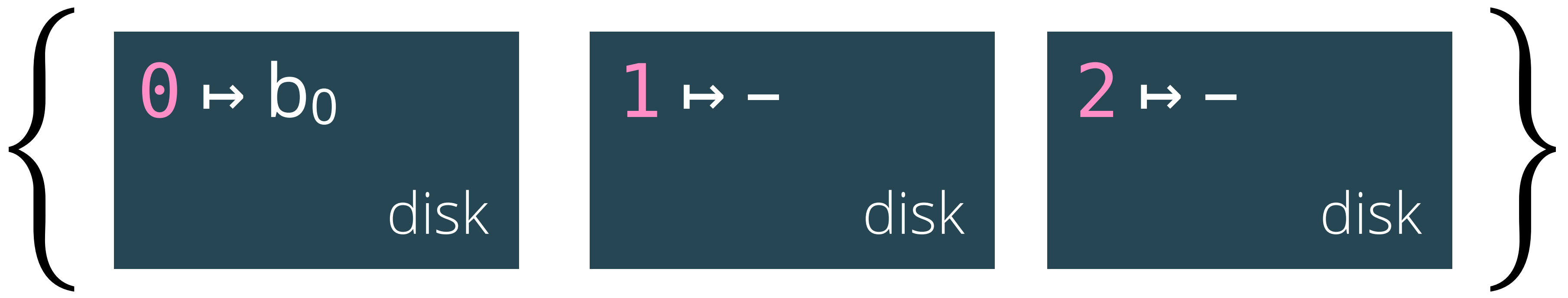


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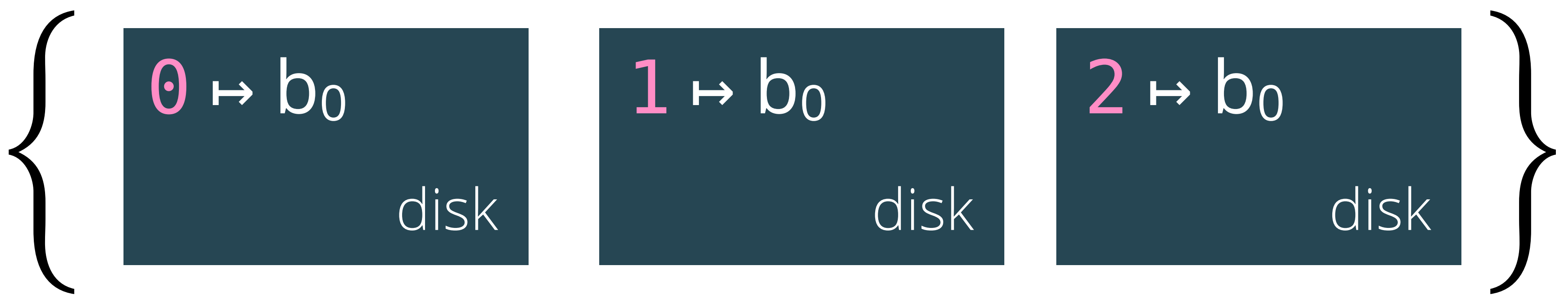


implies any other data is not involved

Introduce assertion for operation's view of disk

"disk points-to"

$1 \mapsto -$

disk

"operation points-to"

$1 \mapsto -$

op

Introduce assertion for operation’s view of disk

“disk points-to”

$1 \mapsto -$

disk

on-disk value of block 1

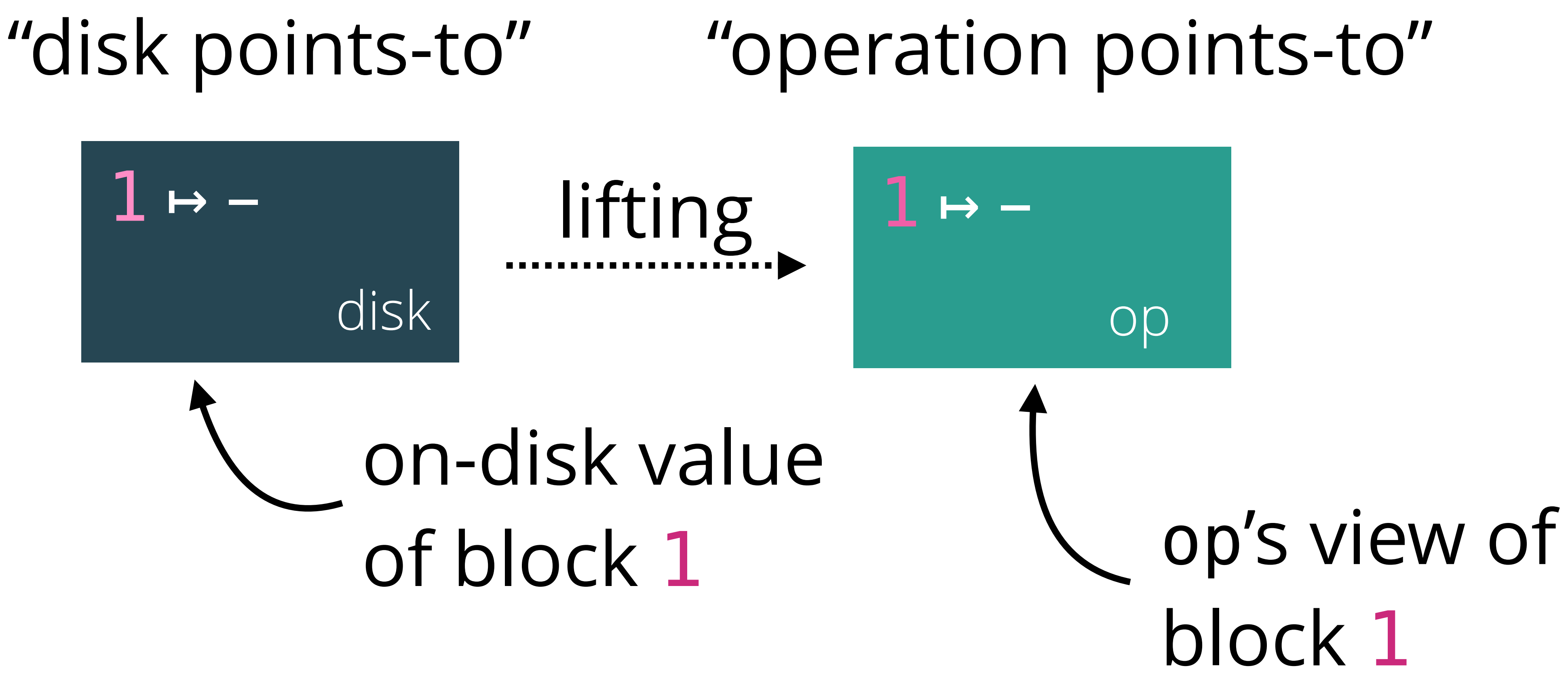
“operation points-to”

$1 \mapsto -$

op

op’s view of block 1

Introduce assertion for operation's view of disk



Key idea: operations manipulate an in-memory view of each object

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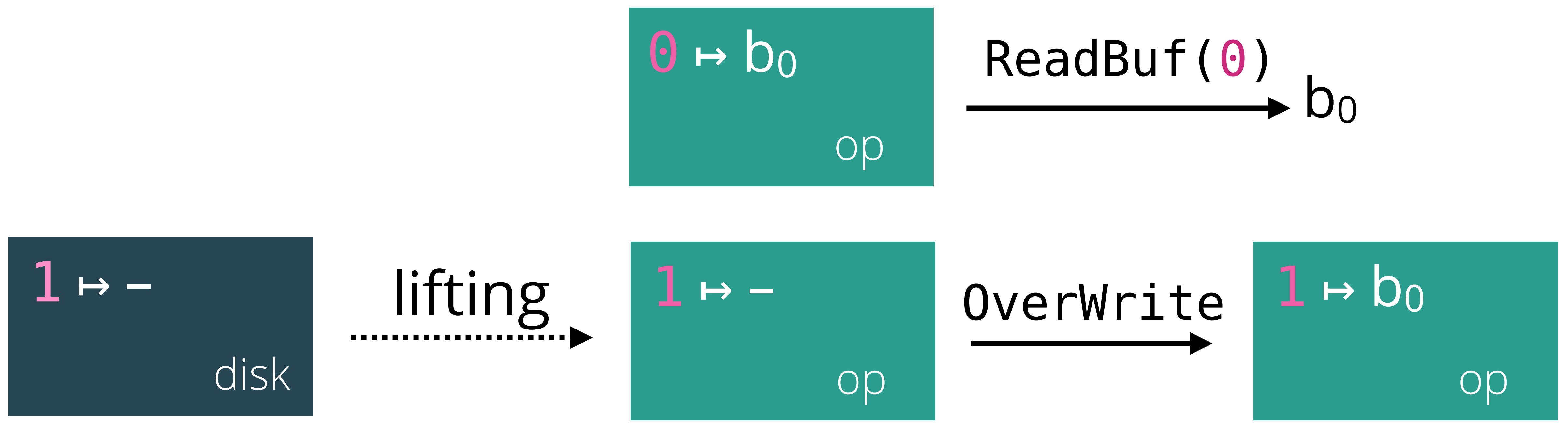

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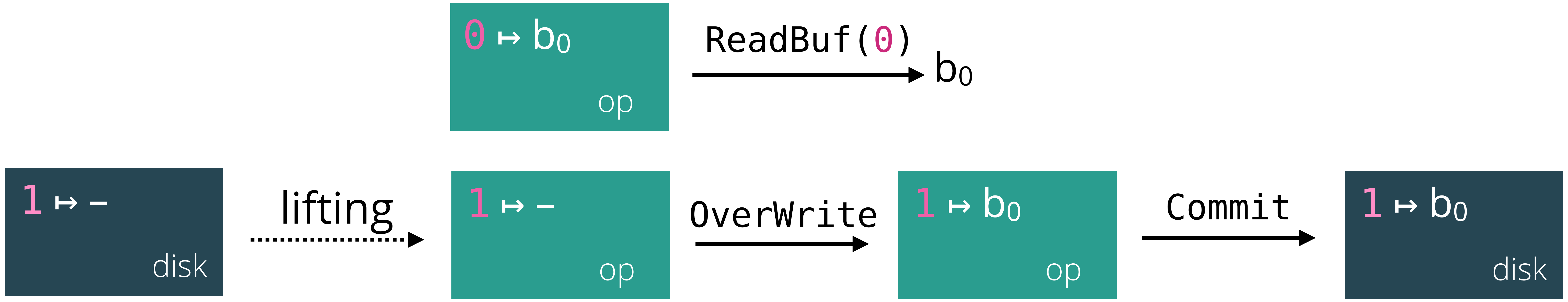

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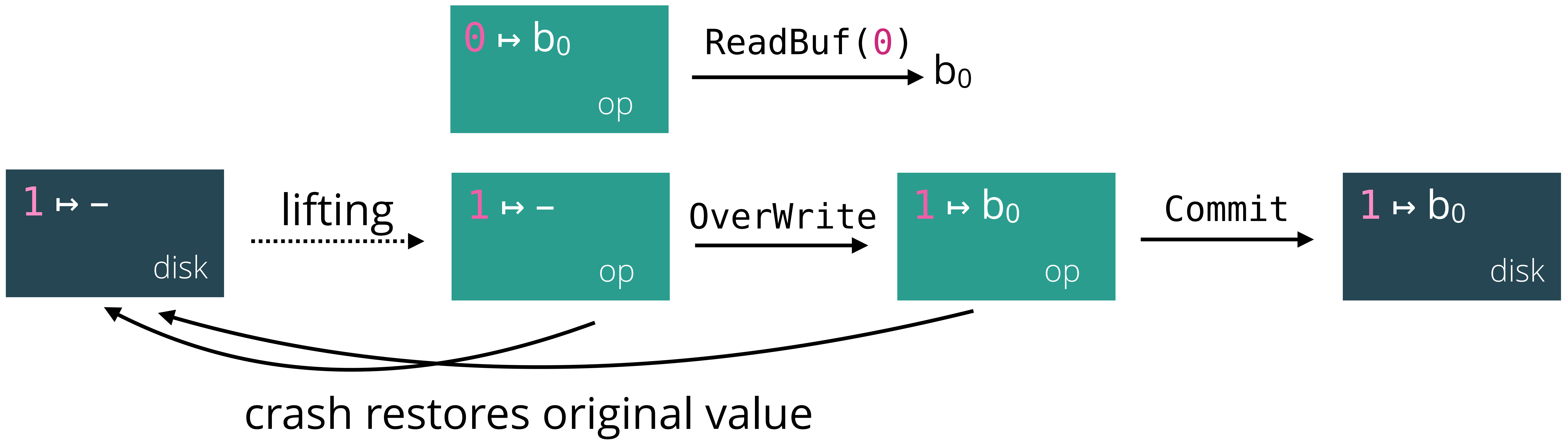

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0 $\mapsto b_0$ disk	1 $\mapsto$ – disk	2 $\mapsto$ – disk

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```
op := jrnl.Begin()
```

lifting

$0 \mapsto b_0$ op	$1 \mapsto -$ op	$2 \mapsto -$ op

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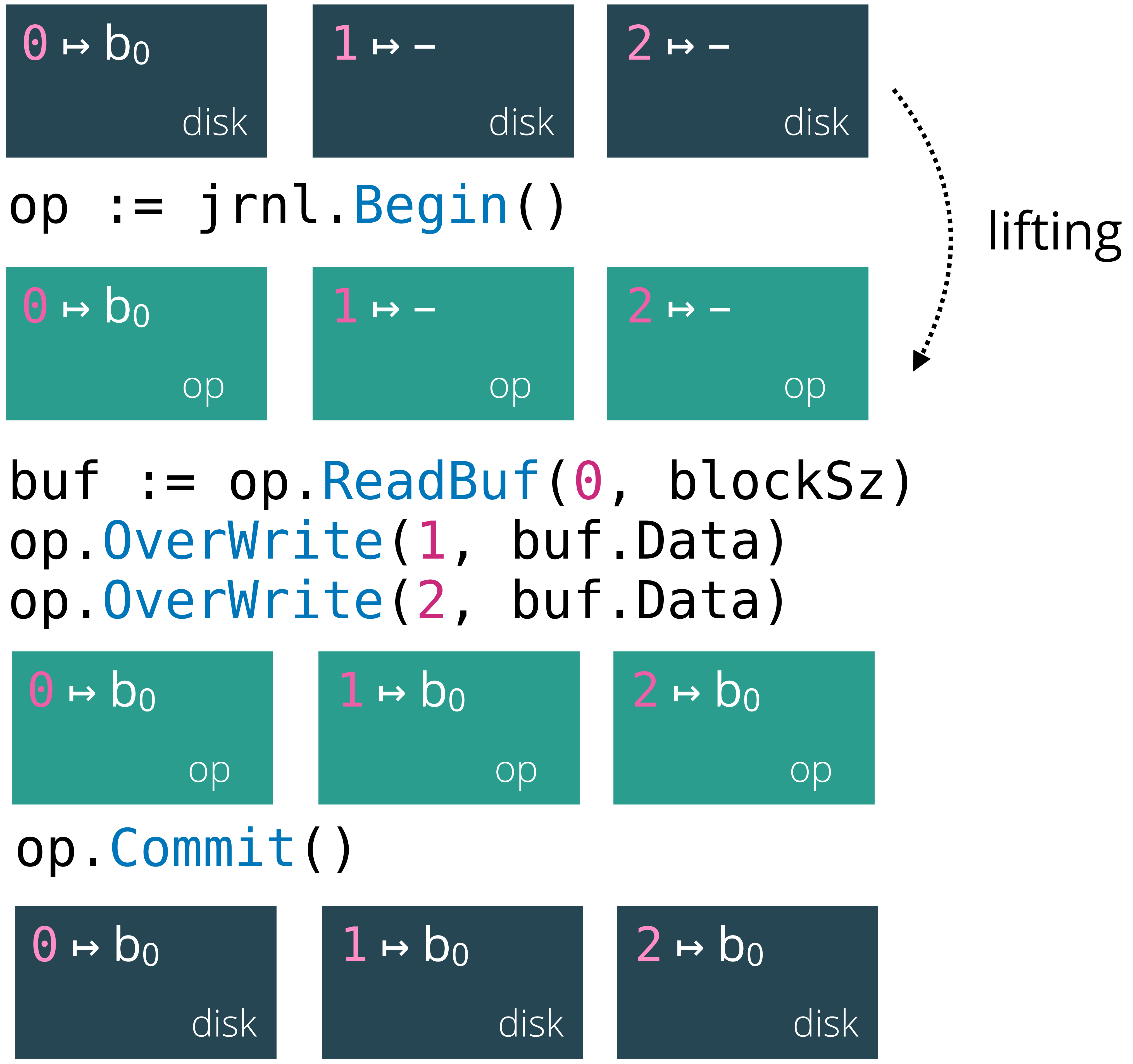

GoJournal has a modular implementation and proof

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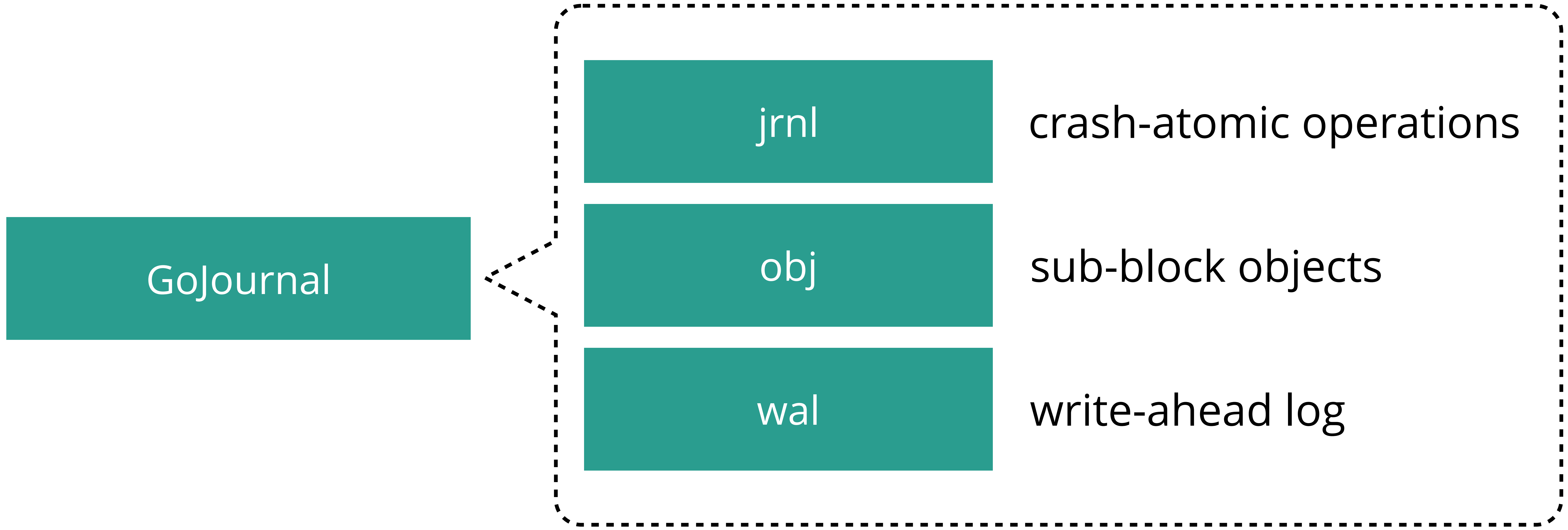
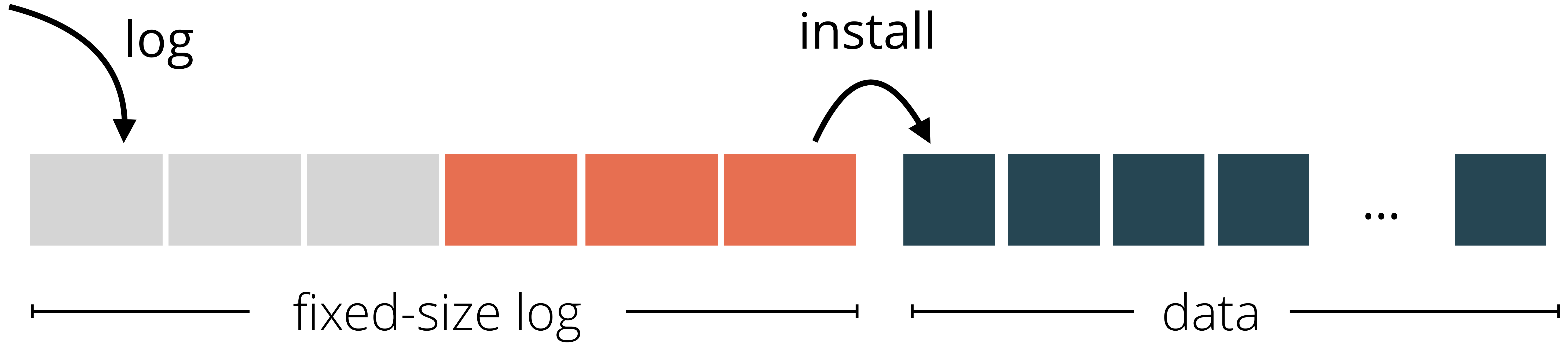


Write-ahead log implements the core atomicity of the journal



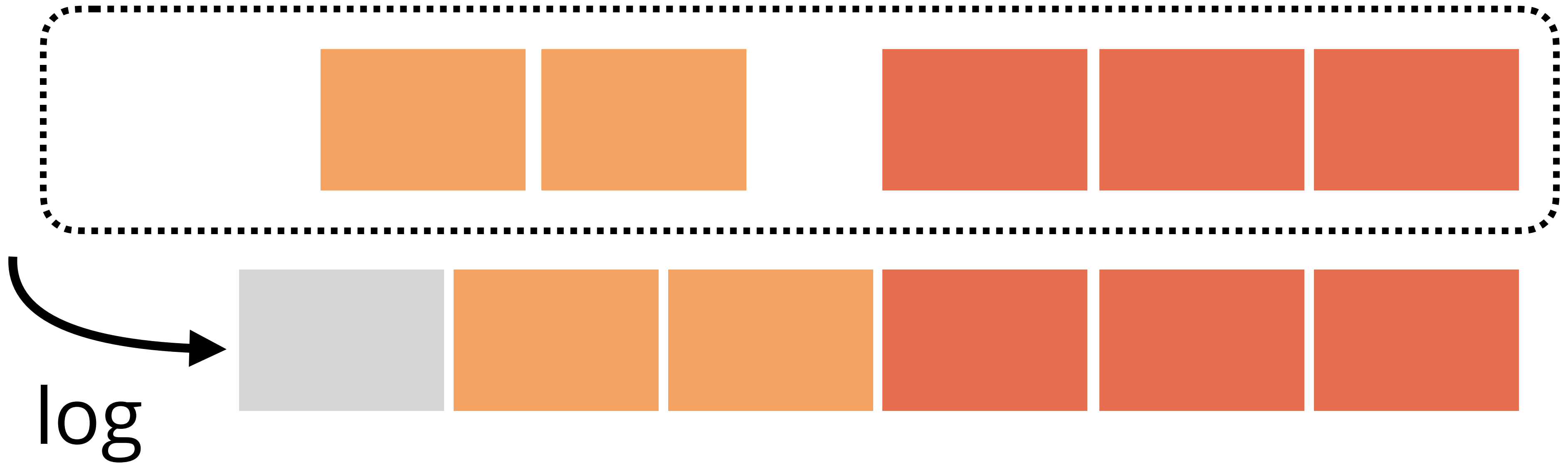
Writes are buffered before being logged

1 write gets buffered

Writes are buffered before being logged

1. write gets buffered

2. write gets logged



Challenge 1:
Reads can observe unstable writes

1 write gets buffered

2 read returns new data

system crashes here

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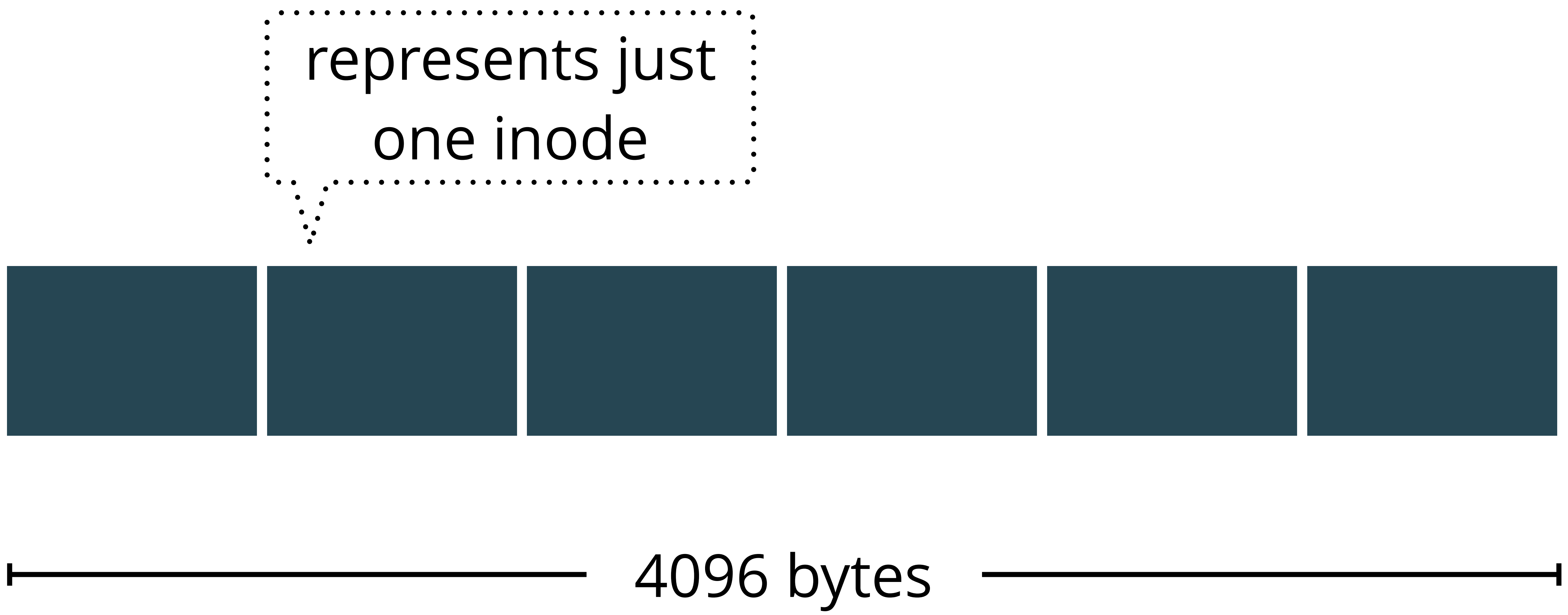
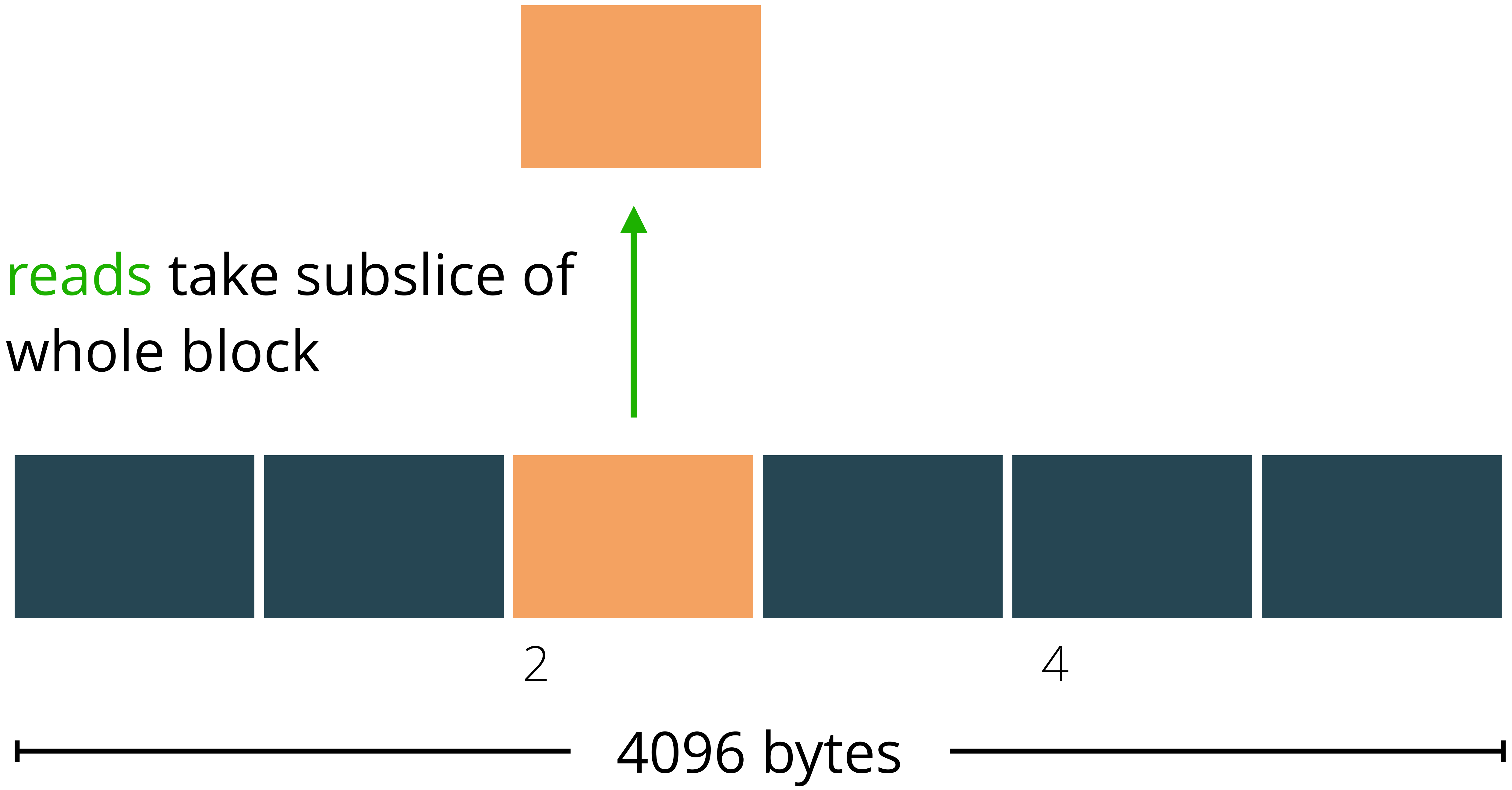
system crashes here

3 **read returns old data**

Object layer implements sub-block object access



Challenge 2:
Reads and writes can proceed concurrently



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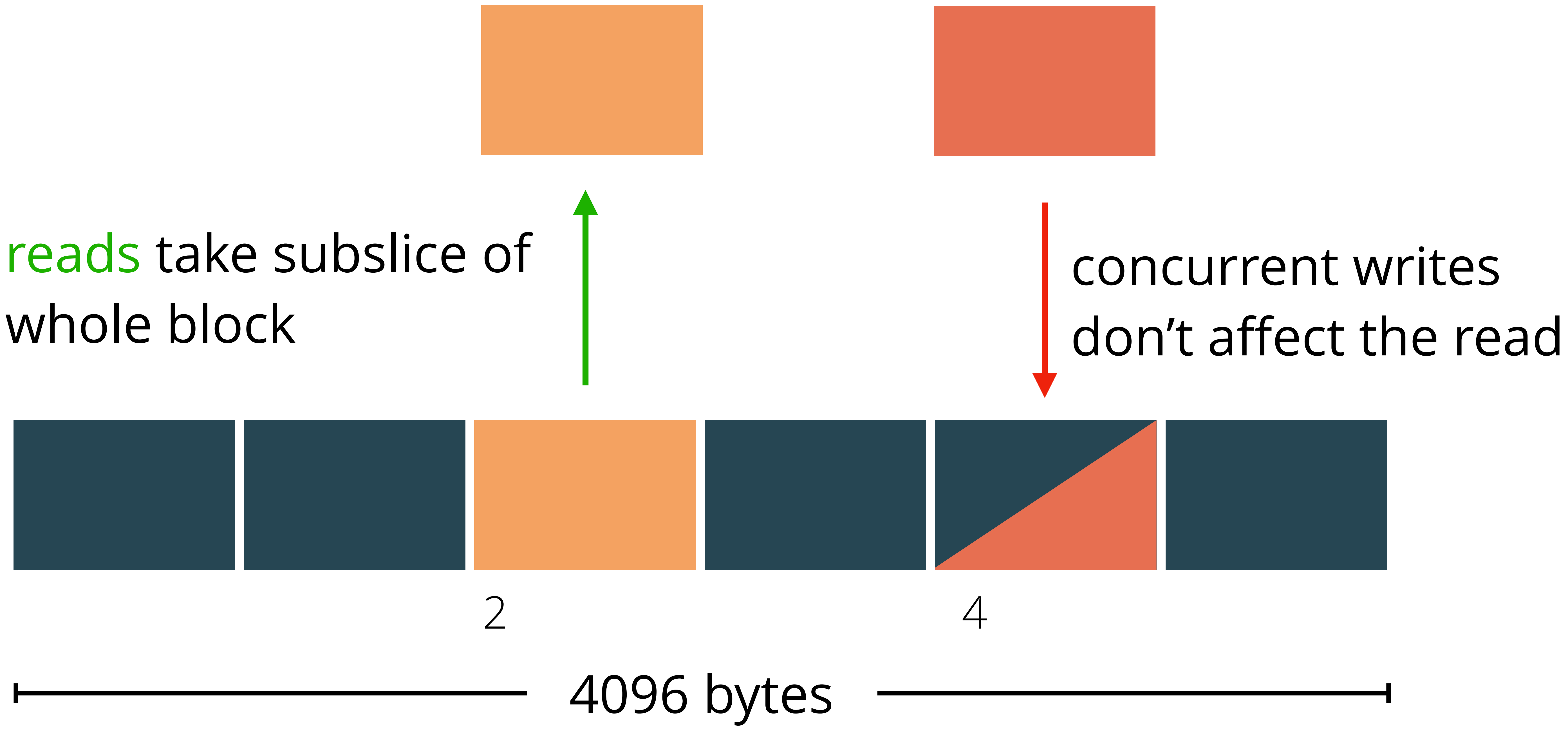
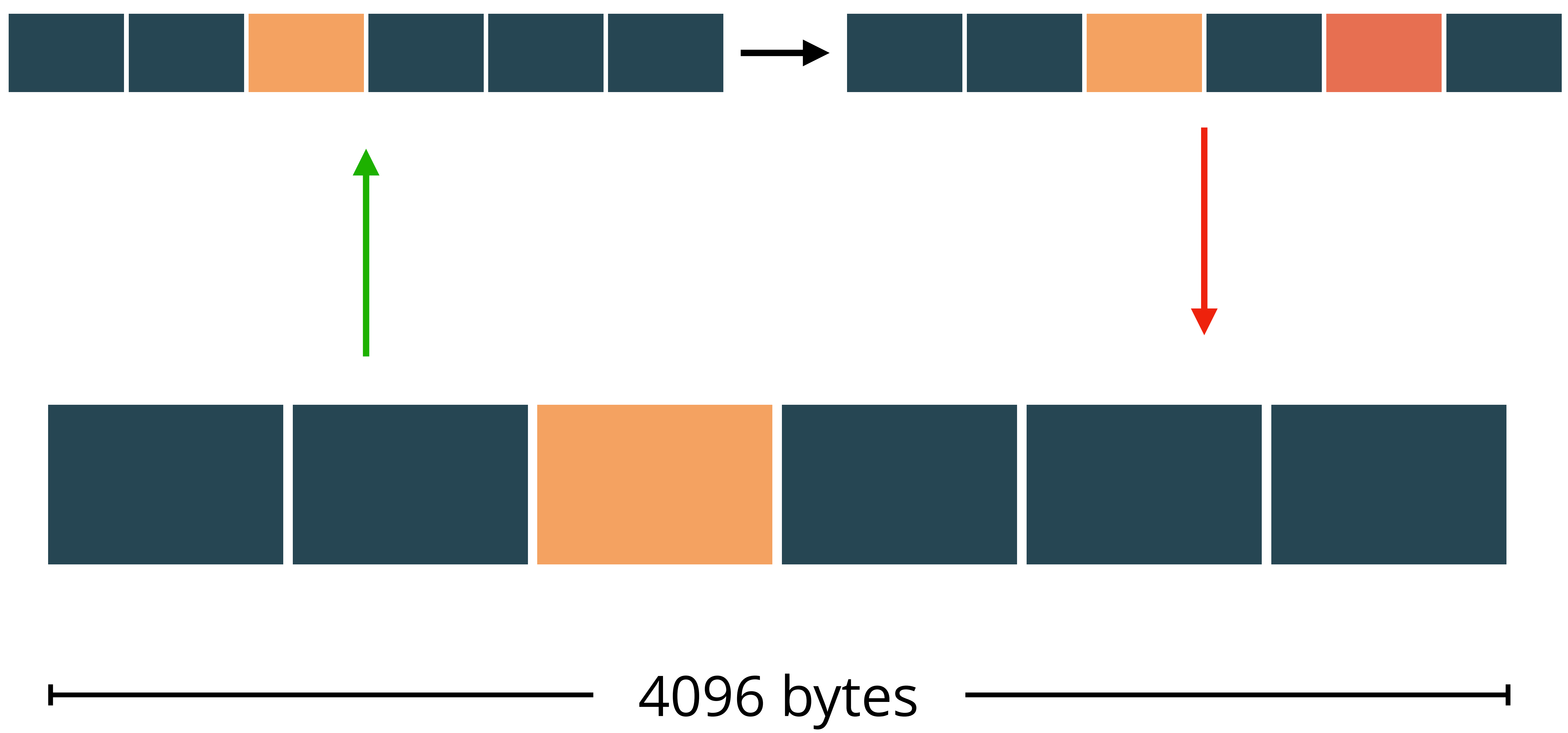


Concurrent writes are unsafe due to read-modify-write sequence



Verification techniques in Perennial 2.0

see paper for details

Logically atomic crash specifications

Lock-free reasoning with monotonic counters

Lifting to specify Commit

Crash-aware lock specification

Implementation overview

1,300 lines

GoJournal

code is available at
https://github.com/mit-pdos/go-journal

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verification framework

20,000 lines

Coq

Iris

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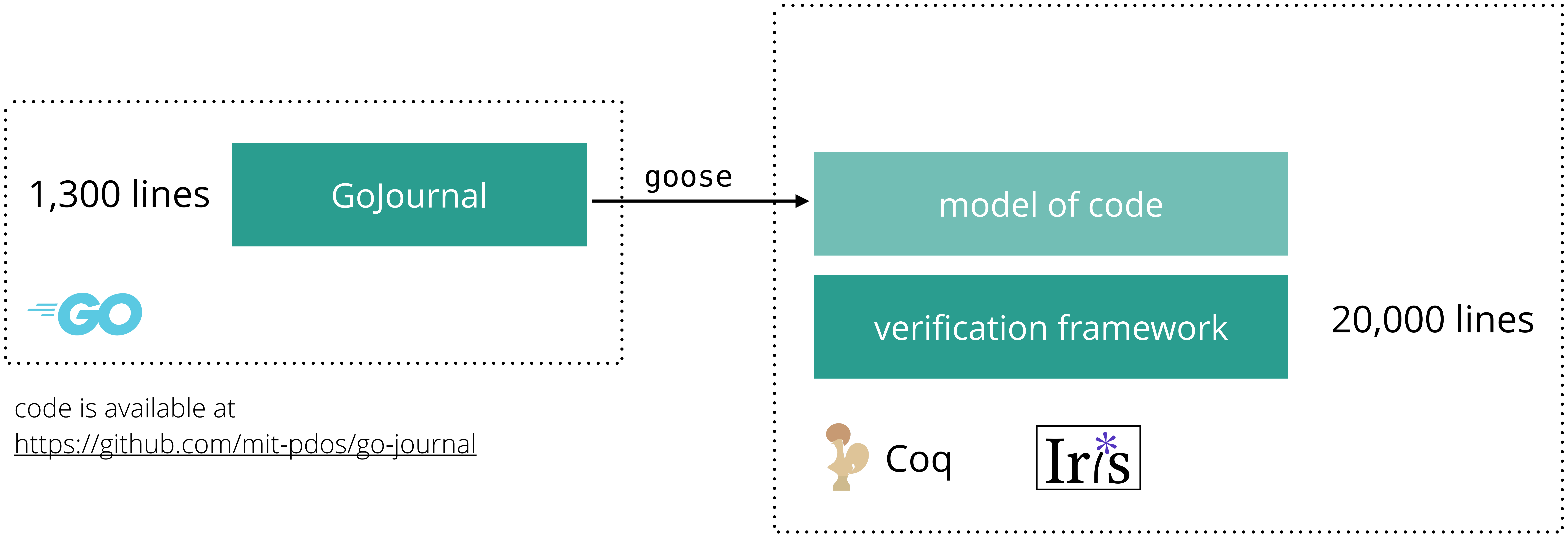

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Implementation overview

1,300 lines GoJournal

goose

Proof of GoJournal — 26,000 lines

model of code

verification framework — 20,000 lines

Coq Iris

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Evaluating GoNFS's performance

Implemented GoNFS, an (unverified) NFS server, on top of GoJournal

Compare against Linux kernel NFS server exporting ext4 (with `data=journal` mode for fair comparison)

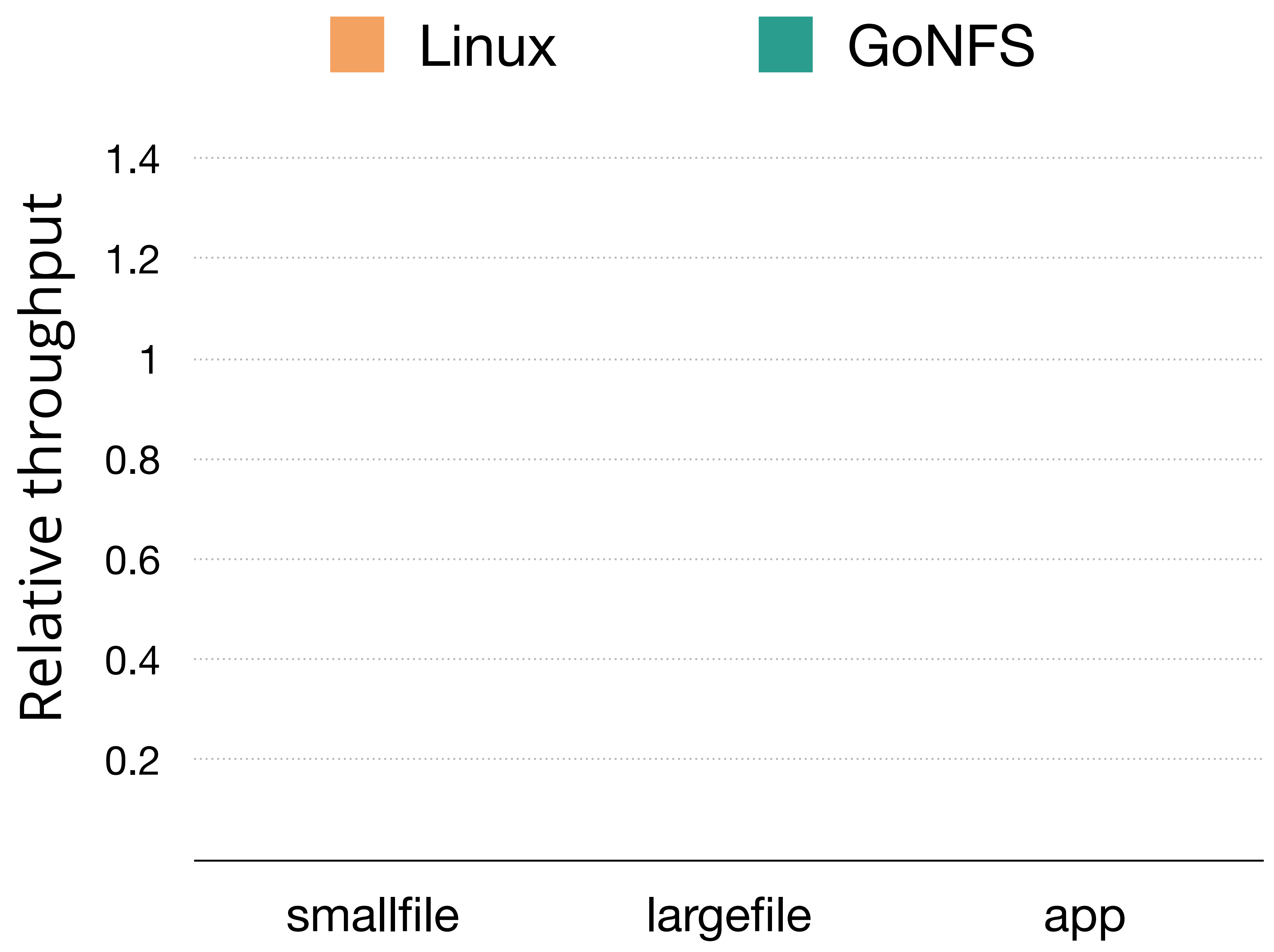
Experimental setup

Hardware: AWS i3.metal
36 cores at 2.3GHz, NVMe SSD

Benchmarks:

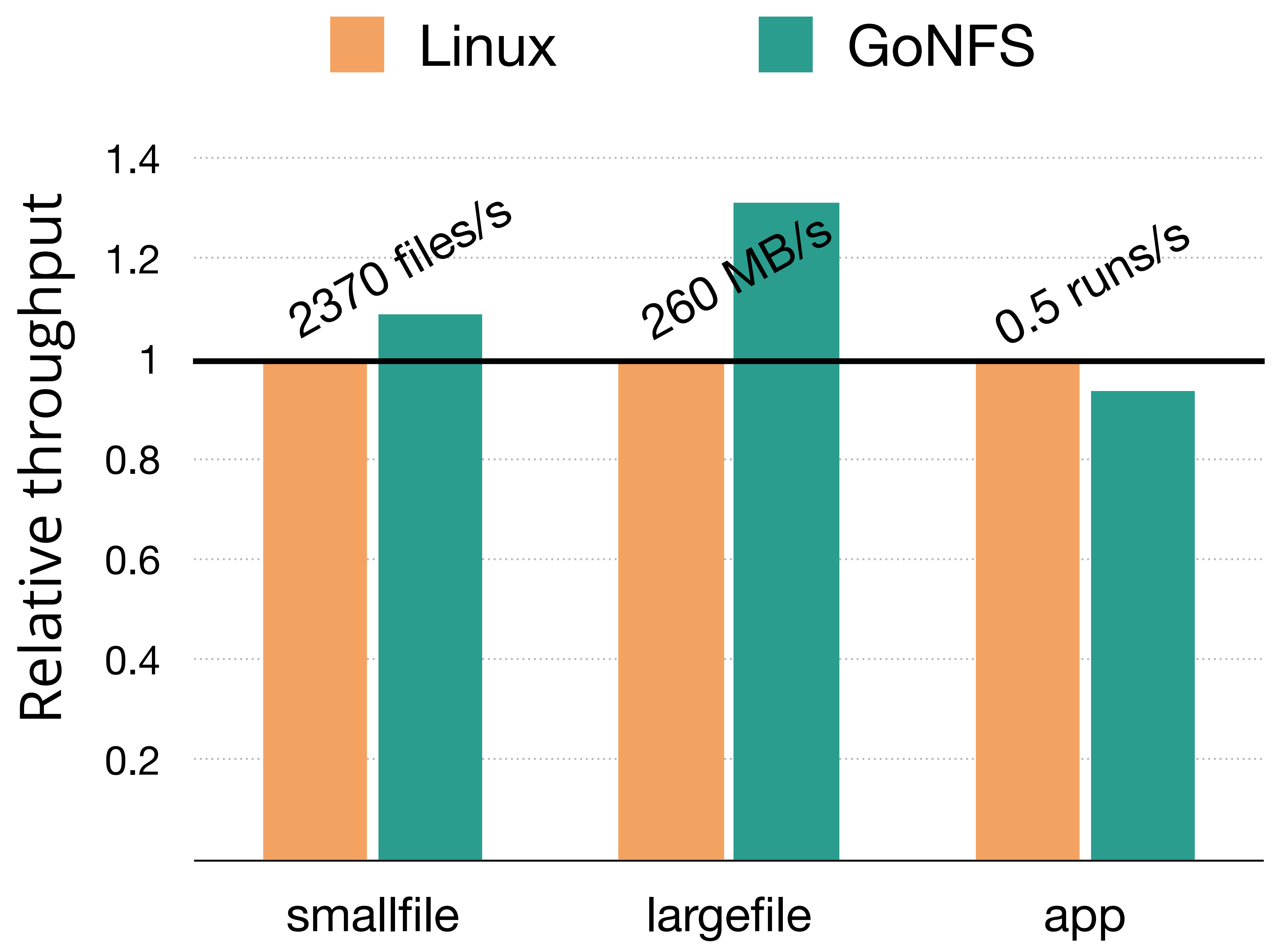
- smallfile: metadata heavy
- largefile: data heavy
- app: `git clone` + `make`

Run using Linux NFS client



Compare GoNFS throughput to Linux, running on an in-memory disk

GoNFS gets comparable performance even with a single client



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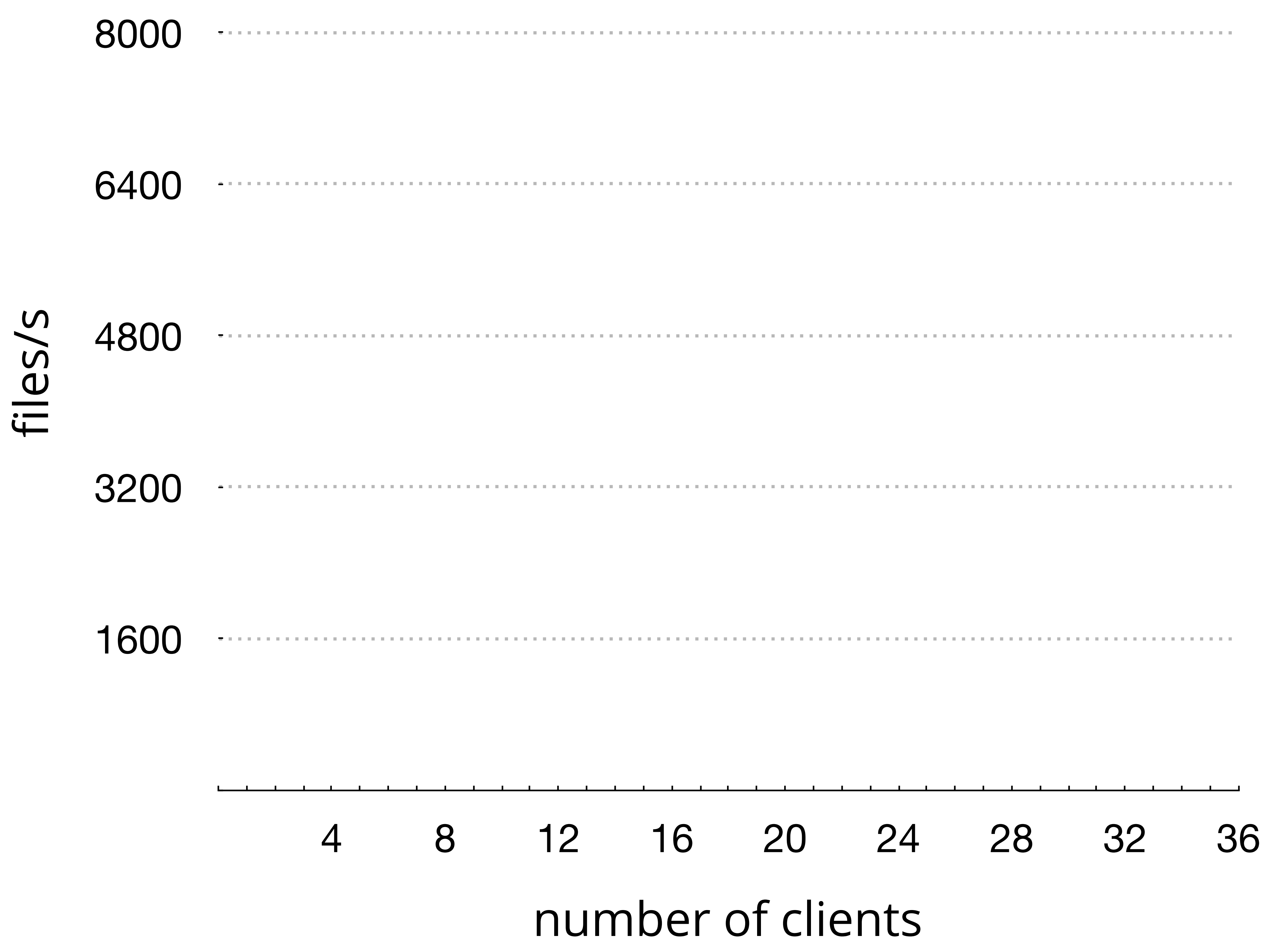
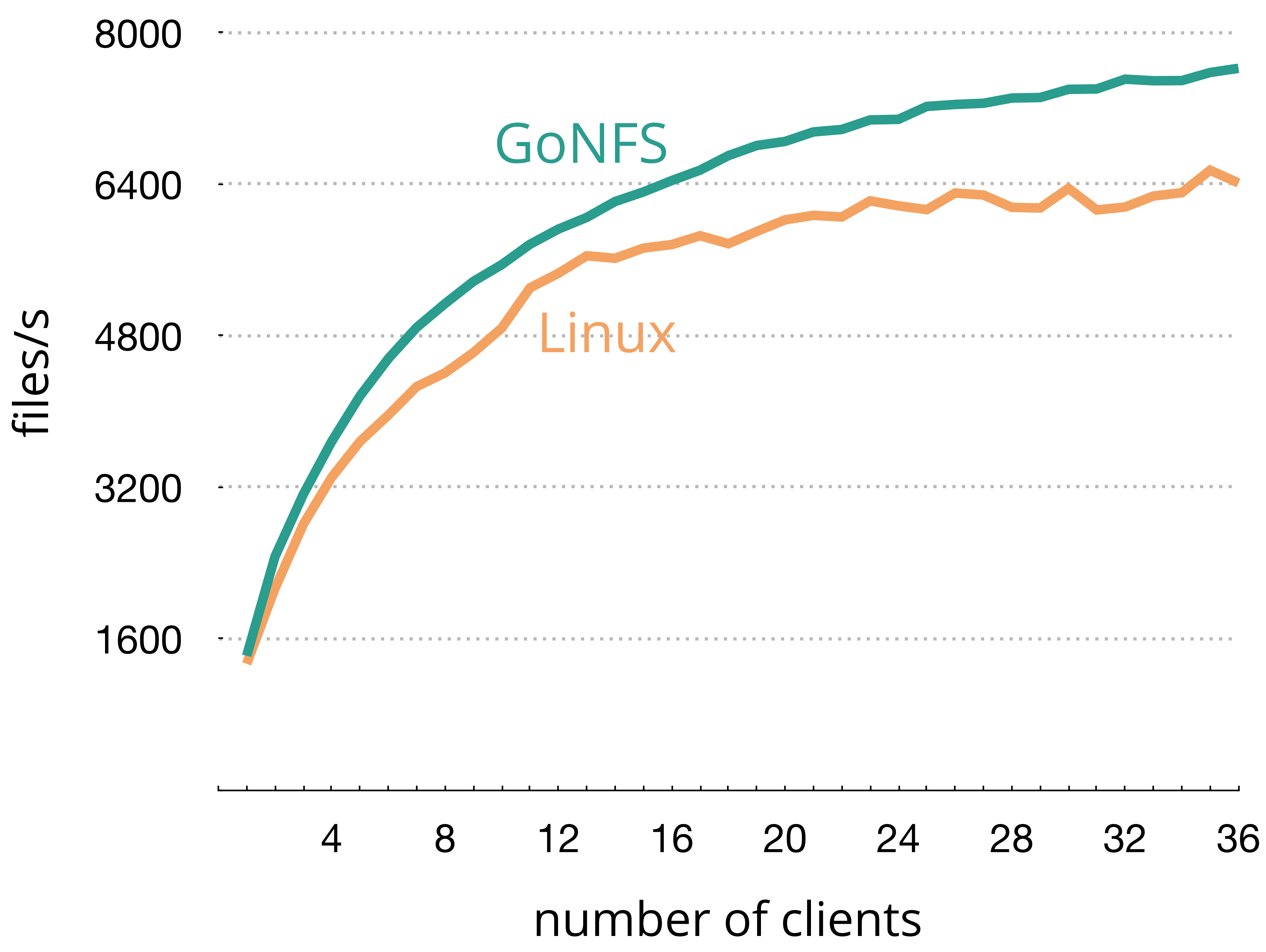


Run smallfile with many clients on an NVMe SSD

GoJournal allows GoNFS to scale with number of clients



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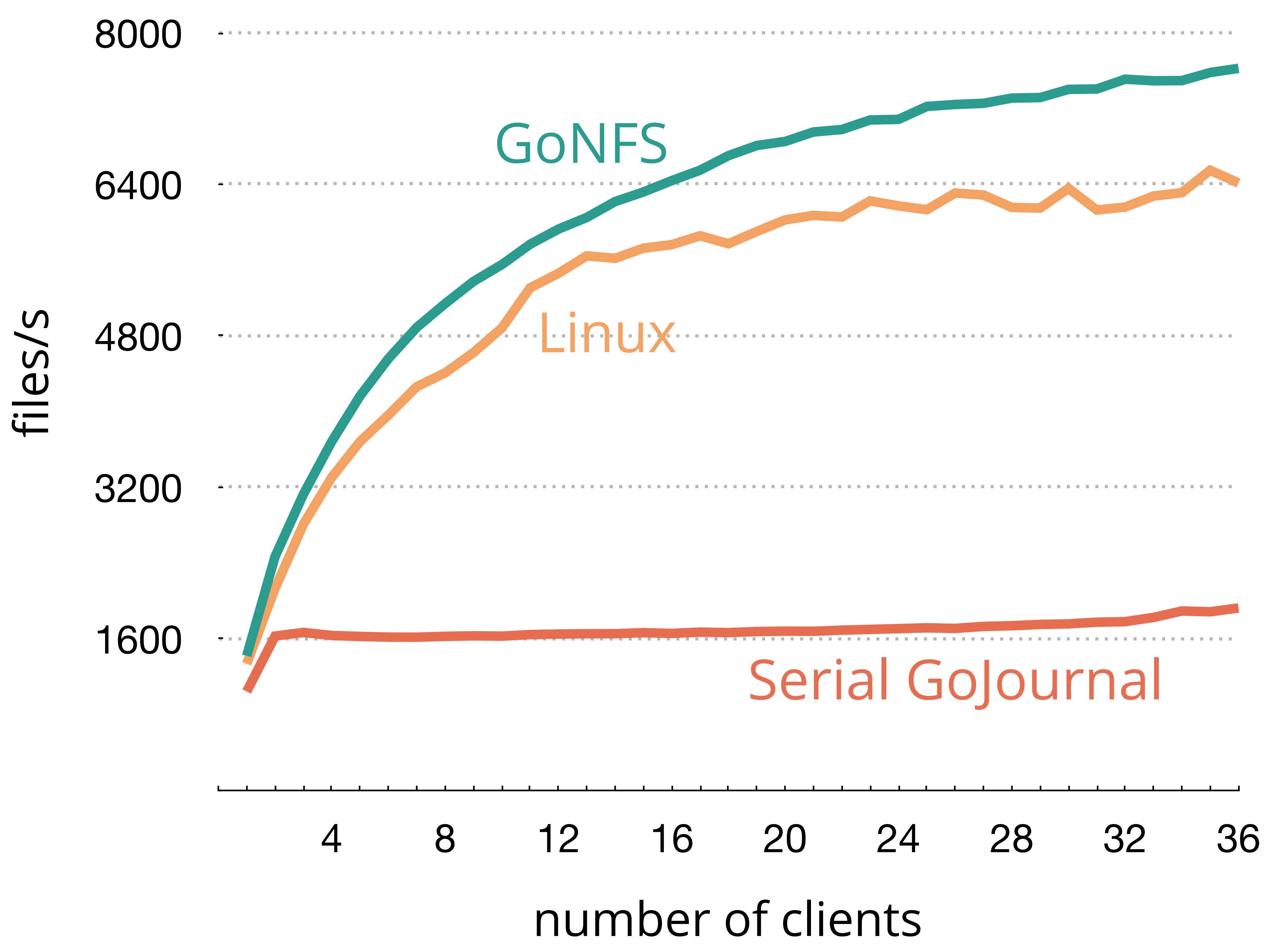
Concurrency in the journal matters



Serial GoJournal has locks around tricky concurrent parts of WAL

Summary

GoJournal is a verified, concurrent, crash-safe journaling system

Many concurrency challenges in verification

Demonstrate good performance with GoNFS

for followup questions you can contact Tej (tchajed@mit.edu)