Verifying the DaisyNFS concurrent and crash-safe file system with sequential reasoning

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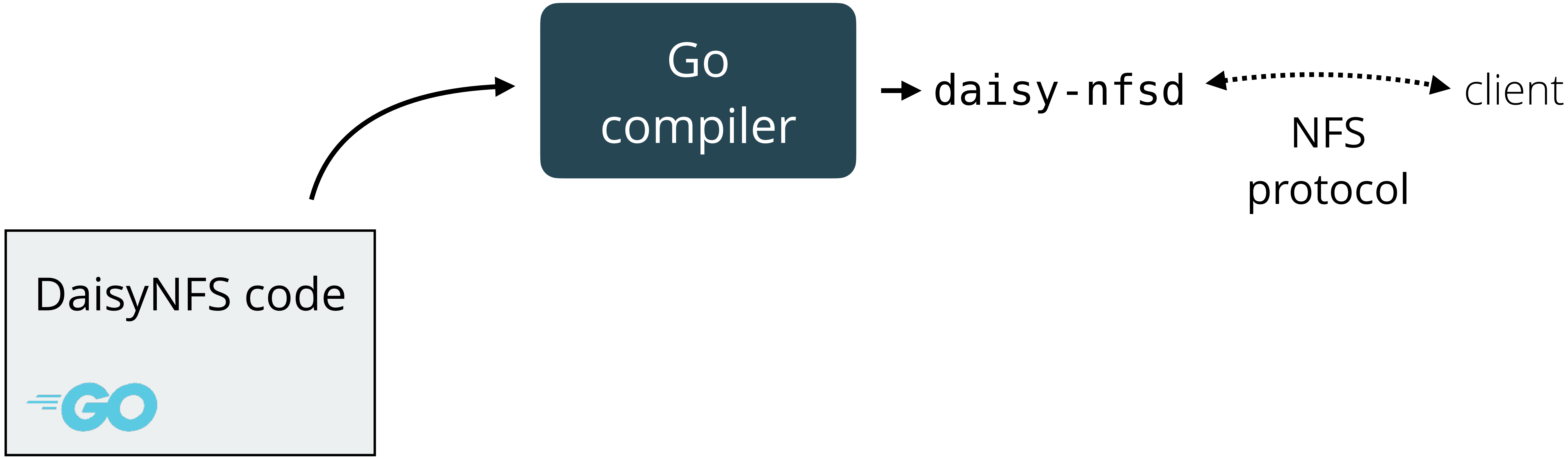
File-system correctness is important but challenging

Applications rely on file system to store data

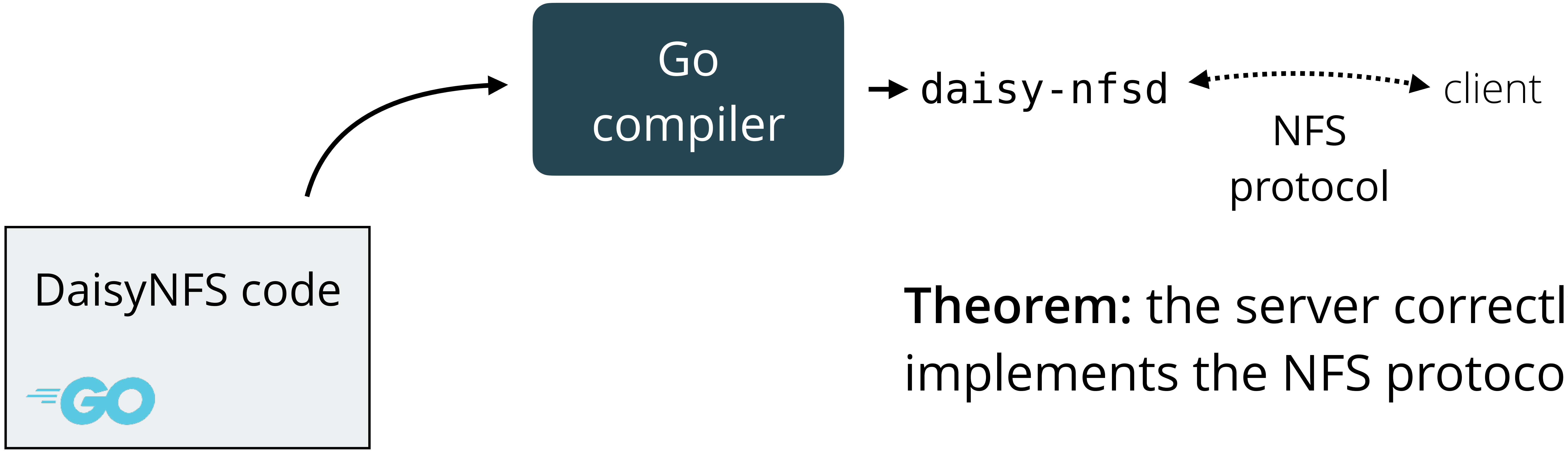
Prone to bugs due to optimizations

Bugs can lead to data loss

Approach: formal verification

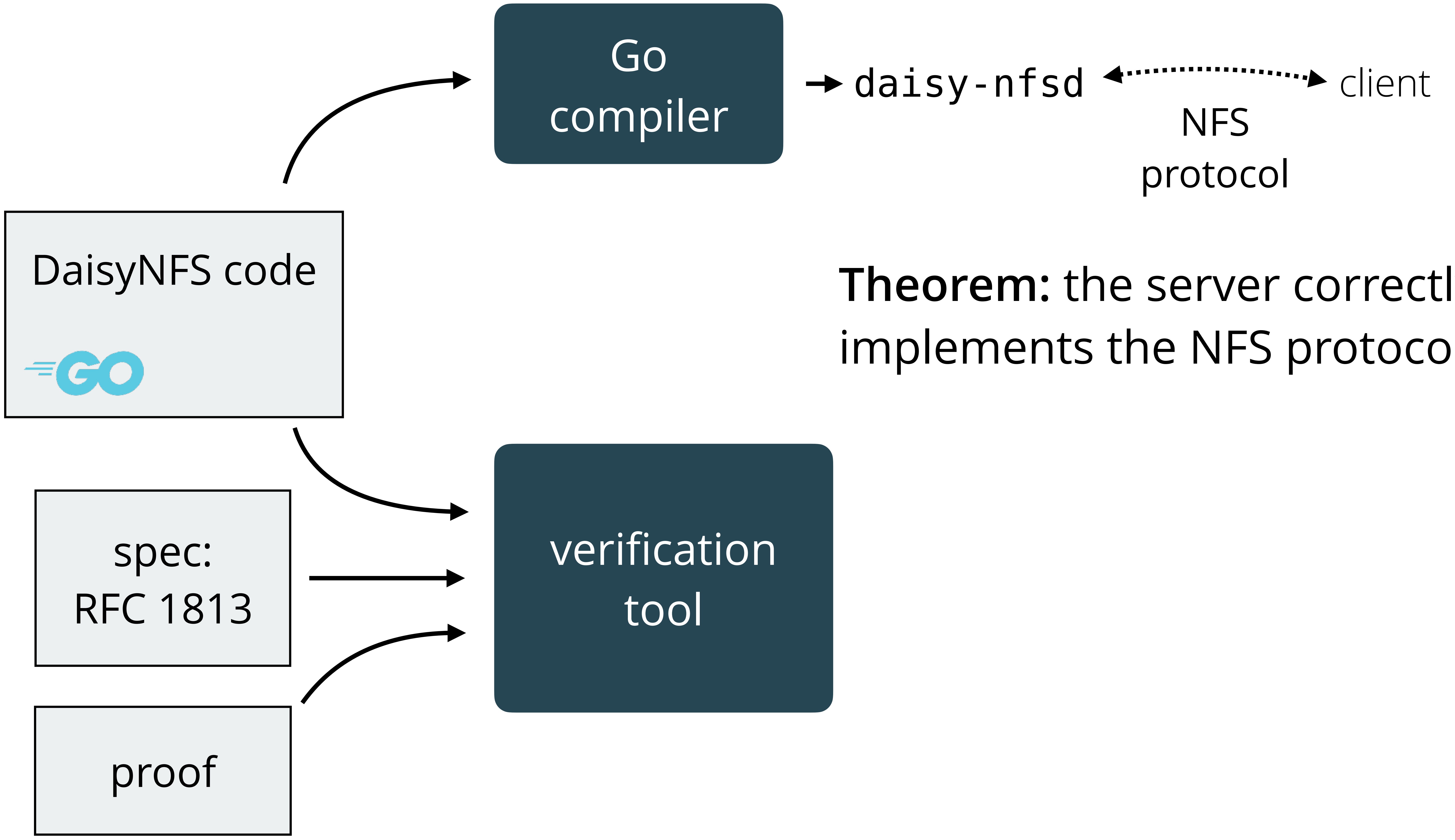


Approach: formal verification



Theorem: the server correctly implements the NFS protocol.

Approach: formal verification



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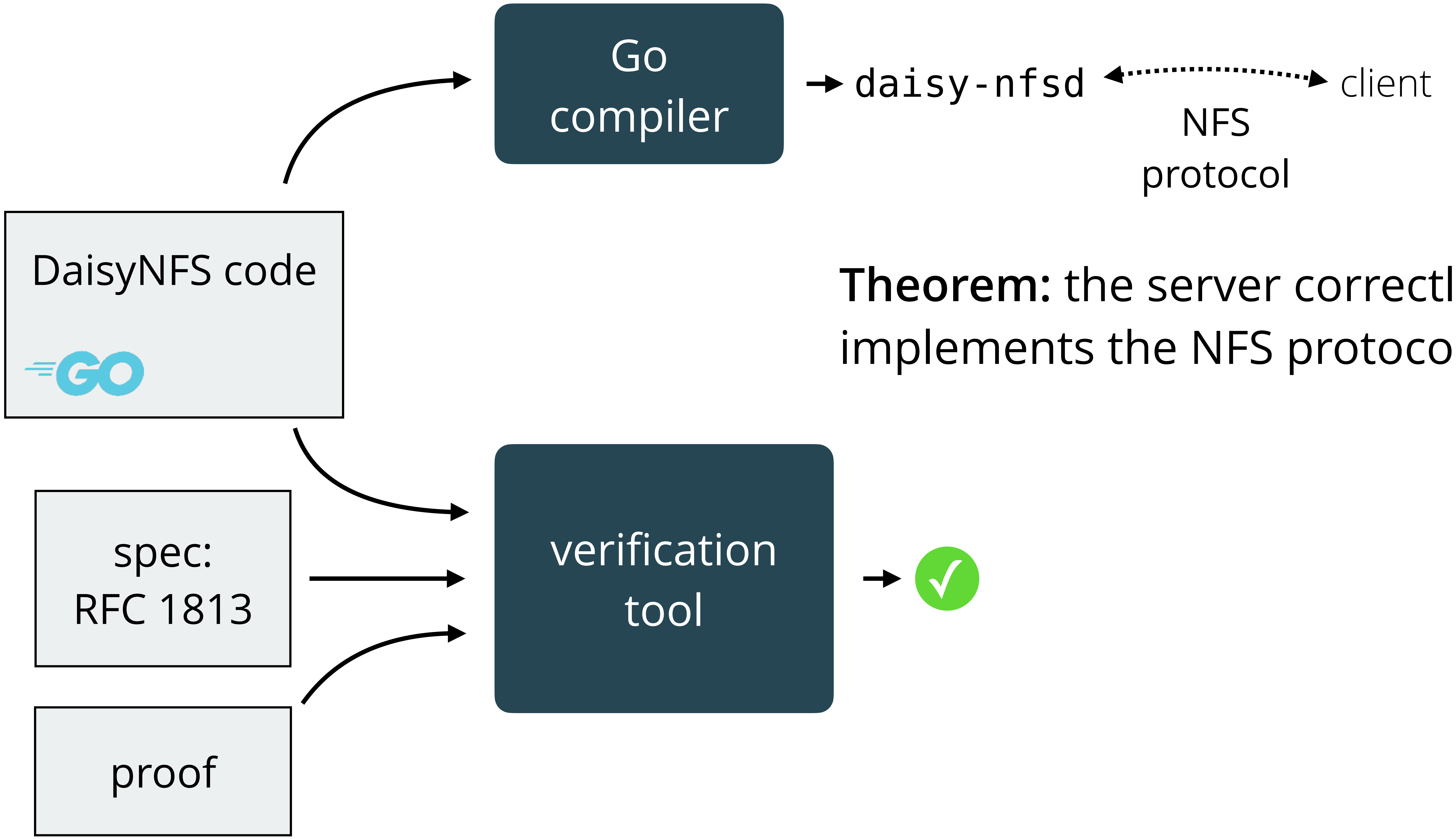
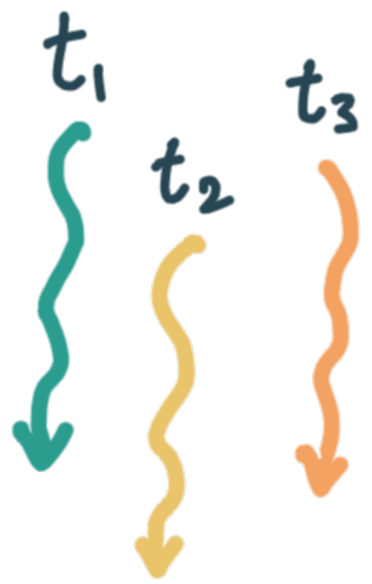


Theorem: the server correctly implements the NFS protocol.

Challenges in verifying a file system

Crashes



Concurrency

Contribution: verification-friendly design

DaisyNFS

File-system code implemented with transactions

GoTxn

Transaction system gives atomicity

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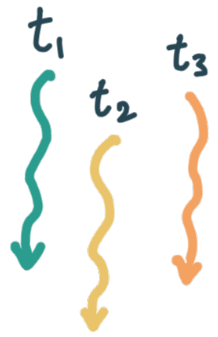

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Sequential reasoning

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Crashes

Concurrency

Contribution: verification-friendly design

DaisyNFS

File-system code implemented with transactions

Sequential reasoning

Simulation-transfer theorem turns sequential reasoning into concurrent & crash-safe correctness

GoTxn

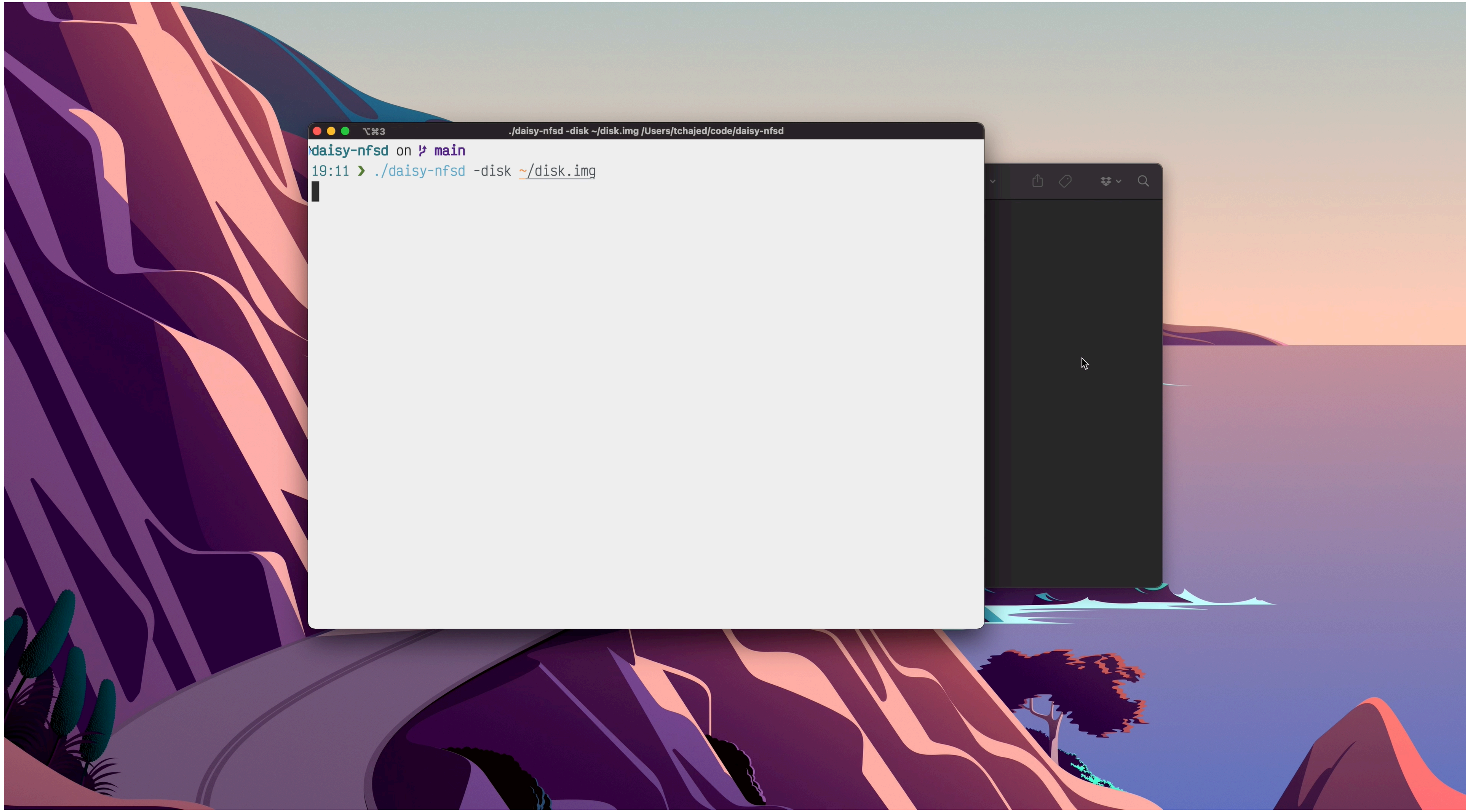
Transaction system gives atomicity

Crashes

t_1 t_2 t_3

Concurrency

DaisyNFS is a real file system



⌥⌘3 ./daisy-nfsd -disk ~/disk.img /Users/tchajed/code/daisy-nfsd

```
daisy-nfsd on main
19:11 ❯ ./daisy-nfsd -disk ~/disk.img
```

System design

```
func handleCommand(req) {
  switch req.cmd {
    case MKDIR: fs.MKDIR(…)
    case LOOKUP: fs.LOOKUP(…)
    …
  }
}
```

Go (unverified)

System design

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method MKDIR(d_ino, name)
method LOOKUP(d_ino, name)
  returns (ino:Ino)
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Dafny (verified)

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method MKDIR(d_ino, name)
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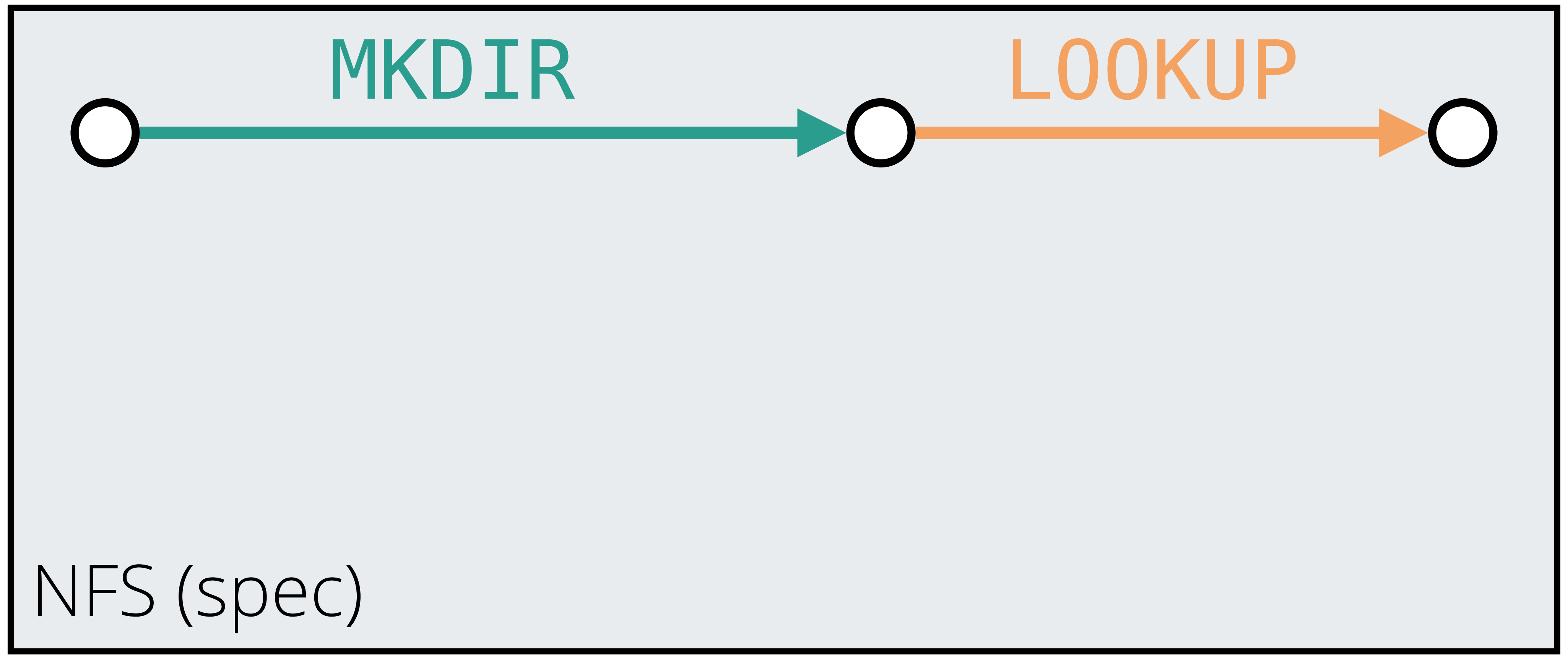
Dafny (verified)

```
tx := Begin()
tx.Read(…)
tx.Write(…)
tx.Commit()
```

Go (verified)

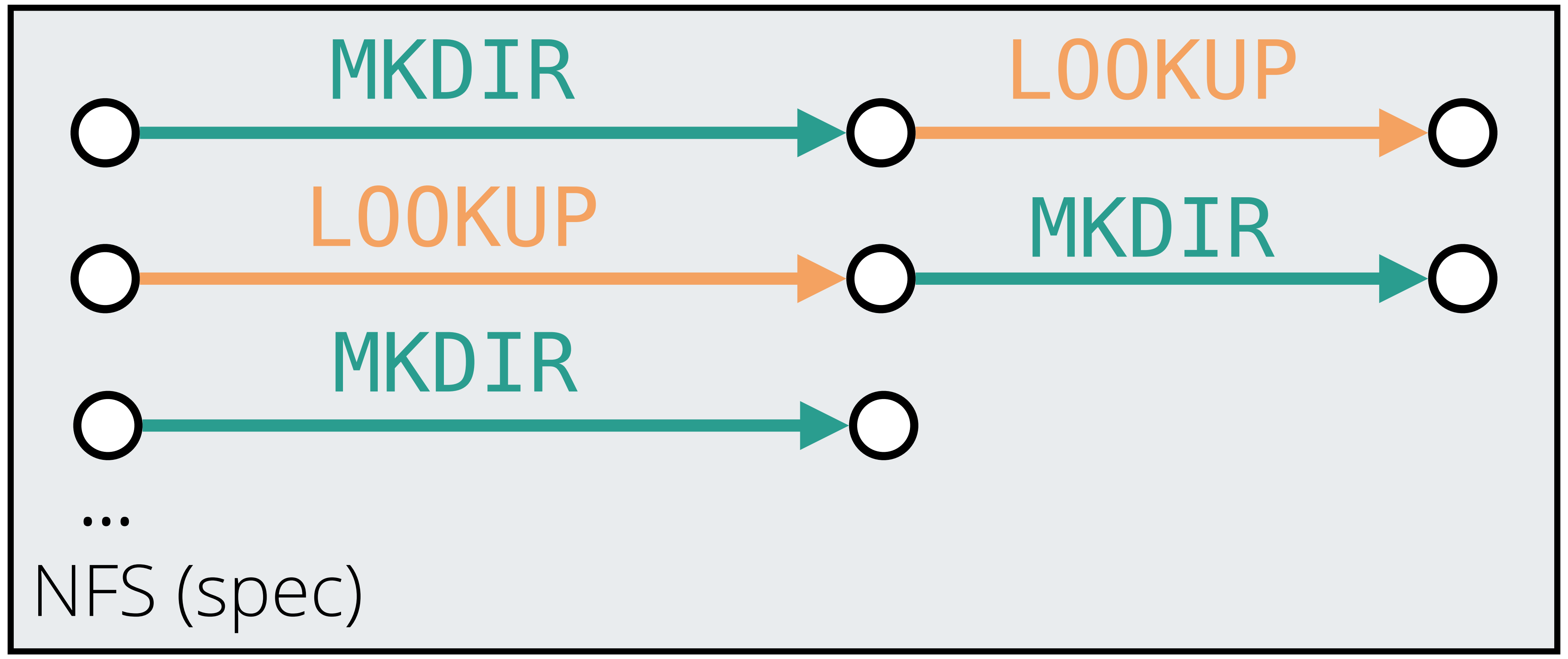
DaisyNFS’s top-level correctness theorem

`MKDIR(…)` ‖ `LOOKUP(…)`



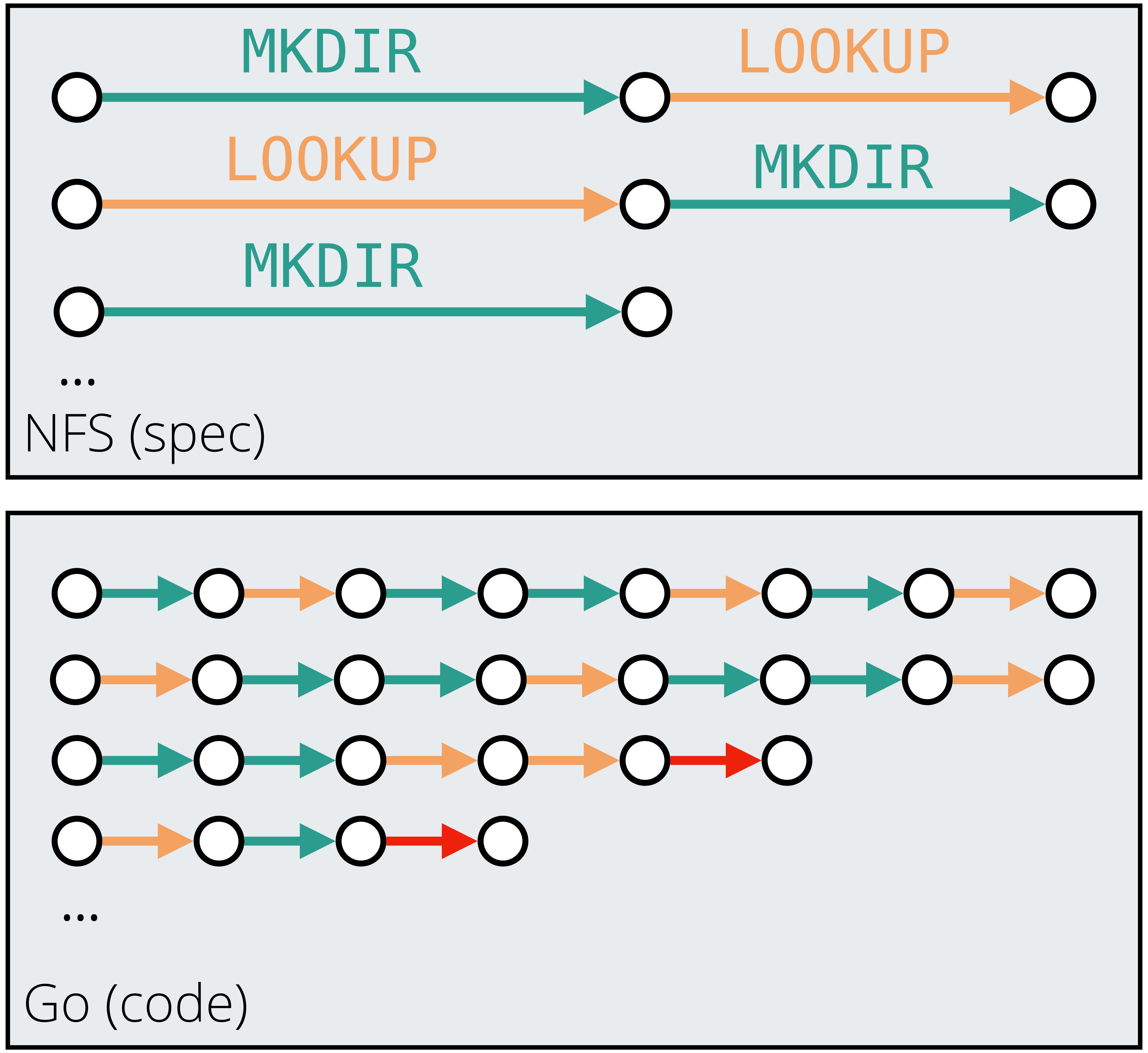
DaisyNFS's top-level correctness theorem

MKDIR(…) ‖ LOOKUP(…)

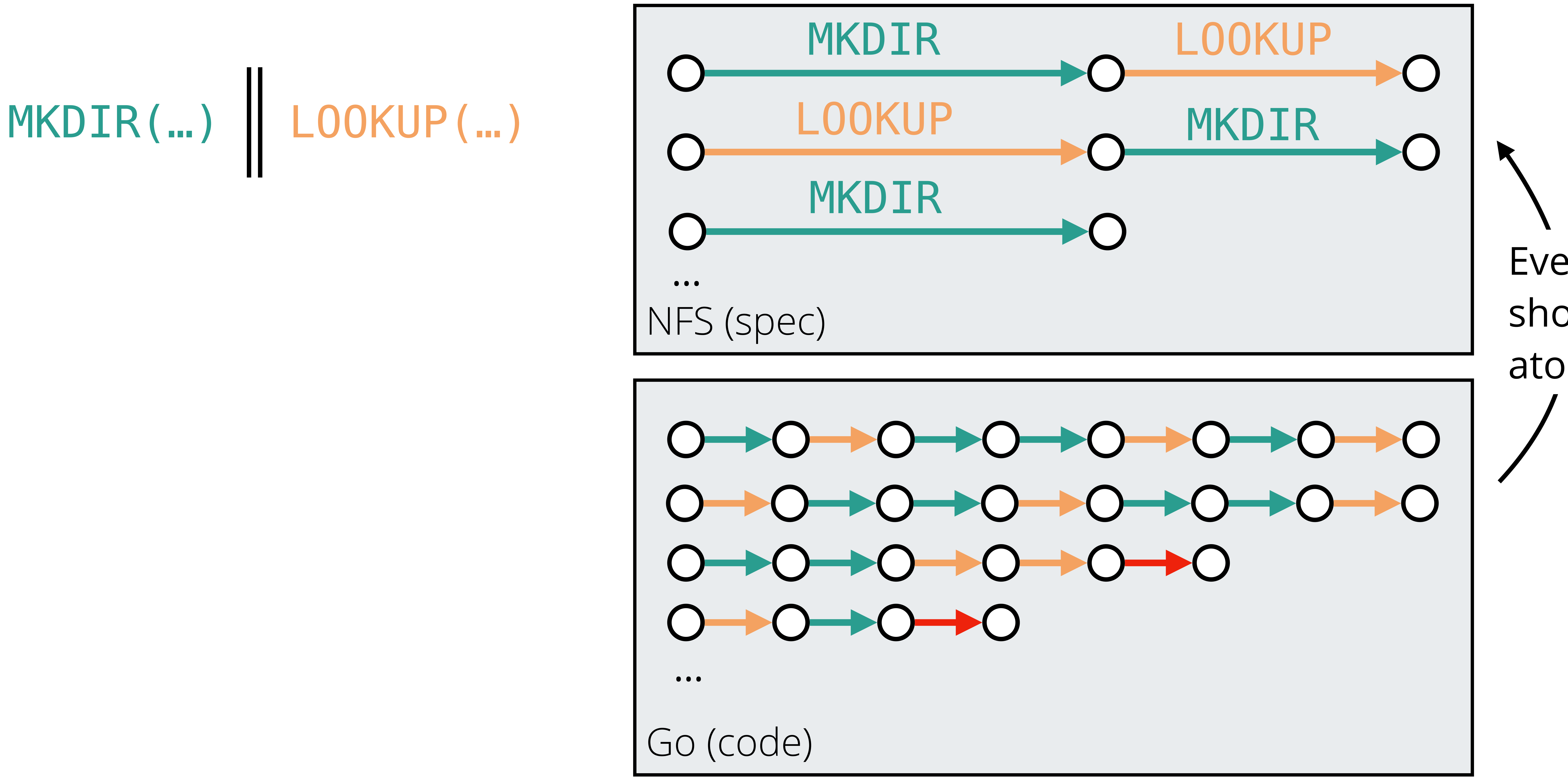


DaisyNFS's top-level correctness theorem

MKDIR(…) || LOOKUP(…)

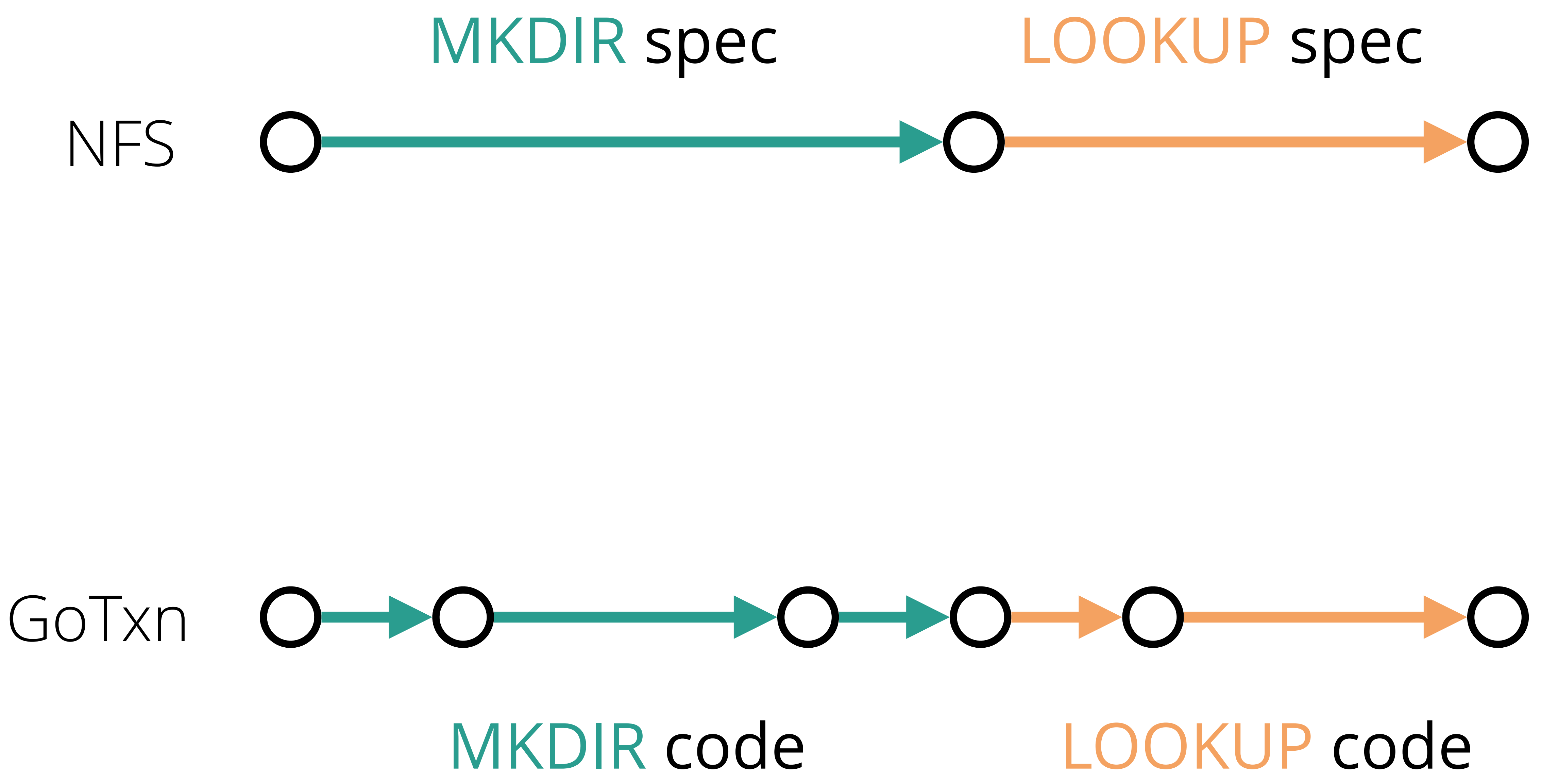


DaisyNFS's top-level correctness theorem



Every `daisy-nfsd` execution should have corresponding atomic execution in spec

Transactions are proven with sequential reasoning



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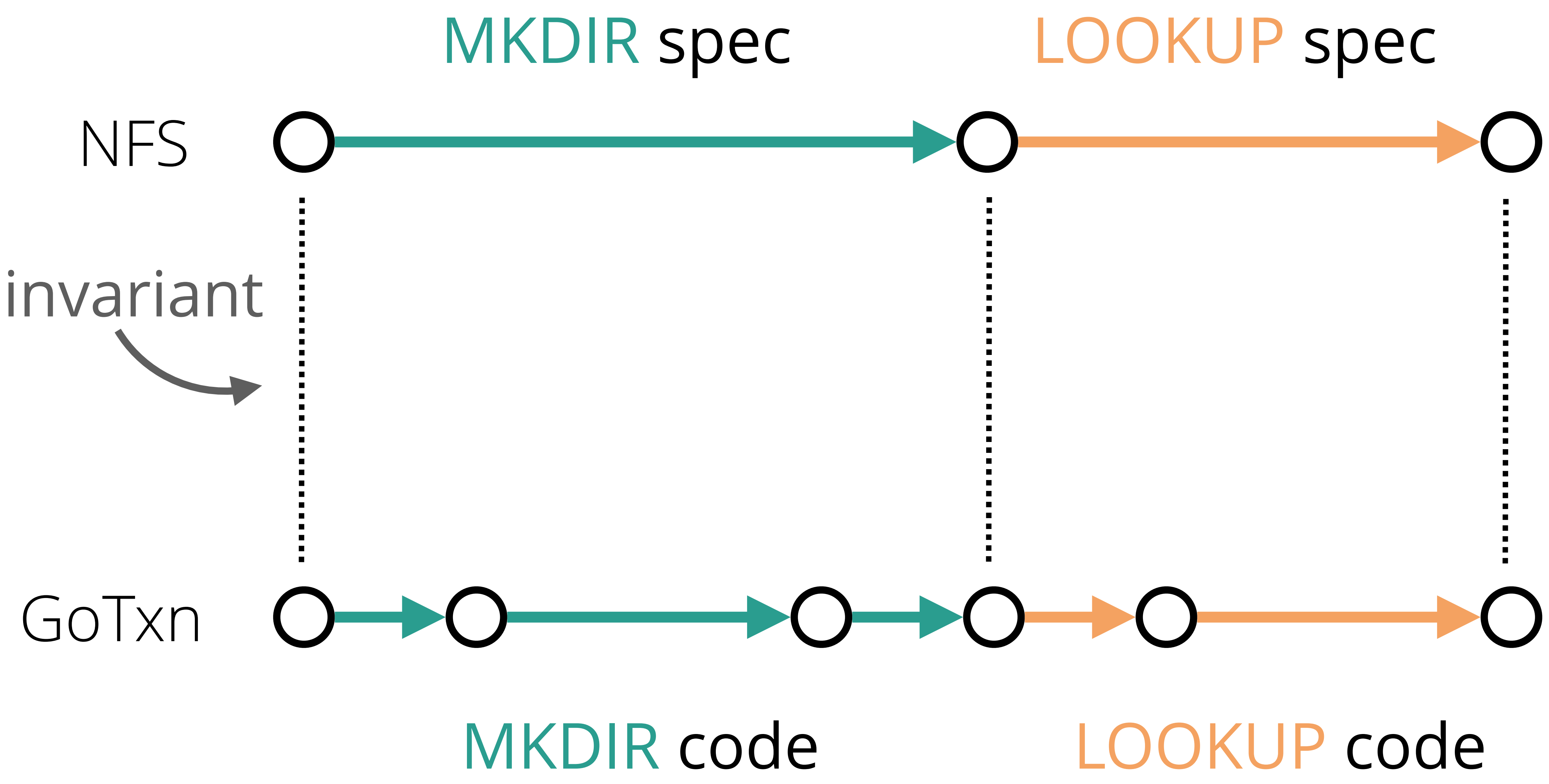

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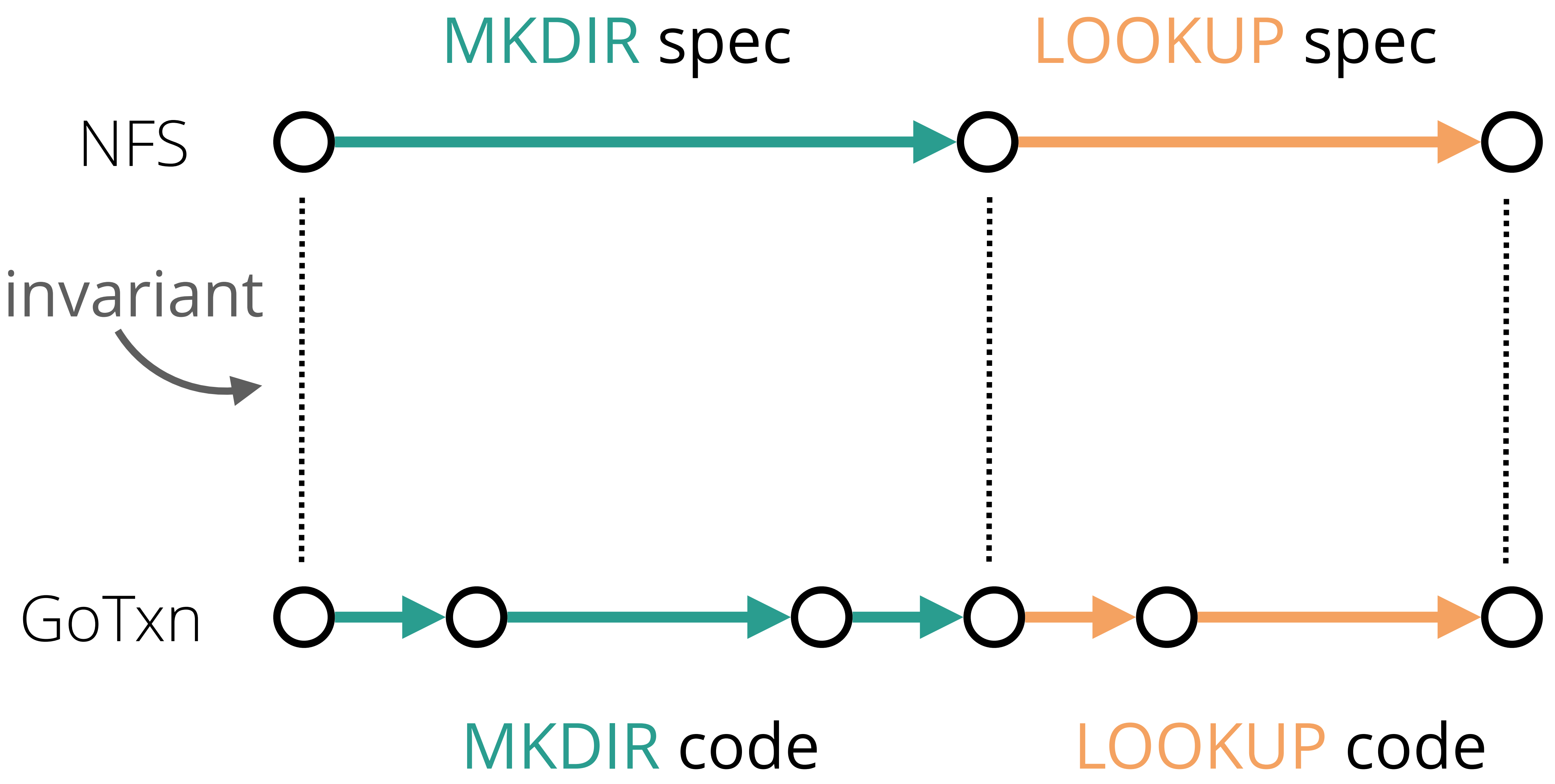
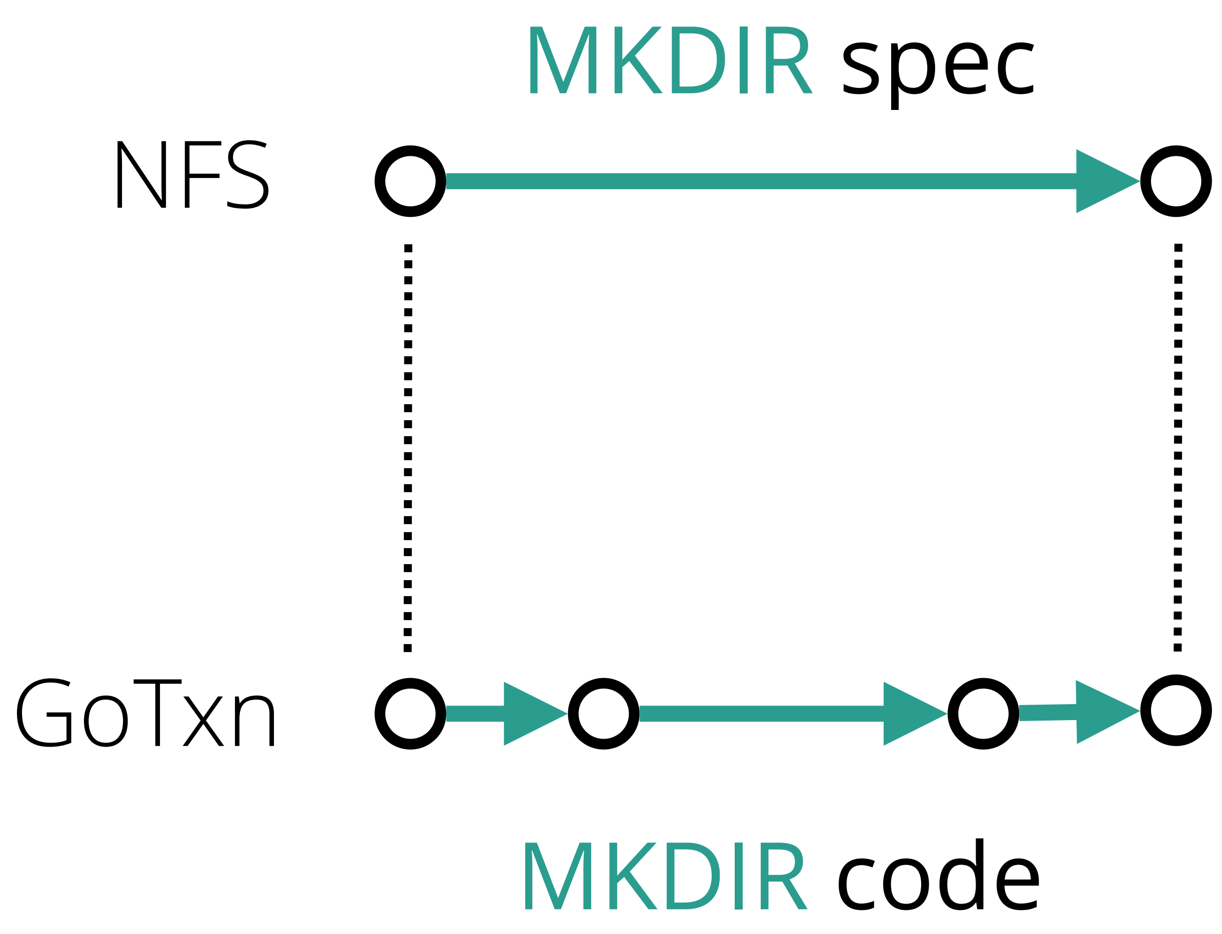


Sequential reasoning has low proof overhead

Simulation-transfer theorem

input: forward simulation for every operation



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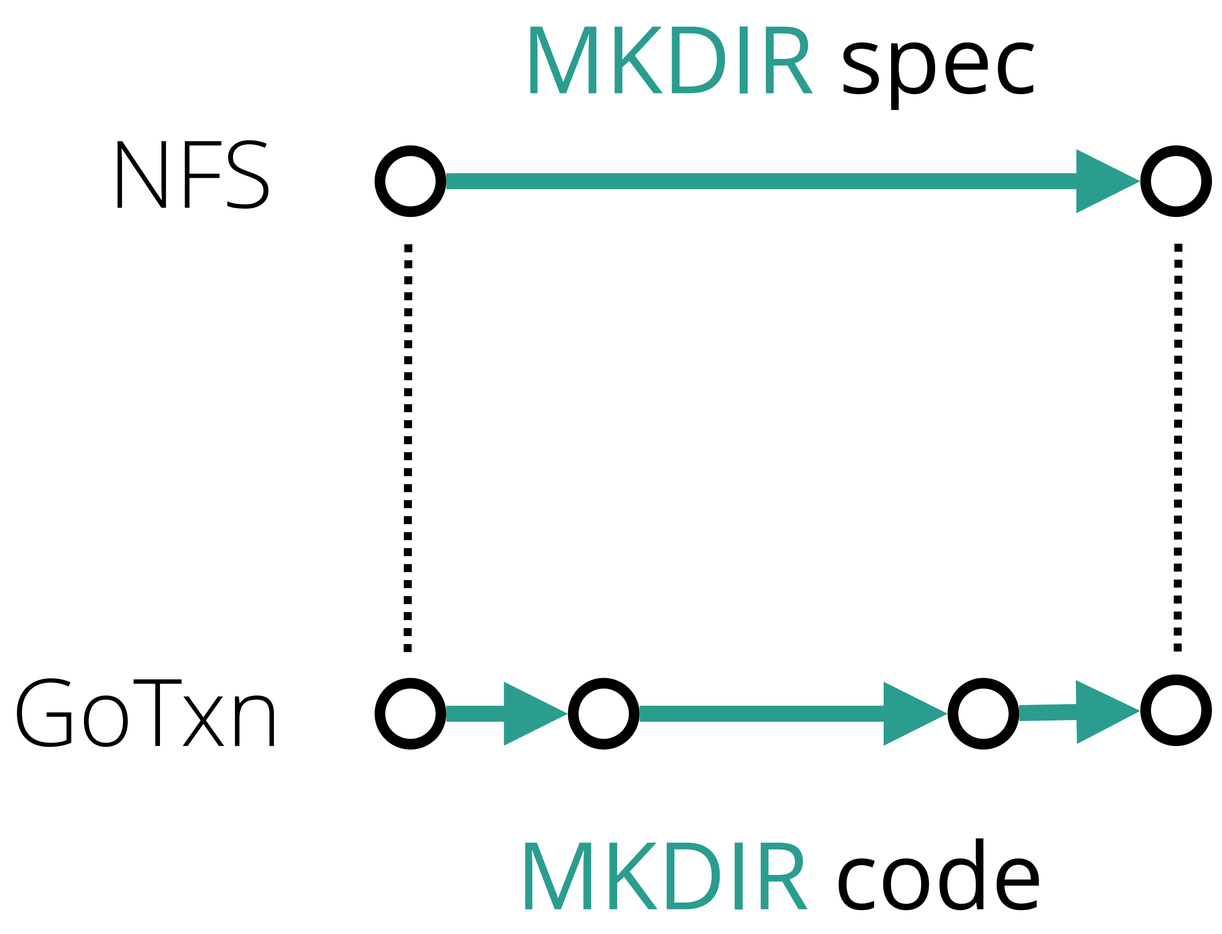
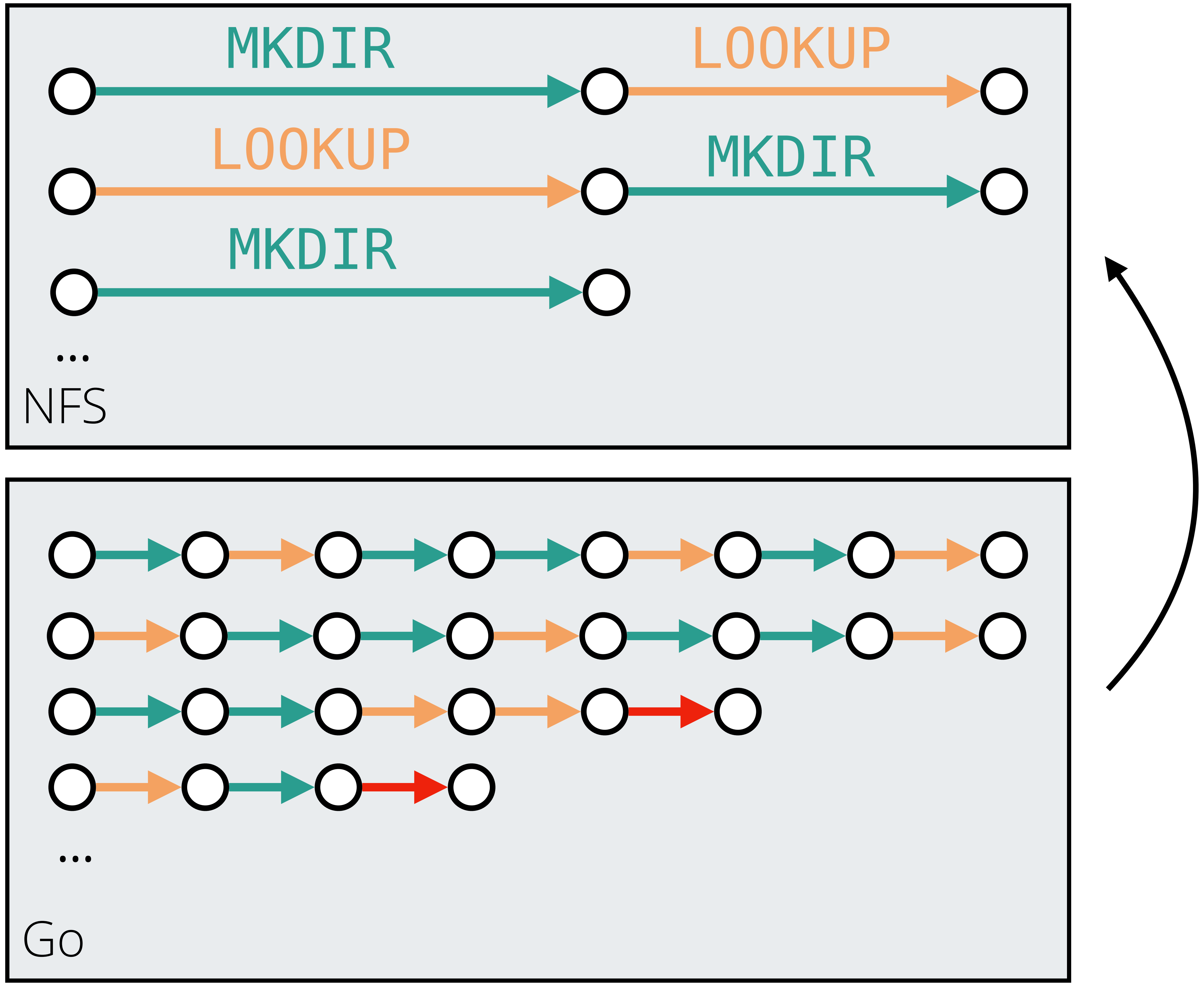
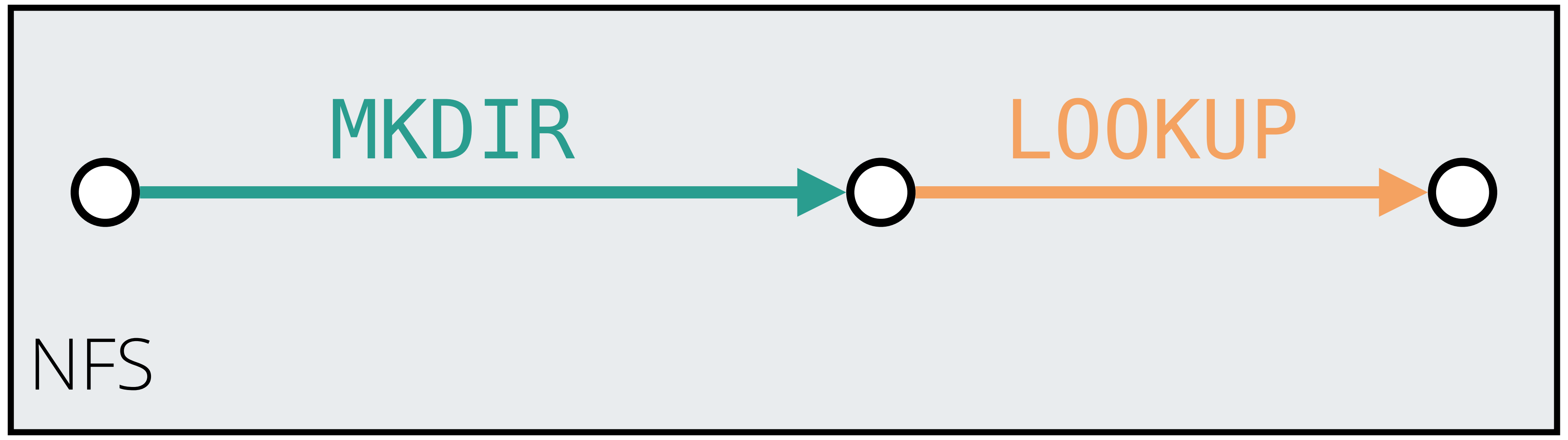


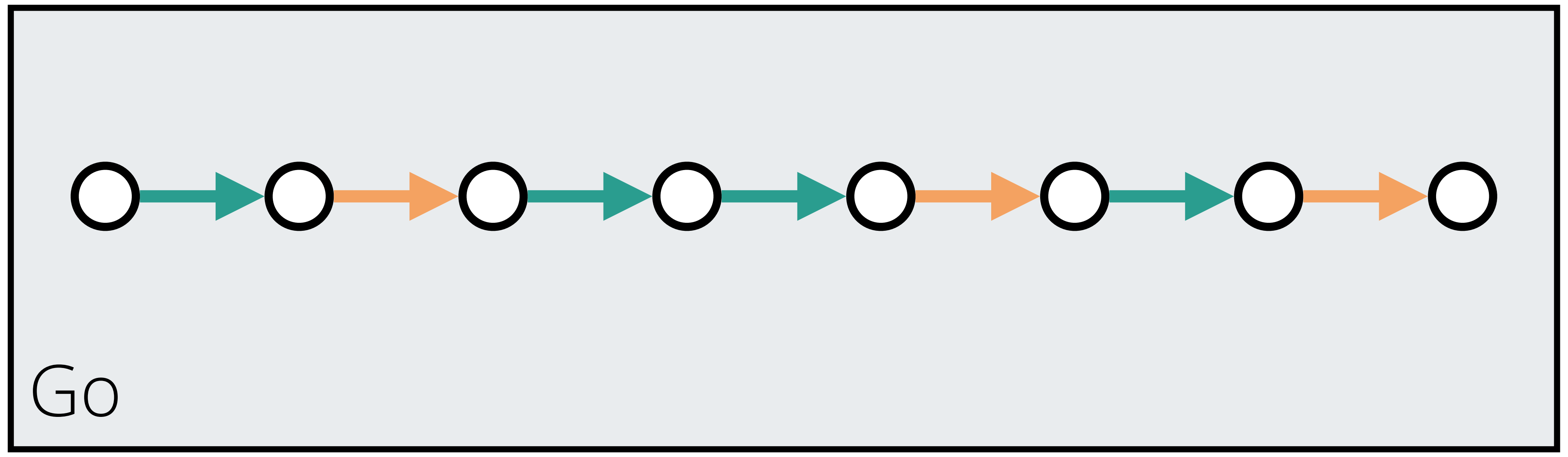
output: concurrent, crash-safe refinement



Proof: compose GoTxn and DaisyNFS proofs

`MKDIR(…) || LOOKUP(…)`





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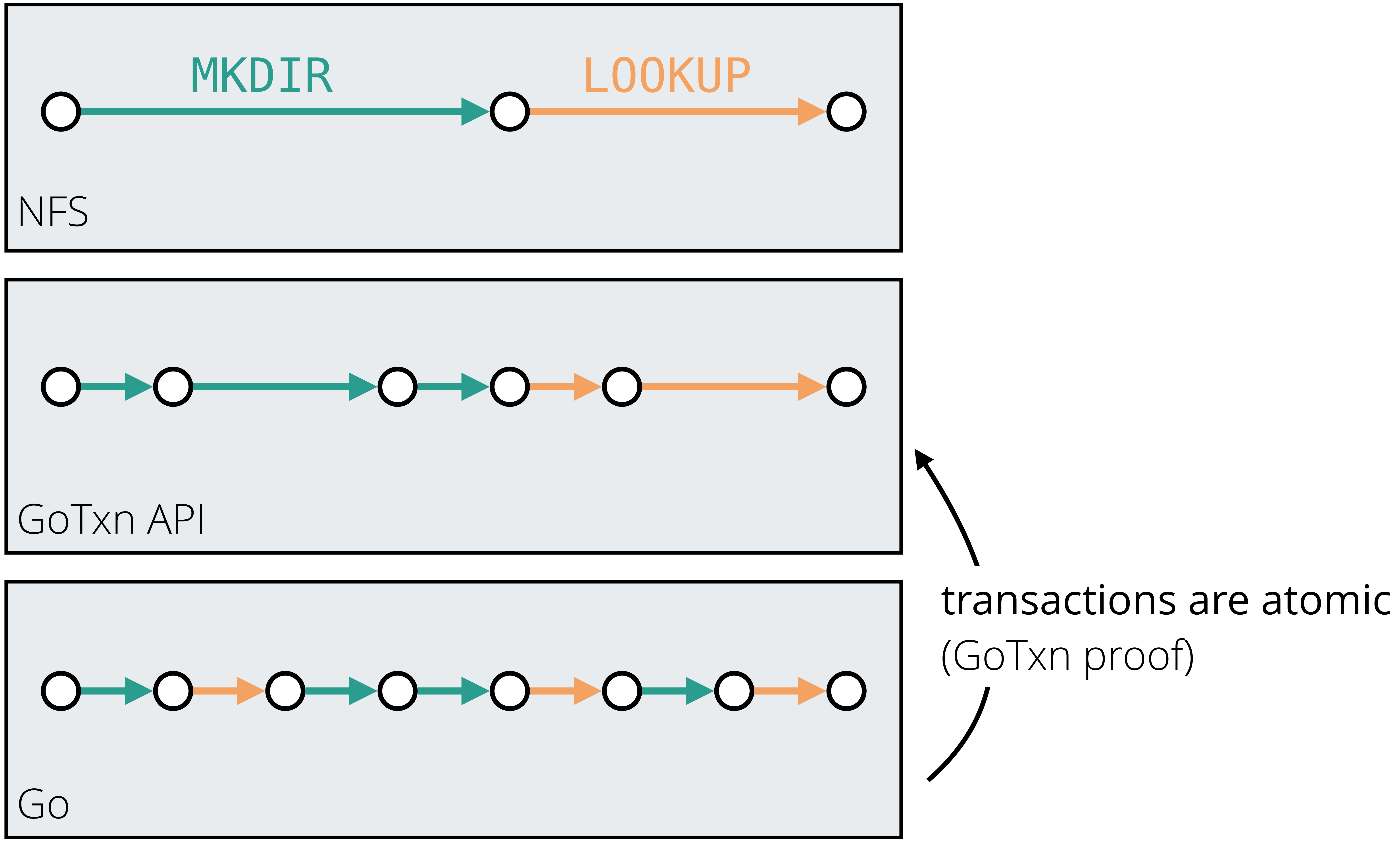

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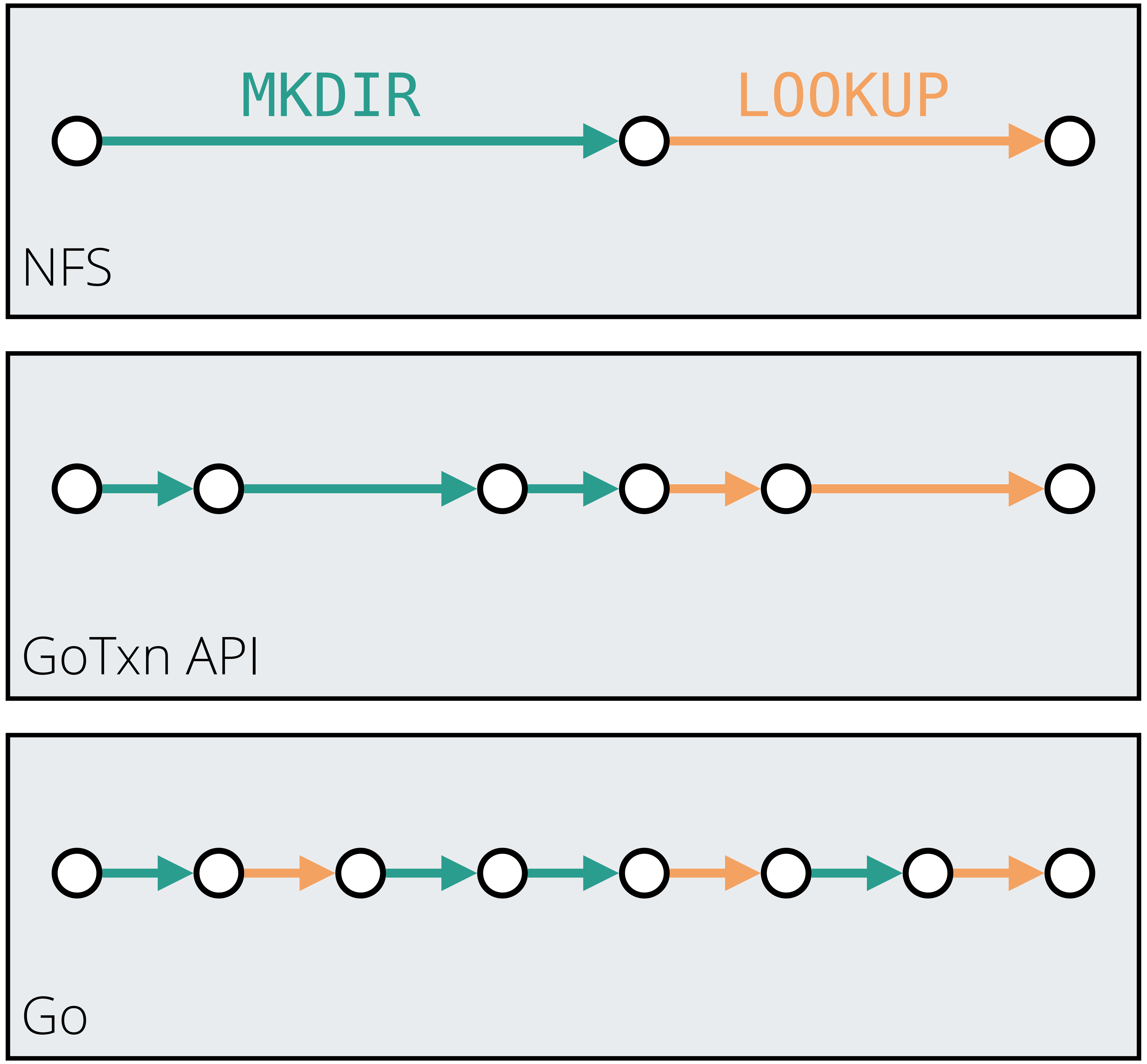

sequential transactions are correct
(DaisyNFS proof)

transactions are atomic
(GoTxn proof)

Theorem needs some assumptions for atomicity

All shared state must go through the transaction system

Theorem needs some assumptions for atomicity

All shared state must go through the transaction system

Challenge: how to integrate in-memory allocator state (for performance reasons)?

Naive in-memory allocator would be slow

```
method WRITE(ino) {
  tx := Begin()
  a := Alloc()
  … // add a to ino
  markUsed(tx, a)
  tx.Commit()
}
```

```
method REMOVE(ino) {
  tx := Begin()
  … // get a from ino
  Free(a)
  markFree(tx, a)
  tx.Commit()
}
```

Naive in-memory allocator would be slow

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method WRITE(ino) {
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allocator
lock

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```

Our solution: use allocator only as hint

```
method WRITE(ino) {
  tx := Begin()
  a := AllocHint()
  if isUsed(tx, a) {
    tx.Abort()
    return ENOSPC
  }
  … // use a as before
  tx.Commit()
}
```

No lock is held after AllocHint call

Rely on-disk allocator as source of truth

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method WRITE(ino) {
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Rely on-disk allocator as source of truth

`AllocHint` has spec that is sound in a transaction

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```

Simulation-transfer theorem explicitly allows `AllocHint` and `Free`

Evaluation

Evaluation results

GoTxn reduces proof burden

Bugs found in unverified code and specification

Good performance compared to Linux

Simulation transfer reduces proof overhead

		Code
	DaisyNFS	4,000 (Dafny)
	GoTxn	1,600 (Go)

Simulation transfer reduces proof overhead

	Code	Proof
DaisyNFS	4,000 (Dafny)	6,800 (Dafny)
GoTxn	1,600 (Go)	35,000 (Perennial)

Simulation transfer reduces proof overhead

	Code	Proof
DaisyNFS	4,000 (Dafny)	6,800 (Dafny)
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2x proof:code

20x proof:code

Bugs found in unverified code and spec

XDR decoder for strings can allocate 2^{32} bytes

File handle parser panics if wrong length

bytes

mic type cast

ed

RENAME can create circular directories

CREATE/MKDIR allow empty name

Proof assumes caller provides bounded inode

RENAME allows overwrite where spec does not

Didn’t find bugs in verified parts

Bugs found in unverified code and spec

XDR decoder for strings can allocate 2^{32} bytes	Unverified glue code
File handle parser panics if wrong length	
Panic on unexpected enum value	
WRITE panics if not enough input bytes	
Directory REMOVE panics in dynamic type cast	
The names "`.`" and "`..`" are allowed	Missing from specification
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Bugs found in unverified code and spec

Bug	Category
XDR decoder for strings can allocate 2^{32} bytes	Unverified glue code
File handle parser panics if wrong length	Unverified glue code
Panic on unexpected enum value	Unverified glue code
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RENAME allows overwrite where spec does not	Missing from specification

Proof had an unintentional precondition

Dafny

```
type Ino = ino:uint64 | ino < NUM_INODES

method REMOVE(ino: Ino)
  requires invariant()
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actually means...

```
method REMOVE(ino: uint64)
  requires invariant()
  requires ino < NUM_INODES
```

Proof had an unintentional precondition

Go (unverified)

```
…
fs.REMOVE(req.ino)
…
```

Go code is *assumed* to meet any preconditions

Dafny

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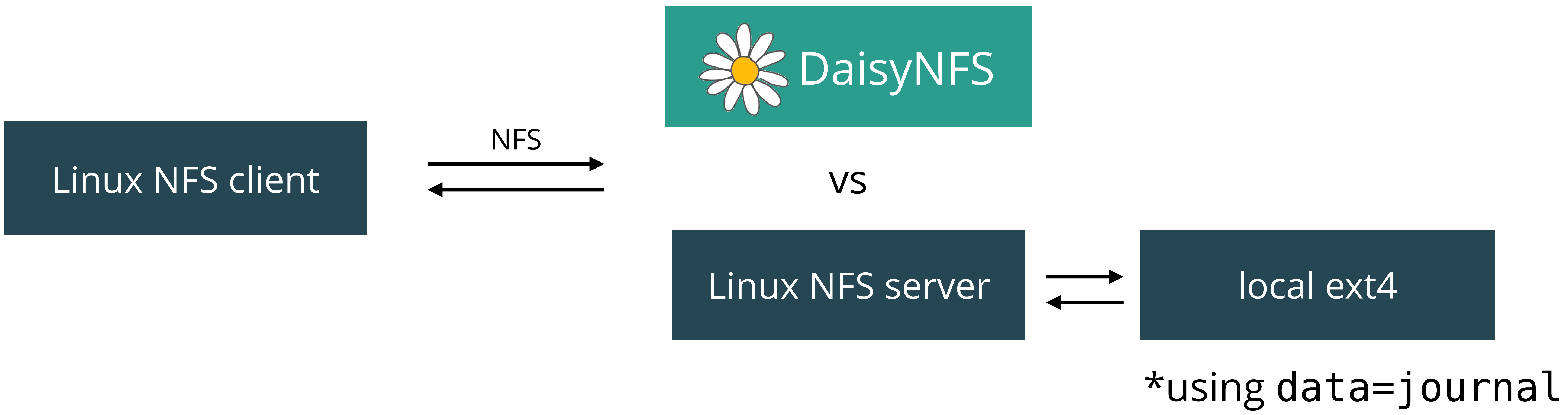
Compare against Linux NFS server with ext4



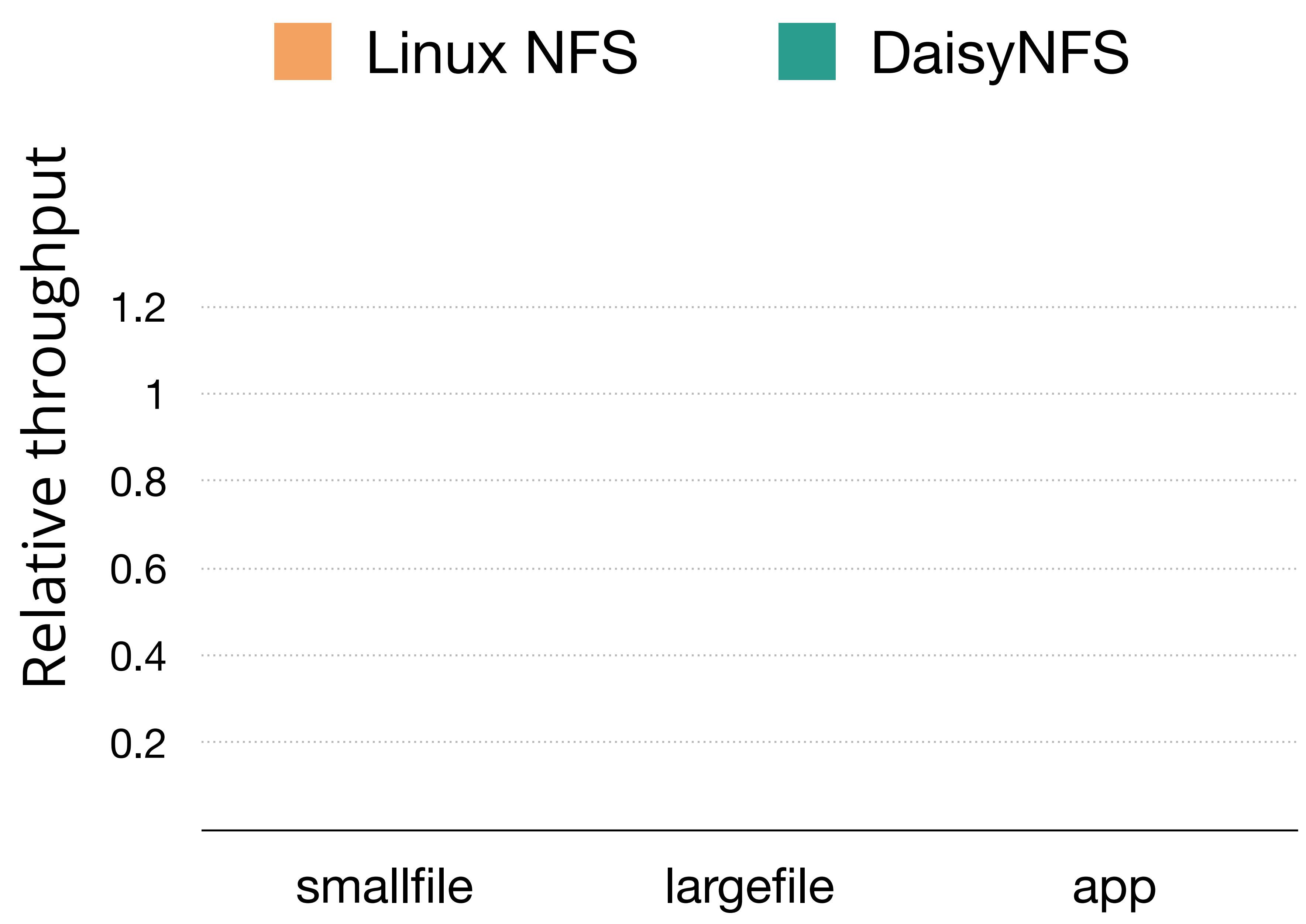
Performance evaluation setup

Hardware: i3.metal instance

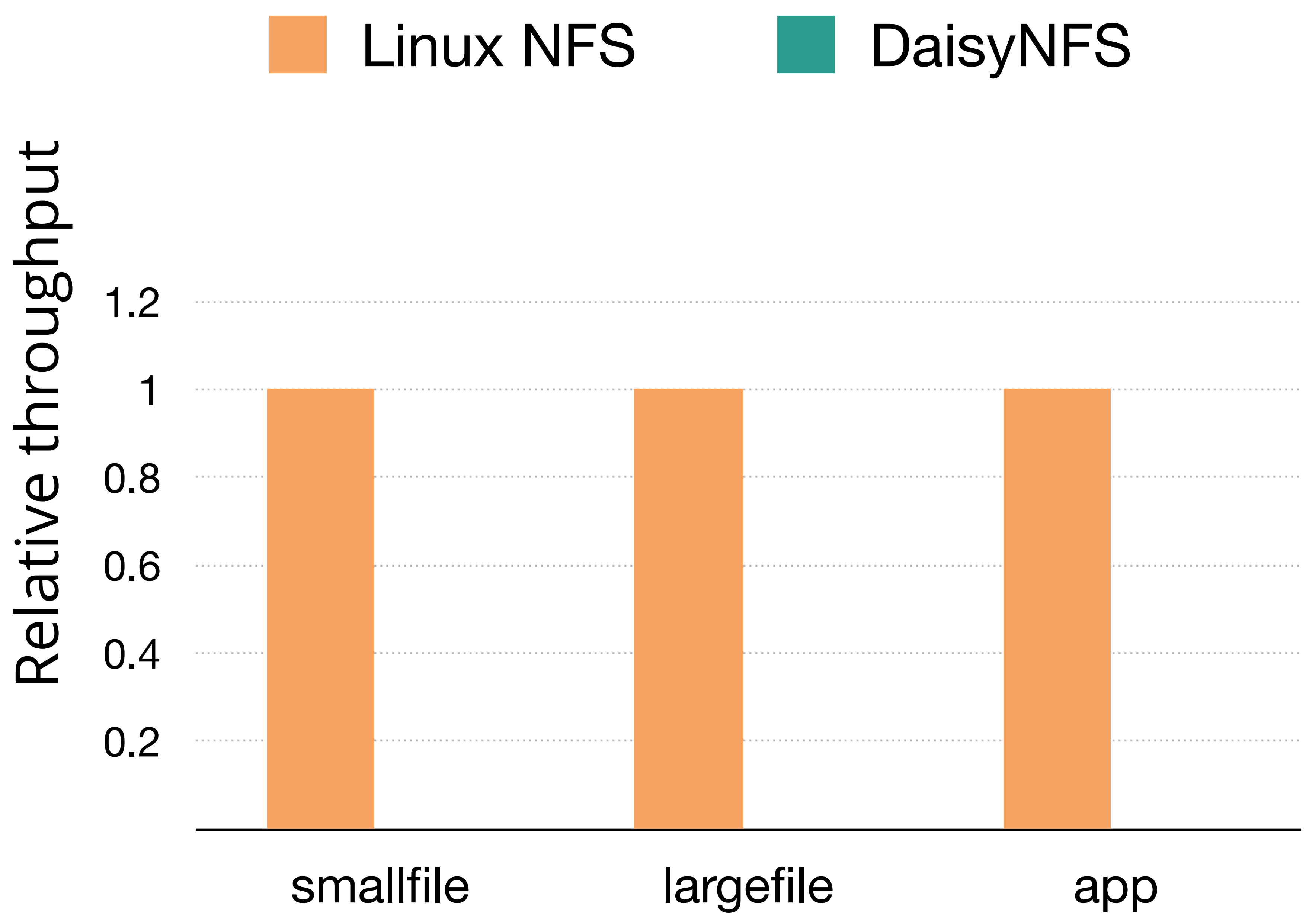
36 cores, fast NVMe drive

Benchmarks:

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

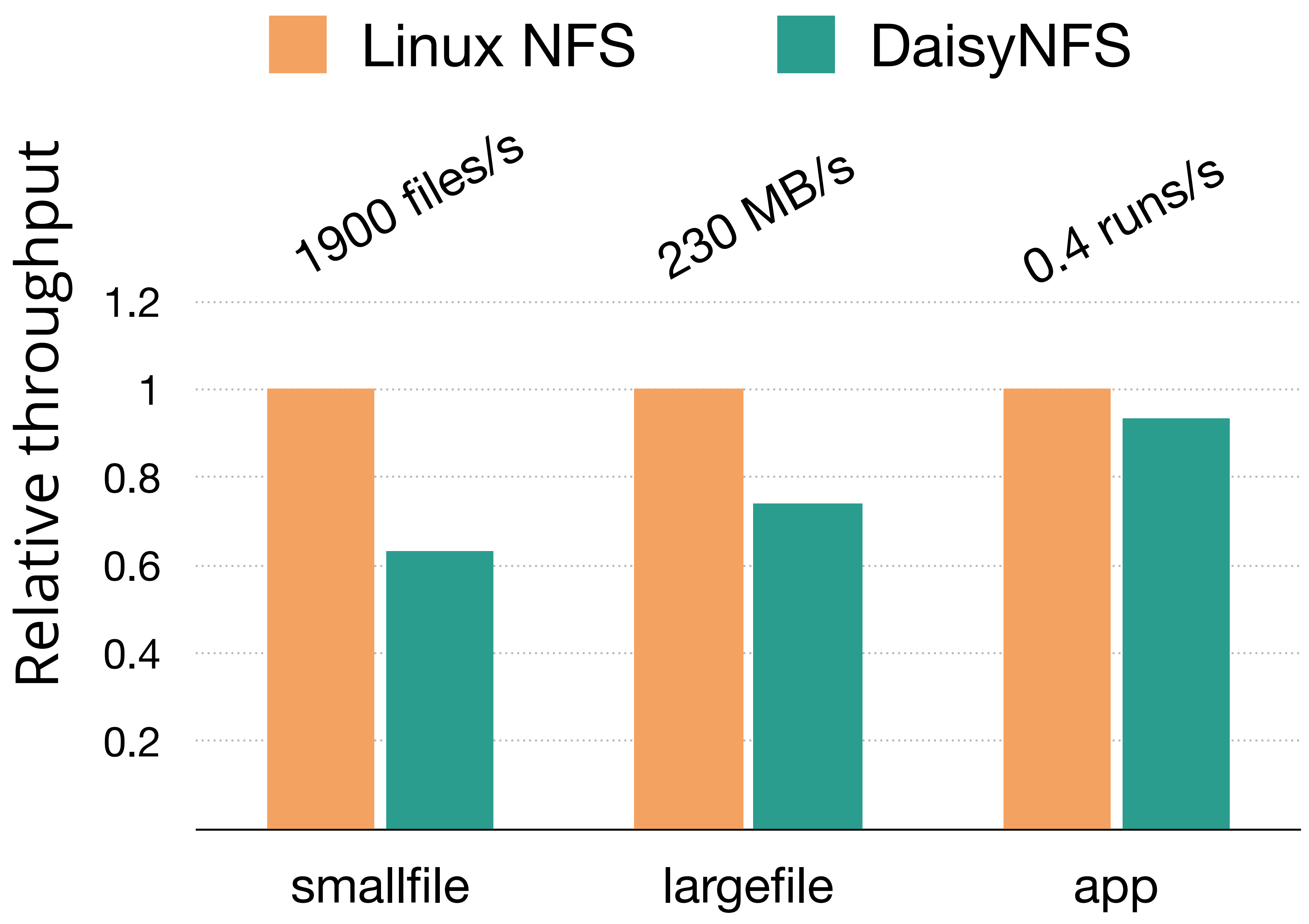


Compare DaisyNFS throughput to Linux, running on an NVMe disk



Compare DaisyNFS throughput to Linux, running on an NVMe disk

DaisyNFS gets good performance with a single client



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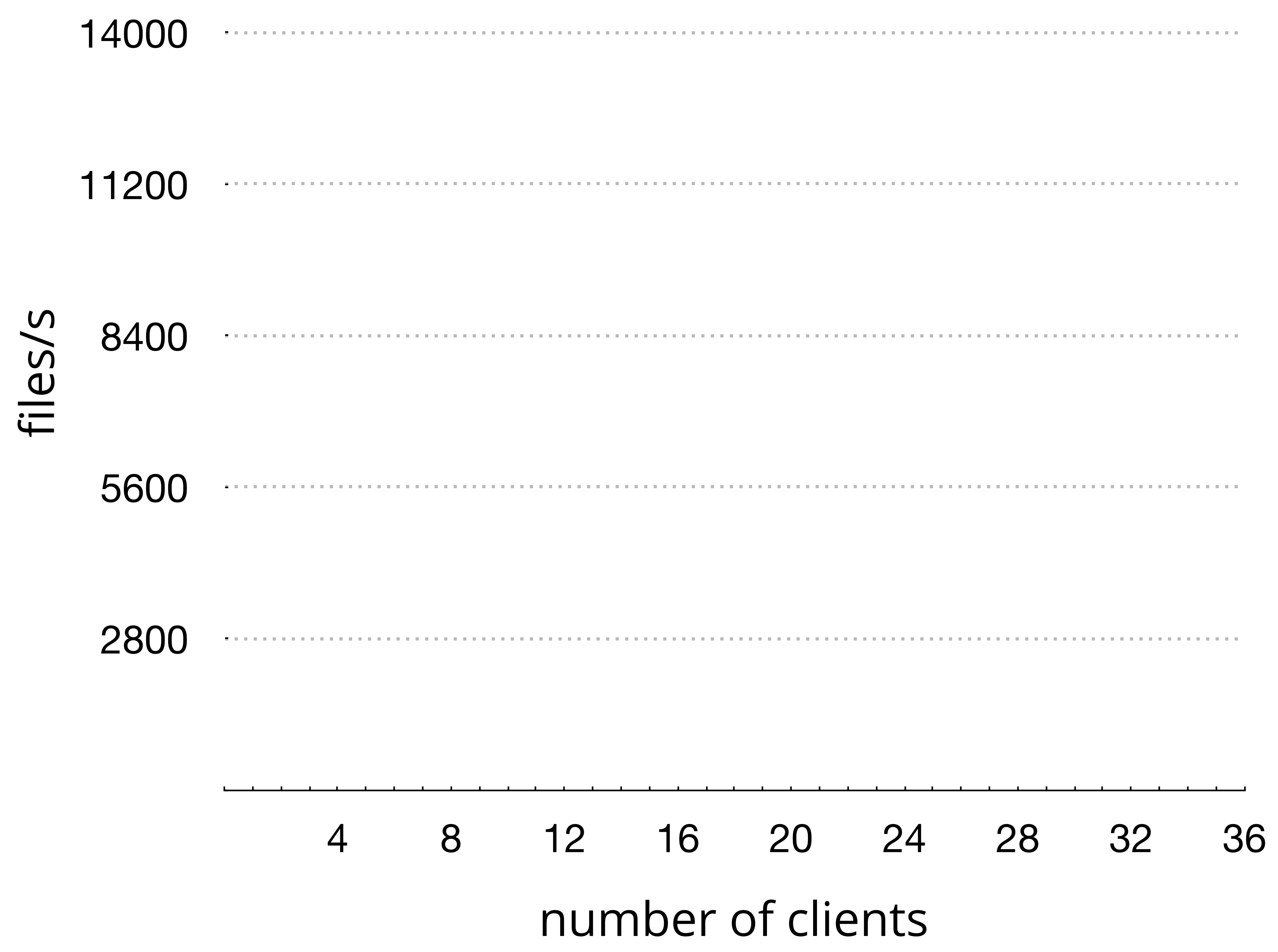
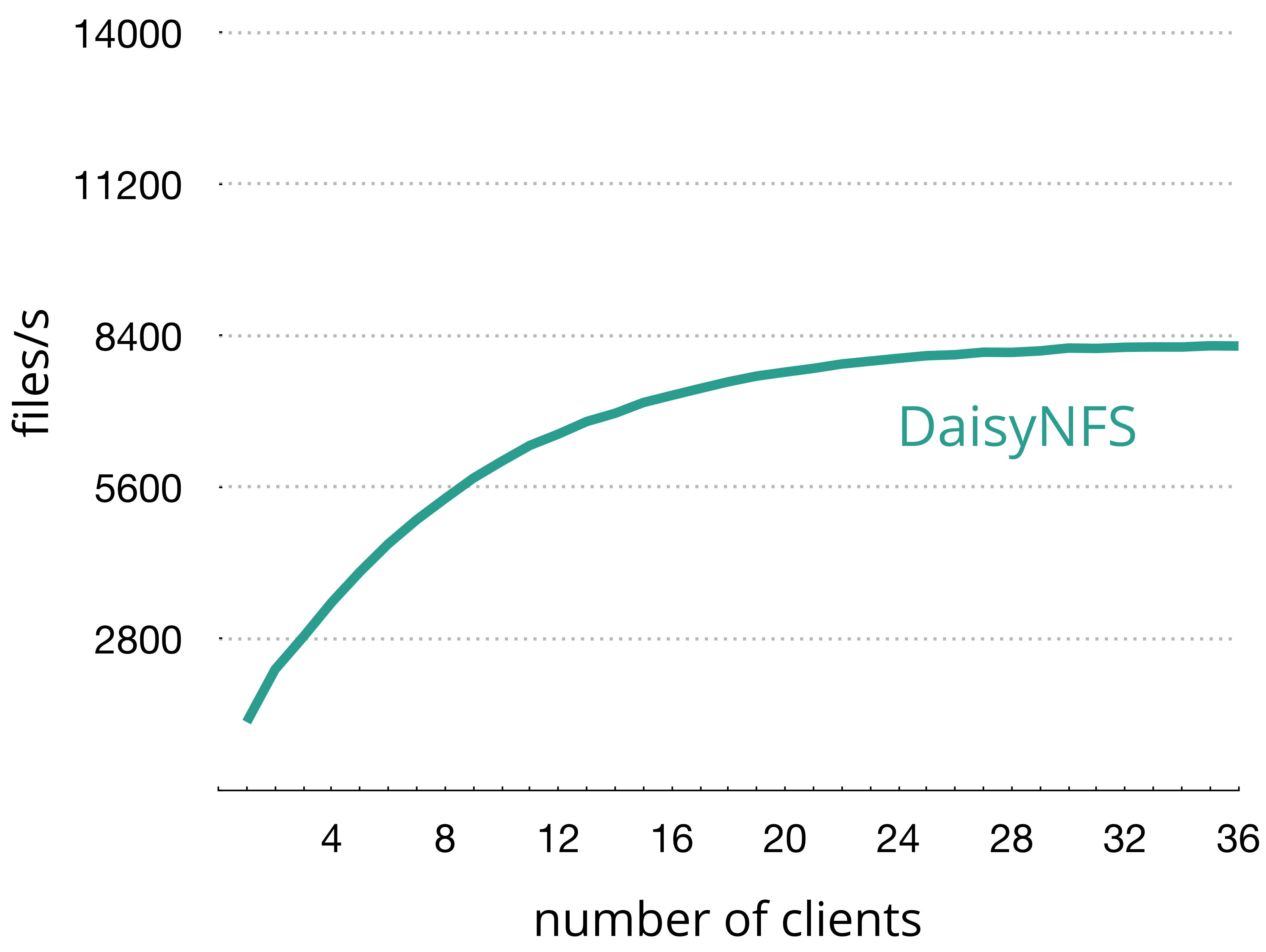


Run smallfile with many clients on an NVMe SSD

DaisyNFS can take advantage of multiple clients



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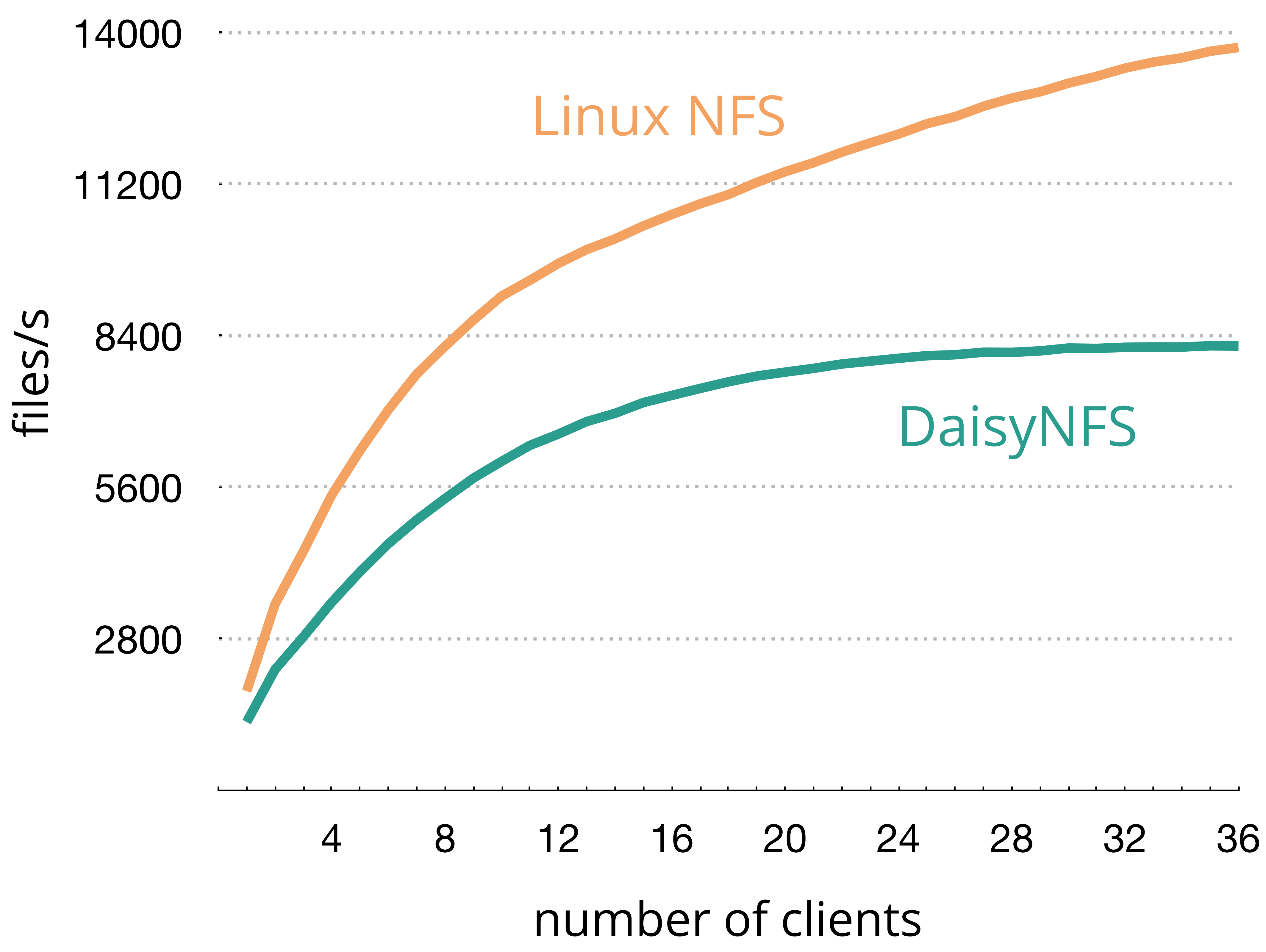

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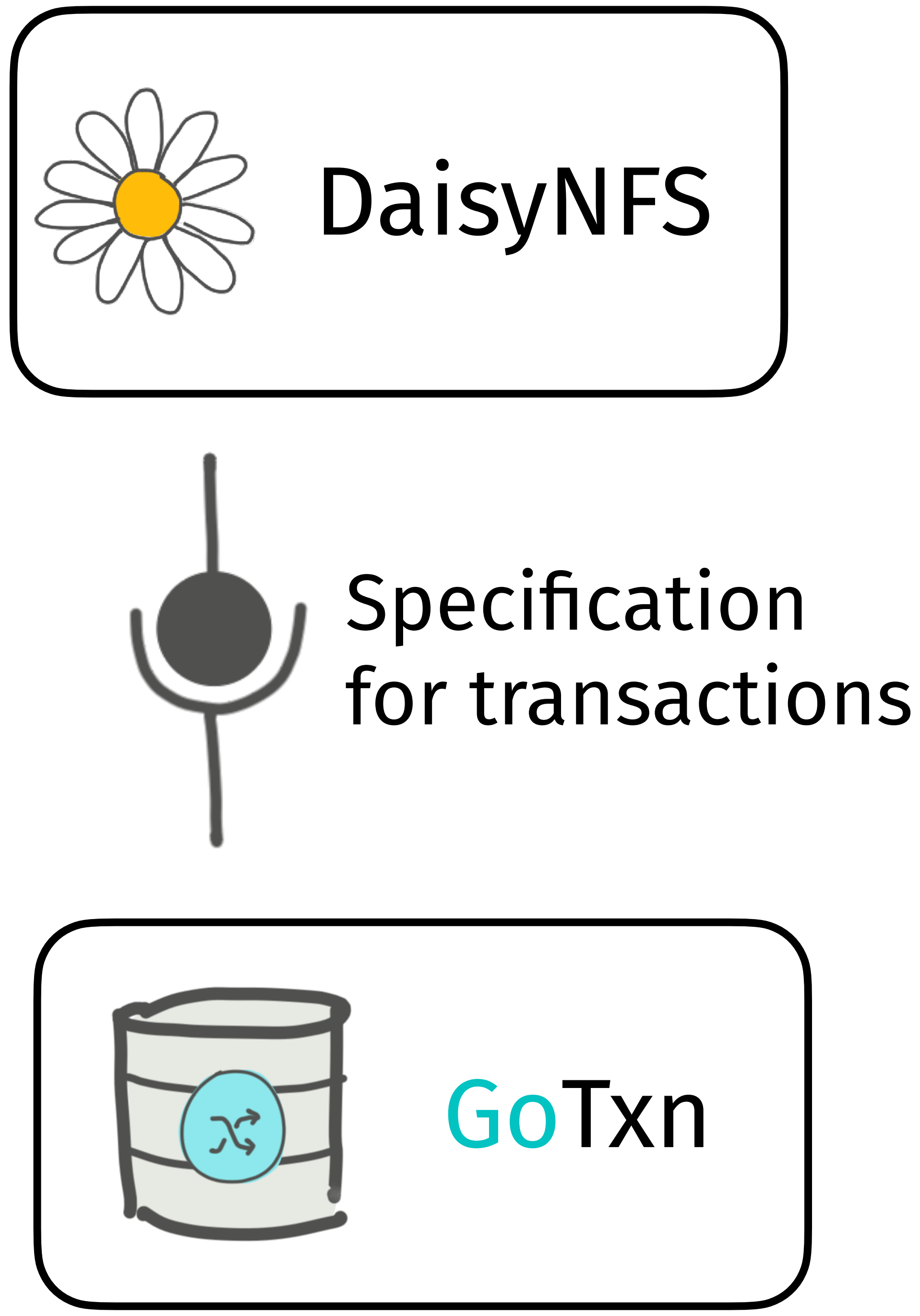
Related work

GoTxn extends GoJournal [OSDI 2021] with two-phase locking

Flashix [2021] is a verified concurrent file system, does not use transactions

Isotope [FAST 2016] has an unverified file system using transactions

Conclusion



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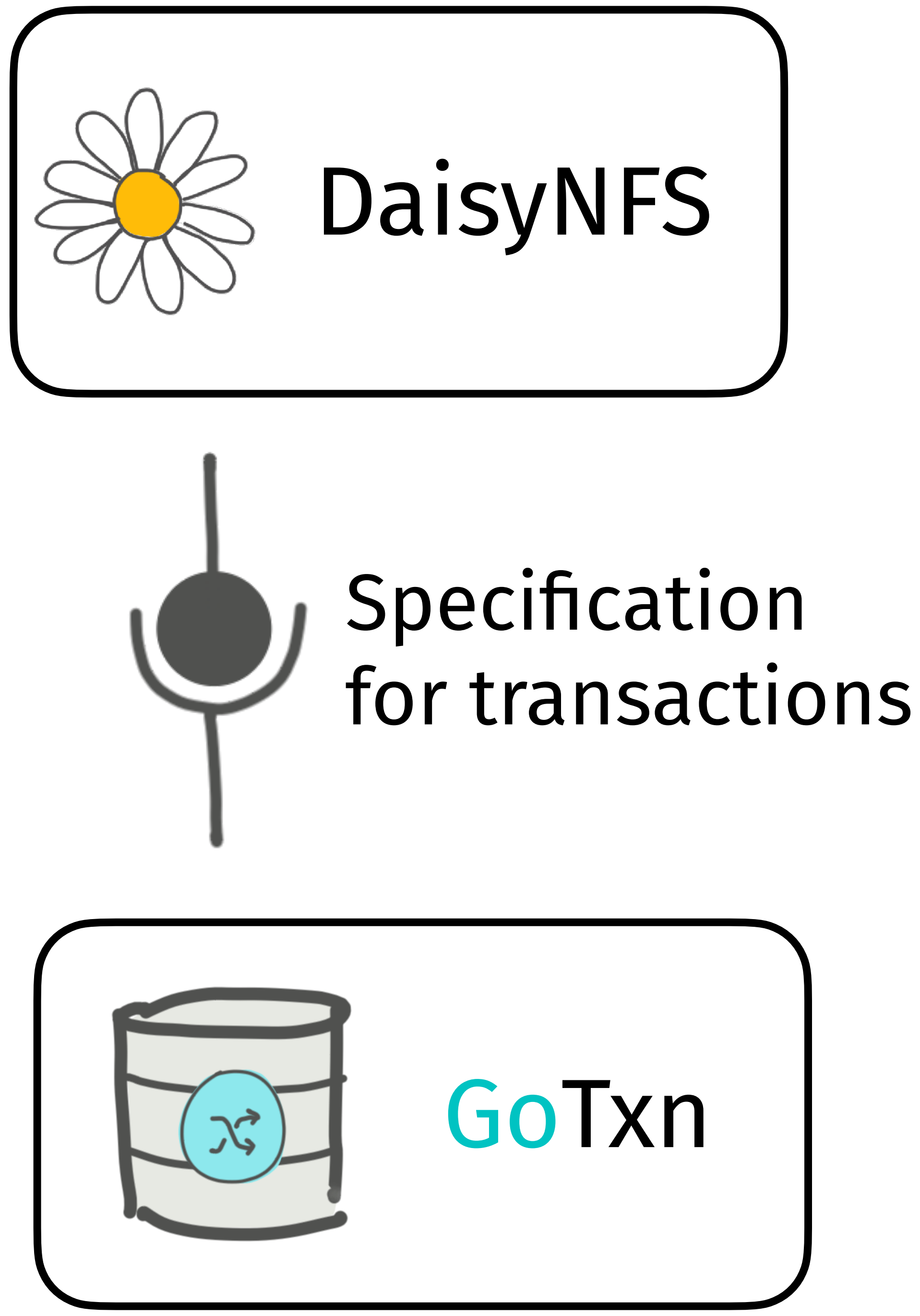

DaisyNFS is a verified, concurrent file system with good performance

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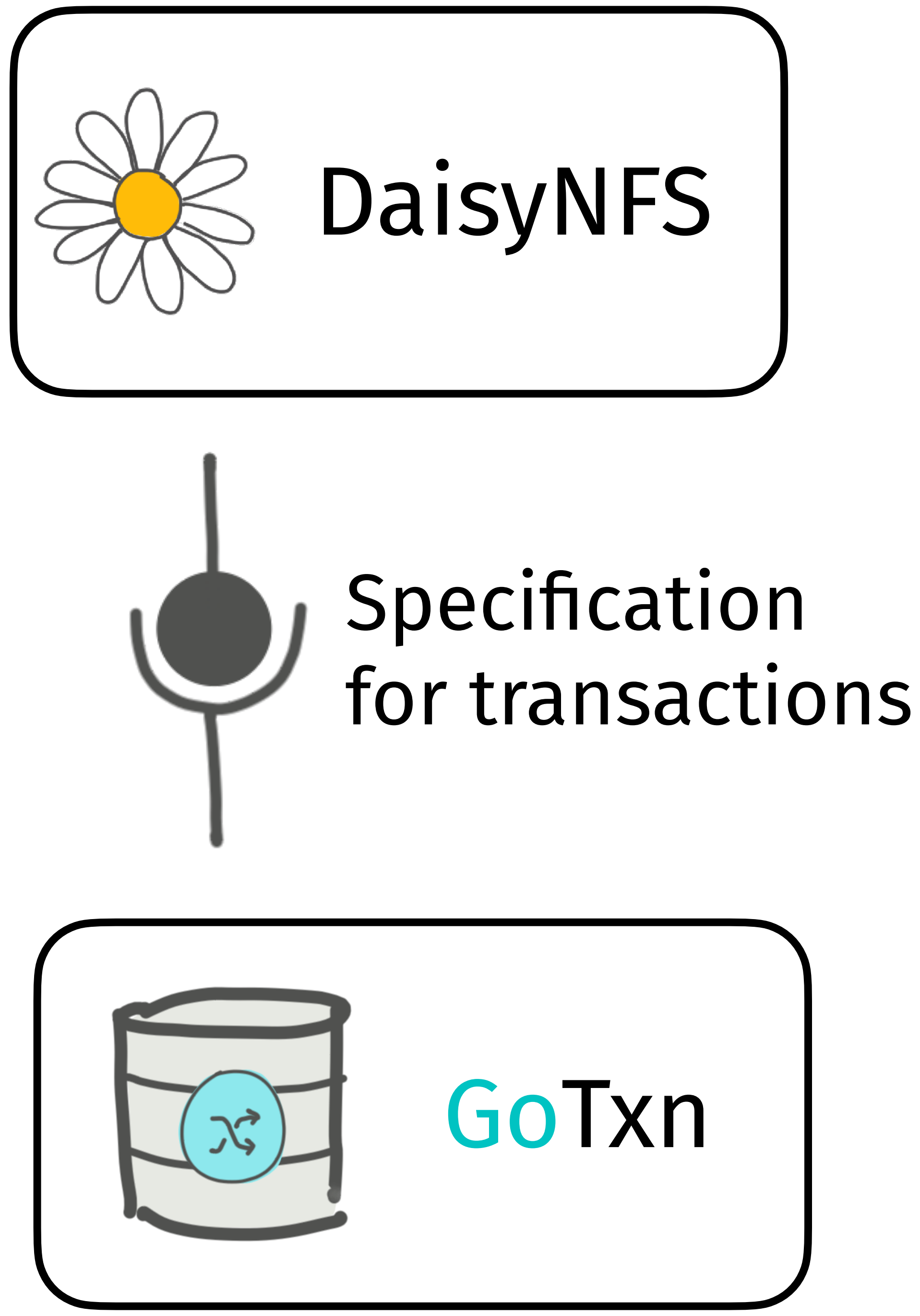

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Simulation-transfer theorem captures how transactions turn sequential reasoning into concurrent & crash-safe correctness