Verifying concurrent storage systems with Armada

Paper #95

Abstract

This paper introduces Armada, a framework for verifying concurrent storage systems with crash safety guarantees. Armada extends the Iris [24] concurrency framework with four techniques to enable crash safety reasoning: recovery ownership, recovery leases, recovery helping, and versioned memory. To ease development and deployment of applications, Armada provides Goose, a translator for importing Go programs into Armada and reasoning about them with a model of Go threads, data structures, and file-system primitives. We implemented and verified a crash-safe, concurrent mail server using Armada and Goose that achieves speedup on multiple cores. Both Armada and Iris use the Coq [35] proof assistant, and the mail server and the framework's proofs are machine checked.

1 Introduction

Concurrent storage systems are difficult to make correct because the programmer must handle many interleavings of threads in addition to the possibility of a crash at any time. Testing interleavings and crash points is difficult, but formal verification can prove that the system always follows its specification, regardless of how threads interleave and even if the system crashes.

Several existing verified storage systems address many aspects of crash safety [7, 9, 12, 33], but they support only sequential execution. There has also been great progress in verifying concurrent systems [6, 14, 15, 20, 23], but none support crash safety reasoning. This paper takes ideas for reasoning about crash safety and applies them to a concurrent verification system called Iris [24].

To understand why reasoning about the combination of crash safety and concurrency is challenging, consider the following example: a concurrent disk replication library (Figure 1) that sends writes to two physical disks and handles read failures on the first disk by falling back to the second. The informal specification for the library is simple: the two disks should behave as a single disk. That is, reading a block should return the last value written to that block, and concurrent reads/writes should be linearizable [19].

Several implementations are possible, but a straightforward one uses a lock per block, which is held during writes and reads. This guarantees that concurrent writes and reads of the same disk block are linearizable. Intuitively, such an implementation is correct because a write is durably stored on both disks before the lock is released. This ensures that a read may failover to the second disk if necessary because both disks agree on the block value when the lock is acquired.

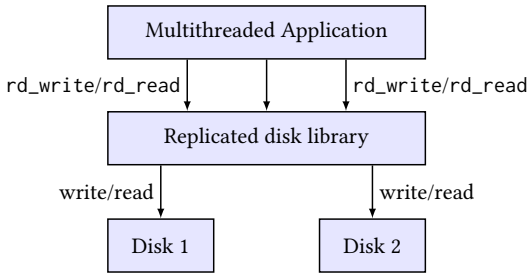

Figure 1. A concurrent, replicated disk library that tolerates a single disk failure using two physical disks. The library provides linearizable reads and writes, and transparently recovers from crashes.

This achieves linearizability, but is not enough for crash safety. A crash that happens in the middle of a write leaves the disks out of sync, so the implementation must run a recovery function on reboot. Because we want writes to be durable when they finish, recovery must not revert or corrupt completed writes. For example, it would be wrong for recovery to make the disks in sync by zeroing them both. A correct recovery procedure can instead copy values from the first disk to the second. This is safe because it *logically completes* write operations that crashed during execution and only overwrites old data.

To *prove* that this justification is correct and that the developer has considered all interleavings and crash points correctly, we need to capture this reasoning using precise rules that lend themselves to concise, machine-checked proofs. Formalizing this argument is challenging.

This paper introduces Armada, which extends the Iris concurrency verification framework [24] with four techniques to incorporate crash safety reasoning. *Recovery ownership* gives recovery ultimate ownership of the resources it needs to run. The ownership is implemented in terms of a crash invariant over durable resources that is true at every crash point. This mirrors the notion of a lock invariant, except that lock invariants can be violated by a crash that causes recovery to observe an intermediate state before a lock could be released. *Recovery leases* reconcile resource ownership with abrupt crashes and recovery by treating recovery as the ultimate owner of all system resources, and providing a logical *lease* on those resources to application code when recovery is not running. *Versioned memory* helps developers precisely reason about contents of memory before and after crashes, since a crash causes the computer to lose the contents of main memory. *Recovery helping* is the final technique, which reconciles what each thread was doing before

a crash with what recovery code will do on its behalf to clean up. This justifies all steps taken by recovery in terms of abstract steps allowed by the specification. For example, if `rd_write` in the replicated disk fails after writing to `Disk1`, recovery will finish up the write to `Disk2`, and recovery helping lets the application developer prove that this finishes up the interrupted execution of `rd_write`.

To verify running systems, we write them in Goose, a subset of the Go language. We implemented a translator to convert this subset of Go to Coq, as well as a formal semantics in Armada. Developers can then run the Go code using the standard Go toolchain, while writing proofs in Armada. Goose includes support for threads, pointers, slices, and a subset of the POSIX file-system API.

We used Armada and Goose to implement and verify Mailboat, which extends CMAIL [6] with crash handling. The proof shows that after recovery all delivered messages are durably stored and that concurrent readers only observe complete messages. To further evaluate whether Armada's reasoning principles suffice for a variety of crash safety patterns, we verified microbenchmark examples involving write-ahead logging and shadow copies.

Our contributions are the following:

- Armada, a system that supports machine-checked proofs of concurrent storage systems that uses *recovery ownership*, *recovery leases*, *recovery helping*, and *versioned memory* to support crash-safety proofs on top of Iris's support for concurrency reasoning.
- Goose, a subset of Go that comes with a translator to Coq and a semantics in Armada for reasoning about Goose programs.
- Mailboat, a mail server written in Goose with a proof of atomicity and durability.

Our prototypes of Armada and Goose have some limitations. Armada does not currently support composing layers of abstraction; we believe that extending multilayered frameworks like CertiKOS [14] and Argosy [7] to the concurrent crash setting is feasible. Armada proofs only cover safety properties and not liveness, as is typical in concurrent verification. Goose does not include the entire Go language and lacks support for interfaces or first-class functions. Goose's file-system model does not support deferred durability, but we believe that this is not a fundamental limitation.

2 Related Work

Verified crash safety. Recently several verification frameworks have tackled the problem of crash safety of sequential systems, including verified file systems [7, 9, 12, 33]. These systems address many issues, including handling crashes during recovery and giving an abstract specification that covers non-crashing and crashing execution separately. None of these systems support concurrency, and as the replicated disk example of §1 illustrates, interactions between concurrency and crashes require new reasoning techniques. The Fault-Tolerant Concurrent Separation Logic (FTCSL) framework of Ntzik et al. [30] does support concurrency, but that work does not prove linearizability for an entire implementation, and it has only been used for pencil and paper proofs of pseudocode, rather than machine-checked proofs about runnable code.

Concurrent verification. There are many approaches to verifying concurrent software [6, 11, 15, 23, 24, 32]. None of these approaches directly supports crash safety reasoning. Incorporating crash safety into an existing verification framework is not obvious because crash safety requires reasoning about a different mode of execution, where crashes can occur at any time and recovery should run after any crash. Additionally, crash safety requires a different specification that distinguishes what is allowed if the system crashes versus if it does not. FTCSL's design highlights this difficulty: Ntzik et al. [30] re-use the Views framework [11], but still require a new logic, an encoding into Views, and a proof that the resulting theorems have the right meaning in the context of recovery execution. This reasoning is all carried out on paper rather than in a machine-checked way; any mistake in this reasoning could render any proofs built on top of the framework invalid. In contrast, Armada introduces techniques to encode crash safety into Iris and then has a machine-checked proof that this encoding is correct.

Distributed Systems. Distributed systems face some of the challenges of concurrency and crash safety. However, of the existing verified distributed systems [17, 26, 36], only Verdi [36] covers reasoning about replication to maintain the consistency of nodes that crash and rejoin a system. Armada can be used to verify the kind of crash-safe, concurrent node-storage system that Verdi assumes.

Connecting verification to runnable code. There are two broad approaches to connecting a running system and its proof. Extraction-based approaches take a model of the system in a form the verification system understands, and transform it into runnable code. Import-based approaches take runnable code and then convert them into proof obligations in the verification system. Both extracting and importing have been explored extensively in prior work [3, 5, 8, 10, 16, 22, 27, 29, 34]. An advantage of importing is that the performance of the verified code is often easier to control and can be understood by developers unfamiliar with the verification tool. However, import systems are usually tightly coupled to the verification framework, and no prior tool exists for Iris. The Goose translator lets us verify concurrent Go code using Armada, thereby taking advantage of Iris's support for concurrency reasoning.

Verified mail servers. There are some existing proofs of mail servers in other concurrency frameworks [2, 6]. We

verified Mailboat, a mail server with similar functionality to CMAIL [6], but with two important distinctions. First, our mail server includes a crash-safety proof in addition to a comparable specification of linearizability. Second, Mailboat is written in Go, whereas CMAIL is written in Coq that extracts to Haskell. Mailboat's proof is therefore carried out at a lower level of abstraction to reason about mutable memory in Go.

3 Overview

This section provides an overview of Armada.Armada uses the standard approach of proving using refinement, which we will explain using the replicated disk as an example (§3.1). As mentioned previously, Armada is built as an extension to the Iris verification framework. However, the correctness properties proved with Armada can be understood by a developer without knowledge of or trust in Iris. After describing the refinement specification, we explain the structure of Armada and the developer workflow (§3.2).

3.1 Refinement

Proving the correctness of a system in Armada requires showing a refinement between the system's code and its spec. Both the code and the spec are *transition systems*: that is, a state that can evolve over time through a sequence of well-defined atomic steps. The spec transitions are calls to the system's top-level operations, whereas the code transitions at a finer granularity for every primitive operation in the programming language. Refinement requires that every sequence of code transitions must correspond to a sequence of spec transitions, with the same external I/O (i.e., invocations and return values of top-level functions). This allows a user of the system to abstract away from the code, and reason purely about the spec, since the spec covers all possible code executions.

To write concise specifications, Armada provides a domain-specific language embedded in Coq for writing transition systems. We show a specification for the replicated disk's operations, `rd_read` and `rd_write`, in Figure 2. The spec says that the replicated disk's state is a single logical disk, represented as a mapping from addresses to disk blocks. The `rd_read(a)` specification looks up the value of address `a` by reading from the state with the `gets` primitive, and giving undefined behavior if the address is out-of-bounds. The `rd_write(a, v)` specification first checks that the address is in-bounds, then updates the that address in the state with the `modify` primitive. Armada's refinement specification for the replicated disk says these two operations are linearizable; that is, they behave as if the transitions described in the spec occur atomically when called from multiple threads.

Armada incorporates recovery execution into its definition of the crash-safety aspect of refinement. The approach is conceptually similar to recovery refinement from Argosy [7],

```
Definition State := Map uint64 block.

Definition rd_read (a:uint64)
  : transition State block :=
  mv <- gets (fun σ => Map.lookup a σ);
  match mv with
  | Some v => ret v
  | None => undefined
  end.

Definition rd_write (a:uint64) (v:block)
  : transition State unit :=
  mv <- gets (fun σ => Map.lookup a σ);
  match mv with
  | Some _ => modify (fun σ => Map.insert a v σ)
  | None => undefined
  end.

Definition crash : transition State unit :=
  return tt.
```

Figure 2. Specification for the replicated disk operations. Callers observe the transitions in these definitions atomically even if the system crashes, and the crash transition specifies no data is lost after recovery.

but Armada also includes concurrency. Armada's definition of linearizability not only covers concurrent calls to the library but also crashes: after the system crashes and then runs recovery, the specification promises that the caller sees behavior consistent with atomic spec operations followed by a spec crash transition. This lets the caller abstract away from the recovery code and reason about the spec's crash transition and atomic operations, which covers all executions of the code followed by recovery. The code may crash and restart recovery multiple times, which is abstracted away by refinement to a single spec crash.

Figure 3 shows a simple implementation of `rd_read` and `rd_write`, which uses locks to ensure linearizability. To handle crashes, the implementation runs a recovery function after a crash that repairs the state of the replicated disks before accepting new `rd_read` and `rd_write` requests. In the absence of recovery, a system running on top of the replicated disk might observe an inconsistency. Initially, calling `rd_read(a)` would return `v` from `Disk1`, but if `Disk1` were to fail, `rd_read(a)` would fail over to `Disk2` and suddenly return the old value that was there before `v` was written, which is disallowed by the specification. One possible implementation of the recovery function is shown in Figure 4, which copies the blocks from `Disk1` to `Disk2` to bring the disks back into a consistent state.

The core of every refinement proof is an *abstraction relation* that both connects the code and spec states as well as defines which states are reachable to begin with. As an example, consider Figure 5, which illustrates refinement using R as the

```
func rd_read(a) {
  lock_address(a)
  v, ok := disk_read(Disk1, a)
  if !ok {
    v, _ = disk_read(Disk2, a)
  }
  unlock_address(a)
  return v2
}

func rd_write(a uint64, v []byte) {
  lock_address(a)
  disk_write(Disk1, a, v)
  disk_write(Disk2, a, v)
  unlock_address(a)
}
```

Figure 3. Go code for replicated disk read and write. These implement the specifications in Figure 2 atomically.

```
func rd_recover() {
  for a := 0; a < DiskSize; a++ {
    v, ok := disk_read(Disk1, a)
    if ok {
      disk_write(Disk2, a, v)
    }
  }
}
```

Figure 4. Go code for replicated disk recovery. Recovery guarantees that writes are atomic and persistent even due to crashes, as specified by `crash` in Figure 2.

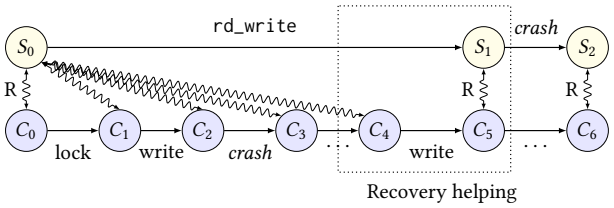

Figure 5. Refinement diagram for one execution with a crash in the middle of `rd_write`. Yellow states are spec states and blue ones are code states. Right arrows in the top row are spec transitions while those in the bottom row are code transitions.

abstraction relation for one possible execution of `rd_write`, with no concurrency but one crash. In this example, the system crashes after writing to `Disk1` but before writing to `Disk2`. The write has not yet logically completed, so in this example, the state in which `rd_write(a, v)` crashed still corresponds to the original spec state; no spec transitions have happened yet. Once the recovery code copies the new value from `Disk1` to `Disk2`, however, the spec takes a transition and appears to have executed `rd_write(a, v)`. Finally,

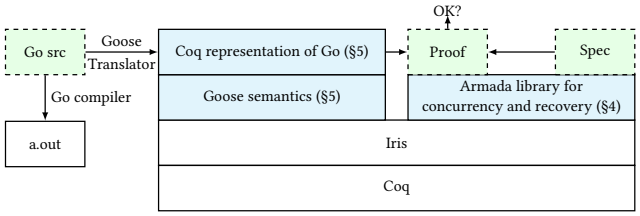

Figure 6. Overview of Armada. Blue boxes are provided by Armada, while green ones with dashed borders are written by the developer. White boxes are inherited by Armada.

after recovery finishes, the spec itself appears to execute a *crash* transition, to reflect the fact that even at the spec level, the executing program crashed and restarted (albeit without having to understand the details of recovery).

To prove refinement for all possible executions, the developer uses a standard technique called forward simulation [28]. Forward simulation requires the developer to show that, starting from any pair of code and spec states connected by the abstraction relation, any valid code-level transition results in a new code-level state that is connected to the same spec-level state, or another spec-level state that is the result of one or more spec-level transitions. Any output from the code (including return values) should be allowed by the spec transition as well. Figure 5 is an example of proving this property for one execution; the complete refinement theorem requires a proof for all possible executions of the code.

3.2 Armada overview

To support refinement proofs that involve concurrency and crashes, Armada is organized as shown in Figure 6. The developer writes the green boxes: code, a spec, and a proof. The proof is machine-checked and, if correct, then all possible code executions are allowed by the specification. The code can be compiled using the standard Go compiler into a binary, and then run.

To prove refinement for an implementation, the Goose translator imports Go code into the Coq proof assistant, linking it with a Goose semantics written in Armada's transition-system language. The semantics define how Go code executes, modeling sequential code execution, shared memory and slices, Go's built-in maps, as well as concurrent execution (including specifying certain operations as undefined behavior, to prohibit racing accesses to slice variables, for example). We describe the Goose semantics in §5.

With the code and specification defined inside of the Coq proof assistant, the remaining job of the developer is a refinement proof. To help develop such a proof, Armada provides a library with reasoning principles. Armada borrows reasoning principles for concurrency from the Iris framework, which reasons about concurrency through *ownership* of resources. For example, shared memory protected by a lock

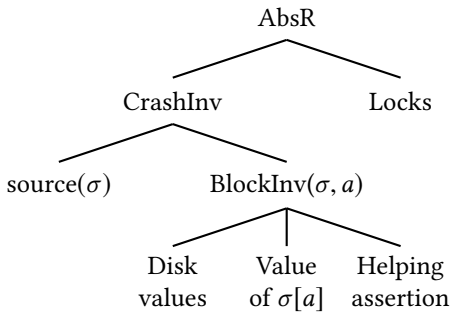

Figure 7. The structure of the abstraction relation for the replicated disk.

$$\begin{aligned}
\text{AbsR} &\triangleq \text{CrashInv} * \text{Locks} \\
\text{CrashInv} &\triangleq \exists \sigma.\, \text{source}(\sigma) * \left(\mathop{\Large *}_{a} \text{BlockInv}(\sigma, a)\right) \\
\text{BlockInv}(\sigma, a) &\triangleq d_1[a] \mapsto v_1 * d_2[a] \mapsto v_2 * \\
&\quad \sigma[a] = v_2 * \\
&\quad \left(v_1 \neq v_2 \to j \Rrightarrow K[\texttt{Write(a, v1)}]\right) \\
\text{Locks} &\triangleq \mathop{\Large *}_{a} \text{is_lock}(m_n[a], \text{LockInv}(a)) \\
\text{LockInv}(a) &\triangleq \text{lease}(d_1[a], v) * \text{lease}(d_2[a], v)
\end{aligned}$$

Figure 8. Abstraction relation for the replicated disk.

is said to be owned by the thread that acquired the lock; acquiring a lock grants ownership, and releasing a lock gives up ownership.

This notion of ownership can also be used for lock-free reasoning. For instance, in a Maildir-based mail server, renaming a message file into the `new` directory transfers ownership of the message from the delivery code to the mailbox itself. If there were a bug in the delivery code that modified the message after `rename`, the proof would not go through, because the code would be modifying a resource that it no longer owns.

Armada extends Iris with four new techniques to reason about concurrency in the presence of crashes, which we describe in the next section.

4 Reasoning about systems with Armada

The first challenge in proving refinement through forward simulation lies in establishing a correct and sufficient abstraction relation. To this end, Armada provides a number of techniques to help application developers write precise abstraction relations that handle both concurrency and crashes. The second challenge lies in considering all possible combinations of threads, and interleavings of their execution, in the context of forward simulation. Here, Armada introduces several proof principles that allow the developer to reason about application code and recovery code using Hoare logic, instead of explicitly considering every possible interleaving of threads and crashes. This section presents Armada's techniques using the replicated disk as a driving example.

4.1 Components of abstraction relation

Figure 7 shows how the abstraction relation is built from smaller components, which we explain one at a time.

At the top level, the abstraction relation AbsR has two components: CrashInv, the crash invariant, and Locks, which governs the in-memory locks. The crash invariant represents durable resources (the blocks on both disks) that are logically *owned by recovery* in Armada as part of crash safety. Though we separate the crash invariant from the rest of the abstraction relation, it contains invariants that are true at all times and are used for proofs about normal execution as well as for crashes. The first sub-component of CrashInv is source(σ), an Iris assertion that states the current abstract state is σ, a single logical disk. This is one of the yellow, spec states in Figure 5 corresponding to the current blue, code state.

Next in the CrashInv is a BlockInv(σ, a) for each disk address a. This invariant captures everything true of address a at all times, including on crash. At a high level it captures two properties. First, $\sigma[a]$, the block in the abstract state, must match the block on the second disk. During `rd_write`, when the first disk has been updated but not the second, the logical abstract disk does not yet change in case the first disk fails during recovery, losing the write. Second, it contains what we call a *helping assertion*, which says that if the two disks have different values at address a, then some thread must be in the middle of writing to that address. The proof of recovery needs this fact to justify copying the value from the first disk to the second.

Finally, the abstraction relation also has a Locks component representing the per-address locks in the replicated disk. Iris reasons about locks in terms of *lock invariants*, a formalization of the intuition that each lock protects access to particular resources. The replicated disk has a lock per address to prevent concurrent reads and writes; formally these locks give exclusive access to the address to avoid races, and guarantee that when the lock is acquired both disks have the same value.

Figure 8 shows how this abstraction relation is stated formally in Armada. It follows the structure of Figure 7, but uses Armada's new techniques, which we describe in the rest of this section.

4.2 Separation logic

Armada uses the Iris variant of separation logic to express the abstraction relation and carry out proofs about the implementation. Originally, separation logic was developed for

reasoning about pointer-based data structures [31]; Iris extends this idea from reasoning only about pointers to general support for reasoning about *ownership*. The central idea of separation logic is the *separating conjunction* $P * Q$, which represents ownership of two logical resources, both P and Q, as long as these resources are disjoint. Resources in separation logic can be interpreted as knowledge of some fact or a capability to modify some value. For example, $a \mapsto v$ represents both the capability for disk address a, as well as knowledge that its current value is v. The replicated disk's abstraction relation uses this "points-to" notation to describe the contents of the disk in the first line of BlockInv. Importantly, resources in separation logic cannot be duplicated in general, so they can represent exclusive ownership and unforgeable capabilities. These permissions are all logical and expressed within the proof, with no runtime enforcement; if the code does not follow the permissions, the proof would not go through.

Putting these together, we use $d_1[a] \mapsto v_1 * d_2[a] \mapsto v_2$ in BlockInv to represent ownership of address a in both disks as well as the blocks on disk. In the replicated disk scenario Armada defines $d_1[a] \mapsto v_1$ to mean Disk 1 has value v_1 at address a *if it has not failed*. This definition is convenient for the replicated disk since it concisely expresses the abstraction relation without many special cases. The block invariant also includes the equality $\sigma[a] = v_2$; as mentioned above, the logical single disk agrees with the second disk. The crash invariant combines the block invariant for every disk address. To represent all of these resources we write $\divideontimes_a \text{BlockInv}(\sigma, a)$ as notation for $\text{BlockInv}(\sigma, 0) * \ldots * \text{BlockInv}(\sigma, \text{DiskSize})$.

4.3 Versioned state

To extend separation logic to work across crashes, Armada introduces versioned state. Traditional separation logic has a strong notion of ownership that does not allow memory or disk locations to change their state while a thread has ownership of them. To reconcile separation logic with the fact that crashes can modify volatile resources, Armada versions all in-memory resources with a generation number, for which we use the variable n. For example, we write $m_n[a]$ for the in-memory addresses, which the replicated disk uses to store the lock variables.

The generation number n corresponds to a crash count; after a crash, the new version number becomes $n + 1$. This allows facts about volatile resources to always be valid, but to no longer apply to the current memory. Returning to the lock example, if a lock were held before a crash, then $m_n[a] \mapsto 1$ would be true. After a crash, recovery always gains exclusive ownership of the new, all-zero memory, including a resource $m_{n+1}[a] \mapsto 0$.

4.4 Recovery leases

Separation logic requires ownership of a resource in order to access it. To ensure recovery can run, we logically give recovery ownership of durable resources ($d_1[a]$ and $d_2[a]$ in the replicated disk example). Recovery ownership is implemented as a crash invariant, which threads can use but must uphold after every atomic step. The same ownership concept applies to locks: each lock logically owns an associated lock invariant, which threads obtain on acquiring the lock and must restore to release it. However, these two conflict when a lock should protect a durable resource: both the lock and recovery cannot simultaneously own the same resource in an invariant or ownership would not truly be exclusive.

Armada addresses this problem by introducing a *recovery lease* to a resource $a \mapsto v$, which we write $\text{lease}_n(a, v)$: the most important feature of the lease is that both the original resource and lease are needed to modify the resource. A lock can protect a durable resource by protecting a lease, while still giving recovery ultimate ownership by leaving the original resource in the crash invariant. Notice that the lease is tied to the current version of memory. The recovery-owned portion also includes a version number, written $a \mapsto_n v$, but we leave it implicit when it is the current generation.

Armada ties leases to the memory version number so that on crash the old leases are invalidated. Just after a crash, the recovery proof can freely take $a \mapsto_n v$ and create a new lease for the next version number, synthesizing $a \mapsto_{n+1} v * \text{lease}_{n+1}(a, v)$. This means that the recovery procedure gains full access to the entire disk right after a crash, and before it returns it can logically give a lease for the new memory version $n + 1$ to the application code — in this case, via each $\text{LockInv}(a)$.

In the replicated-disk abstraction relation, recovery owns $d_i[a] \mapsto v$ facts as part of $\text{BlockInv}(\sigma, a)$ while leases to these resources are protected by locks. In addition to preventing concurrent writes, $\text{LockInv}(a)$ requires that the two disks have the same value.

4.5 Recovery helping

After a crash, the recovery code synchronizes the contents of Disk 1 onto Disk 2. If the disks differ in any location, this needs to be justified with a spec-level transition. Informally, if the disks differed at a before a crash, there must have been a thread writing to a, so when recovery updates the contents of Disk 2, this simulates the spec-level write transition.

To formalize this intuition, Armada introduces the notion of *recovery helping*, where recovery completes the operation of a thread running prior to the crash. The invariant $\text{BlockInv}(\sigma, a)$ states that when the disks disagree at a there must be some thread writing to a, which is represented by an Armada assertion of the form $j \Rightarrow K[\texttt{Write(a, v1)}]$. The recovery proof can then use this fact to formally justify the code writing v_1 to address a on Disk 2, by appearing to finish j's write operation. We borrow the term "helping" from a similar concept in lock-free programming [18] where one thread completes another's operation.

4.6 Hoare triples

To prove the correctness of individual operations in the absence of crashes, the developer proves particular Hoare-logic triples about each operation. A triple $\{P\}\texttt{foo()}\{v.Q(v)\}$ intuitively means that when `foo()` is run with resources P and returns v, it terminates with resources $Q(v)$. More specifically for refinement, the developer must prove a *crash-refinement triple* for each operation, and a *recovery triple* for the recovery procedure. In this section, we discuss the crash-refinement (§4.6.1) and recovery triples (§4.6.2) for the replicated disk.

4.6.1 Operation crash-refinement triples

The crash-refinement triples for `rd_write` is as follows:

$$\{j \Rightarrow K[\texttt{Write(a, v)}] * \text{inv(AbsR)}\}$$
$$\quad \texttt{rd\_write(a, v)}$$
$$\{r.j \Rightarrow K[\text{ret } r]\}$$

This states that, if thread j is invoking `Write(a, v)` at the spec level, then running the code `rd_write(a, v)` will return the correct value r that matches the spec. The inv(AbsR) in the precondition requires that the code maintains the abstraction relation as an *invariant* at all intermediate points, which includes maintaining CrashInv. It is important for every thread to uphold the abstraction relation, since `rd_read` or `rd_write` could be interrupted at any time, and other threads rely on it. Similarly, the crash invariant must hold at every crash point since if the system crashed, recovery would need access to durable resources in the crash invariant.

The write triple proof shows that `rd_write` preserves the crash invariant. The first interesting case is a crash after the first disk has been updated but not the second. If the disks differ, then the proof transfers ownership of the $j \Rightarrow K[\texttt{Write(a, v)}]$ assertion to recovery by putting it in the crash invariant (as part of BlockInv(σ, a)). This later justifies recovery copying from the first disk to the second, if necessary, as described in §4.5. Once both disks are updated, the proof simulates a spec transition for `Write(a, v)`. This preserves, BlockInv(σ, a) now that the value `v` is on the second disk. Note that the linearization point for `rd_write` is either after it updates the second disk or as a part of recovery in the case of a crash, a complexity that Armada is able to reason about precisely.

The read triple (not shown) preserves the crash invariant since it never writes to disk. However, the proof must justify that it reads the correct value, which follows from the lock invariant and AbsR.

4.6.2 Recovery triple

In addition to proving crash refinement triples, the proof engineer must prove a single recovery triple:

$$\{\text{mem\_zeros}_{n+1} * \text{inv(CrashInv)} * \Rightarrow \text{Crashing}\}$$
$$\quad \texttt{recover()}$$
$$\{\Rightarrow \text{Done} * \text{AbsR}\}$$

The recovery triple proof demonstrates that recovery restores the abstraction relation AbsR following a crash. If the system halts at any time, the operation crash-refinement triples guarantee that CrashInv holds. If this invariant uses memory version n, then after a crash the new memory version is $n+1$. The developer must design the crash invariant to hold even after a crash by only referring to durable resources.

The special token $\Rightarrow$ Crashing replaces the $j \Rightarrow K[op]$ tokens for spec-level operations. It represents the spec transition system in a state just before a crash, and can be turned into $\Rightarrow$ Done within the recovery proof to simulate completing that crash. In the case of the replicated disk this step is trivial, since the logical disk in the specification state machine is unaffected by a crash.

Due to the possibility of crashes during recovery, the recovery triple must also preserve the crash invariant in the same way all regular operations do, as specified by inv(CrashInv). The requirement that recovery maintain a crash invariant corresponds to the *idempotence* principle identified in previous sequential verification systems [7, 9, 30, 33], implemented using Iris invariants in Armada.

In the case of the replicated disk, recall that AbsR is divided into two main components: CrashInv and Locks. Recovery already preserves the crash invariant for idempotence, so what is left to restore the abstraction relation is to initialize the locks. Initializing a lock requires two things: a memory address to represent the lock itself, and a proof that the lock invariant initially holds. The memory for the lock variables themselves comes from mem_zeros_{n+1}. To restore the lock invariants, namely LockInv(a), the replicated disk must make the value of both disks equal. The code copies from Disk 1 to Disk 2, which the proof justifies using the $j \Rightarrow K[\texttt{Write(a, v1)}]$ fact from the crash invariant if the disks disagree; this is an example of reasoning about recovery helping.

Finally, the lock invariants need recovery leases for the current version $n + 1$. Recovery has exclusive ownership of $d_i[a] \mapsto v$, so it can freely generate a fresh lease of the form $\text{lease}_{n+1}(d_i[a], v)$ to put in the new lock invariants, replacing the now-invalidated $\text{lease}_n(d_i[a], v)$ from before the crash.

5 Verifying Go programs with Goose

To verify real, runnable systems we developed Goose, a subset of Go amenable to reasoning in Armada. Goose includes the core of the Go language, including slices, maps, structs,

and goroutines (lightweight threads). The developer can directly compile and run this source code using the standard Go compiler toolchain. The most relevant part of Goose for the paper is the encoding of Go resources in Iris, including pointers, files, and OS file descriptors.

5.1 Modeling shared memory

Goose needs a semantics for operations on pointers and slices since these are fundamental components of writing Go programs. Modeling Go's shared memory support requires care: the Go memory model [1] specifies that accessing data simultaneously from multiple goroutines (lightweight threads) requires serialization, for example using locks. This requirement is important to ensure that on real hardware with weak memory (for example, x86-TSO for the Intel x86 architecture) Go can use efficient loads and stores yet ensure threads observe a sequentially-consistent view of memory.

Goose enforces serialized access to shared data (pointers, slice, and maps) by making racy access to the same data undefined behavior. A *race* is formally defined as any instance of unordered accesses to the same object where at least one is a write. We represent this in the semantics by representing writes, such as a store `*p = v`, as two atomic operations, a start and an end. It is undefined behavior in Armada for a program to ever overlap a write with another operation on the same pointer. Our proofs in turn must show that the program never triggers undefined behavior. This is easy to do in Iris since the resource for pointers, written $p \mapsto_n v$, represents *exclusive* access to the pointer p; threads obtain this exclusive access either by allocating a new pointer and not sharing it, or by mediating access with locks. Because this resource is in memory, it refers to the current memory version number n (as described in §4.3).

We use a variant of the same idea to model hashmap iteration, which has a similar problem with iterator invalidation. Goose does not currently support Go's `sync/atomic` package that can be used to build synchronization primitives or do lock-free programming. Our examples did not require these operations, but Goose could be extended to include them. Goose also doesn't support Go's interfaces and first-class functions, because these features are harder to model.

5.2 Modeling the file system

Goose also includes a subset of the POSIX file-system API. The API is mostly a thin wrapper around a selection of system calls, except it requires a fixed directory structure for simplicity. To reason about code that uses the file-system, the Goose file-system semantics uses Iris resources to represent the file system. The resources are fairly low-level to accurately model file-system features like hard links and the difference between paths and file descriptors. Goose logically represents the state of the file system with four different resources:

- Directories: $dir \mapsto N$ states that the directory dir contains the set of file names N. This permission is needed to list the contents of dir and to add/delete files.
- Directory entries: $(dir, name) \mapsto i$ states that the contents of file $name$ in directory dir are in the inode i. We use this to open $name$ or when creating a new hard link to it.
- File descriptors: $fd \mapsto_n (i, md)$ states that the file descriptor fd points to the inode i, with a mode md (corresponding to flags passed to open; we support read and append). It references the current memory version number n since file descriptors are lost on crash.
- Inode contents: $i \mapsto bs$ states that the inode i contains the bytes bs. This is used with a file descriptor to access a file.

The Goose semantics includes a crash model, which describes the effects of a process crashing. As expected, on crash all data structures on the heap are lost. All file data is persisted, but open file descriptors are lost. Goose's semantics for file-system operations state that they are atomic and immediately persisted. Because file descriptors are lost on crash, they are tied to the current memory version, as in §4.3. As with all durable resources, recovery can create leases (as described in §4.4) for directories, directory entries, and inodes. It would be possible to reason about buffered data in the file system to model deferred durability, but our prototype does not do so.

6 Implementation

We implemented Armada using Coq and Goose using a combination of Go for the translator and Coq for the semantics and Iris resources.[1] A breakdown of lines of code is given in Table 1. The framework consists of around 7,800 lines of code, including the transition-system DSL used to write specs. The Go semantics Goose uses is around 2,100 lines of code in Armada, which includes both a model of Go operations as well as the Iris resources to prove Go code correct.

Component	Lines of code
Transition system DSL	1,530
Core framework	6,310
Armada total	7,840
Goose translator (Go)	1,780
Goose library (Go)	200
Go semantics	2,090

Table 1. Lines of code for Armada and Goose.

The Goose translator is an executable called `goose` that translates Go to Coq and links with the Goose semantics. The translator is written in around 1,800 lines of Go. Running `goose` on a supported Go program produces a Coq program ready to import into Armada that represents the Go code.

[1] Our code is open source, but URLs are omitted for double-blind submission.

Example	Lines of code
Two-disk semantics	1,440
Replicated disk	1,170
Single-disk semantics	1,390
Write-ahead logging	840
Shadow copy	340
Group commit	1,380

Table 2. Lines of code for each storage pattern we verified.

Goose uses Go's built-in `go/ast` and `go/types` packages to parse and analyze source code: relying on these official tools helps reduce the chance of a mismatch between `goose` and the Go compiler, which is important since the translator is a trusted tool. Furthermore, the Coq code must type check, which rejects unhandled code that would be difficult to detect with the translator alone. Finally, as a practical matter, `goose` produces human-readable output that is easy to audit.

7 Evaluation

To evaluate Armada, we consider four questions:

1. Can Armada be used to verify a variety of crash-safety patterns in concurrent storage systems?
2. What assumptions do the proofs in Armada rely on?
3. Can Armada and Goose be applied to realistic systems?
4. How much effort is involved in using Armada?

7.1 Crash safety patterns

Storage systems broadly speaking use one of three patterns for crash safety: replication, shadow copies, and write-ahead logging [13]. We wrote small examples illustrating the reasoning that goes into each of these patterns; Table 2 shows a breakdown of the lines of proof for each verified example.

The replicated disk example illustrates proving that failover works correctly in a simple replication system. The shadow copy technique involves making writes to storage atomic by first performing the write on a new copy of the object, then atomically installing the new object (possibly replacing old version). If the system crashes, the shadow copy is invisible and its storage is reclaimed. The mail server uses a shadow copy to deliver mail atomically: first mail is created in a temporary directory, then it is installed atomically with a call to `link`. Recovery reclaims the space used by shadow copies by deleting all temporary files.

The final pattern is write-ahead logging, in which transactions are written to a log before being applied to some other storage. In case of a crash, the recovery procedure uses the log to delete incomplete transactions and finish applying committed transactions. We implemented a simple form of write-ahead logging to atomically update a pair of disk blocks; the "Shadow copy" example in Table 2 implements the same atomic update using a shadow copy. The logging system uses recovery helping to justify completing a committed but unapplied transaction. For better performance logging systems buffer writes in memory before committing them; this enables an optimization called group commit in which multiple transactions are combined, amortizing the cost of committing but potentially losing buffered transactions on crash. We separately wrote and verified a simple group-commit system that does this buffering and specifies precisely when transactions can be lost.

We focused our patterns on crash safety with simple concurrency (i.e., mostly using locks). There are many examples of verification of concurrent systems using Iris, demonstrating its applicability to fine-grained concurrency [25], weak memory [21], and unsafe Rust [20]. One advantage of using Iris is that the ideas in Armada can co-exist with the sophisticated features that are needed to support concurrency proofs.

7.2 Trusted computing base

The proofs in Armada rely on a number of assumptions to hold of the implementation running in the real world. The Coq proof assistant must correctly check the proofs. The Goose model should accurately reflect Go primitives and the running file system, and we trust the Go compiler to produce correct code. The `goose` translator should faithfully represent the source Go program within Armada. We assume programs do not trigger integer overflow, which Goose does not model. Finally, as usual in verification, the user must confirm that the theorem corresponds to their expected guarantees from the system. In particular, Armada's refinement theorems apply to programs that do not trigger undefined behavior in the specification; for example, the mail server proof assumes that `Delete` is called on messages that were previously listed.

7.3 Mailboat: a mail server verified with Armada

We used Goose to write Mailboat, a mail server that uses a Maildir-like format to store messages using the file system. The mail server supports users reading and deleting their mail concurrently with mail delivery. The mail server is structured as a library implementing the core mail management operations that interact with the file system combined with a server that implements SMTP and POP3 and is compatible with existing mail servers. The proof of Mailboat's correctness shows that pickup reads a consistent snapshot of the user's mailbox and that delivery is all-or-nothing even if the system crashes; more generally, all operations in the mail library are linearizable with respect to both concurrency and crashes.

Mailboat is functionally similar to the CMAIL mail server verified using CSPEC [6], although Mailboat's proof includes a crash-safety guarantee and the implementation is lower level, using Go instead of extracted Haskell. The concurrency

aspect of Mailboat's specification is analogous to the guarantees from CMAIL's specification in CSPEC, however there are additional complexities because the API uses mutable Go data structures, instead of immutable Haskell values.

7.3.1 Specification

```
type Message struct {
  ID       string
  Contents string
}

func Init()                              { /* ... */ }
func Pickup(user uint64) []Message       { /* ... */ }
func Deliver(user uint64, msg []byte) { /* ... */ }
func Delete(user uint64, id string)      { /* ... */ }
func Unlock(user uint64)                 { /* ... */ }

func Recover() { /* ... */ }
```

Figure 9. Go signatures for the Mailboat API.

The verified Mailboat library implements the core operations to store, read, and delete user mail. The Go signatures of these functions are shown in Figure 9. In this section we informally describe the behavior of these operations; the Mailboat proof shows the implementation meets a more rigorously-defined specification. Before executing any operations, the library requires that the caller run `Recover` to repair the system following a crash and `Init` to initialize internal state in the library.

The abstract state maintained by the Mailboat library is that of a set of users' mailboxes (one per user ID), where a mailbox is a mapping from message IDs to contents.

To read and delete mail, Mailboat requires holding a per-user lock to prevent messages from being deleted while the user is reading their mail. This lock is implicitly acquired as part of initially listing mail with `Pickup` and released with the `Unlock` operation. In practice the SMTP server calls `Pickup` when a user connects and `Unlock` when they disconnect. For simplicity the library assumes that users only attempt to delete message IDs that were returned by `Pickup`. Mailboat supports mail delivery concurrently at any time, without acquiring locks.

The signatures include mutable slices. To prove the implementation correct, the specification must make precise how these slices can be used. The slice returned from `Pickup` is not retained by the mail library, so the caller can freely mutate it. On the other hand, for delivery to be atomic, the caller must not modify the slice passed to `Deliver`. The formal specification makes this restriction precise by making concurrent modification to the slice undefined behavior.

7.3.2 Implementation

Mailboat stores each user's mailbox as a directory with a file per message. For crash safety, messages are spooled in a separate directory before being atomically stored in the user's mailbox. The library supports several concurrent operations while guaranteeing that on crash delivered mail is not lost. In this section we briefly describe how the implementation handles various concurrent interactions:

Pickup/Delete: `Pickup` reads a list of file names in the user's mailbox directory, and then reads each of these files. To avoid a file being deleted between listing the files and reading them, pickup and delete acquire a common lock per user. The mail server acquires this lock with a pickup when a user connects and releases it the user disconnects.

Pickup/Deliver: Concurrent deliveries are permitted during a pickup, even for the same user. To ensure that pickup does not observe partially written messages, `Deliver` first writes the entire message to a separate `spool` directory. Once the file is stored, the code atomically links the message into the user's mailbox and deletes the temporary file. The linking is the linearization point for delivery, because at that point the message becomes visible to subsequent calls to `Pickup`. Conversely, the linearization point for `Pickup` occurs when it lists the contents of the user's directory: although additional messages can be delivered concurrently after that point, they need not be returned.

Deliver/Deliver: Multiple threads can concurrently deliver, but they all share the same `spool` directory. To avoid filename conflicts, threads randomly generate a name for the temporary and then attempt to create a spool file. If this process fails due to a pre-existing spool file, delivery retries with a new name. Similarly, messages need unique IDs to avoid conflicting names within the user's mailbox, which delivery also generates randomly until the `link` operation succeeds.

Crashes: If the mail server crashes, the spool directory may contain temporary files for partially-written messages that are no longer needed. Thus, `Recover` deletes all of the files in `spool/`. While the specification does not mandate this cleanup, the code does so to free space in the file system.

7.3.3 Proof

We highlight interesting aspects of the Mailboat correctness proof here.

Abstraction relation. The abstraction relation is more complex than that of the replicated disk, so we only describe the

high-level structure:

$$\text{CrashInv}(\sigma) \triangleq \text{source}(\sigma) * \text{MsgsInv}(\sigma) * \text{TmpInv}$$

$$\text{AbsR} \triangleq \exists\sigma.\, \text{CrashInv}(\sigma) * \text{HeapInv}(\sigma) * \text{MailboxLocks}$$

These assertions correspond to the different parts of program state maintained by the mail server:

- MsgsInv(σ): This assertion connects the files representing user mailboxes to the abstract state σ of the specification, which does not mention inodes or file names. It includes resources for accessing the files that hold each user's mail.
- TmpInv: This tracks the temporary files in the `spool/` directory, so that recovery can clean them up after a crash. Because threads coordinate access to temporary files in a lock-free manner using random names and a retry loop, the abstraction relation does not mention locks or leases for temporary files. These leases only show up in the `Deliver` proof since they are thread-local.
- HeapInv(σ): The Mailboat library requires that the caller not concurrently modify a message slice while it is being delivered. HeapInv(σ) tracks when a message slice is being used by delivery to ensure that it is unchanging.
- MailboxLocks: Recall that each mailbox has a pickup/delete lock to prevent a race between reading a user's message and deleting it. MailboxLocks represents these locks and appropriate lock invariants.

Concurrent interactions. Concurrent deliveries allocate a name for a temporary file in the spool directory by trying random numbers until one succeeds. This a lock-free coordination strategy that Iris makes simple to reason about: the `create(fname)` system call can either fail and do nothing (if the destination exists), or succeed and return exclusive access to the newly-created file $(dir, fname) \mapsto i$. Recovery needs ownership to delete the temporary file in case of a crash, so the proof gives recovery ultimate ownership as part of TmpInv and uses a lease to for the rest of delivery.

Each mailbox uses a lock to prevent races between delete and pickup. Intuitively the lock protects the file names in the user's mailbox, the resource $dir \mapsto N$. However, it only prevents concurrent deletes, not concurrent delivery, which does modify the set of files N. We reason about this by using not the standard lease(dir, N) in the mailbox lock invariant, but instead a *lower-bound* lease, lease$_n(dir, \supseteq N)$, that guarantees dir contains at least the files in N. The owner of this lease can delete files while other threads may only create new ones.

Exploiting undefined behavior. The proof exploits the fact that the refinement specification only applies to clients that do not trigger undefined behavior. For example, as mentioned above, clients may not concurrently mutate a message slice during a call to `Deliver`. Because the code writes out the file 4KB at a time, delivery only appears atomic in the absence of such races. Concretely, HeapInv tracks whether a message slice is being read from. Then, during the proof for `Deliver(user, msg)` we argue that `msg` remains unchanged while writing the temporary file, since any modification would trigger undefined behavior in the specification.

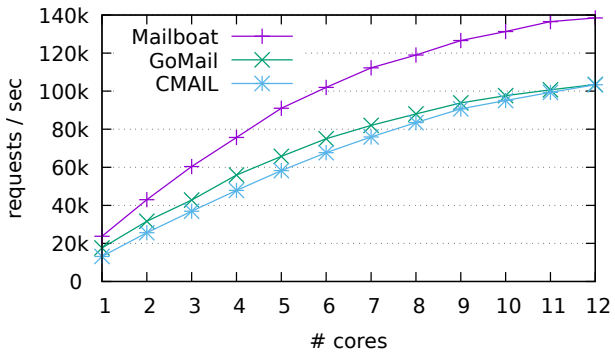

Figure 10. Throughput of Mailboat with a varying number of cores.

Recovery. Mailboat's `Recover` does not involve helping, because it just cleans up the temporary files in the `spool/` directory. With the use of leases, the proof is therefore comparatively straightforward. `Recover` takes ownership of these files via the TmpInv part of AbsR and deletes them.

7.3.4 Experiments

To show that Mailboat's throughput increases with more cores, we replicate the experiment for CMAIL described by Chajed et al. [6]. We use the same mixed workload of SMTP deliveries (i.e., `Deliver` in Mailboat) and POP3 pickups (i.e., `Pickup` followed by `Delete` in Mailboat), with an equal ratio of each. Each request chooses one of 100 users uniformly at random. The experiments were run on a server with two 6-core Intel Xeon CPUs running at 3.47 GHz, with the total requests fixed as we varied the number of cores used. Like CMAIL, Mailboat supports SMTP and POP3 over the network, but we simulated requests on the same machine to measure scalability without network overhead. Similarly, we ran the experiments on tmpfs, Linux's in-memory file system, to keep disk performance from being the limiting factor.

Figure 10 shows the performance in requests per second for different numbers of cores. Mailboat achieves higher performance than CMAIL on a single core for two reasons. First, Mailboat is multithreaded and uses Go locks to protect mailboxes, while CMAIL runs as several processes and uses file locks. Acquiring and releasing a file lock uses several file-system calls (including opening and closing the file), which is more expensive than using in-memory locks. Second, Mailboat is written in Go while CMAIL extracts to Haskell.

Component	Mailboat LOC	CMAIL LOC
Implementation	160 (Go)	215 (Coq)
Proof	3,190	4,050
Framework	7,800 (Armada)	9,500 (CSPEC)

Table 3. Lines of code for Mailboat and CMAIL.

To analyze the impact of each reason, we also measure the performance of GoMail, the unverified comparison from the CMAIL paper. GoMail is a mailserver written in Go in a similar style to CMAIL using file locks. Mailboat is 35% faster than GoMail on a single core because it uses in-memory Go locks instead of file locks, while GoMail is in turn 34% faster than CMAIL on a single core, which we attribute to using Go instead of Haskell. Thus, Armada's Goose translator enables significant performance benefits.

All three mail servers scale in a similar way: throughput increases with cores, but not perfectly. All three achieve speedup because tmpfs can execute the file-system calls in parallel. Mailboat's scalability is limited by lock contention in the runtime during garbage collection.

7.4 Effort

Armada and Goose took two people 5 months to develop, and Mailboat took one person 2 weeks to verify. We compare lines of code for Mailboat and CMAIL in Table 3. Mailboat has a more concise implementation and proof, despite verifying crash safety and reasoning about mutable memory in Go.

Armada is relatively concise compared to CSPEC for a few reasons. The main difference is that Mailboat is verified in a flattened style rather than using multiple layers of refinement. CMAIL's proof requires specifying 11 intermediate interfaces that are only used for the proof and five abstraction relations, while Mailboat's proof uses a single abstraction relation that directly connects the code to a high-level specification. The many layers in the CMAIL proof served two purposes. First, each layer applies one of CSPEC's patterns, and the CMAIL proof uses the abstraction, movers (for reasoning about concurrency), and loop patterns, each multiple times. Second, separate abstraction relations factor out the proof into modular pieces.

Armada does not need layers to solve these problems because separation logic in Iris gives a powerful way to combine multiple reasoning patterns in a modular way. Hoare logic allows a natural decomposition of a subproof for each helper function. Loops are proven using a standard loop invariant approach. The single abstraction relation can be factored into different components that are connected by the separating conjunction $*$, as depicted in §7.3.3. Importantly, Armada supports these three patterns using Iris rather than implementing them from scratch, so the framework itself (omitting Iris) is also fewer lines of code than CSPEC (which has no dependencies beyond Coq).

7.5 Bug discussion

This section highlights a few interesting bugs we encountered while developing Mailboat. One bug was that if a message was larger than 512 bytes, `Pickup` would infinite loop. While we do not prove loops terminate, we nevertheless caught this bug while doing the proof.

A bug we did not catch during the proofs was a resource leak where a file was opened but not closed. Armada's proofs do not cover these kind of guarantees. However, there is research on precise reasoning about resources in Iris [4].

One subtlety that the proof highlighted was that for delivery to be correct, the caller must not concurrently modify the message passed to it. While our mail server did not exhibit this bug, the proof helped us notice this requirement. We were only able to observe this because we verified and modeled Mailboat at a low level, including modeling that `Deliver` might run concurrently with arbitrary Go code.

8 Summary

We introduce Armada, the first framework for verifying concurrent, crash-safe storage systems with machine-checked proofs. The framework is implemented using Iris, inheriting its support for reasoning about concurrency using ownership. Armada extends Iris with four techniques that reconcile crash and recovery reasoning with ownership: *recovery ownership* treats the recovery procedure as the owner of durable resources; *recovery leases* allow threads to coordinate on recovery-owned, durable resources; *recovery helping* allows recovery to complete operations that started prior to a crash; and finally *versioned memory* allows the developer to precisely reason about volatile memory clearing on crash.

To reason about systems using Armada we introduce Goose, a subset of Go, for which we implemented a translator to Coq and a semantics in Armada. Using Armada we were able to verify Mailboat, a mail server written in Goose that achieves feature-parity with a similar prior verified mail server, includes a proof of crash safety, yet takes fewer lines of code by leveraging features of Iris to handle the concurrency aspects of the proof. Mailboat also achieves better performance due to its lower-level implementation, thanks to the Goose approach.

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