Bestow and Atomic: Concurrent Programming using Isolation, Delegation and Grouping

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Abstract

Any non-trivial concurrent system warrants synchronisation, regardless of the concurrency model. Actor-based concurrency serialises all computations in an actor through asynchronous message passing. In contrast, lock-based concurrency serialises some computations by following a lock–unlock protocol for accessing certain data.

Both systems require sound reasoning about pointers and aliasing to exclude data-races. If actor isolation is broken, so is the single-thread-of-control abstraction. Similarly for locks, if a datum is accessible outside of the scope of the lock, the datum is not governed by the lock.

In this paper we discuss how to balance aliasing and synchronisation. In previous work, we defined a type system that guarantees data-race freedom of actor-based concurrency and lock-based concurrency. This paper extends this work by the introduction of two programming constructs; one for decoupling isolation and synchronisation and one for constructing higher-level atomicity guarantees from lower-level synchronisation. We focus predominantly on actors, and in particular the Encore programming language, but our ultimate goal is to define our constructs in such a way that they can be used both with locks and actors, given that combinations of both models occur frequently in actual systems.

We discuss the design space, provide several formalisations of different semantics and discuss their properties, and connect them to case studies showing how our proposed constructs can be useful. We also report on an on-going implementation of our proposed constructs in Encore.

1. Introduction

Concurrency can be defined as coordinating access to shared resources. Synchronisation is naturally a key aspect of concurrent programs and different concurrency models handle synchronisation differently. Pessimistic models, like locks or the actor model [1, 2] serialise computation within certain encapsulated units, allowing sequential reasoning about internal behaviour at the cost of sometimes pruning possible parallel performance gains. In contrast, optimistic models, like lock-free programming [3] or software transactional memory [4] allow concurrent operations on the same data, but require that all operations follow some protocol to exclude unwanted behaviour, or avoid side-effects that cannot be rolled-back in the event of conflicts between threads. In this paper, we focus on pessimistic models.

In the case of the actor model, if a reference to an actor A’s internal state is accessible outside of A, operations inside of A are subject to data-races and sequential reasoning is lost. The same holds true for operations on an aggregate object behind a lock, if a sub-object is leaked and becomes accessible where the appropriate lock is not held.

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In previous work, we designed Kappa [5], a type system in which the boundary of a unit of encapsulation can be statically identified. An entire encapsulated unit can be wrapped inside some synchronisation mechanism, e.g., a lock or an asynchronous actor interface, and consequently all operations inside the boundary are guaranteed to be data-race free. An important goal of this work is facilitating object-oriented reuse in concurrent programming: internal objects are oblivious to how their data-race freedom is guaranteed, and the building blocks can be reused without change regardless of their external synchronisation. Further, making synchronisation tractable simplifies concurrent programming as the portions of a system that are accessed concurrently will be identified, and compilers can verify that the program behaves in accordance with the programmer’s intention, with respect to concurrent accesses.

This paper explores two extensions to the Kappa system, which we explain in the context of the actor model (although they are equally applicable to a system using locks). The first extension, bestow, allows references to an object to escape its unit of encapsulation without escaping its unit of synchronisation; all external operations on private state will be implicitly delegated to the owner of that state, either via message passing, or by acquiring a lock specific to the owner of the private state. This enables several useful programming patterns without relaxing Kappa’s static data-race freedom guarantee. For example, in the context of an actor system, actors may safely leak references to state, effectively allowing many objects to cooperate in constructing the actor’s interface. Similarly, in the context of a lock, it will be possible to hold on to references deep inside a structure, even when the lock is not held, with a guarantee from the type system that these will not be used until the lock is re-acquired.

When encapsulation and synchronisation are decoupled, another extension becomes necessary to group operations together, enabling atomicity of multiple operations on a data structure that potentially has several different entry-points. To this end, we introduce an atomic block scoped construct. In the context of an actor system, this allows, e.g., grouping several messages to prune unwanted interleavings. In the context of a lock-based system, it allows performing several distinct operations without releasing the lock in-between.

This paper makes the following contributions:

1. We discuss (Section 3) the difference between actor systems where data-races are avoided through isolation of an actor’s passive objects and actor systems where data-races are avoided through delegation of operations on passive objects to the actors that own them, and show how both are supported in the Encore programming language [6]. Encore supports delegation through bestowed references, which were introduced in Encore as part of this work. In contrast to systems like E [7] and AmbientTalk [8], Encore’s delegation is purposely not transparent, allowing programmers to reason about the performance and latency of operations and distinguish between operations on local and remote objects (Section 4).

2. We extend the delegation concept with a notion of movement of objects between actors, i.e., implicit and/or automated transfer of ownership. This enables a form of load-balancing of passive objects between actors (Section 4.3, formalised in Section 7).

3. We introduce a block-scoped construct for grouping operations to be performed as an atomic unit that can be applied to both actor-based systems and lock-based systems, as well as systems that combine the two models (Section 5).

4. We explore and formalise three variations of the semantics of bestowed references and atomic blocks, and show that the resulting systems are free from data-races. For simplicity, our formalisations are based on simple λ-calculus models with actors. We provide mechanised versions in Coq for others to build on. (Sections 6–7).

5. We report on a number of small case studies using our proposed constructs (Section 8) and on the on-going implementation of bestowed references and atomic blocks in Encore (Section 9).

This paper extends earlier work [9] by adding the two variations of the semantics (Section 7), mechanising the semantics and their proofs [10], providing case studies (Section 8), reporting on the current state of implementation (Section 9), and adding more in-depth discussions about the work throughout all sections of the paper.
2. Background: Kappa and Encore

This section covers the background needed to understand the context of this work. It explains the basics of Kappa, a type system which guarantees data-race freedom in concurrent programs, and Encore, an actor-based language which uses Kappa to facilitate safe sharing between actors.

Kappa is a type system for concurrent object-oriented programming [5]. Its most important guarantee is that no two concurrent operations will access the same memory address, unless both operations only use this address for reading. Kappa achieves this by preventing the creation of aliases which could be used to cause data-races. A reference can only be shared between threads if all accesses are synchronised (e.g., by using locks) or if all operations available through the reference are non-mutating.

The sharing properties of a reference are specified by its mode, which is tracked by the type system. For example, a reference with the locked mode is implicitly protected by a lock, similar to a Java object whose methods are all synchronized. It may be safely shared between threads, as any concurrent accesses will be synchronised. In contrast, a reference with the subordinate mode may not be shared between threads. In fact, it may not even leak outside of the object that created it (similar to ownership types [11]). This means that a locked object (whose aliases all have the locked mode) may encapsulate additional subordinate objects. Since these objects may only be accessed via the locked object (thus grabbing its lock), they can be operated on without additional synchronisation.

Kappa has been implemented as the type system for Encore, an object-oriented language developed in the context of the UPSCALE project [6]. Encore uses actors to achieve concurrency, and Kappa ensures that objects shared between actors are always accessed without data-races. Encore’s actors are implemented by extending Kappa with an actor mode. References with this mode point to actors and may only be used to send messages. Since all interaction with an actor go via its message queue, operations on it will be synchronised, similar to the operations on a locked object. Just like locked objects, actors can use subordinate references to ensure that their own private state is never accessed by other actors. Additionally, Encore allows sharing of immutable or read-only data, and supports ownership transfer of objects.

The interface of an actor is defined by its class, and the messages in an actor’s message queue are processed in sequence (there is no selective receiving of messages, as in e.g., Erlang [12]). This means that Encore’s actors behave as active objects [13]. The work relating to actors in this paper was done with Encore’s actors in mind, but is applicable to any actor language with active object semantics.

The constructs presented in this paper rely both on the encapsulation guarantees given by the subordinate mode, as well as the synchronisation guarantees given by locks and actors. They are however orthogonal to which synchronisation technique is used (and can be used in a system that uses both). Encore does not yet support Kappa’s locked mode because of the complexity of integrating locks with Orca [14]—Encore’s garbage collection protocol (which is shared with the Pony programming language [15]). Besides implementation, garbage collection is orthogonal to the matters discussed in this paper.

3. Data-Race Freedom: Delegation and Isolation

Actors simplify concurrent programming by enabling sequential reasoning inside each actor. The majority of actor-based programming languages and frameworks—e.g., Akka [16], ProActive [17], ABS [18], Orleans [19], Encore [6], Pony [15] and Joelle [20, 21] rely on isolation, enforced manually by programmer diligence or through compiler support to do so: by preventing references to an actor’s state to leak outside of the actor, the only way to manipulate an actor’s state is by sending it a message. (Compilers and run-time systems may either reject references which would violate encapsulation, or insert instructions to deep-copy message payloads.) Figure 1 (left) shows the key situation to be prevented to avoid data-races. The brown circles denote actors, each with a (logical) thread of control. If the external reference to foo is possible, accesses to foo could be subject to data races.

An alternative model to isolation is found in some actor systems, such as E [7] and AmbientTalk [8] which allows an actor’s state to be arbitrarily referenced, but requires that operations on the state of some other actor is implicitly delegated to that actor. In the isolation model, data-race freedom is achieved through enforcing that all external access go via an asynchronous interface. In the delegation model, an actor can be
thought of having just one method in its interface: perform, and each operation is translated into a perform
call with some appropriate lambda. Internal calls to perform can be carried out synchronously. Figure 1
(right) shows how operations on a passive object belonging to another actor can be enabled by making
the operations asynchronous and asking the actor that owns the passive object to carry them out. Thus, only
the actor owning the object o pointed to by foo will ever operate on o.

The isolation model ties into existing theory on abstraction, modularisation, and encapsulation. In most
languages, it serves to simplify reasoning: operations on passive objects are synchronous and efficient whereas
operations on actors are asynchronous and introduce latency, but also make concurrency and parallelism
possible. The isolation model also helps clearly delimiting actor interfaces. In contrast, the delegation model
is much less restrictive on the object graph of a system, but (in E and AmbientTalk) complicates reasoning
about the performance and latency, and makes an actor’s interface less clearly delimited and defined.

Restricting object graph topologies means limiting aliasing in a system. This is unsurprising since aliasing
is a prerequisite of data-races—but far from all aliasing is bad. Aliasing is commonly used to provide shortcuts
through a data structure, such as a last pointer in a linked list implementation to allow constant-time append
operations. Staying with the linked list example, we now demonstrate how delegation can be useful in an
actor setting. While the example is a little contrived, it demonstrates the importance of allowing the creation
of—and sharing of—aliases.

3.1. Delegation: Motivating Example

We motivate breaking isolation in the context of an object-oriented actor language, with actors serving as
the units of encapsulation, encapsulating zero or more passive objects. Figure 2a shows an Encore program
with a linked list in the style of an actor with an asynchronous external interface. For simplicity we allow
asynchronous calls to return values and omit the details of how this is accomplished (e.g., by using futures,
promises, or by passing continuations). We use the . operator to denote synchronous method calls or field
lookups, and the ! operator to denote asynchronous method calls.

Clients can interact with the list for example by sending the message get with a specified index. With
this implementation, each time get is called, the corresponding element is calculated from the head of the
list, giving linear time complexity for each access. Iterating over all the elements of the list has quadratic
time complexity, which is clearly undesirable.

To allow more efficient element access, lists commonly provide an iterator which holds a pointer to the
current node (Figure 2b). This allows constant-time access to the current element, and linear iteration, but
also breaks encapsulation by providing direct access to nodes and elements without going through the list

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1We deviate from Encore syntax for brevity and omit end keywords in favour of using indentation to show block scoping.
class Node[t]
  var next : Node[t]
  var elem : t
  // getters and setters omitted

actor List[t]
  var first : Node[t]
  def getFirst() : Node[t]
    return this.first
  def get(i : int) : t
    var current = this.first
    while i > 0 do
      current = current.next
      i = i - 1
    return current.elem

class Iterator[t]
  var current : Node[t]
  def init(first : Node[t]) : void
    this.current = first
  def getNext() : t
    val elem = this.current.elem
    this.current = this.current.next
    return elem
  def hasNext() : bool
    return this.current != null

actor List[t]
  def getIterator() : Iterator[t]
    val iter = new Iterator[t]
    iter.init(this.first)
    return iter

Figure 2: (a) A list implemented as an actor. (b) An iterator for that list.

actor List[t]
  ...
  def getIterator() : B(Iterator[t])
    val iter = new Iterator[t]
    iter.init(this.first)
    return bestow iter

Figure 3: A list actor returning a bestowed iterator, and the code for a client using it

interface (cf., [22] for a related discussion of internal vs. external iterators). Since a list is its own actor, with this design, list operations are now subject to data-races, which breaks the single-thread-of-control abstraction.

A middle ground providing linear time iteration without data-races can be implemented by moving the iterator logic into the list actor, so that the calls to getNext and hasNext are synchronised in the message queue of the actor. This requires a more advanced scheme to map different clients to different concurrent iterators, clutters the list interface, creates unnecessary coupling between List and Iterator, and complicates support of e.g., several kinds of iterators.

The next section shows how external accesses to an internal object can be synchronised to preclude data-races, while still avoiding all of the complications mentioned above.

4. Bestow: Adding Delegation to Encore

Encapsulating state behind a synchronisation mechanism allows reasoning sequentially about operations on that state. The Kappa type system in Encore will not allow calls to getIterator() from outside the list actor itself, defeating the purpose of creating the iterator in the first place. In Encore, the Iterator return type of getIterator() has a subordinate mode (cf., Section 2), which is a requirement for allowing the direct reference to the actor’s links. Similar to ownership types [11], calls to methods that return subordinate objects are only allowed on other subordinate objects, i.e., navigation is permitted inside each isolation
domain, but not across. Notably, the this reference of an actor has a subordinate mode, meaning that an actor’s internal type differs from its external.

A call on a non-subordinate receiver thus always denotes a call that crosses from one synchronisation domain into another. To support delegation-based synchronisation in Encore, we extend Kappa with a bestowed mode, written as $B(T)$ when applied to the type $T$. $B(T)$ denotes an external reference to an object of type $T$ which is part of the internal state of an actor. All of $T$’s operations are available through a reference of type $B(T)$, but they will be performed asynchronously by implicitly delegating the operations to the actor that owns the object.

For clarity, we introduce a bestow operation, which lifts a type with subordinate mode to an equivalent type whose mode is instead bestowed. This operation allows a programmer to create a “safe remote reference” to a local passive object, which can be freely shared—and safely, since it adheres to the delegation model. We use the term bestowed reference to mean a reference to a bestowed object, which in turn denotes an object to which there are bestowed references. We call the actor encapsulating the bestowed object its owner.

Figure 3 shows the changes needed to the code in Figure 2b, as well as the code for a client using the iterator, to go from isolation-based to delegation-based data-race freedom. In the list, getIterator() now returns a bestowed iterator which is tractable through the $B(\ldots)$ type\(^2\), and not a passive iterator. In the client code, synchronous calls to hasNext() and getNext() become asynchronous message sends which is reflected by the change from . to !. Notably, messages to the iterator are handled by the list actor and are and are executed in a serialised fashion, interleaved with normal messages sent to the list actor.

The granularity of the delegated operations, and thereby the amount of interleaving allowed, is related to the reach of the objects which are bestowed. Creating an iterator inside the list and returning a bestowed reference to it allows it to access multiple nodes of the list atomically. In contrast, creating an iterator outside the list holding bestowed references to links in the list only gives atomic access to a single link at a time. In the case of returning a bestowed reference to an iterator, entire getNext() operations are performed without interleaved activities in the list actor. In the case of returning bestowed references to individual links, getting the element out of a link, and obtaining a bestowed reference to its next link are two separate operations which may be interleaved with other operations on the list (cf., Figure 4a).

4.1. Bestowed References and Lock-Based Synchronisation

Encore actors are typed by Kappa’s actor mode, which is visible in the code examples so far. There, the actor mode is applied to class declarations to denote that instances of these classes are data-race free because of their asynchronous interface and encapsulated single thread of control. Replacing “actor” with “locked” in the code examples up to this point is sound and preserves data-race freedom of all instances of locked classes by forcing all method calls to first acquire a per-instance lock.

Notably, the bestowed type and bestow operations in Figure 3 are still meaningful if actor is changed for locked. At the type-level, a bestowed reference is oblivious to how an isolated object’s data-race freedom is guaranteed. Dynamically, though, a bestowed reference into a capsule protected by a lock will implicitly acquire the lock associated with that capsule.

4.2. Differences Between Locks and Actors

The small changes needed in Kappa to switch between using locks and actors as a means of protecting access to a group of objects does not reflect the differences between the two concepts. In lock-based programs, data is “dead” and only lives when visited by a thread of control. In actor-based programs, actors are alive, only act upon themselves, and only upon so choosing. The difference is push vs. pull—whether activity is pushed upon an object by a thread, or whether activity happens as a result of the actor pulling a message from its message queue. In lock-based programs, a thread can be denied entrance into an object by another thread holding the appropriate lock. In actor-based programs, an actor may never ask for the next message (for example because it is stuck in an infinite loop) causing another actor’s request to be effectively ignored.

\(^2\)If desired, this type change can be implicit through view-point adaptation [23]; Kappa lets us statically detect when an internal object is crossing its encapsulation boundary. For clarity, we explicitly annotate bestowed return types here.
In an actor-based setting, the owner of a bestowed object will perform all operations on that object. Thus, while the owner will technically never block on an access to an object that it owns, it may instead end up performing operations on behalf of other actors. In some scenarios, this may make the owner of a bestowed object an unintentional bottleneck in a system, especially if delegated operations are long-running, the owner has unproportionally many bestowed objects, or it performs critical operations unrelated to the bestowed object which are now interleaved with delegated tasks. In a lock-based setting, all threads operating on a shared resource take part in performing those operations. Thus, if operations are spread out in time, it is possible that contention is never witnessed in the system and that operations unrelated to the bestowed object are never delayed.

4.3. Towards Actor-Style Delegation-Locks

We note that it is possible to make a bestow-based interpretation of locks by replacing delegation with transfer of ownership: instead of an actor lifting an operation into a closure and passing it to the owner to be performed, the actor simply transfers ownership of the bestowed object to itself and subsequently performs the operation without any delegation.

Because there are no topological restrictions on bestowed references, transfer of ownership of a bestowed object is possible unless the object is currently being used (equivalent to another thread holding a lock). For example, if an actor which owns a collection data structure is currently inactive, another actor with a bestowed reference to this collection could transfer ownership of the collection to itself and operate on it, rather than waking the owning actor to delegate the operation.

If transfer is not possible, the actor attempting the transfer could block (making accesses to bestowed references equivalent to accessing references with locked mode) or fall-back to delegation to avoid blocking. This is similar to queue delegation locks [24] which handle contention by delegating blocking operations to the thread currently holding the lock. This allows operations that would otherwise block to return immediately with a future value which will eventually be fulfilled by some other thread.

Allowing objects’ owners to change prevents giving the owner special access, and thus forces all references to a bestowed object to be bestowed. Accesses must then branch on whether the object is local, and if not, whether or not its ownership can be transferred. For example, whoever is accessing the collection must first check if they are the current owner of the collection, in which case the operation can proceed, and otherwise decide if ownership transfer is possible or if the operation should be delegated. Section 7.1 gives the details on the semantics of transferable bestowed objects.

Encore uses a work-stealing based load-balancing scheme that moves actors across cores. In many ways, allowing transfer of ownership of bestowed objects is a form of load-balancing for passive objects. Just like load-balancing of actors is governed by carefully tuned heuristics, how and when to transfer ownership of a bestowed object is not clear-cut. In many cases, keeping objects local to a core may have locality benefits which favours ownership transfer for actors on the same core, but delegation otherwise. Also, the cost of creating and passing closures may be non-negligible, which may favour keeping ownership among frequent accessors, etc. Run-time optimisation of ownership transfer for bestowed references is an interesting direction for future work.

5. Atomic: Atomicity and Grouping of Operations on Bestowed References

So far, we have discussed data-race freedom. Data-race freedom is important, but not always enough achieve atomicity, i.e., the ability to make a set of changes appear atomic in a system. For example, a data-race free counter in Kappa will correctly handle concurrent increments and decrements, but is not enough to support swapping the values of two counters in the presence of concurrent operations. The root cause is that Kappa’s protection is per-object (notably including its transitive closure of sub-objects), and exchanging values involves more than one object where neither object is nested inside the other.

Additionally, the protection from data-races offered by Kappa only applies to a single top-level operation. For example, operating on a locked file to first open and subsequently read, one cannot exclude the possibility

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3Kappa can overcome this limitation through explicit lock-taking, which is only supported on locked objects, not actors [5].
of a separate thread closing the file in-between. The same holds if the file is an actor: messages are serialised but any messages may be interleaved, meaning that [open, close, read] is a valid mailbox. This problem is exacerbated by more fine-grained operations being added to an interface through bestowed references.

To support atomicity of groups of operations over one or more objects we extend Encore with an atomic block construct. In its simplest form, it supports operations on a single reference whose mode is actor, locked, or bestowed and coalesces operations on the reference making them atomic in the system.

As a concrete, simple example, Figure 4b shows an iterator with a bestowed reference to its current node, and which wraps its operations in an atomic block, preventing any interleaving between the two message sends, thus regaining the same interleaving guarantees as the iterator in Figure 3. The atomic block thereby allows a client to define new operations by composing smaller ones and giving a use-site definition of where atomicity is useful, as opposed to declaration-site. For example, merging elem and next into a single operation in the Node class voids the need for an atomic block in Figure 4b, but in the general case, it is unreasonable to expect declarations to cater to all possible use cases.

The simplest case, a single atomic block of messages whose results are ignored (or void), can be implemented efficiently through coalescing messages to the receiver and delivering them as a single “big message”\(^4\). Figure 5 (left) shows how an atomic block containing two message sends is translated into a single message, containing instructions for performing the two operations in sequence. This avoids interleaving from other actors, but does not support multi-actor atomicity. Similarly, for the case of operations on an object guarded by a lock, an atomic block acts as an explicit locking operation—similar to a synchronized block in Java—voiding the need for an individual lock-release for each operation in the block (cf. [5]).

5.1. Grouping Semantics and Atomicity

Coalescing messages to avoid interleaving is simple and efficient, but also limited. For example, a client of the iterator from Figure 3 may want to atomically perform operations on all the elements of list until a certain element is found. However, a coalescing semantics prevents the client from reacting to results from the iterator except between discrete atomic blocks. Furthermore, it imposes some upper limit on the messages from the client to the list. Last, it will delay the time when the client can start operating on the elements until the right element is found, making it impossible to implement parallel pipelines. Moreover, coalescing semantics is not strong enough to support a notion of atomicity across multiple actors.

Atomicity across actors can be made possible by delaying the processing of messages not originating from within the atomic block until after a particular point. In its simplest form, the actor executing the atomic block will be able to reason about the receiving actor throughout the atomic block enabling e.g., pre- and post condition reasoning. By wrapping several atomic blocks, this extends to multiple actors.

To this end, we explore a richer semantics for atomic blocks which involves the creation of a private mailbox, which is only known by the actor running the atomic block and the receiving actor. Private channels can be found e.g., in Pi calculus [25] and CSP [26], but in our implementation we restrict them to follow a

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\(^4\)In Encore, this may additionally have garbage collection benefits if messages contain overlapping state.
block-scoped, structured programming approach. Under the private mailbox semantics, at the start of an atomic block, the current actor creates a new mailbox, technically a FIFO queue, and passes one end (for receiving) to the target actor in a normal message and keeps the other for sending. Upon receipt of this message, the target actor replaces its normal, public mailbox with the private mailbox, and from this point continues to process only messages from the latter. Since the private mailbox is only known by the sender and receiver, no other messages may interleave their communication. At the end of the atomic block, the target actor is sent a new message to restore its original mailbox, where any other communication has been buffered, and will now be processed in FIFO order. (See Section 8.3 for an example that can be encoded with private mailboxes, but not with coalescing.)

In languages which allow actors to use pattern matching to selectively pick messages from its message queue (e.g., Erlang [12]), this kind of “private conversation” between two actors can be encoded. However, this requires that the receiving actor is implemented with support for atomically processing exactly the messages that the client wanted to send. By using a private queue created by the client, the client can create new atomic operations by composing the operations that a receiving actor provides, without explicit support for this in the receiving actor.

The atomic block notably turns actor-based programs into more structured programs, because the atomic blocks are unidirectional: the only way for the list actor to communicate with a client during the execution of an atomic block in the client is through futures—not message sends, as they will not be processed before the atomic block is finished. Furthermore, only tree-shaped communication is possible inside atomic blocks. If a client of the list has entered an atomic block targeting the iterator, and then enters a nested block targeting some other actor $A$, there is no way for $A$ and the list actor to communicate directly.

5.2. Tractability of Atomic Operations

One reason why lock-based programming is hard in mainstream programming is because there is no way to express what a lock governs in a program. Kappa addresses this by keeping track of synchronisation and encapsulation through modes in types. Imagine an actor $A$ holding a reference the list actor in its field $f$. In its method $m_1$, $A$ enters into an atomic block targeting the list actor. $A$ subsequently calls its method $m_2$ which performs $\textbf{this}.f! \text{getFirst()}$. There is nothing in $f$’s type that expresses the current situation where communication with the list actor is uninterruptible. Should $\textbf{this}.f! \text{getFirst()}$ be considered part of the atomic block or not, i.e., is atomicity $\text{actor-wide}$? If yes, then the tractability of Kappa is significantly weakened. If no, we deviate from the standard behaviour of locks and must additionally solve a problem with tracking bestowing references. A simple approach in the latter case is to tie operations to the lexical scope of the atomic block. This means that $\textbf{this}.f! \text{getFirst()}$ will not be processed by its receiver until after the atomic block is finished. A hybrid approach is to introduce an additional $\text{handle}$ to the subject of an atomic

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5 However, the list actor may return a value to the client which the client subsequently passes to $A$, and similar for $A$. 

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block, whose type reflects its “atomic status”. This handle can be passed to where atomic operations should be performed, allowing `handle ! getFirst()` to take part in the atomic block. This is the route Encore follows; inside the block `atomic x do ...` the type `T` of `x` is changed to `A(T)`, where the new qualifier `A()` expresses that:

1. Operations will not be interleaved with operations from other actors.
2. The reference is stack-bound (or `borrowed`) meaning that for any given scope where the reference occurs, no aliases can be created that survives that scope.
3. The reference is local to the current actor meaning it may not be passed to another actor, either as an element or by returning it.

In Encore, for the message `getFirst()` in `m2` to be be part of the atomic block in `m1`, `m2` must be passed the correct `A()` handle and `this.f ! getFirst()` replaced by `handle ! getFirst()`.

6. Formalising “Vanilla” Bestow and Atomic

To explain bestow and atomic we use a simple lambda calculus with actors and passive objects. For brevity, we only discuss bestow and atomic under one concurrency model, namely actors. We chose actors for two reasons: they have the most compelling design space, and it more closely matches our implementation in Encore. In this section, we formalise the bestow as presented in Section 4 together with the coalescing atomic operations from Section 5. In subsequent sections, we also formalise two variants of the actor-based semantics for bestow and atomic: passive objects with transferable ownership and private mailboxes.

The purpose of these formalisations is to flesh out the details of bestow and atomic, and we abstract away most details that are unimportant for describing the behavior of these constructs. For example, we leave out classes and actor interfaces and simply allow arbitrary operations on values. This makes the formalisation simple and fairly unsurprising. By disallowing sharing of (non-bestowed) passive objects, we show that our language is free from data-races (cf. Section 6.4). The calculus has been mechanised and proven sound in Coq (cf. Section 6.5).

The syntax of our calculus is shown in Figure 6. An expression `e` is a variable `x`, a function application `e e'` or a message send `e!v`. Messages are sent as anonymous functions, which are executed by the receiving actor. We abstract updates to passive objects as `e.mutate()`, which has no actual effect in the formalism, but is reasoned about in Section 6.4. A new object or actor is created with `new τ` and a passive object can be bestowed by the current actor with `bestow e`. Since this version of the semantics uses coalescing semantics for atomic blocks, we don’t yet need a special `atomic` construct in the formalism. Instead we model atomic interactions by composing operations as in Figure 5 (left).

Statically, values are anonymous functions or the unit value `()`. Dynamically, `id` is the identifier of an actor, `ι` is the memory location of a passive object, and `ι_id` is a passive object `ι` bestowed by the actor `id`. A type is an active type `α`, a passive type `p`, a function type `τ → τ`, or the `Unit` type. An active type is either an actor type `c` or a bestowed type `B(p)`. Note that for simplicity, `p` and `c` are not meta-syntactic variables; every passive object has type `p`, every actor has type `c`, and every bestowed object has type `B(p).

6.1. Static Semantics

The typing rules for our formal language can be found in Figure 7. The typing context `Γ` maps variables to types. The “normal” lambda calculus rules `E-VAR` and `E-APPLY` are straightforward. The `new` keyword can create new passive objects or actors (`E-NEW-*`). Passive objects may be mutated (`E-MUTATE`), and may be bestowed activity (`E-BESTOW`).

```
e ::= x | e e | e!v | e.mutate() | new τ | bestow e | v
v ::= λx:τ.e | () | id | ι | ι_id
τ ::= α | p | τ → τ | Unit
α ::= c | B(p)
```

Figure 6: The syntax of a simple lambda calculus with actors and a `bestow` operation.
### Message Sends

Message sends are modelled by sending anonymous functions which are run by the receiver (\textit{E-send}). The receiver must be of active type (\textit{i.e.}, be an actor or a bestowed object), and the argument of the anonymous function must be of passive type \textit{p} (this can be thought of as the \textit{this} of the receiver). Finally, all free variables in the body of the message must have active type to make sure that passive objects are not leaked from their owning actors. This is captured by $\Gamma_\alpha$ which contains only the active mappings $\_ : \alpha$ of $\Gamma$. Dynamically, the body may not contain passive objects \textit{i}. Typing values is straightforward.

#### 6.2. Dynamic Semantics

Figure 8 shows the small-step operational semantics for our language. A running program is a heap \( H \), which maps actor identifiers \( id \) to actors \( (\iota, L, Q, e) \), where \( \iota \) is the \textit{this} of the actor, \( L \) is the local heap of the actor (a set containing the passive objects created by the actor), \( Q \) is the message queue (a list of lambdas to be run), and \( e \) is the current expression being evaluated. The step relation \( \models \) is indexed by the actor \( id \) that is currently scheduled.

An actor whose current expression is a value may pop a message from its message queue and apply it to its \textit{this} (\textit{Eval-Actor-Msg}). Any actor in \( H \) may step its current expression, possibly also causing some effect on the heap (\textit{Eval-Actor-Run}). The relation \( \models (H, e) \xrightarrow{\text{Eval-Actor-Run}} (H', e') \) denotes actor \( id \) evaluating expression \( e \) one step in heap \( H \), resulting in a new heap and expression \( e' \) and \( H' \).

Sending a lambda to an actor prepends this lambda to the receiver’s message queue and results in the unit value (\textit{Eval-Send-Actor}). Sending a lambda \( v \) to a bestowed value instead prepends a new lambda to the queue of the actor that bestowed it, which simply applies \( v \) to the underlying passive object (\textit{Eval-Send-Bestowed}).

Function application replaces all occurrences of the parameter \( x \) in its body by the argument \( v \) (\textit{Eval-Apply}). Mutation is a no-op in practice (\textit{Eval-Mutate}). Bestowing a passive value \( \iota \) in actor \( id \) creates the bestowed value \( \iota_{id} \) (\textit{Eval-Bestow}).

Creating a new object in actor \( id \) adds a fresh location \( e' \) to the set of the actors passive objects \( L \) and results in this value (\textit{Eval-New-Passive}). Creating a new actor adds a new actor with a fresh identifier to the heap. Its local heap contains only the fresh \textit{this}, its queue is empty, and its current expression is the unit value (\textit{Eval-New-Actor}).

We handle evaluation order by using an evaluation context \( E \) (\textit{Eval-Context}).

#### 6.3. Well-formedness

Figure 9 shows our well-formedness rules. A heap \( H \) is well-formed if all its actors are well-formed with respect to \( H \), and the local heaps \( L_i \) and \( L_j \) of any two different actors are disjoint (\textit{WF-Heap}). We use
6.4. Meta Theory

\( \mathcal{L}(H(id)) \) to denote the local heap of actor \( id \). An actor is well-formed if its this is in its local heap \( L \) and its message queue \( Q \) is well-formed. The current expression \( e \) must be typable in the empty environment, and all passive objects \( s \) that are subexpressions of \( e \) must be in the local heap \( L \). Similarly, all actor identifiers in \( e \) must be actors in the system, and all bestowed objects must belong to the local heap of the actor that bestowed it \( (\text{WF-actor}) \).

A message queue is well-formed if all its messages are well-formed \((\text{WF-queue}^*)\). A message is well-formed if it is a well-formed anonymous function taking a passive argument, and has a body \( e \) with the same restrictions on values as the current expression in an actor.

6.4. Meta Theory

We prove soundness of our language by proving progress and preservation in the standard fashion:

**Progress:** In a well-formed heap \( H \), each actor can either be evaluated one step, or has an empty message queue and a fully reduced expression:

\[ \forall id \in \text{dom}(H), \vdash H \rightarrow (\exists H'. H^id \rightarrow H') \lor (H(id) = (\_L, \_E, \_V)) \]

**Preservation:** Evaluation preserves well-formedness of heaps: \( \vdash H \land H^id \rightarrow H' \rightarrow \vdash H' \)

Both properties can be proven to hold with straightforward induction.
Figure 9: Well-formedness rules. $\mathcal{L}H$ gets the local heap from an actor: $\mathcal{L}H((\iota, L, Q, e)) = L$

The main property that we are interested in for our language is data-race freedom. As we don’t have any actual effects on passive objects, we show this by proving that if an actor is about to execute $\iota$.mutate(), no other actor will be about to execute $\iota'$.mutate on the same object:

**Data-race freedom**: In a well-formed system, for any two possible reductions that involve two different actors each mutating a passive object, the respective passive objects can never be the same.

$$
\left( \forall id_1 \neq id_2 . \mathcal{L}H(H(id_1)) \cap \mathcal{L}H(H(id_2)) = \emptyset \right) \Rightarrow \iota \neq \iota'
$$

This property is simple to prove using two observations on what makes a well-formed heap:

1. An actor will only ever access passive objects that are in its local heap (WF-.Actor).
2. The local heaps of all actors are disjoint (WF-Heap).

The key to showing preservation of the first property is in the premise of rule E-Send which states that all free variables and values must have an active type ($\Gamma \alpha . x : p \vdash e : \tau$ and $\not\exists \iota . \iota \in e'$). This prevents sending passive objects between actors without bestowing them first. Sending a message to a bestowed object will always relay it to the actor that owns the underlying passive object (by the premise of WF-Actor: $\forall id_\iota \in e . \iota \in \mathcal{L}H(H(id))$). Preservation of the second property is simple to show since local heaps grow monotonically, and are only ever extended with fresh locations (Eval-New-Passive).

Having made these observations, it is trivial to see that an actor in a well-formed heap $H$ that is about to execute $\iota$.mutate() must have $\iota$ in its own local heap. If another actor is about to execute $\iota'$.mutate(), $\iota'$ must be in the local heap of this actor. As the local heaps are disjoint, $\iota$ and $\iota'$ must be different. Since well-formedness of heaps are preserved by evaluation, all programs are free from data-races.

Finally, we show that atomic blocks indeed provide atomicity. For this version of the semantics, we do not state this property formally; since atomic blocks are implemented as “big messages”, and messages are always run to completion before another message is handled, it follows trivially that atomic operations run without any interleaving in this semantics.

6.5. Mechanisation

The formalism presented in this section has been fully mechanised in Coq, including proofs of progress and preservation [10]. The mechanised version is true to the paper version, modulo uninteresting differences
\[ e ::= x | e \cdot e | e!v | e.\text{mutate}() | \text{new } \tau | v \]
\[ \tau ::= \alpha | p | \tau \rightarrow \tau | \text{Unit} \]
\[ v ::= \lambda x : \tau.e | () | \text{id} | v \cdot t_s \]
\[ \alpha ::= c | T(p) \]

Figure 10: The syntax of a simple lambda calculus with actors and transferable objects.

\[ \Gamma \vdash e : \tau \]
\[ \text{E-NEW-TRANS} \]
\[ \Gamma \vdash \text{new } p : T(p) \]
\[ \text{E-TRANS} \]
\[ \Gamma \vdash t_s : T(p) \]
\[ \text{E-SEND-TRANS} \]
\[ \Gamma \vdash e : \alpha \]
\[ \Gamma, x : p \vdash e' : \text{Unit} \]
\[ \
\n\]
\[ \Gamma \vdash e! \lambda x : p.e' : \text{Unit} \]

Figure 11: New and changed static rules for dealing with transferable objects.

in representation (for example, the heap is a list of actors indexed by actor ids, rather than a map from ids to actors as in Section 6.2). It also includes machinery for generating fresh values.

The whole definition of the semantics is \( \approx 450 \) lines of Coq. The proofs are \( \approx 2100 \) lines, including \( \approx 340 \) lines of auxiliary lemmas about list operations and \( \approx 250 \) lines of tactics specific to this formalism, including automated case analysis for heap operations. The proofs also make use of the LibTactics library [27], as well as the crush tactic [28]. There is still some repetition between similar cases in some of the proofs, which could be broken out to further reduce the size of the proof.

7. Formalising Private Mailboxes and Bestow with Ownership Transfer

This section explores two variations on the semantics presented in Section 6; bestowed objects that may change owner, and atomic message passing using private message queues. Both of these variations have also been fully mechanised and proven sound in Coq [10].

7.1. Transferring Ownership of Bestowed Objects

So far, bestowed objects have always been passive objects owned by some actor, and the owner of these objects never changes. This means that once an object has been bestowed and shared between actors, messages to it will always be relayed to the same actor. If an actor bestows many objects, the (implicit) contention on this actor will be high. If ownership of a bestowed object could be transferred, some of this contention could be alleviated.

Figure 10 shows the syntax of this language variation. A transferable object has type \( T(p) \). Since such an object may move between actors, we cannot allow this object to have aliases of the non-transferable type \( p \). Here, we solve this by requiring the object to be created as transferable with \( \text{new } T(p) \), which voids the need for a \textit{bestow} operation. Dynamically, a transferable object has the value \( t_s \). An actor which evaluates \( t_s!v \) when it is the owner of \( t_s \) will perform \( v \cdot t_s \) synchronously. Other actors will relay to the current owner. Note that transferring ownership of an object does not prevent the previous owner from retaining a reference to the transferred object. The only difference is that messages sent to the transferred object will now be relayed to the new owner instead.

Figure 11 shows the new and changed rules of the static semantics. There are two new rules for typing transferable objects (E-NEW-TRANS, E-TRANS). A subtle change is also needed in the send rule: the body of the message sent must have type \( \text{Unit} \) to preserve the type of the expression when the message is run synchronously (E-SEND-TRANS). This is without loss of generality since actors cannot do anything with the result of a message send.

Figure 12 shows the new and changed rules of the dynamic semantics. To track the current owner of a transferable object, we extend the configuration with a map \( O \) from locations \( \iota \) to actors \( \iota \). Creating a new transferable object adds its creator to the owner map (EVAL-NEW-TRANS). When evaluating \( \iota_s!v \), the owner
7.1.1. Design Considerations for Transferable Objects

Ensure that an object is never both bestowed and transferable. The only place where such an object could be

We allow ownership transfer when the current owner is not running a message (EVAL-ACTOR-TRANS). If ownership could be transferred in the middle of an actor’s behavior, there could be data-races. When ownership of an object is transferred, its location \( \iota \) is also moved between the local heaps of the actors involved in the transfer. Note that there may still be delegated messages in the queue of the old owner, and that these will be forwarded to the new owner when they reach the head of the queue. Ownership transfer is non-deterministic to simulate a run-time or scheduler that does load-balancing between actor behaviors.

Finally, Figure 13 shows the new and changed well-formedness rules. An owner map \( \mathcal{O} \) is well-formed if for all mappings \( \iota \mapsto id \), \( id \) is an actor which has \( z \) in its local heap (WF-OWNERS). For a well-formed actor, its this must not be in \( \mathcal{O} \) (i.e., not be transferable, since this of an actor never changes owner), and for all transferable values in its current expression, there must be some mapping for that location in \( \mathcal{O} \) (WF-ACTOR-TRANS). Similar rules hold for messages, but additionally their locations \( \iota \) may not have transferable ownership (WF-QUEUE-MESSAGE-TRANS), as this would mean that their ownership could be transferred before the message has reached the head of the queue.

The adaptation of the meta-theoretic properties is straightforward, and the same soundness properties hold for this variation of the formalism. The mechanised version of the semantics are \( \approx 470 \) lines of Coq, and the proofs are \( \approx 2600 \) lines with the same \( \approx 600 \) lines of list lemmas and tactics as for the core calculus [10].

7.1.1. Design Considerations for Transferable Objects

For simplicity, this variation does not include the bestowed references from the formalism in Section 6. It is possible to combine both flavors of bestowed references in the same system as long as care is taken to ensure that an object is never both bestowed and transferable. The only place where such an object could be
\[
H \vdash O \quad O; H \vdash (i, L, Q, e) \quad O; H \vdash Q
\]

**Well-formedness**

\[
\text{WF-OWNERS} \\
\forall i \in \text{dom}(O). \ i \in L \quad H; O \vdash
\]

\[
\text{WF-OWNER} \\
\& \quad \therefore \quad \text{Well-formedness}
\]

\[
\text{WF-QUEUE-MESSAGE-TRANS} \\
O; H; L; \vdash \ \ (\lambda x : p . e) \ \ Q
\]

**7.2. Private Message Queues**

The calculus presented in Section 6 encodes atomic operations by batching several operations in a single message. While this gives some control over the interleaving of messages, it does not allow the sending actor to react to intermediate results of the atomic operation. For example, an actor interacting with a list may want to atomically iterate over the list, operating on each element along the way, without allowing interleaved operations on the list in the meantime.

This section extends our core calculus with support for private message queues. An actor can start a private “conversation” with another actor by creating a new queue and passing it as a message. When an actor receives a new queue it will read messages from this queue until it receives a message to end the conversation. Messages sent by other actors will still be enqueued in the actor’s public queue.

On the surface level, two dual operations are added: `atomic` begins a new atomic operation, and `release` finishes it (cf., Figure 14). The target of `atomic` or `release` can be actors or bestowed objects (cf., Figure 15). In the latter case, the owner of the bestowed object gets sent the private queue. The two operations do not have to appear in the same procedure body, and the language does not enforce that an `atomic` expression has a

\[
e ::= x \mid e.\!v \mid e.v \mid e.\text{mutate}(O) \mid \text{new } \tau \mid \text{bestow } e \mid \text{atomic } e \mid \text{release } e \mid v
\]

\[
\tau ::= \alpha \mid p \mid \tau \to \tau \mid \text{Unit}
\]

\[
v ::= \lambda x : \tau . e \mid () \mid id \mid i \mid i_{id}
\]

\[
\alpha ::= c \mid B(p)
\]

Figure 13: New and changed well-formedness rules for dealing with transferable objects.

Figure 14: The syntax of a simple lambda calculus with actors with private message queues.
\[\Gamma \vdash e : \tau\] (Expressions)

\[
\begin{array}{ll}
\text{E-ATOMIC} & \Gamma \vdash e : \alpha \\
\quad \Gamma \vdash \text{atomic } e : \text{Unit} & \Gamma \vdash \text{release } e : \text{Unit}
\end{array}
\]

Figure 15: New static rules for dealing with private message queues.

\[
\langle M; H \rangle \xrightarrow{id} \langle M'; H' \rangle
\]

(Evaluation)

\[
\begin{array}{l}
\text{EVAL-ACTOR-PRIV-RUN} \\
M'(q \mapsto (Q, q')) = M(q \mapsto (Q, v')) \quad H'(id \mapsto (\ell, L, At(q) Q, v'))
\end{array}
\]

\[
\langle M, H \rangle \xrightarrow{id} \langle H', M' \rangle
\]

\[
\begin{array}{l}
\text{EVAL-ACTOR-PRIV-END} \\
M'(q \mapsto \bot) = M[q \mapsto \bot] \quad H'(id \mapsto (\ell, L, Q, v'))
\end{array}
\]

\[
\langle M, H \rangle \xrightarrow{id} \langle H', M' \rangle
\]

Figure 16: New dynamic rules for dealing with private message queues (1/2).

matching \text{release}. In a real programming language, using a blocked construct is probably more practical—this is how \text{atomic} is implemented in Encore.

Dynamically, we need three extensions to the configuration. First, each actor is extended with a map \( C \) of its ongoing conversations. \( C \) maps actors \( id \) to queue identifiers \( q \). Second, a global map \( M \) maps queue identifiers \( q \) to queues and the owner of the queue (the actor who is reading from it). Third, a message can now be a request for starting a private conversation using queue \( q \) (\text{At}(q)) or a request for ending a conversation (\text{End}), or a normal message modelled as anonymous function as before.

Figure 16 shows the two new rules for how actors react to atomic messages. If the head of the actor’s public queue is \text{At}(q), the private queue corresponding to \( q \) is looked up in \( M \) and the first message from this queue is run, leaving the public queue intact (\text{EVAL-ACTOR-PRIV-RUN}). If the head of the private queue is \text{End}, the private queue is dropped from \( M \) and the \text{At}(q) message is popped from the public queue, allowing the actor to continue reading messages normally (\text{EVAL-ACTOR-PRIV-END}).

Figure 17 shows the rest of the new dynamic rules. Since we handle starting and finishing of atomic operations, on both actor and bestowed objects, and these operations can succeed or fail, there is a large number of new rules. The rules in the left column all handle actor targets, and the rules in the left column all handle bestowed targets.

Initiating an atomic operation with actor \( id' \) creates a fresh queue identifier \( q \) and updates the current actor so that its conversation map \( C \) maps \( id' \) to \( q \). The global map is updated so that \( q \) maps to an empty queue belonging to \( id' \), and an atomic request \text{At}(q) is enqueued to the public queue of \( id' \) (\text{EVAL-ATOMIC-ACTOR}). If the current actor already has a private conversation with \( id' \)—that is, \( id' \) is already in \( C \)—the expression is a no-op (\text{EVAL-ATOMIC-ACTOR-FAIL}). The rules for a bestowed target is symmetric (\text{EVAL-ATOMIC-BESTOWED-*}).

Finishing an atomic operation with actor \( id' \) looks up the queue identifier of the conversation with that actor in \( C \) and appends an \text{End} message to the end of the corresponding private queue. Since this denotes the end of the conversation, the mapping from \( id' \) is dropped from \( C \) (\text{EVAL-RELEASE-ACTOR}). If there is no ongoing conversation with \( id' \)—that is, \( id' \) is not in \( C \)—the expression is a no-op (\text{EVAL-RELEASE-
| Rule                                                      |
|-----------------------------------------------------------|
| **EVAL-ATOMIC-AGENT**                                    |
| $H(id) = (i, L, C, Q, e)$  $id' \notin \text{dom}(C)$  $q$ fresh |
| $\mathcal{M}' = \mathcal{M}[q \mapsto (e, id')]$       |
| $H'(id') = (i', L', C', Q', e')$                         |
| $id \vdash \langle \mathcal{M}, H, \text{atomic}\; id' \rangle \hookrightarrow \langle \mathcal{M}', H', () \rangle$ |

| Rule                                                      |
|-----------------------------------------------------------|
| **EVAL-ATOMIC-BESTOWED**                                  |
| $H(id) = (i, L, C, Q, e)$  $id' \notin \text{dom}(C)$  $q$ fresh |
| $\mathcal{M}' = \mathcal{M}[q \mapsto (e, id')]$       |
| $H'(id') = (i', L', C', Q', e')$                         |
| $id \vdash \langle \mathcal{M}, H, \text{atomic}\; id' \rangle \hookrightarrow \langle \mathcal{M}', H', () \rangle$ |

| Rule                                                      |
|-----------------------------------------------------------|
| **EVAL-ATOMIC-AGENT-FAIL**                                |
| $H(id) = (i, L, C, Q, e)$  $id' \notin \text{dom}(C)$  $q$ fresh |
| $\mathcal{M}' = \mathcal{M}[q \mapsto (e, id')]$       |
| $H'(id') = (i', L', C', Q', e')$                         |
| $id \vdash \langle \mathcal{M}, H, \text{release}\; id' \rangle \hookrightarrow \langle \mathcal{M}', H', () \rangle$ |

| Rule                                                      |
|-----------------------------------------------------------|
| **EVAL-ATOMIC-BESTOWED-FAIL**                             |
| $H(id) = (i, L, C, Q, e)$  $id' \notin \text{dom}(C)$  $q$ fresh |
| $\mathcal{M}' = \mathcal{M}[q \mapsto (e, id')]$       |
| $H'(id') = (i', L', C', Q', e')$                         |
| $id \vdash \langle \mathcal{M}, H, \text{release}\; id' \rangle \hookrightarrow \langle \mathcal{M}', H', () \rangle$ |

Figure 17: New dynamic rules for dealing with private message queues (2/2). The left column handles rules for actor targets and the right column handles rules for bestowed targets. The helper function $C$ extracts the conversation map $C$ from an actor. The evaluation context $E$ is also extended with two cases: $E[\bullet] := \ldots | \text{atomic} \; \bullet | \text{release} \; \bullet$. 

18
Well-formedness

\[ H \vdash M ; H ; id \vdash (\ell , L , C ; Q , e) \quad M ; H ; L ; id \vdash Q \]  

**WF-QUEUE-MAP**

\[ \begin{align*}
\beta \ q . \ A t (q') \in Q & \quad M ; H ; L H (H (id)) ; id \vdash Q \\
\text{End} \in Q \Rightarrow \exists id' . \ q \notin \ rng (C (H (id'))) & \\
H \vdash \mathcal{M} q \mapsto (Q, id) 
\end{align*} \]

**WF-HEAP-PRIV**

\[ \begin{align*}
\forall id_1 \neq id_2 . \ \mathcal{L} H (H (id_1)) \cap \mathcal{L} H (H (id_2)) = \emptyset \\
\forall id_1 \neq id_2 . \ \text{rng} \ (C (H (id_1))) \cap \text{rng} \ (C (H (id_2))) = \emptyset \\
\forall id \in \text{dom} (H) . \ H \vdash H (id) & \\
\vdash H 
\end{align*} \]

**WF-QUEUE-ATOMIC**

\[ \begin{align*}
M ; H ; L ; id \vdash Q & \quad M (q) = (Q , id) \\
M ; H ; L ; id \vdash A t (q) Q & \\
M ; H ; L ; id \vdash \text{End} Q 
\end{align*} \]

**WF-QUEUE-END**

\[ \begin{align*}
M ; H ; L ; id \vdash Q & \quad M (q) = (Q , id) \\
M ; H ; L ; id \vdash A t (q) Q & \\
M ; H ; L ; id \vdash \text{End} Q 
\end{align*} \]

Figure 18: New and changed well-formedness rules for dealing with private message queues.

**Actor-fail**. Again, the rules for a bestowed target is symmetric (**EVAL-RELEASE-BESTOWED-*`).

Finally, sending a message to an actor \( id' \) with whom the current actor has a private conversation looks up the queue identifier of this conversation in \( C \) (extracted from the actor using the helper function \( C \)) and adds the message to the corresponding private queue in \( M \) (**EVAL-SEND-ACTOR-ATOMIC**). The case for a bestowed target is symmetric (**EVAL-SEND-BESTOWED-ATOMIC**). The rules for normal message sends (not shown here) are extended with a premise that there is no ongoing private conversation with the receiving actor.

Figure 18 shows the new and changed well-formedness rules. The queue map \( \mathcal{M} \) is well-formed if for each mapping \( q \mapsto (Q , id) \), the private queue \( Q \) is well-formed with respect to actor \( id \) and does not contain any requests for new private conversations (any such new requests would arrive in the public queue of the actor). Additionally, if there is an **End** in the queue, there can be no actor in the heap that has a private conversation through the queue identified by \( q \), since this actor has just ended the conversation (**WF-QUEUE-MAP**).

The rule for well-formed heaps is extended with a premise stating that the ranges of all actors’ private conversations must be disjoint, meaning that no two actors may send messages to the same private queue (**WF-HEAP-PRIV**). The rule for well-formed actors states that each entry in the conversation map has a corresponding entry in the global queue map. The public queue of an actor must not contain **End** messages (since these are necessarily sent to the private queue), and all requests for atomic operations must use distinct queue identifiers (**WF-ACTOR-PRIV**). There are two new well-formedness rules for queues. A request for an atomic operation must have a corresponding private queue waiting in the global queue map (**WF-QUEUE-ATOMIC**). **End** messages are always well-formed (**WF-QUEUE-END**).

To show that our private mailboxes are sound we define an informal property:

**Atomicity**: Once a private conversation between actors \( A \) and \( B \) has been initiated, actor \( B \) will only read messages sent by actor \( A \), up until and including the **End** message.

The key rules for showing that atomic operations run without interleaving are **WF-HEAP-PRIV**, which states that two different actors cannot have a private conversation with the same actor (preventing other actors from “hijacking” the private queue that \( A \) is writing to), and **WF-ACTOR-PRIV**, which states that an ongoing private conversation with actor \( id' \) has a corresponding queue belonging to \( id' \) in the global queue map (guaranteeing that messages sent from \( A \) to \( B \) will indeed end up in the mailbox that \( B \) is reading from). From the dynamic rules **EVAL-ACTOR-PRIV-`** it is easy to see that an actor will keep reading from the same private message queue until it contains an **End** message.
The formulation of the remaining meta-theoretic properties requires adapting the statement of progress to include the state when an actor is waiting for a message to arrive to its current private queue. After this adaptation, the same soundness properties hold for this variation of the formalism as well. The mechanised version of the semantics are \( \approx 670 \) lines of Coq, and the proofs are \( \approx 4000 \) lines with the same \( \approx 600 \) lines of list lemmas and tactics as for the other calculi [10]. The increase in size compared to the other mechanisations is explained by the large number of cases for evaluation as seen in Figure 17. There is room for reducing the code size by applying more automation to similar cases of the proofs.

7.2.1. Design Considerations for Private Queues

The way private mailboxes are formalised here purposely have them behave similar to locks in mainstream programming languages. The \textbf{atomic} and \textbf{release} keywords work like acquire and release on a lock, and all operations carried out by an actor between calls to \textbf{atomic} and \textbf{release} enjoy absence of interleaving.

This is different from the implementation of \textbf{atomic} in Encore, where a new handle to the target actor is created whose type expresses that messages sent to this actor will not be interleaved with messages from other actors. This handle is statically restricted from being passed to other actors and cannot survive its corresponding atomic block (it is effectively borrowed ([cf., [29, 30]])). This forces code to explicitly propagate this handle to everywhere where the handle is needed.

Allowing such a handle to be shared with other actors is possible, as is bounding the duration of the sharing to the static scope of the atomic block. This would extend the number of sources of messages in a private conversation, and re-introduce interleaving in a controlled fashion. We have yet to find compelling enough reasons to support this in real programs.

8. Exploring Bestow and Atomic—Case Studies

In this section, we report on three case studies using bestow and atomic to implement distributed hash tables, distributed graphs, and atomic money transfer. These case studies highlight the usefulness of bestow and atomic and some of their properties, and also serve as more compelling motivating examples (although less pedagogic) than the list example of Section 3.1.

8.1. Case Study: Distributed Hash Tables

The Encore programming language was recently extended with support for “locally distributed” arrays and hash tables. These data structures are backed by several actors to enable true parallel operations on disjoint parts. Distributing a hash table \( T \) over \( N \) different actors allows up to \( N \) operations on \( T \) to be carried out in parallel, provided that there are at least \( N \) cores where the actors are scheduled in parallel\(^6\).

Encore’s distributed hash tables are implemented purely as a library construct. Each client of a hash table holds a single passive object which acts as a proxy for the hash table and to this end keeps a map from hash ranges to actors that it uses to delegate operations to the correct actor. Distributing this ranges-to-actors map across all proxies is key to the parallel performance.

Given the aforementioned map, puts and gets are straightforward to implement. A more complex operation is rehashing, \textit{i.e.}, updating the map, possibly involving changing the number of actors backing the data structure in the process. Rehashing involves stopping all operations in all actors backing the data structure, reconfiguring the map, and resume operations with the new map. Since clients may continue to send messages using an outdated map during rehashing, requests must be buffered until the new map is in place, and possibly rerouted to another actor. The top right of Figure 19 shows excerpts of a \texttt{put} method that buffers messages during rehashing.

Figure 19 (left) shows a high-level implementation of the rehashing function. The important lines with respect to bestow are 16 and 17, iterating over all hash-table proxies and updating their ranges-to-actors maps. The type of each \( p \) is \texttt{B\langle HashMap\rangle} meaning each call to update is wrapped in a closure which is sent to the containing actor. This design requires that all proxies are known by the distributed hash table, which

\(^6\)This is ultimately a decision made by the run-time system, and depends on the available cores, system load, etc.
```python
def rehash() : unit
    
    -- Send a stop message to all actors
    val result = for a <- this.actors do
        a ! stop(new_map)
    
    -- Create a new actor map
    val new_map = this.create_new_map()
    
    -- Block until all actors have stopped
    for r <- result do
        r.get()
    
    -- Update the list of actors
    this.actors = new_map.values()
    
    -- Start actors up using new map
    for a <- this.actors do
        a ! start(new_map)
    
    -- Update all proxies' map
    for p <- this.proxies do
        p ! update(new_map)
```

Figure 19: Using bestow to implement rehashing (simplification).

is easily handled *e.g.*, in a constructor and/or factory method. For simplicity, we omit a versioning scheme checking that the map used by a proxy is up to date (for example, checking that the identity of the client’s map was the same as the actor’s current map). This handles the case when calls are made on an outdated proxy after rehashing is finished.

Without the ability to create bestowed references, we are left with two—problematic—possibilities to implement rehashing:

**Polling for changes to the ranges-to-actors map** In this scenario, proxies would continuously poll for changes to the map. Since polls cross actor boundaries, they would be asynchronous increasing the latency of hash table operations, possibly causing client actors to block waiting for polling responses.

**Forcing actors using hash-tables to implement support methods** In this scenario, actors using hash-tables would be required to implement a special support method for updating client proxies. This has the downsides of pushing internal implementation detail out into the interface, not just for the actors themselves, but any library used inside the actor must somehow be interfaced with by the top-level to support updating ranges-to-actors maps.

As Figure 19 shows, it is possible to avoid these problems through bestowed references as these allow us to *push* changes directly to the hash table proxies—without any special requirements on the clients holding them.

An obvious extension to the atomic construct is the ability to atomically operate on a number of subjects (actors in the current example). In the case of a statically known number of subjects, it is easy to implement

```python
atomic (a, b) ... as syntactic sugar for nested atomic blocks. In the case of a dynamic number, something similar can be done manually through recursion. If we imagine a powerful atomic block able to suspend a number of actors before performing its operations on all of them, and then releasing them, the rehash() function of Figure 19 could be greatly simplified:
```

```python
    def rehash() unit
        
        val new_map = this.create_new_map()
        
        atomic this.actors do -- operate atomically on all actors in this set
            for a <- this.actors do
                a ! update(new_map)
```

Notably this implicitly takes care of any buffering of messages sent to actors backing the hash table while rehashing is taking place. Furthermore, the aforementioned versioning scheme dealing with messages sent via proxies whose maps are out of date could be eliminated if lines 6 and 7 could be made part of the atomic block, but would only be advisable if the number of proxies was very small.

### 8.2. Case Study: Distributed Graphs

Just like distributing a hash table over a collection of actors, there are many cases where it is appropriate to distribute a graph over a collection of actors. A simple representation of a graph is an object structure where objects representing nodes model edges using references, keeping a separate list of weights for edges. When distributing such a model over several actors, different actors own different nodes in the graph, and thus edges must sometimes connect nodes across different actors. Here, bestowed references can be used to abstract whether an edge is inter-actor (meaning it points to a node inside the same actor) or intra-actor.

A straightforward implementation of Dijkstra’s shortest path algorithm can be applied with bestowed edges, but will suffer from added latency due to many lookups of edges or weights changing to asynchronous message sends. This highlights the importance of syntactically highlighting asynchronous sends with `!`, and requiring the act of bestowing to be explicit. Consider for example the following code, which (possibly) updates the shortest paths to the nodes reachable from the current node:

```scala
for (n, dist) <- src ! edges() do
  unless visited.contains(n) then
    val new_distance = distances(src) + dist
    if new_distance < distances(n) then
      distances(n) = new_distance
      predecessors(n) = src
```

On Line 1, we obtain the edges and weights for the neighbours of node `src`. If `src` points to another actor `o`, this lookup will involve an asynchronous call to `o` to obtain the result. If `src` is local to the current actor, this operation can be converted to a fast synchronous lookup. In this code, we only use the identity of `n`, which is a fast operation regardless whether `n` is a bestowed reference or not.

Figure 20 depicts a graph distributed over two actors. The thick path denotes a “hot path” in the system, meaning a path that is traversed often. In a system that is able to load-balance passive objects as discussed in Section 4.3 and formalised in Section 7, traversing the hot path could lead to moving the green objects on the hot path from actor `B` to actor `A`, allowing `A` to operate synchronously on all the objects in the
path, without any latency added by crossing a dashed edge. The figure also illustrates how load-balancing might lead to increasing inter-actor references. The performance impact of increased number of inter-actor references naturally depends on how frequently they are dereferenced.

8.3. Case Study: Money Transfer

Money transfer across bank accounts is a classic example of atomicity. Imagine actors acting as banks, and each bank holding passive objects as bank accounts. Foregoing whether unrestricted external access to a bank account is advisable from a security perspective, bestowed references allows exposing the interfaces of individual bank accounts outside of the banks, and also the construction of an atomic transfer operation even if the banks themselves do not support it. The following function uses a combination of bestowed pointers and atomic blocks to implement transfer in a straightforward fashion:

```python
def transfer(amount : int, from : B(Account), to : B(Account)) : unit
    atomic from do
        atomic to do
            if from ! withdraw(amount) then
                to ! deposit(amount)

Notably, providing syntactic sugar for the nested atomic blocks is straightforward. When this block is executed, if the accounts are owned by the same actor, the whole content of the atomic block can be sent to the owning actor to be performed there in a synchronous fashion. Outside of this special case, because we are nesting atomic blocks, external messages to the actors referenced by `from` and `to` will not be received until after Line 4. Thus, no other actor will be able to witness that `amount` money is “missing” in the system, between Lines 3 and 4.

Notably, a single atomic block can be strong enough to support a limited form of inter-actor atomicity for two actors, if the current actor is one of them, with a small modicum of extra work for the programmer:

```python
def transfer(amount : int, from : Account, to : B(Account)) : unit
    atomic to do
        if from.withdraw(amount) then
            val done = to ! deposit(amount)
            done.get()

On Line 3, `withdraw()` can be called synchronously because `from`’s type captures that it is a local object. Thus, external actors’ inability to witness the change before the end of the `transfer()` method arises naturally from the single-thread-of-control invariant of actors. On Line 4, we capture the future return value of `deposit()` and block on its return on Line 5. Thus, the transfer method will not finish until the money has been deposited in the target account.

Note that because the type of `from` is not bestowed, this version of `transfer()` cannot be called externally by other actors. For that to be possible, there needs to be some way for external actors to identify a particular account, such as a unique account number.

9. Implementation in Encore

A prototypical implementation of bestow and atomic exists in Encore, and is currently being hardened to become part of the main branch. The prototype has been instrumental in understanding the performance implications of the two constructs, especially in relation to Encore’s support for fully concurrent garbage collection [14]. A more comprehensive account of the implementation aspects can be found in [31].

We extend each actor class with an implicit method `perform` which takes a function, applies it to the `this` of the receiver, and returns the result wrapped in a future. A bestowed reference is logically implemented as a pair of values, `owner` and `object`. A message send `x ! m()` on a bestowed reference is translated into the message send `x.owner ! perform((\_ . x.object.m()))`.

The atomic block is implemented using the private mailbox semantics sketched in Section 5 and formalised in Section 7. An atomic block is turned into a pair of matching `acquire` and `release` operations, where the
former creates and installs the private mailbox and returns an atomic reference, and the latter sends the termination message that reinstates the mailbox at the start of the atomic block. Similar to a bestowed reference, an atomic reference is logically implemented as a pair of values target and mailbox, and a message `send x ! m()` on an atomic reference uses a special message sending primitive that directs the message to mailbox instead of the normal mailbox.

\[
\text{atomic } x \text{ do }
\begin{align*}
& x ! \text{foo}(42) \implies x' ! \text{foo}(42) \\
& x ! \text{bar}(-42) \implies x' ! \text{bar}(-42) \\
& \text{release } x'
\end{align*}
\]

In previous work [9, 31], we explored an implementation of atomic with coalescing semantics. While this is less general than the private mailbox semantics, our original assumption was that it might serve as an optimisation in simple uses of atomic. However, an implementation of bestow close to the formal semantics of coalescing (cf., Section 6) involves creation of closures passed from the operating actor to the owner of the passive object. Without special optimisation, the overhead of closure creation, and garbage collection of the closure value is significant. We illustrate this in Figure 21 (left) through a modified version of the Ping benchmark from the Computer Language Benchmark Game [32] where two actors are involved in a ping–pong exchange of messages. The figure shows a fairly constant slowdown for the bestowed version of 11–16× over the non-bestowed counterpart. The main source of this overhead is fully concurrent garbage collection—the closure is being created on the local heap of one actor and then sent to another, which must eventually inform the creating actor when the closure is no longer needed. Passing closures by copy is likely to reduce this overhead. This benchmark clearly demonstrates that programs mostly operating on bestowed pointers might see a noticeable slowdown.

In contrast, the right-hand-side of Figure 21 shows that the combination of bestow and atomic can outperform the actor-only solution. By wrapping the loop containing the message sends in an atomic, the entire loop can be transferred to the receiver where it can be run synchronously. This reduces the number of asynchronous message sends, which involve expensive CAS operations on mailboxes, and enables compile-time optimisations such as inlining.

![Figure 21: Overhead of message sends on bestowed objects, and using atomic closure to reduce the impact of the overhead.](image)

In Section 5.1, we noted that atomic blocks add structure to actor-programs. If desired, this can be leveraged in scheduling. When executing `atomic a do ...`, if the actor denoted by `a` is `idle`, meaning its mailbox is empty, it is possible to turn the asynchronous operations inside ... synchronous, i.e., turning e.g., `a ! ping()` into `a.ping()`. This avoids context switching, enables inlining as well as other optimisations such as removing future indirection which are costly in Encore. Static analysis can be used to determine whether removing asynchrony may also remove possible parallel gains. Making asynchronous operations synchronous allows mixing the methods of several actors on the same stack frame because control flow is guaranteed to match the order that frames are pushed onto and popped from the stack.
An important property of many actor-based systems is that a single actor can be reasoned about sequentially; messages are exchanged concurrently but executed sequentially by the receiving actor. For this property to hold, actors often rely on actor isolation [33], i.e., that the state of one actor cannot be accessed by another. If this was the not the case, concurrent updates to shared state could lead to data-races, breaking sequential reasoning.

Existing techniques for achieving actor isolation are often based on restricting aliasing, for example copying all data passed between actors [12], or relying on linear types to transfer ownership of data [6, 15, 33, 34]. Bestowed objects offer an alternative technique which relaxes actor isolation and allows sharing of data without sacrificing sequential reasoning. Combining bestowed objects with linear types is straightforward and allows for both ownership transfer and bestowed sharing between actors in the same system.

Miller et al. propose a programming model based on function passing, where rather than passing data between concurrent actors, functions are sent to collections of stationary and immutable data called silos [35]. Bestowed objects are related in the sense that sharing them doesn’t actually move data between actors. In the function passing model, they could be used to provide an interface to some internal part of a silo, but implicitly relay all functions passed to it to its owning silo. While the formalism in Section 6 also works by passing functions around, this is to abstract away from unimportant details, and not a proposed programming model.

References to bestowed objects are close in spirit to remote references in distributed programming or eventual references in E [7]. In the latter case, the unit of encapsulation, e.g., an actor or an aggregate object protected by a lock, acts similar to a Vat in E, but with an identifiable boundary and an identity with an associated interface. By bestowing and exposing sub-objects, a unit of encapsulation can safely delegate parts of its interface to its inner objects, which in turn need not be internally aware of the kind of concurrency control offered by their bestower.

The Emerald language [36] has an entire “locatics” system for expressing object placement and mobility combined with an object-based language. Very early, Emerald introduced call-by-move which allowed parameters of a call to a remote object to be moved to the target’s location [37].

Any actor system which supports sharing of mutable state could implement individual bestowed objects by using a wrapper with the same interface as the bestowed object, but where all operations are delegated to some actor. Similarly, in a language with locks, a wrapper object could grab a specified lock before calling the underlying methods. In both cases, this comes at the cost of explicitly creating wrapper objects for all bestowed objects, and requires that the programmer never directly accesses the object inside the wrapper. For actor systems, bestowed references make the most sense when messages are handled in sequence. In languages where messages are explicitly and selectively received by each actor, the owning actor would have to regularly check for incoming delegated operations.

X10 introduces a language construct that is called atomic for executing multiple operations in sequence without interleaving [38], but with different semantics and notably no support for side effects or blocking operations.

Ibrahim et al. introduce the concept of Remote Batch Invocation for combining operations to be run remotely in a distributed system (in Java) [39]. This is similar to the coalescing semantics of atomic blocks, but more advanced since parts of a batch may consist of local computations, allowing the client to react to the results of the remote operations inside the batch, while still only making a single round-trip to the server. The private mailbox semantics of atomic blocks is more flexible than Remote Batch Invocation, but would be more expensive in a distributed setting where each remote call is costly.

The coalescing semantics of atomic blocks can be implemented in any actor language with closures by sending a closure performing the desired operations in a message. This requires that the receiving actor has support for running arbitrary closures, which complicates reasoning about the behaviour of that actor (in our Encore implementation, the perform method is only ever called implicitly as an effect of an atomic block). Languages with selectively receives can encode the kind of “private conversation” between two actors, offered by the private mailbox semantics of atomic blocks, but requires that the receiving actor is implemented with support for atomically processing exactly the messages that the client wanted to send.
To the best of our knowledge, there are no other systems which implicitly delegates locking based on ownership, as when bestowing the internal state of a locked object. Ownership types have been used to enforce strong encapsulation and to allow a single lock to safely govern access to an entire object aggregate, e.g., in Universes for Race Safety [40] or Parameterized Race Free Java (PRFJ) [41]. PRFJ additionally allows the programmer to specify a lock-order and enforces that locks are taken in this order, preventing deadlocks. Kappa does not attempt to prevent deadlocks, and bestowed references to the private state of locked objects may be subject to deadlocks. Universes for Race Safety allow references with unknown owners, possibly crossing encapsulation boundaries, but require explicitly locking these objects before they are accessed. In contrast, accessing a bestowed object only requires locking the owner object (which is done implicitly).

When using locks, the atomic block behaves like Java’s synchronized blocks, but Kappa additionally precludes accidentally bypassing the lock of a locked object. Locked objects in Kappa are protected by a readers-writer lock, which allows a single writer, but multiple concurrent readers (statically enforcing that readers will not cause mutation). A bestowed reference into a locked aggregate which only exposes reading operations can therefore acquire a reading lock, allowing multiple concurrent readers through bestowed references to the same aggregate.

11. Discussion and Conclusion

Although our formal description and all our examples focus on actors, bestow also works with threads and locks. An object protected by a lock can share one of its internal objects while requiring that any interaction with this object also goes via this lock. We believe there is also a straightforward extension to software transactional memory. In the future, we would like to study combinations of these.

Bestowed objects let an actor expose internal details about its implementation. Breaking encapsulation should always be done with care as leaking abstractions leads to increased coupling between modules and can lead to clients observing internal data in an inconsistent state. The latter is not a problem for bestowed objects however; interactions with bestowed objects will be synchronised in the owning actor’s message queue, so as long as data is always consistent between messages, we can never access data in an inconsistent state (if your data is inconsistent between messages, you have a problem with or without bestowed objects).

Sharing bestowed objects may increase contention on the owner’s message queue as messages to a bestowed object are sent to its owner. Similarly, since a bestowed object is protected by the same lock as its owner, sharing bestowed objects may lead to this lock being polled more often. As always when using locks there is a risk of introducing deadlocks, but we do not believe that bestowed objects exacerbate this problem. Deadlocks caused by passing a bestowed object back to its owner can be easily avoided by using reentrant locks (as accessing them both would require taking the same lock twice).

When using locks, atomic blocks are very similar to Java’s synchronized-blocks. With actors, an atomic block groups messages into a single message. For fairness, it may make sense to only allow atomic blocks that send a limited number of messages.

It is possible to synchronise on several locked objects by simply grabbing several locks. Synchronising on several actors is more involved, as it requires actors to wait for each other and communicate their progress so that no actor starts or finishes before the others. The canonical example of this is atomically withdrawing and depositing the same amount from the accounts of two different actors. Interestingly, if the accounts are bestowed objects from the same actor (e.g., some bank actor), this atomic transaction can be implemented with the message batching approach suggested in this paper. We leave this for future work.

Actor isolation is important to maintain sequential reasoning about actors’ behavior. By bestowing activity on its internal objects, an actor can share its representation without losing sequential reasoning and without bloating its own interface. With atomic blocks, a client can create new behavior by composing smaller operations. While bestowed references may not be very efficient, due to their asynchronous nature, they can be used in concert with atomic blocks to move entire operations closer to data operated on, which can not only avoid the negative performance implications of bestowed references, but lead to performance improvements over pure actor-based solutions.

An earlier version [9] of this work quipped “actors without borders”, in the sense of relaxing isolation-based data-race freedom using our bestowed references. The same is true for lock-based synchronisation—bestowed
references allows several objects to sit at the boundary of synchronisation, and share a common lock. In some ways, this is similar to multiple ownership \cite{42, 43}, but extended to a concurrent setting. By tracking bestowed-ness through types, operations on resources owned by others are clearly visible at the use-site, but need no forethought at the declaration-site: the bestowed objects themselves do not need to know why access to them is safe, nor even be aware of their sharing. They can simply trust the safety of living in a world where borders are a means to an end, not an end.

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