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Abstract

TODO

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Chapter 1

Introduction

Traditional, sequential programming has been changing for decades. Over time, languages acquired more and more tools to manage the level of abstraction, such that programs were of higher quality, and with a lower cost to develop [Sha84]. This trend continues to this day. For example, conventionally imperative languages such as Java and C++ have since added functional features, such as closures, to capitalize on their brevity and lack of side-effects. Concurrent programming has undergone a similar process. Various paradigms have emerged to offer their own solutions to managing abstraction. *Coordination languages* attempt to reduce the coupling between the logical coordination of a program from its implementation. Their namesake is their efforts to isolate that which makes concurrency distinct from sequential programming: the coordination of actions into *interactions*. The means by which this is achieved varies. Linda is a well-known example of a coordination language which abstracts away the *implementation* of coordination actions. Programs are written in terms of read and write operations over a global name-space of *tuple* variables. In this manner, coordination actions occupy a higher level of abstraction, and are thus more terse, simple and re-usable [Gel85].

Reo is a coordination language developed at the CWI in Amsterdam. As with Linda, Reo augments another general purpose programming language by allowing a more abstract expression of coordination. Unlike Linda, Reo facilitates the 'extraction' of a program's coordination logic to a self-contained *protocol specification*. Reo does away with action-centricism; protocols constrain the ways in which data is permitted to *flow* through a system of graphical nodes, ie. protocols define their permitted *interactions* [Arb05]. The specification is translated by the *Reo compiler* to a the target language. The result is a *protocol object*, which acts as a coordination medium for the system's actors by distributing a set of *ports* through which they are able to send and receive data. In programming these actors, one is able to rely on the protocol object to coordinate port actions such that the system at large adheres to the protocol specification at runtime. Effectively, programmers are able to act on ports without making any assumptions about the environment beyond.

In this work, we aim to extend the Reo compiler and its related tooling such that it can be integrated into the development pipelines of programs in systems-languages such as C, C++ and Rust. Chapter 3 details the development of a Rust-language target for the Reo compiler, whose outputs are inter-operable with these languages. We discuss the various representation changes that a Reo protocol specification must undergo before valid Rust can be emitted.

Reo has intuitive *value-passing* semantics, such that data moving through ports is transferred in its entirety, without interference from the actions of other ports. In the realm of shared memory, this has an undesirable naïve implementation which must move the contents of large data-types repeatedly. Reo-compiled Java code makes use of an optimization whereby values are kept in place, and their *references* are moved through ports instead. Currently, Reo-generated Java protocol objects are circumstantially subject to *data races* as a result of applying this optimization. This violates Reo's semantics; actors cannot be certain that a value acquired through a local port is not being accessed by someone else concurrently. Chapter 4 explains how our Reo-generated Rust combines the language's systems-level memory management with the explicit protocol descriptions of Reo to perform reference-passing and other optimizations such that Reo's semantics are preserved. Other optimizations are also explored. Chapter 5 provides an evaluation of our implementation at runtime, comparing it to Reo-generated Java, hand-crafted Rust, and breaking down its performance in response to properties of the input Reo specification.

Reo's protocols specify which behaviors systems are and are not permitted to exhibit. At runtime, protocol objects organize actions on their boundary ports into permitted interactions. Actions do not succeed until they are permitted. In this manner, port actions at the wrong time will not cause the program to deviate from the protocol, but may cause a loss of program *liveness* if the operation blocks for an interaction that never comes. For such cases, Chapter 6 explores the design of *static governors*, which allow the programmer to opt-into verifying that local actions will not impede program liveness.

Chapter 2

Background

To begin, we introduce some terminology and background information to be used in the chapters to follow.

2.1 Reo

Reo is a high-level language for specifying protocols. In this section, we touch on the motivation behind Reo's development, and explain how it is used. The language has applicability whenever there is a benefit in being able to formalize a communication protocol. However, this work primarily focuses on Reo's role in automatic generation of glue-code for coordinating interactions within executable programs.

2.1.1 Motivation

Traditionally, coordination programming is approached much like sequential programming, by laying out program logic as sequences of actions, tracing the path of one control-flow at a time. In such programs, concurrency and parallelism are emergent properties; interactions are not represented explicitly, instead they must be derived from actions sprinkled throughout the program [Arb11]. The more complex the program, the more difficult it is for programmers to make sense of this coordination; actions that contribute to interactions become entangled with local computation. Depending on the language, there may also be a large conceptual gap between the coordination's underlying concept and the granular operations the program uses to implement it. The larger the gap, the more tightly-integrated they become, obfuscating the concept within implementation specifics and making it difficult to change one without changing the other.

Over time, various tools and languages have emerged, each with their own way to raise the level of abstraction. For example, various *process calculi* can represent coordination actions symbolically, such that it is more easily understood and manipulated by humans and machines alike. Chapel is an example of a general-purpose programming language with a focus on parallelism, offering a (more traditional) 'local-view' mode for concurrent procedures, but also a 'global-view' mode which has ergonomic syntax *data-parallel* operations that read much like a sequential program [CCZ07]. *Coordination languages* are *domain specific*, characterized by their focus on coordination in particularTODO this is weak. *Linda* is said to be the first of its kind [Wel05]. In Linda, communication between actors takes the form of simple manipulations of *tuples* in a global *tuple space*. Programmers can thereby separate their concerns of *what* coordination logic is implemented from *how* it is implemented [GC92].

Reo is a coordination language founded by the Formal Methods group at the CWI in Amsterdam. It has much in common with Linda, but attempts to do away with what it considers to be a vestige of the world of sequential programming: *action-centricism*. Reo represents a program's coordination logic in terms of *interactions* between participants explicitly; actions of participants can be derived later [Arb11]. As with Linda, Reo is a domain-specific language, intended to take over only the coordination work of a program written in another language. Where Linda embeds *tuple operations* into its host language, Reo embeds *ports*. Program logic is interspersed with (logical) message-passing port-operations. Unlike their Linda equivalents, ports are *local* structures which are entirely oblivious to their environment, exchanging data with an unknown peer in an unknown system context. Actions serve only to drive *local* computation tasks. Building a complex system is a matter of *composing* these modular *components* by interfacing their ports. Reo's main purpose is to provide an interaction-centric, declarative language for the specification of a *protocol* component which acts as an intermediary between other components in the system. The *Reo compiler* sees to the translation from the Reo specification to the equivalent executable code in the target language [Arb11].

Reo's approach to programming comes with two advantages: (1) Programmers may view and manipulate the coordination logic of their program via the Reo specification, whose nature is well-suited for tasks such as verification, and (2) protocol- and compute-components are loosely-coupled to their environment, making it possible to reuse them in different programs, and to understand or alter their behavior in isolation.

2.1.2 Language

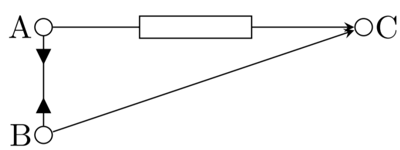
Reo is a graphical language which represents a system as a *connector*, a multigraph which defines the relationships between its nodes [Arb11]. Nodes represent logical 'locations' which may observe a single datum at a time. Ultimately, a connector's relations boil down to Reo's underlying semantics, of which there are several to choose from (explained in Section 2.1.3 to follow). They have in common that they constrain the synchronous observations of data at nodes. For example, a connector may enforce that nodes A and B always observe the same data element. This is known as the *sync* channel, a primitive sufficiently ubiquitous to be represented simply as an arrow ($\longrightarrow$) in Reo's graphical syntax. In this fashion, a connector specifies the ways in which data is permitted to synchronously 'flow' through its nodes. Literature often uses *circuit* as an alternative name for connectors, appropriately evoking the metaphor of electricity, or perhaps fluid pressure as it appears to propagate movement forward and blockages backward synchronously. TODO cite matthijs and micha

A tenet of Reo's design philosophy is compositionality (and consequently, modularity). Rather than defining each and every connector anew in terms of the underlying semantics, all but the simplest primitive connectors are built from the composition of others [Arb11]. At each level of this hierarchy, the connector exposes a subset of its nodes to the connector above, wherein they are called *ports*. The metaphor evokes the transmission of data a harbor to the wider world. The set of a connector's ports is called its *interface*, beyond which is its *environment*. A connector with complex semantics emerges when the ports of its constituent connectors are linked together.

As Reo's various metaphors suggest, we usually think of data as flowing in a particular *direction*. To this end, ports are usually defined along with an annotation of their *orientation*: *input* ports accept data from the environment (moving downward in the connector hierarchry), and *output* ports are the reverse. With these orientations, port interactions orient the direction of their flow from *source* nodes to *sinks*. Connectors can define internal nodes of *mixed* orientation by sources to sinks in various configurations. In this way, connectors can specify complex relationships in their *hidden* (internal) nodes.

Some Reo primitives (and consequently, some connectors that incorporate them) define relationships in terms of variables whose states can persist into the future. In this way, Reo can model *asynchronous* data flow also, breaking up contiguous networks of synchrony, and constraining future observations in terms of its changing state. The primitive *fifo1* connector is canonical for this purpose; in observing some datum X on its single input port, an *empty* connector becomes *full*, whereafter the next observation on its single output port must be X, making it empty once again. Despite its simplicity, *fifo1* is sufficient for the expression of arbitrary asynchronous events and for encoding the persistence of any state[1]. These memory variables is explored further in Section 2.1.3 to follow.

In the literature, Reo is usually expressed using graphical syntax, representing nodes as one would expect. Building a connector graphically involves drawing connections between nodes as *edges* for the usual binary primitives (*sync*, *fifo1*, etc.), or as *boxes*, exposing ports at their boundaries. In this work, we focus instead on Reo's *textual* syntax instead [DA18b], as it makes for a more practical interface between human and compiler. In this context, Reo is fundamentally the same, but relies on textual *identifiers* for nodes and connectors as is typical for general-purpose programming languages. Listing 2.1 demonstrates both methods using a canonical example connector, *alternator2*.




```
alternator2(A?, B?, C!){
  syncdrain(A, B)
  fifo1(A, C)
  sync(B, C)
}
```

Figure 2.1: Reo specification of the *alternator2* connector with input ports $\{A, B\}$, and output port C using graphical and textual syntax. Data flows to C from A and B in an alternating fashion. Connector is distinct from a *sequencer* by B's transmission being *synchronous* with all three ports. Figure is taken from [ZHLS19].

More complete descriptions of how Reo works, how its nodes behave under composition and details about the canonical Reo primitive connectors are available elsewhere [ABRS04, Arb05, Arb11].

2.1.3 Semantic Models

Reo took a number of years to take its present shape. It is recognizable as early as 2001, but was presented as a concept before it was formalized, leaving it as a task for future work [JA12]. Later, This several different approaches to formal semantics were developed. For our purposes, it suffices to concentrate only on the small subset of the semantics to follow. For additional information, the work of Jongmans et a. in particular serves as a good entry point [JA12].

Starting with the fundamentals, a **stream** specifies the value of a variable from data domain D changing over the course of a sequence of events. Usually streams are considered infinite, and so it is practical to define them as a function $\mathbb{N} \mapsto D$. A **timed data stream** (TDS) takes this notion a step further,

[1]The initially-full variant of *fifo1* allows Reo to express connectors initialized with any imaginable initial state.

$\mathbb{R}$	A	B
0.0	0	*
0.1	*	0
0.2	*	*
0.3	1	*
0.4	*	1

Table 2.1: Trace table comprised of TDS's for variables A and B. This trace represents behavior that adheres to the *fifo1* protocol with input and output ports A and B respectively.

annotating each event in the sequence with an increasing *time stamp*. A TDS is defined by some tuple $(\mathbb{N} \mapsto \mathbb{R}, \mathbb{N} \mapsto D)$, or equivalently, $\mathbb{N} \mapsto (\mathbb{R}, D)$ with the added constraints that time must increase toward infinity [ABRS04]. By associating one TDS with each *named variable* of a program, one can represent a *trace* of its execution. TDS events with the same time stamp are considered simultaneous, allowing reasoning about *snapshots* of the program's state over its run time. These traces can be practically visualized as **trace tables**, with variables for columns and time stamps for rows by representing the absence of data observations using a special 'silent' symbol *, referring *silent behavior*. In this work, we use 'trace tables' to refer to both the visualization and to a program trace as a set of named TDS's. The runs of finite programs can be simulated either by bounding the tables (constraining the TDS domain to be finite), or by simulating finite behavior as infinite by extending the 'end' forevermore with silent behavior. Table 2.1 gives an example of a trace table for some program with two named variables.

One of it's earlier *coalegebraic models* represented Reo connectors as **stream constraints** (SC) over such TDS tables in which variables are ports [Arb04]. Here, constraints are usually defined in first-order *temporal logic*, which allows the discrimination of streams according to their values both now and arbitrarily far into the future[2]. This model is well-suited for translating from the kinds of safety properties that are typically desired in practice. Statements such as 'A never receives a message before B has communicated with C' have clear mappings to temporal logic, as often it is intuitive to reason about safety by reasoning about future events. Table 2.1 above shows the trace of a program that adheres the *fifo1* protocol with ports A and B as input and output respectively.

[2]Not all variants of temporal logic are equally (succinctly) expressive. It requires a notion of 'bounded lookahead' to express a notion such as 'P holds for the next 3 states' as something like $\square^{1-3}P$ rather than the verbose $(\square P \wedge \square\square P \wedge \square\square\square P)$.

SC are unwieldy in the context of code generation. In reality, it is easier to predicate one's next actions as a function of the *past* rather than the future. Accordingly, **constraint automata** (CA) was one of the *operational models* for modeling Reo connectors that has a clearer correspondence to stateful computation. Where an NFA accepts finite strings, a CA accepts trace tables. Thus, each CA represents some protocol. Programs are adherent to the protocol if and only if it always generates only accepted trace tables. From an implementation perspective, CA can be thought to enumerate precisely the actions which are allowed at ports given the correct states, and prohibiting everything else by default. A CA is defined with a state set and initial state as usual, but each transition is given *constraints* that prevent their firing unless satisfied; each transition has both (a) the *synchronization constraint*, the set of ports which perform actions, and (b) a *data constraint* predicate over the values of ports in the firing set at the 'current' time step. For example, Listing 2.1 above is accepted by the CA of the *fifo1* connector with all ports of binary data type $\{0, 1\}$. Observe that here the automaton discriminates the previously-buffered value ('remembering' what A stored) by distinguishing the options with states q_{f0} and q_{f1}. As a consequence, it is not possible to represent a *fifo1* protocol for an infinite data domain without requiring infinite states.

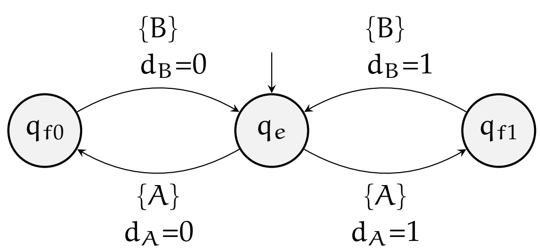


Figure 2.2: CA for the *fifo1* protocol with ports A and B sharing data domain $\{0, 1\}$.

Later, CA were extended to include *memory cells* (or *memory variables*) which act as value stores whose contents *persist* into the future. Data constraints are provided the ability to assign to their *next* value, typically using syntax from temporal logic (eg: m' is the value of m at the next time stamp) [ABdBR07]. Figure 2.3 revisits the *fifo1* protocol from before. With this extension, the task of persistently storing A's value into the buffer can be relegated to m, simplifying the state space significantly. This change also makes it possible to represent connectors for arbitrary data domains, finite or otherwise.

For the purposes of Reo, we are interested in being able to compute the composition of CAs to acquire a model for the compositions of their protocols. Figure 2.4 shows an example of such a composition, producing *fifo2* by

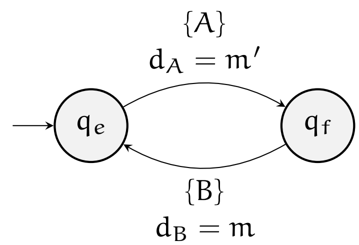


Figure 2.3: CA with memory cell m for Reo connector `fifo1` with arbitrary data domain D common to ports A and B. Two states are used to track to enforce alternation between filling and emptying m.

composing *fifo1* with itself. This new protocol indeed exhibits the desired behavior; the memory cells are able to store up to two elements at a time, and B is guaranteed to consume values in the order that A produced them. Even at this small scale, we see how the composition of such CA have a tendency to result in an *explosion* if state- and transition-space. When seen at larger scales, a *fifo*N buffer consists of 2^N states. The problem is the inability for a CA to perform any meaningful *abstraction*; here, it manifests as the automaton having to express its transition system in undesired specificity. Intuitively, the contents of m_0 are irrelevant when m_1 is drained by B, but the CA requires two transitions to cover the possible cases in which this action is available. In the context of accepting existing trace tables, data constraints are evaluated predictably. However, in the case of code generation we are able to treat the data constraint instead as a pair of (a) the *guard* which enables the transition as a function of the *present* time stamp, and (b) the *assignment*, which may reason about the next time step, and which we are able to guarantee by *assigning* variables. As such, data constraints are broken up into these parts where possible. Figure 2.4 and others to follow formulate their data constraints such that the guard and assignment parts are identifiable wherever it is practical to do so.

Evidently, memory cells provide a new means of enforcing how data persists over time. In many cases, it can be seen that the same connectors can be represented differently by moving this responsibility between state- and data-domains. **Rule-based automata** (RBA) are the cases of CA for which this idea is taken to an extreme by relying only on memory cells entirely; RBAs have only one state [DA18a]. Figure 2.5 models the *fifo1* connector once again, this time as an RBA. Aside from the added expressiveness, RBAs benefit from being cheaper to compose. As the state space is degenerate, RBAs may be easily re-interpreted into forms more easy to work with. **Rule-based form** (RBF) embraces the statelessness of an RBA as a single formula, the *disjunction* of its constraints. In this view, Dokter et al. defines their composition of connectors

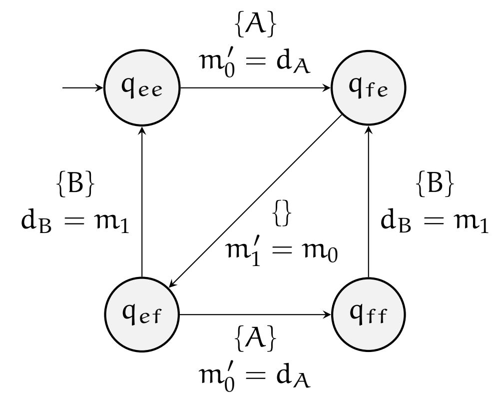


Figure 2.4: CA with memory cells m_0 and m_1 for the *fifo2* connector with an arbitrary data domain for ports A and B. Transitions are spread over the state space such that the automaton's structure results in the *first-in-first-out* behavior of the memory cells in series.

such that, instead of exploding, the composed connector has transitions and memory cells that are the *sum* of its constituent connectors.

RBAs have a structure more conducive to *simplification* of the transition space, such that one RBA transition may represent several transitions in a CA. Figure 2.6 shows how how this occurs for the *fifo2* connector. Where the CA in Figure 2.4 must distinguish the cases where A fills m_0 as two separate transitions, the RBA is able to use just one; likewise for the transitions representing cases where B is able to drain m_1. This 'coalescing' of transitions in RBAs is possible owing to the collapsing of their state space. Even without an intuitive understanding of why such transitions can be collapsed, such cases may often be identified only by inspecting the syntax of the data constraints. For another example of CA, a naïve translation to RBA might produce two transitions with data constraints $m = * \wedge X$ and $m \neq * \wedge X$ for some X, which are both covered by a single data constraint X. As both RBA and RBF share this property, we usually refer to RBA transitions and RBF disjuncts as *rules*, giving these models their name. By distinguishing CA transitions from RBA rules in terminology, we are perhaps more cognizant of the latter's increased ability to *abstract* away needless data constraints.

Typically, Reo has used the Data domains in both CA and RBA as parallels to the data-types of the ports. In most of the languages in which Reo protocols are implemented, the discriminants of such types are not distinguished statically. For example, the C language lacks a way to statically enforce a that function `void foo(int x)` is only invoked when x is prime. Instead, checks at runtime are used to specialize behavior. On the other hand, the state-space is

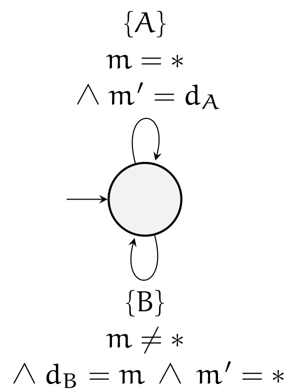


Figure 2.5: RBA of the *fifo1* connector for an arbitrary data domain common to ports A and B. Memory cell m is used both to buffer A's value, and as part of the data constraint on both transitions for *emptying* and *filling* the cell to ensure these interactions are always interleaved. Data constraints are formulated for readability such that the 'guard' and 'assignment' conjuncts are line-separated.

simple enough to afford a practical translation into the structure of the program itself, requiring no checking at runtime. For example, Listing 1 shows an intuitive representation of a connector that alternates between states A and B, getting data x from its environment in A, and emitting x when $x = 3$. Observe that there is no need to protect operations behind a runtime-check of *which* state the corresponding CA is in. This observation has implications for the behavior of implementations of RBAs, as they 'cannot remember' which state they are in and must thus perform more checking. In practice, the overhead of this checking is manageable, and does not *explode* under composition as the state space of CAs tend to do. The representation of automata in programming languages is explored in more detail in Section 2.2.3.

2.1.4 The Reo Compiler

An ecosystem of tooling has emerged around the Reo language, each exploiting Reo's explicit connector specifications for some purpose or another, ranging from verification to code generation. An overview of these tools can be seen on Reo's website[3]. In this work, we are particularly interested in the *Reo compiler*. Previously, code generation was a feature of Reo's *Extensible Coordination Tools* platform plugins for the Eclipse IDE. Since then, the compiler has become a standalone program changing in its design, and being extended to support new

[3] http://reo.project.cwi.nl

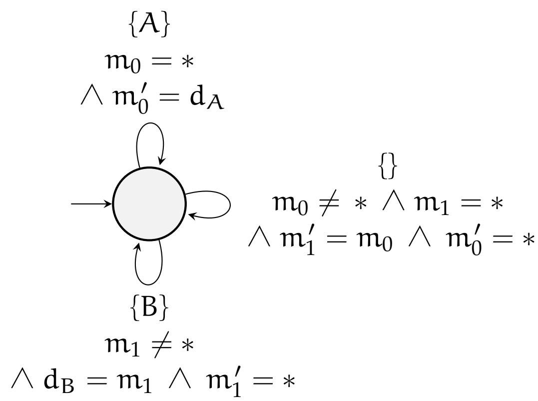


Figure 2.6: RBA of the *fifo2* connector for an arbitrary data domain common to ports A and B. Memory cells m_0 and m_1 are drained by B in the order they are filled by A, and have a capacity of 2 elements. Data constraints are formulated for readability such that the 'guard' and 'assignment' conjuncts are line-separated.

compilation targets in response to the developments as the result of ongoing research [JSS+12, JSA15, DA18a].

Given a textual Reo specification, the Reo compiler generates and emits a *protocol object* with runtime behavior corresponding with the input specification. The output is in a *target language* selected by the user. At time of writing, languages Java, Promela and Maude are supported. C11 is available also, but has been deprecated. Once parsed, the compiler translates the Reo-language representation into that of *Rule-based form*, involving operations *hiding*, *projection*, *merging* and so on. For our purposes, it suffices to trust that the compiler performs this transformation to our satisfaction, resulting in a representation with the intended semantics. Detailed information about this process is available in the literature [Arb04, Arb05, DA18a]. Accordingly, the textual Reo language has support for the definition of primitives in such models directly [DA18b]. Listing 2 demonstrates this with the primitive *fifo1* connector.

In this work, we concentrate on Reo's use for the generation of *glue code* between compute components in a target language, such that the program adheres to the associated Reo specification at runtime. The Reo compiler is responsible for this translation quickly and reliably. Programmers are able to exploit the correspondence between program and specification by using the representation that best fits the task at hand; it runs with all the characteristics of the target language, but programmers may manipulate or verify its coordination properties via its specification.

```java
void stateA() {
  this.value = get();
  if (this.value == 3) {
    stateB();
  } else {
    stateA();
  }
}
void stateB() {
  put(this.value);
  stateA();
}
```

Listing 1: An example of a program which implements a two-state automaton in the Java programming language. Observe that the behavior of states A and B are encoded implicitly in the *structure* of the program, while determining which of the two in A are available A requires a check ar runtime.

```
fifo1(a?, b!) {
  #RBA
  {a, ~b} $m = null, $m' = a
  {~a, b} $m != null, b = $m, $m' = null
}
```

Listing 2: Textual Reo specification of the *fifo1* connector using RBA semantics. Data is asynchronously forwarded from input A to output B by being buffered in-between in memory cell m.

2.2 Target Languages

In this section we introduce terminology relevant to the languages targeted for code generation by the Reo compiler. We identify patterns and properties that are relied upon in later chapters.

2.2.1 Affine Type Systems

In a nutshell, affine types are characterized by modeling values as finite resources, operations on which *consume* them. This notion of 'affinity' has its roots in logic. In a type-theoretic proof system, one can attempt to derive some *judgment* $\Gamma \vdash t : \tau$ with *statements* assigning *types* to *terms*; here term t is stated to have type τ under context Γ. A context is simply a list of statements, which can be thought to correspond with *assumptions* or *premises* [NG14]. The judgment holds if one can construct a proof, starting with the judgment, selecting and applying *rules* until no 'dangling' judgments remain. For example, simply-typed lambda calculus has a type-derivation rule for abstraction, substitution and application. Depending on the type system, *structural rules* may additionally be provided for manipulating ('massaging') the context such that other rules may be applied. Consider the following structural rules:

$$(var) : \frac{}{t : \tau \vdash t : \tau} \quad (weaken) : \frac{\Gamma \vdash \Sigma}{\Gamma, A \vdash \Sigma} \qquad (contract) : \frac{\Gamma, A, A \vdash \Sigma}{\Gamma, A \vdash \Sigma}$$

In order of their appearance, var terminates proof branches by identifying tautologies, statements defined directly by the context. $weaken$ allows us to arbitrarily grow our context, weakening the strength of the formula as a whole by adding to our assumptions. $contraction$ allows us to treat statements as if they are *idempotent*; we are allowed to discard duplicate statements at will.

Depending on the proof system, such structural rules may be necessary to make a formula provable [NG14]. For example, the *weaken* rule is required to prove $A, t : \tau \vdash t : \tau$. var cannot be directly applied, because A is 'in the way'. The set of available rules characterizes the system by determining what can be proven. For example, the ability to arbitrary replicate, discard and re-arrange context expressions characterizes a type system whose context is 'set-like'; in such a system, the order of statements in the context has no impact on whether a formula can be proven.

Affine type systems are characterized by the absence of the *contraction* rule. Proofs cannot replicate statements at will, and thus they are a finite resource in the proof, *consumed* by use in rules [Wal05].

As type systems do in general, type affinity excludes some programs from being expressed. In the context of programming languages, why would we want this? Of course, conventional computer hardware has no problem replicating the bytes representing some integer. Why then do we limit ourselves? This argument can be made for type systems in general; the machine likewise has no problem re-interpreting the bytes storing a string as an integer. This limitation is a feature in and of itself as long as the programs lost are usually somehow 'undesirable'. For example, it is exceedingly common practice to dedicate a memory region to one type for the duration of the program, making a case for the feasibility of statically-typed local variables. These reasons are primarily for programmers and not for the program, strictly enforcing what would otherwise be good programming practices.

2.2.2 The Rust Language

Rust is an imperative, general-purpose, systems-programming language most similar to C++, even (mostly) sharing its C-style syntax. What sets Rust apart is its memory model. Rust is not a memory-managed language, and has no runtime whatsoever. Instead, the language relies on its *ownership system* to predictably insert allocations and deallocations at the right moment such that it *runs* much as C++ would without exposing these details to the programmer. To make this possible, the Rust compiler keeps track of the variable binding which *owns* a value at all times. Owned values are affine, and associating them with new variable bindings invalidates their previous binding. In Rust, this is called *moving*, and doubles (at least conceptually) with the re-location of a value in memory. Listing 3 illustrates how this appears to a programmer; In `main`, the variable `x` is moved into the scope of `func`. The subsequent access of `x` on line 8 is invalid, preventing this program from compiling. Once an owned value goes out of scope, it is no longer accessible, and Rust performs any destruction associated with that type. Along with the RAII ('resource acquisition is initialization') pattern popularized by C++, programmers can rest assured that their resources are created and destroyed on demand, without the need for any bookkeeping at runtime.

Borrowing

On their own, movement is incredibly restrictive; there is no apparent way to use any resource without destroying it. To reclaim some vital functionality, Rust has the *borrow system* to facilitate the creation and management of types whose ownership is *dependent* on others. Similar to those in C++, programmers are able to create *references* to values (also called 'borrows' in Rust terms). These references are new types, and thus do not represent a transference of ownership to a new binding. Listing 4 demonstrates the example from before, but now passing the `x` by reference into `func` such that `x` is not invalidated. The Rust compiler's *borrow checker* relies on variable scoping to keep track of these borrows to ensure they do not out-live their referent, as these would manifest at runtime as *dangling pointers*. This relationship between value and reference is referred to in Rust as the reference's *lifetime*. Rust performs this static analysis at a per-function basis. As such, it is necessary for programmers to fully annotate the input and output types of functions, but they can usually be *elided* within function bodies. This has an important consequence; the compiler does cross the boundaries between functions to interpret their relationship.

For some types there is no practical reason to enforce affinity. This is usually the case for primitives such as integers. For these cases, the language uses the `Copy` trait to opt-out of Rust's affine management of these resources. Copy-types behave in ways familiar to C and C++ programmers. Listing 3 from before would compile just fine if Rust's 4-byte unsigned integer type `u32` was used in place of `Foo`.

C and C++ have no inherent support for preventing data races. The programmer is in full control of their resources. It is all too easy to create data races to C by unintentionally accessing the same resource in parallel precautions. One of the tenets of Rust's design is to use its ownership system to prohibit these data races at compile-time. For this reason, Rust has an orthogonal system for *mutability*. References come in two kinds: mutable and immutable. The distinction is made explicit in syntax with the `mut` keyword. Rust relies on a simple observation of the common ingredient for all data races: mutable aliasing; only *changes* to the aliased (one resource accessible by multiple bindings) resource manifest as data races. Rust's approach is thus simply to prohibit mutable aliasing by preventing these conditions from co-existing. Mutable references must be *unique* (prohibiting aliasing) and immutable references do not allow for any operations that would mutate their referent (prohibiting mutability). This is the same thinking behind the *readers-writer* pattern for the eponymous lock: there is no race condition if readers coexist, but if one writer exists, it must have exclusive access.

```
1 struct Foo;
2 fn func(x: Foo) {
3   // this function takes argument `x` by value.
4 }
5 fn main(){
6   let x = Foo; // instantiate.
7   func(x);     // Ok. `x` is moved into `func`.
8   func(x);     // Error! x is used after move.
9 }
```

Listing 3: Type `Foo` is affine. On line 7, x is moved into function `func`, consuming it. Accessing x is invalid, and so line 8 raises an error.

Traits and Polymorphism

The primary means of polymorphism in Rust is through generic types with *trait bounds*, also called 'type parameters'. Traits are most similar to interfaces in Java, categorizing a group of instantiable types by defining abstract functions for which implementors provide definitions. Unlike Java, Rust traits say nothing about fields and data, thus describing only their behavior. In this manner, Rust traits are somewhat like C's header files, but rather to be defined per implementor type. Elsewhere in the program, functions and structures can make

```
struct Foo;
fn func(x: &Foo) {
  // this function borrows some `Foo` structure by reference.
}
fn main(){
  let x = Foo; // instantiate.
  func(&x);     // &x is created in-line. x remains in place.
  func(&x);     // another &x is created. x remains in place.
}
```

Listing 4: `Foo` is an affine resource. New references to `x` are created and sent into codefunc without changing the ownership of `x`. Rust's **borrow checker** ensures that these borrows do not outlive `x`.

use of *generic* types. These types are arbitrary and thus opaque to any behavior save for those common to all Rust types; for example, any type at all can be *moved* or can be *borrowed* in Rust. To perform more specialized operations on these generic types, they can be *bounded* with traits. This acts as a contract between the generic context and its concrete call-site; the caller promises that the generic type is reified only with a type which implements the specified traits, and thus the generic can be used in accordance with the behavior these traits provide. This is demonstrated in Listing 5. Here, `something` is a function which can be invoked with `T` chosen to be any type implementing trait `T`, such as `String`.

```
pub fn something<T: PrintsBool>() {
    T::print(true);
}
trait PrintsBool {
    fn print(bool);
}
impl PrintsBool for String {
    fn print(b: bool) {
        println!("bool is: {}", b)
}   }
```

Listing 5: Definition of a function `something` generic over some type `T`, where `T` implements trait `PrintsBool`. Types can implement this trait by providing a definition for all the associated functions, in this case, only `print_bool`.

Above, we see how a function can be defined such that it operates on a generic type. However, the function cannot be used until the type is chosen concretely for a particular instance. This choice is called *dispatch*, and Rust offers two options: static and dynamic. *Static dispatch* (also called 'early binding') is used when the called function can be informed which concrete type has been chosen statically, as the caller knows it at the call-site. During compilation, the generic function is *monomorphized* for the type chosen in this manner on a case-by-case basis, generating binary specialized for that type as if there were no generic at all. Static dispatch is used in C++ templates, and opted-out with the keyword `virtual`. This is Rust's second option: *dynamic dispatch* (also called virtual functions or late binding) where the generic function exists as only one instance, and all of the specialized operations on the generic type are resolved to concrete functions at runtime by traversing a layer of indirection: functions are *looked up* in a virtual function table (vtable). Java uses such virtualization extensively, which allows a lot of flexibility such as allowing functions to be *overridden* by downstream inheritants. Precisely how a language represents virtual functions and lays out the data in memory varies from language to language. Rust uses the *fat pointer* representation in its *trait objects*. Concretely, some generic object which is known only to implement trait `Trait` is represented as a pair of pointers; the first pointing to the actual object' data, and the second pointing to a dense structure of meta-data and function pointers for the methods of `Trait`, usually embedded into the text section of the binary by the Rust compiler itself. Both methods of dispatch are exemplified in Listing 6, demonstrating how static dispatch must *propagate* generics to the caller for resolution to concrete types at compile time, while one function using dynamic dispatch is able to handle any virtualized types by resolving their methods at runtime.

Rust uses traits for just about everything. Some traits are defined in the standard library, and have a degree of 'first class' status by having special meaning when used in combination with the language's syntax. For example, `Not` is a trait that defines a single function, `not`, which is invoked when the type is negated using the usual exclamation syntax, ie. `!true`. Some traits have no associated functions, instead exist for the purpose of communicating information to the compiler. Seen before, `Copy` is a trait which disables the Rust compiler's checks of a value's affinity. `Copy`-types may be passed by value. On the other hand, `Drop` associates the `drop` function with a type, which the compiler will invoke when it goes out of scope; this is the parallel to the definition of destructors in C++. It is common practice in Rust to rely upon common traits such as these for frequently-occurring cases. For example, it is considered good practice to implement `Debug` on your custom traits such that they can be printed using *debug print* syntax (eg. `print!(":?", foo)`) for programmers depending on your work.

```
trait Emits {
    fn emit(&self) -> usize;
}
impl Emits for String {
    fn emit(&self) -> usize {
        self.len()
    }
}
fn func_static<T: Emits>(x: &T) -> bool {
  x.emit() > 10
}
fn func_dynamic(x: &dyn Emits) -> bool {
    x.emit() > 10
}
fn main() {
  let value = String::from("Hello!");
  func_static::<String>(&value);
  func_dynamic(&value as &dyn Emits);
}
```

Listing 6: Static and dynamic dispatch in Rust exemplified. `func_static` shows the former, propagating the type parameter to the caller. `func_dynamic` shows the latter, relying on a virtual function table to resolve the concrete function at runtime. Function `main` shows how both appear at the call site.

Enums and Error Handling

As in C, Rust usually relies on `struct` for defining its types. Each is defined as the list of its constituent fields. Creation of these structures necessitates building all of their constituents, and all fields exist at once. By contrast, *sum types* have *variants* only one of which may be present at a time. Arguably, the duck-typing of Python and flexible polymorphism of Java do the work of these sum types; a variable can be bound to *anything* and then its 'variant' can be reflected at runtime using some explicit operations (`ininstance` and `instanceof` respectively). C takes the approach fitting the language's philosophy; `union` types represent any one of its constituents but the program is at the mercy of the programmer to interact with it as the correct variant as they see fit. Rust's solution is similar to C's unions, but its focus on safety required the use of *tags*. In Rust, an `enum` type is defined with a list of variants, only one of which may exist per intance at a time. At runtime, the variant can be descriminated by explicitly *pattern-matching*, inspecting some implicit meta-data field of the enum stores to reflect which of the variants is in use. Like C's unions, each variant can be an arbitrary type (another struct for example), these variants can be of heterogeneous size, and thus are represeted by the largest of their variants *plus* the space for the tag.

Unlike Java and Python, Rust has no mechanism for *throwables* which override the default control flow, usually for the purposes of ergonomically handling errors. Instead, Rust represents all recoverable errors in the data domain as enums. The standard library defines `Option` and `Result` enums, which are monadic in that they *wrap* the 'useful' data as one of the variants, but represent the possibility for *other* variants also. They differ in that `Option::None` carries no data, and thus `Option` is generic only over one type, the contents of the `Some` variant. `Result`, on the other hand, has two generic types, one for its 'successful' `Result::Ok` variant, and one for its 'unsuccessful' `Result::Err` variant. Listing 7 gives an example of typical error-handling in Rust; here, `divide_by` relies on `Result` to propagate the error for the caller to handle. In circumstances where the error is unrecoverable, Rust uses a thread *panic*, which unrolls the control flow (printing debugging information if an environment variable is set). This is somewhat similar to Java's `Error`.

```
struct DivZeroError;  // contains no data

fn divide_by(numerator: f32, divisor: f32) -> Result<f32, DivZeroError> {
    if divisor == 0. {
        Result::Err(DivZeroError)
    } else {
        Result::Ok(numerator / divisor)
}   }

fn main(input: f32) {
    match divide_by(4.5, input) {
        Ok(x) => print!("Success! computed:{}.", x),
        Err(_) => print!("Something went wrong!"),
}   }
```

Listing 7: Demonstrating the Rust idiom of using a `Result` in return position to propagate exceptions to the caller for handling. Here, `main` must `match` the return value to acquire the result contained within the `Result::Ok` variant.

2.2.3 The Type-State Pattern

The *state* or *state machine* pattern refers to the practice of explicitly checking for or distinguishing transitions between and requirements of states in a stateful object[4]. Usually, these states are distinguished in the data domain of one or more types. Even the lowly `Option` type can be viewed as a small state machine as soon as some condition statement specializes operations performed with it. Although its uses are ubiquitous in application development in general, this pattern is particularly useful for those for which the added ability to manage complexity is necessary: video games, for example [Nys14].

As the name suggests, the *type state* pattern is an instance of the state pattern, characterized by encoding states as types, which usually are distinct from *data* in their significance to a language's compiler or interpreter. A common approach is to instantiate one of the state types at a time. As an example, consider the scenario where a program wants to facilitate alternation between invoking some functions `one` and `two` which repeatedly mutate some integer n. Listing 8 gives an example of what this might look like as a *deterministic finite automaton* in the C language. In this rendering, the expression `two(one(START)).n` evaluates to the expected result of $(0 + 1) \cdot 2 = 2$. Even for this simple example, the encoding of states as types in particular has its benefits; the expression `one(two(START))` may appear sensible at first glance, but the compiler is quick to identify the type mismatch on the argument to `one`, making clear that the expression does not correspond to a path through the automaton:

```
note: expected 'DoTwo' but argument is of type 'DoOne'
```

The type state pattern can be applied in any typed language, but it is particularly meaningful in languages where the compiler or interpreter *enforces* its intended use. The example above demonstrates some utility, but a language such as C has no fundamental way to prevent the programmer from *re-using* values. If the programmer misbehaves, they can retain their previous states when given new ones, and then invoke the transition operations as they please. It's not much of a state machine if all states coexist, is it? This is not always a problem in examples such as the previous. Here, the types prevent the construction of mal-formed *expressions*, and perhaps this is enough. However, we cannot so easily protect a resource from any side effects of `one` or `two`; imagine the chaos that would result from these functions writing to a persistent file descriptor.

An affine type system overcomes the shortcoming illustrated above. By treating instances of these types as affine *resources*, the programmer cannot retain old states without violating the affinity of the types. The example looks very similar when translated to Rust, but now a case such as that shown in Listing 9 will result in the compiler preventing the retention of the variable of type `DoOne`.

[4] Usually, we disregard the effects of terminating the program. Equivalently, this pattern only allows one to describe automata in which every 'useful' state reaches some final 'terminated' state.

```c
typedef struct DoOne { int n; } DoOne;
typedef struct DoTwo { int n; } DoTwo;
const DoOne START = { .n = 0 };

DoTwo one(DoOne d1) {
  DoTwo d2 = { .n = d1.n + 1};
  return d2;
}
DoOne two(DoTwo d2) {
  DoOne d1 = { .n = d2.n * 2};
  return d1;
}
```

Listing 8: An example of the type-state pattern in the C language. The alternating invocation of `one` and `two` is translated to type-checking the compiler can guarantee. This example guarantees that well-formed *expressions* can be interpreted as valid paths in some corresponding automaton, as the types must match.

2.2.4 Proof-of-Work Pattern

Section 2.2.3 demonstrates how the type-state pattern can be used as a tool to *constrain* actions the compiler will permit the program to do. Indeed, this is a natural parallel to the affinity of the type system, which guarantees that no resource is consumed repeatedly. The counterpart to affine types is *relevant* types, which defines correctness as each resource being consumed *at least once*. Type systems that are both relevant and affine are *linear*, such that all objects are consumed exactly once.

There is no way to create true relevance or linearity in user-space of an arbitrary affine type system; any program which preserves affinity is able to exit at any time without losing affinity. How are we able to enforce a behavior if it is correct to exit at any time? *Proof-of-work* is a special case of the type-state pattern which allows the expression of a relevant type *under the assumption that the program continues its normal flow*; ie. system exits are still permitted. The trick to enforcing the use of some object `T` is to specify that a type is a function which must *return* some type `R`, and to ensure that `R` can *only* be instantiated by consuming `T`. Clearly, we cannot prevent `T` from being destroyed in some other way, but we are able to prevent `R` from being *created* any other way.

Realistic languages have many tools for constraining what users may access. Java has *visibility* to prevent field manipulations. Rust has *orphan rules* to prevent imported traits from being implemented for imported types. Languages without any such features won't be able to prevent users from creating

```
fn main(d1: DoOne) {
  let d2  = two(d1);
  let d1  = one(d2);
  let d2  = two(d1);
  let d2_again = two(d1); // Error! `d1` has been moved.
}
```

Listing 9: A demonstration of how the type-state encoding shown in Listing 8 can leverage affine types to ensure that not only expressions, but *a trace through execution* can be interpreted as valid paths through some corresponding automaton. The compiler correctly rejects this example, which corresponds with attempting to take transition `two` twice in a row.

the return type `R` without consuming `T`. In these cases, another option is *generative types* which, among other things, allow us to further distinguish types with different origins. Here, generative types may be used to ensure not just *any* `R` is returned, but a particular `R` within our control. As this work uses the Rust language for concrete implementations, we will rely on its ability to prohibit the user from creating `R` by using *empty enum types* for types with no data nor type constraints, and by making its fields and constructors *private* otherwise[Gor].

Consider the following illustrative scenario: We wish to yield control flow to a user-provided function. Within, the user is allowed to do whatever they wish, but we require them to invoke `fulfill` exactly once (which corresponds to 'consuming `R`'). How can we express this in terms the compiler will enforce? Listing 10 demonstrates a possible implementation (omitting all but the essence of 'our' side of the implementation). The user's code would then be permitted to invoke `main` with their own choice of callback function pointer. Our means of control is the interplay between dictating both (a) the *signature* of the callback function and (b) prohibiting the user from constructing or replicating `Promise` or `Fulfill` objects in their own code.

```rust
struct Promise;
struct Fulfilled;

fn fulfill(p: Promise) -> Fulfilled {
  // invoked once per `main`
  return Fulfilled::new();
}

fn main(callback: fn(Promise)->Fulfilled) {
  // ...
  let _ = callback(Promise::new()); // `Fulfilled` discarded.
  // ...
}
```

Listing 10: A demonstration of proof-of-work pattern. Here, the user is able to execute `main` with any function as argument, but it must certainly invoke `fulfill` exactly once.

Chapter 3

Protocol Translation

In this chapter, we describe the process of translating the Reo compiler's internal representation of a protocol specification into an executable *protocol object* in the Rust language.

3.1 Two-Phase Code Generation

In this section, we explain and motivate our approach of segmenting the code generation process into two distinct phases. Throughout, we refer to the precedent set by the existing Reo compiler backend for generating code in the Java language, as it has seen the language most similar to Rust which has seen significant development.

3.1.1 Generation Sub-tasks

Reo specifications represent connectors declaratively as relations between ports. They are thus well-suited to reasoning about the protocol's properties. In contrast, our target imperative languages such as Java and Rust represent computation such that it corresponds more closely to machine instructions; they are imperative, laying out sequences of actions which together emerge as interaction at runtime. Where interactions in the former can be oriented around the synchronous observations of port values, interactions of the latter must be expressed as sequences of actions, laid out over time. Implementing algorithms for translating between these forms must take care that the translation procedure between these forms preserves the semantics as intended; choosing the incorrect ordering can change the nature of the emergent interaction in unexpected ways. For example, reading memory cell *before* writing it corresponds to a different interaction than reading it *after* writing it.

Java, Rust and Reo have in common that they are strongly-typed languages. Reo's specifications are permitted a degree of *type elision*; for the sake of programmer ergonomics, the data-types of ports may be omitted, such that they can later be derived in context. Rust shares this property, and so the Rust compiler works to *resolve* data types during compilation. Circumstantially, these elisions may produce cases for which a correct resolution is impossible, as the type annotations or constraints present are in conflict. Our task is to emulate this work ourselves, assigning concrete types for port objects in our emitted code such that is guaranteed to type-check in the Rust language. Failure to do this correctly would result in Reo emitting code rejected by the Rust compiler. This would not be a threat to correctness, but it results in significant inconvenience to the programmer.

Regardless of the intermediate representation, protocol objects must ultimately be emitted in the target language. Aside from expression in the correct syntax, the end result must make explicit any work required to make it *executable* with the desired runtime behavior. Even simple concepts require the support of auxiliary book-keeping structures to maintain the protocol object's state, and specialized *concurrency primitives* are needed to ensure that actions compose into interactions at runtime in the expected way. Clearly, this is very particular to the target language, as they vary greatly on how they fundamentally express operations on data at a granular level.

In summary, we identify and name three sub-tasks of generating target language protcol objects from a Reo protocol description:

T_{seq} Declarative interactions must be decomposed into sequences of imperative actions.

T_{type} Ports must be given data types such that they agree with any type-annotations in the Reo specification, and successfully type-check in the target language.

T_{run} Details necessary to make the result runnable are included. Symbolic actions are represented as concrete operations on data.

3.1.2 Decoupling the Reo Compiler from Rust

The Reo compiler has an existing backend for generating Java code. It works by generating Java according to the structure of a *template generator*. In this manner, it can be thought of as performing all code-generation sub-tasks at the same time directly from the compiler's intermediate representation. However, the extent to which the Reo compiler is *coupled* to the Java language is reduced through the reliance on a Java library for the granular implementations of structures that are common to all protocol objects; rather than generating these classes each time, the Reo compiler simply generates a dependency. For example, the library defines a `Component` interface, for which the code generator produces a protocol-specific implementor class. Consequently, a significant part of the T_{run} sub-task (sub-tasks are defined in Section 3.1.1) is delegated to this library.

For T_{type}, help comes from the Reo compiler itself, which in its current form was developed with support for Java in mind. This is visible in its internal representation. For example, types for which no explicit data type annotation was included are assigned the `Object` type, which encapsulates all types that may be concretely chosen for transmission through ports. This design essentially uses `Object` as an all-encompassing *sum type*, relegating the task of *type reflection* (determining concretely which 'variant' of `Object`) to the user themselves. This approach is sufficient in the case of Java, as `Object` supports all the behavior relied about by the Reo protocol object at runtime, namely (1) data-equality checks, (2) data movement, and (3) data replication[1].

Only T_{seq} is performed almost entirely by the template generator. For simple protocols, this task is relatively easy, as there is not much to add when actions are largely concurrent. For example, replicating the contents of a memory cell into a set of others is simply-done in Java by first reading an object reference, and then overwriting the others one at a time. However, ordering dependencies must be resolved very carefully in the general case. The current Java code generator is susceptible to erroneously observing value x at memory cell M in the event that the observation is synchronous with M's value being overwritten by x. Even with the help of the template generator, this translation is sufficiently complex to make detection of these bugs difficult.

Rust is able to mimic Java's approach to create a similar backend through the explicit use of *dynamic dispatch*, such that types can be collapsed to something analogous to Java's `Object` class. If done naïvely, the resulting backend would inherit the problems of its predecessor, and new ones to boot; the Java-like approach is not idiomatic in the context of Rust; it would not make good use of the extensive control of systems resources unique to a systems language. Chapter 4 to follow goes into detail about the properties of the protocol runtime. Here, it suffices to say that we wish to implement a runtime that does not rely on heap-allocation of its port-values, and thus cannot rely entirely on dynamic dispatch. Furthermore, our runtime wishes to perform more extensive optimizations, relying on the unique abilities of our systems language to manipulate its resources at a low level. All these extensions pose a problem in particular for T_{run}, as runtime properties directly influence how the

[1] In the chapter to follow we discuss how this approach introduces safety concerns. In a nutshell, Reo-generated Java assumes that the replication of `Object` references preserves Reo's value-passing semantics. This is not the case, as it may result in *data races*.

executable protocol objects are represented. Our work in unremarkable in its solution to this problem: we delegate T_{seq} to a Rust library. However, we make this separation more extreme. In a nutshell, we wish to partition the work of code generation into two clear *phases*, the former of which performs tasks T_{seq} and T_{type}, and the latter of which performs T_{seq}. To minimize coupling between the modules performing these tasks, the interface between phases is made terse, unambiguous and explicit in the definition of a new intermediate representation of protocol connectors: the *imperative form*.

3.1.3 Temporary Simplifications

Our intention is to isolate the Reo backend from Rust's specifics as extensively as possible. In this manner, we decouple the modules responsible for the code-generation subtasks in accordance with good software engineering practices. Furthermore, it facilitates the *re-use* of the first phase of the code generation process for *other* imperative programming language targets. The section to follow defines imperative form to be as target-language agnostic as possible. However, for the sake of minimizing the disturbance to the Reo tooling ecosystem, we still embrace the per-target structure for Reo code generation for now. As such, the Reo compiler still specifies a Rust language target, and emits executable Rust source as a result. Our representation of the *imperative form* is expressed in Rust syntax (as the `ProtoDef` type) such that this reliance on an intermediate representation is invisible to the end user. As far as they are concerned, Reo generates native Rust that just happens to *somehow* make minimal use of Rust-specific syntax. `ProtoDef` corresponds closely to the definition of imperative form, facilitating this decision being overturned in future with minimal effort.

3.2 Imperative Form

In this section, we define our new intermediate representation of Reo protocol specifications. We include an intuitive look at how it captures the details of the Reo compiler's internal representation, but such that only T_{seq} remains to be performed before the finished Rust source code can be emitted.

3.2.1 Concept

The Reo compiler's internal representation does not ergonomically facilitate execution, primarily because it does not define the *order* in which values are accessed, created and moved. Programmers using imperative, sequential languages are very used to thinking in terms of procedures which manipulate the state of variables *in scope* with the order implicit in their control flow. Often, interpreters or compilers provide safety properties by tracking over the execution and emitting errors whenever a variable access is invalid.

Essentially, imperative form makes explicit the ordering between symbolic *actions*; if executed in the specified order, it is guaranteed that (1) variable accesses are always valid, and (2) it is clear at which moment the rule has *fired*.

Relationship to Reo and Target Languages

Imperative form represents a protocol whose translation from Reo to an imperative language has been completed as fully as possible, but stopped short of introducing implementation- and language-specifics. Thus it is still a specification, free from particular syntax, and rendered in terms of *symbolic* identifiers and data types to be resolved in the manner befitting the target language. In terms of the generation sub-tasks defined in Section 3.1.1, imperative form represents the completion of T_{seq} and T_{type}, but not T_{run}.

The translation from Reo's internal representation to imperative form is *lossless*, and so any language compiling from the former would also be able to compile from the latter. However, the utility of this representation is the increase in *explicitness*, which results from the ordering of actions. This ordering follow from the fundamental assumption of imperative form: a value can only be accessed *after* it has been created. It also inherits an assumption of the Reo language itself; namely, all values and their identifiers can be assigned a static data type[2].

Rules as Transactions

The Reo compiler's internal representation partitions the work of a rule into its *guard* and *assignments*. This is already a step in the direction of imperative computation, observing that some work (the guard) must be performed *prior* to deciding whether the rule *fires*, in which case the assignment follows. As the protocol does not define the moments when it will evaluate the guard, it is necessary that this evaluation has no side effects ie. observable effects to the outside world. In essence, Reo's internal representation formulates a rule as a two-element sequence where the first (the guard) is *transient*, and may end the rule's execution early, and the second (the assignment) exhibits *observable effects*, namely, the results of the rules *firing*.

[2]Imperative form assumes that the target language can assign static data types to ports. However, this assumption is shared by Reo itself, and does not present a problem for untyped languages. For imperative languages without types, ports can simply share some `Any` type, satisfying this assumption trivially.

Imperative form adopts this notion of ordering, but generalizes it to a sequence of arbitrary length. For our purposes, it suffices to continue requiring a single *last* action to represent the assignment. For all prior actions:

1. they have a defined means of being *undone*, ie. the action must be reversible. It follows that each action cannot have any immediately-observable effects,

2. they may conditionally trigger an *abort* event, which occurs after their evaluation completes.

Effectively, we represent each of the protocol's rules as a *transaction*. All actions but the last represent work *prior* to commitment, reading from data, creating temporary values or triggering an abort. If the last action is reached without aborting, the rule has *fired* and aborts are no longer possible; the final action is then guaranteed to be executed, complete with any of the rule's observable effects.

Action Granularity

Imperative form represents a protocol's defined interaction as actions to be computed in the specified sequence. At this stage, our representation is still symbolic; actions do not necessarily correspond 1-to-1 with concrete operations in the target imperative language, and their representation of actions is unspecified as long as they preserve the properties of imperative form. To avoid under-specification, we represent actions at the coarsest granularity possible to avoid *over-specifying* the ordering of concurrent operations.

The simplest imperative form rules can be represented with a single action; implicitly, the rule has a trivial guard, and consists entirely of some guaranteed *assignment*. For example, a rule with a trivial data constraint may be represented as a single, trivial action; the rule always fires, to no effect.

Connectors become more complex as they rely on the creation of temporary variables. For example, consider a protocol in RBF with data constraint $\mathsf{X} = \mathsf{f}(\mathsf{X})$ and synchronization constraint $\{\mathsf{X}\}$ with only input (putter) port P. This rule can be understood as "X fires *if* the results of function f on its put-value is equivalent to the value itself". Here, the result of f clearly cannot be inspected until *after* it is computed. We are able to represent this rule with an action sequence of length three: (1) Create temporary value f_X by executing f given argument X. (2) Trigger an abort if $\mathsf{f}_\mathsf{X} \neq \mathsf{X}$. (3) The rule has fired; do nothing other discarding values X and f_X.

Valid Value Access

Imperative languages often prohibit using variables *prior* to definition. Usually, the only case in which a variables access becomes invalid if it goes out of scope. Rust and affine languages generalize this notion, working to keep track of the moment when a value is *consumed*, after which its access is invalid.

For our purposes, it is useful to allow values to *become invalid*. In the context of imperative form, this allows any actions to *empty* memory cells, as long as they still follow the rule (ie. they are able to *undo* the emptying). The motivation behind this extension is Reo's ability to express the access of the value of a memory cell both before and after it is overwritten. We are able to represent these kinds of interactions with sequential actions if we are able to *empty* a filled memory cell's contents elsewhere.

Ultimately, we elaborate our notion of value validity to correspond more closely with the actions an affine-typed compiler would perform: in reading over actions from top to bottom, *inaccessible* identifiers become *accessible* when their values are created, and accessible identifiers become inaccessible if their values are explicitly emptied. A variable access is valid only if it was accessible at the end of the previous action. This formulation makes clear the need of some means of deciding which values are *initially accessible*. Our solution is made apparent in the definition of IF to follow.

3.2.2 Definition

Here we define *imperative form* ('IF') concretely, and explain how its definition corresponds with the intuition behind it. Firstly, an IF contains a structure which corresponds to a *symbol table*; this does the work of assigning symbolic *data types* to ports and memory cells. Ports must also be annotated with an explicit *orientation* (ie. input or output). Other symbols are also represented here, for example, the names and the argument types for any named functions.

More interesting are the *imperative rules* listed for an IF. Each rule is given by (P, I, M) where:

1. **Premise** P
   A tuple of three *identifier* sets (P_R, P_F, P_E). P_R is the *synchronization constraint*, ie. the set of ports identifiers whose values must be 'ready'. P_F and P_E are the sets of *memory variables* which must be known to be full and empty respectively, such that it is known whether they can be read or written from. The rule can certainly not consider firing unless all ports are ready and all memory cells are in the specified states.

2. **Instructions** I
   A list of reversible *instructions* which are performed in sequence. These

instructions have no immediately observable effects, such that they can be reverted in the event of an *abort*. Concretely, each instruction is one of:

- $\mathtt{check}(p)$
  Trigger an *abort* if predicate p over data is satisfied.
- $\mathtt{fill}_P(m, p)$
  Fill an empty memory variable m with the result of a predicate p over available data. The value's data type is implicitly *boolean*.
- $\mathtt{fill}_F(m, f, a)$
  Fill an empty memory variable m with the result of invoking function f with parameters a, a list of references to data variables with length matching the arity of f. It is incorrect for f to *mutate* its arguments, as this would result in observable effects which cannot be rolled back.
- $\mathit{swap}(m_0, m_1)$
  Swap[3] the values in two memory variables m_0 and m_1.

If an abort is triggered by $\mathtt{check}$, any swapped memory cells are swapped back, and any memory cells whose values were created by $\mathtt{fill}_P$ or $\mathtt{fill}_F$ are destroyed.

3. **Movements** M
   A mapping from identifiers of *values* to the identifiers of getter ports and empty memory cells. This represents the final action of an imperative rule executed if and only if the rule *fires*.

Our definition represents an elaboration of the underlying concept. P and I contain only *transient* actions, which have no immediately-observable effects, and are able to handle the rule aborting such that their actions are *undone*. P is distinguished as it serves a dual purpose: (1) it establishes which values are initially *accessible*, and (2) it tersely expresses an immediate conditional abort in the event the ports and memory cells are not in the states defined. M is the final action, performed if and only if the rule commits. It defines what happens to all of the *accessible* values still 'in scope' at the end of the rule's execution. I contains everything else, representing an arbitrary sequence of transient computation. These actions are subject to handling the rule being aborted, and thus our definition includes only reversible actions. Data is prohibited from being irrecoverably lost during I-actions, as otherwise the actions could not be *undone* in the event of the rule aborting. This has three notable consequences:

[3] In principle, any reversible data-agnostic manipulation is possible, but swapping values is sufficiently expressive and intuitive for our purposes.

1. $\mathtt{fill}_F$ can only rely on *pure* functions, ie. their execution in and of itself must not be observable to the outside world.

2. $\mathtt{fill}_F$ and $\mathtt{fill}_P$ can only write to *inaccessible* values, ie. they cannot overwrite accessible values.

3. Accesses of any values must not mutate or consume the original, eg. using a value as an argument in $\mathtt{fill}_F$.

Conceptually, the final, committing action of the rule is able to perform any computation at all (provided it does not break any data-access rules) safe in the knowledge that its actions are allowed to be *irreversible*. However, our definition constrains what M can express significantly. M only defines the fate of the *accessible* values that remain after all other actions are performed. Essentially, M maps each value to the set of locations to which it is moved. This representation makes it trivial to distinguish the cases where values are discarded (0 destinations), moved linearly (1 destination) or replicated (multiple destinations). This design is convenient for languages that require their values to be more explicitly managed. For example, languages with *affine types* (eg. Rust) must simulate the replication of values by creating new affine resources from the original, and managing the replicas explicitly. *Relevant* data types (which must be used *at least once* [Wal05]) must handle empty destination sets by either emitting errors, or simulating destruction[4]. There are many other reasons a language may want to specialize the way its values are used. For example, an implementation in C++ may need to inject `free` calls to avoid leaking memory in cases where pointer-values are discarded.

As an example to demonstrate intermediate representation, the RBA rule in the previous section with data constraint $X = \mathtt{f}(X)$ and synchronization constraint $\{X\}$ can be represented in the imperative-form rule with:

	value
premise	$(\{X\},\ \{\},\ \{\mathtt{f}_X\})$
instructions	$[\mathtt{fill}_F(\mathtt{f}_X, \mathtt{f}, [X]),\ \ \mathtt{check}(X = \mathtt{f}_X)]$
movements	$\{X \to \emptyset,\ \ \mathtt{f}_X \to \emptyset\}$

3.3 Translation Pipeline

In this section be describe how Reo's internal representation ('IR') of protocol specifications is translated to a Rust protocol object. As per the design in

[4] A relevant language may simulate the destruction of a value by moving it to some `Destroyed` destination with special semantics.

Section 3.1, this process involves generation steps partitioned over two distinct phases with imperative form ('IF') in-between. Here, we describe this process beginning to end. Throughout this section, we refer to the generation process in terms of its three distinct subtasks $\{T_{seq}, T_{type}, T_{run}\}$, defined in Section 3.1.1.

3.3.1 Reo Compiler Backend

We extend the Reo compiler with a backend for translating IR to Rust source on which the end user may depend. In this phase, the work is primarily concerned with restructuring IR to IF, involving two of the three sub-tasks for generating to a particular imperative language target, namely T_{seq} and T_{type}.

Action Sequencing

T_{seq} necessitates transforming a each of the protocol's rules into a sequence of symbolic actions. The most significant work occurs as a result of how differently *values* are represented. IR is declarative, representing the result of a rule's firing as an *assignment*, mapping *destinations* (getter ports and empty memory cells) to *terms*. IR already represents a significant transformation from RBF in isolating these values on a per-destination basis.

To begin, we describe the naïve approach to translate IR to IF a rule at a time.

Our translation procedure initializes all three fields $\{P, I, M\}$ of an imperative rule as initially-empty, and populates them incrementally by recursively traversing the IR rule's assignments. Each such assignment is ultimately represented in M, where *terms* are rather represented by identifiers. For some terms the mapping to identifier is trivial. For example, the value put by a port can use the identifier of the port itself. For others, it may be necessary to introduce *fresh* identifiers, representing *temporary variables* to be created. In either case, the *term* is traversed recursively to (1) collect these identifiers, and to (2) populate the premise P such that the rule is fired given access to all of the relevant memory cells and ports.

I is populated last by three kinds of actions. Firstly, the exceptional cases for which memory variable q will be both read and written to are treated. If necessary, a fresh temporary variable is introduced by appending an instruction $swap(q, q_{temp})$ where q_{temp} is some fresh variable; q's previous and next values may be read and written unambiguously, distinguished by identifiers q_{temp} and q respectively. Second, I is appended with $\mathtt{fill}_P$ or $\mathtt{fill}_F$ instructions to create every other temporary variable in a manner befitting the *term* that represented them in the IR's assignments, ie. the result of invoking a function with port values as arguments. Finally, I ends with a single $\mathtt{check}$ to evaluate the rule's guard, initiating an abort if it is evaluates to *false*.

As it was described thus-far, our procedure is able to correctly render any IR rule in IF with the necessary properties. For the sake of minimization or performance at runtime, at least three optimization opportunities may elaborate on this procedure, producing semantically-equivalent results.

1. Terms that occur repeatedly within assignments throughout the same IR rule may have their **values deduplicated** by assigning them all the same *identifier*. Care must be taken to ensure that the instruction to create its value is inserted only once, sufficiently early that its creation precedes its *earliest* access. Note that each original occurrence still corresponds with a *destination* in the resultant M mapping. To clarify, consider the example with getter ports A and B both assigned terms corresponding to $\mathsf{f}(\mathsf{C})$ where f is some function and C is a putter port. Here, one temporary variable f_C to store the result of $\mathsf{f}(\mathsf{C})$ is sufficient; it is simply moved to two distinct destinations, reflected in the mapping $\mathsf{f}_\mathsf{C} \rightarrow \{\mathsf{A}, \mathsf{B}\}$ in M.

2. The large, monolithic *check* instruction that acts as a guard to the rules firing can be fragmented into **numerous guard instructions**. The utility of this is the ability to re-arrange their ordering. For best results, it is beneficial to move checks as early as possible, such that less work is performed prior and subsequently to an abort whenever the check *fails* at runtime. To be correct, care must be taken not to move guards so early such they precede the creation of any temporary variables their evaluation accesses. For example, consider an IR whose guard is $\mathsf{A} \wedge \mathsf{B}$, where A and B are sub-formulas that reason about sub-terms whose evaluation necessitates the creation of temporary values t_A and t_B. By fragmenting $\mathsf{check}(\mathsf{A} \wedge \mathsf{B})$ into $\mathsf{check}(\mathsf{A})$ and $\mathsf{check}(\mathsf{B})$, we are able to move the former such that it follows the creation of A, but not of B. Effectively, the rule is able to *short circuit* its evaluation at runtime, circumstantially avoiding the creation and destruction of the temporary value identified by t_B.

3. **Static analysis** of values may conclude that a *check* instruction is a tautology, making it safe to omit. Similarly, the presence of even one contradictory *check* makes it possible to discard the rule entirely. This optimization is particularly useful in combination with optimization (2).

Type Classification and Constraining

Our backend performs task $\mathsf{T}_{\mathsf{type}}$ to generate the IF such that the identifier of every port, memory cell, and temporary variable is assigned a symbolic type annotation, such that:

1. the types of identifiers match if they exchange values or are checked for equivalence.

2. data types are boolean if they occur in a context in which only boolean-types are permitted, ie. as the predicate of a formula.

3. the type defines all the operations in which it may be involved at runtime. This includes operations for *replication*, checking *equality* of values and so on.

Our backend performs this work in tandem with the work of T_{seq} described in the previous section. Initially, every identifier is assigned s fresh symbolic type with no constraints, representing a data-type unrelated to any other, and having no need of any defined operations. In traversing the IR rules, *constraints* are collected, associating them to the relevant identifiers. Incrementally, *type constraints* are collected, accumulating requirements for the properties of types. For example, the type associated with a value is checked for equality, irrevocably acquiring the `eq` constraint, marking the need for it to define an operation to check value-equality. In some cases, a relationship between identifiers causes their types to be *unified*. For example, a data-movement from putter P to getter G unifies their types, resulting a new type with the union of their constraints. If the requirements on types are *contradictory*, an error is emitted by the Reo compiler. For example, it is an error to provide types A and B with different explicit data type annotations, yet have them exchange data.

Ultimately, the constructed IF associates a symbolic type with every mapping in its symbol table.

Delegated to the Rust Compiler

Section 3.1.3 explains that our current implementation of the Rust backend for the Reo compiler makes the temporary simplification of emitting Rust source code directly. This approach adheres with the Reo compiler's idiom of code generation per target language, but also it simplifies our work overall as we are able to effectively *delegate* some of the translation work to the Rust compiler itself. Both of these simplifications are inspired by Reo's Java code generator, whose direct-to-Java code generator delegates these tasks to the Java compiler in the same manner:

1. **Parsing**
   Per our design, IF should be emitted in a format agnostic to the imperative language target; good contenders are common data serialization formats such as JSON or YAML. Ultimately, IF is translated to the syntax understood by the target language such that it can be integrated into the user's programs. While Rust is the only language target, we are able to unify these steps by emitting Rust syntax as a usable dependency directly.

2. **Type Resolution**
   Our symbolic data types are exposed as *generic types* in the emitted source; effectively, the end-user's Rust compiler makes concrete these symbolic types at the call site, as is idiomatic in the Rust language.

The second task is most interesting, as care must be taken to represent our generic types in a manner that the Rust compiler will accept. Previously, we described how requirements on our symbolic types are discovered throughout T_{type}. Here, these constraints are communicated to the Rust compiler in the generated syntax. This delegates the task of enforcing these constraints to the end-user's Rust compiler. Listing 11 gives an example of a signature for a Reo-generated Rust function with constrained generic types `X` and `Y`. Observe that the majority of the functions contents are the definition of a `ProtoDef` type, which is the Rust-embedding of our IF.

3.3.2 Rust Library

Our work follows the precedent set by the Java code generator in relying on a library in the target language to define the lion's share of the behavior for our runtime protocol objects. For Rust, these definitions are bundled into the **Reo-rs** library, which is added as a dependency to the code generated by the Reo compiler's backend. Chapter 4 explores the architecture and behavior of our executable protocol objects in detail. For now, it suffices to say that our approach is to represent executable protocols as extensively preprocessed *data structures* which then drive the behavior of a lightweight *interpreter* at runtime. This data-representation is often called *commandification* [Nys14].

Protocol Initialization

Listing 11 gives an example of Reo-generated Rust source. Previously, we explain how this representation delegates some of the work of T_{run} to the Rust compiler itself. The remainder of T_{run} is defined in the `build` procedure (visible is the listing on line-23) such that this work is performed at runtime whenever a protocol is *instantiated*. As can be seen in the *return value* of the function in the listing, the end result is the construction of `ProtoHandle`, a handle to an *executable* protocol object, whose properties are explored in Chapter 4.

At this level, the specification used to `build` the `Proto` is split into two distinct types: `ProtoDef` and `MemInitial`. The former describes its *behavior*, corresponding most closely with the conceptual design of IF. The latter isolates a simple structure which contains pre-allocated values for the finished *protocol object*; in effect, it provides the initial values of memory cells. These structures are distinguished for only one reason: `ProtoDef` contains no *values*, such that

```
pub fn build_protocol_1<T: Clone>() -> ProtoHandle {
    ProtoDef {
        let type_info = TypeInfo::of::<T>();
        name_defs: hashmap! {
            "P" => Port { is_putter:true, type_info },
            "C0" => Port { is_putter:false, type_info },
            "C1" => Port { is_putter:false, type_info },
        },
        rules: vec![RuleDef {
            state_guard: StatePredicate {
                ready_ports: hashset! {"P", "C0", "C1"},
                full_mem: hashset! {},
                empty_mem: hashset! {},
            },
            ins: vec![],
            output: hashmap! {
                "P" => (false, hashset!{"C0", "C1"}),
            },
        }],
    }.build(MemInitial::default()).unwrap()
}
```

Listing 11: Example of a Reo-generated Rust output for a simple connector which replicates values of port P to ports $\{C0, C1\}$. The user is able to construct `ProtoHandle`, a handle to an executable protocol object by invoking function `build_protocol_1`. The caller determines the concrete choice of the generic type `T`, but the Rust compiler will enforce that this choice is constrained such that it implements `Clone` (the type's values can be replicated). The contents of the function consist predominantly of the construction of an instance of `ProtoDef`. In combination with `MemInitial`, these types represent the Rust-embedding of the protocol's imperative form specification.

it can be accessed by `build` in a read-only fashion. Although it is not taken advantage of by the Reo-generated program, one is able to define a protocol's behavior *once* to be used for the construction of any number of `Proto` instances.

`Proto` represents the ultimate departure from its original, declarative protocol specification whose purpose is to facilitate execution. Its creation from `(ProtoDef, MemInitial)` involves the last remaining sub-tasks of $T_{\mathtt{run}}$:

1. `Proto` is constructed along with data structures necessary for basic operations at runtime. This includes semaphores, channels for *control messages* and so on. This minutia is detailed in Section 4.3.3.

2. In construction, the behavioral specification (ie. imperative form rules) are *preprocessing* to a form more conducive to efficient execution. For example, symbolic names are replaced with indices, pointers and keys into concrete data structures. The *soundness checks* in the section to follow can be considered preprocessing also, as they ensure a `Proto` is constructed such that it is internally-consistent, ensuring various runtime properties are invariant and need not be checked at runtime.

Soundness Check

Our backend is novel in that the work of constructing the executable protocol object requires crossing an API-boundary. Rather than trusting the well-formedness of the Reo-generated `ProtoDef`, Reo-rs will check that its input is internally-consistent. By adding these checks, the dependency between the Reo compiler and Reo-rs is *unidirectional*; users are free to safely construct protocol objects using Reo-rs in their applications directly. The most obvious advantage to this approach is an additional layer of safety, allowing for the compiler and Reo-rs to be maintained separately, eg. if the compiler acquires a bug from a new update, the error cannot propagate into Reo-rs unnoticed. Another advantage is the avenues for future work this opens up. Our approach treats protocol structures as data, facilitating their mutation at runtime, resulting in *dynamic protocol reconfiguration*, although exploring this further is beyond the scope of this work.

In native Rust, the usual variable scoping rules apply to ensure that a symbolic identifier is resolved to a meaningful memory position. These systems are so familiar to us that we usually take the complexity of their work for granted. Rules that are second nature to us require explicit enforcement to replicate the work of the checker. As `ProtoDef` *commandifies* the behavior to be later executed, the Rust compiler does not interpret these actions in the normal way, and we must mimic its behavior manually. We take this idea a step further by relying on the `ProtoDef`'s *premise* to facilitate a mechanism that mimics the Rust *borrow checker* system; rules trace which variables are *valid* (ie. initialized) throughout the rule's execution top to bottom, tracking changes as a result of actions filling or swapping their values. In this manner, we are able to catch invalid memory accesses during `build`, rather than encountering them at runtime. An additional perk of mimicking this system is our ability to detect the occurrence of values which *must* be consumed during the rule's firing, but whose consumption is not included in the specification. For example, an *imperative rule* may include some putter port `P` in its ready-set (and thus, its synchronization constraint), but associate no *movement* with `P`'s value. A naïve implementation which overlooks such occurrences may introduce *memory leaks* for such cases if it takes the specification at face value. Instead, our custom borrow checker will reach the end of of the specified actions and conclude that as P was not explicitly emptied, it will insert a trivial movement $P \mapsto \{\}$ to ensure the value is consumed. This is analogous to how Rust's borrow checker inserts `drop` calls to destroy local variables which go out of scope unconsumed. By performing this extensive checking, Reo-rs affords an expressive `build` function, capable of giving detailed error information in response to an invalid input. The signature of this function is given in Listing 12.

```
fn build_proto(&ProtoDef, MemInitial) -> Result<ProtoHandle, BuildError>;
type BuildError = (Option<usize>, BuildErrorInfo);
enum BuildErrorInfo {
    ConflictingMemPremise { name: Ident },
    PutterCannotGet { name: Ident },
    MovementTypeMismatch { getter: Ident, putter: Ident },
    GetterHasMuliplePutters { name: Ident },
    InitialTypeMismatch { name: Name },
    /* 15 more variants */
}
type Ident = &'static str; // static string literal type
```

Listing 12: Signature of the `build` function. Its inputs are (1) an immutable reference to a `ProtoDef`, which is used to determine the protocol's behavior, and (2) a `MemInitial`, which stores initialized memory cells to be incorporated into the protocol's state. The return result is an enumeration type, returning `ProtoHandle` upon success, and a tuple on failure, whose elements are, respectively (1) the index of the imperative rule where the error occurred if applicable, and (2) another sum type, communicating the nature of the error with additional information.

By restricting our API such that all executable protocol objects are *only* created by `build`, our runtime interpreter is able to rely on the properties we guarantee and avoid checking them itself. In this way, checking for soundness is also an optimization.

Chapter 4

Protocol Runtime

Previously, Chapter 3 described how a Reo protocol specification is translated by the Reo compiler into the Rust language as an executable *protocol object*. In this chapter we discuss how these objects are able to act as the *communication medium* between a set of communicating *components*. This approach allows the user's component code to exchange data with its environment through the protocol object's exposed *ports*. Components make no assumptions about the world beyond their ports, and consequently, have no notion of the system in which they play a part. From a user's perspective, ports are entirely opaque, and their components may use them to exchange data with their environment without any concern for global coordination.

Internally, protocol objects orchestrate the actions on their boundary ports into *interactions* defined by its protocol specification. As much as possible, the protocol will work to facilitate data flow. However, whenever a boundary port initiates an action which does not yet fall into a suitable interaction, the protocol exercises its power to *block* its completion until the time is right.

Section 4.1 begins by examining the Reo-generated protocol objects for the Java language, allowing us to use this previous work as a touchstone for our own. Within, Section 4.1.3 observes opportunities for our implementation to improve upon it by the addition of safety properties, and exploiting opportunities for optimization. Section 4.2 makes our goals explicit by defining the requirements and guidelines used to inform our design process and determine the assumptions used to facilitate out implemented optimizations. Section 4.3 follows with the implementation of the **Reo-rs** library, which defines our protocol and port objects. Within, Section 4.3.1 explains how we leverage Rust's affine type system to expose a safe user-facing API. Sections 4.3.2–4.3.4 explain how the protocol object behaves at runtime, detailing the implementation of optimizations which enable it to (1) coordinate actions without needing a dedicated thread, (2) increase parallelism by delegating data movement to component threads, and (3) internally perform reference-counting and -passing while preserving Reo's semantics. Finally, Section 4.4 gives an overview of how our requirements and guidelines are satisfied, including references to the sections containing the relevant details.

4.1 Examining the Java Implementation

The Reo compiler has seen extensive development for its Java code generator in particular. In this section, we examine the properties of the source code it generates. Later, Section 4.1.3 makes particular note of opportunities for our own version to improve upon this design, or at least deviate to the end of specializing its implementation to better suit the Rust language.

4.1.1 Architecture

Fundamentally, the generated code adheres closely to Reo's literature, revolving around the interplay between `Port` and `Component` objects. From the perspective of a developer looking to integrate a generated Java protocol into their application, the entry point is the `Protocol` component (where 'Protocol' is the name of the associated Reo connector).

Running a system requires an initialization procedure: (1) a `Port` is instantiated per logical port, (2) a `Component` is instantiated per logical component, and (3) pairs of components are linked by overwriting a port-field for both objects with the same instance of `Port`. To get things going, each component must be provided a thread to enter it's main loop; in idiomatic Java, this manifests as calling `new Thread(C).start()` for each component `C`. A simplified example of the initialization procedure is shown in Listing 13 for the simple 'sync' protocol which acts as a one-way channel. In this example, the ports are of type `String`.

In a sense, this implementation primarily hinges on `Port` as a communication primitive between threads, and equivalently, between components. For matters of concurrency, operations on port-data involves entering a *critical region*. In contrast, `Components` are used only to store their ports and to be used as name spaces for their `run` function which implements their behavior (which corresponds to RBA rules in the case of the protocol component). Essentially, anything that interacts with `Port` objects can reify a logical component, whether or not this is done by an object implementing the `Component` interface.

4.1.2 Behavior

The representation of protocol rules is very intuitive; a rule is implemented as a block of code which operates on a component's ports. Once generated into

```java
Port<String> p0 = new PortWaitNotify<String>();
Port<String> p1 = new PortWaitNotify<String>();

Sender c0 = new Sender();
Receiver c1 = new Receiver();
Sync c2 = new Sync();

p0.setProducer(c0); c0.p0 = p0;
p0.setConsumer(c2); c2.p0 = p0;
p1.setProducer(c2); c2.p1 = p1;
p1.setConsumer(c1); c1.p1 = p1;

new Thread(c0).start();
new Thread(c1).start();
new Thread(c2).start();
```

Listing 13: A simplified example of initialization for a system centered around a `Sync` protocol object, which acts as a channel for transmitting objects of type `String`. Both ports and components are constructed before they are 'linked' in both directions: each port stores a reference to its components, and each component stores references to its ports. The system begins to *run* when each component is given a thread and started.

Java, the only obvious sign that a component was generated from Reo is its linkage to multiple other components[1]. The (simplified) generated `Component` code of the 'sync' protocol from the previous section is shown in Listing 14. This demonstrates that rules are indeed *commandified*, in that their behavior is encoded in discernible structures (appropriately called `Command`).

The behavior and structure of a component go together, and are generated by Reo at a relatively granular level. As such, the encoding of memory cells is natural also. Memory cells can be found next to ports in the fields of a `Component`.

4.1.3 Observations

Reo-generated Java objects have a very clear correspondence to their declarative Reo specification. This carries over to how components and ports are used by an application developer. For example, Port objects act both as points of

[1] The distinction between 'protocol' and 'compute' components is tenuous at the best of times. If compute components are allowed to interact directly with one another, the distinction observed here disappears also.

```
private static class Sync implements Component {
    public volatile Port<String> p0, p1;

    private Guard[] guards = new Guard[]{
        new Guard(){
            public Boolean guard(){
                return (p1.hasGet() && (!(p0.peek() == null)));
    }   },  };

    private Command[] commands = new Command[]{
        new Command(){
            public void update(){
                p1.put(p0.peek());
                p0.get();
    }   },  };

    public void run() {
        int i = 0;
        while (true) {
            if(guards[i].guard())commands[i].update();
            i = i==guard.length ? 0 : i+1;
            synchronized (this) {
                while(true) {
                    if (p1.hasGet() && (!(p0.peek() == null))) break;
                    try {
                        wait();
                    } catch (InterruptedException e) { }
}   }   }   }   }
```

Listing 14: A simplified example of a Reo-generated Java protocol class for the *sync* connector. By convention, it is started by invoking `start`, which is a method inherited from the `Runnable` interface which `Component` extends. This method assumes that all ports are correctly initialized and linked to another 'compute' port. Its RBA-like behavior comes from an array of guards and commands which it iterates over in a loop, firing rules as possible forever.

data exchange and as primitive concurrency mechanisms aligning *put* with *get*. From this design, we observe the following noteworthy properties:

1. **Protocol Event Loop**
   Protocols are fundamentally *passive* in that they do not act until acted upon. Nevertheless, protocols each have their own dedicated thread that waits in a loop for a *notification* from its monitor. Notifications originate from a component's own `Ports` in the event of a `put` or `get` invocation. For this reason, protocols and components are related in both direc-

tions, afforded by setting a port variable in one direction, and functions `setProducer` and `setConsumer` in the other.

True to the intuition behind the RBA model, the protocol must *check* which (if any) commands can be fired, and keep spinning, trying rules while *any* guard is satisfied. This is unfortunate, as this approach requires guards to be evaluated repeatedly. As the protocol relies on the actions of other components to make progress, it is counter-productive for it to spend a lot of system resources evaluating guards to *false*. In cases where threads must share processor time, the excessive work of the protocol component will begin to get in the way of other components making progress, in turn leading yet more guards to evaluate to *false*.

2. **Reference Passing**
Java is a managed programming language whose garbage collector is central to how the language works. To support the transmission of arbitrary data types, `Port` is generic over a type. The language only supports this kind of polymorphism for objects. Unlike primitives (such as `int`), the data for objects is stored on the heap and is garbage collected by the Java Virtual Machine. Variables of such objects are therefore moved around the stack by *reference*. Moving and replicating values is cheap and easy, as they always have a small (pointer-sized) representation on the stack.

   A minor drawback is the need for indirection when performing operations that need to *follow* the reference. For example, comparing two `Integer` objects requires that the `int` primitives backing them on the heap be retrieved and compared. Equality is an example of an operation that the Reo protocol thread can be expected to perform frequently. The cost of this indirection depends on a myriad of factors, but is at its worst when it results in new, spread-out locations each time. This case might arise, for example, if the `Sender` continuously created new `Integer` objects and sent them through its port. Another drawback is the *requirement* to allocate primitives on the heap before they can be sent through a port. This is not usually a problem in the case of Java, as in practice, almost everything is going to be stored on the heap with or without Reo.

   This aspect of the generated Java code will require the most change for the Rust version, as Rust has a very different model for memory management; it does not use a garbage collector by default, and structures are stored first and foremost on the *stack* as in the C language.

3. **Two Hops for Data**
As protocols are components like any other, even the most trivial of data-movements require values to hop at least twice: into the protocol, and out

of the protocol. Fortunately, as stated above, the cost of the 'hop' itself is trivial, as it will always be a small reference. The problem is the time delay *between* the hops, as it will often involve actions of three distinct threads in series (with the protocol in the middle).

4. **Vulnerable to User Error**
   The construction and linking of components with ports is not something the protocol itself is concerned with. Indeed, *every* component assumes that their port-variables will be initialized by their environment. At the outermost level, this environment is in the application developer's hands. Components make no attempt to verify that they are correctly linked according to the specification; currently, there is not any infrastructure in place to support this checking if it were desired. As a result, it is possible make mistakes such as fusing two of a protocol's ports into one. Whether this is a problem worth solving depends on the burden of responsibility that Reo intends to place on the end user. These difficulties cannot be completely avoided, but approaches exist to minimize these opportunities for mistakes.

   While ports are clearly directional 'from the inside out' (ports store distinct references to their producer and consumer components), the same is not so 'from the outside in'. Neither of a port's components is prevented from indiscriminately calling `put` or `get`. The assignment of a port's values for 'producer' and 'consumer' component is in user-space also. As a consequence, these fields may not agree with the components that interact with the ports at all. In fact, any number of components may store a reference to a port, each arbitrarily calling `put` and `get`. If done unintentionally, this would lead to *lost wakeups*; the thread blocking for a notification after calling acting on the port is not the same as the thread receiving the notification. Solutions can be conceived to *wrap* ports in objects that constrain the API of a port to one of the two 'directions'. However, without affine types, there is no obvious way to ensure the *number* of components accessing a port is correct. In Rust, limiting these accesses becomes feasible.

5. **Port Data Aliasing**
   In Reo, it is common for connectors to replicate port data. Owing to the nature of Java, this is currently achieved by duplicating references, where replication is also known as *aliasing*. For immutable objects, aliasing has no observable side effects, and thus does not threaten Reo's value-passing semantics. However, Reo ports permit instantiation with *any* object-type. Even if the operations are thread-safe, this causes *incorrect* behavior, as a component might observe their data changing seemingly under their

feet. Worse still, objects which are not thread-safe can cause undefined behavior. This is a result of Java's view on memory safety having inverted priorities to Rust. In Java, operations are unsafe by default, and the programmer must go out of their way to protect themselves from data races, access of invalid memory and corruption. In Rust, the *ownership system* is based on the prohibition of mutably-aliased variables. Achieving replication in Rust will require some effort to convince the compiler of safety before a program will compile.

6. **Non-Terminating Protocols**
   Currently, Reo-generated protocol objects loop forever unless they raise an exception and crash. For protocols that can perform actions with observable side-effects in the absence of other components, this is perhaps a good idea. However, in the majority of realistic cases, protocols are indeed passive, and cannot do meaningful work as the only component. Reo semantics tend to reason about *infinite* behaviors. However, real programs often do *end*, and it is desirable that the program's exit is not held up by an endlessly-blocked protocol thread.

7. **Protocol Components Cannot be Composed at Runtime**
   (TODO is this the place to explain this?) Ports allow data to move from the putter (or 'producer') and getter (or 'consumer') components as an *atomic* operation by delaying `put` or `get` operations until their counterpart is called also. This causes problems for the implementation of RBAs with rules whose guards are predicated by the data they move. How can a protocol *decide* if it should fire as a function of values it can only obtain *by* firing? This ability to reason about the future is currently still a luxury limited to models such as TDS. The Java implementation gets around this problem by introducing *asymmetry* between 'compute' and 'protocol' components. Protocols are allowed to *cheat*. The `Port` object has additional operations to inspect a value without consuming it: `peek` and `hasGet`. However, this asymmetry means that composing two Java protocol components (by linking them with ports) does *not* result in a component with their composed behavior. Solving this problem in earnest requires continuously-connected protocols to reason about their distributed state, which is a problem beyond the scope of this work. Reo's relationship with *liveness properties* is explored in Section 6.

8. **Sequential Coordination**
   The Java implementation is structured such with *ports* being the critical region between components. As protocols have multiple ports, at first glance it may appear that coordination events could occur in parallel.

However, no communication through protocol `P` happens without the single thread in `P`'s `run` method. Indeed, `put` and `get` operations can be *started* in parallel by the boundary components, but `P` can only complete it's half of these operations sequentially.

4.2 Requirements and Guidelines Defined

Following the observations of Roe-generated Java objects in Section 4.1, we identify and make explicit the design choices and goals that inform the design and implementation of our own protocol objects for the Rust language. First, we identify a number of functional requirements, representing the goals which can be assessed for satisfaction without ambiguity.

$\mathbf{R}_{value}$ Preserve Reo's value passing semantics. No user interaction should contradict these semantics. This precludes data races as a result of *mutably aliasing* resources which the user considers to be independent values.

$\mathbf{R}_{init}$ Prevent the protocol from being initialized in an inconsistent state. Prevent port objects from being unitialized, unsafely accessed in parallel, or incorrectly connected to the protocol.

$\mathbf{R}_{ffi}$ Facilitate a foreign function interface with other systems languages C and C++. Ports and protocol objects should be accessible from those languages as well as Rust, such that they can be constructed, used and destroyed.

Not all useful properties can be meaningfully quantified by strict requirements. For such properties, satisfaction is instead *motivated*. We identify a set of *guidelines* intended to focus the design process, and to form a basis for the assumptions that make meaningful optimizations possible. By their nature, these guidelines cannot be clearly satisfied. Instead, the extent to which guidelines are satisfied is *motivated* by argumentation, and supported by experimental evaluation in Chapter 5 where applicable.

$\mathbf{G}_{data}$ Allow the transmission of large data types without requiring the user to move them from the stack to the heap. Minimize the number of times data must be *moved* in memory such that data transmission remains performant for types with large representations.

$\mathbf{G}_{fast}$ Minimize the overhead of *control operations* for the protocol object to route payloads and perform bookkeeping. In particular, minimize the cost of *evaluating* the rules before one is selected for firing.

G_{end} Facilitate the protocol object being destroyed and its resources freed. Facilitate a means of detecting termination which is correct and ergonomic.

4.3 Protocol Objects

Here, we detail the structure and behavior that cause our Rust protocol object type, `Proto`, to coordinate the actions of boundary ports at runtime in accordance with its associated Reo specification. Section 4.3.1 details the user-facing API, and explaining how its helps to provide safety properties. Protocol objects offer an expansive design surface, and so Section 4.3.2 relates our implementation at a conceptual level to that of the Java version that came before. Section 4.3.3 lays out the structural definition of `Proto`, which is relevant for understanding its connection to the code generation process and *imperative form* explained in Chapter 3. Finally, Section 4.3.4 details the implementation of `Proto`'s behavior at runtime, explaining the roles of the boundary components, how actions are arranged into interactions, and the effects of our implemented optimizations.

4.3.1 Application User Interface

The Reo compiler generates protocol descriptions in imperative form, which then are transformed by Reo-rs into runnable objects. The user therefore interacts mostly with Reo-rs itself, and Reo provides only the entry point for building particularly instances of protocol object. In this section we explain which functionality of Reo-rs is user-facing, focusing primarily on which requirements are satisfied.

Construction and Destruction

Reo-rs is built to interface with the Reo compiler, but it is not dependent on it. The entry point for protocol objects is the `ProtoDef` type, which is a concrete realization of the (logical) imperative form. For a concrete example, the previous chapter includes Listing 11, exemplifying a `ProtoDef` representation of a simple imperative form. Regardless of whether the constructed `ProtoDef` was Reo-generated, it is instantiated along with any initial memory cells (in the `MemInitial` structure) to produce a `ProtoHandle`. This type has a small, pointer-sized shallow representation (ie. 32 or 64 bits) to the `Proto` structure on the heap. The handle is opaque to the user, at first glance offering no functionality other than replication (safely aliasing the `Proto`) or destruction. If the the last handle to a `Proto` instance is destroyed, all of its resources are freed. This is achieved by relying on the Rust-idiomatic `Arc` type, ('atomic reference-counted') for the definition of `ProtoHandle`.

The protocol remains inert until the user acquires some of its *ports*. However, they cannot be constructed independently. Instead, the user must invoke `claim` on a `ProtoHandle`, which identifies the port through the inclusion of a parameter specifying the port's logical *name*; this corresponds with the symbolic name as it appears in the imperative form. By encoding both its *orientation orientation* (ie. `Putter` or `Getter`) and its *data type* as type parameters for each port object, `claim` is able to reflect on these properties and return an error (Section 2.2.2 explains how Rust represents exceptions with enumeration types) if the port's properties are incongruous with the protocol's definition, or if the port of that name is currently claimed. Similarly, port objects notify their `ProtoHandle` that their name is again available to be claimed in the event of their destruction. All together, this API is able to guarantee that (1) every logical port has at most one port object at once, and that (2) the types of ports enforce that their orientation and data type align with their specification.

`Proto` objects are stored on the heap, but their *ownership* is shared between all of their existing `ProtoHandle`s. Internally, ports contain a `ProtoHandle` each also. These handles are thin wrappers around Rust's `Arc` ('atomic reference-counted') type, ensuring that the handles are moved, acted upon and destroyed in a thread-safe manner. Once the last handle is destroyed, the `Proto` is destroyed also, freeing all of its resources in the process without a trace. `Proto` objects do not rely on any static variables, allowing any number of them to be instantiated and used throughout a program without them interfering with one another's execution (except, of course, their sharing of the underlying hardware resources).

Port Operations and Variants

The API that defines `put` and `get` operations for ports is *partitioned* over port types in the expected way. Concretely, ports are represented in Reo-rs by distinct types `Putter<T>` and `Getter<T>`, each generic over their data type, where `get` is only defined for getters, and `put` is only defined for putters. In both cases, the operations rely on Rust's *borrowing* rules to ensure that even if the port objects is shared within the user's program, it is impossible to act on a port from two threads concurrently (without circumventing the Rust compiler with *unsafe* operations). For example, the signature of `get` is specifies that the getter is accessed via a *mutable reference*[2] (written `&mut`).

The `get` operation blocks the calling thread until an element of type `T` is returned. Users are able to customize their involvement in the interaction by

[2]This terminology is often confusing; dispite the name, 'mutability' is more often used to mean 'mutually-exclusive', as is the case here. The Rust compiler will only permit this operation in a context where it is certain that the port is not concurrently being used elsewhere.

invoking one of `get`'s *variants*. For example, `get_timeout` blocks the thread up to a specified *timeout*, and returns an `Option<T>` to distinguish success from failure. The latter case represents the failure to participate in an interaction, allowing the caller to reclaim the control flow and continue working. Getters also have the option of calling `get_signal`, which expresses a wish to participate in an interaction, but no desire to acquire the datum. The utility of this option is that Reo-rs will attempt to avoid the work of acquiring the value at all, potentially avoiding a `clone` operation and other associated overhead (explained in Section 4.3.4). The effects of this variant on performance are shown in Section 5. `get_signal_timeout` is also available, and behaves as expected.

Similarly, putters have access to `put_timeout`, which varies from `put` in the expected way. Both operations have the potential to return the putter's value. This may occur even if the value was involved in an interaction, but was not acquired by any getters. Returning the value allows the user's program to decide what to do with the value. For example, a user may decide to put the value again until it is read. If this behavior is undesired, putters offer the `put_lossy` and `put_timeout_lossy` variants which will not return the value regardless of the actions of getters, *dropping* it if needs be.

Value-Passing API Semantics

The Rust language conflates the movement of values to new variable bindings with two meanings: (1) the value's ownership is transferred to the new binding and scope, and (2) the value's shallowest representation is moved in memory. Reo's semantics require that the data transmitted through ports is truly *moved*, transferring ownership. Clearly, not doing so would violate Reo's semantics; values acquired through ports might be *dropped* or acted upon at the whims of their original *putter*, of which the getter would have no knowledge. As is idiomatic for the Rust language, our API transfers ownership into the scope of `put` and out of the scope of `get` by moving the value itself. Naïvely, this has significant performance implications, as the cost to move a value is dependent on the size of its representation. For example, a 10MB array is significantly more costly to move than a byte. For cases where the relocation of bytes is not necessary, Rust programmers can often rely on LLVM to optimize the memory movements away, passing consumed resources by reference 'under the hood' (but retaining the semantic movement of ownership). However, these optimizations are not guaranteed. Users of the Rust language have grappled with this shortcoming for years, but the search for a satisfying solution remains an open problem [Mat15]. The only way to guarantee that the data is passed by reference at runtime is to expose an *unsafe* API, which relies on the user to pass references and manage the associated ownership manually. Our requirements prioritizing safety ($\mathbf{R}_{value}$) and performance ($\mathbf{G}_{data}$) are in conflict. Our solution is to compromise by exposing these options to the user as variants for `put` and `get`, and allow them to decide on a case-by-case basis:

1. **Value passing.**
   We expose safe functions `put` and `get` to consume and return data *by value*, guaranteeing correctness. Depending on the compilation environment, it may require up to two moves of the data.

2. **Reference passing. User provides correctness.**
   Operations are parameterized by *references* (or raw C-like *pointer* types) which Reo-rs writes to and reads from directly. The caller takes responsibility for ensuring that the value at the pointer's destination is initialized or *dropped* as necessary to correspond with Rust's usual ownership system. For example, this version of `put` is given a pointer to initialize memory, which the operation will initialize.

3. **Value pass a 'referring' type.**
   As far as Reo-rs is concerned, this is indistinguishable from case (1). However, the user intentionally re-interprets the data types of their ports such that they represent indirections. For example, `Box<T>` is a pointer-sized owned type which will be transmitted by Reo-rs much like any other pointer-sized integer, oblivious to the fact that it indirectly represents another type `Q`. Taken to the extreme, a naïve solution replaces all data types with heap-allocated indirections, inheriting the associated downsides shared with the Java implementation. Other approaches may be simple (eg: transmitting an index to a shared vector) or arbitrarily complicated (Several Rust libraries exist for decoupling an object's data from its *ownership*, such as `rent_to_own`, `managed` and `swapper`[3]).

To reflect our prioritization of safely, the 'default' port operations use value passing, corresponding to options (1) and (3). Users are able to take safety into their own hands by opting-into `*_raw` port operation variants. We rely on Rust's idiom of marking such operations as *unsafe*, communicating to the user that they are adopting the responsibility of reading the API documentation to determine and provide the necessary guarantees, as is ususal in languages such as C; this keyword requires the user's code to be explicitly qualified as an *unsafe* block, making it impossible for them to easily overlook this requirement.

Interface with C and C++

Programming languages rely on an *ABI* (application binary interface) for translating functions and types into binary according to a dependable convention.

[3] These libraries are publically available on `crates.io`.

When languages agree on this interface, it ensures that both caller and callee with agree on the minutia of the calling convention, and how structures are laid out in memory. It is common for Rust, C and C++ to interface using the C ABI, and as such, there is syntactic support for selecting the ABI to be used per function and per structure. Reo-rs makes use of this feature to expose C-friendly types and functionality as part of its foreign function interface. In most cases, this requires nothing more than the addition of preprocessor annotations, ie. `#[repr(C)]` and `#[no_mangle]`, and visibility keywords, ie. `extern`.

Rust makes frequent use of generic type-parameters, which rely on the Rust compiler for *dispatch* at the call site (see Section 2.2.2). C has no analog for this feature, and thus, some structures and functions are be provided secondary *concrete* representations. As an example, Rust represents the `Port` structure with a generic argument, affixing its data-type at compile-time. This structure has a *foreign-function* analog type without the generic parameter. Consequently, some of the safety guarantees of Reo-rs are unavailable when accessed via this interface; for such cases, functions are marked with the `unsafe` keyword according to the Rust idiom to communicate that the programmer takes on additional responsibility to invoke these functions only in the event they can guarantee that the relevant requirements are met.

Rust has no analog to C's header files[4]. To facilitate the sort of workflow that is idiomatic to C, whereby definitions and declarations can be distinguished such that *compilation* can be distinguished from *linkage*, the Rust ecosystem offers an addon for *generating* C header files from Rust source. This module can be loaded as the **bindgen**[5] addon to *cargo*, rust's package manager (comparables to *pip* for python, *npm* for node-js, and perhaps *maven* for Java). With this tool, we are able to generate C header files without much friction, and include them in any distributions such that downstream dependents on Reo-rs can incorporate them into their applications as they would do for any other C library. Once compiled and linked, their C or C++ applications would execute as would any other binary, and the use of Rust for compiling Reo-rs is no longer visible. Owing to its nature, calls that cross the Rust-C boundary do not induce any significant overhead at all [KN18].

4.3.2 Design Process

Many designs for the implementation of Reo-like coordinators are possible. Their structure and workings all depend on how information is arranged, and how multiple threads come together to coordinate on an a-priori unknown

[4]Rust does have trait-associated functions, which can declare functions without defining them. However, they are of no use here, as they are not usable from C either, as they are inherently coupled with Rust's generic system.

[5]url: `https://crates.io/crates/bindgen`.

task without stepping on one another's toes. In our case, we concentrate on the case where all participants in the system share a memory address space, which opens up many means of exchanging data between threads. As is typical in multi-threading, the problem is not accessing the data, but rather restraining oneself from accessing the data at the wrong time. Before we can approach any design decisions, we examine what we know for certain: ports invoke `put` or `get`, each from their own thread. They cannot return immediately, as this would not result in the correct system behavior; when not aligned in time, getters will often (unknowingly) read uninitialized data, and putters will write their data, never to be read. They wish to exchange data in accordance with some defined protocol, but a priori have no knowledge of the protocol, nor their role in it. The aim is to facilitate rule firing 'greedily' as opportunity allows: ie. we do not wish to delay the firing of some rule x if some y can be fired sooner.

The Coordinator

The most obvious starting point is asking *who decides which rule to fire?* Reaching consensus prevents the system from reaching some mal-formed state where two rules are being committed to in tandem, violating the protocol or deadlocking on some resource they have in common. It is easy to contrive of such examples where numerous ports are involved. For example, consider a case where two rules disagree on which of two putter ports distribute their datum to a set of getters. If not done carefully, some getters may receive one value, and the rest another. The most approachable solution is to stick more closely to the Reo model by introducing a specialized *coordinator* for each protocol. Consensus is trivial when one participant is elected the leader for every circumstance. Unfortunately, we cannot rely on some port x being involved in every rule firing such that they are the coordinator. Many protocols do not have such an x that can be relied upon to be present. The Java back-end solves this problem by adding a fresh 'protocol' thread whose task is to *only* coordinate the others. This approach is easy to think about, as there is a clear mapping from threads to roles. However, the protocol thread is not *inherently* coupled to the actions of ports. It has to *wait* for opportunities to coordinate, necessitating the transmission of explicit events from compute-threads to the coordinator. These messages can use a channel, or use something like semaphores or monitors to send *signals* instead, and then relying on the coordinator to *re-discover* which ports are ready by reading the state of shared memory. Next, one must decide *who* organizes the actions into an interaction. The Java backend's approach is to spread ports out over space such that they can become ready concurrently[6].

[6]Conceptually this could be in parallel, but the actual implementation the exchange necessitates the use of a *class monitor lock* to prevent interfering with the protocol thread itself.

The coordinator then treats the port structures like messaging pigeonholes, and performs the task of moving data around itself. The coordinator's notification to the ports is subtle; taking the form of `put` and `get` calls which release port-local locks, unblocking the compute-threads, completing the interaction. This solution is effective, but has some downsides, as discussed in Section 4.1.3.

Event Handling

A minor change with the potential for improvement is to remove the necessity of the protocol thread to *re-discover* the nature of the event which generated a wakeup signal. Rather than signals with no payload, we can use *events* which carry explicit information, eg: 'Port x is ready to get!'. With this approach, the coordinator waits in an *event loop*, handling incoming events. The Rust ecosystem has a number of libraries for defining event loops built atop system signal handles. An early implementation made use of the `mio` crate for sending events which communicated *which* port has become ready. With this minor change, the coordinator does not need to inspect the contents of ports directly, which, owing to their modification by multiple threads, inherently cause several *cache misses* for the coordinator. Rather, the coordinator is able to manage a private, dense, *redundant* record of which ports are ready. Aside from the unfortunate data duplication, this optimization contributes greatly to the satisfaction of $\mathbf{G}_{fast}$. Unfortunately, regardless of how fast `mio` may be, the event must still cross the boundary between threads. In over-encumbered systems, this has the consequence of causing context switches.

Threadless Protocol

If the coordinator has its own 'protocol thread', threads focus on their own work; the coordinator coordinates, and port-threads interact with their ports. However, for all interactions that involve one or more ports (which are frequent in practice) we observe that despite the presence of multiple specialized threads, their tasks are not concurrent. Port-threads perform external work *until* they instigate a port operation, until the coordinator is woken up to complete the interaction by firing the rule. Port-threads and coordinator cannot know when to act, and must rely on notifications from one another. Threads must wake up and go to sleep frequently.

One pivotal decision of our final design is to attempt to alleviate this problem. If compute-threads are going to block, waiting for progress anyway, why not have them do the coordination *themselves*? In our approach, we discard the dedicated protocol thread and re-interpret the coordinator as a *role* which the other threads take turns adopting. Conceptually, this change is a minor one; there is ultimately still at most one thread acting as coordinator. Until now, we have taken for granted that the coordinator can complete interactions with impunity; as they are the only elected leader of their kind, there is no concern for data races. In our new model, if *anyone* can be a coordinator, we must go our of our way to prevent two threads from adopting the role at once. Where before the bottleneck existed (implicitly) as a single coordinator thread processing a sequence of events *one at a time*, we now make the lock explicit: upon becoming ready, every thread attempts to acquire the *protocol lock*, the holder of which acts is the only coordinator for the duration.

Delegating the Task of Data Exchange

Owing to our focus on values at the systems level, we do not have the simplifying luxury of the Java backend to presume that moving data is cheap. In Rust, as in C and C++, values are not represented by indirect references by default; often, their shallowest representations are all there is to them. To satisfy $\mathbf{G}_{\mathfrak{data}}$, the Java backend's (admittedly intuitive) representation of ports as data pigeonholes is wasteful. For many realistic Reo protocols, data often moves *through* protocols synchronously, moving from `Putter` to `Getter` without any storage in memory cells in-between.

Our implementation introduces a new idea in an attempt to capitalize on this observation: getters fetch their data directly from the *source*. In this approach, the coordinator does not necessarily handle data itself. Rather, it decides which rule to fire and *delegates* the task of moving the data to the getters themselves. In addition to skipping a redundant 'data hop' from putter to coordinator, this also facilitates the dissemination of a putter's datum to all its getters *in parallel*. This change requires extra messaging form the coordinator, as getters are given more responsibility. Where before a signal from coordinator to getter sufficed ('Your datum is ready!'), coordinators must now communicate the location of the getters' source ('Your datum can be found at P!').

4.3.3 Architecture

`Proto` is a type corresponding closely to its imperative-form specification type, `ProtoDef`. While they represent the same thing, their differences in structure and contents are a result of them being used for different *purposes*. Despite the increase in granularity from Reo's RBA-like form, `ProtoDef` still represents a *specification* of the protocol; as such, it strives to minimize redundancy to simplify parsing and minimize the surface for internal inconsistency. On the other hand, `Proto` is structured to facilitate *execution* at runtime.

1. **Layout optimized for speed.**
   As discussed in Section 3.3.2, the `build` method is the only user-accessible

means of constructing `Proto` instances. The methods of this type can rely on this to assume that their contents are internally consistent, thereby avoiding the cost of performing many checks at runtime. For example, if a *rule guard* includes an equality check between the values in memory cells m_0 and m_1, `Proto` is able to assume that these cells have the same type; it is safe to use the result of m_0's definition of type-equality.

Additionally, concise structures can be re-arranged such that their layout facilitates less computation time. A general example of this paradigm is caching. Here, a clear example is the replacement with symbolic *names* for ports, functions and memory cells (represented by strings in the `ProtoDef` type), using *integers* for keying into vectors, maps and other such structures directly.

2. **Additional data for primitive concurrency.**
   Where `ProtoDef` can leave information implicit, `Proto` must be explicit. Interface ports require some data structures for storing concurrency primitives. For example, coordinators must send *control messages* to getters, as explained in Section 4.3.2 above.

Critical Region

Section 4.3.2 explains how threads initiating actions at boundary ports of a protocol assume the role of coordinator. It is fruitful to examine the fields of `Proto` in accordance to which *roles* access them, and how their access is safely controlled. The most coarse-grained distinction is that between fields inside and outside the protocol's lock-protected *critical region*. This divide is so fundamental, that is is immediately apparent by looking at the definition of `Proto` itself, seen in Listing 15. `ProtoCr` stores all of the fields manipulated only by the coordinator, such as the *allocator*, to which the coordinator delegates the task of storing persistent values. This is explained further in Section 4.3.4 to follow. Also observe the field responsible for managing which ports are *claimed*. While this is not a task traditionally associated with the coordinator, it's mutually-exclusive access between threads necessitates that this structure is protected by the lock.

Spaces

Clearly, `ProtoCr` can contain only the data that is not contended by multiple threads. Some structure is still needed for threads to *rendezvous* such that information can be exchanged and actions can be aligned in time. In the Java implementation, the class `Port` served two distinct purposes: (1) stored the value being exchanged by two threads, and (2) acted as the rendezvous for putter and getter. As explained in Section 4.3.2 above, the former of these tasks does not involve the coordinator in Reo-rs. However, the latter is still relevant. To meet this need, `ProtoR` associates *space* for every identifier (for ports and memory cells alike). The difference is name exists to distinguish them from ports, to which they are certainly related, but not identical. For every identifier, its `Space` contains precisely the data needed for it to communicate with its peers. For ports, this includes a `MsgBox`, which serves as a control-message channel from coordinator to compute-thread. Spaces are discussed further in Section 4.3.4 to follow.

```
pub struct Proto {
    cr: Mutex<ProtoCr>, // accessed by coordinator with lock
    r: ProtoR, // shared access
}
struct ProtoR {
    rules: Vec<Rule>,
    spaces: Vec<Space>,
    name_mapping: Map<Name, LocId>,
    port_info: HashMap<LocId, (IsPutter, TypeInfo)>,
}
struct ProtoCr {
    unclaimed: HashSet<LocId>,
    is_ready: BitSet,
    memcell_state: BitSet, // presence means mem is FULL
    allocator: Allocator,
    ref_counts: HashMap<Ptr, usize>,
}
```

Listing 15: Definitions of the most coarse-grained structures of a protocol instance. `Proto` is the entry-point, composed of `ProtoCr` in the critical section, accessed by only the coordinator, and `ProtoR` outside it, accessed by all.

4.3.4 Behavior

This section explains how the data structures of the `Proto` type comes to life at runtime to emerge as coordination according to the protocol with which it was configured.

Rule Interpreter

Unlike the Java implementation, Reo-rs moves the specification of the protocol type very late into the pipeline from Reo to the final application. Rather than relying on Reo to generate *native* application code, in this work we make more extensive use of the *virtualization* pattern. At runtime, the coordinator traverses rules in data form, performing tasks as a rudimentary *interpreter*. The tasks associated with such a `Rule` correspond closely to the conceptual interpretation of the imperative form. At this granulairty, interactions do not exist explicitly. Rather, the interpreter must perform the work associated with each rule *interaction* as a sequence of actions which, all together, appear to the observer as an interaction. For simple rules, it is clear to see how such interactions can be created. For example, consider a simple rule with constraint $P = C$ where P and C are putter and getter ports respectively. Here, P's value is simply moved to C if both ports are ready. As RBF rules become more complex, more actions become necessary to achieve the results of the interaction. Section 3.2 explains how by imperative form's restrictive representation already captures the result of this action-centric breakdown such that the interpreter does not need to compute it at runtime. These actions preserve their interaction-based semantics by behaving as *transactions*, with actions clearly divided into two sequences around an instant where the rule can be thought to *commit*. As long as they can be *un-rolled*, action prior to the commit can create temporary variables and trigger commit as they please. This approach is flexible enough to represent Reo's *transform* channels, allowing values to be created and destroyed *synchronously* by being represented inside the transaction itself.

Minimizing the Bottleneck

Reo-rs shares its centralized locking architecture with the Java back-end. Regardless of whether the coordinator and the thread that performs the role are decoupled, the importance of providing it mutual exclusion is clear; two coordinators in tandem would not be safe in the knowledge that the state does not change between evaluating the guards and changing the state. Methods exist for *fragmenting* protocols such that the locking becomes finer grained as protocols are into sets of smaller ones. As such, the Reo compiler internally produces a *protocol set* as its output, though the work on this feature is ongoing. Nevertheless, we consider this decomposition an orthogonal concern and consider it no farther. Reo-rs embraces this central lock, but takes measures to minimize the duration for which it is held. In this section we discuss these measures and how they work together to help satisfy $\mathbf{G_{fast}}$. To structure our reasoning, we identify the tasks a coordinator performs from the moment to acquires the lock (accepting its role), to the moment it releases it (relinquishing the role).

1. **Initialization**
   Section 4.3.1 explains how the time spent purely on *overhead* is diminished by avoiding the event-signal interaction used by the Java implementation,

necessary to wake a sleeping protocol thread. Once the coordinator has acquired its lock (a task needed in both versions), transitioning into the work of the coordinator is nothing more than the time taken to invoke the `coordinate` function call.

2. **Checking Readiness and Memory State**
Imperative form shares the explicit representation of the *synchronization set* with RBAs, encoding precisely which ports are involved with the firing. Clearly, a rule cannot fire until all ports involved are *ready*. Per port, this is a boolean property which can be represented by a single bit flag. Owing to the simplicity of this data, each of these sets can be represented as a single *bit-vector*, a data structure for which set-operations are exceptionally fast. Reo-rs takes this optimization a step further by extracting another boolean property per memory cell: *fullness*. The idiomatic encoding for memory cells storing data of type `T` in Rust would be the `Option<T>` type, such that `Option::None` represents *emptiness*. Instead, the relevant flags for fullness are extracted, separated from their data and instead coalesced into another bit-vector. With just a handful of fast bit-wise operations, the coordinator is able to quickly detect whether a rule *cannot* fire, as a result of a port not being ready, or a memory cell being full when it should be empty, or empty when it should be full. In practice, the vast majority of cases where a rule's guard is unsatisfied are detected in this step.

3. **Instructions**
Instructions are relatively expensive compared to the other steps in a rule's interpretation. Their cost scales with their complexity, as they can be defined as arbitrarily large and deep formula terms. Even individually, the cost of each operation can be high, as they include arbitrary user-defined function invocations, arbitrary user-defined equality checks, and allocation space for newly-created data objects. Section 4.3.4 explains how the cost of memory allocation is mitigated such that the allocation itself is amortized to constant time. For the rest of these operations, there is not much that can be done to avoid the cost; for the most part, they would be expensive even if each rule were performed by a native Rust function. Fortunately, the vast majority of rules for Reo connectors require no instructions at all. In practice, Reo connectors tend not to *inspect* the data whose flow they coordinate. The more intrusive the protocol's routing logic becomes, the more it begins to resemble *computation*, a task for which Reo should probably not be optimized. For the protocols without instructions (including *fifo1*, *alternator*, *sequencers*, *sync*, *lossy sync* and

more), the support for instruction parsing costs no more than the time to determine that there are zero instructions to execute.

4. **Movements**
Once a rule is committed, the role of the coordinator is to kick any getters into action, delegating the data exchange to them. Each *movement* encodes one *resource* (`Putter` or memory cell) being distributed amongst a set of *recipients* (each a `Getter` or memory cell). This meta-interaction is not synchronous; getters may take arbitrary time before waking up and actually participating in the data exchange. This is not the case for memory cells; as part of the *state* of the protocol, this is manipulated by the coordinator only. As such, operations which move values *into* memory (where memory cells act as getters) are performed first. Section 4.3.4 explains this procedure in more detail. Here, it suffices to say that the movement of memory between memory cells is fast.

   For port-getters, the coordinator does not move the value itself. Rather, the work is delegated to the compute-thread by sending a *control message* to the getter's `MsgBox`.

   Usually, the coordinator does not have to interact with the resource (acting as putter) at all. It can rely on getters to 'clean up'. The coordinator returns, releasing the protocol lock. The only exception is for movements with *zero getters*. Such cases can represent a resource being destroyed. In these cases, there is no getter to perform the cleanup, and so, the coordinator does it itself. For a `Putter`, this is no more than sending a control message, releasing it. For memory cells, this may require running the *destruction* function associated with the memory cell's data type. Section 4.3.4 provides more detail on how these are managed.

Data Exchange

Eventually, each `Getter` waiting at their `MsgBox` receives a control message from the coordinator, revealing to them the identity of their *resource*. Their task is to locate the corresponding `Space` and contend with an unknown number of fellow getters to complete the *movement*. The correctness of this exchange relies on the satisfaction of a number of properties:

1. **One getter cleans up the resource**
Regardless of whether the resource is a `Putter` or a memory cell, the set of getters are responsible for cleaning up the resource to finish the interaction. In the case of a putter, this takes the form of sending them a *control message*, notifying them that everyone has finished inspecting their datum and they may return to the caller. Clearly it is unsafe for anyone

to release the putter *before* some getter has finished reading the datum; by returning, the putter may *invalidate* the memory region storing the datum.

In the case of a memory cell resource, cleanup takes the form of re-setting its *ready flag* inside `ProtoCr`, signifying that the memory cell is in a stable state can again be involved in rule firings. This is necessary as there is no dedicated thread guaranteed to set this flag in future, as is the case for getters and putters. Section 4.3.4 to follow also explains how these memory cells are *emptied* in these events such that they can again store new values. This manipulates the protocol's state, potentially making new rules' guards satisfiable. As such, this last getter must once again acquire the protocol lock and attempt to *coordinate*.

2. **At least $N-1$ getters `clone`**
Rust generalizes the operation for *replicating* a datum to produce another instance from it. It is idiomatic to rely on the standard trait `Clone` with single operation `clone` to implement this behavior. This approach covers cases for which there is a non-trivial means of replicating objects; sometimes, performing a bit-wise copy of the structure's shallowest representation is not enough. Consider the example of `Arc` ('atomic reference-counted') in Rust's standard library. This type consists of just a pointer to some heap-allocated tuple `(refcount, data)`, and is used for shared, reference-counted ownership of `data`. For this type, coping the pointer to the tuple is not sufficient. Cloning must *follow* the pointer and increment `refcount`.

3. **One getter *moves* instead of cloning**
Data movements represent the *transmission* of data from source to a set of destinations. Generally, the value is no longer present at the source afterwards. Naïvely, the original must be *destroyed* to complete the interaction. However, it is wasteful and illogical to replicate an object only to destroy the original. Instead, we wish to *move* a value between threads, much as Rust's move semantics allow the movement of affine types between bindings. This cannot be done in the conventional way, as movement is defined is generally within the context of a single thread and scope. Regardless of Rust's expressiveness, it is nonetheless an *action-based* language, and does not offer the *interaction* we need.[7]

[7]Rust is able to understand uni-directional movement of values into *new* threads using the same mechanism by which closures can *enclose* variables in their parent scope. More complex types are able to also create their own notions of safe 'movement' by composing actions as we suggest in this section. As in our case, they require the use of `unsafe`, as by definition the Rust compiler cannot reason about their correctness in the usual way.

When orchestrated correctly, we are able to implement a safe *move* operation between threads by invoking a pair of *unsafe* operations, one on either end. In *unsafe Rust* it is possible to *copy* a value without influencing the original. If not done correctly, this can easily lead to *double-frees*. On the other hand, it is possible to leak resource memory with `forget`, an operation of Rust's standard library which causes the compiler to consider the value *moved* without invoking `drop`. These pitfalls should be familiar to C programmers, as *unsafe Rust* gives one the capability to interact with *raw pointers* in a fashion similar to that of C. Together, these actions constitute the inter-thread move primitive we need.

We elaborate our task by requiring an election between getters, such that one is designated the *mover*, and the rest are *cloners*.

4. **All clones must be complete before the move**
It is unsafe to *move* a value before or while performing `clone` on the original. Essentially, every data exchange must proceed in two strict phases such that all clones occur in the first, and the move in the second. Consider again the example of type `Arc` by examining this sequence of events that results in undefined behavior: (1) `Arc` x represented by a pointer to heap region at p is moved to binding y. (2) y goes out of scope, it's `refcount` is reduced to zero, and so its heap allocation is freed. (3) `Arc::clone` is invoked with x, which traverses its pointer to memory position p, and attempts to increment `refcount`. p is no longer allocated, and arbitrary memory corruption ensues. To prevent such cases, Reo-rs must take care to order all clones of some value before it can be moved, as the Rust compiler would do.

Many solutions are possible, but have in common that these getters must exchange some meta-information safely across thread boundaries. Our solution uses a pair of atomic variables for this purpose, *count* and *mover*, initialized by the coordinator a priori to N and *true* respectively. In a nutshell, *mover* is true if no getter has yet claimed the role of mover, which represents both (1) the responsibility to clean up, and (2) the privilege of moving the original value, rather than cloning it. Part of the procedure at large is a *pair* of *elections* between getters to determine a *mover* and a *last* getter. We elect a mover first. The time between the elections gives the losers (the 'cloners') the opportunity to clone, safe in the knowledge that the mover will not clean up until they are finished. If the mover is also elected last, they clean up and return immediately, as all clones must already be complete. Otherwise, the mover must await a signal from whomever is last before cleaning up.

This process is complete enough to implement the desired functionality for Reo-rs. However, we identify two important optimization opportunities which have the unfortunate consequence of complicating the data-exchange procedure further.

1. **Not all getters want data**
   Getters participating as a result of the `get_signal` operation will not return a value. Clearly these getters cannot avoid participating in the mover-election, as then nobody would clean up. These getters specialize their interactions by participating in the last-election first. The intuition is that if they lose this election, it is safe for them to return without participating in the mover-election; clearly this covers the case of no getters wanting the data. It is also safe to re-arrange these elections in this case; these getters have no intention to `clone`, and thus are not a threat to the invariant that required these elections to be ordered in the first place: all clones are complete by the time the last-getter is

2. **`Copy`-types can be replicated without `clone`**
   Section 2.2.2 explains how `Copy` marks types for which have a trivial destructor, and are safe for multiple getters to replicate by *copying* their value bit-wise. This is the case for primitives, and structures composed entirely out of primitives, such as arrays of integers.

   For copy-types, the mover and the *copiers* may copy the original datum in parallel. Afterward, only a last-getter is elected to clean up, safe in the knowledge that all copies are finished.

The full data-exchange procedure is spelled out in Rust-like pseudocode in Listing 4.3.4 in the Appendix.

Memory Cells

Section 4.3.3 explains that per *location* (generalizing ports and memory cells), Reo-rs maintains a persistent `Space` structure at a fixed location on the heap such that threads have a predetermined location to *rendezvous* on communication primitives. Section 4.3.4 follows up, explaining how these structures are also pivotal to data exchange. When getters converge on the space of a `Putter`, they rely on the presence of a prepared *data reference* in the space to the location of the putter's datum on its own stack. In this manner, values moving between ports are never moved to the heap at all. The memory-alignment of the putters datum generally differs per data exchange, necessitating that their space's reference be *updated* to the location of their value each time.

Memory cells differ from putters in that their value *persists* beyond the lifetime of any individual thread participating in the protocol; consequently, the data itself *must* be stored on the heap. A naïve implementation treats memory cells similarly to putters by continuously *updating* the data-reference in the associated `Space` such that it points to a freshly-allocated value on the heap every time the memory cell is filled.

We are able to rely on a property of Reo for an optimization: memory cells have pre-defined types. Instead of shifting the pointer around to a fresh allocation each time, we are able to *pre-allocate* the space needed to store one value per memory cell. In this model, the references do not change. Instead, each has a single allocation which is repeatedly re-used. Whenever the cell is empty, the contents of the allocated space are *uninitialized*. This can be done safely by relying on auxiliary structures for tracking when memory cells are empty; Section 4.3.4 explains how *bit vectors* serve this purpose for Reo-rs. This approach removes the cost of creating and allocating spaces at runtime. Unfortunately, this approach suffers a drawback inherited from its strict interpretation of *value-passing semantics*: moving data between memory cells is expensive. While small optimizations are possible for some circumstances (eg. we are able to swap references when the contents of two memory cells are *swapped*), they are only applicable in a handful of situations.

Requirements $\mathbf{G}_{\mathbf{data}}$ and $\mathbf{G}_{\mathbf{fast}}$ incentivize a more extensive optimization. Reo-rs intentionally decouples memory cells (including their spaces and their fullness flags) from *storage*, which describes where the contents of the cells is kept on the heap. We observe that Reo protocols perform logical replication of values often, while mutating existing values rarely. As such, many situations exist in which we are able to safely *alias* values between memory cells by relying on *reference counting*. We extend the idea of re-using allocations, but rather that fixing them per memory cell, we allow all memory cells of the same data type to draw from a shared pool of re-used allocations; this is often referred to as an *arena allocator*. The intricacies of this process are delegated by the coordinator to the `Allocator`, which tracks which *storage cells* of a type are available (free) and which are occupied. Rules which replicate, destroy or move data between memory cells thus can often moving data altogether, instead manipulating only the references within spaces, and reference counters of storage cells. For example, a rule which empties memory cell m_0 (destroying the contents) needs to only decrement the reference counter. Only when the counter reaches zero does the allocator need to be involved, invoking the value's destructor in-place and freeing the storage slot. This approach has another advantage: `clone` is invoked *lazily*, in some cases being avoided altogether. Consider a connector for which values originate from putters, get stored in memory slots, are replicated repeatedly, only to be destroyed before ever being emitted to a getter. In this example, `clone` is never necessary. This approach has an additional consequence; the data exchange operation explained in Section 4.3.4 may be initialized such that *nobody* is permitted to move. The procedure already given (in Listing 4.3.4) is able to handle this case.

Type Reflection

Section 2.2.2 explains how Rust offers both *static* and *dynamic* dispatch for executing generic code, similar to how it is done for C++. These options offer a trade-off in runtime speed, binary size and flexibility. Reo-rs cannot hope to rely on static dispatch to resolve the concrete types of port data, as they are only discovered later in the moment our `Rule` structures are interpreted. The idiomatic approach to such situations is to rely on *dynamic dispatch*, which virtualizes the operations on some generic type by adding indirection which is resolved at runtime through the traversal of function pointers. As with C++, Rust uses *virtual function tables* ('vtable') for this purpose. Dynamic objects are stored in place with a pointer with the relevant vtable, and operations traverse the table according to a statically-defined layout to resolve the concrete functions. Clearly, this is only possible if the method creating the dynamic object and the operations on it agree on the vtable's contents. To this end, Rust relies on its *trait* system: dynamic objects are created and interacted with in terms of some *trait*, which provides it with both an interface and a type. As such, Reo-rs defines a trait `PortDatum`, which defines all the operations belonging to all port data: (1) how is the object laid out in memory, (2) how are objects checked for equality, (3) how are objects cloned, etc. Two problems present themselves with this idiomatic approach:

1. Who defines `PortDatum` for the user's data types? The idiomatic approach is to expose the trait and simply require the user to implement the trait's associated operations to their type. However, if we do not trust the user entirely, some of our desired optimizations become impossible[8]. For example, users must mark their objects as `Copy`, communicating that they can be safely shallow-copied in memory.

2. How do we express types of `PortDatum` which *do not* implement an equality or clone operator? These may not be defined for the type. One is able to express Reo connectors which will not use these operations (and thus is is correct not to require them), but we cannot know whether they are used statically.

We solve both of these problems by using an experimental feature the Rust language not yet available in the stable version: *specialization*. With this feature,

[8]This is a limitation of Rust's trait system, which prohibits the inclusion of associated functions and properties for traits used for the creation of dynamic objects. Rust does not support representing them in the vtable. This limitation may be removed in future.

we solve the first problem by defining `PortDatum` for every conceivable generic type ourselves, with their fields populated as a function of the type's properties. In this manner, `PortDatum` can be made entirely private, benefiting the user in alleviating their need to implement it, and benefiting Reo-rs by guaranteeing it is implemented correctly for every type. This also solves the second problem; as `PortDatum` is under our control, we can provide dummy implementations for operations which the type does not define, such that *all* `PortDatum`-implementor types can use the same vtable layout, despite differing in the subset of the trait's operations they define. Conceptually, we can represent undefined functions with *null* pointers in the vtable. For safety's sake, we instead use dummy functions which trigger an explicit *panic*, unwinding the stack and throwing unrecoverable errors in the event a programming oversight attempts to traverse these undefined function pointers. Listing 16 gives a simplified[9] view of the `PortDatum` trait, and its implementation for any[10] data type, `T`.

Rust's chosen representation of dynamic objects is the *fat pointer*, which represents a dynamic object as a pair of pointers, one to its *data* (ie. some structure with fields), and one to its *behavior* (ie. the vtable). These trait objects can be thought to carry their behavior around with them; they move with their vtables. While ergonomic in general, this is often redundant in the case of Reo, where values are guaranteed to only move between ports and memory cells of the same type anyway. In our case, we would repeatedly overwrite these tuples to overwrite the *data*, and redundantly overwrite the vtable pointer with an identical one. This is a symptom of Rust's approach to dynamic objects in general; it 'resolves' their concrete type *per operation*. This approach is detrimental to Reo-rs for two reasons:

1. Dynamic objects are accessible through their trait interface. Behind this interface, their concrete types are erased. There is no means to check type-equality between two dynamic `PortDatum` objects, as is needed during the `build` procedure (see Section 3.3.2) to ensure that memory is initialized with the expected type and so on.

2. Dynamic objects carry their vtable pointers with them. This increases the size of their representation significantly (in the case of small types)

[9]The real trait definition contains more fields, and must perform some manipulations of raw pointers to get around Rust's restrictions on which traits may be used for dynamic dispatch. For this reason, it is important for us to control its definition for any type `T`. These details are omitted for brevity.

[10]In the final implementation, we must include some trait bounds for all `PortDatum` types. `Send` and `Sync` are common Rust marker traits for types that can be passed between threads by value and reference respectively. They are implemented by default for all reasonable types such that users almost never need to consider them [KN18] (they are derived for user-defined types by default also), but this requirement covers some prickly safety pitfalls.

Our solution is to implement our own dispatch system that makes use of Rust's native vtables and dynamic dispatch, but without the above properties. Essentially, we split Rust's fat pointers into their *data* and *behavior* components, using the former as data as usual, and using the latter as a *key* to reflect on the concrete type's behavior as needed. Section 3.2 introduced the `TypeInfo` type, which appears to the user as nothing more than some *identifier* for its type. Under the hood, this value is the vtable pointer itself, thereby usable as a *key* to identify the type and to reflect on the behavior of some dynamic `PortDatum` object inside Reo-rs. Listing 17 shows how function `TypeInfo::of` provides the user with the only means of creating a `TypeInfo` for some `T`. Only in the creation of the *imperative form* structure (the `ProtoDef` type) does Reo-rs accept the user's provided `TypeInfo` directly, as it would be unsafe to rely on the user providing some `T` with a matching `TypeInfo`. Instead, the API of Reo-rs includes one layer of *static dispatch* into the library where necessary such that the creation of the `TypeInfo` can be trusted. For example, when populating some `MemInitial` structure with the initial values of memory cells (as described in Section 3.3.1), values can only be input with the `with` function. The user uses Rust's safe dispatch system, oblivious to Reo-rs translating their concrete objects into dynamic ones behind the scenes. For example, the user might see: `MemInit::default()::with("hello")`, and Reo-rs would resolve the `TypeInfo` for `&'static str` type behind the scenes.

Listings 27 and 28 in the appendix demonstrate how `TypeInfo::of` appears in the generated binary.

4.4 Requirements and Guidelines Evaluated

In this section, we give a summary of the means by which the requirements and guidelines of Section 4.2 are satisfied and adhered to respectively. This doubles as an overview of this chapter at large, motivating its points by referring to the relevant subsections above.

$\mathbf{R}_{value}$ Values passing through ports preserve value passing. This is achieved even in the presence of reference-passing optimizations 'under the table' by leaning on the same philosophy that Rust uses to prevent data races: prohibit mutable aliasing. Objects are only aliased (accessible via multiple bindings) if they should be identical. Section 4.3.1 explains how we prohibit aliasing into and out of the protocol by relying on value-passing port operations. On the other hand, Reo-rs aliases values, but only *until* they are mutated. Section 4.3.4 explains how memory values are safely aliased.

Section 3.2 explains how Reo-rs interprets an imperative form protocol description at runtime, relying on a *transaction*-like model to safely allow the creation of new values to be incorporated in synchronous interactions. In this manner, protocols whose rules create and reason about temporary values can be faithfully represented.

R_{init} Section 4.3.1 explains how users are shielded from the granular initialization procedure by exposing an API with explicit constructor functions `build` and `claim` of protocols and ports respectively. Protocol objects are extensively customizable by the expressiveness of *imperative form*, with which `build` is parameterized. At the same time, these structures are kept internally-consistent by the preservation of invariants, and relying on `build` as the only user-facing means of instantiation.

R_{ffi} C and C++ foreign-function interfaces are provided by relying simply declarations with the C ABI where possible. As C cannot support Rust's notion of generics, where necessary, the `ffi` module provides generic-free alternatives for data types and functions where generics are represented as data instead. Reo-rs can thus be compiled once into either a statically- or dynamically-linked library for use in these other languages without any additional runtime overhead.

G_{data} Reo-rs facilitates the transmission of any fixed-size data-types by value. This permits but does require data to be heap-allocated. Sections 4.3.4 and 4.3.4 explains how Reo-rs has a value-passing API, but relies on reference-passing to minimize the number of times values are moved in memory.

G_{fast} Section 4.3.2 explains Reo-rs coordinates the actions of multiple threads while minimizing the overhead of inter-thread communications. Section 4.3.4 explains how meta-operations are represented such that they can be batched, allowing the coordinator to reduce the overhead of processing rules for firing.

G_{end} Section 4.3.2 explains how protocol objects are not given their own threads, trivially facilitating termination detection if no ports remain to interact with it. Section 4.3.1 describes how protocol structures are implicitly cleaned up once all of their ports are destroyed.

```
trait MaybeCopy { // private helper trait
    const IS_COPY: bool = false;
}
impl<T> MaybeCopy for T {} // default case. NOT COPY
impl<T: Copy> MaybeCopy for T { // specialize for COPY TYPES
    const IS_COPY: bool = true;
}
///////////////////////////////////////////////////////////////////////
trait MaybeEq { // private helper trait
    fn maybe_eq(&self, _: &Self) -> bool {
        panic!("This type cannot check equality!")
}   }
impl<T> MaybeEq for T {} // default case. NOT PartialEq
impl<T: Eq> MaybeEq for T {
    fn maybe_eq(&self, other: &Self) -> bool {
        return self == other
}   }
///////////////////////////////////////////////////////////////////////
trait PortDatum { // main PortDatum trait. also private
    fn is_copy(&self) -> bool;
    fn eq(&self, other: &Self) -> bool;
}
impl<T> PortDatum for T {
    fn is_copy(&self) -> bool {
        <Self as MaybeCopy>::IS_COPY
    }
    fn eq(&self, other: &Self) -> bool {
        <Self as MaybeEq>::maybe_eq(self, other)
}   }
```

Listing 16: Using Rust's specialization feature to define `PortDatum` (simplified) for every generic type `T` by relying on `T` always implementing helper traits `MaybeCopy` and `MaybeClone`. `MaybeCopy` can be implemented for any `T`, defining a default behavior in one block, and then overriding it for a more specialized behavior in the other. The Rust compiler will resolve which block to use based on the static properties of `T`, deriving a `PortDatum` implementation with precisely the desired definition. In this manner, `PortDatum` can be made inaccessible to the user, allowing Reo-rs to trust that it was defined in the expected manner. The helper traits are necessary to satisfy the requirements of the specialization feature: there must be a strict ordering on impl-block specificity for the same trait.

```rust
1  struct TypeInfo(VtablePtr); // VtablePtr field is private. User can only interact with
   ↪  `of` function.
2  impl TypeInfo {
3      pub fn of<T>() -> TypeInfo {
4          // 1. fabricate bogus (uninitialized) data pointer to some type T.
5          let x: Box<T> = unsafe { MaybeUninit::uninit().assume_init() };
6          // 2. SAFE cast to trait object (Rust appends PortDatum vtable pointer for T)
7          let fat_x = x as Box<dyn PortDatum>;
8          // 3. convert to "raw" dynamic object: a pair of pointers with UNSAFE cast.
9          let raw: TraitObject = unsafe { transmute(fat_x) };
10         // 4. discard the bogus data. Return wrapped vtable only
11         return TypeInfo(raw.vtable)
12 }   }
```

Listing 17: ‘Tricking’ the Rust compiler into retrieving the vtable of a given type `T` for dynamic dispatch to virtual functions of trait `PortDatum`. The safe cast on line 7 inserts a pointer to a vtable which the compiler will ensure is present in the program text. `TypeInfo` structures can later be used for type reflection, by manually appending this pointer to reconstruct the *fat pointers* that Rust natively uses for dynamic dispatch.

Chapter 5

Benchmarking

In this section we evaluate the performance of the Reo-rs library, focusing primarily on the optimizations described in Section 4. TODO add references to requirements and guidelines from Reo-rs chapter

5.1 Experimental Setup

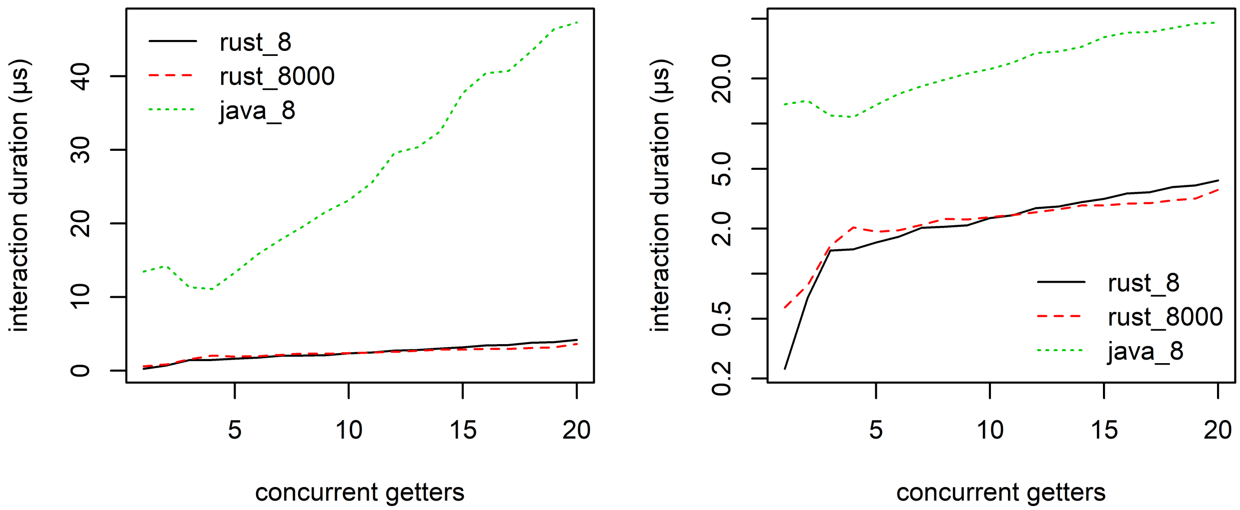
TODO rustc 1.38.0-nightly (bc2e84ca0 2019-07-17) compatible and contemporary with rust version 1.36.0 (a53f9df32 2019-07-03) Windows 10.0.2.1000 intel core i7-7500U CPU @ 2.70 GHz. 12Gb ram, 4 physical (8 logical) 64-x86 architecture processor. Micron 1100 SATA 5122 GB SSD

5.2 Reo-rs in Context

This section compares the performance of Reo-rs to its various competitors: (1) existing Reo back-end for the Java language (2) Hand-crafted Rust protocol code. The goal is to provide the reader with an understanding on the strengths and weaknesses of Reo-rs in a broader context.

5.2.1 Versus the Java Implementation

We begin by making the most intuitive benchmark to get an understanding of how effectively Reo-rs has been optimized for its task; we compare it to the work of the Reo compiler's Java code-generator. This comparison spans two vastly different systems with different goals, but also compare a memory-managed language to a system's language. The reader should bear this in mind when interpreting the measurements. As our test scenario, we have a set of N



(a) (b)

Figure 5.1: Comparison of interaction time for the *fetch* connector for both Java and Rust backends moving small-size values. `rust_8` and `java_8` both move a payload of 8 bytes (to match the reference size of the 64-bit JVM). `rust_8000` gives an example of how the runtime of Reo-rs can change with respect to modest changes in data size. The two subfigures mirror one another except for the linear and logarithmic y-axes respectively.

getters repeatedly copying some memory value M, retained inside the protocol from initialization. By involving a contended resource, we are able to test and compare the *scalability* the generated programs, both in terms of number of ports and the size of the transmitted data.

The unfairness of our comparison cuts both ways, as there is not a clear means of comparing the transmission of large values; the Java version relies entirely on object-aliasing, effectively implementing different semantics. For Java, the size of values transmitted is largely irrelevant. We begin by a comparison on the only common ground; Figure 5.1a shows both Java and Rust are transmitting pointer-sized objects. Aside from the order of magnitude difference in runtime, we observe a different *shape*. Reo-rs is observed to be significantly faster for a single-getter case. This is easy enough to explain; the type relied upon for protecting the coordinator's *critical region* is `Mutex` from the `parking_lot` crate, which provides implementations of these kinds of concurrency primitives. `Mutex` is documented as having a *fast path* optimization for

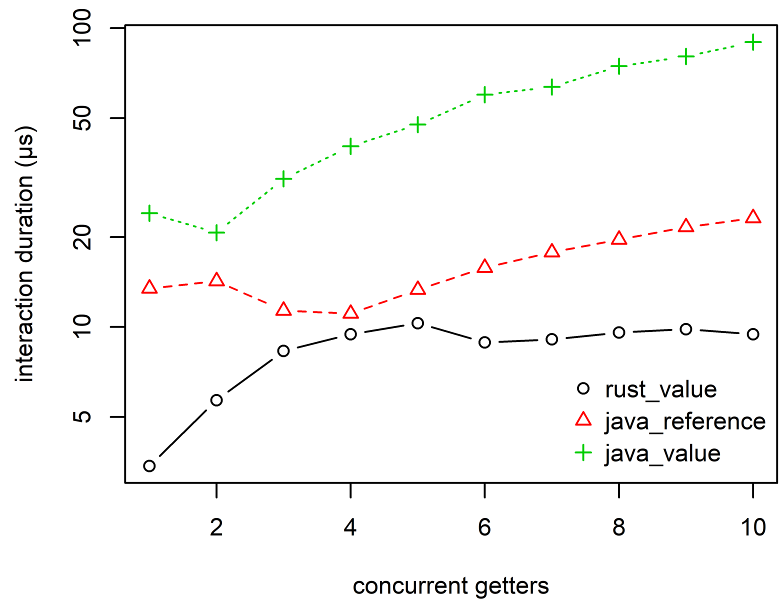


Figure 5.2: Comparison of interaction time for the *fetch* connector for both Java and Rust backends moving 64-kilobyte-sized data. The Rust backend moves the datum by value, while the Java parallel `java_reference` aliases the object (moving by reference). This backend does not support semantics-preserving value-passing. We achieve safety here by the coordinator injecting `clone` operations of byte arrays to mirror Rust's bit-wise copy, called `java_value` . Note the logarithmic y-axis.

when the lock is acquired *uncontested*. Runs with one getter are thus able to take advantage of this optimization every time.

Figure 5.2 attempts to draw the same comparison as before, but in the case of large data-types. The Java-generated protocol objects do not do true value-passing. It is out of the scope of this project to attempt to implement this

5.2.2 Versus Hand-Crafted Programs

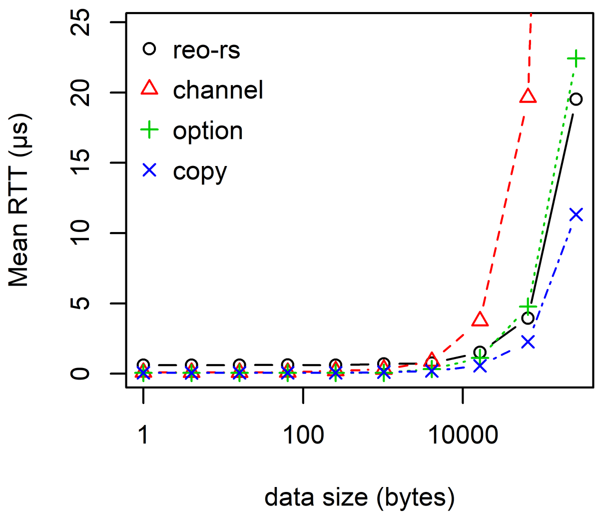
Clearly, Reo-rs cannot out-perform hand-optimized Rust on a case-by-case basis; whatever Reo-rs does, the hand-optimized code can mimic and specialize to surpass its performance. The utility of the library is to handle arbitrary Reo-generated protocol descriptions, hiding the details away from the user with an API that strikes a balance between flexibility, safety and performance. Here, we attempt to gauge the performance gap between Reo-rs for some small examples of connectors.

Firstly, we examine a case for which Reo-rs is expected to do poorly: we compare the Reo-generated solution of a simple protocol to hand-crafted solutions. To make matters worse, we perform the experiment in a circumstance in which explicit synchronization bookkeeping is unnecessary: port operations are accessed sequentially. Concretely, we examine the *fifo1* connector. At these small scales, it matters considerably how we perform our optimization. Figure 5.3 shows runtimes for Reo-rs compared to three hand-crafted solutions. `channel` is the most intuitive solution, relying on the ubiquitous `crossbeam` channel for its efficient channels[1]. `option` uses only the Rust standard library type `Option` to act as a memory variable which can be safely written to and read from using its `replace` and `take` operations. `copy` uses unsafe Rust and shirks Rust's idioms to write to and read from a pre-allocated heap buffer directly. We see that the runtime of Reo-rs is never the fastest solution. Particularly for small port-values, the simplicity of this protocol is not worth the overhead Reo-rs incurs by traversing rules, comparing guards and so on. Still, it is surprising that Reo-rs overtakes the `crossbeam` channel, whose implementation clearly does prioritize the efficient movement of very large values.

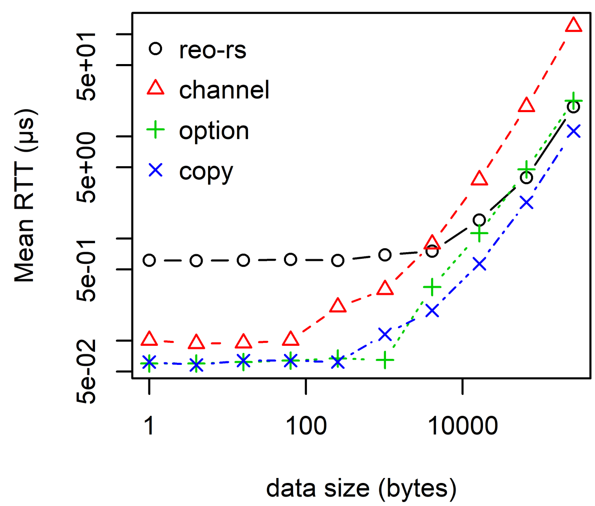
The comparison become more interesting when we apply Reo-rs to less trivial connectors that make use meaningful synchrony and state. The *alternator2* is a canonical Reo circuit that routes messages from putters $\{\mathsf{P}_0, \mathsf{P}_1\}$ to getter G in an alternating fashion (starting with P_0). The semantics of this connector are subtly different from that of a *sequencer*; the first value is transmitted once all ports are synchronously ready, and the second value is transmitted asynchronously.

Listing 5.4 shows how Reo-rs fares against a simple hand-crafted solution which maps Reo-rs channel primitives and the connector's synchronization constraint to `crossbeam`'s channels and the `Barrier` in Rust's standard library, implemented to closely correspond with the specification, available for inspection as Listing 25 in the appendix. Figure 5.4b shows that, as before, the performance of Reo-rs far surpasses that of our hand-crafted solution for very large values, likely as a result of relying on `crossbeam`, whose slowdown was previously observed in Figure 5.3. More interesting is the observation that while Reo-rs is still inferior for small values, the gap has closed significantly across the board, suggesting that the synchronization overhead is more similar in both versions. For completeness sake, and to put out best foot forward, we include the effects of the C-like *unsafe* API variants of Reo-rs port operations explained in Section 4.3.1.

[1]These channels are used for various control messages inside Reo-rs itself.

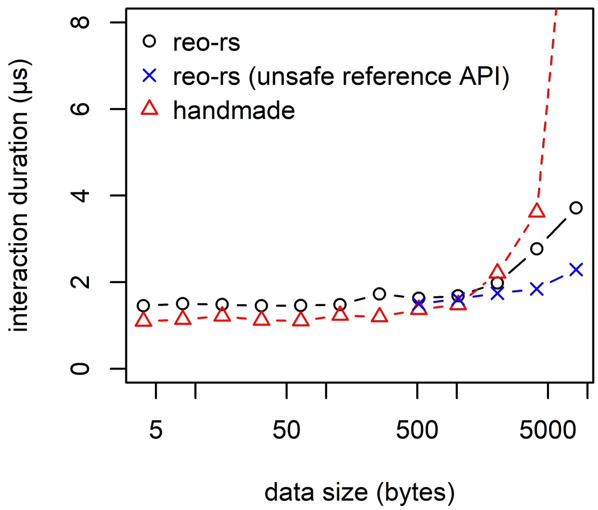


(a)

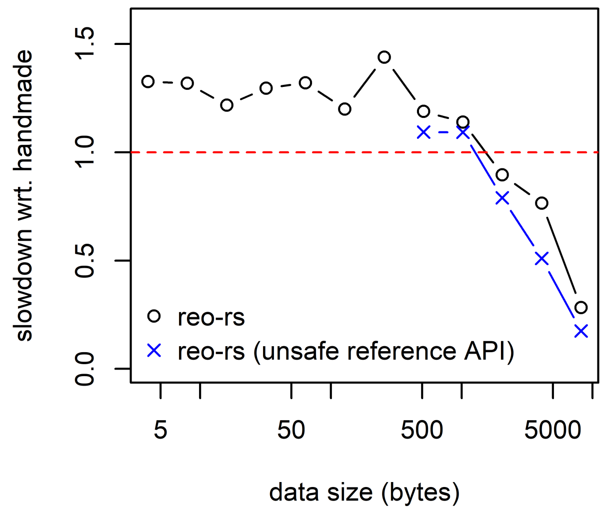


(b)

Figure 5.3: Time from beginning of `put` to end of `get` in connector *fifo1* compared to hand-crafted Rust alternatives of various sorts. `channel` is intuitive, using a `crossbeam` 1-capacity buffered channel. `option` stores the temporary variable in an `Option` type, and writes and reads from it using `replace` and `take` operations. `copy` uses unsafe rust to perform reads and writes to an allocated heap buffer directly. In both figures, the x-axis is logarithmic. The second plot displays information with a logarithmic y-axis also.



(a)



(b)

Figure 5.4: Mean interaction duration of the Reo-generated *alternator2* connector in comparison to an intuitive implementation based on channel primitives in the `crossbeam` crate, and the `Barrier` from the Rust standard library showing (1) absolute runtimes, and (2) the slowdown factor of Reo-rs compared to the handmade code. Note the logarithmic x-axis.

The alternator circuit is still simple enough that the hand-crafted implementation is only a few lines long. It is in our best interest to compare the performance of Reo-rs to hand-crafted solutions closer to the expected level of complexity for the use case of Reo. However, as programs become more complex, it becomes more difficult to design fair 'objective' handcrafted programs such that the results are meaningful, as their complexity will increase the opportunities for optimizations. We a more complete analysis of the performance of Reo-rs to hand-crafted programs to future work. For now, we conclude that Reo-generated Rust is unlikely to out-perform hand-crafted programs for protocols at the expected level of complexity, but will be generally competitive.

5.3 Overhead Examined

Here, we examine the performance characteristics of Reo-rs in more detail under various circumstances. The goal is to understand how Reo-rs uses its computational resources, and how performance responds to properties of the specific protocol.

5.3.1 Parallelism Between Interactions

For connectors as simple as *fifo1*, overhead is overhead. However, we are particularly interested in understanding how this overhead is partitioned; as connectors become more complex, different parts of this overhead impact *parallelism* in different ways. Section 4 explains the nature of the *coordinator* role, and how its operations are performed holding the lock for the `Proto` instance which connects ports as their common communication medium. Table 5.1 shows measurements for an experiment that attempts to understand which proportion of our overhead is incurred *inside* the critical region, ie. by the coordinator. In the case of this experiment, our protocol has rules for movement which can be rendered as a *bipartite graph*, allowing data flow from any putter in $\{P0, P1, P2\}$ to any getter in $\{G0, G1, G2\}$. As explained in Section 4.3.4, movements such as these do not buffer the data elements inside the protocol; getters take values from putters directly. As a consequence, putters are both the first and last to parttake in any of our rule firings' data movements. The table shows the mean duration for which each putter was involved in such a firing. Along with the total duration of the run, we are able to compute to which extent these putters were able to work in parallel. We distinguish between four cases, corresponding to rows in Table 5.1. The first three cases do not involve the `clone` operation, and are observed to have insignificant differences for all measurements. For this experiment, with modestly-sized values, we conclude that there is no large difference in performance between these three cases:

move Values are moved from putter to getter synchonously.

copy Putters retain their values, and getters replicate them with a bit-wise copy that does not mutate the original.

signal Getters do not return any data. They return after releasing putters.

The final **clone** case attempts to observe the effects of intentionally delaying getters outside of the lock by necessitating the use of an explicit `clone` operation whose duration is artificially lengthened[2]. For these runs, putters retained their original values, but the datum was not marked with the `Copy` trait. In all cases, we observed that even at this coarse granularity, there was significant

[2] `sleep` calls were out of the question, as its variability is overwhelming at this scale. Instead, `clone` perform thousands of chaotic integer computations on the replica before returning it. This is intentionally obtuse such that the Rust compiler is unable to identify a trivializing optimization.

	mean active time			run	mean
	p0	p1	p2	duration	parallelism
move	2.68µs	2.594µs	2.993µs	31.1705ms	2.652
copy	2.737µs	2.4µs	2.673µs	28.7161ms	2.720
signal	2.351µs	2.282µs	1.943µs	24.7852ms	2.653
clone	4.451ms	4.461ms	4.416ms	44.609s	2.988

Table 5.1: Runs of 3 putters greedily sending their 2048-byte data directly to any of 3 getters, 10 000 times. The right-most column computes how many rule-firings were per This test was performed with 4 variants, differing on the properties of the data and whether the putter retained the original. The last column is derived, showing to what extent these putters were able to work in parallel.

parallelism. For the majority of the time, new rules were able to fire whilst interactions were being completed outside of the critical region. The final case in particular was within a small rounding error of perfect parallelism.

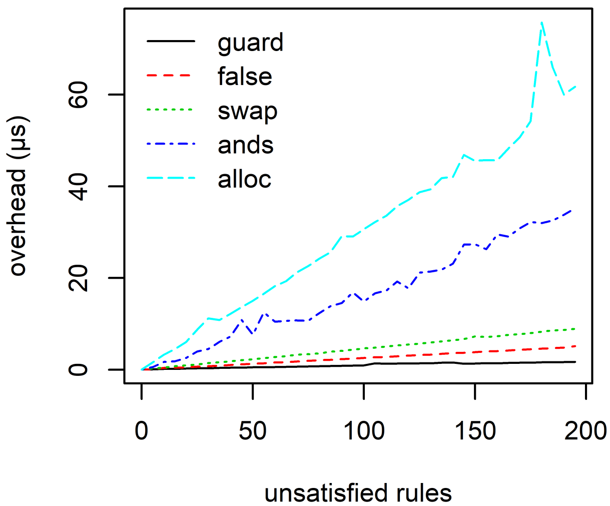
5.3.2 Time Inside the Critical Region

The previous section, we saw an experiment with data moving between putters and getters. These runtimes included the putter's time spent not only on the movement itself, but also on the time spent in the role of *coordinator*. Here, we examine the work that pertains to this role and how changes to the definition of rules influence overhead. Figure 5.5 shows the overhead incurred by a coordinator that traverses *unsatisfied* rules before finding one to fire. It is apparent that in all cases, the overhead scales linearly, as expected. The time taken to evaluate the satisfaction of a rule varies greatly dependent on its definition; the evaluation of a rule involves many different operations mirroring the intricacies of the *imperative form* it models, described in Chapter 3. To represent the possibility space, the figure shows measurements for a simple protocol which encounters replicas of one unsatisfied rule repeatedly, where its nature comes in four distinct variants:

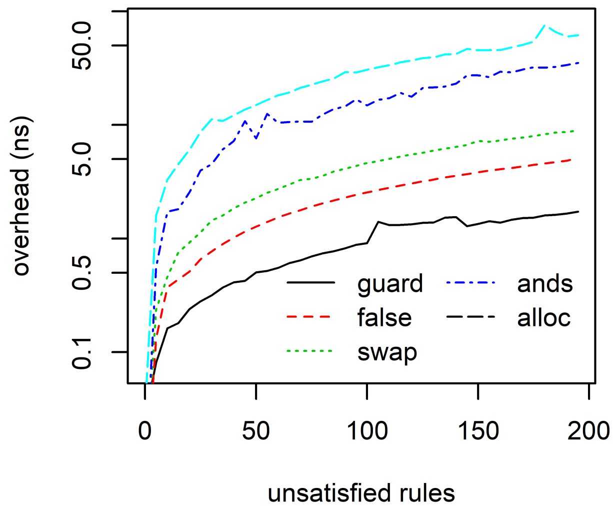
guard A rule where some port is not ready. This is detected almost immediately by cheap *bit vector* operations, as explained in Section 4.3.4. Evaluation takes 8.76ns.

false A rule whose first instruction checks the predicate *false*. Evaluation takes 18.91ns.

ands A rule whose first instruction is a tree-like formula structure of twenty-five conjunctions, only the last of which is *false*. Evaluation takes 180.72ns.



(a)

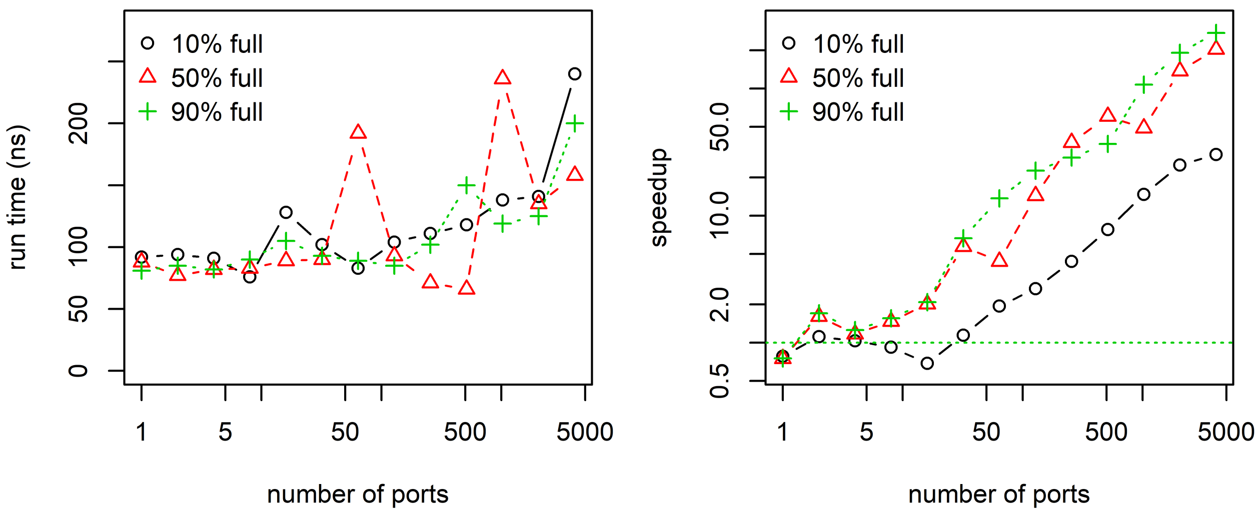


(b)

Figure 5.5: Overhead as a result of evaluating a sequence of identical unsatisfied rules before firing something. Experiment is repeated for four variants of unsatisfied rules varying in the complexity of the operations they before before being deemed unsatisfied. The two sub-figures show the same information, with (b) representing it with a logarithmic y-axis to accentuate the small-scale differences.

alloc A rule whose first instruction allocates a fresh boolean-type resource with value *false*. The second instruction checks that this temporary value is true. Upon failure, the allocation must be rolled back, discarding the temporary value. Evaluation takes 316.51ns.

These results meet our expectations. Rules can be arbitrarily complex, and perform an arbitrary amount of work before concluding that they are not satisfied, and will not fire. Even for this small set of relatively simple examples, we are able to see orders of magnitude in difference between the best case (in which the rule is skipped as early as possible by evaluating a bit-vector), to the worst case (involving several complex instructions). Fortunately, realistic Reo connectors will be defined almost entirely by rules that are either skipped as a result of evaluating these bit-vectors, or not at all. Even more expensive guards can expect to incur overhead in the order of nanoseconds as long as they involve no more than a handful of reasonable instructions.



(a) (b)

Figure 5.6: Run time of the `is_subset` operation for bit vectors and canonical hash sets. This operation is used very frequently by the coordinator to determine whether a rule is satisfied. Figures show (a) run times for the bit vector in response to a changing maximal element, ie. number of ports, and (b) the speedup of the bit vector in comparison to the hash set. Note the logarithmic axes.

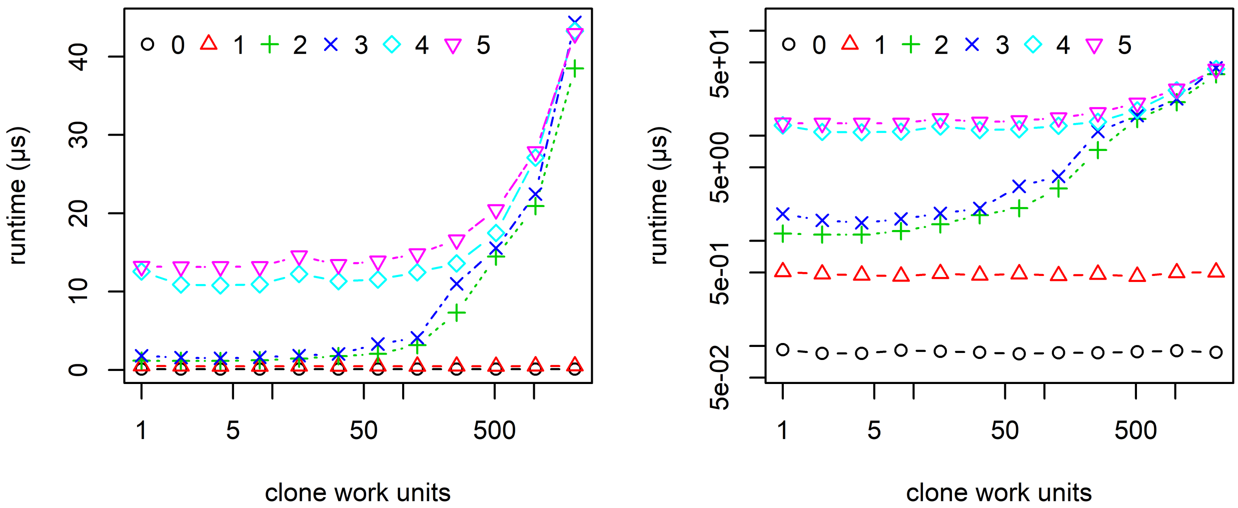
The efficiency of the bit vector *subset* operation is key to the speed of the coordinator. This is the first first three things evaluated for each and every rule, checking whether all involved ports are ready, and if all the relevant memory cells are full or empty. The bit-set capitalizes on how unusually often we need this operation. Figure 5.6 shows how bit vectors are very efficient at checking whether one is a subset of another. Here we see the time taken to evaluate the *positive* case, representing the best-case scenario for our speedup. It is guaranteed to occur at least three times every time a rule fires. Figure 5.6a shows how low the cost of the operation stays, even when there are very many ports involved. Figure 5.6b shows how significant the speedup over the subset operation of canonical `HashSet` type. Admittedly, the majority of realistic Reo circuits are on the low-end with respect to number of ports; if nothing else, this is a result to encourage the development of more complex connectors. Observe that the cost of the operation is agnostic to the *fullness* in the case of the bit-vector. This is not so for the hash set, for which a fuller hash set makes for a more expensive operation.

5.3.3 Parallelism Within Interactions

After data exchanges are initiated by the coordinator, the protocol's lock is released. Time spent exchanging can therefore only impact the threads that play a part directly. Figure 5.7 shows measurements of the *simo* ('single input, multiple output') protocol, which synchronously distributes a putter's datum to a set of getters. Figure 5.7 shows mean interaction times from the putter's perspective, measured in response to the *cost* of the data type's `clone` operation and the number of recipient getters. For the sake of the experiment, we introduce an artificial `clone` operation for our data type, defined such that it spins, performing a predictable amount of bogus value manipulations to simulate some computation of the desired intensity. We use an arbitrary 'work unit' as a relative metric of this duration. It's absolute meaning is not necessary; all that matters is that it is defined such that its contribution to runtime is proportionate.

We observe that with fewer than two getters, the runtime does not scale with the work units. Section 4.3.4 explains that amongst a set of getters, one is elected the *mover*, both responsible for freeing the putter and given permission to *move* the putter's original if possible. The vast difference made by having any getters at all can be explained by the implementation of the `Mutex` type protecting the protocol's critical region. With only one interacting port, the mutex lock is always uncontested, and able to take the *fast path*[3].

[3] Our `Mutex` comes from the `parking_lot` crate. The relevant documentation is found at `https://amanieu.github.io/parking_lot/parking_lot/struct.Mutex.html`.



(a) (b)

Figure 5.7: Mean interaction duration from the perspective of the putter into the *simo* connector. Results are distinguished by how many getters synchronously acquire the putter's datum in each interaction. Results are shown in response to the cost of the `clone` function, in arbitrary *work units*. Note the logarithmic x-axes in both figures, and the logarithmic y-axis in (b)

For few work-units, the duration of the interaction was always greater the more getters were involved. Counter to our expectations, this was not a linear relationship. The precise reason for this is uncertain, but owing to its repeatability, we conclude that it's a property of the system used for testing having to share physical cores. Regardless, we observe that for all cases with numerous getters, their durations converge toward more costly clone operations. Figure 5.8 confirms that as the parallelizable clone-work increases in significance, getters parallelize their work more effectively.

5.3.4 Reference-Passing Optimization

Finally, we perform an experiment to verify that the reference-passing optimization described in Section 4.3.4 is working as intended. Figure 5.9 shows the results of the mean time taken for a datum to pass through a *fifo-m* connector. This protocol makes trivial use of an m-long chain of memory cells. Values originate as input on one end, shifting between cells from head to tail, and

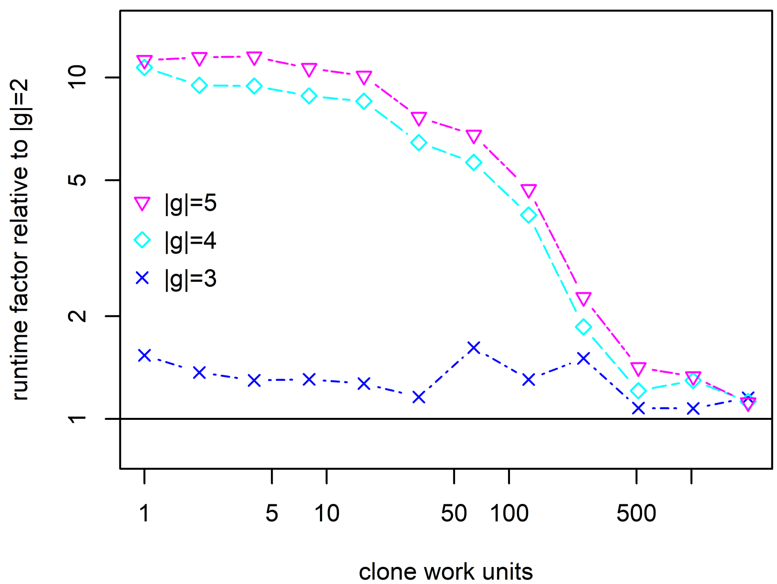
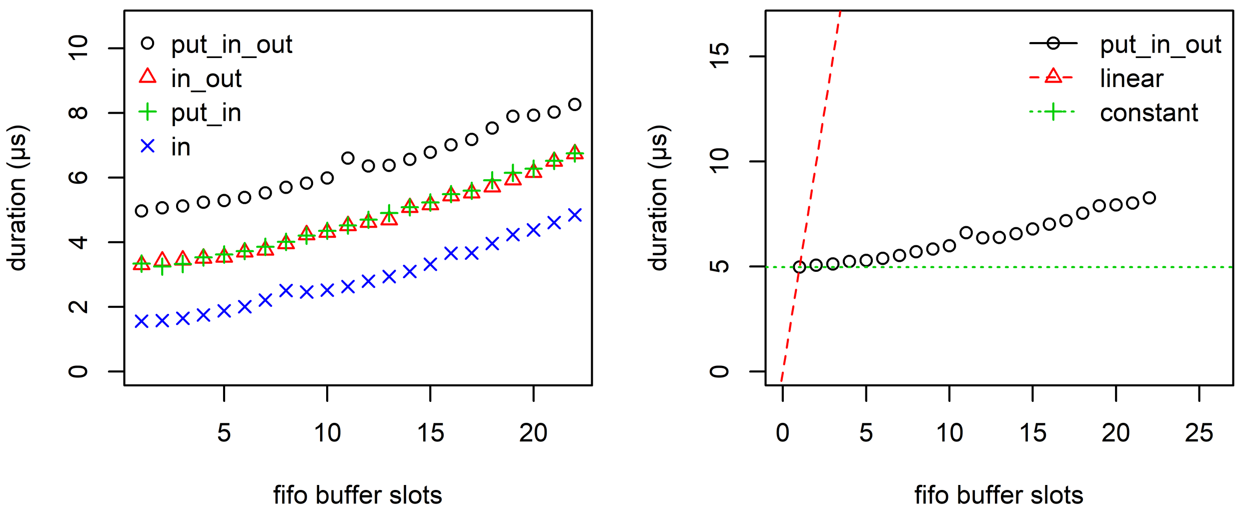


Figure 5.8: Mean interaction duration in the *simo* connector, showing slowdown relative to that of runs with two getters. Results are shown in response to the cost of the `clone` function, in arbitrary *work units*. Note the logarithmic axes.

finally being output at the tail. All measurements are dominated by the work of *moving* the 2^{13}-byte values in memory from one place to another. `shift_get` represents the most intuitive run, where values are moved twice: once *into* the protocol's storage, and once *out* to the getter. For this protocol, the Rust compiler failed to optimize the logical data-movement of the safe API's `put` operation. Runs using this safe variant are prefixed with `put_`, and include an additional value-movement.

As expected, runtimes in Figure 5.9a are seen stratified according to the number of movements they perform. In all cases, longer chains of memory cells indeed require more time (preventing the runtime to be *constant* with respect to `m`), but the overhead is relatively small, and does not appear to be affected by the baseline cost of movement; this is expected, as the cost of reference-passing is unrelated to the value's size, or data type in any way.

Figure 5.9b shows how the cost of reference-passing compares to the best- and worst-case scenarios for the response of interaction time to the length of the chain. Previously we have observed that Reo-rs experiences some constant overhead per port-interaction (eg. in Figure 5.3b), so interaction time would likely remain sub-linear even if it performed value-passing between memory cells naïvely. However, in most examples (including this one) we can safely presume it's slope would be far steeper than it is now.



(a) (b)

Figure 5.9: Round trip time (RTT) of a 2^{13} byte value through a *fifo-m* connector with m ranging from 1 to 20, measuring the time taken from the start of the `put` into the head of the chain, to the end of the `get` out of the tail. (a) The experiment was repeated using variations of port-operations to control the number of *memory copies*. `put_*` runs move the datum using the safe value-passing API, and others use the unsafe C-like reference-passing API. `*_get` runs acquire the output by value, while others participate in synchrony by acquiring a signal. (b) `put_in_out` is compared to the best- and worst-case scenarios for interaction times in response to m.

Chapter 6

Generating Static Governors

A protcol's *governor* acts to ensure that all the actions of some component are *adherent* to the protocol with which it interfaces, guaranteeing that its actions will not violate the protocol. In this section, we develop a means of embedding governors into Rust's affine type system. As a result, an application developer may ergonomically opt-into checking protocol adherence of their own compute-code using their local Rust compiler, whereafter successful compilation guarantees adherence to the protocol.

In more precise terms, let protocol A be *protocol adherent* to protocol B if and only if the *synchronous composition* of A and B is language-equivalent to B; equivalently, A is adherent to B and A adheres to B. This can be understood as A contributing no constraints to the composed system that B did not have already.

6.1 The Problem: Unintended Constraints

A central tenet of Reo's design is the *separation of concerns*, part of which is the desire to minimize the knowledge a compute component must have of its protocol. In this view, coordinating the movements of data is not a concern relevant to the task of computation. A desirable balance is possible with the observation that protocol objects are able to partially impose protocol adherence on their neighbors; External ports may instigate a `put` or `get` at any moment, and the *coordinator* will complete them as soon as the protocol definition allows it. In this way, coordinators possess a crucial subset of the features of *governers*: aligning the *timing* of two actions that compose an interaction. Unfortunately, in the properties of the realm of sequential, action-centric programming itself *implicitly* imposes constraints on the behavior of the system: `put` or `get` block until their interaction is completed, and no subsequent code (potentially, other port operations) will occur until they do. This is beyond the capabilities of the coordinator to influence.

In the context of application development, this has an interesting consequence; the behavior of the system is influenced by the behavior of (potentially) all of its components. This is sensible in theory, but becomes unwieldy in practice. Even small changes to the behavior of a compute component influences the system's behavior in unexpected ways, as we are not used to thinking about synchronous code as a composable protocol, nor are we able to intuit the *outcome* of the composition. For example, Listing 18 gives the definition of a compute function which a user may write to interact with a protocol. When `p` and `g` are connected to a *fifo1* protocol (which forwards `p` to `g`, buffering it asynchronously in-between), it runs forever and the output will be something like: `I saw true. I saw false. I saw true. I saw false. (...)`.
However, when connected with the *sync* protocol (which forwards `p` to `g` synchronously), the system has no behavior. The problem is that even though *fifo1* and *sync* have the same *interface*, `transform_not` is *compatible* (can be made to adhere) with the former and not the latter. By definition, *sync* fires when *both* `p` and `g` are ready, but `transform_rot` does not `put` until the `get` is completed. Once the intricacies of these programs grow beyond a programmer's ability to keep track of these relationships, the composed system may have *unintended* behavior. This property may be obvious at the small scale of this example, but it becomes more difficult the larger and more complex the program becomes. In the worst cases, an innocuous change makes an interaction becoming unreachable, manifesting at runtime as *deadlock*.

```
fn transform_not(p: Putter<bool>, g: Getter<bool>) {
    loop {
        let input: bool = g.get();
        print!("I saw {}.", input);
        p.put(! input);
}   }
```

Listing 18: A function in Rust which can be used as a compute component in a system, connected to a protocol component.

6.2 Governors Defined

In this work, we accept that it is necessary to write compute code that has blocking behavior. Rather than attempting to empower the coordinator with the ability to further influence its boundary components, we introduce explicit governors into our applications such that from the protocol's perspective, the components appear to manage themselves. A particular compute component requires a particular governor as the behavior permitted to the compute component is a function of its *interface* with the protocol.

Ultimately, all governors have in common that they enforce adherence to a given protocol on the components they govern. However, governors may differ on *when* and *how* this enforcement manifest. For example, a governor may intercept and filter network messages at runtime, while another checks for deviations *statically* and emitting compiler errors.

In this work, we leverage the unique expressiveness of the Rust language by creating a tool which generates protocol-specific governor code. When used by an application developer, these governors assess the protocol adherence of compute functions *statically*, and prevent compilation if deviations are detected. As such, these governor are absent from the compiled binary.

6.3 Solution: Static Governance with Types

TODO

6.4 Making it Functional

This section details the workings of the **Governor generator** tool which generates Rust code given (a) a representation of a protocol's RBA, and (b) the set of ports which comprise the interface of the compute component to be governed.

6.4.1 Encoding CA and RBA as Type-State Automata

The *type state* pattern described in Section 2.2.3 provides a means of encoding finite state machines as affine types. Their utility is in guaranteeing that all runtime traces of the resulting program correspond to runs in the automaton. For this class of machines, the encoding is very natural, as there can be a one-to-one correspondence between the states of the abstract automaton, and the types required to represent them. This is also the case for transitions and functions; in the worst case, this mapping is one-to-one also. For an arbitrary transition from states a to b with label x, a function can be declared to consume the type for a, return the type for b, and perform the work associated with x in its body.

The encoding is more complicated for CA, where not only states but data constraints must be encoded into types and must interact with transitions. One approach is to treat *configurations* as *states* were treated before by enumerating them into types. For example, the configuration of state q_0 with memory cell $m = 0$ is represented by type `q_0_0`, while state q_0 with $m = 1$ is represented by `q_0_1`. On a case-by-case basis, one might be able to represent several configurations using one type in the event these configurations are never *distinguished*. For example, a connector may involve positive integers, but only distinguish their values according to whether they are *odd* or *even* and nothing else; in this case {`q_0_0`, `q_0_1`, `q_0_2`, ...} may be collapsed to {`q_0_odd`, `q_0_even`}. For an arbitrary case unique types are needed for every combination of state with every value of every variable. As RBAs are instances of CA, we are able to represent them using the same procedure. As RBAs are used by both the Reo compiler and Reo-rs, they are the model of choice for governors also.

6.4.2 Rule Consensus

The protocol works by firing rules at runtime which correspond to those of the RBA which defines its Reo connector. Section 6.4.1 above explains how various compute-components are able to proceed in lockstep with the protocol's RBA in a type-state automaton of their own. For deterministic RBAs, this is easy enough; everyone can trivially know which action occurs *next*, and they can transition through configuration space independently, safe in the knowledge that their representations of the run will stay aligned. This ignores temporary mis-alignments in *time* for transitions in which the compute component does not communicate with the protocol; for these cases, one may work head, leaving the other in a previous state. However, they will catch up eventually when they both reach a transition that involves them communicating (which is ultimately all that matters). This process becomes more complicated when the protocol can reach configurations with *multiple* choices for the next transitions. Without a priori agreement on how these situations are handled, the choice is defined to be nondeterministic. Clearly, all is well as long as all parties agree on this choice; problems only present themselves when compute components and protocols diagree on what may happen next. If the view of a governor are out of sync with its protocol it is generally unable to guarantee that the actions it permits are adherent, or it may prohibit something it ought not to, resulting in unintended constraints of the intended behavior (in the worst case, deadlock). This is a problem of *consensus*.

Many means of creating consensus exist. We are able to enforce a *meta-protocol* a priori between governors and protocol such that consensus emerges at runtime. This can be achieved without any overhead by making the decision based only on information statically available. For example, peers may rely on a shared, total *priority* ordering on rules to remove all nondeterministic choice. Many such meta-protocols are possible, each making assumptions about the desired system behavior.

This work takes the approach of statically 'electing' the *coordinator* as the leader in every case, and having all governors follow the lead of its arbitrary choice by 'asking' it what to do next *dynamically*. This approach is primarily motivated by its *flexibility*; by supporting an arbitrary choice on the part of the protocol, we make the choice itself an *orthogonal* concern for future work. Electing the coordinator in particular as the leader is also somewhat natural; It is only actor in the system with a complete view of the protocol's state, allowing it to make the choice as a function of the state, ie. the protocol is capable of making the best-informed decisions.

In terms of implementation, we make a modification to the encoding of our governor's automaton such that it can represent all choices available from a particular configuration. Before proceeding, the governor 'collapses' these options to match the choice of the protocol by communicating with the coordinator. Concretely, the Rust function for a rule no longer returns a *particular* type-state token, but rather a `StateSet` which enumerates the options. This object is collapsed as a result of calling `determine`. Handling the returned variants branches the governor's control flow in a manner akin to a `match` (similar to a `switch` statement in other languages), with each arm given a single state token to proceed. Naïvely, this must be encoded as a distinct `enum` type with a variant for every possible outcome. Clearly creating new type definitions for every conceivable combination of branches is prohibitively expensive[1]. Ideally we wish to be able to create enumeration types on-the-fly with precisely the variants needed on a case-by-case basis. Rust provides *tuples* for this purpose in the case of `struct` (product types), it has no parallel for `enum` (sum types). This feature has been requested for some time [rh14]. If it is supported one day, this may be ideal fore representing these `StateSets` with minimal code generation.

Until anonymous sum types are supported, our solution to the problem of representing the generic `StateSet` type relies on Rust's traits to encode the variants as a *tail-recursive* list of nested tuples. Matching the elements of the lists is achieved by repeatedly attempting to match the *head*. Listing 19 shows one possible representation which uses a final *sentinel* list element to make for an ergonomic definition of the `StateSetMatch` trait, which provides distinct head-matching behavior for *singleton* lists from that of larger ones. From the user's perspective, `StateSet` objects are opaque, and prevent the automaton from proceeding with transitions until the object is collapsed to some usable `State` object.

[1] Early versions of our implementation indeed enumerated these types with a relatively effective *powerset* construction. However, it was unable to avoid explosion if there simply were many solutions to be found. The nail in the coffin was the changing from the exponential base from 2 to 3 as a result of the modification explained in Section 6.5.2.

```
trait StateSetMatch {
    type MatchResult;
    fn match_head(self) -> Self::MatchResult;
}
struct StateSet<L> { data: /* omitted */ }
impl<H,Ta,Tb> StateSetMatch for StateSet<(State<H>, (Ta, Tb))> {
// a list with 2+ elements. match_head definition omitted
    type MatchResult = Result(State<H>, StateSet<(Ta,Tb)>>;
}
impl<S> StateSetMatch for StateSet<(State<S>, ())> {
// singleton set. `()` acts as a sentinel element. match_head definition omitted
    type MatchResult = State<S>;
}
fn example(ab_set: StateSet<(State<A>, (State<B>, ()))>) {
    match ab_set.match_head() {
        Ok(a) => /* matched A */,
        Err(b_set) => {
            let b = b_set.match_head();
            /* matched B */
}   }   }
```

Listing 19: Definition of type `StateSet`, which acts as an anonymous sum type by encoding its variants as a tail-recursive tuple in its generic argument. Two non-overlapping definitions of trait `StateSetMatch` are provided to make the type behave as expected in response to associated method `match_head`. Function `example` demonstrates how the arbitrary number of variants are matched two at a time by repeatedly attempting to match the first element of the list (the head), translating it into a conventional `Result` enum which Rust can pattern-match as usual. The result of this match can depend on the contents of field `data`, which is instantiated dynamically at runtime by interacting with the coordinator.

6.4.3 Governed Environment

TODO

6.5 Making it Practical

With a basic outline for the implementation, we are able to realize some functional, yet naïve governors. However, there is a long way to go before these systems can be applied in any realistic scenario. In this section, we explain which problems remain to be solved, whether for the sake of managing complexity, or for the user's ergonomics.

6.5.1 Approximating the RBA

The approach to generating a type-state automaton from an RBA was given in 6.4.1. Our type-state automaton suffer the same state-space explosion of Constraint Automata, prior to the inclusion of memory (explained in Section 2.1.3). We cannot hope to represent realistic programs with this approach alone, as the type-state automata would be wildly unmanageable in its number of states and transitions. In this section, we explain how the type-state automaton is adapted to *approximate* the protocol's configuration space such that we strike a balance between accuracy and simplicity, without any effect on the governor's correctness.

Data Domain Collapse

We abandon the goal of faithfully representing the entirety of the protocol's configuration space in favor of representing an approximation by assuming all data types to be the trivial *unit-type*. With this assumption, memory cells may be in one of two states: (a) empty, (b) filled with 'unit'. Converting existing RBAs may see large sub-expressions of *data constraints* becoming constant, including checks for equality and inequality between port values. This assumption is justified by its relation to Assumption **??** from Section **??**. In this context, it can be understood to mean that *usually*, two configurations that are only distinguished by having different *data values* in memory cells or begin put by putters satisfy precisely the same subset of the RBA's guards. Consequently, they do not need to be distinguished. This simplification greatly reduces the total number of types to encode an RBA's configuration space. However, it is still necessary to consider the possible *combinations* of all empty and full memory cells, requiring potentially 2^N types for N cells. Rather than enumerating these types explicitly, we can rely on the *structure* the RBA provides by simply encoding each automaton configuration as a *tuple* of types `Empty` and `Full`. In a sense, each tuple is indeed its own type, but neither the code generator nor the compiler need to pay the price of enumerating all the combinations eagerly. For example, a configuration of three empty memory cells would be represented by type `(Empty,Empty,Empty)`. For brevity, we will henceforth abbreviate these tuples by omitting commas, and shortening `Empty` and `Full` to `E` and `F` respectively.

As before, we are able to represent an RBA rule as a *function* in the Rust language by encoding a configuration change from q to p determines its *declaration* such that it consumes the type-state of p and returns the type-state of q. The naïve approach of generating functions per type-state is susceptible to the same *exponential explosion* that plagued CAs in the first place. Fortunately, tuple-types have inherent structure which Rust's generic type constraints are able to understand. The use of generics to *ignore* elements of the tuple coincides with an RBA's ability not *ignore* memory values. Consequently only one function definition per RBA rule is required. The way the rule's data constraint manifests is somewhat different, as our function must *explicitly* separate the *guard* and *assignment* parts and represent them as constraints on the parameter-type and return-type respectively. As an example, Listing 20 demonstrates the type definitions and rule functions for the *fifo2* protocol first seen in Section 2.1.3 with the associated RBA shown in Figure 2.6. Observe that the concrete choices for tuple elements act as *value checks* for memory cells in either empty or full states. Omission of a check must be done explicitly using a *type parameter* such that the function is applicable for either case of `Empty` or `Full`, and to ensure the *new* state preserves that tuple element; this causes memory cells to have the expected behavior of *propagating* their values into the future unless otherwise overwritten by assignments. This serves as an example of a case where our simplification coincides with a faithful encoding of the original protocol as *fifo2* never discriminates elements of the data domains of A and B.

```
enum E {} // E for "Empty"
enum F {} // F for "Full"
fn start_state() -> (E,E);

fn a_to_m0<M>(state: (E,M)) -> (F,M);
fn m0_to_m1  (state: (F,E)) -> (E,F);
fn m1_to_b<M>(state: (M,F)) -> (M,E);
```

Listing 20: Type-state automaton for the *fifo2* protocol in Rust. The three latter functions correspond to the three rules seen for the RBA in Listing 2.6. Function bodies are omitted for brevity. Note that `M` is not a type, but rather a generic *type parameter* to be instantiated at the call site.

RBA Projection

When a protocol's interface is provided as-is to a compute component, its model itself (an RBA in our case) defines precisely what it is permitted to do, just with the *direction* of operations reversed; for the component to be compatible, it must put on port P whenever the protocol gets on P, and get on port Q whenever the protocol puts on port Q. In such cases, the procedure for encoding the RBA described in Section 6.5.1 can be applied directly. Otherwise, the interface of a compute component does not subsume the entirety of the interface of its protocol. In such systems, the protocol interfaces with

rule	guard	assignment
0	$m_0 = *$	$\wedge\ m_0' = d_A$
1	$m_0 \neq * \wedge m_1 = *$	$\wedge\ m_1' = m_0 \ \wedge\ m_0' = *$
2	$m_1 \neq *$	$\wedge\ d_B = m_1 \ \wedge\ m_1' = *$

Table 6.1: RBF of the *fifo2* protocol, equivalent to the RBA in Figure 2.6. Formatted with an outermost disjunct per line such that guard and assignment parts per rule are discernible.

several compute components. Indeed such cases form the majority in practice; compute components tend to only play a small role in a larger system.

The contents of Section 6.5.1 are sufficient to generate some functional governors. We consider a system containing protocol P and connected compute component C with interfaces (port sets) I_P and I_C respectively such that $I_P \supseteq I_C$. We wish to generate governor G_C whose task is to ensure that C adheres to P. As a first attempt, we translate P's RBA to Rust functions and types as-is. We would quickly notice that the RBA's data constraints represent port-operations that are excluded from I_C. These interactions involve no actions on C's part; from the perspectives of C and G_C, these actions are *silent*. Equivalently, we do not use the RBA of P directly, but consider instead its *projection* onto I_C, which *hides* all actions that are not in the interface projected upon.

```
fn a_to_m0<M>(state: (E,M)) -> (F,M) {
  // A puts
}
fn m0_to_m1  (state: (F,E)) -> (E,F) {
  // silent
}
fn m1_to_b<M>(state: (M,F)) -> (M,E) {
  // silent
}
```

Listing 21: Type-state automaton rules which govern the behavior of a compute component with interface ports $\{A\}$ for the *fifo2* protocol. Function bodies list the *actions* which the component contributes to the system. Observe that rules but 0 are silent.

As an example, we once again generate a governor for a compute-component with interface $\{A\}$ with the *fifo2* protocol. This time the protocol is represented as an RBF in Table 6.1 to make the correspondence to the generated governor in Figure 21 more apparent. Observe that all but one of its rule functions are *silent*, serving no purpose but to advance the state of the automaton by consuming one type-state and producing the next. As demonstrated here, this approach to generating governors is correct, but has two undesirable properties:

1. **API-clutter**
   The end-user is obliged to invoke functions which correspond with rules in the protocol's RBA. In many cases, these rules will serve no purpose other than to consume a type-state parameter, and return its successor.

2. **Protocol Entanglement**
   The type-state automaton captures the structure and rules of the protocol's RBA in great detail. This is a failure to *separate concerns*, which further couples the compute component to its protocol. This has the immediate effect of making components difficult to re-use (their implementations are more protocol-specific), as well as making them brittle to *changes* to the protocol, making them difficult to maintain.

RBA Normalization

Section 6.5.1 introduced a procedure for generating governors, but also discussed a significant weakness; all governors are represented by type-state automata based on the original protocol's rules. In this section, we introduce a notion of *normalization* that intends to *specialize* the governors according to its needs such that it is still 'compatible' with the protocol's RBA in all ways that matter, but has greatly reduced *api-clutter* and *protocol-entanglement*.

Let an RBA be in normal form if it has no silent rules. We observe that the presence of silent rules contributes to both api-clutter and protocol entanglement. Ideally, we wish to abstract away the workings of the protocol as much as possible; at all times, the governor only needs to know which actions the component must perform *next*. To make this notion more concrete, we introduce some definitions which build on one another to define the term we need: our normalization procedure should generate an RBA with starting configuration which *port-simulates* the protocol's RBA in its starting configuration:

- $\mathrm{Act}(r)$ of an RBA state r:
  The set of ports in r which perform actions (ie: are involved in interactions).

- *Rule sequence* from c_0 to c_1 of RBA R:
  Any sequence of rules in R that can be applied sequentially, starting from configuration c_0 and ending in configuration c_1.

- P-*final* wrt. port set I:
  A rule sequence of RBA R, with *last* rule r_{last} is P-final with respect

to port set I if $\mathrm{Act}(r_{last}) \cap I = \{P\}$ and for all rules r in the sequence, $r = r_{last} \vee \mathrm{Act}(r) \cap I = \varnothing$.

- RBA R_1 in config. c_1 *port-simulates* R_2 in config. c_2 wrt. Interface I:
  If for every P-final rule sequence of R_2 starting in c_2, ending in c_2' there exists some P-final rule sequence of R_1 starting in c_1, ending in c_1' such that R_1 in c_1' port-simulates R_2 in c_2'.

The intuition here is that it does not matter how the governor's RBA structures its rules. It is unnecessary for governors to advance in lockstep with the protocol to the extent that they agree on the protocol's *configuration* at all times. It suffices if the protocol and governor always agree on which *actions* the ports in their shared interface do next. Figure 6.1 visualizes this idea; observe how the normalized RBA has entirely different transitions (different labels and configurations), but is ultimately able to pair actions of the protocol for ports in its interface with its own local actions.

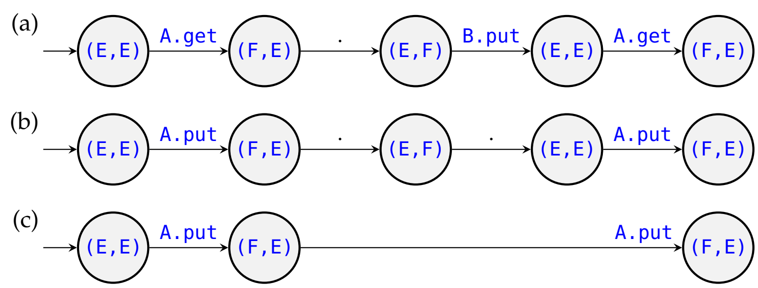


Figure 6.1: Rules being applied to walk three RBAs in lockstep, with time horizontally, showing the (simplified) configurations traversed, and annotating rules by showing which port actions they involve.
(a) RBA of protocol *fifo2*. (b) RBA of *fifo2* projected onto port set $\{A\}$. (c) RBA of *fifo2* projected onto port set $\{A\}$ and normalized to remove silent rules.

The final normalization procedure is given in Listing 22 in the form of simplified Rust code. It works intuitively for the most part: silent rules are removed, and new rules are added to retain their contribution of moving the RBA through configuration space. The function `normalize` ensures that the returned rule set is in the same configuration as the protocol after matching a non-silent, but the configuration is allowed to 'lag behind' while the protocol performs rules which it considers to be silent. New rules must be added to 'catch up' to the protocol after any such sequence of silent rules. The procedure does this by building these *composed* rules from front to back, ie. replacing every silent rule x with a *set* of rules $x \cdot y$, where y is any other rule. Once

```
fn normalize(mut rules: Set<Rule>) -> Set<Rule> {
    let (mut silents, mut not_silents) = rules.partition_by(Rule::is_silent);
    while silents.not_empty() {
        let removing: Rule = silents.remove();
        if removing.changes_configuration() {
            for r in silents.iter() {
                if let Some(c) = removing.try_compose_with(r) {
                    silents.insert(c);
            }   }
            for r in not_silents.iter() {
                if let Some(c) = removing.try_compose_with(r) {
                    not_silents.insert(c);
    }   }   }   }
    return not_silents;
}
```

Listing 22: Normalization procedure, expressed in (simplified) Rust code. In a nutshell: while one exists, an arbitrary silent rule x is removed, and the list of rules is extended with composed rules $x \cdot y$ such that y is another rule.

completed, the RBA may contain rules that are subject to *simplification*. For example, $\{m = * \wedge n = *, m \neq * \wedge n = *\}$ can be represented by only $n = *$.

The normalization algorithm is **correct** as clearly it does not have silent rules once it returns (`not_silent` containing zero silent rules is invariant). Observe that for each silent rule removed, it does not consider composing with *itself*. The immediate result is that the algorithm never inserts some rule $x \cdot x$ for silent rule x. This is not a problem, as all *silent* rules of our approximated RBAs are *idempotent* with respect to their impact on the configuration. The algorithm is able to take for granted that the result any *chain* of silent rules $x \cdot x \cdot x \cdot ...$ is covered by considering x itself. Furthermore, the incremental removal of rules prohibits the creation of any silent cycles at all. This is due to the reasoning above being extended to any sequences also. (TODO PUMPING LEMMA).

The normalization algorithm is **terminating**. It consists of finitely many *algorithm steps* in which the RBA A is replaced by RBA $B = (A \setminus \{r\}) \cup \{r \cdot x | r \in A \setminus \{x\} \wedge \mathrm{composable}(x, r)\}$ for some silent rule $x \in A$. Initially, A is the input RBA with silent rules. The algorithm terminates, returning B when A is replaced by B where B has no silent rules. Let $P(x)$ be the set of *acyclic paths* through RBA x's configuration space. Observe that initially, $P(A)$ is finite. It suffices to show that in each algorithm round, $|P(A)|$ strictly decreases. Within a round, for every 'added' p in $P(B) \setminus P(A)$, p contains a rule $m \cdot n$ such that there exists p' in $P(A) \setminus P(B)$ identical to p but with a 2-long sequence of rules

rule	guard	assignment
0	$m_0 = *$	$\wedge\ m_0' = d_A$
2	$m_1 \neq *$	$\wedge\ d_B = m_1\ \wedge\ m_1' = *$
$1 \cdot 0$	$m_0 \neq * \wedge m_1 = *$	$\wedge\ m_0' = d_A \wedge m_1' = m_0$
$1 \cdot 2$	$m_0 \neq * \wedge m_1 = *$	$\wedge\ m_0' = *$

Table 6.2: RBF of the *fifo2* protocol, projected onto port set $\{A, B\}$ and normalized. Rules 0 and 2 are retained from Table 6.1, and new rules $1 \cdot 0$ and $1 \cdot 2$ are composed of rules from the original RBF.

m, n in the place of x. From this we know that $|P(A)| \geqslant |P(B)|$. However, the 1-long path of x itself is clearly in $P(A) \setminus P(B)$. Thus, $|P(A)| > |P(B)|$. QED.

To demonstrate the normalization procedure, Table 6.2 shows the result of projecting the *fifo2* connector's RBF onto port set $\{A, B\}$ and normalizing. The two additional rules can be understood to 'cover' the behavior lost as a result of omitting the silent rule 1 from the original RBF.

6.5.2 User-Defined Protocol Simplification

Recall, the purpose of a governor is to preserve a system's *liveness*. They do this by ensuring that their governed compute component performs port operations that allow the interfacing protocol (and the system around it) to progress. Governors do this by enforcing that their compute component's implementation *covers* each possible transition with code that performs the required task, and ensuring it is chosen correctly in accordance with the wishes of the protocol. Section 6.4.2 explains how our type-state automaton represents this by each configuration requiring the definition of a *set* of transitions, one for each action. We say the implementation 'covers' each of these cases by defining the component's behavior in each cases, including the invocation of the relevant port operation.

An overzealous governor which requires to cover *additional* (unnecessary) cases would still serve its purpose. In effect, such a governor would enforce adherence to some *other*, more permissive protocol. However, liberty of the protocol means responsibility to the compute-component: the more the protocol *might do*, the more the compute-component *must consider doing*. There is incentive for governors to do this: permissive protocols are simpler to enforce.

This conservatism becomes a problem when it infringes on the component's ability to express its behavior as intended. Consider the example of a compute-component X that forwards values from its input port A to its output port B. Perhaps this component is used in a pipeline as intended such that the component is involved in an endlessly-alternating sequence, represented by regular

rule	guard	assignment
0	$m_0 = *$	$\wedge\, m_0' = d_A$
1	$m_0 \neq * \wedge m_1 = *$	$\wedge\, m_1' = d_A \wedge m_0' = *$
2	$m_0 = m_1 \neq * \wedge m_2 = *$	$\wedge\, m_2' = d_A \wedge m_0' = m_1' = *$
3	$m_0 = m_1 = m_2 \neq *$	$\wedge\, d_B = m_0 \wedge m_0' = m_1' = m_2' = *$

Table 6.3: RBF of the *a7b1* connector, which is characterized by cycling through a predictable sequence of period 8, where A inputs seven times and B outputs once. It works by encoding its configuration in an 8-long cycle as a three-bit integer using the fullness of memory cells m_{0-2}.

expression $(AB)^*$. Perhaps there is a sensible way for X to implement the more permissive protocol which permits B firings to be omitted, expressed $(A(B|\lambda))^*$. P has no problem discarding values input from A. However, if the governor takes it a step further such that 'anything goes' (expressed $(A|B)^*$), X cannot meaningfully represent its work. How on earth can it forward a message to B before receiving it on A? Not even clairvoyance can help; what if A never fires at all? This is how the user would experience the problem of a governor infringing on the component's own behavior; in a sense, P has a protocol of its own which must be preserved on its interface ports which the governor violates.

Nevertheless, there is value in providing a compute-component with a simplified (permissive) view of the protocol where possible. As a motivating example, consider the *a7b1* connector, given as RBF in Table 6.3. This connector uses the fullness of three memory cells to count in binary from zero to seven (using the binary alphabet of memory cell states {`E`, `F`}), and cycling back again to zero. Configurations in this cycle are distinguished by specifying different behaviors on A and B. Here, the projection and normalization of the protocol's RBF is trivial, as no rules are silent. Without the ability to simplify, the Y must be implemented such that it corresponds exactly with the protocol's (predictable) walk through its approximated configuration space, given in Figure 6.2. As all states are distinguishable, so too are their corresponding *state types* distinct. Now consider this protocol interfacing with some compute-component Y, which is always ready to consume and emit some data element Q. Without simplification, the resulting governor would require that the traversal through configuration space be spelled out; the user would be forced to distinguish these states, even though Y has no need for this specificity. Most likely, the resulting implementation will be repetitive and verbose, if the behavior is the same for configurations `(EEE)`, `(EEF)`, et cetera.

Our solution to this problem is to introduce a third type for representing the state of a memory cell which may be *either* full or empty: `Unknown` (ab-

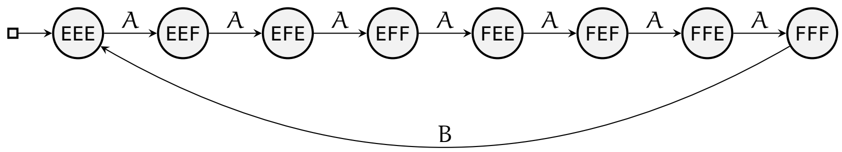


Figure 6.2: Rules transitioning through configuration space of approximated RBAs for *a7b1* connector, with states named after the 'count' the three memory cells represent in base 2 (in binary alphabet {`E`, `F`}). Here, the normalization procedure with interface set {A, B} is trivial as no transitions are silent.

breviated as `U`). Rather than corresponding to a specific configuration of the (approximated) RBA, the governor now reasons about the *set* of states which the protocol may be in. For example, type `(UUE)` encapsulates all the concrete configuration types {`(EEE)`, `(EFE)`, `(FEE)`, `(FFE)`}, and is liable to covering the *union* of the rules applicable to any of those states. In this manner, it is safe for the programmer to arbitrarily 'forget' the state of a memory cell, replacing its element in the tuple type with `U`. To be clear, `U` is not special as far as Rust is concerned; we have changed to a ternary alphabet for representing memory cells in types. However, `U` does not correspond to any real configuration that memory cells are ever 'really' in at runtime; they are always either empty or full. `U` is a stand-in for an empty *or* full memory variable, an abstraction in which the protocol is not (explicitly) involved. With this tool in their belt, the implementation of the compute component is able to arbitrarily *unify* the state-types of multiple branches. Our example component Y above is able to implement its behavior to the satisfaction of its governor with transitions through configuration space in Figure 6.3. This weakening can be communicated quite ergonomically, resulting in something very close to what the user would implement themselves: a single loop where the four rules (numbered 0-3) may be applied to configuration type `(UUU)`, each resulting again in `(UUU)`.

6.5.3 Match Syntax Sugar

Section 6.4.2 explains how the set of transitions to be covered by a configuration type can be represented in Rust's type system as a tail-recursive list. This alleviates the problem of having to explicitly enumerate the needed sets each as their own enumeration type. This is necessary, as the upper-bound[2] of state

[2]Many factors reduce this number drastically in practice. For example, state-sets are usually not large because they are only ever encountered when reached by *transitions* from some state.

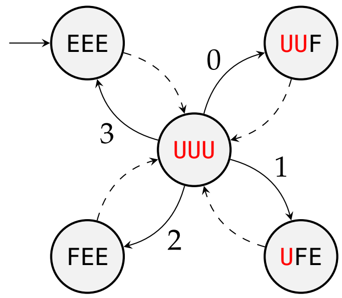


Figure 6.3: Rules transitioning between configurations of the *a7b1* connector shown in Figure 6.2. Here, the user employs *weakening* to convert (dashed arrows) state tokens to configurations to the configuration-set '???' containing *all* concrete configurations. RBA rules firing are shown with solid arrows, annotated with the rule name, corresponding to those given in Table 6.3.

sets is 2^{3^M}, where M is the number of memory cells[3]; suffice it to say, it is *a lot*. Unfortunately, these are not natively-supported enumeration types, and thus cannot be *matched* as is idiomatic in the Rust language. However, Rust has extensive support for abstract syntax tree *macros*, allowing us to have the best of both worlds; the user interacts with `StateSet` types by using a match-like macro which enumerates the branches, but there is no need for concrete `enum` classes to be defined for all the conceivable combinations. Figure 23 gives an example of how these cases compare to one another.

[3]The number of unique state sets is 2^S, where S is the number of configurations (automaton state types). This, in turn is 3^M, as each memory cell's state is represented by a type in {`E`, `F`, `U`}.

```
enum StateSetXyz { X(X), Y(Z), Z(Z) }
fn match_standard(set_xyz: StateSetXyz) {
    use StateSetXyz::{X, Y, Z};
    match set_xyz {
        X(x) => x.foo(),
        Y(y) => y.bar(),
        Z(z) => z.baz(),
}   }
fn match_recursive(set_xyz: StateSet<(X, (Y, (Z, ())))>) {
    use StateList::{Head, Tail};
    match set_xyz.match_head() {
        Head(x) => x.foo(),
        Tail(set_yz) => match set_yz.match_head() {
            Head(y) => y.bar(),
            Tail(z) => z.baz(),
}   }   }
fn match_macro(set_xyz: StateSet<(X, (Y, (Z, ())))>) {
    match_set! { set_xyz;
        x => x.foo(),
        y => y.bar(),
        z => z.baz(),
}   }
```

Listing 23: Example of three methods for matching a *state set*, representing a sum type of three variant types simplified here to `X`, `Y` and `Z`. First, `match_standard` shows how this is done in idiomatic Rust, requiring an enum type `StateSetXyz` be explicitly defined. `match_recursive` shows how the same state set represented by a tail-recursive `StateSet` type can be similarly matched by exhaustively 'unzipping' head elements using a function `match_head`. finally, `match_macro` functions identically to the second case, but relies on a sugaring macro `match_set` to mimic the syntax of Rust's `match` statement, seen in the first function.

Chapter 7

Discussion

In this chapter, we reflect on the work and findings in Chapters 3–5. This includes a subjective assessment of the results of the project as a whole, and identification of promising directions for future work.

7.1 Future Work

As with any project, there was insufficient time to investigate every topic we encountered. In this section, we highlight promising starting-points for future work related to Reo in general, or to our contributions in Chapters 3–6.

7.1.1 Imperative Form Compiler

Chapters 3 and 4 explain how the Reo-rs runtime makes use of a lightweight interpreter to bring life to our protocol objects at runtime according to the appropriate specification. This *commandification* pattern has its advantages; namely, protocol behavior is alterable at runtime by manipulating the interpreted data. However, this flexibility does not come for free. The interpretation steps incur overhead both to the protocol construction procedure, and more importantly, to the work of *port operations*. Fortunately, our *imperative form* does not necessitate the use of an interpreter. Future work could investigate replacing the `build` procedure of Reo-rs with another compilation step such that the behavior is represented in native, directly-executable Rust.

Futhermore, future work might investigate the use of custom *domain specific languages* for compiling imperative form in a manner that it performs the same checking as in `build` *statically*. the obvious means of doing this is to build a compiler from scratch. However, other options exist that can make better use of existing tools. For example, Rust's *procedural macros* allow the programmer to define arbitrary transformations of Rust's *abstract syntax trees* during compilation. Essentially, one is able to invoke arbitrary, pre-compiled Rust code *inside* the user's Rust compiler itself. In this manner, one can embed the needed domain-specific language into the Rust compiler itself.

7.1.2 Distributed Components

This work focuses on coordination between threads in shared memory. This approach can already be applied in the context of distributed components by abstracting ports behind local ones. However, we are unable to distribute our protocol components, as they presuppose a single, monolithic shared state in our current scheme. One can get around this by fragmenting protocols into smaller ones, and distributing those smaller protocols across the system. However, this cannot currently be done in all cases, as this fragmentation does not preserve synchrony.

Reo has a rich academic history in this distributed context. Future work might investigate how our contributions (eg. reference-passing optimizations, static governors, etc.) can be applied in distributed systems.

7.1.3 Optimize Rule Branching

Reo-rs is able to represent protocols whose rules contain *branching*. Rule-based form has already shown us the correspondence between our RBA rules and propositional logic, where the formula corresponds to a protocol, with disjuncts as rules [DA18a]. In the same way such terms can be manipulated until the formula is in *disjunctive normal form*, so too are we able to remove branching from our rules by splitting them. For example, a rule with data constraint $(P_0 = C_0 \vee P_1 = C_1) \wedge P_2 = C_2$ can be converted into two rules with data constraints $P_0 = C_0 \wedge P_2 = C_2$ and $P_0 = C_0 \wedge P_2 = C_2$ respectively. Such transformations are not particularly meaningful to the outside observer; clearly they have no influence on the protocol's semantics[1]. However, they do have interesting implications on performance. It is easy to contrive of examples for both extreme ends of the spectrum for which this splitting is either beneficial or detrimental to the performance of the protocol object, as we are able to both introduce and eliminate redundant work by splitting rules. As an example of a rule *not* worth splitting, consider one with very many *instructions* I before reaching a 3-way branch $a \vee b \vee c$ where the branch is not entirely nondeterministic (ie. there are cases for which a cannot be chosen, etc.). Before splitting, I is computed once, and then one of $\{a, b, c\}$ will occur. After splitting, three

[1] Changing the granularity of rules can be semantically meaningful once it affects our ability to express interesting properties. For example, fine-grained rules can be desirable when the protocol is lifted to consider *preference* between nondeterministic branching.

separate rules for a, b, and c might be considered, each computing I before the third fires successfully.

In our case, only the Reo compiler's internals perform manipulations on protocol rules, while Reo-rs restricts itself to the treatment of tautologies and contradictions. Future work might investigate more extensive manipulation of protocol rules to optimize rules by conditionally splitting them to remove branching.

7.1.4 Runtime Governors

Chapter 6 explains how our design for static protocol governors is able to enforce protocol adherence at compile time. This approach is not always suitable, as it presupposes that we *trust* the compilation process enforcing the governance. If the situation calls for a degree of separation between the compilation process and its use at runtime, this may no longer be a good choice. For example, consider the use of Reo to coordinate peers in a distributed system, where the behavior of a component originates from a remote source, traveling over the network.

Our static governors also have limitations on how finely they can distinguish the states of the protocol. In a perfect world, governors would use perfect models of the protocol's state. Section 6.5.1 gives an example of some practical reasons to approximate the protocol instead, resulting in a governor that attempts to strike a non-trivial balance between accuracy and simplicity of its local automaton. *Dynamic* governors are given a far easier task, as they are able to make choices at runtime, when all the relevant information is available. Generally, these governors can therefore be more accurate. Future work might investigate how these two extremes of the spectrum compare, and to what extent it may be practical to use some facets of **both** to make an application more robust. There may be systems in which redundant checking is worth its cost to runtime performance.

7.1.5 Further Runtime Optimization

Section 4.3.4 discusses various optimizations of Reo-rs's runtime performance applied in this work, chief of which is arguably the use of reference-passing inside the protocol's state as part of the implementation of rules such that it preserves Reo's value-passing semantics. Other optimization opportunities presented themselves during the project, but were not investigated thoroughly as they conflicted with our current goals, or were simply deemed less fruitful than other tasks. Future work might investigate these optimizations:

1. Simplify rules in the context of a known *priority ordering* to break nondeterminism. For example, consider rule r_a with priority over rule r_b. Clearly, r_a must always be given a chance to fire first, allowing r_b to presumes the *negation* of r_a's guard. In practice, this can often allow rules to be meaningfully simplified, particularly when they are created by splitting nondeterministic branches as discussed in Section 7.1.3. For example, consider rules with the data constraints $M_0 = M_1$ and $M_0 \neq M_1$. If they are prioritized in the order of their appearance here, the guard of the second rule becomes trivially *true*.

2. Remove indirection inside Reo-rs when representing values smaller than the pointer-size, by 'stuffing' the value inside the pointer field. This optimization has complex interactions with the *memory storage* system described in Section 4.3.4, which uses pointers as keys to look up a value's reference count. Future work may investigate either (1) conditionally using stuffed pointers when it would not interact with the memory storage system, or (2) finding a way to make the memory storage system disambiguate these stuffed pointers

3. More extensively pre-process the imperative form as its executable object is built (explained in Section 3.3.2). For example, instructions can be fragmented and re-organized such that the effects of a fired rule are unaltered, but rules are able to detect and recover from *unsatisfied guards* by rolling back earlier. In this way, one can minimize the cost of evaluating rules with unsatisfied guards.

4. Reduce the number of atomic operations used for the exchange of meta-information during data exchange (Section 4.3.4). Assuming realistic numbers of ports we are able to collapse several atomic operations into one, aggregating distinct operations by using modulo arithmetic. For example, we are able to increment two (logical) numbers using a single atomic counter by adding $1 + 2^{32}$. In this fashion, the *move* and *countdown* variables may be unified to reduce lock contention and further increase performance and parallelism.

5. Some of the information currently exchanged between threads using atomics can be independently derived by reading the protocol's *rules*. For example, getters can deduce their putter and whether they are permitted to move the datum this way, rather than being told by the coordinator explicitly. It is unclear whether this is an improvement, as these threads must spend extra time recovering this information, performing work redundant to that of the coordinator.

7.1.6 Avoid Lock Re-Entry

Section 4.3.2 motivates the lack of a dedicated coordinator thread to back protocol objects at runtime. As a consequence, port-threads must share the responsibility of manipulating a shared protocol state in accordance with the protocol's movement through its configuration space. Protocols have non-trivial configuration spaces once they involve one or more memory cells in rules. To manipulate their contents safely, *locks* are required around the shared 'bookkeeping' structures that track these cells' states. Section 4.3.4 explains how our design optimizes for the concurrency of rule-firings by moving the work of interacting with memory cells *outside* of the critical reason. A consequence of this approach is the occasional need for threads to *re-enter* the critical region to update the state of a memory cell. For example, the first lock event instigates the rule firing and updates state, but marks memory cell M as 'busy' to ensure it cannot be involved in a rule-firing until all *data movements* outside the critical region have completed. Once done, some thread has the responsibility to mark M as ready once again, necessitating a second lock event.

Future work might investigate more efficient mechanisms for achieving the same effect. As the mechanism is rather intricate, a vast space of possibilities exist. For example, one might investigate the effect of forgoing the second lock-event in favor of leaving a message for a later coordinator to handle. This could take the form of an efficient parallel-queue, highly optimized for the addition of new elements in parallel. More radical changes may also result in superior performance. Perhaps the locking can be avoided entirely if all the data structures representing the protocol's state become lock-free?

7.1.7 Runtime Reconfiguration

Chapter 4.3.4 explains how Reo-rs uses a lightweight interpreter to implement protocol behavior at runtime, reading rules from a dense data structure. A result of this approach is the ability to alter a protocol object's behavior at runtime arbitrarily by manipulating the data representing its rules. Future work might investigate the introduction of a reconfiguration procedure to change the protocol without tearing the instance down or influencing the compute components in motion. The use of an interpreter trivializes the work of manipulating the rules themselves, but care must be taken to change the protocol object's *meta-state* safely such that it results in a new protocol which is again internally consistent (eg. reconfiguring the structures used for primitive concurrency, message channels etc.).

7.2 Conclusion

The chosen design and implementation of a Rust code generator for the Reo compiler achieved satisfactory results. Although our protocol objects were usually slower than hand-written Rust programs, they were competitively performant in the case of non-trivial protocols. This is despite their data-oriented implementation, which has the added benefit of facilitating the *reconfiguration* of a protocol's behavior at runtime. Exploiting this feature was out of the scope of this project, but provides an entrypoint for interesting future work.

By the nature of Reo, *correctness* of a protocol object's behavior was always paramount. Still, this work also emphasized *performance* from its inception, motivating the choice of the Rust language in particular. The hope was to leverage its static *ownership system* to implement a powerful reference-passing optimization employed by the Java backend, but free from the associated safety problems. However, the Rust compiler was stumped by Reo's interactions transferring values between threads and between scopes. Ultimately, our solution followed the Rust idiom of manually managing ownership within a minimal *unsafe* scope, and wrapping it in an API that was safe once again. Here, Rust's ownership and mutual-access semantics were invaluable. This was the case for user-facing functionality in general, including that of creating and destroying protocols and ports. In the end, we were able to provide an API with strong, static safety guarantees provided the user does not intentionally circumvent Rust's semantics with unsafe code; a user can neither create nor encounter ill-formed protocol or port objects, and they cannot experience system behavior that contradicts the specification of the protocol (unintentionally or otherwise). Furthermore, our design avoids relying on specialized threads for protocol objects. Consequently, the user benefits from increased runtime performance for protocol objects repeatedly accessed by a single thread. Coupled with Rust's *drop* semantics, user programs also trivially detect termination of Reo-coordinated systems and free the associated resources.

Rust's affine type system was instrumental in our design of static governors, which allow a programmer to verify that their components do not threaten the liveness of the system at large. This is done almost entirely at compile-time, catching errors as early as possible, and minimizing runtime overhead. Our design demonstrates how an affine type system is able to communicate powerful correctness guarantees across an API boundary. In our case, we are able to embed a complex requirement 'the component does not perform a port-action that contradicts the specification of a stateful protocol' into terms the compiler can understand and enforce: the program type-checks. Users are provided with a means to opt-into tasking their Rust compiler with performing this check, effectively allowing them to extend its verification capabilities with little more than an added library dependency.

The complexity of the translation procedure from Reo to Rust proved to be more complex than was expected. The *imperative form* intermediate representation was added out of necessity to curb the complexity of type-checking and of applying various optimizations without bloating the Reo compiler itself with Rust-specifics. Unexpectedly, the introduction of this new form became integral to our protocol object's design, enabling us to extend its capabilities beyond what was originally intended. When targeting Rust, the Reo compiler supports ergonomic and safe use of more exotic Reo primitives such as *filter* and *transform*, which are able to perform *tentative* computations as part of synchronous interactions. Imperative form also shows promise as an intermediary step for languages similar to Rust; it is conceivable that existing targets such as Java (or others not yet implemented) can leverage this representation to reduce the work of adding new imperative language targets to the Reo compiler.

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Appendices

```
if T::IS_COPY { // irrelevant how many copy
    if let Some(dest) = maybe_dest {
        do_move(dest);
        m.visit();
    }
    let was = count.fetch_dec();
    if was == LAST {
        let [visited_first, retains] = m.visit();
        finalize();
    }
} else {
    if let Some(dest) = maybe_dest {
        let [visited_first, retains] = m.visit();
        if visited_first && !retains {
            let was = count.fetch_dec();
            if was != LAST {
                mover_await();
            }
            do_move(dest);
            finalize();
        } else {
            do_clone(dest);
            let was = count.fetch_dec();
            if was == LAST {
                if retains {
                    finalize();
                } else {
                    mover_release();
        }   }   }
    } else {
        let was = count.fetch_dec();
        if was == LAST {
            let [visited_first, retains] = m.visit();
            if visited_first {
                finalize();
            } else {
                mover_release();
}   }   }   }
```

Listing 24: A getter's procedure for retrieving a value from a putter or memory cell. Getters must coordinate such that one is elected the *mover* with all others cloning. The mover must go last, and once everyone is done, the resource must be cleaned up.

```rust
// initialization
let barrier_g  = Arc::new(std::sync::Barrier::new(3));
let barrier_p0 = barrier_g.clone();
let barrier_p1 = barrier_g.clone();
let (data_0_s, data_0_r) = crossbeam_channel::bounded(0); // synch  (unbuffered)
let (data_1_s, data_1_r) = crossbeam_channel::bounded(1); // asynch (1-buffered)

// port operation functions
let p0_put_function = || {
  barrier_p0.wait();
  data_0_s.send(P0_VALUE).unwrap();
};
let p1_put_function = || {
  barrier_p1.wait();
  data_1_s.send(P1_VALUE).unwrap();
};
let g_get_function = || {
  barrier_g.wait();
  let value_from_p0 = data_0_r.recv().unwrap();
  let value_from_p1 = data_1_r.recv().unwrap();
};
```

Listing 25: Hand-crafted alternator implementation ini Rust based on channels from the `crossbeam` crate and a standard-library `Barrier` for explicit synchronization. This simple design is chosen for its simplicity and its close correspondence to the Reo channels that constitute its specification.

```
        mov     eax, 131096
        call    __rust_probestack
        sub     rsp, rax
        lea     rdi, [rsp + 9]
        mov     edx, 65536
        mov     esi, 2
        call    qword ptr [rip + memset@GOTPCREL]
        mov     byte ptr [rsp + 8], 1
        mov     byte ptr [rsp + 65552], 0
        mov     eax, 32
.LBB0_1:
        movups  xmm0, xmmword ptr [rsp + rax - 24]
        movups  xmm1, xmmword ptr [rsp + rax - 8]
        movups  xmm2, xmmword ptr [rsp + rax + 8]
        movups  xmm3, xmmword ptr [rsp + rax + 24]
        movups  xmm4, xmmword ptr [rsp + rax + 65520]
        movups  xmm5, xmmword ptr [rsp + rax + 65536]
        movups  xmm6, xmmword ptr [rsp + rax + 65552]
        movups  xmm7, xmmword ptr [rsp + rax + 65568]
        movups  xmmword ptr [rsp + rax - 24], xmm4
        movups  xmmword ptr [rsp + rax - 8], xmm5
        movups  xmmword ptr [rsp + rax + 65520], xmm0
        movups  xmmword ptr [rsp + rax + 65536], xmm1
        movups  xmmword ptr [rsp + rax + 24], xmm7
        movups  xmmword ptr [rsp + rax + 8], xmm6
        movups  xmmword ptr [rsp + rax + 65552], xmm2
        movups  xmmword ptr [rsp + rax + 65568], xmm3
        add     rax, 64
        cmp     rax, 65538
        jb      .LBB0_1
        add     rsp, 131096
        ret
```

Listing 26: Snippet out of the x86-64 assembly generated by receiving a large datum through `recv` from a simple channel from the Rust standard library. It unrolls the movement of the entire object into a large sequence of smaller operations rather than invoking a system call. This is the case for the receipt of a `Copy`-type represented by 512 bytes.

```rust
#![feature(raw)]
use std::mem::{MaybeUninit, transmute};
use std::raw::TraitObject;
pub struct TypeInfo(usize);
impl TypeInfo {
    pub fn of<T>() -> TypeInfo {
        let x: Box<T> = unsafe { MaybeUninit::uninit().assume_init() };
        let fat_x = x as Box<dyn PortDatum>;
        let raw: TraitObject = unsafe { transmute(fat_x) };
        TypeInfo(raw.vtable as usize)
}   }
trait PortDatum {
    fn foo(&self) -> u32 { 123 }
}
impl<T> PortDatum for T {}
pub fn test() -> TypeInfo {
    TypeInfo::of::<u32>()
}
```

Listing 27: Example of how the `TypeInfo::of` function (1) ensures the compiled binary includes a vtable for the requested type `T` with `PortDatum` as its interface, and (2) returns the correct pointer to the vtable.

```
1  core::ptr::real_drop_in_place:
2          ret
3  example::PortDatum::foo:
4          mov     eax, 123
5          ret
6  example::test:
7          lea     rax, [rip + .L__unnamed_1]
8          ret
9  .L__unnamed_1:
10         .quad   core::ptr::real_drop_in_place
11         .quad   4
12         .quad   4
13         .quad   example::PortDatum::foo
```

Listing 28: x86-64 assembly of Listing 27. `.L__unnamed_1` shows the binary representation of the vtable of the `u32` (32-bit unsigned integer) type and `PortDatum` trait. Rust's vtables have a predictable structure with three fields followed by trait-defined function pointers. Lines 10–12 store (1) pointer to the concrete type's `drop` function, (2) size of the concrete type in bytes, (3) memory-alignment of the concrete type in bytes.