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MASTER'S THESIS

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Safety and Performance in Generated Coordination Code

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Abstract

Reo is able to act as a domain specific language by compiling a high-level protocol specification to coordination glue code in a target general purpose language. In the case of Java, these generated programs take advantage of optimization opportunities, but struggle to preserve Reo’s semantics. In this work, we extend the Reo compiler to support the Rust language. We show that the resulting program implements several existing and novel performance optimizations, whilst relying on Rust’s expressive type system to preserve meaningful safety and liveness properties at compile time. Our design also facilitates the reconfiguration of the protocol at runtime, but still achieve performance in the order of handcrafted programs for non-trivial protocols.

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Contents

1	Introduction	1
2	Background	3
2.1	Reo	3
2.1.1	Motivation	3
2.1.2	Language	5
2.1.3	Semantic Models	6
2.1.4	The Reo Compiler	11
2.2	Target Languages	13
2.2.1	Affine Type Systems	13
2.2.2	The Rust Language	15
2.2.3	The Type-State Pattern	21
2.2.4	Proof-of-Work Pattern	23
3	Protocol Translation	25
3.1	Structuring the Translation Process	25
3.1.1	Translation Subtasks	26
3.1.2	Pipelining Subtasks	28
3.1.3	Enabling Future Expansion	30
3.2	Imperative Form	31
3.2.1	Concept	31
3.2.2	Definition	34
3.3	Translation Pipeline	36
3.3.1	At Reo Compile-time	36
3.3.2	At Rust Compile-time	39
3.3.3	At Application Runtime	40
4	Protocol Runtime	45
4.1	Examining the Java Implementation	46
4.1.1	Architecture	46
4.1.2	Behavior	46
4.1.3	Observations	47
4.2	Requirements and Guidelines Defined	52
4.3	Protocol Objects	52

4.3.1	Application User Interface.....	53
4.3.2	Design Process.....	57
4.3.3	Architecture	60
4.3.4	Behavior	62
4.4	Requirements and Guidelines Evaluated	72
5	Benchmarking	76
5.1	Experimental Setup.....	76
5.2	Reo-rs in Context	77
5.2.1	Versus the Java Implementation	77
5.2.2	Versus Handcrafted Programs	79
5.3	Overhead Examined	82
5.3.1	Parallelism Between Interactions	83
5.3.2	Time Inside the Critical Region	84
5.3.3	Parallelism Within Interactions	87
5.3.4	Reference-Passing Optimization.....	88
6	Generating Static Governors	92
6.1	Governor Defined	93
6.2	The Problem: Unintended Constraints	94
6.3	Solution: Static Governance with Types.....	95
6.4	Making it Functional	96
6.4.1	Encoding CA and RBA as Type-State Automata.....	96
6.4.2	Rule Consensus.....	97
6.4.3	Governed Environment	99
6.5	Making it Practical.....	100
6.5.1	Approximating the RBA	101
6.5.2	User-Defined Protocol Simplification	107
6.5.3	Match Syntax Sugar	109
7	Discussion	112
7.1	Future Work	112
7.1.1	Imperative Form Compiler	112
7.1.2	Distributed Components.....	113
7.1.3	Optimize Rule Branching	113
7.1.4	Runtime Governors	114
7.1.5	Further Runtime Optimization	114
7.1.6	Avoid Lock Re-Entry	116
7.1.7	Runtime Reconfiguration	116
7.2	Conclusion	117
	Appendices	122

List of Figures

2.1	Graphical and textual specification example.	6
2.2	CA for fifo1 connector.	8
2.3	CA with memory for fifo1 connector.	9
2.4	CA with memory for fifo2 connector.	10
2.5	RBA for fifo1 connector.	11
2.6	RBA for fifo2 connector.	12
3.1	TODO.	30
5.1	Java vs. Rust interaction time for small values.	78
5.2	Java vs. Rust interaction time for large values.	79
5.3	Performance of fifo1 connector vs. handcrafted Rust code.	81
5.4	Handcrafted vs. Reo-generated alternator.	82
5.5	Overhead of evaluating unsatisfied rules.	85
5.6	Bit vector speedup over hashset.	86
5.7	Interaction duration with parallel getters.	88
5.8	Interaction duration in proportion to the 2-getter case.	89
5.9	RTT for fifoN connector with 2^{13} byte values.	91
6.1	RBAs in lockstep with and without normalization.	105
6.2	Configuration space of the a7b1 connector.	109
6.3	Traversed configuration space for a7b1 connector using weakening.	110

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 namespace of tuple variables. In this manner, coordination actions occupy a higher level of abstraction, and are thus more terse, simple and reusable [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-centrism; protocols constrain the ways in which data is permitted to flow through a system of graphical nodes, i.e., 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*, a data structure 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 interoperable 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, handcrafted 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*, structures 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 primarily oriented toward expressing the means by which concurrent systems coordinate the actions of individual actors into interactions. Their domain-specific nature often makes them suitable for augmenting other general-purpose languages by increasing their expressive power. *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 value store it calls the *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*, making explicit only individual actions, relegating interactions to a derived concept. 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 protocol as a *connector*, a multi-graph 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.

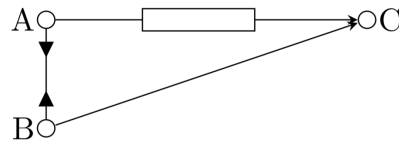
A tenet of Reo’s design philosophy is compositionality (and consequently, modularity). Rather than defining each and every connector anew in terms of the underlying semantics, all but the simplest primitive connectors are built from the composition of others [Arb11]. At each level of this hierarchy, 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 hierarchy), 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 ‘black 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`.



```

1  alternator2(A?, B?, C!){
2      syncdrain(A, B)
3      fifo1(A, C)
4      sync(B, C)
5  }
```

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 al. 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,

¹The 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 to *silent behavior*. In this work, we introduce *trace tables* as a term for both the tabular 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 its 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.

²Not 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 $\Box^1\Box^3P$ rather than the verbose $(\Box P \wedge \Box\Box P \wedge \Box\Box\Box P)$.

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 of state and transition spaces. When seen at larger scales, a `fifoN` 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 reinterpreted 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 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 that a 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 by which state the corresponding CA is in at runtime. 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 website³. 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.

```
1 void stateA() {  
2     this.value = get();  
3     if (this.value == 3) {  
4         stateB();  
5     } else {  
6         stateA();  
7     }  
8 }  
9 void stateB() {  
10     put(this.value);  
11     stateA();  
12 }
```

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 at runtime.

```
1 fifo1(a?, b!) {  
2     #RBA  
3     {a, ~b} $m = null, $m' = a  
4     {~a, b} $m != null, b = $m, $m' = null  
5 }
```

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 judg-

ment 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:

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

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, *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 rearrange 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 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 reinterpreting 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 deallocations (called `drop` in Rust) 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 relocation 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), which are indistinguishable from pointers at runtime, but have special static semantics. 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 outlive 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 inferred 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 coexisting. 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 noth-

```
1 struct Foo;
2 fn func(x: &Foo) {
3     // this function borrows some `Foo` structure by reference.
4 }
5 fn main(){
6     let x = Foo; // instantiate.
7     func(&x);    // &x is created in-line. x remains in place.
8     func(&x);    // another &x is created. x remains in place.
9 }
```

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`.

ing 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 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`.

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

```
1 pub fn something<T: PrintsBool>() {  
2     T::print(true);  
3 }  
4 trait PrintsBool {  
5     fn print(bool);  
6 }  
7 impl PrintsBool for String {  
8     fn print(b: bool) {  
9         println!("bool is: {}", b)  
10    }  
}
```

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`.

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 for these dynamic objects (also called *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's 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, i.e., `!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 ones custom traits such that they have a defined


```
1 trait Emits {
2     fn emit(&self) -> usize;
3 }
4 impl Emits for String {
5     fn emit(&self) -> usize {
6         self.len()
7     }
8 }
9 fn func_static<T: Emits>(x: &T) -> bool {
10     x.emit() > 10
11 }
12 fn func_dynamic(x: &dyn Emits) -> bool {
13     x.emit() > 10
14 }
15 fn main() {
16     let value = String::from("Hello!");
17     func_static::<String>(&value);
18     func_dynamic(&value as &dyn Emits);
19 }
```

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.

means of handling the ‘debug print’ format specifier (e.g., `print!("{}", foo)`), enabling ones types to be used as a parameter to `printf` and so on.

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 (`instance` 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*, an explicit integer to mark the variant to allow for runtime reflection. In Rust, an `enum` type is defined with a list of variants, only one of which

may exist per instance at a time. At runtime, the variant can be discriminated 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 represented 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`.

```
1 struct DivZeroError; // contains no data
2
3 fn divide_by(numerator: f32, divisor: f32) -> Result<f32, DivZeroError> {
4     if divisor == 0. {
5         Result::Err(DivZeroError)
6     } else {
7         Result::Ok(numerator / divisor)
8     } }
9
10 fn main(input: f32) {
11     match divide_by(4.5, input) {
12         Ok(x) => print!("Success! computed:{}, x),", x),
13         Err(_) => print!("Something went wrong!"),
14     } }
```

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 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. Usually, objects with this type do not contain any data at runtime (i.e., they can be represented in memory with zero bytes of field-data). We refer to these objects as *tokens*, suggesting their small size and role as a sort of 'currency' in that they are useless in and of themselves, but may be used to facilitate other things.

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 reusing 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 malformed expressions, and perhaps this is enough. However, we cannot so easily protect a resource from any side effects of `one` or `two`;

⁴Usually, we ignore program termination. Equivalently, this pattern only allows one to describe automata in which every 'useful' state reaches some final 'terminated' state.

imagine the chaos that would result from these functions writing to a persistent file descriptor.

```
1 typedef struct DoOne { int n; } DoOne;
2 typedef struct DoTwo { int n; } DoTwo;
3 const DoOne START = { .n = 0 };
4
5 DoTwo one(DoOne d1) {
6     DoTwo d2 = { .n = d1.n + 1 };
7     return d2;
8 }
9 DoOne two(DoTwo d2) {
10    DoOne d1 = { .n = d2.n * 2 };
11    return d1;
12 }
```

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.

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`.

```
1 fn main(d1: DoOne) {
2     let d2 = two(d1);
3     let d1 = one(d2);
4     let d2 = two(d1);
5     let d2_again = two(d1); // Error! `d1` has been moved.
6 }
```

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.

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; i.e., 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, such as Java’s visibility keywords. 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 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 with the *private* visibility keyword 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.

```
1 struct Promise;
2 struct Fulfilled;
3
4 fn fulfill(p: Promise) -> Fulfilled {
5     // invoked once per `main`
6     return Fulfilled::new();
7 }
8
9 fn main(callback: fn(Promise)->Fulfilled) {
10     // ...
11     let _ = callback(Promise::new()); // `Fulfilled` discarded.
12     // ...
13 }
```

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

The task of the Reo compiler is to translate a Reo protocol specification into the target language. The resulting code must interface with other components written in the language such that, at runtime, the resulting system behaves as specified. In this chapter, we explain how we extend the Reo compiler to support the Rust language target.

Section 3.1 examines the task of the backend, breaking it down into smaller, more specialized subtasks. Section 3.1.2 organizes these subtasks into a pipeline that sees the translation through from Reo specification to executable Rust protocol object. By design, this process transforms the protocol from one form to another. To bridge the gap between Reo and Rust compilers, Section 3 defines *imperative form* as a new representation of a protocol's behavior in a manner conducive to imperative languages. Concretely, the Reo compiler emits Rust source code, whose contents are primarily a Rust-embedded representation of imperative form. Section 3.3 goes into detail about the implementation of the translation pipeline by explaining how the previously-defined subtasks are completed in stages.

3.1 Structuring the Translation Process

In this section, we explore the nature of the task which characterizes the Rust backend for the Reo compiler. Section 3.1.1 breaks the problem down into simpler subtasks, and explains their relationship to one another and how they apply in the case of a different target language. Section 3.1.2 explains how these tasks are organized by defining their place within a translation pipeline. The implementation of the pipeline itself is given in Section 3.3.

3.1.1 Translation Subtasks

The Reo compiler’s frontend parses its Reo input, and performs significant transformations on the resulting internal representation. Everything that follows is the task of the backend, transforming it further until code in the target language can be emitted. We define *Reo Internal Representation* (RIR) to refer to the input of the backend in the sections to follow. Reo and Rust differ significantly in how they represent work. Accordingly, work expressed in the former must be transformed significantly before it can be expressed in the latter. In this section, this task is decomposed into *subtasks*; their inclusion in the thesis serves a dual purpose: (1) smaller tasks are more easily understood, and help to characterize Reo and Rust by identifying their differences, and (2) only isolated subtasks can be separated, facilitating their organization into the translation pipeline shown in Section 3.3.

Input Representation

RIR embodies the completion of several of the operations on Reo connectors described in the literature [BSAR06, DA18a]; namely, *composition*, *merging*, *hiding*, and so on. For our purposes, it suffices to say that IR is presented in a form corresponding closely to an RBA, one of the semantic models described in Section 2.1.3. RIR is self-contained, and defines a list of *rules* which correspond 1-to-1 to interactions between the protocol’s ports. It captures the intuition of an RBA as they are usually understood in an imperative context; rules are subdivided into *guard* and *assignment*. Helpfully, IR presents the latter not as a monolithic formula, but rather as a mapping from identifier to *term*. In our imperative context, terms can be understood as expressions whose evaluation at runtime will create new values.

Conceptual Transformations

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. IR is somewhere in between, per rule, the guard is distinguished from the assignment, distinguishing an ordering of operations at this binary granularity: the guard is evaluated before values are assigned. This granularity requires further transformation

before it can correspond with executable Rust. IR is able to disambiguate the order in which memory cells are read and written to by implying an ordering by annotating their identifiers with temporal *qualifiers*. For example, the assignment corresponding to $m = A \wedge m' = B$ is declarative, but nevertheless suggests an ordering by annotating m with a qualifier to represent its ‘future’ value. Rust’s imperative nature requires that operations on values occur in the order of their appearance in the programs control flow, such that they correspond with the order in which they are executed (Rust compiler optimizations notwithstanding).

Java, Rust and Reo have in common that they are strongly-typed languages. In the broader sense, ‘type’ describes the classification of just about everything in Reo, including connectors and primitives. The Reo compiler’s internals perform transformations that handle the majority of what could be considered ‘type checking’. The only exceptions are (1) the data types of each port, determining the types of values they transmit, and (2) the types of functions applied to values within the channel, which are related to their identifiers by only an identifier. *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.

From Specification to Implementation

Regardless of any intermediate representation, protocols must ultimately be emitted in the target language at the required level of specificity. Imperative languages place the burden of defining *how* their work is performed squarely on the shoulders on the programmer. We refer to this notion as the difference between specification and implementation.¹ For example, where a declarative language might not distinguish *merge sort* from *bubble sort*, Rust certainly does; a Rust programmer operations on variables which correspond (relatively) closely to machine instructions as they will be executed at runtime. This is also true in the case of our problem; what is implied in Reo must be made explicit in

¹These abstract concepts tend to fall apart under scrutiny, as they depend on what is meant by ‘computation’ at all. Nevertheless, this observation is helpful in the context of our problem, as we prescribe the relationship between Reo and Rust by using the former to ‘model’ the latter.

Rust. This includes the initialization of system resources, operations on concurrency primitives, and all the minutia necessary to implement the optimizations described in Section 4.3.4.

It is beneficial to recognize that a significant portion of the translation from Reo to Rust would be shared by the same procedure to a similar language; the more similar language, the more we can expect their respective transformations to have in common. For example, despite their significant differences, Rust and Java are more similar to each other than they are to Reo. Reo’s role is to augment another language with coordination logic. Therefore, it seems to be a reasonable assumption that the majority of languages targeted by the Reo compiler would differ from Reo, such that they can benefit most from the abstractions Reo introduces. Imperative languages are a sensible choice, and so it is reasonable to assume that there is benefit in Reo supporting other imperative languages in future. To this end, we choose to distinguish translation subtasks according to whether they are relevant to Rust in particular, or are generally-applicable to an imperative target language.

It is beneficial to recognize that much of the work required for transforming Reo to Rust would be unchanged if another imperative language were selected as the target. For example, Java required that actions be laid out in accordance with the control flow of the program in the same manner as Rust. To capture this intuition, it helps to split our transformations into *abstract* and *concrete* phases, such that the former is not specific to the target imperative language.

Translation Subtasks Defined

Ultimately, we partition the task of translating from IR to Rust as four subtasks, where those that are *abstract* must precede those that are *concrete*:

	Action	Data Type
Abstract	T_{AA} : From each abstract interaction, a sequence of abstract imperative actions are laid out.	T_{AT} : Ports are mapped to symbolic data types characterized by constraints on their properties.
Concrete	T_{CA} : Abstract actions are reified into concrete, executable Rust operations.	T_{CT} : Each symbolic data type is made concrete, selecting a particular Rust type.

3.1.2 Pipelining Subtasks

Code generation is an unusual problem, as it introduces a spectrum of possibilities in response to questions that usually have trivial answers. For example, in which language is a concept expressed? Reo specifies the coordination behavior of the generated Rust code, but (by design) nothing more. This freedom

makes room for questions of ‘where’ and ‘when’ the behavior that emerges at runtime is made concrete.

We begin by considering one of the most extreme cases: the Reo compiler performs as much of the work as possible. Whatever behavior is desired in the executable program is spelled out in detail, and reflected explicitly in the Rust code the Reo compiler produces. This solution is arguably the most intuitive, and it has many advantages. For example, we are able to ‘front-load’ as much computation work as possible, such that the generated Rust code can represent operations in a preprocessed form. We are also given fine control over the behavior of the final binary. However, this strength is what makes this approach impractical: the Reo compiler’s ability to specify Rust’s behavior in detail also implies a responsibility to do so. By reasoning about the Rust-compiled program directly, Reo would have to model the Rust compiler. Aside from being a poor use of existing resources, this results in Reo being tightly *coupled* to the Rust language. At the same time, all power of flexibility is taken away from the user; they have no ability to influence the translation process. Essentially, this approach trivializes the Rust compiler.

As expected, the opposite extreme trivializes the Reo compiler. If hardly any transformations at all are applied before Rust code is emitted, the representation can only be very similar to that of RIR. As explained previously, these forms are simply too different for the Rust compiler to use as-is. By necessity, either a new Rusty-RIR to Rust translation tool would have to be introduced, or the translation would have to occur inside the Rust-generated program at runtime.

Between these extremes there is a vast spectrum. Ultimately, we wish to choose a balance that partitions the work between the compilers of Reo and Rust in a manner that befits the interests of the language, minimizing the extent to which Reo models Rust or vice versa. Section 3.1.1 touched on the observation that a portion of the work in translating from RIR to Rust is common to other imperative language targets. Our solution is for the Reo compiler to perform only the ‘abstract’ subtasks (T_{AA} , T_{TA}), translating RIR to a form for which imperative computation is natural, but is otherwise as target-language agnostic as possible. Behavior is represented symbolically for the Rust compiler to make concrete. Clearly, this abstract representation must be understood by both Reo and Rust compilers, as it is the representation that crosses the boundary between their steps in the pipeline. Section 3.2 to follow defines this representation as *imperative form*, embodying the behavior of an abstract imperative language.

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 subtasks at

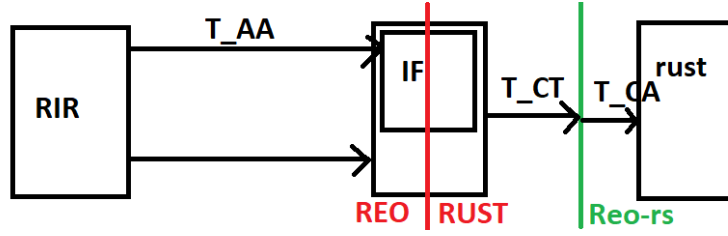


Figure 3.1: The translation pipeline from the Reo compiler’s internal representation (‘RIR’) to executable Rust, expressed in terms of the translation subtasks defined in Section 3.1.1. The majority of the specification is represented in the imperative form (‘IF’), which serves as the representation at the boundary between Reo and Rust.

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} subtask (subtasks are defined in Section 3.1.1) is delegated to this library. Our work follows this precedent by providing the **Reo-rs** library, a Rust library which defines the behavior which all Reo-generated code has in common. The contents of this library are therefore Rust-specific, and effectively implement the remaining pre-processing steps. Section 3.3 explains why T_{CT} is sufficiently trivialized by the Rust compiler itself, such that upon examination, Reo-rs would appear to implement only T_{CA} .

The end result is the pipeline shown in Figure 3.1. Section 3.3 explains the implementation of these subtasks in the order they are performed.

3.1.3 Enabling Future Expansion

Our observation that a significant portion of the Reo compiler’s translation work will be shared between backends for different language targets. In our work, we concentrate on the class of languages we consider to be *imperative* in particular. Section 3.2 makes more explicit what characterizes these language targets by defining imperative form. We observe an opportunity to deduplicate this work by promoting this form a new intermediate representation that the Reo compiler may use to facilitate a hierarchical approach to code generation. This vision would generalize the concept of an intermediate representation,

making it possible to express and exchange the same Reo protocol formulated such that different tradeoffs between generality and specificity can be made.

For this work, we relegate imperative form to a tool unique to the generation of the Rust language. The user is not aware that this form exists, as its usage is not user-facing, known only to the Rust backend and the Reo-rs library as a practical representation of Reo protocols. The Reo compiler emits a Rust source file when targeting the Rust language, such that it adheres to the precedent set by the compiler's other backends: Java, for example. For now, our Reo backend emits code in the Rust language.

3.2 Imperative Form

In this section, we define *imperative form*, a novel intermediate representation for the behavior of Reo protocols, such that they more closely correspond to their final representation in some imperative language. In the protocol translation pipeline, this form is the result of completing translation subtasks T_{AA} and T_{AT} , as they are defined in Section 3.1.1.

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 subtasks 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 follows 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. 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 universal *Any* type, satisfying this assumption trivially.

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 i.e., 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*.

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*, i.e., 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 underspecification, we represent actions at the coarsest granularity possible to avoid *overspecifying* 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 $X = f(X)$ and synchronization constraint $\{X\}$ 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 $f_X \neq X$. (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 (i.e., 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* (i.e., 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*, i.e., 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:

- $\text{check}(p)$
Trigger an *abort* if predicate p over data is satisfied.
- $\text{fill}_P(m, p)$
Fill an empty memory variable m with the result of a predicate p over available data. The value's data type is implicitly *boolean*.
- $\text{fill}_F(m, f, a)$
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.
- $\text{swap}(m_0, m_1)$
Swap the values in two memory variables m_0 and m_1 .

If an abort is triggered by check, any swapped memory cells are swapped back, and any memory cells whose values were created by fill_P or 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:

1. fill_F can only rely on *pure* functions, i.e., their execution in and of itself must not be observable to the outside world.
2. fill_F and fill_P can only write to *inaccessible* values, i.e., they cannot overwrite accessible values.
3. Accesses of any values must not mutate or consume the original, e.g., using a value as an argument in 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* (e.g., 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.² 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 $X = f(X)$ and synchronization constraint $\{X\}$ can be represented in the imperative rule with:

	value
premise	$(\{X\}, \{\}, \{f_X\})$
instructions	$[\text{fill}_F(f_X, f, [X]), \text{check}(X = f_X)]$
movements	$\{X \rightarrow \emptyset, f_X \rightarrow \emptyset\}$

3.3 Translation Pipeline

This section details the implementation of the translation pipeline from the Reo compiler’s internal representation (‘RIR’) of Reo protocols to executable Rust. The section is structured to describe the translation process as a sequence of sequential stages. Unbeknownst to the user, the pipeline extends well after the Reo compiler has emitted Rust code. Subsections are titled according to *when* the translation takes place.

3.3.1 At Reo Compile-time

The Reo compiler is extended with a backend for translating RIR to a Rust source file. This translation stage is concerned with performing $T_{A,A}$ and $T_{A,T}$, and representing them as a single rust *entrypoint* function in the emitted Rust source. The user is able to import this source as a dependency into their own project, whereby the entrypoint serves as a means for their program to construct the Rust object which implements the appropriate Reo protocol specification, as described in 2.1.1.

Action Sequencing

$T_{A,A}$ necessitates transforming 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

²A relevant language may simulate the destruction of a value by moving it to some `Destroyed` destination with special semantics.

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 $\text{swap}(q, q_{\text{temp}})$ 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 fill_P or fill_F instructions to create every other temporary variable in a manner befitting the *term* that represented them in the IR's assignments, i.e., the result of invoking a function with port values as arguments. Finally, I ends with a single check to evaluate the rule's guard, initiating an abort if it 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 $f(C)$ where f is some function and C is a putter port. Here, one temporary variable f_C to store the result of $f(C)$ is sufficient; it is simply moved to two distinct destinations, reflected in the mapping $f_C \rightarrow \{A, B\}$ 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 util-

ity of this is the ability to rearrange 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 $A \wedge B$, where A and B are subformulas that reason about subterms whose evaluation necessitates the creation of temporary values t_A and t_B . By fragmenting $\text{check}(A \wedge B)$ into $\text{check}(A)$ and $\text{check}(B)$, 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 $T_{A,T}$ 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, i.e., 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 $T_{A,T}$ described in the previous section. Initially, every identifier is assigned a 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.

Rust Formatting

Once all the data has been prepared, the Reo compiler emits its contents formatted according to Rust's syntax. Listing 11 gives an example of the result: a single `instantiate` function reflecting the cumulation of the work of this phase. Observe that in this example, a single symbolic data type T was identified. As expected, the majority of the information is contained in the `ProtoDef` type (beginning on line 5), which is nothing more than a Rust-formatted rendering of the protocol's imperative form behavior specification. The sections to follow explain what happens next.

3.3.2 At Rust Compile-time

A Rust programmer makes use of the generated Rust code by importing it into their own program as a library. To interface with its contents, they are required to import `Reo-rs` as well. Section 4.3.1 explains the API this library presents to users for acting on these protocol objects from their own code.

As the name suggests, the `instantiate` function serves as the user's *entrypoint* for instantiating protocol objects. This function is invoked from their own Rust code in the usual way. Section 2.2.2 explains how Rust relies on dispatch for generic type resolution. Previously, Section 3.3.1 explained that the output of the Reo compiler is a Rust source file containing a single entrypoint function. Rather than implementing it ourselves, our solution is for the definition of this function to effectively delegate subtask $T_{C,T}$ to the Rust compiler itself. From the user's perspective, the entrypoint is a function like any other; at the call-site within their own programs, they are able to specify concrete choices for the generic types themselves. This approach has three benefits: (1) We make use of an existing resource, which is not only easier, but is also good practice as it avoids the fragility that would otherwise follow from redundancy, (2) the result is idiomatic for the Rust language, and ergonomic for users to use in conjunction with other generics in their own programs, and (3) once Reo has emitted the entrypoint, a Rust programmer is able to use it to construct protocol instances for any choice of concrete types.

Using the Rust compiler in this way is achieved by the Reo compiler crafting the entrypoint such that its generic type arguments are annotated with the

appropriate Rust trait bounds. In effect, we communicate to the Rust compiler the operations which the user's code chosen types must support. This makes for a pleasant user experience, as their uses of the entrypoint will be checked for correctness by the Rust compiler as is the case for any other aspect of their program.

3.3.3 At Application Runtime

The user's program has been compiled by the Rust compiler, the resulting binary can be directly executed. Represented somewhere within is code which implements the Reo-generated `instantiate` function. This function constructs and returns an instance of `Proto`, indirected behind a `ProtoHandle`. These types and how they work to implement their associated Reo protocol at runtime is explained in Section 4.3. Here, it suffices to say that Reo-rs relies on the Reo-generated `instantiate` function to construct a `Proto` such that its contents facilitate the intended behavior, including specializing it to implement the associated Reo protocol in particular.

At runtime, the user's program is evaluated in the usual way. The final subtask of protocol translation, T_{CA} , occurs only at the moment `instantiate` is invoked. Owing to Rust's imperative nature, what happens next occurs a sequence of four distinct steps, corresponding with the initialization of the four variables in the scope of `instantiate`, as they appear in the Listing 11. Throughout this section we refer this listing to exemplify the translation steps.

Type Erasure: `type_info`

To make it possible to represent any and all protocol objects with the single `Proto` type, it is necessary to *erase* the types of port values, representing them instead as data such that their behavior may be later recovered through *reflection*. The first step of `instantiate` is to perform this erasure. Its counterpart is explained in Section 4.3.4 in the following Chapter. As can be seen in the example, this step is trivially represented by the Reo compiler, relying on the definition of `TypeInfo` in Reo-rs.

Memory Initialization: `mem_init`

In the original textual Reo specification, the initial values of a protocol's memory cells is defined by strings (as a result of the format). To afford the user's choice of arbitrary types, we require that the original text can be translated into a value of the correct type to initialize the protocol's memory cells. Rust defines the `FromStr` trait characterize types which have the property that their instances can be constructed by parsing a string at runtime. The entrypoint

function is safely able to rely on the corresponding `from_str` operation to be defined for the type, as care was taken to include it as a type constraint. The result is a `MemInitial` instance, storing instances of initialized values precisely as specified.

Imperative Specification: `proto_def`

As explained previously, the Reo backend embed the imperative form specification in Rust's syntax such that the result is a dependency which the Rust compiler can understand. At runtime, this step necessitates that a `ProtoDef` instance be built, only to be read on the next line and subsequently discarded. Conceptually, this step could be performed at compiler-time by defining the `ProtoDef` in terms of types that the Rust compiler is able to embed into the text section of the generated binary. This would avoid the work of constructing the `ProtoDef` with every instance, as (to follow) we see that one `ProtoDef` is able to instantiate any number of `Proto` instances. This construction is represented inlined here to facilitate future expansions to Reo-rs in future, allowing protocols objects to be manipulated at runtime. Reformulating `ProtoDef` would inhibit these efforts. As `instantiate` is not a performance-sensitive function, investigating workarounds for this overhead was not a priority in this project.

Construction: `built_proto`

The combination of `ProtoDef` and `MemInitial` represent (a specification of) the behavior, and initial state of an executable protocol object respectively. The final step is to put it all together and perform the only remaining subtask: $T_{C,A}$. Reo-rs encapsulates this work in the `build` method defined for the `ProtoDef` type, visible in Listing 11 on line 32.

Completing subtask $T_{C,A}$ in this context consists of (1) initializing a protocol object complete with auxiliary bookkeeping structures, and (2) translating the imperative form behavioral specification into something conducive to execution. `Proto` structures are instantiated complete with various fields to facilitate the granular operations that are defined by Reo-rs. Structures are added which have no clear parallel in the imperative form specification, but whose precedence is nevertheless essential at runtime: for example, semaphores and control message channels. Imperative form rules are significantly preprocessed before being included in `Proto`. This performs two vital functions:

1. **Optimizes Representation for Execution**

`Proto` represents the ultimate departure from the initial Reo specification. in Chapter 4 to follow, we explain how the contents of `Proto` are accessed directly while in use as a communication medium at runtime.

As such, the representations of `ProtoDef` and `Proto` are not the same. Where `ProtoDef` prioritizes terseness and readability in the use of symbolic port and function names, the translation to `Proto` resolves them to concrete data structures for cheaper access. For example, indexes into a vector replace symbolic port names.

2. Ensures Internal Consistency

In this scope of this project, we are safe in our presumption that the Reo compiler can be trusted to create only internally consistent `ProtoDef` structures. However, the code generation process crosses a boundary between two compilers, and is designed to minimize their coupling by condensing the data that passes between them. As a good practice, Reo-rs will check that the `ProtoDef` describes *some* valid, sensible protocol. Owing to its increased explicitness, imperative form exposes a larger ‘surface area’ for the introduction of inconsistencies, accidental or otherwise. To make error handling ergonomic for the user, `build` returns an informative error structure with information about the inconsistency. Listing ?? shows the resulting type signature of `build`, including some examples of possible error variants.

Listing 11 demonstrates how the result of `build` returns the resulting protocol object directly. Observe that Listing 12 shows the protocol object returned indirectly, via a `ProtoHandle`. The relationship between these objects and the definition of their behavior at runtime is detailed in Chapter 4 to follow.

```

1  use reo_rs::*;
2  fn instantiate<T: FromStr>() -> ProtoHandle {
3      let type_info = TypeInfo::of::<T>();
4      let mem_init = MemInitial::default().with("m", "VALUE".from_str())
5      let proto_def = ProtoDef {
6          name_defs: {
7              "A" => Port { putter: true, type_info },
8              "B" => Port { putter: false, type_info },
9              "m" => Memo(type_info),
10         },
11         rules: [
12             RuleDef {
13                 premise: Premise {
14                     ready_ports: {"A"},
15                     full_mem: { },
16                     empty_mem: {"m"},
17                 },
18                 instructions: [],
19                 movements: { "A" => {"m"} }
20             },
21             RuleDef {
22                 premise: Premise {
23                     ready_ports: {"B"},
24                     full_mem: {"m"},
25                     empty_mem: { },
26                 },
27                 instructions: [],
28                 movements: { "m" => {"B"} }
29             }
30         ],
31     };
32     let built_proto = proto_def.build(mem_init).unwrap();
33     return built_proto;
34 }

```

Listing 11: The Reo-generated Rust source given the fifo1 connector’s Reo specification as input. Section 3.3 explains how this representation bridges the gap between the Reo and Rust languages. The `ProtoDef` type on line 5 specifies the protocol’s behavior in imperative form, as it appears embedded into Rust’s syntax.

```
1 type BuildError = (Option<usize>, BuildErrorInfo);
2 enum BuildErrorInfo {
3     ConflictingMemPremise { name: Ident },
4     PutterCannotGet { name: Ident },
5     MovementTypeMismatch { getter: Ident, putter: Ident },
6     GetterHasMultiplePutters { name: Ident },
7     InitialTypeMismatch { name: Name },
8     /* 15 more variants */
9 }
10 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.

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 our 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 ded-

icated thread, (2) increase parallelism by delegating data movement to component threads, and (3) internally perform reference counting and reference 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 its 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

```

1  Port<String> p0 = new PortWaitNotify<String>();
2  Port<String> p1 = new PortWaitNotify<String>();
3
4  Sender c0 = new Sender();
5  Receiver c1 = new Receiver();
6  Sync c2 = new Sync();
7
8  p0.setProducer(c0); c0.p0 = p0;
9  p0.setConsumer(c2); c2.p0 = p0;
10 p1.setProducer(c2); c2.p1 = p1;
11 p1.setConsumer(c1); c1.p1 = p1;
12
13 new Thread(c0).start();
14 new Thread(c1).start();
15 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. 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 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

```

1 private static class Sync implements Component {
2     public volatile Port<String> p0, p1;
3
4     private Guard[] guards = new Guard[]{
5         new Guard(){
6             public Boolean guard(){
7                 return (p1.hasGet() && !(p0.peek() == null));
8             }, };
9
10    private Command[] commands = new Command[]{
11        new Command(){
12            public void update(){
13                p1.put(p0.peek());
14                p0.get();
15            }, };
16
17    public void run() {
18        int i = 0;
19        while (true) {
20            if(guards[i].guard())commands[i].update();
21            i = i==guards.length ? 0 : i+1;
22            synchronized (this) {
23                while(true) {
24                    if (p1.hasGet() && !(p0.peek() == null)) break;
25                    try {
26                        wait();
27                    } catch (InterruptedException e) { }
28                }
29            }
30        }
31    }

```

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.

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 directions, 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 counterproductive 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`. 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.

- R_{value}** Preserve Reo’s value passing semantics. No user interaction should contradict these semantics. This precludes data races as a result of aliasing values which the user considers to be independent.
- R_{init}** Prevent the protocol from being initialized in an inconsistent state. Prevent port objects from being uninitialized, unsafely accessed in parallel, or incorrectly connected to the protocol.
- 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. 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.

- 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.
- 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 particular 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 ??, 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 (i.e., 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 last handle to a `Proto` instance is destroyed, all of its resources are freed. This is achieved by relying on the canonical `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 (i.e., `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 `ProtoHandles`. 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` specifies that the getter is accessed via a mutable reference¹ (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 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 (ex-

¹This terminology is often confusing; despite 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.

plained 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 (R_{value}) and performance (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 reinterprets 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 `T`. 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`)².

To reflect our priority of safety, 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 usual 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. 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,

²These libraries are publicly available on crates.io.

this requires nothing more than the addition of preprocessor annotations, i.e., `#[repr(C)]` and `#[no_mangle]`, and visibility keywords, i.e., `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 provided secondary concrete representations. As an example, Rust represents the `Putter` and `Getter` types with a generic argument, affixing its data-type at compile-time. Reo-rs preserves safety guarantees by relying more extensively on reflection at run-time for these cases.

Rust has no analog to C's header files; it 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, as they are inherently coupled with Rust's generic system. 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`³ addon to Cargo, Rust's package manager (comparable 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 [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 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.⁴ As is typical in multithreading, 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

³url: <https://crates.io/crates/bindgen>.

⁴This assumption provides context for our work, but is not an inherent assumption of all of our design choices. Wherever possible, we make this distinction in the text.

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: i.e., protocol objects should fire rules as frequently as possible such that the behavior of the system is not constrained *beyond* the constraints of the protocol itself.

The Coordinator

The most obvious starting point is asking ‘who decides which rule to fire?’ Reaching consensus prevents the system from reaching some malformed 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 rediscover 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.⁵ 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.

⁵Conceptually this could be in parallel, but the actual implementation the exchange necessitates the use of a *class monitor lock* (a structure for coordinating actions for all instances of a class) to prevent interfering with the protocol thread itself.

Event Handling

A minor change with the potential for improvement is to remove the necessity of the protocol thread to rediscover 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 G_{fast} . Unfortunately, regardless of how fast `mio` may be, the event must still cross the boundary between threads. In overburdened 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 reinterpret 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 as 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 `Gdata`, 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 from 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!'). Note that this idea is applicable in a context where components are distributed, i.e., they do not all share an address space. In such cases, it becomes vitally important to manage the task of data movement for the sake of performance, which is likely to complicate this optimization further.

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 3.3.3, 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's 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 rearranged 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 it 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* (See Section 4.3.1). While this is not a task traditionally associated with the coordinator, its 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 a `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.

```
1 pub struct Proto {
2     cr: Mutex<ProtoCr>, // accessed by coordinator with lock
3     r: ProtoR, // shared access
4 }
5 struct ProtoR {
6     rules: Vec<Rule>,
7     spaces: Vec<Space>,
8     name_mapping: Map<Name, LocId>,
9     port_info: HashMap<LocId, (IsPutter, TypeInfo)>,
10 }
11 struct ProtoCr {
12     unclaimed: HashSet<LocId>,
13     is_ready: BitSet,
14     memcell_state: BitSet, // presence means mem is FULL
15     allocator: Allocator,
16     ref_counts: HashMap<Ptr, usize>,
17 }
```

Listing 15: Definitions of the most coarse-grained structures of a protocol instance. `Proto` is the entrypoint, 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 granularity, 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 their effects can be reversed, 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 backend. 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 set of protocols 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 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 constraint 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 (i.e., not coordination), a task for which Reo should probably not be optimized. For the protocols without instructions (including `fifo1`, `alternator`, `sequencer`, `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 configuration 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 [drop](#) 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 identifier from which they must fetch their value. 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 resetting 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 dropped 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-centric language, and does not offer the interaction we need.⁶

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 influenc-

⁶Rust 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.

ing 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 rearrange 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 the 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 putter's 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 predefined types. Instead of shifting the pointer around to a fresh allocation each time, we are able to *preallocate* 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 reused. 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 (e.g., 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}_{data} and \mathbf{G}_{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 reusing allocations, but rather than fixing them per memory cell, we allow all memory cells of the same data type to draw from a shared pool of reused 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 **drop** function 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.⁷ For example, users must mark their objects as `Copy`, communicating that their shallow representation can be safely 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 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, 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

⁷This 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.

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 simplified⁸ view of the `PortDatum` trait, and its implementation for any⁹ 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* (i.e., some structure with fields), and one to its *behavior* (i.e., 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 3.3.3) 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)

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,

⁸The 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.

⁹In 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.

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.

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 are be identical. Section 4.3.1 explains how protocols limit aliasing to their internals 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.


```
1 trait MaybeCopy { // private helper trait
2     const IS_COPY: bool = false;
3 }
4 impl<T> MaybeCopy for T {} // default case. NOT COPY
5 impl<T: Copy> MaybeCopy for T { // specialize for COPY TYPES
6     const IS_COPY: bool = true;
7 }
8 ///////////////////////////////////////////////////////////////////
9 trait MaybeEq { // private helper trait
10     fn maybe_eq(&self, _: &Self) -> bool {
11         panic!("This type cannot check equality!")
12     }
13 }
14 impl<T> MaybeEq for T {} // default case. NOT PartialEq
15 impl<T: Eq> MaybeEq for T {
16     fn maybe_eq(&self, other: &Self) -> bool {
17         return self == other
18     }
19 }
20 ///////////////////////////////////////////////////////////////////
21 trait PortDatum { // main PortDatum trait. also private
22     fn is_copy(&self) -> bool;
23     fn eq(&self, other: &Self) -> bool;
24 }
25 impl<T> PortDatum for T {
26     fn is_copy(&self) -> bool {
27         <Self as MaybeCopy>::IS_COPY
28     }
29     fn eq(&self, other: &Self) -> bool {
30         <Self as MaybeEq>::maybe_eq(self, other)
31     }
32 }
```

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 the specificity of implementation blocks for the same trait.

```
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

Chapters 4 described protocol objects generated by Reo for the Rust language. In this chapter, we evaluate the performance of these objects at runtime. To begin, we place their performance in context with their Java counter parts, and with handcrafted Rust code in Section 5.2. Their performance characteristics are examined more closely in Section 5.3, investigating the effect the implemented optimizations, and examining the relationship between properties of the input specification and performance at runtime.

5.1 Experimental Setup

For experiments throughout this chapter, we used a machine with the properties given in Table 5.1. Our experiments are available for inspection in the source code in `experiments.rs`. For all tests, the Rust compiler (`rustc`) used was version 1.38.0-nightly (bc2e84ca0 2019-07-17) contemporary with stable release version 1.36.0 (a53f9df32 2019-07-03). This nightly compiler was necessary to support our use of two of Rust’s currently-experimental features: (1) specialization and `raw`, both of which are used for reflecting on types at runtime, as explained in Section 4.3.4.

Experiments were run using the inbuilt testing functionality of Rust’s package manager (i.e., invoking `cargo test`), with using release-level compiler optimizations. All measurements shown are the mean of all measurements of runtimes for which protocol structures were built A times, and then runs were measured B times for each, i.e., the mean of $A \times B$ total repetitions. The values of A and B are specified in the captions of figures or tables in which the measurements appear. If left unspecified, A and B are 100 and 1000 respectively.

Component	Properties
Operating System	Windows 10.0.2.1000
Processor	4 × 2 intel core i7-7500U CPU (64-bit) at 2.70 GHz
Memory	12Gb DDR4 2400MHz
Storage	Micron 1100 SATA 5122 GB SSD

Table 5.1: Component properties of the machine used for experiments in this chapter, included for the sake of reproducibility.

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) Handcrafted 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, and focus primarily on the differences in performance relative to other measurements of the same system, i.e., we are most interested in comparing the ‘shapes’ of each curve. As our test scenario, we have a set of N 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 in the fetch connector. Aside from the order of magnitude difference in runtime, we observe a different *shape*. Reo-rs is observed to be significantly faster in the case of a single getter. 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

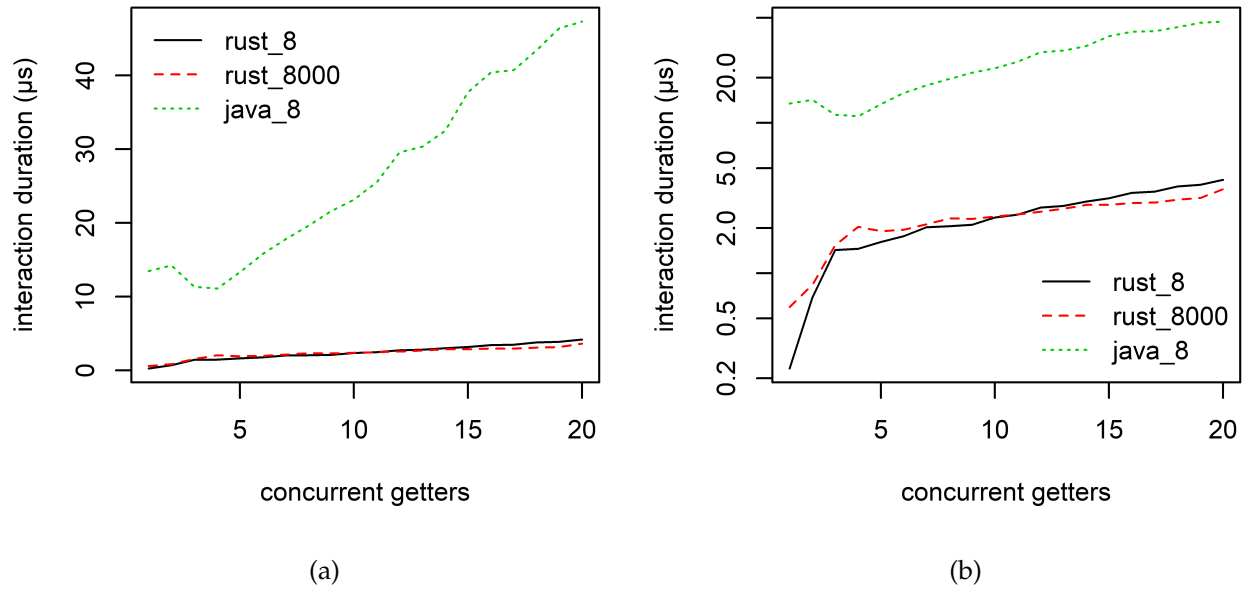


Figure 5.1: Comparison of interaction time for the fetch connector for both Java and Rust backends moving small values. `rust_8` and `java_8` both move a payload of 8 bytes (to match the reference size of the 64-bit JVM). `rust_8000` gives an example of how the runtime of Reo-rs can change with respect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

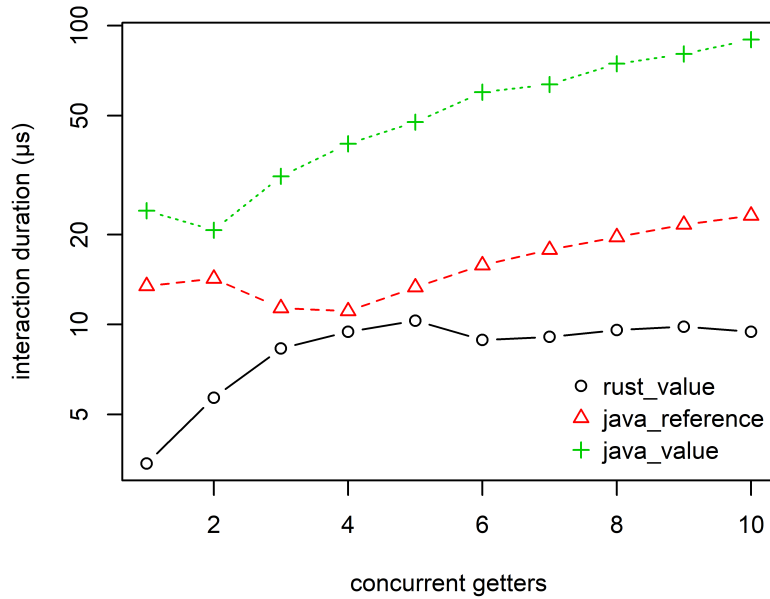


Figure 5.2: Comparison of interaction time for the fetch connector for both Java and Rust backends moving 64-kilobyte-sized data. The Rust backend moves the datum by value, while the Java parallel `java_reference` aliases the object (moving by reference). This backend does not support value-passing that preserves Reo’s semantics. 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.

path’ optimization for 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 Handcrafted Programs

Clearly, Reo-rs cannot outperform 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 handcrafted 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 handcrafted solutions. `channel` is the most intuitive solution, relying on the ubiquitous `crossbeam` channel for its efficient channels. `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 $\{P_0, P_1\}$ 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 handcrafted 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 handcrafted 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.

The `alternator` circuit is still simple enough that the handcrafted implementation is only a few lines long. It is in our best interest to compare the

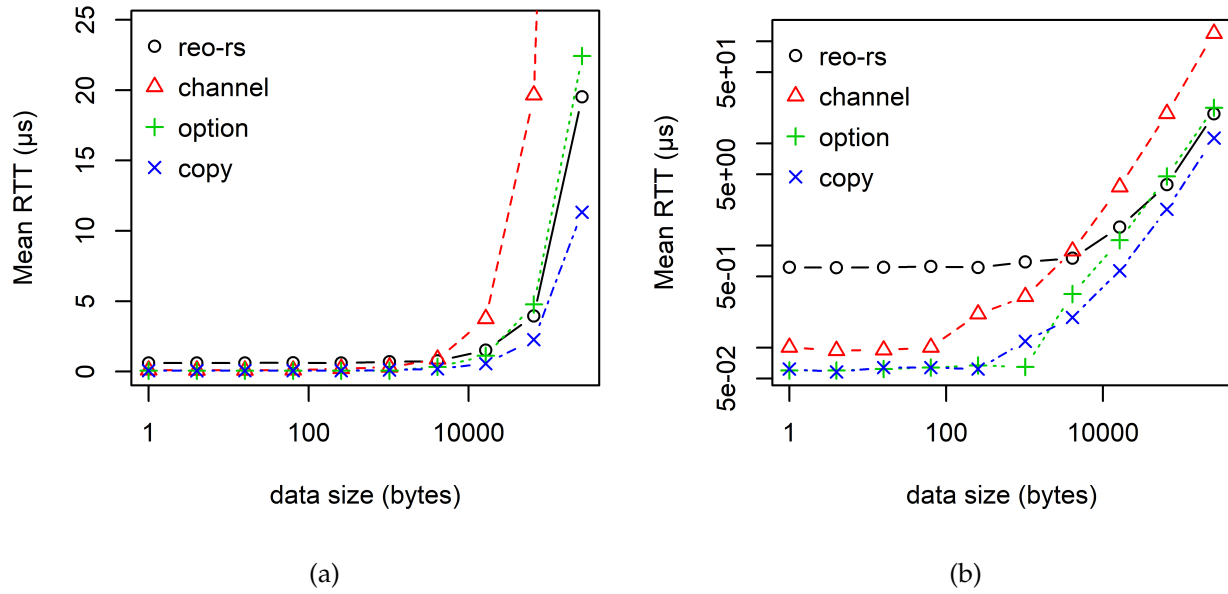


Figure 5.3: Time from beginning of `put` to end of `get` in connector `fifo1` compared to handcrafted Rust alternatives of various sorts. `channel` is intuitive, using a `crossbeam` 1-capacity buffered channel. `option` stores the temporary variable in an `Option` type, and writes and reads from it using `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. Results are the mean of 100×1000 measurements

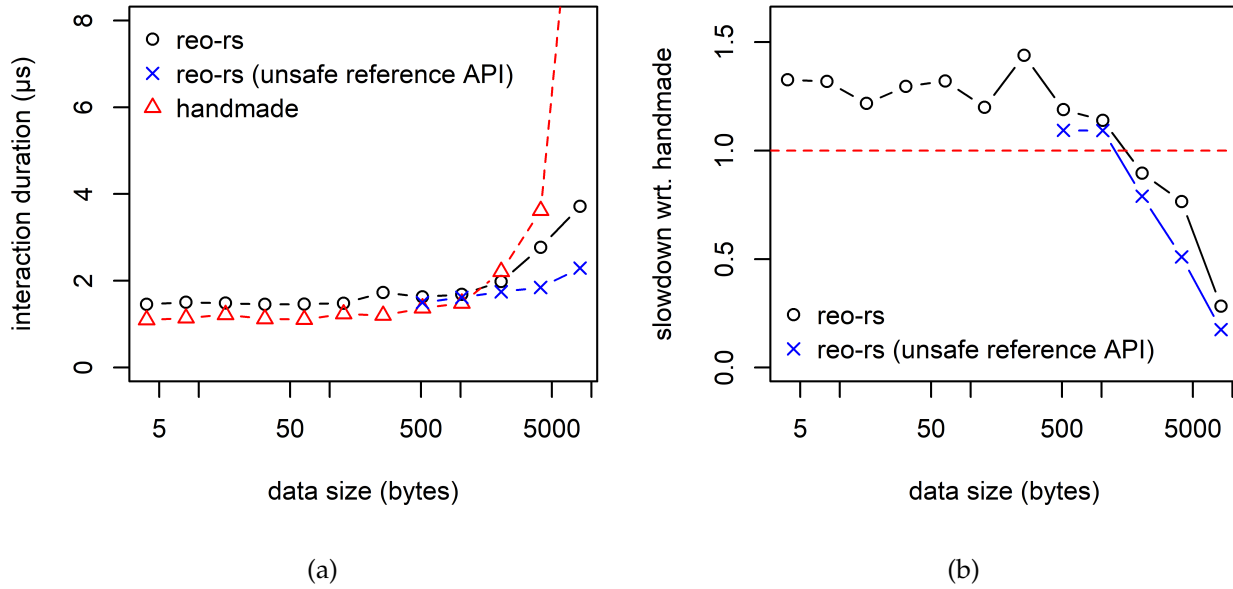


Figure 5.4: Mean interaction duration of the Reo-generated alternator2 connector in comparison to an intuitive implementation based on channel primitives in the `crossbeam` crate, and the `Barrier` from the Rust standard library showing (1) absolute runtimes, and (2) the slowdown factor of Reo-rs compared to the handmade code. Note the logarithmic x-axis. Measurements are the mean of 500×5000 repetitions.

performance of Reo-rs to handcrafted 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 handcrafted programs to future work. For now, we conclude that Reo-generated Rust is unlikely to outperform handcrafted 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 5.2 shows measurements for an experiment that attempts to understand which proportion of our overhead is incurred *inside* the critical region, i.e., 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 partake 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 5.2. 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 synchronously.

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. At this scale, `sleep` calls were out of the question, as its variability overwhelms any meaningful measurements. Instead, `clone` perform thousands of chaotic integer computations on the replica before returning it. 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 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.

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

Table 5.2: Runs of 3 putters greedily sending their 2048-byte data directly to any of 3 getters, 10 000 times. The rightmost 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. Measurements are the mean of $100 \times 10\,000$ repetitions.

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.

alloc A rule whose first instruction allocates a temporary false value. The second instruction checks that this temporary value is true. Upon fail-

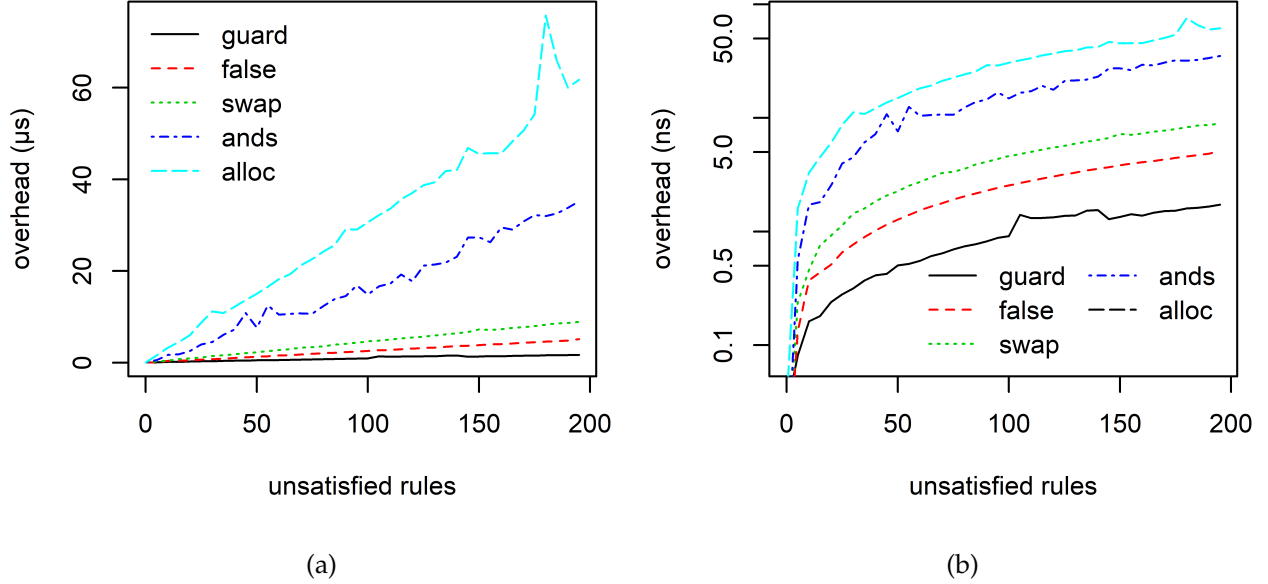


Figure 5.5: Overhead as a result of evaluating a sequence of identical unsatisfied rules before firing something. Experiment is repeated for four variants of unsatisfied rules varying in the complexity of the operations they before before being deemed unsatisfied. The two sub-figures show the same information, with (b) representing it with a logarithmic y-axis to accentuate the small-scale differences. Measurements are the mean of $100 \times 10\,000$ repetitions.

ure, 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.

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,

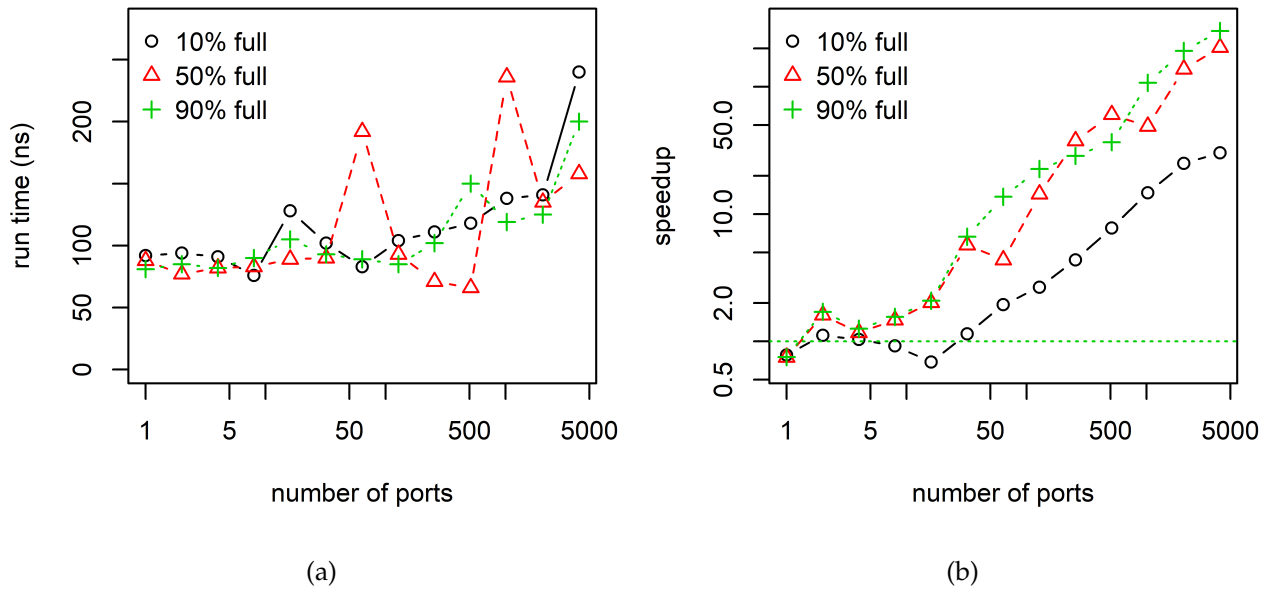


Figure 5.6: Run time of the `is_subset` operation for bit vectors and canonical hash sets. This operation is used very frequently by the coordinator to determine whether a rule is satisfied. Figures show (a) run times for the bit vector in response to a changing maximal element, i.e., number of ports,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

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. Its 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'.¹

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

¹Our `Mutex` comes from the `parking_lot` crate. The relevant documentation is found at https://amanieu.github.io/parking_lot/parking_lot/struct.Mutex.html.

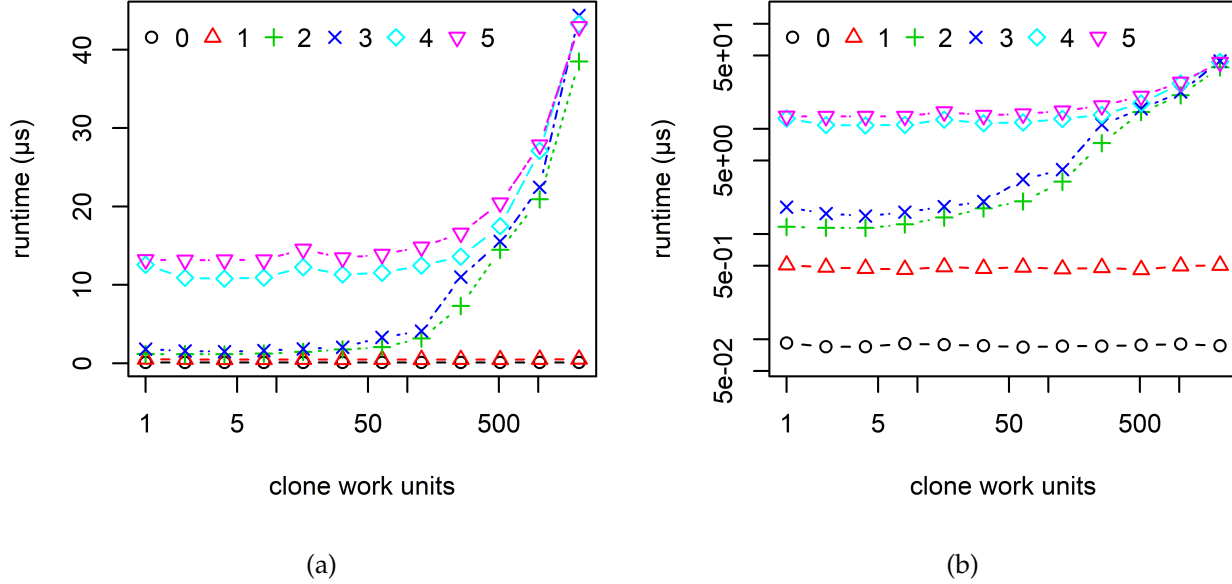


Figure 5.7: Mean interaction duration from the perspective of the putter into the simo connector. Results are distinguished by how many getters synchronously acquire the putter’s datum in each interaction. Results are shown in response to the cost of the `clone` function, in arbitrary *work units*. Note the logarithmic x-axes in both figures, and the logarithmic y-axis in (b). Measurements are the mean of 100×3000 repetitions.

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 `fifoN` 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 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`

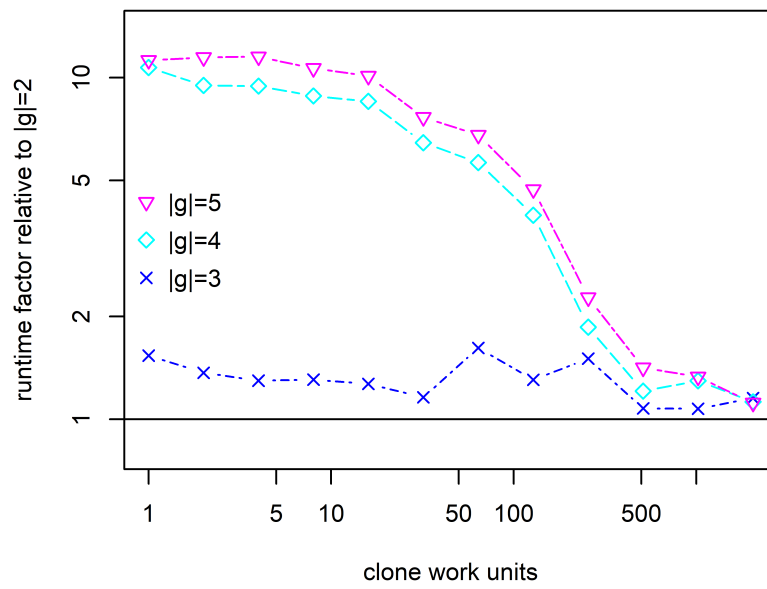


Figure 5.8: Mean interaction duration in the simo connector, showing slowdown relative to that of runs with two getters. Results are shown in response to the cost of the `clone` function, in arbitrary *work units*. Note the logarithmic axes. Measurements are the mean of 100×3000 repetitions.

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 (e.g., in Figure 5.3b), so interaction time would likely remain sublinear 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.

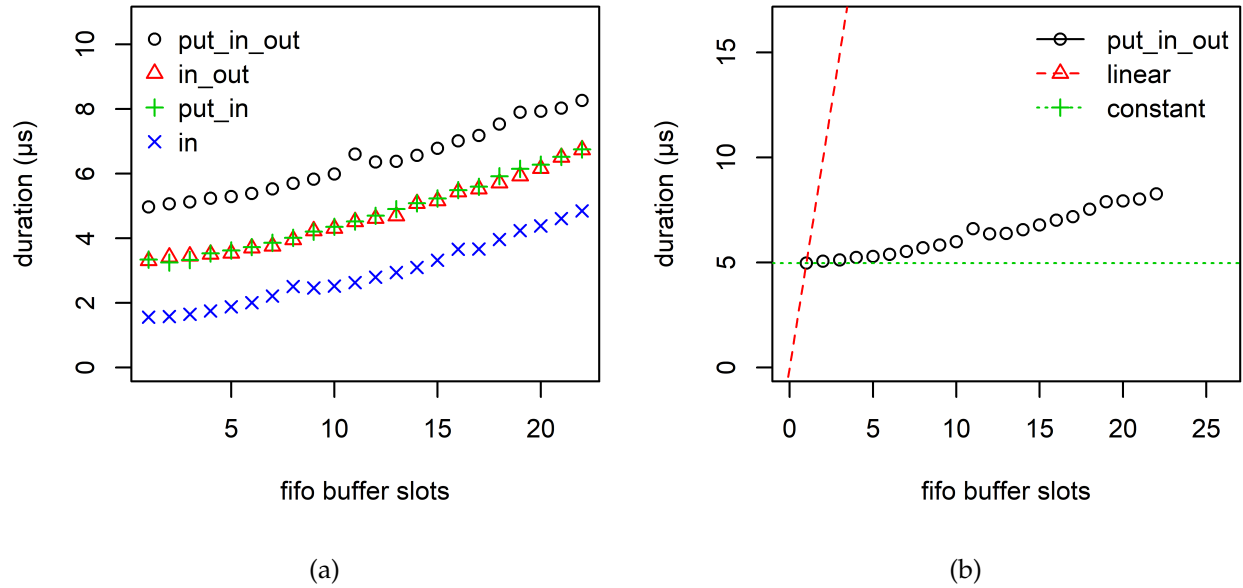


Figure 5.9: Round trip time (RTT) of a 2^{13} byte value through a `fifoN` connector with `m` ranging from 1 to 20, measuring the time taken from the start of the `put` into the head of the chain, to the end of the `get` out of the tail. (a) The experiment was repeated using variations of port operations 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`. Measurements are the mean of $100 \times 10\,000$ repetitions.

Chapter 6

Generating Static Governors

The cumulation of the previous chapters describe a standalone contribution to the Reo compiler. We have seen that users are able to generate Rust source code from a Reo specification (Chapter 3) which may be used in conjunction with their own Rust code to behave according to the corresponding protocol specification at runtime (Chapter 4). The programmer is able to rely on these protocol objects to constrain the behavior of their program at runtime such that no deviations from the protocol specification may be observed.

In this chapter, we design the **governor generator**, a tool to augment the user's Reo-coordinated Rust programs. As with the Reo compiler before, this tool generates a Rust source file from the Reo protocol specification which the user may import as a dependency. Within, a Rust type which corresponds with a *governor*. If integrated into the implementation of the user's components, the Rust compiler will enforce that the user's code does not inhibit the behavior of the system at large. In effect, users are provided an ergonomic means to opt into their Rust compiler enforcing liveness properties of their programs.

Section 6.1 provides the formal definition of governors, and how they relate to protocols, components and liveness. Section 6.2 describes the problem the **governor generator** aims to solve from the perspective of a Rust programmer relying on Reo to coordinate their components' communication. Section 6.3 gives a high-level overview of our corresponding solution. Section 6.4 explains in detail how the governor generator works, concentrating only on what is required to make it minimally functional. Finally, Section 6.5 elaborates on the means by which the solution is made ergonomic and practical.

6.1 Governor Defined

A Reo protocol specification defines which interactions are permitted between its boundary ports. In other words, protocols constrain the behavior of any system of which they are a component. This is the result of Reo’s semantics, which guarantees that the behavior of a system is the composition of its components at any granularity. However, protocols do not prevent their boundary components from adding constraints of their own. As a consequence, the definition of a component viewed in isolation does provide any guarantees on which interactions *are* observable in the system at large. To make this possible, a component needs some knowledge about the behavior of the system beyond its own ports. Fortunately, Reo specifications take us halfway there, as they make explicit which behaviors they permit in an unambiguous form that can be transformed and inspected. To proceed, we define the *governor*.

Protocol P with interface ports I_P defines G_{P,I_P} , its governor with respect to its interface ports. G_{P,I_P} shares interface I_P with P itself, and also constrains the interactions between them in the same manner as P . However, all port actions in G_{P,I_P} are the complement of those in P , i.e., all **puts** are **gets** and vice versa. G_{P,I_P} characterizes the behavior of a component that, if connected to P with interface I_P , would result in a composite system with the same behaviors of P itself. In other words, G_{P,I_P} describes the behavior which P would permit to occur, from the perspective of a component interfacing with all of P ’s ports.

Governors are generalized such that they are defined for any subset of a protocol’s interface ports, i.e., a protocol P with interface I_P defines a set of governors $\{G_{P,x} \mid x \subseteq I_P\}$. Governors characterize the reverse-oriented behaviors as before, but such that these behaviors are *projected* onto the governor’s own interface; projection is defined precisely by Baier et al. [BSAR06], and is explained in Section 6.5.1 when it is needed. Here, it suffices to say that the behavior as constrained by the governor omits the actions of all ports not in the governor’s interface. This captures the intuition that the governor only specifies the interactions of its own boundary ports, not constraining the actions of other ports at all. As such, the behavior of a governor is at most as constrained as that of the protocol itself; for every port not included the interface, the governor potentially becomes more ‘lenient’. This is made clear for the trivial case of a governor with the empty interface, which has no constraints whatsoever.

The utility of this construction is that it provides a means by which a component interfacing with some protocol P with any of its ports may compute precisely which behavior the protocol permits. By relying on the fact that protocol objects will facilitate any and all permitted interactions as possible at runtime, this boundary component is able to predict precisely the behavior the component that arises from its composition with the protocol. In the simplest

case, one is able to enforce that the resulting behavior matches the constraints of the protocol; equivalently, the protocol's boundary components do not contribute any behavioral constraints that the protocol itself did not define already. For such systems, one may understand the entirety of the system's coordination behavior by inspecting the definition of the protocol alone. In these cases, we say that the component is *adherent* to the protocol.

6.2 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 protocol will complete them as soon as the protocol definition allows it. In this way, coordinators possess a crucial subset of the features of governors: 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 adherent to the former protocol, but 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 adds a new constraint such that no next interaction exists, manifesting at runtime as deadlock.

```
1 fn transform_not(p: Putter<bool>, g: Getter<bool>) {  
2     loop {  
3         let input: bool = g.get();  
4         print!("I saw {}. ", input);  
5         p.put(! input);  
6     } }
```

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

6.3 Solution: Static Governance with Types

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 empower the boundary components with the ability to manage themselves by exposing the behavior of their protocols. Specifically, we create a means by which we are able to generate the relevant governor for a given protocol and interface. With this information exposed, we ensure that the implementation is adherent to the protocol by prohibiting it from adding any new constraints. Counter-intuitively, this takes the form of disallowing the component from performing the ‘wrong’ port operation, as the resulting blocking behavior would inhibit its ability to perform the ‘right’ port operation.

There is a vast possibility space for facilitating this enforcement on the users code given a governor as it is defined in Section 6.1; any solution that results in protocol adherence is sufficient. A user with a keen eye would be able to check protocol adherence manually by reasoning about the relationship between their component’s control flow. Instead, we opt for a more ergonomic approach that leverages a tool the user is guaranteed to have at their disposal anyway: the Rust compiler. Our solution involves the interplay between two novel facets of the Rust language that follow from its affine type system;

1. We are able to model the protocol’s underlying constraint automaton (see Section 2.1.3) as a type-state automaton (see Section 2.2.3), such that the Rust compiler is continuously aware of the protocol’s **state** throughout control flow of the user’s code wrt. its execution at runtime,

2. and we are able to protect the API of Reo-rs's port objects (see Section 4.3.1) such that the Rust compiler statically allows their use only if doing so in the current **state** preserves protocol adherence.

From the user's perspective, they are able to opt into the Rust compiler enforcing protocol adherence in their component code. Concretely, they are able to modify their implementation such that it takes the form of a function with a declaration (i.e., type signature) as defined in the Rust dependency generated by the governor generator. The user defines the function with `put` and `get` operations interspersed with arbitrary Rust code as usual. However, any port operations that would violate protocol adherence will result in the Rust compiler generating a static type error; if their implementation is completed without type errors, the user can be certain that their component's behavior at runtime will be protocol adherent.

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.

We extend this idea to the first of the two tenets of our design, as they appear in Section 6.3. Namely, we model the current configuration of the protocol as a type, updating it throughout our control flow such that it always corresponds with the protocol's configuration. From the user's perspective, they have precisely only token type in scope at all times. As defined previously, we are able to simulate 'updating' this type by overwriting it with a replacement token as the return result from a functions whose behavior alters the type. Concretely, our transition function consumes the old token (taking it by value as a parameter), and produces the new token as part of its return value. It follows that at all times we have precisely one token, whose type corresponds with the configuration of the protocol.

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 misalignments 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 disagree 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 protocol itself 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, as it is only actor in the system with a complete view of the protocol’s state, and can thus make the choice as a function of the state, i.e., 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 for 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

¹Early 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.

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  trait StateSetMatch {
2      type MatchResult;
3      fn match_head(self) -> Self::MatchResult;
4  }
5  struct StateSet<L> { data: /* omitted */ }
6  impl<H,Ta,Tb> StateSetMatch for StateSet<(State<H>, (Ta, Tb))> {
7      // a list with 2+ elements. match_head definition omitted
8      type MatchResult = Result<State<H>, StateSet<(Ta,Tb)>>;
9  }
10 impl<S> StateSetMatch for StateSet<(State<S>, ())> {
11     // singleton set. `()` acts as a sentinel element. match_head definition omitted
12     type MatchResult = State<S>;
13 }
14 fn example(ab_set: StateSet<(State<A>, (State<B>, ()))>) {
15     match ab_set.match_head() {
16         Ok(a) => /* matched A */,
17         Err(b_set) => {
18             let b = b_set.match_head();
19             /* matched B */
20 } } }
```

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

So far, this section has described only the first of two facets of our design, as they appear in Section 6.3. Namely, we are able to model the protocol's configuration space, and trace its changes throughout the control flow of the user's component by continuously updating the type of a singleton token in

scope. What remains is the step that connects this protocol configuration to its relationship with a given port operation.

We define the `Governed<Putter>` and `Governed<Getter>` types as wrappers for the `Putter` and `Getter` types existent in Reo-rs, corresponding to (logical) input and output ports respectively. As is idiomatic in the Rust language, our `Governed` type offers a type-safe means of ‘changing’ the API of the type it wraps, without altering the underlying data structure as it is represented at runtime. In other languages, this may be achieved with function overloading.

Everything comes together with the alteration of the API of our wrapper types such that its port operations are specified to consume a particular token, and produce a replacement. For this to work as intended, the function’s requirement for the functions’ input and output token types must correspond with a transitions in the type-state automaton. In other words, we rely on our ability to determine the API of our `Governed` type such that we enforce the conflation of two otherwise orthogonal actions such that one cannot occur without the other: for every port action α which changes the protocol’s configuration from C_x to C_y (1) α occurs, (2) the token’s type for C_x is updated to the type for C_y . The effect is the (static) prohibition of port operations which do not correspond to transitions through the protocol’s configuration space, i.e., they do not occur ‘next’ for a protocol in the state matching the type of the token.

For cases where the token corresponds with a protocol configuration in which there are several possible next actions (described in Section 6.4.2), the user’s component cannot safely commit to any choice, as it would necessarily constrain the component’s behavior, violating its protocol adherence. Such cases are detected statically by having a `StateSet` with two or more elements. At runtime, this problem is solved by ‘asking’ the protocol which branch to take, after which we have a single state token and proceed as before. Statically, the choice is not yet known, and so the programmer must provide the definition of the resultant behavior for each case. Section 6.4.2 explains that our solution emulates matching by recursively defining behavior in response to suffixes of a list whose elements match those of the `StateSet`.

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 subexpressions 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.

```

1  enum E {} // E for "Empty"
2  enum F {} // F for "Full"
3  fn start_state() -> (E,E);
4
5  fn a_to_m0<M>(state: (E,M)) -> (F,M);
6  fn m0_to_m1 (state: (F,E)) -> (E,F);
7  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 orientation 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* ports not in the interface projected upon, omitting the actions of those ports from the specification.

```

1 fn a_to_m0<M>(state: (E,M)) -> (F,M) {
2   // A puts
3 }
4 fn m0_to_m1 (state: (F,E)) -> (E,F) {
5   // silent
6 }
7 fn m1_to_b<M>(state: (M,F)) -> (M,E) {
8   // silent
9 }

```

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 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 reuse (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:

- **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 $\text{Act}(r_{\text{last}}) \cap I = \{P\}$ and for all rules r in the sequence, $r = r_{\text{last}} \vee \text{Act}(r) \cap I = \emptyset$.
- 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.

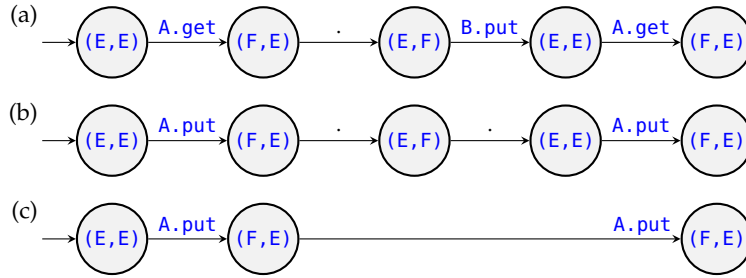


Figure 6.1: Rules being applied to walk three RBAs in lockstep, with time horizontally, showing the (simplified) configurations traversed, and annotating rules by showing which port actions they involve.

(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

```

1 fn normalize(mut rules: Set<Rule>) -> Set<Rule> {
2     let (mut silents, mut not_silents) = rules.partition_by(Rule::is_silent);
3     while silents.not_empty() {
4         let removing: Rule = silents.remove();
5         if removing.changes_configuration() {
6             for r in silents.iter() {
7                 if let Some(c) = removing.try_compose_with(r) {
8                     silents.insert(c);
9                 }
10            }
11            for r in not_silents.iter() {
12                if let Some(c) = removing.try_compose_with(r) {
13                    not_silents.insert(c);
14                }
15            }
16        }
17    }
18    return not_silents;
19 }

```

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.

does this by building these *composed* rules from front to back, i.e., replacing every silent rule x with a set of rules $x \cdot y$, where y is any other rule. Once 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 $x \cdot x \cdot x \cdot \dots$ 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 also².

The normalization algorithm is **terminating**. It consists of finitely many algorithm steps in which the RBA A is replaced by RBA $B = (A \setminus \{r\}) \cup \{r \cdot x \mid r \in A \setminus \{x\} \wedge \text{composable}(x, r)\}$ for some silent rule $x \in A$. Initially, A is the input RBA with silent rules. The algorithm terminates, returning B when A is

²The reader may note the similarity between this observation and that made by the pumping lemma for regular languages [Lin06]. In both cases, we observe that an arbitrary sequence of ‘idempotent’ cycles as part of a walk through configuration space have no influence on the rest of the path.

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.

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 m, n in the place of x . From this we know that $|P(A)| \geq |P(B)|$. 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 by providing 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.

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} .

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 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 distin-

guish 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.

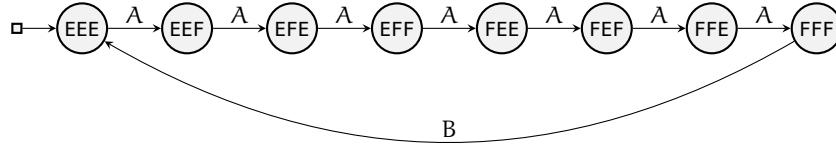


Figure 6.2: Rules transitioning through configuration space of approximated RBAs for the a7b1 connector, with states named after the ‘count’ the three memory cells represent in base 2 (in binary alphabet {E, F}). Here, the normalization procedure with interface set {A, B} is trivial as no transitions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

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** (abbreviated 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

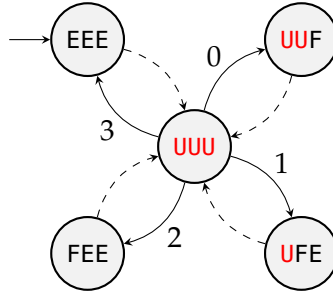


Figure 6.3: Rules transitioning between configurations of the a7b1 connector shown in Figure 6.2. Here, the user employs weakening to convert (dashed arrows) state tokens to configurations to the configuration set ‘???’ containing all concrete configurations. RBA rules firing are shown with solid arrows,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

alleviates the problem of having to explicitly enumerate the needed sets each as their own enumeration type. This is necessary, as the upper bound³ of state sets is 2^{3^M} , where M is the number of memory cells;⁴ suffice it to say, it is a large number. 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.

³Many 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.

⁴The 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 $\{E, F, U\}$.

```
1 enum StateSetXyz { X(X), Y(Z), Z(Z) }
2 fn match_standard(set_xyz: StateSetXyz) {
3     use StateSetXyz::{X, Y, Z};
4     match set_xyz {
5         X(x) => x.foo(),
6         Y(y) => y.bar(),
7         Z(z) => z.baz(),
8     }
9 fn match_recursive(set_xyz: StateSet<(X, (Y, (Z, ())))>) {
10     use StateList::{Head, Tail};
11     match set_xyz.match_head() {
12         Head(x) => x.foo(),
13         Tail(set_yz) => match set_yz.match_head() {
14             Head(y) => y.bar(),
15             Tail(z) => z.baz(),
16         }
17 fn match_macro(set_xyz: StateSet<(X, (Y, (Z, ())))>) {
18     match_set! { set_xyz;
19         x => x.foo(),
20         y => y.bar(),
21         z => z.baz(),
22     }
```

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, precompiled 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 (e.g., 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 (i.e., logical disjunction). 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 $P_1 = C_1 \wedge P_2 = C_2$ 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 (i.e., 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.

¹Changing 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.

After splitting, three 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 non-determinism. 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 presume 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 preprocess the imperative form as its executable object is built (explained in Section 3.3.3). For example, instructions can be fragmented and reorganized 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 reenter 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 (e.g., 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 handwritten 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 malformed protocol or port objects, and they cannot experience system behavior that contradicts the specification of the protocol (unintentionally or otherwise). Furthermore, our design includes other novel optimizations that result in benefits to the user. For example, protocols function without dedicated threads, increasing performance for sequentially accessed protocols, and trivializing the detection of a protocol's termination.

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

```

1  if T::IS_COPY { // irrelevant how many copy
2      if let Some(dest) = maybe_dest {
3          do_move(dest);
4          m.visit();
5      }
6      let was = count.fetch_dec();
7      if was == LAST {
8          let [visited_first, retains] = m.visit();
9          finalize();
10     }
11 } else {
12     if let Some(dest) = maybe_dest {
13         let [visited_first, retains] = m.visit();
14         if visited_first && !retains {
15             let was = count.fetch_dec();
16             if was != LAST {
17                 mover_await();
18             }
19             do_move(dest);
20             finalize();
21         } else {
22             do_clone(dest);
23             let was = count.fetch_dec();
24             if was == LAST {
25                 if retains {
26                     finalize();
27                 } else {
28                     mover_release();
29                 }
30             }
31         }
32     } else {
33         let was = count.fetch_dec();
34         if was == LAST {
35             let [visited_first, retains] = m.visit();
36             if visited_first {
37                 finalize();
38             } else {
39                 mover_release();
40             }
41         }
42     }
43 }

```

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.

```

1  // initialization
2  let barrier_g = Arc::new(std::sync::Barrier::new(3));
3  let barrier_p0 = barrier_g.clone();
4  let barrier_p1 = barrier_g.clone();
5  let (data_0_s, data_0_r) = crossbeam_channel::bounded(0); // synch (unbuffered)
6  let (data_1_s, data_1_r) = crossbeam_channel::bounded(1); // asynch (1-buffered)
7
8  // port operation functions
9  let p0_put_function = || {
10     barrier_p0.wait();
11     data_0_s.send(P0_VALUE).unwrap();
12 };
13 let p1_put_function = || {
14     barrier_p1.wait();
15     data_1_s.send(P1_VALUE).unwrap();
16 };
17 let g_get_function = || {
18     barrier_g.wait();
19     let value_from_p0 = data_0_r.recv().unwrap();
20     let value_from_p1 = data_1_r.recv().unwrap();
21 };

```

Listing 25: Handcrafted alternator implementation in 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.

```

1      mov     eax, 131096
2      call    __rust_probestack
3      sub     rsp, rax
4      lea     rdi, [rsp + 9]
5      mov     edx, 65536
6      mov     esi, 2
7      call    qword ptr [rip + memset@GOTPCREL]
8      mov     byte ptr [rsp + 8], 1
9      mov     byte ptr [rsp + 65552], 0
10     mov     eax, 32
11     .LBB0_1:
12         movups xmm0, xmmword ptr [rsp + rax - 24]
13         movups xmm1, xmmword ptr [rsp + rax - 8]
14         movups xmm2, xmmword ptr [rsp + rax + 8]
15         movups xmm3, xmmword ptr [rsp + rax + 24]
16         movups xmm4, xmmword ptr [rsp + rax + 65520]
17         movups xmm5, xmmword ptr [rsp + rax + 65536]
18         movups xmm6, xmmword ptr [rsp + rax + 65552]
19         movups xmm7, xmmword ptr [rsp + rax + 65568]
20         movups xmmword ptr [rsp + rax - 24], xmm4
21         movups xmmword ptr [rsp + rax - 8], xmm5
22         movups xmmword ptr [rsp + rax + 65520], xmm0
23         movups xmmword ptr [rsp + rax + 65536], xmm1
24         movups xmmword ptr [rsp + rax + 24], xmm7
25         movups xmmword ptr [rsp + rax + 8], xmm6
26         movups xmmword ptr [rsp + rax + 65552], xmm2
27         movups xmmword ptr [rsp + rax + 65568], xmm3
28         add     rax, 64
29         cmp     rax, 65538
30         jbe     .LBB0_1
31         add     rsp, 131096
32         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.

```

1  #![feature(raw)]
2  use std::mem::{MaybeUninit, transmute};
3  use std::raw::TraitObject;
4  pub struct TypeInfo(usize);
5  impl TypeInfo {
6      pub fn of<T>() -> TypeInfo {
7          let x: Box<T> = unsafe { MaybeUninit::uninit().assume_init() };
8          let fat_x = x as Box<dyn PortDatum>;
9          let raw: TraitObject = unsafe { transmute(fat_x) };
10         TypeInfo(raw.vtable as usize)
11     }
12 trait PortDatum {
13     fn foo(&self) -> u32 { 123 }
14 }
15 impl<T> PortDatum for T {}
16 pub fn test() -> TypeInfo {
17     TypeInfo::of::<u32>()
18 }

```

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 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 the concrete type's (1) `drop` function pointer, (2) size in bytes, (3) memory alignment in bytes.