Shared Memory Implementations of Protocol Programming Languages

Citation for published version (APA):

DOI:
10.1145/3242947.3242952

Document status and date:
Published: 17/07/2018

Document Version:
Peer reviewed version

Document license:
CC BY

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
https://www.ou.nl/taverne-agreement

Take down policy
If you believe that this document breaches copyright please contact us at:
pure-support@ou.nl
providing details and we will investigate your claim.
Abstract
Protocol programming languages are domain-specific languages that offer higher-level abstractions for programming of synchronization and communication protocols among participants. However, most implementations of protocol programming languages on shared memory architectures use pointer passing to exchange data in communications, so programs can still run into data races. We report on our ongoing efforts toward the first shared memory implementation of a protocol programming language that guarantees freedom of data races, without excessive copying, by leveraging the programming language Rust and its type system.

CCS Concepts  • Software and its engineering → Concurrent programming languages;

Keywords protocol languages, Rust, Reo

1 Introduction
With the advent of multicore processors, concurrent programming has become an indispensable skill for many general-purpose programmers to master. However, concurrent programming remains difficult: despite new features in general-purpose programming languages that offer higher-level abstractions on top of bare threads and locks (e.g., the fork/join framework in Java; actor-based concurrency in Scala and

Erlang; channel-based message-passing in Go and Rust), programmers continue to struggle with classical concurrency errors, such as deadlocks and data races.1

A major challenge that programmers of concurrent programs face, pertains to the implementation of protocols (i.e., synchronization and communication patterns) among participants (i.e., concurrent computations): while general-purpose programming languages offer concurrency primitives to program the local actions of participants (e.g., lock/unlock; send/recv), they lack linguistic support to ensure local actions truly result in the global interactions of the protocol (e.g., “a synchronization between threads $T_1$ and $T_2$ is followed by a communication between $T_2$ and thread $T_3$”). Aggravated by the many possible interleavings in which threads can be scheduled, purely action-centric protocol programming techniques are hard to reason about and error-prone to use.

In recent years, several interaction-centric protocol programming techniques have been developed that offer several advantages. The idea is that programmers continue to use an existing base language (e.g., Java, C, etc.) to program the sequential computations of a program. Complementary, programmers are also provided a supplemental language specifically for protocols (i.e., a domain-specific language), in which they can program the interactions of protocols directly and explicitly. Using such a supplemental language, specifically, programmers can program the desired data exchanges using higher-level and more appropriate abstractions, and automatically generate lower-level code that uses concurrency primitives in the base language. Thus, protocols programmed in the supplemental language are ultimately compiled into code in the base language, after which the whole program can be compiled/run using the base language’s standard tools.

This way of working has several key advantages: the protocol code can be considered modularly from the actual computation code, enabling protocol code and computation code to be formally verified separately (e.g., model-checking protocol code [8], or type-checking computation code against local protocol specifications [4]). Modularity also simplifies reuse of both computation code and protocol code in other programs, as the sequential parts can be replaced by other algorithms. Premier examples of interaction-centric protocol programming languages are Reo [1] and Scribble [9].

1E.g., Gartner (a leading IT advisory company in industry) recently reported that “multicore programming is generally seen as a hard-to-achieve and time-consuming task, so many programmers avoid it as far as possible” [3].

*Work-in-progress paper

ICOOOLPS’18, July 17, 2018, Amsterdam, Netherlands
© 2018 Copyright held by the owner/authors(s). Publication rights licensed to ACM.
This is the author’s version of the work. It is posted here for your personal use. Not for redistribution. The definitive Version of Record was published in 13th Workshop on Implementation, Compilation, Optimization of Object-Oriented Languages, Programs and Systems (ICOOOLPS’18), July 17, 2018, Amsterdam, Netherlands. ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3242947.3242952.
2 Research Questions

To avoid data races, a key assumption in the designs of many supplemental languages for protocols (including Reo and Scribble) is that every participant has private memory—even if the base language supports shared memory—and that all interaction proceeds via message-passing; under this assumption, data races by definition cannot occur. In the implementations of these languages, however, this assumption is not always upheld. Specifically, for base languages with shared memory, the following two approaches have been used to implement communications between participants:

**ALWAYS-COPY** The runtime system for the protocol programming language always makes a copy of every value communicated. The advantage is that freedom of data races is statically guaranteed, because the private memory assumption is faithfully “simulated” by always copying. The disadvantage is that excessively many copies of data may be created (e.g., if a sender does not use a value after sending, no copy is necessary).

**NEVER-COPY** The runtime system never makes a copy, relying on the programmer to make a copy upon send and/or receive. The advantage is that the programmer can fine-tune the number of copies to improve performance; the disadvantage is that the programmer may make too few copies—intentionally (e.g., to maximize performance) or by mistake—so freedom of data races is no longer statically guaranteed.

For instance, the most recent Java implementation of Reo uses only the second approach [6]; the Java implementation of Scribble works with both approaches [5].

In an ongoing research project, we aim to find a middle ground between these two approaches, consolidating their strengths, while alleviating their weaknesses. Specifically, taking the more practical NEVER-COPY approach as our basis, we seek answers to the following research questions:

**Q1a** How to statically guarantee, using NEVER-COPY, that if a participant P sends a value \( v \), P will not use \( v \) after it has sent \( v \)? (i.e., P can only use a copy of \( v \).)

**Q1b** How to statically guarantee, using NEVER-COPY, that if a participant P receives a value \( v \), no other participant will use \( v \) after P has received it? (i.e., every other participant can use only copies of \( v \).)

**Q2** What is the trade-off between freedom of data races and maximal performance (i.e., use NEVER-COPY and knowingly run the risk of data races)?

To resolve Q1a and Q1b, we need an analysis tool to reason about usage of heap data and aliasing. The type system of the Rust programming language does exactly this. Our approach is, thus, to adopt Rust as a base language, compile an existing supplemental language for protocols to Rust, and leverage Rust’s type system to statically guarantee freedom of data races. Doing so, we aim to develop the first shared memory implementation of a protocol programming language that guarantees freedom of data races, without excessive copying.

3 Rust

The Rust programming language was initiated at Mozilla and has, for instance, been used to reimplement the rendering code in Firefox. The syntax is similar to C++, but the memory management model is based on a linear type system (the Rust terminology is ownership and borrowing), without the aid of a garbage collector, as explained next.

**Ownership** Rust gives strong guarantees about the relationship between values and variables: each value is assigned to a unique variable, called its owner. A value can be reassigned to a different variable, thereby moving it to a different owner, but the type system forbids further mutations or accesses of that value through the original variable after the move (statically checked). The memory occupied by a value is automatically freed whenever its owner goes out of scope.

**Borrowing** Although every value has a unique owner, Rust’s type system does allow other variables to temporarily borrow mutation or access rights to a value from the owner, without moving ownership, using references (akin to pointers and references in languages like C++ and Java). However, references are bound to rules: at any one time, either there is exactly one reference that allows mutation of the value, or there are zero or more references that allow (read) accesses.

Essentially, ownership and borrowing remove the root cause of data races, namely having a shared mutable state.

The ownership model enables the refinement of NEVER-COPY implementations, providing a third alternative: whereas in the existing NEVER-COPY implementations in Java, C, etc., a sender transfers only a reference, in our new implementation in Rust, a sender transfers also ownership during the transfer to the receiver. Thus, in the event that a sender must access or modify a value after sending it, it must create a copy before sending, or it will be in violation of the rules set out by Rust’s type system. Such a violation is treated by the Rust compiler as a programming error and will cause the compiler to emit an error message instead of a binary executable.

4 Reo in Rust

We are currently developing a Rust implementation of Reo, a premier example of a supplemental language for protocols.
**Background.** Reo [1] is a graphical language to draw protocols among participants as graphs. Figure 1 shows examples. To send a value, a participant can perform a blocking put operation on an input vertex of a graph (e.g., A or B in Figure 1a). The put method initially suspends the participant: only once the graph is ready to accept the value, the put will complete, and the participant resumes. Similarly, to receive a value, a participant can perform a blocking get operation on an output vertex of a graph (e.g., C in Figure 1a). Once a graph has accepted a value through input vertices, it transports that value along its edges, possibly through one or more anonymous internal vertices (e.g., the middle vertex in Figure 1b), and dispenses it through one or more output vertices. Every edge has a type that determines its local transport behavior. The graphs in Figure 1 feature edges of three different types: a sync edge has synchronous channel semantics (e.g., the edge between A and C in Figure 1a); a fifo1 edge has asynchronous channel semantics, with an internal buffer of capacity 1 (e.g., the edge between B and C; the box signifies an internal buffer); a synchrout edge has synchronous drain semantics (e.g., the edge between A and B in Figure 1a); other channel types appear in the literature [1].

Recent implementations of Reo are based on its operational semantics [2, 7]. The idea is to model the behavior of a Reo graph as a finite-state automaton, where states model configurations of the graph (e.g., buffer emptiness/fullness), and transitions model synchronous value transports along the edges. Figure 2 shows examples. Every transition label consists of two elements: the set of input and output vertices that collectively participate in the transition (e.g., {A,B,C}), called the synchronization constraint, and a specification that states how values are transported from input vertices to output vertices (e.g., \[ C := A; x := B \]), called the data constraint. For instance, the bottom transition in Figure 2a states that a value accepted through A is dispensed through C, while synchronously, a value accepted through B is stored in local variable \( x \) (i.e., the internal buffer of the diagonal fifo edge in Figure 1a); the top transition states that the value previously stored in \( x \) is dispensed through C.

To compile a Reo graph to code in a base language, in its most basic form, the Reo compiler takes the following steps. First, the compiler determines for every constituent of the graph (i.e., vertices and edges) a "small automaton" that models the local transport behavior only of that constituent. Next, the compiler composes the small automata into one "large automaton", using a synchronous product operator; in this step, the compiler also abstracts away all internal vertices. Finally, the compiler translates the automaton to a piece of state machine code in the base language.

**Compilation to Rust.** The final compilation step, when Rust is used as the base language, is implemented as a code generator. This generator takes a tuple representing an automaton as input. The output consists of a Rust application in source code form. This application can then be compiled into a binary executable, using the standard Rust toolchain. Every participant is programmed as a sequential Rust function, executed in its own Rust thread. The moment the thread is started, the function is called and passed a generated Automaton struct, which offers the following interface:

```rust
pub fn put(&mut self, vertex: usize, val: Message)
pub fn get(&mut self, vertex: usize) -> Message
```

Whenever put or get is called, the calling thread "enters" the generated protocol code, tries to find an enabled transition from the current state, and if one exits, actually fires that transition. A transition is enabled iff every vertex in its synchronization constraint has a pending put or get; a transition has fired iff values have been distributed according to its data constraint. Specifically, to distribute data, the generated code has separate variables to temporarily store values to be exchanged, namely one for every vertex and local variable controlled by the automaton (e.g., A, B, C, \( x \) for the automaton in Figure 2a); it simply transfers data from inputs to outputs according to the data constraint. For instance, \( [C := A; x := B] \) in Figure 2a is morally translated to:

```rust
... // puts write to aut.val_A and aut.val_B
aut.val_C = aut.val_A; // move ownership
aut.val_x = aut.val_B; // move ownership
... // get reads from aut.val_C
```

If there are no enabled transitions (e.g., puts have been issued on vertices A and B, but a get has not been issued yet on vertex C in Figure 2a), the thread "leaves" the generated protocol code, and suspends; it resumes whenever another transition is enabled.

---

1We omit a number of optimizations from this overview, which are essential to improve performance, but beyond our current scope.

2Specifically, `Arc<Mutex<Automaton>>`, to allow mutually sharing the same protocol among all participant functions.

3The assignments in the actual implementation are a bit more involved, to ensure the `aut` struct is left in a valid state (i.e., fields have values).
thread successfully fires a transition later on (e.g., after a
gain on C). A mutex ensures that only one thread can fire a
transition at a time. Figure 3 summarizes the structs.

Resolving Q1a and Q1b. Both the `put` function and the `get`
function make use of `pass-by-value` to pass in a message-to-
send, or to retrieve a message-to-receive via the return value.
In Rust, passing by value implies a transfer of ownership as
the type system prescribes that a value can only be assigned
to a unique variable. Indeed, after transferring ownership,
the Rust compiler will emit a detailed error message if the
participant tries to mutate or access the value. For instance:

```rust
error[E0382]: use of moved value: `v`
```

Thus, we statically guarantee that if a participant sends a
value, it loses ownership (i.e., it cannot use that value in the
future), and that if a participant receives a value, it gains
ownership (i.e., no other participant can use that value in the
future). The former resolves Q1a; the latter almost resolves
Q1b, but special care is needed to support multi-casts.

The problem with multi-casts pertains to our translation
of data constraints. Specifically, by assigning the value of one
vertex to another, ownership of the value is transferred. This
allows for a copy-free transport of the value, but because the
type system guarantees that the value cannot be assigned
to multiple variables, it does not work with multi-casts. This
situation arises if a vertex in a Reo diagram is attached to
multiple edges (e.g., the middle vertex in Figure 1b). In that
case, the message value needs to be transported to all receiv-
ving vertices, which cannot be achieved by means of transferal
of ownership. The solution is to make an explicit copy of
the value and assign ownership of the copies. For instance,
[B := x; C := x] in Figure 2b is translated to:

```rust
... // prev. transition wrote to aut.val_x
aut.val_B = aut.val_x.clone(); // explicit copy
aut.val_C = aut.val_x; // move ownership
... // get calls read from aut.val_B and aut.val_C
```

Our code generator recognizes such multiple assignments
of a value and inserts the appropriate `clone` calls in the data
constraint statements. Importantly, the copies are made internally
by the generated code, transparent to the programmer.

With this extra multi-cast care, Q1b is resolved as well.

Toward resolving Q2. We are currently setting up experi-
m ents to study the performance trade-offs between always-
copy, never-copy, and never-copy+ownership. Our plan
is to use the Rust code that is generated for Reo graphs
as described above for never-copy+ownership, to simulate
always-copy by adding additional copying to the generated
code, and to simulate never-copy by always passing the
same tiny value around (1 byte, so the costs of copying are
negligible). In this way, we can compare the performance
of the three approaches within the same framework.

We are planning two kinds of benchmarks. In protocol
benchmarks, we aim to measure purely the overhead of copy-
ning for a representative set of Reo graphs, by running the
generated code among “zealous” participants (i.e., participants
that try to put/get as often as possible, without performing
any real computations). In whole-program benchmarks,
we aim to measure the effect of copying in real(istic) concurrent
programs, such as pipelined computations where the same
large data is processed by multiple threads in sequence.

5 Conclusion

We reported on our ongoing efforts toward the first shared
memory implementation of a protocol programming lan-
guage that guarantees freedom of data races, without exces-
sive copying, by leveraging the programming language Rust
and its type system. To this end, we briefly explained how
protocol programming language Reo can be implemented in
Rust to resolve Q1a and Q1b, and we outlined our plans to
resolve Q2. Other future work includes:

- **Improve static guarantees.** We are curious to study how,
  and to what extent, Rust’s type system can also be
  leveraged to implement linear session type systems [4]
  (i.e., Scribble’s theoretical foundation).
- **Optimize.** The existing Java implementation of Reo has
  optimizations that have not been implemented yet in
  our Rust implementation (e.g., the Java implementa-
  tion parallelizes execution of the generated code).
- **Relaxations.** In practice, it may be desirable to relax
  the model to allow senders to keep a read-only reference
  to sent data (e.g., to improve performance). We are
  interested to investigate how to balance this relaxed
  setting with freedom of data races.

References

2005. Modeling component connectors in Reo by constraint automata.
Multiparty Session Types. In FASE (Lecture Notes in Computer Science),
Programming with Automata. In TACAS (Lecture Notes in Computer Science),