Compositional Reasoning for Side-effectful Iterators and Iterator Adapters

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Abstract. Iteration is a programming operation that traditionally refers to visiting the elements of a data structure in sequence. However, modern programming systems such as Rust, Java, and C# generalise iteration far beyond the traditional use case. They allow iterators to be parameterised with (potentially side-effectful) closures and support the composition of iterators to form iterator *chains*, where each iterator in the chain consumes values from its predecessor and produces values for its successor. Such generalisations pose three major challenges for modular specification and verification of iterators and the client code using them: (1) How can parameterised iterators be specified modularly and their (accumulated) side effects reasoned about? (2) How can the behaviour of an iterator chain be derived from the specifications of its component iterators? (3) How can proofs about such iterators be automated? We present the first methodology for the modular specification and verification of advanced iteration idioms with side-effectful computations. It addresses the three challenges above using a combination of inductive two-state invariants, higher-order closure contracts, and separation logiclike ownership. We implement and our methodology in a state-of-the-art SMT-based Rust verifier. Our evaluation shows that our methodology is sufficiently expressive to handle advanced and idiomatic iteration idioms and requires modest annotation overhead.

Keywords: Deductive verification · Verified software · Iterators · Rust.

1 Introduction

Iterators are a ubiquitous programming idiom traditionally used to abstractly and simply enumerate the elements of a collection. Verification of such simple use cases comes down to proving that an iterator yields all elements of a collection in a specified linear order and showing that the used iterator does not get invalidated e.g. by concurrent modifications of the underlying collection [5].

Modern programming languages such as C#, Java, Python, and Rust support iteration patterns that go far beyond the traditional use case. For instance, iterators are used to perform computations over streams of values, such as computing a moving average; the computation itself is typically *parameterisable* by

custom code such as closures. In general-purpose languages, both the iterators themselves and these closures may perform side effects, e.g. to modify the data structure in-place or to accumulate computations based on the values seen so far; code which uses such iterators depends on properties of this modified state.

Moreover, it is increasingly prevalent for languages to support the *composition* of iterators, where an iterator processes values produced by another iterator (rather than obtained directly from a collection data structure). We follow the Rust terminology and call this kind of iterator an *iterator adapter* (*adapter* for short). Iterator adapters may be composed to form *iterator chains*, where each iterator in the chain consumes the values from its predecessor in the chain and produces values for its successor; the overall chain acts as a composite iterator.

It is common for imperative languages to provide a variety of iterator adapters, e.g. Java's Streams API, C#'s LINQ, Python's iterables, and Rust's iterator adapters all support potentially-side-effectful variants of common functional programming operations such as filter, fold, and map. These languages also allow developers to implement their own custom iterators and iterator adapters.

The following *Rust* example illustrates the use of iterators and adapters:

1	let mut sum = 0;		
2	some_vector	//	start with a vector of integers
3	.iter()	//	create an iterator over the vector
4	$map(x { sum += x; sum })$	//	running totals of seen elements
5	.filter(x x < 10)	//	only keep totals smaller than 10
6	<pre>.collect::<vec<_>>();</vec<_></pre>	//	collect the results into a vector

The function iter yields a traditional iterator for the underlying vector, which provides the input to the iterator chain. The map adapter is parameterised with a closure, which mutates the captured variable sum. The subsequent filter adapter, also parameterised with a closure for the filter criterion, removes elements, and finally collect stores the produced elements in another vector.

Such advanced iteration patterns lead to concise and readable code, but they also pose several challenges for modular specification and verification. Modularity is important to give correctness guarantees for libraries, to make verification scale, and to reduce the effort for re-verification when parts of a codebase change. The three main challenges are:

1. How to specify parameterised iterators modularly. The behaviour of iterators such as map depends on their argument closures. Modular reasoning aims at verifying the iterator implementation against a specification that accounts for all possible closures that may be used by the client code. This requires a specification that is parametric in the argument closure, which is especially challenging for closures that have side effects such as the closure in line 4 of our example. The specification of the iterator must be strong enough (1) to prove how the side effects affect the values produced by the iterator and (2) to determine the accumulated side effects of all calls to the iterator and its related closures by the time the iterator terminates. The latter is relevant because variables mutably captured by a closure, such as sum in the

motivating example, become accessible to the client code once again when the iterator terminates (and, by extension, the closure expires).

In our example, assume that some_vector contains the values 6, 2, 9. map's specification must be strong enough to prove (1) that the iterator produces the sums of the prefixes of the values it iterates over, that is, 6, 8, 17, and (2) that the final value of sum is 17.

2. How to reason modularly about iterator chains. Modular verification requires that we can prove the behaviour of an iterator chain based on the specifications of its component iterators. In particular, verification of a chain must not require re-verification of its component iterators (whose code might not even be available); it should not be necessary to adapt the specification of an iterator for each and every instantiation and composition. Instead, the specification of an iterator must be agnostic to the source of values it consumes and to the downstream processing of the values it produces.

In our example, we want to prove that the final vector contains the values 6 and 8, without requiring the specifications of the intermediate adapters to either refer to the initial vector or depend on the subsequent adapters.

3. How to automate verification of modern iterator and adapter patterns. The behaviour of iterator chains depends on the behaviour of their component iterators, which may in turn depend on their argument closures. This hints at the need for higher-order logics (specifications which depend on specifications), which greatly complicate proof automation; we aim instead for proofs which can be automated with first-order SMT solvers.

State of the art. Prior work on iterator verification only partially addresses the challenges outlined above. Pereira [13] defines a modular verification technique using two predicates per iterator to specify the sequence of produced values and a termination condition. This technique is automated using Why3 [4]. It partially addresses Challenge 1 by providing abstract, implementation-independent specifications for individual iterators. However, although higher-order iterators are discussed, this only refers to simple iterators parameterised by side-effect-free functions, as in a functional fold operation. Support for iterators with side effects (for instance, to prove the final value of sum in our example) is discussed as future work in the form of a tool which rewrites client code into equivalent loops, leaving the appropriate specification and verification to manual proof effort. Iterator composition is not addressed.

Verification of higher-order functions such as fold in Rust is partially addressed in existing work on *closure* verification [16], allowing one to reason modularly about side-effectful closures, such as the argument to map in our example. However, this technique does not provide specification or verification support for iterators and adapters that *use* closures in well-known but functionally complex ways (e.g. as an argument to a fold).

This work. We present the first modular specification and verification technique for advanced iteration patterns that addresses the three challenges above. To address Challenge 1, we associate iterators with four key specifications: (1) the sequence of elements, produced, returned by the iterator so far, (2) a completed predicate that expresses when iteration terminates, (3) a two-state postcondition step that relates two consecutive iterator states and (4) a two-state predicate leads to that inductively relates any previous state of the iterator to any more recent state. The first two points are inspired by Pereira [13], but importantly our technique can also handle side-effectful iterators by characterising the intermediate states occurring during an iteration, not only the returned elements. We employ so-called call descriptions [16] to parameterise the step and leads predicates with the behaviour of closures (e.g. for the map and filter iterators above). In order to reason about the accumulated effects of an iterator, we prove that each call to next satisfies the transitive two-state invariant leadsto. Consequently, this invariant also holds between the initial and the final state of the entire iteration and, thus, is able to characterise its overall effects.

We show that our newly developed methodology generalises directly to iterator chains (Challenge 2): the leadsto predicate of an iterator adapter may refer to the leadsto predicate and the produced sequence of its predecessor in an iteration chain to specify the successor's behaviour in terms of the behaviour of the predecessor. In particular, these specification ingredients let the successor maintain ghost data structures that keep track of all states of the predecessor iterator and of any argument closures that occur during the iteration. We can then reason about side effects via invariants over these ghost structures.

Our methodology builds exclusively on specification constructs for which automated verification techniques exist (ghost fields, invariants, and closure call descriptions). It can, thus, be automated in SMT-based verifiers, as we demonstrate through an extension of the Rust verifier Prusti [1] (Challenge 3).

We present our technique in the context of Rust, whose ownership type system complements our methodology by preventing concurrent modifications of an iterated-over data structure, or undesirable interference between iterators. However, our technique would apply equally to other languages if augmented with an alternative ownership-like technique such as separation logic [14].

Contributions and outline. The main contributions of our paper are:

- We present the first specification and verification methodology for general side-effectful iterators (\rightarrow Sec. 3, Sec. 4).
- We demonstrate how to use this methodology to reason about the effects and resulting values of complex iterator chains (\rightarrow Sec. 5).
- We show how to express these specifications modularly for existing iterator hierarchies (\rightarrow Sec. 6).
- We implement our work in the Prusti verifier [1] and demonstrate its expressiveness on several challenging examples (\rightarrow Sec. 8).

Additionally, we provide the necessary background on Rust (\rightarrow Sec. 2), explain why our approach is sound (\rightarrow Sec. 7), and discuss related work (\rightarrow Sec. 9).

2 Background

In this section we briefly describe Rust, focusing on its ownership type system $(\rightarrow \text{Sec. } 2.1)$, then we discuss the relevance of this type system to verification in general and our methodology in particular ($\rightarrow \text{Sec. } 2.2$).

2.1 Rust

Rust [10] is a modern systems programming language that is rapidly gaining popularity. Among mainstream languages, it is unique due to its *ownership* type system, which eliminates certain categories of common software bugs, such as data races, use-after-free bugs, dangling pointers, and null pointer dereferences.

The Rust type system maintains a crucial invariant: any value is either mutable or shared, but never both. To maintain this invariant, values are categorised as: *owned*, *mutably borrowed*, or *immutably borrowed*. All values have a single *owner*, which by default has exclusive (read/write) capabilities on the data. Since ownership is exclusive, no other thread or function can access the owned value without *borrowing it* via a reference. A value can be *mutably borrowed* to create exactly one mutable reference. While the mutable reference exists, it has the unique capability to read from and modify the borrowed value. Immutable, or *shared* references, on the other hand, have a *read-only* capability for the borrowed value. Unlike mutable references, a value can be immutably borrowed any number of times. When all borrows expire (go out of scope) the borrowed-from value becomes writable again. The following snippet demonstrates some of these concepts; for a full overview of Rust we refer the reader to the Rust Book [8].

```
struct Point { (A)
1
        x: i32, y: i32,
^{2}
   }
3
   fn origin() -> Point { (B)
 4
        Point { x: 0, y: 0 }
 \mathbf{5}
   }
 6
   fn get_point_x(pt: &Point) -> &i32 { (C)
 7
 8
        &pt.x
   }
9
   fn set_point_x(pt: &mut Point, x: i32) { (D)
10
11
        pt.x = x;
12
   }
```

The above code declares a 2D point structure (A) consisting of two integer coordinates. The origin method (B) returns an owned Point to the caller with both coordinates at zero (types not prefixed with an & are owned). get_point_x (C) takes a shared reference to a point (indicated by &Point), and returns a shared reference to its x coordinate. Finally, set_point_x (D) takes a mutable reference to a point (indicated by &mut Point), and sets its x coordinate to the given value. The following code makes use of these methods:

```
1 let mut pt = origin();
2 set_point_x(&mut pt, 5);
```

³ let x = get_point_x(&pt);

```
4 // set_point_x(&mut pt, 6); // not allowed!
5 println!("xucoordinate_is:u{}", *x);
act_point_x(&mut pt, 7);
```

```
6 set_point_x(&mut pt, 7);
```

The variable pt is an owned Point instance. The first call to set_point_x is made with a mutable reference to pt. The x variable creates a shared borrow into pt. The mutable borrow in the call to set_point_x (on line 5) is rejected by the type system because it would create a mutable reference to a Point object while an immutable reference to its x field still exists.

The Rust type system supports concrete types (such as structs, enums, and unions) and *traits*. Traits make it possible to define an interface shared across many types, optionally including default implementations for its methods. Traits are also used to declare the iterator interface in Rust, as we will see in Sec. 4.3.

2.2 Deductive verification in a Rust setting

The notion of ownership in Rust's type system is closely connected to ownership in separation logic (SL) [14]. Earlier work on the Prusti verifier [1] exploits this correspondence to automatically extract memory safety proofs in SL from Rust type and borrow information. This *core proof* contains all information to enable *framing*, that is, proving that a given heap property is not affected by a heap modification. As a result, user-specified functional annotations can be proved easily by conjoining them to the assertions of the core proof. Prusti verifies the combined program using the Viper verification framework [11].

Our verification methodology for iterators leverages Rust's ownership system in two ways. First, ownership defines the heap fragment that an iterator and its argument closures may access and modify, and prevents concurrent modifications. Second, we can focus on the essential functional properties of iterators and rely on Rust's type system for memory safety and framing, analogously to Prusti. Nevertheless, we are confident that our methodology can be combined with SL to handle languages without a built-in ownership system.

3 Methodology

In this section we introduce a general-purpose methodology for reasoning about iterators. We describe a model of iterators (\rightarrow Sec. 3.1), introduce four predicates that allow one to specify the behaviour of iterators (\rightarrow Sec. 3.2), and present the proof obligations needed to verify that an iterator implementation satisfies this specification (\rightarrow Sec. 3.3). We illustrate our methodology on two examples (\rightarrow Sec. 3.4). Finally, we summarise how our methodology addresses the challenges outlined in the introduction (\rightarrow Sec. 3.5).

3.1 Iteration model

An *iterator* can be queried repeatedly for values using a next method, producing a sequence of values (v_0, v_1, \ldots) in the diagrams below). Calls to the next method change the internal state of the iterator (I_0, I_1, \ldots) below).

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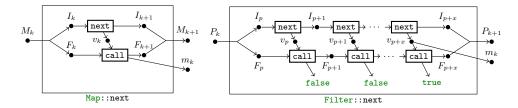
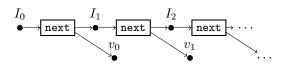
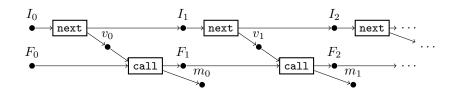


Fig. 1. State diagrams for a call to Map::next (left) and a call to Filter::next (right).



The sequence of produced values can be finite or infinite. In the former case, next yields a designated value \perp to signal that the iteration has completed³. We assume that once an iterator has completed, it will remain completed, which is the case in many programming languages. In Rust, this assumption corresponds to a so-called *fused* iterator (FusedIterator trait), and it is satisfied by the vast majority of Rust's standard library iterators.

Iterator adapters are iterators which use the results of a previous iterator to produce their values. For instance, the Map adapter applies a function \mathbf{f} to the outputs v_0, v_1, \ldots of the previous iterator to produce its result values m_0, m_1, \ldots . The function \mathbf{f} may itself be a closure with potentially mutable captured variables, which means it has its own state (F_0, F_1, \ldots) :



The overall state of the Map adapter M_i comprises (and encapsulates) the state of the previous iterator I_i and that of its argument closure F_i . Map's next method internally manipulates both state components as shown in Fig. 1 (left).

Each call to Map's next method triggers exactly one call to the predecessor's next method. Other adapters have more complex behaviours. For instance, the Filter (Fig. 1 (right)) adapter calls its predecessor's next method until the provided value satisfies the filter criterion determined by an argument closure (or the predecessor has completed) A specification and verification methodology for advanced iterators must be able to capture the evolution of such composite iterator states and the interactions between different iterators.

³ In Rust, this corresponds to an Option::None.

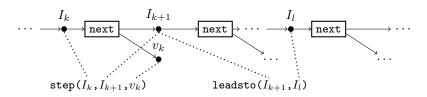
3.2 Specification components

Our methodology uses four specification components to specify the states of and values returned by iterators. We introduce them here using a mathematical notation and show a concrete syntax in Rust later, in Sec. 4.3.

As in prior work [13], we associate each iterator with two ghost (specificationonly) functions to specify the *values* returned by the iterator. Function produced yields the sequence of elements returned so far: $produced(I_k) = [v_0, v_1, \ldots, v_{k-1}]$. Function completed yields true iff the iterator has completed. In other words, a call to next with the initial state I_k returns \perp iff completed(I_k) holds.

The evolution of an iterator's *state* across a single call to next is characterised using the third component of our methodology: a two-state predicate step. For a call to next with the initial iterator state I_k , the updated iterator state I_{k+1} and the returned value v_k , step (I_k, I_{k+1}, v_k) must hold.

To reason about the *accumulated* effects of an iterator, in general concerns an *unbounded* number of **next** calls. This motivates our fourth key component: we associate each iterator with a predicate **leadsto** that represents an *inductive*, *two-state* invariant. This invariant relates the current iterator state to any previous iterator state. It represents the reflexive, transitive closure of the two-state postcondition step (which relates *consecutive* iterator states): **leadsto**(I_k, I_l) \Leftrightarrow ($\forall i \cdot k \leq i < l \Rightarrow \text{step}(I_i, I_{i+1},)$) for any $0 \leq k \leq l$.



When an iterator is used in a loop, we can naturally make use of leadsto in the loop invariant: leadsto(I_0 , I_k) must hold at every iteration, where I_0 is the state of the iterator before the loop, and I_k is the current state.

3.3 Proof obligations

To use our methodology, programmers need to define the four specification components described in the previous subsection for each concrete iterator implementation. Our methodology then imposes the following proof obligations. First, we check that leadsto includes the reflexive, transitive closure of step (see previous subsection). If this well-formedness check fails, the program is rejected. Second, we check whether the definitions of the four components correctly reflect the behaviour of the iterator implementation. This can be done by verifying that the implementation of the next method satisfies the following five postconditions. In these conditions, I_k , I_{k+1} , and v_k denote the prestate, poststate, and result value of next, respectively. For simplicity we assume that the iterator has no methods that modify its state, other than next. Compositional Reasoning for Side-effectful Iterators and Iterator Adapters

- $-Q_1 \equiv \text{step}(I_k, I_{k+1}, v_k)$: step reflects the behaviour of a single call to next.
- $-Q_2 \equiv \text{completed}(I_k) \Leftrightarrow v_k = \perp$: completed reflects correctly whether the iterator returns a value.
- $-Q_3 \equiv \text{completed}(I_k) \Rightarrow \text{produced}(I_{k+1}) = \text{produced}(I_k)$: if the iterator has completed, the produced sequence is left unchanged.
- $-Q_4 \equiv \neg \text{completed}(I_k) \Rightarrow \text{produced}(I_{k+1}) = \text{produced}(I_k) + [v_k]: \text{ if the iterator}$ has not completed, the produced sequence is extended by the returned value.
- $-Q_5 \equiv \text{completed}(I_k) \Rightarrow \text{completed}(I_{k+1})$: iterator completion is monotonic.

As usual, these postconditions may be assumed after each call to next, which allows client code to reason about the results and effects of an iterator. We show examples in the next subsection.

3.4 Examples

In this subsection, we show how to instantiate our specification components for an iterator and an iterator adapter. In both examples, we assume that the concrete iterator implementation maintains a ghost field p that contains the elements produced so far; produced is then defined to simply return p. Proof obligations Q_3 and Q_4 above ensure that the next method updates p correctly. In the definitions below, we still use mathematical notation over named states (as in our diagrams). We will define a suitable concrete specification syntax in Sec. 4.

Counter iterator. A counter iterator that yields the numbers between 0 and bound can be (partially) specified as follows. Here, **ctr** is the field of the iterator that stores the next number to return.

$$\begin{array}{ll} \forall 0 \leq k \leq l \cdot & \texttt{completed}(C_k) \triangleq C_k . \texttt{ctr} = C_k . \texttt{bound} \\ & \texttt{step}(C_k, C_{k+1}, v_k) \triangleq v_k = C_k . \texttt{ctr} \land C_k . \texttt{ctr} + 1 = C_{k+1} . \texttt{ctr} \\ & \texttt{leadsto}(C_k, C_l) \triangleq C_k . \texttt{ctr} \leq C_l . \texttt{ctr} \end{array}$$

The leadsto definition declares that the counter is monotonically increasing. Thus, even across a statically unknown number of calls (e.g. across a loop), we always know that the counter will not emit values lower than ones we have previously observed.

This specification omits various details about the returned values. To obtain a more comprehensive specification, step and leadsto need to constrain produced, for instance to express that produced[i] contains the value i. We omit the details for simplicity, but our methodology can easily express them when desired.

Map iterator adapter. As explained, a Map iterator adapter produces a value by calling a closure on the next value from the iterator it adapts. We specify

this as follows: (1) The Map iterator has completed iff the input iterator has completed. (2) Each execution of next performs a step on the input iterator and calls the map's closure on the returned value. (3) The state of the Map iterator evolves according to the specifications of the input iterator and the closure.

The following definitions reflect this intuition. As before, M_i is the state of the entire Map iterator, consisting of the state of the input iterator I_i and of the closure F_i . Note that these states include the identities of those sub-objects; that is, F_i includes the information of which closure to call, along with the values of any captured variables. In the definition of **step**, we use a *call description*, which has been proposed by Wolff et al. [16] to specify the invocation of closures. $(F_k, v_k) \rightsquigarrow (F_{k+1}, m_k)$ expresses that one call to the closure with state F_k is made with argument v_k , resulting in an updated closure state F_{k+1} and return value m_k . The changes to the closure state are constrained by the closure's *history invariant* hist_inv, a two-state invariant relating any previous closure state to any new closure state. We use this history invariant in the definition of leadsto. We will describe call descriptions in more detail in Sec. 4.1.

$$\begin{array}{ll} \forall 0 \leq k \leq l \cdot & \texttt{completed}\left(M_k\right) \triangleq \texttt{completed}\left(I_k\right) \\ & \texttt{step}(M_k, M_{k+1}, m_k) \triangleq \exists v_k \cdot \texttt{step}(I_k, I_{k+1}, v_k) \wedge \\ & \wedge (F_k, v_k) \rightsquigarrow (F_{k+1}, m_k) \\ & \texttt{leadsto}(M_k, M_l) \triangleq \texttt{leadsto}\left(I_k, I_l\right) \wedge \texttt{hist_inv}(F_k, F_l) \end{array}$$

A client that knows the concrete input iterator and closure can combine this knowledge with this specification together with the postcondition of **next** to determine the values returned by the Map iterator.

3.5 Challenges revisited

The introduction presented three main challenges for the specification and verification of advanced iterators. In this subsection we summarise how our novel methodology addresses each of them.

How to specify parameterised iterators modularly. We capture the result and effects of a single call to next using the two-state step predicate. When the iterator is parameterised with a closure (as in the Map example), we use the call descriptions from earlier work [16] as a means of abstractly and generically describing the results and effects of calls to the closure.

We capture the *accumulated* results and effects of an iteration using the **produced** sequence and the reflexive, transitive **leadsto** predicate. When the iterator state includes closures, we use two-state invariants on the *closure* state (again following Wolff et al.) to express how they evolve during an iteration.

Postconditions for the next method tie together these predicates with the concrete implementation of the iterator. They allow clients to determine the behaviour of a single call to next (using step) as well as of a full iteration (using leadsto). In particular, clients, which are aware of the concrete argument

closure passed to the iterator, can use these postconditions to determine both the sequence of returned values and all relevant accumulated side-effects (e.g. on closure-captured state).

How to reason modularly about iterator chains. To handle iterator chains, the specification of iterator adapters may refer to the step and leadsto predicates of the previous iterator in the chain. This makes the specification of the adapter *parametric* in the behaviour of the input iterator. Clients, which are aware of the concrete iterator used as input to the adapter, know how to resolve this parameterisation to obtain the concrete behaviour of the adapter. In particular, neither the input iterator nor the adapter need to be re-verified when forming an iterator chain.

How to automate verification of modern iterator and adapter patterns? As noted in Sec. 1, this challenge is addressed by encoding the methodology into first-order logic components suitable for verification with SMT-based verifiers. The four predicates defined above are encoded as uninterpreted functions, their argument states are encoded using snapshots (explained in Sec. 4.2). A suitable first-order encoding of call descriptions is provided in prior work [16].

4 Specifying individual iterators

In this section, we define a concrete Rust-like specification language for expressing the specifications required by our methodology (\rightarrow Sec. 4.1) and describe the idea of a *snapshot abstraction* to express properties of the entire state of a data structure (\rightarrow Sec. 4.2). We use the language to instantiate the methodology introduced in Sec. 3 (\rightarrow Sec. 4.3), and finally illustrate the methodology on a simple, unchained iterator (\rightarrow Sec. 4.4).

4.1 Specification language

Contracts are attached to methods using Rust attributes for each kind of specification, e.g. pre- and postconditions are annotated as follows:

```
1 #[requires(a ==> b)] // method precondition
2 #[ensures(result > 0)] // method postcondition
```

3 fn example(a: bool, b: bool) -> i32 { ... }

The expressions in parentheses after the **requires** or **ensures** keyword are side-effect-free Boolean Rust expressions, with a few (but powerful) extensions:

- Implications, represented as antecedent ==> consequent.
- Universal and existential quantifiers, represented as:
 - forall(|qvar_ident: QvarType| body_of_quantifier)
 - exists(|qvar_ident: QvarType| body_of_quantifier)
- Mathematical types, particularly GhostSeq<T>, a generic type representing a sequence of instances of type T.

- 12 A. Bílý et al.
- Logical equality, represented as lhs === rhs. This operation is distinct from the Rust equality lhs == rhs (note double equals in Rust) and represents a deep structural comparison, i.e. a comparison of all the memory reachable from each operand. Further discussion can be found in Sec. 4.2.
- Call descriptions, represented as F → |args...| { pre } { post }. This expression states that a call to the method F has happened, the assertion pre held in the prestate of that call, the assertion post held in the poststate, and the arguments of the call are bound to the names args... and the return value to a reserved name result in the assertions pre and post. The specific case of a closure call is a call to the method FnMut::call_mut, with the closure state constrained using the pre- and poststate assertions. Similarly, the use of an iterator is a call to the method Iterator::next. This notation is based on prior work on closure verification [16].

Ghost functions are functions used only from within specifications and are also allowed to use the extended expression syntax:

```
1 fn all_false(x: GhostSeq<bool>) -> bool {
2     forall(|idx: usize| 0 <= idx && idx < x.len() ==> !x[idx])
3 }
```

4.2 Abstract data structure states

Specifications in our methodology concern properties of the *state* of a data structure such as an iterator, a closure, or the values returned by an iterator. For instance, **produced** needs to contain the values returned during an iteration. Moreover, **step** and **leadsto** typically compare states of data structures, and there are examples that need to quantify over the states of data structures, for example, to express the effects of multiple closure calls. In all of these cases, the meanings of our specifications need to refer to the entire current state of a data structure in memory (such as an iterator), not just its identity.

To enable such specifications, we introduce a canonical abstraction of each data structure that captures its structure and values, but abstracts away concrete addresses. We refer to the abstract value of a data structure as its *snapshot*. Since data structures in (safe) Rust are always tree-shaped, a snapshot can be represented easily as terms of a (mathematical) abstract data type. For instance, the snapshot of a Point object (Sec. 2.1) is a mathematical tuple of two integers.

It is common for separation logic specifications to relate the memory reachable from a given program expression to a user-defined abstract value using (possibly recursive) predicate definitions [12]. Our snapshots are similar to these abstract values, but the abstraction is derived automatically from the declarations of types and fields.

Snapshots allow our specifications to conveniently express properties of entire states of data structures. For instance, logical equality (===) is simply a comparison of two snapshots. Similarly, function produced yields a snapshot that includes the snapshots of all values returned by the iterator so far. Snapshots also allow

cleanly integrating state-dependent properties with logical features such as quantifiers and mathematical functions. For example, in Prusti [1], following Smans et al. [15], ghost functions which operate on Rust data are transparently encoded to mathematical functions which operate on snapshots. The same approach has been applied to encoding quantifiers and call descriptions [16], as used in our work (instead of quantifying over expressions in different states, one quantifies over their snapshots as mathematical values).

A (possibly surprising) consequence of the snapshot interpretation of our specifications is that a ghost function can take parameters that represent multiple versions of the *same* data structure, which is not directly possible in actual Rust code. This allows us to encode two-state predicates such as **step** and **leadsto** as standard ghost functions that take two snapshots as arguments, representing the iterator state *at different points* in the program execution.

Since snapshots are simply terms of a mathematical data type, they have a straightforward encoding into SMT, which partly addresses the automation challenge mentioned in the introduction. In fact, several automated program verifiers employ similar notions of snapshots internally in their encodings, for instance, Smallfoot [15], VeriFast [7], and Viper [11].

4.3 Defining the specification components

In Rust, iterators are types which implement the Iterator trait. This is achieved with an explicit syntactic declaration (impl Iterator for SomeType) which also declares the element type and provides the definition of one required method: next. The implementation of this method can modify the current state of the iterator and must output an Option which may contain the next element, or it may be None to signal completion. The Iterator trait defines a large number of other methods, such as map or filter; these all have default implementations, which are inherited into any concrete iterator.

Conceptually, we can represent the four key components of our iterator specifications (see Sec. 3.2) as ghost functions of the **Iterator** trait. Because we provide no default implementations, every concrete iterator would then need to provide definitions for these functions. Our implementation uses an alternative approach that does not require any changes to functions declared in the **Iterator** trait, see Sec. 6.

```
1 trait Iterator {
2  fn produced(&self) -> GhostSeq<Self::Item>;
3  fn step(i_p: &Self, i_c: &Self, r: &Option<Self::Item>) -> bool;
4  fn leadsto(i_p: &Self, i_c: &Self) -> bool;
5  fn completed(&self) -> bool;
6  // other Iterator methods
7 }
```

The produced method is a getter⁴ for a ghost sequence of values. The twostate predicates step and leadsto takes references to two copies (a previous

⁴ Traits in Rust cannot declare fields or properties, thus we must use a getter method.

version and a current version) of the iterator type. step additionally takes a reference to the returned value, represented in Rust as an Option to allow for None to signal the end of iteration. As noted in Sec. 4.2, it is possible to give the two-state predicates step and leadsto different versions of the same instance using snapshots. Finally, completed defines the stopping condition. Since these methods are ghost code, we allow them to use non-executable constructs such as quantifiers in their definitions in implementations of the Iterator trait.

Finally, we express the proof obligations from Sec. 3 as postconditions of the next method, which must be satisfied by each implementation of next. Here, &result denotes a shared reference to the value returned by the method.

```
trait Iterator {
1
   (Q1) #[ensures(IteratorSpec::step(old(&self), &self, &result))]
2
   (Q<sub>2</sub>) #[ensures(old(self.completed()) == (result === None))]
3
       #[ensures(old(self.completed()) ==> (
   (Q_3)
4
            self.produced() === old(self.produced())
\mathbf{5}
        ))]
 6
   (Q_4) #[ensures(!old(self.completed()) ==> (
 7
               result === Some(self.produced().last())
 8
            && self.produced().len() == old(self.produced().len()) + 1
9
            && GhostSeq::prefix(old(self.produced()), self.produced())
10
11
        ))]
   (Q<sub>5</sub>) #[ensures(old(self.completed()) ==> self.completed())]
12
        fn next(&mut self) -> Option<Self::Item>;
13
14
        11
15
   }
```

This specification uses logical equality ===, described in Sec. 4.1. Using == would require a PartialEq trait-bound on the iterator's elements, restricting its interface (not all iterators' elements need have a Rust definition of equality).

4.4 Example

We illustrate our methodology by specifying a simple iterator returning a range of consecutive numbers. In Rust, we can define such an iterator like this:

```
struct Counter { (A)
1
       pos: i32.
2
3
        end: i32,
   }
4
   impl Counter {
 \mathbf{5}
        #[ensures(Iterator::leadsto(&result, &result))]
 6
        fn new(end: i32) -> Self { ... } (B)
7
   }
8
   impl Iterator for Counter { (C)
9
       type Item = i32; (D)
10
       fn next(&mut self) -> Option<Self::Item> { (E)
11
            if self.pos <= self.end {</pre>
12
13
                self.pos += 1;
14
                Some(self.pos - 1)
            } else {
15
                None
16
```

15

17 } 18 } 19 // ... 20 }

The code above first (A) defines a type which represents our iterator. Its state contains two variables: its current position and its stopping point. (B) defines a convenience constructor for the counter, which must ensure that the two-state invariant leadsto is (reflexively) satisfied to begin with. (C) is the declaration that marks Counter to be an iterator, consisting of a declaration of the type of elements emitted by this iterator (D), and an implementation of the next method (E). The latter checks if the limit has been reached yet: if so, no more items are emitted (as signalled by a None return value), otherwise the internal position is updated and its old value is returned (wrapped in a Some to distinguish it from the previous case).

To specify this iterator, we provide definitions of the four ghost methods declared in the **Iterator** trait, starting with completed:

```
1 fn completed(&self) -> bool {
2    !(self.pos <= self.end)
3 }</pre>
```

This definition is sufficient to show that a counter with a non-empty range will return at least one value:

```
1 let mut counter = Counter::new(2);
2 assert!(counter.next().is_some());
```

The two-state postcondition step defines how the state is updated. Here, i_p and i_p refer to the iterator snapshot before and after the execution of next:

This definition is sufficient to prove assertions in a non-looping client:

```
1 let mut counter = Counter::new(1);
2 assert!(counter.next().unwrap() == 0);
3 assert!(counter.next().unwrap() == 1);
4 assert!(counter.next().is_none());
```

Note that the conjunct (A) would follow from knowledge about the produced sequence, and the conjuncts (B) are actually stating an invariant that is true between any two states of the counter, not just consecutive ones. We can thus simplify the definition of step and provide a definition of leadsto:

```
1 fn step(i_p: &Self, i_c: &Self, r: &Option<Self::Item>) -> bool {
2     !i_p.completed() ==> (i_c.pos == i_p.pos + 1)
3  }
4 fn leadsto(i_p: &Self, i_c: &Self) -> bool {
```

5	\bigcirc i_p.end == i_c.end
6	<pre>D && i_p.pos <= i_c.pos</pre>
7	(E) && 0 <= i_c.pos && i_c.pos <= i_c.end + 1
8	(F) && i_c.produced().len() == i_c.pos as usize
9	G && forall(x: i32 0 <= x && x < i_c.pos ==>
10	<pre>i_c.produced()[x as usize] == x)</pre>
11	}

In this definition, \bigcirc end remains constant. \bigcirc pos is monotonically increasing, and E it remains within bounds. F the number of produced elements is given by the difference between the current position and the lower bound. Finally, G the value of every produced element can be defined by its position in the sequence.

The advantage of this more verbose definition is that Counter can be used across unboundedly many calls, such as in a loop:

```
1 let mut counter = Counter::new(90);
2 let val_pre = counter.next().unwrap();
3 assume!(n < 80);
4 for i in 0..n {
5 counter.next().unwrap();
6 }
7 assert!(counter.next().unwrap() > val_pre);
```

At this point we have specified a simple iterator. We have used all four of the methodology components we defined in Sec. 3. Although the approach is relatively heavy for Counter (the definition of leadsto in particular), we will shortly see it pays off when considering more advanced (and idiomatic) cases. A similar specification can be used for iterating over a slice or Vec.

5 Specifying iterator chains

In this section, we gradually introduce our technical solutions to the second challenge described in Sec. 1: modular reasoning about iterator chains. To introduce iterator adapters in Rust, we specify a simple doubling iterator adapter (\rightarrow Sec. 5.1). Approaching the real Map type from the standard library, we specify an adapter with side-effectful closures (\rightarrow Sec. 5.2). For the real Map specification, we also need to account for transitive side effects, i.e. side effects of any nested iterators (\rightarrow Sec. 5.3).

5.1 Simple iterator adapters

In Rust, iterator adapters are types which wrap an instance of the Iterator trait while implementing the Iterator trait themselves. When the adapter's next method is invoked, it calls the previous iterator's next method some number of times, adapting its result. As an example, the Map adapter applies a closure to every element produced by the previous iterator, while the Filter adapter uses a closure as a logical predicate to decide whether each value from the previous iterator should be returned or not.

The Rust standard library provides many such iterator adapters for a variety of common use cases. The iterator chain in the code example shown in Sec. 1 is actually composed of iterator adapters, albeit hidden behind some convenience syntax (e.g. x.map(...) wraps the iterator x in a Map adapter).

As stated before, our goal is to write single, generic specifications, that apply regardless of the exact iterator that precedes the adapter in the chain or any specific closure parameters. We first show that we can specify simple adapters by characterising their produced sequence in terms of the produced sequence of the previous iterator. For example, consider the following Double iterator adapter which simply doubles the values coming from the previous iterator:

```
struct Double<I (A)> {
1
       prev_iter: I, B
^{2}
  }
3
  impl<I: Iterator<Item = i32>> Iterator for Double<I> {
4
       type Item = i32;
\mathbf{5}
       fn next(&mut self) -> Option<Self::Item> {
6
            self.prev_iter.next().map(|v| v * 2) (C)
\overline{7}
8
       }
  }
9
```

This iterator adapter is able to adapt any iterator type that yields integers. It thus has a type parameter A, which stands for the type of the previous iterator. To be able to refer and mutate the previous iterator, the struct contains (or *owns*) the previous iterator B. Finally, we implement the **Iterator** trait for **Double** with a straightforward mapping⁵ of values C.

We omit the straightforward definition of step. A possible (abridged) definition of leadsto and completed is:

```
1 fn leadsto(i_p: &Self, i_c: &Self) -> bool {
   (\mathbf{A})
          i_c.produced().len() == i_c.prev_iter.produced().len()
2
   (B)
3
      && forall(|idx: usize| idx < i_c.produced().len() ==>
4
           i_c.produced()[idx] == i_c.prev_iter.produced()[idx] * 2)
\mathbf{5}
  }
  fn completed(&self) -> bool {
6
\overline{7}
   (C) self.prev_iter.completed()
8
  }
```

In the definition of leadsto, we (A) state that the length of the produced sequence of the previous iterator and the adapter Double is the same, and we (B) use a quantifier to relate each element. We also (\bigcirc) re-use the previous iterator's stopping criterion. This definition is sufficient to verify properties of the values produced when Double is used over an iterator (such as the previously defined Counter):

```
1 let counter = Counter::new(2);
2 let mut double_iter = Double::new(counter);
3 assert!(double_iter.next().unwrap() == 0);
4 assert!(double_iter.next().unwrap() == 2);
```

⁵ The map method on an Option type applies the given closure on the value contained in a Some, but leaves None intact.

```
18 A. Bílý et al.
5 assert!(double_iter.next().unwrap() == 4);
6 assert!(double_iter.next().is_none());
```

The contract of next implies that if a Some result is obtained, produced was extended by one element. For each of the first three calls to next the verifier thus learns about a new element of this sequence, the value of which is related to the corresponding element of the previous iterator's produced sequence. This establishes a concrete relationship between the elements yielded by Counter and those yielded by Double, sufficient to imply all asserted properties about these resulting values.

5.2 Side-effectful closures in adapters

Although Double is indeed an iterator adapter, it is rather simple. The action it performs is functionally a fixed one-to-one *mapping* of values. The Map iterator adapter performs exactly this action, but let's the user supply the function to be applied. To this end, the Map type has two type parameters: one to represent the previous iterator in the chain and one to represent the closure⁶:

```
1 struct Map<I, F> {
2    prev_iter: I, // the wrapped iterator
3    f: F, // the closure parameter
4 }
```

When mapping values from the previous iterator, Map invokes the closure:

```
1 fn next(&mut self) -> Option<Self::Item> {
2    self.prev_iter.next().map(&mut self.f)
3 }
```

To provide a generic specification of Map, we must account for the side effects of the closure call, even when the exact type of the closure is unknown; this property of side effects on the *closure*'s mutable state cannot be captured using the **produced** sequences alone. Instead, we use a call description to connect the effect of an iteration step to the effects of a call to the closure itself:

```
fn step(i_p: &Self, i_c: &Self, r: &Option<Self::Item>) -> bool {
1
^{2}
   (A) !i_p.prev_iter.completed() ==>
        (B) FnMut::call_mut → |cl_self, arg|
3
             (\mathbf{C})
                       i_p.f === cl_self
                 {
4
             (\tilde{D})
                    && arg === i_c.prev_iter.produced().last() }
\mathbf{5}
             (E)
                       i_c.f === cl_self
                 {
6
             (\mathbf{F})
                   && r === Some(result) })
7
8
   }
```

For each step we know (if the previous iterator has not completed yet A) that B there is a call to the closure, with C the original state of the closure stored in field f of the original state of Map, and E the new state of the closure stored in field f of the new state of Map. For the call, D the argument given to the

⁶ The actual declaration has a third type parameter to represent the return type of the closure, omitted here for brevity.

19

closure is the last element yielded by the previous iterator, and (F) the element yielded by Map (r) is the result of the closure (Some(result)).

This definition of step allows us to verify the *side effects* of individual calls to next on the corresponding closure's *captured state*:

```
1 let counter = Counter::new(2);
2 let mut sum = 0;
3 let cl = #[ensures(sum == old(sum) + arg && result == arg * 2)]
4 |arg| { sum += arg; arg * 2 };
5 let mut map_iter = Map::new(counter, cl);
6 assert!(map_iter.next().unwrap() == 0);
7 assert!(map_iter.next().unwrap() == 2);
8 assert!(sum == 1);
```

The final assertion (after map_iter and cl expire) follows from the call description describing the call Map makes to the closure, which establishes the postcondition of the concrete closure known concretely in this client code⁷.

5.3 Multiple adapters

The Map specification in the previous subsection refers to the values produced by the previous iterator, but does not account for changes to its state. To address *transitive* side effects of next calls (i.e. those on closures earlier in the iterator chain), we must directly capture information about the calls to the previous iterator. Our call description feature can also be used to describe this necessary connection, this time relating each change to the current iterator to the corresponding pre- and poststate of a call to next on the *previous* iterator, all the while keeping the specification generic with respect to the previous iterator's type. The following definition of step exemplifies this powerful idiom, using two nested call descriptions:

```
fn step(i_p: &Self, i_c: &Self, map_res: &Option<Self::Item>) -> bool {
 1
    (A) Iterator::next → |it_self|
 2
         B { i_p.prev_iter === it_self }
 3
         (C) { let prev_iter_res = result;
 4
         (\overline{D})
 \mathbf{5}
                   i_c.prev_iter === it_self
         (\widetilde{\mathbf{E}})
 6
               && (prev_iter_res.is_some() ==>
              (F) FnMut::call_mut \rightsquigarrow |cl_self, arg|
 \overline{7}
                       i_p.f === cl_self
                  ſ
 8
                    && Some(arg) === prev_iter_res }
 9
                  {
                       i_c.f === cl_self
10
                    && map_res === Some(result) } )
11
         (G)
               && prev_iter_res.is_none() ==> map_res.is_none() }
12
13 }
```

In this version of step, we begin by (A) describing that a call to the previous iterator *will happen*, where ((B)) the original state of the previous iterator is stored in field prev_iter of the original state of the Map iterator, and (D) the

⁷ We assume the closures themselves to be annotated with standard pre/postcondition specifications; for simple closures such as this one, the required specifications could be inferred by a static analysis, but this is orthogonal to our presented technique.

new state of the previous iterator is as stored in field prev_iter of the resulting state of Map. To avoid confusion, we ⓒ used a let expression to name the result of the previous iterator prev_iter_res; the result returned from the Map is map_res. ⓒ If the previous iterator returned an element, we ⓒ describe how this relates a call to the closure, as before. ⓒ Otherwise, no element is returned from the Map iterator either.

The overall structure of this definition of step mirrors the Map model presented in Fig. 1 (left): each call description corresponds to one box in the diagram, and values from the previous iterator flow through the closure.

With the richer specifications, we can prove facts about transitive side effects:

```
1 let counter = Counter::new(2);
2 let mut sum = 0;
3 let cl_1 = #[ensures(sum == old(sum) + arg && result == arg + 1)]
4 |arg| { sum += arg; arg * 2 };
5 let map_iter_1 = Map::new(counter, cl_1);
6 let cl_2 = #[ensures(result == arg * 2)] |arg| arg * 2;
7 let mut map_iter_2 = Map::new(map_iter_1, cl_2);
8 assert!(map_iter_2.next().unwrap() == 2);
9 assert!(sum == 0);
```

The final assertion requires that the knowledge about the effect of cl_1 on its captured variable is propagated through the invocation of map_iter_1, which happens inside map_iter_2. Note that the specification is the same for both Map iterators, and that map_iter_2 in particular cannot even know that the previous iterator in the chain is related to a closure.

Finally, reasoning about *unboundedly many iteration steps* (e.g. when calling **next** in a loop), simply requires us to suitably define **leadsto** for Map. To store the intermediate states of the closures and the iterators, we add a ghost sequence field **st**: **GhostSeq**<(**F**, **I**)> to Map, where every element is a tuple containing a closure state and an iterator state.

```
fn leadsto(i_p: &Self, i_c: &Self) -> bool {
 1
           i_c.produced().len() == i_c.prev_iter.produced().len()
2
   (A) && i_p.st.is_prefix_of(i_c.st)
3
   (B) && i_c.st.len() == i_c.produced().len() + 1
 4
   (C) && i_c.st.last() === (i_c.f, i_c.prev_iter)
 5
       && forall(|idx: usize| idx < i_c.produced().len() ==>
 6
        (D) I::next \rightsquigarrow |iter_self|
 7
                {
                    i_c.st[idx].1 === iter_self }
 8
                     i_c.st[idx + 1].1 === iter_self
 9
                {
                  && result === Some(i_c.prev_iter.produced()[idx])
10
                  && FnMut::call_mut ~>> |cl_self, arg|
11
                              i_c.st[idx].0 === cl_self
                         {
12
                            && arg === i_c.prev_iter.produced()[idx] }
13
14
                         ſ
                              i_c.st[idx + 1].0 === cl_self
                            && result === i_c.produced()[idx] }})
15
16
  }
```

In this definition of leadsto, we establish a connection between the ghost sequence st and the concrete data stored in the Map struct. In particular, ^(B) states there are as many intermediate states as there are yielded elements, plus

one for the current state. \bigcirc The last tuple in the st sequence corresponds to the current data stored in Map. For each yielded element \bigcirc we re-use our nested call descriptions to establish the connection between consecutive intermediate states. We also A state that the state sequence is expanded monotonically, i.e. the intermediate states in any previous version of Map are a prefix of the intermediate states of any newer version of Map.

Equipped with such a specification, we can prove code which uses a Map parameterised by a closure with captured state, applied to an unbounded number of elements, such as this vector summation:

```
1 #[ensures(result == GhostSeq::of_vec(&vec).sum())]
2 fn sum_vec(vec: Vec<i32>) -> i32 {
       let vec_vals = GhostSeq::of_vec(&vec);
3
        // ghost state of closure
4
       let mut pos = Ousize;
 \mathbf{5}
 6
       let mut sum = 0;
\overline{7}
        // summation closure
 8
9
       let cl = #[requires(pos < vec_vals.len() && x == vec_vals[pos])]</pre>
                 #[ensures(pos == old(pos) + 1 && ret == sum)]
10
                 #[invariant( 0 <= pos && pos <= vec_vals.len()</pre>
11
                              && sum == vec_vals[0..pos].sum())]
12
                  |x| { sum += x; pos += 1; sum };
13
^{14}
15
        // iterate values of vector
       let mut map_iter = vec.into_iter().map(cl);
16
        #[invariant(pos == map.prev_iter.pos)]
17
       for el in map_iter {}
18
19
20
        sum
21 }
```

In this example, leadsto is maintained for map_iter throughout the loop, which also implies the closure history invariant. Once the loop exits, it is known that the position of the vector iterator reached the end of the vector, and so sum == vec_vals[0..pos].sum() collapses to sum == vec_vals.sum().

6 Out-of-band contracts

So far, we assumed that Rust traits, including those from the standard library, can be extended with additional methods. To avoid such changes to existing code, Spec# proposed *out-of-band contracts* as a mechanism to attach specifications to libraries. In this section, we present a refined notion of out-of-band contracts that allow one to attach contracts *conditionally*, depending on whether a type implements a trait.

6.1 Specification extension traits

Instead of changing Rust's **Iterator** trait, we declare the four (specification-only) methods of our methodology in a new trait:

```
A. Bílý et al.
trait IteratorSpec : Iterator { A
fn produced(&self) -> GhostSeq<Self::Item B>;
fn leadsto(i_p: &Self, i_c: &Self) -> bool;
fn step(i_p: &Self, i_c: &Self,
r: &Option<Self::Item C)> -> bool;
fn completed(&self) -> bool;
```

In the above, we (A) declare IteratorSpec and use Iterator as its super-trait. This means that any type that implements IteratorSpec must also implement Iterator. Apart from declaring the same methods we have already seen before, one notable feature is (B), (C) re-using the associated type Item from the Iterator supertrait, such that the implementation of IteratorSpec does not need to repeat the element type that is already declared in Iterator.

Declaring methodology components in traits should be familiar to Rust programmers because they represent a shared behaviour. Like regular traits, any given implementation of IteratorSpec can define these methods to specify concrete iterators.

In our implementation, the method declarations in IteratorSpec are additionally annotated with either #[predicate] or #[pure]. Both annotations indicate that the given method is usable in specifications, and #[predicate] additionally allows the use of non-executable features such as quantifiers.

6.2 Type-dependent contracts

The specification extension trait IteratorSpec allows us to remove the four function declarations from the Iterator trait, but does not provide a way to express the postconditions of the next method (Rust does not allow a sub-trait to override methods of a super-trait). To provide a specification for next without changing the Iterator trait, we use an out-of-band contract for the trait, that is, a specification provided in a separate file. For example, we could (erroneously) specify Iterator::next to always return a result:

```
1 #[extern_spec] // out-of-band contract
2 trait Iterator {
3     #[ensures(result.is_some())]
4     fn next(&mut self) -> Option<Self::Item>;
5 }
```

However, such an extern spec for Iterator cannot use the methods from IteratorSpec, because not every implementation of Iterator also implements IteratorSpec. To solve this issue, we introduce type-dependent contracts, that is, contracts that apply *only* to implementations of a given trait. The following extern spec for Iterator uses this feature to impose postconditions on next *only* for implementations that also implement IteratorSpec:

```
1 #[extern_spec]
2 trait Iterator {
3 #[type_dependent(Self: IteratorSpec, [ B
4 Q1 ensures(IteratorSpec::step(old(&self), &self, &result)),
```

```
ensures(old(self.completed() == (result === None))),
        (Q_2)
        (Q_3)
            ensures(old(self.completed()) ==> (
 6
7
                self.produced() === old(self.produced())
8
            )),
9
        (Q_4) ensures(!old(self.completed()) ==> (
                   result === Some(self.produced().last())
10
                && self.produced().len() == old(self.produced().len()) + 1
11
                && GhostSeq::prefix(old(self.produced()), self.produced())
12
            )),
13
        (Q<sub>5</sub>) ensures(old(self.completed()) ==> self.completed()),
14
15
        1)1
        fn next(&mut self) -> Option<Self::Item>;
16
17
   }
```

As before, (A) an extern spec is added to the **Iterator** trait. The (B) **type_dependent** attribute introduces postconditions $(Q_1) - (Q_5)$ only for implementations that also implement **IteratorSpec**. As a result, it is allowed to refer to methods of **IteratorSpec**, e.g. to call self.completed().

Note that the type-dependent contract is defined on the type *being extended*, i.e. it is part of the specification of **Iterator::next**, not part of the specification extension trait **IteratorSpec**. This decision is motivated by Rust's *coherence* rules.

To ensure that our type-dependent contracts are sound, we require that any type-dependent contract refines its base contract. This consists of the usual *behavioural subtyping* checks: the precondition must be weakened and the postcondition must be strengthened.

7 Soundness

Our methodology builds on standard techniques to reason about method implementations and calls, and on call descriptions to reason about closure calls [16]. Consequently, its soundness relies on a sound verification technique for these features. Such techniques support two-state postconditions such as our step predicate (typically expressed via logical variables or old-expressions), which are checked for each method implementation and assumed for each call.

The only non-standard component of our methodology is the leadsto predicate, which may be assumed between any two iterator states occurring during an iteration. If next is the only method mutating the iterator state, this assumption is justified by the fact that each call to next satisfies step, and leadsto includes the reflexive, transitive closure of step. Consequently, leadsto holds between two iterator states, no matter how many calls to next occur between those states.

If the iterator state may be modified by methods other than next, one can interpret leadsto as a standard two-state invariant on the iterator type. Such an invariant must be maintained by all mutating methods, such that the above inductive argument applies.

Test (implementation	n) LoS	LoC	VT (s)	Test (client code)	LoS	LoC
counter	32	30	9.53	counter	0	14
double	43	25	9.95	double	1	6
filter.vpr	90*	109*	18.24^{*}	filter.vpr	10^{*}	27^{*}
map	67	38	42.12	map	14	22
option_intoiter	36	19	7.41	option_intoiter	0	4
vec_intoiter	42	13	7.05	vec_intoiter	4	19
zip	79	32	84.46	zip	2	6

Table 1. Evaluation. LoS and LoC represent the line of specifications and lines of code, respectively. VT represents the verification time, measured as the wall-clock runtime averaged over 7 runs using an Intel Core i9-10885H 2.40GHz CPU with 16 GiB of RAM, excluding the slowest and fastest runs. Test cases ending in .vpr were encoded manually into Viper: our methodology supports these test cases, but issues in the underlying Prusti tool (independent from the contributions of this paper) currently prevent our implementation from supporting the analogous examples in Rust. These Viper encoded examples are more verbose and run through a simpler tool chain; for these reasons we mark the data with *s in the tables here.

8 Evaluation

We implemented our technique as a prototype extension to the Prusti verifier [1]. Following the design laid out in Sec. 4.1, our iterator methodology is implemented primarily in user-facing Rust code (which can be packaged into a standard library of specifications) and not as an *ad hoc* feature of Prusti.

To enable annotating key standard library types, we added support for declaring external specifications for trait types as well as for our novel type-dependent contracts. Most other extensions were routine; this suggests that layering our methodology onto existing tools is fairly lightweight. Due to this lightweight integration, we don't treat leadsto as a built-in type invariant, but rather as a postcondition on next; intended properties such as transitivity are therefore not checked by default (but proofs relying on them would of course fail otherwise).

We evaluated our work on a number of challenging test cases, modelling various combinations of idiomatic iterators found in the Rust standard library, as well as custom iterator implementations discussed in this paper. The results of our evaluation are shown in Table 1 (in terms of lines of specification, code and verification times). Generally, the specification overhead is heavier (roughly oneto-one with code) for the generic library functions such as Map, but these specifications need only be written once. Importantly, for client code *using* these iterators, the specification overhead is typically lighter. A substantial body (roughly 340 LoC) of common specifications were also necessary as our implementation neither builds in pre-defined support for common types such as Option, or our new **GhostSeq** type. These specifications need only be written once can could in principle be added as a "standard library" of specifications. We consider the verification times using our prototype implementation to be generally reasonable,

25

but with some expensive outliers; we suspect that these require some additional effort to control quantifier instantiation in the underlying solver [2].

9 Related work

The two works most closely related to this paper (Pereira et al. [13] and Wolff et al. [16]) were already discussed in detail in Sec. 1.

One of the first formulations of the challenges of specifying and verifying iterators appeared in the 2006 SAVCBS workshop [5] (although the problem has been studied for longer), which posed the research question in the context of Java/C# collections and iterators over such collections. Various papers were submitted as solutions to the challenge: Jacobs [6] focuses on C# iterators, which are suspendable functions that can "yield" values to a consumer. The iteration itself is characterised by invariants over the sequence of produced values, similarly to Pereira [13]. C# iterators are analogous to Rust generators (or "coroutines") which can be turned into an Iterator instance⁸. Although Prusti does not yet support Rust generators, our methodology should apply to this case as well: the state of an iterator would become the state of the generator and the leadsto two-state type invariant would be maintained over the generator.

Krishnaswami [9] proposed specifications for Java-like iterators in a higherorder separation logic. The application of separation logic facilitates proofs of memory safety, and prevents concurrent modifications of a collection while an iterator over it exists. However, functional specifications are left as abstract higher-order predicates, which are problematic for automation.

Creusot [3] is another Rust verifier. Its prophetic approach to encoding Rust references simplifies the specification of some reborrowing patterns, which means the signature of traits such as IterMut are supported, unlike in Prusti at the time of writing. Creusot's public tests include functional specifications based on the Pereira methodology (both tools are based on Why3). If the contributions of this paper were adapted to Creusot, we believe it would be possible to specify richer properties of side-effectful iterator chains in this tool as well, as enabled by our novel methodology. More generally, our technique is largely agnostic as to the underlying verifier and its handling of e.g. the program memory, provided that our snapshot interpretation of specifications can be appropriately supported.

10 Conclusion

We have presented a novel methodology for modularly specifying and verifying the complex iterator patterns found in modern programming languages. This methodology is designed to be compatible with basic techniques for reasoning

⁸ Since generators and asynchronous code in Rust is still unstable in general, such adaptation is not yet part of the standard library. It is possible with relatively little boilerplate code, see https://stackoverflow.com/questions/16421033.

about side-effectful programs, such as Rust's ownership system and formal techniques such as separation logic; the underlying technical requirements are commonly found in many deductive verifiers. We have evaluated our methodology in Rust, which has rich iterator support in its standard library, as well as a type system which can be used to automatically take care of these ownership requirements. Applying our methodology in languages without such a type system would require specifications to govern side-effects, but the adaptation of our novel methodology would nonetheless be straightforward.

To ensure our methodology is usable in real-world codebases and integrates well with other verification efforts, we have prioritised modularity in our extension to the state-of-the-art Rust verifier Prusti. To this end, we have introduced novel type-dependent contracts, which, combined with specification extension traits, allow specifying standard-library iterators without modifying the source code of the standard library itself.

27

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