

Resource Specifications for Resource-Manipulating Programs

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Specifications for modular program verifiers are expressed as constraints on program states (e.g. preconditions) and relations on program states (e.g. postconditions). For programs whose domain is managing *resources* of any kind (e.g. cryptocurrencies), such state-based specifications must make explicit properties that a human would implicitly understand for free. For example, it's clear that depositing into your bank account will not change other balances, but classically this must be stated as a *frame condition*. As a result, specifications for resource-manipulating programs quickly become verbose and difficult to interpret, write and debug.

In this paper, we present a novel methodology that introduces user-defined first-class resources in the specification language, allowing resource-related operations and properties to be expressed directly and eliminating the need to reify implicit knowledge in the specifications. We implement our methodology as an extension of the program verifier Prusti, and use it to verify a key part of a real-world blockchain application. As we demonstrate in our evaluation, specifications written with our methodology are more concise, syntactically simpler, and easier to understand than alternative specifications written purely in terms of program states.

1 INTRODUCTION

The goal of program verification is to ensure that a program will always operate in accordance with a formal specification. In practice, this requires encoding the desired properties in the specification language of a program verifier that will be used to check conformance to such properties. The difference between our intuitive, human language description of desired properties and their representation in the specification language is called the *semantic gap* [Hein 2010]. The larger this gap is in practice, the more difficult it becomes to write, read, maintain, and debug specifications.

In modular program verifiers, specifications are written and checked for each function separately. Specification preconditions describe requirements on the program state at function call sites, and postconditions describe the corresponding guarantees about the program state at return sites; the verifier reasons about function calls with respect to these specifications rather than the function's implementation. For example, the specification for a function `sort()` that sorts a list in-place could be written as an expression relating the values of the input list both before and after the call; namely, stating that the latter should be a sorted version of the former. This design effectively minimises the semantic gap for properties naturally expressed as relations on program states, such as sortedness.

However, properties about programs that manipulate resources, such as money, are more challenging to specify correctly in this manner. For example, in a banking application, one might consider describing the effect of a function `deposit(acct_id, amt)`, using a postcondition:

```
#[ensures(balance(acct_id) == old(balance(acct_id)) + amt)]
```

which specifies that after calling `deposit()` the balance for `acct_id` will have increased appropriately. However, this specification misses an important property: the balance of all *other* accounts

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in the bank must remain *unchanged* after the call. To address this, it is necessary to add a *frame condition* [McCarthy and Hayes 1981] to the specification, resulting in the postcondition:

```
#[ensures(balance(acct_id) == old(balance(acct_id)) + amt) &&
  forall(|a_id: AcctId| a_id != acct_id ==> balance(a_id) == old(balance(a_id)))]
```

This specification is longer and more complicated; most of the complexity stems from describing what’s *unchanged* by `deposit()` (this extra complexity grows rapidly for more complicated functions). But in terms of an intuitive understanding of bank deposits, this property simply doesn’t *need* to be stated: it’s obvious to humans that depositing money into one account will not change other balances. This suggests a wide semantic gap between the way we think about resources in the real-world, and what can be expressed in classical techniques for formal specification.

In this paper, we present a novel specification methodology that narrows this gap by introducing custom resources and a language of resource properties and operations as *first-class elements* of our specification language. Our methodology allows resource-related properties to be expressed directly, and eliminates the need to reify properties that are implicit in our intuitive understanding of resources, while building in ubiquitous properties by default, e.g. that the amount of a resource should remain constant unless explicitly created or destroyed.

The usage of our custom resources in specification methodology is an abstraction decoupled from the underlying program representations of these notions. However, our technique allows *coupling invariants* to be defined, specifying once and for all the mapping between abstract resource notions and concrete program states. Specifications per function can be written concisely and more simply using resource abstractions, and the coupling invariants automatically and implicitly entail the right proof obligations concerning changes to and constraints on concrete program states.

Our paper makes the following main contributions:

- (1) We demonstrate the typical problems that arise when writing specifications of resource-manipulating programs in terms of program states (Sec. 2)
- (2) We present a methodology to solve these problems using first-class resources (Sec. 3)
- (3) We implement our methodology, extending the Prusti verifier [Astrauskas et al. 2019] (Sec. 4)
- (4) As a case study, we apply our methodology and implementation to verify a key component of a real-world Rust implementation of a cross-chain token transfer protocol (Sec. 5)
- (5) We perform a comparative evaluation of our methodology, showing that it enables users to write shorter and simpler specifications for resource-manipulating programs (Sec. 6)

2 MOTIVATION

To motivate our methodology, we first present the challenges that arise when writing specifications for a resource-manipulating program. Throughout this section, we consider a Rust implementation of a multi-account bank that stores (dollar) balances, shown in Fig. 1. The struct `Bank` manages the balances for multiple accounts in the field `map`, each account is identified by a corresponding `AcctId`. Clients of the `Bank` cannot access `map` directly; they interact with the `Bank` object via the functions `balance()`, `deposit()`, and `withdraw()`, within the `impl Bank { ... }` block.

These functions take as first parameter a reference to the `Bank` instance. The syntax `&self` indicates a Rust *shared reference*, with which the `balance` function cannot modify the `Bank`, while a *mutable reference* such as the `&mut self` parameter of the other functions allows modifications. A `Bank` stores account balances in a `U32Map` that maps account identifiers to `u32` values. The `balance()` function looks up an account identifier in the map, returning `0` if there is no entry. The functions `deposit()` and `withdraw()` update the map, overwriting any existing entry.

```

1 struct Bank { map: U32Map<AcctId> };
2 impl Bank {
3     pub fn balance(&self, acct_id: AcctId) -> u32 {
4         self.map.get(acct_id).unwrap_or(0) // 0 returned if no entry in map
5     }
6     pub fn deposit(&mut self, acct_id: AcctId, amt: u32) {
7         let bal = self.balance(acct_id); self.map.insert(acct_id, bal + amt);
8     }
9     pub fn withdraw(&mut self, acct_id: AcctId, amt: u32) {
10        let bal = self.balance(acct_id); self.map.insert(acct_id, bal - amt);
11    }
12 }

```

Fig. 1. Rust code defining a Bank struct and implementation of banking operations. Account balances are stored in a U32Map mapping AcctIds to u32 values; deposits and withdrawals update the map entries.

```

1 #[ensures(
2     forall(|acct_id2: AcctId| if acct_id == acct_id2 {
3         self.balance(acct_id) == old(self.balance(acct_id)) + amt
4     } else {
5         self.balance(acct_id2) == old(self.balance(acct_id2))
6     })
7 )]
8 fn deposit(&mut self, acct_id: AcctId, amt: u32) { ... }
9 #[requires(self.balance(acct_id) >= amt)]
10 #[ensures(
11     forall(|acct_id2: AcctId| if acct_id == acct_id2 {
12         self.balance(acct_id) == old(self.balance(acct_id)) - amt
13     } else {
14         self.balance(acct_id2) == old(self.balance(acct_id2))
15     })
16 )]
17 )]
18 fn withdraw(&mut self, acct_id: AcctId, amt: u32) { ... }

```

Fig. 2. Specifications for the deposit() and withdraw() functions. Each includes an explicit frame condition; specification lines used to encode the frame condition are highlighted in red.

Specifications for the Bank API play two main roles: defining what it means for the *implementation* of these functions to be correct (e.g. withdraw must correctly update the right balance), and defining what *client code* should consider when using this API. For example, withdrawing more than the current balance should be forbidden, while to specify (and modularly verify) a client function such as transfer below relies on having suitable specifications for withdraw and deposit:

```

1 fn transfer(bank: &mut Bank, from: AcctId, to: AcctId, amt: u32) {
2     bank.withdraw(from, amt); bank.deposit(to, amt);
3 }

```

Our bank example is substantially less complex than typical real-world code, but writing correct specifications for it in a classical fashion can nonetheless be challenging and subtle. We now demonstrate three specific issues that we encounter when trying to specify this kind of code.

```

1  #[requires(from != to && bank.balance(from) >= amt)]
2  #[ensures(forall(|a_id: AcctId|
3    if      a_id == from { bank.balance(a_id) == old(bank.balance(a_id)) - amt }
4    else if a_id == to   { bank.balance(a_id) == old(bank.balance(a_id)) + amt }
5    else                { bank.balance(a_id) == old(bank.balance(a_id))      }))]
6  fn transfer(bank: &mut Bank, from: AcctId, to: AcctId, amt: u32) { ... }

```

Fig. 3. A specification for the `transfer()` function, which makes calls to `withdraw()` and then `deposit()`

```

1  fn withdraw2(bank: &mut Bank, acct_id1: AcctId, acct_id2: AcctId) {
2    bank.withdraw(acct_id1, 1); bank.withdraw(acct_id2, 2);
3  }

```

Fig. 4. A function that performs two withdrawals in sequence. When `acct_id1` and `acct_id2` are the same, this function performs two operations on the same account.

2.1 Three Issues of Specifying Resource-Manipulating Programs

A typical specification for our Bank implementation would define postconditions for `deposit()` and `withdraw()` in terms of calls to `balance()`. As discussed in the introduction, an intuitive (but ultimately insufficient) postcondition for `deposit()` could be written as follows:

```

1  #[ensures(self.balance(acct_id) == old(self.balance(acct_id) + amt))]
2  fn deposit(&mut self, acct_id: AcctId, amt: u32) { ... }

```

Although this is a correct postcondition for the implementation, it is not sufficient for (modular) client reasoning: it specifies the change to `balance(acct_id)` but doesn't say anything about *other* balances (which should be unchanged). The standard solution is to extend the postcondition with a *frame condition*, specifying that the balances of all other accounts remain unchanged. The `withdraw()` function also requires similar frame conditions. A correct such specification for `deposit()`, and the analogous specification for `withdraw()`, are presented in Fig. 2. Adding frame conditions makes the resulting specifications more complex: much of the specification effort is concerned with precisely specifying what does *not* change. Similar frame conditions are also necessary for any function with a mutable reference to the Bank, such as `transfer()` above, whose postcondition must specify overall what has not changed.

Deriving a frame condition for `transfer()` is not simply a matter of, say, conjoining those for the two called functions; instead, one should rethink these specifications as describing *state updates*, mentally compose these updates, and deduce the right end-to-end specification of their composition: the appropriate postcondition of `transfer()` is presented in Fig. 3. Note that the postcondition does not directly use the specification expressions from `deposit()` or `withdraw()`.

This demonstrates the first issue with classical specifications in this context:

Issue 1: Specifying resource operations using program states requires frame conditions

Deriving frame conditions for the composition of multiple operations requires syntactic and mental overhead. But similar composition issues can arise even without consideration of frame conditions. For example, consider the function `withdraw2()` in Fig. 4, which performs two withdrawal operations in sequence. When we consider how to specify the precondition of this function, based on the precondition of the `withdraw()` function (Fig. 2), we might consider using:

```

1  #[requires(if(acct_id1 == acct_id2) { bank.balance(acct_id1) >= 3 }
2     else { bank.balance(acct_id1) >= 1 && bank.balance(acct_id2) >= 2 })]
3  #[ensures(if(acct_id1 == acct_id2) {
4     bank.balance(acct_id1) == old(bank.balance(acct_id1) - 3)
5   } else {
6     bank.balance(acct_id1) == old(bank.balance(acct_id1) - 1) &&
7     bank.balance(acct_id2) == old(bank.balance(acct_id2) - 2)
8   } && forall(|acct_id: AcctId| (acct_id != acct_id1 && acct_id != acct_id2) ==>
9     bank.balance(acct_id) == old(bank.balance(acct_id)))
10 )]]
11 fn withdraw2(bank: &mut Bank, acct_id1: AcctId, acct_id2: AcctId) { ... }

```

Fig. 5. The specifications for the `withdraw2()` function in Fig. 4. The conditional in the precondition is necessary to handle the possible aliasing between `acct_id1` and `acct_id2`. The postcondition includes an analogous conditional, as well as a frame condition stating that other account balances remain unchanged.

```

1  #[requires(bank.balance(from) >= amt)]
2  fn transfer(bank: &mut Bank, from: AcctId, to: AcctId, amt: u32) {
3     bank.withdraw(from, amt); bank.deposit(to, amt); bank.deposit(to, amt);
4  }

```

Fig. 6. A buggy transfer function that performs two deposits instead of one

```
#[requires(bank.balance(acct_id1) >= 1 && bank.balance(acct_id2) >= 2)]
```

This precondition is not strong enough however: when `acct_id1 = acct_id2`, the `withdraw2()` function would withdraw \$3 from the account. Therefore, a precise precondition needs to explicitly branch on whether both identifiers are the same. Furthermore, the analogous issue exists with the *postcondition*: the way we represent the change in program state differs depending on the aliasing of the parameters. An accurate specification for the `withdraw2()` function is presented in Fig. 5.

Again, to systematically derive such a specification requires considering the *updates* described by the specifications of the called functions, mentally composing these side-effects, and mapping the resulting transformation back to a state-based specification (case-splitting for aliasing as needed). The complexity of this process increases significantly as the number of operations increases. For example, the specification for a hypothetical `withdraw3()` function would need to branch on all of the aliasing possibilities between three parameters. This illustrates the second issue:

Issue 2: Specifications of resource operations using program states do not easily compose

The specifications for the Bank should dictate how clients are allowed to interact with it. They prevent e.g. overdrawing an account via the precondition `self.balance(acct_id) >= amt` on `withdraw()`. But they doesn't enforce *inherent* properties of how resources should behave. Note that `deposit` does not have a precondition: the specifications do not restrict calls to `deposit()`.

Fig. 6 shows an alternative (faulty) transfer implementation: it deposits more money in account to than was withdrawn from account from, effectively creating money out of nowhere. The

specifications of the Bank do not prevent this behaviour: the `transfer()` function verifies. Technically, `transfer()` is underspecified: with the complete functional specification of its intended effect on the to account, the function *would* fail to verify. But the conceptual source of the bug is clear from the code even with a weak specification: it's wrong for a resource acquired once to be spent twice. Intuitively, the money spent by `deposit` should come from somewhere, but this relies on an understanding of the specific resources the program works with, and of properties *all* resources should have, that is only partially explicit in the program state and its classical specifications.

Issue 3: Specifications using program states cannot easily enforce resource properties

The root cause underlying all three of these issues is that program states are not the ideal abstraction for expressing and reasoning about the behaviour of resource-manipulating programs. Intuitively, we think about such programs in terms of their operations on resources (e.g. spending money), including implicit common-sense understanding of how resources work in reality: for example, resources cannot be duplicated. The key idea behind our work is to make this abstraction directly available in the specification language, reifying this informal intuition and all its benefits in a formal technique. Our technique is presented concretely in the next section, but the basic idea is to allow (possibly multiple) custom resource types to be declared for a given program: we might use a resource type to represent money known to be stored in the bank and/or a resource type to represent money taken *out* of the bank. The notion of *how much* of each of these resources is currently held is made a (ghost) part of the program state (the *resource state*), and new specification features are provided that define how much resource is *transferred* in and out of function calls.

The default interpretation of these transfers is that if we don't specify that one happens, it *cannot*, allowing specifications to describe local updates without explicit frame conditions (Issue 1). Since resource transfers directly express *changes* to the resource state, they compose easily (Issue 2). Using a custom resource to represent *withdrawn* money prevents the faulty code in Fig. 6, since the attempt to spend a resource which is no-longer held can be made explicit with our first-class resources and the built-in properties that come with our resource model (Issue 3).

In the next section, we demonstrate how our methodology enables this kind of reasoning.

3 METHODOLOGY

The core idea of our approach is to enable program behaviour to be specified directly in terms of notions of resource relevant to the program. *Resources* in our methodology are conceptually a pair of a *resource type* and a *resource amount* (an integer). Resource types are organised into parameterised *resource kinds*: a named *resource constructor* with fixed arity (possibly zero) and corresponding parameter types; each instantiation of these parameters yields a distinct *resource type*. For example, we might use a resource kind `Money` with a single parameter representing an account ID to represent currency known to be deposited in the corresponding bank account.

In our Prusti implementation, such a resource kind is declared as a Rust struct annotated with a `#[resource_kind]` tag, listing its parameter types; resource types are denoted by instantiating the struct with appropriate (Rust) expressions. For example, we can declare a resource constructor for the amount of money belonging to a particular account as follows:

```
#[resource_kind] struct Money(AcctId);
```

Resources of the same type are always aggregated to the sum of their amounts, and resources of different types are incomparable. In our example, the fact that for two *different* account IDs `id1` and `id2`, the corresponding resource types `Money(id1)` and `Money(id2)` are different encodes the

```

1  impl Bank {
2    #[ensures(resource(Money(acct_id), amt))]
3    fn deposit(&mut self, acct_id: AcctId, amt: u32) {
4      ...; produce!(resource(Money(acct_id), amt));
5    }
6    #[requires(resource(Money(acct_id), amt))]
7    fn withdraw(&mut self, acct_id: AcctId, amt: u32) {
8      ...; consume!(resource(Money(acct_id), amt));
9    }
10 }

```

Fig. 7. The specification of Bank, described in terms of the resource Money.

property that money in different accounts should not be fungible; withdrawing money from your account should have a meaning distinct from withdrawing from someone else's!

We use the syntax `resource(rtype, amt)` to denote resources, where *rtype* is a resource type, and *amt* is the amount. For example, the expression `resource(Money(a_id), amt)` refers to an amount *amt* of money for the account associated with the identifier *a_id*.

3.1 Resource Operations

Our methodology defines three *resource operations*: resources can be *created*, *destroyed*, and *transferred*. We denote creation and destruction by `produce!()` and `consume!()` respectively. In our Bank example, using the resource type `Money(a_id)` to represent deposited currency, deposits should create resource and withdrawals destroy it. This idea is realised by instrumenting the bodies of the `deposit` and `withdraw` functions as shown in Fig. 7.

Intuitively, it is only possible to destroy a resource if it is currently held: our methodology requires that the resource `resource(Money(acct_id), amt)` is available to destroy at the point of the `consume!()` inside `withdraw()` (otherwise verification will fail). Conceptually, the caller of `withdraw` needs to give up this resource: we express that they must *transfer* it from their (calling) context by specifying the resource in the function precondition (cf. Fig. 7). Analogously, we specify that `deposit()` transfers a resource back to the caller by placing it in the function's postcondition.

3.2 Resource State

Our methodology associates every stack frame with a *resource state*, tracking the resources currently held by the function invocation. This is *ghost state*; we use it as a concept for static reasoning about the program only, but it need not (and will not) actually exist at runtime. A resource state is a map from resource types to resource amounts, and resource operations are interpreted with respect to the current resource state. Creation of resource increments the corresponding map entry, while destruction decrements it. Destruction operations entail a proof obligation: we need to prove that sufficient resource is held before it is destroyed, otherwise a verification error is raised.

Resources are transferred between stack frames at call (and return) sites. The resource state of each frame is initialised with *only* the resources transferred to it from its caller, according to the function's precondition. Resources in a function's postcondition are those it transfers back to its caller. Transfers also entail proof obligations: the verifier must prove that the resources transferred away are actually held. This model of resource state is suitable for modular verification: each function's initial resource state is determined purely by its precondition, independently of call site.

3.3 Resource State Expressions

The specifications presented in Fig. 7 suffice to characterise the behaviour of the program in terms of its resource operations. Reifying these resource transfers make some important properties of the program clearer: e.g. it is impossible to overdraw an account because withdrawals require a resources representing at least part of the current balance (see Fig. 8).

```

1 fn bad(bank: &mut Bank, acct_id: AcctId, amt: u32) {
2   bank.deposit(acct_id, amt); bank.withdraw(acct_id, amt);
3   bank.withdraw(acct_id, amt); // ERROR: insufficient permission to resource
4 }
```

Fig. 8. An example program that would not verify after annotating Bank with resource operations. The first withdraw() is permitted, because sufficient resource Money(acct_id) is made available by the preceding deposit() call. A verification error is raised because there is no resource available for the second withdraw().

However, our resource specifications so far are completely independent of the *actual* implementation state used to track resources. In particular, there is no specified relationship between resource operations and Bank.balance() calls. Working towards this, we introduce *resource state expressions*, which are used inside specifications to introspect on the resource state. These expressions are written holds(rtype), and (when used *outside* of function specifications (e.g. as inline assertions) denote the amount of resource type rtype held in the current resource state. For example, holds(Money(acct_id)) denotes the amount of acct_id's money in the current state.

When holds() is used in function specifications, we define its semantics differently, considering the fact that the caller and callee resource states may differ. In such positions, our technique interprets holds() expressions with respect to the *amount of resource transferred so far* by the corresponding pre-/post-condition; this notion has the same meaning for both caller and callee.

Fig. 9 illustrates this semantics. The first precondition #[requires(resource(Money(a), 1))]
at line 1 specifies a resource to be transferred from caller to callee. As that is the only resource transferred so far, the (commented) assertion holds(Money(a)) == 1 holds at ①. The subsequent line specifies the same resource transfer again, resulting in holds(Money(a)) == 2 (②).

The first postcondition old(holds(Money(a))) == 2) at ③ concerns (via old) the amount of Money(a) transferred *from the caller* (this refers to the overall transfers made by the preconditions together), while the second (④) states that no money has been transferred by the *postconditions* up to this point. At ⑤, located after the postcondition transferring resource(Money(a), 1) to the caller, the commented assertion holds(Money(a)) == 1 would instead be true.

3.4 Coupling Invariants

Finally, we use our resource state expressions to define connections between the resource state and the actual program state. In our methodology, users declare *coupling invariants* to define these connections. Coupling invariants are expressed as two-state expressions (using old to describe the prior state, as in a postcondition) that relate the program *and* resource states at two points in the program; these invariants are enforced at function return sites. Coupling invariants are expressed using annotations of the form #[invariant_twostate(t)], where *t* is an expression that can include specification constructs such as holds() and old() expressions. Although declared once per type, a coupling invariant *t* is interpreted as an additional, implicit postcondition on *every*


```

1  #[requires(resource(Money(a), 1))] // holds(Money(a)) == 1 ①
2  #[requires(resource(Money(a), 1))] // holds(Money(a)) == 2 ②
3  #[ensures(old(holds(Money(a))) == 2)]                      ③
4  #[ensures(holds(Money(a)) == 0)]                          ④
5  #[ensures(resource(Money(a), 1))] // holds(Money(a)) == 1 ⑤
6  fn take2return1(bank: &mut Bank, a: AcctId){ bank.withdraw(a, 1); }
7
8  #[requires(resource(Money(a),3))]
9  fn client(bank: &mut Bank, a: AcctId){ take2return1(bank, a); }

```

Fig. 9. A program demonstrating resource operations and resource state expressions in specifications.

```

1  #[invariant_twostate(forall(|a_id: AcctId|
2    holds(Money(a_id)) - old(holds(Money(a_id))) ==
3    self.balance(a_id) - old(self.balance(a_id)))]

```

Fig. 10. A coupling invariant for the Bank struct, which is enforced between the beginning (via old) and end of each function involving a mutable reference to a Bank.

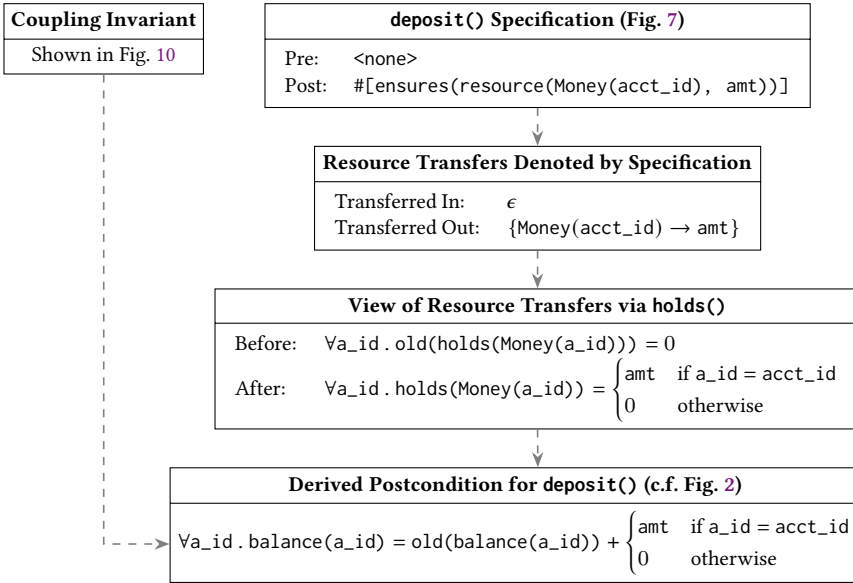


Fig. 11. A diagram indicating how the coupling invariant from Fig. 10 combines with resource operations of deposit() (Fig. 7) to derive a postcondition specifying the effect deposit() has on the value of balance(). The derived postcondition is equivalent to the manually written postcondition of Fig. 2.

function taking a mutable reference to this type as a parameter; effectively, it is equivalent to adding the postcondition $\#[\text{ensures}(t)]$ to all such functions (this happens implicitly).

Fig. 10 shows a suitable coupling invariant for our Bank struct. It states that (across each function it applies to) the change in the value of balance(a_id) should correspond to the change in

```

1 #[requires(from != to)]
2 #[requires(resource(Money(from), amt))]
3 #[ensures(resource(Money(to), amt))]
4 fn transfer(bank: &mut Bank, from: AcctId, to: AcctId, amt: u32) { ... }

```

Fig. 12. The specification of `transfer()`, described in terms of the resource `Money`.

resource `Money(a_id)` for all account identifiers `a_id`. To demonstrate the implications of this invariant, we can consider how it applies to the `deposit()` function (depicted graphically in Fig. 11).

The function’s specifications using resource assertions prescribe the resources to be transferred into and out of the function call; in this example, none for the (empty) precondition and `resource(Money(acct_id), amt)` for the postcondition. This is elaborated (automatically) to a complete pointwise specification of the effects on all resource types, making explicit the cases of *no* transfer via e.g. `holds(Money(a_id) == 0` constraints. By conjoining the coupling invariant, this logically implies a precise specification relating the values of balance calls between the pre-state and post-state; exactly the complex postcondition that had to be written manually for `deposit()` in Fig. 2. The combination of our novel resource specifications describing only the effects that *do* happen, our native resource semantics and an appropriate coupling invariant, results implicitly in a logically-equivalent specification expressed much more simply.

Coupling invariants apply to *all* functions that take a (mutable) reference to a `Bank` (in particular, they cannot be forgotten/ignored for a function; they define a constraint on operations on this type in general). Fig. 12 shows the specifications for the `transfer()` function implemented using our methodology; unlike the original version in Fig. 3, the specification does not require explicit frame conditions, and (with the exception of the extra precondition `from != to`) is a simple composition of the corresponding specifications of `withdraw()` and `deposit()` from Fig. 7. Important resource notions such as non-duplicability and a built-in notion of resource amount are built-in: in short, our new methodology addresses the three main specification issues detailed in Sec. 2.

4 IMPLEMENTATION

We implemented our verification technique as an extension of the Rust program verifier Prusti. Prusti verifies Rust code by encoding the program and specifications into the intermediate verification language Viper [Müller et al. 2016], which supports permission-based reasoning using a variant of implicit dynamic frames [Smans et al. 2009]. Although Prusti does not allow users to directly access Viper’s permission primitives in specifications, it uses Viper permissions to encode the guarantees provided by Rust’s ownership model. Our methodology uses Viper’s permission-based reasoning capabilities to extend Prusti with support for our novel resource reasoning technique.

4.1 The Viper Intermediate Verification Language

Viper is an imperative intermediate verification language, in the spirit of Boogie [Leino 2008] and Why3 [Bobot et al. 2011]. Program verifiers are built to translate source language (in our case, Rust) verification problems into Viper programs, which can then be checked by a Viper verifier.

A Viper program consists of a set of methods; Viper methods (whose bodies are statements) are similar to functions in an imperative language. Viper statements include variable assignments and method calls, as well as `assume` and `assert` statements that are interpreted in the standard way. Viper also includes `label` statements: the statement `label l` associates the point in the method

where the statement appears with the label l . The labels are used in Viper's old expressions: the expression $\text{old}[l](e)$ refers to the value of the expression e at the program point l .

Viper supports separation-logic style reasoning: its language and logic has its own notion of resource state, used to track a variety of *resource assertions* [Müller et al. 2016]. For the purposes of this paper, the only relevant Viper resources are *abstract predicate instances*. Viper allows the declaration of custom *abstract predicates* using the syntax $\text{predicate } P(x_1 : T_1, \dots, x_n : T_n)$, where P is the predicate name, and $x_1 : T_1, \dots, x_n : T_n$ are the names and types of its arguments. Each instantiation $P(e_1, \dots, e_n)$ of the predicate is treated as a type of resource to be tracked.

Expressions $\text{acc}(p, \text{amt})$ denote an amount amt of the predicate instantiation p . Viper statements $\text{inhale } e$ and $\text{exhale } e$ add/remove resources described by acc expressions in e ; for non-resource expressions they behave as assume/assert statements. Removing (via exhale) resources not in the state causes a verification error. Viper also supports $\text{perm}()$ expressions that query an amount of resource: an expression $\text{perm}(p)$ refers to the amount of the predicate instantiation p .

4.2 Encoding of Resources into Viper

An overview of our translation from our resource specifications into Viper is shown in Fig. 13. The (overloaded) syntax $\llbracket \cdot \rrbracket$ denotes the translation of Prusti declarations, Rust statements, and Rust types into Viper. We omit the translation of types, which is unchanged from the prior Prusti encoding [Astrauskas et al. 2019]. Prusti's encoding of pre-existing features is unchanged, except for adding additional `label` statements (used for encoding our `holds()` expressions).

The syntax $\llbracket \cdot \rrbracket_c^o$ denotes the encoding of a Prusti expression in the context c, o . The context changes the way that `holds()` expressions are translated into Viper. The first element, c , represents the *current context*: either *no label* ϵ , or a *signed label* $-l$ or $+l$ (denoting whether we are currently removing or adding resources). The second element, o , represents the *old context* taking the form of either $\text{old}(l)$ or $\text{cur}(l)$. These contexts prescribe where (with respect to which existing label) generated `perm()` expressions should be evaluated and how they should be composed. For example, the context $+l', \text{old}(l)$, is used to encode `old(holds())` expressions that occur in the postcondition of a called function; and are computed by taking the difference of the `perm()` expressions taken before and after exhaling the function precondition, corresponding to labels l and l' respectively.

4.2.1 Resources and Resource Operations. As described previously, resource types (via their Resource constructors) are declared in Prusti as a Rust struct, annotated with the tag `#[resource_kind]`. We encode resource constructors as abstract predicates in Viper; the fields of the struct are encoded as the arguments to the abstract predicate. We chose this encoding because abstract predicates in Viper are used to model resources in Viper's resource model. Accordingly, we translate `resource()` expressions directly into `acc()` expressions in Viper. Our `produce!()` and `consume!()` statements are encoded as `inhale` and `exhale` statements in Viper; these provide our desired semantics directly.

`holds()` expressions in the body of a Rust function are encoded as `perm()` expressions in Viper. However, as described in Sec. 3.3, our `holds()` expressions have a different semantics in pre-/post-conditions (while Viper's `perm()` expressions do not). Encoding our semantics requires a more-complex translation, using the contexts on our translation function to calculate the correct differences between `perm()` expressions at different points in the program.

4.3 Coupling Invariants and Reborrowing

We directly encode coupling invariants (declared with `#[invariant_twostate(t)]` annotations on Rust structs) as postconditions on the corresponding translated Viper methods. One restriction of our current methodology is that we do not support Rust functions that *reborrow* mutable

Declarations

$$\llbracket \#[\text{resource_kind}] \text{ struct } R(T_1, \dots, T_n); \rrbracket \rightsquigarrow \text{predicate } R(\text{arg1} : \llbracket T_1 \rrbracket, \dots, \text{argn} : \llbracket T_n \rrbracket)$$

$$\left\llbracket \begin{array}{l} \#[\text{requires}(f_{pre})] \\ \#[\text{ensures}(f_{post})] \\ \text{fn } f(x_1 : T_1, \dots, x_n : T_n) \{s_1; \dots; s_m\} \end{array} \right\rrbracket \rightsquigarrow \begin{array}{l} \text{method } f(x_1 : \llbracket T_1 \rrbracket, \dots, x_n : \llbracket T_n \rrbracket) \{ \\ \text{inhale } \llbracket f_{pre} \rrbracket_{\epsilon}^{cur(l_{\epsilon})}; \text{ label pre}; \\ \llbracket s_1 \rrbracket; \dots; \llbracket s_m \rrbracket \\ \text{label post}; \text{ exhale } \llbracket f_{post} \rrbracket_{-post}^{cur(pre)} \\ \} \end{array}$$

Statements

$$\llbracket \text{produce}!(t); \rrbracket \rightsquigarrow \text{inhale } \llbracket t \rrbracket_{\epsilon}^{cur(pre)} \quad \llbracket \text{consume}!(t); \rrbracket \rightsquigarrow \text{exhale } \llbracket t \rrbracket_{\epsilon}^{cur(pre)}$$

$$\llbracket f(t_1, \dots, t_n); \rrbracket \rightsquigarrow \begin{array}{l} \text{label } l_{pre}; \text{ exhale } \llbracket f_{pre}[x_1 := t_1, \dots, x_n := t_n] \rrbracket_{-l_{pre}}^{cur(l_{\epsilon})} \\ \text{label } l_{post}; \text{ inhale } \llbracket f_{post}[x_1 := t_1, \dots, x_n := t_n] \rrbracket_{+l_{post}}^{cur(l_{pre})} \end{array}$$

Expressions

$$\llbracket \text{old}(t) \rrbracket_c^{cur(l)} \rightsquigarrow \llbracket t \rrbracket_c^{old(l)}$$

$$\llbracket R(t_1, \dots, t_n) \rrbracket_c^o \rightsquigarrow R(\llbracket t_1 \rrbracket_c^o, \dots, \llbracket t_n \rrbracket_c^o) \quad \llbracket \text{resource}(r, t) \rrbracket_c^o \rightsquigarrow \text{acc}(\llbracket r \rrbracket_c^o, \llbracket t \rrbracket_c^o)$$

$$\llbracket \text{holds}(r) \rrbracket_{\epsilon}^{cur(l)} \rightsquigarrow \text{perm}(\llbracket r \rrbracket_{\epsilon}^{cur(l)}) \quad \llbracket \text{holds}(r) \rrbracket_{\epsilon}^{old(l)} \rightsquigarrow \text{old}[l](\text{perm}(\llbracket r \rrbracket_{\epsilon}^{old(l)}))$$

$$\llbracket \text{holds}(r) \rrbracket_{+l'}^{cur(l)} \rightsquigarrow \text{perm}(\llbracket r \rrbracket_{\epsilon}^{cur(l)}) - \text{old}[l'](\text{perm}(\llbracket r \rrbracket_{\epsilon}^{cur(l)}))$$

$$\llbracket \text{holds}(r) \rrbracket_{+l'}^{old(l)} \rightsquigarrow \text{old}[l](\text{perm}(\llbracket r \rrbracket_{\epsilon}^{old(l)})) - \text{old}[l'](\text{perm}(\llbracket r \rrbracket_{\epsilon}^{old(l)}))$$

$$\llbracket \text{holds}(r) \rrbracket_{-l'}^{cur(l)} \rightsquigarrow \text{old}[l'](\text{perm}(\llbracket r \rrbracket_{\epsilon}^{cur(l)})) - \text{perm}(\llbracket r \rrbracket_{\epsilon}^{cur(l)})$$

$$\llbracket \text{holds}(r) \rrbracket_{-l'}^{old(l)} \rightsquigarrow \text{old}[l](\text{perm}(\llbracket r \rrbracket_{\epsilon}^{old(l)}))$$

Fig. 13. Encoding of Prusti resource constructs into Viper. Labels l_{pre} and l_{post} are assumed to be fresh. The label l_{ϵ} denotes an arbitrary fresh label that is never referenced, i.e., a placeholder label used where old expressions are not permitted.

references, returning to the caller a live mutable reference to e.g. the internals of the Bank. An example of such a function is shown in Fig. 14, where a mutable references to one of the balances is handed out to the caller. Technically, this requires that the *client code* would become responsible for maintaining the Bank’s two-state invariant. For untrusted client code (such as smart contracts running on a blockchain infrastructure), this should not be relied upon, and rejecting such functions (as we currently do) is the right approach. A similar issue and its solution has been discussed in the context of *single-state* invariants for Prusti [Astrauskas et al. 2022]. However, for *trusted* client code (e.g. other verified layers of the same software stack), we believe an adaptation of this idea to support reborrowing with our two-state invariants, as future work (it remains to consider exactly which pairs of states we would use to enforce our two-state invariants in potential extension). This feature has not been needed in practice when applying our methodology to examples (likely because this additional reliance on client code for correctness is often not desirable for such programs).

With this encoding in place (and implemented), we can verify Rust code specified in our methodology directly and automatically, as we evaluate in the following sections.

```

1 struct Bank { balances: HashMap<AcctId, u32> }
2 impl Bank {
3     fn get_balance_ref(&mut self, acct_id: AcctId) -> &mut u32 {
4         self.balances.get_mut(acct_id).unwrap()
5     }
6 }

```

Fig. 14. A function that performs a reborrow. The variable `self` is inaccessible at the end of the function call and the returned reference can modify its internal state; the Bank’s two-state invariant cannot yet be re-established.

5 CASE STUDY

In this case study, we take the core of a Rust implementation [Informal Systems Inc. and ibc-rs authors 2022] of a cryptocurrency token transfer application running on the Interblockchain Communication Protocol (IBC) [Goes 2020]. The token transfer application enables tokens to be sent from one blockchain to another, without the need for a trusted intermediary; a bug in the application could inadvertently cause tokens to be destroyed or duplicated.

5.1 The Fungible Token Transfer Application

The IBC token transfer specification allows tokens to be sent between blockchains with different implementations and consensus mechanisms. Its design requires that each chain track token ownership for accounts on the chain, but not for those on other chains. The application has access to a ledger on each chain; allowing it to mint and burn tokens for arbitrary accounts on that chain. It “transfers” a token between chains by making ledger updates on both chains.

A naïve token transfer implementation could operate by destroying the tokens on one chain and creating them on another. However, the naïve approach has two issues. First, a chain may not have the capacity to mint some kinds of tokens, i.e., tokens with fixed supply. Second, this approach would allow an exploit allowing unrestricted minting of a token on one compromised chain to allow obtaining an arbitrary amount of that token on any connected chain. In particular, if a chain *A* had a vulnerability allowing malicious arbitrary minting, an attacker could mint on *A* a token that exists on chain *B*, and then transfer it to chain *B*.

Instead, the fungible token transfer application performs a token transfer from chain *A* to chain *B* by first sending the token to a special *escrow account* on chain *A*, and then minting a *voucher token* on chain *B* (shown in Fig. 15a). The denomination of the voucher token is created by prefixing the denomination of *A*’s token with the identifier of the channel connecting the two chains.

Intuitively, the voucher token on *B* corresponds to the escrowed token on *A*. In particular, when the application transfers the voucher token back to *A*, it is burned on chain *B*, and the tokens in the escrow account in chain *A* are sent to the recipient (as shown in Fig. 15b). The advantage of this design is that it does not require the token transfer application to mint or burn *native* (i.e., non-voucher) tokens. Because this design ensures that native tokens are never minted, exploits on one chain cannot use the protocol to inflate the supply of native tokens on other chains.

When a voucher token is transferred to a chain other than its originating chain, it is treated the same as any other token. This enables tokens to be transferred transitively across multiple chains. For example, suppose *A*, *B* and *C* are blockchains, and *B* is connected to both *A* and *C*. Then, a token on *A* can be sent to *C* by first making a transfer from *A* to *B*, and sending the voucher minted on *B* to *C*. *C* ends up with a voucher for the token on *B*, which itself is a voucher for the token on *A*.

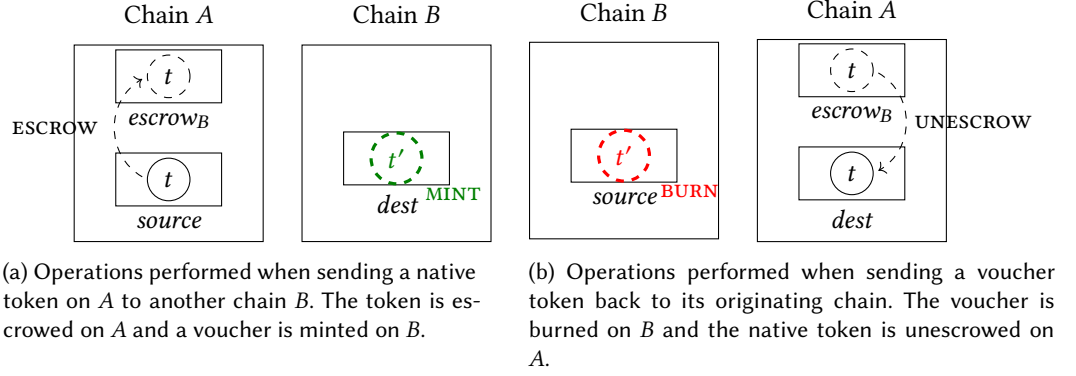


Fig. 15. Operations of the Token Transfer Application.

```

1 struct PrefixedDenom {trace_path: TracePath, base_denom: BaseDenom}
2 struct PrefixedCoin {denom: PrefixedDenom, amount: u32}
3 trait BankKeeper {
4   fn send_tokens(&mut self, from: AccountId, to: AccountId, coin: PrefixedCoin);
5   fn burn_tokens(&mut self, from: AccountId, coin: PrefixedCoin);
6   fn mint_tokens(&mut self, to: AccountId, coin: PrefixedCoin);
7 }

```

Fig. 16. The BankKeeper interface

5.2 Application Architecture

The token transfer application is defined with respect to the BankKeeper trait shown in Fig. 16. The application uses the BankKeeper to manage the ledger on a particular chain; transfers are accomplished by interacting with instances of the BankKeeper trait on both chains.

The struct AccountId identifies an account; within BankKeeper these refer to local accounts (not those on other chains). The struct PrefixedCoin consists of a token denomination and an integer amount; this type is used in the bank interface to specify which token should be minted, burned, or transferred. The struct PrefixedDenom refers to a token denomination: base_denom is the name of the token on the originating chain, and trace_path denotes the sequence of token transfers necessary to exchange a token of this denomination with the one on its original chain.

5.3 Properties of the Fungible Token Transfer Application

For our case study, we focused on verifying two key properties of the token transfer application. We decided on the properties based on suggestions from collaborators at Informal Systems (responsible for the code). The properties are as follows:

- **Two-Way Peg:** After transferring a token from one chain to another, it should be possible to send the token back to the original account. Performing this round-trip token transfer should not result in any balance changes on either chain.
- **Preservation of Supply:** For any given native token, the sum of the native token (excluding tokens in escrow accounts) and all derived voucher tokens should remain constant.

These properties originate from the IBC specification [Goes 2022], although the two-way peg property we consider is stronger than the version in the original specification. To verify the implementation, it was necessary to make some changes to the code in order to workaround limitations of Prusti. For example, the `TracePath` data structure is implemented using data structures that are not fully supported by Prusti, therefore, we simplified the definitions of such types. However, these changes are orthogonal to our verification methodology.

In addition, we have not yet implemented support for coupling invariants on *traits*, therefore, to verify the implementation we changed the interface to define `BankKeeper` as a struct instead. As the expected properties and behaviour of the `BankKeeper` remain the same, this change is not significant, and the results of our verification are still applicable to the original design.

The token transfer application relies on implementations of the IBC core standards [IBC Standards Committee 2023] to coordinate communication across chains. For example, executing code on the remote chain involves generating cryptographic proofs, serialising message data, and routing messages appropriately. These aspects are unrelated to the application logic itself, furthermore, verification of these aspects would likely not benefit from our resource reasoning methodology. Therefore, we assume that these components function correctly.

5.4 Encoding the Specification with Resources

We present our specification by first explaining the resource types that are used to model the resources in the program (Sec. 5.4.1). We then demonstrate the specifications for the `BankKeeper` (Sec. 5.4.2) and constituent functions of the token-transfer application (Sec. 5.4.3). In Sec. 5.4.4 we present the specifications used to verify the properties.

5.4.1 Representing Tokens with Resource Types. We begin our presentation by identifying appropriate resource types for use in specifications. First, we note that the two properties above refer to different aspects of tokens: the two-way peg property is concerned with the tokens in each account, while the preservation of supply considers the sum of unescrowed tokens across all accounts. The latter property does not distinguish between native and voucher tokens, however this distinction is relevant for the former. Therefore, we define *two* different resource constructors, each corresponding to a different aspect of the same tokens. We declare the first constructor, which is used to encode the two-way peg property, as follows:

```
#[resource_kind] struct Money(BankID, AccountId, PrefixedDenom)
```

Resources constructed using the constructor `Money` have distinct resource types if they belong to different banks, differ in denomination, or have different owners. We can ensure the two-way peg property by showing that round-trip transfers do not change the amount of tokens of this type in the resource state.

Proving the second property requires showing that the total amount of all unescrowed tokens of a particular base denomination remain unchanged. For this property, we use a different resource constructor, that treats tokens as having the same type when they are in the same bank and have the same base denomination. We declare the constructor as follows:

```
#[resource_kind] struct UnescrowedCoins(BankID, BaseDenom);
```

As previously mentioned, each resource constructor corresponds to a different view of the same token. Therefore, operations on real tokens should affect the corresponding resources for each view in a uniform manner. Therefore, we can define a macro to describe these real-world operations in terms of how they effect each view of the resource; this macro simplifies the specification, since it eliminates the need to write resource operations for each view separately.

```

1 macro_rules! transfer_money { ($bank_id:expr, $to:expr, $coin:expr) => {
2   resource(Money($bank_id, $to, $coin.denom), $coin.amount) &&
3   if !is_escrow_account($to) {
4     resource(UnescrowedCoins($bank_id, $coin.denom.base_denom), $coin.amount)
5   } else { true }
6 }}

```

Fig. 17. A macro that specifies what Prusti resources are changed (i.e., either created or destroyed) in response to token operations. An operation on tokens will always change the Money resource, and also changes the UnescrowedCoins resource if the target account is not an escrow account.

```

1 impl BankKeeper {
2   #[requires(transfer_money!(self.id(), from, coin))]
3   #[ensures(transfer_money!(self.id(), to, coin))]
4   fn send_tokens(&mut self, from: AccountId, to: AccountId, coin: PrefixedCoin);
5
6   #[requires(transfer_money!(self.id(), from, coin))]
7   fn burn_tokens(&mut self, from: AccountId, coin: PrefixedCoin);
8
9   #[ensures(transfer_money!(self.id(), to, coin))]
10  fn mint_tokens(&mut self, to: AccountId, coin: PrefixedCoin);
11 }

```

Fig. 18. The BankKeeper annotated with the appropriate resource operations.

The resulting macro is presented in Fig. 17. The macro states that a transfer of a token should always move an instance of the Money resource constructor, but should only move the corresponding UnescrowedCoins resource if the account \$to is not an escrow account.

5.4.2 Specifying the BankKeeper. We use the `transfer_money()!` macro to annotate BankKeeper’s associated functions with appropriate resource operations, as presented in Fig. 18.

We then connect the resource operations to properties about the program state by establish coupling invariants on the BankKeeper function, which describe how changes to Money and UnescrowedCoins in the resource state correspond to changes in functions `balance` and `unescrowed_coin_balance` respectively. These invariants are shown in Fig. 19.

5.4.3 Verifying the Application Logic. We now focus our attention to the logic of the token-transfer application itself. The application performs a token transfer from a chain *A* to chain *B* in two steps. The first step is performed by calling the function `send_fungible_tokens()` (Fig. 20) on chain *A*, which disposes of the tokens on *A* by either escrowing or burning them. In the second step, it effectively causes the function `on_recv_packet()` to be called on chain *B*, which produces the tokens by either minting or unescrowing tokens as necessary¹.

Fig. 20 shows a specification and implementation of the `send_fungible_tokens()` function (we simply some details for presentation here), which performs the initial step in the cross-chain

¹Technically, `on_recv_packet()` in the original version is a callback that is triggered when a relayer sends a message to chain *B*, however for verification we consider this as a regular function call. The routing of callbacks is implemented as part of the IBC core standard, which we assume to be correct and do not attempt to verify.

```

1  #[invariant(forall(|acct_id: AccountId, denom: PrefixedDenom|
2    holds(Money(self.id(), acct_id, denom)) -
3    old(holds(Money(self.id(), acct_id, denom))) ==
4    self.balance(acct_id, denom) - old(self.balance(acct_id, denom))))]
5  #[invariant(forall(|coin: BaseDenom|
6    holds(UnescrowedCoins(self.id(), coin)) -
7    old(holds(UnescrowedCoins(self.id(), coin))) ==
8    self.unescrowed_coin_balance(coin) - old(self.unescrowed_coin_balance(coin))))]

```

Fig. 19. Invariants connecting the resources Money and UnescrowedCoins to the methods balance() and unescrowed_coin_balance() respectively.

```

1  #[requires(transfer_money!(bank.id(), sender, coin))]
2  #[ensures(!coin.denom.trace_path.starts_with(port, channel) ==>
3    transfer_money!(bank.id(), escrow_address(channel), coin))]
4  fn send_fungible_tokens(bank: &mut Bank, coin: &PrefixedCoin, sender: AccountId,
5    port: Port, channel: ChannelEnd) {
6    if coin.denom.trace_path.starts_with(port, channel) { bank.burn(sender, coin); }
7    else { bank.send(sender, escrow_address(channel), coin); }
8  }

```

Fig. 20. The first step of the fungible token transfer.

token transfer. The arguments `port` and `channel` identify the chain that tokens will be transferred to. The condition on line 8 checks if the token being sent is a voucher for a token on that chain. If so, then the voucher is burned on this chain (and the next step will unlock the corresponding token on the other chain). Otherwise, the token is moved to an escrow account on this chain.

The precondition of `send_fungible_tokens()` specifies that calling the function transfers the token out of the sender's account. The postcondition indicates that when the token did not originate on the opposite chain (i.e., the chain identified by `port` and `channel`), it will be transferred to the escrow account. Due to space constraints, we do not present the specifications of the second step of the transfer here; the relevant specification is available in our supplementary material [Anonymous Authors 2023].

5.4.4 Verifying the Desired Properties. With the above specifications, we can then prove that the token transfer application satisfies the properties described in Sec. 5.3. To prove the two-way peg property, we construct a method that performs a round trip token transfer, and show that the balances of all accounts are unchanged after the transfer. The relevant specifications are presented in Fig. 21 (the body of the method is omitted for brevity). We verify the preservation of supply property by showing that the supply is preserved after an arbitrary transfer; the specifications are presented in Fig. 22. The specifications of both properties are expressed in terms of the functions `balance()` and `unescrowed_coin_balance()` respectively.

In conclusion, we've shown that our methodology can be applied to a real-world resource-manipulating program. Using our methodology, we were able to prove two important properties about the token-transfer application: that it maintains a two-way peg and preserves total token supply. Our technique allow us to verify the desired properties in a straightforward manner by describing resource operations directly, without having to write frame conditions.

```

1  #[ensures(forall(|acct_id2: AccountId, denom: PrefixedDenom|
2      bank1.balance(acct_id2, denom) == old(bank1).balance(acct_id2, denom)))]
3  #[ensures(forall(|acct_id2: AccountId, denom: PrefixedDenom|
4      bank2.balance(acct_id2, denom) == old(bank2).balance(acct_id2, denom)))]
5  fn round_trip(bank1: &mut Bank, bank2: &mut Bank, coin: &PrefixedCoin,
6      sender: AccountId, receiver: AccountId, ...) { ... }

```

Fig. 21. The relevant specifications for the two-way peg property. The function `round_trip()` performs a token transfer from account `sender` to `receiver`, and then performs the same transfer in the opposite direction.

```

1  #[ensures(forall(|c: BaseDenom|
2      bank1.unescrowed_coin_balance(c) + bank2.unescrowed_coin_balance(c) ==
3      old(bank1.unescrowed_coin_balance(c) + bank2.unescrowed_coin_balance(c)))]
4  fn transfer(bank1: &mut Bank, bank2: &mut Bank, coin: &PrefixedCoin,
5      sender: AccountId, receiver: AccountId, ...) { ... }

```

Fig. 22. The relevant specifications for the supply preservation property. The function `transfer()` performs a token transfer from account `sender` to `receiver`.

6 EVALUATION

To evaluate our technique, we consider how specifications written using our methodology compare to alternative specifications written in terms of program states. We consider four research questions:

RQ1 (*Conciseness*): Are our specifications *smaller* than the alternative?

RQ2 (*Complexity*): Are our specifications *simpler* than the alternative?

RQ3 (*Interpretability*): Are our specifications *easier to understand compared* to the alternative?

RQ4 (*Verification Time*): Do our specifications *require more time to verify* than the alternative?

To answer these questions, we compare the specifications we developed in Sec. 5 to an alternative version we constructed, that verifies the same implementation using specifications written without using our methodology. In addition, we also apply our methodology to a simplified implementation of the IBC Non-Fungible Token (NFT) Transfer application [Xi 2022], again comparing the results to an alternative version of the specification. The NFT transfer application has a similar architecture to the token transfer application. We wrote the implementation ourselves, based on pseudocode in the specification. We are not aware of a functioning Rust implementation of the protocol; ultimately we intend to develop our prototype into a verified reference implementation. A key difference in the application of our methodology between the two protocols, is that we use resources to model the *permission* to change ownership of a token, rather than modelling the token itself. The specifications and implementation of the NFT transfer application are included in our supplementary material [Anonymous Authors 2023].

We now consider each research question in order, describing how we compared the specifications and presenting our results. We discuss the results in Sec. 6.5.

Context	Usage	Without Resources	With Resources
TT-Resources	Resource Constructors	N/A	4
	Coupling Invariants	N/A	21
	transfer_money!() macro	N/A	10
TT-Bank	burn()	27	1
	mint()	26	1
	send()	41	2
TT-App	send_fungible_tokens()	13	3
	on_recv_packet()	19	6
TT-Properties	send_preserves()	16	26
	round_trip()	19	23
NFT-Resources	Resource Constructors	N/A	2
	Coupling Invariants	N/A	5
	transfer_tokens!() macro	N/A	5
NFT-Bank	burn()	8	2
	mint()	9	3
	send()	8	3
	create_or_update_class()	4	0
NFT-App	send_nft()	12	13
	on_recv_packet()	17	11
NFT-Properties	round_trip()	21	24
Total		240	165

Table 1. Comparison of the number of specification lines required for the specifications written with and without resources. Rows prefixed with TT- refer to the token transfer specifications, those prefixed with NFT- refer to the NFT transfer specifications.

6.1 Conciseness

To measure conciseness, we compared the number of lines of code used to specify resource-related operations in both specifications. Lines that are unrelated to resource operations, which are identical in both versions, are not considered in the comparison. Table 1 provides a comparison between the number of specification lines required for both specification versions. In total, the specifications concerned with resource properties (including invariants and helper macro definitions) consist of 165 lines of code. Encoding the equivalent specifications without resources required 240 lines.

Our methodology requires fewer lines of code to encode the specifications for the token transfer application's BankKeeper implementation, as well as the two main functions of the fungible token transfer application. Our specifications of the final properties require more lines of code, because they also indicate the resource operations of `send_preserves()` and `round_trip()`. However, the trade-off is acceptable, because these extra lines also make the specification more expressive compared to the alternative specification. Furthermore, a larger difference would be seen if we considered a program with more functions, because the invariants only need to be written once. The function `create_or_update_class()` in the NFT transfer application does modify token ownership, and therefore does not require any specifications in our specification; in contrast, the alternative specification requires four lines of code to explicitly state this property.

Context	Usage	Without Resources			With Resources		
		Size	Depth	Uniq.	Size	Depth	Uniq.
TT-Resources	Resource Constructors	N/A	N/A	N/A	7	2	2
	Coupling Invariants	N/A	N/A	N/A	90	9	9
	transfer_money!() macro	N/A	N/A	N/A	26	7	8
TT-Bank	burn()	92	10	12	5	3	2
	mint()	84	10	11	5	3	2
	send()	136	11	14	10	3	2
TT-App	send_fungible_tokens()	34	6	7	20	6	5
	on_rcv_packet()	45	6	7	20	5	4
TT-Properties	send_preserves()	47	7	9	79	7	10
	round_trip()	53	6	8	72	6	7
NFT-Resources	Resource Constructors	N/A	N/A	N/A	4	2	2
	Coupling Invariants	N/A	N/A	N/A	42	10	10
	transfer_tokens!() macro	N/A	N/A	N/A	9	4	5
NFT-Bank	burn()	29	8	7	10	3	3
	mint()	37	8	7	18	3	3
	send()	31	8	7	16	3	3
	create_or_update_class()	14	6	5	0	0	0
NFT-App	send_nft()	56	9	8	50	6	8
	on_rcv_packet()	67	9	8	55	7	6
NFT-Properties	round_trip()	65	6	7	81	6	8

Table 2. Comparison between the syntactic complexity of specifications written with and without resources. Each column considers the ASTs of the specification expressions for the function in that row. **Size** refers to the total number of nodes in the ASTs. **Depth** refers to the height of the tallest AST. **Uniq.** refers to the number of distinct node types occurring in the ASTs.

6.2 Syntactic Complexity

More concise specifications are not necessarily simpler or more desirable. For example, a longer specification may be preferable to a shorter one if the latter involves complex nesting of conditionals, implications, and quantifiers. To evaluate syntactic complexity, we considered the AST nodes of `#[requires()]` and `#[ensures()]` clauses, as well as those of associated specification-related expressions². We quantify the complexity of an AST using three metrics: the total number of nodes in the AST, the maximum depth of the AST, and the number of unique node types occurring within the AST. We classify the node types by differentiating arithmetic and comparison operators, and among Prusti constructs such as `forall` and `old`, while disregarding children in the classification and treating variables and constants uniformly. For example, the expression `a + (b - c)` has three different node types: identifiers (`a`, `b`, and `c`), addition, and subtraction. An overview of the different node types we consider, and the program we implemented to calculate AST complexity, are available in our supplementary material [Anonymous Authors 2023].

We present our results in Table 2. Our results demonstrate that the specifications written using our methodology are syntactically simpler in most cases. In particular, specifications related to BankKeeper compare favourably to the alternative w.r.t. all three metrics: specifications are less

²For example, the function `burn_tokens_post()`, which expresses the postcondition of `burn()`, is also used in the specification of `send_fungible_tokens()`. We associate the body of `burn_tokens_post()` towards the count of `burn()`, rather than `send_fungible_tokens()`.


```

1  pub fn transfer_tokens_post(&self, old_bank:&Self, from:AccountId, to:AccountId, coin:&PrefixedCoin) -> bool {
2      self.unescrowed_coin_balance(coin.denom.base_denom) ==
3      if (is_escrow_account(to) && !is_escrow_account(from)) { ... }
4      else if (!is_escrow_account(to) && is_escrow_account(from)) { ... }
5      else { old_bank.unescrowed_coin_balance(coin.denom.base_denom) } &&
6      forall(|acct_id2: AccountId, denom2: PrefixedDenom|
7          self.balance(acct_id2, denom2) ==
8          if(acct_id2 == from && coin.denom == denom2) { ... }
9          else if (acct_id2 == to && coin.denom == denom2) { ... }
10         else { old_bank.balance(acct_id2, denom2) }) &&
11      forall(|c: BaseDenom| c != coin.denom.base_denom =>
12          self.unescrowed_coin_balance(c) == old_bank.unescrowed_coin_balance(c)
13      )
14  }

```

(a) The postcondition for BankKeeper's `send_tokens()` function, specified in terms of program states.

```

1  #[requires(transfer_money!(self.id(), from, coin))]
2  #[ensures(transfer_money!(self.id(), to, coin))]

```

(b) The specification of `send_tokens()` written using resource reasoning constructs. The macro `transfer_money!()` is defined in Fig. 17.

than $1/10^{\text{th}}$ the size, $1/3^{\text{rd}}$ of the depth, and contain less than $1/5^{\text{th}}$ as many unique nodes. The only area where our specifications are markedly more complex is with respect to the size of the specifications for `send_preserves()` (79 vs 47) and `round_trip()` (72 vs 53). As mentioned in the prior subsection, this is due to the requirement to indicate the resource operations of the functions in addition to the program-state properties. We note that although the size of the coupling invariants is relatively large (comparable with the size of `mint()` and `burn()`), the invariant only needs to be written once, regardless of the number of functions in the program. Therefore, we expect that our methodology would compare even more favourably if applied to larger programs.

6.3 Interpretability

Interpretability, refers to how easy it is to understand the meaning of a specification. We approximate interpretability by considering how much of the specification expresses the *essential aspects* of the program, that is, aspects that would also be explicit in a human language description of the program. For example, the part of a postcondition for `mint()` that specifies the balance will increase is essential, however frame conditions in the specification would not. Intuitively, specifications that mix essential and non-essential aspects are challenging to interpret, because the reader must differentiate between the two in order to understand the intent of the specification.

Our specifications compare favourably w.r.t. this metric: by design, our methodology only considers essential aspects of resource operations. We have not formally quantified how much non-essential code is present in the alternative specifications; however, we note that most of the annotations for BankKeeper express non-essential aspects. For example, the postcondition of `send_tokens()`, shown in Fig. 23a consists mostly of non-essential code. In particular, it includes frame conditions, and also considers separately different cases depending on whether `from` and `to` are escrow accounts. In contrast, our specification using resources (Fig. 23b) expresses the essential aspects in just lines: the first specifying that the sender's tokens are destroyed, and the second specifying that the receiver's tokens are created.

Application	Without Resources (mean / sd)	With Resources (mean / sd)
Token Transfer	65.12s / 0.15s	83.00s / 0.78s
NFT Transfer	57.04s / 0.23s	59.88s / 0.36s

Table 3. Comparison of verification time for the specifications written in the different styles. Results are presented for five runs of the verifier.

6.4 Verification Time

We compared the runtime of the specification written using our methodology, and the alternate version. For each version, we performed five runs, all runs were performed a 10-core Apple M1 Max. Our results are presented in Table 3. The verification time for the NFT transfer application is similar for both versions (59.88s vs 57.04s). There is a larger difference w.r.t. token transfer application: the specification using resources is 27% slower (83s vs 65.12s). This is most likely due to the overhead of casting between the types used to represent resource amounts and the types representing bank balances in the underlying Viper encoding: changing the specification to instead express balance using Viper's permission amount types (i.e., rational numbers as opposed to integers) eliminates the difference (resulting in timings of 88.74s vs 90.38s respectively). As future work, we believe it could be possible to reduce the performance overhead associated with such casts.

6.5 Analysis / Conclusion

Our evaluation shows that specifications written in our methodology compare favourably to specifications written in terms of program states. Our specifications require fewer lines of code and syntactically simpler. Specifications written using our methodology are also easier to interpret: this is demonstrated by the observation that specifications written in terms of program states must express many non-essential properties in their specifications (e.g. frame conditions). Although our specifications sometimes require more time to verify, the increase in time is a reasonable trade-off to make for the simpler specifications. Furthermore, our evaluation indicates that the increase is due to the behaviour of the underlying Viper verifier rather than a fundamental consequence of using our methodology.

7 RELATED WORK

Effect systems [Lucassen and Gifford 1988] extend a type system to include the side-effects via effect types, which typically over-approximate the side-effects an expression is allowed to perform. Our resource specifications can be seen as similar to a kind of effect, but are *precise*, and apply only to changes to our ghost resource state. This distinction (and indirection via our coupling invariants) is crucial to obtaining strong frame properties while still writing local specifications.

Separation logic [Reynolds 2002] enables verification of heap-manipulating programs using local reasoning: assertions describe only the relevant part of the heap, rather than the heap as a whole. Our resource reasoning technique takes clear inspiration from this idea of local reasoning, although our technique intentionally avoids explicit resource reasoning about the concrete program state. Extensions of separation logic facilitate abstraction with user-defined predicates [Parkinson and Bierman 2005], but we note that an abstraction of our e.g. Bank data structure via abstract predicates would typically suffer from the same need for frame conditions about *how* the internals change over a side-effectful function. Our `holds()` construct, which allows introspection on the local resource state, does not have an analogue in separation logic. However, the Viper

intermediate language [Müller et al. 2016] supports resource reasoning and resource introspection via the `perm()` expressions explained in Sec. 4. In contrast to our `holds()` construct, Viper’s `perm()` expressions cannot be used directly in method pre- and postconditions in a generally-sound way; their semantics is not consistent between how a caller and callee interpret their meaning [Müller et al. 2016]. Being an intermediate language, Viper provides features powerful enough to encode our reasoning principles, but places the burden on the user to use these features soundly. In contrast, our `holds` expressions can be used freely in pre- and post-conditions without fear of unsoundness, and the trickier parts of our encoding (Sec. 4) take care of a correct mapping to Viper automatically.

There is substantial prior work focused on verification of smart contracts themselves [Ahrendt and Bubel 2020][Bräm et al. 2021][Mohajerani et al. 2022]: while not the specific focus of our work, these are clearly resource-manipulating programs (used to handle cryptocurrency assets). The verification tool 2Vyper [Bräm et al. 2021] is closest to our work: it provides its own resource reasoning via effect clauses for smart contracts in the Vyper language: these can specify possible resource transfers, and users can also define invariants that connect the resource state to the runtime state. However, there are several technical differences with our work: unlike our system, 2Vyper’s resource specifications describe approximations (in the style of effect systems) of a function’s behaviour, and over representations of the entire resource state; there is no way to partition the resource state into a only a local part that a function is concerned with, which is what eliminates heavyweight frame conditions in our work.

2Vyper’s effect-clauses consist of a multiset of the operations that will occur in their execution, but these only refer to the resource operations performed directly by the function itself: because 2Vyper considers interactions with unverified external code, it is not possible to reason in general about external resource operations. In contrast, because we do not allow untrusted external calls, the specifications in our methodology effectively summarise the resource operations that occur within a method call. We have not yet applied our technique to verify interactions with untrusted code; doing so could be interesting future work.

Ahrendt and Bubel verify Solidity contracts with a proof technique centred around two-state invariants [Ahrendt and Bubel 2020]. They show that *differences* between *wei* amounts (the built-in currency) are powerful for expressing such invariants, similar to the encoding of our `holds` feature into Viper. They address untrusted code and security properties while we do not; on the other hand, their work does not support custom notions of resource, build in resource-like properties, or address data structure framing; their technique is concerned specifically with currency in Solidity.

Other prior work has focused on verification of smart contracts by modelling them as extended finite state machines [Mohajerani et al. 2022]. Our approach is more general, as it is not limited to the domain of smart contracts and does not assume any particular program architecture.

The specification language Chainmail [Drossopoulou et al. 2020] enables user-defined invariants using holistic specifications, which can be used to enforce a wide range of security-related properties, including some related to resources in the program. For example, it is possible to define an invariant that ensures any change in the balance of a particular account is associated with a call to `deposit()` referencing that account. Specifications in Chainmail must still ultimately be phrased in terms of program states; leading to less direct and more-complex specifications. In contrast, our methodology, which treats resources as first class, allows specifications concerning resource operations directly.

Various smart contract languages provide first-class support for resources. The Move language [Blackshear et al. 2019], originally developed by Facebook for the Diem blockchain, supports first-class resources that are implemented with linear types. Obsidian [Coblenz et al. 2020] uses both linear types and

typestate to prevent bugs related to improper handling of resources. Flint [Schrans et al. 2018] supports asset types that encapsulate unsafe operations and provide a safe interface. None of these support static verification concerning resource quantities, or built-in rules to enforce e.g. that are by-default preserved.

8 CONCLUSION

In this paper, we examined the challenges encountered when writing specifications of resource manipulating programs in terms of program state. When using a modular verifier, this approach requires users to explicitly write frame conditions in specifications, and these frame conditions make specifications lengthier and harder to interpret. Furthermore, such specifications do not easily compose, and are not expressive enough to rule out certain kinds of resource-related bugs.

The root cause of these issues is the semantic gap between our high-level, intuitive expectations of how resources behave, and the language used to write specifications in the code. Therefore, we developed a new methodology to support reasoning about resources directly inside specifications, thereby narrowing the semantic gap.

The methodology we developed extends a program verifier with a first-class notion of resources, without requiring support for resources in the source language. Instead, we allow users to define coupling invariants to connect resource operations to program state. These invariants are checked by the verifier, allowing users to describe the behaviour of their program in terms of resource operations rather than as relations on program states.

We implemented our methodology as an extension to the program verifier Prusti, and evaluated our design by using our extended version of Prusti to verify a real-world resource-manipulating program. Our evaluation shows that, compared to a standard Prusti specification written in terms of program states, specifications written using our methodology are more concise, syntactically simpler, and easier to understand.

For future work, we would like to extend our methodology to facilitate interactions with untrusted or external code, as such interactions are typical in dealing with smart contracts. In particular, enforcing coupling invariants for functions that reborrow could increase the applicability of our technique. Finally, we could consider applying our methodology to reason about resources within a program, such as locks, database connections, or file handles.

REFERENCES

- Wolfgang Ahrendt and Richard Bubel. 2020. Functional Verification of Smart Contracts via Strong Data Integrity. In *Leveraging Applications of Formal Methods, Verification and Validation: Applications - 9th International Symposium on Leveraging Applications of Formal Methods, ISOFA 2020, Rhodes, Greece, October 20-30, 2020, Proceedings, Part III (Lecture Notes in Computer Science, Vol. 12478)*, Tiziana Margaria and Bernhard Steffen (Eds.). Springer, 9–24. https://doi.org/10.1007/978-3-030-61467-6_2
- Anonymous Authors. 2023. Supplementary Material. Supplementary material for the paper: Resource Specifications for Resource-Manipulating Programs.
- Vytautas Astrauskas, Aurel Bilý, Jonáš Fiala, Zachary Grannan, Christoph Matheja, Peter Müller, Federico Poli, and Alexander J Summers. 2022. The Prusti Project: Formal Verification for Rust. In *NASA Formal Methods: 14th International Symposium, NFM 2022, Pasadena, CA, USA, May 24–27, 2022, Proceedings*. Springer, 88–108.
- Vytautas Astrauskas, Peter Müller, Federico Poli, and Alexander J Summers. 2019. Leveraging Rust Types for Modular Specification and Verification. *Proceedings of the ACM on Programming Languages* 3, OOPSLA (2019), 1–30.
- Sam Blackshear, Evan Cheng, David L Dill, Victor Gao, Ben Maurer, Todd Nowacki, Alistair Pott, Shaz Qadeer, Dario Rossi Rain, Stephane Sezer, et al. 2019. Move: A Language with Programmable Resources. *Libra Assoc* (2019), 1.
- François Bobot, Jean-Christophe Filliâtre, Claude Marché, and Andrei Paskevich. 2011. Why3: Shepherd Your Herd of Provers. In *Boogie 2011: First International Workshop on Intermediate Verification Languages*. 53–64.
- Christian Bräm, Marco Eilers, Peter Müller, Robin Sierra, and Alexander J Summers. 2021. Rich Specifications for Ethereum Smart Contract Verification. *Proceedings of the ACM on Programming Languages* 5, OOPSLA (2021), 1–30.

- Michael Coblenz, Reed Oei, Tyler Etzel, Paulette Koronkevich, Miles Baker, Yannick Bloem, Brad A Myers, Joshua Sunshine, and Jonathan Aldrich. 2020. Obsidian: Typestate and Assets for Safer Blockchain Programming. *ACM Transactions on Programming Languages and Systems (TOPLAS)* 42, 3 (2020), 1–82.
- Sophia Drossopoulou, James Noble, Julian Mackay, and Susan Eisenbach. 2020. Holistic Specifications for Robust Programs.. In *FASE*. 420–440.
- Christopher Goes. 2020. The Interblockchain Communication Protocol: An Overview. *arXiv preprint arXiv:2006.15918* (2020).
- Christopher Goes. 2022. ICS-20 Fungible Token Transfer Specification. <https://github.com/cosmos/ibc/tree/main/spec/app/ics-020-fungib>
- Andreas M Hein. 2010. Identification and Bridging of Semantic Gaps in the Context of Multi-domain Engineering. In *Forum on Philosophy, Engineering & Technology*. 58–57.
- IBC Standards Committee. 2023. Interchain Standards. <https://github.com/cosmos/ibc>
- Informal Systems Inc. and ibc-rs authors. 2022. ibc-rs. <https://github.com/cosmos/ibc-rs>
- K Rustan M Leino. 2008. This is Boogie 2. *manuscript KRML* 178, 131 (2008), 9.
- J. M. Lucassen and D. K. Gifford. 1988. Polymorphic Effect Systems. In *Proceedings of the 15th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages* (San Diego, California, USA) (POPL '88). Association for Computing Machinery, New York, NY, USA, 47–57. <https://doi.org/10.1145/73560.73564>
- John McCarthy and Patrick J Hayes. 1981. Some Philosophical Problems from the Standpoint of Artificial Intelligence. In *Readings in artificial intelligence*. Elsevier, 431–450.
- Sahar Mohajerani, Wolfgang Ahrendt, and Martin Fabian. 2022. Modeling and Security Verification of State-Based Smart Contracts. *IFAC-PapersOnLine* 55, 28 (2022), 356–362.
- Peter Müller, Malte Schwerhoff, and Alexander J Summers. 2016. Viper: A Verification Infrastructure for Permission-based Reasoning. In *Verification, Model Checking, and Abstract Interpretation: 17th International Conference, VMCAI 2016, St. Petersburg, FL, USA, January 17-19, 2016. Proceedings* 17. Springer, 41–62.
- Matthew Parkinson and Gavin Bierman. 2005. Separation Logic and Abstraction. In *Proceedings of the 32nd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages* (Long Beach, California, USA) (POPL '05). Association for Computing Machinery, New York, NY, USA, 247–258. <https://doi.org/10.1145/1040305.1040326>
- John C Reynolds. 2002. Separation Logic: A Logic for Shared Mutable Data Structures. In *Proceedings 17th Annual IEEE Symposium on Logic in Computer Science*. IEEE, 55–74.
- Franklin Schrans, Susan Eisenbach, and Sophia Drossopoulou. 2018. Writing Safe Smart Contracts in Flint. In *Companion Proceedings of the 2nd International Conference on the Art, Science, and Engineering of Programming*. 218–219.
- Jan Smans, Bart Jacobs, and Frank Piessens. 2009. Implicit Dynamic Frames: Combining Dynamic Frames and Separation Logic. In *ECOOP 2009—Object-Oriented Programming: 23rd European Conference, Genoa, Italy, July 6-10, 2009. Proceedings* 23. Springer, 148–172.
- Haifeng Xi. 2022. ICS-721 Non-Fungible Token Transfer Specification. <https://github.com/cosmos/ibc/tree/main/spec/app/ics-721-nft-tra>