Fast and Reliable Formal Verification of Smart Contracts with the Move Prover[⋆]

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Abstract. The Move Prover (MVP) is a formal verifier for smart contracts written in the Move programming language. MVP has an expressive specification language, and is fast and reliable enough that it can be run routinely by developers and in integration testing. Besides the simplicity of smart contracts and the Move language, three implementation approaches are responsible for the practicality of MVP: (1) an alias-free memory model, (2) fine-grained invariant checking, and (3) monomorphization. The entirety of the Move code for the Diem blockchain has been extensively specified and can be completely verified by MVP in a few minutes. Changes in the Diem framework must be successfully verified before being integrated into the open source repository on GitHub.

Keywords: Smart contracts · formal verification · Move language · Diem blockchain

1 Introduction

The Move Prover (MVP) is a formal verification tool for smart contracts that intends to be used routinely during code development. The verification finishes fast and predictably, making the experience of running MVP similar to the experience of running compilers, linters, type checkers, and other development tools. Building a fast verifier is non-trivial, and in this paper, we would like to share the most important engineering and architectural decisions that have made this possible.

One factor that makes verification easier is applying it to smart contracts. Smart contracts are easier to verify than conventional software for at least three reasons: 1) they are small in code size, 2) they execute in a well-defined, isolated environment, and 3) their computations are typically sequential, deterministic, and have minimal interactions with the environment (e.g., no explicit I/O operations). At the same time, formal verification is more appealing to the advocates for smart contracts because of the large financial and regulatory risks that smart contracts may entail if misbehaved, as evidenced by large losses that have occurred already [?,?,?].

The other crucial factor to the success of MVP is a tight coupling with the *Move* programming language [?]. Move is developed as part of the Diem blockchain [?]

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[⋆⋆] *Correspondence to*: `wgrieskamp@gmail.com` and is designed to be used with formal verification from day one. Move is currently co-evolving with MVP. The language supports specifying pre-, post-, and aborts conditions of functions, as well as invariants over data structures and over the content of the global persistent memory (i.e., the state of the blockchain). One feature that makes verification harder is that quantification can be used freely in specifications.

Despite this specification richness, MVP is capable of verifying the full Move implementation of the Diem blockchain (called the Diem framework [**?**]) in a few minutes. The framework provides functionality for managing accounts and their interactions, including multiple currencies, account roles, and rules for transactions. It consists of about 8,800 lines of Move code and 6,500 lines of specifications (including comments for both), which shows that the framework is extensively specified. More importantly, *verification is fully automated and runs continuously with unit and integration tests*, which we consider a testament to the practicality of the approach. Running the prover in integration tests requires more than speed: it requires reliability, because tests that work sometimes and fail or time out other times are unacceptable in that context.

MVP is a substantial and evolving piece of software that has been tuned and optimized in many ways. As a result, it is not easy to define exactly what implementation decisions lead to fast and reliable performance. However, we can at least identify three major ideas that resulted in dramatic improvements in speed and reliability since the description of an early prototype of MVP [**?**]:

- an *alias-free memory model* based on Move's semantics, which are similar to the Rust programming language;
- *fine-grained invariant checking*, which ensures that invariants hold at every state, except when developer explicitly suspends them; and
- monomorphization, which instantiates type parameters in Move's generic structures, functions, and specification properties.

The combined effect of all these improvements transformed a tool that worked, but often exhibited frustrating, sometimes random [**?**], timeouts on complex and especially on erroneous specifications, to a tool that almost always completes in less than 30 seconds. In addition, there have been many other improvements, including a more expressive specification language, reducing false positives, and error reporting.

The remainder of the paper first introduces the Move language and how MVP is used with it, then discusses the design of MVP and the three main optimizations above. There is also an appendix that describes injection of function specifications.

2 Move and the Prover

Move was developed for the Diem blockchain [**?**], but its design is not specific to blockchains. A Move execution consists of a sequence of updates evolving a *global persistent memory state*, which we just call the *(global) memory*. Similar to other blockchains, updates are a series of atomic transactions. All runtime errors result in a transaction abort, which does not change the blockchain state except to transfer some currency ("gas") from the account that sent the transaction to pay for cost of executing the transaction.

Fig. 1: Account Example Program

```
module Account {
  struct Account has key {
    balance: u64,
  }

  fun withdraw(account: address, amount: u64) acquires Account {
    let balance = &mut borrow_global_mut<Account>(account).balance;
    assert(*balance >= amount, Errors::limit_exceeded());
    *balance = *balance - amount;
  }

  fun deposit(account: address, amount: u64) acquires Account {
    let balance = &mut borrow_global_mut<Account>(account).balance;
    assert(*balance <= Limits::max_u64() - amount, Errors::limit_exceeded());
    *balance = *balance + amount;
  }

  public(script) fun transfer(from: &signer, to: address, amount: u64)
  acquires Account {
    assert(Signer::address_of(from) != to, Errors::invalid_argument());
    withdraw(Signer::address_of(from), amount);
    deposit(to, amount);
  }
}
```

The global memory is organized as a collection of resources, described by Move structures (data types). A resource in memory is indexed by a pair of a type and an address (for example the address of a user account). For instance, the expression `exists<Coin<USD>>(addr)` will be true if there is a value of type `Coin<USD>` stored at `addr`. As seen in this example, Move uses type generics, and working with generic functions and types is rather idiomatic for Move.

A Move application consists of a set of *transaction scripts*. Each script defines a Move function with input parameters but no output parameters. This function updates the global memory and may emit events. The execution of this function can abort because of an abort instruction or implicitly because of a runtime error such as an out-of-bounds vector index.

Programming in Move In Move, one defines transactions via *script functions* which take a set of parameters. Those functions can call other functions. Script and regular functions are encapsulated in *modules*. Move modules are also the place where structs are defined. An illustration of a Move contract is given in Fig. 1 (for a more complete description see the Move Book [**?**]). The example is a simple account which holds a balance in the struct `Account`, and offers the script function `transfer` to manipulate this resource. Scripts generally have *signer* arguments, which are tokens which represent an account address that has been authenticated by a cryptographic signature. The `assert` statement in the example causes a Move transaction to abort execution if the condition is not met. Notice that Move, similar as Rust, supports references (as in `&signer`) and mutable references (as in `&mut T`). However, references cannot be part of structs stored in global memory.

Fig. 2: Account Example Specification

```
module Account {
  spec transfer {
    let from_addr = Signer::address_of(from);
    aborts_if from_addr == to;
    aborts_if bal(from_addr) < amount;
    aborts_if bal(to) + amount > Limits::max_u64();
    ensures bal(from_addr) == old(bal(from_addr)) - amount;
    ensures bal(to) == old(bal(to)) + amount;
  }

  spec fun bal(acc: address): u64 {
    global<Account>(acc).balance
  }

  invariant forall acc: address where exists<Account>(acc):
    bal(acc) >= AccountLimits::min_balance();

  invariant update forall acc: address where exists<Account>(acc):
    old(bal(acc)) - bal(acc) <= AccountLimits::max_decrease();
}
```

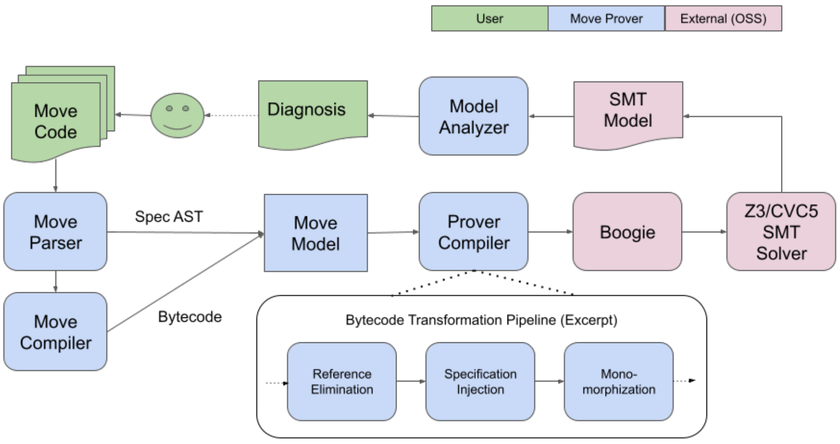
Specifying in Move The specification language supports *Design By Contract* [?]. Developers can provide pre and post conditions for functions, which include conditions over parameters and global memory. Developers can also provide invariants over data structures, as well as the contents of the global memory. Universal and existential quantification over bounded domains, such as like the indices of a vector, as well as effectively unbounded domains, such as memory addresses and integers, are supported. Quantifiers make the verification problem undecidable and cause difficulties with timeouts. However, in practice, we notice that quantifiers have the advantage of allowing more direct formalization of many properties, which increases the clarity of specifications.

Fig. 2 illustrates the specification language by extending the account example in Fig. 1 (for the definition of the specification language see [?]). This adds the specification of the `transfer` function, a helper function `bal` for use in specs, and two global memory invariants. The first invariant states that a balance can never drop underneath a certain minimum. The second invariant refers to an update of global memory with pre and post state: the balance on an account can never decrease in one step more than a certain amount. Note that while the Move programming language has only unsigned integers, the specification language uses arbitrary precision signed integers, making it convenient to specify something like `x + y <= limit`, without the complication of arithmetic overflow.

Specifications for the `withdraw` and `deposit` functions have been omitted in this example. MVP supports omitting specs for non-recursive functions, in which case they are treated as being inlined at caller site.

Running the Prover MVP is fully automatic, like a type checker or linter, and is expected to finish in a reasonable time, so it can be integrated in the regular development workflow. Running MVP on the `module Account` produces multiple errors. The first is this one:

Fig. 3: Move Prover Architecture



```
error: abort not covered by any of the ‘aborts_if‘ clauses
   -- account.move:24:3
    |
13  |       let balance = &mut borrow_global_mut<Account>(account).balance;
    |                          ----------------- abort happened here
    |
    =     at account.move:18: transfer
    =         from = signer{0x18be}
    =         to = 0x18bf
    =         amount = 147u8
    =     at ...
```

MVP detected that an implicit abort condition is missing in the specification of the `withdraw` function. It prints the context of the error, as well as an *execution trace* which leads to the error. Values of variable assignments from the counterexample found by the SMT solver are printed together with the execution trace. Logically, the counterexample presents an assignment to variables where the program fails to meet the specification. In general, MVP attempts to produce readable diagnostics for Move developers without the need of understanding any internals of the prover.

There are more verification errors in this example, related to the global invariants: the code makes no attempt to respect the limits in `min_balance()` and `max_decrease()`. The problem can be fixed by adding more `assert` statements to check that the limits are met (see Appendix B).

The programs and specifications MVP deals with are much larger than this example. The conditions under which a transaction in the Diem framework can abort typically involve dozens of individual predicates, stemming from other functions called by this transaction. Moreover, there are hundreds of memory invariants specified, encoding access control and other requirements for the Diem blockchain.

3 Move Prover Design

The architecture of MVP is illustrated in Fig. 3. Move code (containing specifications) is given as input to the tool chain, which produces two artifacts: an abstract syntax tree (AST) of the specifications, and the generated bytecode. The *Move Model* merges both bytecode and specifications, as well as other metadata from the original code, into a unified object model which is input to the remaining tool chain.

The next phase is the actual *Prover Compiler*, which is a pipeline of bytecode transformations. We focus on the transformations shown (Reference Elimination, Specification Injection, and Monomorphization). The Prover uses a modified version of the Move VM bytecode as an intermediate representation for these transformations, but, for clarity, we describe the transformations at the Move source level.

The transformed bytecode is next compiled into the Boogie intermediate verification language [**?**]. Boogie supports an imperative programming model which is well suited for the encoding of the transformed Move code. Boogie in turn can translate to multiple SMT solver backends, namely Z3 [**?**] and CVC5 [**?**]; the default choice for the Move prover is currently Z3.

3.1 Reference Elimination

The reference elimination transformation is what enables the alias-free memory model in the Move Prover, which is one of the most important factors contributing to the speed and reliability of the system. In most software verification and static analysis systems, the explosion in number of possible aliasing relationships between references leads either to high computational complexity or harsh approximations.

In Move, the reference system is based on *borrow semantics* [**?**] as in the Rust programming language. The initial borrow must come from either a global memory or a local variable on stack (both referred to as *locations* from now on). For local variables, one can create immutable references (with syntax `&x`) and mutable references (with syntax `&mut x`). For global memories, the references can be created via the `borrow_global` and `borrow_global_mut` built-ins. Given a reference to a whole struct, field borrowing can occur via `&mut x.f` and `&x.f`. Similarly, with a reference to a vector, element borrowing occurs via native functions `Vector::borrow(v, i)` and `Vector::borrow_mut(v, i)`. Move provides the following guarantees, which are enforced by the borrow checker:

– For any location, there can be either exactly one mutable reference, or n immutable references. Enforcing this rule is similar to enforcing the borrow semantics in Rust, except for global memories, which do not exist in Rust. For global memories, this rule is enforced via the `acquires` annotations. Using Fig. 1 as an example, function `withdraw` `acquires` the `Account` global location, therefore, `withdraw` is prohibited from calling any other function that might also borrow or modify the `Account` global memory (e.g., `deposit`).
– The lifetime of references to data on the stack cannot exceed the lifetime of the stack location. This includes global memories borrowed inside a function as well—a reference to a global memory cannot be returned from the function, neither in whole nor in parts.

These properties effectively permit the *elimination of references* from a Move program, eliminating need to reason about aliasing.

Immutable References Immutable references are replaced by values. An example of the applied transformation is shown below. We remove the reference type constructor and all reference-taking operations from the code:

```
fun select_f(s: &S): &T { &s.f } ⇝ fun select_f(s: S): T { s.f }
```

When executing a Move program, immutable references are important to avoid copies for performance and to enforce ownership; however, for symbolic reasoning on correct Move programs, the distinction between immutable references and values is unimportant.

Mutable References Each mutation of a location `l` starts with an initial borrow for the whole data stored in this location. This borrow creates a reference `r`. As long as `r` is alive, Move code can either update its value (`*r = v`), or derive a sub-reference (`r' = &mut r.f`). The mutation ends when `r` (and the derived `r'`) go out of scope.

The borrow checker guarantees that during the mutation of the data in `l`, no other reference can exist into the same data in `l` – meaning that it is impossible for other Move code to test whether the value has mutated while the reference is held.

These semantics allow mutable references to be handled via *read-update-write* cycles. One can create a copy of the data in `l` and perform a sequence of mutation steps which are represented as purely functional data updates. Once the last reference for the data in `l` goes out of scope, the updated value is written back to `l`. This converts an imperative program with references into an imperative program which only has state updates on global memory or variables on the stack, with no aliasing. We illustrate the basics of this approach by an example:

```
fun increment(x: &mut u64) { *x = *x + 1 }
fun increment_field(s: &mut S) { increment(&mut s.f) }
fun caller(): S { let s = S{f:0}; update(&mut s); s }
⇝
fun increment(x: u64): u64 { x + 1 }
fun increment_field(s: S): S { s[f = increment(s.f)] }
fun caller(): S { let s = S{f:0}; s = update(s); s }
```

Dynamic Mutable References While the setup in above example covers a majority of the use cases in every day Move code, the general case is more complex, since the referenced location may not be known statically. Consider the following Move code:

```
let r = if (p) &mut s1 else &mut s2;
increment_field(r);
```

Additional information in the logical encoding is required to deal with such cases. When a reference goes out of scope, we need to know from which location it was derived in order to write back the updated value. Fig. 4 illustrates the approach for doing this. Essentially, a new type `Mut<T>`, which is internal to MVP, is introduced to track both the location from which `T` was derived and the value of `T`. `Mut<T>` supports the following operations:

– `Mvp::mklocal(value, LOCAL_ID)` creates a new mutation value for a local with the given local id. A local id uniquely identifies a local variable in the function.

Fig. 4: Elimination of Mutable References

```
fun increment(x: &mut u64) { *x = *x + 1 }
fun increment_field(s: &mut S) {
  let r = if (s.f > 0) &mut s.f else &mut s.g;
  increment(r)
}
fun caller(p: bool): (S, S) {
  let s1 = S{f:0, g:0}; let s2 = S{f:1, g:1};
  let r = if (p) &mut s1 else &mut s2;
  increment_field(r);
  (s1, s2)
}
⇝
fun increment(x: Mut<u64>): Mut<u64> { Mvp::set(x, Mvp::get(x) + 1) }
fun increment_field(s: Mut<S>): Mut<S> {
  let r = if (s.f > 0) Mvp::field(s.f, S_F) else Mvp::field(s.g, S_G);
  r = increment(r);
  if (Mvp::is_field(r, S_F))
    s = Mvp::set(s, Mvp::get(s)[f = Mvp::get(r)]);
  if (Mvp::is_field(r, S_G))
    s = Mvp::set(s, Mvp::get(s)[g = Mvp::get(r)]);
  s
}
fun caller(p: bool): S {
  let s1 = S{f:0, g:0}; let s2 = S{f:1, g:1};
  let r = if (p) Mvp::mklocal(s1, CALLER_s1)
          else Mvp::mklocal(s2, CALLER_s2);
  r = increment_field(r);
  if (Mvp::is_local(r, CALLER_s1))
    s1 = Mvp::get(r);
  if (Mvp::is_local(r, CALLER_s2))
    s2 = Mvp::get(r);
  (s1, s2)
}
```

- Similarly, `Mvp::mkglobal(value, TYPE_ID, addr)` creates a new mutation for a global with given type and address.
- With `r' = Mvp::field(r, FIELD_ID)` a mutation value for a sub-reference is created for the identified field.
- The value of a mutation is replaced with `r' = Mvp::set(r, v)` and retrieved with `v = Mvp::get(r)`.
- With the predicate `Mvp::is_local(r, LOCAL_ID)` one can test whether `r` was derived from the given local, and with `Mvp::is_global(r, TYPE_ID, addr)` for a specific global location. `Mvp::is_field(r, FIELD_ID)` tests whether `r` is derived from the given field.

MVP implements the illustrated transformation by construction a *borrow graph* from the program via data flow analysis. This graph tracks both when references are released as well as how they relate to each other: e.g. `r' = &mut r.f` creates an edge from `r` to `r'` labeled with `f`, and `r' = &mut r.g` creates another also starting from `r`. The borrow analysis is inter-procedural, requiring computed summaries for the borrow graph of called functions.

The resulting borrow graph is then used to guide the transformation, inserting the operations of the `Mut<T>` type as illustrated in Fig 4. Specifically, when the borrow on a reference ends, the associated mutation value must be written back to its parent mutation or the original location (e.g. line 29 in Fig. 4). The presence of multiple possible origins leads to case distinctions via `Mvp::is_X` predicates; however, these cases are rare in actual Move programs.

3.2 Global Invariant Injection

Correctness of smart contracts is largely about the correctness of the blockchain state, so global invariants are particular important in the move specification language. For example, in the Diem framework, global invariants can capture the requirement that an account be accompanied by various other types that are be stored at the same address and the requirement certain state changes are only permitted for certain accounts by the access control scheme.

Most software verification tools prove that functions preserve invariants by assuming the invariant at the entry to each function and proving them at the exit. In a module or class, it is only necessary to prove that invariants are preserved by public functions, since invariants are often violated internally in the implementation of a module or class. An earlier version of the Move Prover used exactly this approach.

The current implementation of the Prover takes the opposite approach: it ensures that invariants hold after every instruction, unless explicitly directed to suspend some invariants by a user. This *fine-grained* approach has performance advantages, because, unless suspended, *invariants are only proven when an instruction is executed that could invalidate them*, and the proofs are often computationally simple because *the change from a single instruction is usually small*. Relatively few invariants are suspended, and, when they are, it is over a relatively small span of instructions, preserving these advantages. There is another important advantage, which is that invariants hold almost everywhere in the code, so they are available to approve other properties, such as abort conditions. For example, if a function accesses type `T1` and then type `T2`, the access to `T2` will never abort if the presence of `T1` implies the presence of `T2` at every state in the body of the function. This situation occurs with some frequency in the Diem framework.

Invariant Types and Proof Methodology *Inductive* invariants are properties declared in Move modules that must (by default) hold for the global memory at all times. Those invariants often quantify over addresses (See Fig. 2 for example.) Based on Move's borrow semantics, inductive invariants don't need to hold while memory is mutated because the changes are not visible to other code until the change is written back. This is reflected by the reference elimination described in Sec. 3.1,

Update invariants are properties that relate two states, a previous state and the current state. Typically they are enforced after an update of global memory. The `old` operator is used to evaluate specification expressions in the previous state.

Verification of both kinds of invariants can be *suspended*. That means, instead of being verified at the time a memory update happens, they are verified at the call site of the function which updates memory. This feature is necessitated by fine-grained invariant checking, because invariants sometimes do not hold in the midst of internal computations of a module. For example, a relationship between state variables may

Fig. 5: Basic Global Invariant Injection

```
fun f(a: address) {
  let r = borrow_global_mut<S>(a);
  r.value = r.value + 1
}
invariant [I1] forall a: address: global<S>(a).value > 0;
invariant [I2] update forall a: address:
    global<S>(a).value > old(global<S>(a).value);
⇝
fun f(a: address) {
  spec assume I1;
  Mvp::snapshot_state(I2_BEFORE);
  r = <increment mutation>;
  spec assert I1;
  spec assert I2[old = I2_BEFORE];
}
```

not hold when the variables are being updated sequentially. Functions with external callers (public or script functions) cannot suspend invariant verification, since the invariants are assumed to hold at the beginning and end of each such function.

Inductive invariants are proven by induction over the evolution of the global memory. The base case is that the invariant must hold in the empty state that precedes the genesis transaction. For the induction step, we can assume that the invariant holds at each verified function entry point for which it is not suspended, and now must prove that it holds after program points which are either direct updates of global memory, or calls to functions which suspend invariants.

For update invariants, no induction proof is needed, since they just relate two memories. The pre-state is some memory captured before an update happens, and the post state the current state.

Modular Verification We wish to support open systems to which untrusted modules can be added with no chance of violating invariants that have already been proven. For each invariant, there is a defined subset of Move modules (called a *cluster*). If the invariant is proven for the modules in the cluster, it is guaranteed to hold in all other modules – even those that were not yet defined when the invariant was proven. The cluster must contain every function that can invalidate the invariant, and, in case of invariant suspension, all callers of such a function. Importantly, functions outside the cluster can never invalidate an invariant. Those functions trivially preserve the invariant, so it is only necessary to verify functions defined in the cluster.

MVP verifies a given set of modules at a time (typically one). The modules being verified are called the *target modules*, and the global invariants to be verified are called *target invariants*, which are all invariants defined in the target modules. The cluster is then the smallest set as specified above such that all target modules are contained.

Basic Translation We first look at injection of global invariants in the absence of type parameters. Fig. 5 contains an example for the supported invariant types and their injection into code. The first invariant, `I1`, is an inductive invariant. It is assumed on function entry, and asserted after the state update. The second, `I2`, is an

Fig. 6: Global Invariant Injection and Genericity

```
invariant [I1] global<S<u64>>(0).value > 1;
invariant<T> [I2] global<S<T>>(0).value > 0;
fun f(a: address) { borrow_global_mut<S<u8>>(0).value = 2 }
fun g<R>(a: address) { borrow_global_mut<S<R>>(0).value = 3 }
⇝
fun f(a: address) {
  spec assume I2[T = u8];
  <<mutate>>
  spec assert I2[T = u8];
}
fun g<R>(a: address) {
  spec assume I1; spec assume I2[T = R];
  <<mutate>>
  spec assert I1; spec assert I2[T = R];
}
```

update invariant, which relates pre and post states. For this a state snapshot is stored under some label `I2_BEFORE`, which is then used in an assertion.

Global invariant injection is optimized by knowledge of the prover, obtained by static analysis, about accessed and modified memory. Let `accessed(f)` be the memory accessed by a function, and `modified(f)` be the memory modified. Let `accessed(I)` by an invariant (including transitively by all functions it calls).

- Inject `assume I` at entry to `f` *if* `accessed(f)` has overlap with `accessed(I)`.
- Inject `assert I` after each program step if one of the following is true (a) the step modifies a memory location `M in accessed(I)` or, (b) the step is a call to function `f'` in which `I` is suspended and `modifies(f')` intersects with `accessed (I)`. Also, if `I` is an update invariant, inject a save of a memory snaptshot before the update or call.

Genericity Generic type parameters make the problem of determining whether a function can modify an invariant more difficult. Consider the example in Fig. 6. Invariant `I1` holds for a specific type instantiation `S<u64>`, whereas `I2` is generic over all type instantiations for `S<T>`.

The non-generic function `f` which works on the instantiation `S<u8>` will have to inject the *specialized* instance `I2[T = u8]`. The invariant `I1`, however, does not apply for this function, because there is no overlap with `S<u64>`. In contrast, `g` is generic in type `R`, which could be instantiated to `u64`. So, `I1`, which applies to `S<u64>` needs to be injected in addition to `I2`.

The general solution depends on type unification. Given the accessed memory of a function `f<R>` and an invariant `I<T>`, we compute the pairwise unification of memory types. Those types are parameterized over `R` resp. `T`. Successful unification results in a substitution for both type parameters, and we include the invariant with `T` specialized according to the substitution.

3.3 Monomorphization

Monomorphization is a transformation which removes generic types from a Move program by *specializing* the program for relevant type instantiations. In the context

Fig. 7: Basic Monomorphization

```
struct S<T> { .. }
fun f<T>(x: T) { g<S<T>>(S(x)) }
fun g<S:key>(s: S) { move_to<S>(.., s) }
⤳
struct T{}
struct S_T{ .. }
fun f_T(x: T) { g_S_T(S_T(x)) }
fun g_S_T(s: S_T) { move_to<S_T>(.., s) }
```

of verification, the goal is that the specialized program verifies if and only if the generic program verifies in an encoding which supports types as first class values. We expect the specialized program to verify faster because it avoids the problem of generic representation of values, supporting a multi-sorted representation in the SMT logic.

To verify a generic function for all possible instantiations, monomorphization skolemizes the type parameter, i.e. the function is verified for a new type with no special properties that represents an arbitrary type. It then specializes all called functions and used data types with this new type and any other concrete types they may use. Fig. 7 sketches this approach.

However, this approach has one issue: the type of genericity Move provides does not allow for full type erasure (unlike many programming languages) because types are used to *index* global memory (e.g. `global<S<T>>(addr)` where `T` is a generic type). Consider the following Move function:

```
fun f<T>(..) { move_to<S<T>>(s, ..); move_to<S<u64>>(s, ..) }
```

Depending on how `T` is instantiated, this function behaves differently. Specifically, if `T` is instantiated with `u64` the function will always abort at the second `move_to`, since the target location is already occupied.

The important property enabling monomorphization in the presence of such type dependent code is that one can identify the situation by looking at the memory accessed by code and injected specifications. From this one can derive *additional instantiations of the function* which need to be verified. In the example above, verifying both `f_T` and an instantiation `f_u64` will cover all relevant cases of the function behavior.

The algorithm for computing the instances that require verification works as follows. Let `f<T1,..,Tn>` be a verified target function which has all specifications injected and inlined function calls expanded.

– For each memory `M in modified(f)`, if there is a memory `M' in modified(f) + accessed(f)` such that `M` and `M'` can unify via `T1,..,Tn`, collect an instantiation of the type parameters `Ti` from the resulting substitution. This instantiation may not assign values to all type parameters, and those unassigned parameters stay as is. For instance, `f<T1, T2>` might have a partial instantiation `f<T1, u8>`.
– Once all partial instantiations are computed, the set is extended by unifying the instantiations against each other. If `<T>` and `<T'>` are in the set, and they unify under the substitution `s`, then `<s(T)>` will also be part of the set. For example, consider `f<T1, T2>` which modifies `M<T1>` and `R<T2>`, as well as accesses `M<u64>`

and `R<u8>`. From this the instantiations `<u64, T2>` and `<T1, u8>` are computed, and the additional instantiation `<u64, u8>` will be added to the set.
– If after computing and extending instantiations any type parameters remain, they are skolemized into a given type as described earlier.

To understand the correctness of this procedure, consider the following arguments (a full formal proof is outstanding):

– *Direct interaction* Whenever a modified memory `M<t>` can influence the interpretation of `M<t'>`, a unifier must exist for the types `t` and `t'`, and an instantiation will be verified which covers the overlap of `t` and `t'`.
– *Indirect interaction* If there is an overlap between two types which influences whether another overlap is semantically relevant, the combination of both overlaps will be verified via the extension step.

Notice that even though it is not common in regular Move code to work with both memory `S<T>` and, say, `S<u64>` in one function, there is a scenario where such code is implicitly created by injection of global invariants. Consider the example in Fig. 6. The invariant `I1` which works on `S<u64>` is injected into the function `g<R>` which works on `S<R>`. When monomorphizing `g`, we need to verify an instance `g_u64` in order to ensure that `I1` holds.

4 Analysis

Reliability and Performance The three improvements described above resulted in a major qualitative change in performance and reliability. In the version of MVP released in September 2020, correct examples verified fairly quickly and reliably. But that is because we needed speed and reliability, so we disabled some properties that always timed out and others that timed out unpredictably when there were small changes in the framework. We learned that incorrect programs or specifications would time out predictably enough that it was a good bet that examples that timed out were erroneous. However, localizing the error to fix it was *very* hard, because debugging is based on a counterexample that violates the property, and getting a counterexample requires termination!

With each of the transformations described, we witnessed significant speedups and, more importantly, reductions in timeouts. Monomorphization was the last feature implemented, and, with it, timeouts almost disappeared. Although this was the most important improvement in practice, it is difficult to quantify because there have been many changes in Diem framework, its specifications, MVP, and even the Move language over that time.

It is simpler (but less important) to quantify the changes in run time of MVP on one of our more challenging modules, the `DiemAccount` module, which is the biggest module in the Diem framework. This module implements basic functionality to create and maintain multiple types of accounts on the blockchain, as well as manage their coin balances. It was called `LibraAccount` in release 1.0 of MVP, and is called `DiemAccount` today. The comparison requires various patches as described in [**?**]. The table below lists the consolidated numbers of lines, functions, invariants, conditions (requires, ensures, and aborts-if), as well as the verification times:

Module	Lines	Functions	Invariants	Conditions	Timing
LibraAccount	1975	72	10	113	**9.899s**
DiemAccount	2554	64	32	171	**7.340s**

Notice that `DiemAccount` has significantly grown in size compared to the older version. Specifically, additional specifications have been added. Moreover, in the original `LibraAccount`, some of the most complex functions had to be disabled for verification because the old version of MVP would time out on them. In contrast, in `DiemAccount` and with the new version, all functions are verified. Verification time has been improved by roughly 20%, *in the presence of three times more global invariants, and 50% more function conditions*.

We were able to observe similar improvements for the remaining of the 40 modules of the Diem framework. All of the roughly half-dozen timeouts resolved after introduction of the transformations described in this paper.

Causes for the Improvements It's difficult to pin down and measure exactly why the three transformations described improved performance and reliability so dramatically. We have explained some reasons in the subsections above: the alias-free memory model reduced search through combinatorial sharing arrangments, and the fine-grained invariant checking results in simpler formulas for the SMT solver.

We found that most timeouts in specifications stemmed from our liberal use of quantifiers. To disprove a property P_0 after assuming a list of properties, $P_1, \ldots p_n$, the SMT solver must show that $\neg P_0 \wedge P_1 \wedge \ldots \wedge P_n$ is satisfiable. The search usually involves instantiating universal quantifiers in $P_1, \ldots, P_n$. The SMT solver can do this endlessly, resulting in a timeout. Indeed, we often found that proving a postcondition false would time out, because the SMT solver was instantiating quantifiers to find a satisfying assignment of $P_1 \wedge \ldots \wedge P_n$. Simpler formulas result in fewer intermediate terms during solving, resulting in fewer opportunities to instantiate quantified formulas.

We believe that one of the biggest impacts, specifically on removing timeouts and improving predictability, is monomorphization. The reason for this is that monomorphization allows a multi-sorted representation of values in Boogie (and eventually the SMT solver). In contrast, before monomorphization, we used a universal domain for values in order to represent values in generic functions, roughly as follows:

```
  type Value = Num(int) | Address(int) | Struct(Vector<Value>) | ...
```

This creates a large overhead for the SMT solver, as we need to exhaustively inject type assumptions (e.g. that a `Value` is actually an `Address`), and pack/unpack values. Consider a quantifier like `forall a: address: P(x)` in Move. Before monomorphization, we have to represent this in Boogie as `forall a: Value: is#Address(a)=> P(v#Address(a))`. This quantifier is triggered where ever `is#Address(a)` is present, independent of the structure of `P`. Over-triggering or inadequate triggering of quantifiers is one of the suspected sources of timeouts, as also discussed in [?].

Moreover, before monomorphization, global memory was indexed in Boogie by an address and a type instantiation. That is, for `struct R<T>` we would have one Boogie array `[Type, int]Value`. With monomorphization, the type index is eliminated, as we create different memory variables for each type instantiation. Quantification over memory content works now on a one-dimensional instead of an n-dimensional Boogie array.

Discussion and Related Work Many approaches have been applied to the verification of smart contracts; see e.g. the surveys [?,?]. [?] refers to at least two dozen systems for smart contract verification. It distinguishes between *contract* and *program* level approaches. Our approach has aspects of both: we address program level properties via pre/post conditions, and contract ("blockchain state") level properties via global invariants. To the best of our knowledge, among the existing approaches, the Move ecosystem is the first one where contract programming and specification language are fully integrated, and the language is designed from first principles influenced by verification. Methodologically, Move and the Move prover are thereby closer to systems like Dafny [?], or the older Spec# system [?], where instead of adding a specification approach posterior to an existing language, it is part from the beginning. This allows us not only to deliver a more consistent user experience, but also to make verification technically easier by curating the programming language.

In contrast to other approaches that only focus on specific vulnerability patterns [?,?,?,?], MVP offers a universal specification language. To the best of our knowledge, no existing specification approach for smart contracts based on inductive Hoare logic has similar expressiveness. We support universal quantification over arbitrary memory content, a suspension mechanism of invariants to allow non-atomic construction of memory content, and generic invariants. For comparison, the SMT Checker build into Solidity [?,?,?] does not support quantifiers, because it interprets programming language constructs (requires and assert statements) as specifications and has no dedicated specification language. While in Solidity one can simulate aspects of global invariants using modifiers by attaching pre/post conditions, this is not the same as our invariants, which are guaranteed to hold independent of whether a user may or (accidentally) may not attach a modifier, and which are optimized to be only evaluated as needed.

While the expressiveness of Move specifications comes with the price of undecidability and the dependency from heuristics in SMT solvers, MVP deals with this by its elaborated translation to SMT logic, as described in this paper. The result is a practical verification system that is fully integrated into the Diem blockchain production process, running in continuous integration, which is (to the best of our knowledge) a first in the industry.

The individual techniques we described are novel each by themselves. *Reference elimination* relies on borrow semantics, similar as in the Rust [?] language. We expect reference elimination to apply for the safe subset of Rust, though some extra work would be needed to deal with references aggregated by structs. However, we are not aware of that something similar has been attempted in existing Rust verification work [**?**,**?**,**?**,**?**]. *Global invariant injection* and the approach to minimize the number of assumptions and assertions is not applied in any existing verification approach we know of; however, we co-authored a while ago a similar line of work for *runtime checking* of invariants in Spec# [**?**], yet that work never left the conceptual state. *Monomorphization* is well known as a technique for compiling languages like C++ or Rust, where it is called specialization; however, we are not aware of it being generalized for modular verification of generic code where full type erasure is not possible, as it is the case in Move.

Future Work MVP is conceived as a tool for achieving higher assurance systems, not as a bug hunting tool. Having at least temporarily achieved satisfactory performance and reliability, we are turning our attention to the question of the goal of higher assurance, which raises several issues. If we're striving for high assurance, it would be great to be able to measure progress towards that goal. Since system requirements often stem from external business and regulatory needs, lightweight processes for exposing those requirements so we know what needs to be formally specified would be highly desirable.

As with many other systems, it is too hard to write high-quality specifications. Our current specifications are more verbose than they need to be, and we are working to require less detailed specifications, especially for individual functions. We could expand the usefulness of MVP for programmers if we could make it possible for them to derive value from simple reusable specifications. Finally, software tools for assessing the consistency and completeness of formal specifications would reduce the risk of missing bugs because of specification errors.

However, as more complex smart contracts are written and as more people write specifications, we expect that the inherent computational difficulty of solving logic problems will reappear, and there will be more opportunities for improving performance and reliability. In addition to translation techniques, it will be necessary to identify opportunities to improve SMT solvers for the particular kinds of problems we generate.

5 Conclusion

We described key aspects of the Move prover (MVP), a tool for formal verification of smart contracts written in the Move language. MVP has been successfully used to verify large parts of the Diem framework, and is used in continuous integration in production. The specification language is expressive, specifically by the powerful concept of global invariants. We described key implementation techniques which (as confirmed by our benchmarks) contributed to the scalability of MVP. One of the main areas of our future research is to improve specification productivity and reduce the effort of reading and writing specs, as well as to continue to improve speed and predictability of verification.

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Fig. 8: Requires, Ensures, and AbortsIf Injection

```
  fun f(x: u64, y: u64): u64 { x + y }
  spec f {
    requires x < y;
    aborts_if x + y > MAX_U64;
    ensures result == x + y;
  }
  fun g(x: u64): u64 { f(x, x + 1) }
  spec g {
    ensures result > x;
  }
  ⇝
  fun f(x: u64, y: u64): u64 {
    spec assume x < y;
    let result = x + y;
    spec assert result == x + y;     // ensures of f
    spec assert                      // negated abort_if of f
      !(x + y > MAX_U64);
    result
  } onabort {
    spec assert                      // abort_if of f
      x + y > MAX_U64;
  }
  fun g(x: u64): u64 {
    spec assert x < x + 1;           // requires of f
if inlined
    let result = inline f(x, x + 1);
elif opaque
    if (x + x + 1 > MAX_U64) abort;  // aborts_if of f
    spec assume result == x + x + 1; // ensures of f
endif
    spec assert result > x;          // ensures of g
    result
  }
```

A Injection of Function and Data Specifications

In this appendix we describe, for the interested reader, the design of function and data specification injection (requires, ensures, aborts_if, modifies, emits, and data invariants). While the impact on speed and reliability of verification might have been not that significant, these designs were fine tuned over time as well. With this, a comprehensive coverage of the translation of all specification constructs in MVP is provided.

A.1 Function Specifications

The injection of basic function specifications is illustrated in Fig. 8. An extension of the Move source language is used to specify abort behavior. With `fun f(){ .. } onabort { conditions }` a Move function is defined where `conditions` are assume or assert statements that are evaluated at every program point the function aborts (either implicitly or with an `abort` statement). This construct simplifies the presentation and corresponds to a per-function abort block on bytecode level which is target of branching.

Fig. 9: Modifies Injection

```
fun f(addr: address) { move_to<T>(addr, T{}) }
spec f {
  pragma opaque;
  ensures exists<T>(addr);
  modifies global<T>(addr);
}
fun g() { f(0x1) }
spec g {
  modifies global<T>(0x1); modifies global<T>(0x2);
}
⇝
fun f(addr: address) {
  let can_modify_T = {addr};       // modifies of f
  spec assert addr in can_modify; // permission check
  move_to<T>(addr, T{});
}
fun g() {
  let can_modify_T = {0x1, 0x2};  // modifies of g
  spec assert {0x1} <= can_modify_T; // permission check
  spec havoc global<T>(0x1);       // havoc modified memory
  spec assume exists<T>(0x1);      // ensures of f
}
```

An aborts condition is translated into two different asserts: one where the function aborts and the condition must hold (line 21), and one where it returns and the condition must *not* hold (line 17). If there are multiple `aborts_if`, they are or-ed. If there is no abort condition, no asserts are generated. This means that once a user specifies aborts conditions, they must completely cover the abort behavior of the code. (The prover also provides an option to relax this behavior, where aborts conditions can be partial and are only enforced on function return.)

For a function call site we distinguish two variants: the call is *inlined* (line 25) or it is *opaque* (line 27). For inlined calls, the function definition, with all injected assumptions and assertions turned into assumptions (as those are considered proven) is substituted. For opaque functions the specification conditions are inserted as assumptions. Methodologically, opaque functions need precise specifications relative to a particular objective, where as in the case of inlined functions the code is still the source of truth and specifications can be partial or omitted. However, inlining does not scale arbitrarily, and can be only used for small function systems.

Notice we have not discussed the way how to deal with relating pre and post states yet, which requires taking snapshots of state (e.g. `ensures x == old(x)+ 1`); the example in Fig. 8 does not need it. Snapshots of state are discussed for global update invariants in Sec. 3.2.

Modifies The `modifies` condition specifies that a function only changes specific memory. It comes in the form `modifies global<T>(addr)`, and its injection is illustrated in Fig. 9.

A type check is used to ensure that if a function has one or more `modifies` conditions all called functions which are *opaque* have a matching modifies declaration.

Fig. 10: Emits Injection

```
 1  use Std::Event;
 2  struct E has drop, store { m: u64 }
 3  fun f(h: &mut Event::EventHandle<E>, x: u64) {
 4    Event::emit_event(h, E{m:0});
 5    if (x > 0) {
 6      Event::emit_event(h, E{m:x});
 7    }
 8  }
 9  spec f {
10    emits E{m:0} to h;
11    emits E{m:x} to h if x > 0;
12  }
13  ⇝
14  fun f(h: &mut Event::EventHandle<E>, x: u64) {
15    es = Mvp::ExtendEventStore(es, h, E{m:0}); // emitting event
16    if (x > 0) {
17      es = Mvp::ExtendEventStore(es, h, E{m:x}); // emitting event
18    }
19    let actual_es = Mvp::subtract(es, old(es)); // events emitted by f
20    let expected_es = Mvp::CondExtendEventStore( // specified events
21      Mvp::ExtendEventStore(Mvp::EmptyEventStore, E{m:x}, h),
22      E{m:x}, h, x>0);
23    spec assert Mvp::includes(expected_es, actual_es); // spec completeness
24    spec assert Mvp::includes(actual_es, expected_es); // spec relevance
25  }
```

This is important so we can relate the callees memory modifications to that what is allowed at caller side.

At verification time, when an operation is performed which modifies memory, an assertion is emitted that modification is allowed (e.g. line 14). The permitted addresses derived from the modifies clause are stored in a set `can_modify_T` generated by the transformation. Instructions which modify memory are either primitives (like `move_to` in the example) or function calls. If the function call is inlined, modifies injection proceeds (conceptually) with the inlined body. For opaque function calls, the static analysis has ensured that the target has a modifies clause. This clause is used to derive the modified memory, which must be a subset of the modified memory of the caller (line 19).

For opaque calls, we also need to *havoc* the memory they modify (line 20), by which is meant assigning an unconstrained value to it. If present, ensures from the called function, injected as subsequent assumptions, are further constraining the modified memory.

Emits The injection for the `emits` clause is illustrated in Fig. 10. The `emits` clause specifies the events that a function is expected to emit. It comes in the form `emits message to handle if condition` (e.g., line 11). The condition part (i.e., `if condition`) can be omitted if the event is expected to be emitted unconditionally (e.g., line 10).

The function call to `Event::emit_event` (e.g., line 4) is transformed into the statement to extend `es` with the event to emit (e.g., line 15). `es` is a global variable

Fig. 11: Data Invariant Injection

```
struct S { a: u64, b: u64 }
spec S { invariant a < b }
fun f(s: S): S {
  let r = &mut s;
  r.a = r.a + 1;
  r.b = r.b + 1;
  s
}
⇝
fun f(s: S): S {
  spec assume s.a < s.b;      // assume invariant for s
  let r = Mvp::local(s, F_s); // begin mutation of s
  r = Mvp::set(r, Mvp::get(r)[a = Mvp::get(r).a + 1]);
  r = Mvp::set(r, Mvp::get(r)[b = Mvp::get(r).b + 1]);
  spec assert                 // invariant enforced
    Mvp::get(r).a < Mvp::get(r).b;
  s = Mvp::get(r);            // write back to s
  s
}
```

of type `EventStore` which is a map where the key is an event handle and the value is the event stream of the handle (modeled as a bag of messages).

In line 19, `actual_es` represents the portion of the EventStore that only comprises the events that the program (i.e., `f`) actually emits. In line 20, `expected_es` is constructed from the `emits` specification which contains all of the expected events specified by the `emits` clauses. Having these, two assertions using `Mvp::includes` (multiset inclusion relation per event handle) are injected.

- One asserts that `expected_es` includes `actual_es`, meaning that the function only emits the events that are expected (e.g., line 23). This would be violated if there is any event emitted by `f` that is not covered by some `emits` clause.
- The other asserts that `actual_es` includes `expected_es`, meaning that the function emits all of the events that are expected (e.g., line 24). This would be violated if `f` does not emit the expected event which a `emits` clause specifies.

We also handle opaque calls properly although it is not illustrated in Fig. 10. Suppose `f` is an opaque function, and another function `g` calls `f`. In the transformation of `g`, the event store `es` extends with the expected events of `f` (i.e., the events specified by the `emits` clauses of `f`) in a similar way to how `expected_es` is constructed in line 20.

A.2 Data Invariants

A data invariant specifies a constraint over a struct value. The value is guaranteed to satisfy this constraint at any time. Thus, when a value is constructed, the data invariant needs to be verified, and when it is consumed, it can be assumed to hold.

In Move's reference semantics, construction of struct values is often done via a sequence of mutations via mutable references. It is desirable that *during* such mutations, assertion of the data invariant is suspended. This allows to state invariants which reference multiple fields, where the fields are updated step-by-step. Move's borrow semantics and concept of mutations provides a natural way how to defer invariant evaluation: at the point a mutable reference is released, mutation ends, and the data invariant can be enforced. In other specification formalisms, we would need a special language construct for invariant suspension. Fig. 11 gives an example, and shows how data invariants are reduced to assert/assume statements.

The implementation of data invariants hooks into reference elimination, described in Sec. 3.1. As part of this the lifetime of references is computed. Whenever a reference is released and the mutated value is written back, we also assert the data invariant. In addition, the data invariant is asserted when a struct value is directly constructed.

B Corrected Account Example

To fix the verification errors from the account example in Fig. 1 and Fig. 2, the following changes would need to be made:

```
module Account {
  ...

  fun withdraw(account: address, amount: u64) acquires Account {
    assert(amount <= AccountLimits::max_decrease(), Errors::
        invalid_argument()); // MISSING
    let balance = &mut borrow_global_mut<Account>(account).balance;
    assert(*balance >= amount, Errors::limit_exceeded());
    assert(*balance - amount >= AccountLimits::min_balance(), Errors
        ::invalid_argument()); // MISSING
    *balance = *balance - amount;
  }

  spec transfer {
    ...
    aborts_if !exists<Account>(from_addr); // MISSING
    aborts_if !exists<Account>(to); // MISSING
    aborts_if amount > AccountLimits::max_decrease(); // MISSING
    aborts_if bal(from_addr) - amount < AccountLimits::min_balance();
         // MISSING
  }
}
```