Formal Verification of Workflow Policies for Smart Contracts in Azure Blockchain

Yuepeng Wang[1], Shuvendu K. Lahiri[2], Shuo Chen[2], Rong Pan[1]
Isil Dillig[1], Cody Born[3], Immad Naseer[3], and Kostas Ferles[1]

[1] University of Texas at Austin, USA
`{ypwang, rpan, isil, kferles}@cs.utexas.edu`
[2] Microsoft Research, USA
`{Shuvendu.Lahiri, shuochen}@microsoft.com`
[3] Microsoft Azure, USA
`{Cody.Born, imnaseer}@microsoft.com`

Abstract. Ensuring correctness of smart contracts is paramount to ensuring trust in blockchain-based systems. This paper studies the safety and security of smart contracts in the *Azure Blockchain Workbench*, an enterprise Blockchain-as-a-Service offering from Microsoft. In particular, we formalize *semantic conformance* of smart contracts against a state machine workflow with access-control policy and propose an approach to reducing semantic conformance checking to safety verification using program instrumentation. We develop a new Solidity program verifier VeriSol that is based on translation to Boogie, and have applied it to analyze *all* application contracts shipped with the Azure Blockchain Workbench and found previously unknown bugs in these published smart contracts. After fixing these bugs, VeriSol was able to successfully perform full verification for all of these contracts.

1 Introduction

As a decentralized and distributed consensus protocol to maintain and secure a shared ledger, the blockchain is seen as a disruptive technology with far-reaching impact on diverse areas. As a result, major cloud platform companies, including Microsoft, IBM, Amazon, SAP, and Oracle, are offering Blockchain-as-a-Service (BaaS) solutions, primarily targeting enterprise scenarios, such as financial services, supply chains, escrow, and consortium governance. A recent study by Gartner predicts that the business value-add of the blockchain has the potential to exceed $3.1 trillion by 2030 [3].

Programs running on the blockchain are known as *smart contracts*. High-level languages such as Solidity and Serpent have been developed to enable traditional application developers to author smart contracts. However, since blockchain transactions are immutable, bugs in smart contract code have devastating consequences, and vulnerabilities in smart contracts have resulted in several high-profile exploits that undermine trust in the underlying blockchain technology. For example, the infamous `TheDAO` exploit [1] resulted in the loss of almost $60 million worth of Ether, and the `Parity Wallet` bug caused 169 million USD worth of ether to be locked forever [5]. The only remedy for these incidents was to hard-fork the blockchain and revert one of the forks back to the state before the incident. However, this remedy itself is devastating as it defeats the core values of blockchain, such as immutability and decentralized trust.

Motivated by the serious consequences of bugs in smart contract code, recent work has studied many types of security bugs such as reentrancy, integer underflow/overflow, and issues related to delegatecalls on Ethereum. While these low-level bugs have drawn much attention due to high-visibility incidents on public blockchains, we believe that the BaaS infrastructure and enterprise scenarios bring a set of interesting, yet less well-studied security problems.

In this paper, we present our research on smart contract correctness in the context of Azure Blockchain, a BaaS solution offered by Microsoft [4]. Specifically, we focus on a cloud service named *Azure Blockchain Workbench* (or Workbench for short) [8, 9]. The Workbench allows an enterprise customer to easily build and deploy a smart contract application integrating active directory, database, web UI, blob storage, etc. A customer implements the smart contract application (that meets the requirements specified in an application policy) and uploads it onto the Workbench. The code is then deployed to the underlying blockchain ledger to function as an end-to-end application.

Customer contracts in the Workbench architecture implement complex business logic, starting with a high-level finite-state-machine (FSM) *workflow* policy. Intuitively, the workflow describes (a) a set of categories of users called *roles*, (b) the different states of a contract, and (c) the set of enabled actions (or functions) at each state restricted to each role. The high-level policy is useful to design contracts around state machine abstractions as well as specify the required *access-control* for the actions. While these state machines offer powerful abstraction patterns during smart contract design, it is non-trivial to decide whether a given smart contract faithfully implements the intended FSM. In this paper, we define *semantic conformance checking* as the problem of deciding whether a customer contract correctly implements the underlying workflow policy expressed as an FSM. Given a Workbench policy π that describes the workflow and a contract $\mathcal{C}$, our approach first constructs a new contract $\mathcal{C}'$ such that $\mathcal{C}$ semantically conforms to π if and only if $\mathcal{C}'$ does not fail any assertions.

In order to automatically check the correctness of the assertions in a smart contract, we develop a new verifier called VeriSol for smart contracts written in Solidity. VeriSol is a general-purpose Solidity verifier and is not tied to Workbench. The verifier encodes the semantics of Solidity programs into a low-level intermediate verification language Boogie and leverages the well-engineered Boogie verification pipeline [15] for both verification and counter-example generation. In particular, VeriSol takes advantage of existing bounded model checking tool Corral [24] for Boogie to generate witnesses to assertion violations, and it leverages practical verification condition generators for Boogie to automate correctness proofs. In addition, VeriSol uses monomial predicate abstraction [17, 22] to automatically infer so-called *contract invariants*, which we have found to be crucial for automatic verification of semantic conformance.

To evaluate the effectiveness and efficiency of our approach, we have performed an experiment on all 11 sample applications that are shipped with the Workbench. In the experiment, we find 4 previously unknown defects in these published smart contracts, all of which have been confirmed as true bugs by the developers. The experimental results also demonstrate the practicality of VeriSol in that it can perform full verification of all the fixed contracts with modest effort; most notably, VeriSol can automatically verify 10 out of 11 of the fixed versions of sample smart contracts within 1.7 seconds on average.

Contributions. This paper makes the following contributions:

– We study the safety and security of smart contracts present in Azure Blockchain Workbench, a BaaS offering.
– We formalize the Workbench application policy language and define the *semantic conformance* checking problem between a contract and a policy.
– We propose an approach to reducing semantic conformance checking to safety property verification using program instrumentation.
– We describe a new formal verifier called VeriSol for verifying smart contracts written in Solidity based on translation to Boogie [13, 30].
– We evaluate our approach by verifying semantic conformance on all the sample application contracts shipped with Workbench, and report previously unknown bugs that have been confirmed by developers.

2 Overview

In this section, we give an example of a Workbench application policy for a sample contract and describe our approach for semantic conformance verification.

2.1 Workbench Application Policy

Workbench requires every application to provide a *policy* (or *model*) representing the high-level workflow of the application[4]. The policy consists of several attributes such as the application name, a set of *roles*, as well as a set of *workflows*.

For example, Figure 1 provides an informal pictorial representation of the policy for a simple application called `HelloBlockchain`[5]. The application consists of two *global* roles (see "Application Roles"), namely Requestor and Responder. Informally, each role represents a set of user addresses and provides access control or permissions for various actions exposed by the application. We distinguish a global role from an *instance role* in that the latter applies to a specific instance of the workflow. It is expected that the instance roles are always a subset of the user addresses associated with the global role.

As shown in Figure 1, the simple `HelloBlockchain` application consists of a single workflow with two states, namely `Request` and `Respond`. The data members (or fields) include instance role members (`Requestor` and `Responder`)

[4] `https://docs.microsoft.com/en-us/azure/blockchain/workbench/configuration`
[5] The details can be found on the associated web page: `https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench/application-and-smart-contract-samples/hello-blockchain`

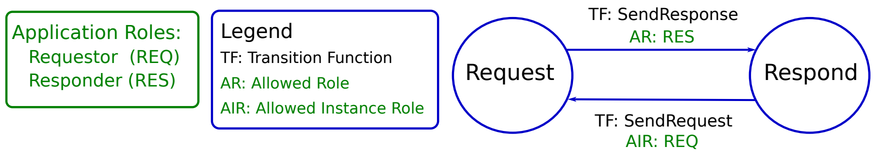

Fig. 1. Workflow policy diagram for HelloBlockchain application.

```
contract HelloBlockchain {
    enum StateType {Request, Respond} // set of states
    // list of properties
    StateType public State;
    address public Requestor;
    address public Responder;
    string  public RequestMessage;
    string  public ResponseMessage;
    // constructor function
    function HelloBlockchain(string message) constructor_checker() public {
        Requestor = msg.sender;
        RequestMessage = message;
        State = StateType.Request;
    }
    // call this function to send a request
    function SendRequest(string requestMessage) SendRequest_checker() public {
        if (Requestor != msg.sender) revert();
        RequestMessage = requestMessage;
        State = StateType.Request;
    }
    // call this function to send a response
    function SendResponse(string responseMessage) SendResponse_checker() public {
        Responder = msg.sender;
        ResponseMessage = responseMessage;
        State = StateType.Respond;
    }
    <modifier definitions>
}
```

Fig. 2. Solidity contract for HelloBlockchain application.

that range over user addresses. The workflow consists of two actions (or functions) in addition to the constructor function, `SendRequest` and `SendResponse`, both of which take a string as argument.

A transition in the workflow consists of a start state, an action or function, an access control list, and a set of successor states. Figure 1 describes two transitions, one from each of the two states. For example, the application can transition from `Request` to `Respond` if a user belongs to the RESPONDER role (`AR`) and invokes the action `SendResponse`. An "Application Instance Role" (`AIR`) refers to an instance role data member of the workflow that stores a member of a global role (such as `Requestor`). For instance, the transition from `Respond` to `Request` in Figure 1 uses an `AIR` and is only allowed if the user address matches the value stored in the instance data variable `Requestor`.

2.2 Workbench Application Smart Contract

After specifying the application policy, a user provides a smart contract written in Solidity to implement the workflow. Figure 2 describes a Solidity smart contract that implements the `HelloBlockchain` workflow in the `HelloBlockchain` appli-

```
function nondet() returns (bool); // non-deterministic boolean value

// checker modifiers
modifier constructor_checker() {
  _;
  assert (nondet() /*global role REQUESTOR*/
            ==> State == StateType.Request);
}
modifier SendRequest_checker() {
  StateType oldState = State;
  address oldRequestor = Requestor;
  _;
  assert ((msg.sender == oldRequestor && oldState == StateType.Respond)
            ==> State == StateType.Request);
}
modifier SendResponse_checker() {
  StateType oldState = State;
  _;
  assert ((nondet() /*global role RESPONDER*/ && oldState == StateType.Request)
            ==> State == StateType.Respond);
}
```

Fig. 3. Modifier definitions for instrumented HelloBlockchain application.

cation. For the purpose of this sub-section, we start by ignoring the portions of the code that are `underlined`. The contract declares the data members present in the configuration as state variables. Each contract implementing a workflow defines an additional state variable `State` to track the current state of a workflow. The contract consists of the constructor along with two other functions defined in the policy, with matching signatures. The functions set the state variables and update the state variables appropriately to reflect the state transitions.

Although the smart contract drives the application, the policy is used to expose the set of enabled actions at each state for a given user. Discrepancies between the policy and Solidity program can lead to unexpected state transitions. To ensure the correct functioning and security of the application, it is crucial to verify that the Solidity program semantically conforms to the application policy.

2.3 Semantic Conformance Verification

Given an application policy and a smart contract, we define the problem of *semantic conformance* that ensures the smart contract respects the policy (Section 3.2). Moreover, we reduce the semantic conformance verification problem to checking assertions on an instrumented Solidity program. For the `HelloBlockchain` application, the instrumentation is provided by adding the underlined *modifier* invocations in Figure 2. A *modifier* is a Solidity construct that allows wrapping a function invocation with code that executes before and after the function body.

Figure 3 shows the definition of the modifiers used to instrument for conformance checking. Intuitively, we wrap the constructor and functions with checks to ensure that they implement the FSM state transitions correctly. For example, if the FSM transitions from state `Respond` to state `Request` upon the invocation of function `SendRequest` by a user with instance role `Requestor`, then we instrument the definition of `SendRequest` to ensure that any execution starting in `Respond` with instance role `Requestor` should transition to `Request`.

Finally, given the instrumented Solidity program, we discharge the assertions statically using a new formal verifier for Solidity called VeriSol. The verifier can find counterexamples (in the form of a sequence of transactions involving calls to the constructor and public functions) as well as automatically construct proofs of semantic conformance. Note that, even though the simple `HelloBlockchain` example does not contain any unbounded loops or recursion, verifying semantic conformance still requires reasoning about executions that involve unbounded numbers of calls to the two public functions. We demonstrate that VeriSol is able to find deep violations of the conformance property for well-tested Workbench applications, as well as automatically construct inductive proofs for most of the application samples shipped with Workbench.

3 Semantic Conformance Checking

In this section, we formalize the Workbench application policy and the semantic conformance checking problem, and then explain our approach to checking if an application smart contract is semantically conformant to its policy.

3.1 Formalization of Workbench Application Policies

The Workbench policy for an application allows the user to describe (i) the *data members* and *actions* of an application, (ii) a high-level *state-machine* view of the application, and (iii) role-based *access control* for *state transitions*. The role-based access control provides security for deploying smart contracts in an open and adversarial setting; the high-level state machine naturally captures the essence of a *workflow* that progresses between a set of states based on actions of the user.

More formally, a *Workbench Application Policy* is a pair $(\mathcal{R}, \mathcal{W})$ where $\mathcal{R}$ is a set of *global roles* used for access control, and $\mathcal{W}$ is a set of *workflows* defining a kind of finite state machine. Specifically, a workflow is defined by a tuple $\langle \mathcal{S}, s_0, \mathcal{R}_w, \mathcal{F}, \mathcal{F}_0, ac_0, \gamma \rangle$ where:

- $\mathcal{S}$ is a finite set of *states*, and $s_0 \in \mathcal{S}$ is an *initial state*
- $\mathcal{R}_w$ is a finite set of *instance roles* of the form $(id : t)$, where id is an identifier and t is a role drawn from $\mathcal{R}$
- $\mathcal{F}(id_0, \ldots, id_k)$ is a set of *actions (functions)*, with $\mathcal{F}_0$ denoting an initial action (constructor)
- $ac_0 \subseteq \mathcal{R}$ is the *initiator role* denoting users that can create an instance
- $\gamma \subseteq \mathcal{S} \times \mathcal{F} \times (\mathcal{R}_w \cup \mathcal{R}) \times 2^{\mathcal{S}}$ is a set of transitions. Given a transition $\tau = (s, f, ac, S)$, we write $\tau.s, \tau.f, \tau.ac, \tau.S$ to denote the source state s, action f, access control ac, and target states S of transition τ, respectively

Intuitively, $\mathcal{S}$ defines the different "states" that the contract can be in, and γ describes which state can transition to what other states by performing certain actions. The transitions are guarded by roles (either global or instance roles) that qualify which users are allowed to perform those actions. As mentioned earlier in Section 2, each "role" corresponds to a set of users (i.e., addresses on the blockchain). The use of instance roles in the workbench policy allows different instances of the contract to authorize different users to perform certain actions.

3.2 Semantic Conformance

Given a contract $\mathcal{C}$ and a Workbench application policy π, *semantic conformance* between $\mathcal{C}$ and π requires that the contract $\mathcal{C}$ faithfully implements the policy specified by π. In this subsection, we first define some syntactic requirements on the contract, and then formalize what we mean by semantic conformance between a contract and a policy.

Syntactic conformance. Given a client contract $\mathcal{C}$ and a policy $\pi = (\mathcal{R}, \mathcal{W})$, our syntactic conformance requirement stipulates that the contract for each $w \in \mathcal{W}$ implements all the instance state variables as well as definitions for each of the functions. Additionally, each contract function has a parameter called *sender*, which is a blockchain address that denotes the user or contract invoking this function. Finally, each contract should contain a state variable s_w that ranges over $\mathcal{S}_w$, for each $w \in \mathcal{W}$.

Semantic conformance. We formalize the semantic conformance requirement for smart contracts using Floyd-Hoare triples of the form $\{\phi\}\ S\ \{\psi\}$ indicating that any execution of statement S starting in a state satisfying ϕ results in a state satisfying ψ (if the execution of S terminates). We can define semantic conformance between a contract $\mathcal{C}$ and a policy π as a set of Hoare triples, one for each pair (m, s) where m is a method in the contract and s is a state in the Workbench policy. At a high-level, the idea is simple: we insist that, when a function is executed along a transition, the resulting state transition should be in accordance with the Workbench policy.

Given a policy $\pi = (\mathcal{R}, \mathcal{W})$ and workflow $w = \langle \mathcal{S}, s_0, \mathcal{R}_w, \mathcal{F}, \mathcal{F}_0, ac_0, \gamma \rangle \in \mathcal{W}$, we can formalize this high-level idea by using the following Hoare triples:

1. **Initiation**.
$$\{\mathit{sender} \in ac_0\} \;\; \mathcal{F}_0(v_1, \ldots, v_k) \;\; \{s_w = s_0\}$$
The Hoare triple states that the creation of an instance of the workflow with the appropriate access control ac_0 results in establishing the initial state.
2. **Consecution**. Let $\tau = (s_1, f, ac, \mathcal{S}_2)$ be a transition in γ. Then, for each such transition, semantic conformance requires the following Hoare triple to be valid:
$$\{\mathit{sender} \in ac \wedge s_w = s_1\} \;\; f(v_1, \ldots, v_k) \;\; \{s_w \in \mathcal{S}_2\}$$
Here, the precondition checks two facts: First, the *sender* must satisfy the access control, and, second, the start state must be s_1. The post-condition asserts that the implementation of method f in the contract results in a state that is valid according to policy π.

3.3 Instrumentation for Semantic Conformance Checking

As mentioned in Section 2, our approach checks semantic conformance of Solidity contracts by (a) instrumenting the contract with assertions, and (b) using a verification tool to check that none of the assertions can fail. We explain our instrumentation strategy in this subsection and refer the reader to Section 4 for a description of our verification tool chain.

Our instrumentation methodology uses the `modifier` construct in Solidity. A modifier has syntax similar to a function definition in Solidity with a name and list of parameters and a body that can refer to parameters and globals in scope. The general structure of a modifier definition without any parameters is [2]:

```
modifier Foo() { pre-stmt; _; post-stmt; }
```

where `pre-stmt` and `post-stmt` are Solidity statements. When this modifier is applied to a function `Bar` such as

```
function Bar(int x) Foo() { Bar-stmt; }
```

the Solidity compiler transforms the body of `Bar` to execute `pre-stmt` (resp. `post-stmt`) before (resp. after) `Bar-stmt`. This provides a convenient way to inject code at multiple return sites from a procedure and can also inject code before the execution of the constructor.

We now define helper predicates before describing the actual checks. Let $P(ac)$ be a predicate that encodes the membership of *sender* in the set ac:

$$P(ac) \doteq \begin{cases} \mathit{false}, & ac = \{\} \\ \texttt{msg.sender} = q, & ac = \{q \in \mathcal{R}_w\} \\ \texttt{nondet}(), & ac = \{r \in \mathcal{R}\} \\ P(ac^1) \vee P(ac^2), & ac = ac^1 \cup ac^2 \end{cases}$$

Here `nondet` is a side-effect free Solidity function that returns a non-deterministic Boolean value at each invocation. For the sake of static verification, one can declare a function without any definition. This allows us to model the membership check $\mathit{sender} \in ac$ conservatively in the absence of global roles on the blockchain.

We also define a predicate for membership of a contract state in a set of states $\mathcal{S}' \subseteq \mathcal{S}$ using $\alpha(\mathcal{S}')$ as follows:

$$\alpha(\mathcal{S}') \doteq \begin{cases} \mathit{false}, & \mathcal{S}' = \{\} \\ s_w = s, & \mathcal{S}' = \{s \in \mathcal{S}\} \\ \alpha(\mathcal{S}_1) \vee \alpha(\mathcal{S}_2), & \mathcal{S}' = \mathcal{S}_1 \cup \mathcal{S}_2 \end{cases}$$

Using these predicates, the source code transformations are defined as below:

Constructor. We add the following modifier to constructors:

```
modifier constructor_checker() { _; assert (P(ac_0) ⇒ α({s_0})); }
```

Here, the assertion ensures that the constructor sets up the correct initial state when executed by a user with access control ac_0.

Other functions. For a function g, let $\gamma^g \doteq \{\tau \in \gamma \mid \tau = (s_1, g, ac, \mathcal{S}_2)\}$ be the set of all transitions where g is invoked.

```
modifier g_checker() {
   StateType oldState = s_w; // copy old State
   ... // copy old instance role vars
   _;
   assert ⋀_{τ∈γ^g} (old(P(τ.ac) ∧ α({τ.s_1})) ⇒ α(τ.S_2));
}
```

Here, the instrumented code first copies the s_w variable and all of the variables in $\mathcal{R}_w$ into corresponding "old" copies. Next, the assertion checks that if the function is executed in a transition τ, then state transitions to one of the successor states in $\tau.\mathcal{S}_2$. The notation $\texttt{old}(e)$ replaces any occurrences of a state variable (such as s_w) with the "old" copy that holds the value at the entry to the function. As an example, Figure 3 shows the modifier definitions for our running example `HelloBlockchain` described in Section 2. Although we show the `nondet`() to highlight the issue of global roles, one can safely replace `nondet`() with *true* since the function only appears negatively in any assertion.

4 Formal Verification using VeriSol

In this section, we present our formal verifier called VeriSol for checking the correctness of assertions in Solidity smart contracts.

4.1 General Methodology

Let $\mathcal{C} = \{\lambda\vec{x_0}.f_0,\ \lambda\vec{x_1}.f_1,\ \ldots,\ \lambda\vec{x_n}.f_n\}$ be a smart contract annotated with assertions where:

- $\lambda\vec{x_0}.f_0$ is the constructor
- $\lambda\vec{x_i}.f_i$ for $i \in [1, n]$ are public functions

Our verification methodology is based on finding a *contract invariant* $\mathcal{I}$ satisfying the following Hoare triples:

(1) $\models \{\texttt{true}\}\ f_0\ \{\mathcal{I}\}$
(2) $\models \{\mathcal{I}\}\ f_i\ \{\mathcal{I}\}$ for all $i \in [1, n]$

Here, the first condition states the contract invariant is established by the constructor, and the second condition states that $\mathcal{I}$ is inductive — i.e., it is preserved by every public function in $\mathcal{C}$. Note that such a contract invariant suffices to establish the validity of all assertions in the contract under *any* possible sequence of function invocations of the contract. To see why this is the case, consider a "harness" that invokes the functions in $\mathcal{C}$ as in Figure 4.

```
call f0(*);
while (true) {
    if (*) call f1(*); else if (*) ...
    else if (*) call fn(*);
}
```

Fig. 4. Harness for Solidity contracts

This harness first creates an instance of the contract by calling the constructor, and then repeatedly and non-deterministically invokes one of the public functions of $\mathcal{C}$. Observe that the Hoare triples (1) and (2) listed above essentially state that $\mathcal{I}$ is an inductive invariant of the loop in this harness; thus, the contract invariant $\mathcal{I}$ overapproximates the state of the contract under any sequence of the contract's function invocations. Furthermore, when the functions contain assertions, the Hoare triple $\{\mathcal{I}\}\ f_i\ \{\mathcal{I}\}$ can only be proven if $\mathcal{I}$ is strong enough to imply the assertion conditions. Thus, the validity of the Hoare triples in (1) and (2) establishes correctness under all possible usage patterns of the contract.

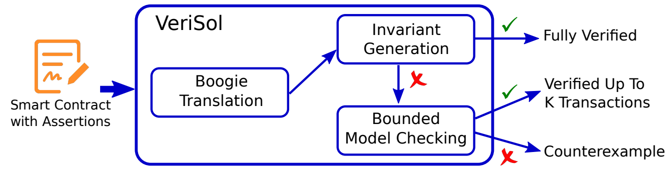

Fig. 5. Schematic workflow of VeriSol.

4.2 Overview

We now describe the design of our tool called VeriSol for checking safety of smart contracts. VeriSol is based on the proof methodology outlined in Section 4.1, and its workflow is illustrated in Figure 5. At a high-level, VeriSol takes as input a Solidity contract $\mathcal{C}$ annotated with assertions and yields one of the following three outcomes:

- *Fully verified:* This means that the assertions in $\mathcal{C}$ are guaranteed not to fail under any usage scenario.
- *Refuted:* This indicates that VeriSol finds at least one transaction sequence of the contract $\mathcal{C}$ under which one of the assertions is guaranteed to fail.
- *Partially verified:* When VeriSol can neither verify nor refute contract correctness, it performs bounded verification to establish that the contract is safe up to k transactions. This essentially corresponds to unrolling the "harness" loop from Figure 4 for k times and then verifying that the assertions do not fail in the unrolled version.

VeriSol consists of three modules, namely (a) *Boogie Translation* from a Solidity program, (b) *Invariant Generation* to infer a *contract invariant* as well as loop invariants and procedure summaries, and (c) *Bounded Model Checking* to explore assertion failures within all transactions up to a user-specified depth k. In what follows, we discuss each of these components in more detail.

4.3 Solidity to Boogie Translation

In this subsection, we formally describe our translation of Solidity source code to the Boogie intermediate verification language. We start with a brief description of Solidity and Boogie, and then discuss our translation.

Solidity Language. Figure 6 shows a core subset of Solidity that we use for our formalization. At a high level, Solidity is a typed object-oriented programming language with built-in support for basic verification constructs, such as the `require` construct for expressing pre-conditions.

Types in our core language include integers, strings, addresses, and contracts. As is standard, expressions in Solidity include constants, local variables, *state variables* (i.e., fields in standard object-oriented language terminology), unary/binary operators (denoted **op**), and `msg.sender` that yields the address of the contract or user that initiates the current function invocation. Statements in our core Solidity language include assignments, conditionals, loops, requires, assertions,

$$\begin{array}{rcl} st \in \mathit{SolTypes} & ::= & \mathit{integer} \mid \mathit{string} \mid \mathit{address} \mid C \\ se \in \mathit{SolExprs} & ::= & c \mid \mathtt{x} \mid \mathbf{op}(se, \ldots, se) \mid \mathtt{msg.sender} \\ sst \in \mathit{SolStmts} & ::= & \mathtt{x} := se \mid sst; sst \mid \mathtt{require}(se) \mid \mathtt{assert}(se) \\ & \mid & \mathtt{if}\ (se)\ \{sst\}\ \mathtt{else}\ \{sst\} \mid \mathtt{while}\ (se)\ \mathtt{do}\ \{sst\} \\ & \mid & se := \mathtt{f}(\vec{se}) \mid se := se.\mathtt{f}(\vec{se}) \mid se := \mathtt{new}\ C(\vec{se}) \end{array}$$

Fig. 6. A subset of Solidity language. C denotes a contract and `f` denotes a function.

$$bbt \in \mathit{BoogieElemTypes} ::= \ \mathbf{int} \mid \mathbf{Ref} \qquad bt \in \mathit{BoogieTypes} ::= \ bbt \mid [bbt]bt$$

$$\begin{array}{rcl} e \in \mathit{Exprs} & ::= & c \mid \mathtt{x} \mid \mathbf{op}(e, \ldots, e) \mid \mathtt{uf}(e, \ldots, e) \mid \mathtt{x}[e] \mid \forall i : bbt :: e \\ st \in \mathit{Stmts} & ::= & \mathbf{skip} \mid \mathbf{havoc}\ \mathtt{x} \mid \mathtt{x} := e \mid \mathtt{x}[e] := e \\ & \mid & \mathbf{assume}\ e \mid \mathbf{assert}\ e \mid \mathbf{if}\ (e)\ \{st\}\ \mathbf{else}\ \{st\} \\ & \mid & st; st \mid \mathbf{while}\ (e)\ \mathbf{do}\ \{st\} \mid \mathbf{call}\ \vec{\mathtt{x}} := f(e, \ldots, e) \end{array}$$

Fig. 7. A subset of Boogie language.

internal and external function calls, and contract instance creation[6]. Solidity differentiates between two types of function calls: internal and external. An *internal* call $se := \mathtt{f}(\vec{se})$ invokes the function `f` and keeps `msg.sender` unchanged. An *external* call $se := se_0.\mathtt{f}(\vec{se})$ invokes function `f` in the contract instance pointed by se_0 (which may include `this`), and uses `this` as the `msg.sender` for the callee.

Boogie Language. Since our goal is to translate Solidity to Boogie, we also give a brief overview of the Boogie intermediate verification language. As shown in Figure 7, types in Boogie include integers (**int**), references (**Ref**), and arrays/maps. Expressions (*Exprs*) consist of constants, variables, arithmetic and logical operators (**op**), uninterpreted functions (`uf`), map lookups, and quantified expressions. Statements (*Stmts*) in Boogie consist of skip, variable and map assignment, sequential composition, conditionals, and loops. The **havoc** `x` statement assigns an arbitrary value of appropriate type to a variable `x`. A procedure call (**call** $\vec{\mathtt{x}} := f(e, \ldots, e)$) returns a vector of values that can be stored in local variables. The **assert** and **assume** statements behave as no-ops when their arguments evaluate to true and terminate execution otherwise. An assertion failure is considered as a failing execution, whereas an assumption failure blocks.

From Solidity to Boogie types. We define a function $\mu : \mathit{SolTypes} \rightarrow \mathit{BoogieTypes}$ that translates a Solidity type to a type in Boogie as follows:

$$\mu(st) \doteq \begin{cases} \mathbf{int}, & st \in \{\mathit{integer}, \mathit{string}\} \\ \mathbf{Ref}, & st \in \{\mathit{address}\} \cup \mathit{ContractNames} \end{cases}$$

Specifically, we translate Solidity integers and strings to Boogie integers; addresses, and contract names to Boogie references. Note that we represent Solidity strings as integers in Boogie because Solidity only allows equality checks on strings.

From Solidity to Boogie expressions. We present our translation from Solidity to Boogie expressions using judgments of the form $\vdash e \hookrightarrow \chi$ in Figure 8, where e is a Solidity expression and χ is the corresponding Boogie expression. While Solidity local variables and the expression `msg.sender` are mapped directly into

[6] We omit several aspects of the language such as arrays and mappings due to space limit. More details can be found in the extended version of this paper [30].

$$\frac{\mathtt{x} \in \mathit{LocalVars}}{\vdash \mathtt{x} \hookrightarrow \mathtt{x}}\ (\text{Var1}) \qquad \frac{\mathtt{x} \in \mathit{StateVars(C)}}{\vdash \mathtt{x} \hookrightarrow \mathtt{x}^C[\mathtt{this}]}\ (\text{Var2})$$

$$\frac{\mathit{Type}(c) \neq \mathit{string}}{\vdash c \hookrightarrow c}\ (\text{Const1}) \quad \frac{\mathit{Type}(c) = \mathit{string} \quad c' = \mathit{Hash}(c)}{\vdash c \hookrightarrow \mathit{StrToInt}(c')}\ (\text{Const2})$$

$$\frac{v = \mathtt{sender}}{\vdash \mathtt{msg.sender} \hookrightarrow v}\ (\text{Sender}) \quad \frac{\vdash e_i \hookrightarrow \chi_i \quad i = 1, \ldots, n}{\vdash \mathbf{op}(e_1, \ldots, e_n) \hookrightarrow \mathbf{op}(\chi_1, \ldots, \chi_n)}\ (\text{Op})$$

Fig. 8. Inference rules for encoding Solidity expressions to Boogie expressions. *Type*(e) is a function that returns the static type of Solidity expression e.

Boogie local variables and parameters respectively, state variables in Solidity are translated into map lookups. Specifically, for each state variable `x` in contract C, we introduce a mapping $\mathtt{x}^C$ from contract instances to the value stored in its state variable `x`. Thus, reads from state variable `x` are modeled as $\mathtt{x}^C[\mathtt{this}]$ in Boogie. Next, we translate string constants in Solidity to Boogie integers using an uninterpreted function called *StrToInt* that is applied to a hash of the string[7]. As mentioned earlier, this string-to-integer translation does not cause imprecision because Solidity only allows equality checks between variables of type string.

From Solidity to Boogie statements. Figure 9 presents the translation from Solidity to Boogie statements using judgments of the form $\vdash s \rightsquigarrow \omega$ indicating that Solidity statement s is translated to Boogie statement ω. Since most rules in Figure 9 are self-explanatory, we only explain our translation for function calls. Functions in Solidity have two implicit parameters, namely `this` for the receiver object and `msg.sender` for the Blockchain address of the caller. Thus, when translating Solidity calls to their corresponding Boogie version, we explicitly pass these parameters in the Boogie version. However, recall that the value of the implicit `msg.sender` parameter varies depending on whether the call is external or internal. For internal calls, `msg.sender` remains unchanged, whereas for external calls, `msg.sender` becomes the current receiver object. For both types of calls, our translation introduces a conditional statement to deal with dynamic dispatch. Specifically, our Boogie encoding introduces a map τ to store the dynamic type of receiver objects at allocation sites, and the translation of function calls invokes the correct version of the method based on the content of τ for the receiver object. In the case of contract creation (labeled NewCont in Figure 9), the Boogie code we generate updates the τ map mentioned previously in addition to allocating new memory. Specifically, using the global auxiliary `Alloc` map to indicate whether a reference is allocated or not, we obtain a freshly allocated reference v. Then we initialize $\tau[v]$ to be C and also call C's constructor as required by Solidity semantics.

4.4 Invariant Generation

As mentioned earlier, translating Solidity code into Boogie allows VeriSol to leverage the existing ecosystem around Boogie, including efficient verification

[7] We assume that the hash function is collision-free. In our implementation, we enforce this by keeping a mapping from each string constant to a counter.

$$\frac{\vdash e \hookrightarrow \chi}{\vdash \texttt{require}(e) \rightsquigarrow \textbf{assume } \chi}\ (\text{Req}) \qquad \frac{\vdash e \hookrightarrow \chi}{\vdash \texttt{assert}(e) \rightsquigarrow \textbf{assert } \chi}\ (\text{Asrt})$$

$$\frac{\vdash s_1 \rightsquigarrow \omega_1 \quad \vdash s_2 \rightsquigarrow \omega_2}{\vdash s_1; s_2 \rightsquigarrow \omega_1; \omega_2}\ (\text{Seq}) \quad \frac{\vdash e \hookrightarrow \chi \quad \vdash s_1 \rightsquigarrow \omega_1 \quad \vdash s_2 \rightsquigarrow \omega_2}{\vdash \texttt{if } (e)\ \{s_1\} \texttt{ else } \{s_2\} \rightsquigarrow \textbf{if } (\chi)\ \{\omega_1\} \textbf{ else } \{\omega_2\}}\ (\text{Cond})$$

$$\frac{\vdash e_1 \hookrightarrow \chi_1 \quad \vdash e_2 \hookrightarrow \chi_2}{\vdash e_1 := e_2 \rightsquigarrow \chi_1 := \chi_2}\ (\text{Asgn}) \quad \frac{\vdash e \hookrightarrow \chi \quad \vdash s \rightsquigarrow \omega}{\vdash \texttt{while } (e) \texttt{ do } \{s\} \rightsquigarrow \textbf{while } (\chi) \textbf{ do } \{\omega\}}\ (\text{Loop})$$

$$\frac{\begin{array}{c}\vdash e_r \hookrightarrow \chi_r \quad \vdash e_i \hookrightarrow \chi_i \quad i = 1, \dots, n \quad \text{fresh } v \quad C_j <: \mathit{Type}(\mathit{this}) \quad j = 1, \dots, m \\ \omega \equiv \textbf{if } (\tau[\texttt{this}] = C_1)\ \{\textbf{call } v := f^{C_1}(\texttt{this}, \chi_1, \dots, \chi_n, \texttt{sender});\ \chi_r := v\} \textbf{ else if} \dots \\ \textbf{else if } (\tau[\texttt{this}] = C_m)\ \{\textbf{call } v := f^{C_m}(\texttt{this}, \chi_1, \dots, \chi_n, \texttt{sender});\ \chi_r := v\}\end{array}}{\vdash e_r := f(e_1, \dots, e_n) \rightsquigarrow \omega}\ (\text{ICall})$$

$$\frac{\begin{array}{c}\vdash e_r \hookrightarrow \chi_r \quad \vdash e_i \hookrightarrow \chi_i \quad i = 0, \dots, n \quad \text{fresh } v \quad C_j <: \mathit{Type}(e_0) \quad j = 1, \dots, m \\ \omega \equiv \textbf{if } (\tau[\chi_0] = C_1)\ \{\textbf{call } v := f^{C_1}(\chi_0, \chi_1, \dots, \chi_n, \texttt{this});\ \chi_r := v\} \textbf{ else if } \dots \\ \textbf{else if } (\tau[\chi_0] = C_m)\ \{\textbf{call } v := f^{C_m}(\chi_0, \chi_1, \dots, \chi_n, \texttt{this});\ \chi_r := v\}\end{array}}{\vdash e_r := e_0.f(e_1, \dots, e_n) \rightsquigarrow \omega}\ (\text{ECall})$$

$$\frac{\begin{array}{c}\vdash e_r \hookrightarrow \chi_r \quad \vdash e_i \hookrightarrow \chi_i \quad i = 1, \dots, n \quad \text{fresh } v \\ \omega \equiv \textbf{havoc } v;\ \textbf{assume } \neg\texttt{Alloc}[v];\ \texttt{Alloc}[v] := \texttt{true}; \\ \textbf{assume } \tau[v] = C;\ \textbf{call } f_0^C(v, \chi_1, \dots, \chi_n, \texttt{this});\ \chi_r := v\end{array}}{\vdash e_r := \texttt{new } C(e_1, \dots, e_n) \rightsquigarrow \omega}\ (\text{NewCont})$$

Fig. 9. Inference rules for encoding Solidity statements to Boogie statements. $\mathit{Type}(e)$ is a function that returns the static type of Solidity expression e. Symbol f^C denotes the function f in contract C, and f_0^C denotes the constructor of contract C. The $<:$ relation represents the sub-typing relationship.

condition generation [25]. However, in order to completely automate verification (even for loop and recursion-free contracts), we still need to infer a suitable contract invariant as discussed in Section 4.2.

VeriSol uses monomial predicate abstraction [17, 22, 23] to automatically infer contract invariants. Specifically, the inference algorithm conjectures the conjunction of all candidate predicates as an inductive invariant and progressively weakens it based on failure to prove a candidate predicate inductive. This algorithm converges fairly fast even on large examples but relies on starting with a superset of necessary predicates. In the current implementation of VeriSol, we obtain candidate invariants by instantiating the predicate template $e_1 \bowtie e_2$ where $\bowtie$ is either equality or disequality. Here, expressions e_1, e_2 can be instantiated with variables corresponding to roles and states in the Workbench policy as well as constants. We have found these candidate predicates to be sufficiently general for automatically verifying semantic conformance of most Workbench contracts; however, additional predicates may be required for other types of contracts.

4.5 Bounded Model Checking

If VeriSol fails to verify contract correctness using monomial predicate abstraction, it employs an assertion-directed bounded verifier, namely Corral [24], to

Name	Description	Orig SLOC	Inst SLOC	Init Stat	After Fix	Time (s)
`AssetTransfer`	Selling high-value assets	192	444	×	✓	2.1
`BasicProvenance`	Keeping record of ownership	43	95	✓	✓	1.5
`BazaarItemListing`	Multiple workflow scenario for selling items	98	175	×	✓	2.3
`DefectCompCounter`	Product counting for manufacturers	31	68	✓	✓	1.3
`DigitalLocker`	Sharing digitally locked files	129	260	×	✓	1.7
`FreqFlyerRewards`	Calculating frequent flyer rewards	47	90	✓	✓	1.3
`HelloBlockchain`	Request and response (Figure 1)	32	78	✓	✓	1.3
`PingPongGame`	Multiple workflow for two-player games	74	136	×	M	2.1
`RefrigTransport`	Provenance scenario with IoT monitoring	118	187	✓	✓	2.2
`RoomThermostat`	Thermostat installation and use	42	99	✓	✓	1.3
`SimpleMarketplace`	Owner and buyer transactions	62	118	✓	✓	1.4
Average	-	79	159	-	-	1.7

Table 1. Experimental results. ✓ denotes fully verified, × denotes refuted, and M denotes fully verified with manual effort.

look for a transaction sequence leading to an assertion violation. Corral analyzes the harness in Figure 4 by unrolling the loop k times and uses a combination of *abstraction refinement* techniques (including lazy inlining of nested procedures) to look for counterexamples in a scalable manner. Thus, when VeriSol fails to verify the property, it either successfully finds a counterexample or verifies the lack of any counterexample with k transactions.

5 Evaluation

In this section, we evaluate the effectiveness and efficiency of our approach to checking semantic conformance against Workbench application policies. All experiments are conducted on a machine with Intel Xeon(R) E5-1620 v3 CPU and 32GB of physical memory, running the Ubuntu 14.04 operating system.

Benchmarks. We have collected all sample smart contracts that are shipped with Workbench and their corresponding application policies on the Github repository of Azure Blockchain [6]. These smart contracts and their policies depict various workflow scenarios that are representative in real-world enterprise use cases. The smart contracts exercise various features of Solidity such as arrays, nested contract creation, external calls, enum types, and mutual recursion. For each smart contract $\mathcal{C}$ and its application policy π, we perform program instrumentation as explained in Section 3.3 to obtain contract $\mathcal{C}'$. Note that no assertion failure of $\mathcal{C}'$ is equivalent to the semantic conformance between $\mathcal{C}$ and π, so we include such instrumented smart contracts in our benchmark set.

Main Results. Table 1 summarizes the results of our experimental evaluation. Here, the "Description" column describes the contract's usage scenario. The next two columns give the number of lines of Solidity code before and after the instrumentation described in Section 3.3. The last three columns present the main verification results: In particular, "Init Stat" shows the result of applying VeriSol on the original smart contract, and "After Fix" presents the result of VeriSol after we manually fix the bug (if any). Finally, "Time" shows the running time of VeriSol in seconds when applied to the fixed contracts.

Our experimental results demonstrate that VeriSol is useful for checking semantic conformance between Workbench contracts and the policies. In particular, VeriSol finds bugs in 4 out of 11 well-tested contracts and precisely pinpoints the trace leading to the violation. Our results also demonstrate that VeriSol can effectively automate semantic conformance proofs, as it can successfully verify all the contracts after fixing the original bug. Moreover, for 10 out of the 11 contracts, the invariant inference techniques sufficed to make the proofs completely push-button. Our candidate templates for contract invariant did not suffice for the `PingPongGame` contract mainly due to the presence of mutually recursive functions between two contracts. This required us to manually provide a function summary for the mutually recursive procedures that states an invariant over the state variable s_w of the sender contract (e.g. $s_w[\texttt{msg.sender}] = s_1 \vee s_w[\texttt{msg.sender}] = s_2$ where s_i are states of the sender contract). This illustrates that we can achieve the power of the sound Boogie modular verification to perform non-trivial proofs with modest manual overhead. We are currently working on extending the templates for contract invariant inference to richer templates for inferring postconditions for recursive procedures.

Bug Analysis. The four bugs found by VeriSol can be categorized into two classes: (i) incorrect state transition, and (ii) incorrect initial state. We briefly discuss these two classes of bugs.

Incorrect state transition. This class of bugs arises when the implementation of a function in the contract violates the state transition stated by the policy. VeriSol has found such non-conformance in the `AssetTransfer` and `PingPongGame` contracts. Let us consider `AssetTransfer` [7] as a concrete example. In this contract, actions are guarded by the membership of `msg.sender` within one of the roles or instance role variables. VeriSol found the transition from state `BuyerAccepted` to state `Accepted` in the `Accept` function had no matching transitions in the policy. Specifically, the policy allows a transition from `BuyerAccepted` to `SellerAccepted` when invoking the function `Accept` and `msg.sender` equals the instance role variable `InstanceOwner`. However, the implementation of function `Accept` transitions to the state `Accepted` instead of `SellerAccepted`. From the perspective of the bounded verifier, this is a fairly deep bug, as it requires at least 6 transactions to reach the state `BuyerAccepted` from the initial state.

Incorrect initial state. This class of bugs arises when the initial state of a smart contract is not established as instructed by the corresponding policy. We have found such non-conformance in `DigitalLocker` and `BazaarItemListing`. For instance, the policy of `DigitalLocker` requires the initial state to be `Requested`, but the implementation ends up incorrectly setting the initial state to `DocumentReview`. In the `BazaarItemListing` benchmark, the developer fails to set the initial state of the contract despite the policy requiring it to be set to `ItemAvailable`.

6 Related Work

In this section, we discuss prior work on ensuring the safety and security of smart contracts. Existing techniques can be roughly categorized into several categories, including static approaches for finding vulnerable patterns, formal verification techniques, and runtime checking. In addition, there has been work on formalizing the semantics of EVM in a formal language such as the $\mathcal{K}$ Framework [20]. There are also several works that discuss a survey and taxonomy of vulnerabilities in smart contracts [14, 26, 28].

Static analysis. The static analysis tools are based on a choice of data-flow analysis or symbolic execution to find variants of known vulnerable patterns. Such patterns include reentrancy, transaction ordering dependencies, sending ether to unconstrained addresses, use of block time-stamps, mishandled exceptions, calling `suicide` on an unconstrained address, etc. Tools based on symbolic execution include Oyente [26], MAIAN [28], Manticore [10], and Mythril++ [11]. Several data-flow based tools also exist such as Securify [29] and Slither [12]. MadMax [18] uses static analysis to find vulnerabilities related to out-of-gas exceptions. These tools neither check semantic conformance nor verify assertions. Instead, they mostly find instances of known vulnerable patterns. On the other hand, VeriSol does not reason about gas consumption since it analyzes Solidity code, and it also needs the vulnerabilities to be expressed as formal specifications.

Formal verification. F* [16] and Zeus [21] use formal verification for checking correctness of smart contracts. These approaches translate Solidity to the formal verification languages of F* and LLVM respectively and then apply F*-based verifiers and constrained horn clause solvers to check the correctness of the translated program. Although the F* based approach is fairly expressive, the tool only covers a small subset of Solidity without loops and requires substantial user guidance to discharge proofs of user-specified assertions. The design of Zeus shares similarities with VeriSol in that it translates Solidity to an intermediate language and uses SMT based solvers to discharge the verification problem. However, one of the key contributions of this paper is the semantic conformance checking problem for smart contracts, which Zeus does not address. Unfortunately, we were unable to obtain a copy of Zeus, making it difficult for us to perform an experimental comparison for discharging assertions in Solidity code.

Other approaches. In addition to static analyzers and formal verification tools, there are also other approaches that enforce safe reentrancy patterns at runtime by borrowing ideas from linearizability [19]. Another related work is FSolidM [27], which provides an approach to specify smart contracts using a finite state machine with actions written in Solidity. Although there is a similarity in their state machine model with our Workbench policies, they do not consider access control, and the actions do not have nested procedure calls or loops. Finally, the FSolidM tool does not provide any static or dynamic verification support.

7 Conclusion

In this work, we described one of the first uses of automated formal verification for smart contracts in an industrial setting. We formalized the semantic conformance checking problem between Workbench contracts and application policies, and proposed to use program instrumentation to enforce such policies. We also developed a new verifier VeriSol using the Boogie tool chain and demonstrated its effectiveness and efficiency for smart contract verification and bug-finding.

References

1. Explaining the dao exploit for beginners in solidity. https://medium.com/@MyPaoG/explaining-the-dao-exploit-for-beginners-in-solidity-80ee84f0d470, 2016.
2. Solidity: Function modifiers. https://solidity.readthedocs.io/en/v0.4.24/structure-of-a-contract.html#function-modifiers, 2016.
3. Forecast: Blockchain business value, worldwide, 2017-2030. https://www.gartner.com/en/documents/3627117, 2017.
4. Microsoft azure blockchain. https://azure.microsoft.com/en-us/solutions/blockchain/, 2017.
5. Parity: The bug that put $169m of ethereum on ice? yeah, it was on the todo list for months. https://www.theregister.co.uk/2017/11/16/parity_flaw_not_fixed, 2017.
6. Applications and smart contract samples for workbench. https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench/application-and-smart-contract-samples, 2018.
7. Asset transfer sample for azure blockchain workbench. https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench/application-and-smart-contract-samples/asset-transfer, 2018.
8. Azure blockchain content and samples. https://github.com/Azure-Samples/blockchain, 2018.
9. Azure blockchain workbench. https://azure.microsoft.com/en-us/features/blockchain-workbench/, 2018.
10. Manticore. https://github.com/trailofbits/manticore, 2018.
11. Mythril classic: Security analysis tool for ethereum smart contracts. https://github.com/ConsenSys/mythril-classic, 2018.
12. Slither, the solidity source analyzer. https://github.com/trailofbits/slither, 2018.
13. Verisol: A formal verifier and analysis tool for solidity smart contracts. https://github.com/Microsoft/verisol, 2018.
14. Nicola Atzei, Massimo Bartoletti, and Tiziana Cimoli. A survey of attacks on ethereum smart contracts (sok). In *Principles of Security and Trust - 6th International Conference, POST , Uppsala, Sweden, April 22-29, 2017, Proceedings*, pages 164–186, 2017.
15. Michael Barnett, Bor-Yuh Evan Chang, Robert DeLine, Bart Jacobs, and K. Rustan M. Leino. Boogie: A modular reusable verifier for object-oriented programs. In *Formal Methods for Components and Objects, 4th International Symposium, FMCO 2005, Amsterdam, The Netherlands, November 1-4, 2005, Revised Lectures*, pages 364–387, 2005.
16. Karthikeyan Bhargavan, Antoine Delignat-Lavaud, Cédric Fournet, Anitha Gollamudi, Georges Gonthier, Nadim Kobeissi, Natalia Kulatova, Aseem Rastogi, Thomas Sibut-Pinote, Nikhil Swamy, and Santiago Zanella Béguelin. Formal verification of smart contracts: Short paper. In *Proceedings of the 2016 ACM Workshop on Programming Languages and Analysis for Security, PLAS@CCS 2016, Vienna, Austria, October 24, 2016*, pages 91–96, 2016.
17. Cormac Flanagan and K Rustan M Leino. Houdini, an annotation assistant for esc/java. In *International Symposium of Formal Methods Europe*, pages 500–517. Springer, 2001.

18. Neville Grech, Michael Kong, Anton Jurisevic, Lexi Brent, Bernhard Scholz, and Yannis Smaragdakis. Madmax: surviving out-of-gas conditions in ethereum smart contracts. *PACMPL*, 2(OOPSLA):116:1–116:27, 2018.
19. Shelly Grossman, Ittai Abraham, Guy Golan-Gueta, Yan Michalevsky, Noam Rinetzky, Mooly Sagiv, and Yoni Zohar. Online detection of effectively callback free objects with applications to smart contracts. *PACMPL*, 2(POPL):48:1–48:28, 2018.
20. Everett Hildenbrandt, Manasvi Saxena, Nishant Rodrigues, Xiaoran Zhu, Philip Daian, Dwight Guth, Brandon M. Moore, Daejun Park, Yi Zhang, Andrei Stefanescu, and Grigore Rosu. KEVM: A complete formal semantics of the ethereum virtual machine. In *31st IEEE Computer Security Foundations Symposium, CSF 2018, Oxford, United Kingdom, July 9-12, 2018*, pages 204–217, 2018.
21. Sukrit Kalra, Seep Goel, Mohan Dhawan, and Subodh Sharma. ZEUS: analyzing safety of smart contracts. In *25th Annual Network and Distributed System Security Symposium, NDSS 2018, San Diego, California, USA, February 18-21, 2018*, 2018.
22. Shuvendu Lahiri and Shaz Qadeer. Complexity and algorithms for monomial and clausal predicate abstraction. In *International Conference on Automated Deduction (CADE '09)*. Springer Verlag, March 2009.
23. Shuvendu K. Lahiri, Shaz Qadeer, Juan P. Galeotti, Jan W. Voung, and Thomas Wies. Intra-module inference. In *Computer Aided Verification, 21st International Conference, CAV 2009, Grenoble, France, June 26 - July 2, 2009. Proceedings*, pages 493–508, 2009.
24. Akash Lal, Shaz Qadeer, and Shuvendu K. Lahiri. A solver for reachability modulo theories. In *Computer Aided Verification - 24th International Conference, CAV 2012, Berkeley, CA, USA, July 7-13, 2012 Proceedings*, volume 7358, pages 427–443. Springer, 2012.
25. K. Rustan M. Leino. Efficient weakest preconditions. *Inf. Process. Lett.*, 93(6):281–288, 2005.
26. Loi Luu, Duc-Hiep Chu, Hrishi Olickel, Prateek Saxena, and Aquinas Hobor. Making smart contracts smarter. In *Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security, Vienna, Austria, October 24-28, 2016*, pages 254–269, 2016.
27. Anastasia Mavridou and Aron Laszka. Tool demonstration: Fsolidm for designing secure ethereum smart contracts. In *Principles of Security and Trust - 7th International Conference, POST 2018, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2018, Thessaloniki, Greece, April 14-20, 2018, Proceedings*, pages 270–277, 2018.
28. Ivica Nikolic, Aashish Kolluri, Ilya Sergey, Prateek Saxena, and Aquinas Hobor. Finding the greedy, prodigal, and suicidal contracts at scale. In *Proceedings of the 34th Annual Computer Security Applications Conference, ACSAC 2018, San Juan, PR, USA, December 03-07, 2018*, pages 653–663, 2018.
29. Petar Tsankov, Andrei Marian Dan, Dana Drachsler-Cohen, Arthur Gervais, Florian Bünzli, and Martin T. Vechev. Securify: Practical security analysis of smart contracts. In *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, CCS 2018, Toronto, ON, Canada, October 15-19, 2018*, pages 67–82, 2018.
30. Yuepeng Wang, Shuvendu K. Lahiri, Shuo Chen, Rong Pan, Isil Dillig, Cody Born, and Immad Naseer. Formal specification and verification of smart contracts in azure blockchain. `https://arxiv.org/abs/1812.08829/`, 2018.