Formal Specification and Verification of Smart Contracts for Azure Blockchain

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Abstract
In this paper, we describe the formal verification of Smart Contracts offered as part of the Azure Blockchain Content and Samples on github. We describe two sources of formal verification problems: (i) semantic conformance checking of smart contracts against a state-machine and access control based Azure Blockchain Workbench application configuration, and (ii) safety verification for smart contracts implementing the authority governance in Ethereum Proof-of-Authority (PoA) on Azure. We describe a new program verifier VeriSol for Solidity based on a translation to Boogie and leveraging the Boogie verification toolchain. We describe our experience applying VeriSol to Workbench sample contracts and Proof of Authority governance contracts in Azure, and finding previously unknown bugs in well-tested smart contracts. We provide push-button unbounded verification for the semantic conformance checking for all the sample contracts shipped in Workbench, once the bugs are fixed.

1 Introduction
The advent of blockchain (decentralized and distributed consensus protocol to maintain and secure a shared ledger) is seen as a disruptive technology with far-reaching impact on diverse areas of society such as cryptocurrencies, banking, escrow and governance. According to the Microsoft’s Coco Framework white paper[29]

Blockchain technology is poised to become the next transformational computing paradigm. It promises to disrupt existing business processes, to reduce the friction of doing business, and to unlock new business models, especially shared processes across organizations. According to Gartner, the business value-add of blockchain will grow to slightly more than $176 billion by 2025, and then it will exceed $3.1 trillion by 2030.

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Smart Contracts are applications that run on blockchains such as Ethereum, and are an essential ingredient for democratizing the use of blockchain technology beyond cryptocurrencies (e.g. bitcoin). Smart contracts often encode expressive workflows encoded in a Turing-complete programming language. For example, the Ethereum blockchain provides a low-level stack-based bytecode language that executes on top of the Ethereum Virtual Machine (EVM). High level languages such as Solidity and Serpent have been developed to enable traditional application developers to author smart contracts.

There are at least two compelling reasons to apply formal specifications and verifications to smart contracts:

• Smart contract vulnerabilities. Unlike traditional programs written in high-level programming languages, smart contracts have unique security and integrity characteristics. First, smart contracts manage, hold, and transfer digital assets such as Ether, which make them susceptible to theft. Second, smart contracts are mostly immutable after deployment and hence the need to ensure their safety and security operating in an open and adversarial context is of paramount importance. Vulnerabilities in smart contracts have resulted in several high-profile exploits that undermine the trust in the underlying blockchain technology. For example, the infamous TheDAO exploit [2] resulted in the loss of almost 60 million USD worth of Ether, and resulted in an undesirable hard fork in Ethereum. Several other smart contract vulnerabilities have resulted in the loss of substantial value of Ether [15], including the Parity Wallet bug that resulted in 169 million USD worth of ether to be locked forever [5].

• High-level specifications. Smart contracts are often low-level implementations of a high-level workflow that comprises a state machine with different actions predicated by suitable access control to determine who has the permission to execute a given action. These high-level workflows are
often designed by domain experts, who may not be proficient programmers with knowledge of subtle semantics of programming constructs. Thus, there is a strong need for a high-level specification language for expressing the intent of the workflow, which can be implemented in a smart contract. Specifying the high-level workflow abstractly also allows targeting different languages (e.g., Solidity) or ledgers (Ethereum vs. Hyperledger Fabric [1]) with relative ease.

In this work, we explore the use of formal specification and verification for Solidity smart contracts that constitute the Azure Blockchain content and samples on github [8]. Azure Blockchain consists of a set of components and services that allow businesses to rapidly prototype and deploy blockchain applications on the Azure cloud [4]. Among other services, it currently consists of two main products (a) Azure Blockchain Workbench (or simply Workbench henceforth), and (b) Ethereum on Azure, which are interesting from the perspective of smart contract analysis. Several aspects of these smart contracts make them interesting targets for verification:

1. First, many of the sample contracts constitute proof of concepts for real-world enterprise scenarios.
2. Second, a Workbench application consists of a JSON file that expresses the state machine with access control that a smart contract has to implement. Once formalized, these can serve as implicit specifications that can be checked statically or at runtime.
3. Finally, the smart contracts that constitute the Ethereum on Azure (namely, the PoA governance contracts) have been deployed several thousand times by Azure Blockchain customers. Thus, the safety and security issues in such contracts have serious real-world consequences.

Although several static analysis approaches have been proposed recently to scan for known vulnerabilities in smart contracts [27, 31], they do not offer the users the ability to specify and verify formal specifications (see Related Work in Section 8 for further explanation). For the purpose of this paper, we distinguish a formal verifier from static analysis in that a violation of a formal specification is always considered a bug, not just a bad coding practice.

Contributions. The paper makes the following contributions:

1. We provide a formalization to the JSON-based Workbench application configuration that allows formal tools to interpret and enforce it.
2. We define a semantic conformance checking problem between a JSON-based Workbench application configuration and a smart contract, and provide an automatic program instrumentation to enforce the specification in a Solidity smart contract.
3. We describe a new prototype formal verifier VeriSol for Smart Contracts written in Solidity. The verifier encodes the semantics of Solidity programs into Boogie and leverages the well-engineered Boogie verification pipeline [16]. The verifier is generic and not tied to the Azure Blockchain examples.
4. We use VeriSol to discover previously unknown semantic conformance bugs in Workbench samples using transaction-bounded verification; we then report full verification of the property on the fixed examples using invariant inference.
5. Finally, we report a detailed case study of VeriSol on a PoA governance contract in Azure Blockchain and find previously unknown bugs.

Organization. The paper is organized as follows: In Section 2, we provide an overview of the Azure Blockchain components and the smart contracts available as part of Azure Blockchain Content and Samples; we introduce a simple running example and informally describe the Workbench JSON application configuration language for specifying access control and state transitions. In Section 3 we provide formal semantics for the Workbench JSON application configuration (Section 3.1). In Section 4 we describe the problem of semantic conformance for a smart contract C implementing a Workbench JSON configuration W. In Section 5, we provide an encoding of a subset of the Solidity language in Boogie intermediate verification language. In Section 6, we describe a formal verifier VeriSol for Solidity, that leverages the Boogie translation and uses various Boogie based (bounded and unbounded) verification tools. In Section 7, we provide our experience of running VeriSol on the smart contracts that constitute the Azure Blockchain. We discuss related work in Section 8 and finally conclude.

2 Overview of Azure Blockchain Content and Samples

Azure Blockchain consists of a set of components and services that allow businesses to rapidly prototype and deploy blockchain applications on the Azure cloud. Among other services, it currently consists of two products that are somehow independent (a) Azure Blockchain Workbench, and (b) Ethereum on Azure, which are interesting from the perspective of smart contract analysis. Azure Blockchain Workbench is primarily focused on the application level, whereas Ethereum on Azure is a product offering at the ledger level. This section gives an overview about the two.

2.1 Azure Blockchain Workbench

Workbench consists of services that allow users to deploy blockchain applications on the Azure cloud. An enterprise smart contract application requires not only a bare ledger,
but also services for user authentication, identity mapping, messaging, REST APIs, web UI, source code control, etc. Azure Blockchain Workbench (abbr. Workbench) is a product that allows such an application scaffold to be created on Azure very easily, so that a user can focus on building the smart contract application. In Workbench, the smart contract application consists of two components: (i) a JSON file describing the application configuration or interface, and (ii) a smart contract that implements the application business logic. Once an application is uploaded into Workbench, users can add more members, and members can drive the application to different states by taking suitable actions. We informally describe the configuration language (formally described in Section 3.1) and an associated Solidity smart contract in the next few paragraphs.

2.1.1 Workbench Application Configuration

Workbench requires a JSON based configuration file that is used to populate the application information, which can be queried by users through REST APIs to interact with a Workbench application. The JSON interface of an application consists of several attributes such as application name and description, set of roles, along with a set of workflows. Figure 1 provides an informal pictorial representation of the JSON for a simple application called HelloBlockchain. The actual JSON and the example related details can be found on the associated web page. The application consists of two roles (referred under "APPLICATION ROLES") namely REQUESTOR and RESPONDER. Informally, each role represents a set of user addresses; roles are used to provide access control or permissions for various actions exposed by an application.

A workflow informally consists of a name, description along with a set of states, data members, functions (or actions), and state transitions. The simple HelloBlockchain application consists of a single workflow with the same name as the application. As seen from Figure 1, the workflow consists of two states: Request and Respond. The data members (or fields) consists of Requestor, Responder, RequestMessage and ResponseMessage to store the last message (not shown in the figure). 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.

Finally, the state transitions specify the initial state (Request) and the transitions between the states. A transition 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 from the Requestor (categorized as "Allowed Role" (AR) under "Legend" box) invokes the action SendResponse. An "Application Instance Role" (AIR) refers to a data member of the workflow that stores a member of a global role (also called Requestor for the example) – a transition such as from Respond to Request that uses an AIR checks if the user address matches the value stored in the instance data variable.

2.1.2 Workbench Application Smart Contract

After specifying an application configuration in JSON, a user provides a smart contract for the appropriate blockchain ledger to implement the workflow. Currently, Workbench supports the popular language Solidity for targeting applications on Ethereum. Figure 2 describes a Solidity smart contract that implements the HelloBlockchain workflow in the HelloBlockchain application. For the purpose of this section, we will ignore the portions of the code that are
pragma solidity ^0.4.20;

contract HelloBlockchain {
    // Set of States
    enum StateType {Request, Respond}

    // 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
    {
        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
}

Figure 2. Solidity contract for HelloBlockchain application.

underlined — we will refer to them when describing the conformance checking in Section 4.2. The contract declares the data members present in the JSON configuration as state variables with suitable types. 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 function along with the two functions defined in the JSON configuration, with matching signatures. The functions set the state variables and update the state variable appropriately to reflect the state transitions.

The Workbench service allows a user to upload the JSON, the Solidity code, and optionally adding users and perform various actions permitted by the configuration. To ensure the correct functioning and security of the application, it is crucial to verify that the Solidity program semantically conforms to the intended meaning of the JSON configuration.

2.2 Proof of Authority Governance Contracts

Separate from the application level Workbench offering, Azure Blockchain also offers ledger level services. One of them is Ethereum on Azure. The Ethereum blockchain comes with a choice of consensus protocols for a decentralized system: (i) the conventional Proof of Work (PoW) and the (ii) the Proof of Authority (PoA). The consensus algorithm has to decide which node wins the privilege to append the latest block to the blockchain.

The PoW is the widely used consensus algorithm for traditional public (permissionless) blockchain to guard against Sybil attacks in the presence of anonymous nodes, e.g., in the BitCoin network. A malicious party could easily create many nodes to be disproportionately powerful. However, PoW consensus is computationally expensive as it relies on miners solving a difficult cryptographic puzzle, and therefore it limits the throughput (the number of transactions that can be mined per unit of time) of the blockchain network.

The PoA is proposed as an alternative to PoW for permissioned consortium networks where the identities cannot be forged, as they are linked to off-chain identities. It differs from a public blockchain in that the consortium is formed by running an election to accept new members, each having an identity. The members share the responsibility/authority of validating transactions and appending them in the ledger. It allows for a superior throughput in the case of consortium blockchain applications.

Enterprise customers and other systems such as Azure Blockchain Workbench can deploy a PoA network on Azure based on the Parity implementation of Ethereum. The network consists of a set of nodes running the PoA protocol and validating transactions. Every node is assigned a distinct Ethereum address, which is called the validator address. The validator set is a contract managing a set of validator addresses (shown as “validators” for brevity). Adding or removing a validator address will result in its corresponding node to be added into or removed from the PoA network.

Parity Ethereum implementation exposes a ValidatorSet contract interface that is implemented by the Ethereum on
Azure deployment. Governing a PoA network requires a set of contracts shown in Figure 3. Validators belong to different organizations, such as companies A, B and C in the figure. Each organization is represented by an admin contract. Initially, the PoA network is created by one admin, who naturally becomes the only elected admin of the network. Later, for another admin to become an elected admin, it needs to win a majority vote among existing elected admins. An elected admin is allowed to bring in a number of validators. The admins can also vote against each other. If more than half of the existing elected admins vote against one of them, the admin will be evicted, and its validators are removed consequently. The above protocol for admin voting and validator set management is implemented as a set of contracts that implement the Parity Ethereum’s ValidatorSet contract interface, and available as part of Azure Blockchain content and samples [9, 10]. It consists of the following smart contract implementations totaling around 600 lines of Solidity code.

- **SimpleValidatorSet**: A simple implementation of the ValidatorSet that handles adding validators.
- **AdminValidatorSet**: Inherits from SimpleValidatorSet, and introduces the concept of Admins for different organizations and voting. It allows an admin to control their validator set and vote for other admins.
- **Admin**: A contract representing a Consortium member; it tracks votes for or against a given member.
- **AdminSet**: Contract used for performing constant time operations on a set of Admins.

The smart contracts use several features that make it a challenging benchmark for Solidity smart contract reasoning. We outline some of them here:

- The contracts use multiple levels of inheritance since the top-level contract AdminValidatorSet derived from the contract SimpleValidatorSet which in turn derives from ValidatorSet interface.
- It uses sophisticated access control using Solidity modifiers to restrict which users and contracts can alter states of different contracts.
- The contracts maintain deeply nested mappings and arrays to store the set of validators for different admins.
- The contracts make use of nested loops and procedures to iterate over the arrays, and make use of arithmetic operations to reason about majority voting.

3 Formalizing Workbench Application Configuration

In the next couple of sections we describe the problem of ensuring that a smart contract $C$ correctly implements the Workbench Application Configuration provided in the JSON file. We first formalize the Workbench Application Configuration (WBAC) that we informally introduced in Section 2. The description can be seen as a mathematical representation of the official schema documentation of WBAC as described by the Azure Blockchain Conference’17, July 2017, Washington, DC, USA.

3.1 Workbench Application Interface

The Workbench Application Interface (WBAC) is described in a JSON file. The WBAC for an application allows the user to describe the data members of an applications, role-based access control for various functions or actions, and finally a high-level state-machine based view of the application. 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 some actions from the user.

We assume that each function is associated with a sender, which is the address of a user or another workflow that invokes the function. In Solidity, this is denoted by msg.sender parameter within a function. The invocation of a function can be restricted to users that belong to certain roles — we refer to this as the access control.

Formally, a Workbench Application Configuration $\text{App} (\mathcal{R}, \mathcal{W}, \mathcal{T})$ consists of the following:

- A set of global roles $\mathcal{R}$, common to all workflows, that is used for access control for functions.
- A set of types $\mathcal{T}$, which can either be an (i) integer, or a (ii) string, or an (iii) address of a contract or user, or a (iv) role $r \in \mathcal{R}$, or a (v) workflow $w \in \mathcal{W}$ (as defined next).
- A set of workflows $\mathcal{W}$, where a workflow $w \in \mathcal{W}$ is a tuple $(\mathcal{S}_w, s^0_w, \mathcal{P}_w, Q_w, \mathcal{F}_w, \mathcal{AC}_w, ac^0_w, f_w)$:
  - $\mathcal{S}_w$, a bounded set of states,
  - $s^0_w \in \mathcal{S}_w$, an initial state,
  - $\mathcal{P}_w$, a set of properties where a property $(id : t) \in \mathcal{P}_w$ has a type $t \in \mathcal{T}$ and a string identifier $id$.
  - A subset of properties $Q_w \subseteq \mathcal{P}_w$ are instance roles, where the types are roles from $\mathcal{R}$. That is, for any $(id : t) \in Q_w$, $t$ is a member of $\mathcal{R}$. The intuition is that a specific instance of a workflow may designate only a subset of members from a given role to execute certain action. The instance role variables capture such instance specific users who are members of a given role $t \in \mathcal{R}$.
  - A set of function types $\mathcal{F}_w$, where each function type $f(id_0 : t_0, \ldots, id_{k-1} : t_{k-1}) \in \mathcal{F}_w$ consists of:
    - The function name $f$.
    - Empty list of return parameters,
    - An arity $k \geq 0$ of the input parameters,
    - A type $t_i \in \mathcal{T}$ and an identifier $id_i$ for the i-th parameter $(i \in [0, k])$, counting from zero.
  - A constructor type $w(x_0 : t_0, \ldots, x_{k-1} : t_{k-1}) \in \mathcal{F}_w$ where the function name equals the workflow name.
  - The access control set $\mathcal{AC}_w = Q_w \cup \mathcal{R}$ is a set over the union of the instance role properties $Q_w$ and the set of

[^1]: https://docs.microsoft.com/en-us/azure/blockchain/workbench/configuration
global roles in $R$. One can restrict the invocation of a function within a transition by insisting that the sender belongs to a subset of $AC_w$.

- The initiator access control $ac_w^0 \subseteq R$ for restricting users who can create an instance of the contract by calling the constructor.

- Finally, a set transitions $\gamma_w \subseteq S_w \times T_w \times AC \times 2^{S_w}$. Intuitively, a transition $(s_1, f, ac_w, s_2) \in \gamma_w$ indicates the system can transition from state $s_1$ to one of states in $S_2 \subseteq S_w$ (non-deterministically) by invoking the function $f \in T_w$ provided the “sender” of $f$ is a member of the access control set $ac_w$.

3.2 Example

Consider the WBAC for the HelloBlockchain application described in Section 2:

- Set of roles $R \equiv \{\textsc{Requestor}, \textsc{Responder}\}$
- Set of types $T \equiv \{\textsc{Requestor}, \textsc{Responder}\} \cup \{\text{integer}, \text{string}\} \cup \{\text{HelloBlockchain}\}$
- A single workflow $W \equiv \{\text{HelloBlockchain}\}$ (we drop the $w$ suffix) with:
  - Set of workflow states $S \equiv \{\text{Request, Respond}\}$
  - The start state $s_0 \equiv \text{Request}$
  - The set of properties (or fields) $P \equiv \{\text{RequestMessage : string, ResponseMessage : string, Requestor : \textsc{Requestor}, Responder : \textsc{Responder}\}$
  - The set of instance role properties are $Q \equiv \{\text{Requestor, Responder : Responder} \} \subseteq P$.
  - The set of 3 functions:
    * The constructor HelloBlockchain(message : string),
    * Two functions SendRequest(requestMessage : string) and SendResponse(responseMessage : string).
  - The access control set $AC \equiv \{\textsc{Requestor, Responder}\} \cup \{\textsc{Requestor, Responder}\}$, with the initiator access control $ac_0^0 \equiv \{\textsc{Requestor}\}$.
  - Finally, there are two state-transitions in $\gamma$ as depicted in Figure 1.
    * (Request, SendResponse, {Responder}, {Respond}), and
    * (Respond, SendRequest, {Requestor}, {Request}).

4 Semantic Conformance Checking for Workbench

Given a WBAC $App$ in the form of a JSON file and a smart contract $C$ (say a Solidity file), we would like to ensure that the smart contract $C$ correctly implements the interface and the state transitions described in $W$. This is crucial to ensure that the high-level workflow specified in the application configuration file $App$ by the designer is correctly implemented in the smart contract.

We can divide this task into (a) structural and (b) semantic conformance checking. The structural conformance checking ensures that the data members, states and types specified in $W$ match those in $C$. The semantic conformance checking ensures that the smart contract $C$ (that is structurally conformant with $App$) correctly implements the access control and state transitions in $W$. Whereas the structural checking problem can be stated purely in terms of the abstract syntax tree of $C$, the semantic checks require reasoning over the dynamic runtime states of $C$. In Section 4.1, we formalize the problem of semantic conformance by providing an axiomatic semantics over an abstract smart contract language. Next, we describe a program instrumentation technique for runtime enforcement of these checks, and provide a concrete implementation for Solidity based smart contracts.

We first state an abstract version of structural conformance checking in this Section — the concrete details rely on the choice of language in which the smart contract is expressed (e.g. Solidity). Given a WBAC $App(R, W, T)$ and a smart contract $C$, the structural conformance checker enforces the following for each workflow $w \in W$: (i) There exists a contract or class named $w$ in $C$, and the the matched class for $w$ contains (a) a member variable named $\text{State}$ whose range is $w,S$, the set of states in $w$, (b) a matching member variable or field for each $p \in w,P$ with compatible types, and (c) a matching constructor function and public functions that match the constructor and the functions in the workflow. Each function needs to have matching name as well as matching parameter name list, with compatible types. The Workbench system already provides one such structural conformance checker for Solidity.

4.1 Semantic Conformance

In this section, we show how to ensure that a structurally conformant smart contract implements the access control and state transitions according to the WBAC specification. We formalize these checks using an axiomatic semantics for a generic smart contract that supports constructors and function invocation. We use the Floyd-Hoare triple notation for partial correctness

$$\{ \phi \} \; c \; \{ \psi \}$$

to denote that for any execution $\sigma$ of the statement $c$ from a state satisfying the predicate $\phi$, $\sigma$ does not fail any assertions and, upon termination, will end up in a state satisfying the predicate $\psi$. We do not require the execution to terminate however.

Let $x$ be an instance of workflow $w$. At a high-level, the idea is simple: we insist that when a function (respectively, the constructor) is executed along a transition (respectively, during contract creation), the resulting state transition should be in accordance with the workbench application specification.

1. **Constructor.** We ensure that a successful termination of the constructor (of arity $k$) during the creation of an
We first describe a challenge in enforcing the checks related to global roles. We then provide program instrumentation to add the conformance checks for ensuring correct initial state and state transitions.

### 4.2.1 Global Roles

Although a Workbench Application configuration declares a set of global roles in $\mathcal{R}$, Workbench currently does not maintain the information on the blockchain. Workbench maintains the membership of different roles in databases outside of the blockchain. As a result, Solidity smart contracts for a Workbench application cannot refer to global role information in the body of any function. Validations of access control in $\mathcal{AC}$ for a transition is performed by the Workbench system directly at the time a function is invoked. This poses an interesting dilemma for statically verifying the semantic conformance: we can either model the state of the role database in addition to the smart contract code, or we perform a conservative verification where the content of each global role is completely non-deterministic. We adopt the latter for two reasons: (i) First, since the smart contracts cannot refer to global roles in current Workbench, any modification to the set of global roles (e.g., adding a user to the Requestor in the HelloBlockchain application) will never be interleaved with a transaction that executes a function in a workflow (given the deterministic execution semantics of EVM). (ii) Second, given that the global roles can change arbitrarily before invoking a function, one has to assume a completely non-deterministic value of the global roles for soundness. Therefore, we do not introduce any spurious behaviors by assuming the global roles as being completely arbitrary sets.

### 4.2.2 Program Instrumentation

To instrument the checks we formalized in the prior section, we use the `modifier` construct from Solidity. A modifier has syntax very 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 (we refer users to Solidity documentation of modifiers [3]) is:

```solidity
modifier Foo() {
    _; // placeholder
    post-statements;
}
```

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

```solidity
function Bar(int x) Foo() {
    Bar-statements;
}
```
the Solidity compiler transforms the body of Bar to execute pre-statements (respectively, post-statements) before (respectively, after) Bar-statements. This provides a convenient way to inject code at multiple return sites from a transition function 

We now define a couple of helper predicates before describing the actual checks. Let us first define a Solidity predicate \( \pi(ac) \) to encode a sender to be a member of an access-control set \( ac \):

\[
\pi(ac) \triangleq \begin{cases} 
\text{false}, & ac = \{} \\
\text{msg.sender} == q, & ac = \{ q \in Q_w \} \\
\text{NonDetFunc}, & ac = \{ r \in R \} \\
\pi(ac^1) \lor \pi(ac^2), & ac = ac^1 \lor ac^2 
\end{cases}
\]

Here \( \text{NonDetFunc} \) is a side-effect free Solidity function that returns a non-deterministic Boolean value at each invocation.

For the sake of static verification as we describe in this paper, one can declare a function without any definition. This allows us to model the membership check \( \text{sender} \in ac \) conservatively in the absence of global roles on the blockchain. However, this solution is not suitable for installing actual runtime checks since a truly non-deterministic function such as \( \text{NonDetFunc} \) cannot be realized; we discuss the actual runtime checks in the Appendix A.

Next, we define a predicate for membership of a contract state in a set of states \( S \subseteq S_w \) using \( \alpha(s) \) as follows:

\[
\alpha(S) \triangleq \begin{cases} 
\text{false}, & S = \{ \} \\
\text{State} == \text{StateType.s}, & S = \{ s \in S_w \} \\
\alpha(S_1) \lor \alpha(S_2), & S = S_1 \lor S_2 
\end{cases}
\]

We use these predicates to define the source code transformations below:

- **Constructor.** For a workflow \( w \), we add the following modifier to constructor.

```solidity
modifier constructor_checker() {
    require (msg.sender != tx.origin ||
        NonDetFunc()); // global role REQUESTOR

    assert (State == StateType.Request);
}
```

It is not hard to see that the assertion ensures that the constructor sets up the correct initial state. The precondition consists of two parts. The first disjunct \( \text{msg.sender} \neq \text{tx.origin} \) checks that the constructor is invoked by another contract and not a user (the global variable \( \text{tx.origin} \) tracks the user address that initiates a transaction); this is an implementation of the \( \neg \text{isUser(sender)} \) predicate abstractly stated in earlier section. The second disjunct \( \pi(ac^0) \) checks the access control for the \( \text{msg.sender} \) for the case when it is a user address.

- **Transition Function** For a function \( g \), let there be multiple transitions \( y^k \triangleq \{ t \in \gamma_w \mid t.f == g \} \) where \( g \) is invoked. Let \( k \) be the arity of \( g \).

```solidity
modifier g_checker() {
    // copy old State
    StateType oldState = State;
    // copy old instance role vars
    ...
    ...
    assert (\( \forall t (w(t,ac^0) \land \alpha(t.w)) \Rightarrow \alpha(t.S_w) \));
}
```

First, we copy the \( \text{State} \) variable and all of the variables in \( Q_w \) into corresponding “old” copies. Next, the assertion checks that if the function is executed in a transition \( t \), then state (denoted by \( \text{State} \)) transitions to one of the successor states in \( t.S \). The notation \( \text{old}(e) \) replaces any occurrences of a state variable (such as \( \text{State} \)) with the “old” copy that holds the value at entry to the function; this is required since the value of the state variables can change during the execution of the procedure. Finally, since conjunction distributes over assertions, we can replace the single assertion with an assertion for each transition in the implementation.

### 4.2.3 Instrumented Running Example

Figure 4 shows the modifier definitions for our running example HelloBlockchain described in Section 2. The modifiers are applied to the user-written smart contract in Figure 2, and shown by the underlined statements. We add a comment for the lines where a reference to a global role in the specification is replaced by a call to the non-deterministic function \( \text{NonDetFunc} \).

```solidity
function NonDetFunc() returns (bool); // no definition

// Checker modifiers
modifier constructor_checker() {
    require (msg.sender != tx.origin ||
        NonDetFunc()); // global role REQUESTOR

    assert (State == StateType.Request);
}
```

```solidity
modifier SendRequest_checker() {
    StateType oldState = State;
    address oldRequestor = Requestor;

    assert ((msg.sender == oldRequester &&
        oldState == StateType.Respond) =>
        State == StateType.Request);
}
```

```solidity
modifier SendResponse_checker() {
    StateType oldState = State;

    assert ((NonDetFunc() && // global role RESPONDER
        oldState == StateType.Request) =>
        State == StateType.Request);
}
```

Figure 4. Modifier definitions for instrumented HelloBlockchain application.
5 Encoding Solidity

In the next two sections, we describe the design of a formal verifier for Solidity smart contracts. In this section, we first describe a translation of Solidity program to a program in the Boogie intermediate verification language [16]. Boogie has a small language with formalized semantics, such that verification tasks can be encoded into a formula in Satisfiability Modulo Theory (SMT), and can be discharged by SMT solvers such as Z3 [19]. The ability to go from a Boogie program to a SMT formula allows us to leverage various bounded and unbounded verification techniques for Boogie.

5.1 Boogie

We first describe a small subset of Boogie language that we use to formalize our translation from Solidity.

Boogie types are integers (int), references (Ref) or arrays; arrays can be nested in that each index of an array can store an array. Booleans are syntactic sugar over integers.

\[
\begin{align*}
    bt \in \text{BoogieElemTypes} &::= \text{int} | \text{Ref} \\
    st \in \text{BoogieTypes} &::= bt | [bbt]bt
\end{align*}
\]

\[
\begin{align*}
e \in \text{Exprs} &::= c | x | \text{op}(\ldots, e) | x[e] | \forall i: bbt ::= e \\
st \in \text{Stmts} &::= \text{skip} | \text{havoc} x | x := e | x[e] | [e] := e | \text{assume} e | \text{assert} e | \text{call} \bar{x} := f(e, \ldots, e) | \text{st}; st | \\
\text{if} (e) \{ st \} \text{ else } \{ st \} | \text{while} (e) \text{ do } \{ st \}
\end{align*}
\]

Figure 5. Simple subset of Boogie language.

Figure 5 describes the expressions and statements in the language. Expressions (Exprs) consist of constants, variables, operations over expressions and array lookups, and quantified expressions. Expressions can have one of the Boogie types described above, except \( \forall \) expressions that have type Boolean. Standard statements (Stmts) in Boogie consist of skip (skip), variable and array assignment, sequential composition, conditional statements, and loops. The havoc \( x \) statement assigns an arbitrary value of appropriate type to a variable \( x \). A procedure call (call \( \bar{x} := f(e, \ldots, e) \)) can return a vector of values that can be stored in local variables. The assert and assume statements behave as skip when the the Boolean valued argument evaluates to true in the state. When the argument evaluates to false, then assert fails the execution and assume blocks the execution.

A state \( \sigma \in \Sigma \) is a valuation of variables in scope. Evaluation of an expression \( e \in \text{Exprs} \), is denoted by \( (e)_\sigma \), and defined inductively. We can define the standard operational (big-step) semantics \( \sigma_1 \Downarrow st \Downarrow \sigma_2 \) that denotes that executing a statement \( st \in \text{Stmts} \) in a state \( \sigma_1 \) can transition to a state \( \sigma_2 \). We skip the details for the sake of brevity in this document.

5.2 Solidity

We now define a subset of Solidity language that is sufficiently expressive and yet concise enough to demonstrate the translation.

5.2.1 Types

We start with the set of Solidity types. Solidity types can be one of integer, string, address, a contract name, mappings or arrays over them. We unify a mapping type \( \text{mapping}(t_1 \Rightarrow t_2) \) and an array type \( t_2[t_1] \) in Solidity as \( t_1 \Rightarrow t_2 \) where \( t_2 \) could be a nested array. In general, we use the Solidity type \( t_1 \Rightarrow t_2 \Rightarrow \ldots \Rightarrow t_k \Rightarrow t \) to stand for \( t_1 \Rightarrow t_2 \Rightarrow \ldots \Rightarrow t_k \Rightarrow t \) for \( k = 1 \) and \( t_1 \Rightarrow (t_2 \Rightarrow \ldots(t_k \Rightarrow t) \ldots) \) for \( k > 1 \).

\[
\begin{align*}
ct &\in \text{ContractNames} \\
ct &\in \text{SolElemTypes} ::= \text{integer} | \text{string} | \text{address} \\
st &\in \text{SolTypes} ::= \text{ct} | ct \downarrow ct \Rightarrow st
\end{align*}
\]

We define a mapping \( \mu : \text{SolTypes} \rightarrow \text{BoogieTypes} \) that translates a Solidity type to a type in Boogie as follows:

\[
\mu(st) \doteq \begin{cases}
    \text{int}, & st \in \{\text{integer}, \text{string}\} \\
    \text{Ref}, & st \in \{\text{address}\} \cup \text{ContractNames}
    \begin{cases}
        \mu(\text{ct}), & \mu(st) \doteq \text{ct} \\
        \mu(st) \doteq \mu(st) \doteq \text{ct} \doteq \text{st}
    \end{cases}
\end{cases}
\]

As described later, we represent a Solidity string as an uninterpreted integer in Boogie. Solidity by default treats a string as an uninterpreted value that can only be compared for equality.

5.2.2 Variables

To model the semantics of an object-oriented language such as Solidity, each generated Boogie program consists of a set of variables in global scope:

- An array DType : [Ref]ContractNames that maps an address to a contract name corresponding to its dynamic type.
- An array Alloc : [Ref]bool that maps an address to its allocation status.
- An array Length : [Ref]int that maps the address (of an array) to the size of the array.
- For each scalar state variable \( F \) of type \( t \) in a contract \( C \in \text{ContractNames} \) in Solidity, we introduce a map \( \text{F}_C : [\text{Ref}]\mu(t) \)
- For an array or mapping state variable \( F \), we introduce a map \( \text{F}_C : [\text{Ref}]\text{Ref} \).
- For any array type \( t_1 \Rightarrow \ldots \Rightarrow t_k \Rightarrow t \in \text{SolTypes} \) (either as state variable or local variable) (where \( t_i \in \text{SolElemTypes} \) for \( i \in [1, k] \)), we add a set of maps:
  - \( \text{M}_\text{bk}_\text{b} : [\text{Ref}][\mu(t_k)]\mu(t), \) and
  - a set of at most \( k - 1 \) distinct maps:

\[
\{ \text{M}_\text{bi}_\text{Ref} : [\text{Ref}][\mu(t_i)]\text{Ref} \mid i \in [1, k - 1] \}
\]

Here \( \text{bk} \) (respectively \( \text{b} \)) is the string representation of \( \mu(t_k) \) (respectively \( \mu(t) \)); for example, if \( \mu(t_k) \) is int, then \( \text{bk} \) is "int".
Consider the example contracts in Figure 9 to illustrate the modeling.

- First, for the state variable \( a \) in contract \( C \) of scalar type \( A \in \text{ContractNames} \), we introduce a map \( a.C \) of type \([\text{Ref}]\text{Ref}; \) an access to a inside a contract instance is treated as \( a.C[\text{this}] \). Here this is a parameter to the enclosing method to refer to the address of the current object or contract instance (corresponds to Solidity \text{this}).
- Second, since there is an array type \( \text{int} \Rightarrow \text{int} \Rightarrow \text{int} \in \text{SolTypes} \) in the program as the type of \( n \) in contract \( A \), we introduce the maps \( \text{M\_int\_Ref}: \text{[Ref]}\text{[int]}\text{Ref} \) and \( \text{M\_int\_int}: \text{[Ref]}\text{[int]}\text{int} \).
- An array access in Solidity such as \( n.A[0] \) is translate as
  \[
  \text{M\_int\_int}[\text{M\_int\_Ref}[\text{n\_A[\text{this}]]}[0]][0]
  \]
  where \( \text{n\_A[\text{this}]} \) looks up the value of \( n \) for this instance,
  \( \text{M\_int\_Ref}[\text{n\_A[\text{this}]]}[0] \) looks up the map at index 0, which is finally used to index into the \( \text{M\_int\_Ref} \) map again at index 0 to obtain the scalar value. We define the formal translation of expressions later in this section.

In addition to the set of globals, the set of variables in \textit{local scope} consists of

- A formal parameter \( x \) of type \( \mu(t) \) for each solidity parameter \( x \) of type \( t \).
- A formal parameter \( \text{msg\_sender} \) of type \text{Ref}, and a formal parameter \( \text{this} \) of type \text{Ref}. These variable models the implicit Solidity parameters \text{msg\_sender} and \text{this} respectively.
- A local variable \( x \) of type \( \mu(t) \) for each Solidity local variable \( x \) of type \( t \).

### 5.2.3 Expressions

Figure 10 describes the set of Solidity expressions (\textit{SolExprs}). Most expressions are standard; the expression \( x.\text{length} \) refers to the length of a static or dynamically allocated array \( x \). Figure 11 describes translation of a Solidity expression (denoted by the function \( \Gamma() : \text{SolExprs} \rightarrow \text{Exprs} \)) to an expression in Boogie. We highlight the non-trivial cases here. For a string literal, we use an uninterpreted function \textit{StrToInt()} to map it to an integer; one can think of this as a hash of the string. For a state variable \( x \) in contract \( C \), the translation \( \Gamma(x) \) indexes into \( x.C \) with the \text{this} parameter. The translation of array access \( x[se] \) indexes into a global array after recursively translating \( x \) and \( se \). The choice of array depends on the Solidity type of \( x[se] \). If the Solidity type is an array then the resulting expression has type \text{Ref} in Boogie to represent the address of such an array; we index into the array \( \text{M\_t\_Ref} \). Otherwise, we index into the array \( \text{M\_t\_t2} \) where \( t2 \) is the translated type of \( x[se] \).

### 5.2.4 Statements

Figure 10 also describes the set of statements in Solidity that we translate to Boogie. The \textit{require(se)} aborts execution when executed in a state when \( se \) is false, and can be used for adding preconditions to functions. In contrast, \textit{assert(se)} is used to terminate execution when an internal invariant \( se \) does not hold. We distinguish between two types of procedure calls (a) \textit{internal} \( x = \text{Foo}(\bar{e}) \) which invokes a method \text{Foo} within the same contract, and (b) \textit{external} \( x = y.\text{Foo}(\bar{e}) \) that invokes a method on a contract instance pointed to by \( y \) (which may include \text{this}). For an array variable \( x, x.push(se) \) adds an element with value \( se \) to the end of the array and increments the \( x.\text{length} \).

### Assignments

Figure 12 provides the translation of Solidity statements to Boogie statements using the function \( \Delta \). We translate \textit{require(se)} (respectively \textit{assert(se)}) using \textit{assume} (respectively, \textit{assert}), given that these statements terminate execution when the argument is false and we do not allow exceptions to be caught in our subset of Solidity. An assignment \( x = se \) in Solidity can either be a simple top-level assignment (of a value or address) or a deep-copy (in the case of certain arrays). Figure 13 shows the cases where an array assignment in Solidity is treated as assigning the reference (\textit{Ref}) or performing a deep-copy (\textit{Deep}) [14]. Our translator currently does not handle programs that contain deep copy; this is denoted by the \( \perp \) when we encounter the need for a deep copy. Translation of an array assignment \( \Delta(x[se]) = y \) (that does not correspond to a deep-copy) uses \( \Gamma((x[se])) \) to determine the array to be updated.

### Functions

A function in Boogie has two additional input parameters that correspond to the implicit parameters in a Solidity function. We add a first formal parameter with the name \text{this} that holds the value the receiver object, and the last formal parameter with the name \textit{msg\_sender} that holds the user or contract address (\textit{msg\_sender} in Solidity) that invokes the function. The translation of internal function calls is more or less straightforward; note that the \textit{msg\_sender} is unchanged for an internal call. An external call first needs to perform a case-split based on the dynamic type of the receiver object to handle dynamic dispatch due to inheritance; we assume a closed program where all the types are known at compile time. Recall that the dynamic type of an object is stored in the \text{DType} array. Once the dynamic type \( \text{DType}(\Gamma(y)) \) is determined (say \( B \)), the call is dispatched to the copy of \text{Foo} (say, \text{Foo}_B) that is in scope for the dynamic type. For a given type, the \text{Foo} in scope may be defined in one of the base contracts. Since Solidity supports multiple inheritance, we traverse the list of \textit{linearized} base contracts (as provided by the compiler) to find the first function with matching signature as \text{Foo} starting from the most derived
// Solidity code with nested mappings
pragma solidity ^0.4.24;

contract A {
    mapping (int => int[]) n;
    constructor() {
        n[0].push(22);
    }

    function F() returns (bool) {
        return false;
    }
}

contract B is A {
    mapping (int => int[]) m;
    constructor() {
        require (n[0].length == 1);
        m[0] = 11;
        m[1] = 21;
        //m[0] does not alias m[1]
        assert (m[0][0] == 11);
        //m[0][1] does not alias m[*]
        assert (m[0][1] == 21);
    }

    function F() returns (bool) {
        return true;
    }
}

contract C {
    mapping (int => int[]) n;
    constructor() {
        a = new B();
    }

    function F() returns (bool) {
        return false;
    }
}

Figure 6. Solidity source code

// global declarations
type Ref;
type ContractName;
var DType: [Ref]ContractName;
var M_int_int: [Ref][int]int;
var M_int_ref: [Ref]intRef;
var M_int_ref: [Ref][int]int;
var Alloc: [Ref]bool;
// Allocate a new address
procedure Fresh(): (newRef: Ref) {
    havoc newRef; assume (!Alloc[newRef]);
    Alloc[newRef] := true;
}

// Allocates an unbounded set of new addresses
procedure AllocUnboundedAddresses() {
    var oldAlloc: [Ref]bool;
    oldAlloc := Alloc; havoc Alloc;
    // ensure old allocated addresses remain
    // allocated
    assume (forall i:Ref :: oldAlloc[i] == Alloc[i]);
}

Figure 7. Boogie prelude

// Boogie code
const unique A, B, C: ContractName;
var n_A, m_B, a_C: [Ref]Ref;

// A's constructor
proc A_Ctor(this: Ref, msg_sender: Ref) {
    // start of initialization
    // Make array/mapping vars distinct for n
    call tmp := Fresh(); assume (Length[tmp] == 0);
}

// nested array initialization
assume (∀ i:int :: (Length[M_int_Ref[tmp][i]] == 0));
assume (∀ i:int :: !(Alloc[M_int_Ref[tmp][i]]));
call AllocUnboundedAddresses();
assume (∀ i, j:int :: (i == j || M_int_Ref[tmp][i] != M_int_Ref[tmp][j]));
assume (∀ i, j:int :: M_int_int[tmp][i][j] == 0);
n_A[this] := tmp;
// end of initialization

var l := Length[M_int_Ref[n_A[this][0]]];
M_int_int[M_int_Ref[tmp][0]][l] := 22;
M_int_int[M_int_Ref[tmp][0]][l + 1] := 1 + 1;

proc F_A(this:Ref, msg_sender: Ref) returns (r:bool) {
    r := false;
}

// B's constructor
proc B_Ctor(this: Ref, msg_sender: Ref) {
    call A_Ctor(this, msg_sender);
}

// start of initialization
// Make array/mapping vars distinct for m
call tmp := Fresh(); assume (Length[tmp] == 0);

// Initialize Integer mapping m
assume (forall i:int :: M_int_int[tmp][i] == 0);
M_B[this] := tmp;
// end of initialization

assume (Length[M_int_Ref[n_A[this][0]]] == 1);
M_int_int[M_B[this][0]][0] := 11;
M_int_int[M_B[this][0]][1] := 21;
assert (M_int_int[M_B[this][0]][0] == 11);
assert (M_int_int[M_int_Ref[n_A[this][0]]][0] == 22);

proc F_B(this:Ref, msg_sender: Ref) returns (r:bool) {
    r := true;
}

// C's constructor
proc C_Ctor(this: Ref, msg_sender: Ref) {
    call x := Fresh();
    assume (DType[x] == B);
    call B_Ctor(x, this);
    a_C[this] := x;
    if (DType[a_C[this]] == B) { /* dyn dispatch */
        call y := F_B(a_C[this], this); /* msg.sender update */
    } else if (DType[a_C[this]] == A) {
        call y := F_A(a_C[this], this);
        assert (y);
    }
}

Figure 8.Translated Boogie code.

Figure 9. Example Solidity code and translated Boogie code that includes the program-independent prelude and program-specific translation.
and install similar assumptions for ensuring non-aliasing of nested addresses at level $j$ with any previously allocated addresses. Finally, for the last level $k$, we also zero initialize the contents.

Contract allocation of type $C$ invokes $\text{Fresh}$ to allocate a fresh address, sets the dynamic type of the address and then calls the constructor $\text{C}\_\text{Ctor}$ with appropriate arguments and returns the fresh address. A call to a constructor function $\text{C}\_\text{Ctor}$ has several steps: (i) executes the constructors of the base classes in the linearized order of inheritance, (ii) allocates and initializes the static state variables including arrays and mappings, and (iii) executes the statements in $\text{C}\_\text{Ctor}$.

Example 5.1. We briefly go over the set of initializations that we perform in the constructor using an example; by default, values are unconstrained retaining soundness. Figure 9 illustrates a simple Solidity program (sub Figure 6), and the translated Boogie program (sub Figures 7 and 8). The example is inspired by the PoA governance contracts (Section 2.2) that contain several nested mappings and array state and local variables. Ensuring initialization and non-aliasing of nested arrays and mappings at contract allocation is crucial for establishing any non-trivial property. The assertions present in the constructor of contract $B$ model several such example non-aliasing properties.

For this example, we only describe the initialization within the constructors; the translation of the remaining statements follow a straightforward application of $\Delta$ to each Solidity statement. Consider the constructor $\text{A}\_\text{Ctor}$ for contract $A$. $A$ has a nested mapping $\text{n}$ from integers to an array of integers; we treat it as $\text{integer} \Rightarrow \text{integer} \Rightarrow \text{integer}$ mapping. Lines 10 to 20 in Figure 8 perform initialization related to $\text{n}$ by following the translation of nested mapping initialization from Figure 12.

5.2.5 Features in progress

We currently handle a subset of the Solidity language. Most of theUnhandled features are orthogonal to the current translation, and thus can be added modularly. We discuss some of these missing features in the current translation. First, we are working on designing a sound semantics for the deep-copy array assignments; we currently require simplifying the source code to turn such assignments into assignments of references. Second, we do not support low-level call statements using $\text{call}$ that looks up a function using a hash of the signature; such calls are discouraged in favor of high-level procedure calls that we support [6]. Third, we do not support balance related logic for payable contracts for exchanging ether, including $\text{send}$ and $\text{transfer}$ operations; interestingly, many enterprise workflow related contracts do not use payable contracts and instead use an implementation of some standard tokens (e.g. ERC20). Finally, we also currently do not support modifiers, libraries, structs and inlined
\[\Gamma(c) \equiv \begin{cases} c, & \text{if } c \text{ is an integer, address constant literal} \\ \text{StrToInt}(c), & \text{if } c \text{ is a string constant literal} \\ x, & \text{if } x \text{ is a local or parameter} \end{cases}\]

\[\Gamma(x) \equiv \begin{cases} \text{msg\_sender}, & \text{if } x \text{ is msg\_sender} \\ x_C[\text{this}]. & \text{if } x \text{ is a state variable in contract } C \end{cases}\]

\[\Gamma(\text{op}(se_1, \ldots, se_k)) \equiv \text{op}(\Gamma(se_1), \ldots, \Gamma(se_k))\]

\[\Gamma(x[se]) \equiv \begin{cases} \text{M\_t\_Ref}[\Gamma(x)](\Gamma(se)), & \text{if } \mu(\text{SolTypeOf}(se)) \text{ is } t \text{ and } x[se] \text{ is array type} \\ \text{M\_t\_t2}[\Gamma(x)](\Gamma(se)), & \text{if } \mu(\text{SolTypeOf}(se)) \text{ is } t \text{ and } \mu(\text{SolTypeOf}(x[se])) \text{ is } t2 \end{cases}\]

\[\Gamma(x.\text{length}) \equiv \text{Length}[\Gamma(x)]\]

\[\Gamma(\bar{s}e) \equiv \Gamma(se_0), \ldots, \Gamma(se_{k-1}), \text{ where } k = |\bar{s}|\]

**Figure 11.** Translation of Solidity expressions to Boogie.

\[\Delta(\text{require}(se)) \equiv \begin{cases} \text{assume } (\Gamma(se)) \end{cases}\]

\[\Delta(\text{assert}(se)) \equiv \begin{cases} \text{assert } (\Gamma(se)) \end{cases}\]

\[\Delta(x = se) \equiv \begin{cases} (\Gamma(x) := \Gamma(se), \text{ if } x \text{ is a scalar variable, or the assignment is by reference} \\ \bot, \text{ throw an exception for any deep copy} \end{cases}\]

\[\Delta(x[se] = y) \equiv \Gamma(x[se]) := \Gamma(y)\]

\[\Delta(sts_1; sts_2) \equiv \Delta(sts_1); \Delta(sts_2)\]

\[\Delta(\text{if } (e) \{ s_1 \} \text{ else } \{ s_2 \}) \equiv \begin{cases} \{ (\Gamma(e)) \{ s_1 \} \} \text{ else } \{ \Delta(s_2) \} \end{cases}\]

\[\Delta(\text{while } (e) \{ s \}) \equiv \begin{cases} \{ \text{while } (\Gamma(e)) \{ s \} \} \end{cases}\]

\[\Delta(x = \text{Foo}(\bar{se})) \equiv \{ \text{call tmp } := \text{Foo}(\text{this}, \Gamma(\bar{se}), \text{msg\_sender}); \Gamma(x) := \text{tmp}; \}, \text{ // internal function call and static dispatch} \]

\[\Delta(x = y.\text{Foo}(\bar{se})) \equiv \begin{cases} \{ \text{// external call, dynamic dispatch} \\ \text{if } (\text{DType}[\Gamma(y)] == A) \{ \text{call tmp } := \text{Foo}_A(\Gamma(y), \Gamma(\bar{se}), \text{this}); \Gamma(x) := \text{tmp}; \} \text{ else if } (\text{DType}[\Gamma(y)] == B) \{ \text{call tmp } := \text{Foo}_B(\Gamma(y), \Gamma(\bar{se}), \text{this}); \Gamma(x) := \text{tmp}; \} \end{cases} \]

\[\Delta(x.\text{push}(se)) \equiv \Delta(x.x.\text{length}++) = se); \text{// pushing a new array element} \]

\[\Delta(x = \text{new } t[\Gamma(se)]) \equiv \begin{cases} \{ \text{// allocating a new dynamic array of type } t \in \text{SolElemTypes} \}
\end{cases} \]

\[\Delta(x = \text{new } (t_1 \ldots t_k \Rightarrow t)(\bar{se})) \equiv \begin{cases} \{ \text{//initializing a nested mapping } s.t. t_i \text{ is } \mu(t_i) \text{ and } t \text{ is } \mu(t) \}
\end{cases} \]

\[\Delta(x = \text{new } C(\bar{se})) \equiv \begin{cases} \text{// } C \in \text{ContractNames} \}
\end{cases} \]

**Figure 12.** Translation of Solidity statements to Boogie. We do not translate statements that involve a deep copy.
Figure 13. Semantics of Solidity array assignment LHS = RHS.

assembly instructions. Recall that our semantic conformance checking in Section 4.2 used modifiers to add the runtime checks. Our current implementation uses a slightly more involved variant using a derived class to add similar checks without the need for modifiers. We plan to add modifiers to our translation soon as it is a fairly common way to enforce preconditions including access control. We currently do not distinguish the different variants of integers such as unsigned integers or integers of fixed width, and model them all as unbounded integers.

6 Formal Verification

We now describe VeriSol, a formal verifier for Solidity smart contracts. The verifier has three main components: (i) it first uses the Solidity to Boogie translation from Section 5 to generate a Boogie program, (ii) harness construction to create a closed program to be fed to a verifier, and (iii) use of bounded and unbounded verification techniques for Boogie programs. We focus on (ii) and (iii) in the next two subsections.

6.1 Harness Construction

The Boogie program derived from a Solidity program consists of a set of contracts, with specifications modeled as assertions in code. However, a program verifier requires a closed program with a main method to obtain a well-defined verification problem. We describe the process of “closing” an open Boogie program as harness construction.

Let us start with the case of a single contract C present in the Solidity program. Let $\Delta(C)$ be the translated Boogie program. We augment $\Delta(C)$ with a main procedure in Boogie as follows:

- Non-deterministically initialize the blockchain state (such as block.blockhash, block.number, tx.origin) to an arbitrary state.
- Choose a non-deterministic address $\text{this}_C$.

Although the harness construction is fairly standard for any object-oriented program, the subtlety lies in changing the blockchain states non-deterministically before any procedure invocation from C. This is used to model the interleaving of transactions involving other contract instances of C or other contracts between transactions involving an instance $\text{this}_C$ of C. Since Solidity does not allow a transaction to directly mutate a state variable of a contract, we do not need to modify the state variables in between two transactions involving the instance $\text{this}_C$. Finally, the ability to choose a $\text{msg}_\text{sender}$ non-deterministically for every call allows us to model transactions submitted by different users. Together, it is not difficult to see that the traces of main contain the effect of all user-submitted transactions that involve one instance of C. Hence, if we can prove that every execution of main satisfies all the assertions present in C, then we can establish that C does not fail any assertion at runtime.

We should observe that the harness soundly captures all transactions even for cases of multiple contracts with a single top-level contract that performs nested contract creation using new. However, the harness is no longer sound for cases of two or more interacting contract instances, each of which may be independently updated by user transactions. In such cases, we first require the user to create a Solidity meta contract with state variables for the different instances, and a union of the functions from the different contracts, before applying the above harness construction.

6.2 Boogie-based Verifiers

- Invoke the translated constructor of C in Boogie file with $\text{this}_C$ for this parameter, non-deterministic arguments for the remaining parameters including $\text{msg}_\text{sender}$.
- Repeat 0 or more times
  - Non-deterministically initialize the blockchain state (such as block.blockhash, block.number, tx.origin) to an arbitrary state.
  - Non-deterministically choose from one the public functions in C, say $f$.
  - Invoke $\Delta(f)$ with $\text{this}_C$ and non-deterministic arguments for the remaining parameters including $\text{msg}_\text{sender}$.

There are approaches to define the problem of verifying open programs such as angelic verification [18] that we do not consider in this paper.

![Figure 14. VeriSol tool flow.](image-url)
Figure 14 shows the high-level block diagram of VeriSol. Given a Boogie program $\Delta(C)$ with a main method, we can either use the verifier to find a counterexample or look for a proof. A counterexample corresponds to a sequence of transactions $t_1, \ldots, t_k$ where $t_1$ creates an instance of the top-level contract in $\Delta(C)$ and $t_k$ is the first transaction in the sequence that reverts due to a violation of some assertion in $C$. On the other hand, a proof corresponds to the guarantee that no sequence of transactions for the top-level contract in $\Delta(C)$ can result in an assertion failure at runtime.

**Unbounded Verification.** Observe that the problem of verifying the correctness of the translated Boogie program is undecidable due to the presence of unbounded integers and a top-level unbounded loop for the harness. Hence, we can only resort to sound but necessarily incomplete invariant generation schemes to prove the absence of runtime errors. We currently use the Houdini algorithm [20] and its implementation in Boogie [25] for constructing an inductive invariant over a set of candidate predicates. The 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. The algorithm converges fairly fast on large examples but relies on starting with the a superset of necessary predicates. VeriSol first tries Houdini to look for a proof; it only reports a successful proof to the user. Note that an inductive invariant for the top-level loop in the harness corresponds to a module invariant — a fact that is established by the constructor and preserved by public functions of the module.

**Transaction-bounded Verification.** If Houdini fails to find a proof, VeriSol uses a property-directed bounded verifier Corral [26] to look for a trace in the main program leading to an assertion violation. Corral uses a combination of abstraction refinement techniques and stratified inlining of procedure calls to look for a counterexample in a scalable manner. Corral requires a bound $k$ on unrolling of loops and recursive calls — this corresponds to a $k$ transaction-bounded analysis of the contract $C$ due to the top-level loop in the harness. Corral either successfully finds a counterexample or verifies the lack of any counterexample with $k$ transactions. VeriSol also comes with a defect viewer that allows a user to view the failing trace by stepping through the Solidity code, including values of various variables along the trace.

### 7 Results

In this Section, we detail the use of VeriSol on smart contracts present in the Azure Blockchain content and samples on github [7]. In Section 7.1, we describe the application to 8 Workbench sample contracts to check semantic conformance with respect to their state machine based Workbench Application Configuration (Section 4). Next, in Section 7.2 we describe the application to check safety properties for the contracts for PoA governance. We describe previously unknown bugs that have been found, confirmed and fixed by the authors of these contracts, and also report on unbounded verification for Workbench samples with respect to their specifications. All experiments were run on a Intel Xeon 3.6HGz machine with 32 GB RAM running Windows 10.

#### 7.1 Workbench Samples

Table 1 summarizes the eight sample smart contracts that are offered as part of the Azure Blockchain Workbench. We have already described one of the samples HelloBlockchain in detail as our running example in Section 2. The remaining examples similarly demonstrate some customer scenario workflow. For example, AssetTransfer is a workflow for selling a high-value asset such as a house that involves several parties such as a seller, buyers, inspector, appraisers etc. DigitalLocker illustrates a workflow for sharing a digitally locked file. RefrigSupport demonstrates the integration of events from IoT temperature sensor devices to monitor if a refrigerated shipment has not gone bad. For each of these samples, we use a utility tool AppEnforcer to instrument the Solidity code with checks for semantic conformance similar to that described in Section 4.2. The resulting Solidity program is fed to VeriSol to verify the assertions.

#### 7.1.1 Bugs Found

We report on three bugs that VeriSol found in the sample, related to incorrect initial state and state transition.

**AssetTransfer.** Figure 15 provides a pictorial description of the the access control and state transitions for the contract AssetTransfer\(^7\). It is a fairly non-trivial state transition system where the actions are guarded by membership of msg.sender within one of the roles or instance role variables. VeriSol found a bug where the transition from the

\(^7\)https://github.com/Azure-Samples/blockchain/tree/master/blockchain-workbench/application-and-smart-contract-samples/asset-transfer
Figure 15. AssetTransfer access control and state transition specification.

function Accept() public
{
    if (msg.sender != InstanceBuyer &&
        msg.sender != InstanceOwner) {
        revert();
    }
    ...

    if (msg.sender == InstanceBuyer) {
        ...
    }
    else {
        // msg.sender has to be InstanceOwner
        // from the revert earlier
        if (State == StateType.NotionalAcceptance) {
            State = StateType.SellerAccepted;
        }
        else if (State == StateType.BuyerAccepted) {
            // BUG: Should be StateType.SellerAccepted
            State = StateType.Accepted;
        }
        ...
    }
}

Figure 16. Function Accept of AssetTransfer.

state BuyerAccepted to SellerAccepted was incorrectly implemented in the accompanying smart contract. The specification allows a transition between the two states when invoking the function Accept when msg.sender equals the instance role variable InstanceOwner (abbreviated as IO in the diagram). However, the implementation of the function Accept in Solidity transitions to the state Accepted instead under the same transition.

This is an example of a fairly deep bug, as it requires at least 6 transactions to reach the state BuyerAccepted from the initial state, each executing a function with several lines of Solidity code. We can speculate that the author of this sample either did not have tests that exercised such deep transactions, or test oracles to observe the incorrect transition. The defect trace is an interprocedural trace terminating with Accept. The trace within Accept consists of lines 3, 9, 15, 18 and 20. The transaction bounded verification using Corral found this bug within 5.96 seconds. In the process, it inlined 954 procedures indicating the non-trivial search required to discover the defect.

DigitalLocker. VeriSol found a bug related to incorrect initial state of the smart contract. According to the specification, the start state of the contract should be Requested, however the constructor terminates in DocumentReview.
This was confirmed as a true bug and was introduced while porting the smart contract and an older code, for which the initial state was indeed DocumentReview; the configuration was updated to the new initial state, however the smart contract initial state was not refreshed.

**BazaarItemListing.** We also found a similar bug where the initial state of a nested contract was not set according to the one specified in the JSON specification. This is an interesting contract that consists of two separate contracts BazaarItemListing and ItemListing, where a function in the former creates an instance of the latter contract using dynamic allocation new ItemListing(...). The state of the newly created ItemListing contract was set using a later function call. The source of the bug was related to the semantics of the Workbench JSON configuration specification for the case of nested contract creation. Our bug pointed the developers to the ambiguity of the specification and the semantics was resolved in favor of fixing the bug.

All the three bugs have been confirmed by the developers of Azure Blockchain content and samples, and have been fixed in their internal repositories and their internal tests have been updated; some of the bugs (e.g. BazaarItemListing) have been fixed for the external code on github, and others will be updated in one of their future releases\(^8\).

### 7.1.2 Unbounded Verification

Although the Corral based transaction-bounded verification allows us to explore fairly deep into the state space of the contracts, it does not offer any guarantees about arbitrarily large numbers of transactions. Besides, for a correct program, the verification takes longer as the transaction-bound is increased. For example, for the AssetTransfer contract, verifying the fixed version for bounds 6, 8, 10, 12 take respectively 5, 29, 79, 184 seconds.

Once we fix the bugs in the sample contracts, we use the Houdini-based unbounded verification for the contracts. Recall that Houdini requires the user to specify a candidate set of predicates at different program points (procedure entry and exit, and loop heads). A good choice of predicates relies on the property under consideration. For the semantic conformance checking, we observe that most invariants relate to the values of the instance role variables. For example, the smart contract code for Accept in Figure 16 relies on comparisons of msg.sender with various instance role variables such as InstanceOwner and InstanceBuyer. Based on this observation, we generate a set of candidate predicates for the top-level loop in the harness main generated for a contract. Since the only variables in scope at the loop head are the state variables, we consider all possible aliasing and non-aliasing predicates between state variables of instance role type. That is, if \( x \) and \( y \) are state variables of some role type, we generate the following set of candidate predicates \( \{ x = y, x \neq y, x = 0x0, x \neq 0x0, y = 0x0, y \neq 0x0 \} \).

With these candidate predicates, Houdini infers safe inductive invariant that is (i) established by the constructor, and (ii) preserved by the execution of any public function of the contract, and (iii) verifies all the assertions present in the Boogie programs. For all the sample contracts, the invariant inference takes in the order of few seconds. For the case of the AssetTransfer smart contract, we infer the following safe inductive invariant:

\[
(this.\text{InstanceOwner} \neq 0x0) \land (this.\text{InstanceOwner} \neq this.\text{InstanceBuyer})
\]

### 7.2 PoA Governance Contracts

In this section, we describe the application of VeriSol to the PoA Governance contracts that we described earlier in Section 2.2. For these contracts, we check the correctness of assertions already present in the contracts, as well as additional safety specifications. We have applied the bounded verification to these properties and report several injected and previously unknown bugs.

Recall that the PoA governance smart contracts implement the Parity ValidatorSet interface for managing PoA networks. The ValidatorSet has the following interface, where getValidators returns the current set of validators. The event InitiateChange is issued to signal a desire to change the validator set, and a call to finalizeChange to persist the change.

```solidity
contract ValidatorSet {
    event InitiateChange(bytes32 indexed _parent_hash ,
        address[] _new_set);
    function getValidators() constant
        returns (address[] _validators);
    function finalizeChange();
}
```

**Figure 17.** Parity ValidatorSet interface.

In Figure 18, we describe the properties we check for these contracts. Pr1 states that the system should always have at least one admin present; the network is initialized with a single admin at bootstrapping. In case this invariant does not hold, the entire network will enter into a livelock state where any subsequent transaction will revert. Pr2 ensures that no validator becomes orphaned; if an admin is voted out of the system, then all the validators that belong to the admin should also be removed from the list of validators. The developer of the contract informed us that this was one of the known bug that existed in a prior version of the contract that had since been fixed. Pr3 ensures that a validator does not belong to multiple admins; it can lead to unexpected consequences for the governance protocol. Next, recall that the AdminSet is a contract that exposes a set interface to perform constant time operations such as lookup; since Solidity does not permit enumerating all the keys in a mapping.

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\(^8\)As of December 12, 2018
the set is implemented as a combination of an array of members addressList and a Boolean mapping inSet to map the members to true. Pr4 checks the coupling between these two data structures — (i) addressList has no repeated elements, (ii) inSet[a] is true if an only if there is an index j such that addressList[j] == a. For the purpose of verification, we introduced a ghost variable that maintains the index j into addressList for an address a. Finally, Pr5 checks that a call to a helper method deleteArrayElement is only invoked with an element present in the array; this is one of the assertions present in the original contract. Most of the properties except Pr4 require reasoning over all the contracts; Pr4 requires reasoning about AdminSet and Admin contracts only, as it checks the set abstraction exposed by the AdminSet contract.

| Property | Description |
|----------|-------------|
| Pr1      | There is at least one elected admin |
| Pr2      | Every validator belongs to an elected admin |
| Pr3      | No validator belongs to two elected admins |
| Pr4      | AdminSet implements a set |
| Pr5      | deleteArrayElement deletes an element |

Figure 18. Properties for PoA governance contracts.

7.2.1 Bugs Found
We now describe some of bugs that we found using the bounded verifier:

**Pr5.** We describe a sequence of transactions that results in violation of this property. The user issues a transaction to create an instance of AdminValidatorSet. Let x be one of the validators that are added for the first admin (say admin0) at the bootstrapping time. The admin0 issues a transaction to remove the validator x from its list of validators that results in a call to emit InitiateChange event after removing x (using deleteArrayElement) from an internal validator set called pendingValidatorSet; a call to finalizeChange would persist this change. However, if admin0 issues another transaction to remove x, then the call to deleteArrayElement fails the Pr5 invariant, since x has already been removed from the pendingValidatorSet. Although this particular defect results in reverting certain (illegal) transactions, the scenario can be extrapolated to other buggy scenarios where an admin fails to add validators to the network. The bug resulted from a missing modifier that disallows two consecutive calls to InitiateChange without an call to finalizeChange.

**Assert as require.** VeriSol was able to find counterexamples to several Solidity assert in the code that were actually meant to check for certain preconditions. Although both require and assert failures revert an execution, Solidity recommends using assert only for violations of internal invariants that are not expected to fail at runtime. Most of them could have been spotted during a code review as they were present in the first few lines of a public function; most of them checked for access control or avoid adding a duplicate validator or admin already present in the system by performing a lookup in a mapping. However, there were a few asserts that were deeply nested inside private methods and relied on finding an element in an array (e.g. finding if a validator that is a candidate for removal is present in an array in an internal method removeValidatorsInternal).

We note that these previously unknown defects in PoA contracts only lead to safety violations, and as far as we could see, do not lead to security issues that can be exploited by a malicious user.

**Injected bugs** In addition to the bugs above, we were able to use VeriSol to find bugs that existed in prior versions of the contracts. For example, we found a counterexample to Pr2 when the code to cleanup validators after removing an admin was commented out. Similarly, when we commented out a precondition that ensured that the number of validators should never fall below 2, we were able to create a sequence of transactions where admin0 was able to vote itself out from the system, resulting in a livelock.

The unknown bugs have been confirmed by the developer and have been fixed in the latest binary releases; the code on github will be updated in a future release. The complexity of several nested mappings, arrays, and inheritance required precise initialization of arrays and nested mappings to eliminate spurious aliasing between multiple mappings, or arrays at two different indices within a nested mapping. Unlike the Workbench samples, we were only able to scale the bounded verification for the fixed contracts up to a transaction-depth of 4 (13 hours), with depth 3 taking 11 seconds. The huge difference in time can be partially attributed to the difference in the number of procedures inlined by Corral (77 for depth 3 vs 831 for depth 4). For property Pr4 that only involved the AdminSet, we were able to explore transaction depths 5, 6, 7 within 14, 50, 242 seconds respectively.

8 Related Work
In this work, we formalized a specification for smart contracts and described a new formal verifier VeriSol for verifying Solidity smart contracts. In this section, we discuss prior works on ensuring the safety and security of smart contracts. The set of techniques for design and analysis of smart contracts can be roughly categorized into the following groups: (i) static analysis approaches for finding vulnerable patterns, (ii) formal verification based approaches, and (iii) runtime checking, and (iv) high-level languages. In addition, there has been work on formalizing the semantics of EVM in a formal language such as the K Framework [23]. Finally, there
are several works that discuss a survey and taxonomy of vulnerabilities in smart contracts [15, 27, 30].

The set of 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 the use of reentrancy, transaction ordering dependencies, sending ether to unconstrained addresses that may lead to lost ether, use of block time-stamps, mishandled exceptions, calling suicide on an unconstrained address, etc. Tools based on symbolic execution include Oyente [27], MAIAN [30], Manticore [11], and Mythril++ [12]. On the other hand, several data-flow based tools also exist such as Securify [31] and Slither [13]. Finally, the MadMax tool [21] performs static analysis to find vulnerabilities related to out-of-gas exceptions. These tools do not support high-level state machine based specifications or formal specifications, and mostly find instances of known vulnerable patterns (Securify allows users to write their own patterns) and do not provide any soundness or completeness guarantees. These tools cannot be used to analyze the conformance problem for the Workbench contracts, nor can detect the data structure consistency properties such as PR4 for PoA contracts. On the other hand, VeriSol does not reason about gas consumption since it analyzes Solidity code, and also needs the vulnerabilities to be expressed as formal specifications.

Approaches based on program verifiers have been proposed such as based on F* [17] and Zeus [24]. These approaches translate Solidity to the formal verification languages of F* and LLVM respectively. Then verifiers based on F* and LLVM-based constrained horn clause solvers respectively are applied to verify the translated program. Zeus also provides a policy language to allow specifying safety and fairness policies. 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 similarity with VeriSol in translating to an intermediate language and using SMT based solvers to discharge the verification problem. However, there are several differences in the capabilities of the two works. First, the Zeus policy language does not seem to express state machine based specification that we formalize for Workbench. Second, Zeus only provides an informal description of the translation to LLVM, unlike our formal treatment of the translation to Boogie. The memory model in the presence of nested arrays and mappings is not defined; the meaning of array assignments depends on the context (see Figure 13) but such distinction is not made in the translation. Unfortunately, we were unable to obtain a copy of Zeus to try on our examples, making it difficult for us to perform a qualitative treatment on our examples.

In addition to the static analyzers and verifiers, there are approaches for enforcing safe reentrancy patterns at runtime by borrowing ideas from linearizability [22]. Finally, FSolidM [28] provides an approach to specify a smart contract using a finite state machine with actions written in Solidity. Although, there is similarity in the state machine model with the Workbench specification, there is no mention of access control and (as far as we can tell) the actions do not have nested procedure calls or loops. Finally, the tool does not provide any static or dynamic verification support.

9 Conclusion
In this work, we described one of the first uses of automated formal verification for smart contracts in an industrial setting. We provided formal semantics to the Workbench application configuration, and performed automatic program instrumentation to enforce such specifications. We described a new formal verification tool VertiSol using the Boogie tool chain, and illustrate its application towards non-trivial smart contracts verification and bug-finding. For the immediate future, we are working on adding more features of Solidity language that are used in common enterprise workflows, and explore horn-clause based invariant inference. We also plan to apply VertiSol for verifying assertions for Solidity smart contracts present in the Ethereum eco-system.

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A Runtime Checking for Semantic Conformance

We briefly discuss some choices for realizing runtime checks in the presence of a non-deterministic function such as NonDetFunc. We do this by essentially eliminating (quantifying out) NonDetFunc from any expression it appears in. Consider a predicate $\phi$ containing a call to NonDetFunc that appears in either require or assert as part of the instrumentation described above; further let $\phi$ contains $k$ calls to NonDetFunc. We have two such options:

1. Replace $\phi$ with $\phi_0 \land \ldots \land \phi_{k-1}$, where $\phi_i$ replaces the vector of calls to NonDetFunc with the Boolean vector for the integer $i$. For example, if there are two calls to NonDetFunc in $\phi$, then we get $\phi_0$ by replacing the calls with $\{false, false\}$; similarly, we get $\phi_2$ by replacing calls with $\{true, true\}$ respectively.

2. Convert $\phi$ to a negation-normal form $\hat{\phi}$ where a call to NonDetFunc either appears negatively or positively. Next, we replace any negative (respectively, positive) occurrence of the call with false (respectively, true).

The first check is sound but overly conservative as it will fail many require that mention a global role. For runtime checking it is undesirable to revert transactions conservatively in the absence of information about global roles. Since global roles are already being checked by Workbench, we would like to revert a transaction only when we are guaranteed that it fails the specification. In contrast, the second check weakens the predicate $\phi$ and therefore a failure will be a true violation of the intended specification we outlined in Section 4.1. In essence, the second transformation replaces...
calls to the non-deterministic function in \texttt{require} (respectively, \texttt{assert}) with \texttt{true} (respectively, \texttt{false}). We therefore use the second transformation of $\phi$ for installing runtime checks.

Figure 19 describes the actual checks that are inserted for runtime enforcement using the second transformation described above. We show the original expressions in comments. As noted, the (positive) occurrence of \texttt{NonDetFunc} in \texttt{require} statements are replaced with \texttt{true} making the \texttt{require} in \texttt{constructor_checker} \texttt{true}. The (negative) occurrence of \texttt{NonDetFunc} in \texttt{SendResponse_checker} is replaced with \texttt{false} making the \texttt{assert} \texttt{true}. Therefore, for this example, we only check two assertions related to initial state and state transition when invoking \texttt{SendRequest}.

```solidity
// Checker modifiers
modifier constructor_checker() {
    require (msg.sender != tx.origin || NonDetFunc()));
    require (true);
    assert (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 ((NonDetFunc() &&
             oldState == StateType.Request)
             ==> State == StateType.Respond);
    assert (true);
}
```

\textbf{Figure 19.} Modifier definitions for instrumented \texttt{HelloBlockchain} application for runtime checking.