SolSEE: A Source-Level Symbolic Execution Engine for Solidity

Shang-Wei Lin
shang-wei.lin@ntu.edu.sg
Nanyang Technological University, Singapore

Palina Tolmach
palina001@ntu.edu.sg
Institute of High Performance Computing, A*STAR
Nanyang Technological University, Singapore

Ye Liu
li0003ye@ntu.edu.sg
Nanyang Technological University, Singapore

Yi Li
yi_li@ntu.edu.sg
Nanyang Technological University, Singapore

ABSTRACT

Most of the existing smart contract symbolic execution tools perform analysis on bytecode, which loses high-level semantic information presented in source code. This makes interactive analysis tasks—such as visualization and debugging—extremely challenging, and significantly limits the tool usability. In this paper, we present SolSEE, a source-level symbolic execution engine for Solidity smart contracts. We describe the design of SolSEE, highlight its key features, and demonstrate its usages through a Web-based user interface. SolSEE demonstrates advantages over other existing source-level analysis tools in the advanced Solidity language features it supports and analysis flexibility. A demonstration video is available at: https://sites.google.com/view/solsee/.

CCS CONCEPTS

- Software and its engineering → Development frameworks and environments: Software verification and validation.

KEYWORDS

Smart contract, symbolic execution

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ESEC/FSE ’22, November 14–18, 2022, Singapore, Singapore
© 2022 Association for Computing Machinery.
ACM ISBN 978-1-4503-9413-0/22/11...
https://doi.org/10.1145/3540250.3558923

1 INTRODUCTION

Symbolic execution is a program analysis technique which explores multiple execution paths of a program by assigning symbolic—instead of concrete—values to variables. For each analyzed execution path, a symbolic execution engine maintains a path condition—a first-order Boolean formula that describes the conditions satisfied by the branches taken along that path, and a symbolic memory store that maps variables to symbolic expressions or values.

An off-the-shelf constraint solver is typically used to determine the feasibility of each explored path based on the generated path condition formula [3].

Symbolic execution is commonly used to systematically explore the program space and detect property violations as well as security vulnerabilities. In recent years, symbolic execution has been extensively applied on smart contracts—computer programs that run on blockchain and govern billions of dollars [19], which brings paramount importance to the security and correctness of the contract code [27]. Most smart contracts are written in Solidity [1]—a high-level programming language of the Ethereum blockchain platform, which compiles into EVM bytecode for deployment and execution on the blockchain. Listing 1 shows a sample Solidity implementation of a token smart contract. In Ethereum, users interact with a smart contract by initiating transactions that invoke its functions with public or external visibility. Token’s deposit() function (lines 18–20) allows the contract to accept ETH, a native cryptocurrency of Ethereum, and records the deposited amount (msg.value) in a balances mapping entry associated with a transaction sender (msg.sender). The recover() function (lines 21–23) sends all ETH balance of Token to its owner, the address that performed contract deployment (i.e., creation) which involved the execution of a constructor function (lines 14–17). Access control on recover() is implemented using the functionality of the Ownable smart contract (lines 1–10) that Token inherits from (line 11). Thus, the signature of recover() (line 21) contains an invocation of the onlyOwner modifier (lines 7–8). The modifier adds additional behavior, such as a prerequisite (line 7), to a function body which replaces “_;” in a modifier code (line 8). The transfer of ETH (line 22) is performed via Ethereum’s built-in .call.value()() function call.

Given a smart contract written in Solidity, SolSEE symbolically represents the (storage/memory) configuration of the smart contract and executes each statement based on the operational semantics of Solidity [1, 8]. Our developed operational semantics for Solidity supports many important features including inheritance, modifiers, ETH transfer, and others. During symbolic execution, this representation is directly used to determine satisfiability of the generated path constraints using Z3 SMT-solver [4]. To facilitate efficient exploration of interesting smart contract behaviors in a realistic setting, SolSEE supports user-defined harness function that specifies the sequence of function calls to be analyzed symbolically. The harness definition follows exactly the syntax and semantics of Solidity, which is intuitive and easy to use for developers.

Listing 2 illustrates how to define a harness in SolSEE. The _MAIN_.contract serves as the entry point (similar to the main()
function in C), and the harness is defined as a constructor of it. The harness contains the declaration of a symbolic variable which should come with the prefix "$" (line 4) and the creation of the Token smart contract which involves transferring a symbolic amount of ETH to this contract (line 6). The harness also includes a call to the Token's `recover()` function, which is executed successfully, because the call is invoked by the _MAIN_ contract, satisfying the onlyOwner modifier. Lines 10–12 show the definition of a fallback function—another Solidity-specific feature supported by SolSEE. Here, the fallback function is invoked when ETH is transferred to a smart contract, i.e., upon the execution of the “call.value()()” in Listing 1, line 22. Since the execution of `recover()` succeeds, the assertion in Listing 2, line 8, should always be satisfied. The assertion in a harness contract can also be used to declare a property, which can be constructed using Solidity operators and variables available in the _MAIN_ contract. In addition, SolSEE allows assumptions to be specified in terms of smart contract’s variables using the ___assume()___ statement. For example, line 5 in Listing 2 indicates that the analysis will only be concerned with the paths where the ETH balance of the _MAIN_ contract is not less than the amount of ETH being sent to Token upon its creation.

**Related Work.** Most of the existing symbolic execution tools for smart contracts operate on bytecode (rather than source-code) level, which retains limited semantic information about the smart contract and, hence, complicates reasoning about high-level properties of a smart contract. Most of these tools focus on detecting well-known vulnerabilities based on a certain pattern appearing in smart contract bytecode, e.g., OYENTE [14], MYTHril [17], MAIAN [18], etc. MANTICORE [16] is a bytecode-level symbolic execution engine which supports property-based symbolic execution and provides users with some control over the state exploration process. While MANTICORE also offers a GUI plugin, it visualizes low-level bytecode instructions, which are difficult, for a developer, to match with their original Solidity source code statements. Meanwhile, existing source-level tools for Solidity smart contracts offer limited support for Solidity features and/or do not allow customization of the function call sequence and the environment to be analyzed. For example, VERISMART [23] is a smart contract verifier that is also used in SmartTest [22] to perform symbolic execution of smart contracts. These tools do not precisely handle the execution of fallback functions and inter-contract function calls, which constitute essential functionality of smart contracts. Inter-contract function calls are also not analyzed precisely by SMTChecker [2, 5]—a built-in verifier within the Solidity compiler. Two other source-level tools, solc-verify [7] and VeriSmart [30], translate Solidity code into Boo-gie intermediate language, which can introduce discrepancy between the analyzed code translation and original Solidity semantics. In addition, they also lack support of certain Solidity functionality and do not allow customization of the harness function and analyzed environment, which leads to multiple false positives reported by these tools, as shown in Sect. 3. ESBMC-SOLIDITY [24] translates Solidity into an intermediate representation of ESBMC, which may introduce semantics discrepancy, and it does not support certain Solidity features such as polymorphism and inheritance.

**Contribution.** In this demonstration paper, we present SolSEE, a user-friendly symbolic execution engine for analyzing source code of one or several interacting smart contracts written in Solidity. The key features of SolSEE can be summarized as follows:

- **Precise operational semantics.** SolSEE symbolically represents the configuration of smart contracts and executes each program statement based on the exact operational semantics for Solidity version 0.5.
- **User-defined harness function.** SolSEE facilitates analysis and debugging of smart contracts by allowing users to define the harness function to control the function call sequence for verification. SolSEE detects and reports unsigned integer under- and overflow and checks the validity of assertions, which can be used to specify custom high-level properties of the analyzed smart contracts.
- **Smart contract debugging.** With the symbolic paths generated by SolSEE, users can debug smart contracts. Users are able to visualize the execution details corresponding to the symbolic paths step by step in a Web user interface.

2 METHODOLOGY

In this section, we introduce the design and usage of SolSEE.
2.1 Design

SolSEE was implemented with 7,521 lines of C++ code and currently supports smart contracts written in Solidity v0.5. Figure 1 demonstrates an overview of the tool architecture. SolSEE takes one or more smart contracts and a harness function as input, which should be provided using a Web UI. In its backend, SolSEE uses a Solidity compiler solc to generate the AST for the given contracts. Then, SolSEE symbolically executes each statement by traversing the AST based on the Solidity operational semantics. The (storage/memory) configuration of the smart contract is encoded symbolically as Z3 types [4]. Also, the SMT solver is used to discharge the feasibility queries of symbolic paths and validity queries of assertions. The latter helps prove or disprove the user-defined properties encoded as assertions in the harness function. SolSEE does not bound the loop iterations and may unroll the loops infinitely. This can be addressed by requesting the user to provide a loop invariant or generating one automatically [11, 12], which is left for future work.

The frontend of SolSEE is based on the Remix IDE [21], which is implemented as a ReactJS [20] application. The frontend of SolSEE communicates with its backend via restful APIs. SolSEE also provides a debugging capability and helps developers examine the operation of a smart contract by visualizing its (symbolic) execution in detail. Its usage is presented in Sect. 2.2.

The symbolic execution module of SolSEE supports a majority of the Solidity language features, including the intra- and inter-contract function calls, multiple inheritance, library support via the “using…” for construct, low-level function calls such as “.call.value()()” with the associated fallback mechanism, modifiers, and many others. Similarly to the Solidity compiler, SolSEE automatically generates getter functions for public smart contract variables of elementary types. Similar to other source-level analyzers for smart contracts [7, 23, 30], SolSEE does not support inline assembly. SolSEE also introduces a supplementary __assume__( ) statement that can be used to specify assumption conditions when verification is performed, as shown in Listing 2, line 5.

In Solidity, require() and assert() have different semantics, although in Solidity, both functions could lead to a transaction with all its effects on the state being reverted, if the required/asserted condition is not satisfied. In Solidity, require() is used to check a condition that is expected to fail occasionally, e.g., a guard condition on function input arguments. Thus, should the expression enclosed in require() evaluate to false, SolSEE rollbacks all effects of the transaction on the smart contract state. We consider each statement in the harness function as one transaction. Semantics of assert() correspond to its purpose in Solidity: it is used to check conditions that should never evaluate to false. SolSEE stops execution and reports a violation if the asserted condition is violated.

In addition, SolSEE also reports possible integer under- and overflows—a common issue in Solidity smart contracts, which heavily utilize unsigned integers to store important information such as token balances [28]. SolSEE takes a modular arithmetic approach to handling unsigned integers of various sizes (from uint8 to uint256): it models them using Z3 integers by range assertions to follow the semantics of unsigned integer arithmetic operations in Solidity. Although using bitvectors is another popular approach to model unsigned integers, it has been shown to have scalability issues. To model one- and multi-dimensional arrays and mappings, SolSEE relies on the array theory.

The symbolic execution process of a smart contract is guided by the harness function provided by the user to orchestrate the interactions with the analyzed smart contract(s). During path exploration and assertion/property checking, SolSEE relies on Z3 [4], an SMT-solver, to resolve constraints. Using a harness function makes symbolic analysis performed by SolSEE highly configurable, which is necessary to effectively and efficiently analyze complex smart contract code in a realistic setting, which is demonstrated by our evaluation shown in Sect. 3. Additionally, a harness can also be used to encode properties about the execution trace or smart contract invariants in a form of assertions. To optimize tool performance, smart contract variables in a harness or analyzed smart contracts are assumed to have concrete (default) values unless they are declared as symbolic. Ethereum balance of a harness (_MAIN_) smart contract is assumed to be symbolic too.

2.2 Usage

SolSEE has both a command-line interface and a GUI. Given a file that contains Solidity source code of all smart contracts to be analyzed, e.g., Token.sol, symbolic execution via SolSEE can be invoked using the following command:

./SolSEE-symexe-main ./Token.sol

Figure 2 shows the Web GUI of SolSEE. The UI is built on the Remix IDE framework and allows users to do the following:

1. Develop smart contracts in the “Smart Contract Panel”.
2. Customize the _MAIN_ contract serving as the harness for analysis and verification in the “Harness Contract Panel”.
3. Click on the “Symbolic Execution Button” to trigger the symbolic execution of SolSEE to obtain a set of symbolic paths;
4. Visualize the detail of each symbolic path in the “Result Panel”;
5. Click on the “Debugging Button” for further debugging.

The detailed description of each step can be found in the Appendix.

In SolSEE, we consider a small-step operational semantics. Thus, if a statement includes several function calls, users need to separate function calls into different statements. For example, the following statement with two function calls: a = f() + g(); can be rewritten into three statements: t1 = f(); t2 = g(); a = t1 + t2. While it is not convenient in syntax, it forces the developer to explicitly specify the order of function evaluation, which is not specified in the official Solidity document [5]. This enforcement eliminates ambiguity for analysis and verification, especially when...
both \( f() \) and \( g() \) have side effects on state variables, and different execution orders may lead to different results.

### 3 EVALUATION

In this section, we demonstrate the capabilities of SolSEE and compare it with other source-level tools for Solidity smart contracts. The tools we compare with include solc-verify \([7, 25]\), VeriSol v0.1.5 \([15, 30]\) and its modified version used in SmartPulse \([26, 29]\) (denoted as VeriSol-SP in Table 1), VeriSmart \([10, 23]\), and SMTChecker \([5]\) included in solc v0.5.11. All these tools claim to process a \( \text{uint} \) array in \( \text{NewBytesArray} \), while variables of type \text{struct} are not supported by SMTChecker (witness: Structs).

In addition, our results show that the analyzed tools report potential violation of numerous assertions, which are, in fact, false positives (e.g., solc-verify supports most Solidity features used in experimental smart contracts, but in many of them it reports all assertions as potentially failing). We attribute this fact to the lack of harness function support and missing or incorrect handling of Solidity language features and their semantics. For example, none of these tools, except SolSEE and SmartPulse, correctly implement C3 Linearization that Solidity uses to decide the order in which methods are inherited in the presence of multiple inheritance (witness: MultipleInheritance). Besides, while VeriSmart and SMTChecker process some of our smart contracts correctly, they can only do so if all the functionality is stored in a single contract, i.e., no external function calls allowed. In terms of the speed of analysis, our tool is as efficient as other tools used for comparison.

In closing, SolSEE has a unique source-level GUI that visualizes the symbolic execution process, which facilitates debugging.

### 4 CONCLUSION

This paper presents SolSEE, a user-friendly symbolic execution engine for smart contracts written in Solidity. SolSEE offers a large degree of customization which enables highly effective symbolic analysis of real-world smart contracts under realistic settings. Our evaluation shows that SolSEE is useful in analyzing interacting smart contracts in an efficient manner based on the user-defined harness function and assertions. SolSEE also facilitates analysis and debugging of Solidity smart contracts through a source-level visualization of symbolic execution in a GUI.

### 5 DATA AVAILABILITY

The binary of SolSEE and experimental smart contract dataset used for the evaluation are available on our website \([13]\). The release of SolSEE source code is pending approval from the funding agency.

#### Table 1: Evaluation results.

<table>
<thead>
<tr>
<th>Smart contract</th>
<th>Feature</th>
<th>SolSEE</th>
<th>VeriSol</th>
<th>VeriSol-SP</th>
<th>solc-verify</th>
<th>VeriSmart</th>
<th>SMTChecker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Token</td>
<td>Token implementation</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>MultipleModifiers</td>
<td>Two modifiers applied to one function</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>FallbackFunction</td>
<td>Fallback function execution</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>GetterFunction</td>
<td>Auto-generated getter functions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>SafeMathLibrary</td>
<td>Using library functions on uint</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>MultipleInheritance</td>
<td>Multiple inheritance via C3 linearization</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Structs</td>
<td>Arithmetic operations on struct</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>NewBytesArray</td>
<td>New dynamic memory array of bytes32</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>UintOverflow</td>
<td>uint8 overflow detection</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Revert</td>
<td>Proper handling of revert() in a function</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>

* The code is analyzed correctly only in the absence of external function calls; † Non-default modular arithmetic mode must be used.
REFERENCES


A SOLSEE WALK-THROUGH

In this section, we demonstrate the usage of SolSEE with a step-by-step walk-through on the analysis and debugging of smart contracts. The basic workflow consists of (1) the writing of smart contracts and the harness, (2) contract analysis and verification, and (3) contract debugging.

Step 1: Implementing smart contracts and the harness. Figure 3 shows the user interface (UI) which allows editing smart contract code including the target contract and the (harness) _MAIN_ contract. By reusing the Remix IDE framework, SolSEE also allows the user to upload the smart contracts via the UI. Consider the Solidity file assert.sol that is shown in Fig. 3. This file contains the definitions of two smart contracts: Bank and _MAIN_. SolSEE considers a variable symbolic if its name is prefixed with “$”. This variables are, then, used to explore multiple symbolic paths of a smart contract simultaneously. As shown in Fig. 3, the _MAIN_ contract has two symbolic state variables: $a$ and $b$.

Figure 3: The writing of smart contract and _MAIN_ contract.

Step 2: Analysis and verification of smart contracts. Figure 4 shows the user interface of the analysis and verification of smart contracts. Users can click on the button “SolSEE xxx.sol” to start the symbolic analysis. The obtained results are shown as a set of symbolic paths as well as the corresponding verification result. In Fig. 4, there are two symbolic paths and both of them satisfy the assertion “assert(c + d > c)”. Users can click on the “Debug” button to trigger the concrete execution of each symbolic path.

Figure 4: The analysis and verification of smart contract.

Step 3: Debugging of smart contracts. Figure 5 shows the debugging user interface. Users can observe the concrete execution of a smart contract path statement by statement. The program context shown in the UI consists of “Statements”, “Solidity State”, “Solidity Locals”, and “Function Stack” boxes. “Solidity Locals” and “Solidity State” demonstrate the most recent values of local and state variables along each statement, respectively. To facilitate the debugging, users can also set breakpoints and then let the debugger jump to those breakpoints.

Figure 5: The debugging of smart contract.

Summary. We have demonstrated the main usage and key features of SolSEE. The tool’s website is currently hosted at http://xyz.smartcontractsecurity.org/solsee.